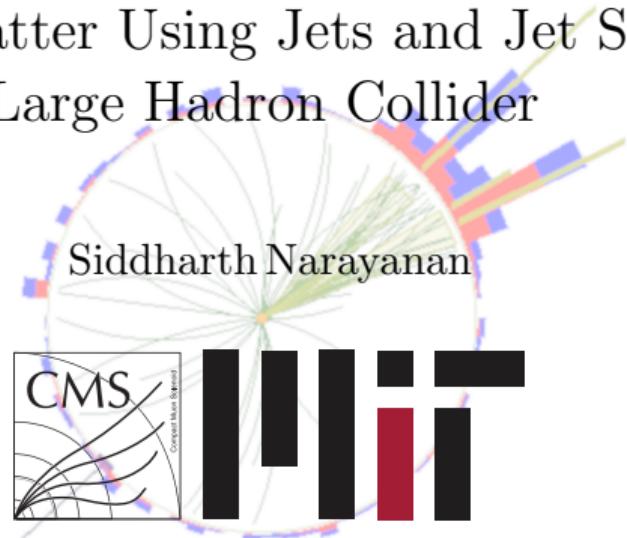


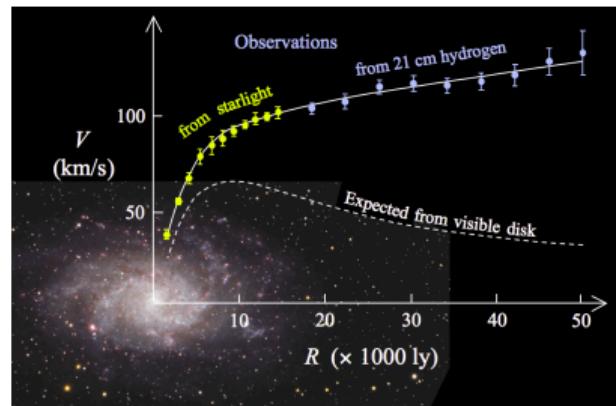
Searching for Dark Matter Using Jets and Jet Substructure at the Large Hadron Collider



Ph.D. Thesis Defense - 2019/01/22

Dark matter - in space

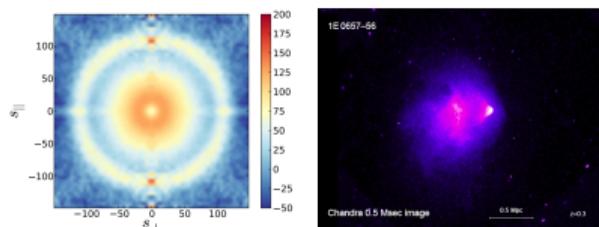
Strong astrophysical evidence for DM:



[1,2]



[3]

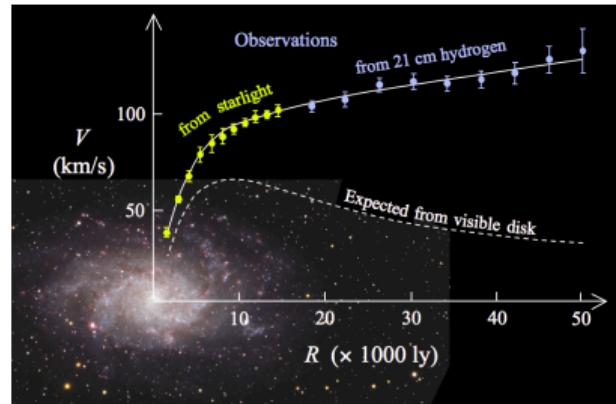


[4]

[5]

Dark matter - in space

Strong astrophysical evidence for DM:



Weakly Interacting Massive Particles

- ▶ Weakly: DM-SM coupling $g_\chi \sim g$
- ▶ Massive: mass $m_\chi \sim 100$ GeV
- ▶ Close to measured relic density:

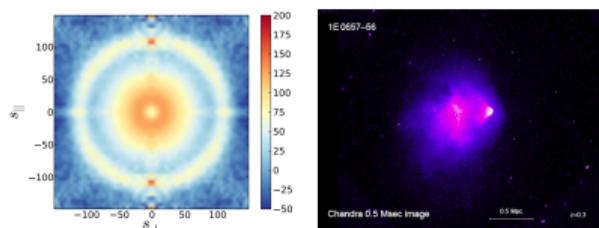
$$\Omega \propto \frac{\rho}{\rho_c} \propto \frac{1}{\langle \sigma v \rangle}$$

$$\Omega_{\text{meas.}} = 0.12, \quad \Omega_\chi \sim 0.1$$

- ▶ Particle colliders can probe WIMPs



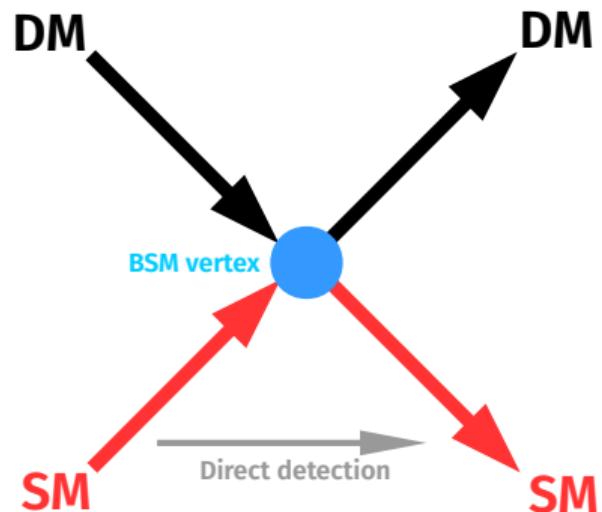
[3]



[4]

[5]

Dark matter - in a laboratory



Search for DM-SM interactions as Earth moves through DM halo

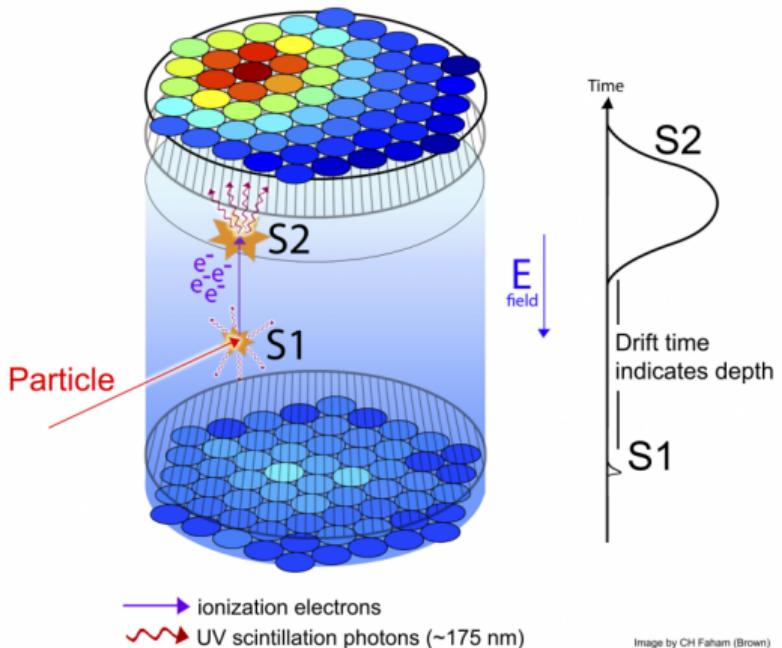
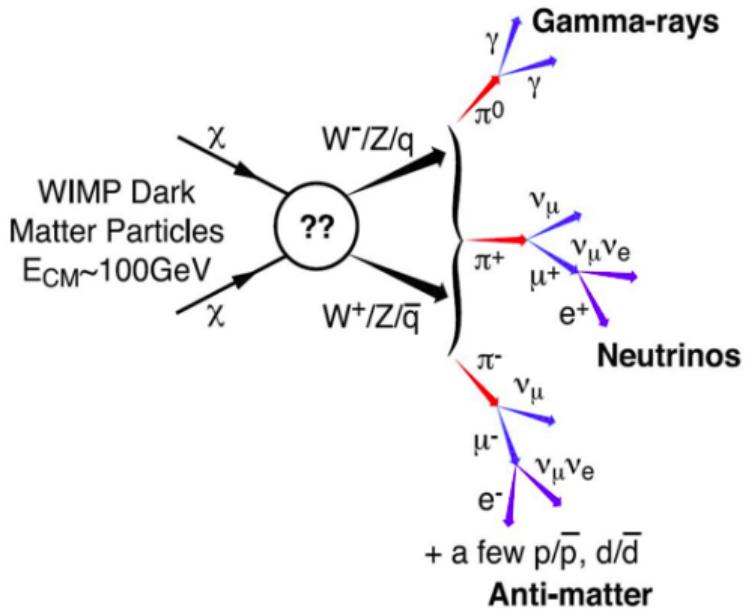
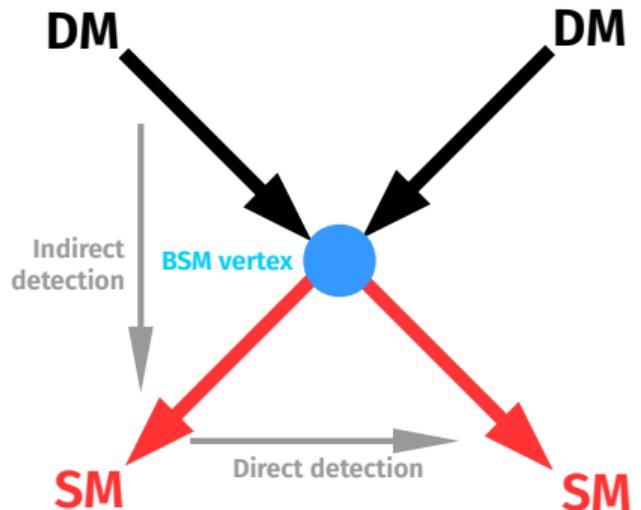


Image by CH Faham (Brown)

[6]

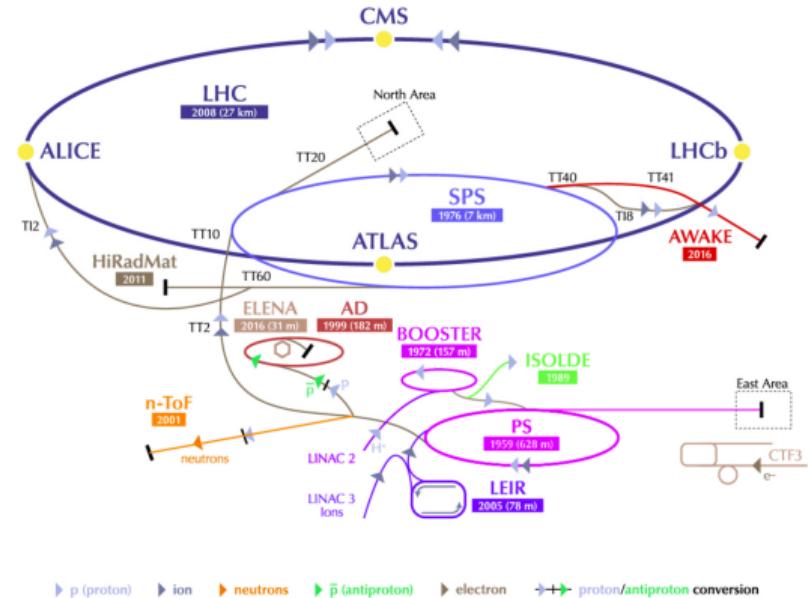
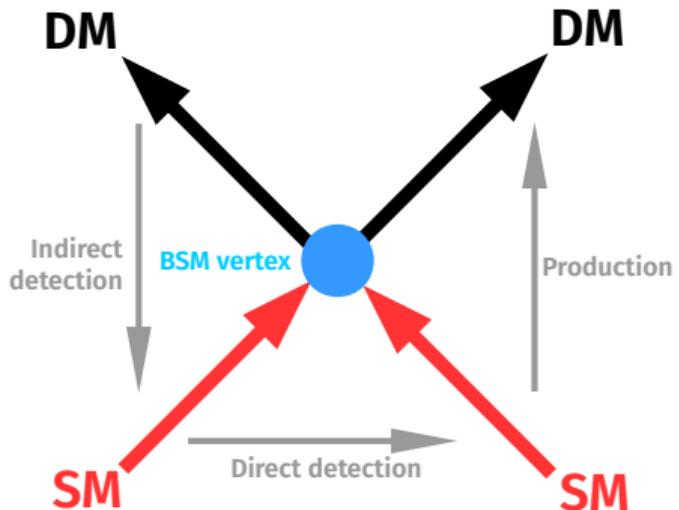
Dark matter - in a laboratory



[7]

Look for SM remnants of DM-DM
annihilation in space

Dark matter - in a laboratory

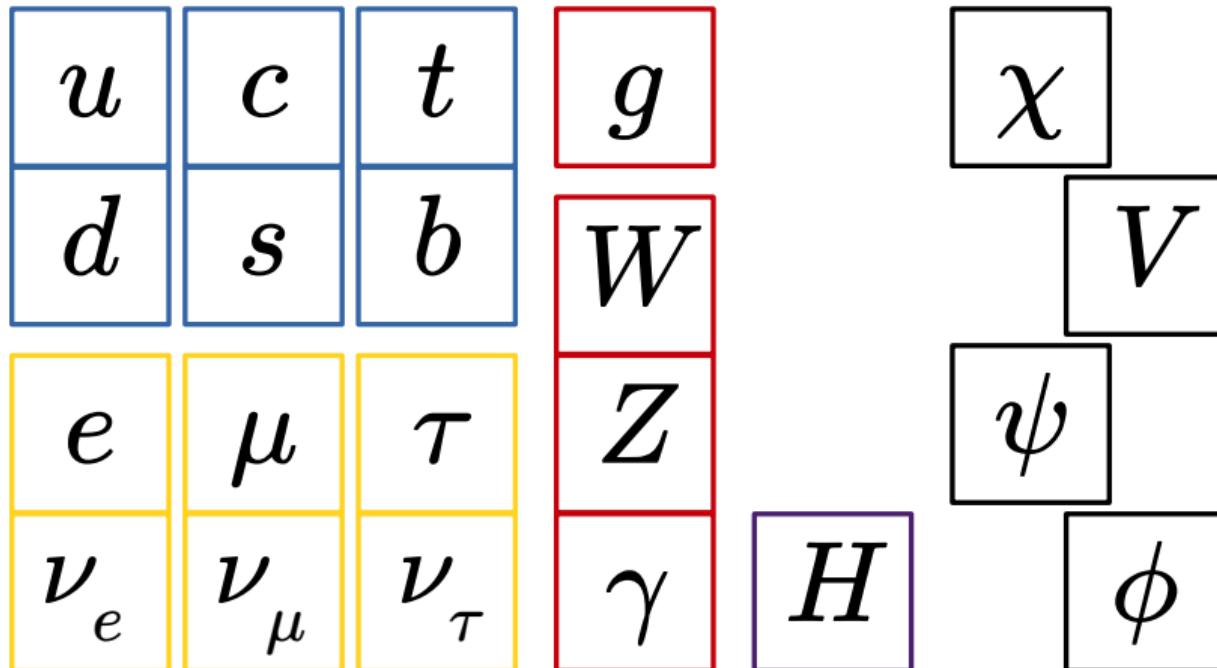


Exploit DM-SM interaction to produce DM
in a laboratory

Assumptions for production of WIMPs at LHC

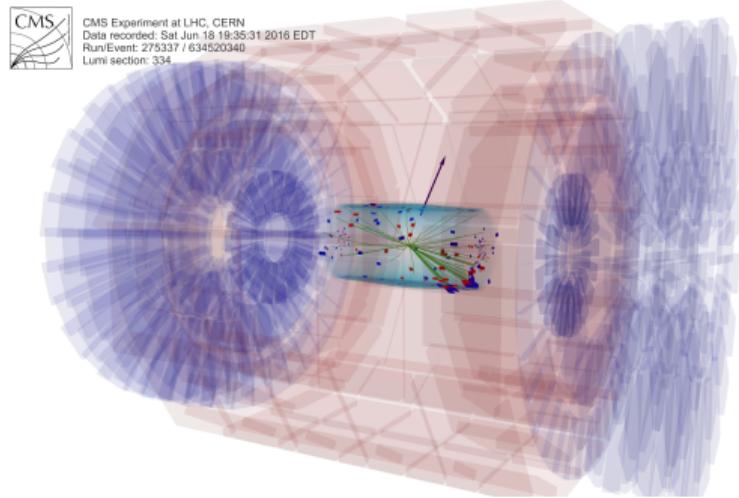
Effective coupling to quarks/gluons $\gtrsim 10^{-4}$

Masses $\lesssim \sqrt{s}$



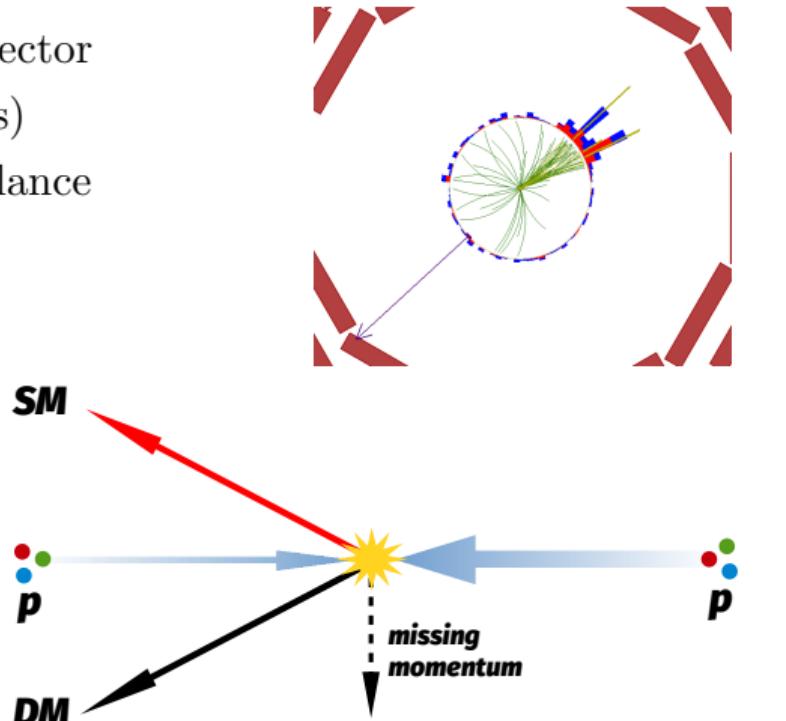
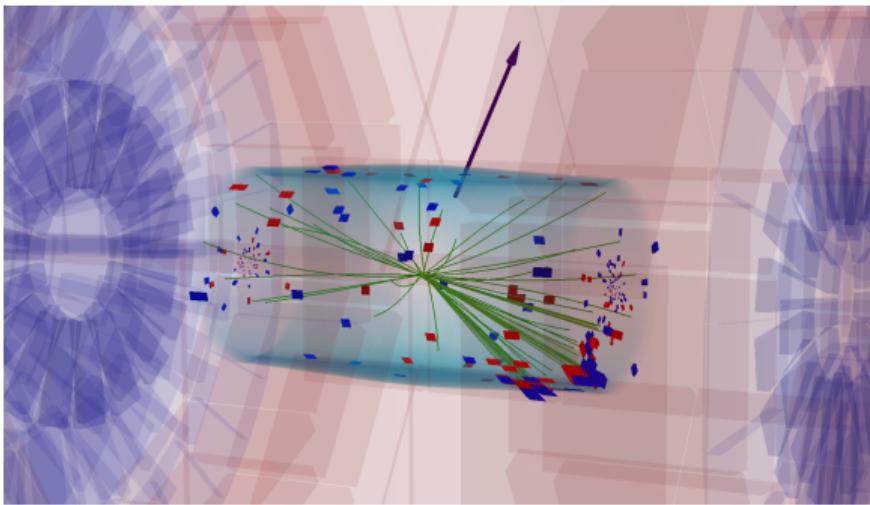
Seeing the invisible at a hadron collider

- By definition, DM will not interact with a detector



Seeing the invisible at a hadron collider

- ▶ By definition, DM will not interact with a detector
- ▶ Look for production of DM with SM particle(s)
- ▶ Key observable is transverse momentum imbalance



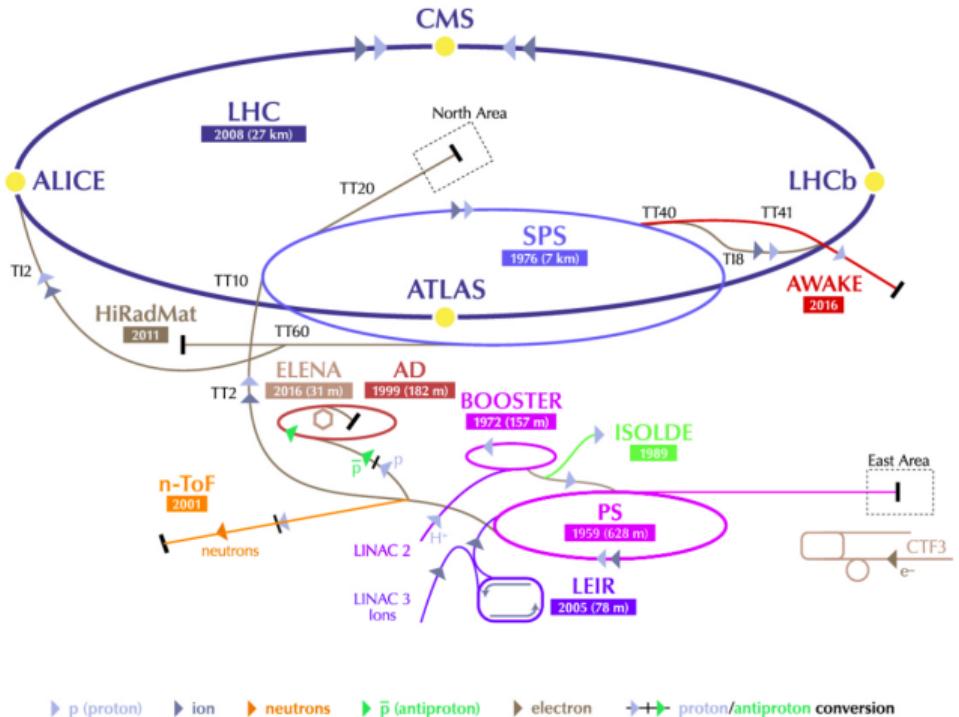
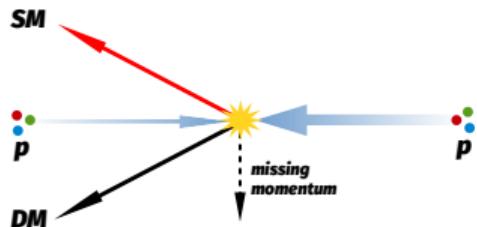
Which SM particle(s)?

Many to choose from. SM particle choice \Leftrightarrow type of DM you can look for

	SM particle	Minimal extension	Higgs-like	Extra dimensions	Extended Higgs sector	Flavor violation
Quarks	$q(g)$					
	t					
	qq'					
	$t\bar{t}$					
	$b/b\bar{b}$					
Gauge bosons	γ					
	$V \rightarrow q\bar{q}'$					
	$Z \rightarrow \ell^+\ell^-$					
Higgs	$H \rightarrow x\bar{x}$					

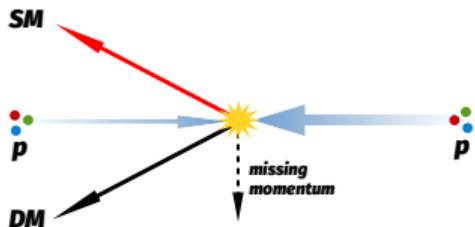
p_T^{miss} at the LHC

- CMS records collisions from the LHC
 - Today: $\sqrt{s} = 13 \text{ TeV}$ pp collision data from 2016
- Missing momentum:



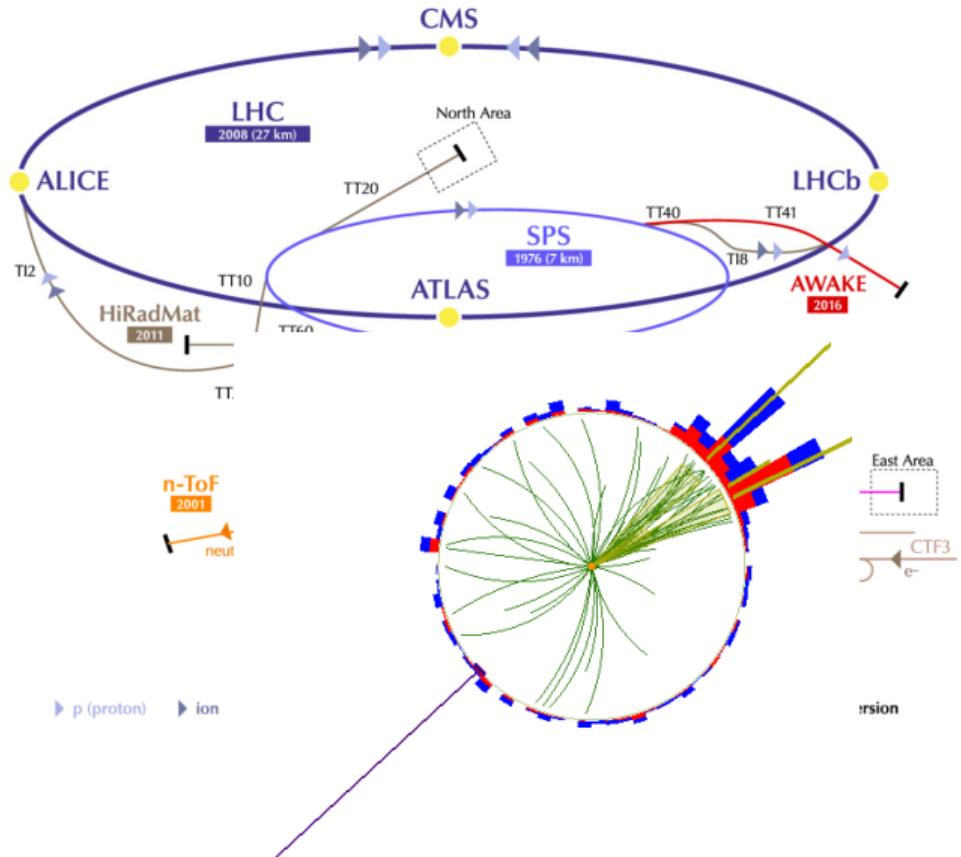
p_T^{miss} at the LHC

- ▶ CMS records collisions from the LHC
 - ▶ Today: $\sqrt{s} = 13 \text{ TeV}$ pp collision data from 2016
- ▶ Missing momentum:

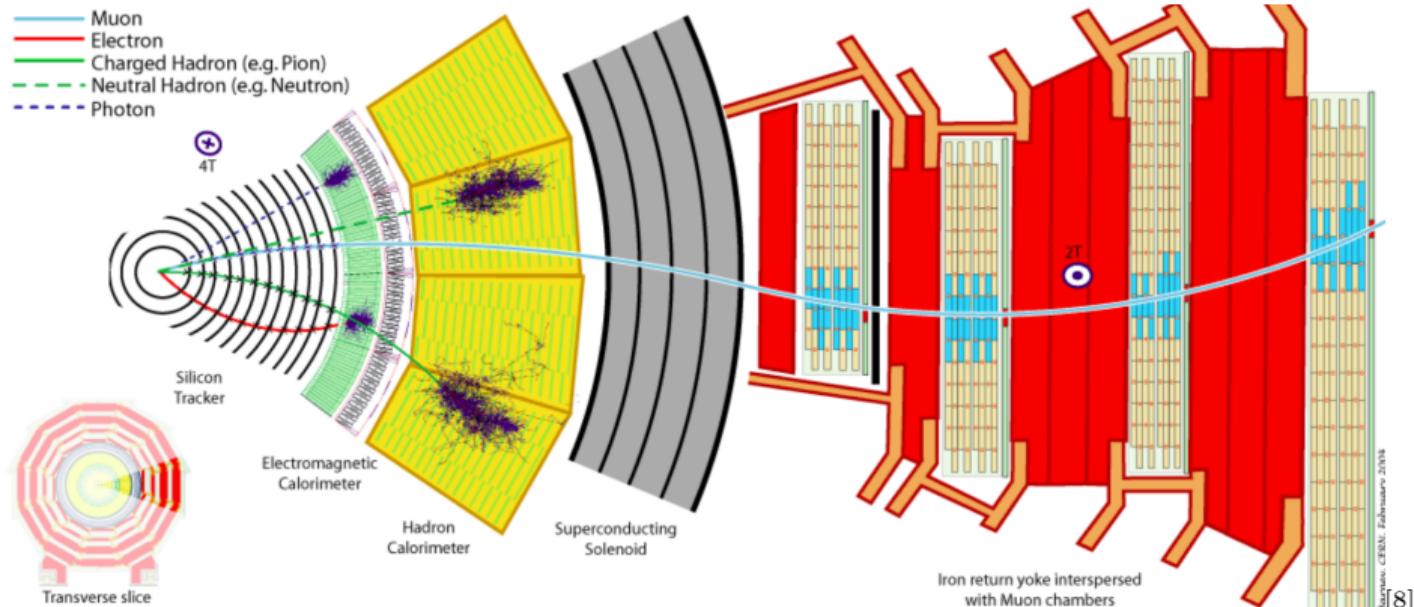


- ▶ turns into:

$$\vec{p}_T^{\text{miss}} = - \sum_{i \in \text{particles}} \vec{p}_{T,i}$$



The Compact Muon Solenoid



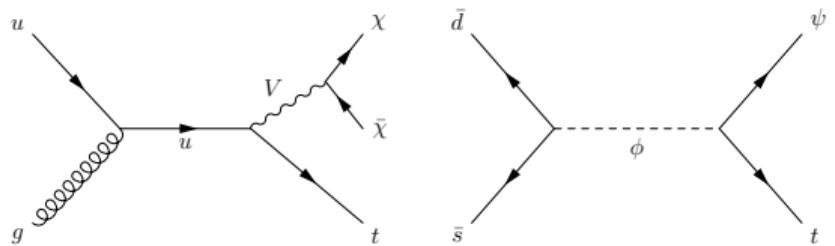
Tracker	ECAL	HCAL	Muon
$\frac{0.015\% \cdot p_T}{\text{GeV}} \oplus 0.5\%$	$\frac{3\%}{\sqrt{E/\text{GeV}}} \oplus \frac{12\%}{E/\text{GeV}} \oplus 0.3\%$	$\frac{85\%}{\sqrt{E/\text{GeV}}} \oplus 7.4\%$	3% at 100 GeV

Outline of this talk

DM production mode

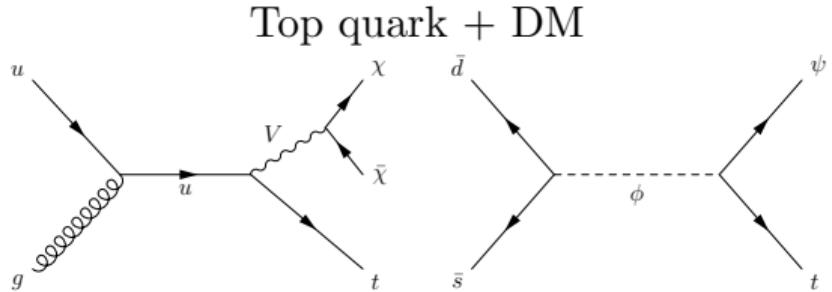
Highlights

Top quark + DM



Outline of this talk

DM production mode



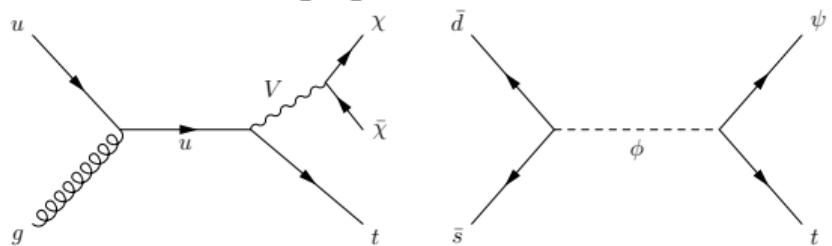
Highlights

Jet substructure
Invisible background estimation

Outline of this talk

DM production mode

Top quark + DM

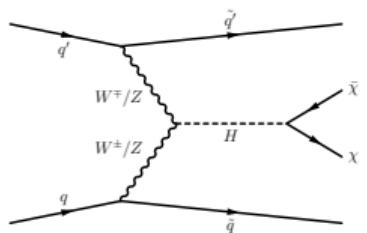


Highlights

Jet substructure

Invisible background estimation

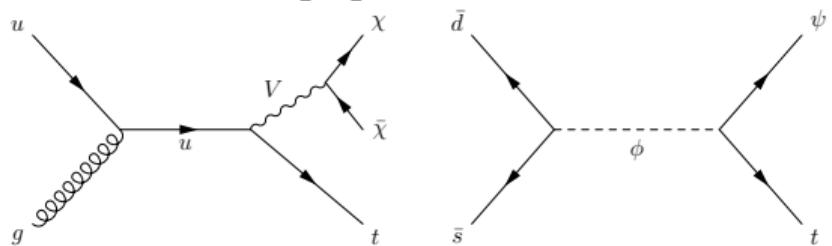
Higgs \rightarrow DM



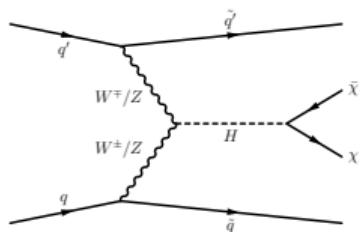
Outline of this talk

DM production mode

Top quark + DM



Higgs \rightarrow DM



Highlights

Jet substructure

Invisible background estimation

Electroweak SM backgrounds
Forward jets

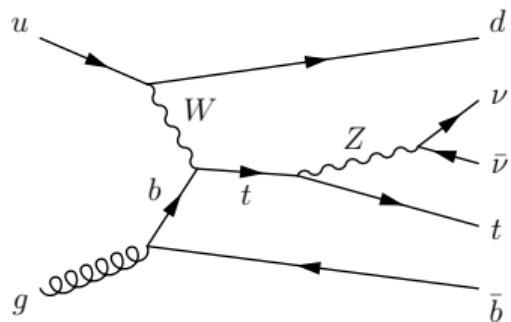
Mono-Top

Hallmarks of top quark+ p_T^{miss}

- ▶ Final state violates flavor conservation
 - ▶ SM will have b quark in the final state
- ▶ Excess mono-top production \Rightarrow flavor-changing BSM

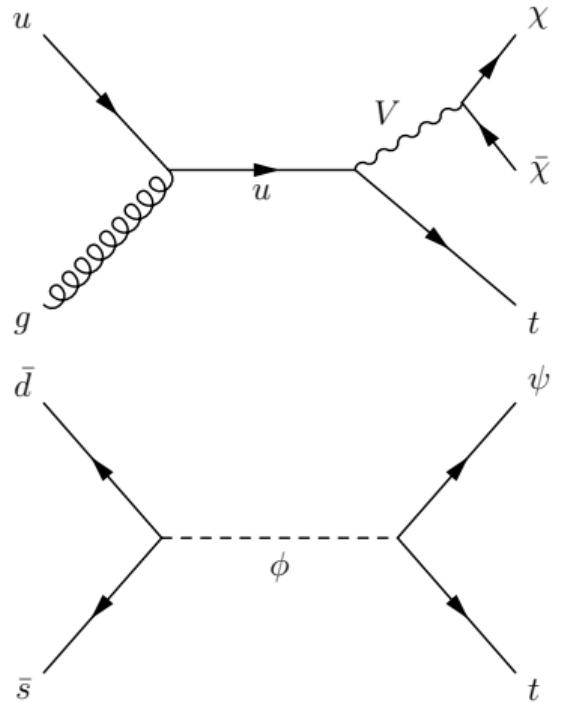
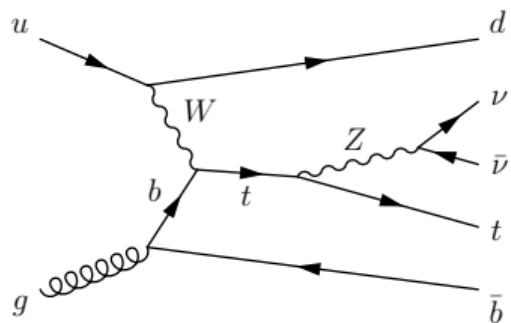
Hallmarks of top quark+ p_T^{miss}

- ▶ Final state violates flavor conservation
 - ▶ SM will have b quark in the final state
- ▶ Excess mono-top production \Rightarrow flavor-changing BSM
- ▶ SM process is tiny: 0.14 pb \Rightarrow 5000 events in 36/fb



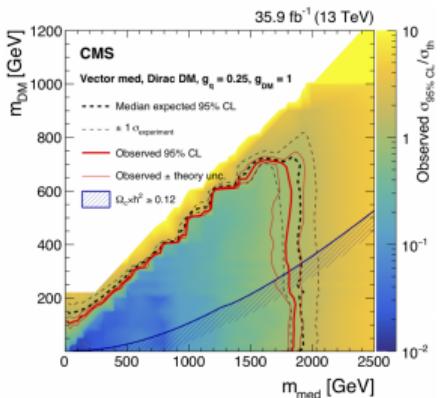
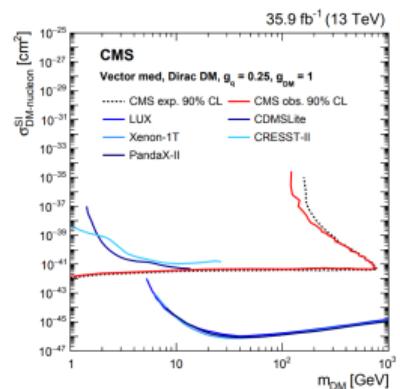
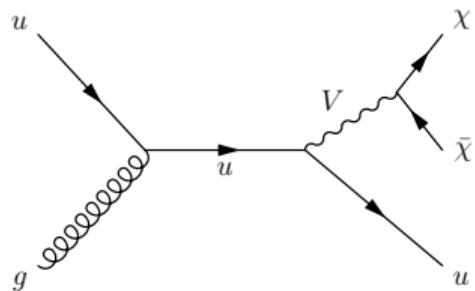
Hallmarks of top quark+ p_T^{miss}

- ▶ Final state violates flavor conservation
 - ▶ SM will have b quark in the final state
- ▶ Excess mono-top production \Rightarrow flavor-changing BSM
- ▶ SM process is tiny: 0.14 pb \Rightarrow 5000 events in 36/fb

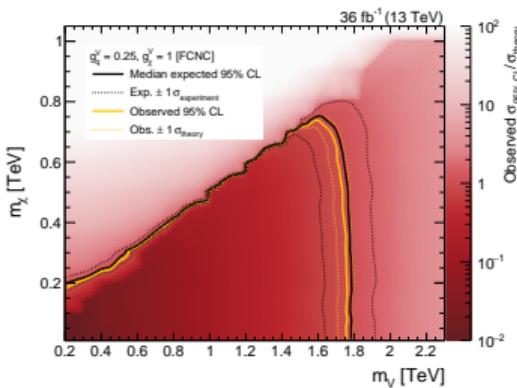
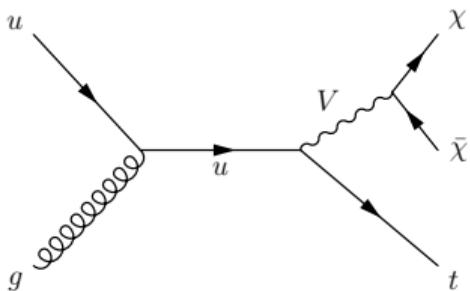


Connection to canonical DM models

Flavor conserving: diagonal g_u^V

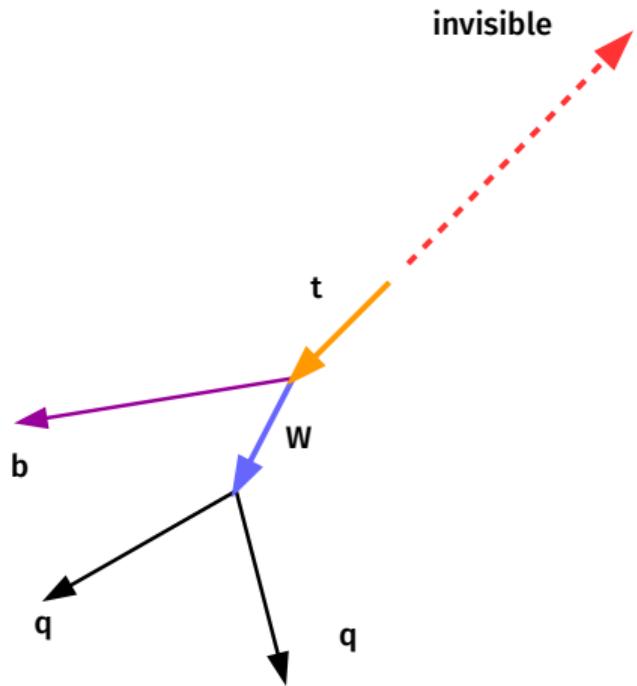


Flavor violating: off-diagonal g_u^V



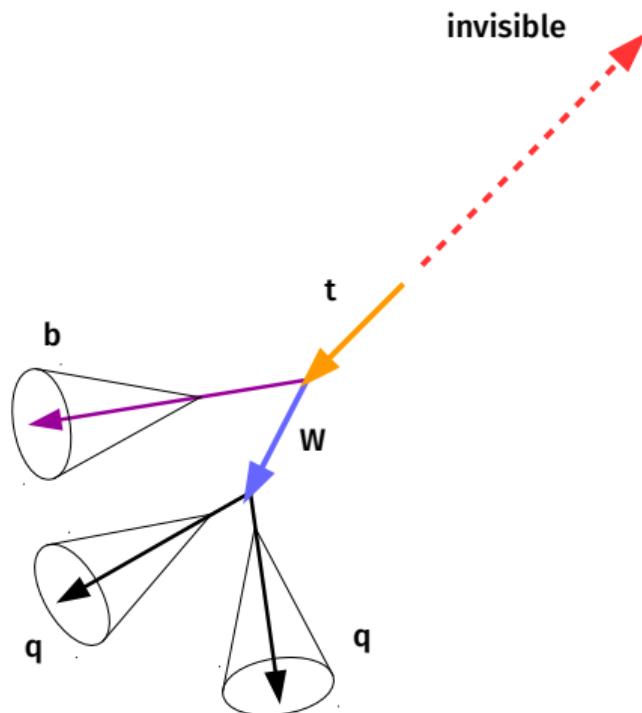
Anatomy of a mono-top event

Hadronic decay \Rightarrow larger \mathcal{B} , no p_T^{miss}

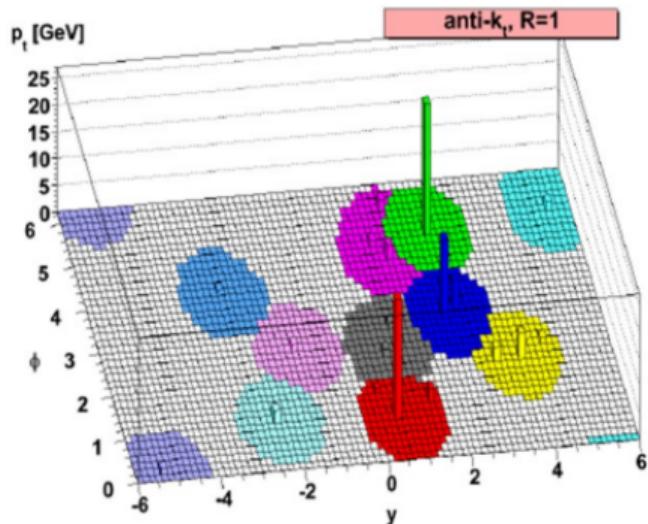


Anatomy of a mono-top event

Bare quarks hadronize into jets

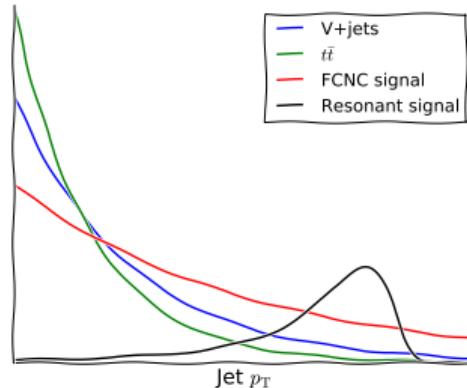
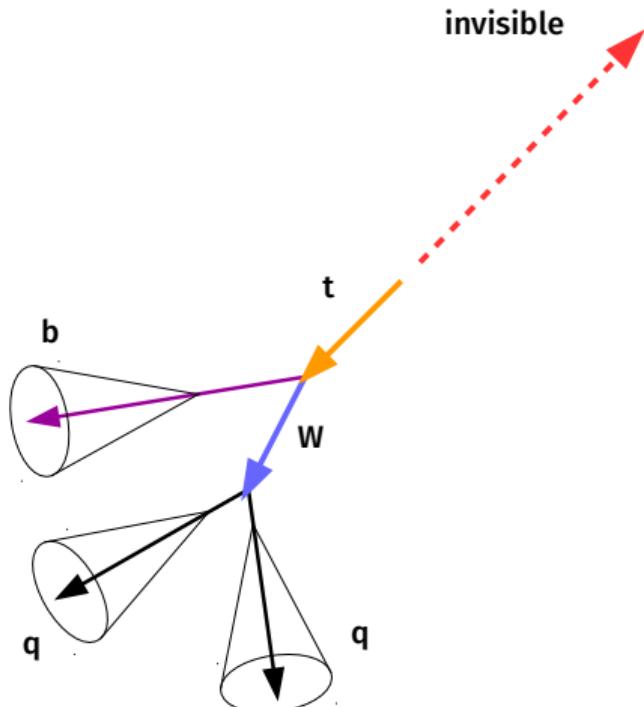


- ▶ Soft and collinear splittings \Rightarrow parton shower
- ▶ Color confinement \Rightarrow hadronization
- ▶ “Jets” are reconstructed using iterative algorithms at LHC



Anatomy of a mono-top event

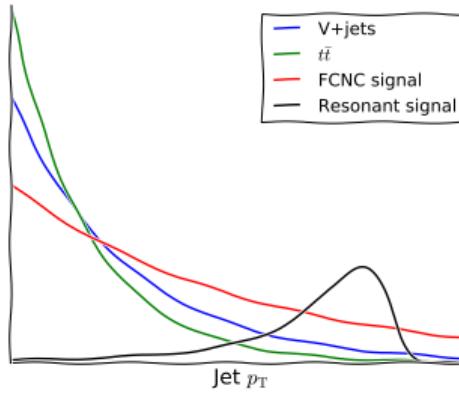
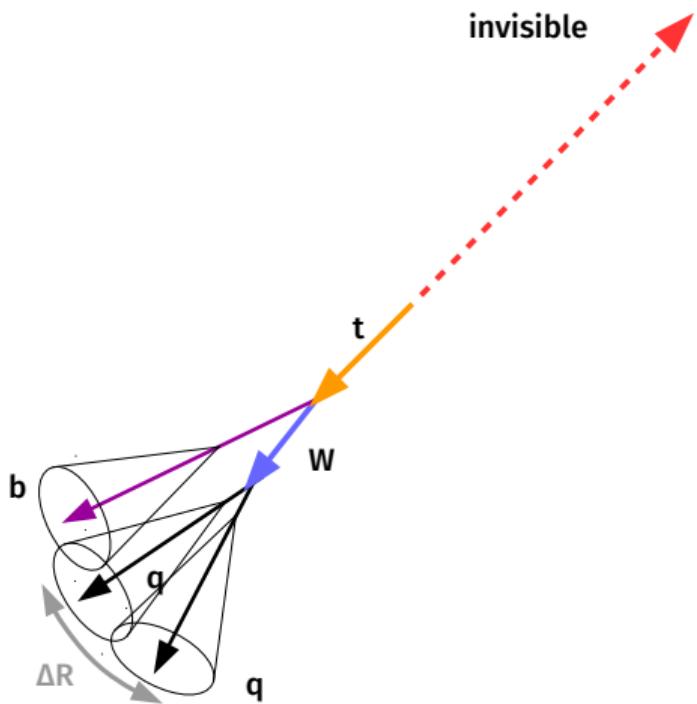
Bare quarks hadronize into jets



- ▶ Signal events generally more energetic than SM events
- ▶ Want to increase S/B? Look for very energetic top quarks!

Anatomy of a mono-top event

Decay products collimate



- ▶ Signal events generally more energetic than SM events
- ▶ Want to increase S/B? Look for very energetic top quarks!
- ▶ Separation between jets: $\Delta R \sim 2m_t/p_T$
 - ▶ $p_T > 250 \text{ GeV} \Rightarrow \text{jets } (R = 0.4) \text{ overlap}$

References

- [1] https://en.wikipedia.org/wiki/Galaxy_rotation_curve
- [2] arXiv:astro-ph/9909252
- [3] hubblesite.org/image/1276/news_release/2003-01
- [4] chandra.harvard.edu/photo/2006/1e0657/more.html
- [5] arXiv:astro-ph/1202.0090
- [6] [https://kipac.stanford.edu/highlights/
let-there-be-light-upon-dark-digging-deeper-dark-matter-lux](https://kipac.stanford.edu/highlights/let-there-be-light-upon-dark-digging-deeper-dark-matter-lux)
- [7] <https://fermi.gsfc.nasa.gov/science/eteu/dm/>
- [8] <https://cms-docdb.cern.ch/cgi-bin/PublicDocDB>ShowDocument?docid=4172>
- [6] physik.uzh.ch/en/researcharea/lhcb/outreach/StandardModel.html
- [7] arXiv:hep-ph/0802.1189
- [8] arXiv:hep-ph/1609.07473

BACKUP

Compact Muon Solenoid

All particles in sum \Rightarrow
all subdetectors help measure p_T^{miss} !

- ▶ Solenoidal magnet
 - ▶ 3.8 T B field
- ▶ Silicon tracker
 - ▶ Charged particles' \vec{p}
 - ▶ Track vertices
- ▶ Calorimeters
 - ▶ EM and hadronic
 - ▶ Good energy resolution
 - ▶ Large coverage
- ▶ Muon chambers
 - ▶ ID muons
 - ▶ Help measure \vec{p}

