SEARCHES FOR DARK MATTER MEDIATORS WITH THE CMS DETECTOR CMS DARK MATTER MEDIATORS

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Javier Duarte **Fermilab**

OUTLINE

• What can we do with dijet searches?

• Dark Matter & Dijets

- How can we do more with dijet searches?
	- A new trigger-to-analysis paradigm
		- Data Scouting
	- Twist on a classic search
		- Boosted Dijets
- Summary and outlook

CMS DARK MATTER MEDIATORS

DARK MATTER & DIJETS

EXAMPLE DARK MATTER MEDIATOR

• At colliders, we search for dark matter production with large missing energy and some radiation to trigger on $(MET+X)$

• Mediator may directly produce a **low-mass dijet** resonance Z0 *^B*(*m*med) a low-mass diic

DIJET EVENT IN CMS [PLB 769 \(2017\) 520](https://doi.org/10.1016/j.physletb.2017.02.012) [EXO-16-056](https://cds.cern.ch/record/2256873)

• Dijet mass $m_{ii} = 7.7$ TeV

CMS Experiment at the LHC, CERN Data recorded: 2016-May-11 21:40:47.974592 GMT Run / Event / LS: 273158 / 238962455 / 150

 $p_T = 3.4$ TeV

$p_T = 3.6$ TeV

BASICS OF A DIJET SEARCH

- Collect data with a trigger based on H_T (sum of all transverse jet energies in the event)
- Cluster and select two "wide jets"
- Search for a **bump** on top of the *smoothly falling QCD dijet background*

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Javier Duarte Fermilab size **a** $\frac{1}{4}$ was used to confirm that no additional parameters are needed to model these needed to model these needed to model these needed to model the second to model the second to model the second to model the sec distributions, *i.e.* in the low-mass search including an additional term *P*⁵ ln (*x*) ance the low-mass data, $2^{2}/\sqrt{2}$

• A simplified model of a dark matter mediator

• Precision measurements of the Z boson width from LEP

• UA2 dijet search at the SppS at CERN, 1993

• CDF dijet search at the Tevatron at Fermilab, 2009

• CMS dijet search the LHC (8 TeV), 2012

DARK MEDIATOR [PLB 769 \(2017\) 520](https://doi.org/10.1016/j.physletb.2017.02.012) [EXO-16-056](https://cds.cern.ch/record/2256873)

Higher energy only let us exclude new physics at high mass

DARK MEDIATOR [PLB 769 \(2017\) 520](https://doi.org/10.1016/j.physletb.2017.02.012) [EXO-16-056](https://cds.cern.ch/record/2256873)

How can we look for weakly-coupled new physics at low mass?

TWO METHODS

• Data scouting: lower trigger thresholds by recording only information necessary to perform certain analyses (to get around data-taking constraints) Z0 *^B*(*m*med) g nly informati

• Boosted dijets + associated ISR jet: Use ISR jet to get above the trigger thresholds $\frac{1}{\sqrt{1-\frac{1$ μ decays into μ

 $Z'_{B}(m_{\text{med}})$

 $q \longleftarrow q$ q_0

 $\overline{\mathsf{q}}$

Figure B.10: Representative Feynman diagrams showing the pair produc-

q

 g'_{q}

q

191

q

 $\overline{\mathfrak{q}}$

q

CMS DARK MATTER MEDIATORS

DATA SCOUTING

TWO-LEVEL TRIGGER

- Level-1 Trigger (hardware)
	- 99.75% rejected
	- decision in ~4 µs
- High-Level Trigger (software)
	- 99% rejected
	- decision in ~100s ms
- After trigger, 99.99975% of events are gone forever

TWO-LEVEL TRIGGER

• After trigger, 99.99975% of events are gone forever

TRIGGER LIMITATIONS

- Two limitations for standard stream given data acquisition and computing resources:
- CPU time $<$ ~100s ms
- Total Bandwidth = event size \times event rate \lt ~1 GB/s $=$ 1 MB \times 1 kHz $<$ ~1 GB/s

TRIGGER LIMITATIONS

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Can we shrink size to increase rate?

D. Anderson "Data Scouting at CMS" [2015 IEEE NSS/MIC](http://www.nss-mic.org/2015/public/welcome.asp)

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DATA SCOUTING

- Calo Scouting **AK4 Calo Jets** • Reconstruct & store only the 4 kHz \times 3 kB information necessary to **MET Vertices** $= 12$ MB/s (opportunistically saved) perform certain analyses $\boldsymbol{\rho}$ \rightarrow record many A.U. $H_T > 250$ GeV: more events **Calo Scouting Scouting with Calo jets and muons** • Peak rate: **4 kHz** • Monitoring dataset (~1/200 of events) is fully reconstructed • "Calo Scouting" HT (GeV) gets down to (Not to scale) **900 GeV 250 GeV** $H_T > 250$ GeV
	- **Lowest unprescaled HT trigger**

DARK MEDIATOR [PLB 769 \(2017\) 520](https://doi.org/10.1016/j.physletb.2017.02.012) [EXO-16-056](https://cds.cern.ch/record/2256873)

 $\frac{1}{255}$

ter and quarks respectively: (*m*med, *m*DM, *g*DM, *g*⁰

CMS DARK MATTER MEDIATORS

BOOSTED DIJET

DIJET TOPOLOGY

Z'

- At low p_T , the quarks are resolved into separate jets
- Difficult to trigger and buried under QCD q background q

q

 \overline{q}

initial state (left) and the pair production of quarks (right) via a vector or

q

q

EXECUTIVE SUMMARY

- Online selection:
	- jet p $_{\rm T}$ > 360 GeV (m > 30 GeV) $\rm \underline{\smile}_{\rm collinear}$ or $H_T > 900$ GeV
- Offline selection:
	- jet $p_T > 500$ GeV, $|\eta| < 2.5$
- Substructure selection:
	- Soft drop jet mass > 40 GeV
	- N^12^{DDT} (5% QCD eff. WP)
- Backgrounds:
	- QCD
	- SM Candles: $W/Z + jets$

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EXECUTIVE SUMMARY

here, and angle between two collinear particles, which is the angle between angle between angle between angle b collinear particle and a soft particle. In an EFT context, overlaps between soft and collinear

Here, ✓*cc* is the angle between two collinear particles, while ✓*cs* is the angle between a collinear particle. In and a soft particle. In an EFT context, over \mathcal{L}

Javier Duarte • Online selection: • jet p $_{\rm T}$ > 360 GeV (m > 30 GeV) $\rm \underline{\smile}_{\rm collinear}$ or $H_T > 900$ GeV • Offline selection: • jet $p_T > 500$ GeV, $|\eta| < 2.5$ • Substructure selection: • Soft drop jet mass > 40 GeV • N^12^{DDT} (5% QCD eff. WP) • Backgrounds: • QCD • SM Candles: $W/Z + jets$ Soft) θ_{cc} *zs* Collinear Collinear Soft Soft C-Soft C-Soft) $\sum_{i=1}^{n}$)
)
)
) ✓*cc* ✓*cc* ✓¹² *zs zcs* \sim (a) Schematic of a 1-prong jet, showing the dominant soft (green) and collinear s CMS CMS $CUIL$ $35.9~fb⁻¹ (13~TeV)$ proposed the dominant soft \overline{E} and \overline{E} and \overline{E} (green), collinear (collinear \overline{E} and \overline{E} and **radiation as a contract as a contract as a contract as contracteristic scales,** *z***^{***c***}(qq) m²
** *z(cc***),** *zcc***),** *zcc***, and ***i* $\frac{m}{\epsilon}$ is the structure. The jetting of the jetting of the jetting $\frac{m}{\epsilon}$ and angular structure. α in the e α lines are using the e α in the e α For example, in Soft Collinear E<mark>∟ective Theory (SCET)</mark> in Soft Collinear Election Theory (SCET) in Social Theory (SCET) in S the approximate $\mathbf{a}^2 = \mathbf{a}^2 - \mathbf{a}^2$, we are the particular set of measurements. The $\mathbf{a}^2 - \mathbf{a}^2$ In the context of power counting, soft and collinear emissions are defined by the collinear emissions are parametric scalings. A soft emission, denoted by *s*, is defined by *z^s* ⌧ 1 *,* ✓*sx* ⇠ 1 *.* (2.12) Here, *z^s* is the momentum fraction, as defined in Eq. (2.2), and ✓*sx* is the angle to any **outher particle in the including other soft particles. The society of the soft particles in the scaling of the scal** $\overline{\mathsf{S}}$ is not assigned any parametric scaling associated with the measurement. A collinear N^1_2 emission, denoted by *c*, is defined by *z k i c ms/ i* $\frac{1}{2}$ VS. $\lim\text{ear}\quad/$ \mathbf{b} <u>arXiv:1609.07483</u>) $\left\{ \right.$ $\Bigg\}$ $\theta_{cc}^{}$ $\theta_{c}c$ θ_{12} *zs* z *cs* \overline{a} since 3: (a) Schematic of a 1-prong jet, showing the dominant soft (green) and collinear soft (green) an \overline{E} and dominant soft \overline{E} and dominant soft (green), collinear (collinear \overline{E} and collinear \overline{E} and collinear \overline{E} and collinear \overline{E} and \overline{E} and collinear \overline{E} and \overline{E} and $\overline{E$ \overline{C} **radiation** \overline{C} *z* $\overline{$ $\mathfrak{B}_{\text{max}} = \frac{1}{2} \sum_{i=1}^{N} \sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{j=1}^{N}$ α in the external theory (EFT) community field theory (EFT) community. Eqtival theory (EFT For example, in Soft Collinear E<mark>∟ective Theory (SCET)</mark> in The United to identify the interval to identify the i the appropriate $\mathbf{f} = \mathbf{f} \cdot \mathbf{f} = \mathbf{f} \cdot \mathbf{f} = \mathbf{f} \cdot \mathbf{f}$ and $\mathbf{f} \cdot \mathbf{f} = \mathbf{f} \cdot \mathbf{f} \cdot \mathbf{f}$ In the context of power counting, some counting, some collinear emissions are defined by the collinear emission parametric scalings. A soft emission, denoted by *s*, is defined by *z^s* ⌧ 1 *,* ✓*sx* ⇠ 1 *.* (2.12) Here, *z^s* is the momentum fraction, as defined in Eq. (2.2), and ✓*sx* is the angle to any other particle *x* in the jet, including other soft particles. The scaling ✓*sx* ⇠ 1 means that \Box ³ is not assigned any parametric scaling assigned with the measurement. A collinear N_2^1 emission, denoted by *c*, is defined by *<i>z is i*^{*s*} *i*^{*s*} 1-prong. 2-prong. 1 \mathcal{L} 0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5 Events / 0.02 units 10 10^2 10^{3} 10^{4} 10^{5} $10⁶$ $10'$ 10^8 \equiv \sim QCD (k-factor 0.74) W(qq)+jets tt(qq)+jets Z(qq)+jets Single-t(qq)
Z'(qq) m_ = 100 GeV
Z'(gg) m^{Z'} = 150 GeV $Z'(qq)$ m $Z' = 150$ GeV
Data Data MC uncert. (stat.) 1 N_2^1 0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5 Data/Simulation 0.5 1 1.5 **CUT** SIGNA REGION

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BACKGROUNDS [PRL 119, 111802](https://doi.org/10.1103/PhysRevLett.119.111802)

• QCD jet mass spectrum prediction methods:

[\(2017\)](https://doi.org/10.1103/PhysRevLett.119.111802)

- Monte Carlo simulation (can we trust it?)
- Pure parametric fit (large uncertainties)
- Data-driven sideband prediction

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SIDEBAND QCD PREDICTION

- Core idea: predict QCD jet mass distribution from failing region
- Problem: cut on N¹2 sculpts jet mass distribution!

SIDEBAND QCD PREDICTION

• Solution: define new substructure variable intended to be decorrelated from jet mass

MORE REALISTIC

• In real data, signal region and control region have slightly different shapes α decomposition to a part and control require have slightly nh pass (*m*) = $\frac{1}{2}$, $\frac{1}{2}$, $\frac{1}{2}$, $\frac{1}{2}$, $\frac{1}{2}$, $\frac{1}{2}$

$FITTING TRANSFER FACTOR$ fail (*m*SD, *p*T) (2)

• Fit directly for a parametrized transfer factor d transfer factor

BOOSTED DIJET FIT

• Fit results per p_T bin

[JHEP 01 \(2018\) 097](https://doi.org/10.1007/JHEP01(2018)097)

QCD multijet background from

control region failing substructure

× transfer factor $R_{p/f}(\rho, p_T)$

SM candles: W/Z(qq) peak provides in-situ constraint of Z'(qq) signal systematics

• Fit results per p_T bin

[JHEP 01 \(2018\) 097](https://doi.org/10.1007/JHEP01(2018)097)

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• Fit results per p_T bin

BOOSTED DIJET [JHEP 01 \(2018\) 097](https://doi.org/10.1007/JHEP01(2018)097)

• Expanded CMS reach down to 50 GeV

SENSITIVITY TO DARK MATTER

• Sensitive to large range of *dark matter* parameter space by looking directly for resonant production of the *mediator*

med!3/2

SENSITIVITY TO DARK MATTER

• Converted to plane of nucleon-dark matter cross section versus dark matter mass

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NOTE: MODEL DEPENDENT

CMS DARK MATTER MEDIATORS

SUMMARY AND OUTLOOK

SUMMARY AND OUTLOOK

• More to dijets than meets the eye

SUMMARY AND OUTLOOK

• More to dijets than meets the eye

• Looking forward to the rest of Run 2 and Run 3!

CMS DARK MATTER MEDIATORS

BACKUP

$BOOSTED H \rightarrow BB$ [PRL 120, 071802](https://doi.org/10.1103/PhysRevLett.120.071802) [\(2018\)](https://doi.org/10.1103/PhysRevLett.120.071802)

• Simultaneous search for Z(bb) and H(bb)

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1.5σ, $\mu_{H} = 2.3 + 1.8$ _{-1.6}

SENSITIVITY TO DARK MATTER

• Sensitive to large range of *dark matter* parameter space by looking directly for resonant production of the *mediator*

initial state (left) and the pair production of quarks (right) via a vector or

12*p*

med!3/2

SENSITIVITY TO DARK MATTER

• Converted to plane of nucleon-dark matter cross section versus dark matter mass

NOTE: MODEL DEPENDENT

DARK MATTER MEDIATOR $\frac{1}{2}$. $\frac{1}{2}$ as a function of its mass $\frac{1}{2}$. $\frac{1}{2}$ DARK MATTER MEDIATO

- If our leptophobic Z' couples to dark matter as well quarks, then it acts as mediator between the dark sector and visible sector (SM) $\begin{array}{ccc} \n\hline\n1 & 1 \quad 1 \quad 1 \quad 2 \quad 1\n\end{array}$ Previous exclusions obtained with similar searches at various collider ener**guarks**, liferified dus $\left\{ \begin{array}{c} \mathcal{L}_{B}(m_{\text{med}}) \\ \mathcal{L}_{C} \end{array} \right\}$
- mediator change as we turn q a leptophobic vector (V) or a leptophobic vector (V) or a left of a leptophobic vector (AV) mediator change as we turn • How do our limits on the similar sim on $g_{DM} > 0$ and $m_{DM} < m_M/2$? $\mathsf{on}\,\mathsf{g}_\mathsf{DM} > \mathsf{U}$ and $\mathsf{m}_\mathsf{DM} < \mathsf{m}_\mathsf{M}/\mathsf{Z}:$

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$$
\mathcal{L}_V = -g_{DM} Z'_{B\mu} \overline{\chi} \gamma^{\mu} \chi - g'_{q} \sum_{q} Z'_{B\mu} \overline{q} \gamma^{\mu} q
$$

q *c*(*m*DM) S_P and S_q , $S<$ *AD* parameter space: gpm, gd <u>e</u> 4D parameter space: **g_{DM}, g_q, m_{DM}, m_M**

SENSITIVITY TO DARK MATTER CENSITIVITY TO DARK MATT $C1$ TIVLITV TO DADI MATTED also be included. As in the mass-mass plots, we recommend to explicitly specify details of $C \cap N$ (CITIV/ITV/ $T \cap N$ N N N N N N T T T and *g*DM = 1. The LHC SI exclusion contour is compared with the LUX, CDMSLite and the SI (SD) plane is for a vector (axial-vector) mediator, Dirac DM and couplings *g^q* = 0*.*25 and *g*DM = 1. The LHC SI exclusion contour is compared with the LUX, CDMSLite and NSITIVITY TO DARK MATTER $NITV T $\cap N$$ also be included. As in the mass-mass plots, we recommend to explicitly specify details of the SI (SD) plane is for a vector (axial-vector) mediator, Dirac DM and couplings *g^q* = 0*.*25 and *g*DM = 1. The LHC SI exclusion contour is compared with the LUX, CDMSLite and $S\mathrel{\mathop{\rule{.5pt}{.mathrm{S}}}}\mathrel{\mathop{\rule{.5pt}{.}}\mathrel{\cap}}\mathrel{\mathop{\rule{.5pt}{.5pt}}\mathrel{\cap}}\mathrel{\mathop{\rule{.5pt}{.5pt}}\mathrel{\cap}}\mathrel{\mathop{\rule{.5pt}{.5pt}}\mathrel{\cap}}\mathrel{\mathop{\rule{.5pt}{.5pt}}\mathrel{\cap}}\mathrel{\mathop{\rule{.5pt}{.5pt}}\mathrel{\cap}}\mathrel{\mathop{\rule{.5pt}{.5pt}}\mathrel{\cap}}\mathrel{\mathop{\rule{.5pt}{.5pt}}\mathrel{\cap}}\mathrel{\mathop{\rule{.5pt}{.5pt}}\math$ and **g** and **g** in the LUX, the L_UX, CDMS is compared with the LUX, CDMSLite and CDMSLite and CDMSLite and CDMSLite and CDMSLite and CDMSLite and CD $\triangle A R K M$ $g \rightarrow \pm$ TTE \overline{a} *^m*med ◆⁴

• We can convert these limits in the (m_M , m_{DM}) plane into limits in the (m_{DM}, σ_{SD}) plane to compare with ID/DD DM experiments σ) play μ , σ _{SD}) plane to compare with ID/DD DM experiments. the (m_{DM}, σ_{SD}) plane to compare with ID/DD DM experiments • We can convert these limits in the (m_M, m_{DM}) plane into lim $\bullet\,$ vve can convert these limits in the (m $_{\rm M}$, m $_{\rm DM}$) plane into limits in $\bullet\,$ the (m_{DM}, σ_{SD}) plane to compare with ID/DD DM experiments The Call Convert diese minds in the μ ilim, mondi piane mito minds in the SD of SD of SD of SD of SD of SD o $\,$ an convert these limits in the (m $_{\mathsf{M}},$ m $_{\mathsf{DM}}$) plane into limits in $\frac{1}{2}$ and $\frac{1}{2}$ ($\frac{1}{2}$ $\frac{1}{$

where \mathbf{h} $\mathcal{F}^{\text{P}} = \int_{\mathcal{F}^{\text{P}}} \mathcal{F}^{\text{P}}(x) \mathcal{F}^{\text{P}}(x) dx$ couping g_q, mearator-nucleon couping is *L*DD = *L*^S = tor mediator with universal quark $\mu_{p} = \mu_{p} = \rho_{32}$ (¯)(¯*qq*) For axial-vector mediator with universal quark the proton are slightly distribution distribution distribution $f^p = fⁿ = 0.32 g_q'$. the proton theorem is the proton of $f^p = f^n = 0.32g_q'$. tor with u For axial-vector mediator with universal quark and the same of the set of ator with different sar qualk $f^p = fⁿ = 0.32g'_{q}$. t_{max} For axial-vector mediator with universal quark coupling g_q' , mediator-nucleon coupling is

coupling g_q, mediator-nucleon coupling is
\n
$$
\sigma_{\text{DM-p}}^{\text{SD}} = \frac{3f^2(g'_q)g_{\text{DM}}^2 \mu_{\text{N}\chi}}{\pi m_{\text{med}}^4}
$$
\n
$$
\approx 2.4 \times 10^{-42} \text{ cm}^2 \cdot \left(\frac{g'_q g_{\text{DM}}}{0.25}\right)^2 \left(\frac{1 \text{ TeV}}{m_{\text{med}}}\right)^4 \left(\frac{\mu_{\text{N}\chi}}{1 \text{ GeV}}\right)^2
$$

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Javier Duarte Fermilab where, in general, the factor *f*(*g*0 trons and depends separately on the individual quark-mediator couplings For the vector mediator, and hence 4.1.2 SD case: Axial-vector mediator For the axial-vector mediator, the scattering is SD and the corresponding cross section can For the axial-vector mediator, the scattering is SD and the corresponding cross section can be written as 4.1.2 SD case: Axial-vector mediator For the axial-vector mediator, the scattering is SD and the corresponding cross section can For the axial-vector mediator, the scattering is SD and the corresponding cross section can be written as

T

 $f^n = 0.32g'_0$.

1 GeV

^s = 0*.*043. The values for

 $\frac{1}{q}$.

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DM COMPLEMENTARITY

DM COMPLEMENTARITY

QCD TRANSFER FACTOR D TRANSFER FACTO

• If tagger were completely uncorrelated from jet mass and p_T in data, the transfer factor would be flat ϵ

$$
N_{\text{pass}}^{\text{QCD}}(m_{\text{SD}}, p_{\text{T}}) = R_{\text{p/f}}(\rho, p_{\text{T}}) \cdot N_{\text{fail}}^{\text{QCD}}(m_{\text{SD}}, p_{\text{T}})
$$

$$
N_{\text{pass}}^{\text{QCD}}(m_{\text{SD}i}, p_{\text{T}j}) = a_{00} \cdot N_{\text{fail}}^{\text{QCD}}(m_{\text{SD}i}, p_{\text{T}j})
$$

QCD TRANSFER FACTOR D TRANK

- If tagger were completely uncorrelated from jet mass and p_T in data, the transfer factor would be flat
- Taylor expand as a polynomial in ρ and p_T to parameterize any small correlations **and the set of product**
- order of polynomial er F-test to parameterize 1st order in p_T is sufficient • Fisher F-test to determine needed to fit the ratio: 2rd order in **p** and

$$
N_{\text{pass}}^{\text{QCD}}(m_{\text{SD}}, p_{\text{T}}) = R_{\text{p/f}}(\rho, p_{\text{T}}) \cdot N_{\text{fail}}^{\text{QCD}}(m_{\text{SD}}, p_{\text{T}})
$$

$$
N_{\text{pass}}^{\text{QCD}}(m_{\text{SD}i}, p_{\text{T}j}) = \left(\sum_{k,\ell} a_{k\ell} \rho_{ij}^{k} p_{\text{T}j}^{\ell} \right) \cdot N_{\text{fail}}^{\text{QCD}}(m_{\text{SD}i}, p_{\text{T}j})
$$

BACKGROUND STRATEGY

- Backgrounds estimated from data
	- QCD (90%): from failing double b-tag × transfer factor
	- tt+jets (3%): from 1μ control region
- Backgrounds estimated from corrected simulation:
	- $W/Z + jets$ (5%)
	- single-t, VV (<1%)

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CLASSIC DIJET

• Classic dijet search @ LHC (CMS, 8 TeV)

[arXiv:1501.04198](http://arxiv.org/abs/1501.04198)

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CMS DETECTOR

PARTICLE FLOW [arXiv:1706.04965](https://arxiv.org/abs/1706.04965)

• Efficient combination of complementary detector subsystems

PARTICLE FLOW [arXiv:1706.04965](https://arxiv.org/abs/1706.04965)

- Efficient combination of complementary detector subsystems
- Holistic particle interpretation of the event improves energy/ spatial resolution for jets, among many other things…

trimming [53], product a set of the mass drop tagging $[5, 5]$. For group tagging $[6, 5]$. For group $[6, 5]$ $\sqrt{7}$ <u>[arXiv:1307.0007](https://arxiv.org/abs/1307.0007)</u> [arXiv:1402.2657](https://arxiv.org/abs/1402.2657)

JET MASS $p \cdot \mathbf{V}$ t the angle of the most commonly used in $J \sqsubset I$ if $N \sqcup A$ J J

- Provides good separation between W/Z/H-jets and q/g jets derstood with the help of logarithmic resummation. Armed with this analytic understanding tion t $\frac{1}{\sqrt{2}}$ and $m \neq 1$ 1 I V $\overline{}$
- Grooming removes soft and wide-angle radiation (soft drop / modified mass drop tagger) which exhibits some surprising features in the resulting group \mathbf{r} and in-the resulting group \mathbf{r} cluding the absence of Sudakov double logarithms, the absence of non-Recursively decluster jet. Remove sub-clusters not alop / modified mass drop tagger) ing removes soft and wide-angle

[arXiv:1609.07483](https://arxiv.org/abs/1609.07483)

1209.07483 JET SUBSTRUCTURE

- How many "prongs" are in the jet?
- Generalized energy correlation functions are sensitive to N-point correlations within a jet
	- Two-pronged jets have $2e_3 \ll (1e_2)^2$ 100 -pronged jets nave $2e_3 \le (1e_2)^2$ 2-point 3-point

SD/*p*²

• Stable under grooming and variable we conclude that the most discrimination of the most of the most of the most of \mathcal{L} ⁴²⁴ power and shows similar discrimination power as *t*²¹

r = *log*(*m*²

$$
{}_{1}e_{2}^{\beta} = \frac{1}{p_{\text{T}J}^{2}} \sum_{1 \leq i < j \leq n_{J}} p_{\text{T}i} p_{\text{T}j} \Delta R_{ij}^{\beta}
$$
\n
$$
{}_{2}e_{3}^{\beta} = \frac{1}{p_{\text{T}J}^{3}} \sum_{1 \leq i < j < k \leq n_{J}} p_{\text{T}i} p_{\text{T}j} p_{\text{T}k} \min\{\Delta R_{ij}^{\beta} \Delta R_{ik}^{\beta}, \Delta R_{ij}^{\beta} \Delta R_{jk}^{\beta}, \Delta R_{ik}^{\beta} \Delta R_{jk}^{\beta}\}
$$

55

Javier Duarte Fermilab ^T ⁴²⁹). Since the QCD (quark or gluon-initated) jet mass scales with *p*T, decorrelat-⁴³⁰ ing a given substructure variable as a function of *r* and *p*^T is a well-bounded procedure. ⁴³¹ The decorrelation procedure applied is derived for a specific background efficiency point. The

 $N_{2}^{\beta}=% {\textstyle\sum\nolimits_{\alpha}} g_{\alpha}\gamma_{\alpha}^{\alpha}$ 2*e b* 3 (1*e* $\binom{\beta}{2}$ ² $\beta = 1$

>))

ment itself allows for a powerful understanding of the jet's energy and angular structure.

C-Soft

))

zs

 \mathbf{r}

zcs

)

zs

)

C-Soft

zs

ment itself allows for a powerful understanding of the jet's energy and angular structure.

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- [D. Anderson "Data Scouting at CMS"](http://www.nss-mic.org/2015/public/welcome.asp)
- How can we trigger below $H_T = 900$ GeV?
- *Reconstruct/save*

only necessary information to perform analysis \rightarrow record more events

• "PF Scouting" is more flexible but limited by **timing** @ HLT (tracking)

Lowest unprescaled HT trigger

[\(2018\)](https://doi.org/10.1103/PhysRevLett.120.071802)

[PRL 120, 071802](https://doi.org/10.1103/PhysRevLett.120.071802) ANALYSIS SELECTION

Substructure: two prong discrimination, 50% sig. efficiency, 26% bkg. efficiency

Double-b tagger: 30% sig. efficiency, 1% bkg. efficiency (tight working point)

MULTIPLE APPROACHES

- Based on standard b-tagging algorithm
- Not designed for two b's in the same jet

- Defines sub-jets
- Standard b-tagging applied to each subject
- Identifies two b hadron decay chains in the same fat jet
- Does not define subjects, but uses N-subjettiness axes

SIGNAL COMPOSITION [HIG-17-010](http://cms.cern.ch/iCMS/analysisadmin/cadilines?line=HIG-17-010)

- Analysis is inclusive in Higgs production mode
- Dominant contribution is ggF (74%)
	- 12% VBF
	- 8% VH
	- \bullet 6% ttH

\mathbf{P} [arXiv:1407.6013](https://arxiv.org/abs/1407.6013)

PUPPI (**P**ile**U**p **P**er **P**article **I**d): based on PF paradigm PUPPI

- $\bullet\,$ PUPPI (PileUp Per Particle Id): general framework that determines, $\,$ per particle, a weight for **how likely** a particle is from PU
- \bullet Key insight: using OCD ansatz to infer neutral pileup contribution • Key insight: using QCD ansatz to infer neutral pileup contribution

[1] define a local discriminant, α, between pileup (PU) and leading vertex (LV)

$$
\alpha_i^C = \log \left[\sum_{j \in \text{Ch,LV}} \frac{p_{T,j}}{\Delta R_{ij}} \Theta(R_0 - \Delta R_{ij}) \right]
$$

[2] get data-driven α distribution for PU using charged PU tracks

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[2] get data-driven α distribution for PU using charged PU tracks

[3] for the neutrals, ask "how un-PU-like is α for this particle?", compute a weight

[4] reweight the four-vector of the particle by this weight, then proceed to interpret the event as usual

[arXiv:1407.6013](https://arxiv.org/abs/1407.6013)

PUPPI

- PUPPI (PileUp Per Particle Id): general framework that determines, per particle, a weight for **how likely** a particle is from PU
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- Signal systematic uncertainties from merged W sample in semi-leptonic ttbar events (external constraint) **Solution 5.8** constitutes the first observation of the first of the first of the α signal of the α $\frac{1}{2}$ boson strength is provinction of the strength is $\frac{1}{2}$ jet topology, further values the substructure and b-tagging strategy for the substructure
- SM candles: presence of W/Z(bb) in final jet mass distribution provides in-situ constraint \mathcal{L} higgs boson search in the same topology. The measured cross section of the \mathcal{L} $\bullet\,$ SM candles: presence of W/Z(bb) in final jet The measured H boson signal strength is *µ*^H = 2.3+1.8 $\mathbf{1} \cdot \mathbf{1} \cdot \mathbf{$ **p** mass distribution provides in-situ constraint rindoo diberituation provided in orea conserunte
- Higgs p $_{\sf T}$ correction uncertainty of 30% observed (expected) significance is 1.5*s* (0.7*s*). Tab. 2 summarizes the measured signal strengths and significances for the Higgs and Z boson

DATA RATES, SIZES, AND TIMING

LONG HISTORY OF DIJET SEARCHES

- Dijet resonance searches are EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH fundamental discovery probes at **CERN-EP/88-54** April 28th, 1988 hadron colliders
	- Two Jet Mass Distributions at the CERN Proton Antiproton Collider

UA1 Collaboration, CERN, Geneva, Switzerland

HIGGS PT MODELING [HIG-17-010](http://cms.cern.ch/iCMS/analysisadmin/cadilines?line=HIG-17-010)

- LO H+0-2jet Pythia CKKW-L merged, finite m_t
- NLO H+1jet finite m_t up to $1/m_t^4$ expansion: [arXiv:1609.00367](https://arxiv.org/abs/1609.00367)
- NNLO H+1jet, $m_t = \infty$, p_T ^H up to ~200 GeV [arXiv:1508.02684](http://arxiv.org/abs/1508.02684)
- Two factorized systematic uncertainties:
	- 30% overall normalization
	- 30% linear change in slope (no effect on overall norm.)

$$
GF H(NNLO + m_t) = (1 \text{ jet } m_t \to \infty) \times \frac{MG \text{ LO } 0 - 2 \text{ jet } m_t}{(1 \text{ jet } m_t \to \infty)} \times \frac{NLO \text{ 1 jet } m_t}{LO \text{ 1 jet } m_t} \times \frac{NNO \text{ 1 jet } m_t \to \infty}{NLO \text{ 1 jet } m_t \to \infty}
$$

$$
CKKW \text{ merged} \qquad \text{factor of 2} \qquad \text{factor of 1.25}
$$

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ONLINE CALO M_{JJ} CALIBRATION

• Fit to correct Online Calo jet p_T

ONLINE CALO MJJ CALIBRATION

• Ratio of Online Calo m_{ii} to Offline PF m_{ii}

DARK MATTER MEDIATOR G*cc* VI L L *m*2 DM med!1/2

- **mDM** and **gDM** affect mediator decay branching ratios
	- Smaller m_{DM} < $m_M/2$ and larger g_{DM} > 0 gives
		- larger $BR(Z' \rightarrow \chi \chi)$
		- smaller $BR(Z' \rightarrow qq)$
- Same dijet cross section upper limit at $g_{DM} = 0$ translates into weaker coupling limit at $g_{DM} > 0$ (smaller branching to dijets)

$$
\sigma[Z'_{B} \rightarrow q\overline{q}|g'_{B}, g_{DM}] = \sigma(Z'_{B} \rightarrow q\overline{q}|g_{B}, g_{DM} = 0)
$$

\n
$$
\Rightarrow \frac{(g'_{B})^{4}}{\Gamma^{q\overline{q}}(g'_{B}) + \Gamma^{X\overline{X}}} = \frac{g_{B}^{4}}{\Gamma^{q\overline{q}}(g_{B})}
$$

\n
$$
\Rightarrow \frac{(g'_{B})^{2}}{\Gamma^{q\overline{q}}(g'_{B})^{2}} = \frac{g_{B}^{2}}{2} \left(1 + \sqrt{1 + 4 \frac{\Gamma^{X\overline{X}}}{\Gamma^{q\overline{q}}(g_{B})}}\right)
$$

, (B.6)

SENSITIVITY TO DARK MATTER

For nucleons, $C_{n,p}$ are related to axial-vector current matrix elements by generalized Goldberger-Treiman relations,

$$
C_p = (C_u - \eta)\Delta u + (C_d - \eta z)\Delta d + (C_s - \eta w)\Delta s,
$$

\n
$$
C_n = (C_u - \eta)\Delta d + (C_d - \eta z)\Delta u + (C_s - \eta w)\Delta s.
$$
\n(9)

Here, $\eta = (1 + z + w)^{-1}$ with $z = m_u/m_d$ and $w = m_u/m_s \ll z$ and the Δq are given by the axial vector current matrix element $\Delta q S_{\mu} = \langle p | \bar{q} \gamma_{\mu} \gamma_5 q | p \rangle$ with S_{μ} the proton spin.

Neutron beta decay and strong isospin symmetry considerations imply $\Delta u - \Delta d = F + D = 1.269 \pm 0.003$, whereas hyperon decays and flavor SU(3) symmetry imply $\Delta u + \Delta d - 2\Delta s =$ $3F - D = 0.586 \pm 0.031$ [25]. The strange-quark contribution is $\Delta s = -0.08 \pm 0.01_{\text{stat}} \pm 0.05_{\text{syst}}$ from the COMPASS experiment [26], and $\Delta s = -0.085 \pm 0.008_{exp} \pm 0.013_{there} \pm 0.009_{evol}$ from HERMES [25], in agreement with each other and with an early estimate of $\Delta s = -0.11 \pm 0.03$ [27]. We thus adopt $\Delta u = 0.84 \pm 0.02$, $\Delta d = -0.43 \pm 0.02$ and $\Delta s = -0.09 \pm 0.02$, very similar to what was used in the axion literature.

MANY SIGNAL MODELS

- quark-quark
	- axigluons: axial-vector particles predicted in a model where the QCD symmetry group $SU(3)_C$ is replaced by the chiral symmetry $SU(3)_L \times SU(3)_R$
	- colorons: vector particles predicted by the flavor-universal coloron model, in which the $SU(3)_C$ is embedded in a larger gauge group
	- W', Z', \ldots
	- dark matter mediators
- quark-gluon
	- excited quarks: predicted in quark compositeness models
	- string resonances, ...
- gluon-gluon
	- RS graviton: predicted in the RS model of extra dimensions, with 5-dimensional anti de Sitter space and reduced Planck mass
	- S8 (color octet scalar) resonances, …

WIDE JETS

- Jets initially reconstructed with anti- k_T algorithm with R=0.4
- "Wide jet" algorithm uses two leading jets as seeds
	- Adds neighboring jets to nearest leading jet if within $\Delta R < 1.1$
	- Recover loss in mass response due to radiation

WIDE JETS

- Gluon-gluon resonances are wider than quark-quark resonances due to greater radiation (gluon color factor) n resonances a RMS x 0.05793
- Mass resolution improved with wide jets even in gluon-gluon case \bullet $\overline{}$

Probability

0

0.02

0.04

0.06

0.08

0.1

0.12

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DOUBLE-B TAGGER

- Combines tracking and vertexing information in a multivariate classifier with 27 observables **d** Combines tracking $\sum_{i=1}^{n}$ multiparticle approach $\sum_{i=1}^{n}$
- Targets the bb signal with additional aims: er additional aims[.]
	- \bullet jet mass and p_T independent
- cover a very wide p_T range • **training strategy** is designed to cover a very wide pt range of the state of th
- inputs are chosen to avoid p $_\top$ $|$ *correlation*
	- e.g. no ΔR-like variables, no substructure info

DOUBLE-B TAGGER INPUTS properties of secondary vertices coming from b hadron decay have been investigated. Using tracks with *p*^T *>* 0.8 GeV, secondary vertices are identified through the Inclusive Vertex Finder (IVF) [4, 10] algorithm. This algorithm is not seeded from tracks associated to the reconstructed

- **•** The first four SIP values for selected tracks ordered in decreasing SIP;
	- *•* For each *t*-axis we consider the first two SIP values for their respective associated tracks ordered in decreasing SIP, to further discriminate against single b quark and light flavor jets from QCD when one or both SV are not reconstructed due to IVF inefficiencies;
	- *•* The measured IP significance in the plane transverse to the beam axis, 2D SIP, of the first two tracks (first track) that raises the SV invariant mass above the bottom (charm) threshold of 5.2 (1.5) GeV;
	- The number of SV associated to the jet;
	- The significance of the 2D distance between the primary vertex and the secondary vertex, flight distance, for the SV with the smallest 3D flight distance uncertainty, for each of the two *t*-axes;
	- The ΔR between the SVs with the smallest 3D flight distance uncertainty and its *t*-axis, for each of the two *t*-axes;
	- *•* The relative pseudorapidity, *h*rel, of the tracks from all SVs with respect to their *t*axis for the three leading tracks ordered in increasing η_{rel} , for each of the two τ -axes;
	- *•* The total SV mass, defined as the total mass of all SVs associated to a given *t*-axis, for each of the two *t*-axes;
	- The ratio of the total SV energy, defined as the total energy of all SVs associated to a given *t*-axis, and the total energy of all the tracks associated to the fat jet that are consistent with the primary vertex, for each of the two *t*-axes;
	- *•* The information related to the two-SV system, the *z* variable, defined as:

$$
z = \Delta R(SV_0, SV_1) \cdot \frac{p_{T,SV_1}}{m(SV_0, SV_1)}
$$
\n
$$
(2)
$$

where SV_0 and SV_1 are SV_5 with the smallest 3D flight distance uncertainty. The z variable helps rejecting the bb background from gluon splitting relying on the different kinematic properties compared to the bb pair from the decay of a massive resonance.

EFFICIENCY IN DATA **Efficiency measurement in data**

- Using g(bb) jet as proxy in double muon tagged jet sample **24**
	- Associated data/MC uncertainty 3-5%

LARGE HADRON COLLIDER

• Proton-proton collisions at 13 TeV in 2016

1 May 1 Jun $2 J^{\overline{u} \overline{l}}$ **1 AuJ 1** Sep 1 0^{ct} Date (UTC) **0 5 10 15 20 25 30 35 40 45 7R tal** Inte <u>ចា</u> **U D t H d L u mLn R sLt y (**fb −1 **)** Data included from 2016-04-22 22:48 to 2016-10-27 14:12 UTC **LHC** Delivered: 40.82 fb⁻¹ **CMS Recorded: 37.76** fb⁻¹ **0 5 10 15 20 25 30 35 40 45**

COMPACT MUON SOLENOID

- 3.8 T magnetic field bends particle trajectories allowing for excellent tracking
- ECAL: PbWO₄ crystals (high density, short radiation length and Molière radius)
- HCAL: plastic scintillator and brass absorber interleaved
- Muon system: drift tubes (DT), resistive plate chambers (RPC), and cathode strip chambers (CSC)

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