Look at the dark side
- Dark sector and jet physics with the ATLAS experiment -

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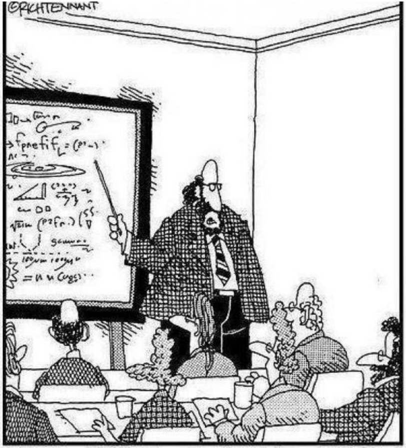
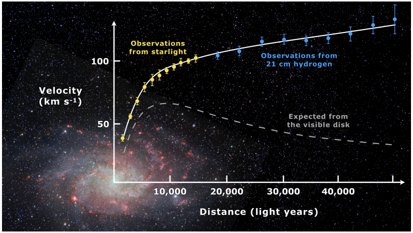
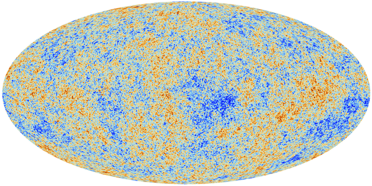
Outline

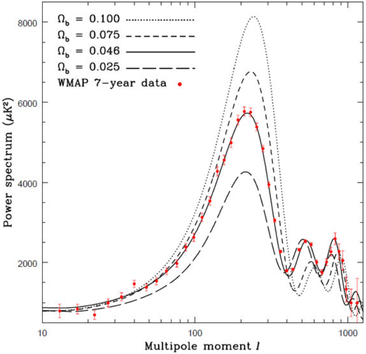
1. Introduction
   - What is Dark Matter (DM)?
   - From WIMP to strong DM
   - The ATLAS experiment at CERN
2. Searches for new signatures with the ATLAS detector
   - Dark jets
   - Semi-visible jets
   - Trigger-Level-Analysis
3. Data quality monitoring
4. Conclusions



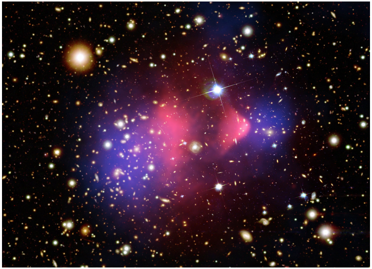
"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."







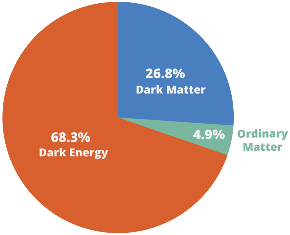
Clip of galaxy rotation

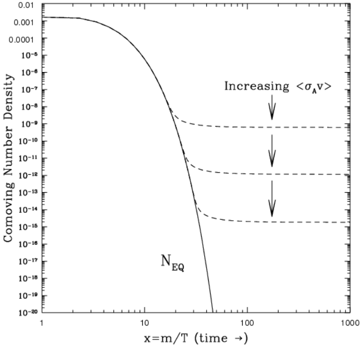


We have strong evidence that Dark Matter (DM) exists, but...

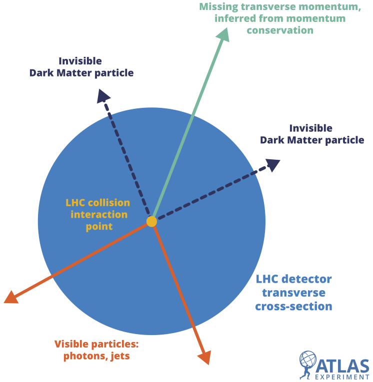
"What is it?"

Estimated matter-energy content of the Universe

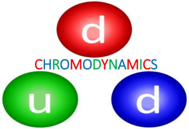




- DM - is it just a **W**eakly **I**nteracting **M**assive **P**article?
  - Stable, interacts via gravity → think of massive neutrinos
  - What would we see in a particle detector? "Something is missing"
    - Look for large p_T^{miss} recoiling against reference object (e.g. a QCD jet)
  - Attractive candidate: lightest supersymmetric particle
    - Predicted by many Supersymmetry models, not yet observed

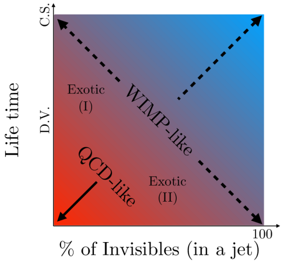


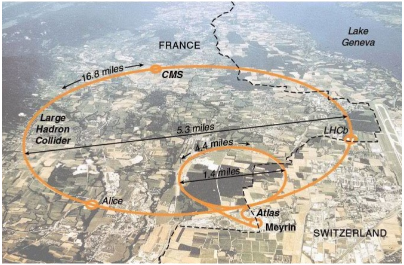
- Visible matter makes up 5% of the universe's matter-energy content
  - Described via complex $U(1) \times SU(2) \times SU(3)$ theory with ≈ 37 particles
  - DM makes up 25% - why should it be 1 particle with 1 interaction?
- Assume more complex dark sector with possibly **strong** interactions



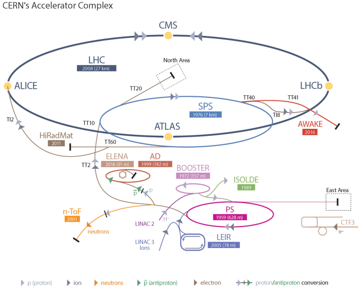
- Infinitely complex models about DM possible . . .
- Perhaps dark sector similar to SM, but DM $\leftrightarrow$ SM interactions strongly suppressed $\rightarrow$ how can we test this idea?

1. step: only consider models that we can actually test in experiments!
2. step: many dark sector scenarios possible
   - want to test as many models simultaneously as possible
   - inclusive search strategy





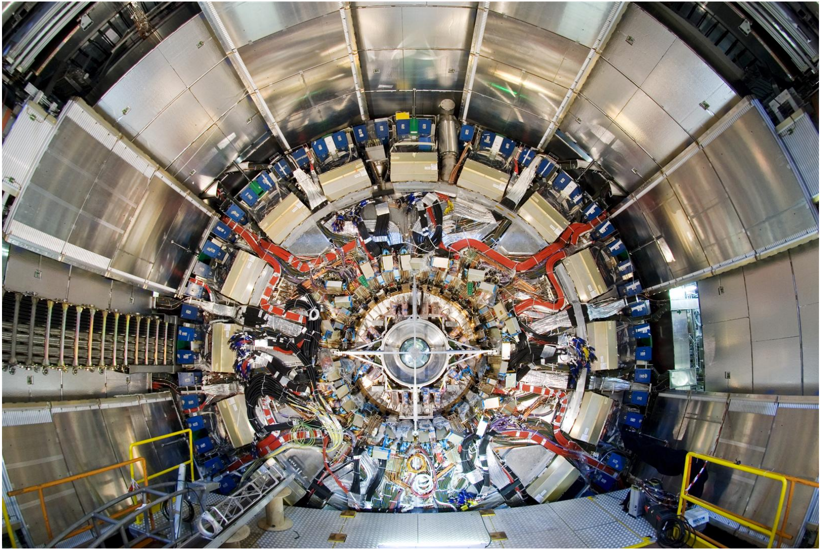
FRANCE
Lake Geneva
16.8 miles
CMS
Large Hadron Collider
5.3 miles
LHCb
4.4 miles
1.4 miles
Alice
Atlas
Meyrin
SWITZERLAND



CERN's Accelerator Complex
CMS
LHC
2008 (27 km)
North Area
ALICE
TT20
LHCb
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
2011
TT60
ELENA
2016 (31 m)
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
n-ToF
2001
PS
1959 (628 m)
CTF3
LINAC 2
neutrons
LINAC 3
Ions
LEIR
2005 (78 m)
p (proton)
ion
neutrons
p̄ (antiproton)
electron
proton/antiproton conversion

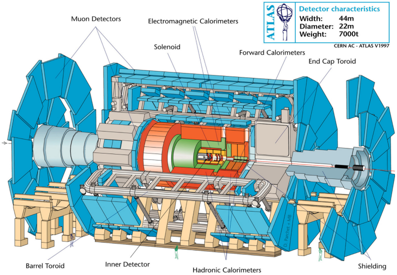
Particle colliders in the quest to uncover DM

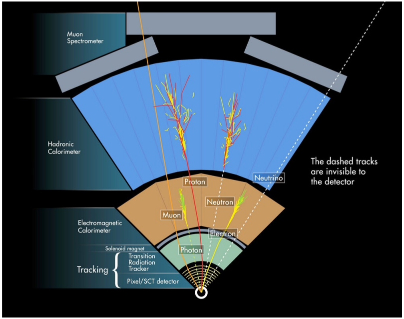
The ATLAS detector



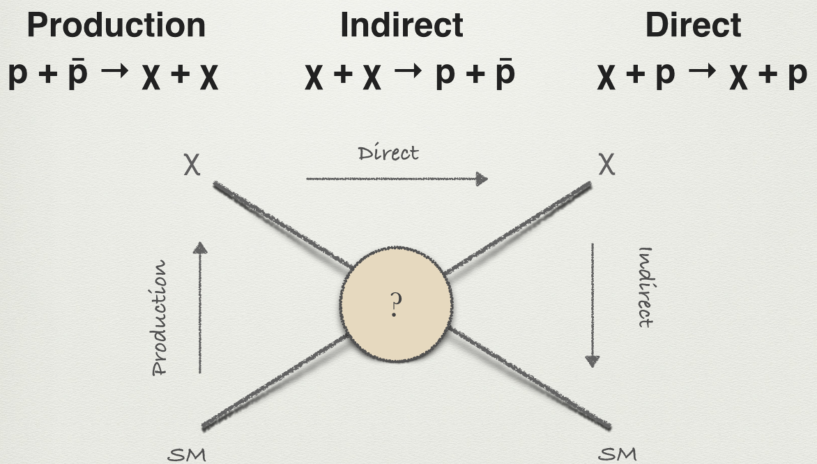
Particle colliders in the quest to uncover DM

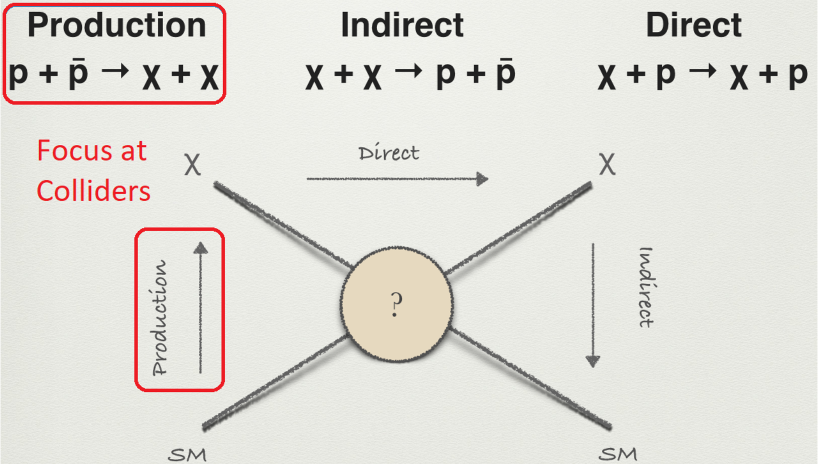
The ATLAS detector





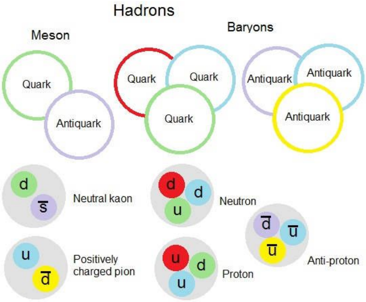
How can this ~~magic cylinder~~ ingeniously engineered masterpiece help us search for DM?

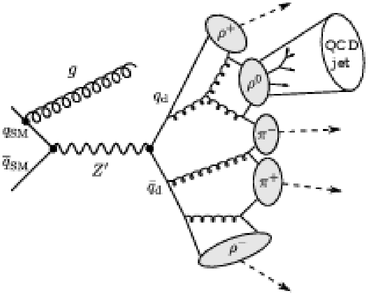

Production
p + p̄ → χ + χ
Indirect
χ + χ → p + p̄
Direct
χ + p → χ + p
Direct
χ
χ
Production
?
Indirect
SM
SM



Production
p + p̄ → χ + χ
Indirect
χ + χ → p + p̄
Direct
χ + p → χ + p
Focus at
Colliders
χ
Direct
χ
Production
?
Indirect
SM
SM

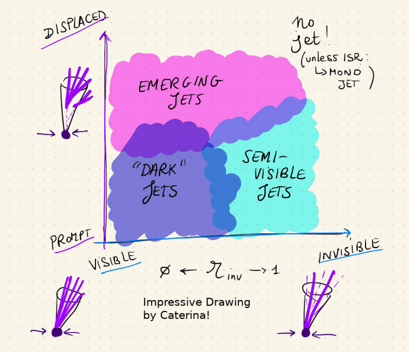
- Ideas for more complex DM models that we can probe at the LHC?
- SM $\leftrightarrow$ **dark sector** $\Rightarrow$ new particles & interactions
- Assume dark QCD structure exists within dark sector $\rightarrow$ dark **quarks**!
- Dark quarks produced at LHC which form dark mesons and baryons
  $\Rightarrow$ DM produced in QCD-like dark shower followed by hadronisation





We have produced DM - **what happens next**?

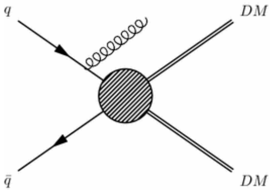
1. DM is collider-stable
   - Particles escape detector
   - Covered by mono-X searches
2. DM has collider-finite lifetime
   - We see displaced vertices → emerging jets!
3. LU ATLAS group's main focus: DM promptly decays back to SM (quarks)
   - Unexplored territory, offers interesting signatures

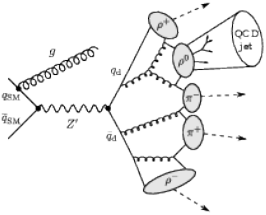


Quick break after formal introduction

Dark Matter - is it just a WIMP?

- Stable, only **weakly** interacting → think massive/cold neutrinos
- Simple signal at colliders: large p_T^{miss} recoils against reference object (e.g. a QCD jet)
- Attractive candidate: lightest supersymmetric particle





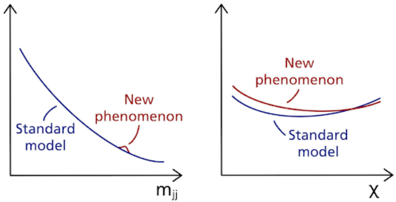
"Strong" DM in a dark sector?

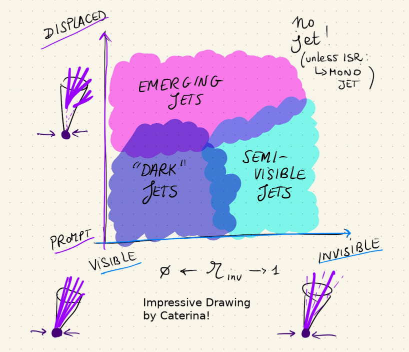
- Visible matter makes up 5% of the universe's matter-energy content
  - Described via complex $U(1) \times SU(2) \times SU(3)$ theory with ≈ 37 particles
  - DM makes up 25%; why should it be 1 particle & 1 interaction?
- Assume more complex **dark sector** with possibly strong interactions

The Dark Sector models the LU ATLAS group focuses on

The two DM signatures that we consider

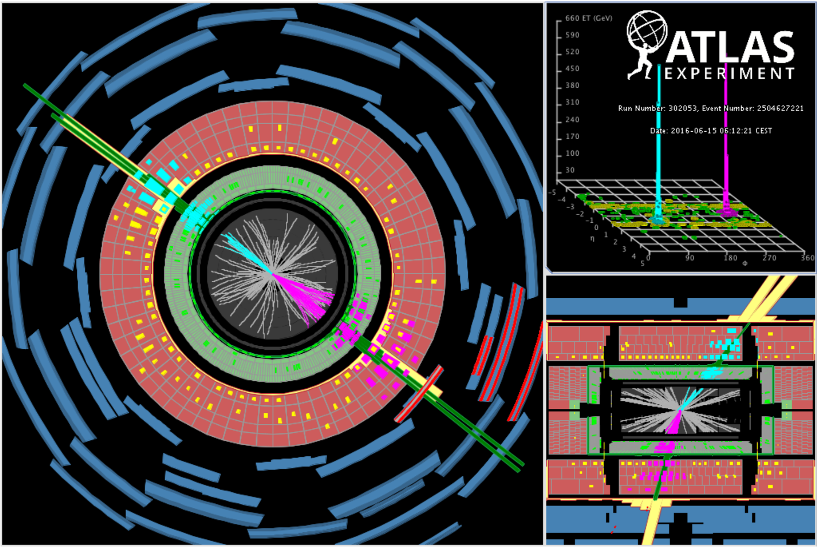
- Consider mainly two cases:
  1. Resonance with dark jets
  2. Semi-visible jets
- Only prompt decays, no displaced vertices
- Internal jet structure discriminates them from SM background



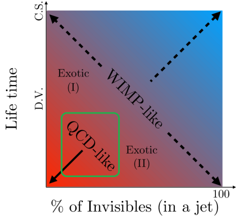


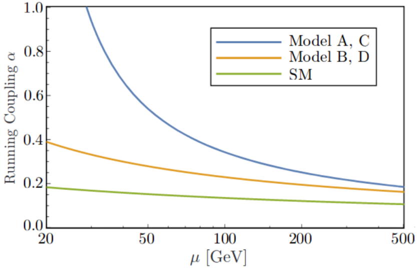
Signatures and search strategies

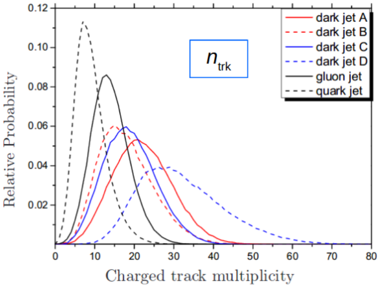
A high-mass dijet event in searches for new physics



- $q_{SM} q_{SM} \to Z' \to q_d q_d \to$ dark shower
- Dark hadrons **promptly** decay back to SM hadrons (`10.1103/PhysRevD.100.115009`)
- Dark jets models assume larger running QCD coupling
- Signature: two QCD-like jets with different <u>internal structure</u>, e.g. higher $N^{\text{charged}}_{\text{particles}}$







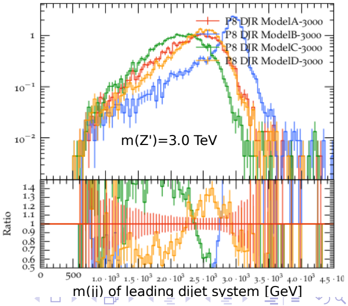
Signatures and search strategies

Dark Jets model parameters and decay branching ratios

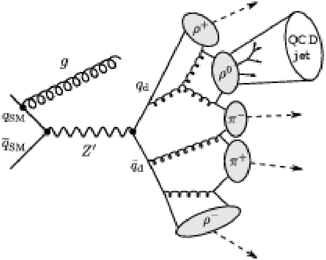
	N_d	n_f	Λ_d (GeV)	$\tilde{m}_{q'}$ (GeV)	m_{π_d} (GeV)	m_{ρ_d} (GeV)	π_d Decay Mode	ρ_d Decay Mode
A	3	2	15	20	10	50	$\pi_d \to c\bar{c}$	$\rho_d \to \pi_d\pi_d$
B	3	6	2	2	2	4.67	$\pi_d \to s\bar{s}$	$\rho_d \to \pi_d\pi_d$
C	3	2	15	20	10	50	$\pi_d \to \gamma'\gamma'$ with $m_{\gamma'} = 4.0$ GeV	$\rho_d \to \pi_d\pi_d$
D	3	6	2	2	2	4.67	$\pi_d \to \gamma'\gamma'$ with $m_{\gamma'} = 0.7$ GeV	$\rho_d \to \pi_d\pi_d$

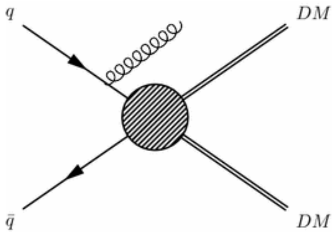
γ' decay modes

- Model C: $d\bar{d}$ (6%), $u\bar{u}$ (22%), $s\bar{s}$ (6%), $c\bar{c}$ (22%), e^+e^- (17%), $\mu^+\mu^-$ (17%), $\tau^+\tau^-$ (10%)
- Model D: e^+e^- (15%), $\mu^+\mu^-$ (15%), $\pi^+\pi^-$ (70%)



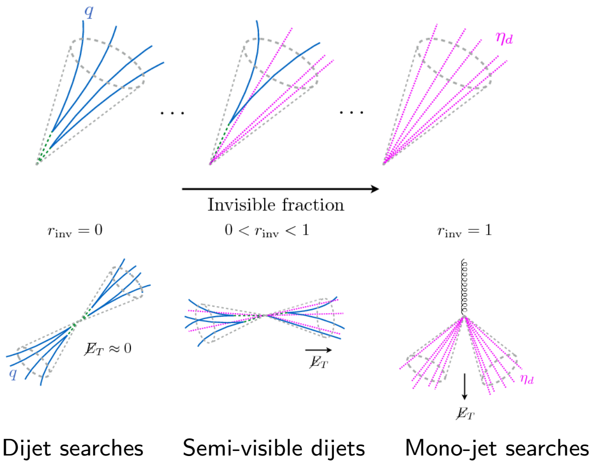
- Basic idea: two different dark quark flavours
  - Combine to form **dark versions** of $\pi^+, \pi^-, \pi^0, \rho^+, \rho^-, \rho^0$
- $q_{SM} q_{SM} \rightarrow \Phi/Z' \rightarrow q_d q_d \rightarrow$ dark shower
  - Only ρ_d^0 is unstable and (promptly) decays to SM quarks
  - Other mesons are (collider-)stable $\rightarrow$ invisible
- Signature of semi-visible jets = jets with p_T^{miss} inside $\rightarrow$ **closely aligned**
  - Typical mono-jet searches require p_T^{miss} to be **far away** from jets!

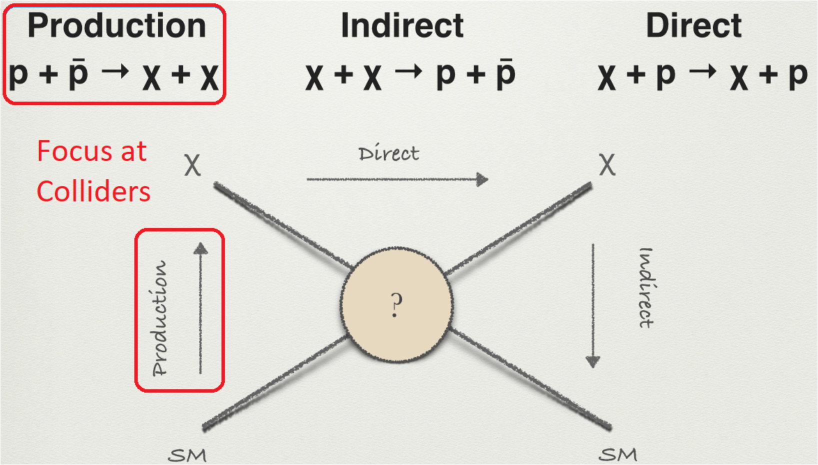




(10.1103/PhysRevLett.115.171804, 10.1007/JHEP11(2017)196, 10.1007/JHEP01(2020)162)

- Fraction of stable/invisible hadrons wrt all hadrons: $r_{\rm inv} \equiv \langle \frac{\#\text{stable hadrons}}{\#\text{all hadrons}} \rangle$
- $r_{\rm inv}$ regulates detector signature $\rightarrow$ **search strategy**




Production
p + p̄ → χ + χ
Indirect
χ + χ → p + p̄
Direct
χ + p → χ + p
Focus at
Colliders
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Direct
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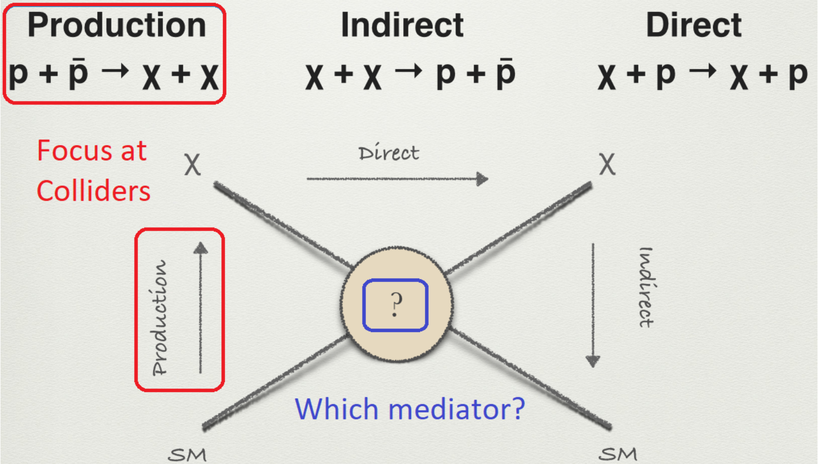
Production
?
Indirect
SM
SM


Production
$p + \bar{p} \rightarrow \chi + \chi$
Indirect
$\chi + \chi \rightarrow p + \bar{p}$
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$\chi + p \rightarrow \chi + p$
Focus at Colliders
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Production
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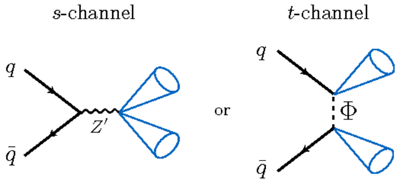
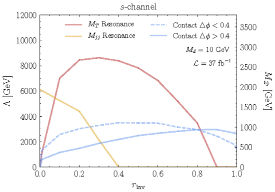
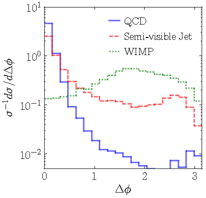
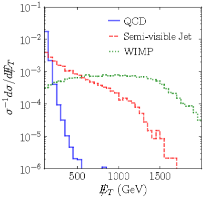
SM
SM



- *s*-channel: resonance search in
  - Dijet invariant mass m_{jj} (low r_{inv}); or
  - Transverse mass m_T (high r_{inv})
- *t*-channel: use p_T^{miss} & $\Delta\phi(p_T^{\text{miss}}, \text{closest jet})$ to select signal jets



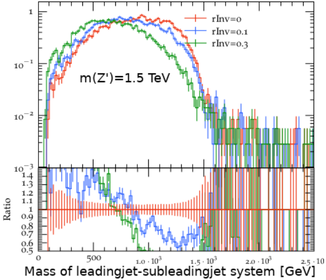


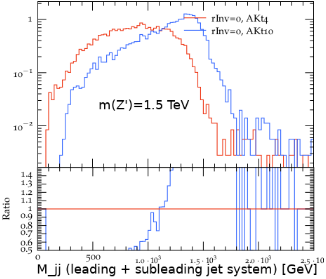


Signatures and search strategies

Jet Substructure & Size

Dark showering & hadronisation simulated by Pythia8 Hidden Valley module (10.1016/j.cpc.2015.01.024)





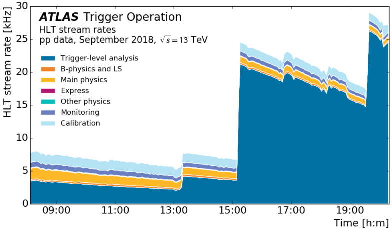
Significant features

- Dark jets & semi-visible jets tend to radiate more than QCD jets
  - Jets are **wider & larger** wrt QCD jets
  - Dark jets produce higher number of tracks in detector
- Semi-visible jets closely aligned with p_T^{miss} and higher number of distinct subjets in contrast to background (10.21468/SciPostPhys.10.4.084)

- 40 MHz *pp* collisions at LHC → too much data?!
  - Solution: two stage trigger system as event filter → 1 kHz event rate
- What if new physics is hidden in discarded events?

Stream	Average event size
Physics, express	1 MB
Trigger-level analysis	6.5 kB
Calibration	1.3 kB to 1 MB
B-physics and light states	1 MB

- TLA: analyse events at trigger level using only reduced information
  - Select your events of interest ⇒ significantly increased **statistical power**

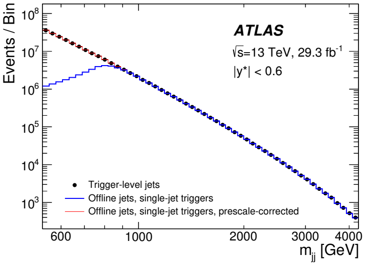


(ATLAS Run 2 Trigger performance: JINST15(2020)P10004)

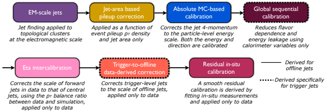
Trigger-Level-Analysis (TLA) with jets

Analysis strategy

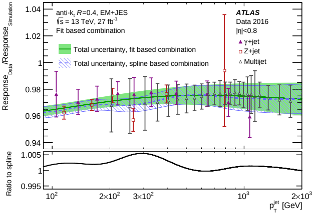
- Early Run 2 paper: `Phys.Rev. Lett.121(2018)081801`
- Look for low mass dijet resonance with $|y^{\star}| = \frac{1}{2}|y^{j1} - y^{j2}|$
- Jet trigger fired? $\rightarrow$ look at m_{jj} spectrum $\rightarrow$ deviation from SM?
  - Go **as low as possible** in m_{jj}
  - Limit: trigger threshold!



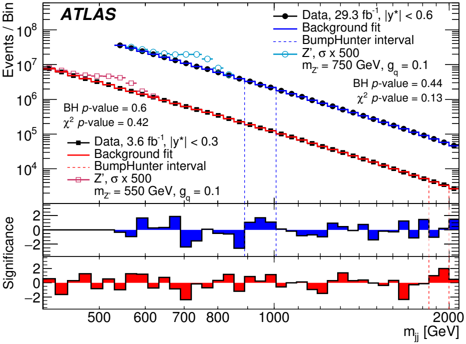
- Need to develop custom calibration for trigger-level jets



- With LU student A. Ekman: Check if calibration introduces fake bump into jet p_T (m_{jj}) spectrum

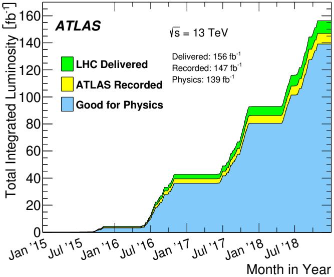


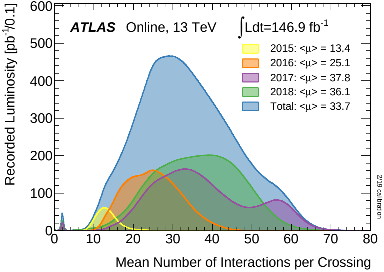
- Early Run 2 result offers proof of principle



Ongoing work

- Analysis on full Run 2 dataset
- TLA core software optimisation for Run 3 → much more data to come





- Data recorded by ATLAS should be of highest quality; amount of data as close as possible to what LHC delivers ⇒ DQ monitoring essential

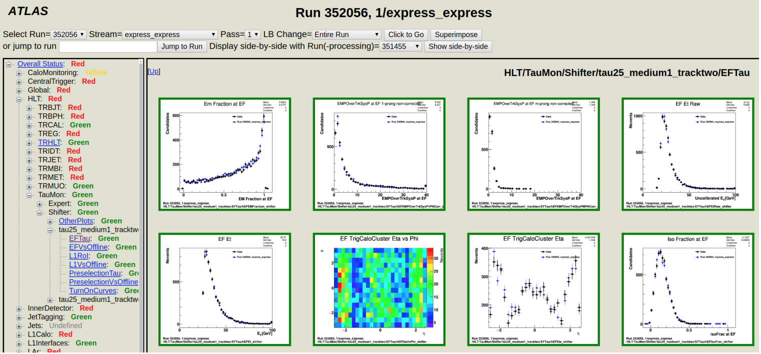
Possible concerns:

- Different detector/accelerator conditions between runs
- Dead regions, pileup, technical readout issues, sub-system failure
- Jet calibration, unclean jets, tracking in boosted high multiplicity jets

Data Quality monitoring in ATLAS

Monitoring of online + offline jets

- Aim: optimal performance of SM jets ↔ background description
- L1/HLT/offline jets; multi-jet triggers; trigger efficiencies; pileup removal
- Jet kinematics; depositions in different detector regions; jet 4-momenta at different calibration steps; cuts placed on jets . . .
- Upgrading software framework & webdisplay towards Run 3



(ATLAS Run 2 DQ operation & performance: JINST15(2020)P04003)

Conclusions

Take-home points

- Dark sector phenomenology can lead to interesting jet signatures in collisions at the LHC
- Studied jet signatures show significant difference wrt traditional QCD-like & WIMP-like scenarios → require optimal background description
- Searches for dark & semi-visible jets at colliders can be complementary to traditional resonance & WIMP searches in the hunt for DM

⇒ Shift mindset: search for signatures instead of specific models

Opportunities for future DM searches (at colliders)

- Analyses of LHC Run 2 data in full swing → largest *pp* collision dataset to date
  - Maximise statistical power using Trigger-Level-Analyses
- Run 3 of LHC starts next year → more than twice the current data!
- **This is a team effort:** strive to collaborate → combine collider results with (in-)direct searches to maximise our knowledge about DM

Thank you for your attention!

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Extra material

Semi-visible jets modelling

- Hard interaction simulated with MadGraph5 MC generator using "DMsimp" model (https://github.com/smsharma/SemivisibleJets)
- Afterwards, dark showering via Pythia8 Hidden Valley module (10.1016/j.cpc.2015.01.024)