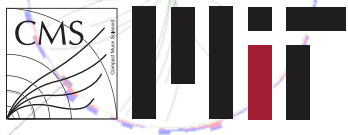
Searching for Dark Matter Using Jets and Jet Substructure at the Large Hadron Collider

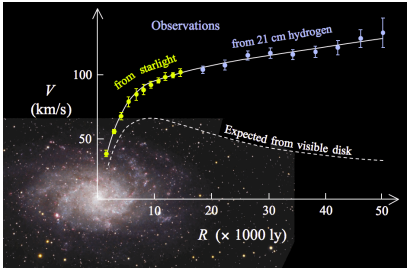
Siddharth Narayanan



Ph.D. Thesis Defense - 2019/01/23

Dark matter - in space

Strong astrophysical evidence for DM:



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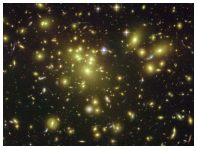
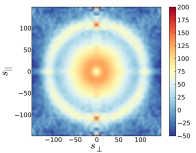


[3]



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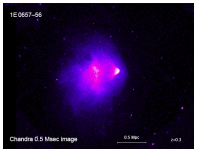

[5]

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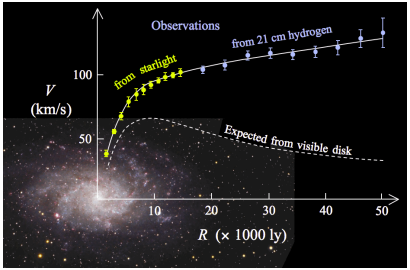

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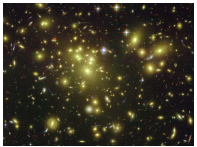

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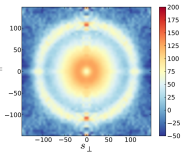

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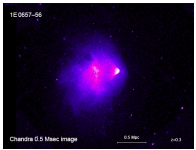


[5]

Weakly Interacting Massive Particles

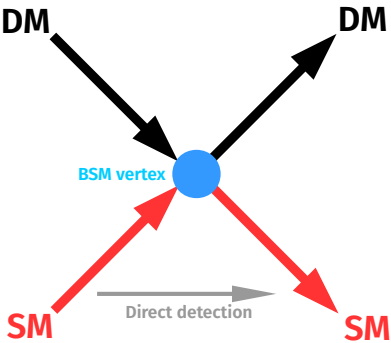
- Weakly: DM-SM coupling $g_\chi \sim g$
- Massive: mass $m_\chi \sim 100$ GeV
- Close to measured relic density:

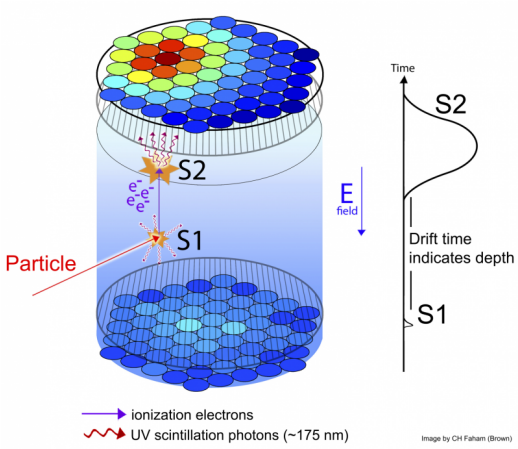
$$\Omega \propto \frac{\rho}{\rho_c} \propto \frac{1}{\langle \sigma v \rangle}$$

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

- Particle colliders can probe WIMPs

Dark matter - in a laboratory

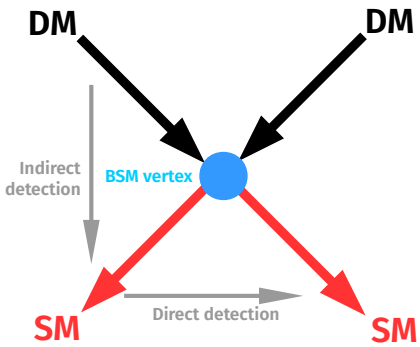


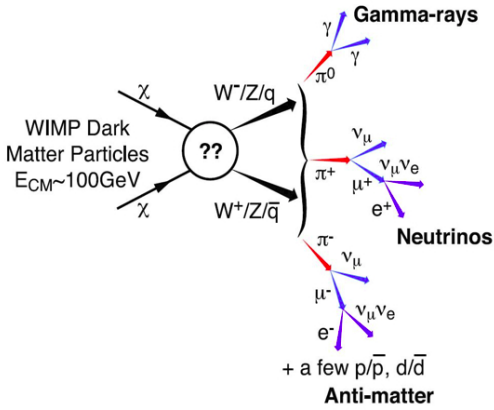


Search for DM-SM interactions as Earth moves through DM halo

[6]

Dark matter - in a laboratory





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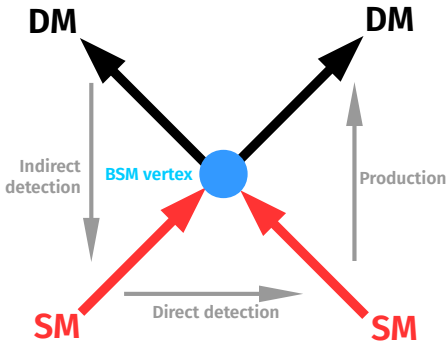
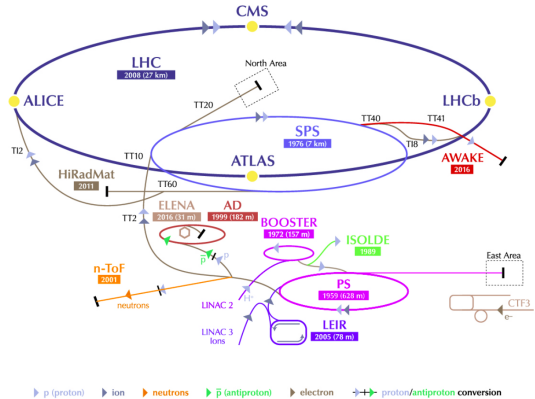
Look for SM remnants of DM-DM annihilation in space

Dark matter - in a laboratory



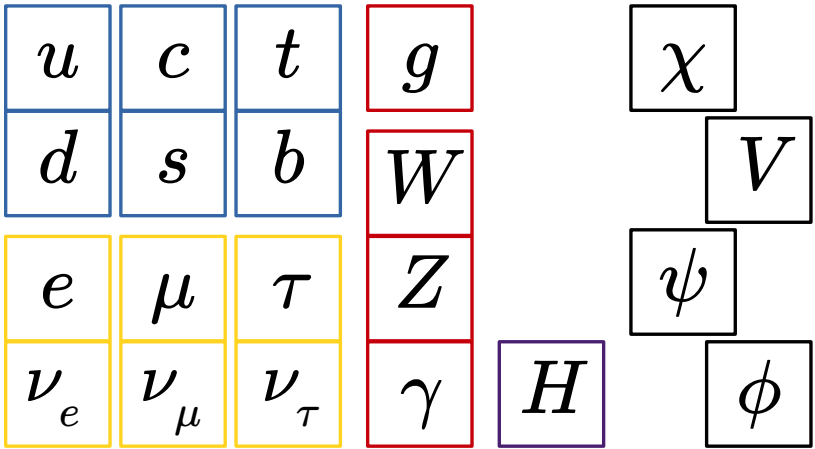


Exploit DM-SM interaction to produce DM in a laboratory

Production of WIMPs at a hadron collider

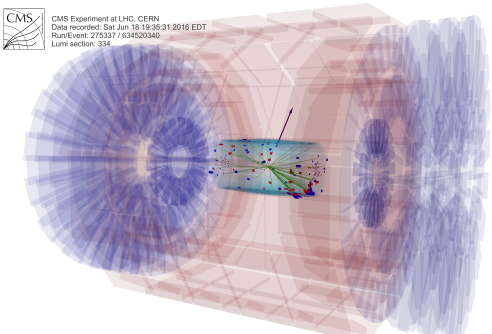
Effective coupling to quarks/gluons $\gtrsim 10^{-4}$

Masses $\lesssim \sqrt{s}$



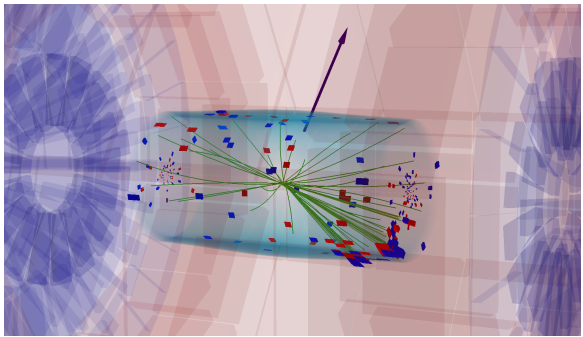
Seeing the invisible at a hadron collider

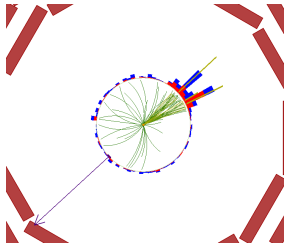
- By definition, DM will not interact with a detector

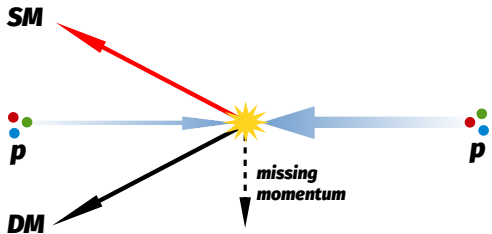


Seeing the invisible at a hadron collider

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







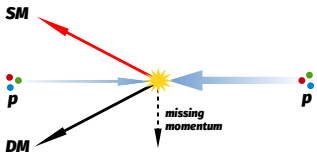
Which SM particle(s)?

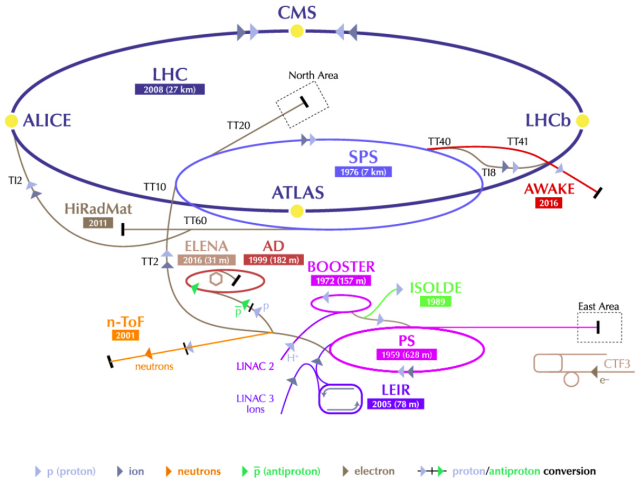
Many to choose from. SM particle choice ⇔ type of DM you can look for

	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					
	$V \to q\bar{q}'$					
	$Z \to \ell^+\ell^-$					
Higgs	$H \to x\bar{x}$					

$p_{\mathrm{T}}^{\mathrm{miss}}$ at the LHC

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





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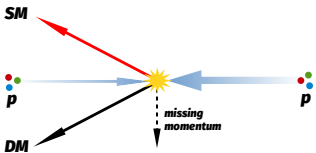
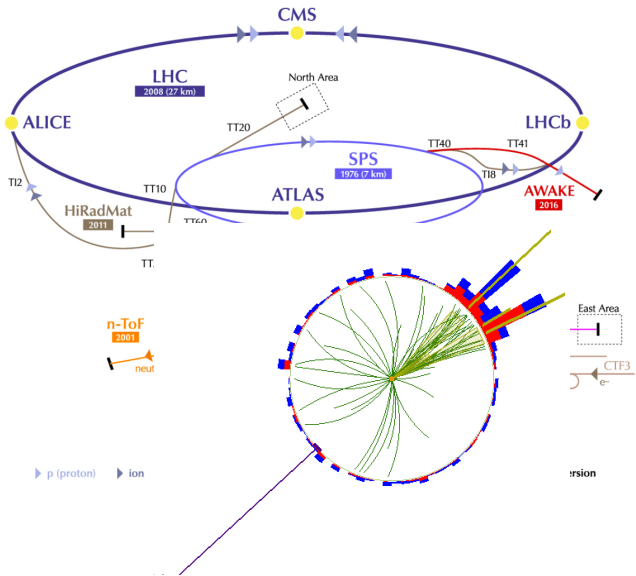
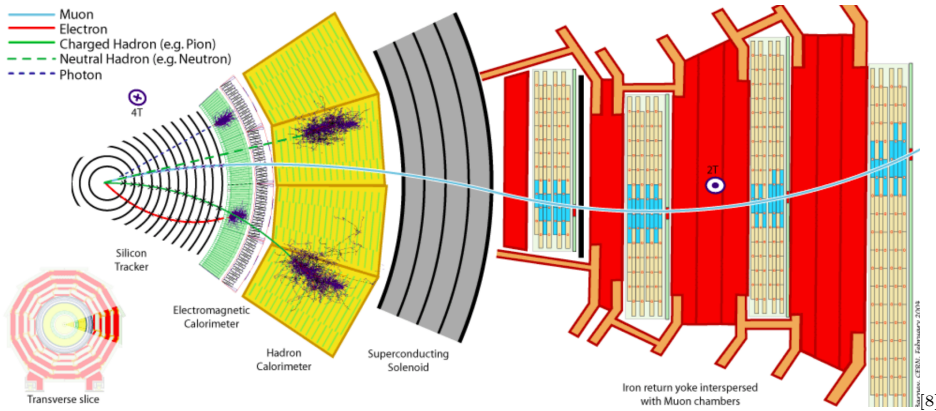


- turns into:

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



The Compact Muon Solenoid



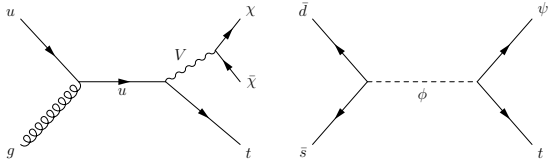
Tracker	ECAL	HCAL	Muon
$\frac{0.015\% \cdot p_{\mathrm{T}}}{\mathrm{GeV}} \oplus 0.5\%$	$\frac{3\%}{\sqrt{E/\mathrm{GeV}}} \oplus \frac{12\%}{E/\mathrm{GeV}} \oplus 0.3\%$	$\frac{85\%}{\sqrt{E/\mathrm{GeV}}} \oplus 7.4\%$	3% at 100 GeV

Outline of this talk

DM production mode

Highlights

Top quark + DM



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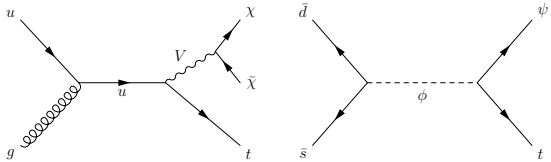

Highlights

Jet substructure
Invisible background estimation

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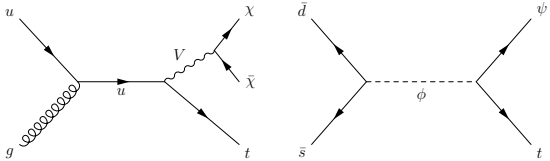
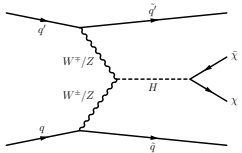
DM production mode

Top quark + DM



Higgs → DM



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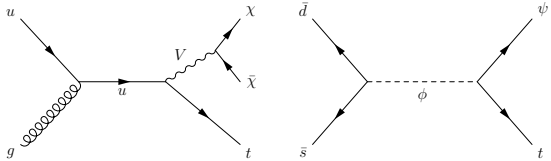

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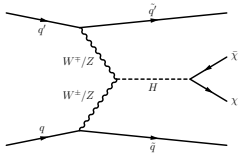

Highlights

Jet substructure
Invisible background estimation

Electroweak SM backgrounds
Forward jets

Mono-Top

Hallmarks of top quark+$p_{\mathrm{T}}^{\mathrm{miss}}$

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

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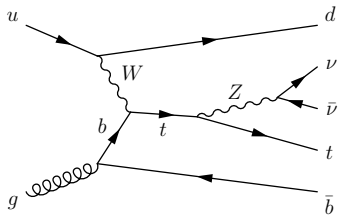

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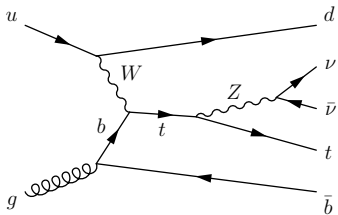
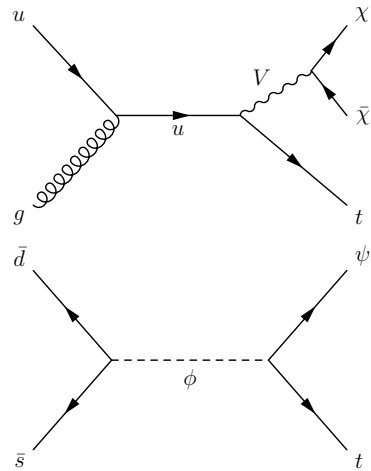
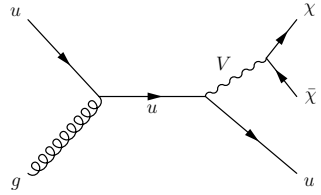


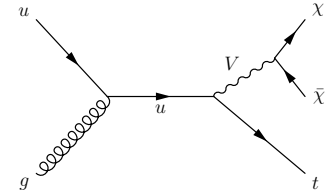


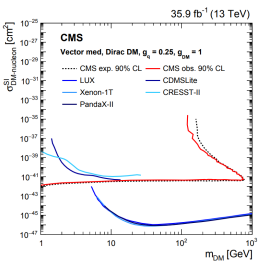
Connection to canonical DM models

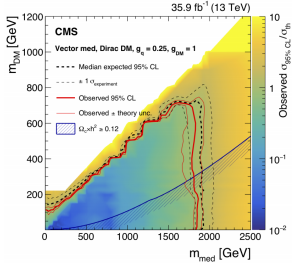
Flavor conserving: diagonal g_u^V

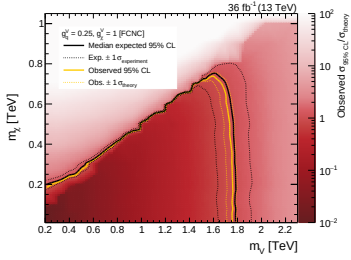


Flavor violating: off-diagonal g_u^V



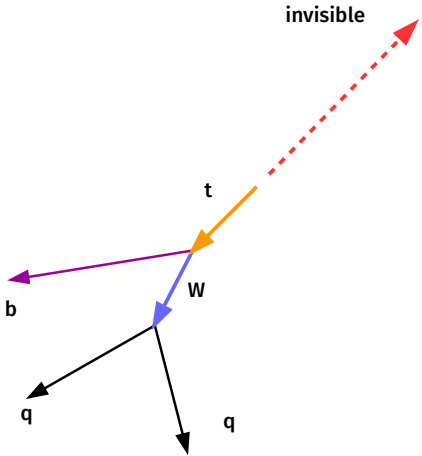






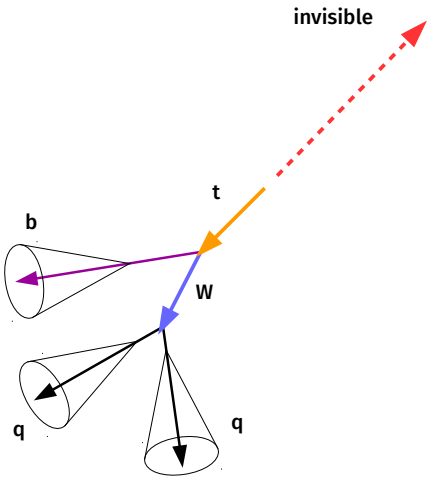
Anatomy of a mono-top event

Hadronic decay $\Rightarrow$ larger $\mathcal{B}$, no $p_{\mathrm{T}}^{\mathrm{miss}}$

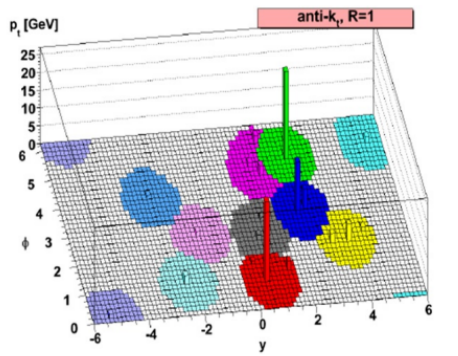


Anatomy of a mono-top event

Bare quarks shower into jets



- Soft and collinear splittings ⇒ parton shower
- Color confinement ⇒ hadronization
- "Jets" are reconstructed using iterative clustering algorithms at LHC



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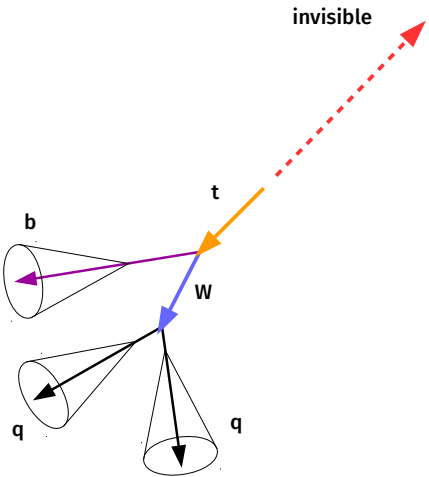
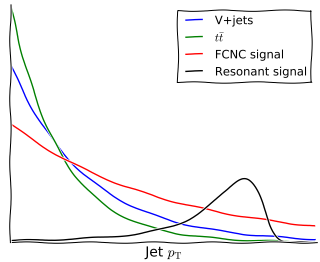
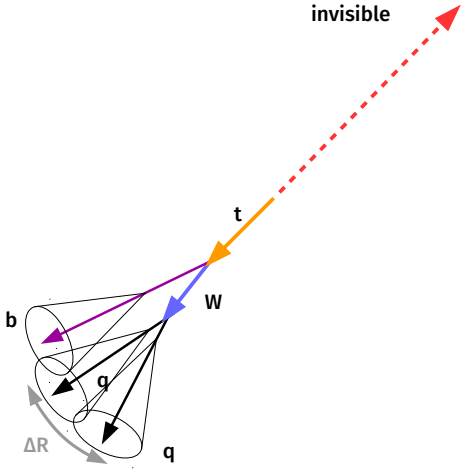


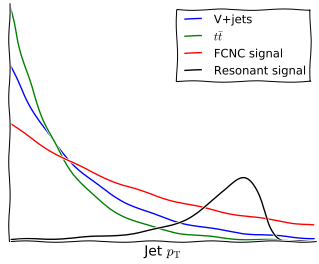


- Signal more energetic than SM
- Maximize S/B $\Rightarrow$ large jet p_{T}

Anatomy of a mono-top event

Decay products collimate



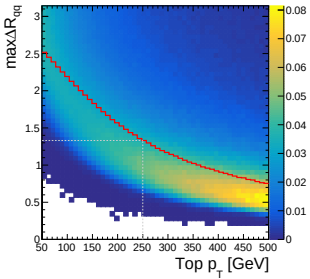


- Signal more energetic than SM
- Maximize S/B $\Rightarrow$ large jet p_T
- Separation between jets: $\Delta R \sim 2m_t/p_T$
  - $p_T > 250\,\text{GeV} \Rightarrow$ jets ($R = 0.4$) overlap

Reconstruction of top quark jet

Clustering

- Three $R = 0.4$ jets $\rightarrow$ single $R = 1.5$ jet



- These are huge jets: half the detector!
- Many extra particles

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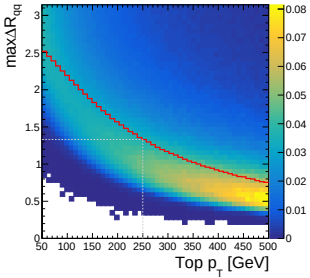

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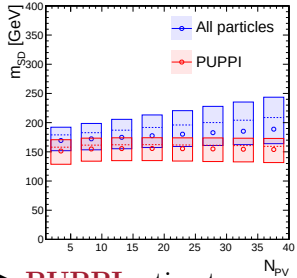
Pileup particles

- 10-25 vertices per collision
- PU particles are isotropic



- **PUPPI** estimates $P(\mathrm{PU}|p_\mathrm{T}, \eta, \phi)$ from proximity to PV particles

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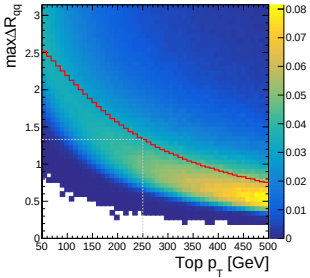

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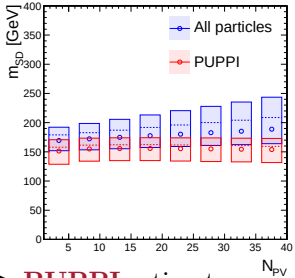
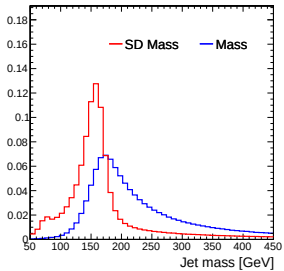
- 10-25 vertices per collision
- PU particles are isotropic



- **PUPPI** estimates $P(\mathrm{PU}|p_\mathrm{T}, \eta, \phi)$ from proximity to PV particles

Non-PS radiation

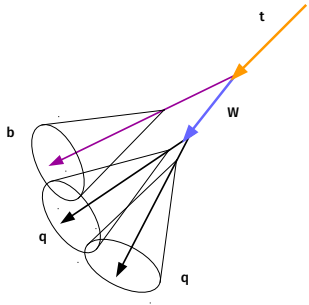
- Initial state radiation, underlying event, multi-parton interactions

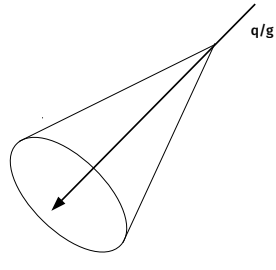


- **Soft drop** removes wide-angle and soft radiation from jet

Jet substructure

- Top quark $\rightarrow$ 3q $\Rightarrow$ top jet has 3 "prongs": regions of correlated radiation





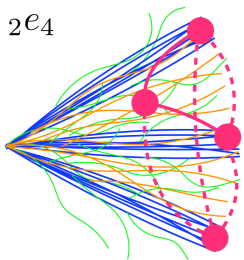
- **Substructure** observables are sensitive to such features
  - N-subjettiness, subjet algorithms, ECFs,...

Energy correlation functions

ECFs are **N**-point distance-weighted correlation functions among particles of the jet

$$e(a, \mathbf{N}, \alpha) \sim \sum_{\mathbf{N} \text{ particles} \in J}$$

sets of **N** particles



[9]

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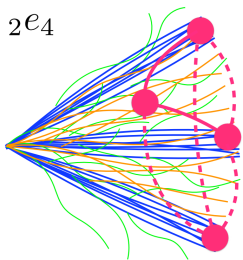
$$e(a, \mathbf{N}, \alpha) \sim \sum_{\mathbf{N} \text{ particles} \in J} \left[\prod_{p \in \text{particles}} \frac{E_p}{E_J} \right]$$

sets of **N** particles energy fractions



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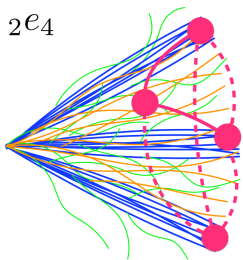
sets of **N** particles | energy fractions | opening angle

$_2e_4$



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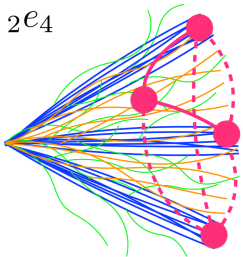
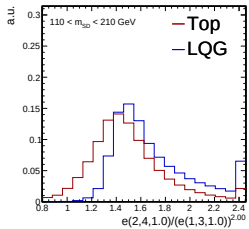
sets of **N** particles — energy fractions — opening angle

$2e_4$



[9]



$e(4)/e(3)$

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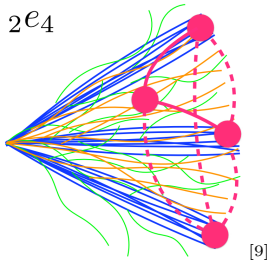

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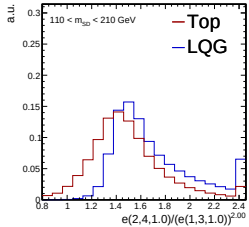

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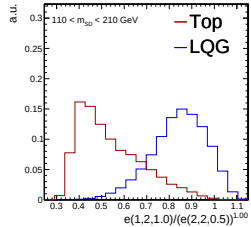
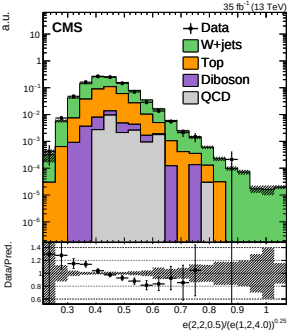


$e(2)/e(2)$

Building a combined tagger

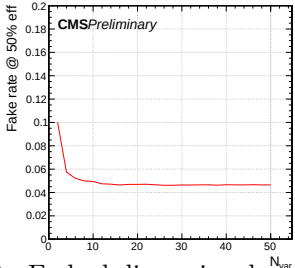
Modeling issues

- PS model does not perfectly describe all ECF ratios



Dimensional reduction

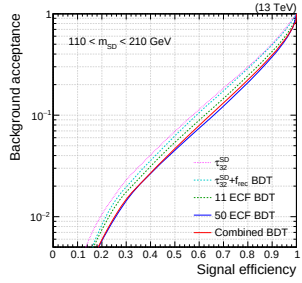
- Large ECF ratio space
- Expensive to compute



- Embed dimensional reduction into boosted decision tree training

Combined tagger

- Final discriminator combines ECFs, τ_{32}, f_{rec}



- 30% better background rejection

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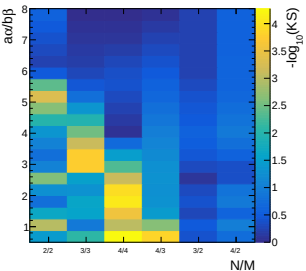

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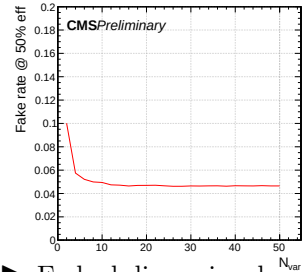

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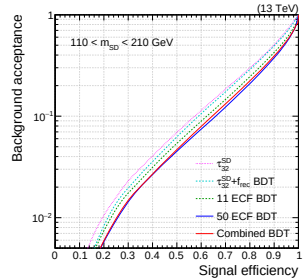

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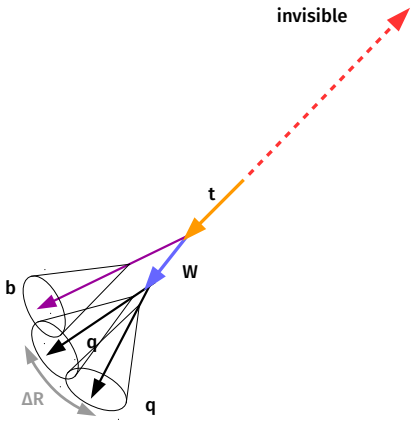
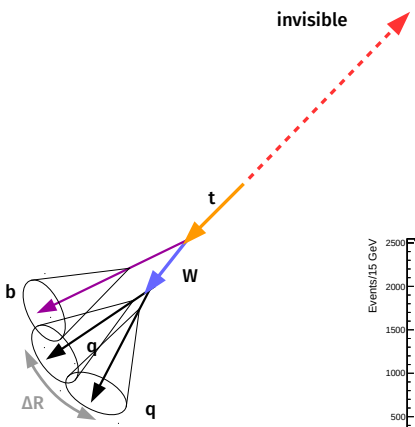
Selecting mono-top events

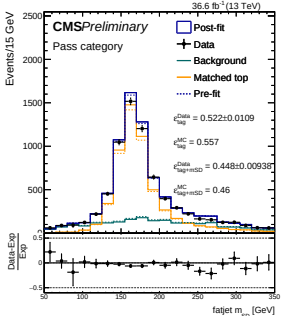


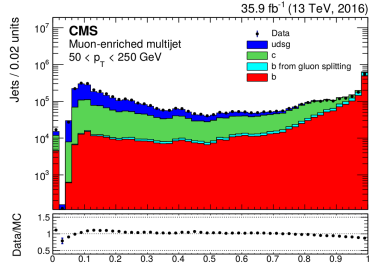
- $p_{\mathrm{T}}^{\mathrm{miss}} > 250\,\mathrm{GeV}$ (trigger)
- CA15 jet, $p_{\mathrm{T}} > 250\,\mathrm{GeV}$
  - Selected by BDT

Selecting mono-top events



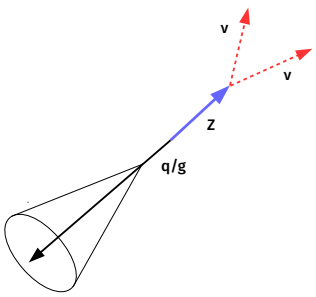
- $p_{\mathrm{T}}^{\mathrm{miss}} > 250\,\mathrm{GeV}$ (trigger)
- CA15 jet, $p_{\mathrm{T}} > 250\,\mathrm{GeV}$
  - Selected by BDT
  - Mass consistent with m_t
  - Signature of B meson decay inside jet
    - Lab frame $c\tau \sim \mathcal{O}(\mathrm{mm})$





SM backgrounds

$Z \to \nu\nu$ (30%)



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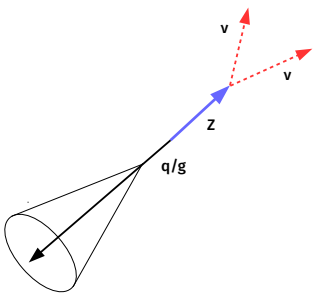
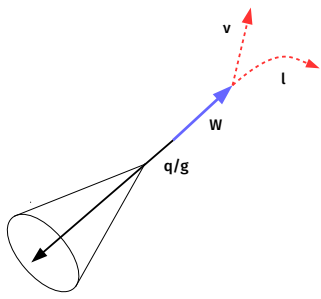


$W \to (\ell)\nu$ (15%)



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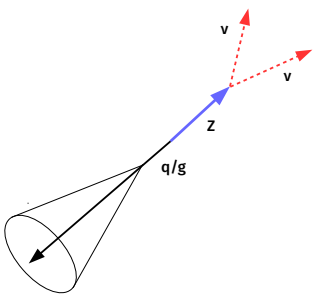

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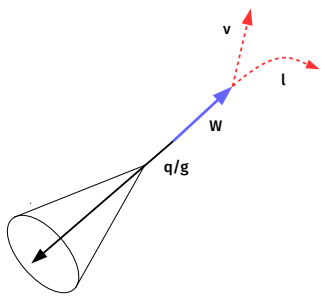
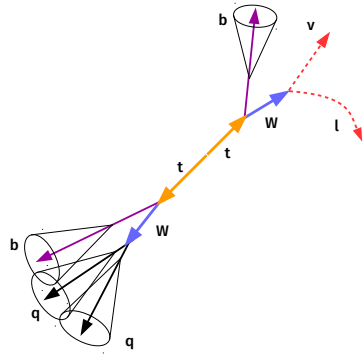


t quark pair (50%)



SM backgrounds

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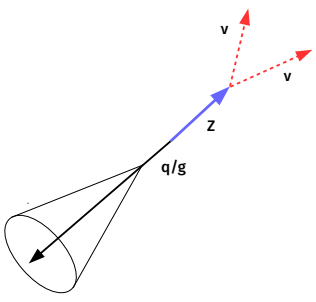
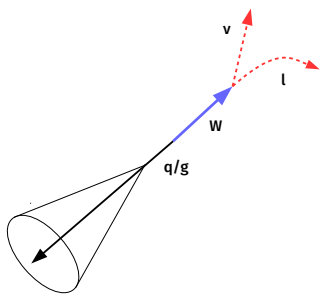


$W \to (\ell)\nu$ (15%)



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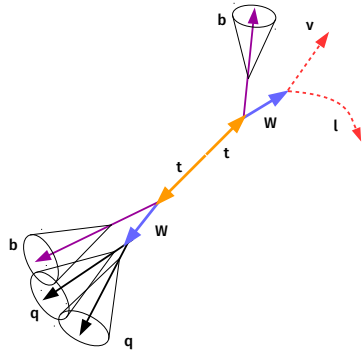

Note that $p_{\mathrm{T}}^{\mathrm{miss}}$ is the transverse momentum of the **vector boson**

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
[7] https://fermi.gsfc.nasa.gov/science/eteu/dm/
[8] https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/ShowDocument?docid=4172
[9] arXiv:1609.07473
[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 ⇒
all subdetectors help measure $p_{\mathrm{T}}^{\mathrm{miss}}$!

- 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 $\vec{p}$