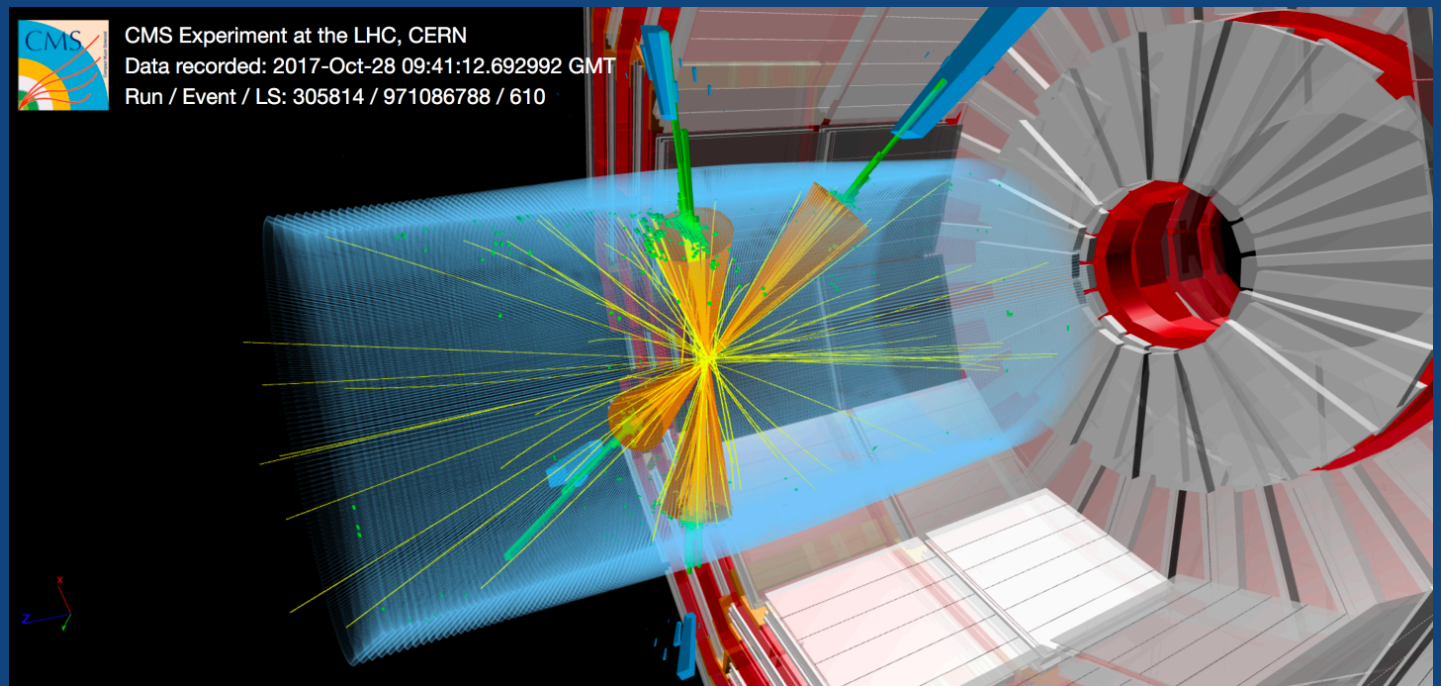
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Phenomenology of Physics Beyond the Standard Model

Exp Lecture 6 : Hidden Valley searches

Annapaola de Cosa adecosa@phys.ethz.ch

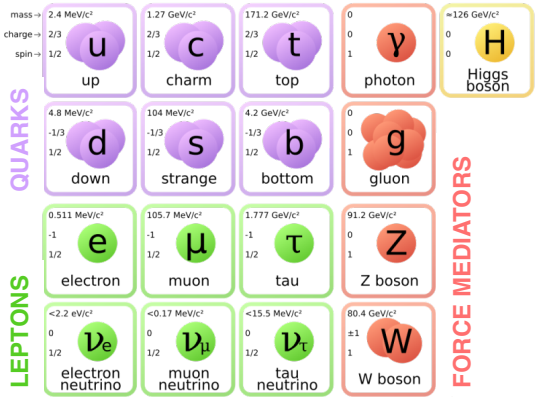


In today's class

- Probing Hidden Valley models
  - New and rich phenomenology
  - Unconventional signatures requiring dedicated identification algorithms (and a good knowledge of the detector)
  - Different topology of backgrounds (from detector effects to cosmic muons)
  - Inclusive search strategy

Hidden Valley models

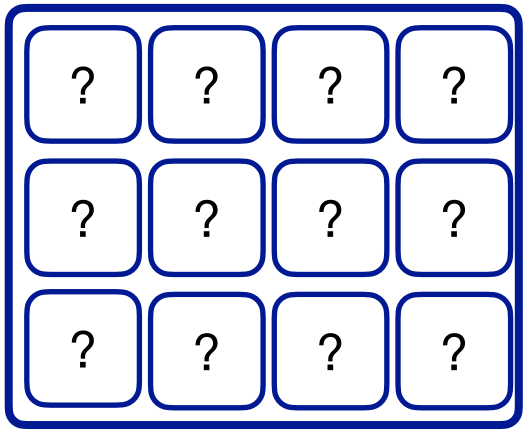
Visible Sector



Mediator

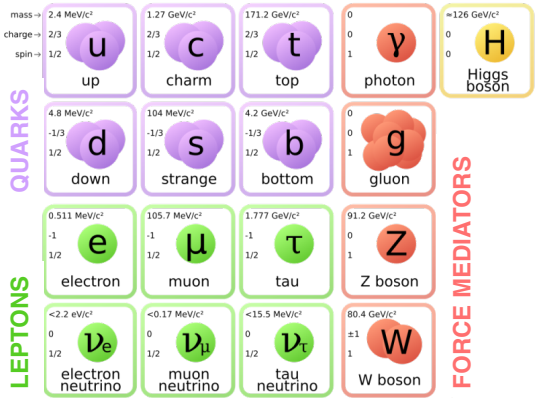


Hidden sector



Hidden Valley models

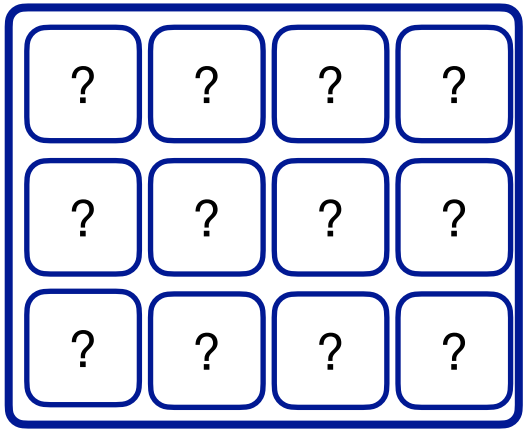
Visible Sector



Mediator



Hidden sector



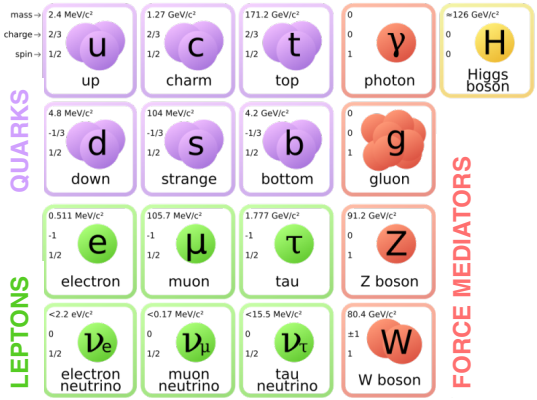
Hidden Valley Models predict extended sectors of particle content weakly coupled to the visible one

New hidden symmetries with new hidden particles

Some dark particles are stable → good DM candidates

Hidden Valley models

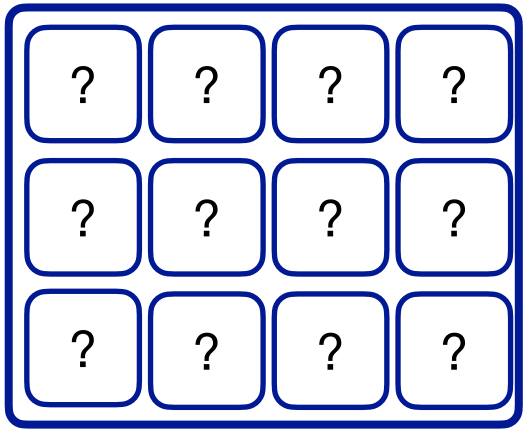
Visible Sector



Mediator



Hidden sector



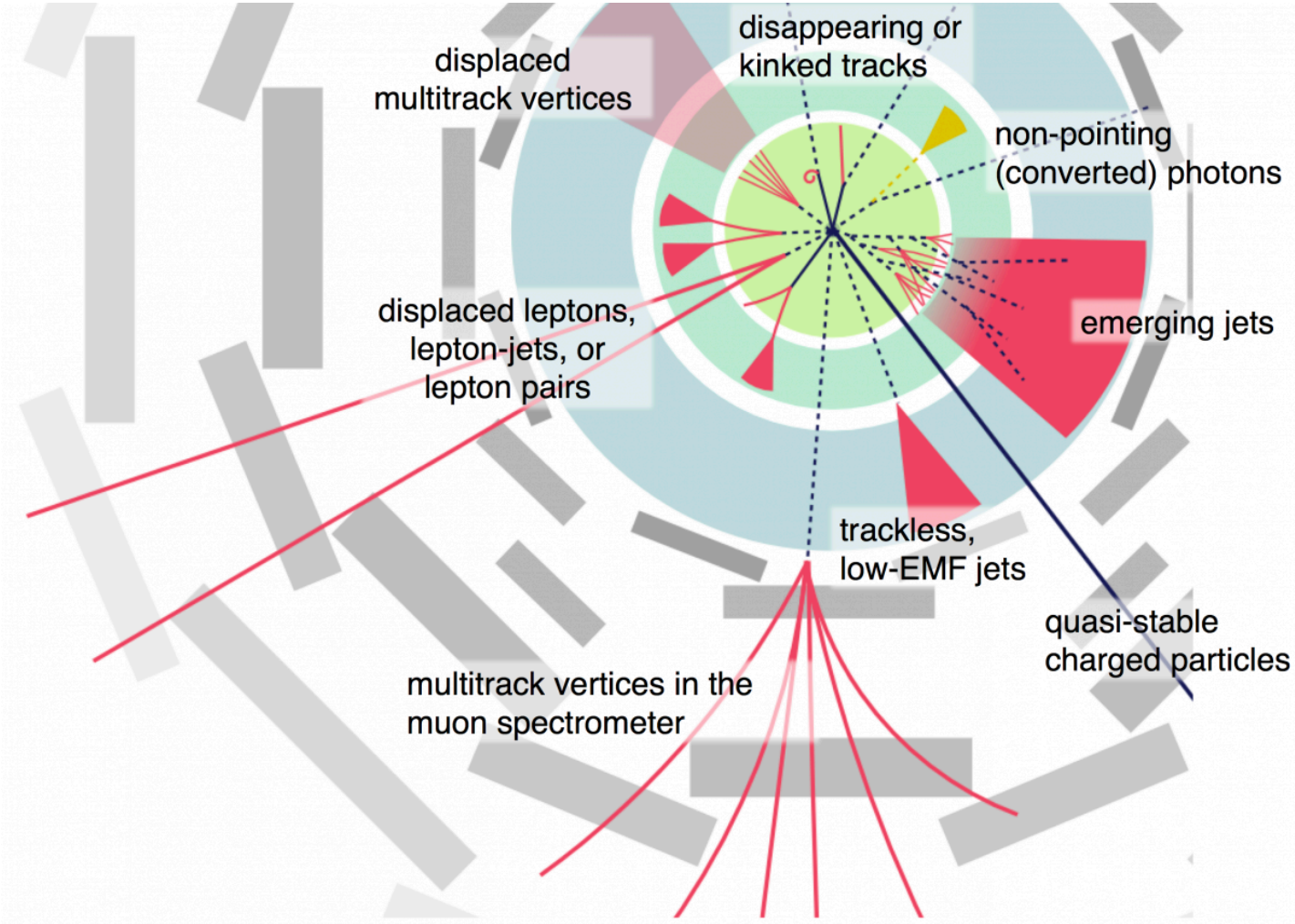
Hidden Valley Models predict extended sectors of particle content weakly coupled to the visible one

New hidden symmetries with new hidden particles

Some dark particles are stable → good DM candidates

High energies probed at the LHC may enable SM DM communication

Conquering an Hidden Valley



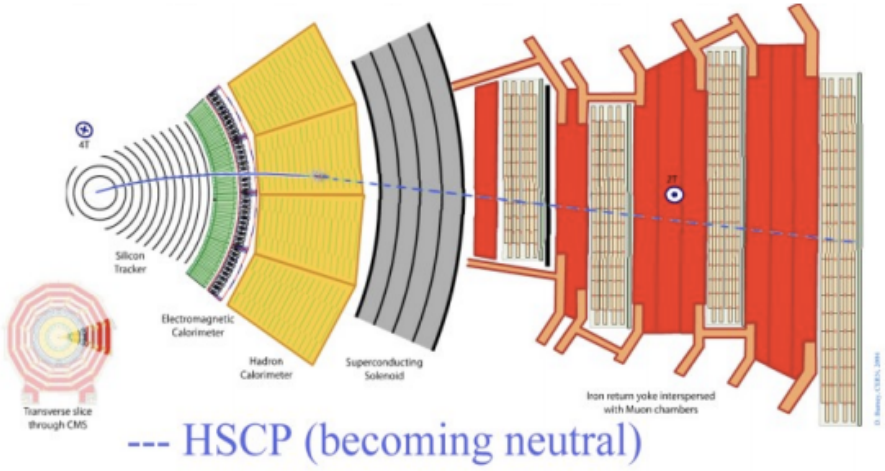
Novel signatures: *Emerging jets, Trackless jets, displaced leptons, lepton-jets, disappearing tracks, …*

Long Lived Particles

- Many BSM scenarios, such as SUSY or Hidden Valley models, predict new processes with long lived particles and non-conventional final-states, e.g.:
  - Displaced vertices, Disappearing tracks, Lepton Jets, Heavy Stable Charged Particles
- Such signatures need non-standard analysis strategies
  - Ad hoc trigger algorithms
  - Dedicated reconstructions

Long-lived particles

Large dE/dx



Large TOF

Emerging jets

10.1007/JHEP02(2019)179

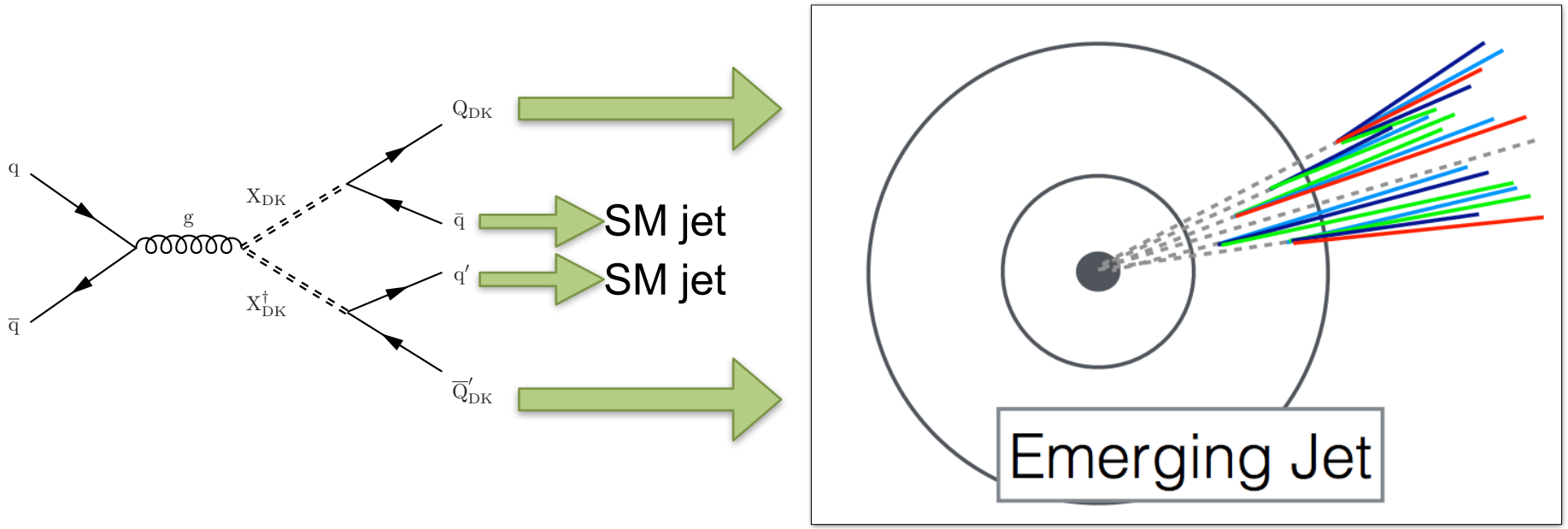
One class of models includes dark quarks (Q_{DK})

- new electrically neutral fermions
- not charged under SM forces
- self-interaction within the dark sector
  - Dark QCD: confining properties similar to SM QCD

Emerging jets

Dark QCD model of Bai, Schwaller, Stolarski and Weiler (BSSW) predicts ***emerging jets*** signature

Mediator charged under both dark force and SM QCD



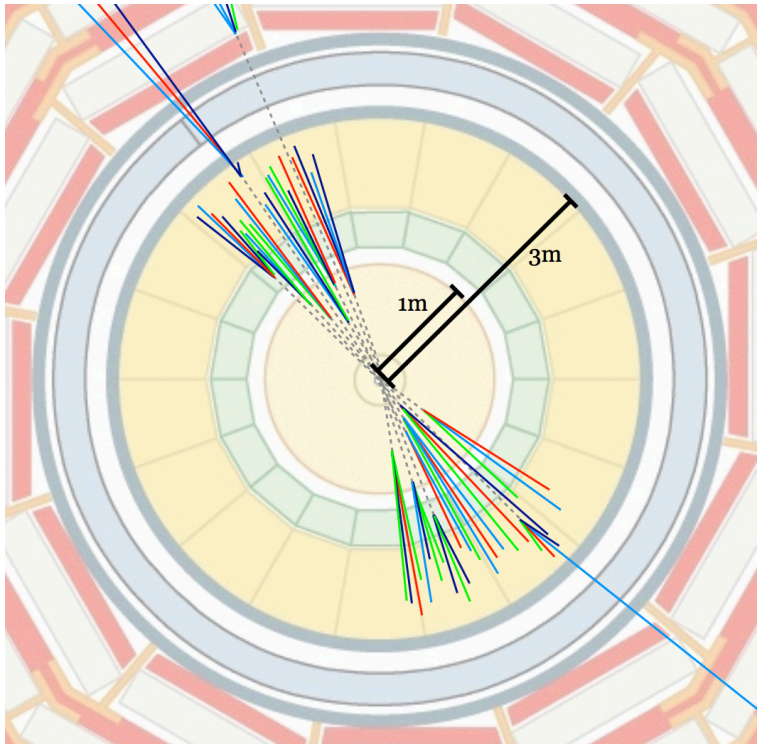
Signature: 2 SM jets + 2 Emerging jets

Emerging jets signature

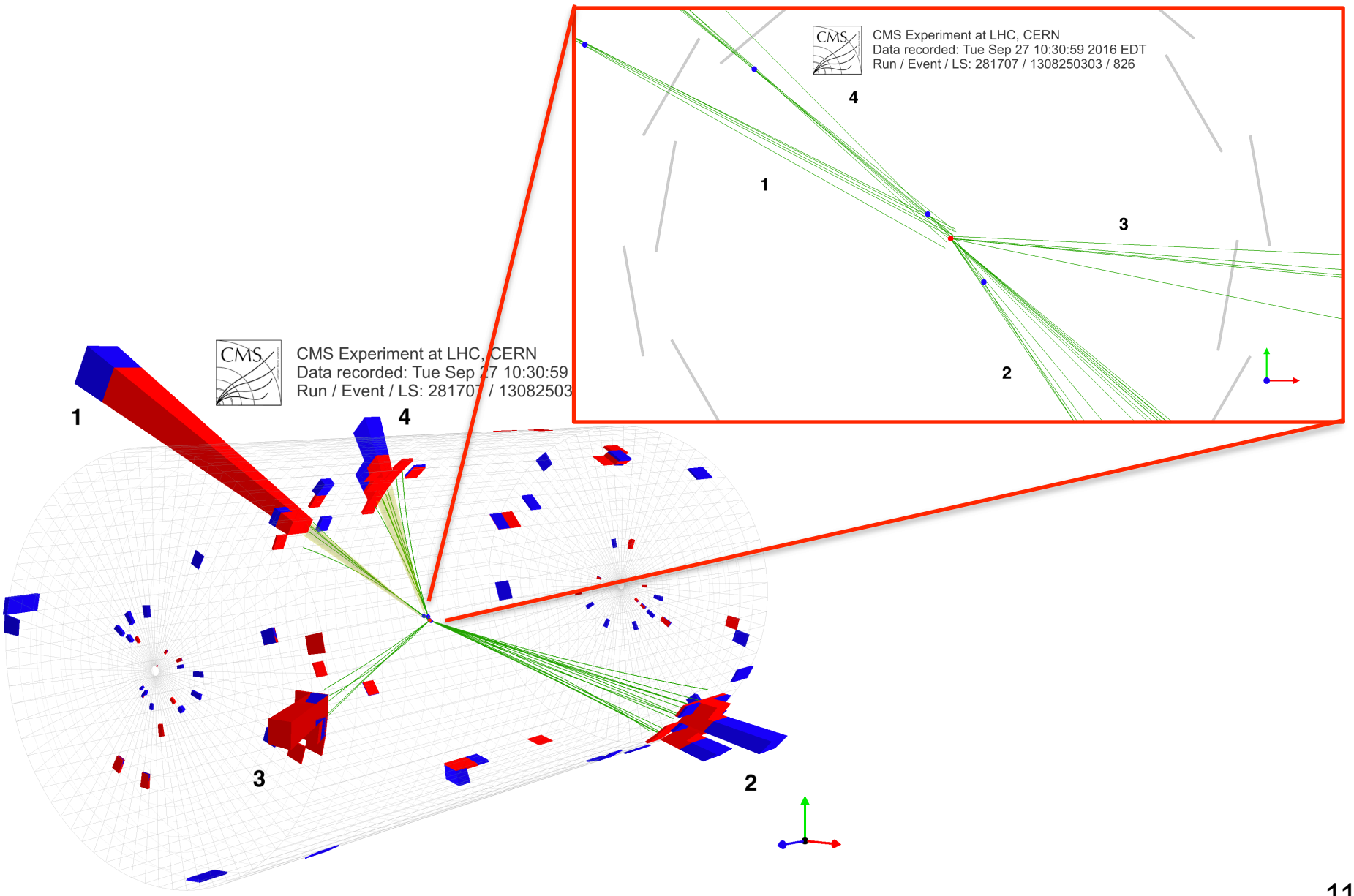
Decay length of the lightest dark meson (dark pion)

$$c\tau \approx 80\,\mathrm{mm}\left(\frac{1}{\kappa^4}\right)\left(\frac{2\,\mathrm{GeV}}{f_{\pi_{\mathrm{DK}}}}\right)^2\left(\frac{100\,\mathrm{MeV}}{m_{\mathrm{down}}}\right)^2\left(\frac{2\,\mathrm{GeV}}{m_{\pi_{\mathrm{DK}}}}\right)\left(\frac{m_{\mathrm{X_{DK}}}}{1\,\mathrm{TeV}}\right)^4$$

- Emerging jet signature:
  - Many displaced vertices from dark pion decays
  - Can have large p_T^{miss} if dark hadron decay lengths comparable with detector size



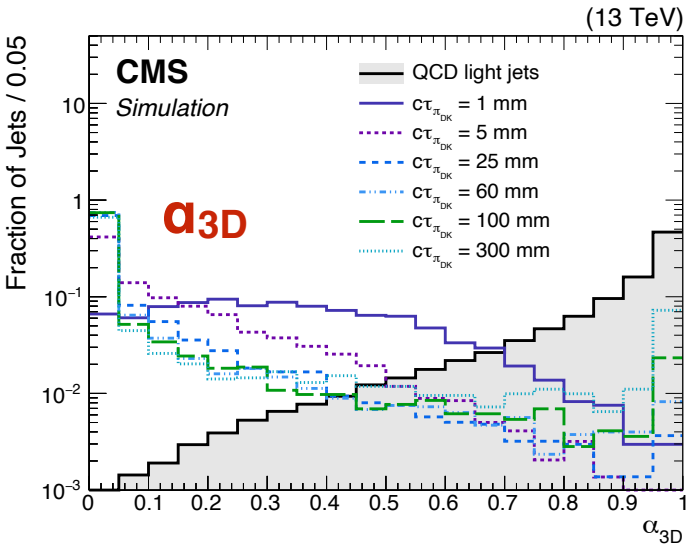
Emerging jets signature

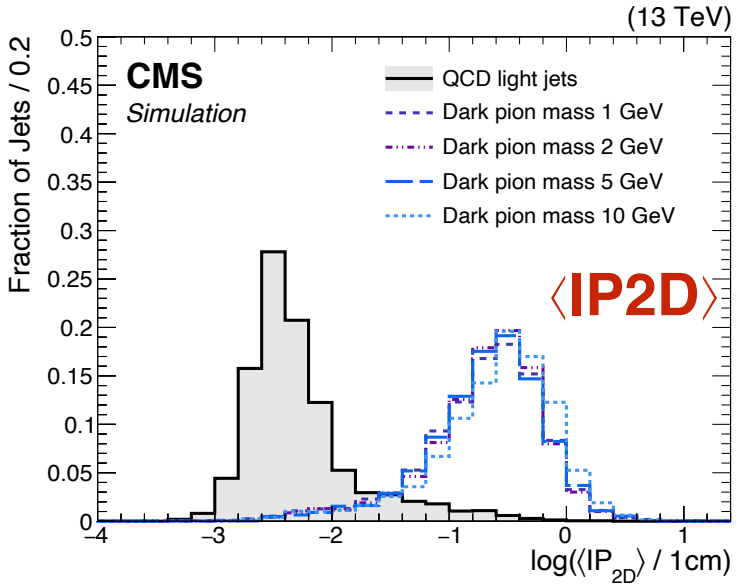


Selecting emerging-jets-like data

EJ have multiple displaced vertices → vertices far from the interaction point

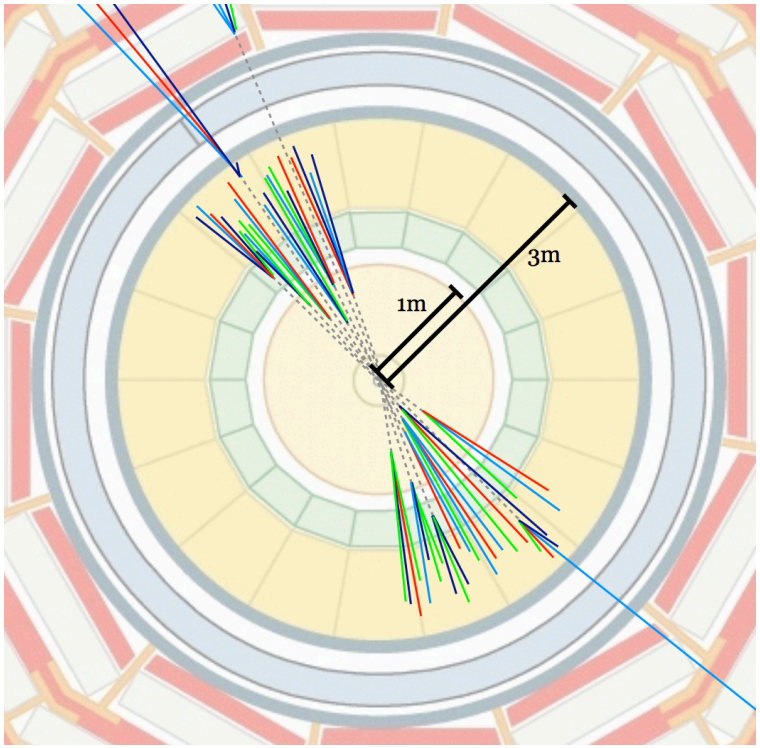
- Transverse impact parameters ($\langle IP_{2D} \rangle$) of tracks associated to the jet correlated to dark meson proper decay length
  - expected small $\langle IP_{2D} \rangle$ for SM jets
- Fraction of the jet P_T associated to prompt tracks (α_{3D})
  - expected large α_{3D} for SM jets





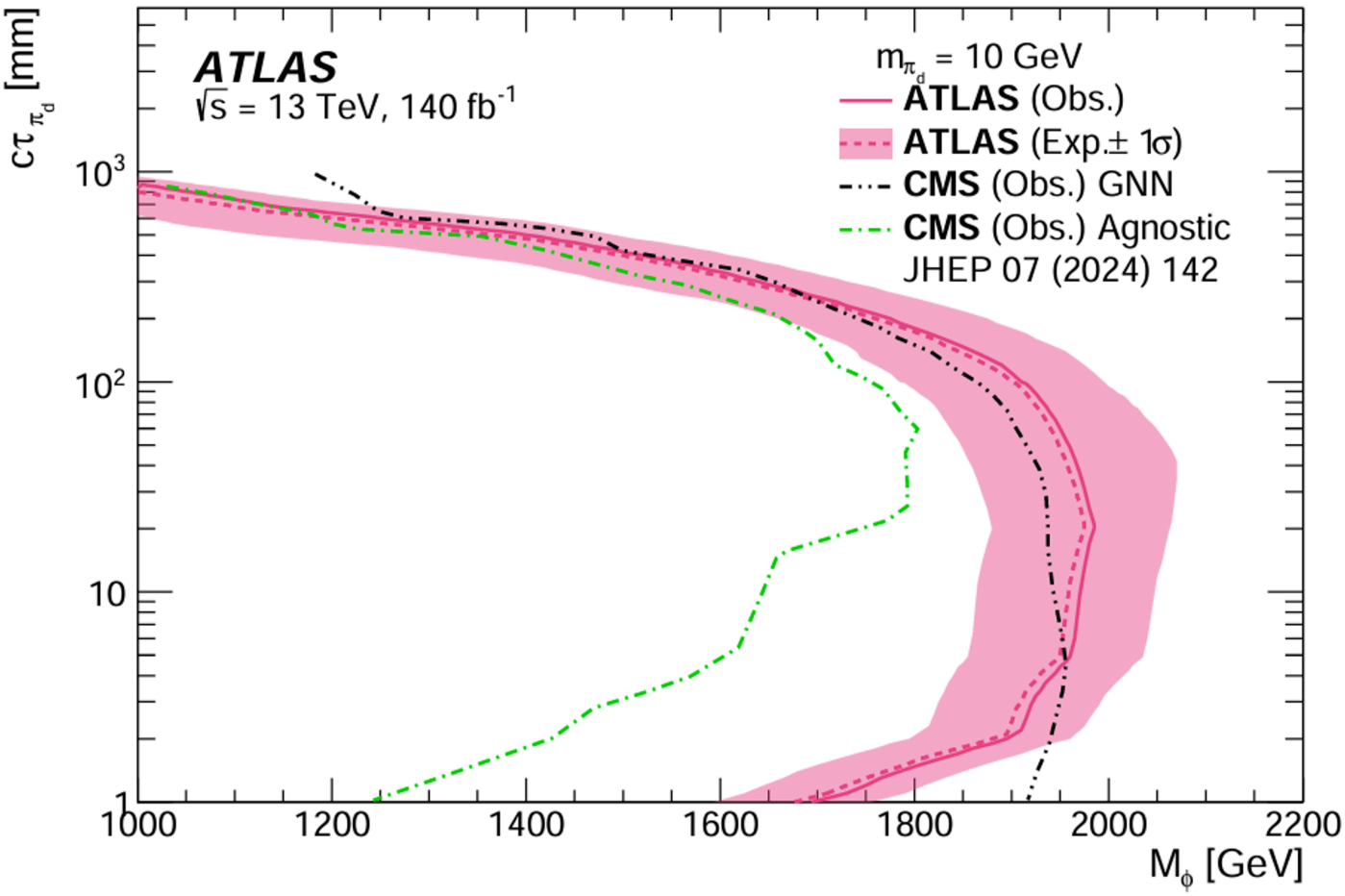
Emerging jets: backgrounds

- Main Background from multijet processes
  - Long-lived B meson content
  - Track misconstruction
  - Artificial p_T^{miss} due to jet energy mismeasurement



Emerging jets: results

No significant excess observed over SM background expectation



Semivisible jets

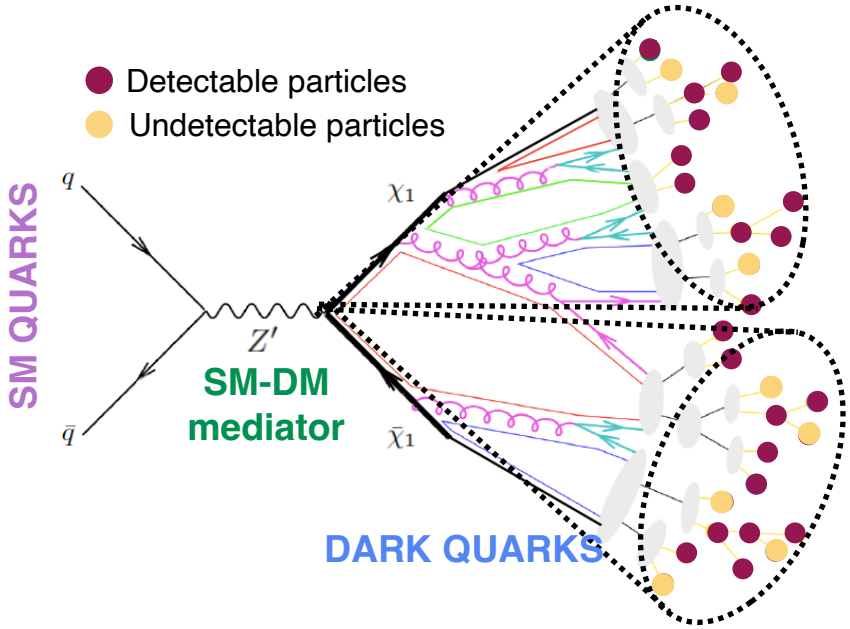
In other Dark QCD models, dark quarks undergo parton shower and hadronization similarly to SM quarks, producing dark jets at colliders

Stable dark hadrons remain invisible
Unstable dark bund states decay to visible SM hadrons

What we can observe

An hadronic jet containing visible and invisible particles

Semivisible Jets

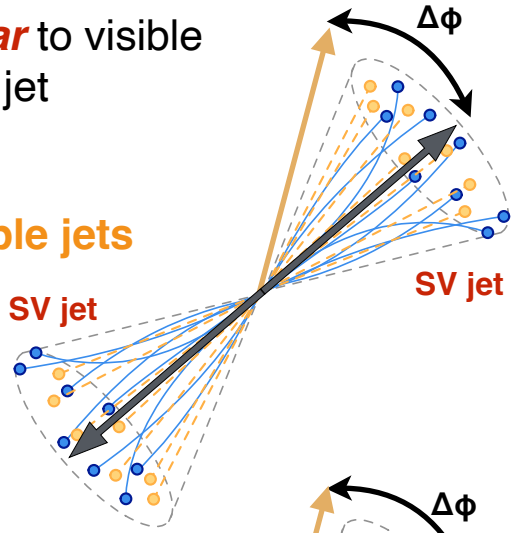


Showing a mix of techniques from 10.1007/JHEP06(2022)156 and CMS-PAS-EXO-24-029, but the story is consistent between the two

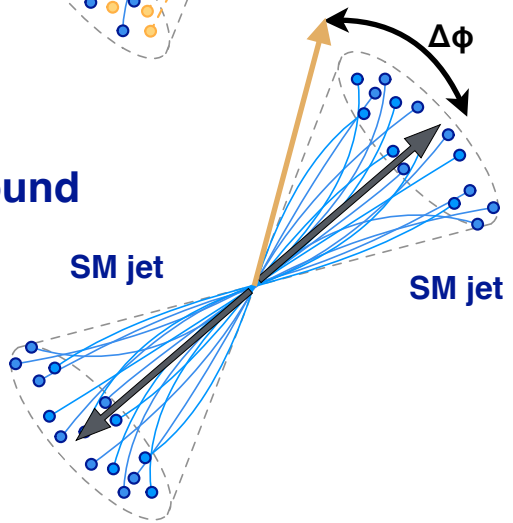
Semivisible jets characteristics

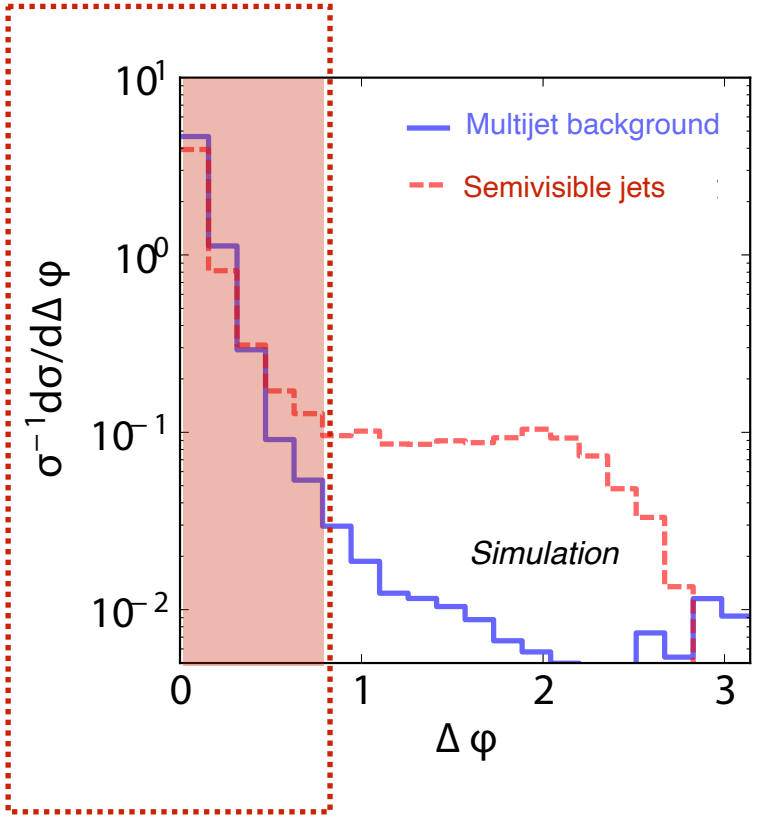
Missing momentum ***collinear*** to visible jet

Semivisible jets



Background





SV jets lays in a region affected by multijet background

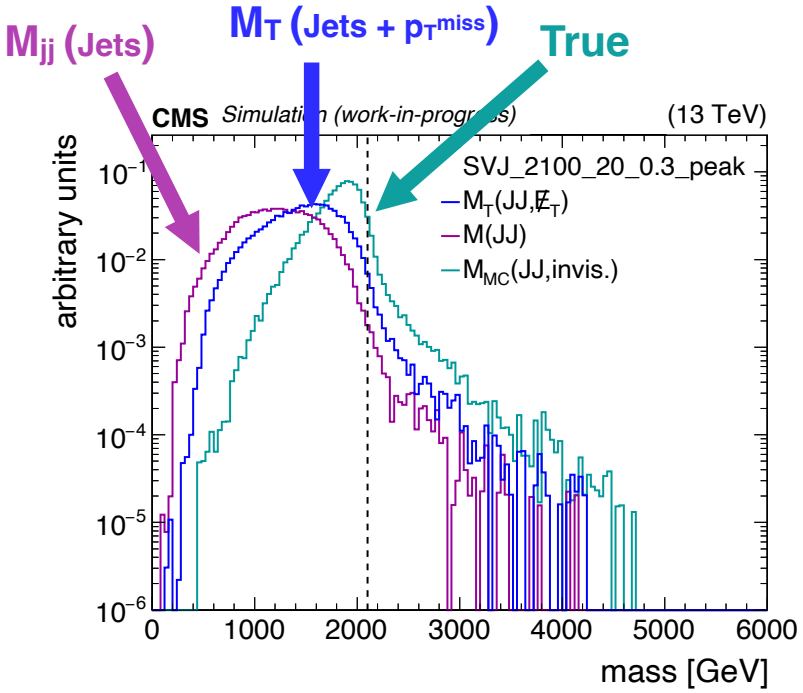
Mediator reconstruction

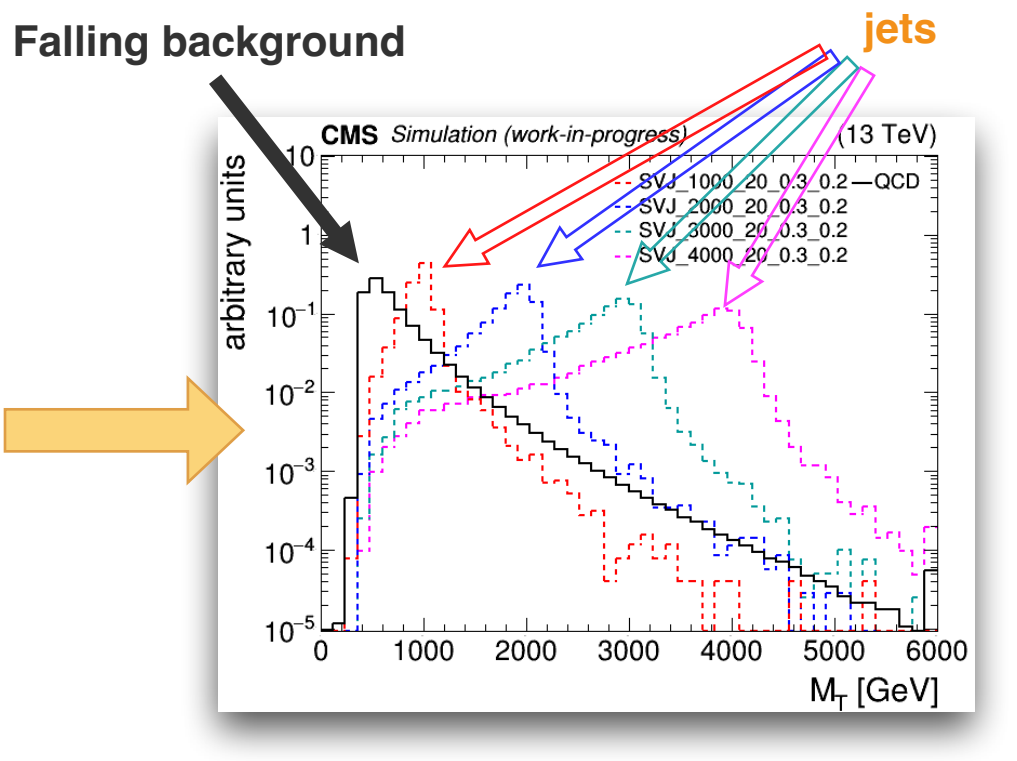
The mediator mass can be partially reconstructed

- Reconstruction of mediator mass from visible jets and p_T^{miss}

$$M_T^2 = M_{jj}^2 + 2\left(\sqrt{M_{jj}^2 + p_{T,jj}^2 p_T^{miss}} - \vec{p}_{T,jj} \cdot \vec{p}_T^{miss}\right)$$

M_T has a better resolution than M_{jj} endpoint at $M_{Z'}$



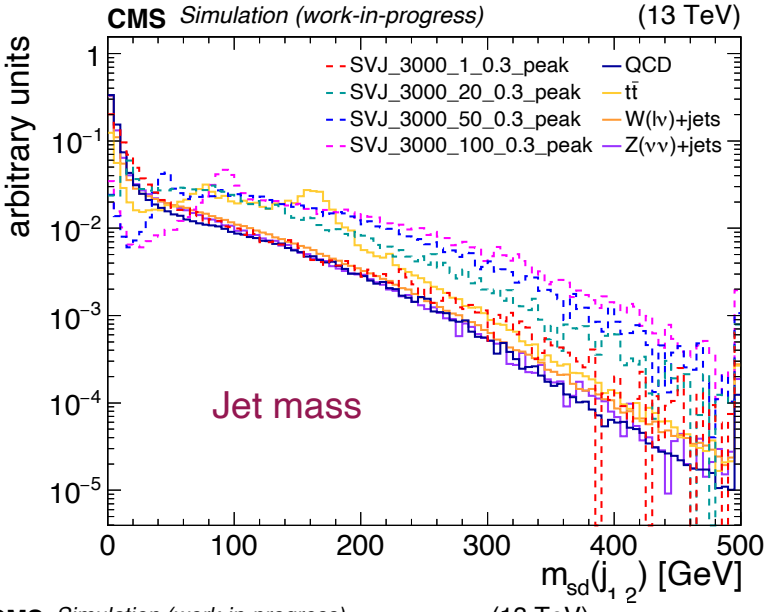


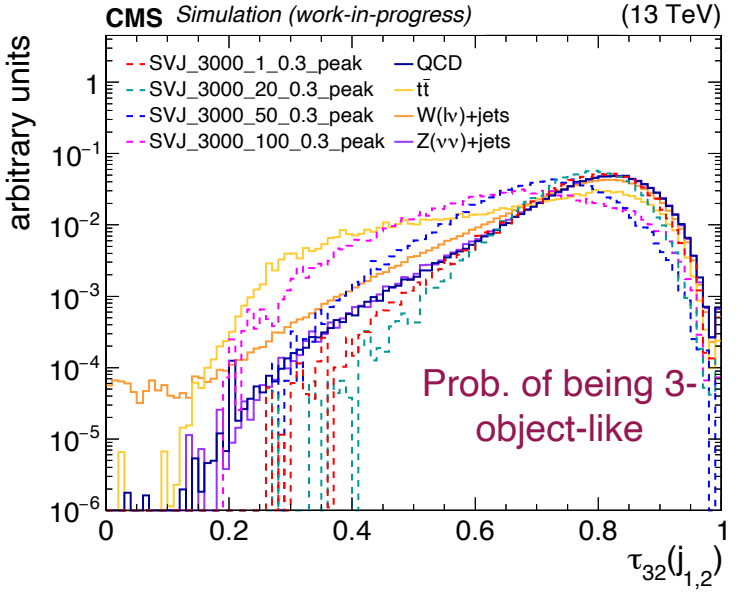
SVJ Identification

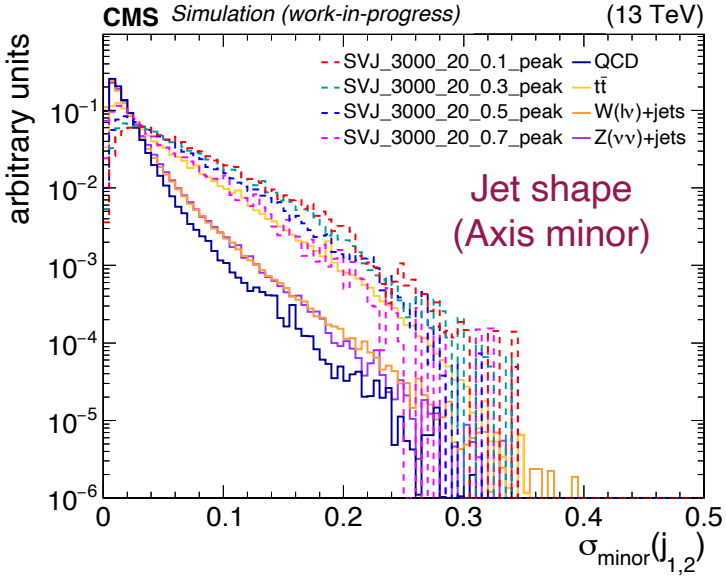
Make use of Different underlying interactions between SM and dark quarks translate in a different development of the shower

- Jet internal structure reflects the shower and hadronization process
- ML techniques used to push the discrimination power of substructure variables

Multijet
$t\bar{t}$
Signal

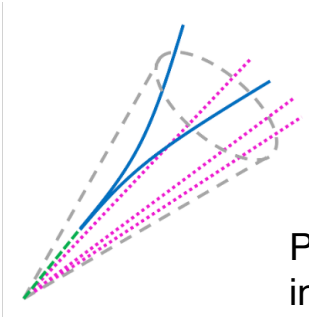




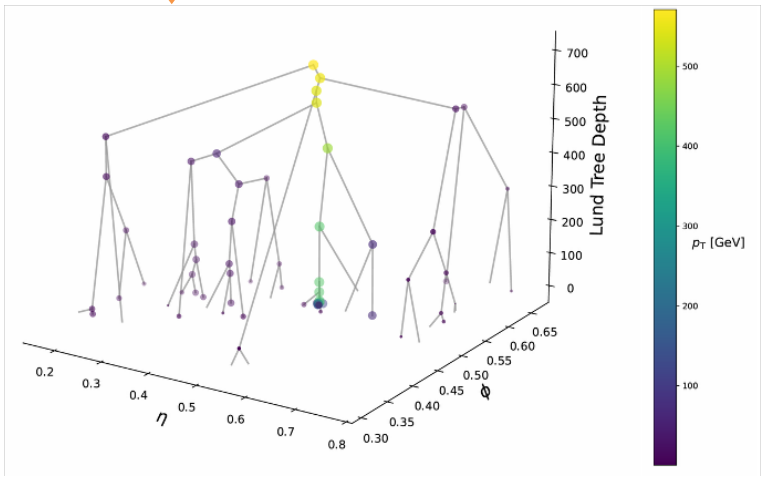


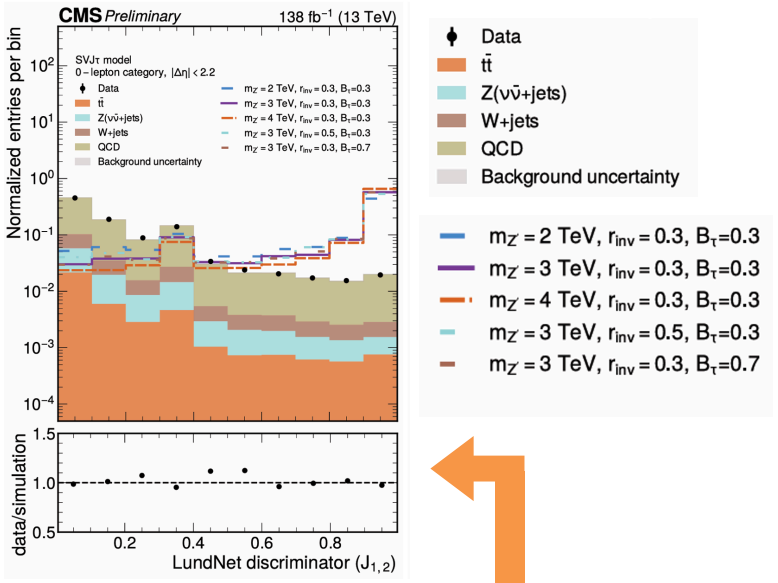
SVJ Identification

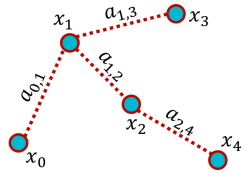
Exploiting the internal jet structure helps in rejecting the otherwise irreducible QCD background



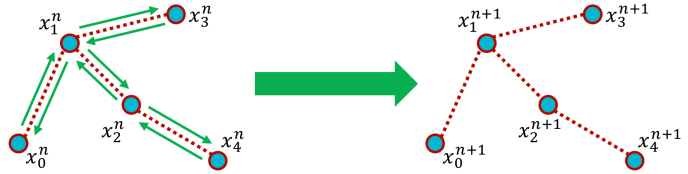
Particles are clustered into jets, and the entire clustering history is saved encoded into a tree





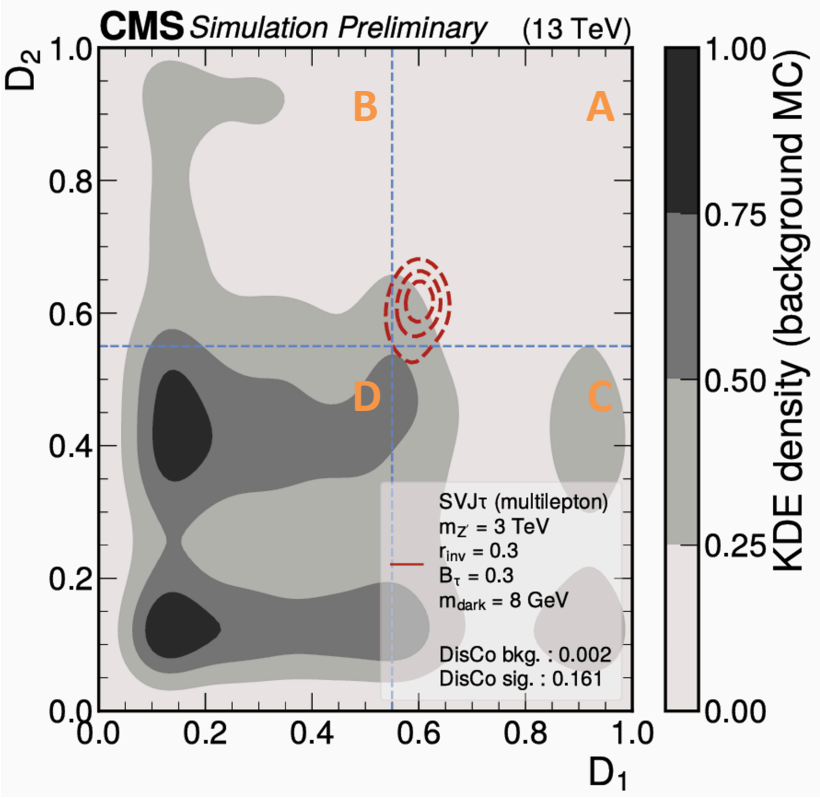


The tree is fed to a graph neural network and transformed into a prediction



Background estimation

Data-driven estimation of the background: a pair of networks are trained simultaneously to be both **discriminative** and **independent**



If $p(D_{1,2} \mid D_{2,1}) = P(D_{1,2})$, then we can write:

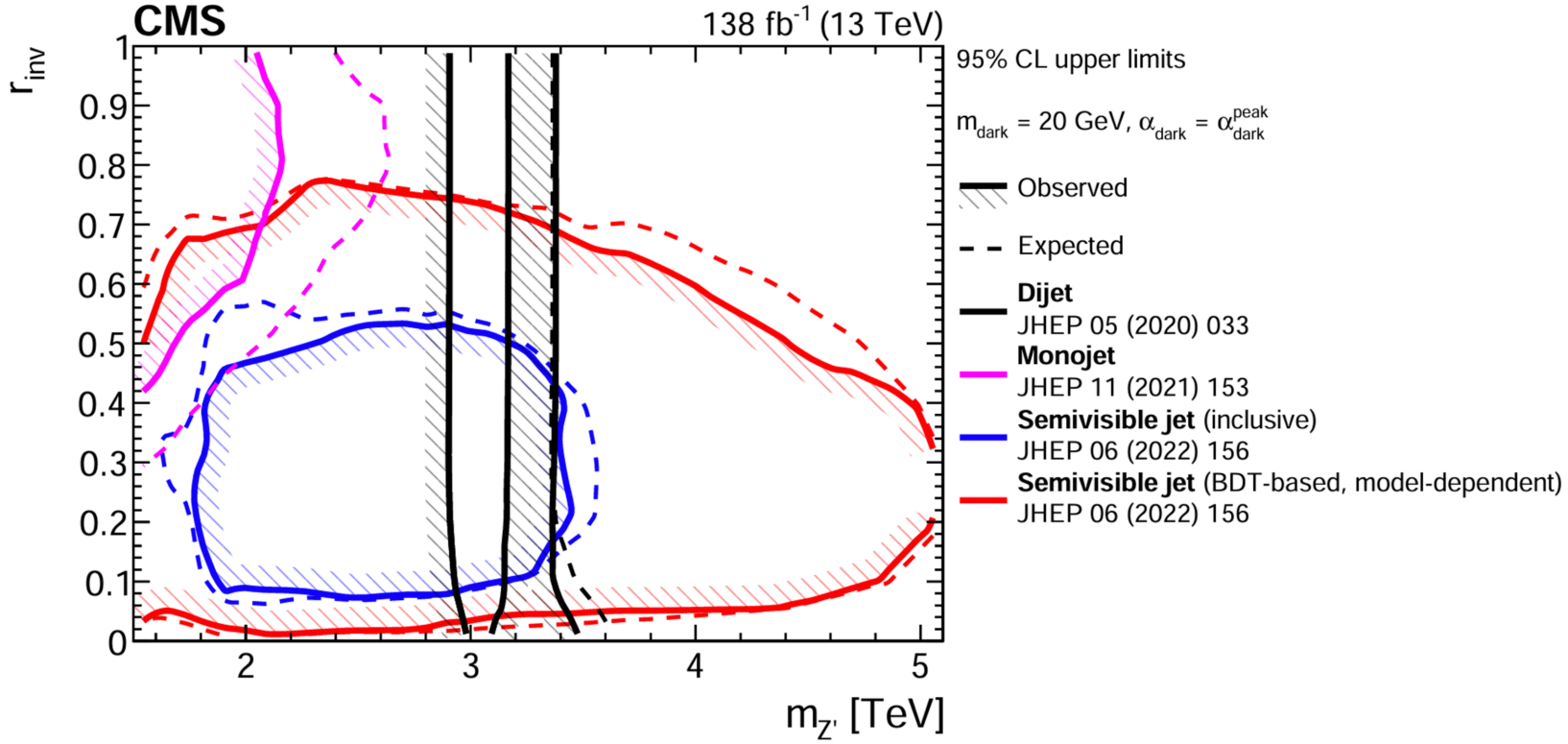
$$N_A/N_B = N_C/N_D \Longrightarrow N_A = \frac{N_C}{N_D} N_B$$

We do this in every bin of M_T and get a data-driven description of the background!

Results interpretation

Specifically targeting dark QCD signature significantly improves over standard searches

Looking into the internal jet structure pushes a lot our sensitivity to dark QCD models



Summary

- Hidden Valley models lead to a variety of atypical signatures at colliders
  - Many new searches looking for Long Lived Particles (LLP), often sensitive to other BSM too
- Current collider experiments designed to detect prompt particles
  - New reconstruction and selection algorithms conceived to cope with this limitation
- More obvious searches are quite consolidated
  - Searches for Hidden Valley models are just at a start

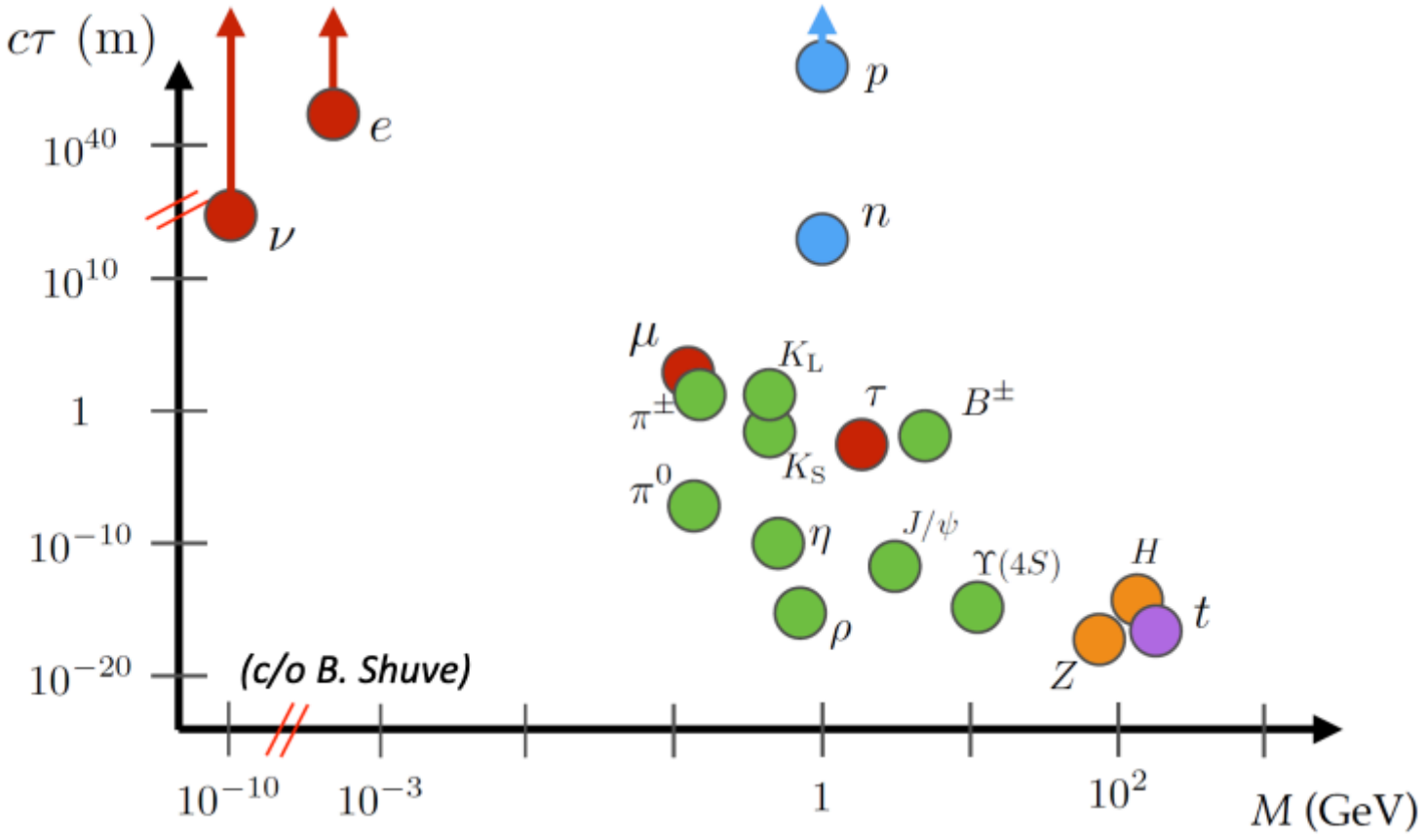
References

- CMS Public Results
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
- ATLAS Public Results
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Additional material

Long-lived particles in SM

The SM is full of long-lived particles



BSM world may be full of long-lived particles too