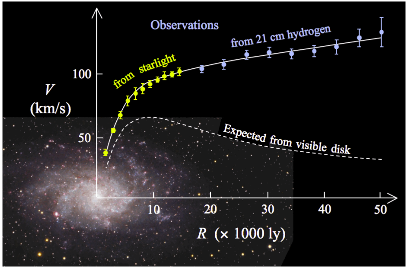
Searching for Dark Matter Using Jets and Jet Substructure at the Large Hadron Collider

Siddharth Narayanan

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

Dark matter - in space

Strong astrophysical evidence for DM:



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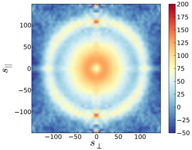

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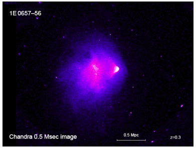

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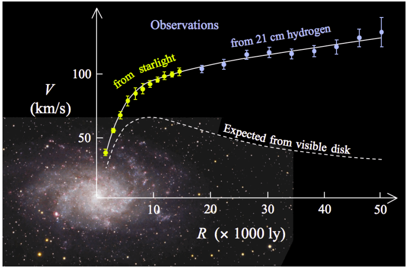

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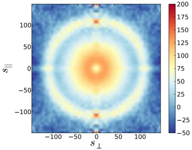

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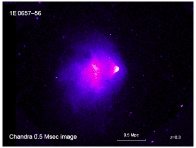


[5]

Weakly Interacting Massive Particles

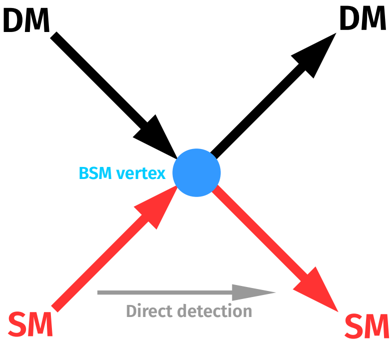
- Weakly: DM-SM coupling $g_\chi \sim g$
- Massive: mass $m_\chi \sim 100$ GeV
- Close to measured relic density:

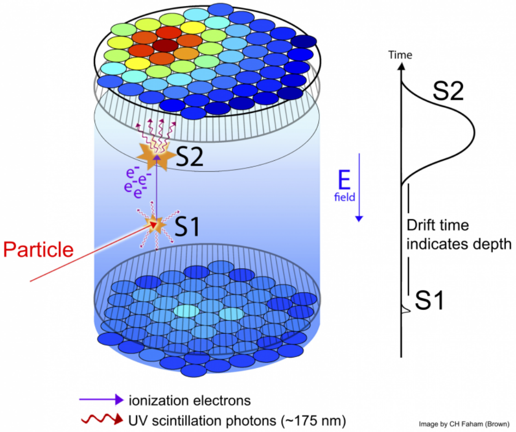
$$\Omega \propto \frac{\rho}{\rho_c} \propto \frac{1}{\langle \sigma v \rangle}$$

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

- Particle colliders can probe WIMPs

Dark matter - in a laboratory





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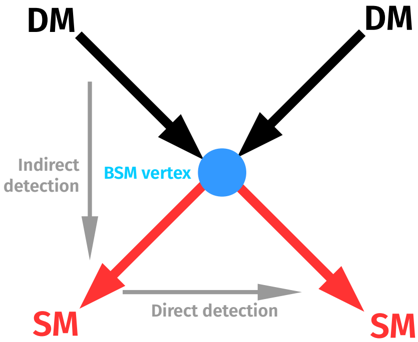
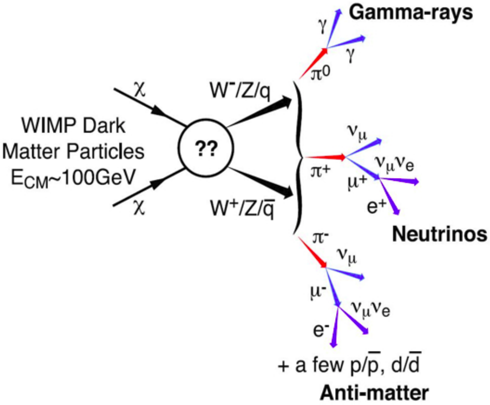
Search for DM-SM interactions as Earth moves through DM halo

Dark matter - in a laboratory

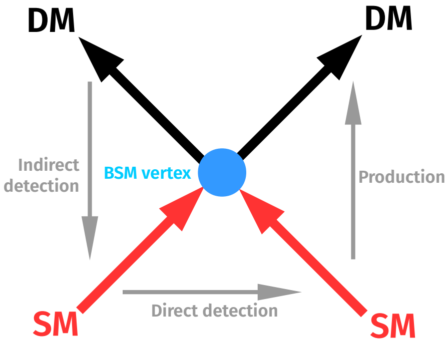


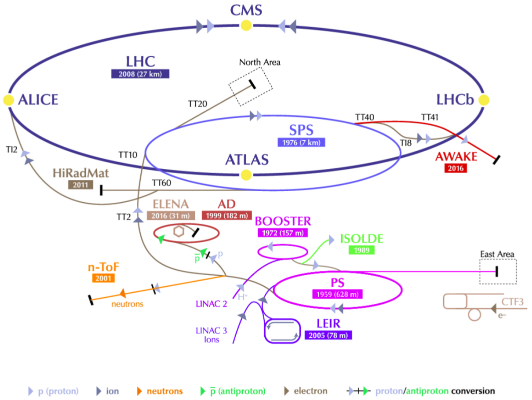


[7]

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

Production of WIMPs at a hadron collider

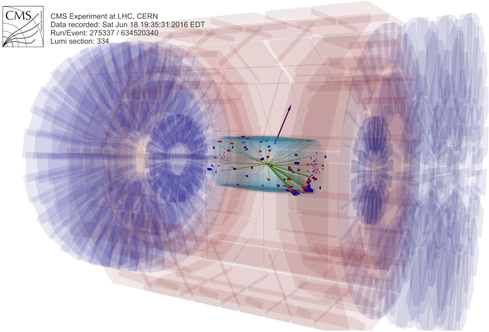
Effective coupling to quarks/gluons $\gtrsim 10^{-4}$

Masses $\lesssim \sqrt{s}$

u	c	t	g		χ
d	s	b	W		V
e	μ	τ	Z		ψ
ν_e	ν_μ	ν_τ	γ	H	ϕ

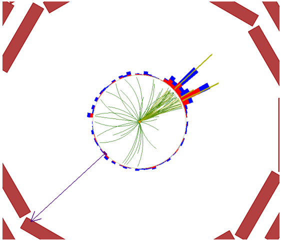
Seeing the invisible at a hadron collider

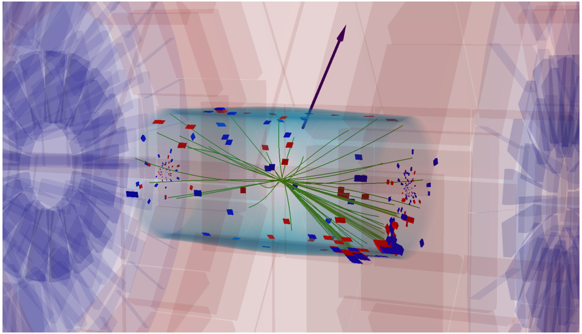
- By definition, DM will not interact with a detector

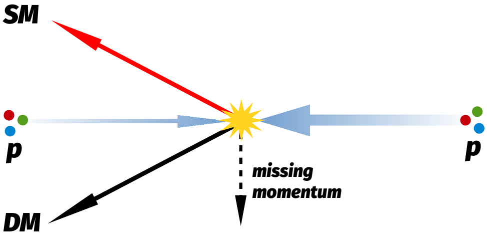


Seeing the invisible at a hadron collider

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







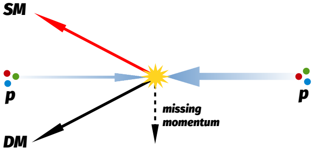
Which SM particle(s)?

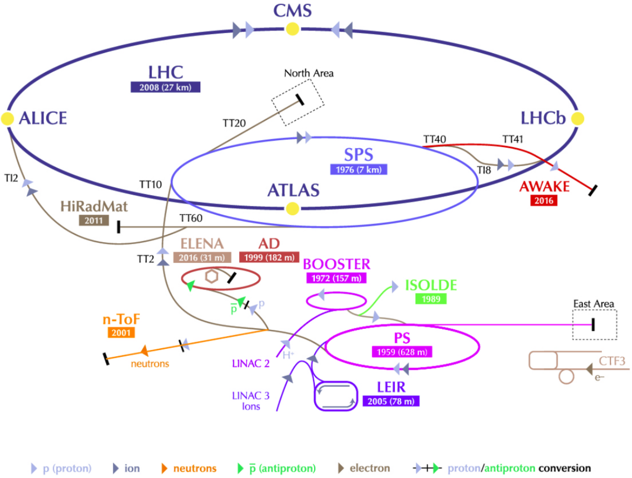
Many to choose from. SM particle choice $\Leftrightarrow$ type of DM you can look for

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

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:





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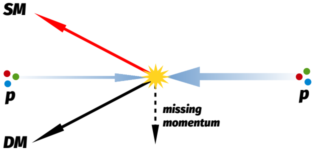
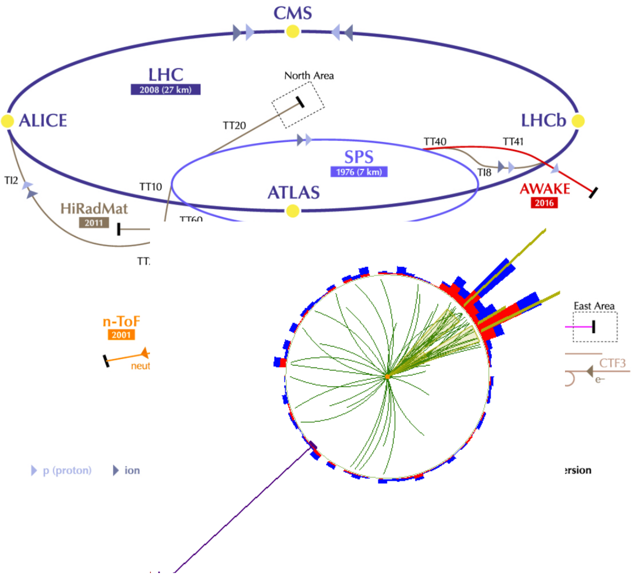
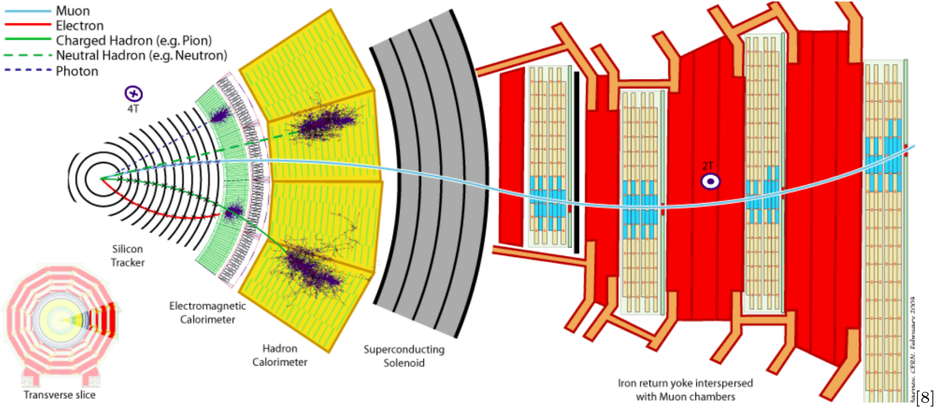


- turns into:

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



The Compact Muon Solenoid



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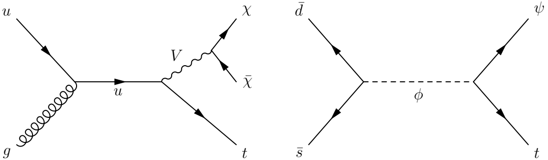
Tracker	ECAL	HCAL	Muon
$\frac{0.015\%\cdot p_{\mathrm{T}}}{\mathrm{GeV}} \oplus 0.5\%$	$\frac{3\%}{\sqrt{E/\mathrm{GeV}}} \oplus \frac{12\%}{E/\mathrm{GeV}} \oplus 0.3\%$	$\frac{85\%}{\sqrt{E/\mathrm{GeV}}} \oplus 7.4\%$	3% at 100 GeV

Outline of this talk

DM production mode

Top quark + DM



Highlights

Outline of this talk

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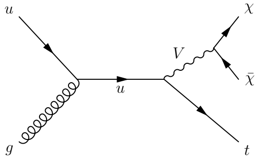

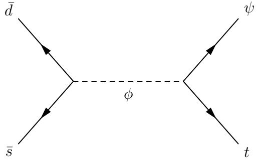

Highlights

Jet substructure
Invisible background estimation

Outline of this talk

DM production mode

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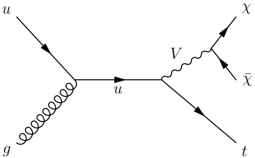
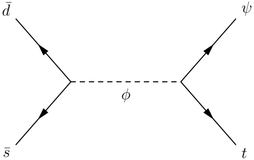
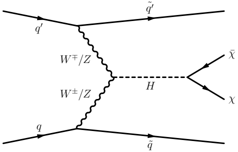




Higgs $\rightarrow$ DM



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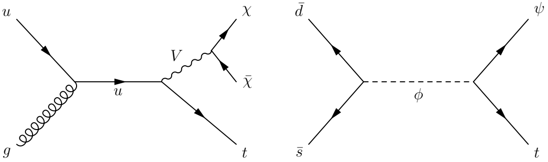

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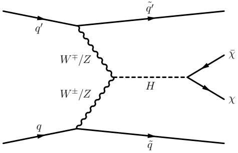
Invisible background estimation

Higgs $\to$ DM



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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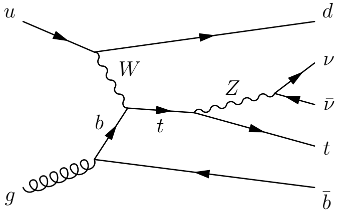
- SM process is tiny: 0.14 pb $\Rightarrow$ 5000 events in 36/fb



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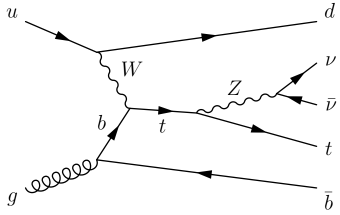
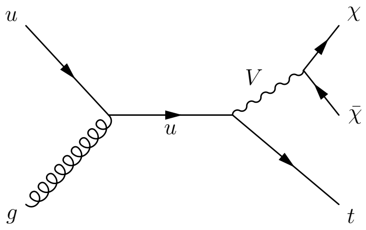
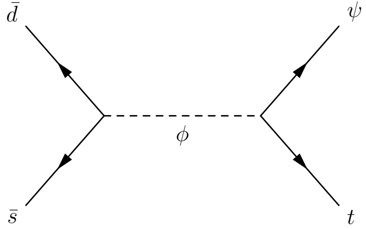
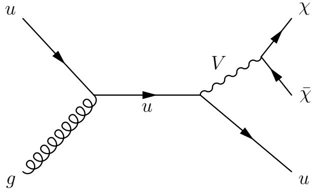




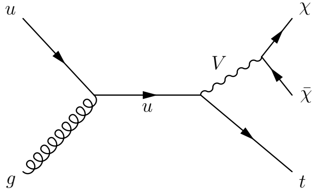


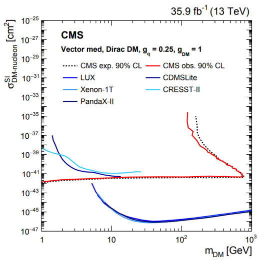
Connection to canonical DM models

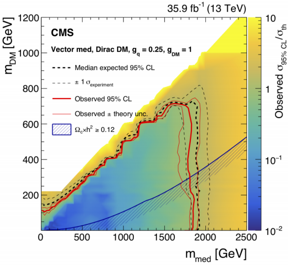
Flavor conserving: diagonal g_u^V

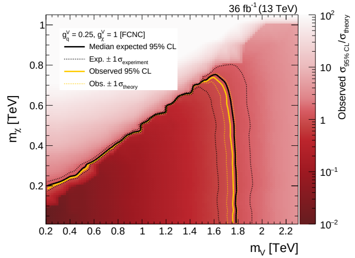


Flavor violating: off-diagonal g_u^V



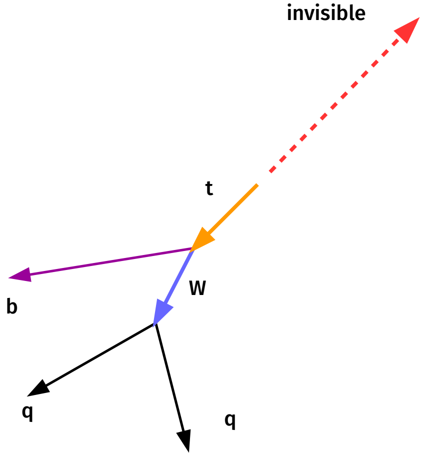






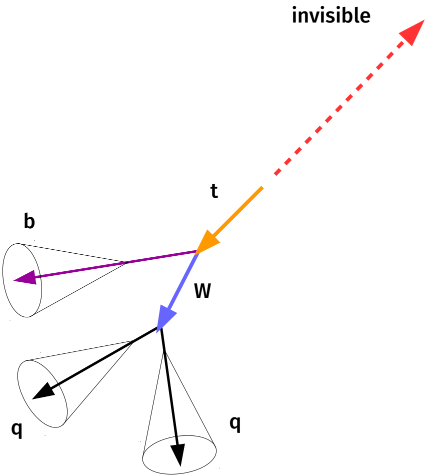
Anatomy of a mono-top event

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

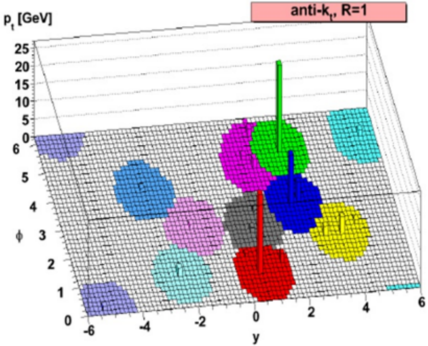


Anatomy of a mono-top event

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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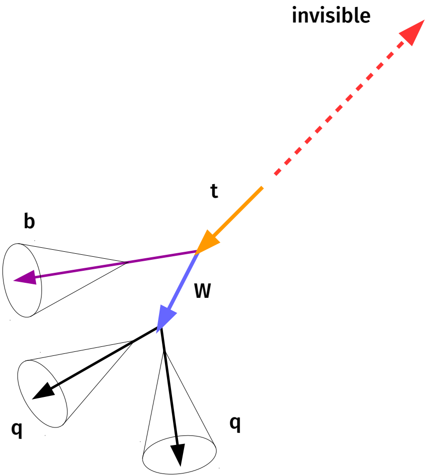
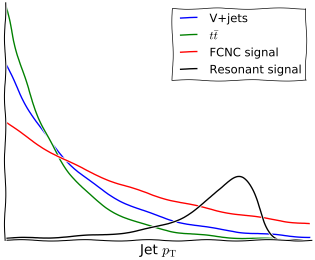
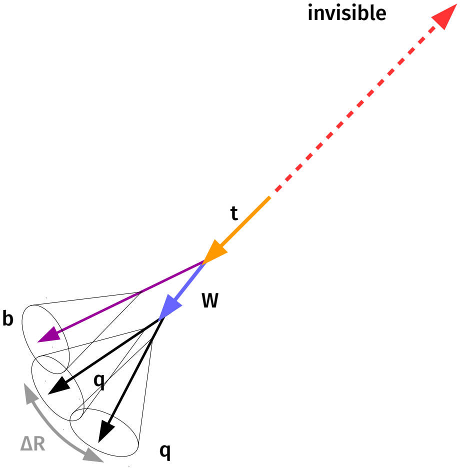


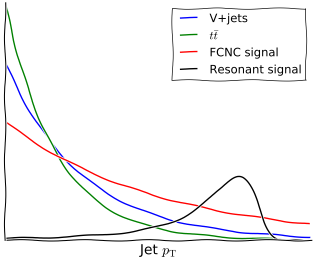


- Signal more energetic than SM
- Maximize S/B $\Rightarrow$ large jet p_{T}

Anatomy of a mono-top event

Decay products collimate



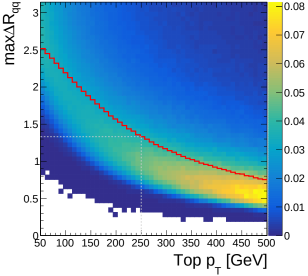


- Signal more energetic than SM
- Maximize S/B $\Rightarrow$ large jet p_{T}
- Separation between jets: $\Delta R \sim 2m_t/p_{\mathrm{T}}$
  - $p_{\mathrm{T}} > 250\,\mathrm{GeV} \Rightarrow$ jets ($R = 0.4$) overlap

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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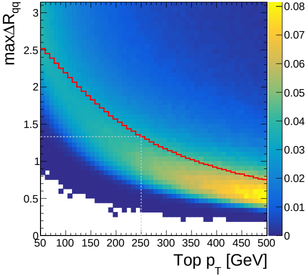

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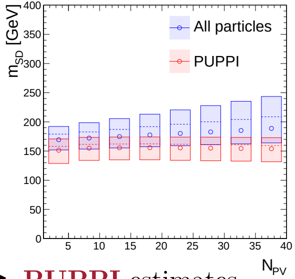
Pileup particles

- 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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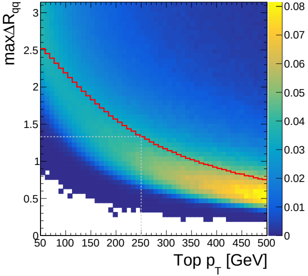

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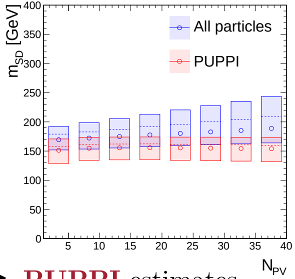

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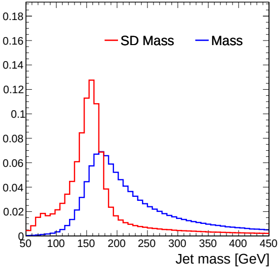
Non-PS radiation

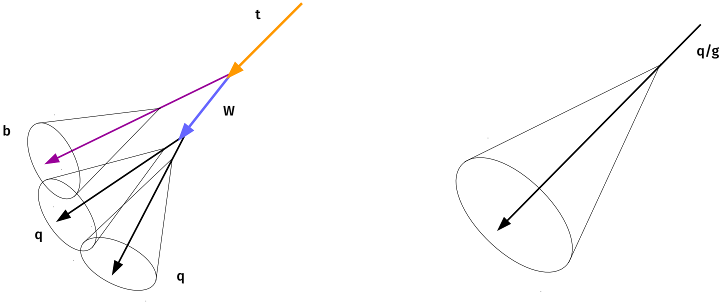
- Initial state radiation, underlying event, multi-parton interactions



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

Jet substructure

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



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

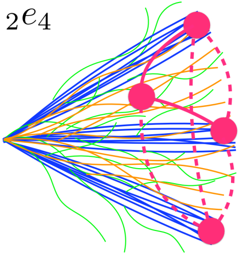
Energy correlation functions

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

$_2e_4$



[9]

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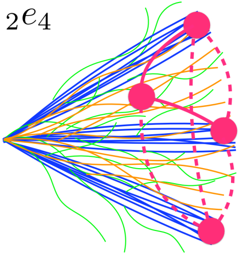
sets of **N** particles energy fractions

$_2e_4$



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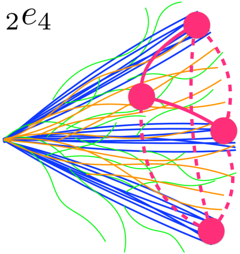
sets of **N** particles   energy fractions   opening angle

$_2e_4$



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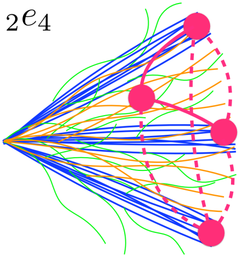
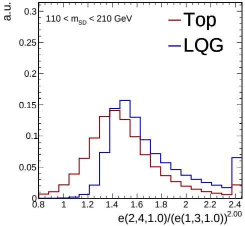
sets of **N** particles energy fractions opening angle



[9]



$e(4)/e(3)$

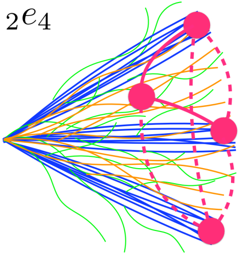
Energy correlation functions

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

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

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

$_2e_4$



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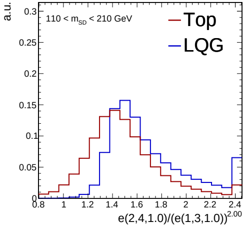
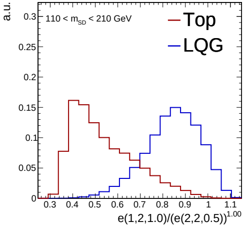


$e(4)/e(3)$



$e(2)/e(2)$

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BACKUP

Compact Muon Solenoid

All particles in sum $\Rightarrow$
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 $\vec{p}$