Annapaola de Cosa
on behalf of the organising committee

Summary of the Semivisible Jets Workshop

July 2022, Zurich

LHC DM WG Meeting
12 January 2023

Organising committee

Suchita Kulkarni

Matt Strassler

Tim Cohen

Marcella Bona

Annapaola de Cosa

The workshop

Semivisible Jets Workshop

5–7 Jul 2022
ETH Honggerberg
Europe/Zurich timezone

Enter your search term

5-7 July 2022

ETH Honggerberg Campus, Zurich

https://indico.cern.ch/event/1133166/

Recordings available on the agenda

Invited talks

- **Kathryn Zurek**: "Theory of Hidden Sector Dark Matter"
- **Huegues Beauchesne** : "Phenomenology of Hidden Sector Dark Matter"
- **Torbjorn Sjostrand:** "Hidden Valleys in Phythia"
- **Simon Plaetzer:** "Hidden Valleys in Herwig"
- **Suchita Kulkarni:** "Dark Showers - Snowmass paper"
- **Thea Aarrestad:** "Machine Learning Applications: an experimental perspective"
- **Barry Dillon:** "Machine Learning Applications: a theoretical perspective"
- **Kevin Pedro:** "Semivisible Jets at CMS"
- **Sukanya Sinha:** "Semivisible Jets at ATLAS"
- **Frederic Dryer:** "Jet Substructure Overview"
- **Alejandro Gomez Espinoza:** "Jets at CMS"
- **Matt Le Blanc:** "Jets at ATLAS"

Plus talks from Working Groups
(focus of this presentation)

Disclaimer

Not an exhaustive overview of the workshop

We had lots of interesting talks and amazing conversations

This is a personal selection of the topic discussed that does not make justice to the work done by the workshop participants!

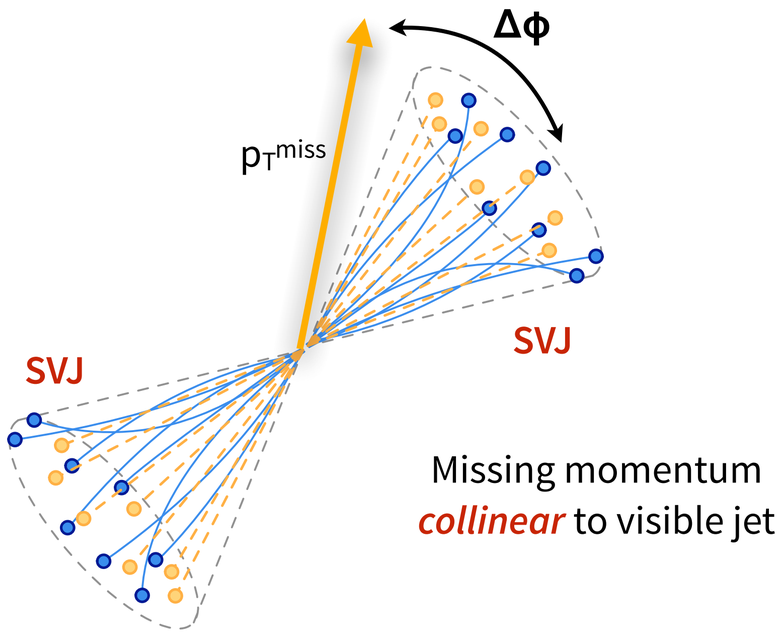
The idea behind

Field of QCD-like DM models predicting semivisible jets (SVJs) signatures still undeveloped both theoretically and experimentally

- **Theoretically:** What does dark QCD look like? Can our MC tools simulate it in an adequate way? How can we connect the theory landscape to actual experimental searches? How can we drive searches?
- **Experimentally:** How far can we reach? Where shall we look for SVJs? How can we handle QCD background? What's the sensitivity reach? Can we look inside the jet?

Need for a set of benchmark models that can drive the search strategies and adequate tools to mitigate backgrounds

Scope of the workshop: Foster experimental and theory communities collaboration to establish a set of realistic benchmark models giving SVJs signatures



The Working groups

5 Working groups (WGs) composed of theorists and experimentalists

- **WG 1: All hadronic final states -** Elias Bernreuther, Adrian Carmona, Fatemeh Elahi, Alison Eliot, Aran Garcia-Bellido, Nukulsinh Parmar, Kevin Pedro, Christiane Scherb, Pedro Schwaller
- **WG 2: Jet Substructure -** Elena Busch, Cari Cesarotti, Nishita Desai, Thomas Klijnsma, Suchita Kulkarni, Akanksha Singh, Matthew Strassler
- **WG 3: Heavy Flavour final states -** Cesare Cazzaniga, Ammar Ellaboudy, Florian Eble, Simon Knapen, Bingxuan Liu, Daniel Stolarski
- **WG 4: Long-Lived and alternative signatures -** Hsin-Chia Cheng, Lingfeng Li, and Ennio Salvioni, Cristiano Alpigiani, Yi-Mu Chen, Benedikt Maier, Sara Nabili, Long Wang
- **WG 5: Final states with leptons -** C. Cazzaniga, T. Fitschen , H. Beauchesne, C. Doglioni and G. Grilli di Cortona

Pre-workshop activities carried out from WG teams led to a very intense and interesting discussion at the workshop

WG1: All hadronic

Material from K.Pedro and N.Desai - WG1, SVJ Workshop

WG1
All hadronic

Topics of discussion:

- Concrete models with benchmarks that give fully-hadronic SVJs signatures;
- Understand the connection between kinematics, effective parameters and model parameter space;
- Improvements to search strategies depending on production mechanism, and effective parameters;
- Explore the need for separate portal couplings for production versus decay.

Issue: HV model space immense, signature space also huge

- **Priority: cover large range of possibilities**
- **Practical approach: implement simplified models**
  - Capture a vast range of kinematics declinations * with as few parameters as possible
  - Important to do this with MC tools, need to simulate reasonable processes
  - Can work in categories to reduce scan over parameters:
    - e.g presence of leptons/HFquarks/LLP in the final tate, production mode, etc.
- **Define a complete model in PYTHIA, implement a version of simplified models and validate it**

(*) relevant to design a search

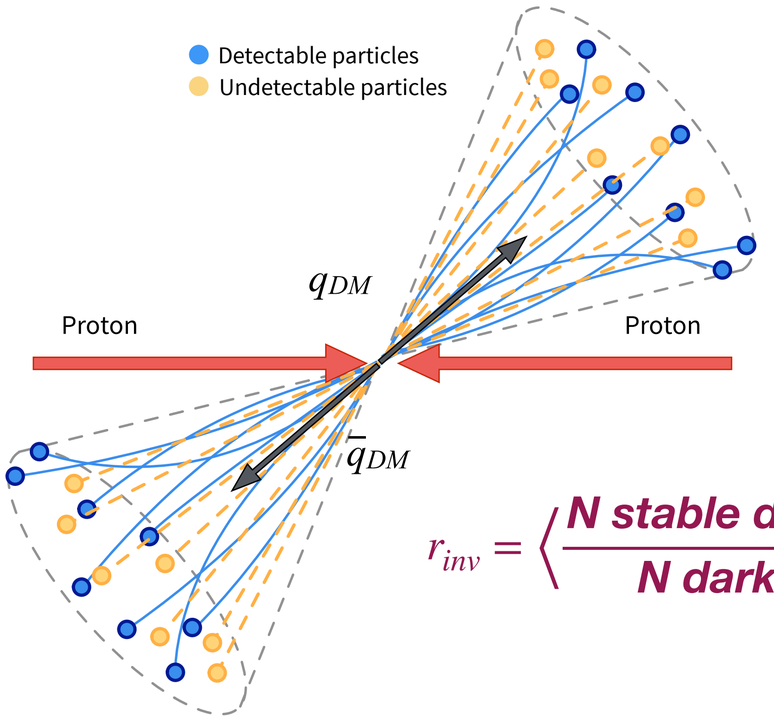
Invisible fraction: r_{inv}

What's r_{inv}?

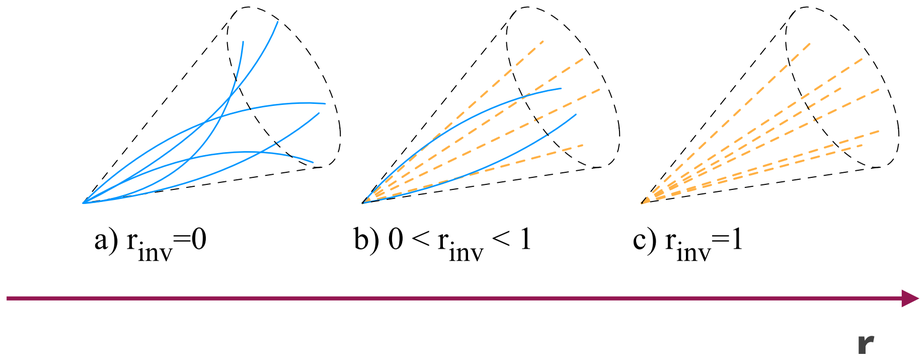
- It's an effective parameter defined as the average fraction of stable dark hadrons *

rinv encapsulate the effect of several model parameters:

- N_c^{dark}, N_f^{dark}, dark quark mass splitting, dark hadron mass spectrum, dark G-parity, mass mechanism plus more



$$r_{inv} = \left\langle \frac{\text{N stable dark hadrons}}{\text{N dark hadrons}} \right\rangle$$



(*) as defined in T.Cohen et al. Phys. Rev. Lett. 115, 171804 (2015)

A series of open questions

Open Questions

1. Is the list of r_{inv}-influencing parameters complete?
   a. Is the proposed scheme to extend the definition of rinv to 3-body decays adequate?
2. How many details can be simplified to create simplified models?
3. Proposed study: are there any major kinematic differences between simplified models and realistic models?
   a. If so, how can we account for them?
   b. Which parameters of complete models can be accurately simulated in Pythia?
4. How much do the "other considerations" (next slide) influence rinv and related kinematics toward simplified models?
5. What is a minimal mediator setup that allows r_inv to be close to any value between 0 and 1?

(e.g: dark hadron life time, decay pattern, production mechanisms)

slide from K.Pedro, WG1 SVJ Workshop

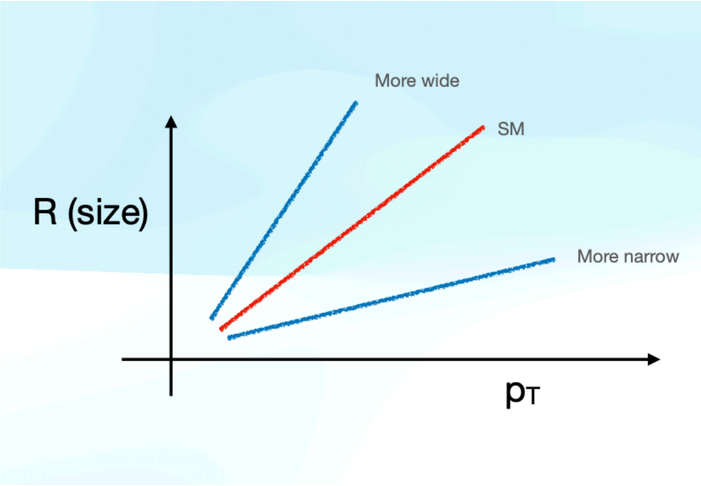
A simplified model for SVJs

We don't know much about dark confining sector

- **Parametrise the jet properties:** Spread of jet (based on pt), r_{inv}, mass of visibly decaying hadrons, pT distribution of visibly decaying hadrons (**proposal from Nishita Desai**)
- **Start from simpler scenarios**, parametrise based on extreme situations

Avoid tuning the parameter space of which we don't know the range of validity

Spread of jet based on pT

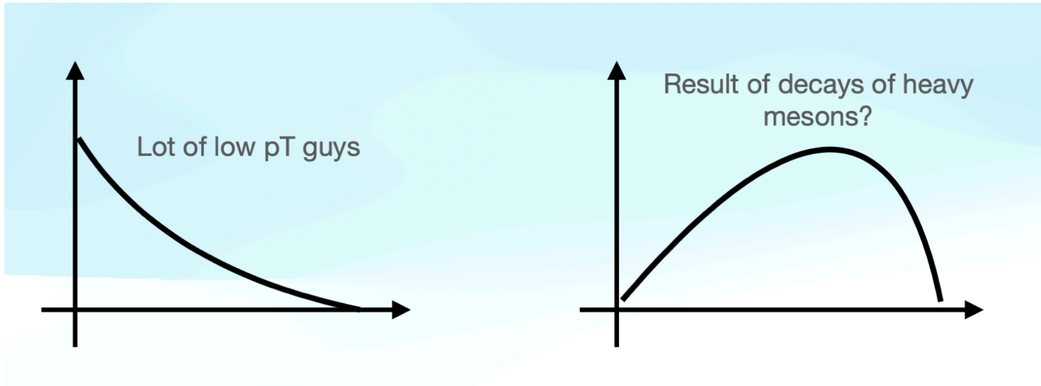


Jets spread depends on multiple dark sector parameters, e.g showering

Can be parametrised by the slope (1parameter)

Linear is a first approximation

pT distribution of visible decaying hadrons



Can choose between two extreme situations (exponential vs gaussian)

WG2: Jet Substructure

Material from T.Klijnsma - WG2, SVJ Workshop

WG2
JSS

Need to look inside the jet to reach higher sensitivity

- SVJs are quite QCD-like
- Jet substructure variables required to achieve higher sensitivity,
- Existing ones based on the identification of prongs
  - not necessarily suitable for SVJ signatures

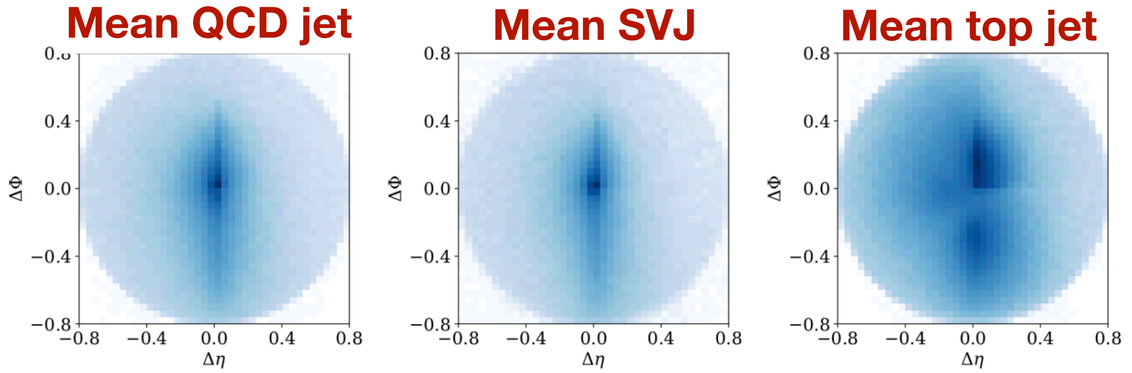
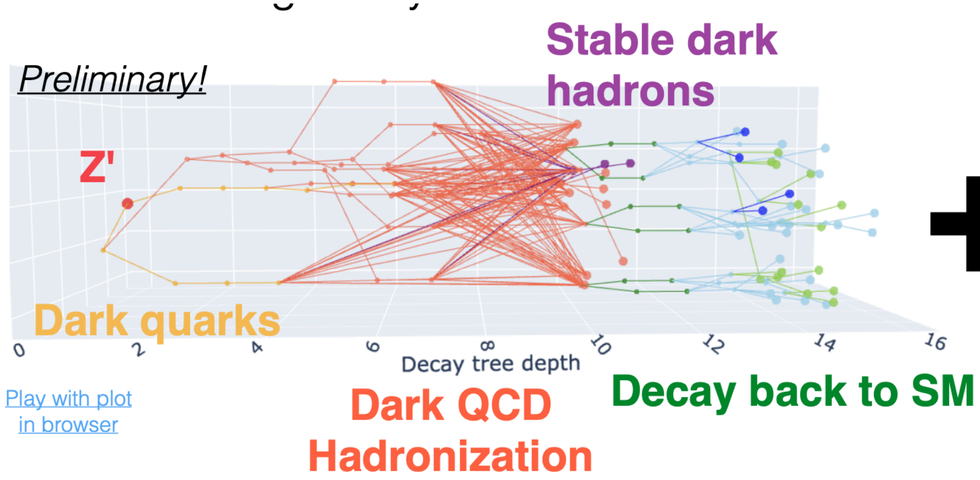


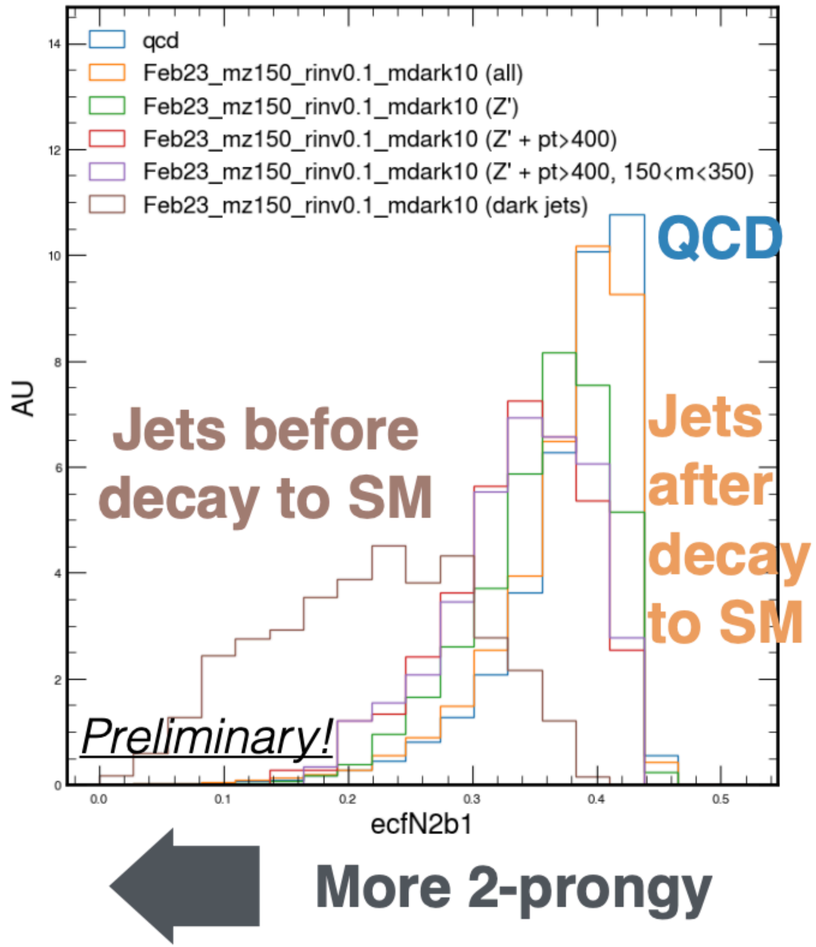
Image from F. Kahlhoefer

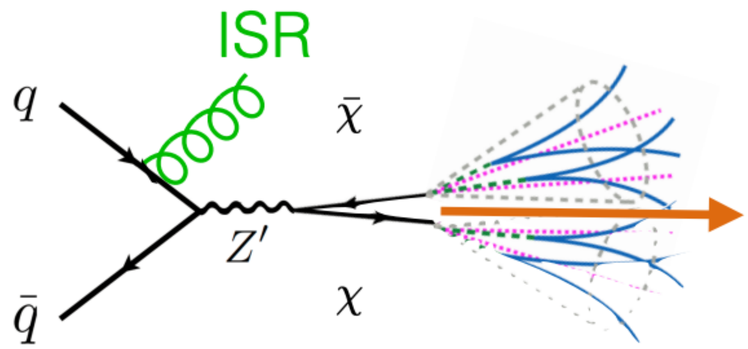
SVJs product of a long decay chain:

- Decay and hadronization in the SM and Dark sector
- Do hadronization features survive through the multiple steps?
  - Does it appear in substructure variables?



Can we see the dark hadronization features?

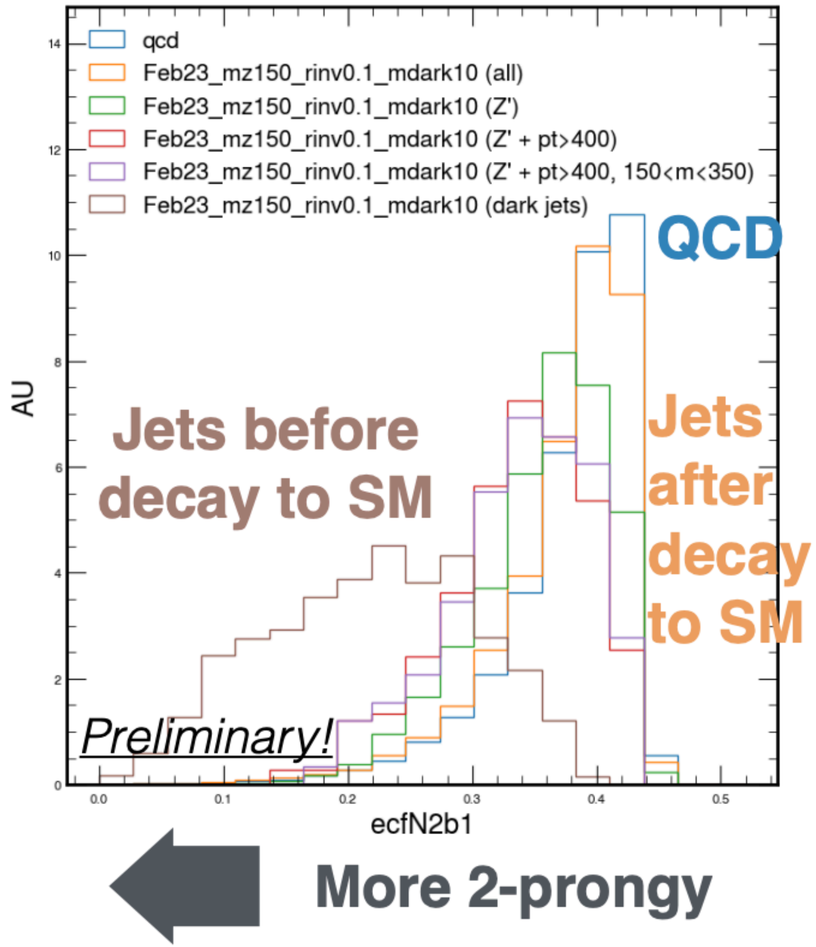


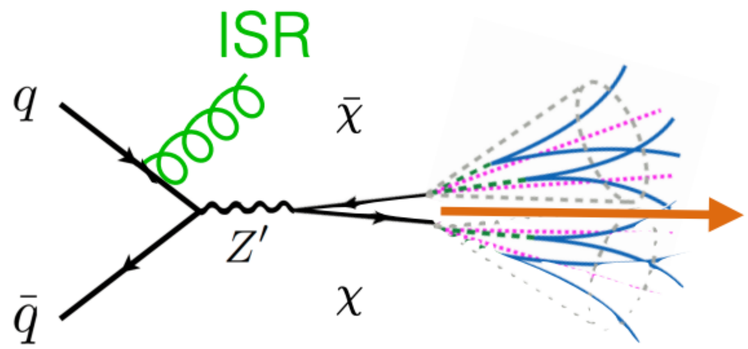


Example: Boosted SVJs production

- Boosted Z' production: fat jet from 2 dark quarks
- Naively expect to see 2 prongs
- Jets clusters after dark hadronization are still 2prongs-like
- 2-prong structure lost after decay to SM

Can we see the dark hadronization features?





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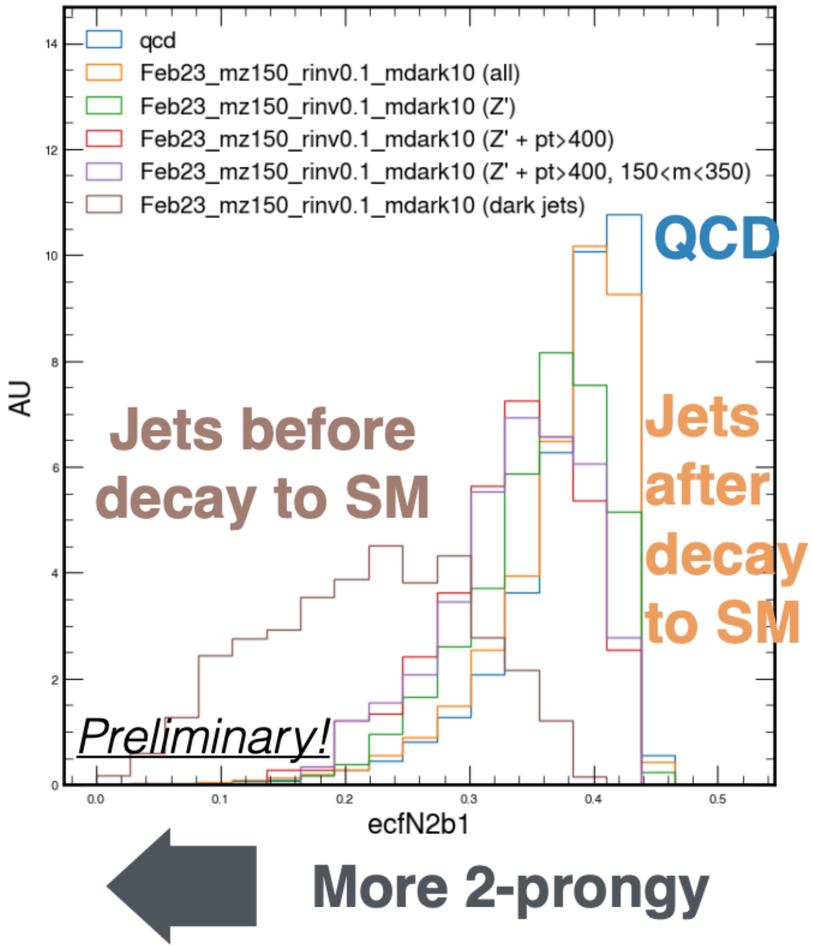
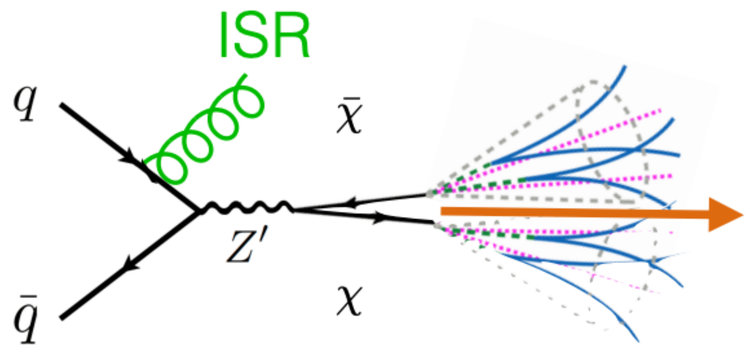
1st observation: Do we really understand substructure as a function of model parameters?

- Need to get insight in substructure dependence on model parameters

Can we see the dark hadronization features?





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2nd observation: Want to balance sensitivity and generality

- Covering a large number of cases

Role of subjet mass

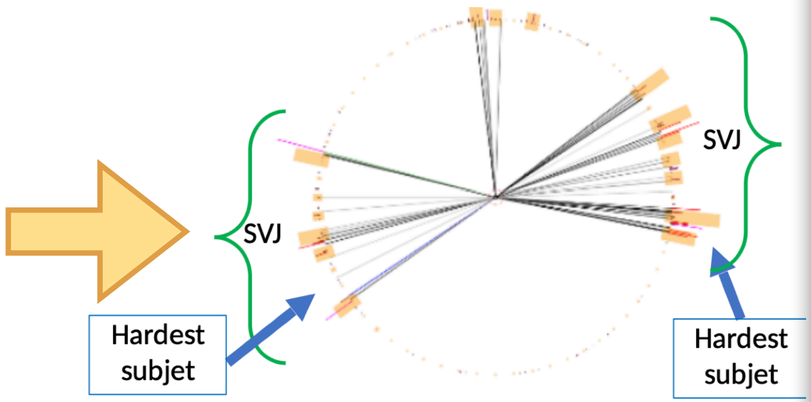
From Strassler 0806.2385

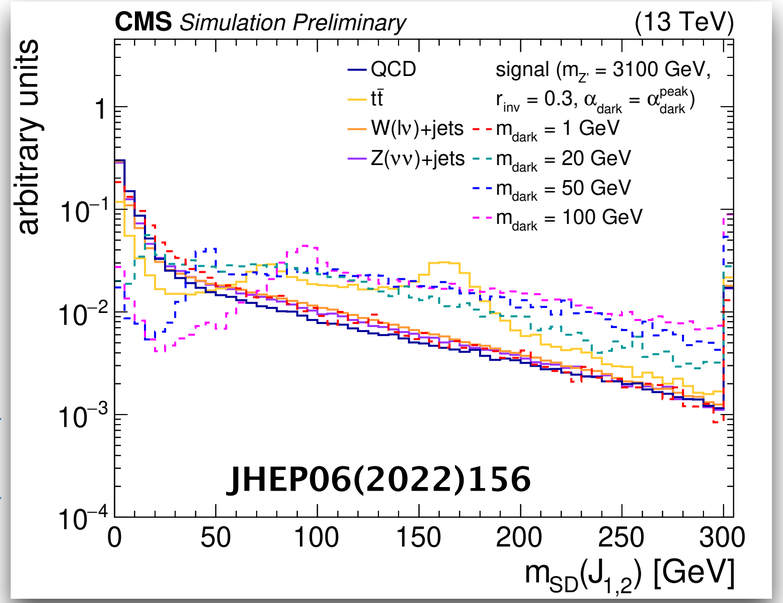
Model-Quasi-Independent Fact:

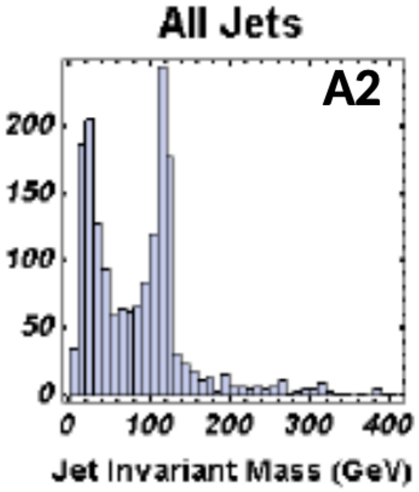
A jet, or its hardest sub-jet, is often a single boosted hidden hadron!

- Self-identifying
- Self-isolating
- Self-analyzing

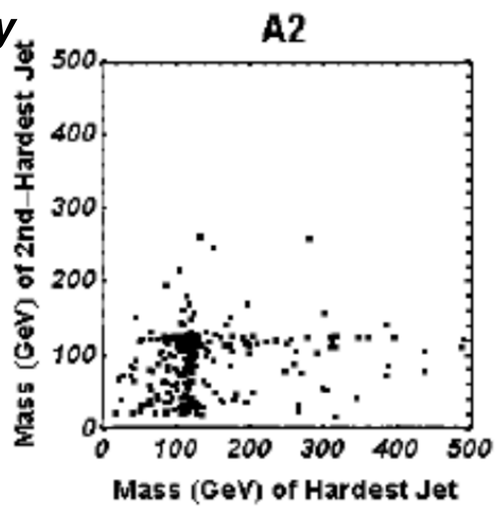
Therefore $m_{(sub)jet} \approx m_{hadron}$ in many SVJs!







Theory study



Both SVJs in an event may have jet/subjet with the same mass

Would be convincing evidence of a signal after SVJ identification

Q: what is the best strategy using modern substructure methods?

ML: supervised vs unsupervised

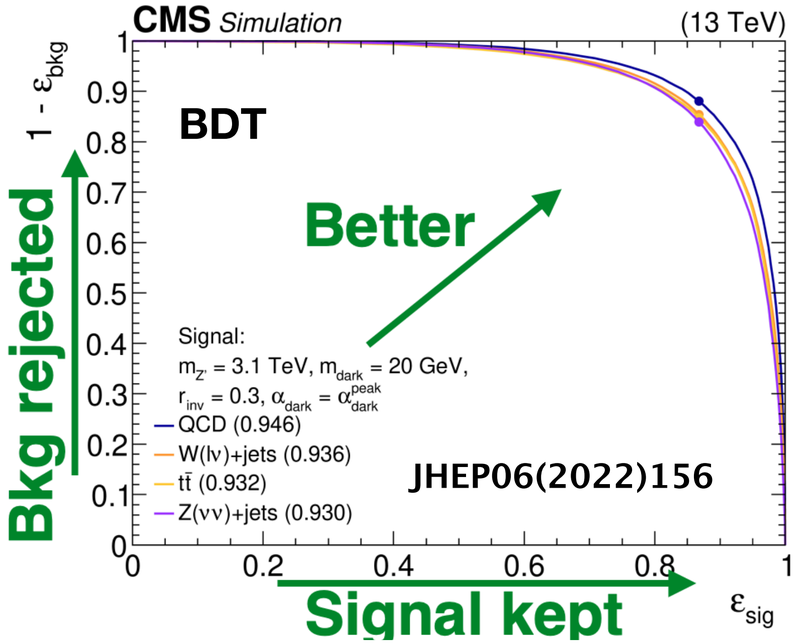
No JSS variable strongly discriminating by itself, but combination leads to pretty nice discrimination

Can gain more from using constituents (Graph Neural Networks)

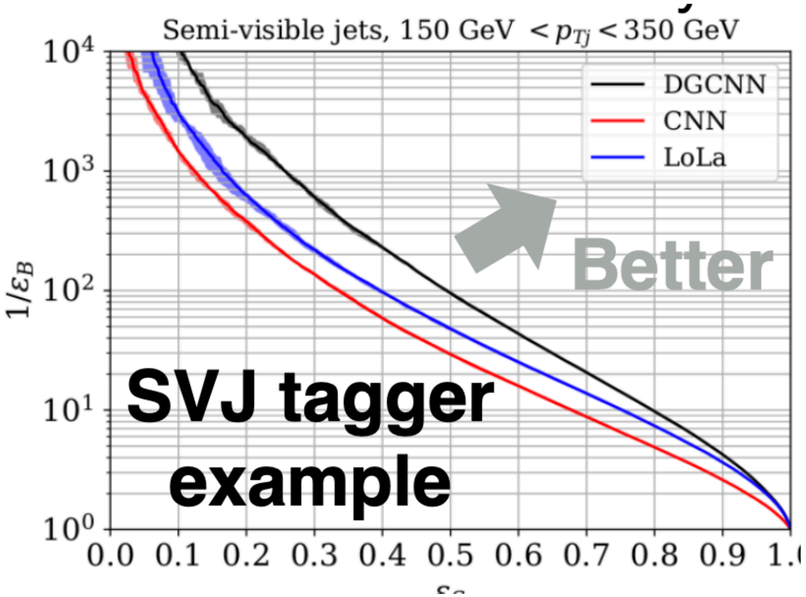
- Strong model dependence

Alternatively going for anomaly detection techniques

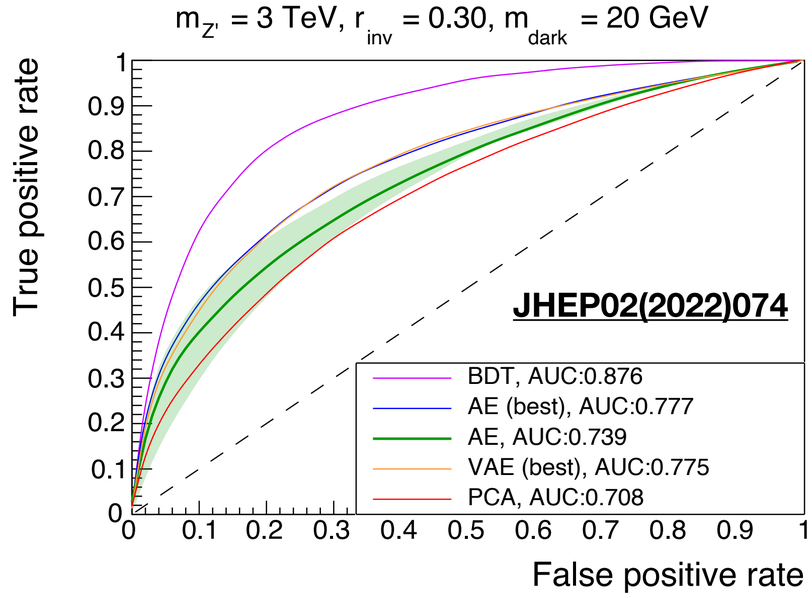
- Trained on background only, very model independent
- Less sensitive than fully supervised approaches



Source: F. Kahlhoefer



Autoencoder based on high level features



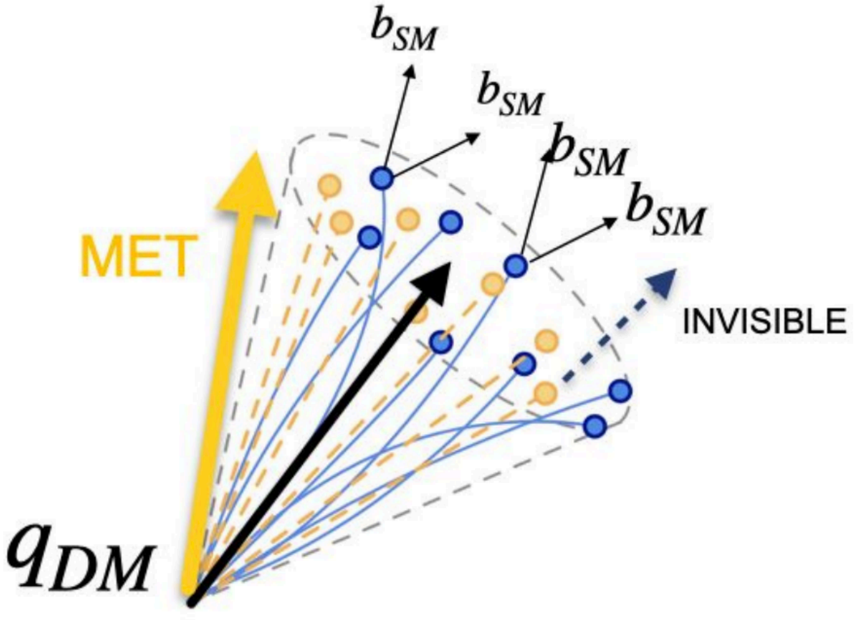
WG3: Heavy-flavoured SVJs (SVJ*b*)

Material from F.Eble - WG3, SVJ Workshop

WG3 SVJ-HF

Study of a HF enriched SVJ: SVJb

- Z' decaying to dark sector quarks
- Nc=3, Nf=2
- Lightest (pseudo-)scalar can mix with H or back to SM via mass insertion with Z': if mS>2mb —> b-enriched final state



High multiplicity of b-hadrons

- High displaced vertex multiplicity
- High displaced track multiplicity
- High lepton multiplicity
- Inside the jet di-vertex mass peaks corresponding to the dark pion mass

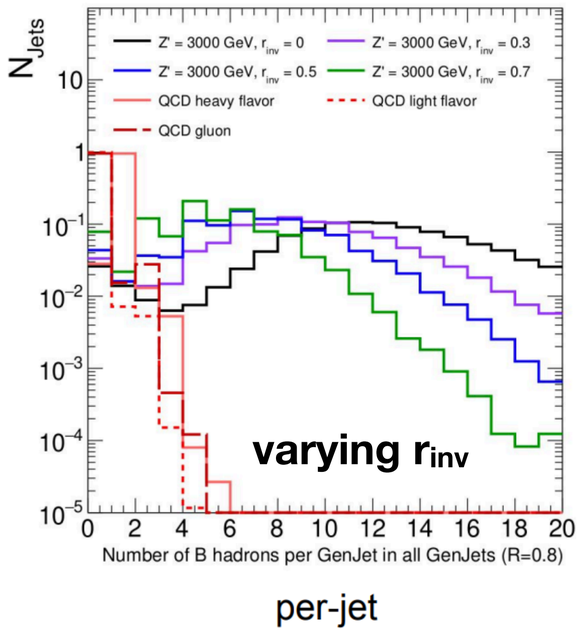
Standard b-tagging algos that use displaced tracks, secondary vertices (SV) and high track multiplicity might be sensitive to SVJ*b*

SVJ*b*: few considerations

WG3 studies focused on systematic studies of

- Number of b-hadrons
- Impact parameter of jet constituents
- Complementarity with JSS-based tagger

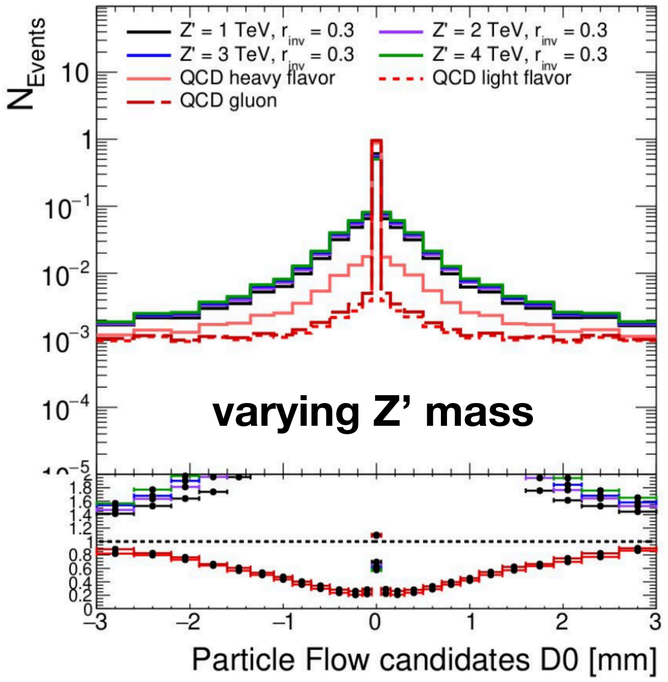
as a function of r_{inv}, m_π and $m_{Z'}$



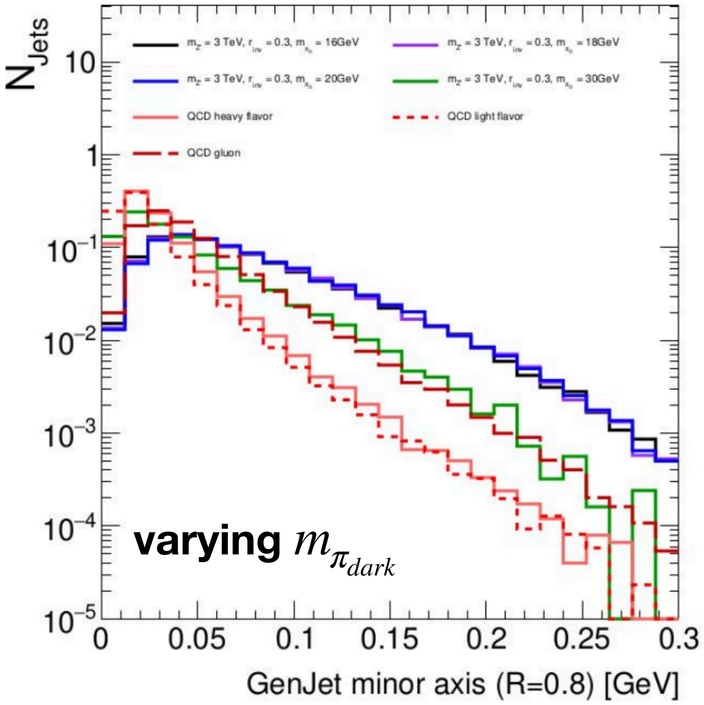
per-jet

Large number of b-hadrons per jet (Nbtag>2)

Large displacement



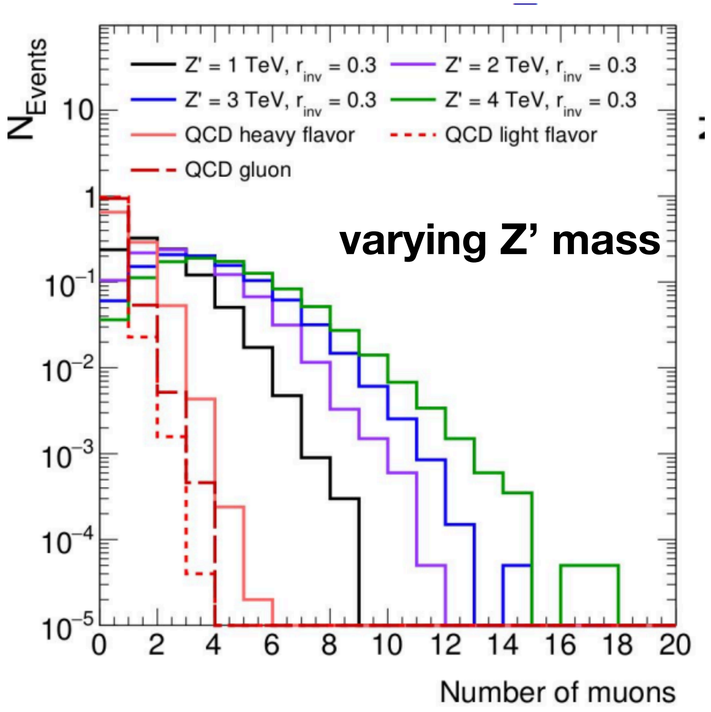
Large spread of jet constituents

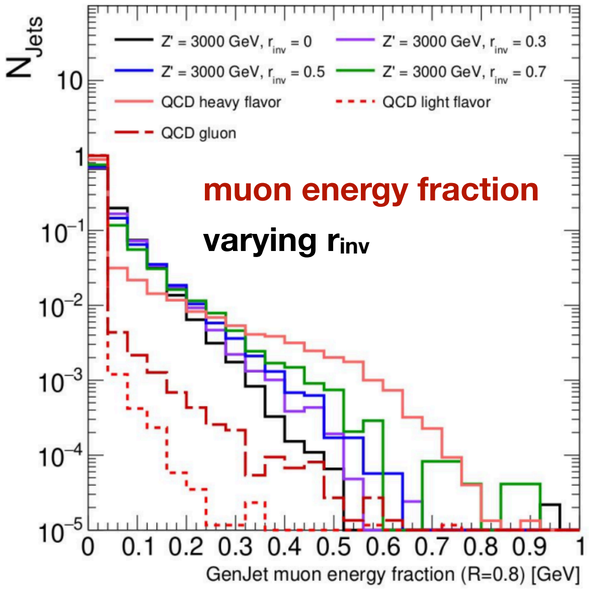


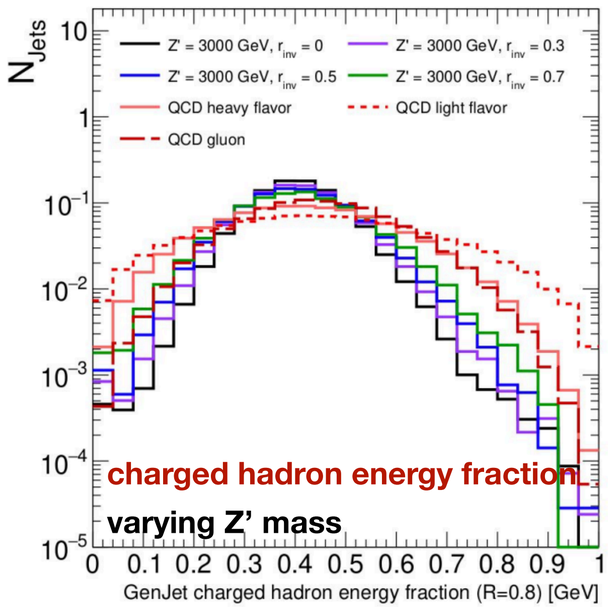
SVJ*b*: muon content and JSS

High muon multiplicity

- Soft leptons
- Higher Z' gives more and harder muons
- Muons in dark QCD jets from cascade decays
  - More spread/ dispersion in pt?







Large differences in energy fractions (EF) for QCD LF/ gluon and SVJ

- Difference in hadronization visible also between QCD HF and SVJs

JSS for SVJs more similar to SM gluon jets

- Relevant difference wrt QCD LF/HF

SVJ*b*: handles against multijet bkg

	SVJ vs gluon	SVJ vs SM light q	SVJ vs SM b
JSS			
EF			
N muons			
N SV			

More sensitivity

Complementarity of JSS, EF, muon multiplicity, SV multiplicity

- Large number of b-hadrons and muons for a wide range of model parameter
- Potential large # of SV (to be checked)

Proposed developments:

- Develop a multi-b SVJ tagger (might be interesting for all hadronic SVJs **WG 1**)
- Pheno study on usage of soft muons (leptons) -> collaboration with **WG5** (SVJ-leptons)
- Explore displaced vertices multiplicity -> connection to **WG4** (SVJ-LLP)

WG4: SVJs with LLPs

Material from L.Feng and C. Alpigiani - WG3, SVJ Workshop

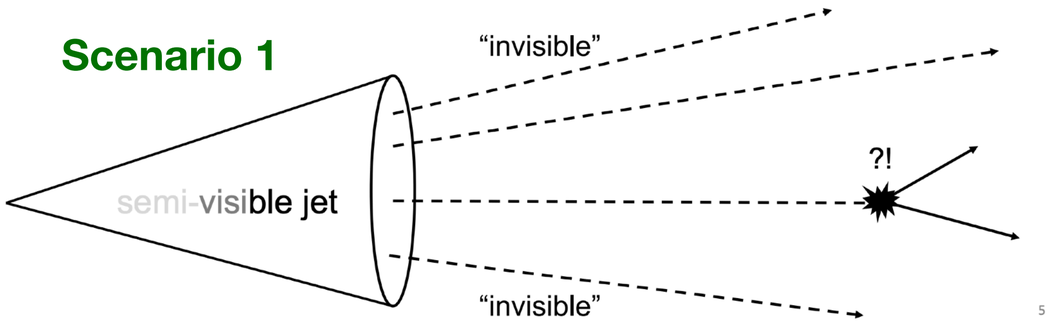
WG4 SVJ-LLP

WG4 thought about different production and decay scenarios to have LLPs in SVJs

- `**Opt 1**: Assigning very long lifetime to original invisible components
- **Opt 2:** Assigning very short but finite lifetime to the prompt component
- Different background scenarios demanding different reconstruction and identification strategies

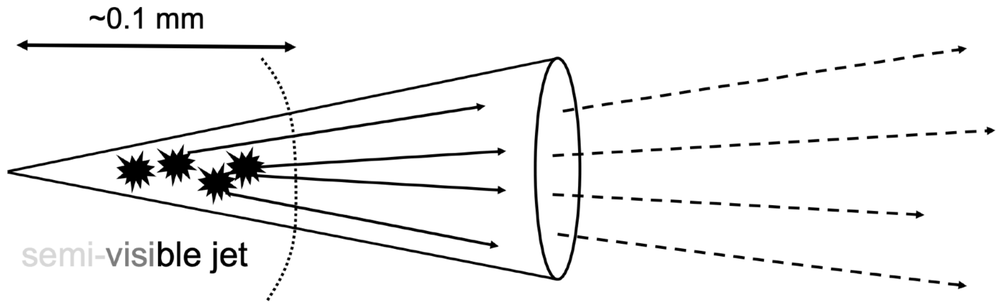
- Scenario 1: Assign a very long (but not infinite) lifetime to the original "missing" components.

  A semi-visible jet and an occasional LLP show up at the far end of the detector (HCAL, Muon System, Far detectors …).



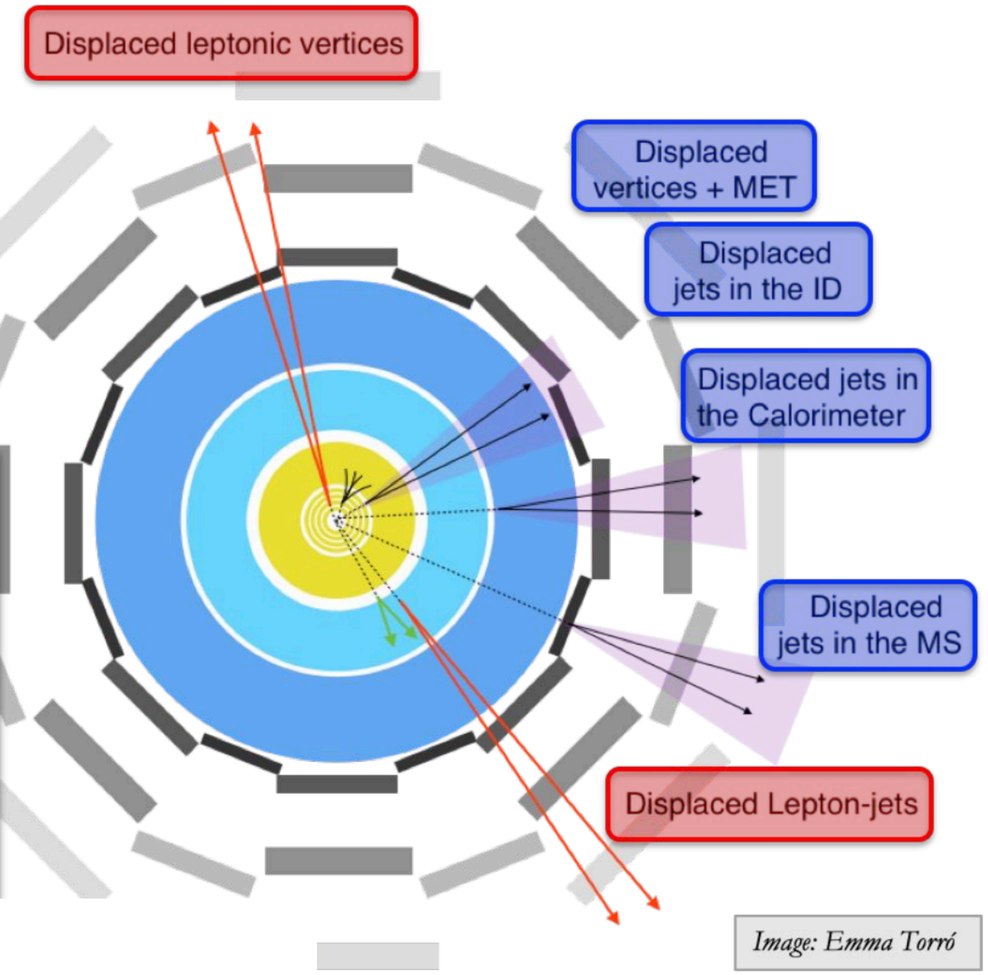
- Scenario 2: Assign a very short but finite lifetime to the original "prompt" components.

  A semi-visible jet with a high multiplicity of small impact parameter tracks/vertexes.



Scenario 2

WG4: are SVJ-LLP covered by LLP searches?



LHC detectors optimised to detect prompt SM particles

Are SVJ-LLP already covered by LHC LLP searches?

- Search for displaced hadronic jets in the muon detector
- **Bkg rejection based on identification of isolated displaced vertices**
  - If SVJ has LL components, these will be surrounded by the prompt track from prompt dark hadron decays
  - **SVJ-LLP discarded by current strategy**

Trigger: are we missing SVJ LLP signals?

- LLP algos not relying on isolated SVs: Hit multiplicity triggers and Cluster triggers
- Should give a good coverage

WG5: SVJs-leptons

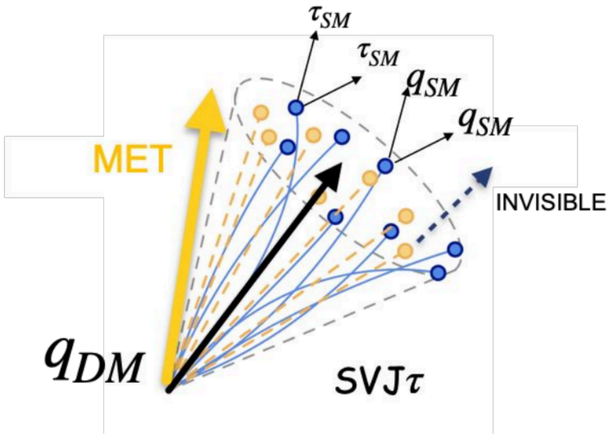
Material from C.Cazzaniga-WG3, SVJ Workshop

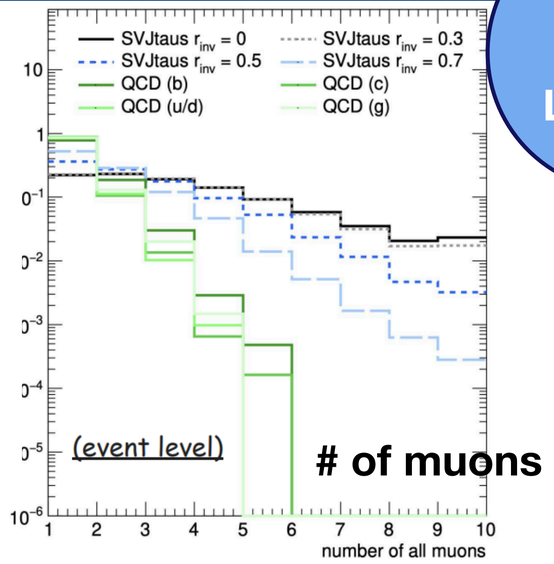
WG5 SVJ-Leptons

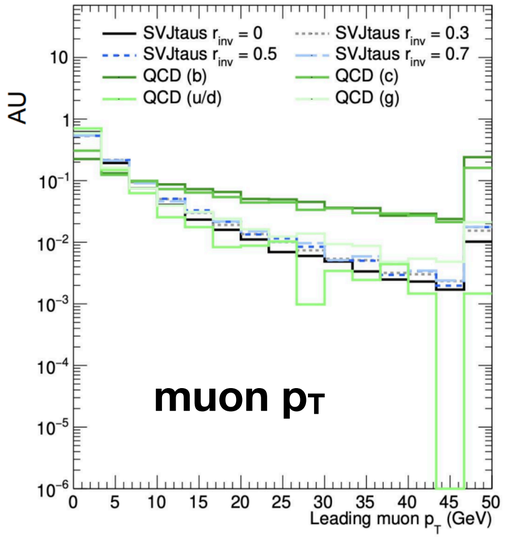
WG5 focused on models leading to τ-enriched SVJs

New challenges (and handles):

- Mixture of hadronization in SM sector and τ decays following hadronization in the dark sector
- Neutrinos from τ decays plus soft leptons
- Standard isolation not efficient
- Work summarised in a paper draft [arXiv:2212.11523]
  - More details in **Cesare's talk**

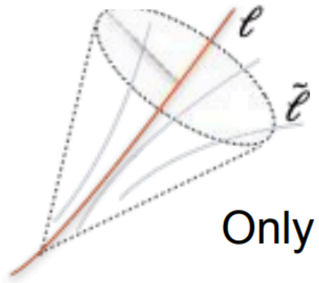






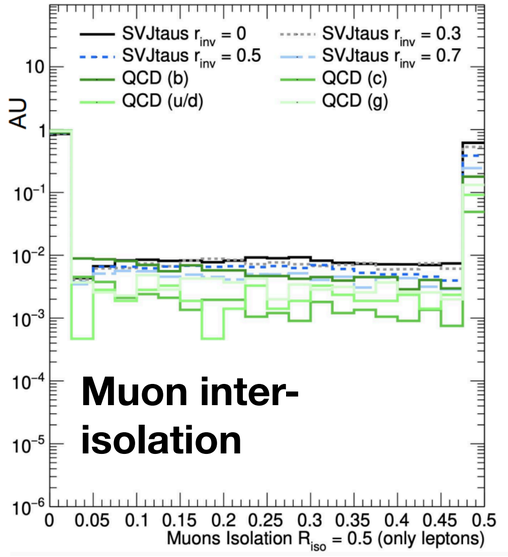
inter-isolation

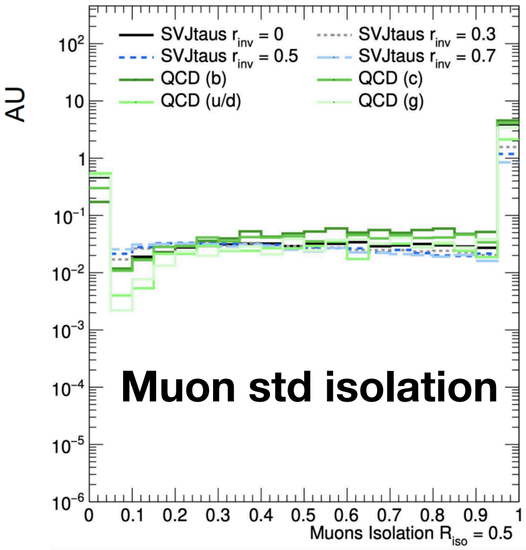
$R_{iso}^{max} = 0.5$



Only sum over leptons

Eur. Phys. J. C 82, 793 (2022)





What did we learn?

Strong connections across WGs

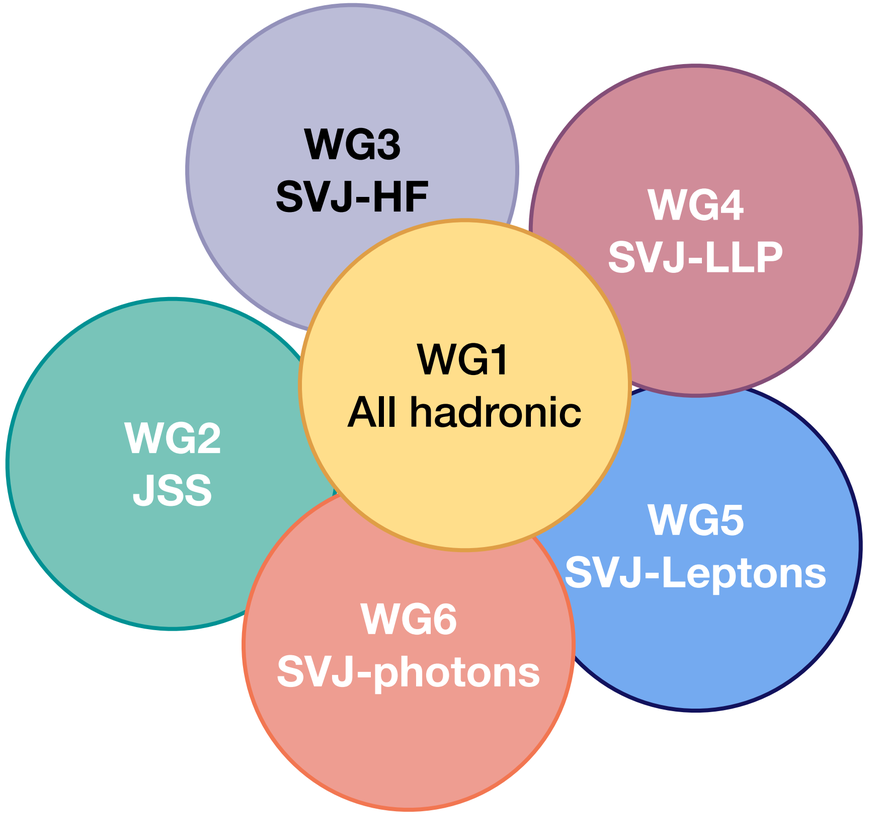
- Lots of open questions and ideas for developments

New possibilities for final state signatures:

- SVJ*b*, SVJ*LLP*, SVJ*lep*, SVJτ, SVJγ *(?)*

Urgent issues (including those not discussed here):

- Simplified models
- Definition of r_{inv}
- Jet substructure tools development
- Better trigger/reconstruction algorithms
- Better background understanding
- PYTHIA validation for non degenerate dark quarks
- ***Plus more!***



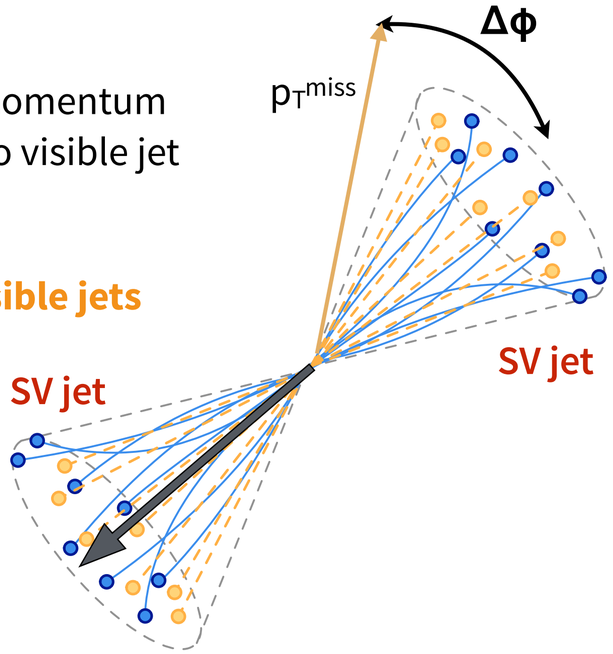
Much more to come in the search for SVJs

Backup

SVJ vs WIMPs signature

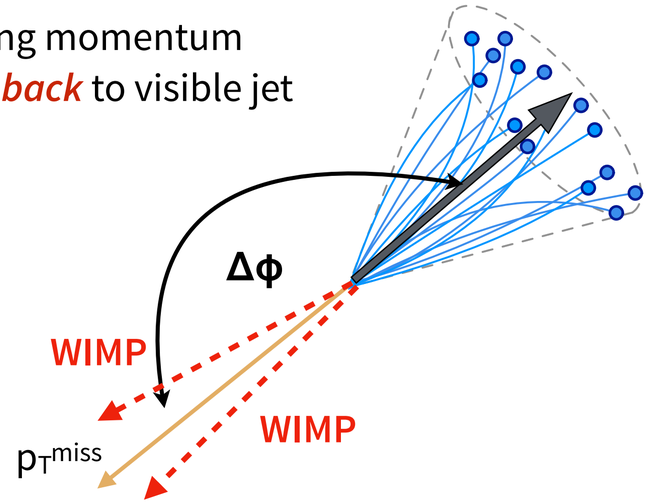
Missing momentum
collinear to visible jet

Semivisible jets

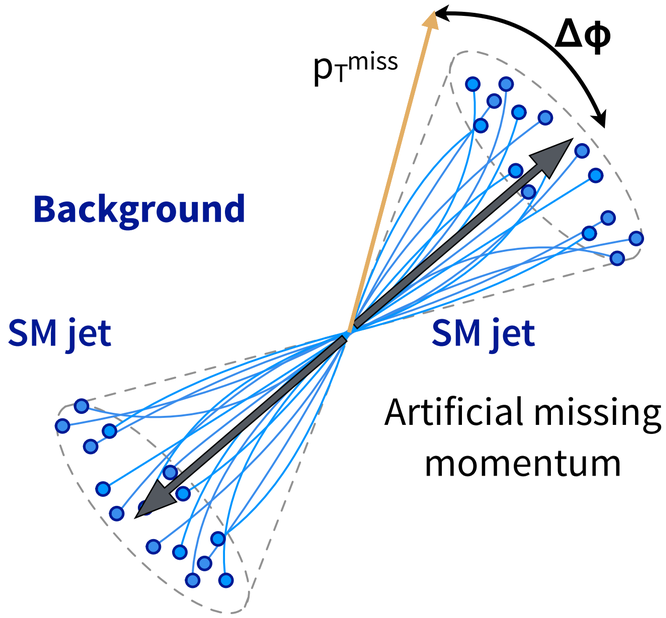


Mono jet

Missing momentum
back-to-back to visible jet



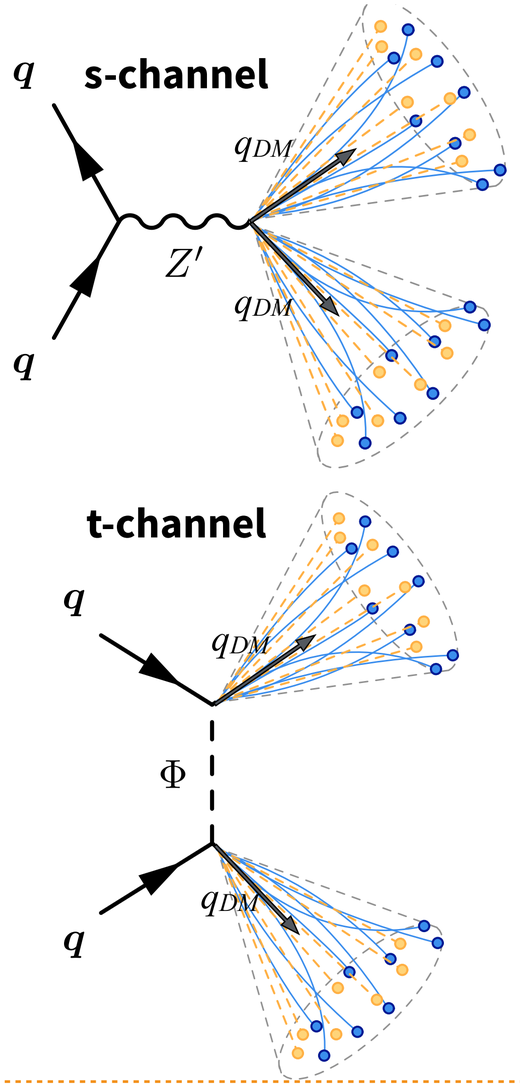
Background



Artificial missing
momentum

A simplified look at the problem

Production modes



Model parameters