Dark Matter Analysis at Florida Tech

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Introduction to Dark Matter

- We don't know what most of the universe is made of!
- Dark matter is some invisible entity that warps spacetime
- Evident in galactic rotation curves, galaxy collisions/interactions
- Muon g-2 (Must be more forces), LHC Exotic matter (quark matter), Hubble constant tension

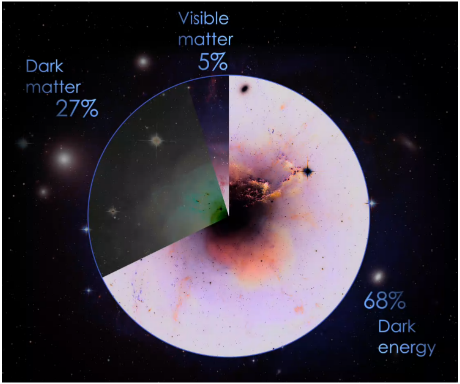

Figure: Current* measured composition of the universe via the Planck telescope [1]

Introduction to Dark Matter

But what *is* DM?

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Two groups: new particle?

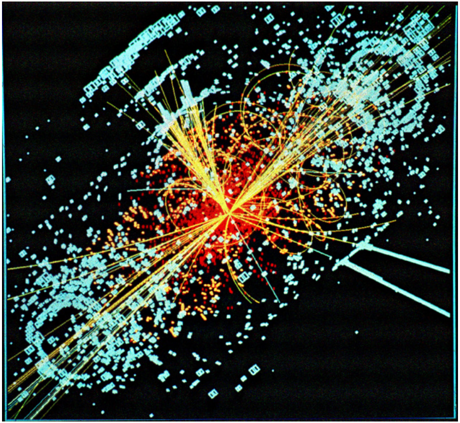

Figure: [2]

Introduction to Dark Matter

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Modified Newtonian Dynamics (MOND)

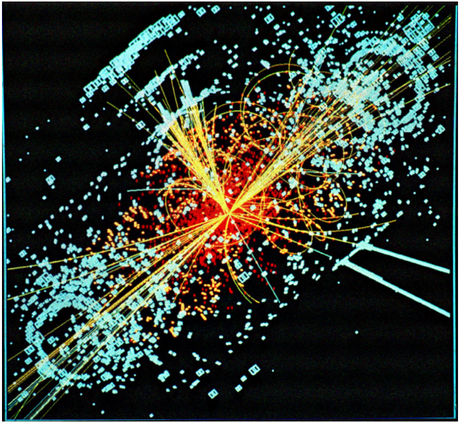


Figure: [2]

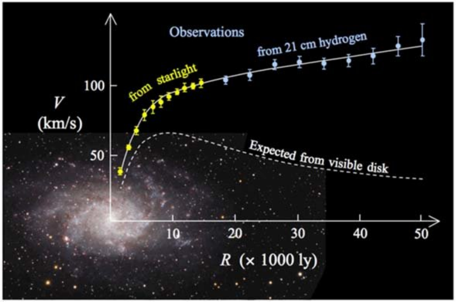


Figure: [3]

The CMS Detector and Particle Physics Lingo

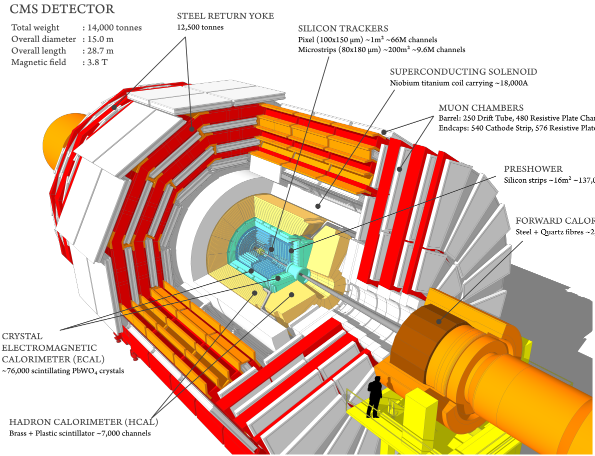


Figure: CMS Experiment at LHC. Collisions occur in the center and spread out through hundreds of subdetectors [4]

The CMS Detector and Particle Physics Lingo

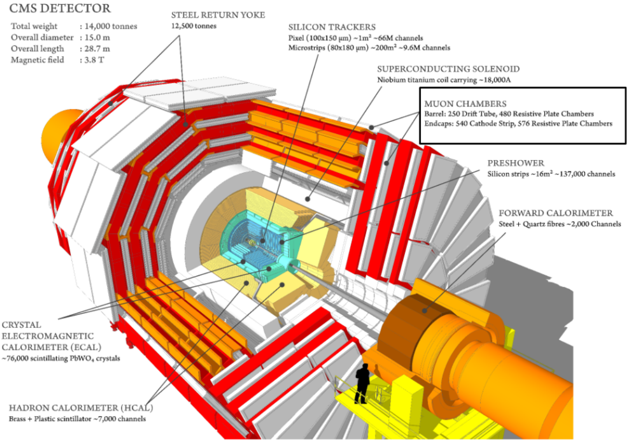


Figure: Muon Subsystem in outer barrel and endcap measures radiation coordinates and momentum of muons [4]

The CMS Detector and Particle Physics Lingo

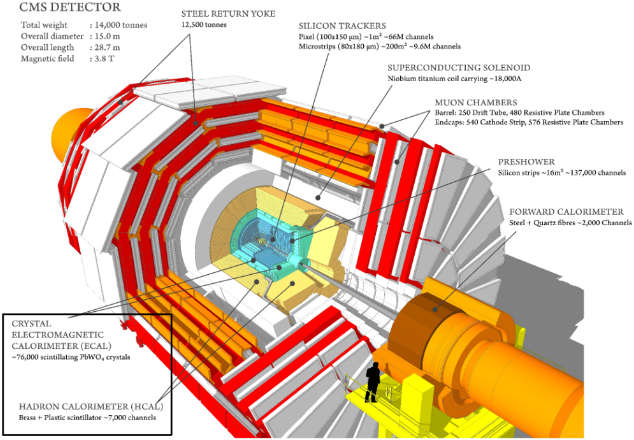


Figure: Electron Calorimeter (ECAL) and Hadron Calorimater (HCAL) Subsystem in inner barrel to measure energy of electrons, photons, and light hadrons (mesons/baryons) [4]

The CMS Detector and Particle Physics Lingo

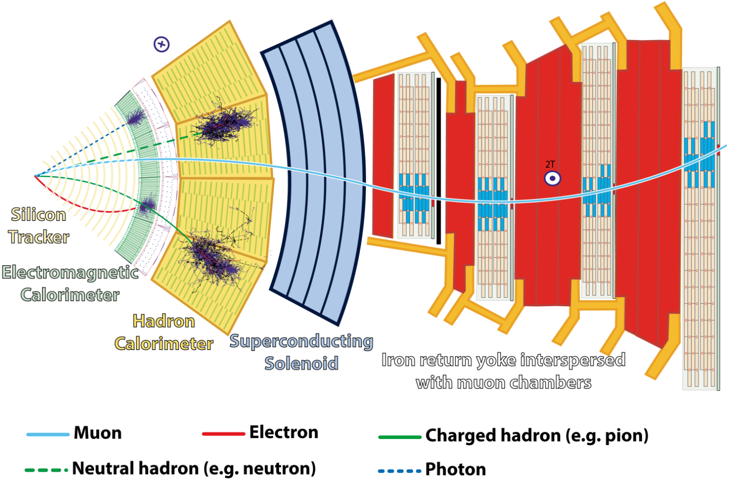


Figure: The various subsystems are designed to react with specific particles (hadrons/leptons/bosons) [5]

The CMS Detector and Particle Physics Lingo

- Cylindrical detectors → cylindrical coordinates (ϕ, η, z)
- Relativistic QM → Lorentz invariant coordinates = easier math

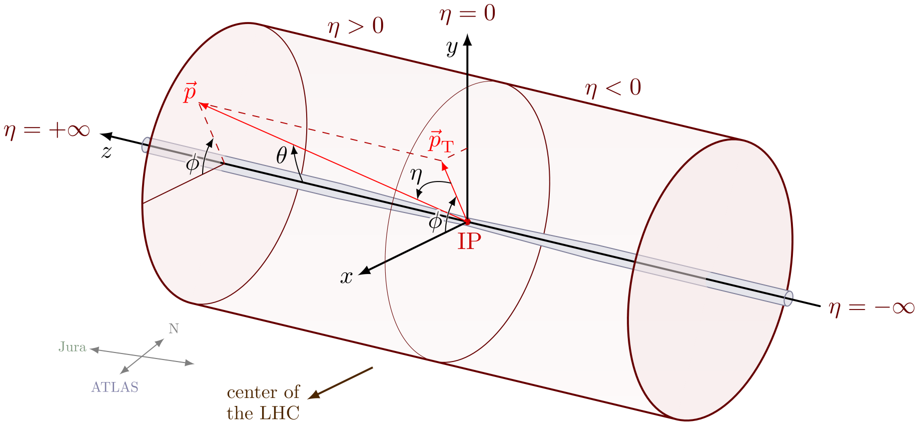


Figure: CMS detector coordinate system [6]

The CMS Detector and Particle Physics Lingo

- Relevant boundaries for CMS detector subsystems
- Nothing detected past $|\eta| \gtrsim 3$
- $1.44 \leq \eta \leq 1.57$ gap in calorimeters (Poor reconstruction)
- Muon reconstruction requires $|\eta| < 2.4$

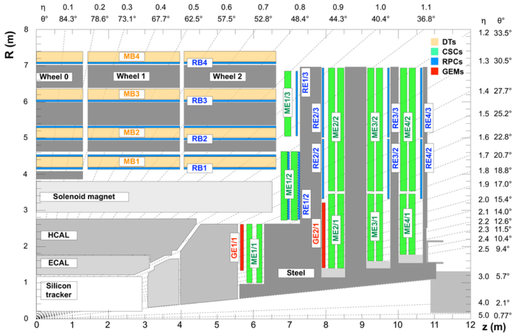
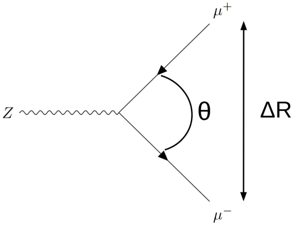


Figure: CMS detector quadrant with coordinate system interlayed [7]

The CMS Detector and Particle Physics Lingo

Particle decay

- $$\mathrm{M_{inv}} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$
- $$\Delta R = \sqrt{(\eta_1 - \eta_2)^2 + (\phi_1 - \phi_2)^2}$$
  - Angular distance
- $\theta \propto$ (M_P - m), P_P
- Large mass to two small masses $\rightarrow$ highly collimated



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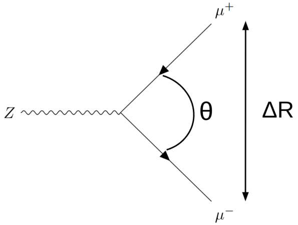
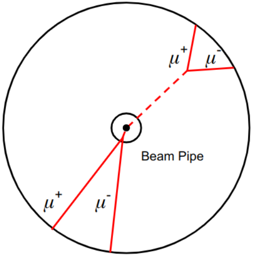


Long Lived particles

- $c\tau$ = decay length
- Central vertices = most common
- Dark matter = no interaction!
  - Large $c\tau$



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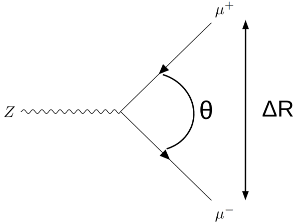

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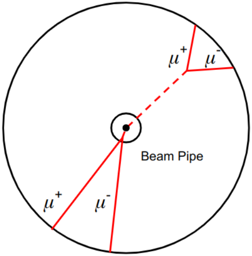
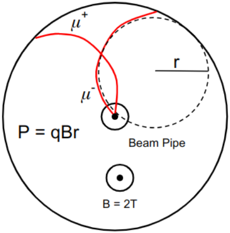


Momentum Calculation

- Large B field (Solenoid)
- charged particles make S shape
- Momentum measured from curvature
- P = qBr



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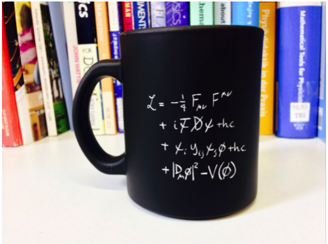

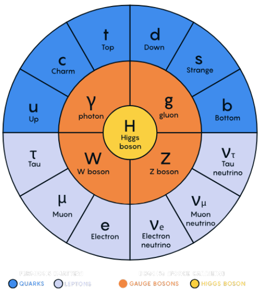

[8]

- Standard Model (SM) Lagrangian
  - Describes the fundamental forces and their interactions
  - $-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \rightarrow$ Electromagnetism (F), Weak Force (B), Strong Force (G)
  - $V(\phi) \rightarrow$ Higgs potential
- Most precise theory
- Bosons $\rightarrow$ Force carriers
- Fermions $\rightarrow$ Quarks, Leptons

HAHM basics

- Hidden Abelian Higgs Model (HAHM)
- What if *some* particles can produce DM
- Simplest extension to SM to include particles that could behave like DM
- Introduces dark Higgs and dark Z boson
- Free parameters: state mixing and masses
  - ϵ, M_{zd} - κ, M_{hd}

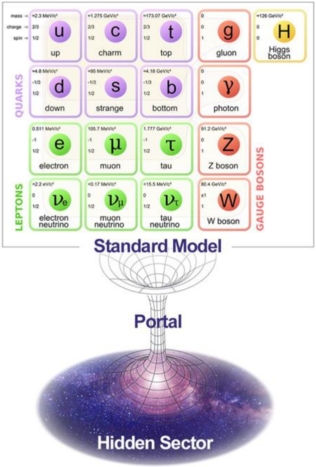

Figure: Standard model with a portal to a dark SM [9]

HAHM basics

$$\mathcal{L}_{SM} = \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}G^{\mu\nu}_{\alpha}G^{\alpha}_{\mu\nu} + \ldots + V_0$$

- Start with the Standard Model
- Transform Hyperweak field: B $\rightarrow$ B$^{\mu\nu}$ $+$ $\frac{\epsilon}{\cos(\theta_W)}Z^{\mu\nu}$
- Similar in H field
- New kinetic terms controlled by ϵ and κ

$$\mathcal{L}_{HAHM} = \frac{1}{4}Z^{\mu\nu}Z_{\mu\nu} + \frac{\epsilon}{2\cos(\theta_W)}B^{\mu\nu}Z_{\mu\nu} + \frac{1}{2}m^2_{zd}Z^{\mu\nu}Z_{\mu\nu}$$

$$V_0(H,S) = -\mu^2|H|^2 + \lambda|H|^4 - \mu^2_S|S|^2 + \lambda_S|S|^4 + \kappa|S|^2|H|^2$$

HAHM basics

So basically,

$$\begin{pmatrix} Z_{D,0} \\ B \end{pmatrix} = \begin{pmatrix} \sqrt{1 - \frac{\epsilon^2}{\cos^2\theta}} & 0 \\ -\frac{\epsilon}{\cos\theta} & 1 \end{pmatrix} \begin{pmatrix} \hat{Z}_D \\ \hat{B} \end{pmatrix}$$

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$$\Gamma(h \to Z_D Z_D) = \kappa'^2 \frac{1}{32\pi} \frac{v^2}{m_h} \sqrt{1 - \frac{4m_{Z_D}^2}{m_h^2}} \frac{(m_h^2 + 2m_{Z_D}^2)^2 - 8(m_h^2 - m_{Z_D}^2)m_{Z_D}^2}{m_h^4}$$

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$$m_{Z,Z_D}^2 = \frac{1}{2}\left(1 + \delta^2 + \eta^2 \, \sin^2\theta \pm \mathrm{Sign}(1 - \delta^2)\sqrt{(1 + \delta^2 + \eta^2 \, \sin^2\theta)^2 - 4\,\delta^2}\right)$$

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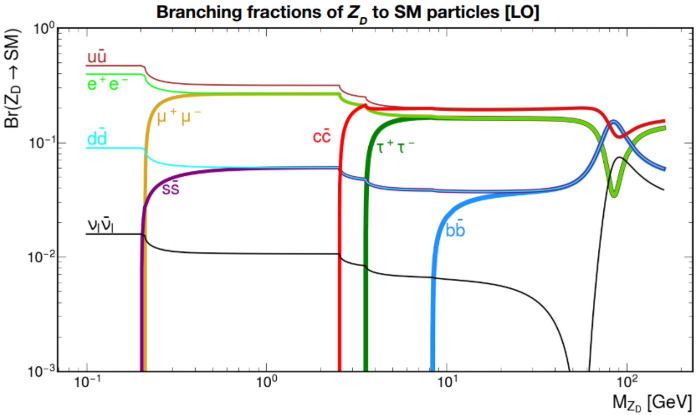
$$\Gamma(Z_D \to \bar{f} f) = \frac{N_c}{24\pi m_{Z_D}} \sqrt{1 - \frac{4m_f^2}{m_{Z_D}^2}} \left(m_{Z_D}^2 \left(g_L^2 + g_R^2\right) - m_f^2 \left(-6 g_L g_R + g_L^2 + g_R^2\right)\right)$$

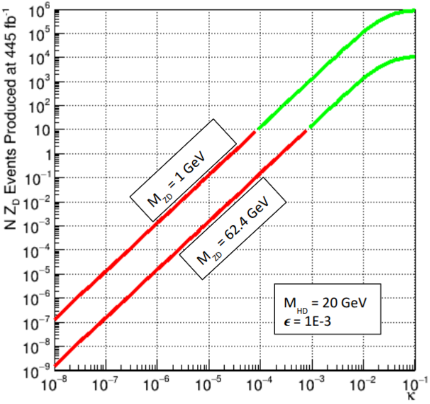
[9]

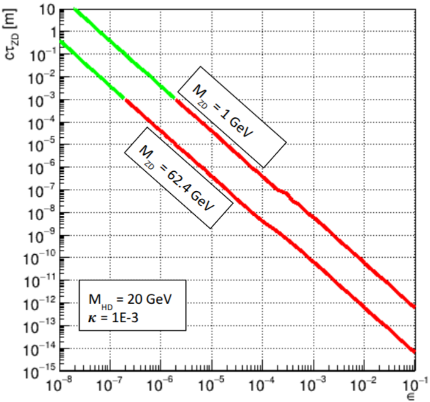
HAHM basics



- Branching Ratios of Z_D to SM
  - How often does Z_D decay to each fermion pair based on M_{Z_D}
- $Br_{familys}$ equal as $M_{Z_D} \geq 2m_f$
- Any lepton is good!

HAHM basics



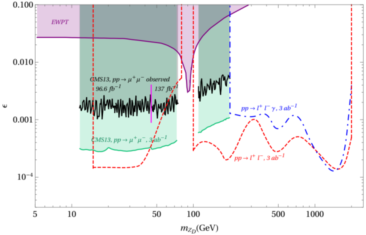


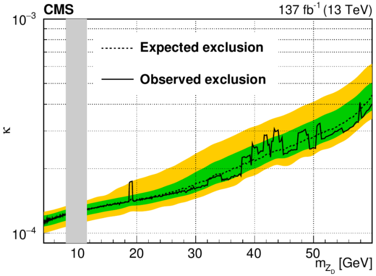
- $Br(h \rightarrow Z_D Z_D) \propto \kappa^2$
- $\sigma_{Prod}(h \rightarrow Z_D Z_D \rightarrow llll) \propto \kappa^2$
- We want κ large $(> 10^{-2})$

- $\Gamma(Z_D \rightarrow ff) \propto \epsilon^2$
- $\tau = \frac{\hbar}{\Gamma} \therefore c\tau \propto \epsilon^{-2}$
- We want ϵ small $(< 10^{-5})$

HAHM Basics

- But *Why* HAHM?
- Improving LLP sensitivity greatly expands detectable ϵ
- Current Limits on ϵ and κ [10][11]
    - All Prompt and κ small to supress $h \to h_D h_D$





CMS simulation process

Model Building

- FeynRules to encode the new lagrangian and its constants
- Mathematica to check that the model is internally consistent

Event Generation

- MadGraph to simulate hard scattering interactions
- Pythia8/Geant4 to simulate these events in CMS and add QCD background + pileup effects

Reconstruction

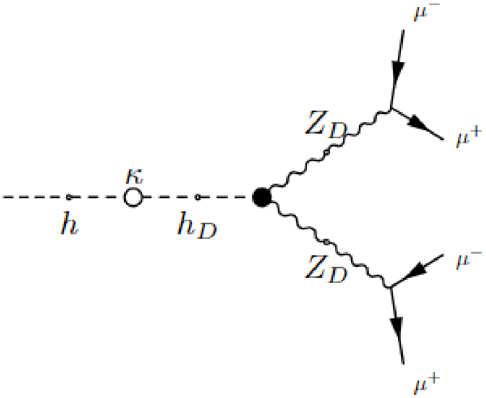
- Reconstruct tracks
- Apply sub detector resolution smears
- Digitize the detector signals
- Record momentum/PID/ energy of Dark Z events
- Apply triggers
- Store as Ntuple file

Signal and Background Data Selection

- Dark Z boson events simulated
- CMS centrally produced data for similar end state events
  - ZZ -> (ll)(ll)
  - QCD
  - Z*/γ*

Four-Muon Final State

- Muons interact very weakly with detector material, so they can travel through the inner layers and reach the muon system.
- This makes muons very clean and easy to identify.
- The 125-GeV Higgs boson (h) is assumed to mix with a dark Higgs boson (h_D) through Higgs mixing κ
- Kinetic mixing ϵ could give Z_d small coupling to dimouns
- $h \to Z_D Z_D \to 2\mu^+ 2\mu^-$ is dominate if, $\epsilon \ll \kappa$, $m_{h_D} > \frac{m_h}{2}$, and $m_{Z_D} < \frac{m_h}{2}$



Four-Muon Final State – Signal Cutflow (50Gev, 50 mm Sample)

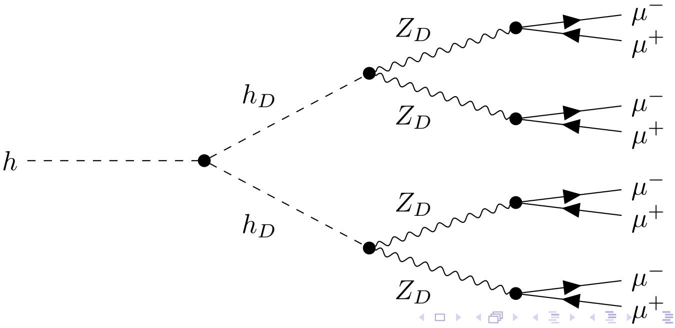
#	Cut	Events	Rel. Eff (%)	Total Eff (%)
0	All events	10000	–	100.0
1	GEN 1st μ $p_T > 24$, $\|\eta\| < 2$	8639	86.4	86.4
2	GEN 2nd μ $p_T > 24$, $\|\eta\| < 2$	6329	73.3	63.3
3	GEN 3rd μ $p_T > 10$, $\|\eta\| < 2.4$	6114	96.6	61.1
4	GEN 4th μ $p_T > 10$, $\|\eta\| < 2.4$	4513	73.8	45.1
5	GEN pixel/tracker fiducial	4042	89.6	40.4
6	RECO 1st μ $p_T > 24$, $\|\eta\| < 2$ (rel. to Cut4)	4474	99.1	44.7
7	RECO 2nd μ $p_T > 24$, $\|\eta\| < 2$	3936	88.0	39.4
8	RECO 3rd μ $p_T > 10$, $\|\eta\| < 2.4$	3936	100.0	39.4
9	RECO 4th μ $p_T > 10$, $\|\eta\| < 2.4$	3936	100.0	39.4
10	Good PV	3794	96.4	37.9
11	fitValid + prob < 0.01	2525	66.5	25.3
12	Valid pixel hit	2394	94.8	23.9
13	DY veto	2394	100.0	23.9
14	Iso_eachMuon < 2.3	1655	69.1	16.6
15	Signal HLT	1653	99.9	16.5
16	STA quality	1627	98.4	16.3
17	Mass consistency	1369	84.1	13.7

- Efficiency (vs cut5) $\approx 1369/4042 \sim 33\%$
- Efficiency (vs cut4) $\approx 1369/4513 \sim 30\%$

Eight Muon Endstate

- h can also decay into h_D
- h_D can decay into SM particles
- If $m_{h_D} > 2m_{Z_D}$, then Br($h_D \to Z_D Z_D$)∼100%
- Also, Br($h \to h_D h_D$)$\sim \kappa^2$

- Pros
  - Nearly no background
  - h_D decay promptly to Z_D
- Cons
  - Limits range for M_{h_D} and M_{Z_D}
  - Easy to lose muons



Eight Muon Endstate – Pros

- Nearly background free process
  - Results normalized to Run2
  - $M_{Z_D} = 30\text{GeV}$, $M_{h_D} = 62\text{GeV}$
- h_D decays promptly to Z_D
  - h_D is short lived
  - Displacement only from Z_D

Background ($ZZ \to 4\ell$) – 181,525 Events

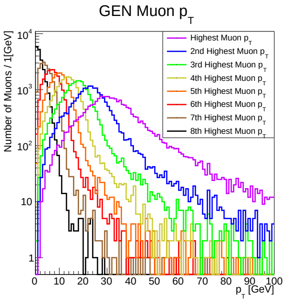
Num. RECO Muon	No Cuts	$p_T > 2\text{GeV}$	$p_T > 3\text{GeV}$	$p_T > 4\text{GeV}$	$p_T > 5\text{GeV}$
7	2735	27	16	6	3
8	1235	5	3	1	0
9 or more	909	34	19	7	4
7 or more	4879	66	38	14	7
7 or more	100%	1.34%	0.78%	0.29%	0.14%

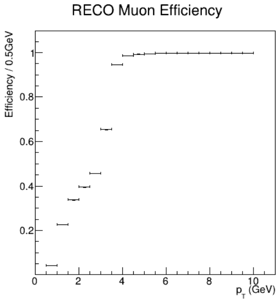
Signal ($h \to h_D h_D$) – 20,000 Events

Num. RECO Muon	No Cuts	$p_T > 2\text{GeV}$	$p_T > 3\text{GeV}$	$p_T > 4\text{GeV}$	$p_T > 5\text{GeV}$
7	3727	3595	3479	3219	2823
8	8728	8485	8148	7454	6494
9 or more	1574	1562	1529	1453	1329
7 or more	14029	13642	13156	12126	10646
7 or more	100%	97.24%	93.78%	86.44%	75.89%

Eight Muon Endstate – Cons

- Limits mass of h_D and Z_D
  - Require $M_{h_D} < \frac{1}{2} M_h$
  - Require $M_{Z_D} < \frac{1}{2} M_{h_D}$
  - If either is not satisfied, this process is heavily suppressed
- Easy to lose muons
  - Energy split across 8 muons
  - Low energy muons cannot be reconstructed reliably
  - Long lived Z_D can decay outside of CMS
  - Want 8 muons in an event
  - Might only see 7 or less





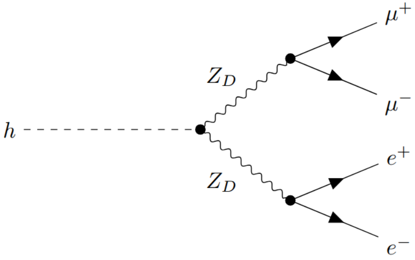
Eight Muon Endstate – Current and Future Work

- Generate Samples for Run 3
  - Samples spanning over:
    - $1\text{GeV} < M_{Z_D} < 30\text{GeV}$
    - $2M_{Z_D} < M_{h_D} < 62\text{GeV}$
    - $0\text{mm} < c\tau < 1000\text{mm}$
  - Samples are currently undergoing simulation
- Perform muon selection and muon pairing on samples
  - Make sure all muons selected are of good quality
  - Can also used this to reject some background
  - Currently working on improving this
- Ensure that background is nearly zero
  - Shown that $ZZ \to 4\ell$ is nearly completely removed
  - Need to show QCD background has the same behavior
  - Will then have to do data driven background estimation
- Discover new physics / place limits $\text{Br}(h \to h_D h_D)$

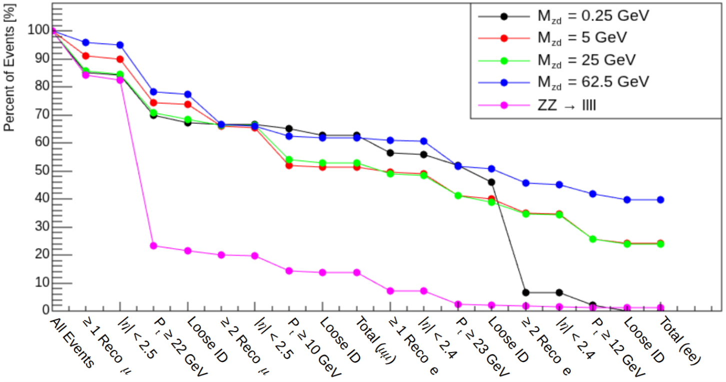
Two Electrons, Two Muons

- Include electrons in the analysis
- Set $M_{hd} = 130$ GeV
  - Not produced
- $M_{zd} \in [0.25, 62.5]$ GeV
- $c\tau \in [0, 1000]$ mm

- Pros
  - Increases signal events
  - Can still trigger on $(\mu\mu)$ events
- Cons
  - Electrons have large QCD background
  - if $M_{zd} < 10$ GeV, $(\Delta R_{ee} < 0.1)$!

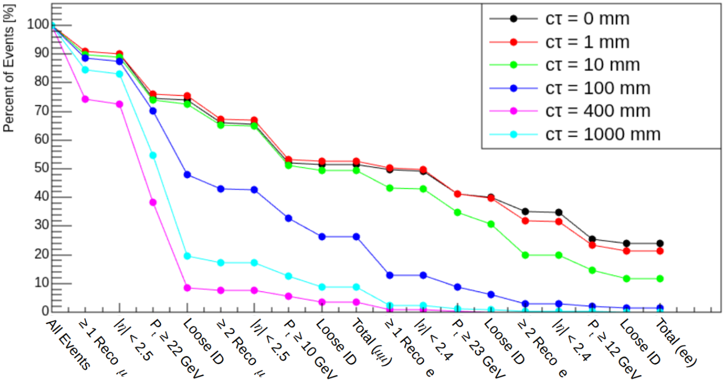


Two Electrons, Two Muons



- Apply selection criteria for "good" signal
  - Within certain η or P_t so its detectable (geometric acceptance)
- Background reduced to 1.2%

Two Electrons, Two Muons



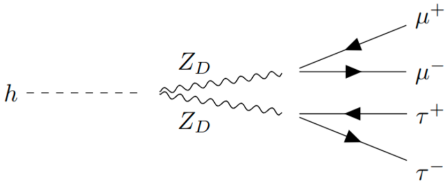
- We can also vary $c\tau$
  - Largest losses are due to identifying these leptons
- Large $c\tau$ suffers with current CMS software

Two Electrons, Two Muons

Whats left to do?

- Optimize cuts applied to signal and background
- Apply offline triggers
- Better electron track identification
  - There are different kinds of lepton objects depending on the identification technique
- Currently reworking reconstructed lepton pairing
  - Naive: take the top two leptons with highest P_t
  - Now: Find (ee) $(\mu\mu)$ such that ΔM_{Inv} is smallest
- Potential to apply ML/NN to differentiate signal from background topology if kinematic separation isn't good enough
  - Especially for low mass dielectron resonance

Two Muons, Two Taus



τ leptons decay promptly and are never observed directly. They are only ever seen as their decay modes: τ_e, τ_μ, τ_h

We choose the decay mode pairs with the highest branching fractions: $\tau_\mathrm{h}\tau_\mathrm{h}$, $\tau_\mu\tau_\mathrm{h}$, $\tau_e\tau_\mathrm{h}$, $\tau_e\tau_\mu$

τ_e and τ_μ are reconstructed using standard electron and muon algorithms. τ_h requires special techniques...

Decay mode	Resonance	$\mathcal{B}$ (%)	
Leptonic decays		35.2	
$\tau^- \to \mathrm{e}^-\overline{\nu}_\mathrm{e}\nu_\tau$			17.8
$\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$			17.4
Hadronic decays		64.8	
$\tau^- \to \mathrm{h}^-\nu_\tau$			11.5
$\tau^- \to \mathrm{h}^-\pi^0\nu_\tau$	$\rho(770)$		25.9
$\tau^- \to \mathrm{h}^-\pi^0\pi^0\nu_\tau$	$\mathrm{a}_1(1260)$		9.5
$\tau^- \to \mathrm{h}^-\mathrm{h}^+\mathrm{h}^-\nu_\tau$	$\mathrm{a}_1(1260)$		9.8
$\tau^- \to \mathrm{h}^-\mathrm{h}^+\mathrm{h}^-\pi^0\nu_\tau$			4.8
Other			3.3

$$\mathrm{Br}(\tau_h\tau_h) = 0.648^2 = 0.420$$

$$\mathrm{Br}(\tau_\mu\tau_h) = 2\cdot 0.174\cdot 0.648 = 0.226$$

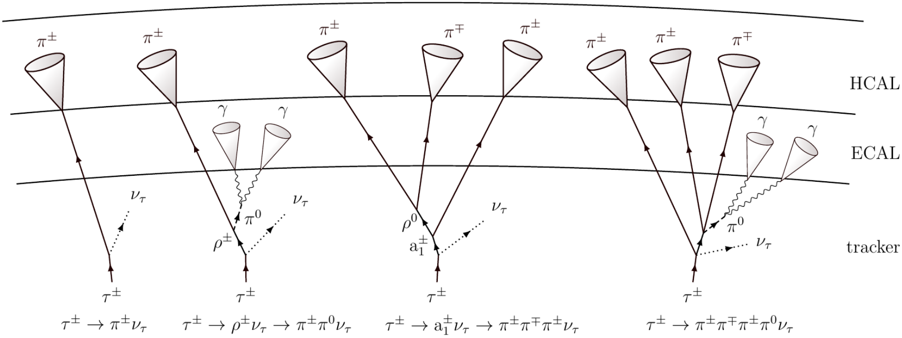
$$\mathrm{Br}(\tau_e\tau_h) = 2\cdot 0.178\cdot 0.648 = 0.231$$

$$\mathrm{Br}(\tau_e\tau_\mu) = 2\cdot 0.178\cdot 0.174 = 0.062$$

$$\mathrm{Br}(\tau_e\tau_e) = 0.178^2 = 0.032$$

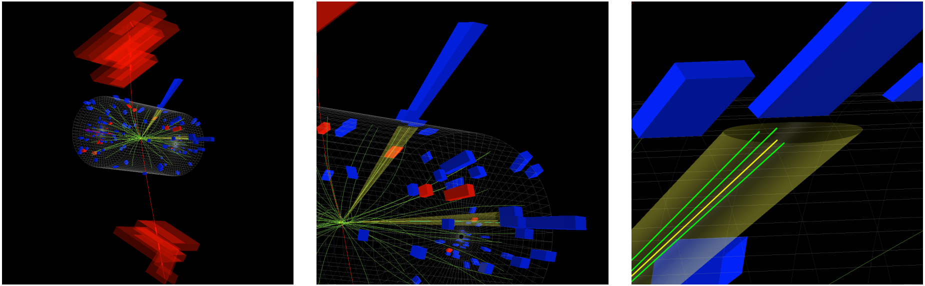
$$\mathrm{Br}(\tau_\mu\tau_\mu) = 0.174^2 = 0.030$$

Hadronic Tau Reconstruction



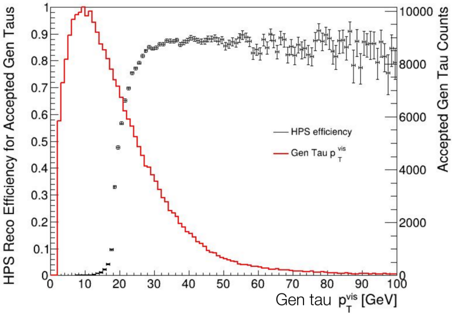
τ_h encompasses many different decay modes involving tracks, ECAL hits, and HCAL hits. The Hadrons Plus Strips (HPS) algorithm is the default.

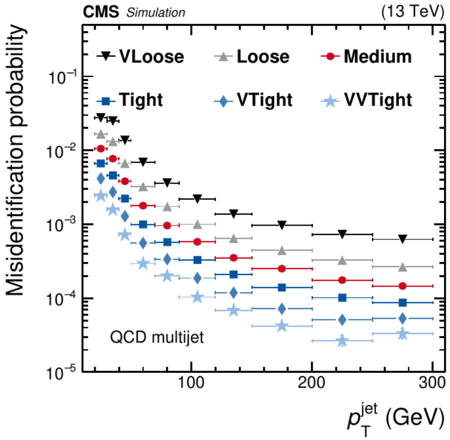
A Good HPS Example



HPS has identified the three charged pion tracks (green) and the HCAL deposit (blue) as a τ_h reconstruction candidate (yellow).

Limitations of the HPS Algorithm





Our signal has relatively low momentum taus ($p_T < 20$GeV)

HPS has low efficiency and high fake rate in this region.

HPS performance is our biggest limitation.

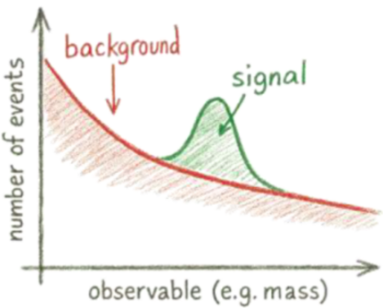
Beyond HPS

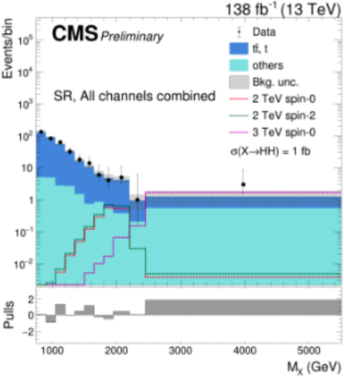
We are doing a direct follow-up to a 2017 CMS study that uses HPS with a $\mu\mu\tau\tau$ final state. We are investigating alternative methods that have been developed since then:

- DeepTau NN applied on top of HPS candidates. Reduces fake rate but doesn't help efficiency.
- Scouting HPS developed for higher efficiency at low p_{T}, but for "scouting" datasets. Perhaps we can adapt it to our datasets.
- Custom NN to classify jet seeds.

Conclusions and Future plans

- Improving LLP sensitivity in CMS
  - We all must present our work to other BSM/LLP working groups
- Convince the community of our findings
  - $N_{Sig} > \sqrt{N_{bkgd}}$
- Release our analysis programs onto real CMS data (unblinding)
- Look for anomalies! [12]





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