Novel ways to Probe Dark Sector at Colliders

Deepak Kar
University of Witwatersrand

4th World Summit on
Exploring **The Dark Side**
of the **Universe**
7-11 novembre, 2022
La Réunion, France

Prologue

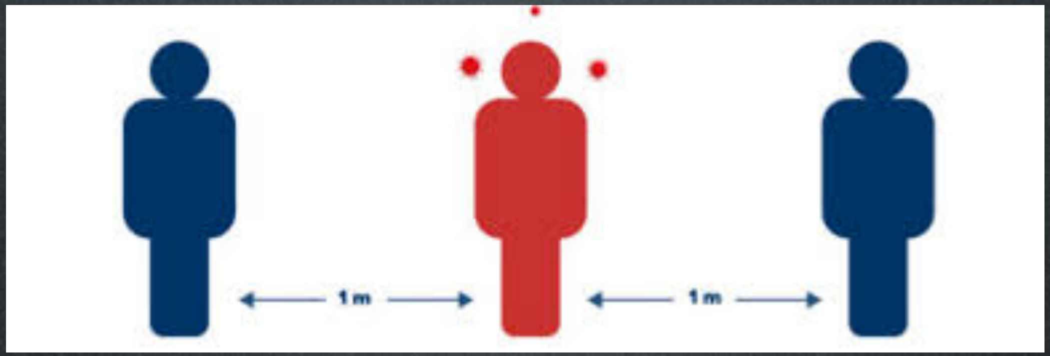
Novel?

Unexplored signatures ignored so far ...


All we see is this


.... whereas this
may be hiding!

Principle of (social) distancing in object reconstruction!



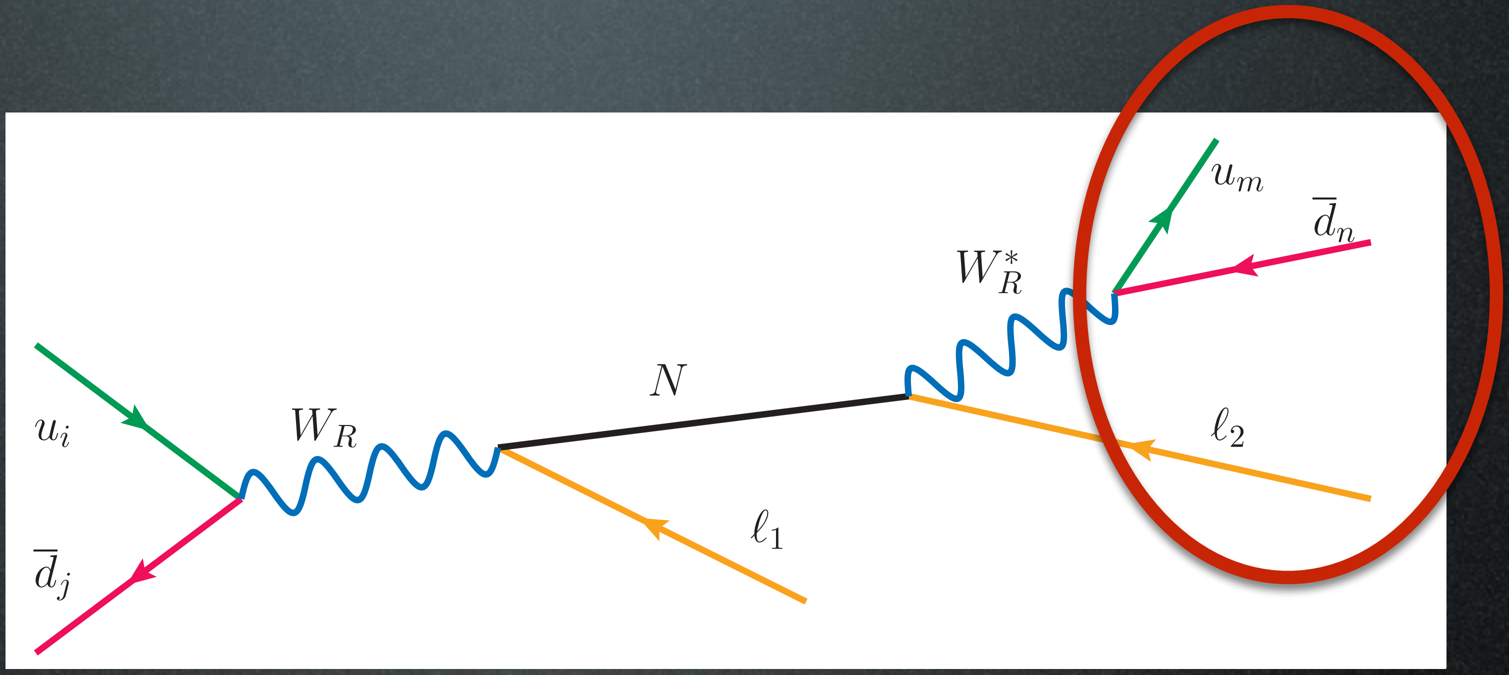
we followed it before it was cool ...

Principle of (social) distancing in object reconstruction!

- Object reconstruction algorithms run independent of one another
- Same detector signature can result in multiple objects being reconstructed, results in fakes!
- Electrons as jets, and vice versa (jets contain neutral pions!)
- Overlap removal to address the double counting

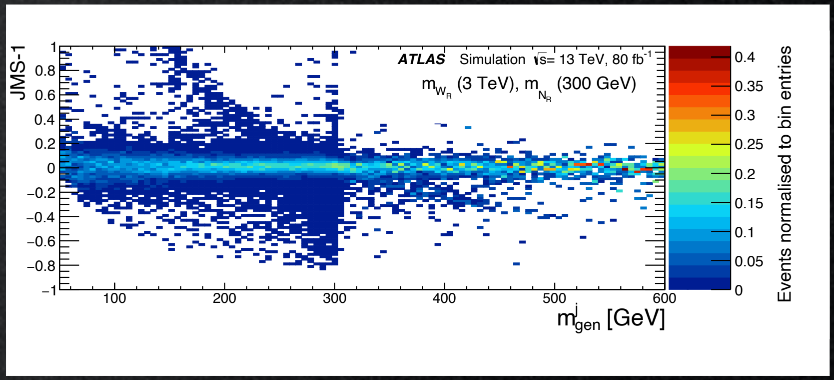
But who ordered that?

Covered in the talk
By Antonia Struebig
on Monday



Boosted heavy neutrino search:
electron in a large-radius jet

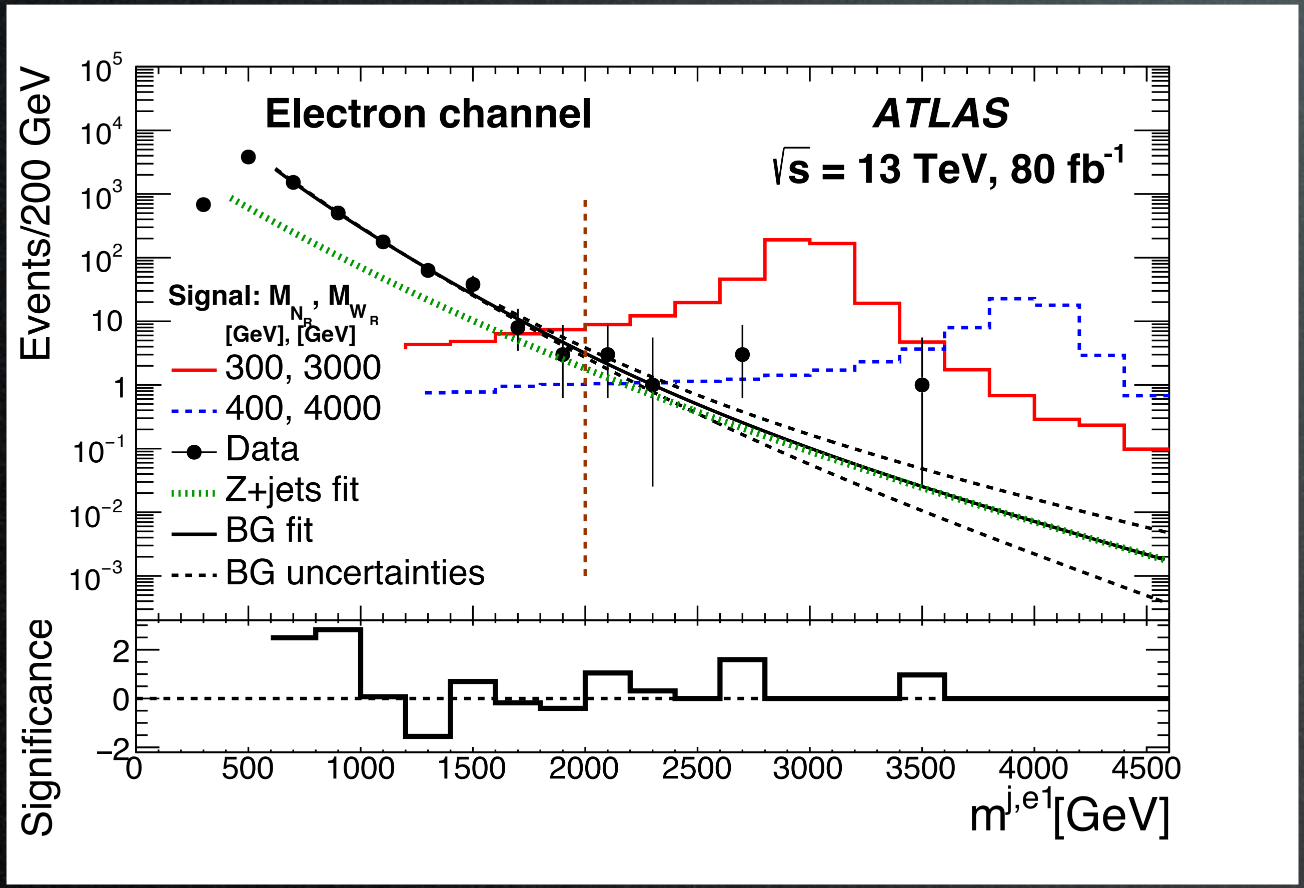
In ATLAS electron reconstruction assumed no nearby real jet, and applies implicit isolation requirement. That reduces signal efficiency, and the presence of such a jet affects the electron performance numbers



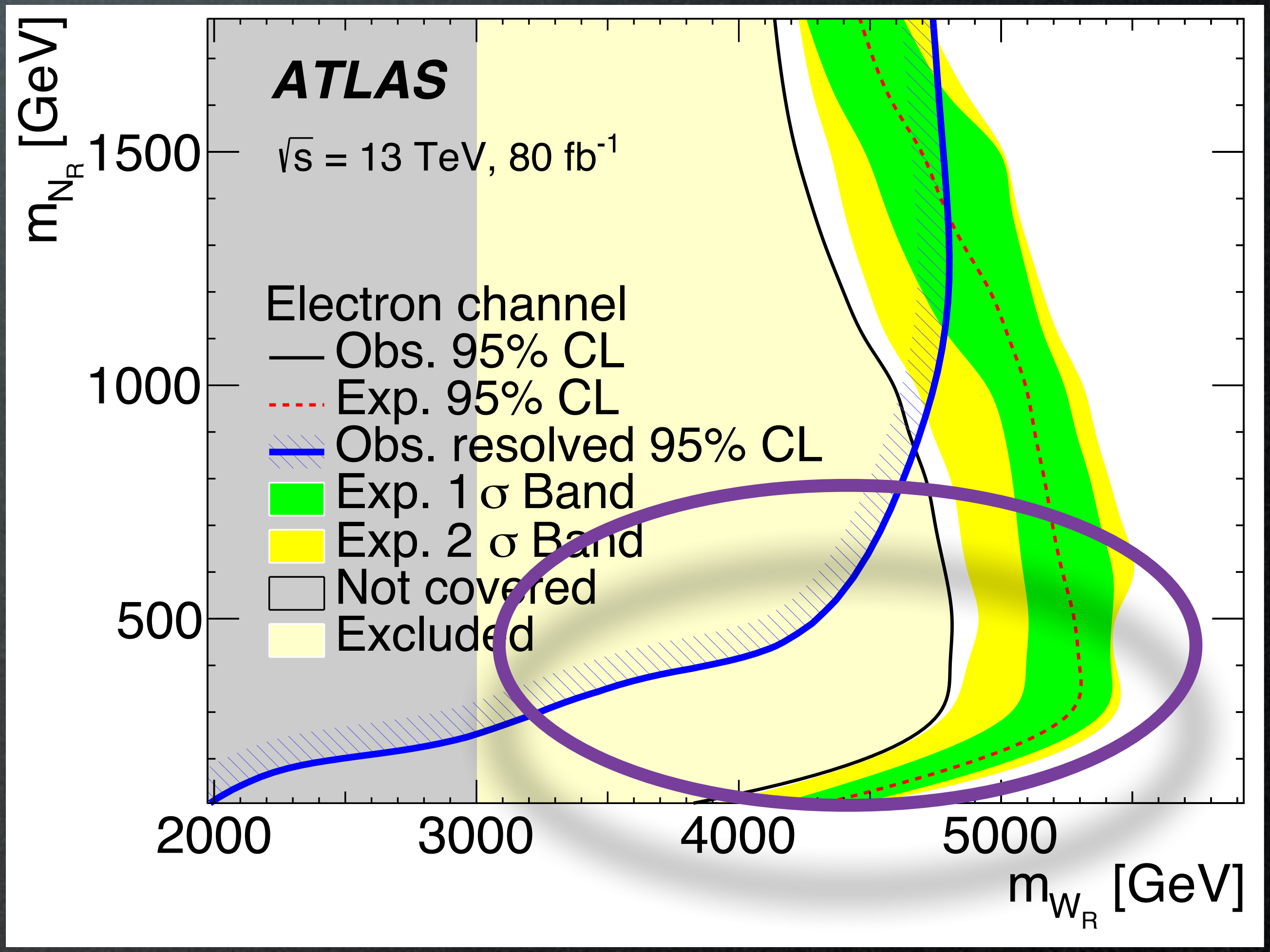
JMS well modelled

Phys. Lett. B 798 (2019) 134942

Boosted Heavy Neutrino Search

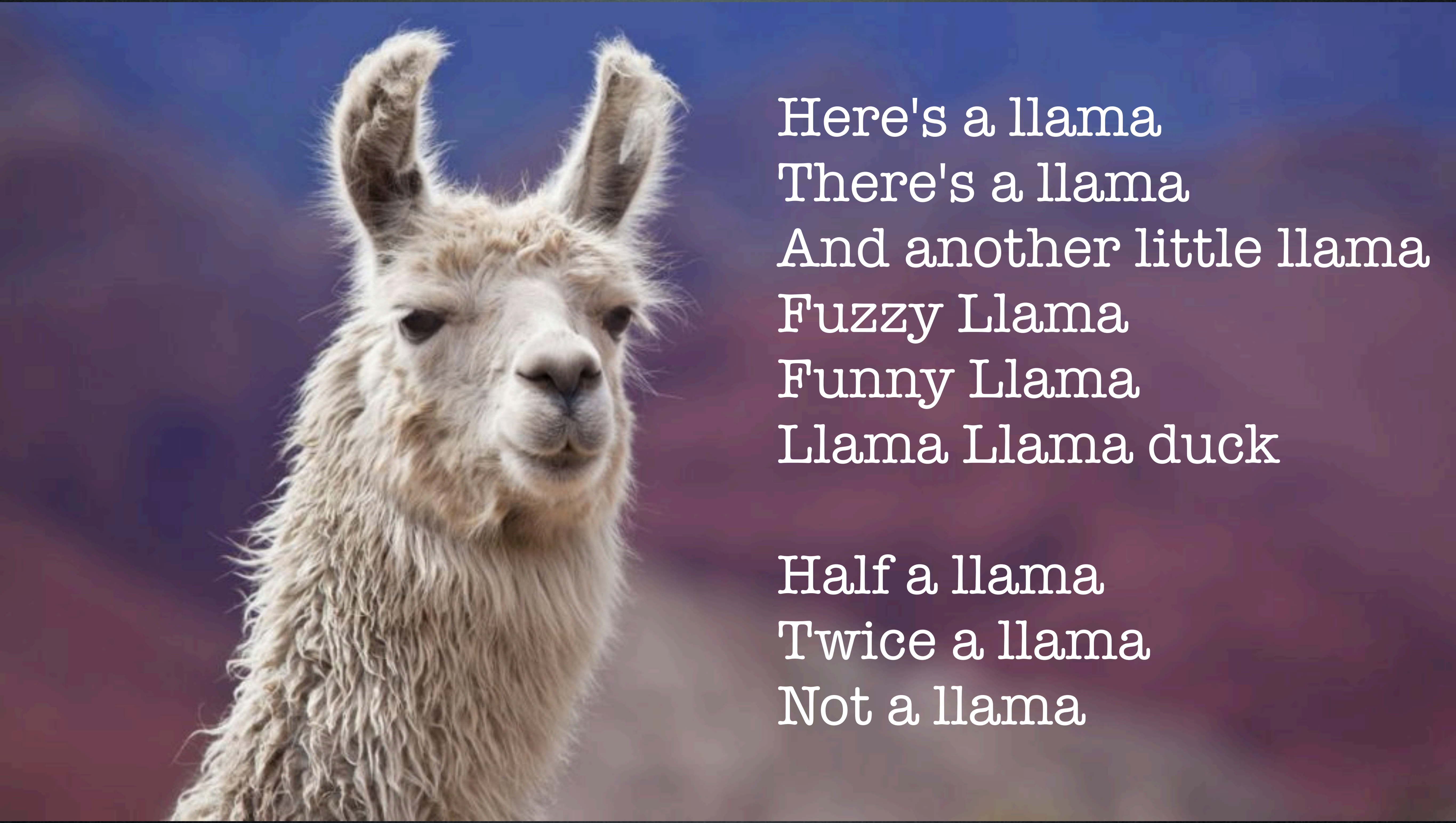


Very small background
due to the extreme topology

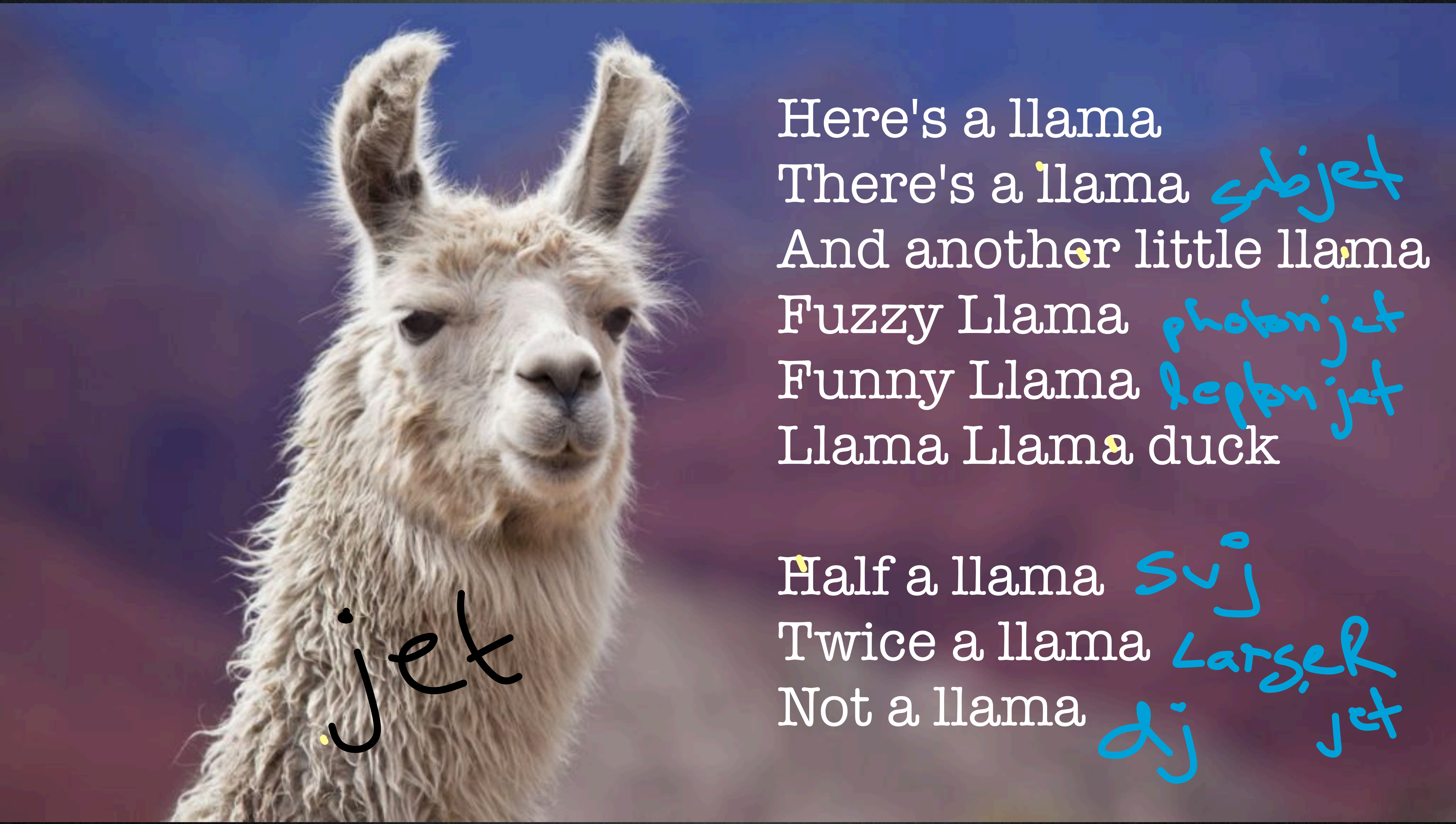


Complementary strength
from resolved analysis

Why stop at electrons?

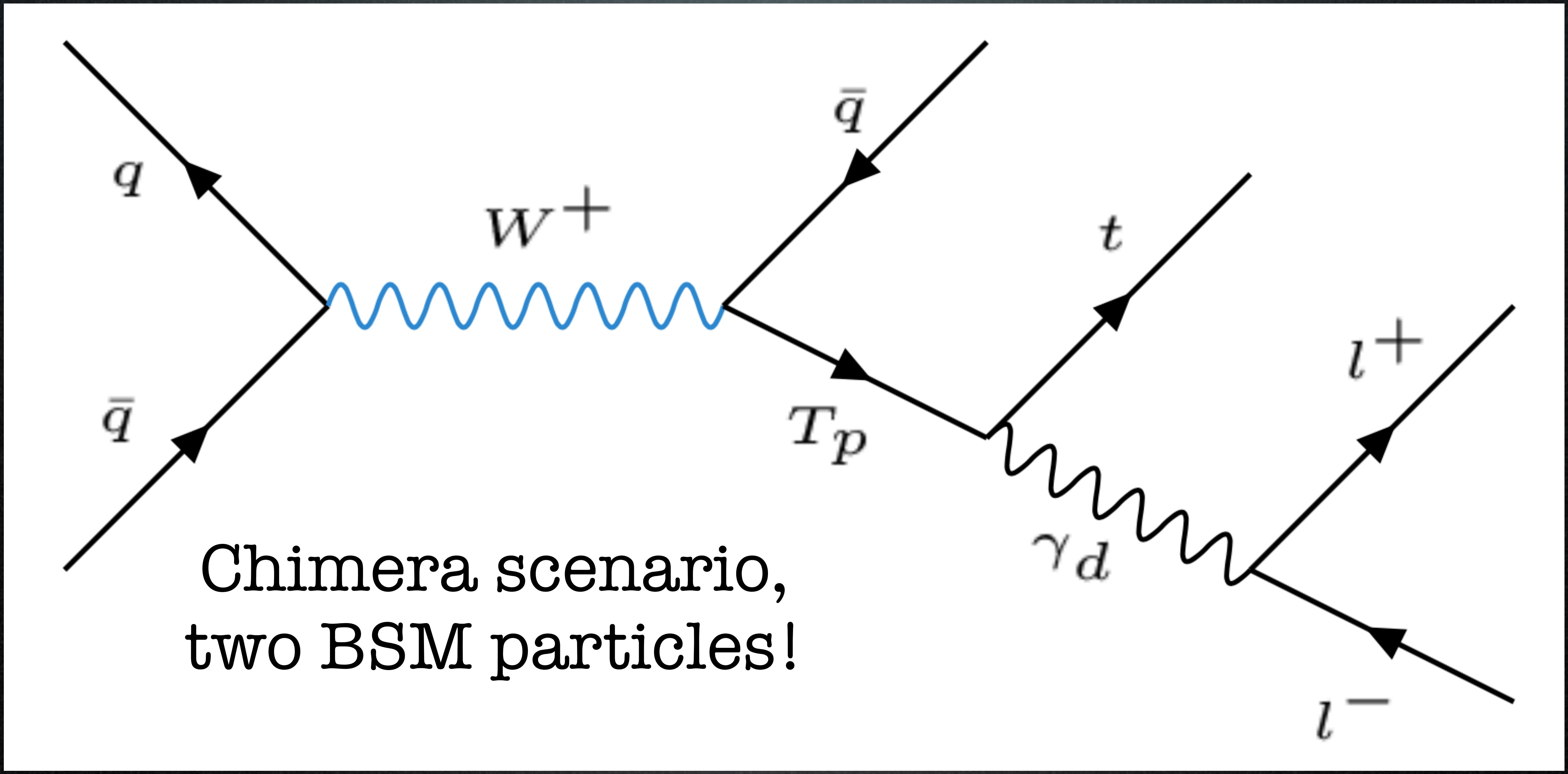

Here's a llama
There's a llama
And another little llama
Fuzzy Llama
Funny Llama
Llama Llama duck

Half a llama
Twice a llama
Not a llama


Here's a llama
There's a llama
And another little llama
Fuzzy Llama
Funny Llama
Llama Llama duck
Half a llama
Twice a llama
Not a llama
subjet
photonjet
leptonjet
Larger jet
jet

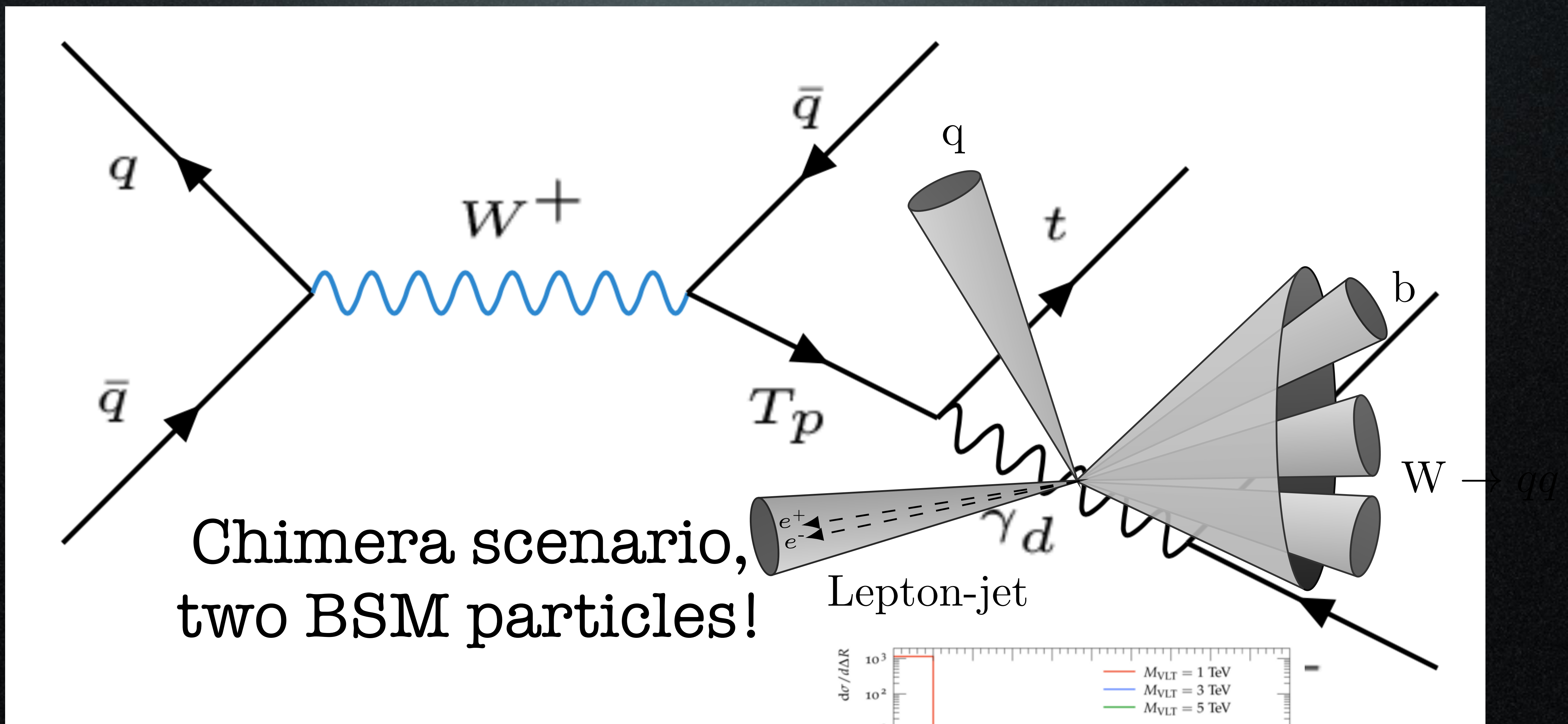
Lepton jet from dark photon

... with Karien du Plessis, M. Flores, S. Sinha, and H. van der Schyf, SciPost Phys. 13, 018 (2022)

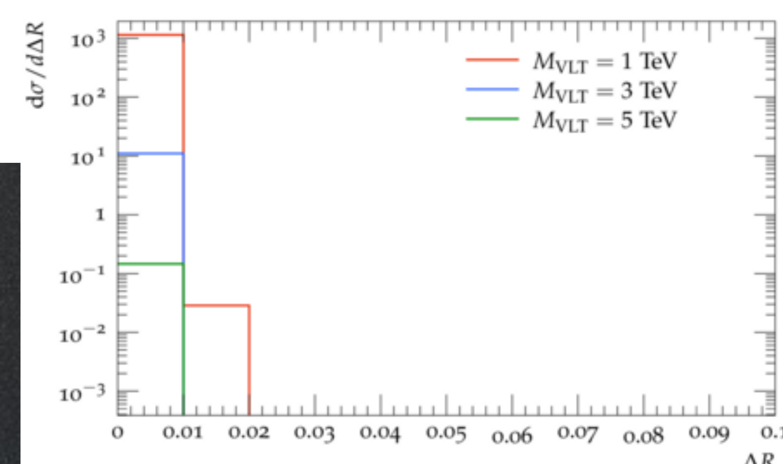


SciPost Phys. 13, 018 (2022)

Lepton jet from dark photon



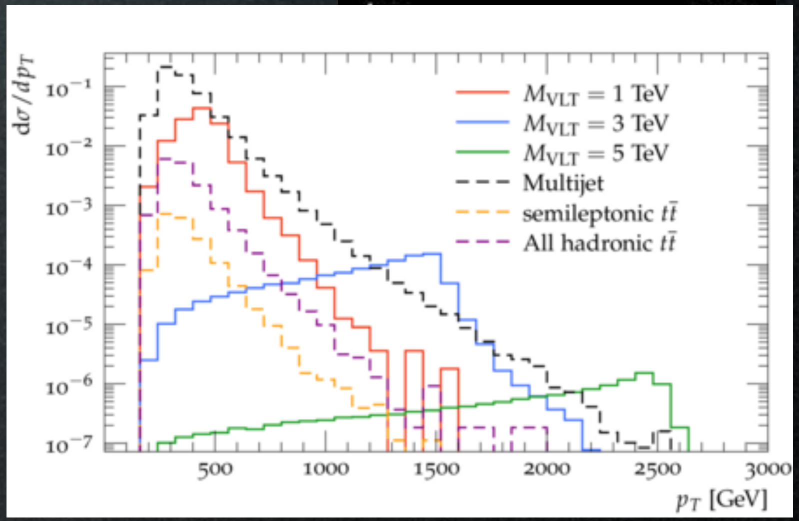
Chimera scenario,
two BSM particles!

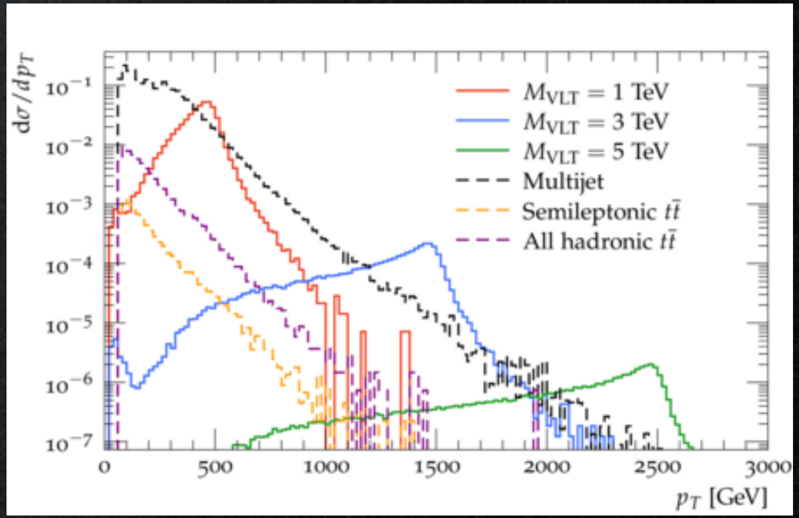


For dark photon masses < 200 MeV

SciPost Phys. 13, 018 (2022)

Search Strategy (hadronic channel)



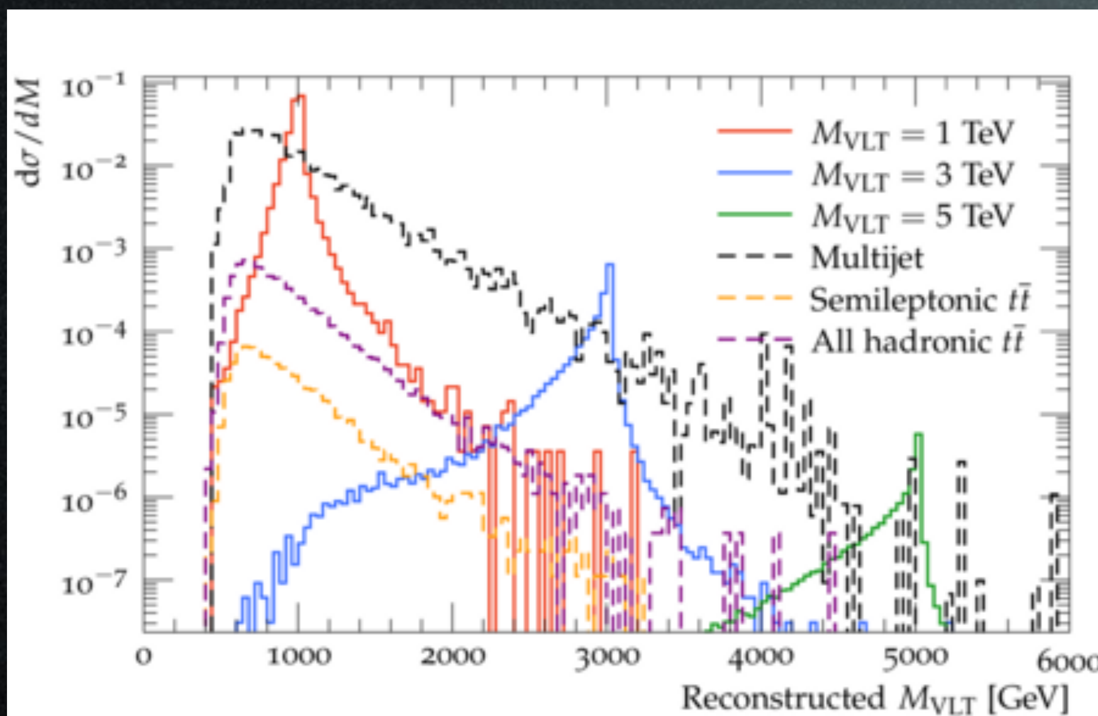


- Light lepton jet and heavy top jet, both boosted!
- Electron multiplicity -> misleading
- Cannot reconstruct the lepton jet mass
- Largest background: multijet

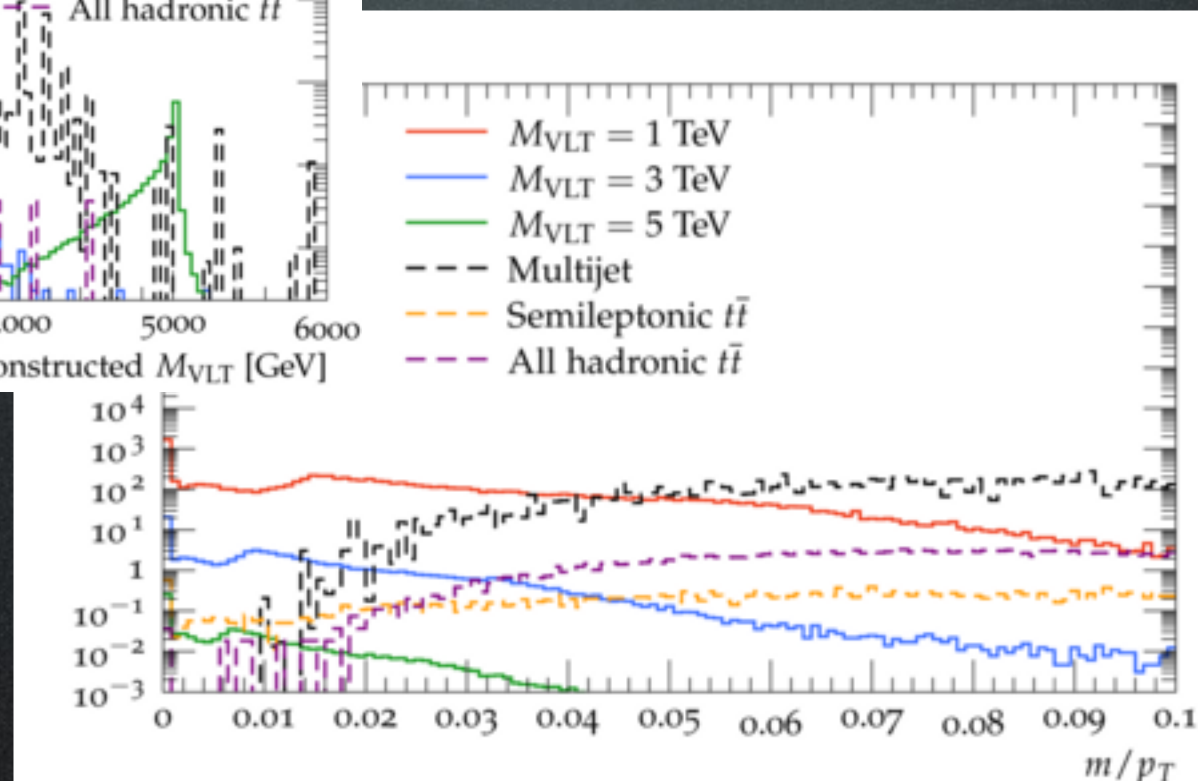
Not covering the lepton channel result, but mostly same considerations apply

SciPost Phys. 13, 018 (2022)

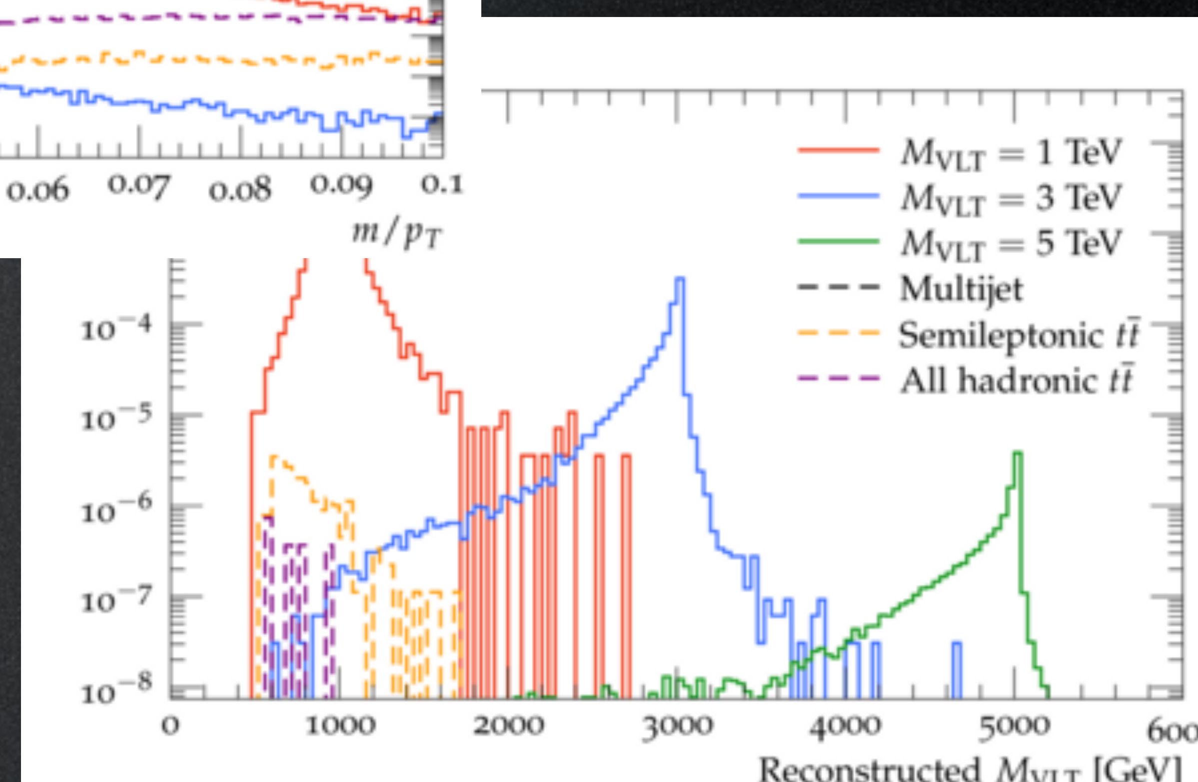
Then what?



Lepton jet m/p_T ratio is a strong discriminant

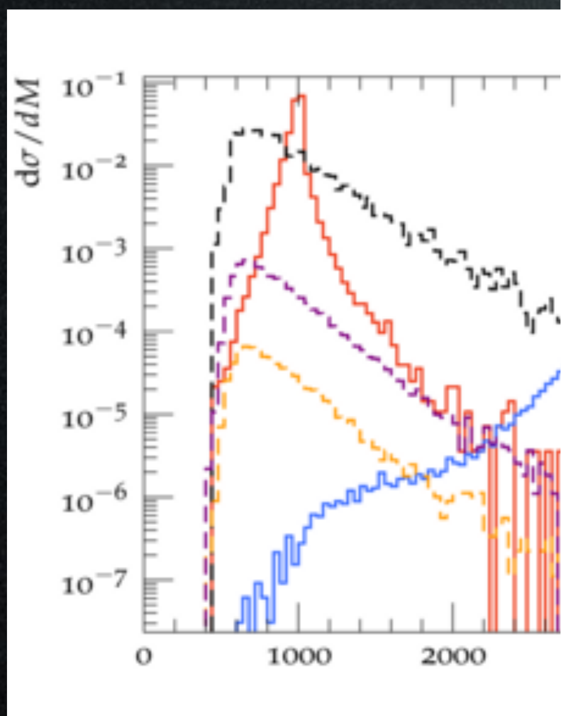


Results in an almost zero background search!



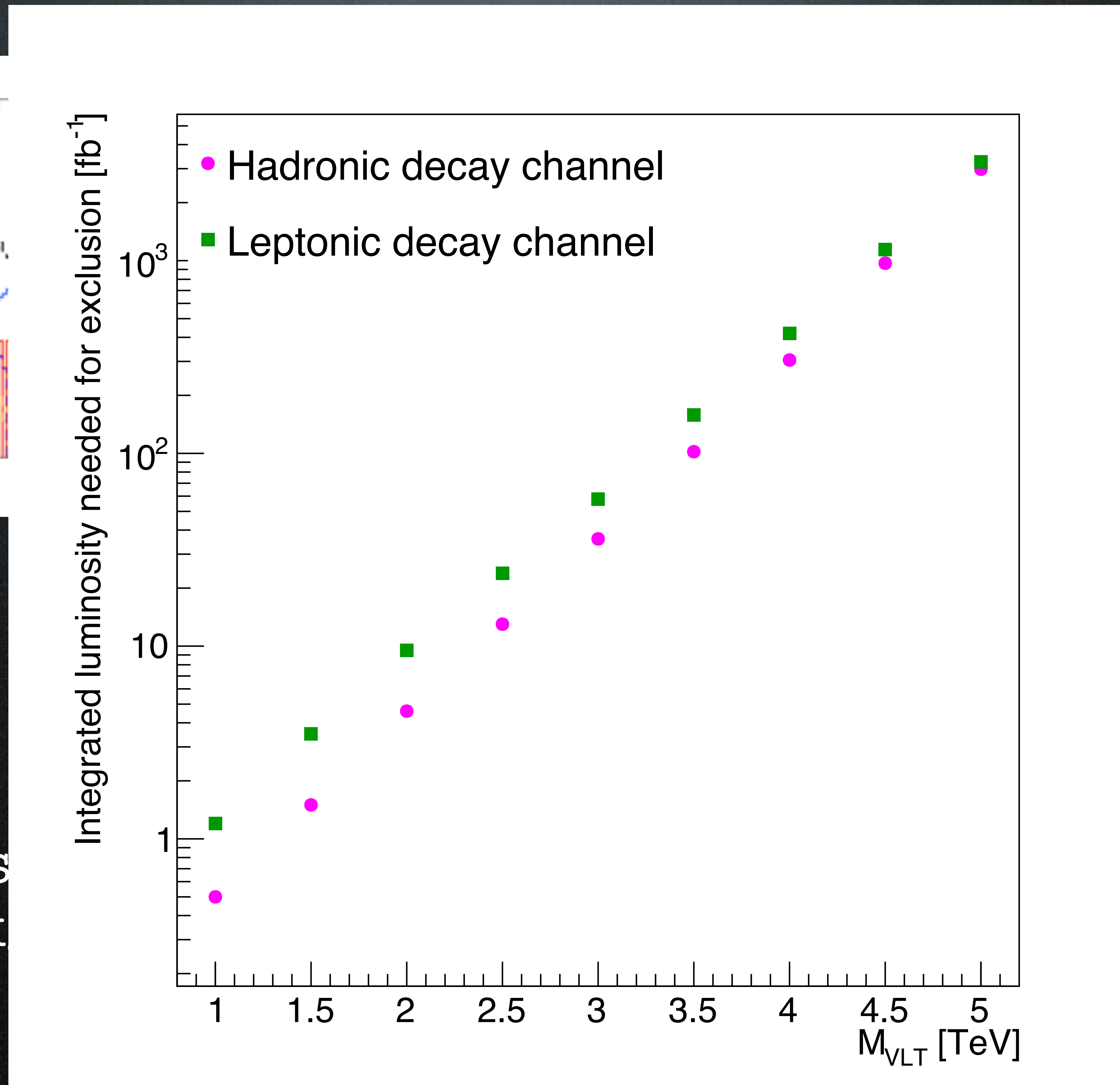
SciPost Phys. 13, 018 (2022)

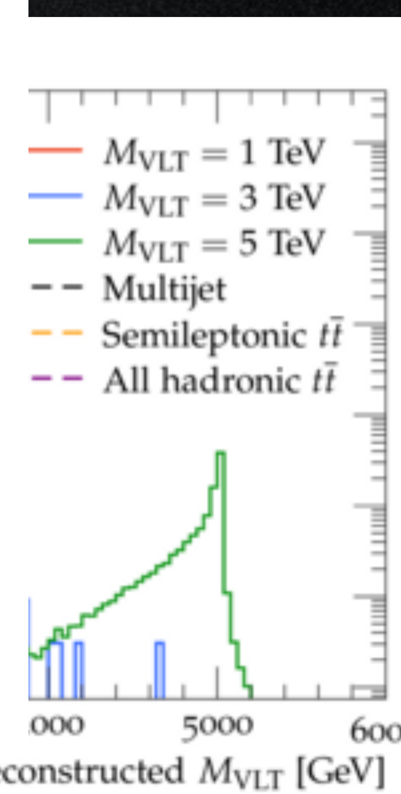
Then what?



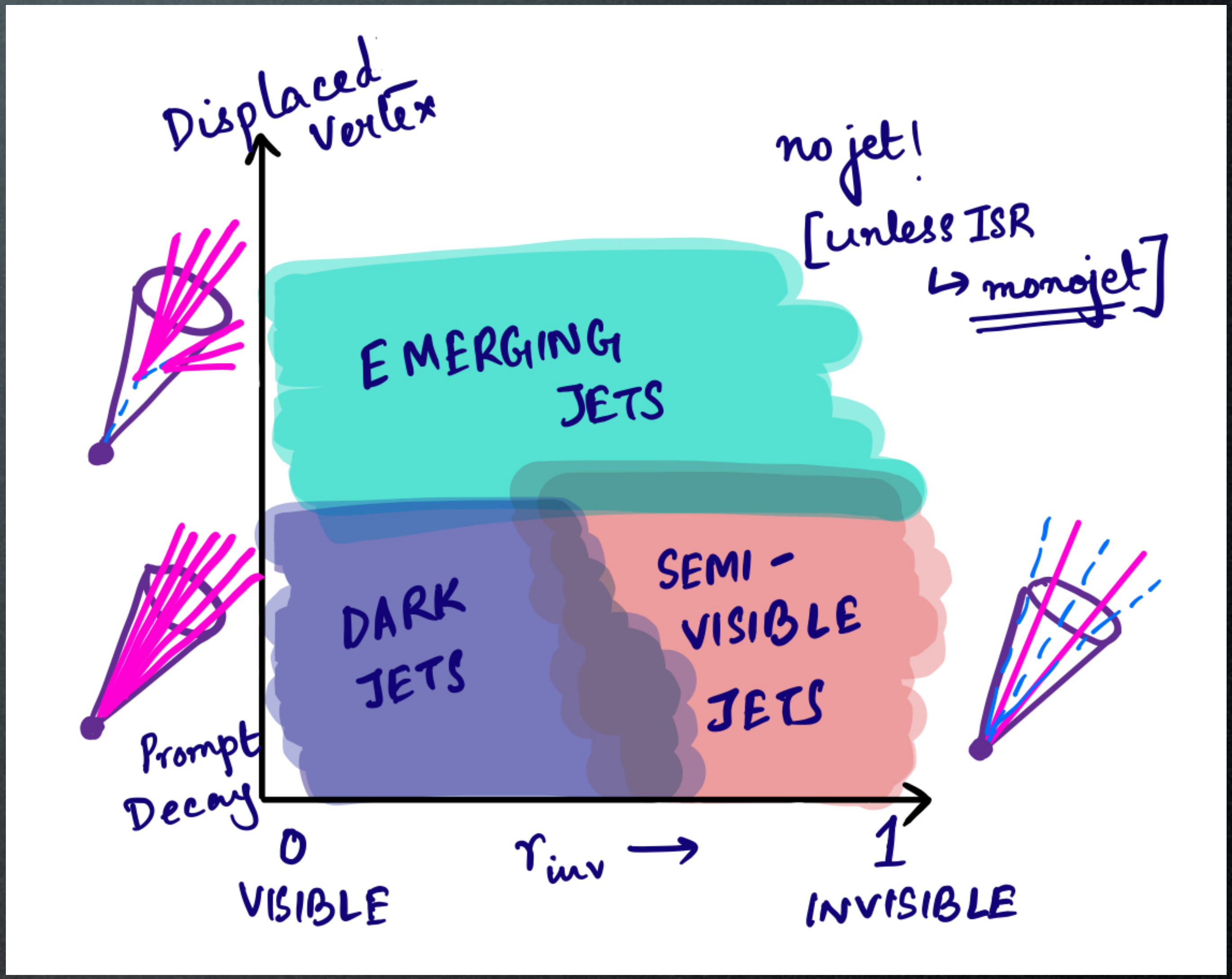
…s a

Results
back…





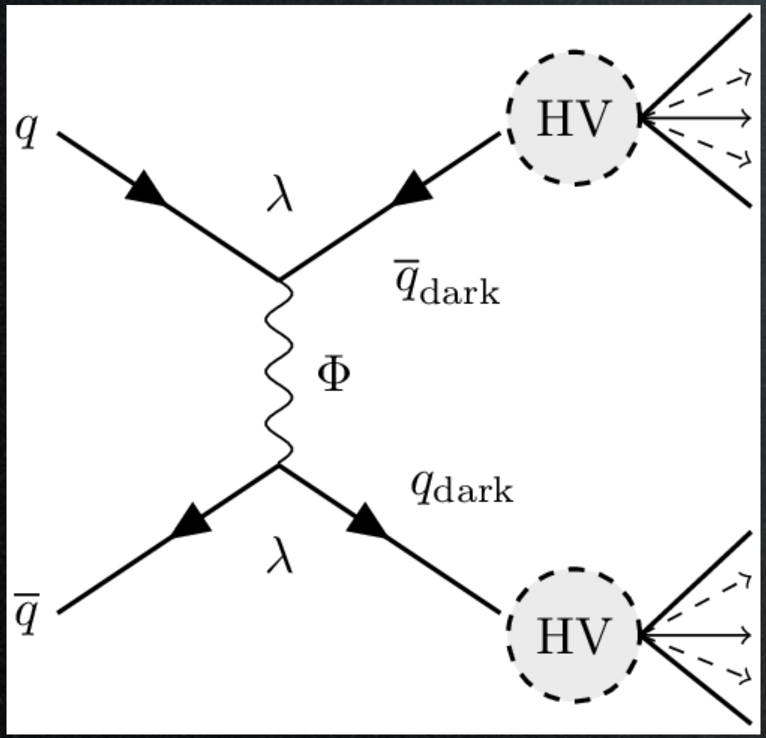
Dark and semi-visible jets



ATLAS result covered in the talk by Sukanya Sinha on Wednesday: ATLAS-CONF-2022-038

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)

A quick detour: the topology and the challenges for SVJ

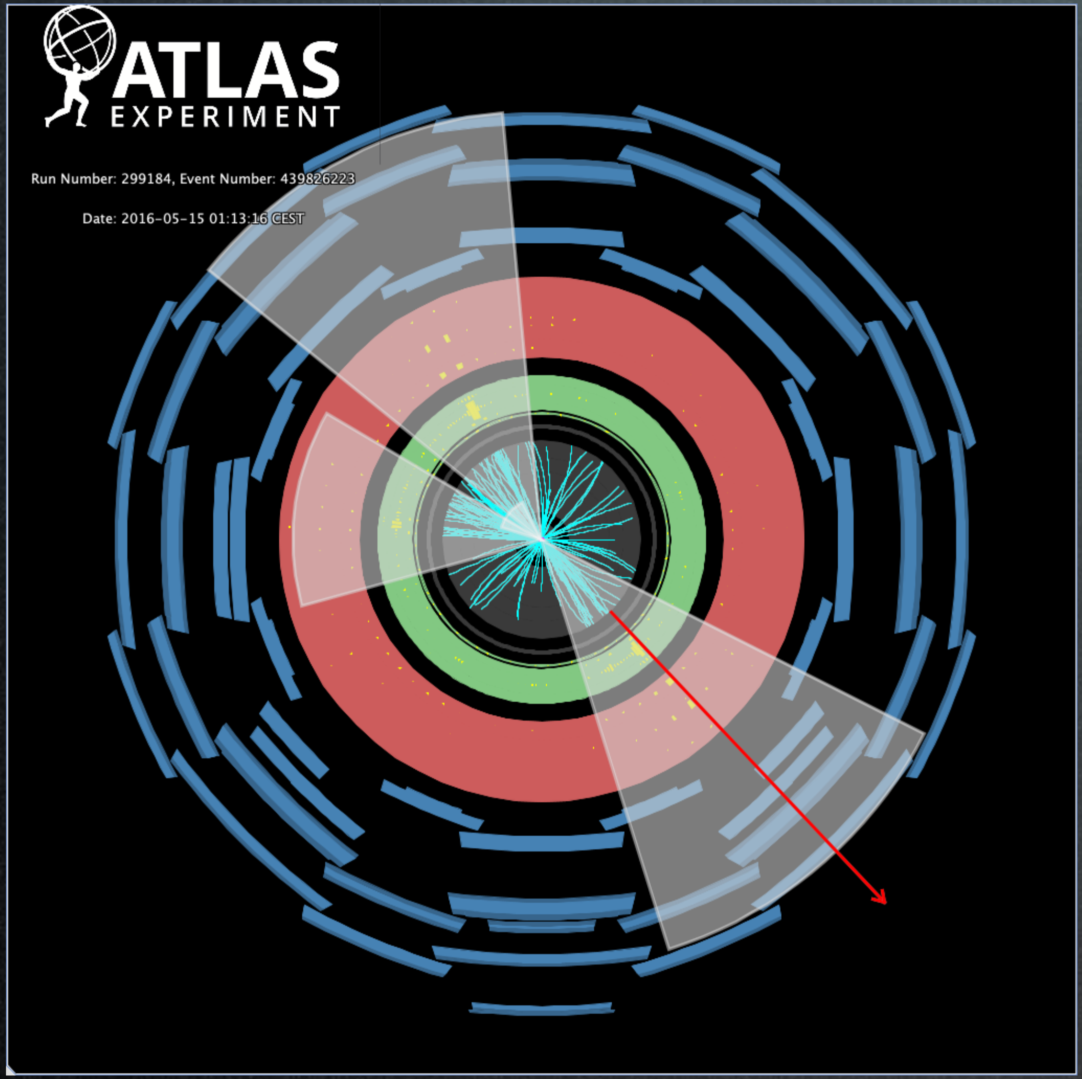


ATLAS-CONF-2022-038

Same fraction
of dark hadrons
In each jet

Why any MET?

A quick detour: the topology and the challenges



A real event will look like this!

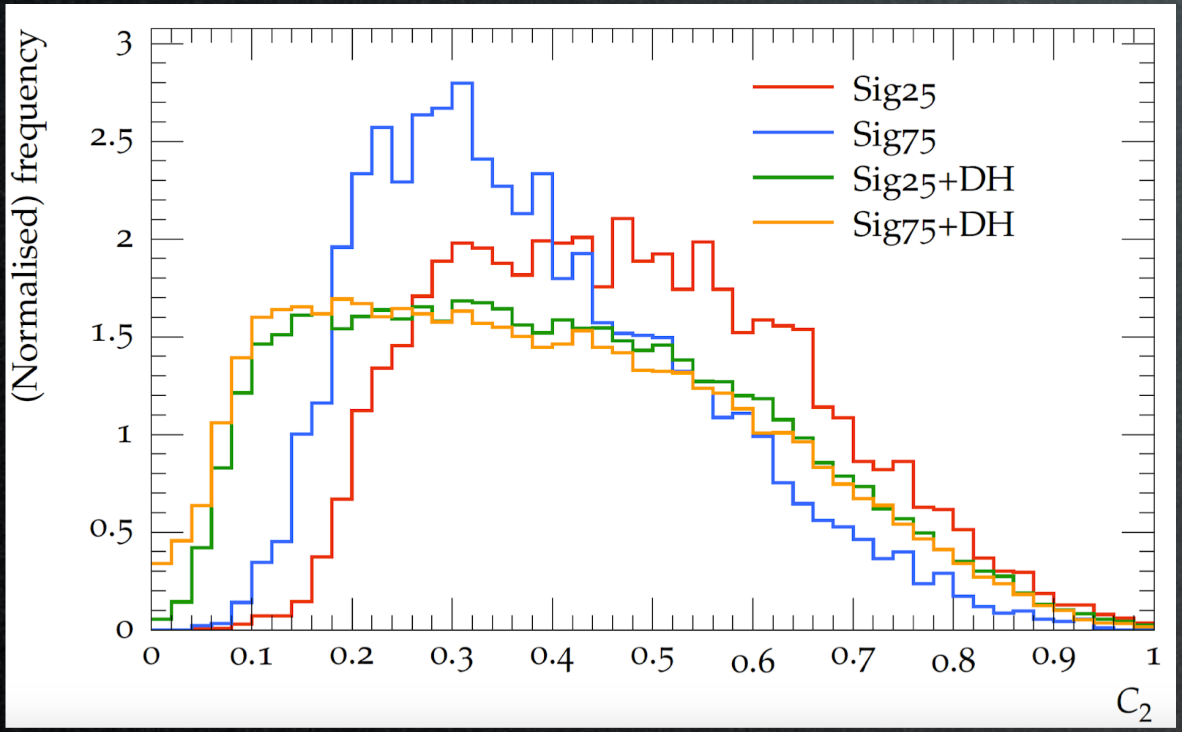
Quantum fluctuations, and boost by extra jets

Therefore MET

Not detector noise? Not an easy answer, but check mismodelling in different multi jet VRs of lower H_T or MET thresholds

Exploratory study using jet substructure observables

... with S. Sinha, SciPost Phys. 10, 084 (2021)



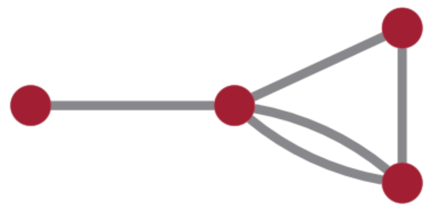
Substructure becomes less two-pronged with visible and dark hadrons in them, and the absence of the dark hadrons create the two-pronged structure → The substructure is created by the interspersing of visible hadrons with dark hadrons.

Can use ML algorithms, jet images …

Use of Energy Flow Polynomials

... with A. Buckley and S. Sinha, arXiv:2209.14964

- A complete IRC-safe linear basis:



$$= \sum_{i_1=1}^{M} \sum_{i_2=1}^{M} \sum_{i_3=1}^{M} \sum_{i_4=1}^{M} z_{i_1} z_{i_2} z_{i_3} z_{i_4} \theta_{i_1 i_2} \theta_{i_2 i_3} \theta_{i_2 i_4}^2 \theta_{i_3 i_4}$$

JHEP 04 (2018) 013

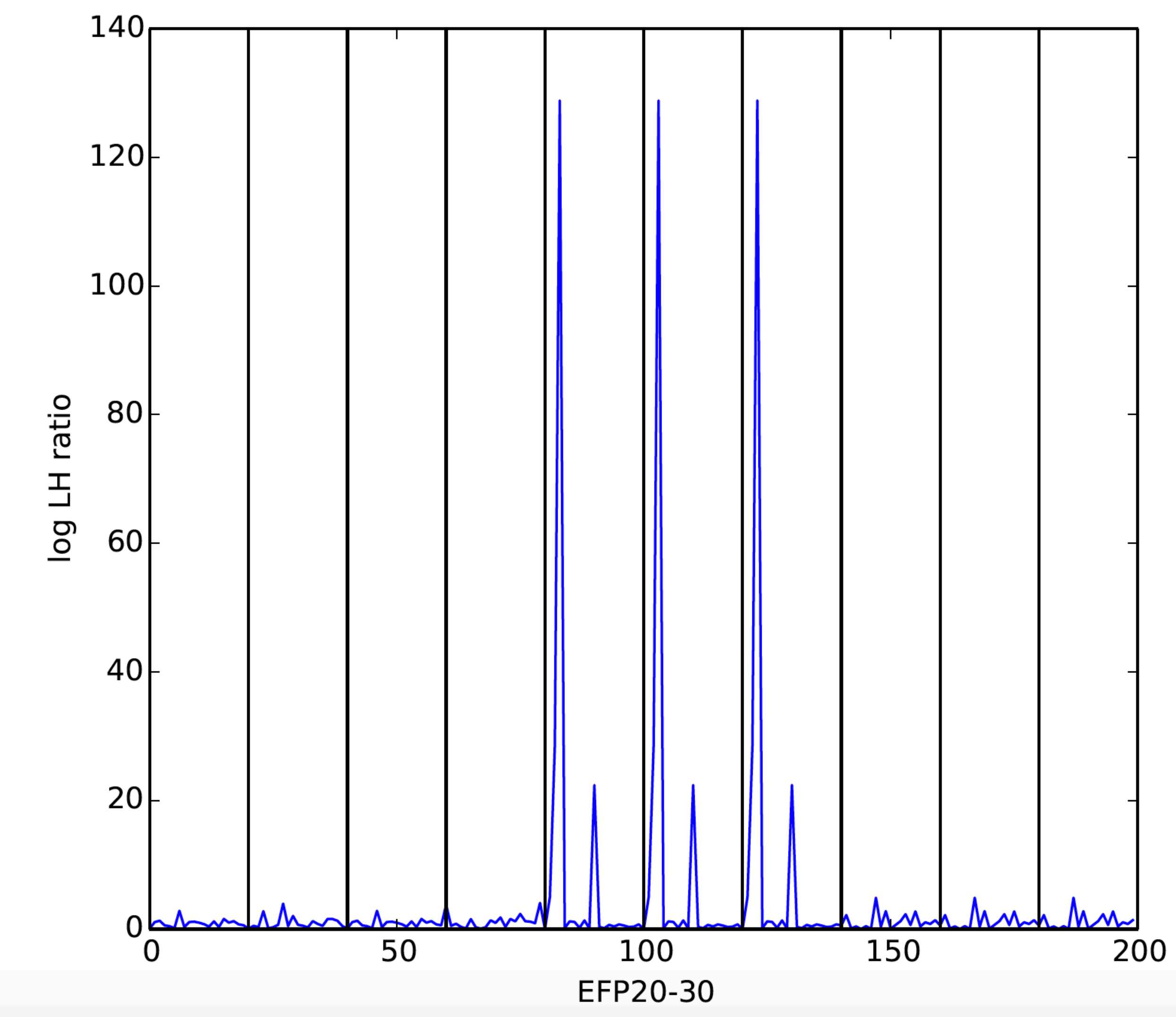
- Use some sensible truncation scheme

- Check if they offer any discriminating power (and compare to usual JSS observables)

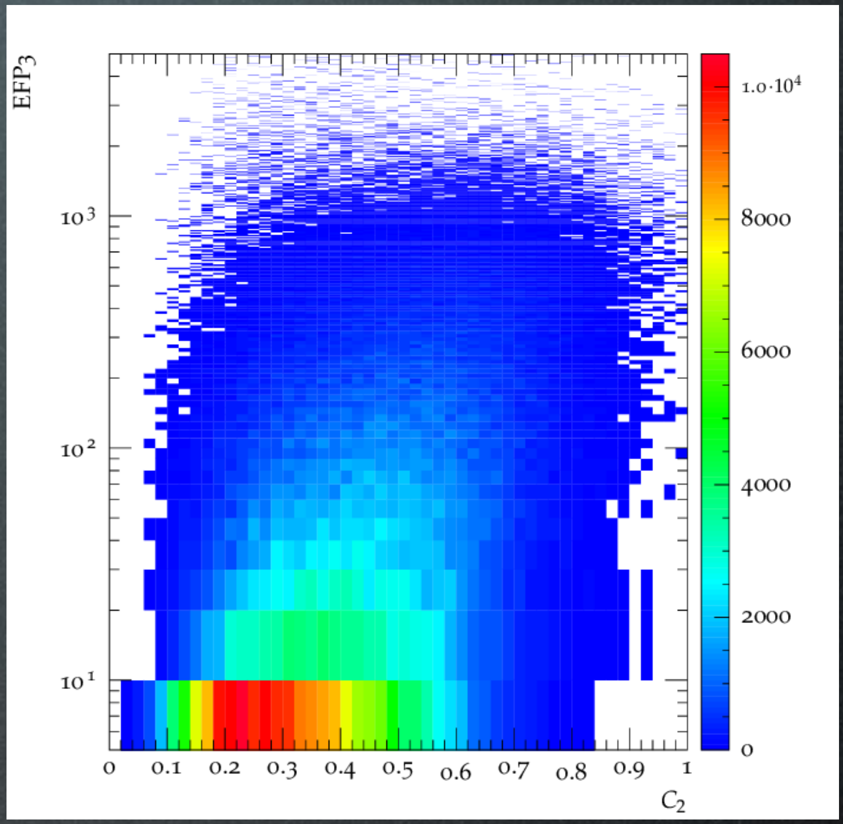
- ... and possibly construct new (JSS-like) observables!

arXiv:2209.14964

Use of Energy Flow Polynomials



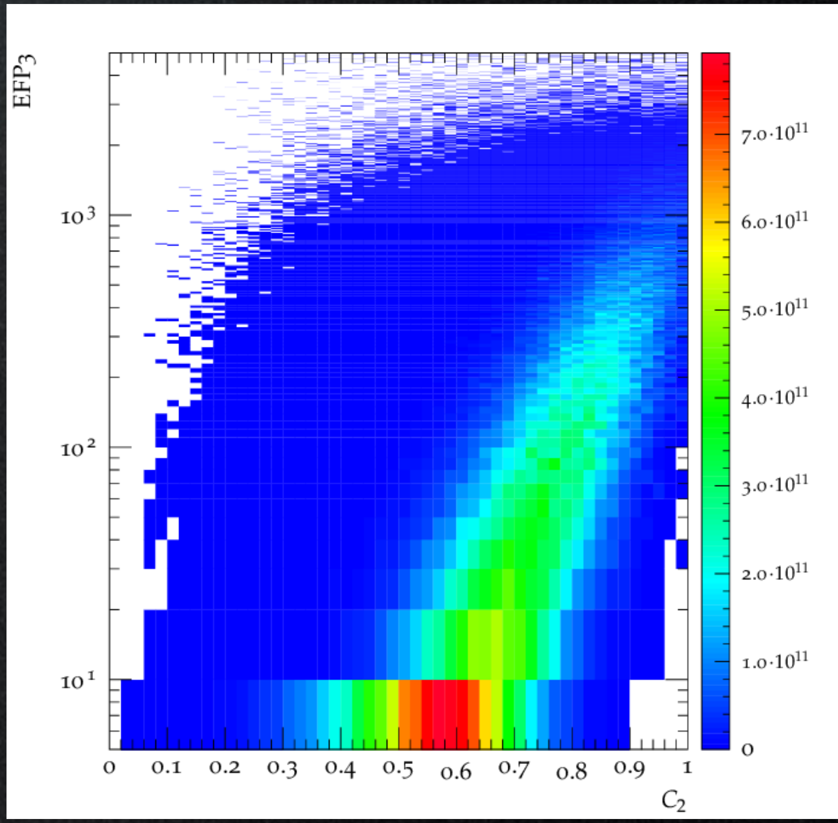
Certain EFP diagrams seem to have some bins that multijet background does not populate at all, in which the SVJ signal dominates…



Signal

... but strong correlation with standard JSS observables

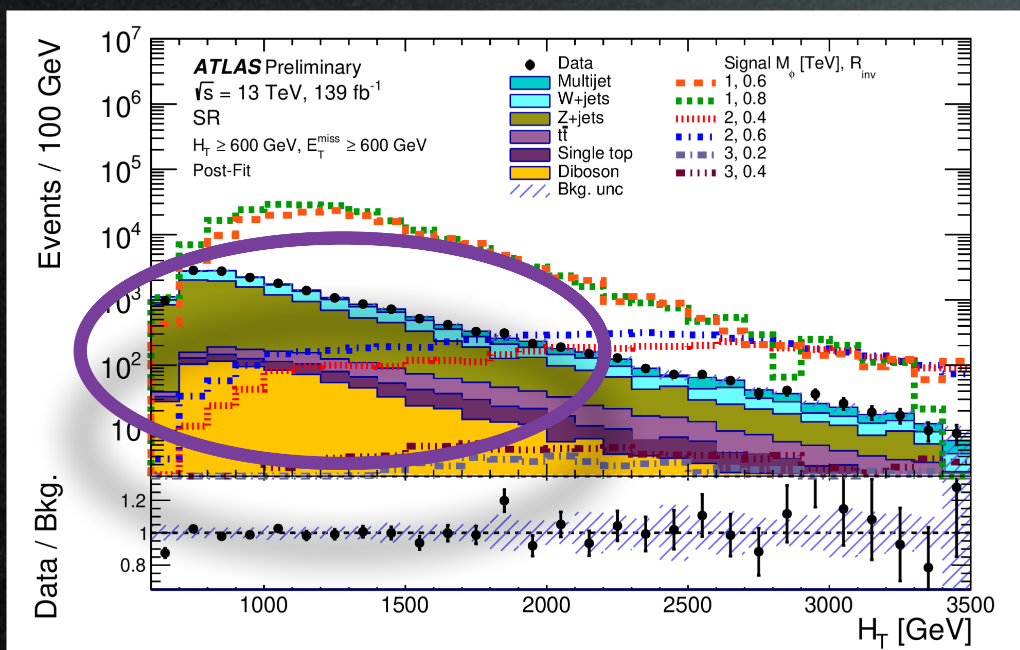
BG



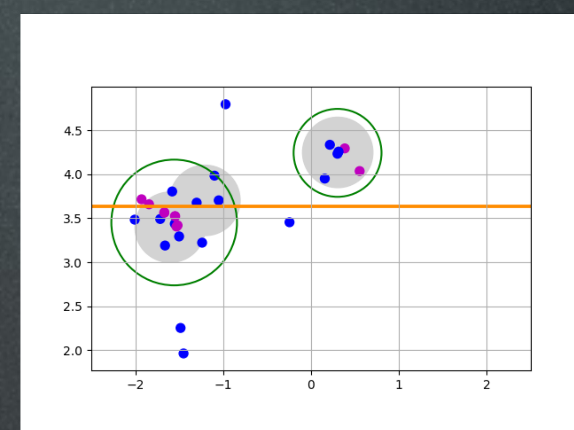
SVJ with Heavy Flavour

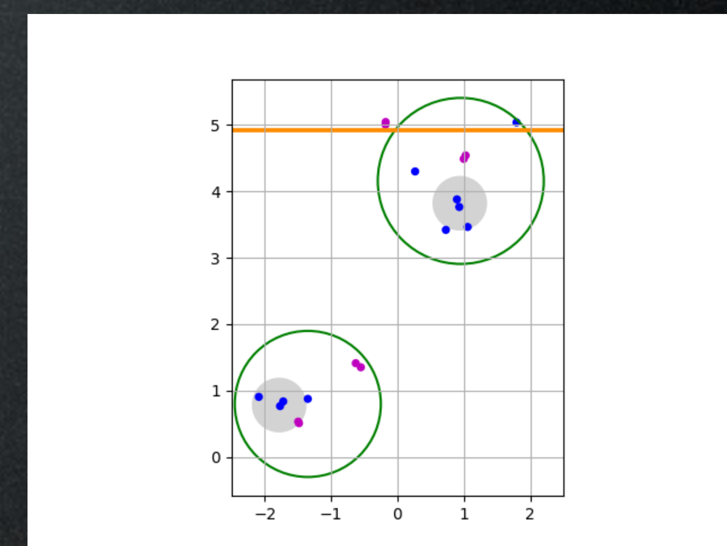
... with S. Sinha, arXiv:2207.01885

ATLAS-CONF-2022-038



Better handle on identifying/ reconstructing the SVJ!

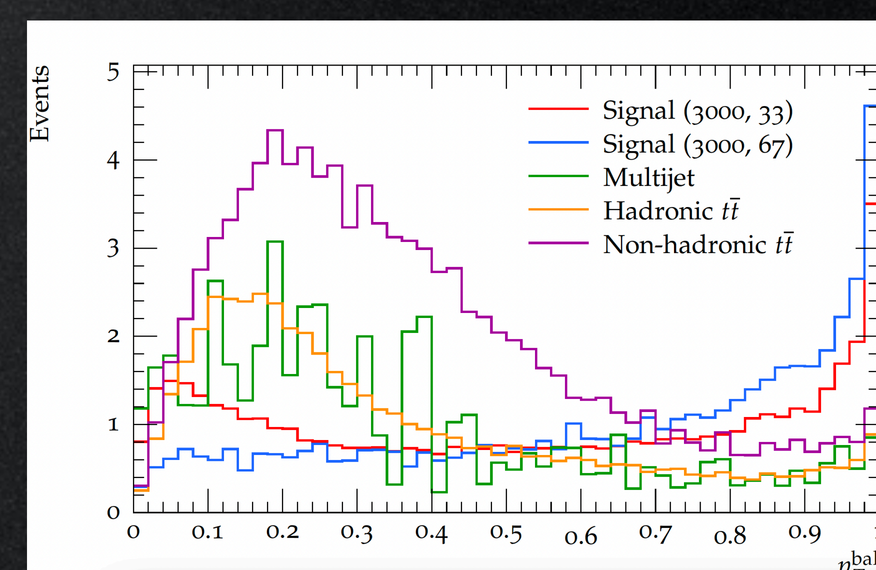




Can we reduce non dominant backgrounds?

-> Better reconstruction with Variable Radius jets (JHEP 0906:059,2009)

What if SVJ is produced exclusively with b-jets? Turns out it is a theoretically well motivated scenario!



Summary

We have this beautiful LHC dataset, with potential doubling of integrated luminosity in a few years.

Let us explore the unexplored, the dark stuff hidden in plain day light!

Supporting Material

ECF

Over all constituents (beta: angular exponent):

$$\mathrm{ECF}(1,\beta) = \sum_i p_{Ti}$$

$$\mathrm{ECF}(2,\beta) = \sum_{i<j} p_{Ti}\, p_{Tj}\, (R_{ij})^\beta \leftarrow$$ [see Banfi, Salam, Zanderighi; Jankowiak, Larkoski]

$$\mathrm{ECF}(3,\beta) = \sum_{i<j<k} p_{Ti}\, p_{Tj}\, p_{Tk}\, (R_{ij} R_{jk} R_{ki})^\beta$$

$$\mathrm{ECF}(N,\beta) = \sum_{\text{sets of } N} (N \text{ energies}) \times \left(\binom{N}{2} \text{ angles} \right)^\beta$$

ECF(N+1) << ECF(N)
for N subjets

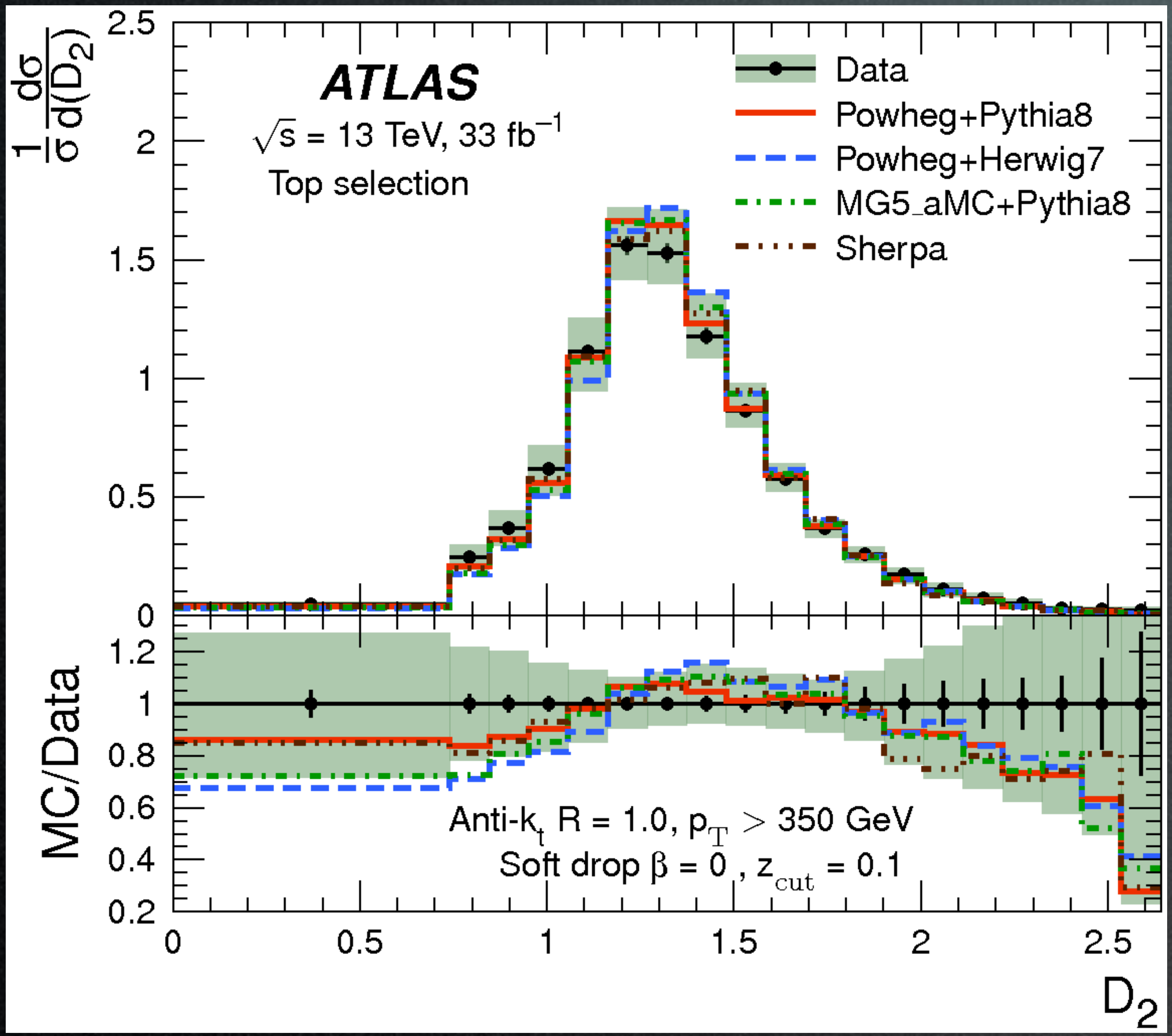
Define (double) ratio = [ECF(N+1)/ECF(N)]/[ECF(N)/ECF(N-1)]

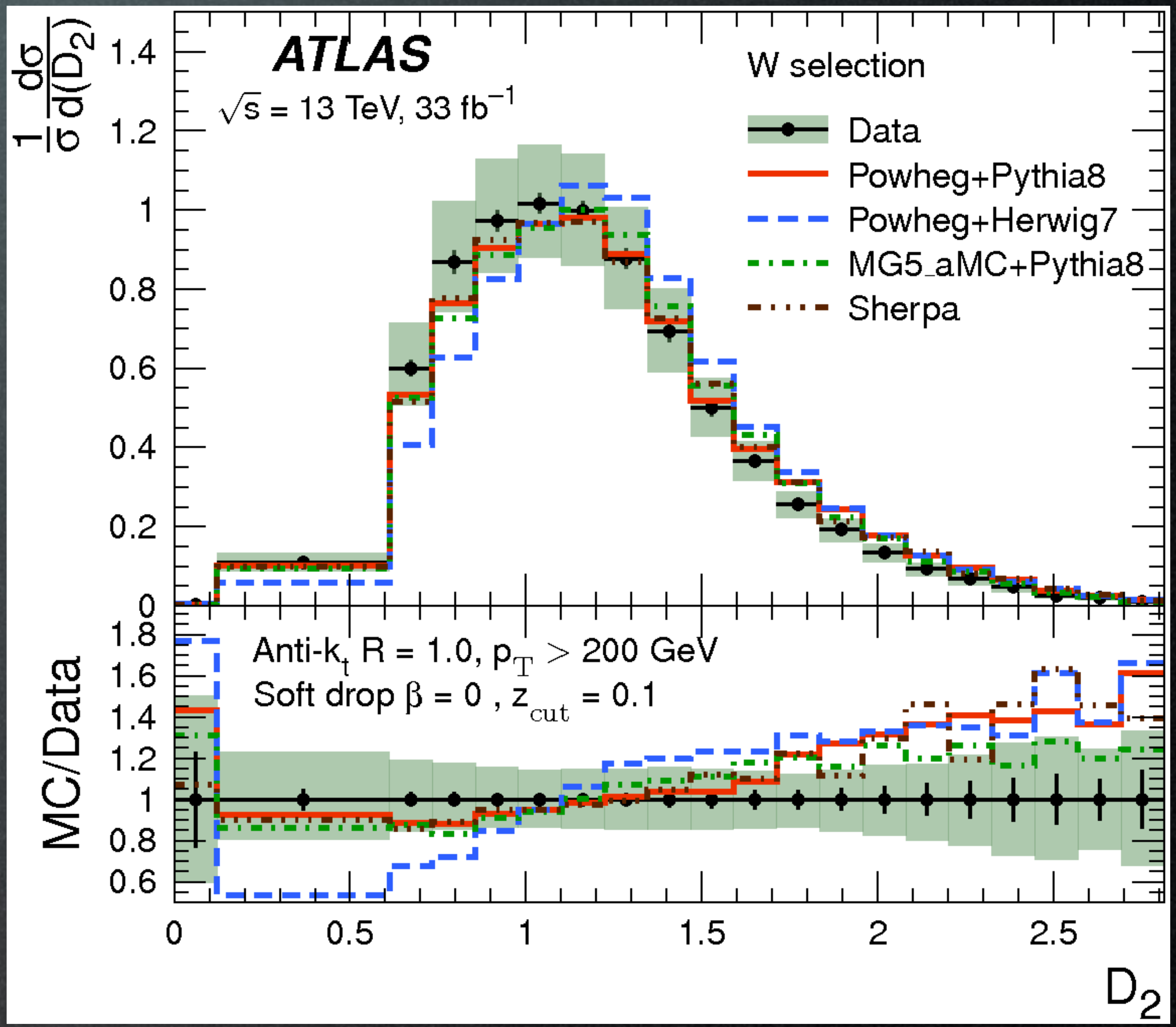
$$C_N^{(\beta)} = \frac{\mathrm{ECF}(N+1,\beta)\,\mathrm{ECF}(N-1,\beta)}{\mathrm{ECF}(N,\beta)^2}$$

Analogous to Nsubjettiness ratio

Large C_N: more than N subjets, extra radiation is not correlated with leading order N subjets.
For small C_N: the additional radiation is soft/collinear

D2





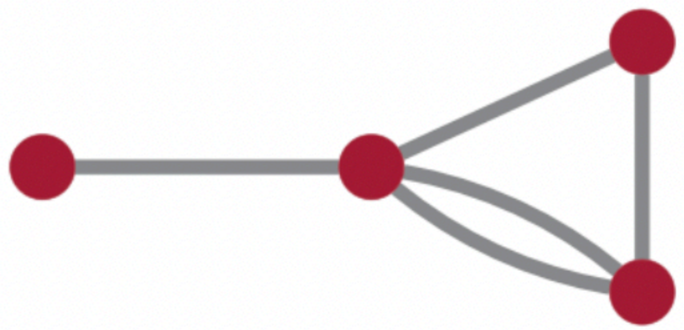
Again shifted peak in W, models overestimating gluon radiation

How to compute EFPs?

$$\bullet_j \Longleftrightarrow \sum_{i_j=1}^{M} z_{i_j} \qquad k \text{ ——— } \ell \Longleftrightarrow \theta_{i_k i_\ell}$$

Each edge (k,l) in a multigraph is in one-to-one correspondence with a term θ in an angular monomial

Each vertex j in the multigraph corresponds to a factor of z and summation over i_j in the EFP



$$= \sum_{i_1=1}^{M}\sum_{i_2=1}^{M}\sum_{i_3=1}^{M}\sum_{i_4=1}^{M} z_{i_1} z_{i_2} z_{i_3} z_{i_4} \theta_{i_1 i_2} \theta_{i_2 i_3} \theta_{i_2 i_4}^2 \theta_{i_3 i_4}$$

4 particles/constituents in a jet ---> 4 energy fractions, 5 angularity values ----> degree 5 polynomial

Because the EFP basis is infinite, a suitable organization and truncation scheme is necessary to use the basis in practice.

47

How to compute EFPs?

	d	1	2	3	4	5	6	7	8	9	10
N	2	1	1	1	1	1	1	1	1	1	1
	3		1	2	3	4	6	7	9	11	13
	4			2	5	11	22	37	61	95	141
	5				3	11	34	85	193	396	771
	6					6	29	110	348	969	2 445
	7						11	70	339	1 318	4 457
	8							23	185	1 067	4 940
	9								47	479	3 294
	10									106	1 279
	11										235

Several combinations for diagrams possible

How to compute EFPs?

	d	1	2	3	4	5	6	7	8	9	10
N	2	1	1	1	1	1	1	1	1	1	1
	3		1	2	3	4	6	7	9	11	13
	4			2	5	11	22	37	61	95	141
	5				3	11	34	85	193	396	771
	6					6	29	110	348	969	2 445
	7						11	70	339	1 318	4 457
	8							23	185	1 067	4 940
	9								47	479	3 294
	10									106	1 279
	11										235

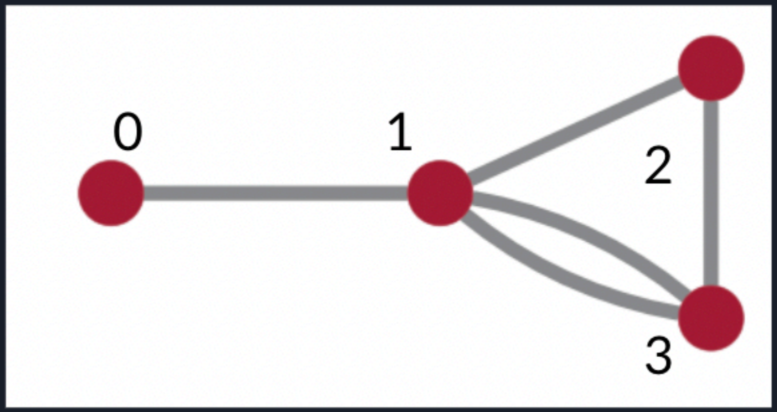
Several combinations for diagrams possible

Restricting ourselves to this regime...

The linked paper discusses in great detail how different EFP combinations lead to well-known jss observables

What we ideally want to achieve with EFPs?

- Implement EFPs in Rivet and see if any particular combination of EFPs helps to distinguish between standard q/g jets and more unconventional jets
  - Might lead to a new jet-substructure observable for dark shower discrimination
- Setup working (computing EFP multigraphs till N = 7, d = N - 1, N, N + 1) → python code taking into account the different possible orientations of the input "particles" and designing an array of possible EFP diagrams as a grid



EFP diagram to "particle" pair translation

{{0, 1}, {1, 2}, {2, 3}, {1, 3}, {1, 3}}

N=4,d = N - 2	0	1	2	3
0	-	-	-	-
1	1	-	1	2
2	-	-	-	-
3	-	-	1	-