Dark Matter Searches at CMS at $\sqrt{s} = 13$ TeV

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Bristol Student Seminar

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University of BRISTOL

CMS

Motivation

What is dark matter?

- Short answer:

What is dark matter?

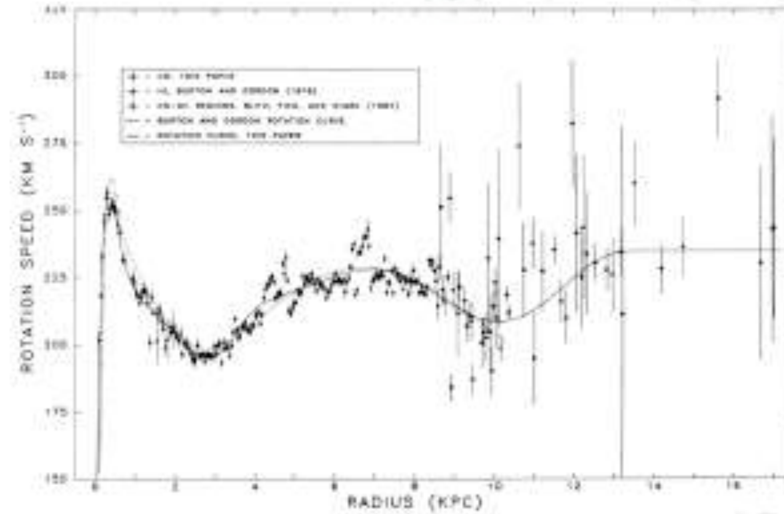
◎ Short answer: we don't really know!

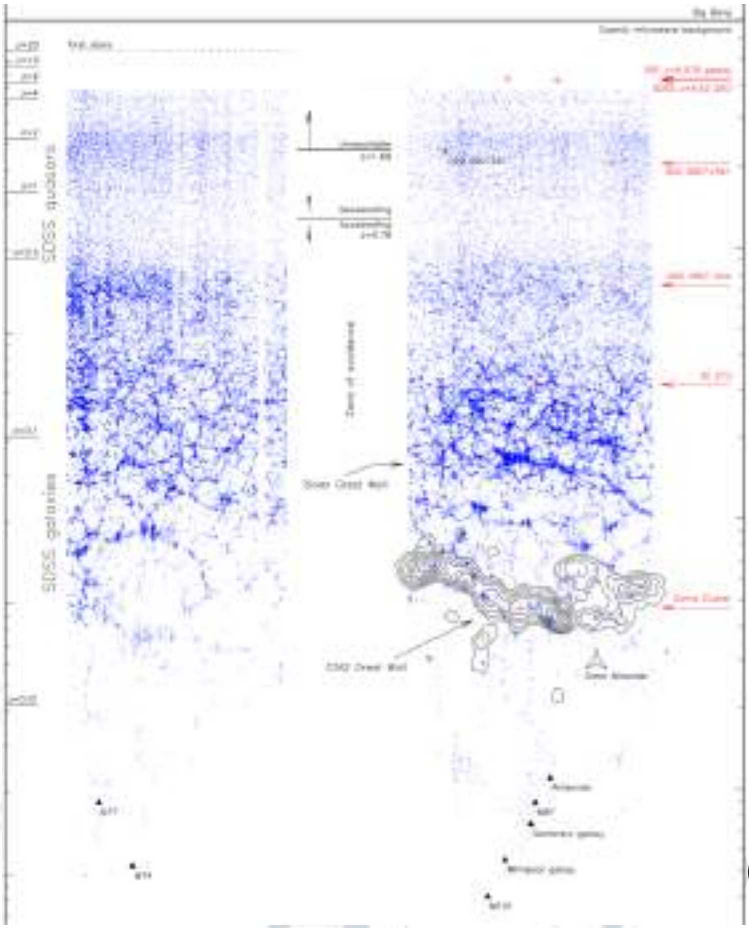
What is dark matter?

◎ But there are many observations that imply its existence:

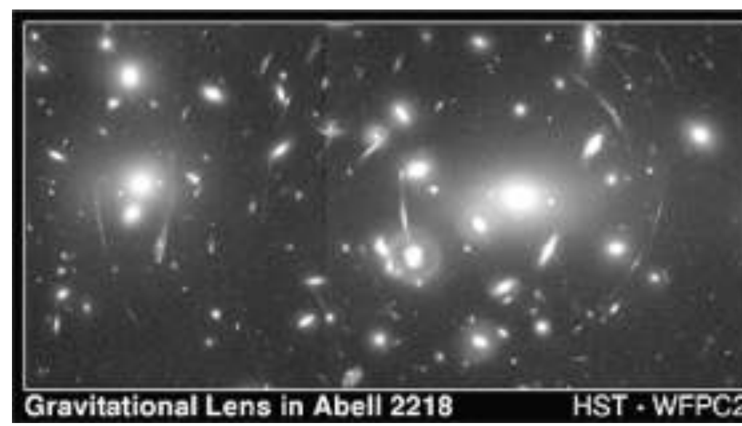
- Flat galactic rotation curves
- Gravitational lensing of galaxies and clusters
- Evolution of structure in the universe

D. P. Clemens, *ApJ* **295** (1985), p. 422





Gott et al., *ApJ* **624** (2005), p. 463



What is dark matter?

◎ From observations, we can infer dark matter (DM) is

- Electrically neutral
- Non- or weakly-interacting with regular matter and itself
- Non-relativistic
- Stable, at least on the timescale of the age of the universe
- Very abundant in the universe (accounts for ~85% of matter, ~27% total energy)

◎ Many models and theories exist to explain dark matter: axions, sterile neutrinos, supersymmetry…

◎ Most popular DM candidates are WIMPs (weakly interacting massive particles)

What is dark matter?

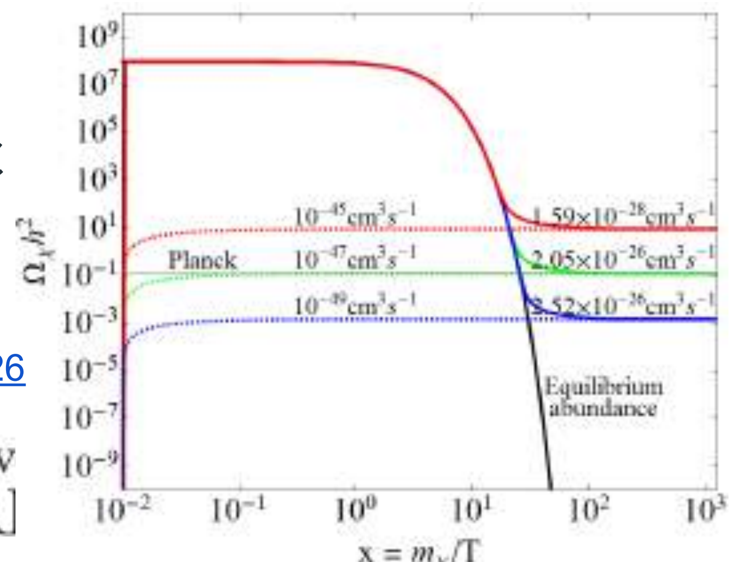
◎ WIMPs may interact through the weak force or a new fundamental force ≤ the weak scale, as well as gravity

◎ "Freeze out" method for thermal relic abundance:

- In early, high-temperature universe, DM was plentifully pair produced
- Once temperature dropped too low, production ceased (production freeze out)
- If self-annihilating, relic abundance can decrease
- But universe expands → density and annihilation rate decrease ($n_{DM} \sim$ frozen)

◎ Cosmological constraints and some assumptions (coupling, etc.) give WIMP mass $O(10^2\ \mathrm{MeV} - \mathrm{TeV})$: **WIMP miracle!**

◎ Possible to probe mass range at the LHC



DOI: 10.3389/fphy.2014.00026

Experiment

The LHC

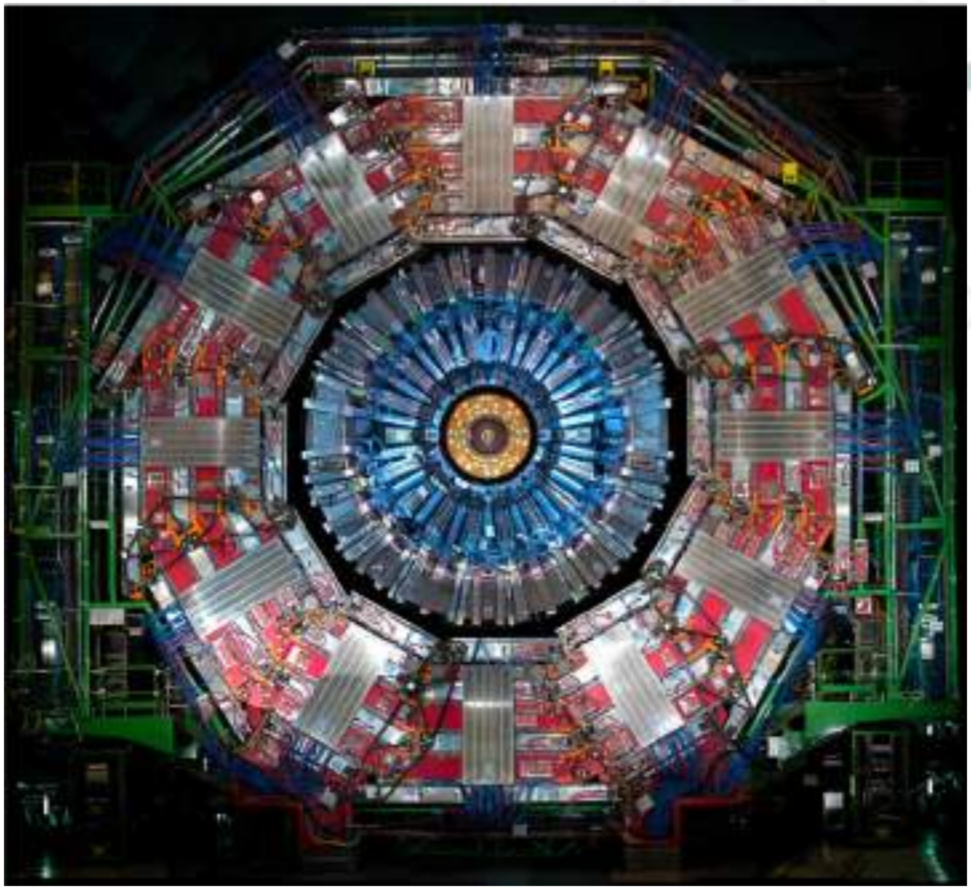
- Big proton collider

The LHC

◎ Big proton collider…like, really big!

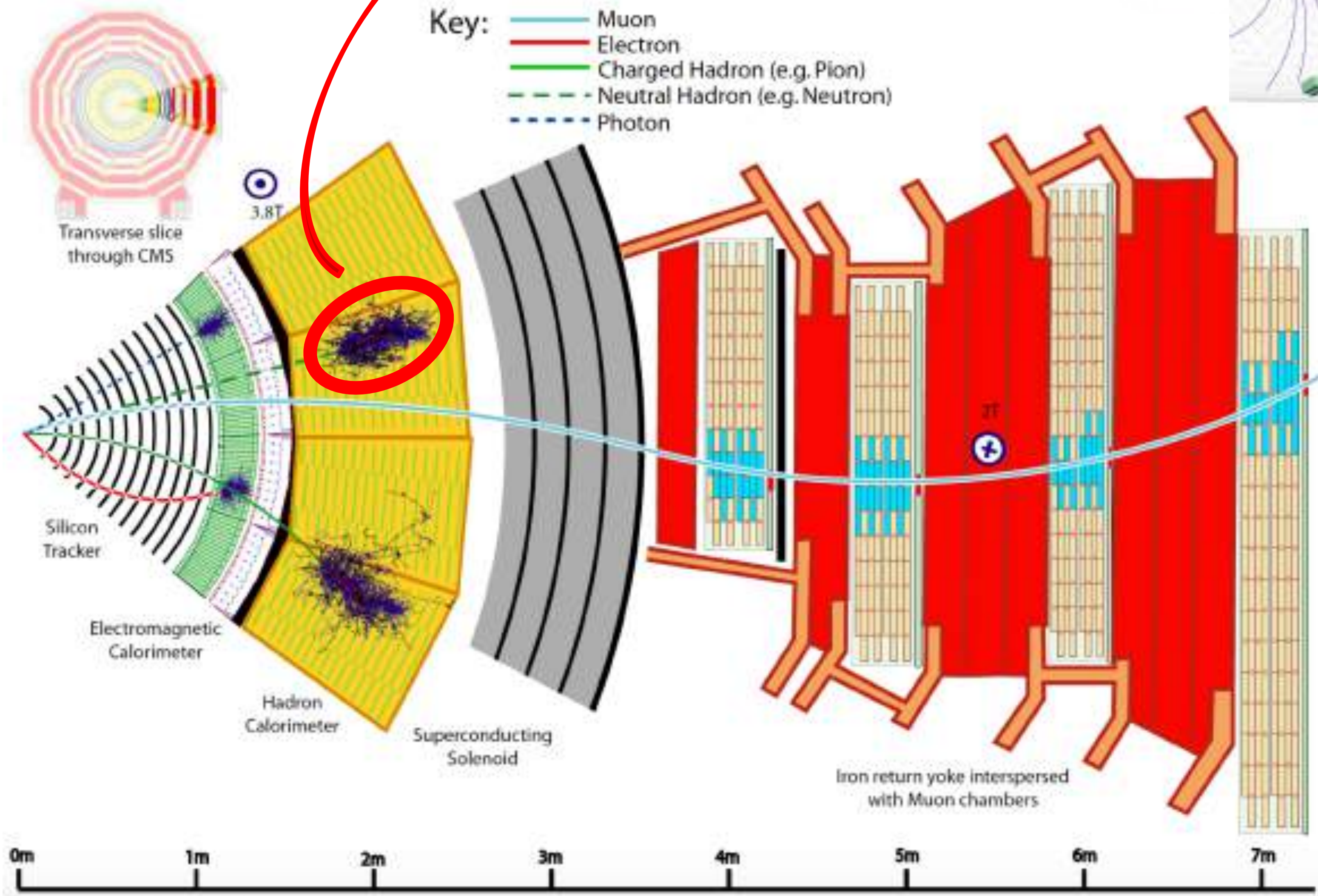
CMS

- General purpose detector
- Weighs 14,000 tons
- 4T magnet storing 2.7GJ of energy
- Level-1 and High Level Triggers reduce event rate from 40 MHz to ~1 khZ: O(GB/s) written to disk
- Better than ATLAS
- Analyses on supersymmetry & exotic searches, Higgs, top, *b*-physics, precision measurements, heavy ions



CMS

Hadronic jet: high-energy quarks, gluons fragment into collimated spray/shower of hadrons



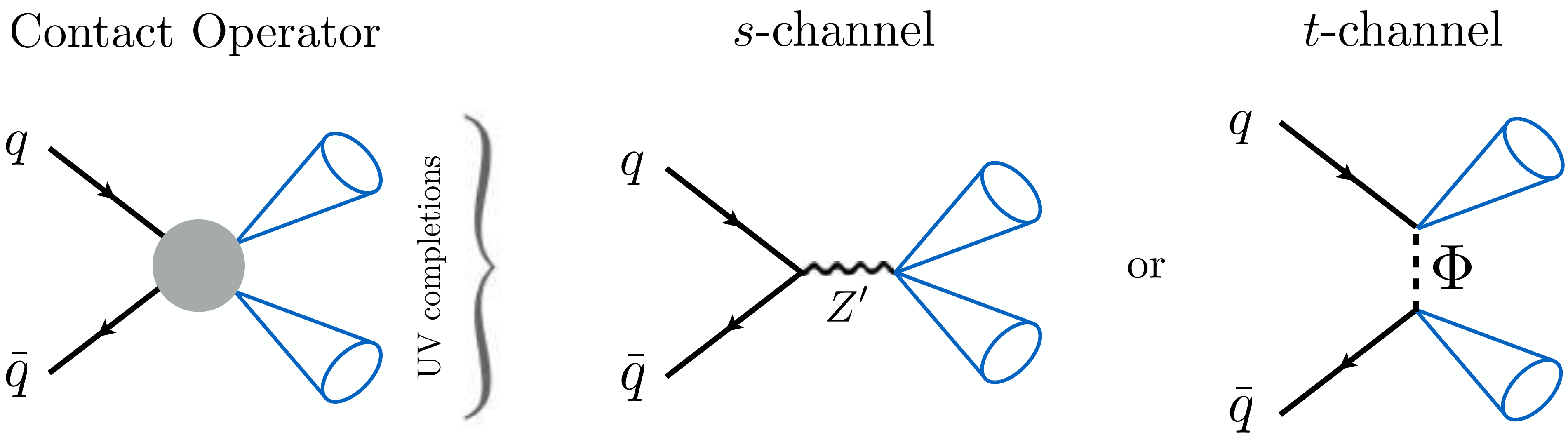
Research

Semi-visible jets: theory

◎ Model behind this exotic search detailed in DOI: [10.1007/JHEP11(2017)196](https://doi.org/10.1007/JHEP11(2017)196)

◎ Authors propose QCD-esque dark force with portal to Standard Model (SM)

◎ Two main production modes: *s*-channel (resonant *Z'*), *t*-channel (exchange of bifundamental Φ)



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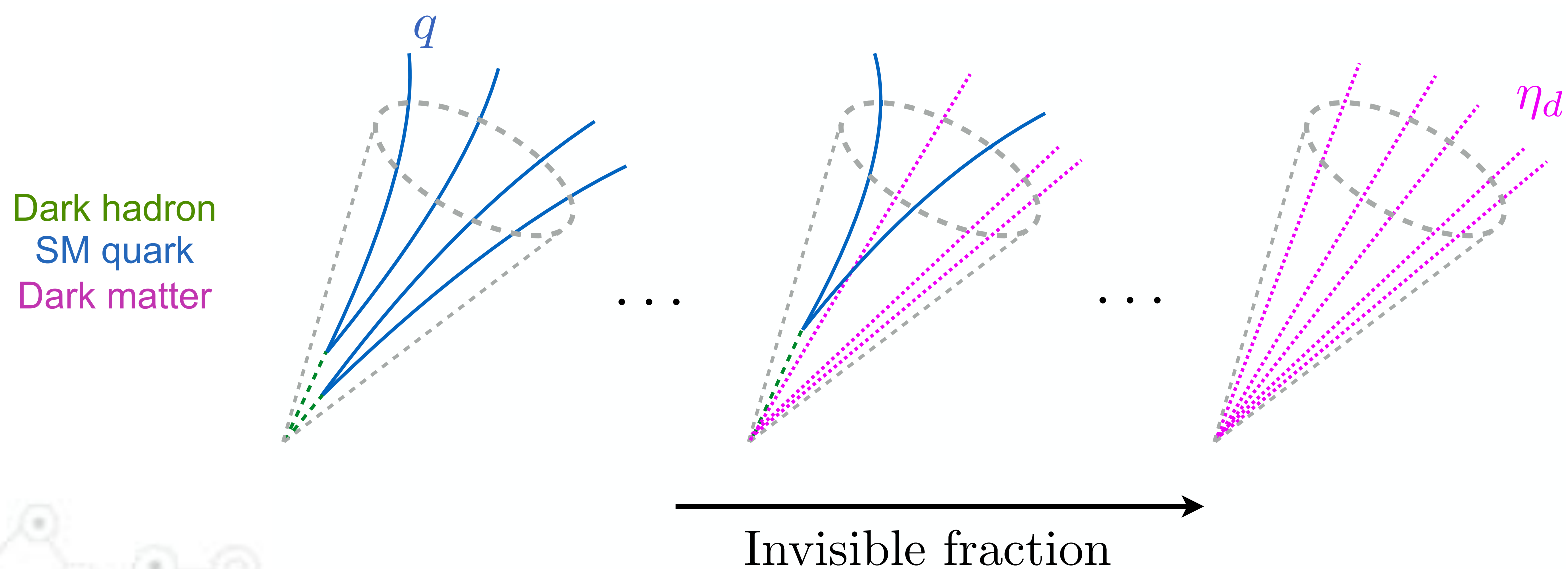
Semi-visible jets: theory

◎ Mediator interaction leads to production of dark quarks that hadronise, similar to QCD

◎ Depending on flavour of dark hadron, can decay into stable dark matter or back into visible states

◎ Final state contains hadronic jet with invisible component: **semi-visible jet** (SVJ)



Semi-visible jets: theory

◎ Several free parameters:

- α_d or Λ_d – running dark coupling / dark confinement scale
- $m_{Z' \text{or } \Phi}$ – mass of mediator
- m_d – dark quark mass
- r_{inv} – probability of a dark hadron remaining invisible

$$\Lambda_d = 1000[\text{GeV}]e^{\frac{-2\pi}{\alpha_d b}}$$

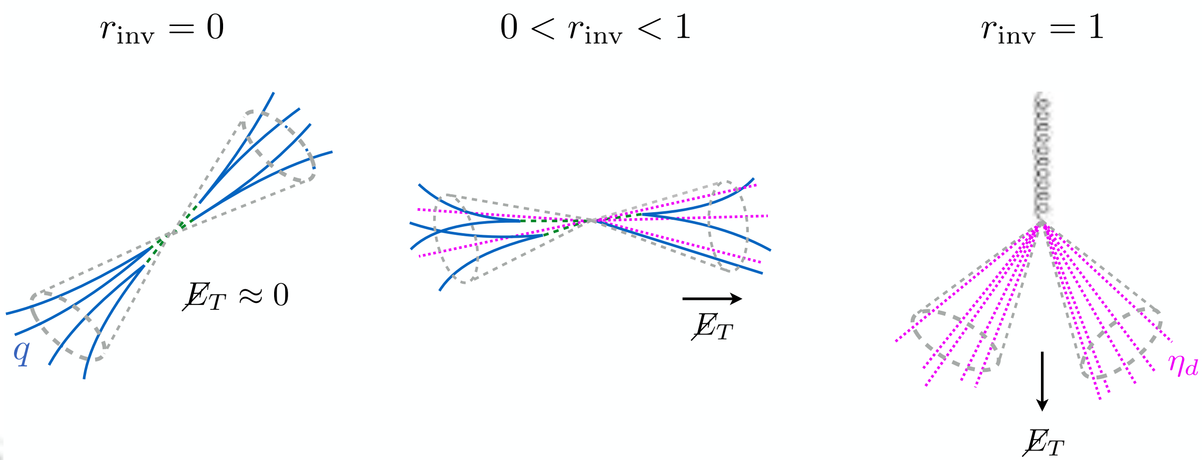
◎ Many free parameters means large phase space, but can be reduced when considering constraints of LHC

Semi-visible jets: theory

◎ Typical event contains 2 semi-visible jets, so missing transverse energy (MET or $E_{\mathrm{T}}^{\mathrm{miss}}$) direction dependent on r_{inv}

◎ Search is essentially hadronic final state with large MET

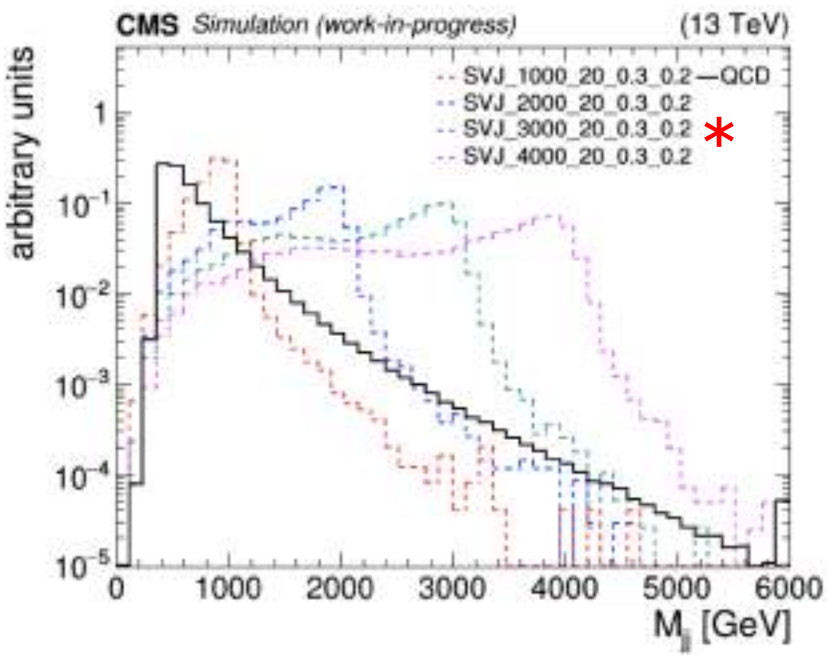
◎ Difficult search as signal resembles mismeasured QCD. But tagging and jet substructure techniques have come a long way in the last few years

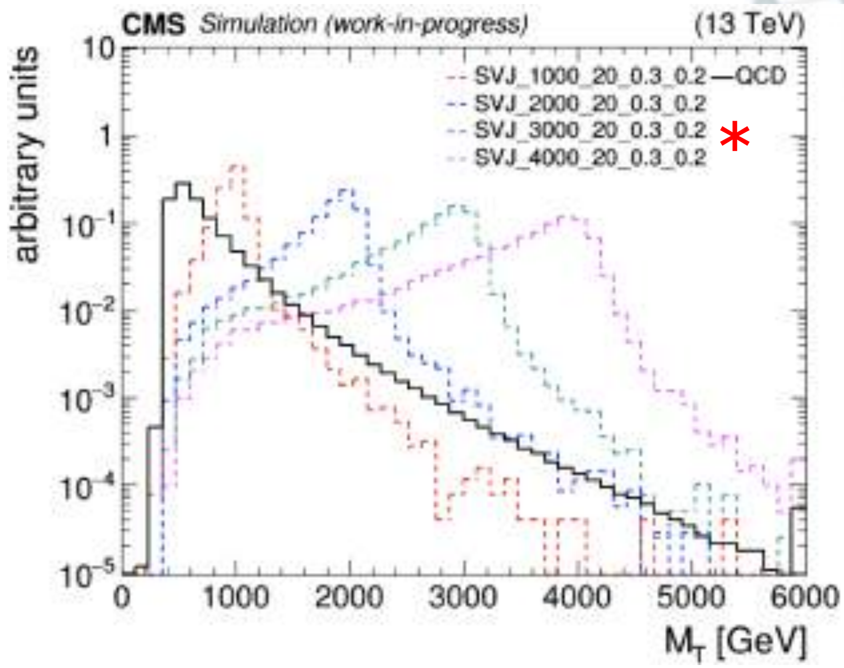


Semi-visible jets: kinematics

∗ Naming convention: SVJ_<$m_{Z'}$>_<m_d>_<r_{inv}>_<α_d>

◎ As most events are dijet, can use dijet mass M_{jj} or transverse mass $M_{\text{T}}(\text{jj}, E_{\text{T}}^{\text{miss}})$ to reconstruct Z' in s-channel



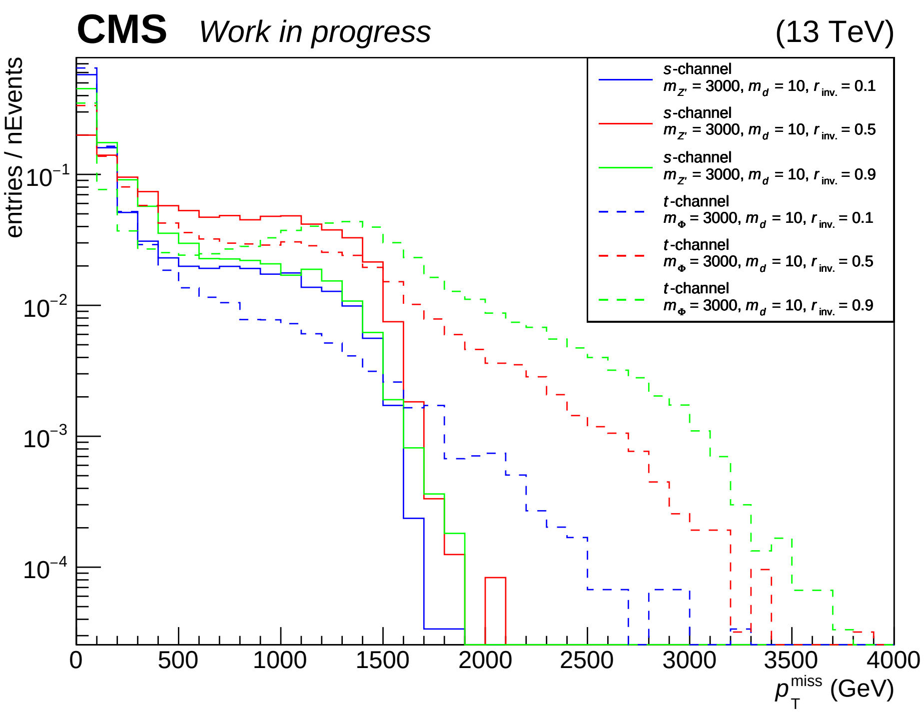


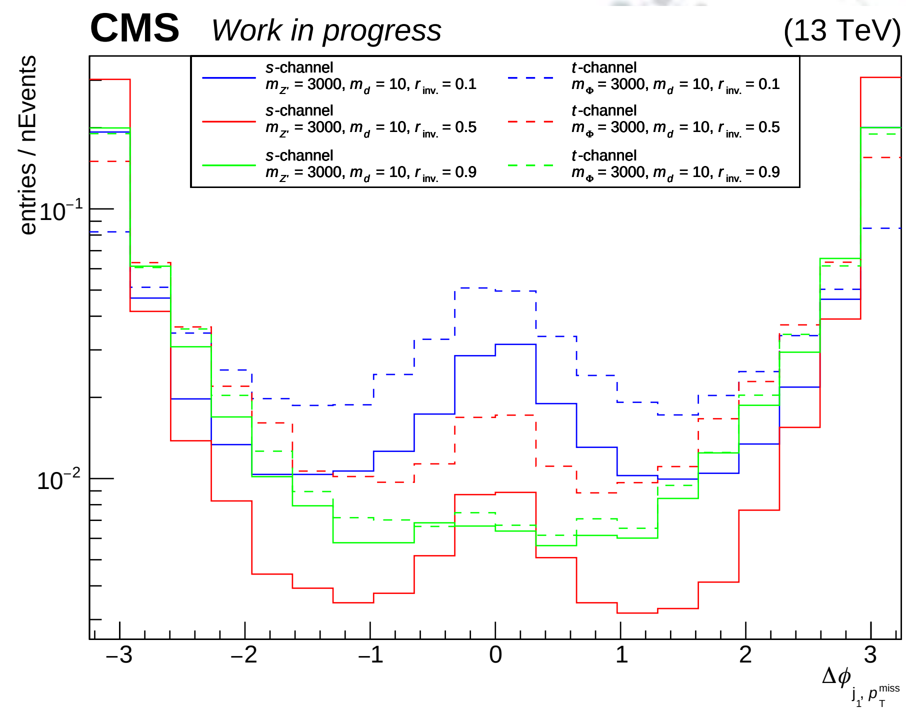
◎ Essentially will be performing bump hunt in M_{T} (better resolution that M_{jj})

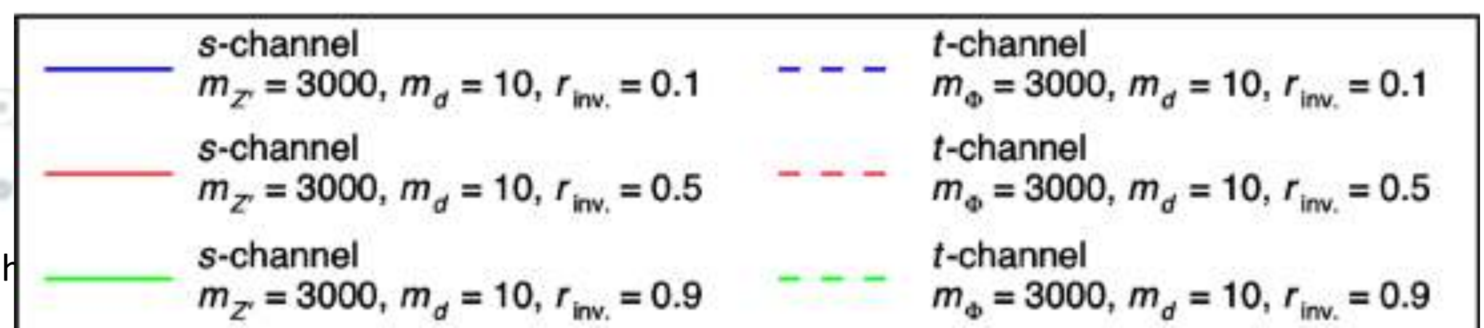
◎ t-channel more complicated, no obvious way to extract signal…

Semi-visible jets: kinematics

◎ $E_{\mathrm{T}}^{\mathrm{miss}}$ and $\Delta\phi\left(\mathrm{j}_1, E_{\mathrm{T}}^{\mathrm{miss}}\right)$ distributions for *s*- and *t*-channel







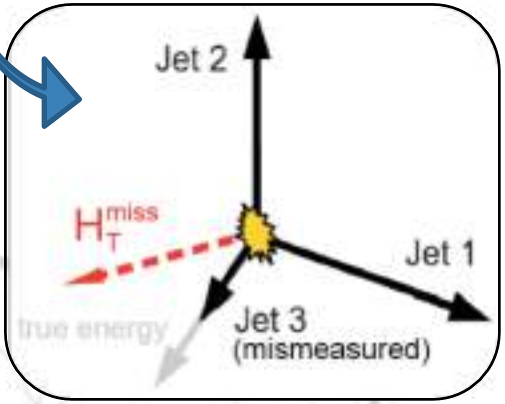
Semi-visible jets: analysis strategy

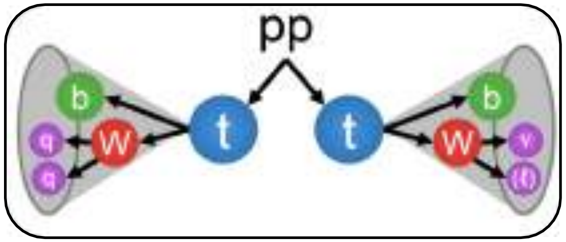
◎ Sample production for signal MC uses MADGRAPH5_AMC@NLO (hard scatter) and PYTHIA8 (showering and hadronisation)

◎ Possible to set all free parameters in config file

◎ Dominant backgrounds:

- QCD – jet mismeasurement induces MET aligned with jet
- $t\bar{t}$ – boosted tops, lost leptons, neutrinos aligned with jets
- $W(\ell\nu)$ + jets – lost leptons, hadronic tau, high σ
- $Z(\nu\nu)$ + jets – real MET from $\nu\nu$, but less likely to be aligned with jet





Semi-visible jets: analysis strategy

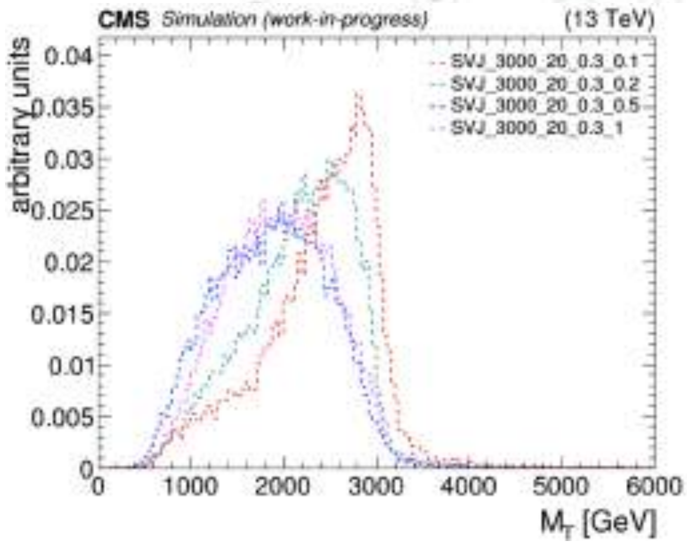
◎ Third jet studies:

- Varying α_d in signal changes behaviour of shower (higher α_d $\rightarrow$ more fragmentation)
- Dijet mass resolution degrades so need to include 3rd jet (which can come from fragmentation of 1st or 2nd jet)
- But 3rd jet is from ISR in some events
- Increases MET, but degrades M_{jj} and M_{T}

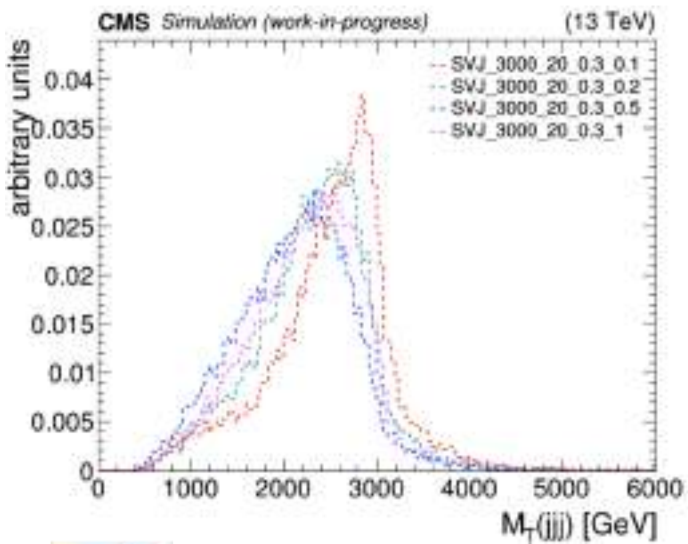
◎ Looked at using soft drop algorithm: decluster jets to remove ISR and pileup contributions

◎ Also considered $\max[\Delta\phi(\mathrm{j}, E_{\mathrm{T}}^{\mathrm{miss}})]$: Z' recoils from ISR jet so large $\Delta\phi$

◎ But non-trivial. Still investigating

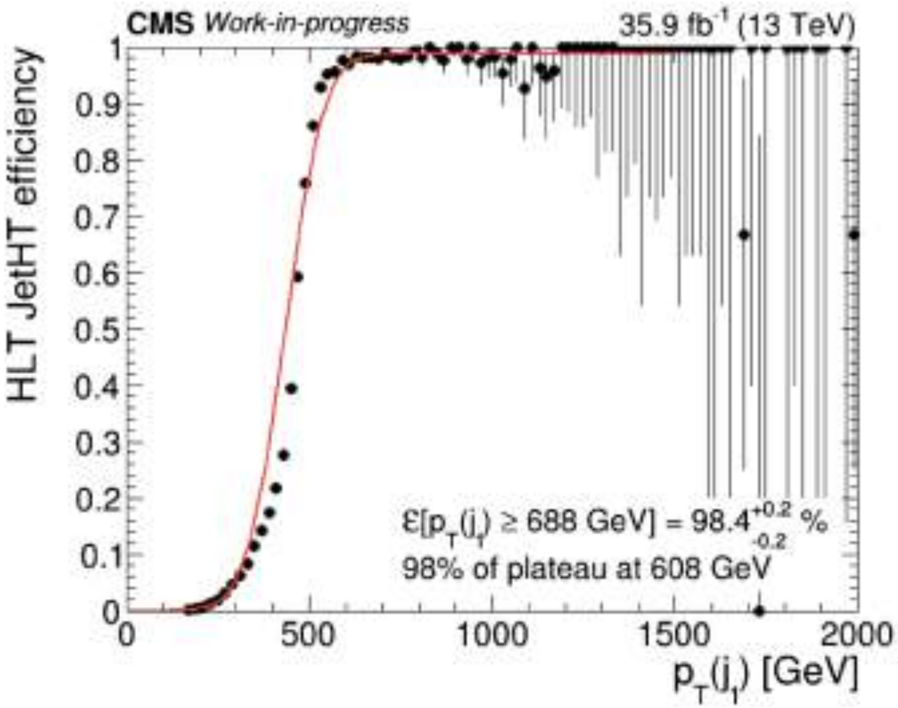


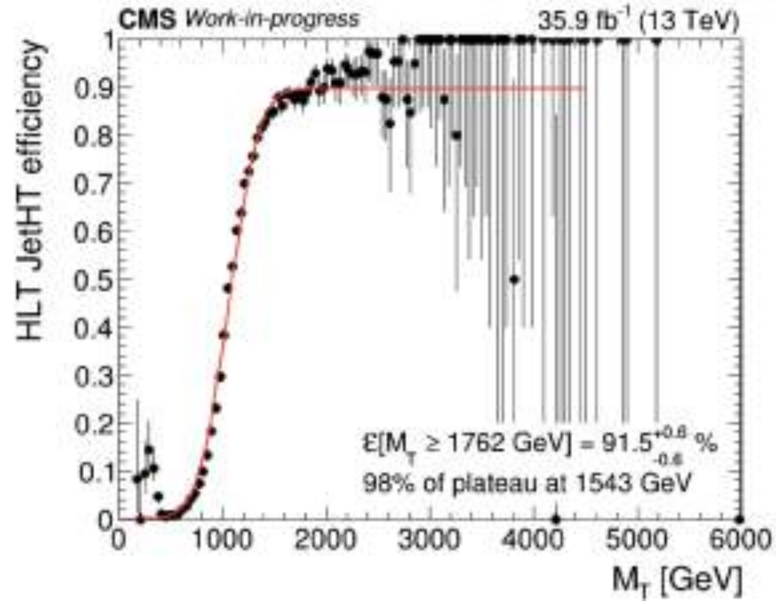
3 jet events: ↑ = dijet M_{T}, ↓ = trijet M_{T}

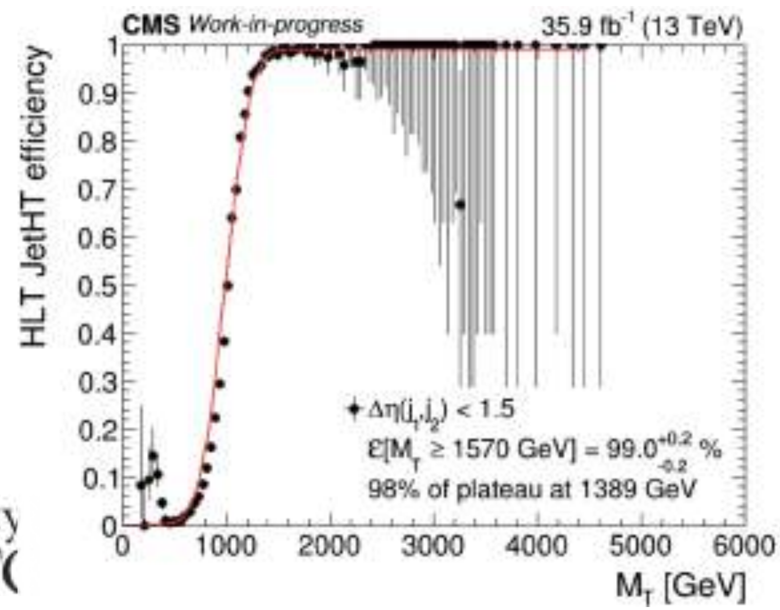


Semi-visible jets: analysis strategy

◎ Triggers also being investigated. 2016, SingleMuon dataset:







Semi-visible jets: analysis strategy

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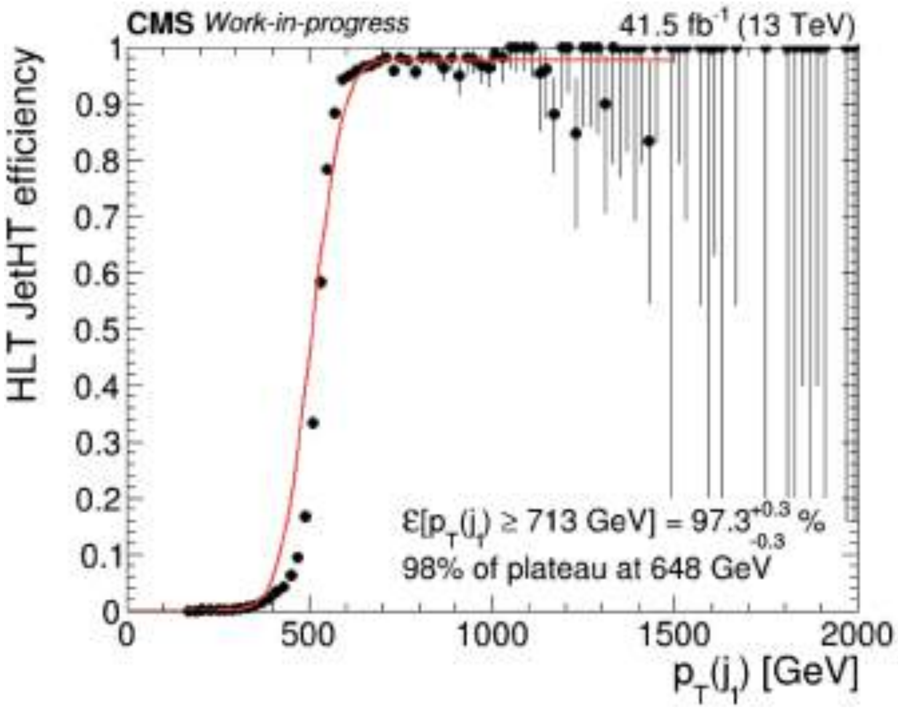
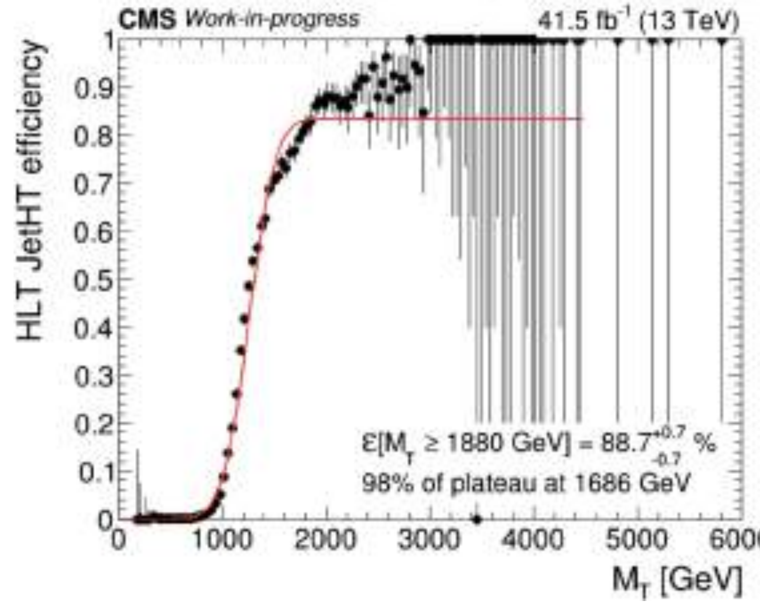
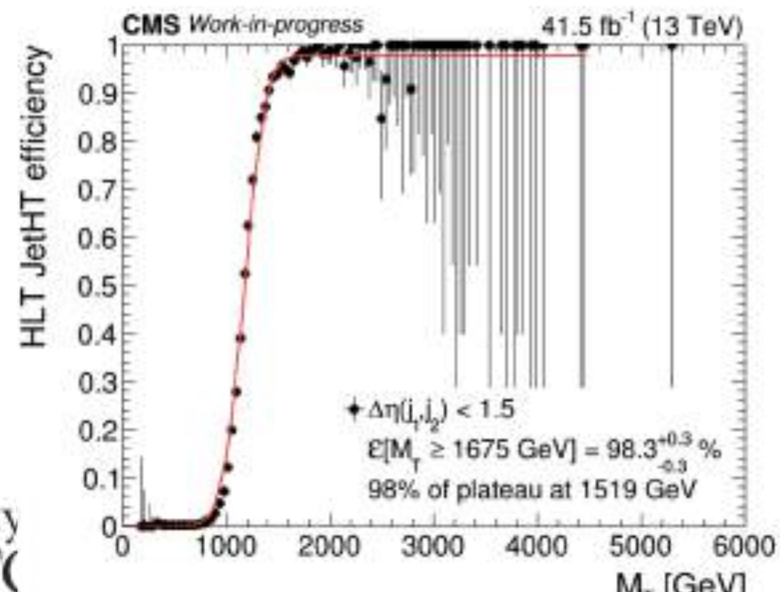


◎ M_T turn on poor unless cuts applied (M_{jj} comes from jet mass/energy *or* angle between jets, but triggers only select for jet energy)





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Semi-visible jets: analysis strategy

◎ Tagger being developed to distinguish SVJs and QCD jets

◎ Using BDT trained against QCD background events

◎ Input variables:

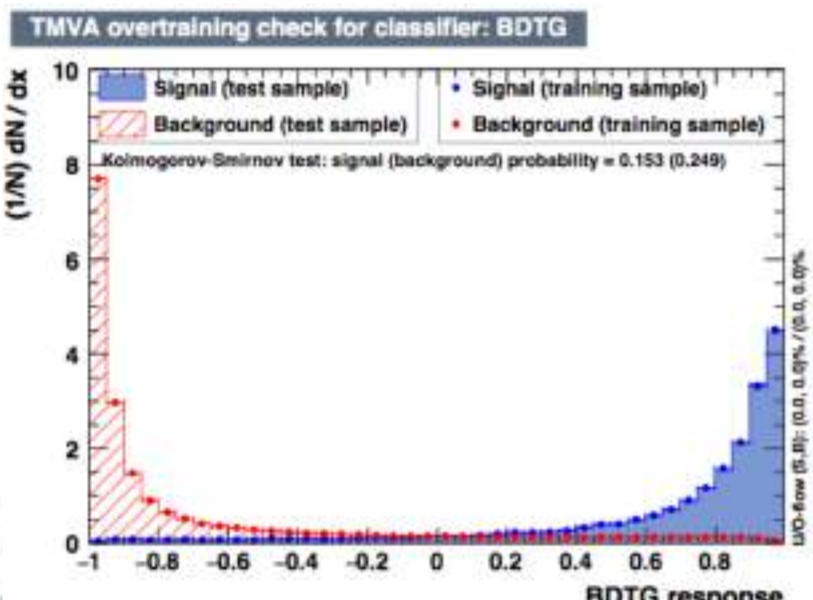
- Soft drop mass
- Jet constituent multiplicity
- Minor axis of $\eta - \phi$ ellipse
- $\Delta\phi\left(\mathrm{j}_1, E_{\mathrm{T}}^{\mathrm{miss}}\right)$
- N-subjettiness ratios $\tau_{21} = \tau_2/\tau_1, \tau_{32} = \tau_3/\tau_2$
- Girth $g = \sum_{i \in \mathrm{jet}} \frac{p_{\mathrm{T}}^{i}}{p_{\mathrm{T}}^{\mathrm{jet}}} |r_i|$

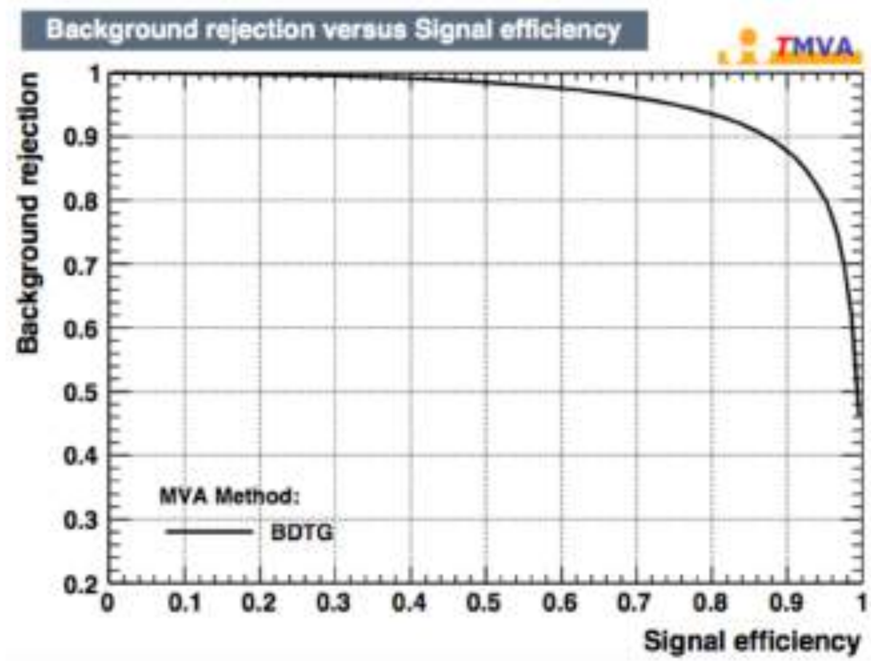
Semi-visible jets: analysis strategy

◎ ROC curve looks good. Area below curve = 0.954

◎ Overtraining checked. Distributions look fine but poor K-S test results

◎ Optimisations still ongoing. Considering use of other variables, dividing input variables by p_T to remove correlations, using combinations of different signal models for robustness





Semi-visible jets: timeline

◎ Many areas of analysis still need to be investigated

- Finalising signal MC production and event selection
- Continuing development of SVJ tagger and other studies (3rd jet, triggers)
- Data/MC comparisons in control regions and background estimation

◎ Current plan is to present complete analysis at Moriond 2019 (ambitious) with 2016+17 data, *s*-channel signal models

◎ Second paper planned with full Run-II data that also includes *t*-channel signal (will require very different strategy to s-channel)

Thanks for listening!

Backup

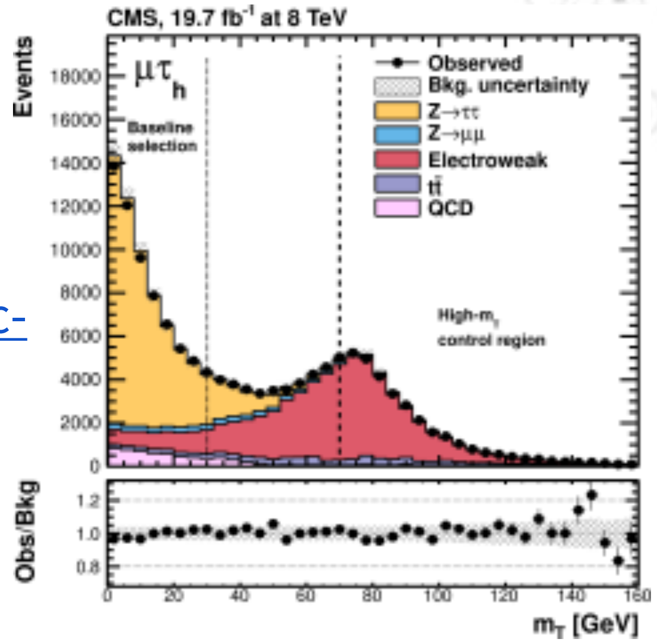
Transverse mass (M_T)

◎ Useful variable when considering decay into one visible particle and one invisible

◎ $M_T \equiv \sqrt{2 p_T E_T^{miss} (1 - \cos(\Delta\phi))}$

◎ Example: reconstruct W mass from $W \to \ell\nu(?)$

◎ http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-13-004/



Soft drop algorithm

- Jet declustering algorithm to remove wide-angle soft radiation from a jet
- Can mitigate effects of ISR and pileup
- First, decluster each jet into two subjets
- Check condition $\frac{\min(p_{Tj1}, p_{Tj2})}{p_{Tj1} + p_{Tj2}} > z_{cut} \times \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$
- CMS uses $z_{cut} = 0.1, \beta = 0$
- If condition met, keep entire jet. Else, keep higher-p_{T} subjet and repeat
- See DOI: 10.1007/JHEP05(2014)146 for more information

Current signal event selection

Preselection

- $N_{jet} \geq 2$
  (AK8 PFCHS jets, $p_T > 170$ GeV)
- Loose PFJetID for $j_{1,2}$
- $p_T(j_1) > 600$ GeV **OR** $\Delta\eta(j_1, j_2) < 1.5$
- $\not{E}_T/M_T > 0.15$
- e/μ veto ($p_T > 10$ GeV)

Full Selection

- (MET filters)
- $M_T > 1400$ GeV
- $\not{E}_T/M_T > 0.25$
- $\Delta\varphi_{min}(j_{1,2}, \not{E}_T) < 0.75$

Reject QCD

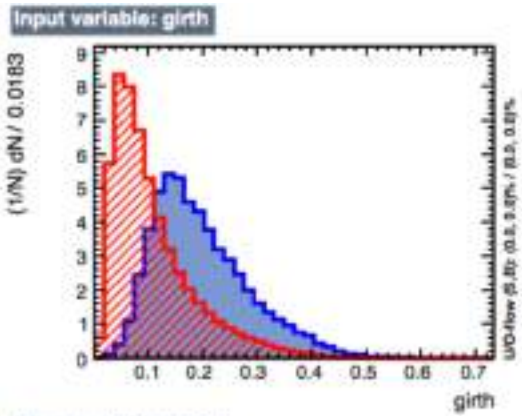
Reject $t\bar{t}$, $W(\ell\nu)$ + jets

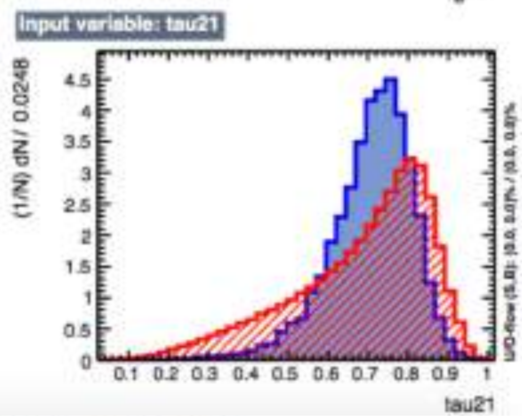
◎ M_T cut in full selection avoids sculpting

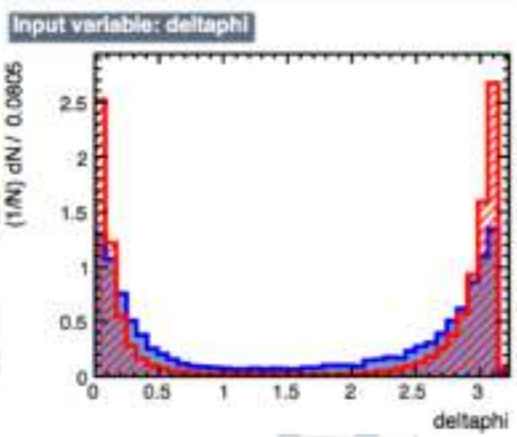
◎ MET filters cut out a lot of QCD

◎ The **OR** in preselection boosts trigger efficiency

SVJ Tagger input variables

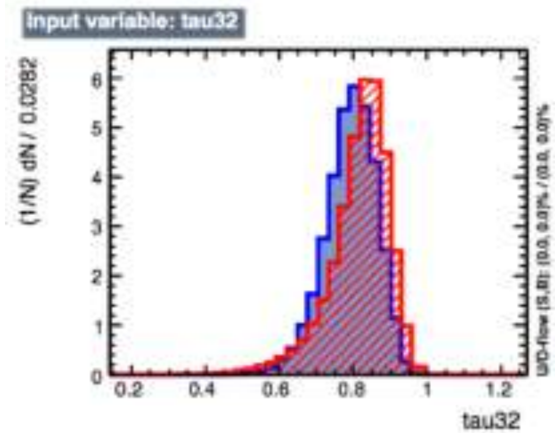


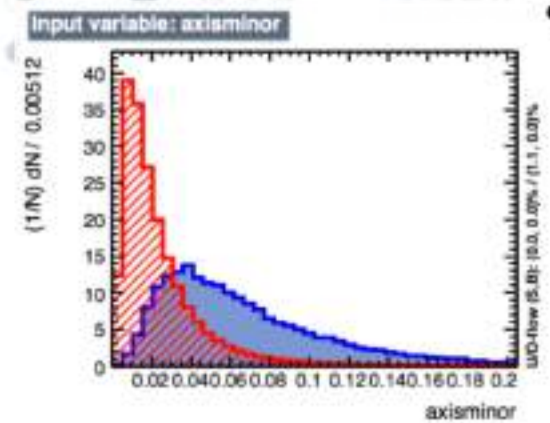


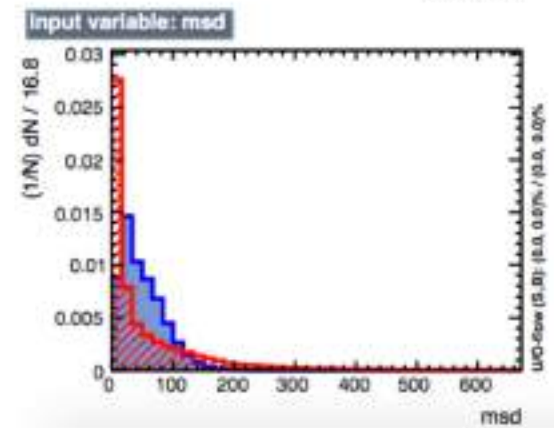


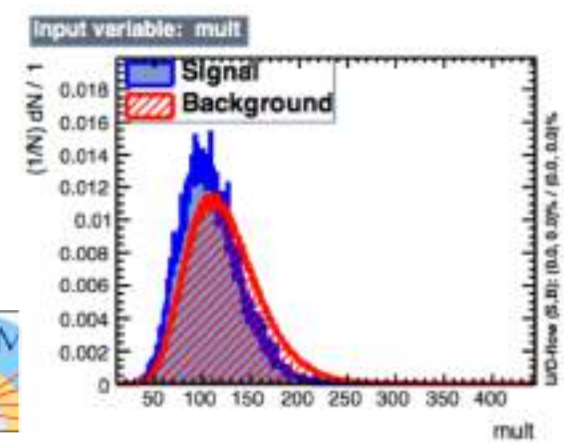
Variable ranking from TMVA:

1	axisminor	4.052e-01
2	girth	3.051e-01
3	msd	1.981e-01
4	tau21	1.008e-01
5	deltaphi	9.642e-02
6	tau32	5.268e-02
7	mult	4.853e-02









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