Searches for *Dark Matter* with boosted topologies in CMS

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on behalf of the CMS Collaboration

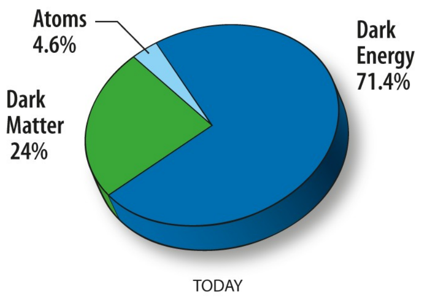
BOOST 2015 – U. Chicago

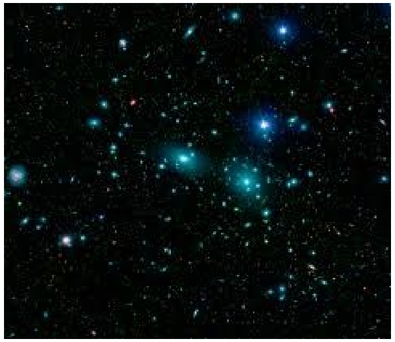
August 10, 2015

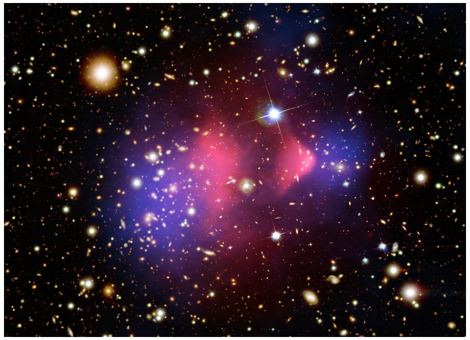
Why Dark Matter?

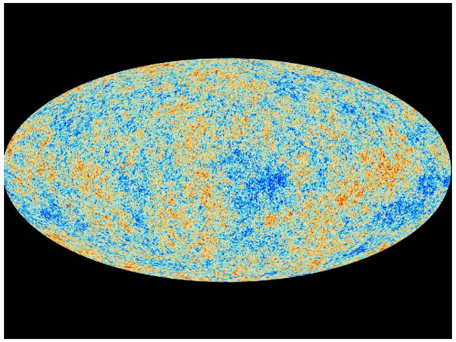
A compelling case for new physics!

– Mounting cosmological evidence ...









Coma (1930s) ► M33 (1970s) ► Bullet (2006) ► Planck (2013-15)

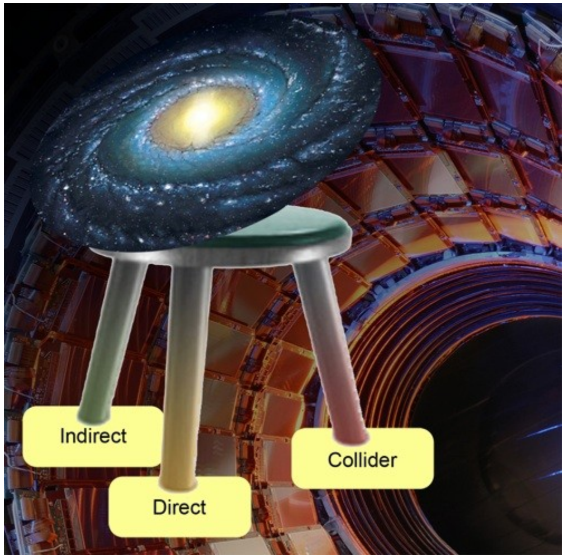
– WIMPs : a new weakly interacting, massive (≤ ~TeV) particle can explain cosmological observations

– Tantalizing (albeit conflicting) results from direct detection (DD) experiments

Why Dark Matter @ BOOST?

Dark Matter (DM) a major focus of Run-2 LHC

- Collider searches *complementary* to DD and ID experiments
  - Backgrounds easier to understand (vs ID) and control (vs DD)
  - Higher sensitivity to low DM masses, spin-dependent interactions
  - Possible on-shell production of DM mediators



Fancy image credit : PBS!

- Extended DM reach in Run-2
  - Larger √s → higher masses, weaker couplings
  - *DM searches @ 13 TeV ripe for boosted techniques !*

Outline

Focus on most recent CMS DM result (Run-1: 19.7 fb-1)

- 1st simplified DM models @ LHC
- 1st combined DM model interpretation
- 1st use of boosted techniques for a DM search at CMS
- Novel resolved V-tagging

Available on the CERN CDS information server — **CMS PAS EXO-12-055**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-exotica@cern.ch — 2015/07/20

Search for New Physics in the V/jet + MET final state

The CMS Collaboration

Abstract

A search is presented for an excess of events with a high energy jet in association with a large missing transverse momentum in a data sample of proton-proton interactions at centre-of-mass energy of 8 TeV. The data correspond to an integrated luminosity of 19.7 fb^{-1} collected by the CMS detector at the LHC. Additional sensitivity is achieved by tagging events consistent with the jet originating from a hadronically decaying vector boson. Limits are obtained on the branching ratio of a standard model Higgs boson decaying invisibly. The search is also interpreted in terms of dark matter production to place constraints on the parameter space of simplified models.

Similar efforts underway for Run-2

The rest of this talk:

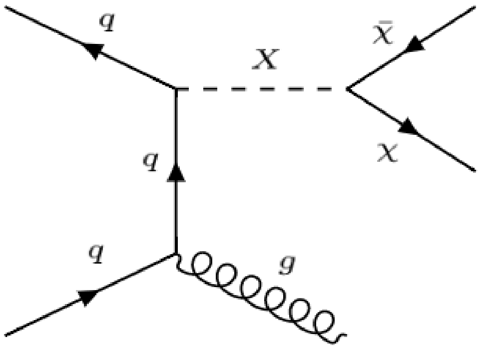
- Some phenomenological background
- Analysis strategy
- Data selection (boosted / non-boosted)
- Results & interpretation

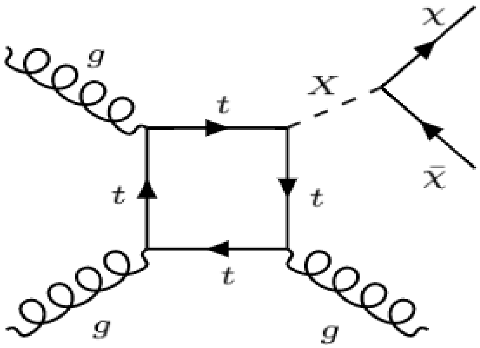
CMS PAS: http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-12-055/index.html

Monojet

DM @ colliders historically probed via ISR tagging

- *DM must recoil against something to be detectable!*

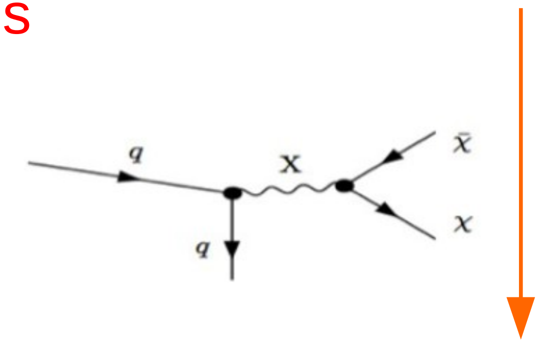




- Signal: <u>large missing transverse energy</u> (MET) + high-pT jet
- Backgrounds: SM processes with real MET
  - Search for DM in the tails of MET distributions

Analogous processes in DD, but rotated

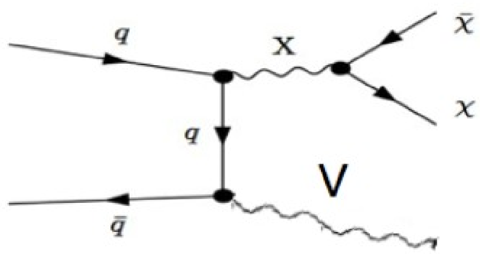
- Can directly compare results!



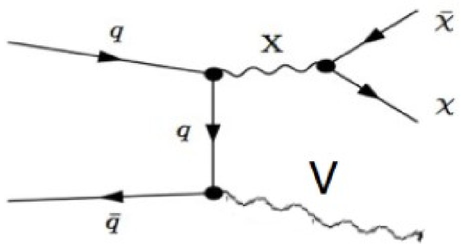
Mono-V

DM couplings imply additional topologies, eg:

- Mono-V: final states with large MET & a W/Z boson
  - Vector / axial couplings: analogous to monojet



$g_{\mathrm{DM}} Z'_\mu \bar{\chi}\gamma^\mu\chi$



$g_{\mathrm{DM}} Z''_\mu \bar{\chi}\gamma^\mu\gamma^5\chi$

See : Bai & Tait, arxiv:1208.4361

Counterpoint : Bell *et al*, arxiv:1503.07874

- Enhancement vs monojet possible via interference (ξ = 0,-1)

  - Scalar / pseudoscalar couplings

$g_{\mathrm{DM}} S\, \bar{\chi}\chi$

$g_{\mathrm{DM}} P\, \bar{\chi}\gamma^5\chi$

- Scalar: model as a Higgs, V-strahlung dominant
- Pseudo: enhanced V pT

High pT V recoil ... boosted techniques can recover the hadronic V!

Simplified Models

Transition from EFT models to explicit mediators

Signal models consistent with prescriptions of the LHC Dark Matter Forum

- See the report for details

arXiv.org > hep-ex > arXiv:1507.00966

Search or Article-id

High Energy Physics - Experiment

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

Daniel Abercrombie, Nural Akchurin, Ece Akilli, Juan Alcaraz Maestre, Brandon Allen, Barbara Alvarez Gonzalez, Jeremy Andrea, Alexandre Arbey, Georges Azuelos, Patrizia Azzi, Mihailo Backović, Yang Bai, Swagato Banerjee, James Beacham, Alexander Belyaev, Antonio Boveia, Amelia Jean Brennan, Oliver Buchmueller, Matthew R. Buckley, Giorgio Busoni, Michael Buttignol, Giacomo Cacciapaglia, Regina Caputo, Linda Carpenter, Nuno Filipe Castro, Guillelmo Gomez Ceballos, Yangyang Cheng, John Paul Chou, Arely Cortes Gonzalez, Chris Cowden, Francesco D'Eramo, Annapaola De Cosa, Michele De Gruttola, Albert De Roeck, Andrea De Simone, Aldo Deandrea, Zeynep Demiragli, Anthony DiFranzo, Caterina Doglioni, Tristan du Pree, Robin Erbacher, Johannes Erdmann, Cora Fischer, Henning Flaecher, Patrick J. Fox, et al. (94 additional authors not shown)

(Submitted on 3 Jul 2015)

This document is the final report of the ATLAS-CMS Dark Matter Forum, a forum organized by the ATLAS and CMS collaborations with the participation of experts on theories of Dark Matter, to select a minimal basis set of dark matter simplified models that should support the design of the early LHC Run-2 searches. A prioritized, compact set of benchmark models is proposed, accompanied by studies of the parameter space of these models and a repository of generator implementations. This report also addresses how to apply the Effective Field Theory formalism for collider searches and present the results of such interpretations.

Subjects: **High Energy Physics - Experiment (hep-ex)**; High Energy Physics - Phenomenology (hep-ph)

Cite as: **arXiv:1507.00966 [hep-ex]**
(or **arXiv:1507.00966v1 [hep-ex]** for this version)

Mono-jet / V Analysis Strategy

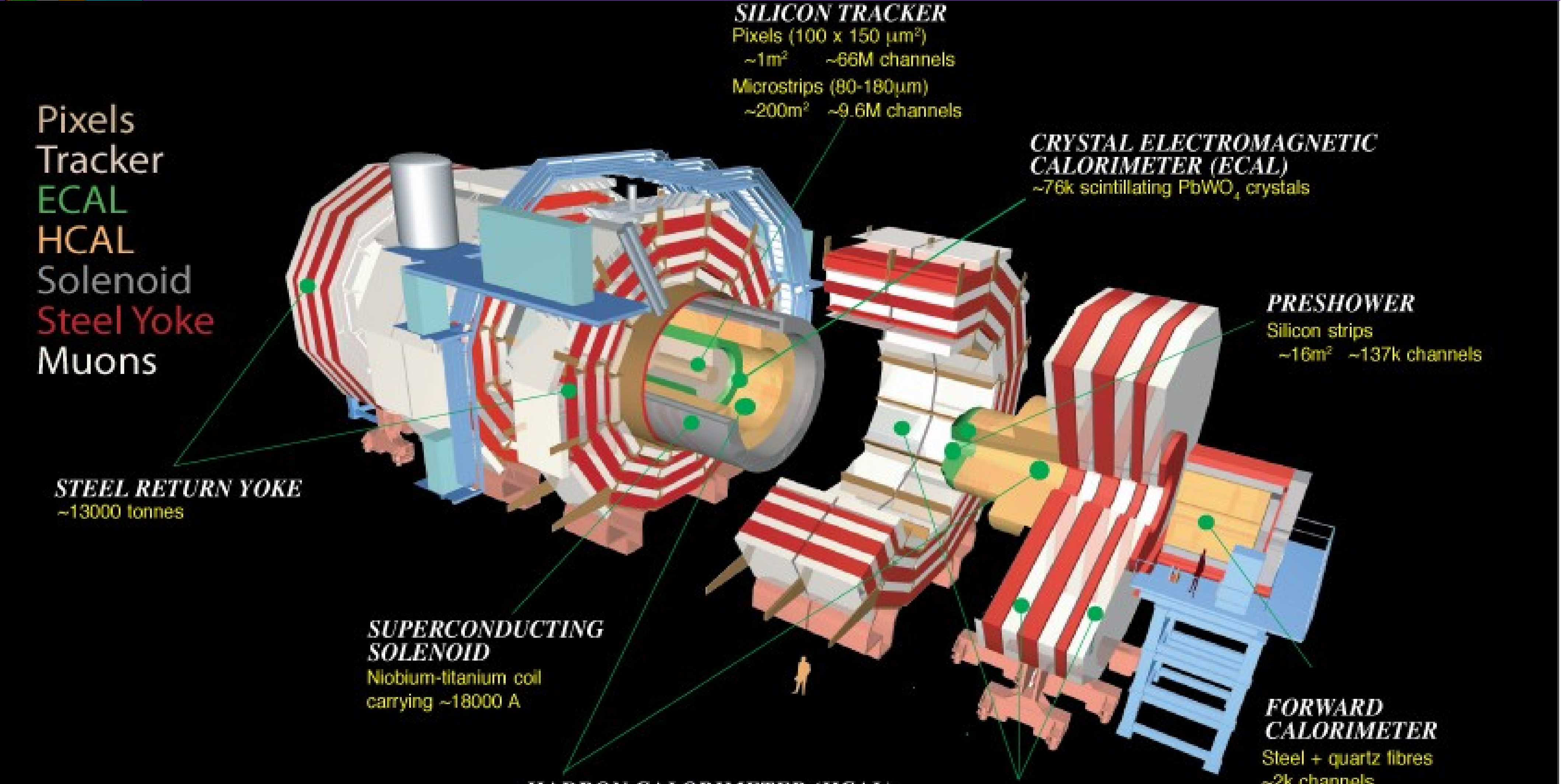
Divide and conquer!

- Exclusive jet-based categorization:
  - Boosted mono-V
  - Resolved mono-V
  - Monojet

Combine and ... re-conquer!

- Simultaneous fit to MET discriminant across signal categories
- Interpret with combined monojet and mono-V signal models

CMS Detector



Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

CMS Detector

To find "nothing", you must reconstruct everything!

Datasets & Objects

Online selection via MET-based triggers

- Raw calorimeter MET > 120 GeV
- Dedicated monojet trigger:
  - Particle Flow MET > 95/120 GeV, muon removal
  - Particle Flow jet > 80 GeV, max neutral hadron requirement

Offline objects, baseline selection :

- anti-kT 0.5 (ak5), Cambridge-Aachen 0.8 (ca8) jets
  - $|\eta| < 2.5$, $p_T > 30$, loose particle flow and pileup jet ID
- PFMET > 200 GeV, recoil-corrected (details later)
- Veto loose ID'ed leptons (photons) $p_T > 10$ (15) GeV
- Reject event if >2 jets with |eta| < 2.5

Categorization

Boosted V

- PFMET > 250 GeV
- CA8 jet pT > 200 GeV passing Boosted V-tag
- Dijet topological cuts

Resolved V

- Not Boosted-V
- PFMET > 250 GeV
- 2 AK5 jets passing Resolved V-tag
- Mjj = [60,110] GeV
- B-jet veto (top)

Monojet

- Not Boosted-V or Resolved-V
- AK5 jet, |eta| < 2.0, pT > 150 GeV
- Dijet topological cuts

Categories are mutually exclusive

Topological cuts

- $\Delta\varphi$(j,MET) > 2
- $\Delta\varphi$(j,j) < 2
- ΔR(ak5,ak5|ca8) > 0.5

Boosted-V Selection

Based on studies presented at BOOST 2014

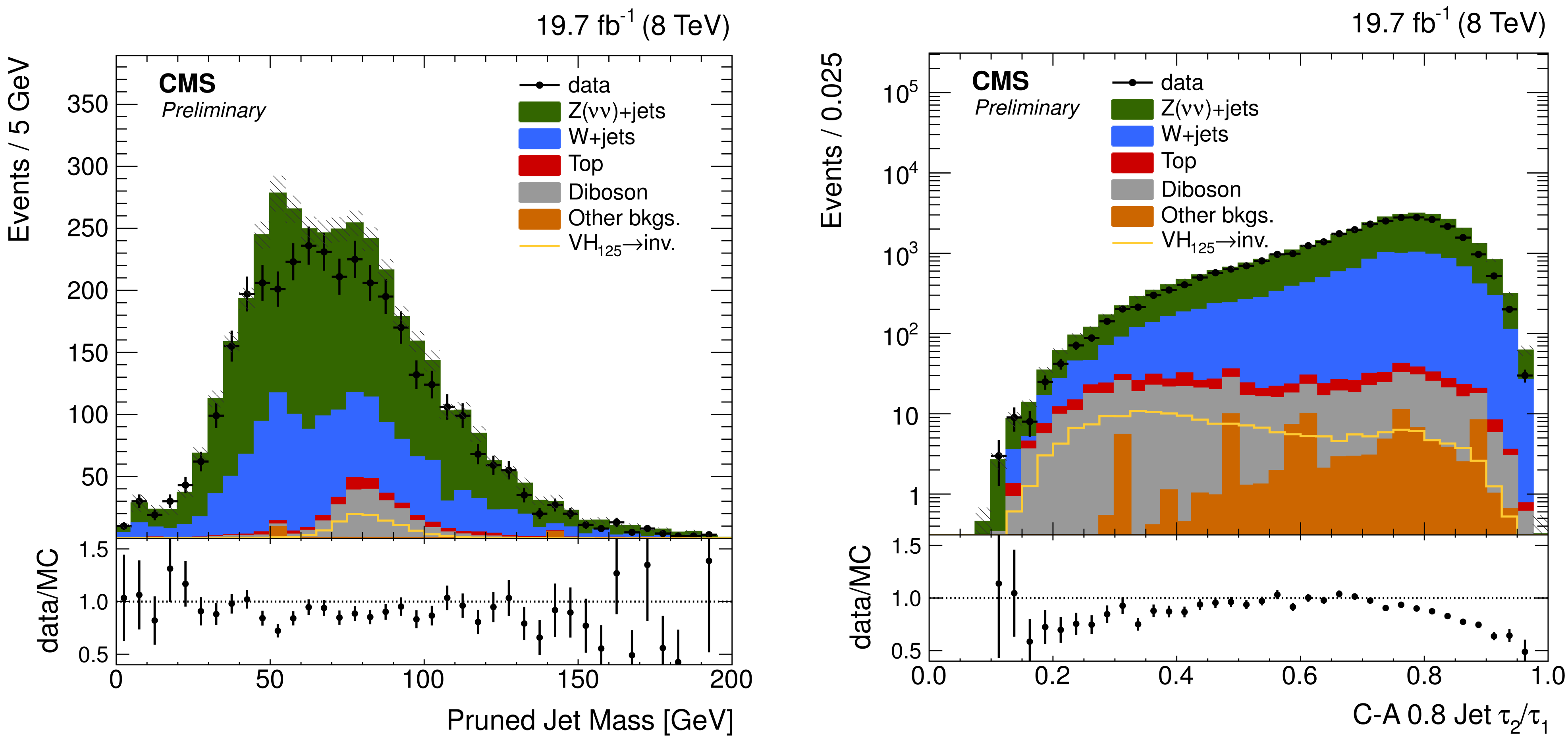
https://indico.cern.ch/event/302395/session/17/contribution/32/attachments/571654/787373/boost2014_10.pdf
https://cms-physics.web.cern.ch/cms-physics/public/JME-14-002-pas.pdf

Here, a *cut-based* selection for boosted V tagging

- N-subjettiness ratio (arXiv:1011.2268)
  - Measure of two-prongness
  - $\tau_2 / \tau_1 < 0.5$
- Pruned CA8 jet mass (arXiv:0903.5081)
  - momentum fraction > 0.1
  - distance < 0.5
  - M_{prune} = [60,110] GeV

Cut-based, 2 observables :
a distillation of the MVA
discriminant from JME-14-002

Boosted Selection (2)

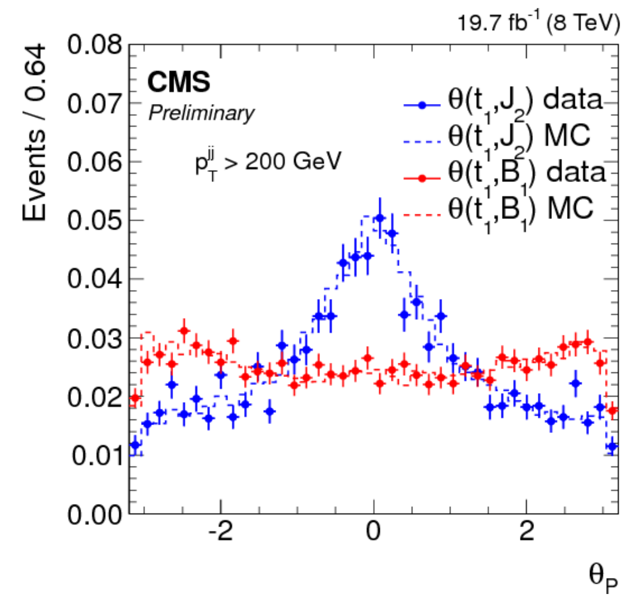


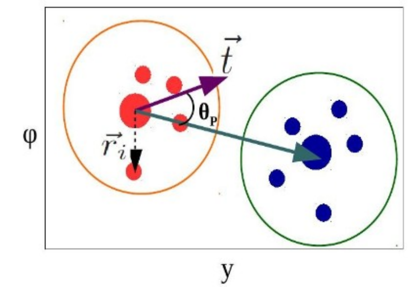
- m_{prune} distribution after cut on τ_2 / τ_1
- τ_2 / τ_1 distribution before cut on m_{prune}

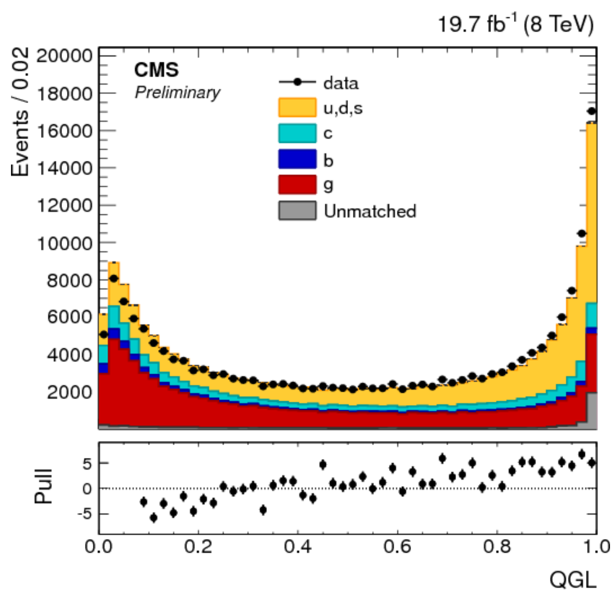
Based on studies presented at BOOST 2014

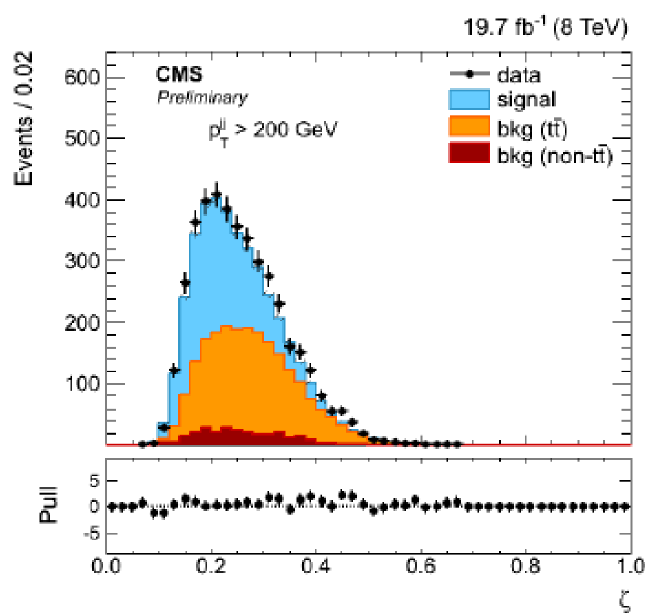
https://indico.cern.ch/event/302395/session/17/contribution/32/attachments/571654/787373/boost2014_10.pdf
https://cms-physics.web.cern.ch/cms-physics/public/JME-14-002-pas.pdf

- Modified mass drop (arXiv:1407.7037)
- Quark/Gluon likelihood
- Color flow / pull angle (arXiv:1001.5027)
- pT(jj)/M(jj)



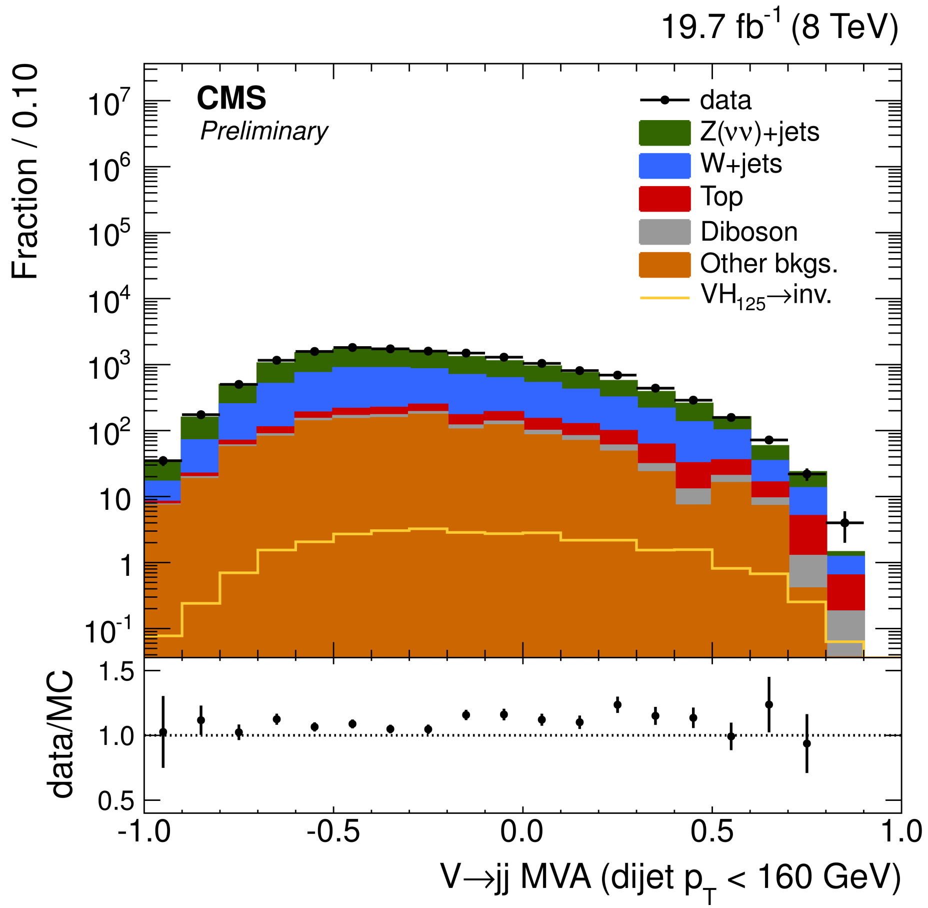


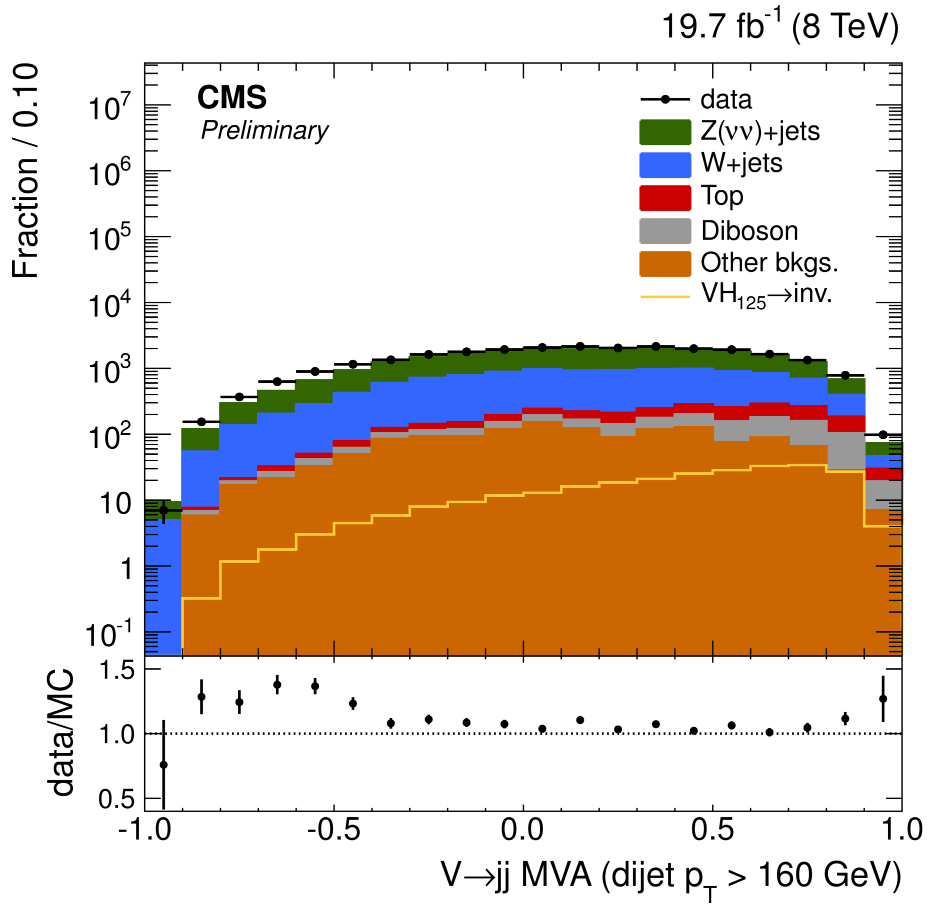




Observables combined in an MVA (BDT) discriminant

- Trained for high (>160 GeV) and low (<160 GeV) V-pT
- Require MVA > 0.6



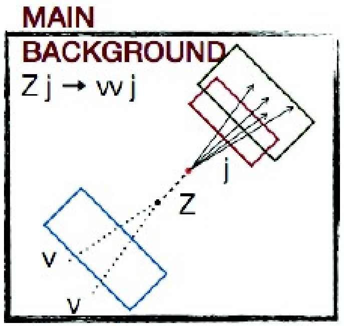


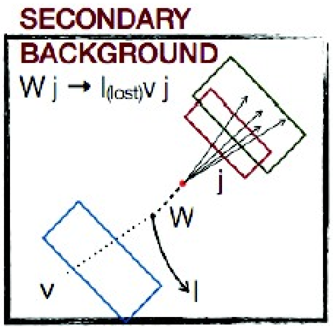
More on V-tagging

Red meat for BOOST
in the Back Up

SM backgrounds:

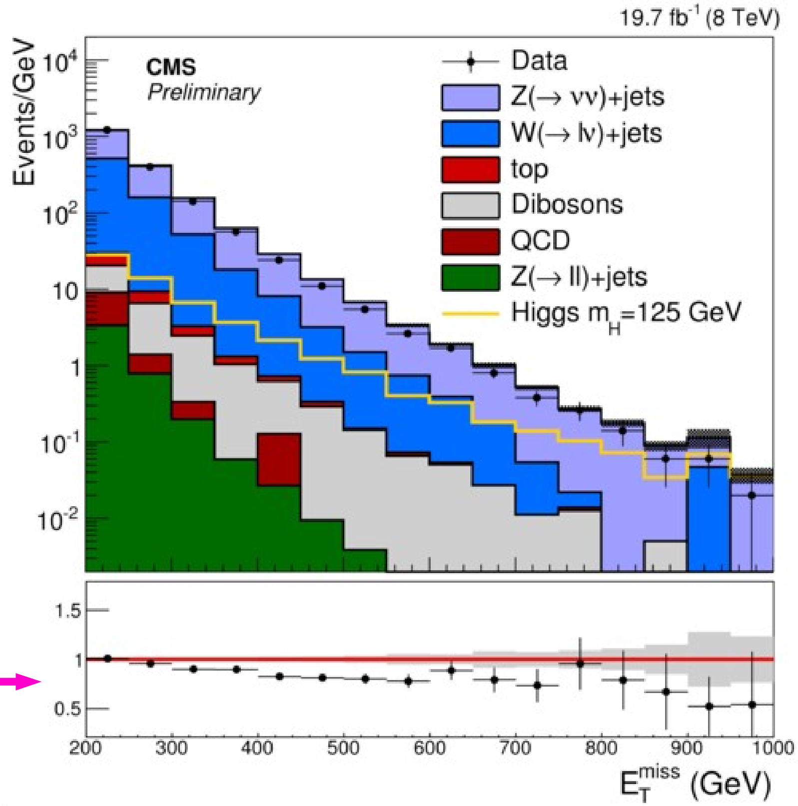
- Z(ν,ν) + jets
- W(l,ν) + jets





Challenging to accurately model MET from these sources

- Detector effects (eg: energy scale, calibration, etc)
- Theoretical predictions (eg: missing higher-order corrections, etc)



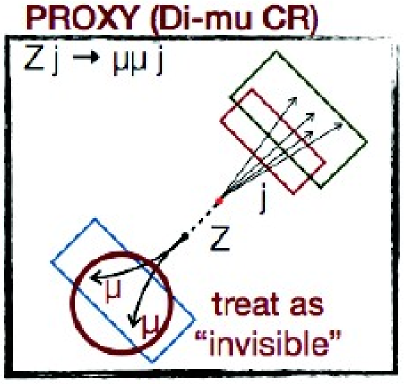
"Out-of-the-box" data/MC MET comparison

Must <u>correct</u> our predicted SM MET distributions!

MET Corrections : Recoil

Use events in control regions (C.R.) with no real MET

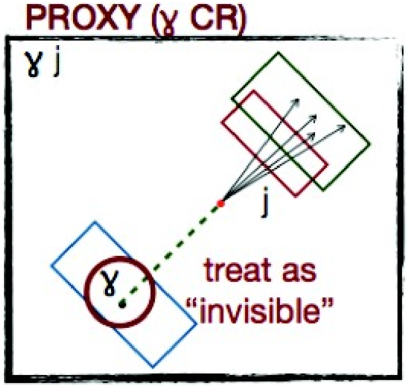
- Low pT: Z(μ,μ)+j
- high pT: γ+j (much higher stats!)



Recoil vector: $\vec{\mu} = -\overrightarrow{MET} - \Sigma\, \overrightarrow{pT}(l,l)$ or $\overrightarrow{pT}(\gamma)$

Correct MC recoil to data

- Scale recoil response
- smear recoil resolution



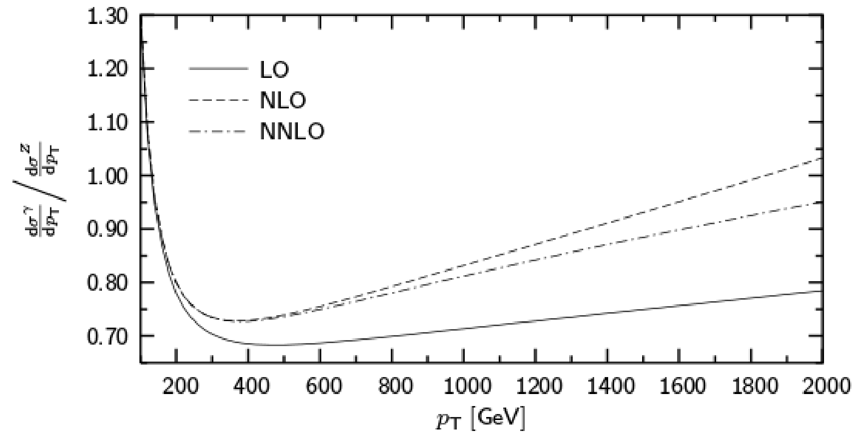
Photon footprint corrections included

More on recoil in first CMS MET paper:
http://arxiv.org/abs/1012.2466

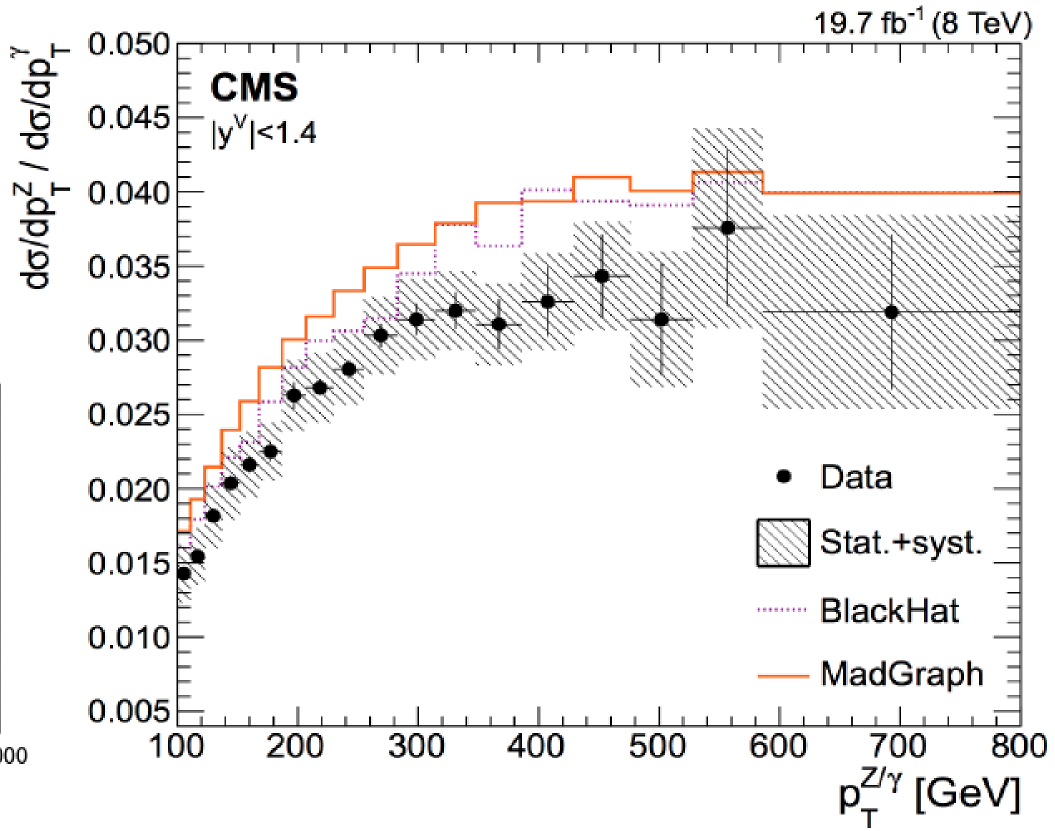
γ + jet C.R.

Higher stats from γ+j , but ...

- Z+j vs γ+j kinematics inconsistent?
- This plot missing NLO EWK corrections!



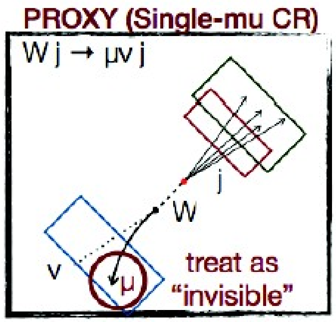
hep-ph/0508253



Good agreement after corrections, γ+j C.R. viable!

Control Regions

Use recoil-corrected Z(μ,μ) / γ+j & W(l,μ) C.R.s to model background MET in S.R.



- Can not use C.R distributions wholesale ...
  - Expect differences due to acceptance, efficiency, kinematics ...

Relate C.R. yields to predicted BG yields in the S.R. (μ_i)

$$N_i^{Z_{\mu\mu}|\gamma} = \frac{\mu_i^{Z\to\nu\nu}}{R_i^{Z|\gamma}},$$

$$N_i^{W} = \frac{\mu_i^{W\to l\nu}}{R_i^{W}},$$

- R: transfer factor accounting efficiency & BR
- R_i: for different MET bins in different categories
- Include NLO k-factor as a function of pT(V)

Control Regions (2)

Simultaneous fit of C.R.s to produce expected MET shape (μ_i) in S.R

$$\mathcal{L}_c(\mu^{c,Z\to\nu\nu},\mu^{c,W\to l\nu},\theta,\phi)=\prod_i \text{Poisson}\left(d_i^{c,\gamma}|B_i^{c,\gamma}(\phi)+\frac{\mu_i^{c,Z\to\nu\nu}}{R_i^{c,\gamma}(\theta)}\right)$$
$$\times\prod_i \text{Poisson}\left(d_i^{c,Z}|B_i^{c,Z}(\phi)+\frac{\mu_i^{c,Z\to\nu\nu}}{R_i^{c,Z}(\theta)}\right)$$
$$\times\prod_i \text{Poisson}\left(d_i^{c,W}|B_i^{c,W}(\phi)+\frac{\mu_i^{c,W\to l\nu}}{R_i^{c,W}(\theta)}\right)$$

Include uncertainties as nuisances (φ,θ)

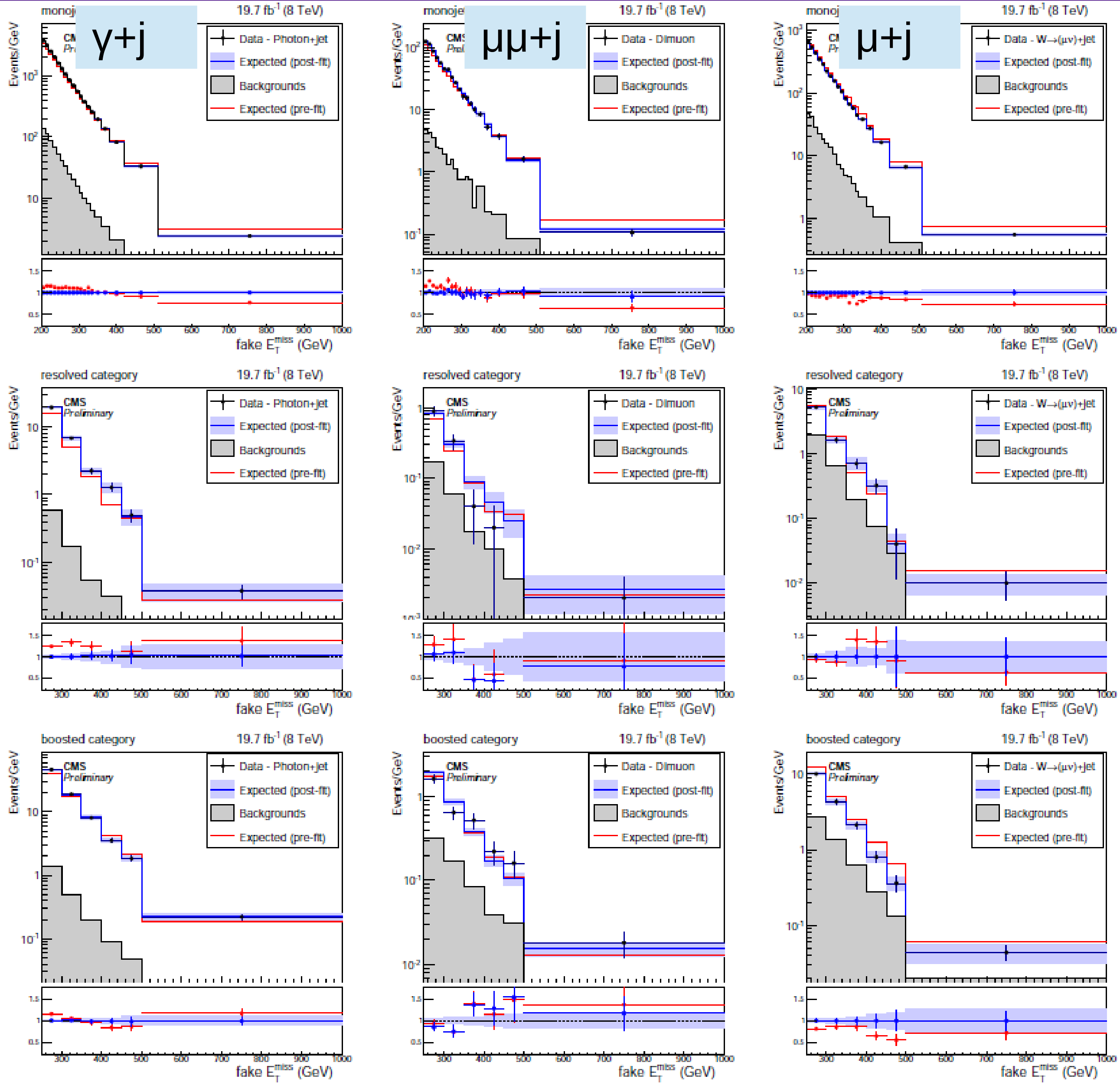
- Experimental: efficiency, recoil, JES ...
- Theory: renormalization/factorization, PDF, EWK ...

Use μ_i to re-weight V+j predictions for the S.R.

Post-fit Control Regions

Excellent post-fit agreement in all C.R.s !

Boosted / resolved / monojet

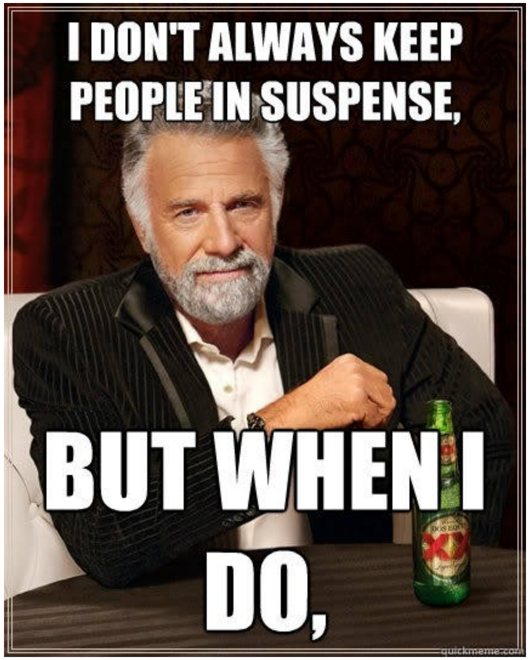


Signal Extraction

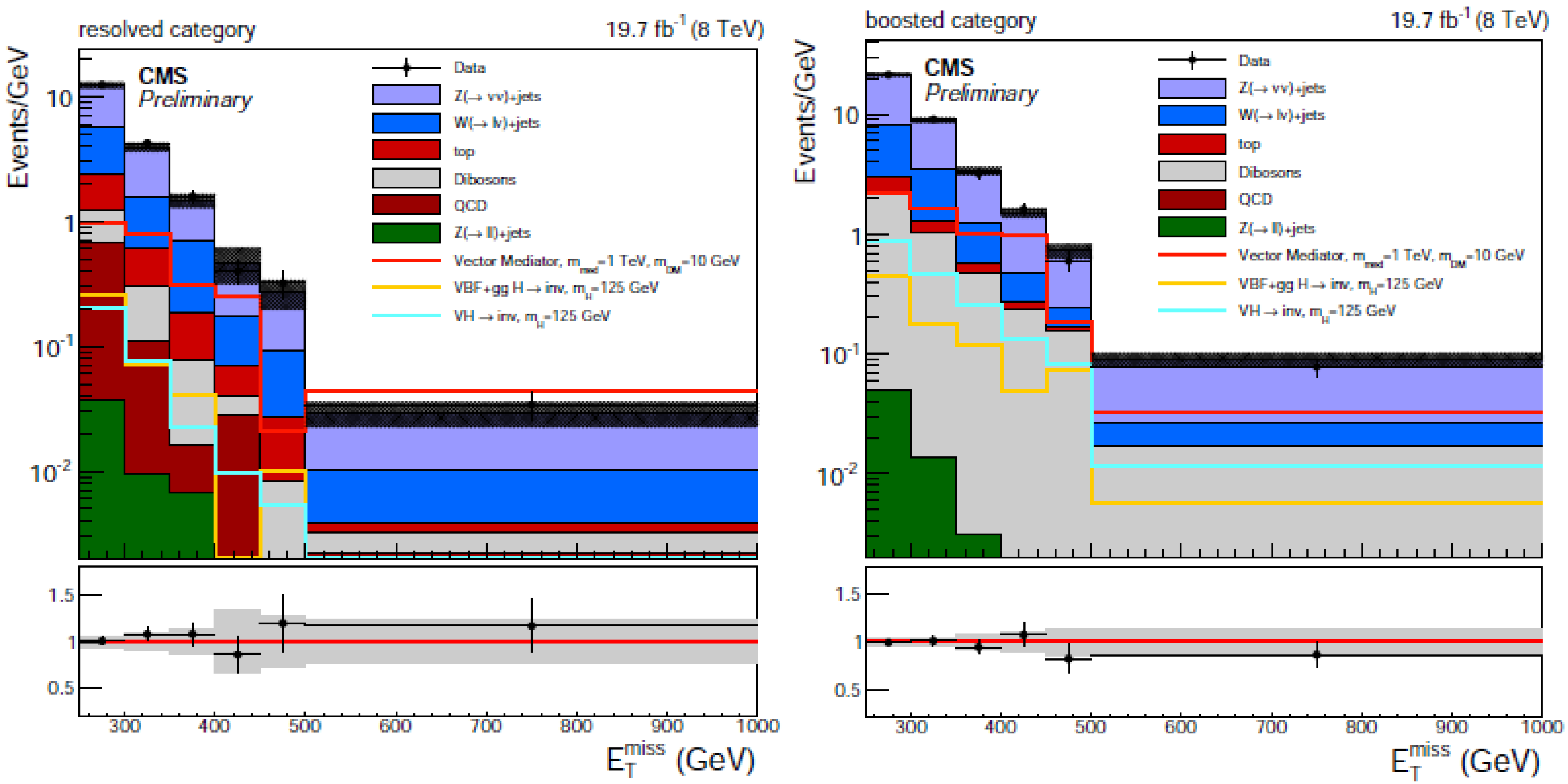
Simultaneous likelihood fit in S.R.'s, across all MET bins in all categories

- Using re-weighted V+j MET shapes from C.R. fit

Signal would appear as an excess in the MET distributions ...



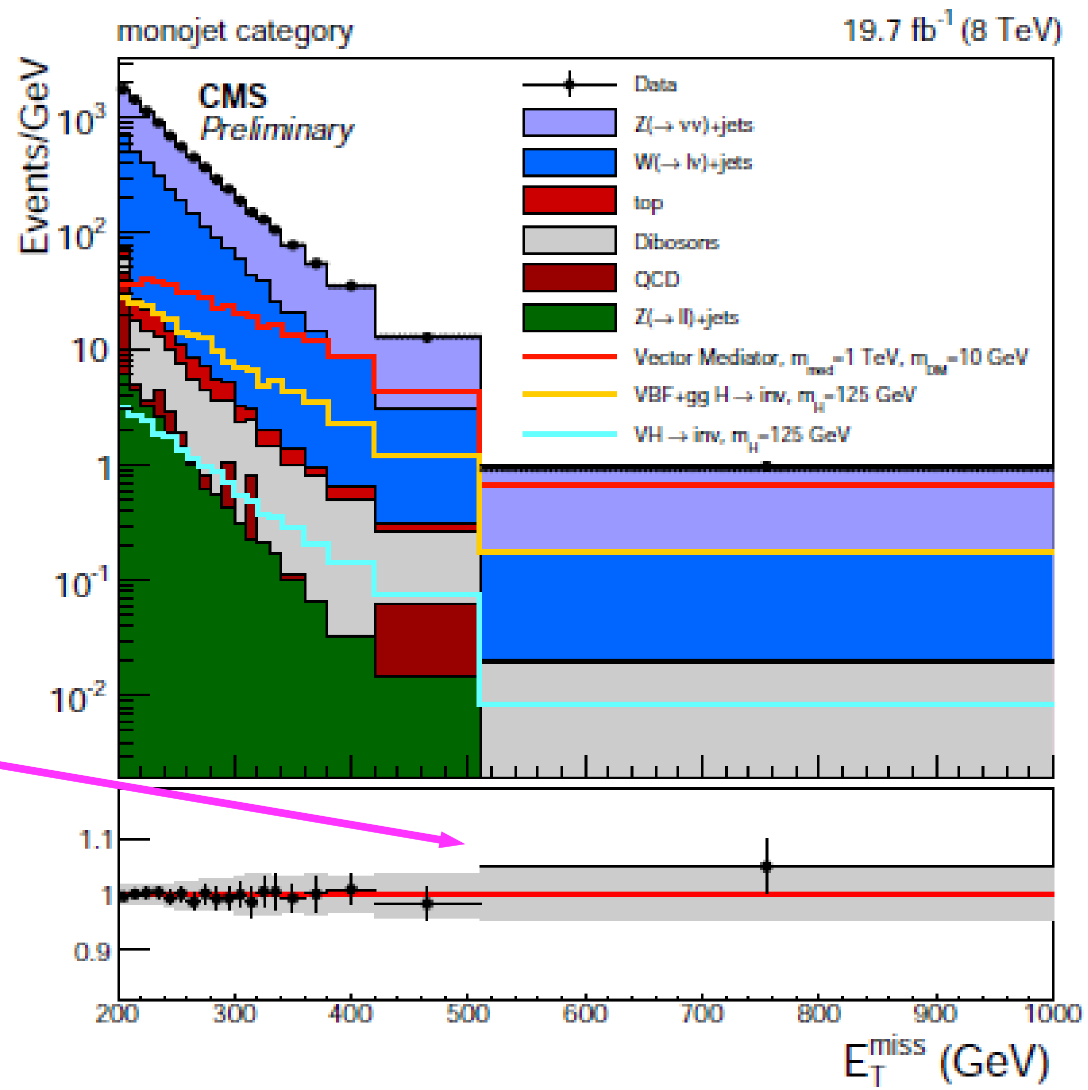
Results: mono-V



- Data consistent with SM backgrounds
- Comparison with reference Z' [1TeV], VBF+gg, VH signals

Results: monojet

- Data consistent with SM backgrounds
- Comparison with reference Z' [1TeV], VBF+gg, VH signals
- Largest excess: 1.9σ local significance



Interpretation

Vector

$$g_{\mathrm{DM}} Z'_{\mu} \bar{\chi} \gamma^{\mu} \chi$$

EWK style coupling
(equal to all leptons)

Axial

$$g_{\mathrm{DM}} Z''_{\mu} \bar{\chi} \gamma^{\mu} \gamma^{5} \chi$$

EWK style coupling
(equal to all leptons)

Scalar

$$g_{\mathrm{DM}} S \, \bar{\chi} \chi$$

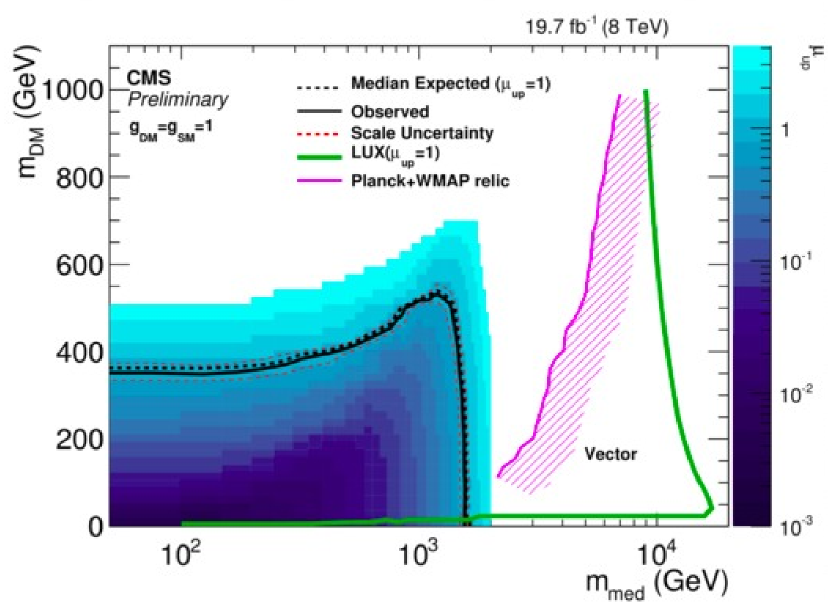
Yukawa style coupling
(Mass based coupling)

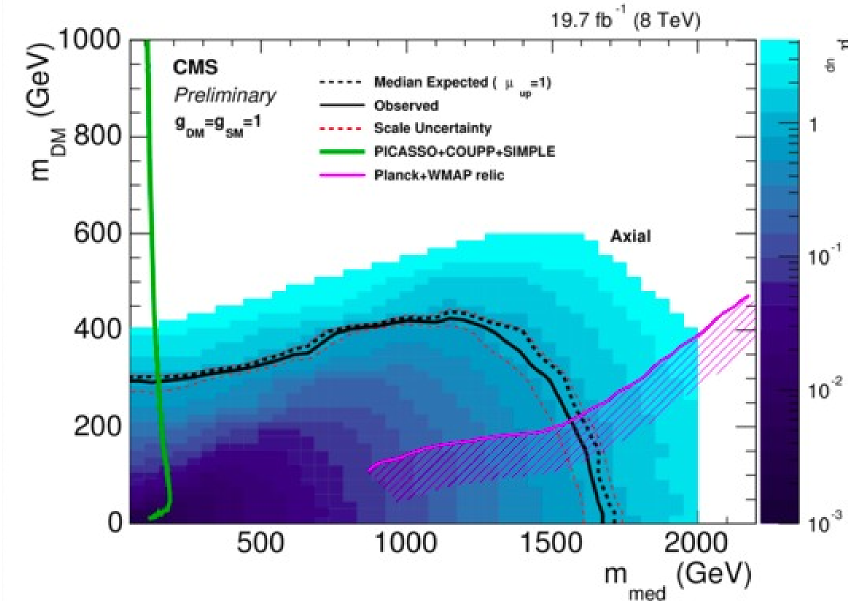
Pseudoscalar

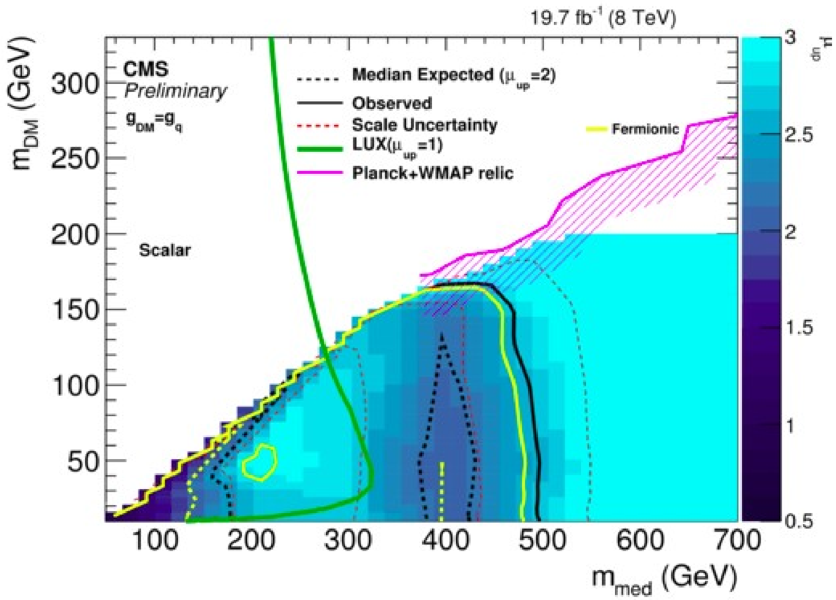
$$g_{\mathrm{DM}} P \, \bar{\chi} \gamma^{5} \chi$$

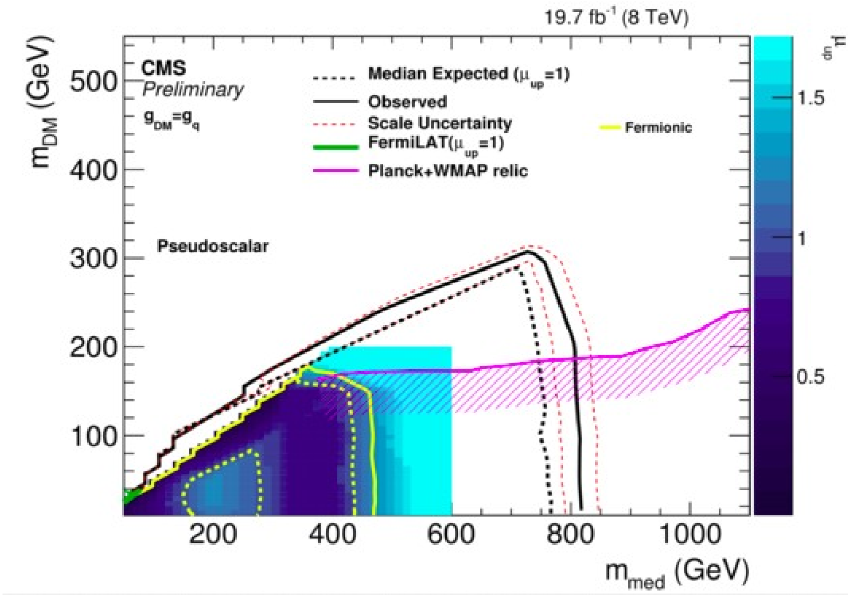
Yukawa style coupling
(Mass based coupling)

M(DM) vs M(mediator)

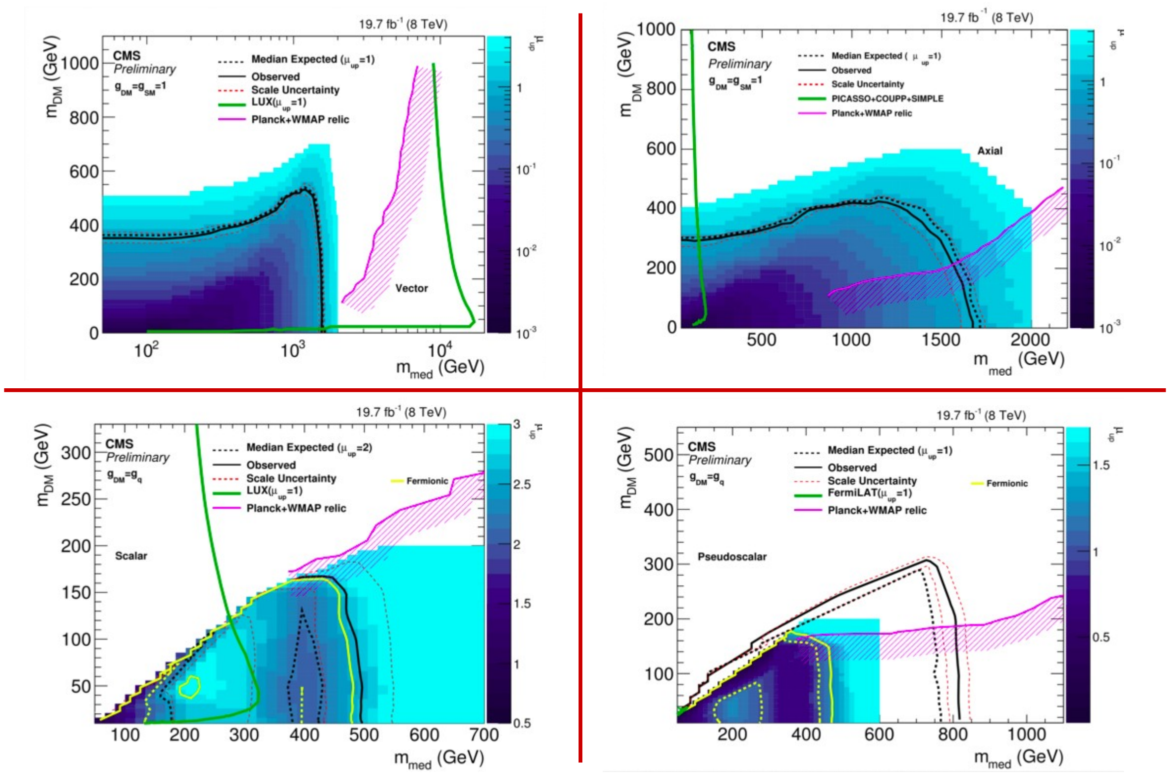








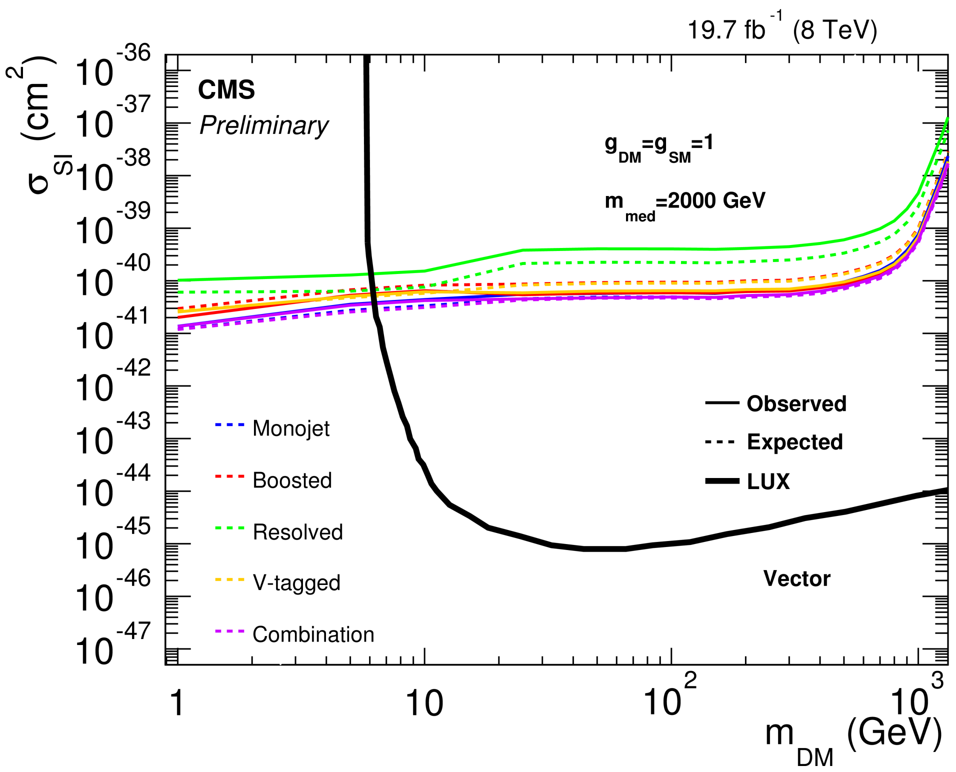
M(DM) vs M(mediator)

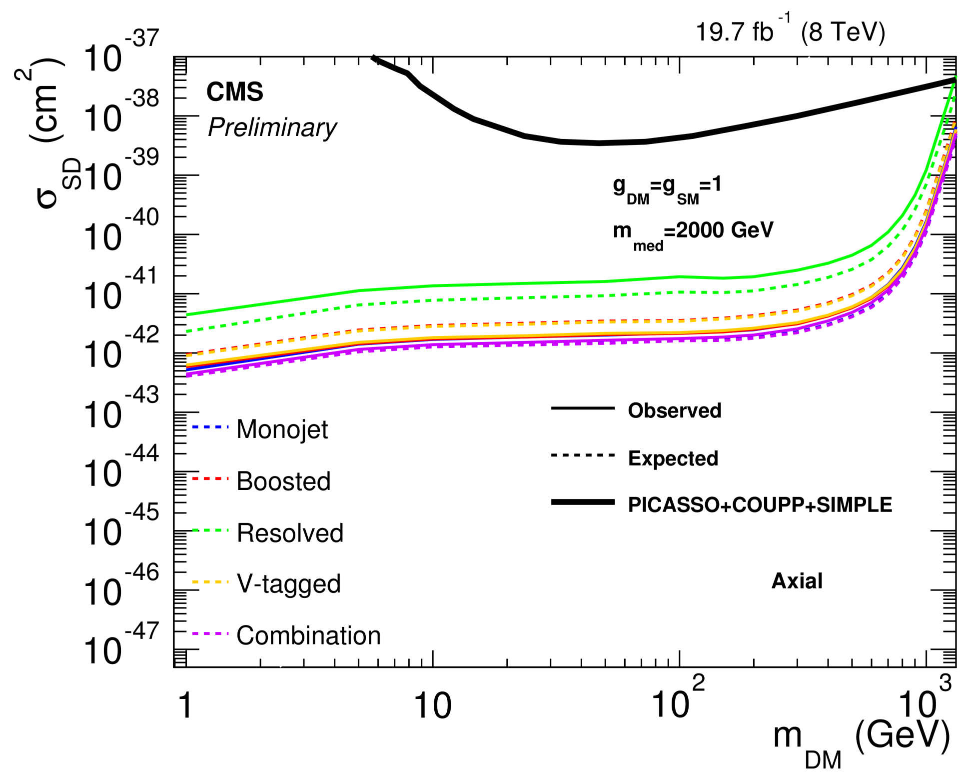


(same plots as previous slide)

- Vector: CMS contributes at low m_{DM}
- Scalar: LHC / DD complementarity!
- Axial & Pseudo: Strongest constraints from CMS!

[σ,M(DM)] Constraints

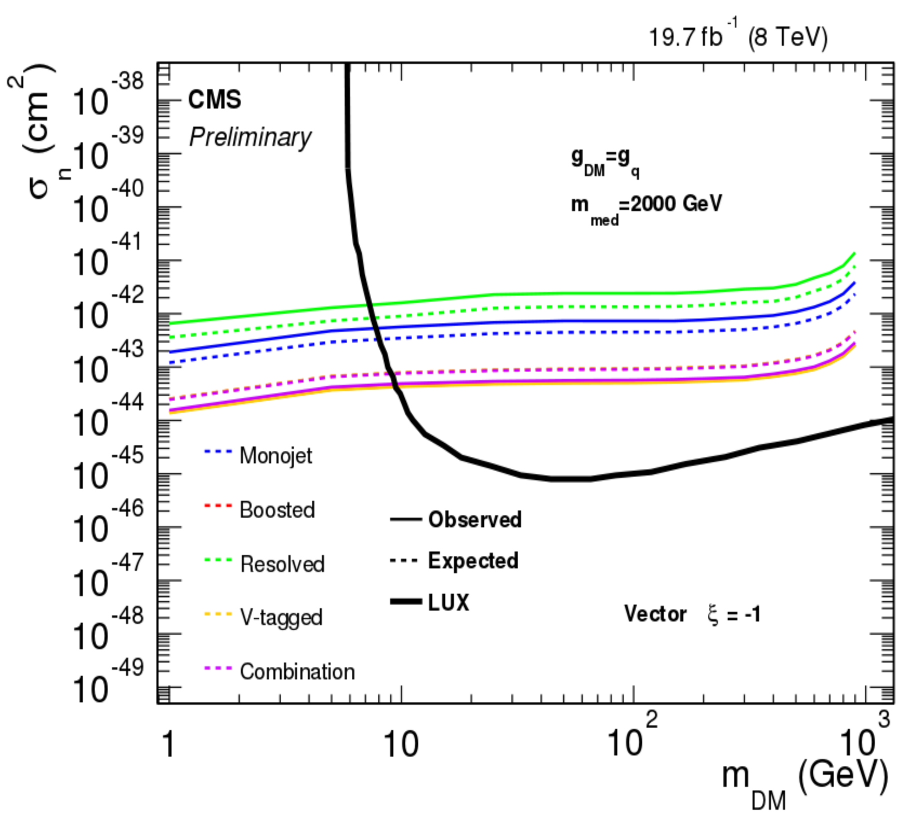


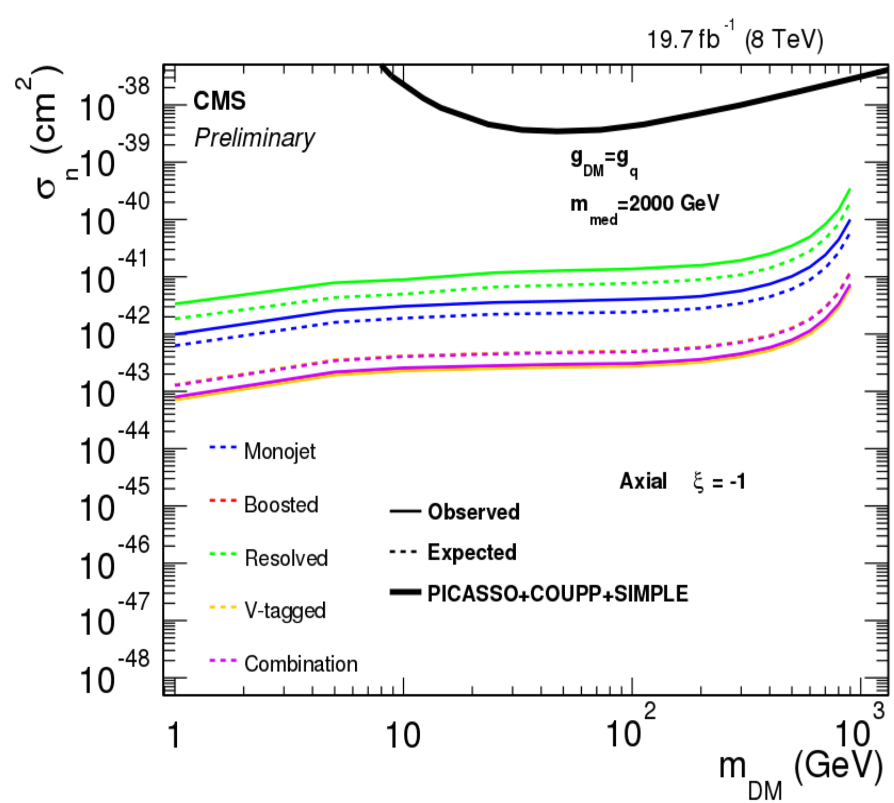


M_{Φ} = 2 TeV: Vector (left), Axial (right)

- CMS contributes significantly at low m_{DM} !
- Impact of resolved smallest due to high MET cut ...

[σ,M(DM)] Constraints

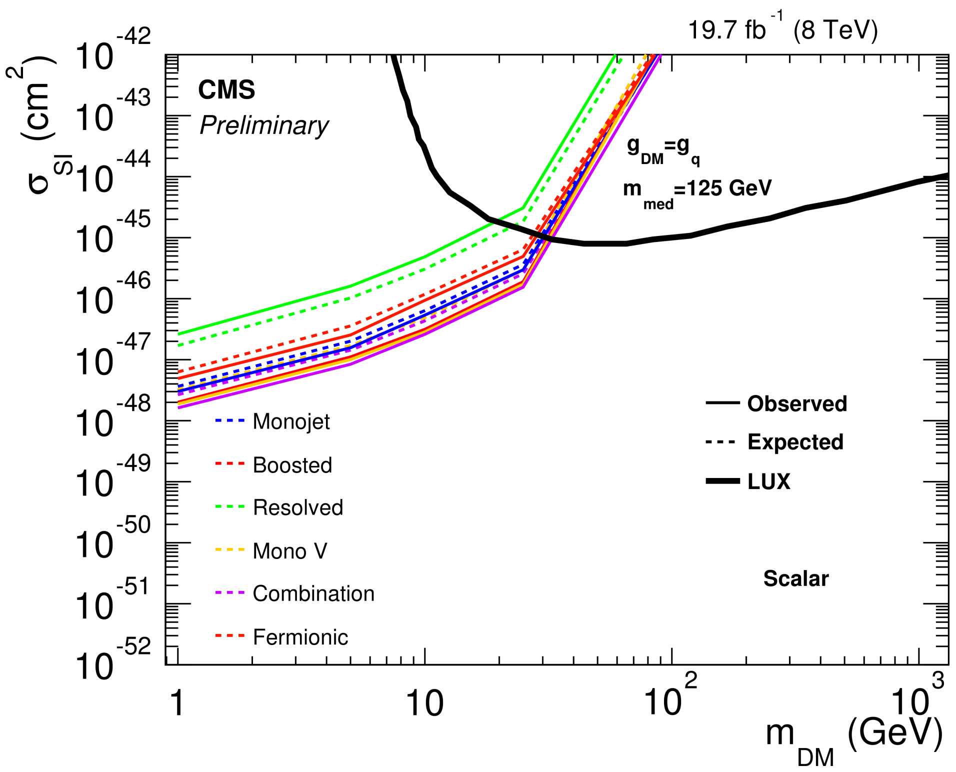


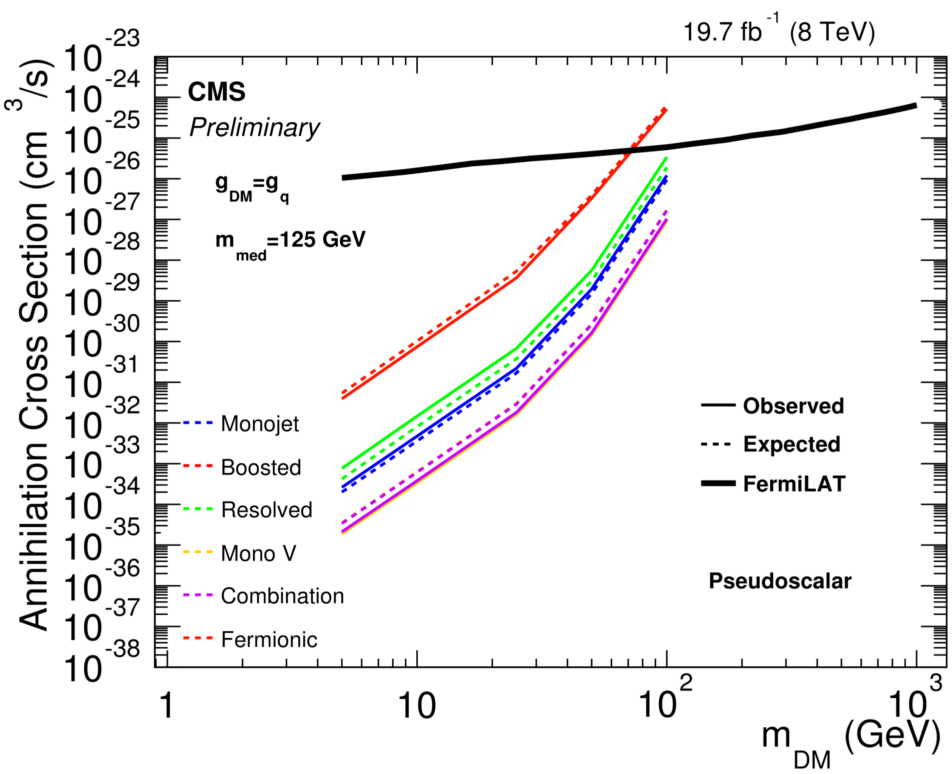


M_{Φ} = 2 TeV, ξ = -1 (constructive): Vector (left), Axial (right)

- CMS complementary to DD – particularly at low m_{DM} !
- Boosted category out-performs monojet

[σ,M(DM)] Constraints

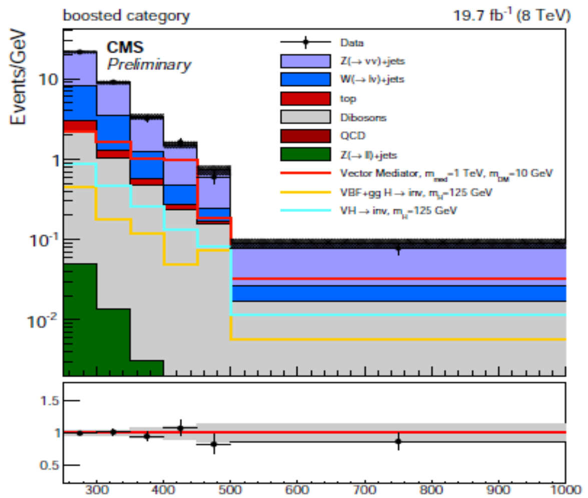




M_Φ = 125 TeV: Scalar (left), Pseudo (right)

- CMS complementary to DD – particularly at low m_{DM} !
- Boosted drives the pseudoscalar limit!

Mono-jet / V Summary

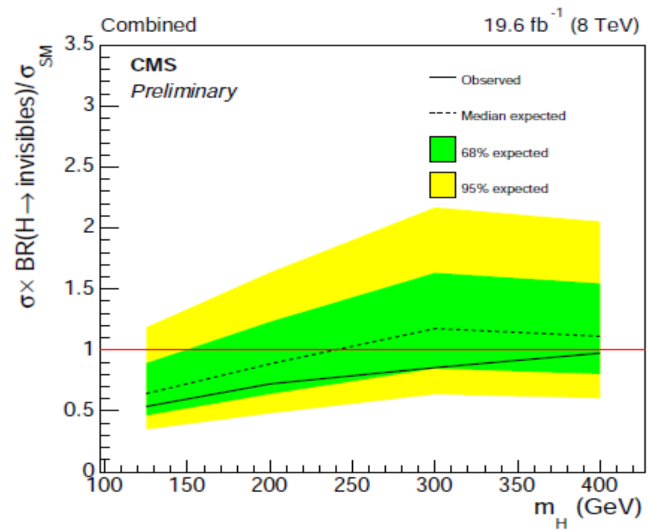


New CMS DM Results

- Combines monojet & mono-V
- 1st boosted search for DM in CMS!
- Novel resolved V tagging!

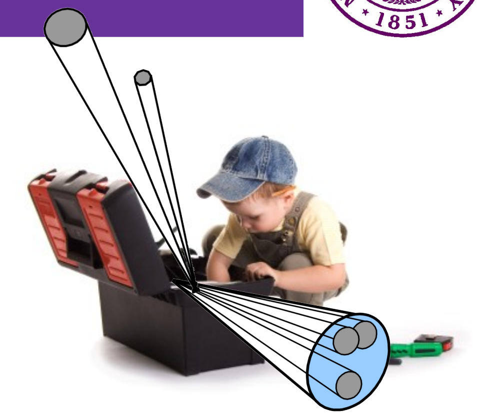
No significant excess observed

- 1.9σ excess in the most sensitive bin
- CMS limits *complementary* to DD!
- Limit on σxBR(H→inv)/ σ_{SM-H} < 0.53



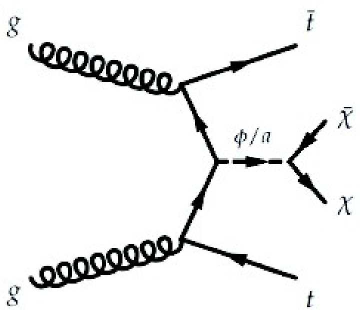
► *Run-1 monojet / mono-V is just a start ...* ◄

Outlook

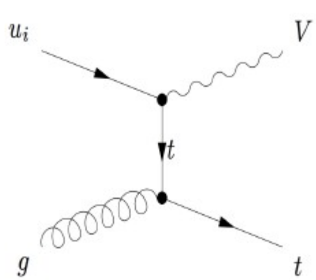


Reach *further* into the boosted / substructure toolbox for DM in Run-2!

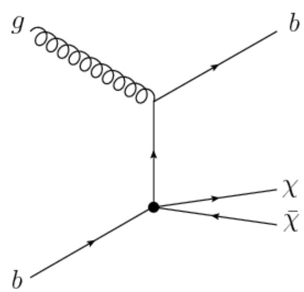
– In addition to mono-V ... heavy flavor + DM!



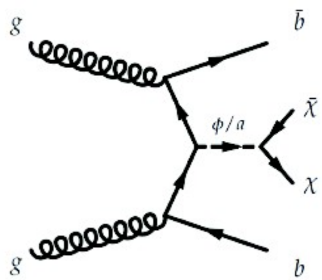
tt+DM



monotop



mono-b



bb+DM

Latest CMS heavy flavor results (non-boosted):

0.1007/JHEP06(2015)121

PhysRevLett.114.101801

– On-going studies of top tagging, subjet b-tagging, V-tagging, *etc.*

Work with the community to develop new algorithms & techniques for more sensitive DM searches!

Thanks!

Back Up

Signal Generators

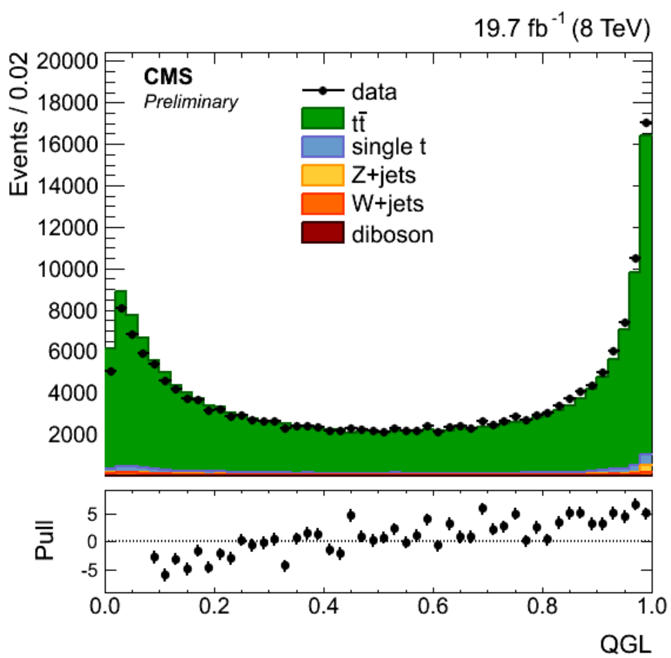
- Monojet:
  - V & A & S & P : MCFM
- Mono-V:
  - V & A : MadGraph
  - S & P : JHUGen
- Relic:
  - MadDM

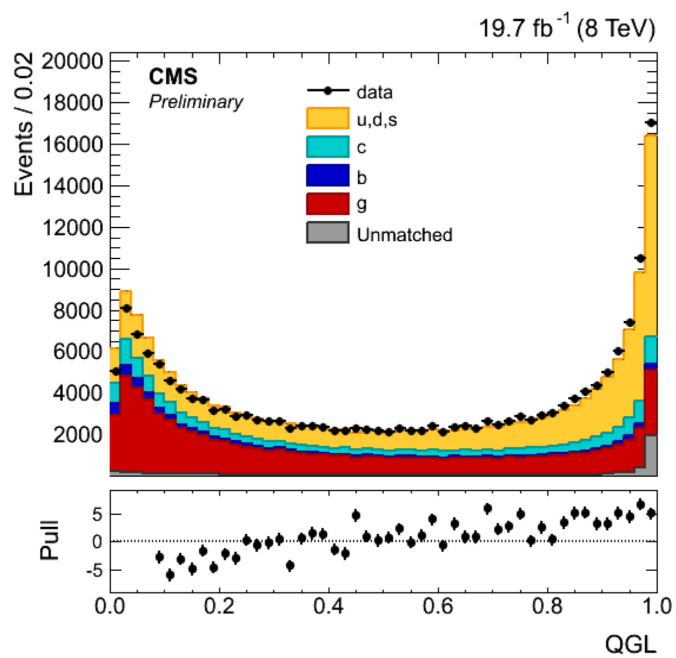
Resolved V-tagger

Quark/Gluon Likelihood

From JME-14-002

- Likelihood based discriminator
  - Input: Constituent multiplicity, $p_T D$, jet minor axis
- Gluons have higher multiplicity, softer fragmentation, broader jet width compared to light quarks
- MC corrections applied for $|\eta| < 2.5$
  - https://twiki.cern.ch/twiki/bin/viewauth/CMS/GluonTag#Recommended_Systematic_Smearings





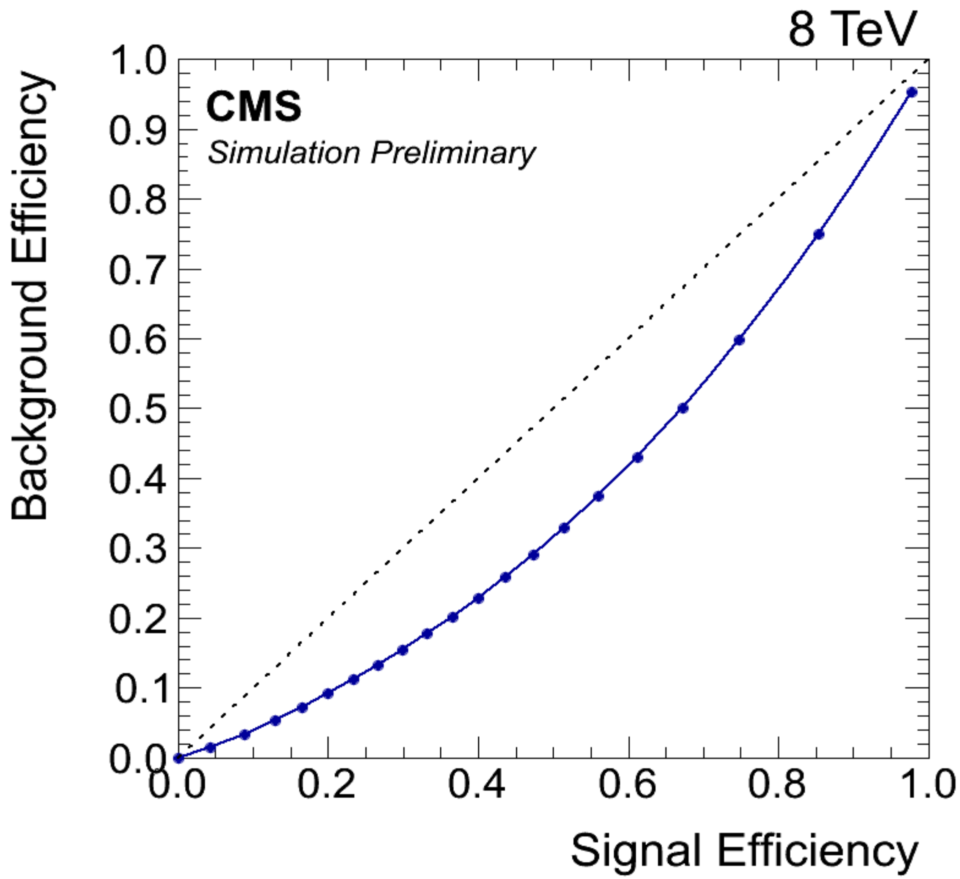
Gluon-initiated jets form large part of combinatorial background

QGL can help!

QGL: Performance

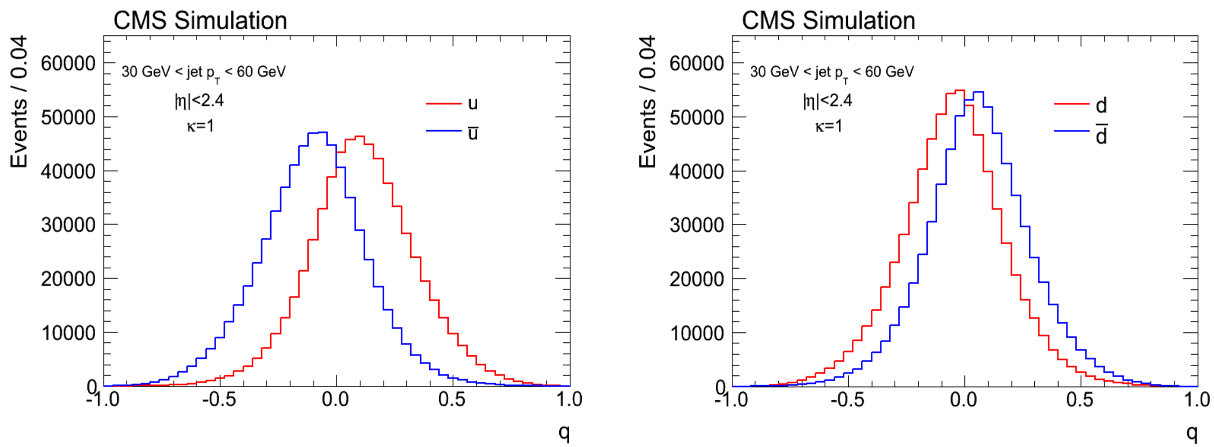
From JME-14-002

- Scan cuts applied on both jets
- Sig: Dijets matched to W→qq'
- Bkg: Dijets not matched to W→qq'
- Compute ROC curve for W-tagging performance in $t\bar{t}$ MC
- ε_{bkg} = 32% for ε_{sig} = 50%

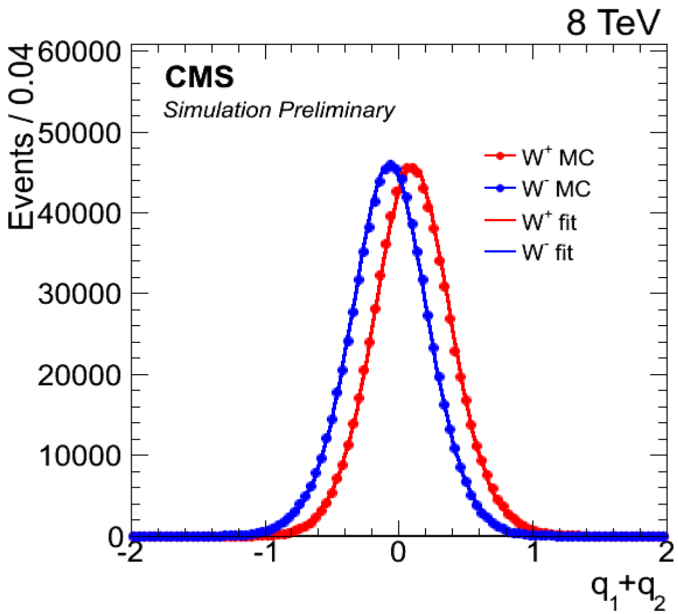


From JME-14-002

$$q = \sum_i q_i \cdot \left(\frac{(p_{\mathrm{T}})_i}{(p_{\mathrm{T}})_{\mathrm{jet}}} \right)^{\kappa}$$



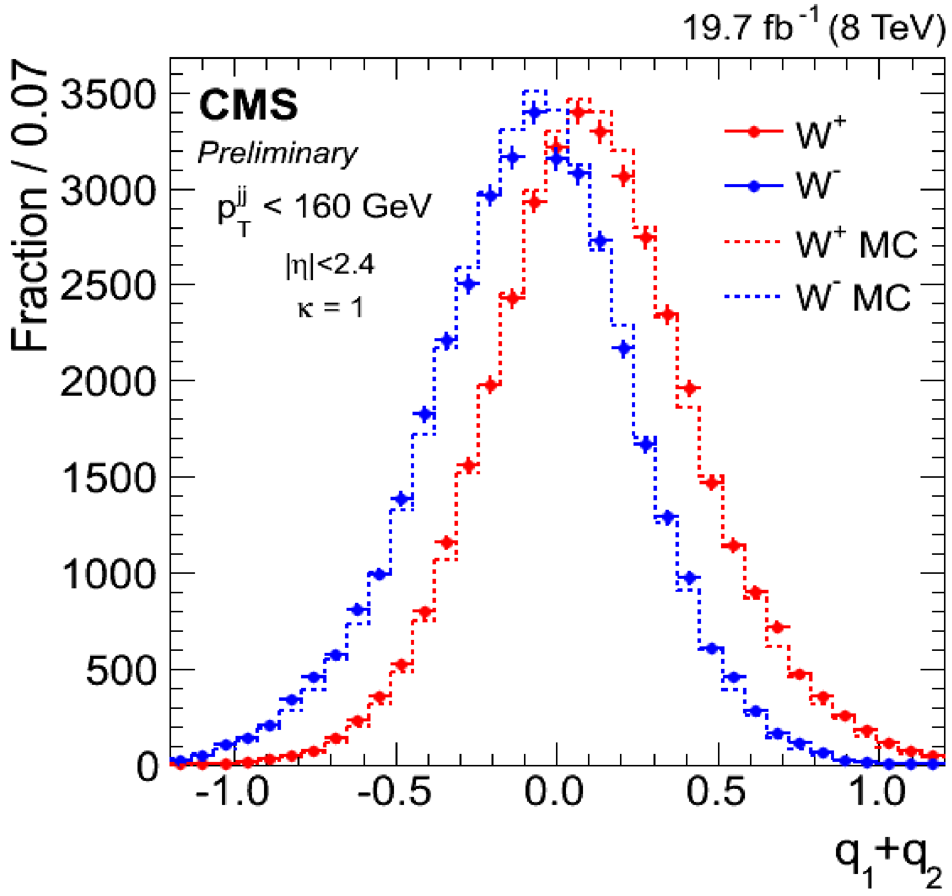
- Well defined only in tracker volume, i.e. jets with |η| < 2.4
- 0 < κ ≤ 1 ; lower κ gives softer constituents higher relative weight
  - κ = 1 found to be best working point for CMS
- For W tagging, quantity of interest is *sum of jet charges in dijet pair*
- Can achieve ***1.8σ separation*** of W^+ vs. W^- with 10 events
  - Shape is well-modeled by double Gaussian



Charge Sum: Data vs. MC

From JME-14-002

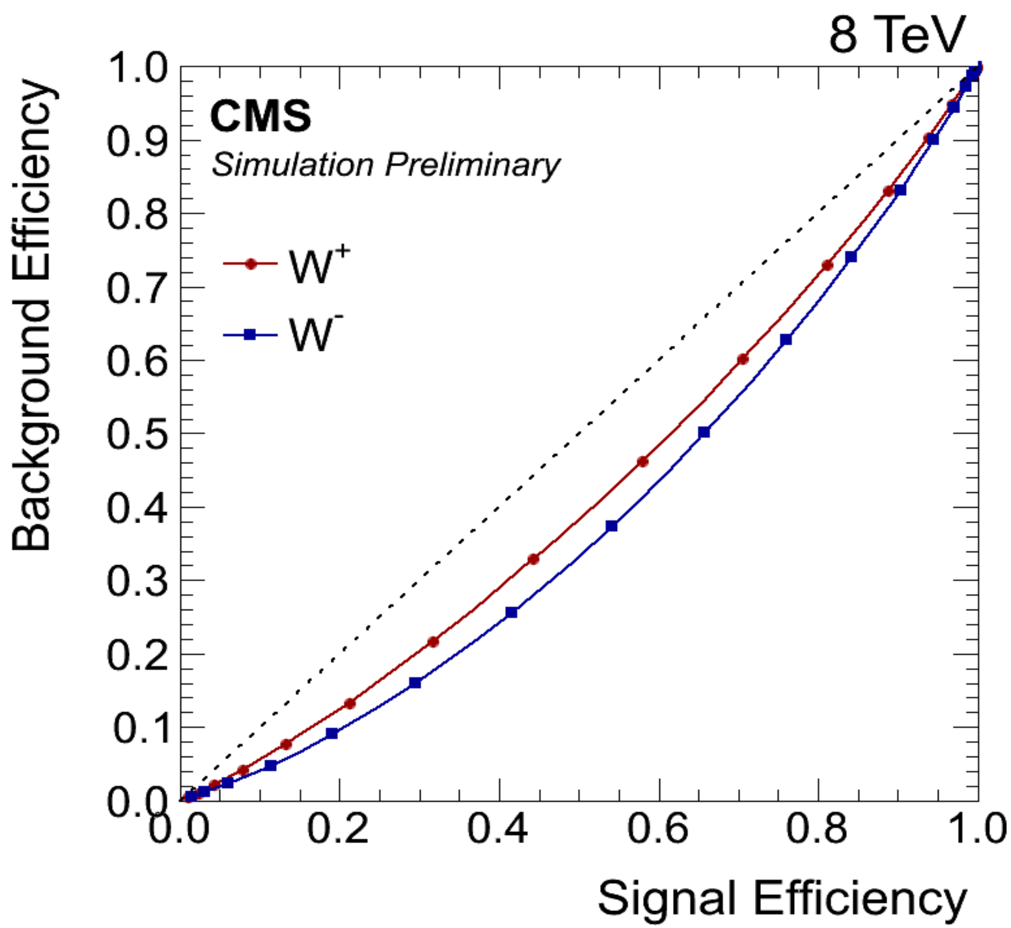
- Good agreement between data and MC
- Observe more "background under signal" for W^+ than for W^-
  - Due to charge asymmetry of background in proton-proton environment



Charge Sum: Performance

From JME-14-002

- Scan on charge sum of dijet
  - Charge of selected muon determines expected W charge
- Compute ROC curve for W-tagging performance in $t\bar{t}$ MC
  - Sig: dijets matched to W→qq'
  - Bkg: dijets not matched to W→qq'
- Performance is slightly worse for W^+ than for W^-
  - see previous slide
- ε_{bkg} = 38%/33% for ε_{sig} = 50%

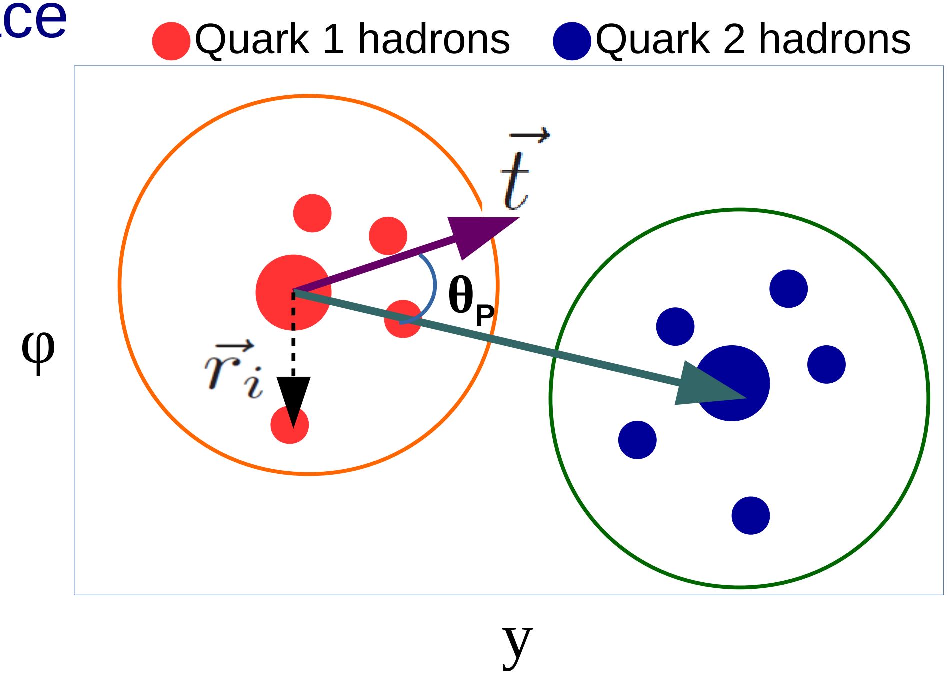


Jet Pull: Definition

- Compute weighted vector sum of constituent displacements relative to the jet axis in y-φ space

$$\vec{t} = \sum_i \frac{(p_T)_i \, |r_i|}{(p_T)_{\text{jet}}} \vec{r}_i$$

$$\vec{r}_i = (\Delta y_i, \Delta \phi_i)$$

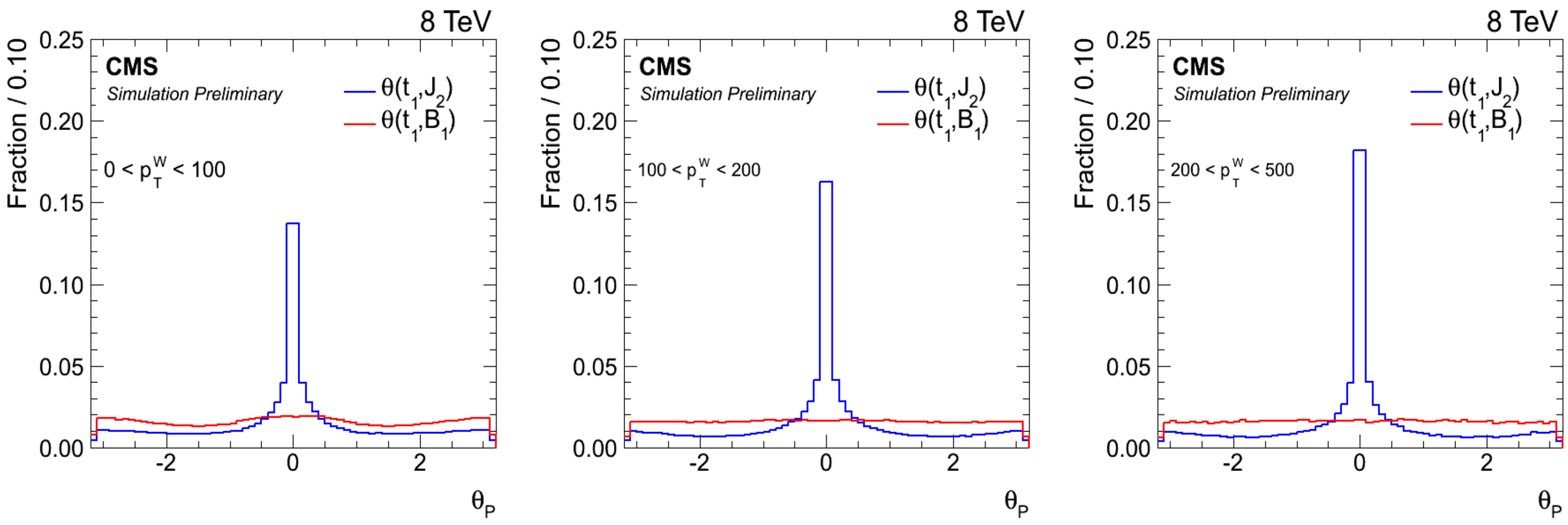


- For color connected jet pairs (e.g. W→qq'), constituents are pulled towards the partner's jet axis
- The angle between the pull vector and the relative displacement of another jet is the *pull angle*, θ_P
  - θ_P should peak around zero for color connected jet pairs and uniformly distributed for unconnected jet pairs

Pull Angle: Gen

- Compute pull vector using GEN particles
- Peak at θ_P~0 grows larger with higher W p_T
- Pull angle using a W-quark paired with a b-quark gives representative shape of background color unconnected pair

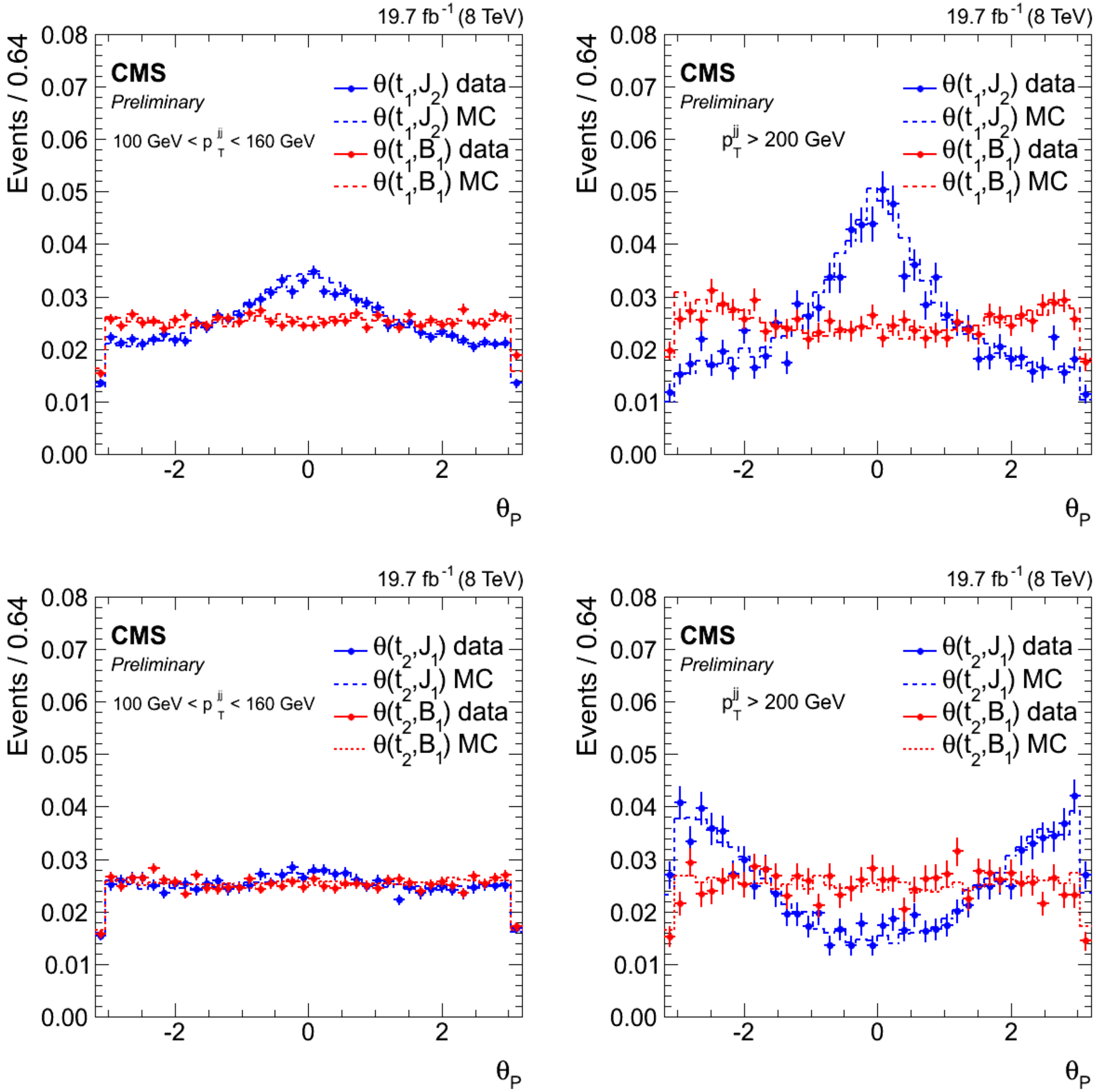
From JME-14-002



Pull Angle: Reco

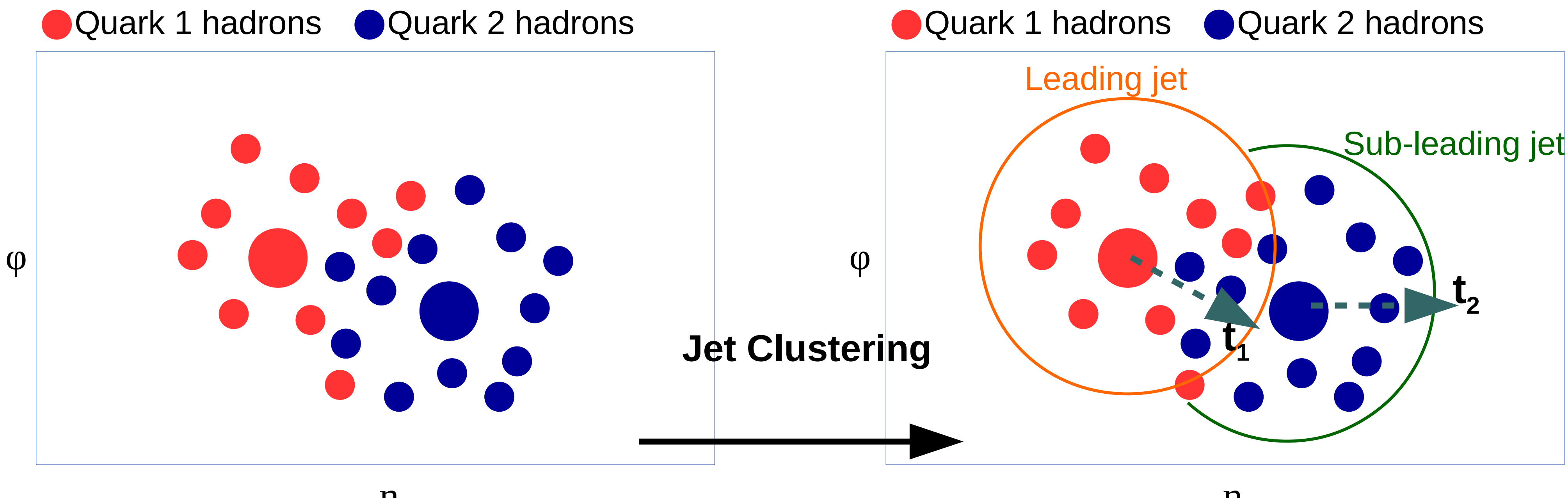
From JME-14-002

- Good data/MC agreement for θ_P computed using pull vector from leading and sub-leading jets
- Weak separation at low dijet p_T
- At high dijet p_T, θ_P shows opposing behavior between leading and sub-leading jets
  - Consequence of jets overlapping...



Pull Angle: Overlapping Jets

- The asymmetric behavior with reco jets is the effect of *partially merged jets* from the W and *jet clustering* of the reconstruction

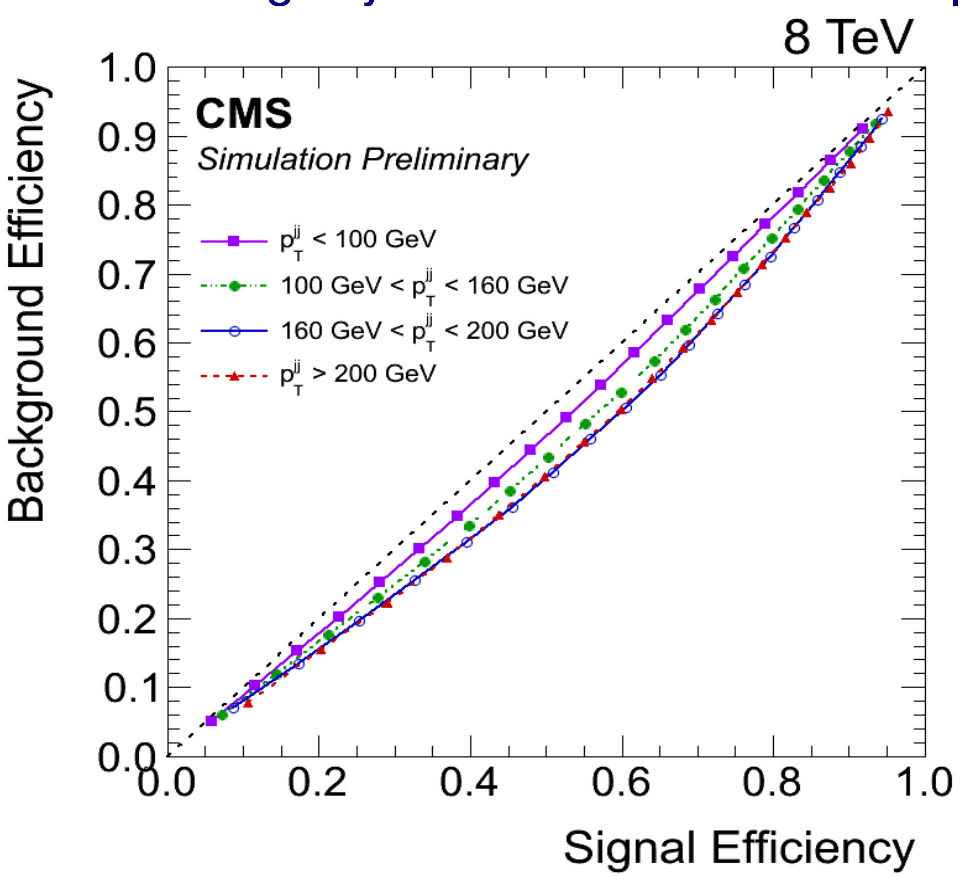


- Leading jet “gobbles up” some hadrons from the other quark
- Consequences:
  - Sub-leading jet pull points away from leading jet, having lost constituents that are “closer” to the leading jet
  - θ_P peak can be enhanced as leading jet absorbs hadrons of other jet

Pull Angle: Performance

- Scan on $|\theta_P|$ of dijet pair in different bins of dijet p_T
- Compute ROC curve for W-tagging performance in $t\bar{t}$ MC
  - Sig: dijets matched to W→qq'
  - Bkg: dijets not matched to W→qq'

From JME-14-002



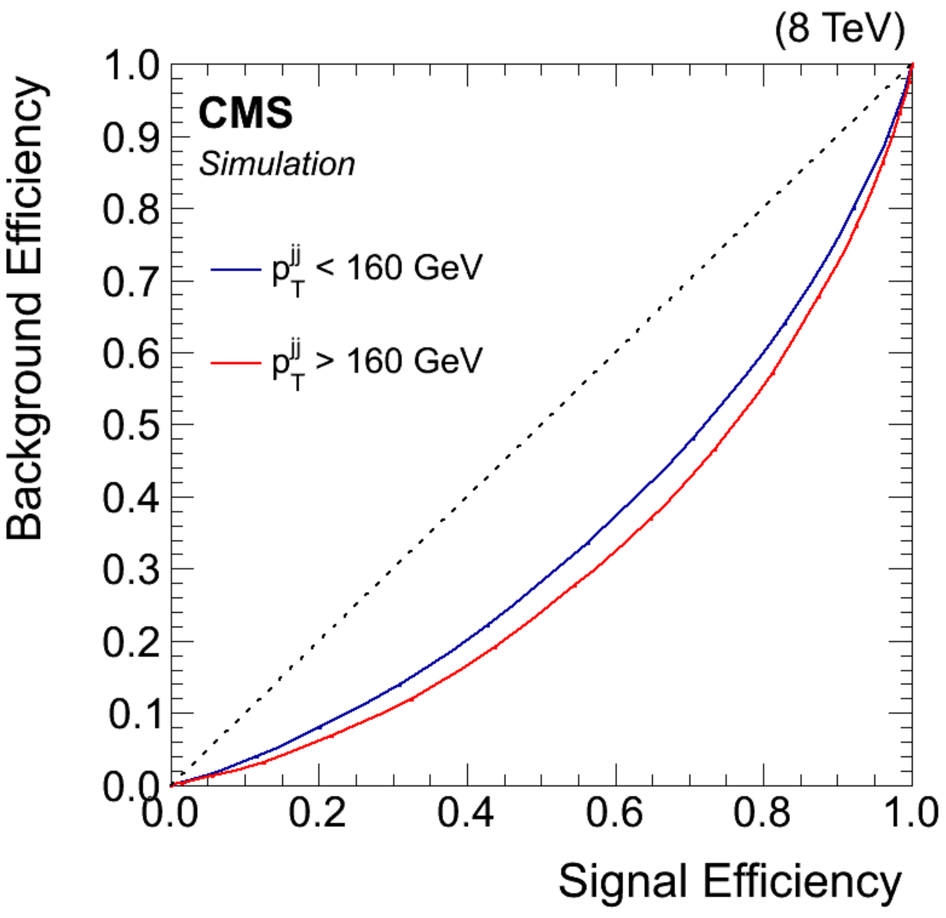
- At lowest dijet p_T, the S/B separation is weak
- At very high dijet p_T, there's significant effect from *overlap*

On its own, the pull angle is not a great discriminator, but provides added value in an MVA W-tagger

Resolved Jets Summary

- QGL, q_1+q_2, θ_P each provide some separation for W tagging
- Combine observables into BDT to make a discriminator
  - Input variables very weakly correlated
- Restrict to jets with $|\eta| < 2.4$
- Separate training for dijet p_T greater/less than 160 GeV
- $\epsilon_{bkg} = 25\%$ for $\epsilon_{sig} = 50\%$

From JME-14-002

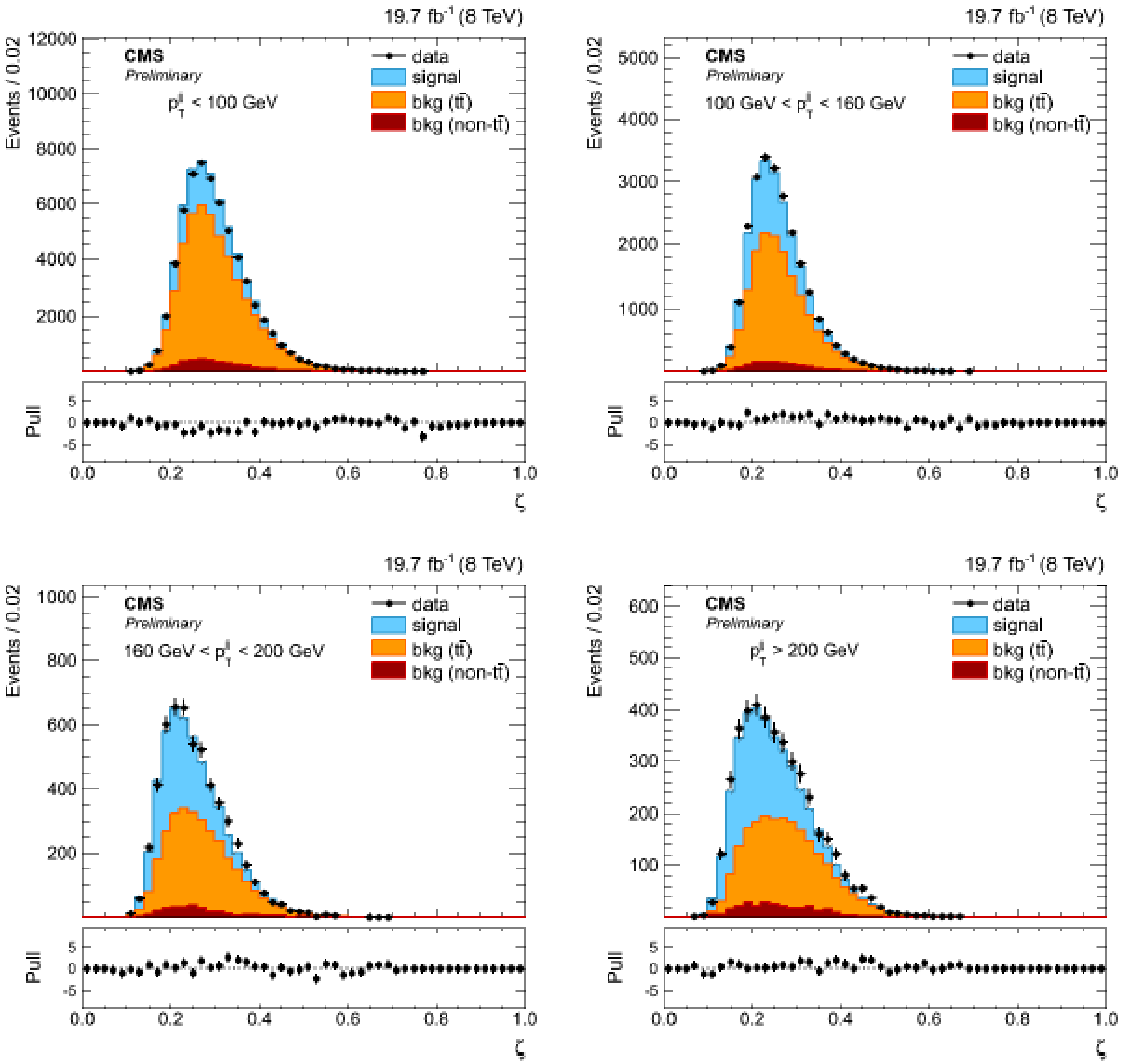


Modified Mass Drop: Intro

- "Mass drop" principle used in fat jets to separate boosted resonance from QCD background
  - Mass drop = $\max(m_{j1}, m_{j2})/m_J$
  - For signal jet, mass drop is small because subjets corresponds to high energy daughter quarks (i.e. low subjet masses)
  - For QCD jet, mass drop is large because mass is "acquired" from sequence of wide angle emissions (i.e. high subjet masses)
- For resolved dijets, average mass drop is ~constant for signal, is ~$1/\Delta R_{12}$ for background, over dijet p_T range
  - Mass drop decreases for background dijets with large ΔR_{12}; *cutting on mass drop is less effective at low dijet p_T*
- Modified mass drop for dijet: $\zeta = \Delta R_{12} \cdot \max(m_{j1}, m_{j2})/m_{jj}$
  - **ζ is still small for signal and now is more constant for background**
  - arXiv:1407.7037: "A New Observable for Identifying Dijet Resonances"
  - Boost 2014: https://indico.cern.ch/event/302395/session/17/contribution/55/material/slides/1.pdf

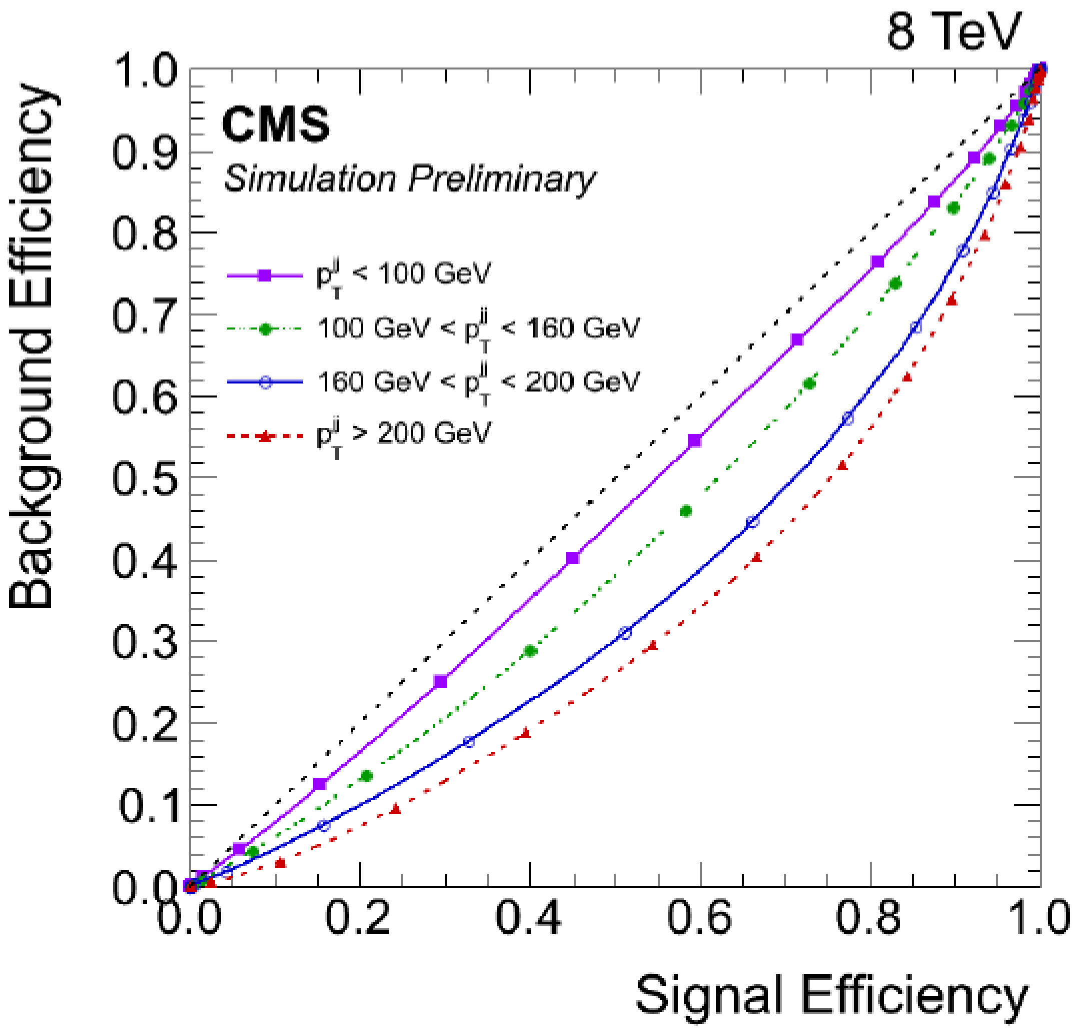
Modified Mass Drop

- ζ plotted in different dijet p_T bins
- Good data/MC agreement
- For increasing p_T (i.e. decreasing ΔR_{12}), average ζ decreases for signal but remains similar for background
- Discrimination is better at higher p_T



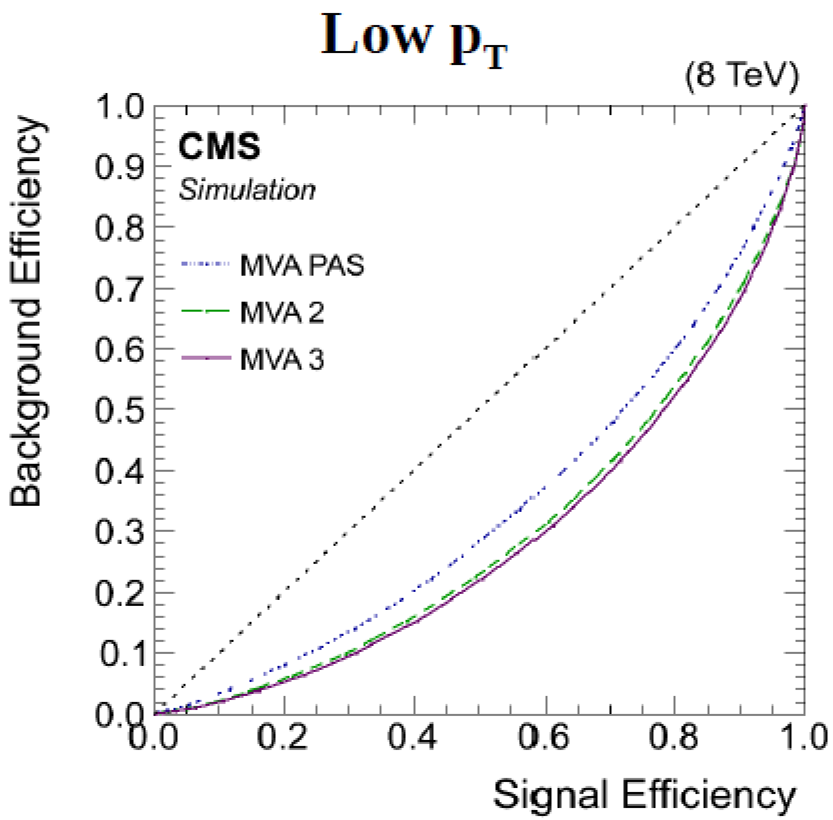
Performance

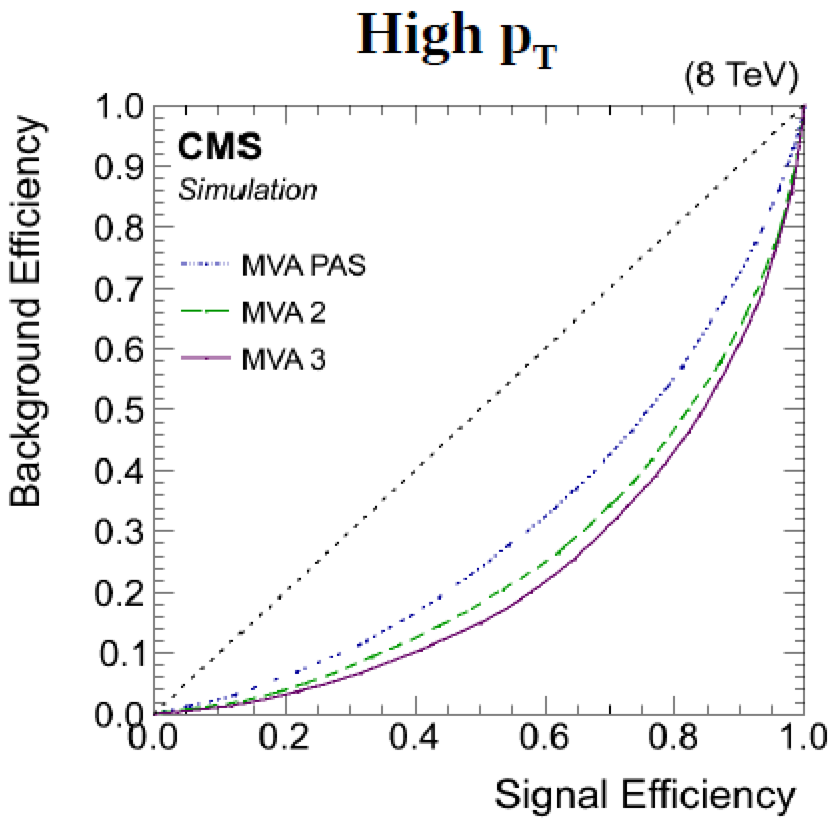
- Performance is better at higher dijet p_T



In the MVA

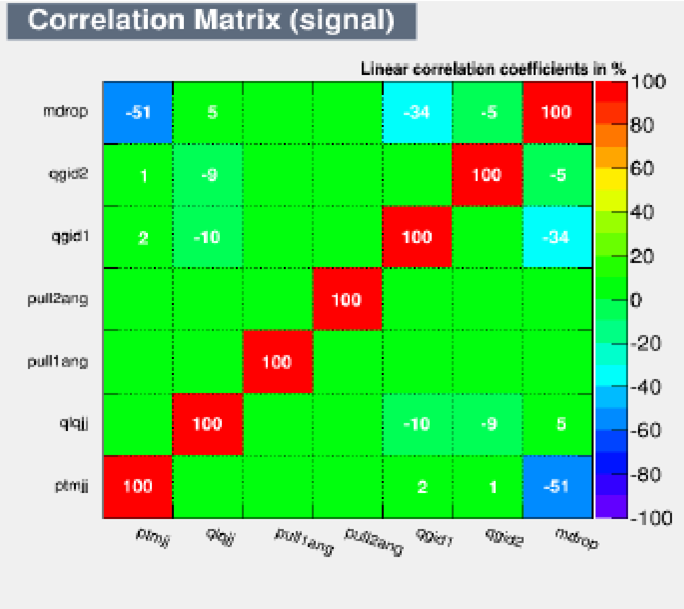
- Mass drop brings small improvement to MVA tagger
  - Split training between dijet p_T greater/less than 160 GeV
  - “MVA PAS” = MVA from JME-14-002
  - “MVA 2” = “MVA PAS” + $\theta_P(t_2, J_1)$ + $p_{T,jj}/m_{jj}$
  - “MVA 3” = “MVA 2” + ζ

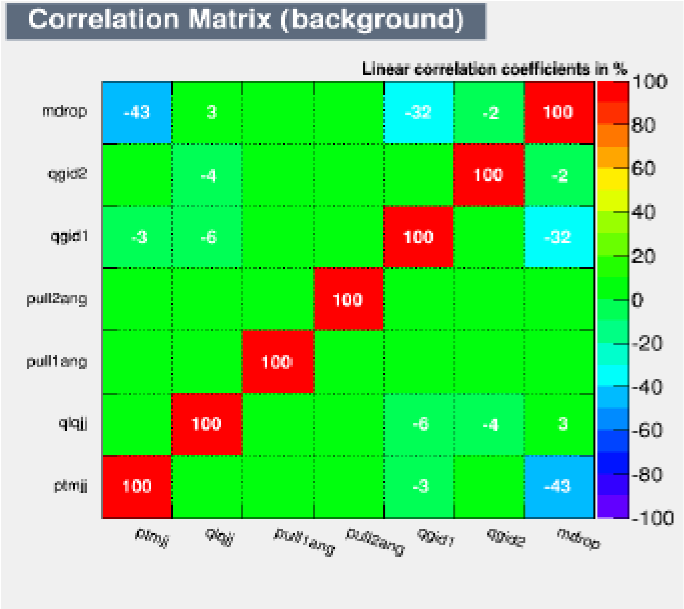




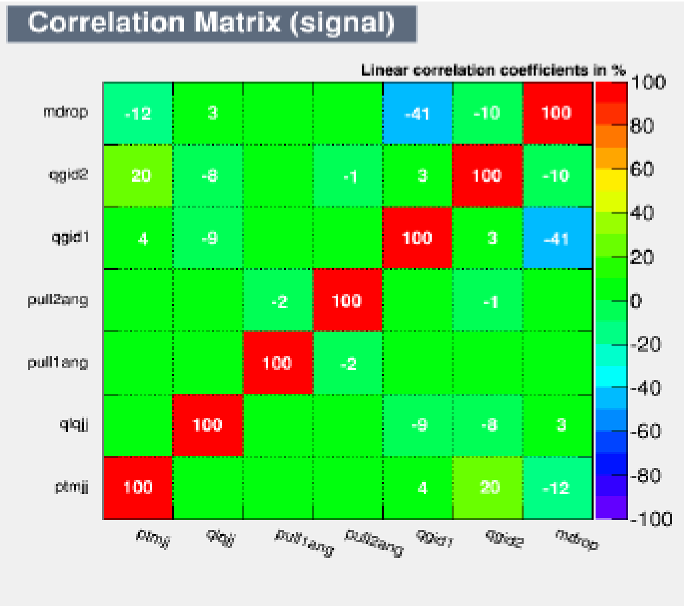
Correlations

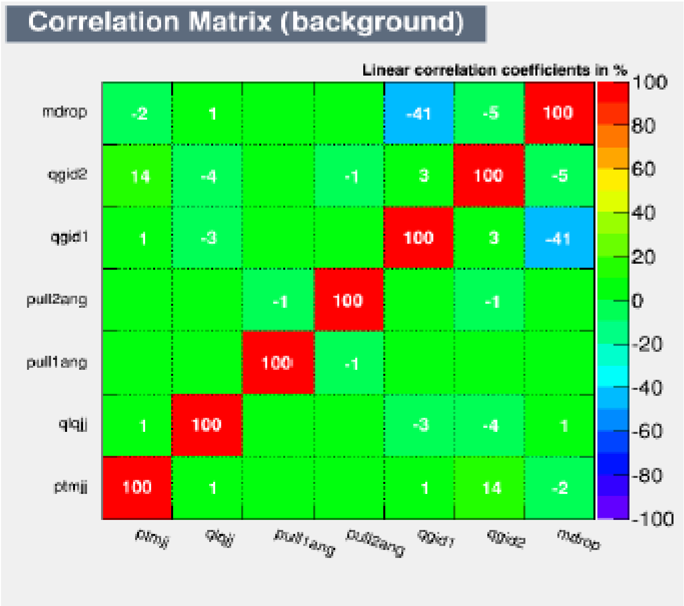
Low p_T





High p_T





Boosted V-tagger

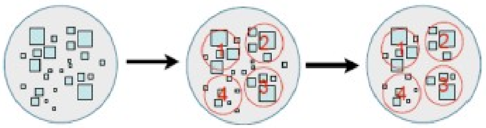
Introduction

- For sufficiently boosted W/Z, decay products can be merged into single reconstructed jet (aka “fat” jet)
  - e.g. W p_T > ~200 for R=0.8 jets
- Analyze substructure in “fat” jet to accurately identify subjets and properties
- Observables can be grouped into following algorithms/properties:
  - Groomed Jet Mass
    - Reduces soft, wide-angle radiation from jet, effects from PU and UE
  - N-prong tagging
    - Identify jet to originate from N-prong decay
  - QGL *(same likelihood function as in resolved jets case)*
  - Subjet pull *(same defintion as in resolved jets case)*
  - Q-jets
    - Gives statistical description of jet substructure by considering numerous possible recombinations of constituents

Selection

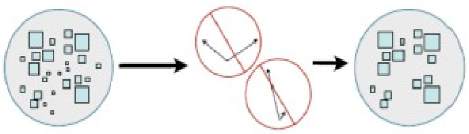
- Obtain sample of W bosons and combinatorial background in semi-leptonic $t\bar{t}$ events, and also background pure sample in Z+jets events
  - Trigger: `HLT_IsoMu24_eta2p1`
  - Muon $p_T > 30$, $|\eta| < 2.1$
  - *tt: veto on good electron or additional good muon*
  - *Z+jets: select second muon with $p_T > 10$ and $|M_{\mu\mu} - M_Z| < 15$*
  - Two b-tagged AK5 jets, $p_T > 30$
  - "fat" jet selection:
    - AK8 CHS, $p_T > 250$, $|\eta| < 2.5$
    - Exclude jet that overlap with the muon ($\Delta R > 0.3$)
    - Exclude jet that overlaps with a b-tagged AK5 jet
    - Require "fat" jet combined with closest b-tagged jet has mass < 300
    - For subjet quantities, consider only $p_T > 20$ GeV

Groomed Jet Mass



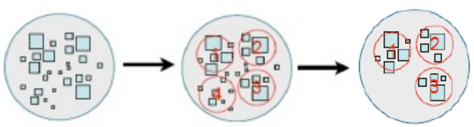
Trimming: k_T *clustering*, $R_{subjet}=0.1$, $p_{T,frac}=0.03$ (arXiv:0912.1342)

- Creates subjets using constituents above $p_{T,frac}$ threshold



Pruning: *CA clustering*, $z_{cut}=0.1$, $d_{cut}=0.5$ (arXiv:0903.5081)

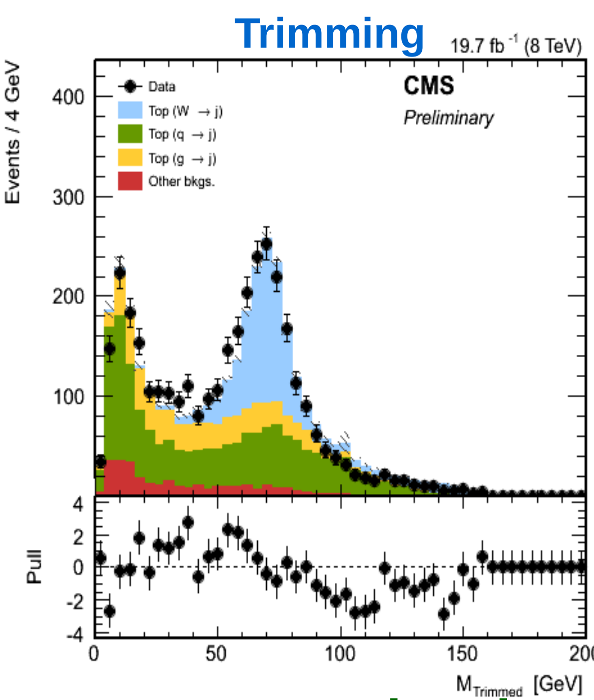
- Apply z_{cut} and d_{cut} at each reclustering of jet constituents

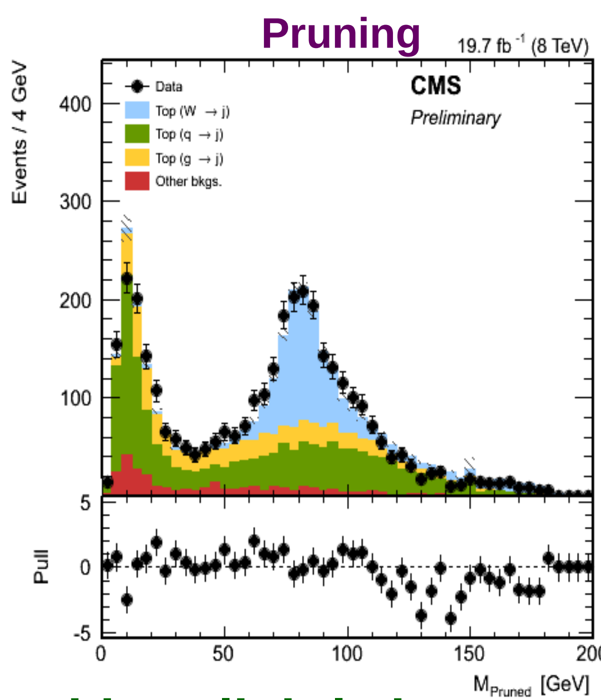


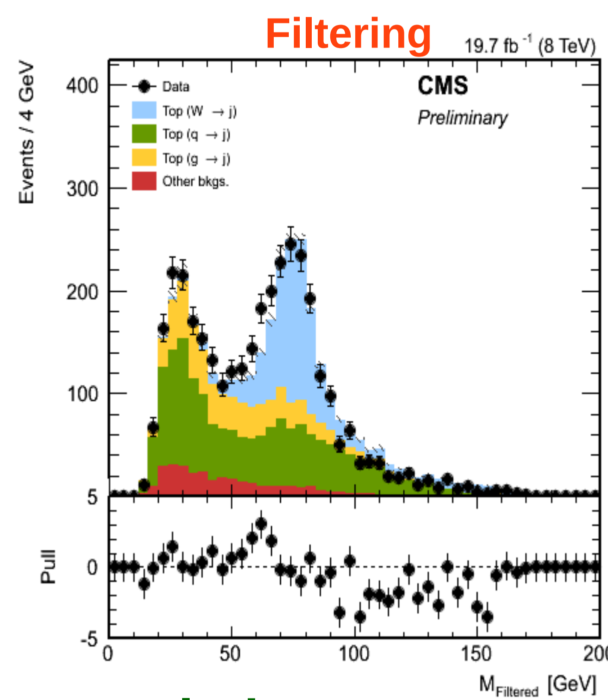
Filtering: *CA clustering*, $R_{subjet}=0.2$ (arXiv:0912.0033)

- Keep 3 hardest subjets

From JME-14-002







Trimming provides slightly better mass resolution

Groomed Jet Mass: Soft Drop

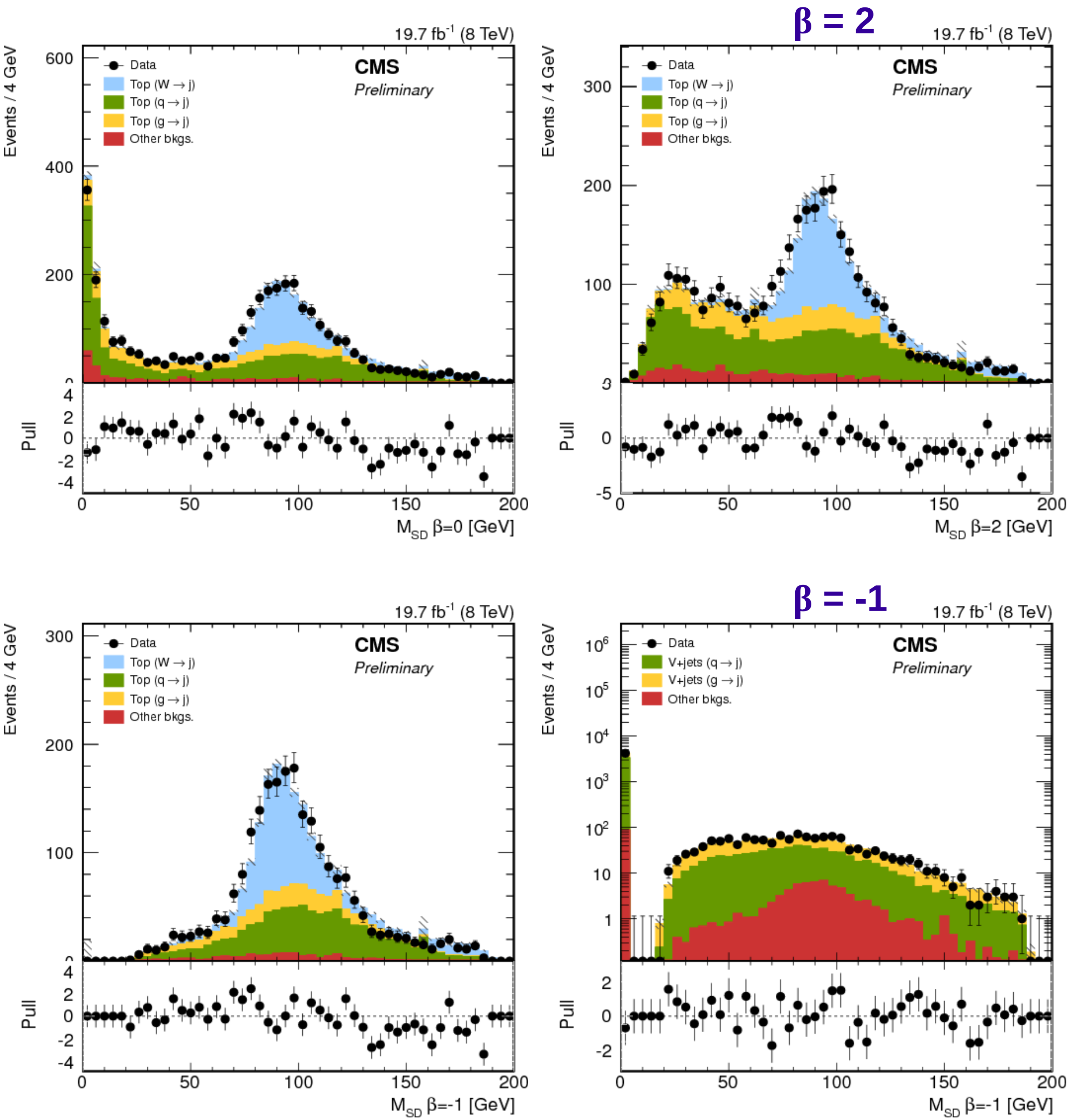
From JME-14-002

- arXiv:1402.2657
- Recluster jet (CA), then decluster, recursively splitting subjets in two until following condition fails:

$$\frac{min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \left(\frac{\Delta R}{R_0} \right)^{\beta}$$

then the softer subjet is *dropped*

- z_{cut}=0.1, R_0=0.8
- Studied β = -1,0,1,2; *lower β drops more aggressively*
- Good data/MC agreement



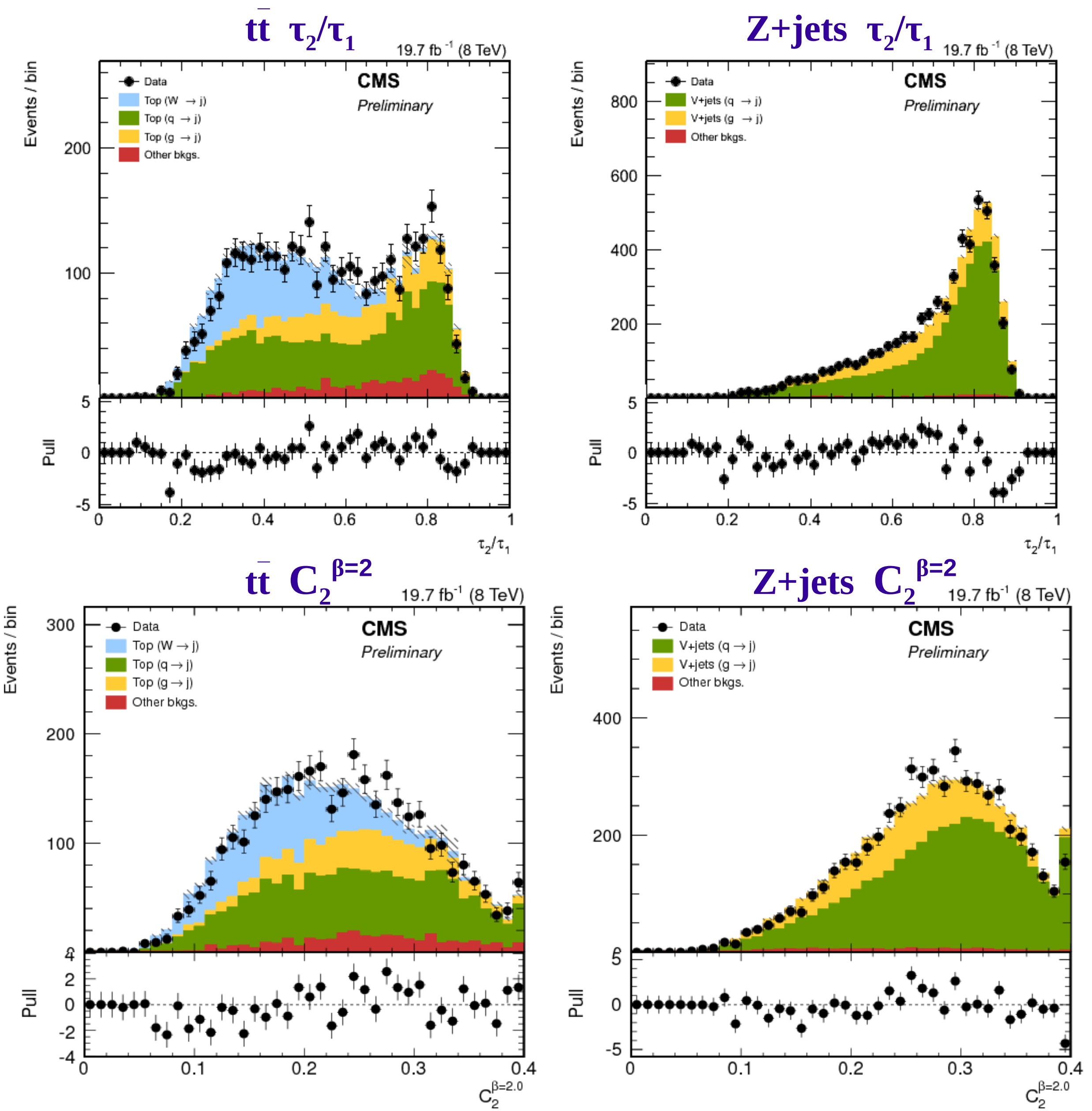
N-prong Tagging

- Quantify most likely number of prongs (subjet axes) that is consistent with the jet's substructure
- Identify 2-pronged jets for V tagging
- Two algorithms:
  - N-subjettiness (arXiv:1011.2268)
    - k_T clustering, "winner-take-all" scheme
    - τ_N is small if jet is consistent with N or less prongs
    - For V tagging, quantity of interest is the ratio: τ_2/τ_1
  - Energy Correlation Function (ECF) (JHEP06(2013)108)
    - Identifies number of prongs without reclustering; uses only jet constituent p_T and pair-wise displacements
    - For V tagging, quantity of interest is: $C_2^{\beta} = [ECF(3,\beta)/ECF(2,\beta)] / [ECF(2,\beta)/ECF(1,\beta)]$
    - Consider β = 0, 0.2, 0.5, 1, 2

N-prong Tagging

From JME-14-002

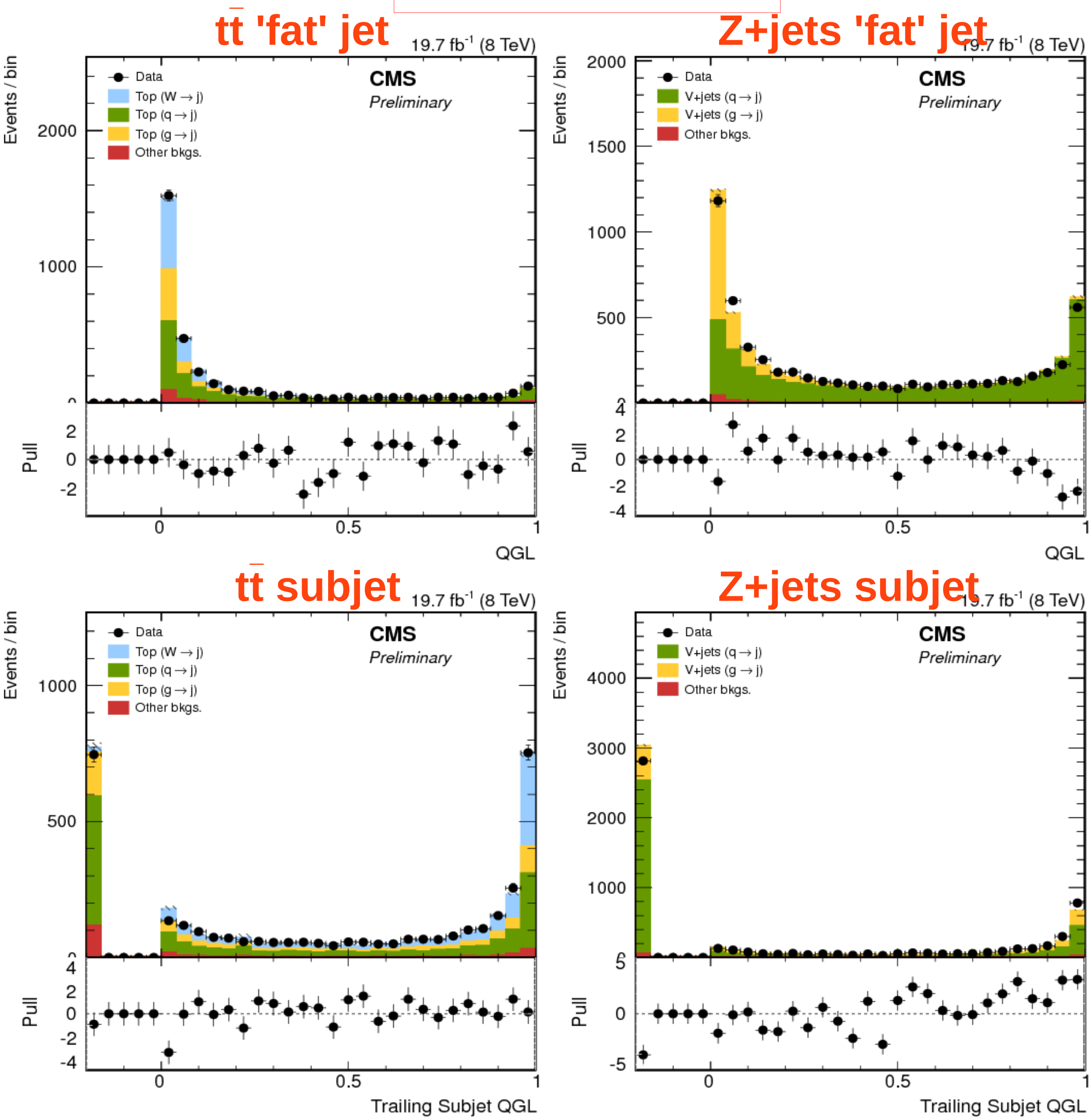
- Low values corresponds to more likely 2-pronged
- τ_2/τ_1 and C_2^β in data fairly well described by MC



QGL

- "Fat" jet appears very gluon-like to QGL
- Subjet QGL recovers expected behavior
- Trailing subjet QGL shows more discriminating power than leading subjet QGL
  - Negative entries from events with only 1 subjet above 20 GeV
- Linear combo of leading and sub-leading subjet QGLs also show more discriminating power
  - $QGL_1 + 2 \bullet QGL_2$

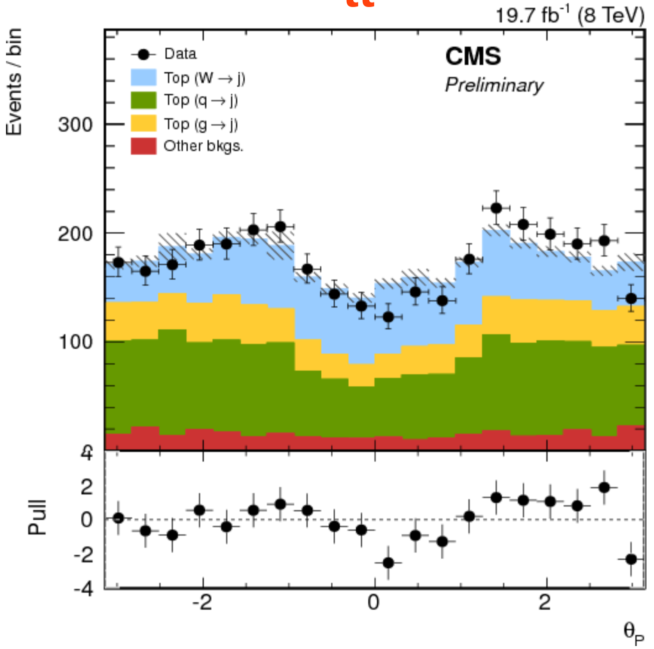
From JME-14-002



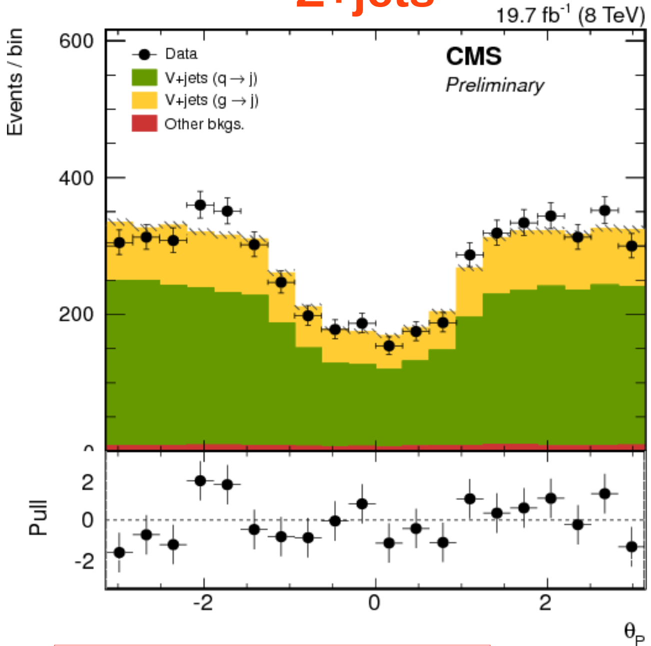
Subjet Pull

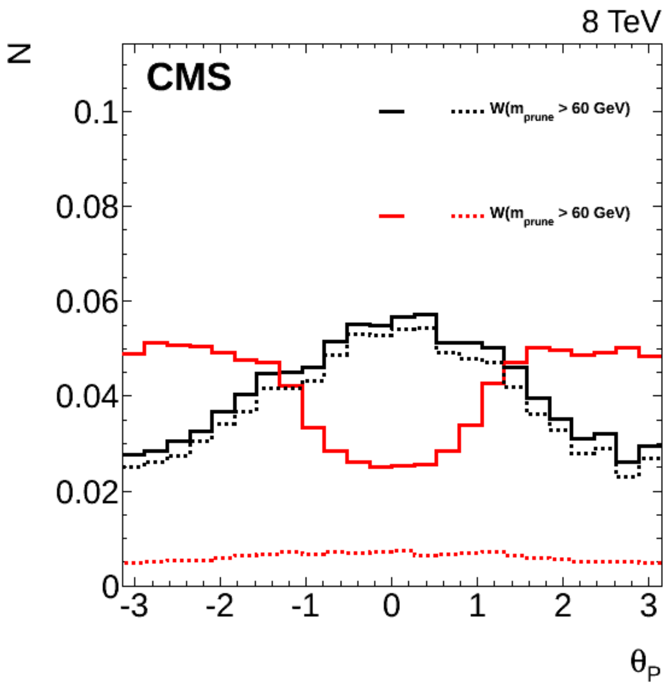
- Compute pull vector for leading subjet and θ_P to sub-leading subjet
  - Signal show expected peak θ_P ~ 0
  - “Valley” structure in background come from low mass jets
- Pull vector magnitude also considered, but brings little improvement

$t\bar{t}$



Z+jets





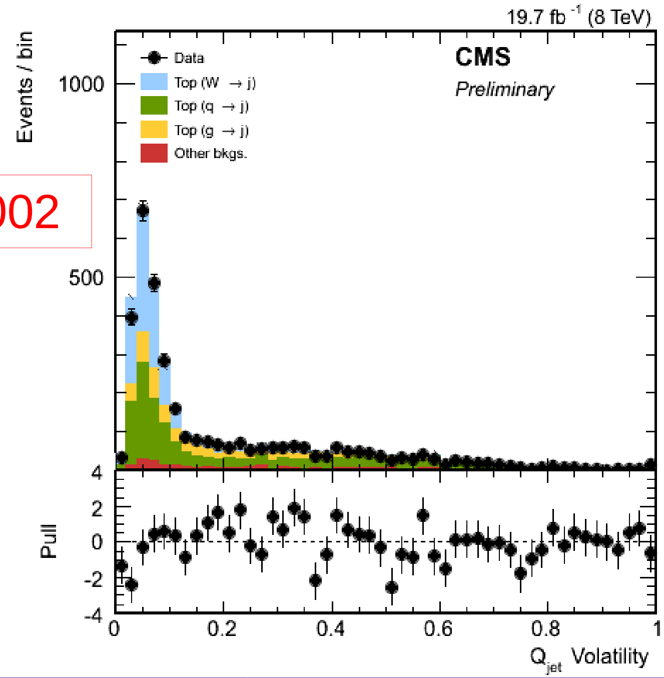
From JME-14-002

Q-jet Volatility

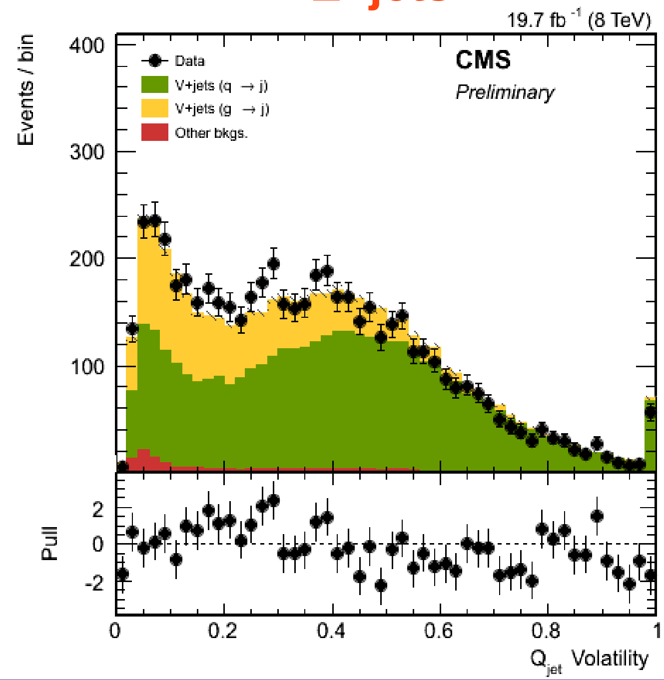
- *Q-jets* approach randomly samples many possible recombinations of jet constituents to obtain statistical description of the jet (arXiv:1201.1914)
  - Weight each recombination based on distance metric of clustering algorithm; CA is used here
  - Distributions of jet properties are formed from different clustering “histories”
- Q-jet Volatility, Γ_{Qjet}, is RMS of pruned jet mass distribution

From JME-14-002

$t\bar{t}$



Z+jets

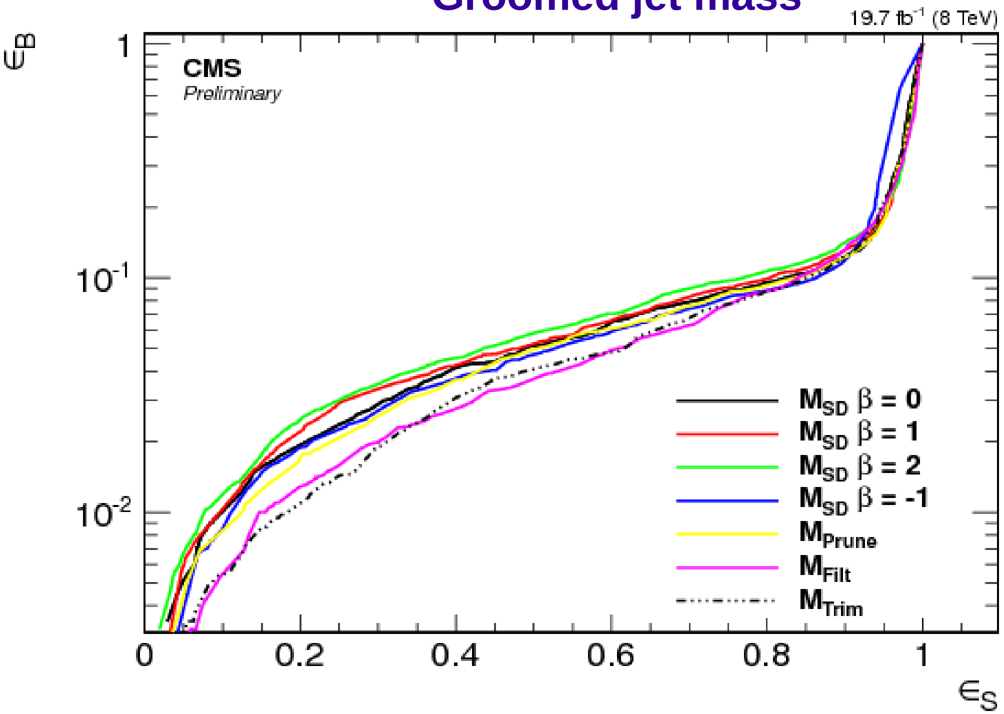


Performance

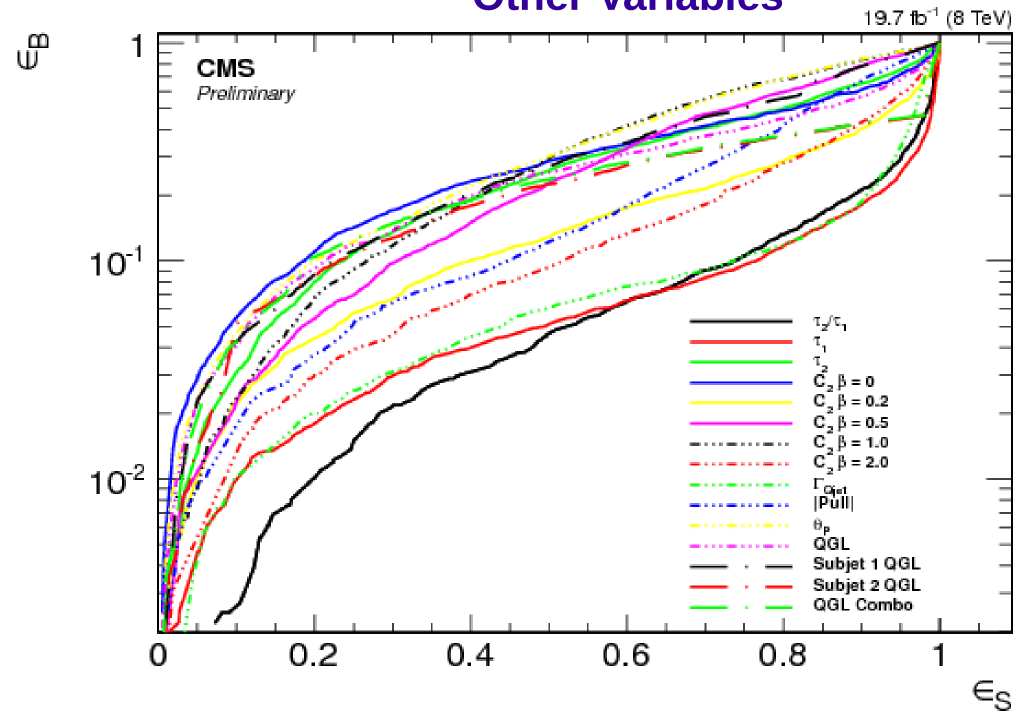
- Compute ROC curve for signal from W-jets in $t\bar{t}$ MC and background from Z+jets data
- Best of groomed jet mass: **M_{Trim}** and **M_{filt}**
- Best of other variables: **τ_2/τ_1** and **Γ_{Qjet}**

From JME-14-002

Groomed jet mass



Other Variables

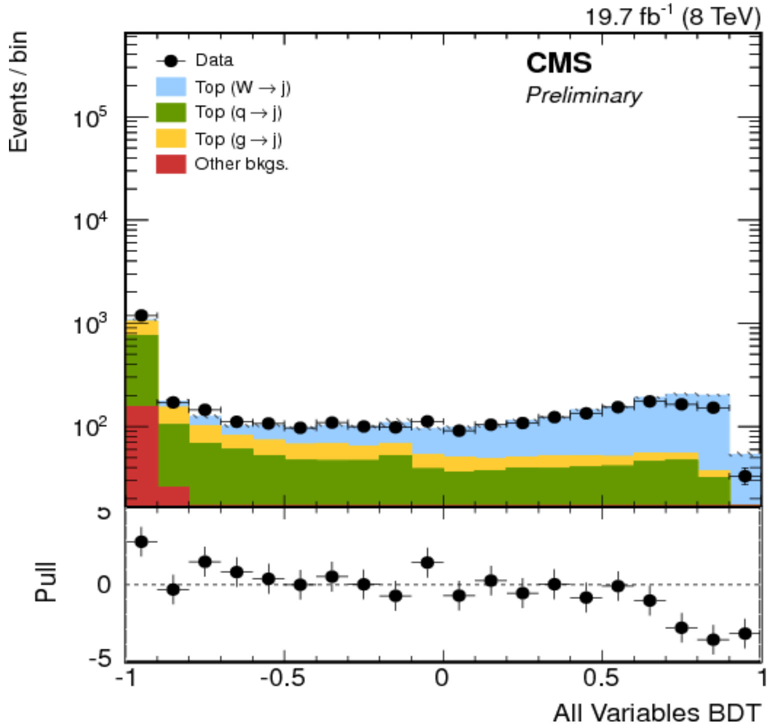


All Variables BDT

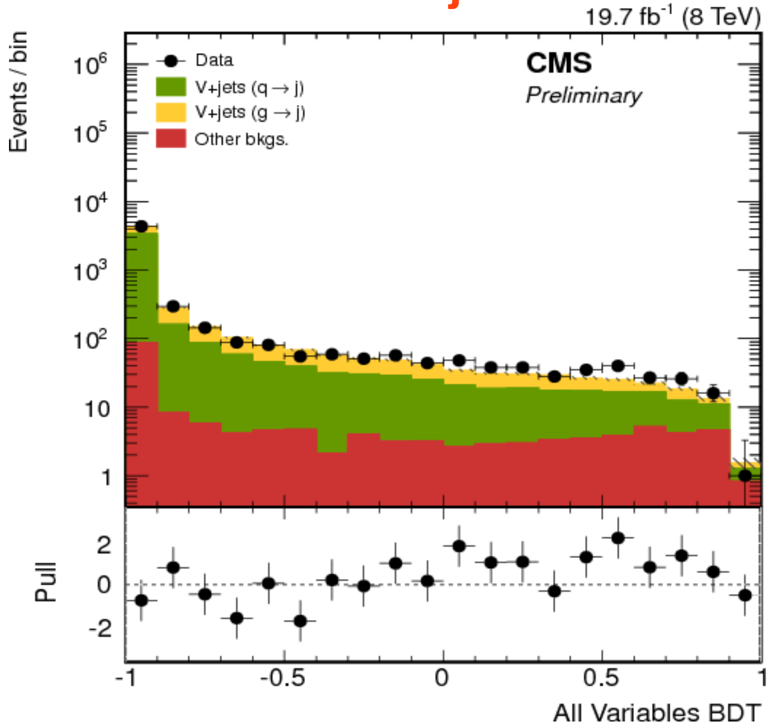
From JME-14-002

- *Let's mix in all the ingredients!*
  - BDT score distributions show fair data/MC agreement

$t\bar{t}$



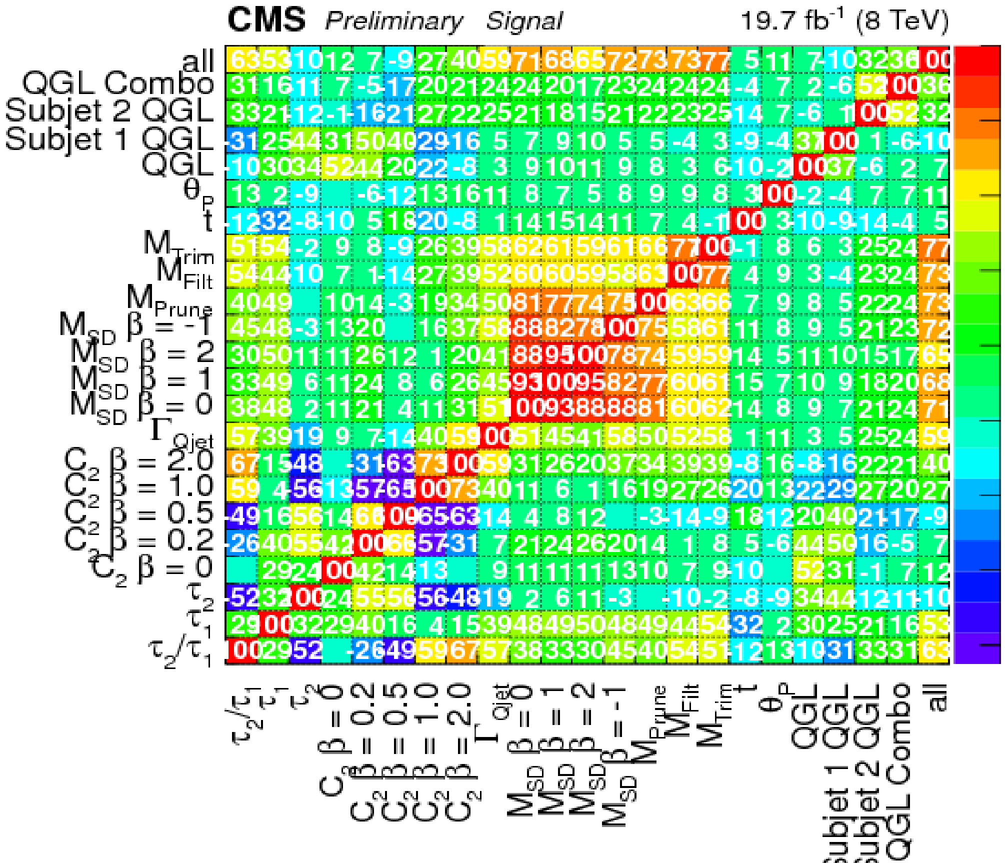
Z+jets

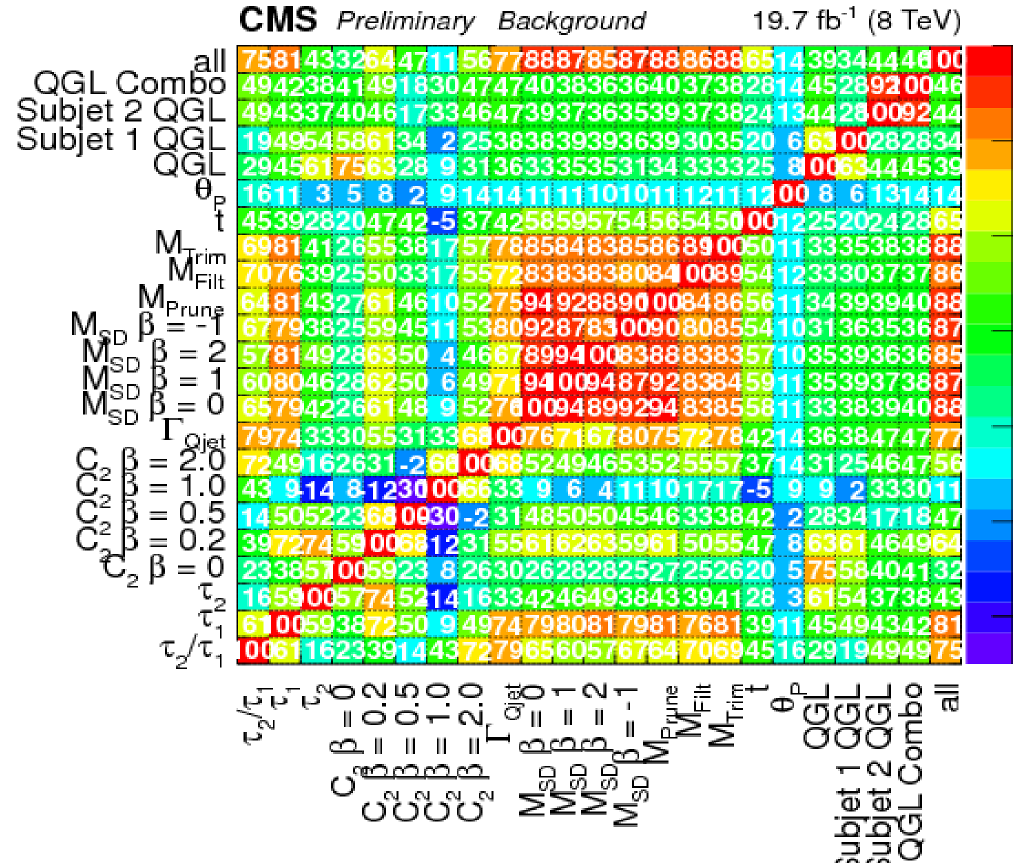


Correlations

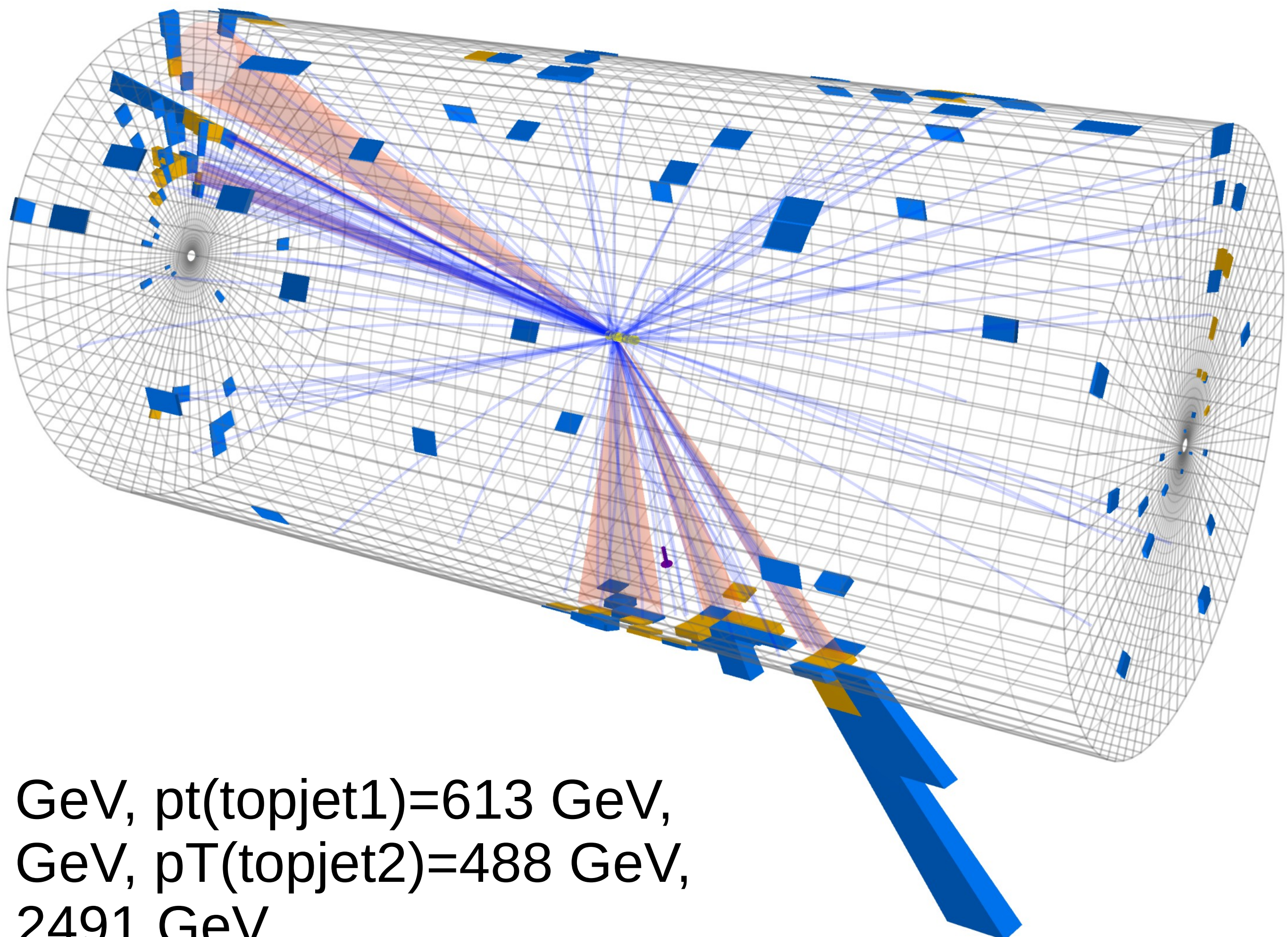
- A lot variables, a lot of correlations... not every observable brings something new to the table since several do similar things
- Matrix values in %

From JME-14-002





CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 07:25:11 2015 CEST
Run/Event: 251562 / 111132974
Lumi section: 122
Orbit/Crossing: 31722792 / 2253



Kinematics:
m(topjet1)=177 GeV, pt(topjet1)=613 GeV,
m(topjet2)=176 GeV, pT(topjet2)=488 GeV,
ditopjet mass = 2491 GeV,
1 btagged subjet (CSVIVFv2 medium OP)

CMS Magnet

- The restart of the CMS magnet after LS1 was more complicated than anticipated due to problems with the cryogenic system in providing liquid Helium.
- Inefficiencies of the oil separation system of the compressors for the warm Helium required several interventions and delayed the start of routine operation of the cryogenic system.
- Currently the magnet can be operated, but the continuous up-time is still limited by the performance of the cryogenic system, requiring more frequent maintenance than usual.
- A comprehensive program to re-establish its nominal performance is underway.
- These recovery activities for the cryogenic system will be synchronized with the accelerator schedule in order to run for adequately long periods.
- A consolidation and repair program for the cryogenic system is being organized for the next technical stops and the longer technical stop at the end of the year.
- The Collaboration appreciates the priority being given to this issue by CERN's Technology Department, which is responsible for the maintenance and operation of the CMS magnet external cryogenic system.