Searching for New Physics in

Soft Unclustered Energy Patterns

at the LHC

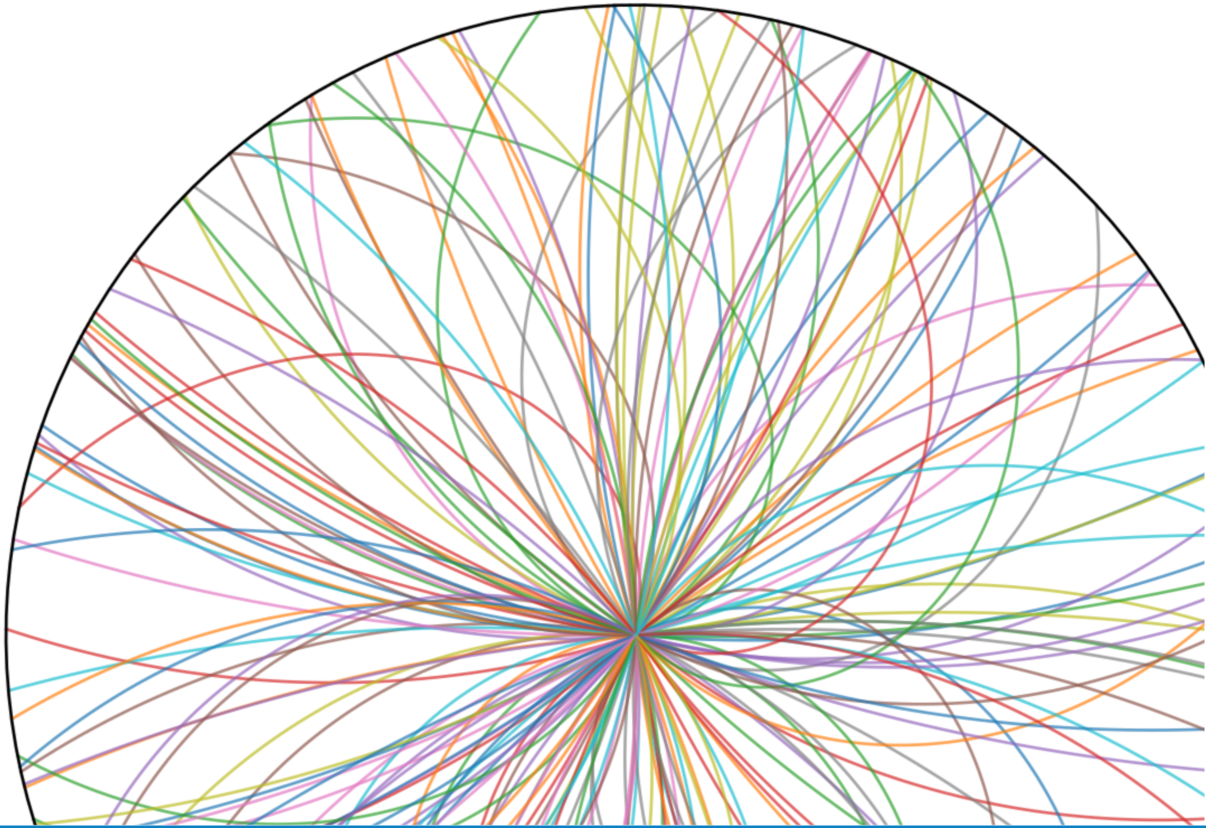
DPG Frühjahrstagung 2025 - Göttingen

Alexander Lory

LMU Munich, AG Biebel

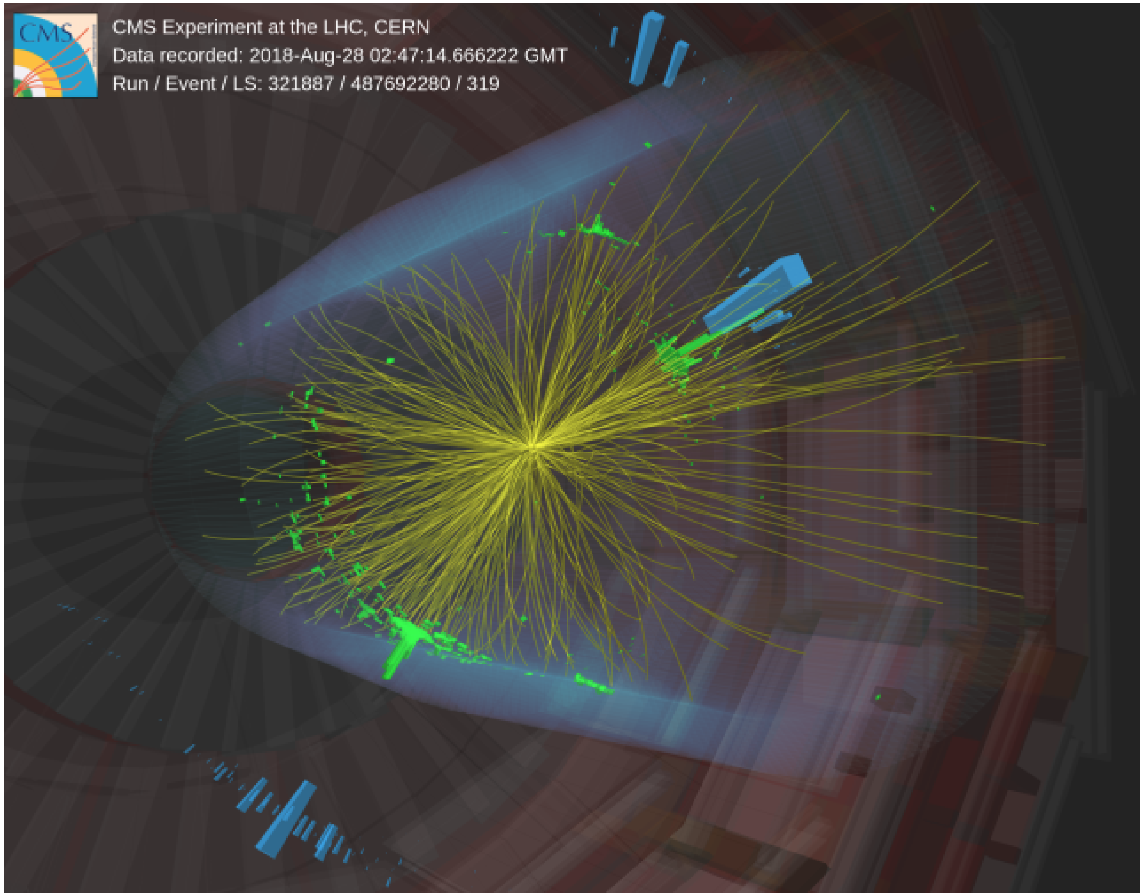
LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

FSP ATLAS Erforschung von Universum und Materie



Soft Unclustered Energy Patterns (SUEPs)

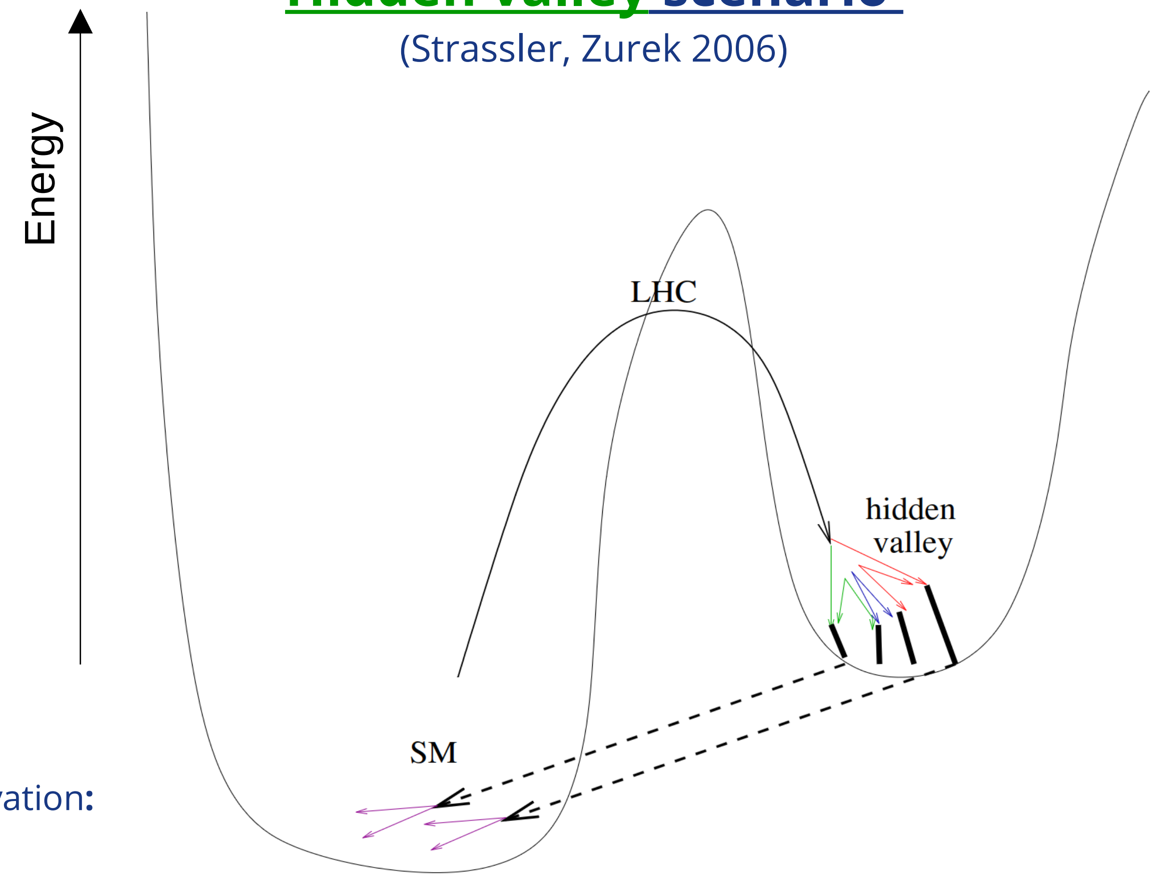
- High particle multiplicity (100 – 10’000)
- Soft particles (few GeV or below)
- Spherically distributed → In contrast to SM QCD



A sign for a strongly coupled, quasi-conformal Hidden Valley (HV)

Hidden valley scenario

(Strassler, Zurek 2006)



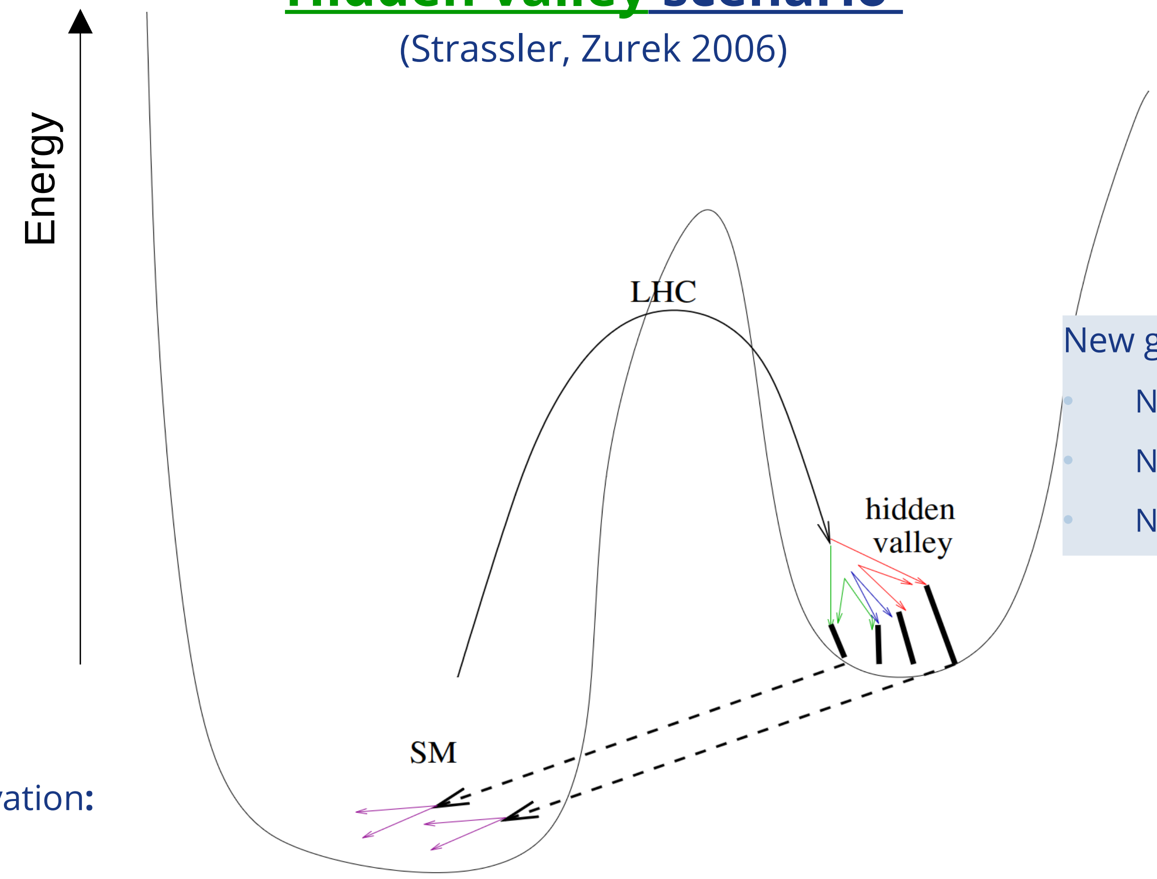
Hidden valley motivation**:**

- String theory

Adapted from: arXiv:0801.0629

Hidden valley scenario

(Strassler, Zurek 2006)



New gauge group

- New interaction
- New light particles (~ GeV)
- Not charged under SM

Hidden valley motivation**:**

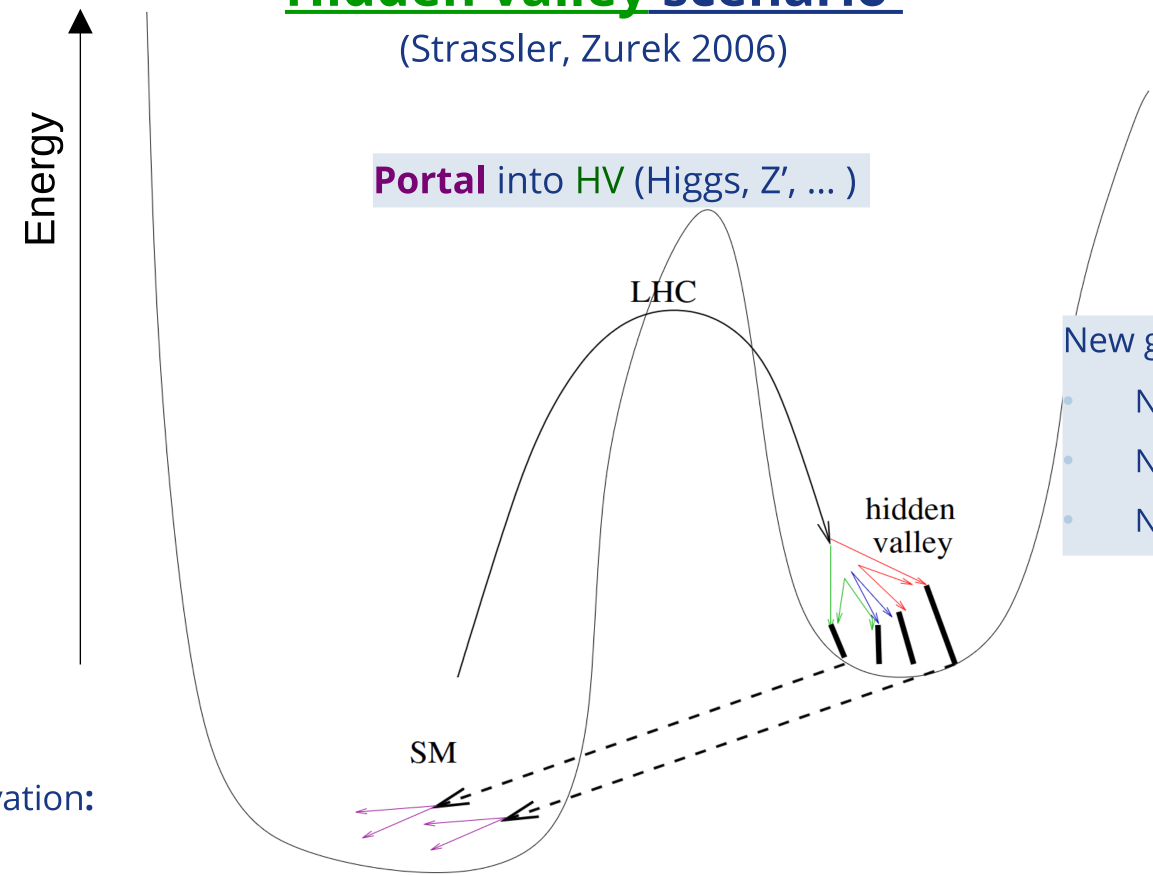
- String theory

Adapted from: arXiv:0801.0629

Hidden valley scenario

(Strassler, Zurek 2006)

Portal into HV (Higgs, Z', ...)



New gauge group

- New interaction
- New light particles (~ GeV)
- Not charged under SM

Hidden valley motivation**:**

- String theory

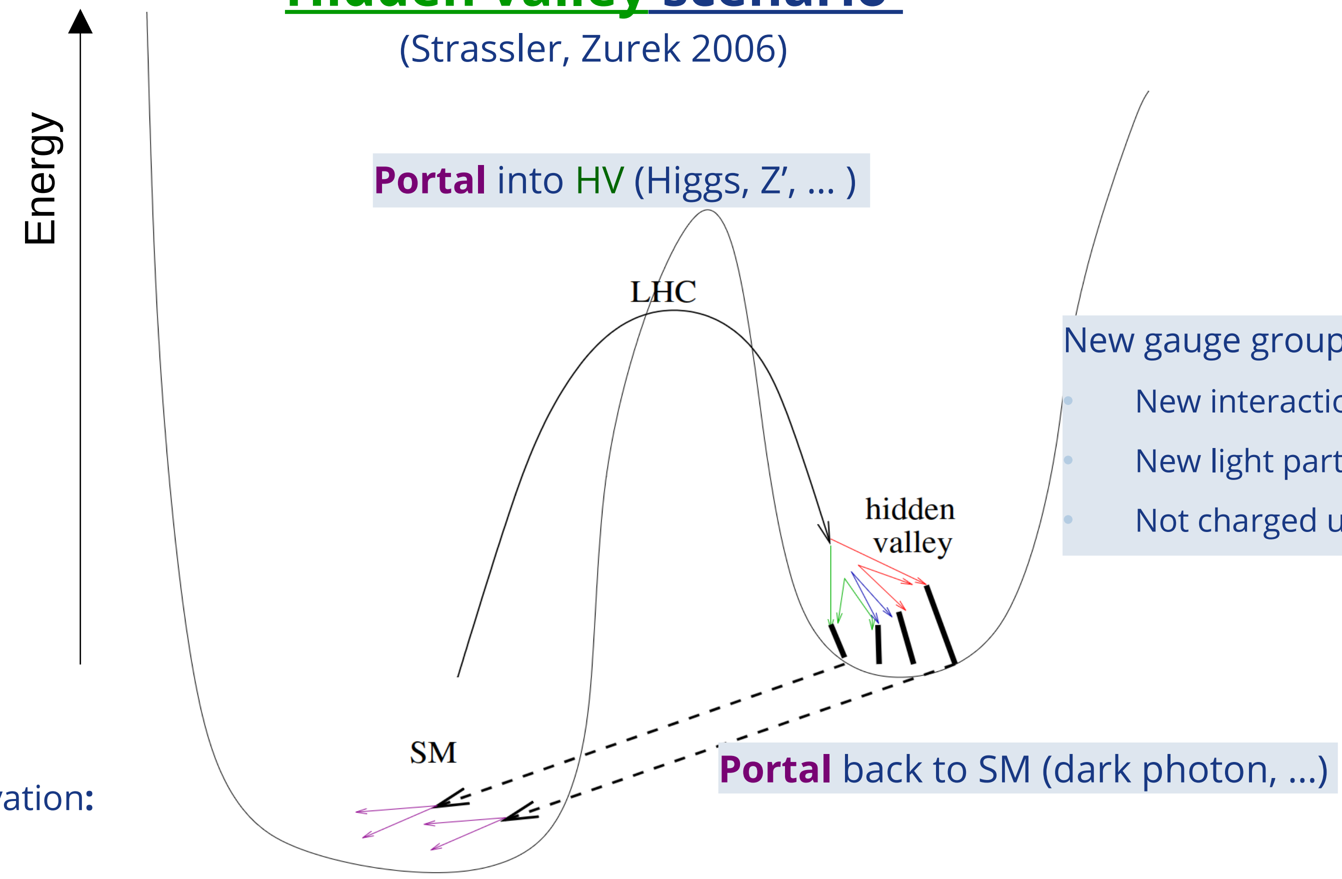
Portal interaction:

- **Any allowed interaction** connecting the sectors
- Examples:
  - Into the HV: **exotic Higgs decay**

Adapted from: arXiv:0801.0629

Hidden valley scenario

(Strassler, Zurek 2006)



New gauge group

- New interaction
- New light particles (~ GeV)
- Not charged under SM

Hidden valley motivation**:**

- String theory

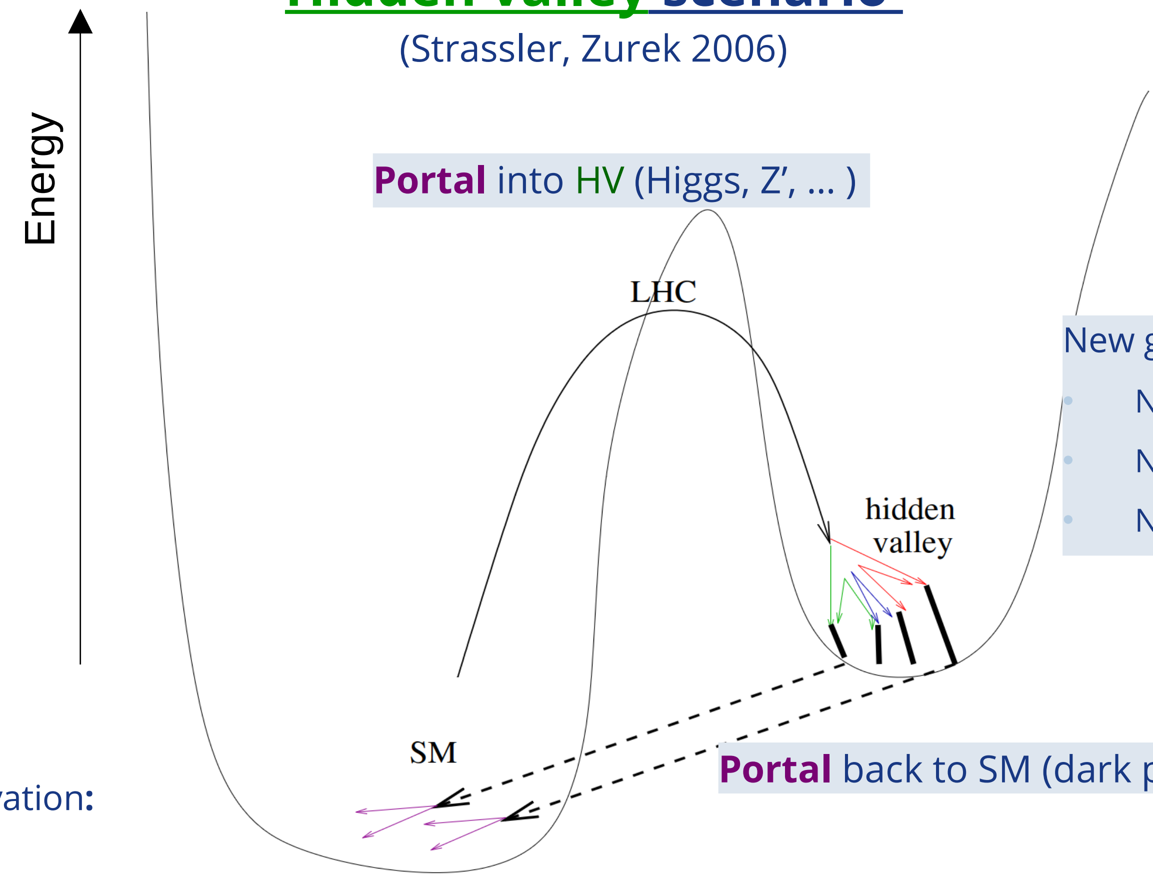
Portal interaction:

- **Any allowed interaction** connecting the otherwise uncharged sectors
- Examples:
  - Into the HV: **exotic Higgs decay**
  - Back to the SM: kinetic mixing of photon – **dark photon**

Adapted from: arXiv:0801.0629

Hidden valley scenario

(Strassler, Zurek 2006)



Portal into HV (Higgs, Z', …)

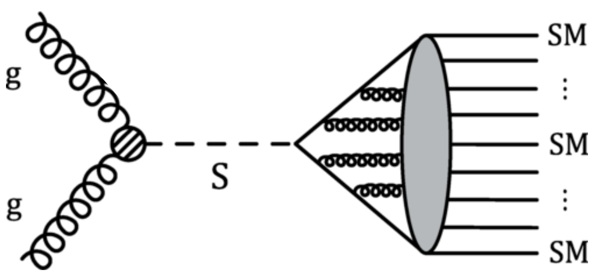
New gauge group
- New interaction
- New light particles (~ GeV)
- Not charged under SM

Portal back to SM (dark photon, …)

Hidden valley motivation**:**
- String theory

Strongly coupled hidden valley:

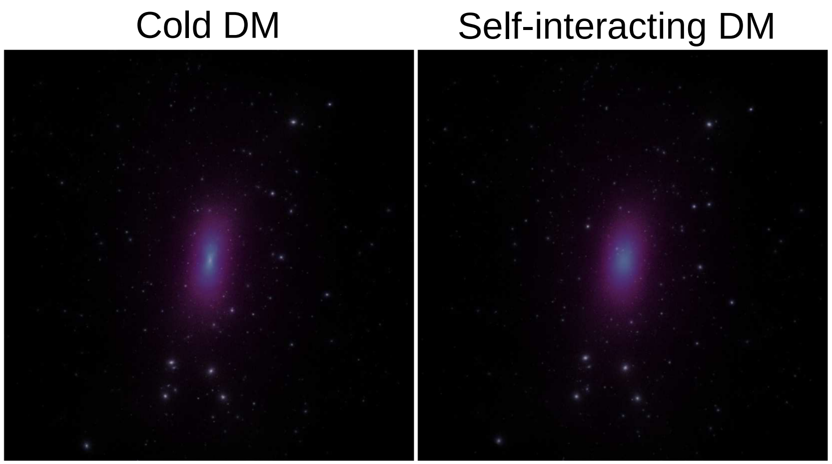
- New interaction is a QCD-like, **strong interaction**
- Dark quarks form **bound states** (dark mesons, baryons, …)
- At LHC: ***dark showers*** ("hidden" showers)



Adapted from
Phys. Rev. Lett. 133, 191902

Strongly coupled Hidden sectors as Dark Matter (DM)

- Good DM candidate:
  - **Stable** dark hadrons
  - **No interaction** with the SM
  - Sizeable **self interaction**
    - "Cusp-core problem"
    - …

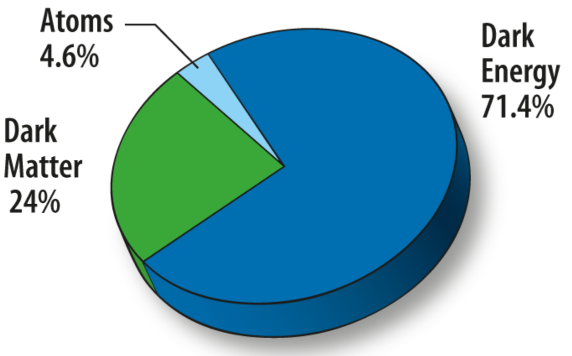


Adapted from: Rocha et al. (2013), MNRAS, 430, 81–104

- DM relic density:
  - **matter – antimatter asymmetry** shared between DM and baryonic matter
    - *Asymmetric Dark Matter* Phys. Rev. D 79, 115016 (2009)

  → portal interaction allows sharing the asymmetry

  ~ 5 GeV DM

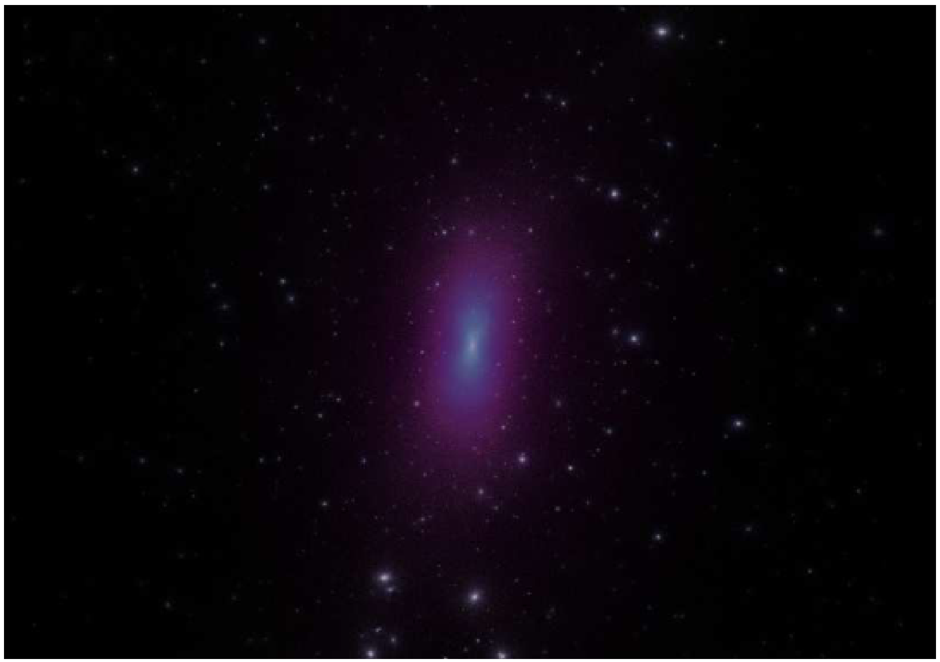


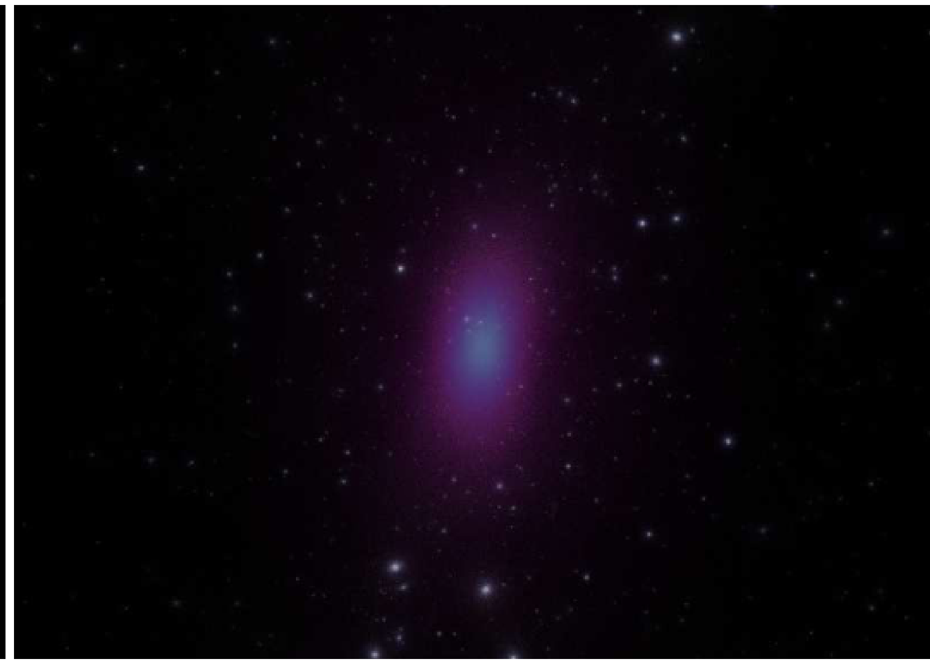
wmap.gsfc.nasa.gov

Galaxy halos - ***cusp-core problem***

Cold DM
(simulation)

Self-interacting DM
(simulation)





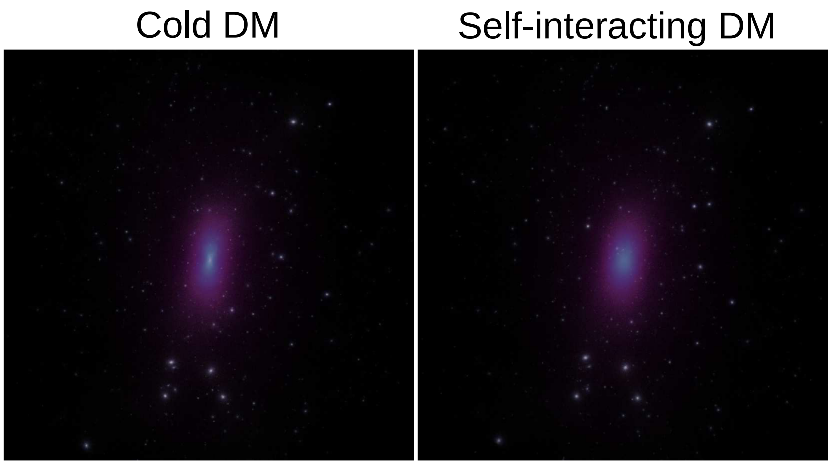
Adapted from: Rocha et al. (2013), MNRAS, 430, 81–104

“Cuspy” core
(not observed)

Washed out core
(what we observe)

Strongly coupled Hidden sectors as Dark Matter (DM)

- Good DM candidate:
  - **Stable** dark hadrons
  - **No interaction** with the SM
  - Sizeable **self interaction**
    - “Cusp-core problem”
    - …

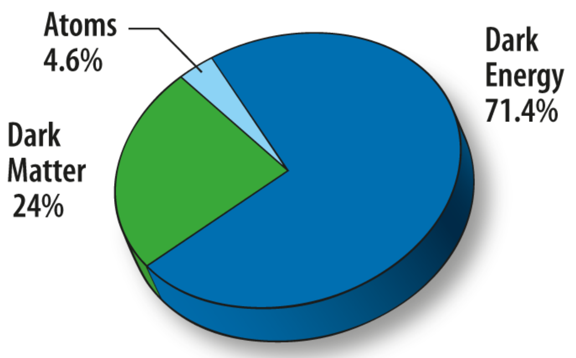


Adapted from: Rocha et al. (2013), MNRAS, 430, 81–104

- DM relic density:
  - **matter – antimatter asymmetry** shared between DM and baryonic matter
    - *Asymmetric Dark Matter* Phys. Rev. D 79, 115016 (2009)

  → portal interaction allows sharing the asymmetry

  ~ 5 GeV DM

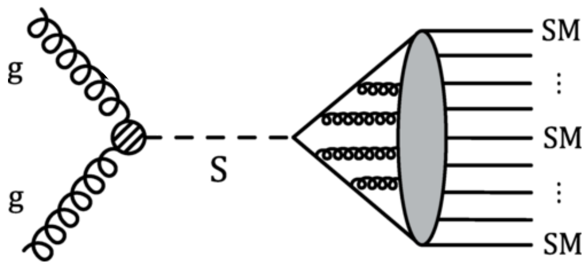


wmap.gsfc.nasa.gov

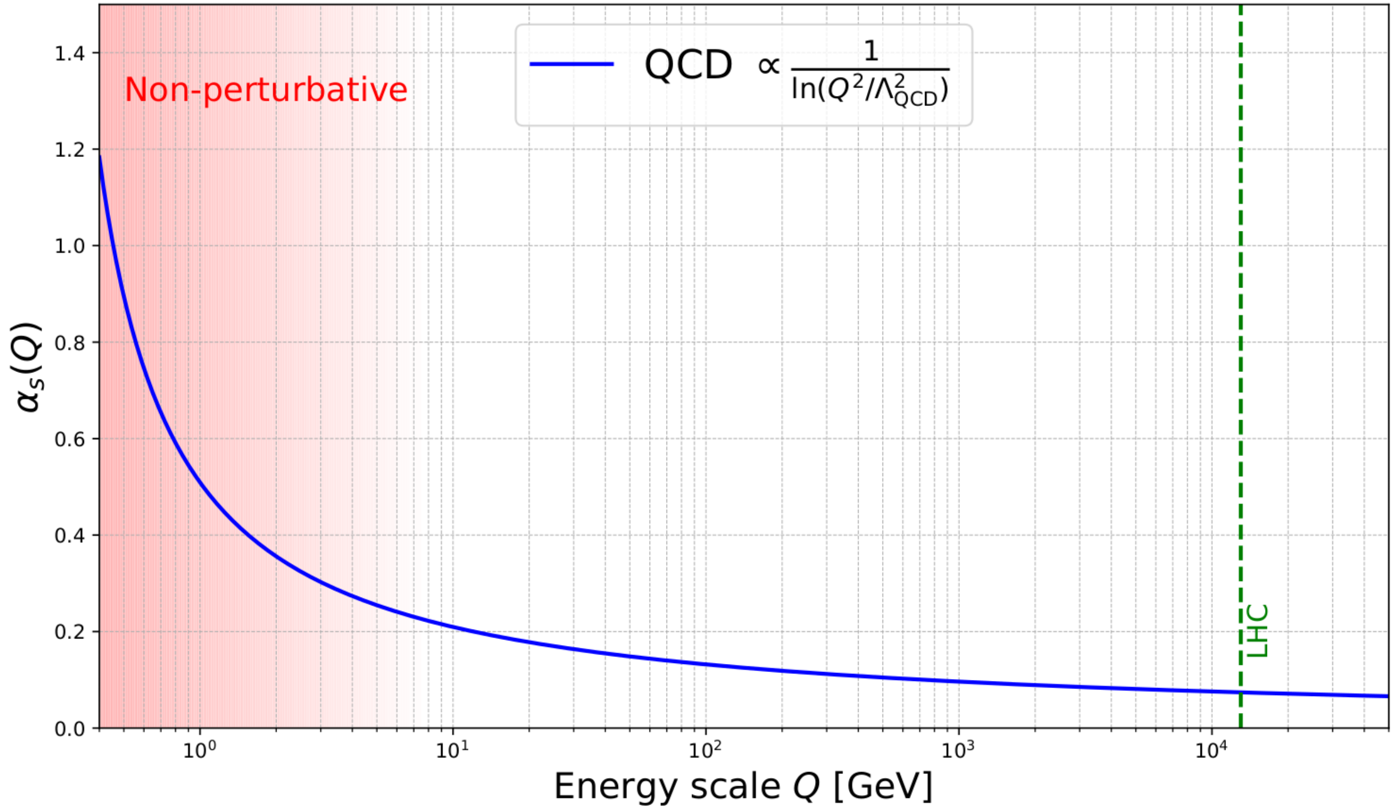
What to expect from a **dark shower** at the LHC (1/2)

The strong coupling dictates the shape of the shower

- Coupling similar to SM QCD?
  - → shower with enhanced emission of soft and collinear partons
  - → **jet formation**



Adapted from
Phys. Rev. Lett. 133, 191902



Searches for dark showers **with jet formation**

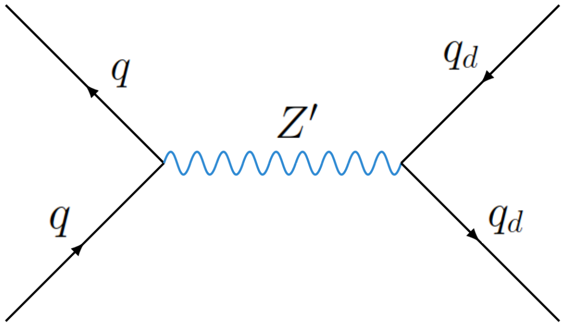
(examples)

- Searches for **heavy dijet resonances**
  ATLAS: J. High Energ. Phys. 2020, 145 (2020)
  CMS: J. High Energ. Phys. 2023, 161 (2023)

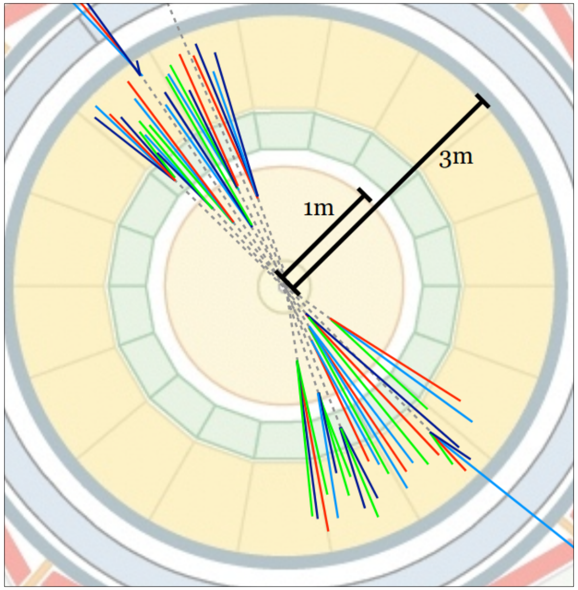
- Search for dark quarks (**"unusual" jets**)
  ATLAS: J. High Energ. Phys. 2024, 128 (2024)

- Displaced decays of dark hadrons: ***Emerging jets***
  CMS: J. High Energ. Phys. 2024, 142

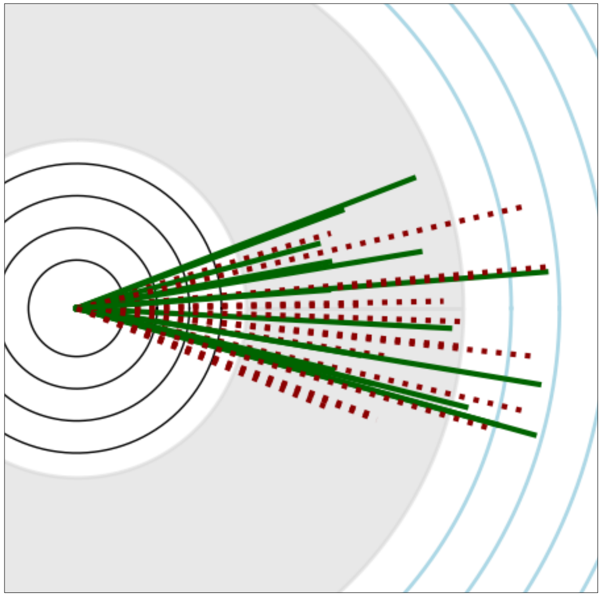
- Containing some stable dark hadrons: ***Semi-visible jets***
  ATLAS: Phys. Lett. B 848 (2024) 138324
  CMS: J. High Energ. Phys. 2022, 156 (2022)



Adapted from:
J. High Energ. Phys. 2024, 128 (2024)



Emerging jets
adapted from: J. High Energ. Phys. 2015, 59 (2015)



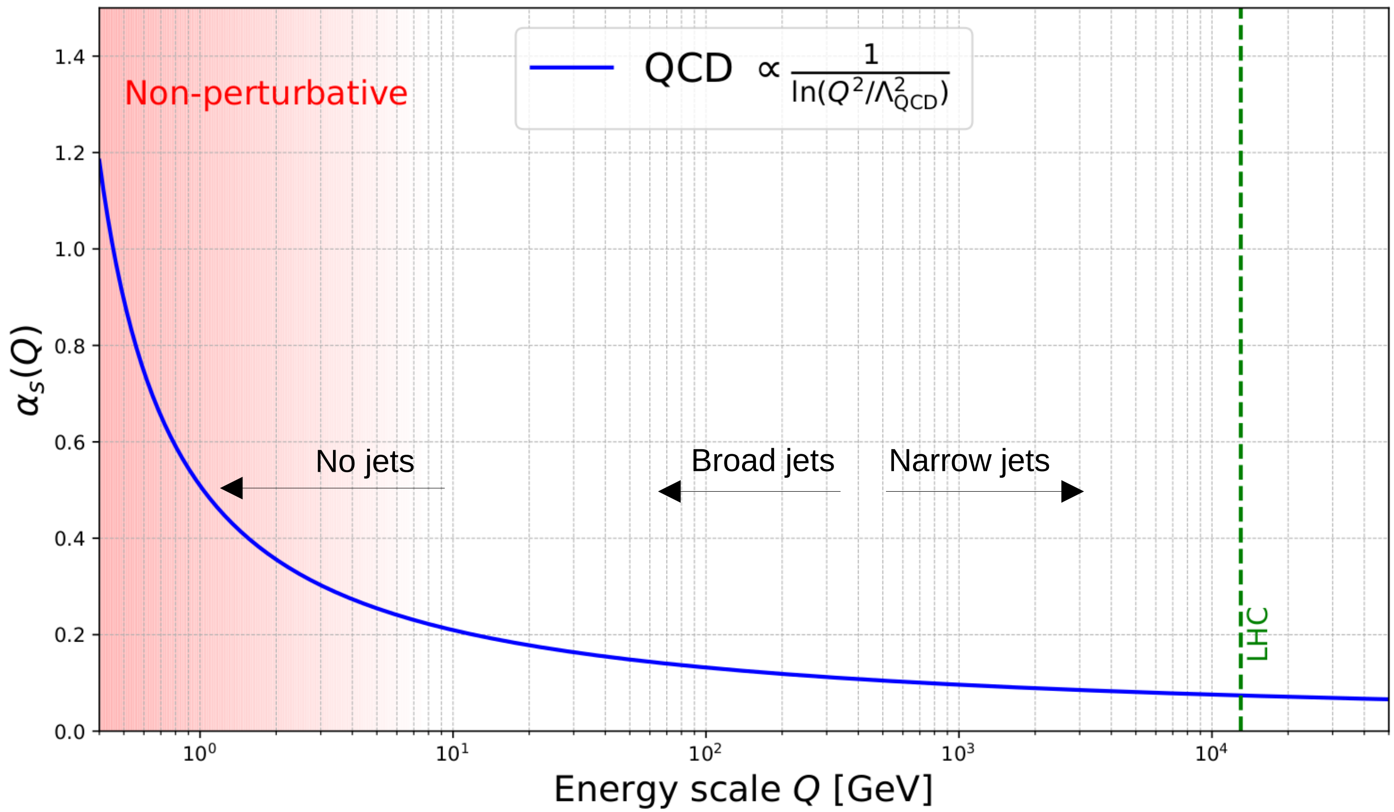
Semi-visible jets

No sign of new physics in the dark shower searches so far

So what if the dark shower doesn’t produce jets?

What to expect from a **dark shower** at the LHC (2/2)

- QCD: no jet formation below ~ 10 GeV
- Using anti-de-Sitter/conformal field theory correspondence:
  - Spherically symmetric distributions are expected for collisions in the non-perturbative region
    J. High Energ. Phys. 2008, 012 (2008)



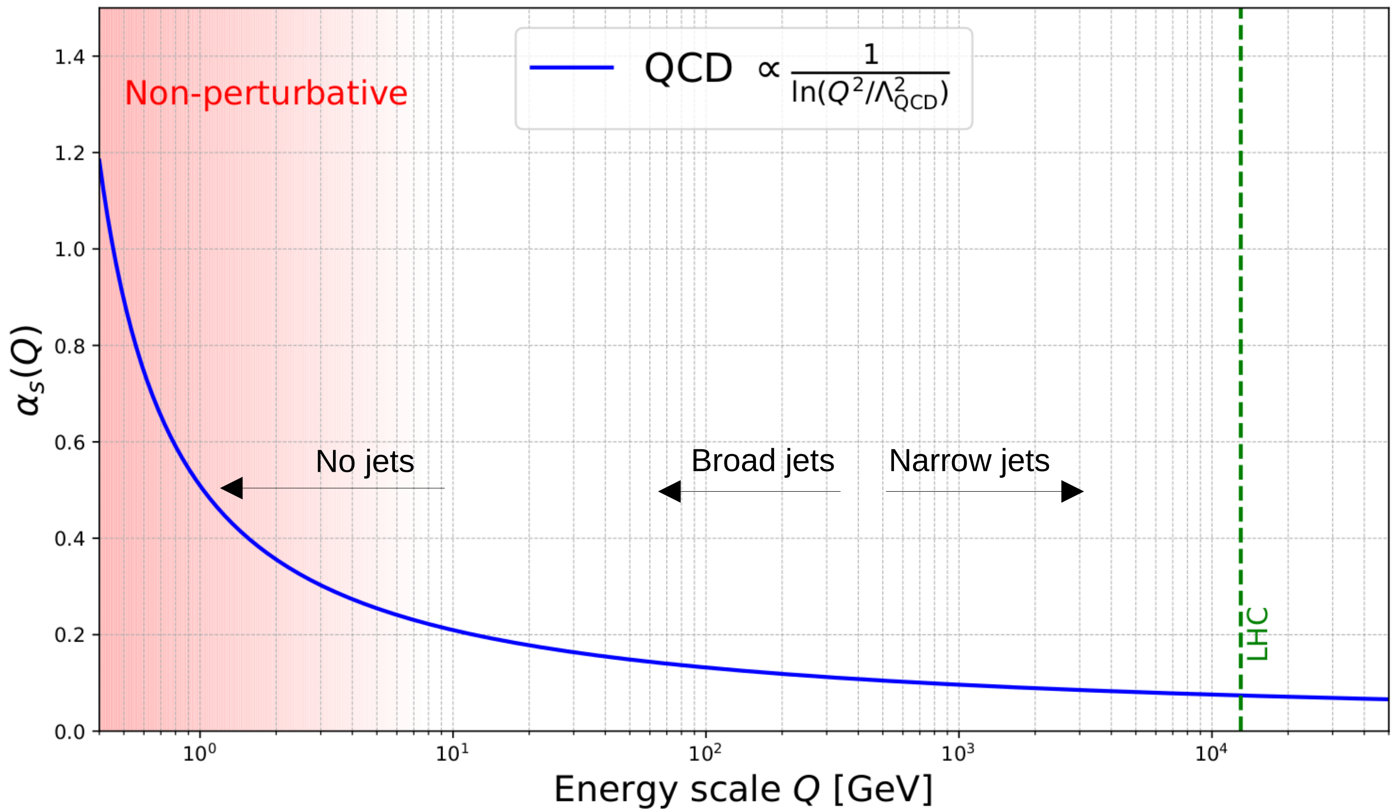
What to expect from a **dark shower** at the LHC (2/2)

- QCD: no jet formation below ~ 10 GeV
- Using anti-de-Sitter/conformal field theory correspondence:
  - Spherically symmetric distributions are expected for collisions in the non-perturbative region

    J. High Energ. Phys. 2008, 012 (2008)

SUEP: Extended the non-perturbative regime towards high energies

→ slow running of the coupling (quasi-conformal)



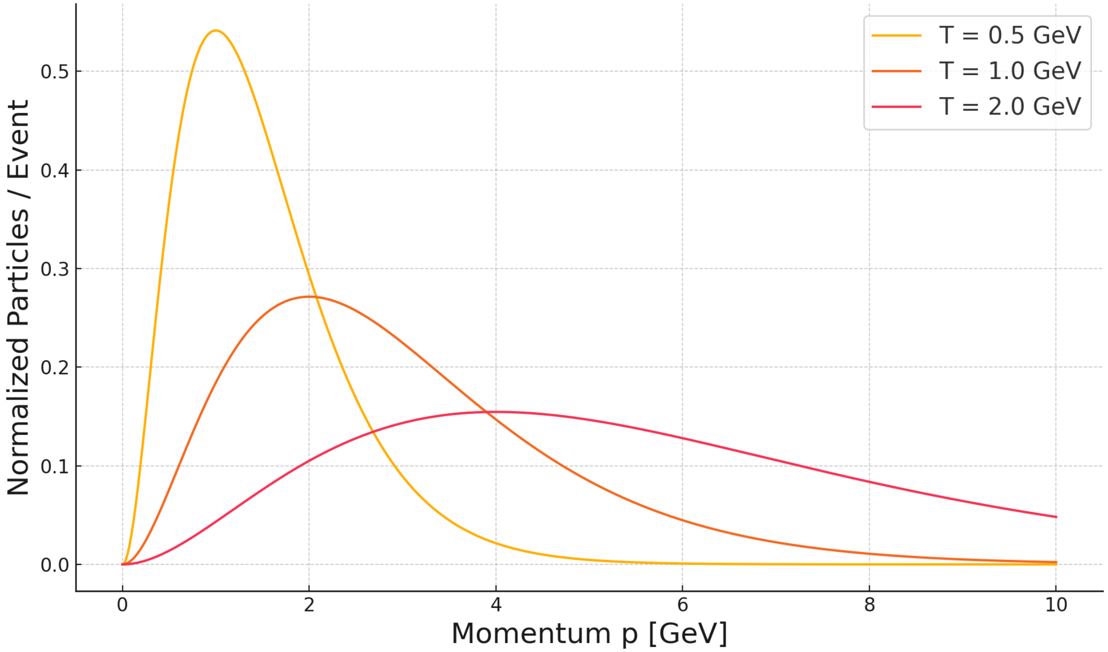
A SUEP is a plausible manifestation of a dark shower inspired by the non-perturbative regime of QCD

SUEP simulation https://gitlab.com/simonknapen/suep_generator

- Non-perturbative → Statistical model: Maxwell-Boltzmann

$$\frac{dN}{d^3\mathbf{p}} \sim \exp\left\{-\sqrt{\boldsymbol{p}^2 + m^2}/T\right\}$$

Parameters:
- "Temperature" ***T***
- Dark meson mass ***m***



→ Instead of simulating vertices, draw random values

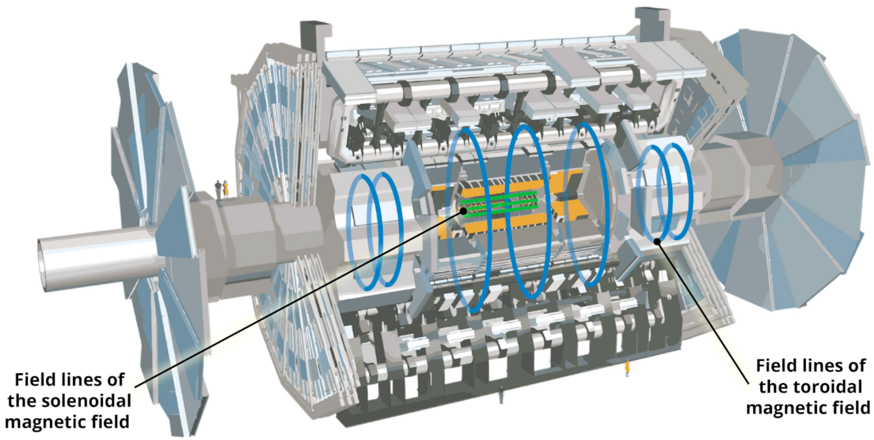
- For simplicity let's fix m = T (approx. true in SM QCD)

  → $T \sim p_T$ (for unboosted events)

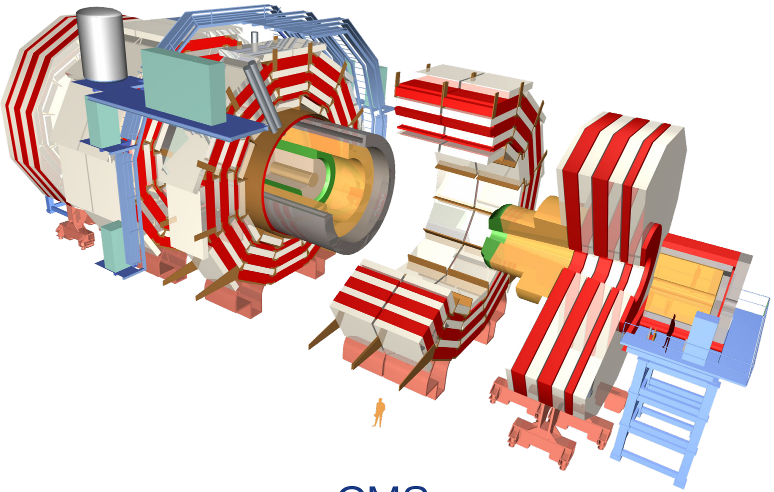
- Parameter space: T = [0.1:10] GeV
  - Below 0.1 GeV: Not many possible decays to the SM
  - Above 10 GeV: not "SUEPy": lower multiplicities, higher momenta (other searches are sensitive)

ATLAS and CMS: general purpose detectors at the LHC

- Explore the **TeV scale** in p – p collisions
  - Test the **Standard Model (SM)** at extreme energies
  - Search for new **high mass** particles (supersymmetry, dark matter, …)
- Structure:
  - **Inner Detector (ID)**: Tracks charged particles and reconstructs vertices
  - **Calorimeters**: Measure energies of electrons, photons, and hadrons
  - **Muon system**: tracks muons
- Optimized to reconstruct **high-momentum** particles
  - **Strong magnetic fields** enable precise momentum measurements



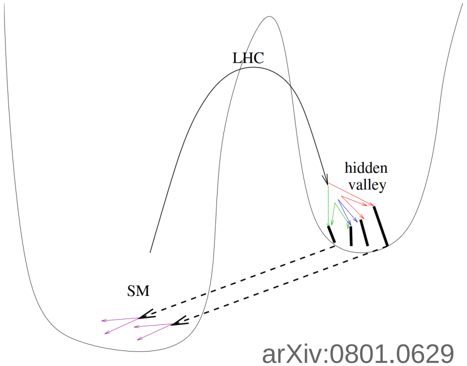
ATLAS
ATLAS-PHOTO-2021-029



CMS
CMS-OUTREACH-2018-057

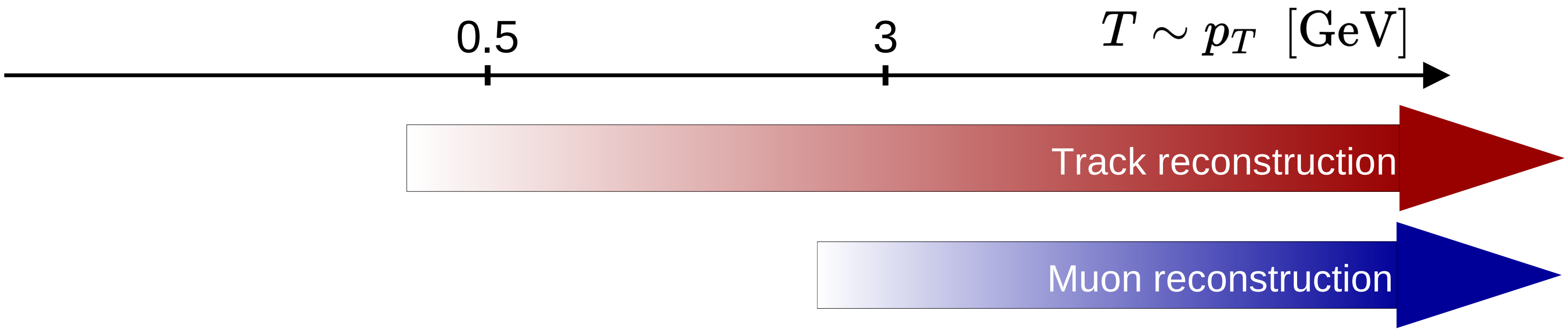
Reconstructing SUEP constituents:

- Final state particle nature set by portal back to SM
  → Can be hadrons, leptons, a mix, …



arXiv:0801.0629

- Challenge:
  - Large magnetic fields limit reconstruction of low transverse momentum

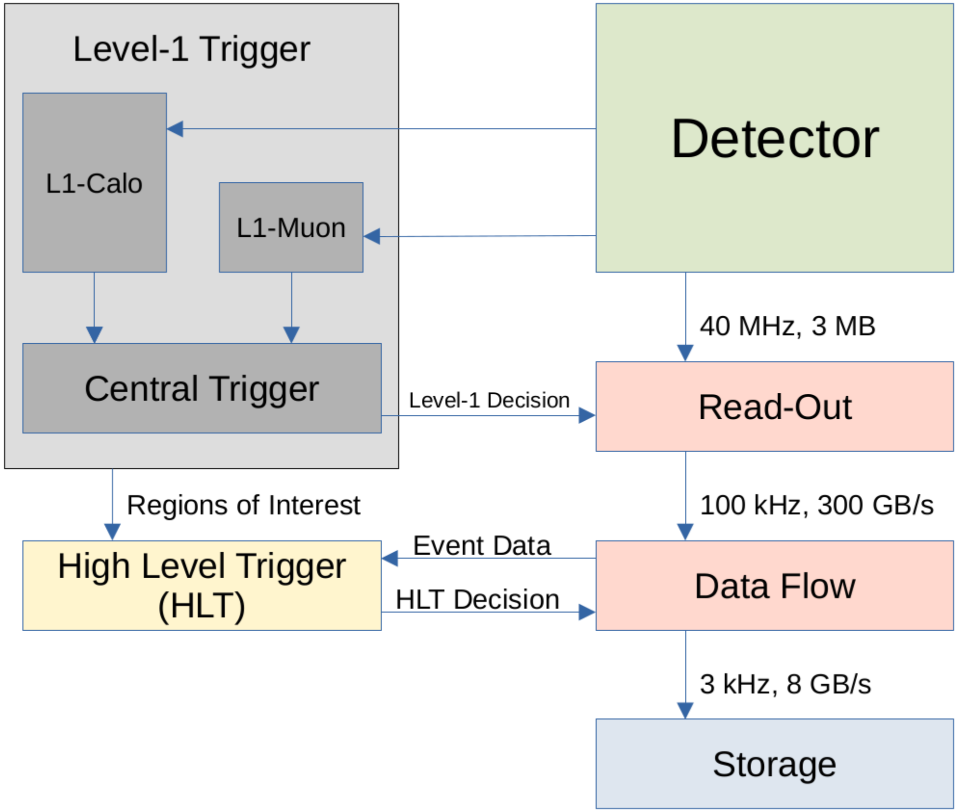


Muons are only present in a subset of scenarios

→ For an inclusive search ID tracks will be our first choice for the reconstruction of SUEP constituents

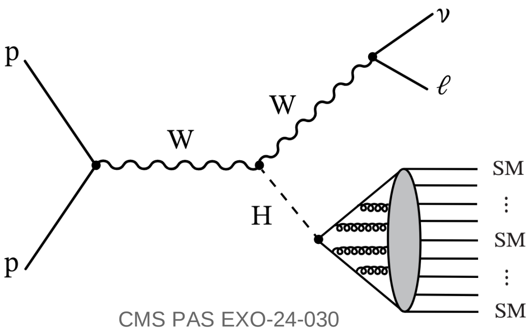
Trigger system (ATLAS)

- Record 3 MB every 25 ns
  → real-time event selection
- **Level-1**: very fast
  → only calorimeters and muon system
- **HLT**: more time available
  → includes tracking,
  but limited to regions of interest or subset of events



Strategies:

1) H_T trigger (sum of calorimeter measurements ≳ 1 TeV)
   - very heavy mediators or recoils against energetic QCD jet
2) For exotic Higgs decays: associated production
   - Efficient triggers, but lower cross-section
3) Multi-muon triggers
4) Pixel cluster-based

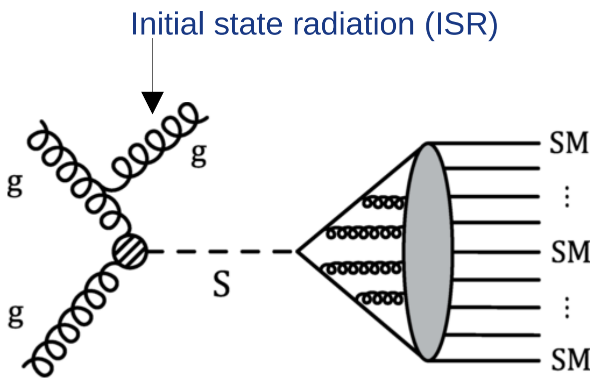


CMS PAS EXO-24-030

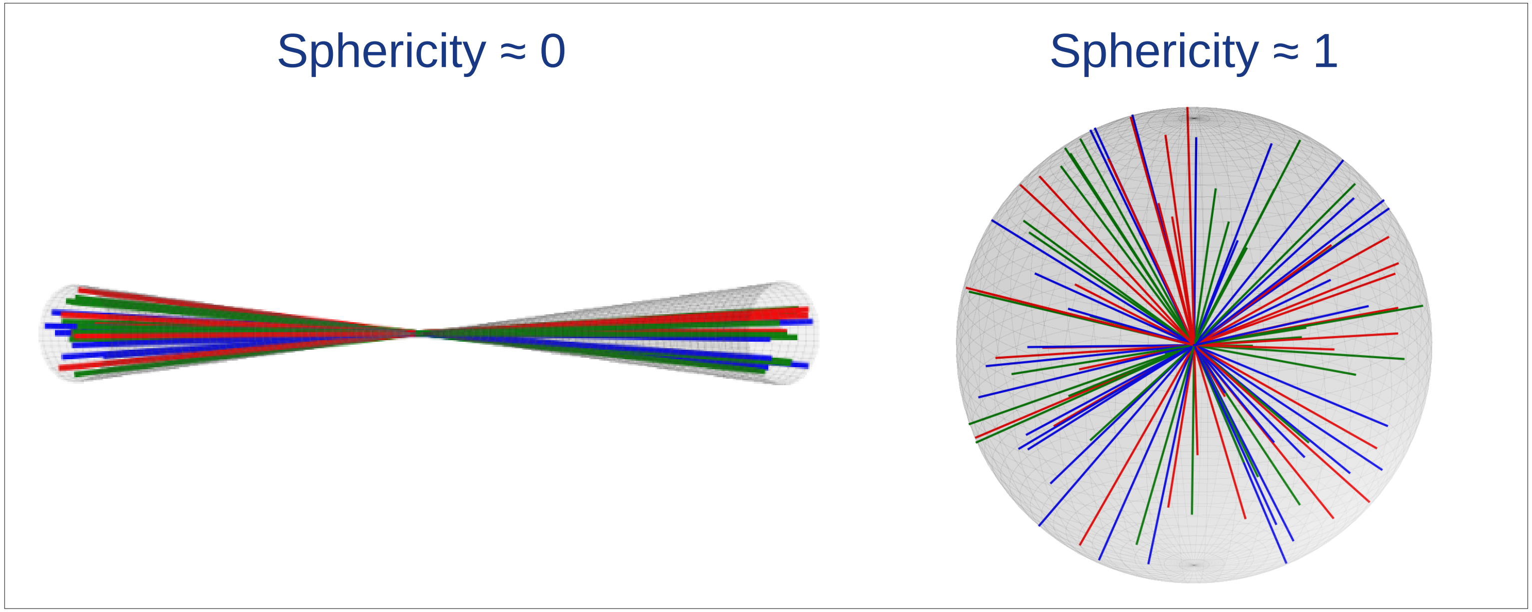
- 1) H_T-based search (CMS)

Phys. Rev. Lett. 133, 191902

  - Trigger: H_T > 1200 GeV
  - Requires strong ISR jet
  - Compute the **sphericity** in the SUEP frame
  - Event selection:
    - high sphericity
    - high ID track multiplicity matched to the SUEP
  - Data-driven background estimate
  - Binned likelihood fit on number of tracks

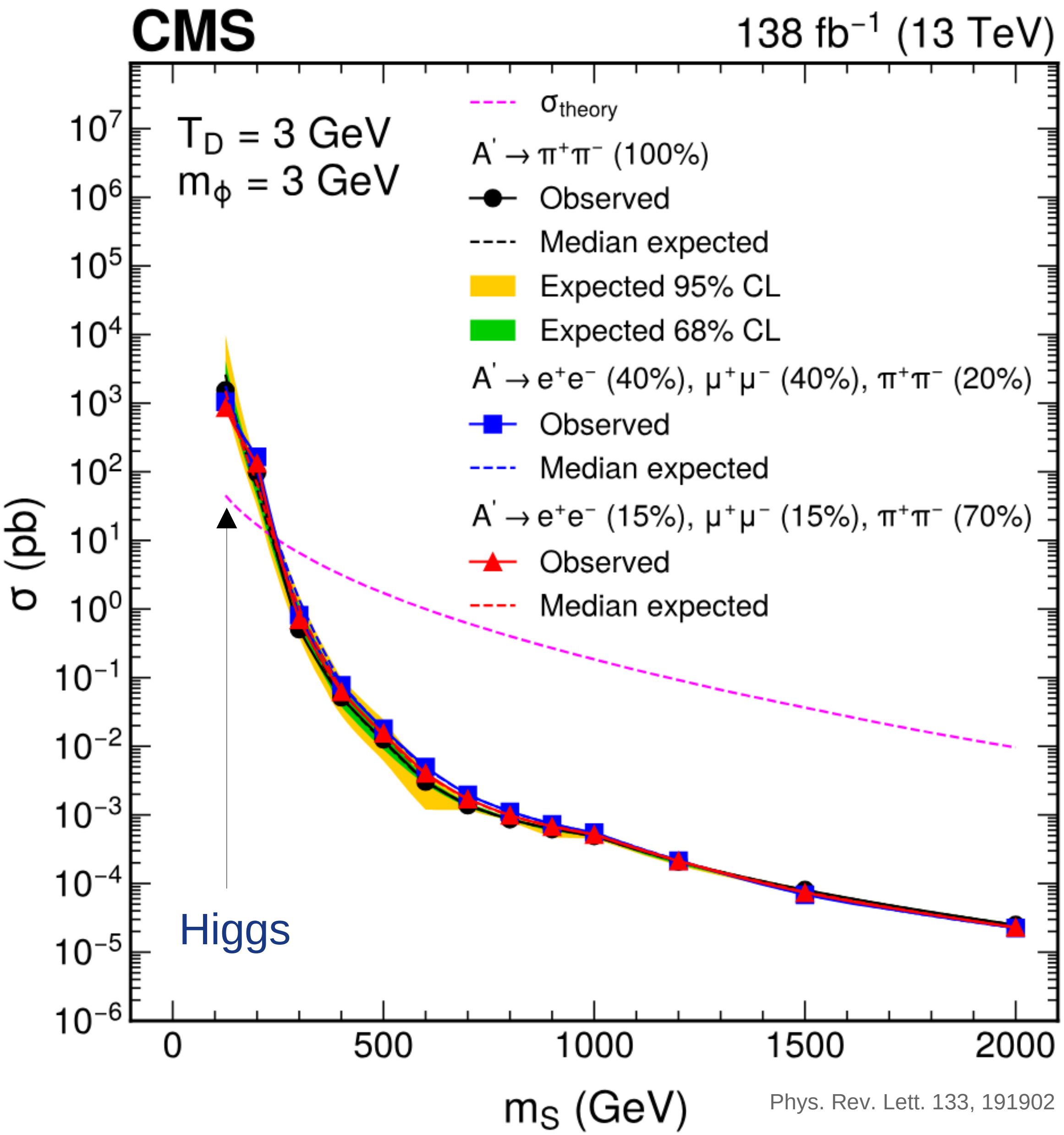


Adapted from
Phys. Rev. Lett. 133, 191902

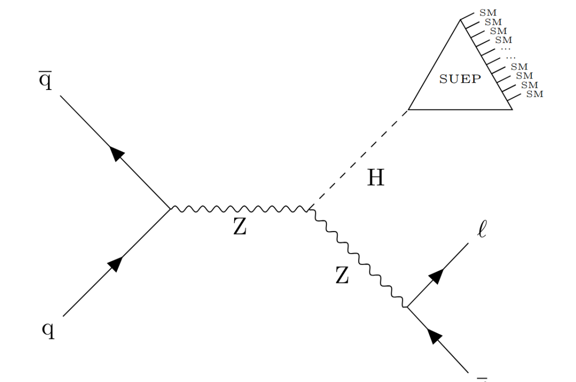


1) H_T-based search results

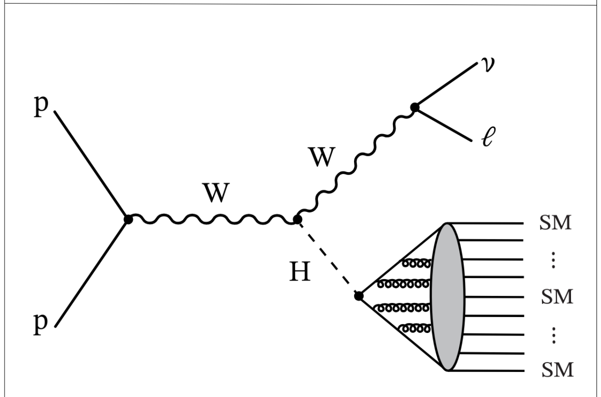
- No sign of new physics
- Good limits for heavy mediators
- limited by trigger for lower mediator masses



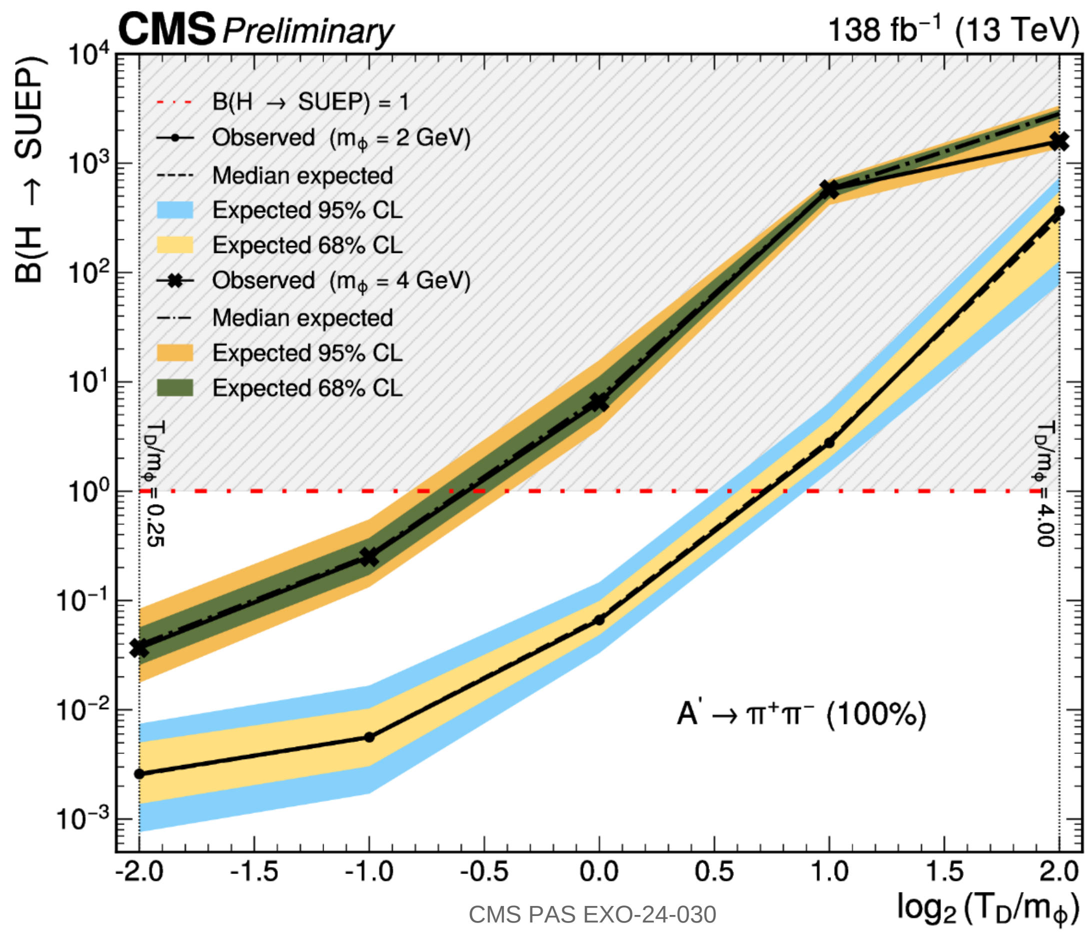
2) Exotic Higgs decays with associated production (CMS)



CMS PAS EXO-23-003



CMS PAS EXO-24-030



CMS PAS EXO-24-030

No sign of new physics

→ limits down to BR ≈ 0.2% for T≈ 0.5 GeV

→ weaker limits for higher T

3) Muon-based search

- Targets only signals containing muons
  - Realistic scenario:
    kinetic mixing with a dark photon

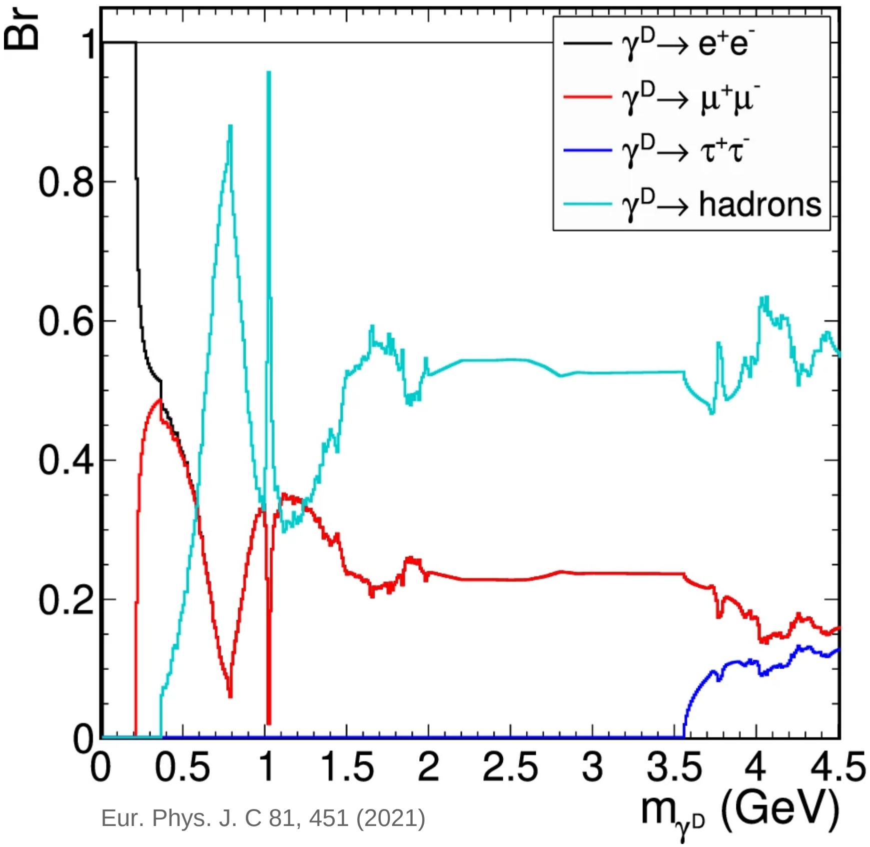
- Multi muon triggers
  (e.g. 4 muons @ 4 GeV)

- Event selection:
  - High muon multiplicity
  - High track multiplicity
  - High sphericity

- Muons are rare in the SM
- Almost background free searches possible

  → limits in the fb range in Run 2

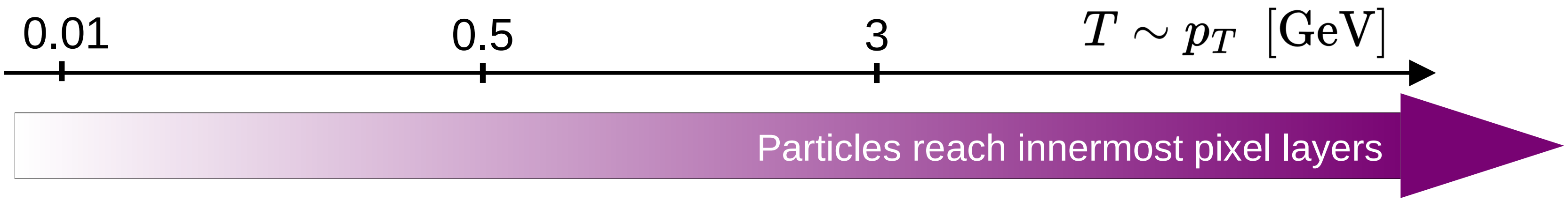
  → probing the Higgs portal at branching ratios < 1%



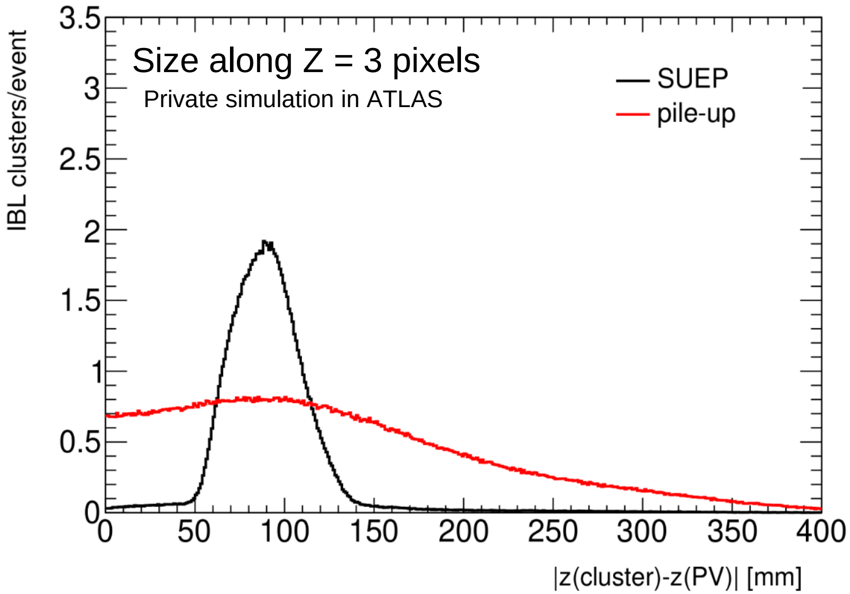
Eur. Phys. J. C 81, 451 (2021)

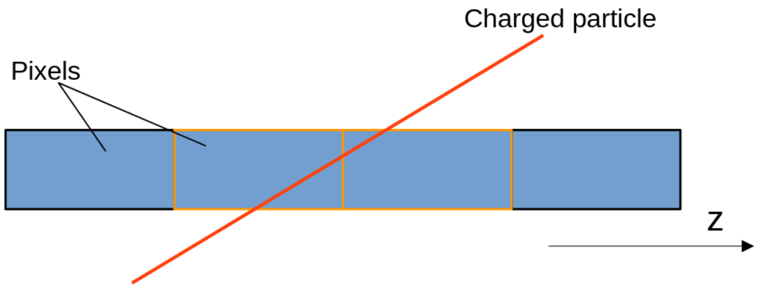
O(0.1) fraction of muons

4) Pixel clusters

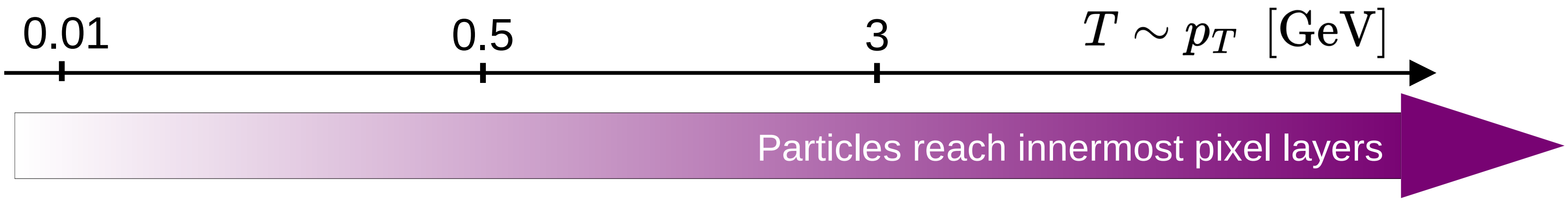


- Very high multiplicities! (> 10 k)
- Tracks can point to a vertex, pixel clusters can't
- But size along beam direction correlates strongly with angle of incidence
  - Luminosity measurement using pixel cluster counts in ATLAS
    Nuclear Inst. and Methods in Physics Research, A 924 (2019) 275–278
- Size = 3 clusters:





4) Pixel clusters



- Very high multiplicities! (10'000 – 100'000)
- Tracks can point to a vertex, pixel clusters can't
- But size along beam direction correlates strongly with angle of incidence
  - Luminosity measurement using pixel cluster counts in ATLAS
    Nuclear Inst. and Methods in Physics Research, A 924 (2019) 275–278

- Efficient reconstruction at low T

	ID tracks	pixel clusters
$m = T = 1$ GeV	52%	62%
$m = T = 0.25$ GeV	7.2%	62%
$m = T = 0.1$ GeV	1.2%	66%

$$\text{Efficiency: } \frac{\text{object multiplicity}}{\text{total charged particles}}$$

4) Trigger strategy?

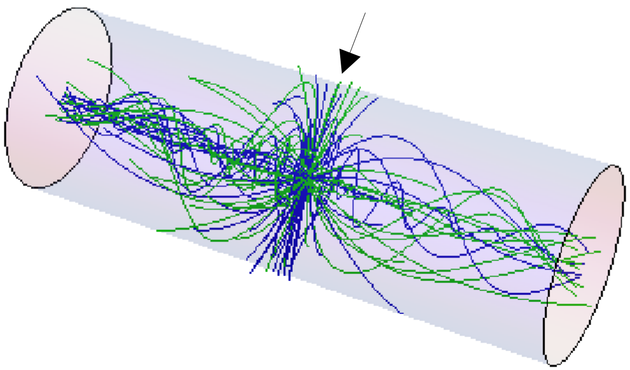
M (GeV)	$m = T$ (GeV)	HLT_xe70_mht_L1XE50	HLT_xe110_mht_L1XE55	HLT_xe110_pufit_L1XE55	Total
125	0.1	16.2	11.6	10.2	16.2
125	0.25	8.2	2.2	1.8	8.2
125	1	2.4	0.8	0.5	2.4

E_T^{miss} trigger efficiencies [%]

- Level-1 for T < 0.5 GeV:
  - Many particles never reach the calorimeters
  - Small ISR jet → imbalance → missing transverse energy
  - Also for semi-visible SUEPs

- HLT: Belt of fire in the innermost pixel layer:

J. High Energ. Phys. 2017, 76 (2017)



Summary & Outlook

- QCD-like hidden sector: excellent **DM candidate**
- At the LHC: **dark showers**
- SUEP: subclass of dark showers

- **T > 0.5 GeV**
  - **H_T trigger for high mediator masses** (result available)
  - **Associated production for exotic Higgs decays** (result available)
  - **Muon-based** (no result yet)
- **T < 0.5 GeV:**
  - **Pixel cluster counting**, both for HLT and offline
  - **Missing transverse energy at level-1**, especially for semi-visible SUEPs

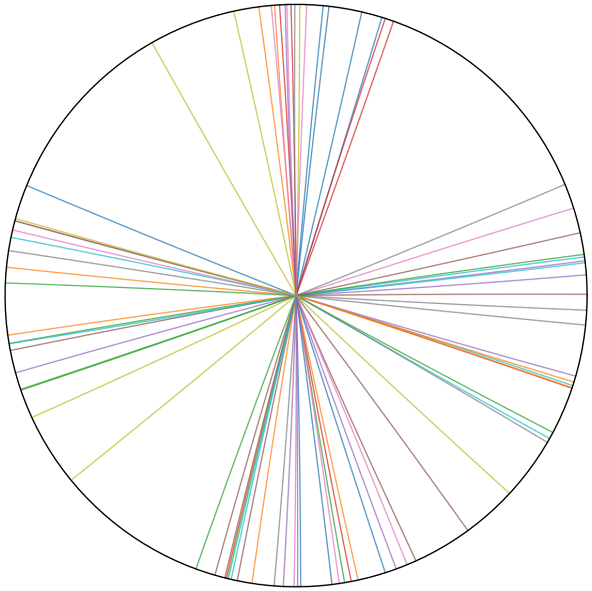
- ML algorithms, especially for SUEPs that deviate from the ideal spherical picture
  Unsupervised Hadronic SUEP at the LHC. J. High Energ. Phys. 2021, 129 (2021)
  Autoencoders for real-time SUEP detection Eur. Phys. J. Plus 139, 281 (2024)

- High luminosity LHC: more pile-up collisions

Thank you!

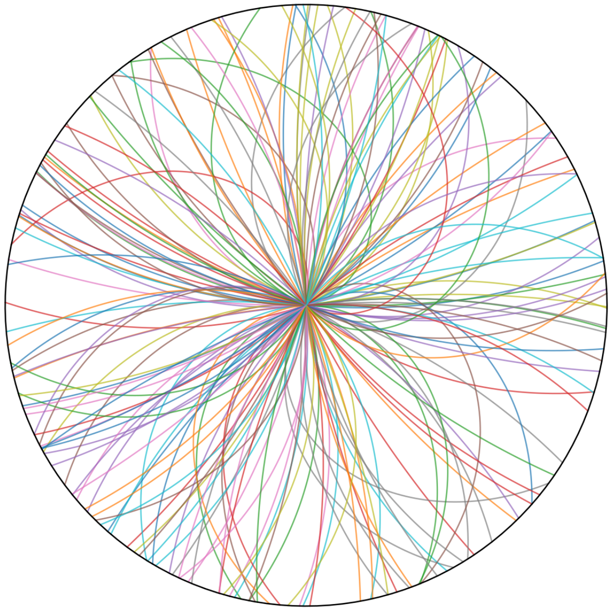
In the inner detector of an LHC experiment

QCD multijet event

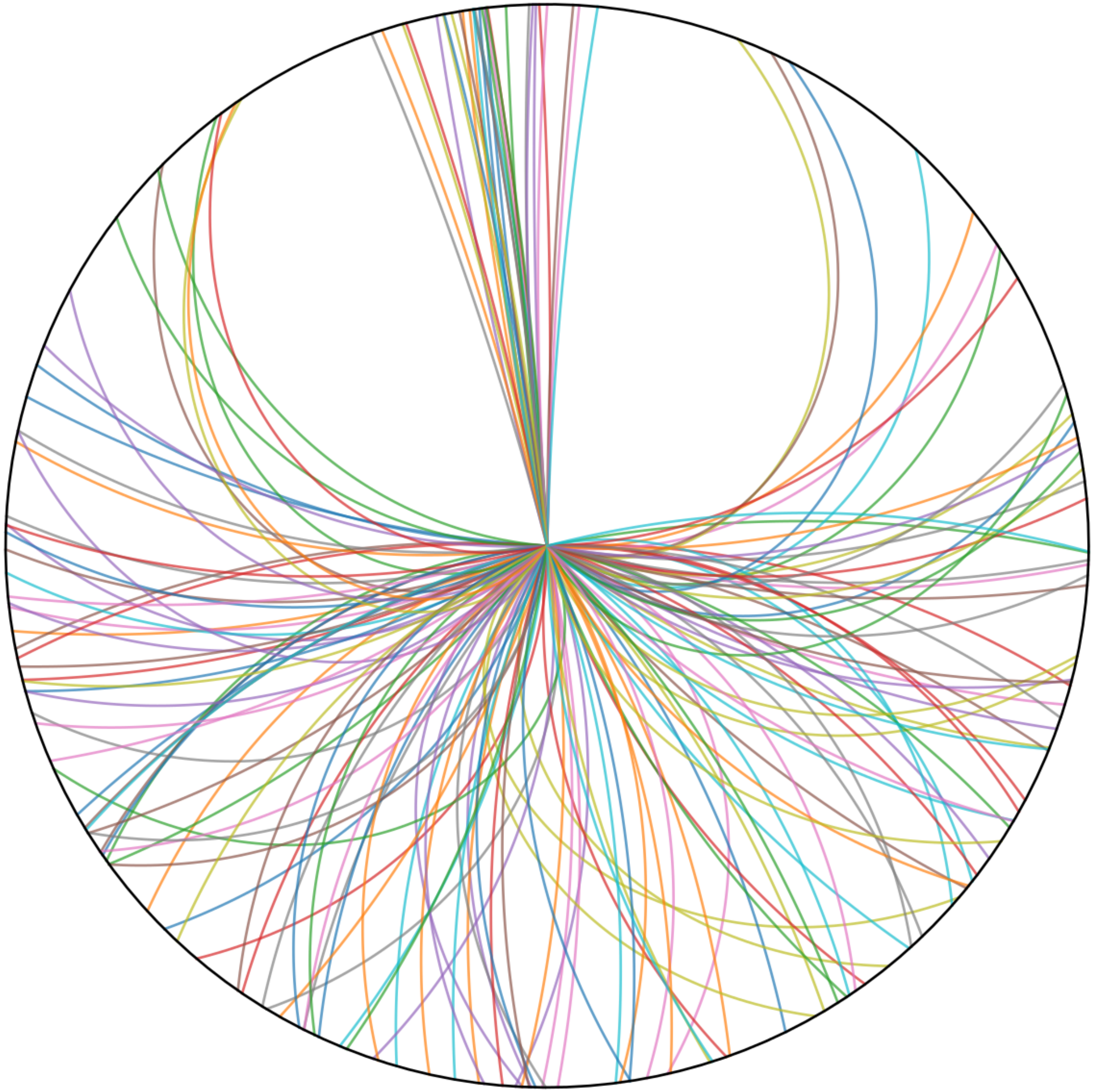


Particles cluster into jets

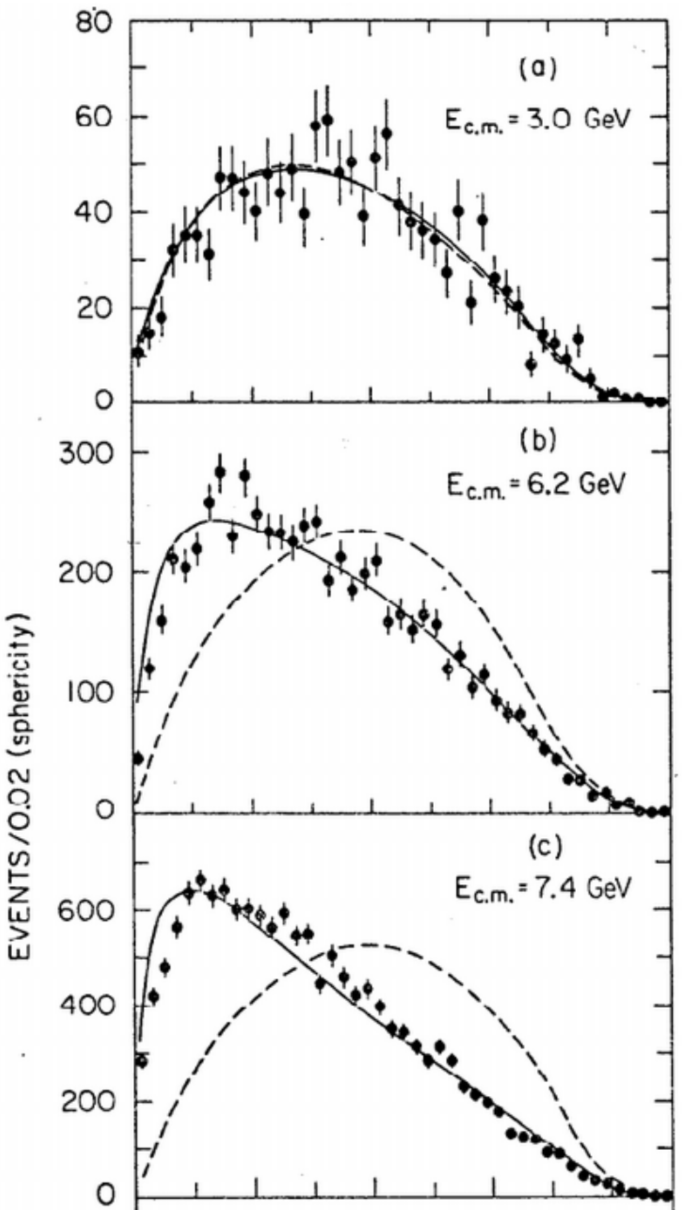
Soft Unclustered Energy Pattern (SUEP)



A soft, isotropic spray of particles



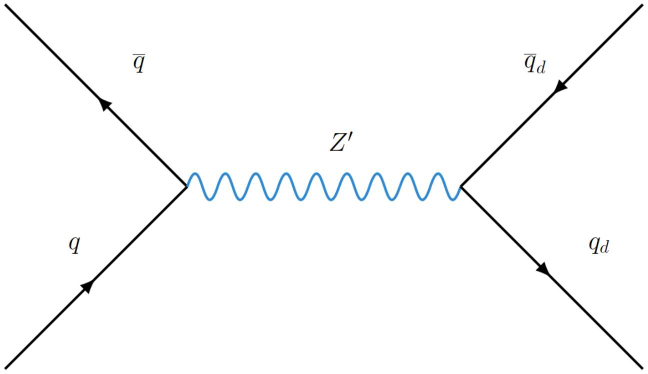
- Sphericity distribution in ee→ hadrons (SLAC-LBL @ SPEAR storage ring)
  - S = 0: pencil-like event shape
  - S = 1: maximally isotropic distribution
- Above 6.2 GeV: jet model
- 3.0 GeV : isotropic phase space model

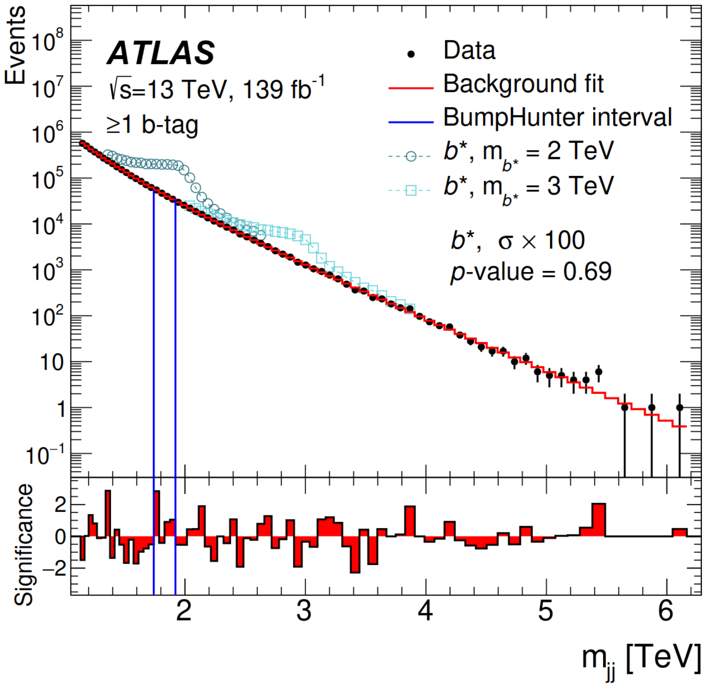


Physical Review Letters 35 (12, 1975)

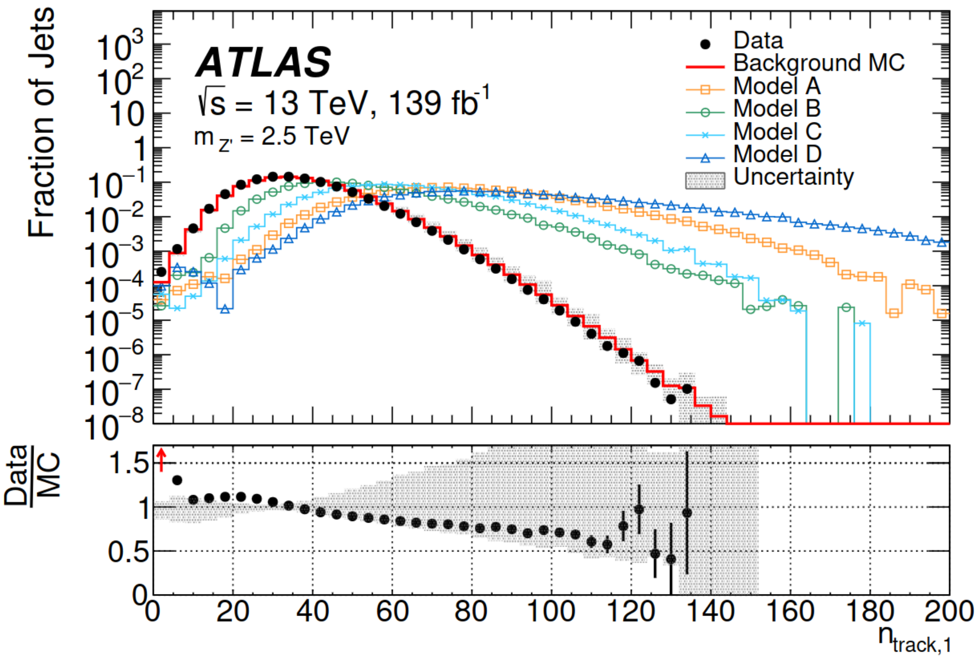
Searches for dark showers **with jet formation**

- Prompt decays to the SM:
  - ***Dijet resonance***
  - ***Jet substructure***





Search for dijet resonance
J. High Energ. Phys. 2020, 145 (2020)



Search for dark quarks
JHEP02(2024)128