BSM searches with Jets at CMS

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On Behalf of the CMS Collaboration

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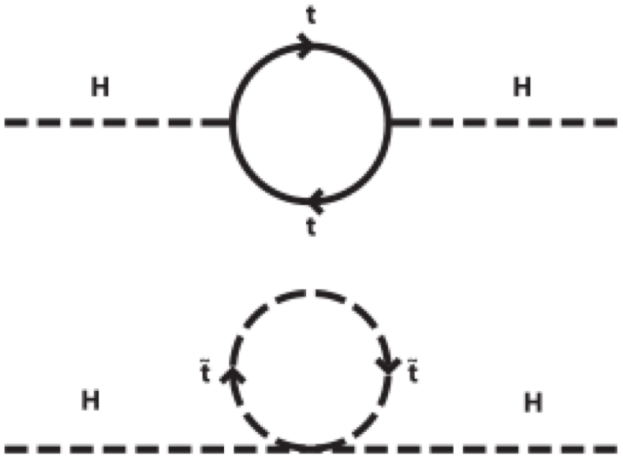
Outline

- Introduction
- Brief overview of the CMS Experiment
- Particle Flow Jets, Jet Substructure and Jet Mass in CMS
- Selected new physics searches with jets
- Summary and Outlook

SM is incomplete

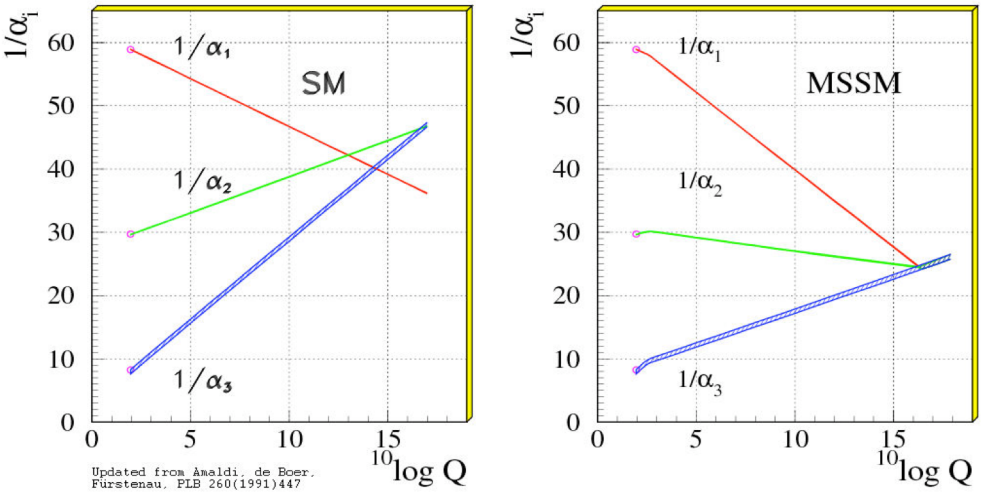
Theoretical point of view

- **Quantum Gravity** : *SM describes three of the four fundamental interactions at the quantum level (microscopically) BUT gravity is only treated classically.*



- **Hierarchy Problem** : *Why is $M_{Pl}/M_{EW} \sim 10^{15}$ What is the mechanism of cancelation of quadratic divergencies?*

- **Unification of Gauge couplings** *: Why couplings are so different?*



- **Origin of generations :** Why three?

SM is incomplete

Experimental point of view

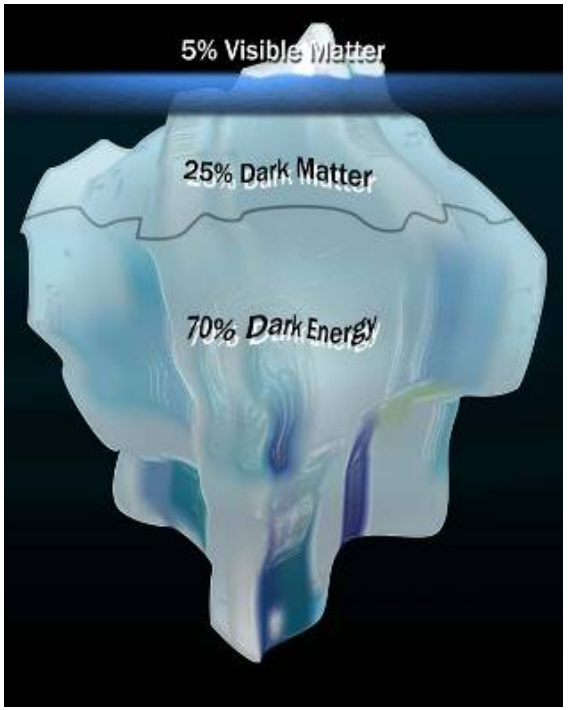
- **Dark matter – Dark Energy :** *What is 95% of the Universe made off?*

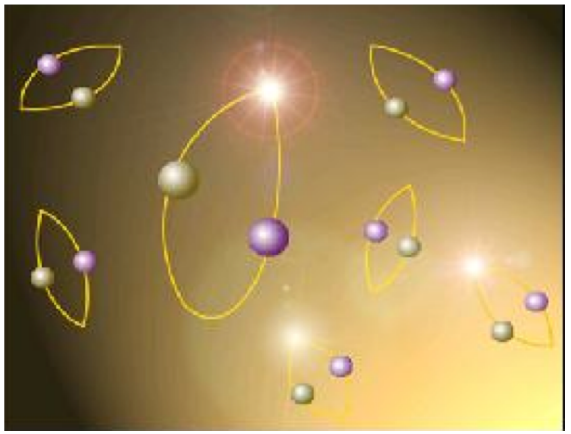
- **Cosmological constant** *: Why is vacuum energy SO small?*

  $$\rho_{VAC} = M_{Pl}^4 = 10^{120}\rho_{VAC}^{obs} \quad (!!!)$$

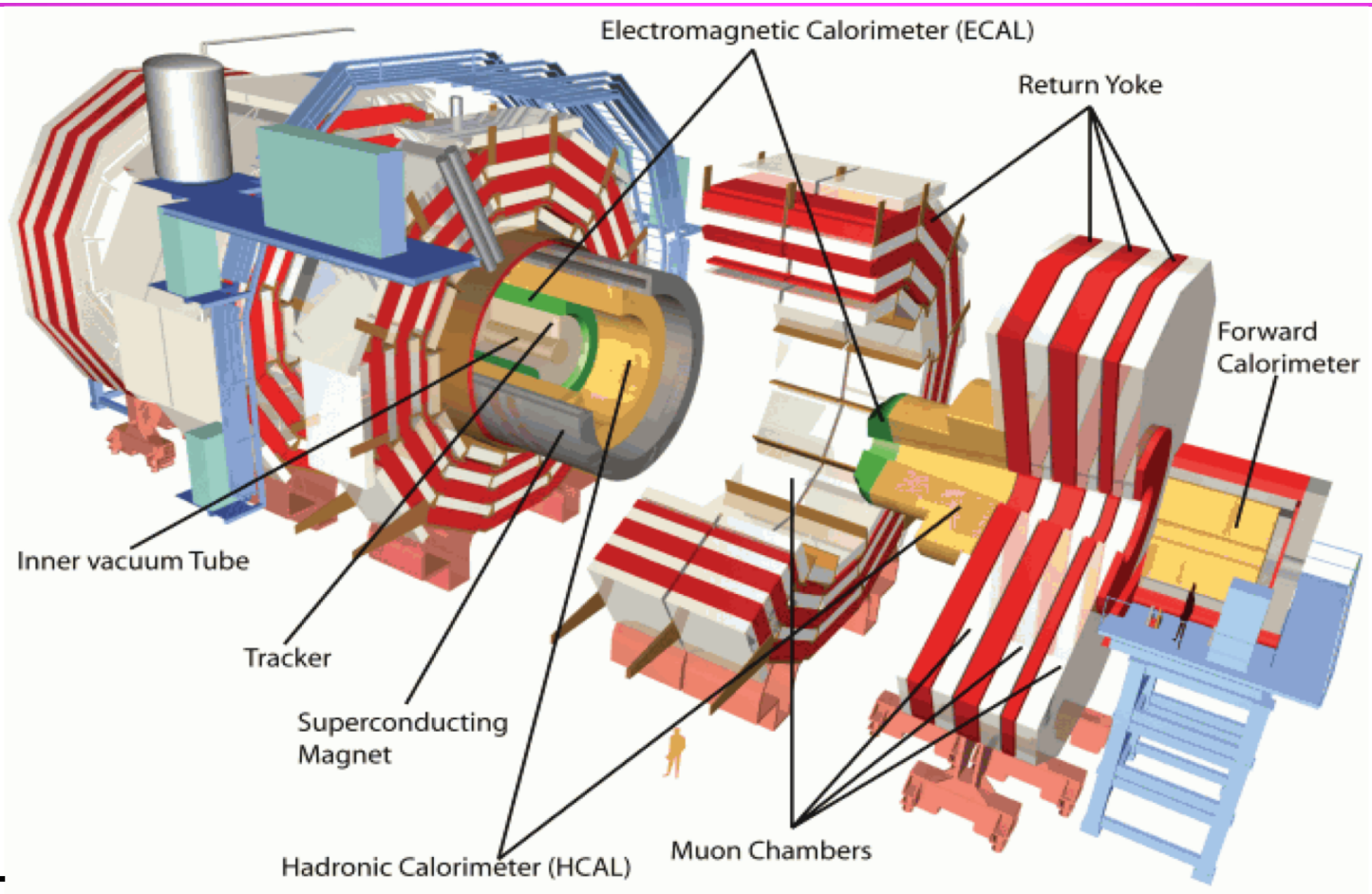
- **CP Violation***: Why are we here? OR What is the source of the dramatic matter-antimatter asymmetry in the Universe?*

- **Neutrino masses and mixings** *: What is the Origin of neutrino masses, what is the nature of neutrino, why are ν mixings so different than quark ones?*





The CMS Detector



3.8 T

Pixels

$\sigma/pT \sim 1.5 \cdot 10^{-4} pT(GeV) \oplus 0.005$

Electromagnetic Calorimeter

$\sigma E/E \approx 2.9\%/\sqrt{E(GeV)} \oplus 0.5\% \oplus 0.13 GeV/E$

Hadronic Calorimeter

$\sigma E/E \approx 120\%/\sqrt{E(GeV)} \oplus 6.9\%$

Muon Spectrometer

$\sigma pT/pT \approx 1\%$ for low pT muons

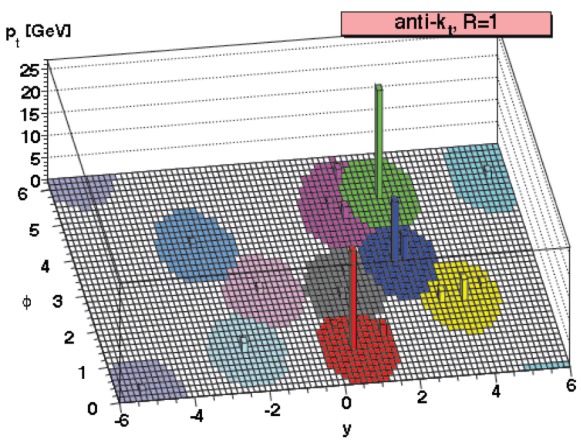
$\sigma pT/pT \approx 5\%$ for 1 TeV muons

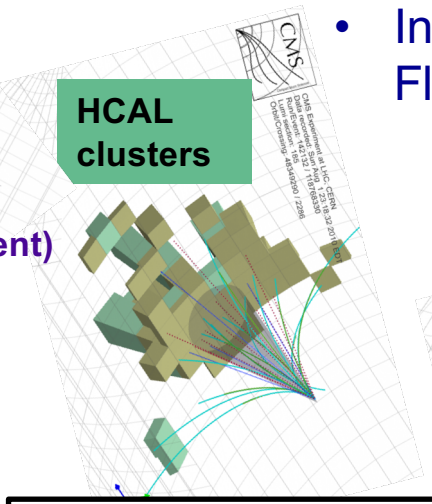
Jet Reconstruction

- Particle Flow Algorithm combines all information from several sub-detector systems
- Individual particles are reconstructed with Particle Flow Algorithm and then clustered into jets.

complete jet
(All the visible particles in the event)

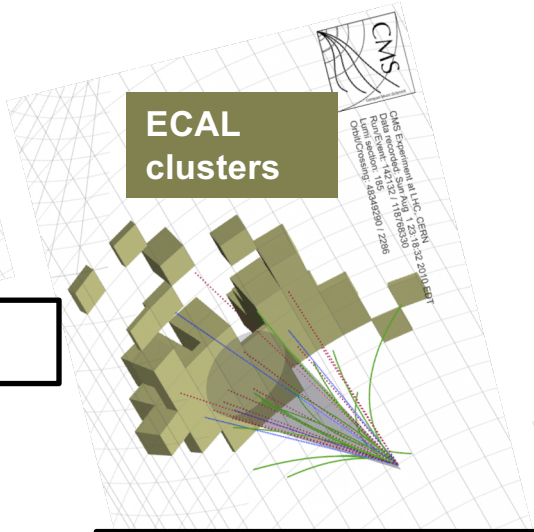
HCAL+ECAL+Tracker info
μ, $e^{\pm}$, γ, $\pi^{\pm}$, $K^{\pm}$, p, K^0, π^0,…





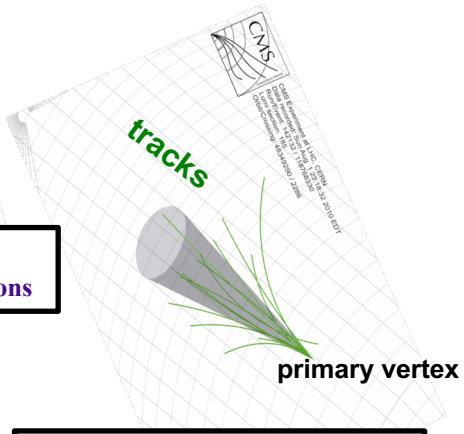
HCAL clusters

HCAL info
Charged and neutral hadrons



ECAL clusters

ECAL info
$e^{\pm}$, γ and neutral and charged hadrons



Silicon Tracker info
μ, $e^{\pm}$, and all charged hadrons

Anti-kt clustering algorithm : with R = 0.4 and 0.8 for CMS. It is infrared and collinear safe, geometrically well defined, and tends to cluster around the hard energy deposits.

Jet Calibration

Physics Object

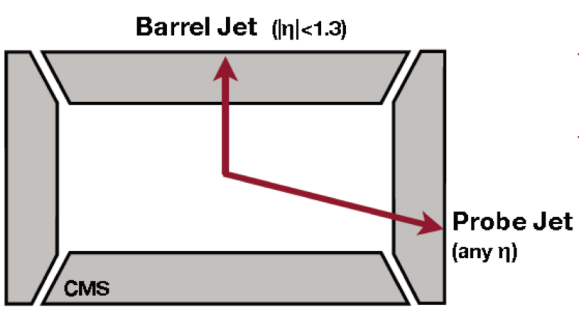
Raw Jet × Offset Correction (pile up) × Relative Response (vs. η) × Absolute Response (vs. p_T) = Calibrated Jet

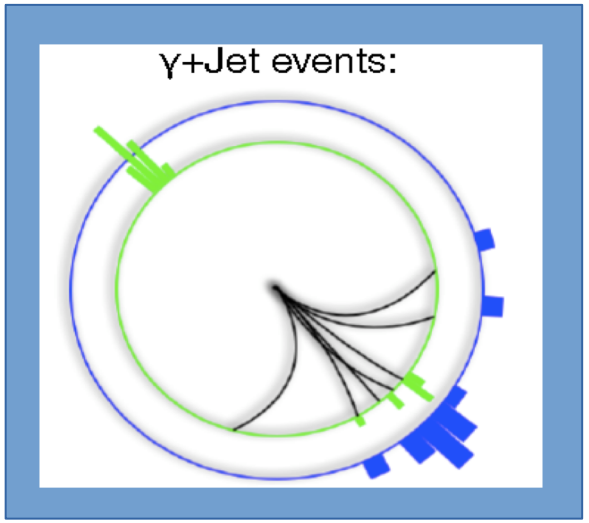
$$E_{corrected} = (E_{uncorrected} - E_{offset}) \times C_{rel}(\eta, pT'') \times C_{Abs}(pT')$$

where p_T'' is the transverse momentum of the jet corrected for offset and $p_T'' = p_T \times C_{Rel}(\eta, p''T)$

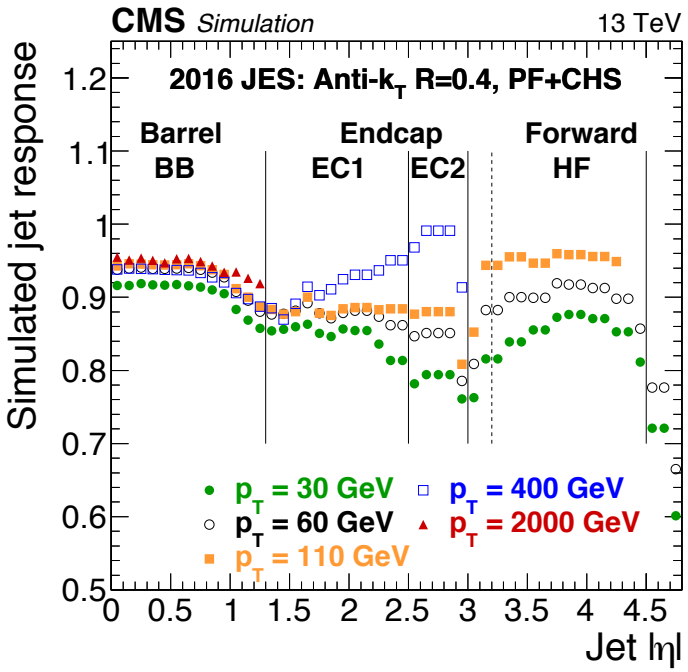
Data driven methods used for the residual corrections

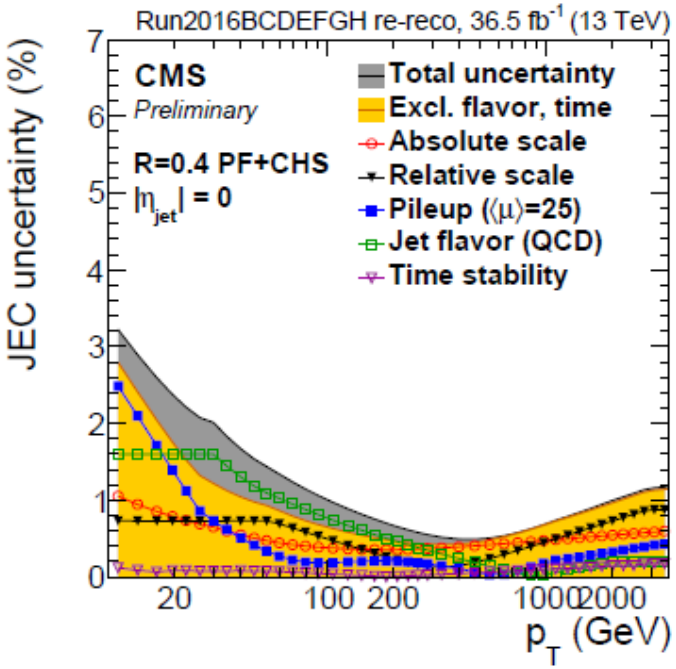
Dijet asymmetry

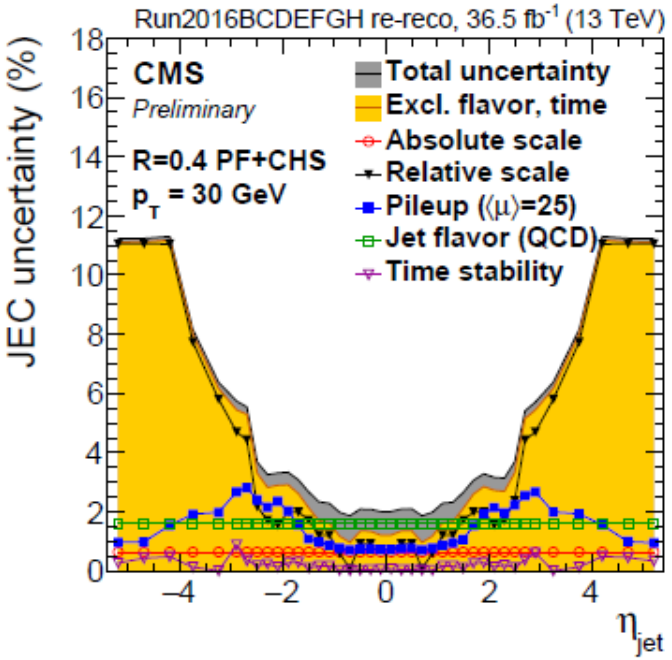




Jet Calibration







CMS DP-2016/020

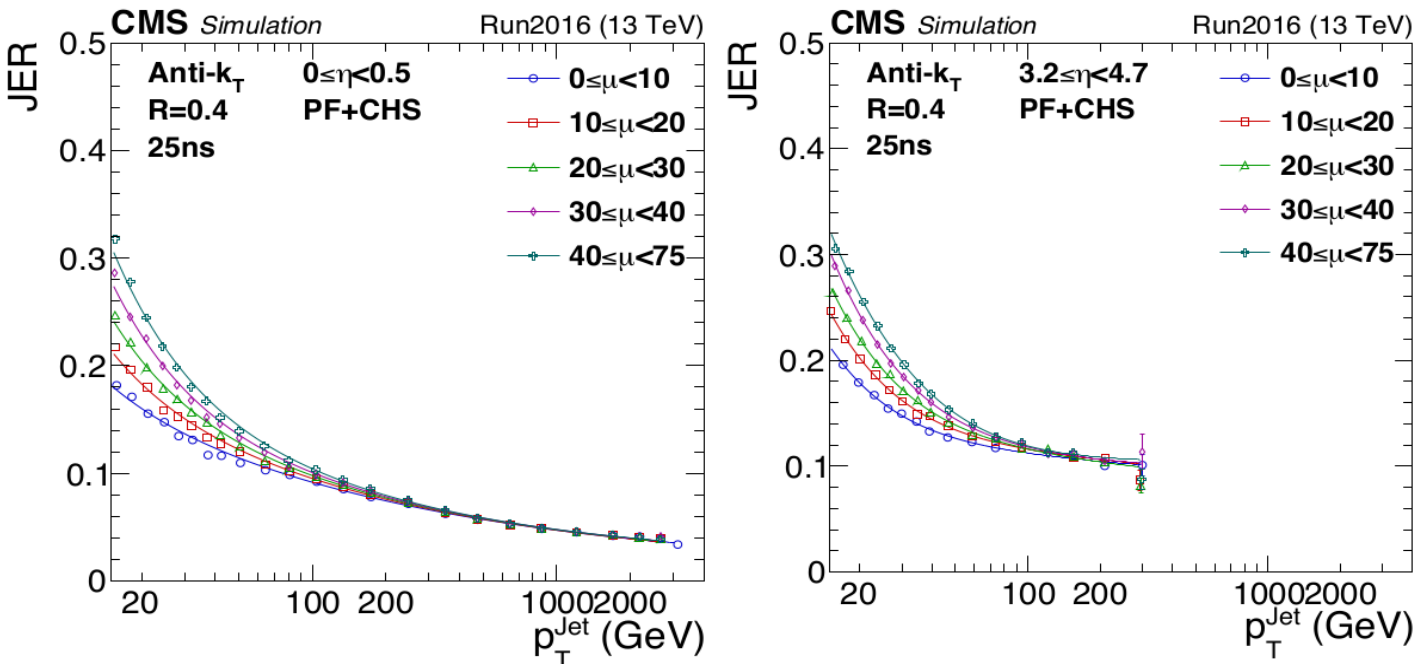
- Response very close to unity for PF jets.
- Uncertainties <1% for pT>100 GeV

Jet Resolution

JINST 6 (2011)

$$\mathcal{A} = \frac{p_T^{Jet1} - p_T^{Jet2}}{p_T^{Jet1} + p_T^{Jet2}} \qquad \sigma_{\mathcal{A}}^2 = \left|\frac{\partial \mathcal{A}}{\partial p_T^{Jet1}}\right|^2 \cdot \sigma^2(p_T^{Jet1}) + \left|\frac{\partial \mathcal{A}}{\partial p_T^{Jet2}}\right|^2 \cdot \sigma^2(p_T^{Jet2}) \qquad \boxed{\frac{\sigma(p_T)}{p_T} = \sqrt{2}\,\sigma_{\mathcal{A}}}$$

CMS DP-2016/020

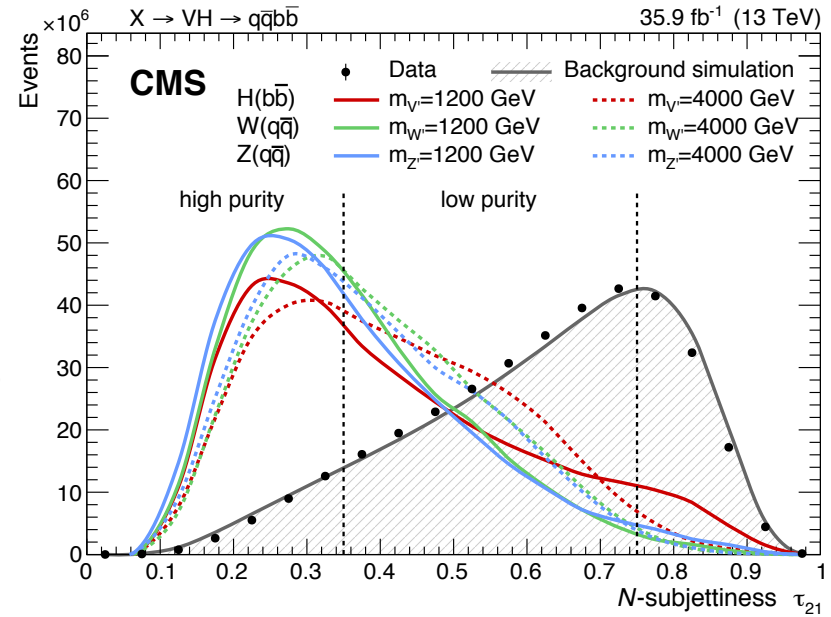


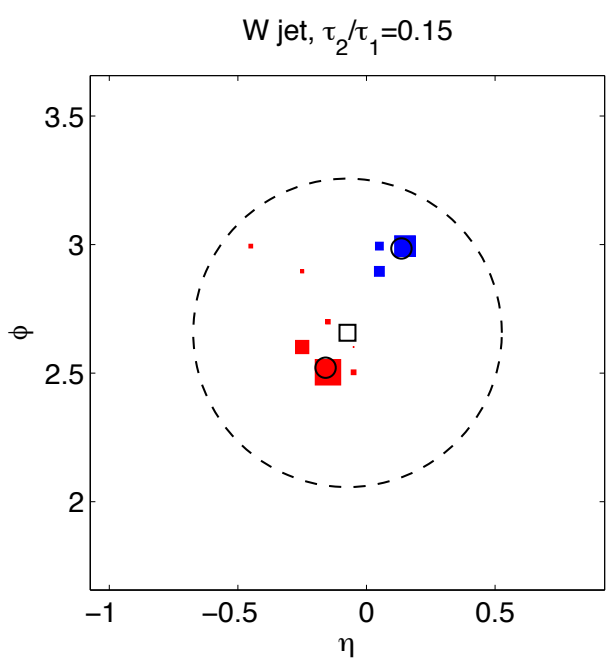
Better than 10% (5%) resolution above 100GeV (1TeV).

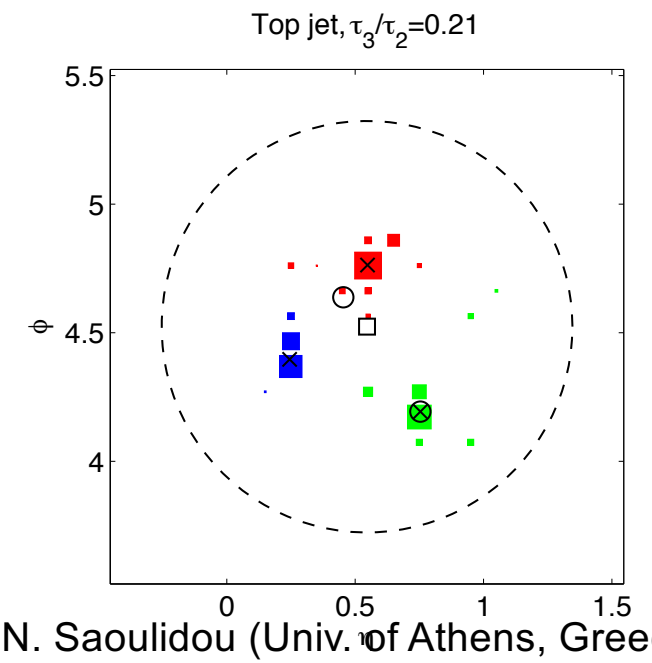
Jet Substructure

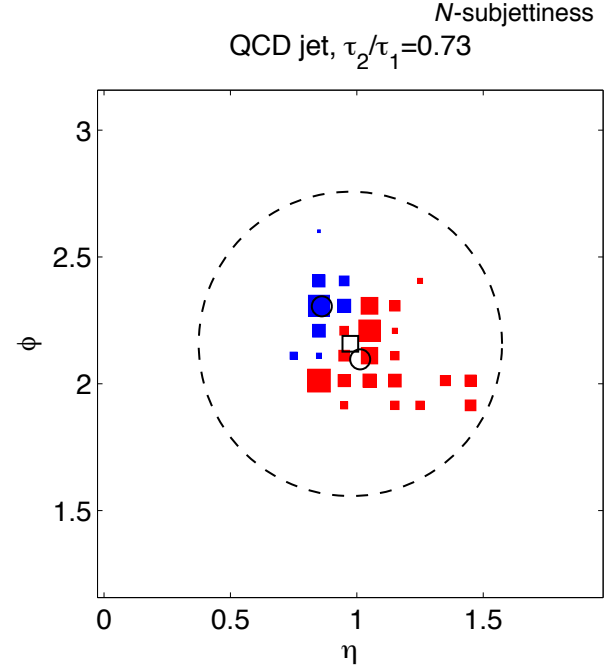
- Main discriminating variables between a "uniform" jet and one experiencing inner "sub-structure" are the N-subjetiness ones **[JHEP 1103:015,2011].**

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$$





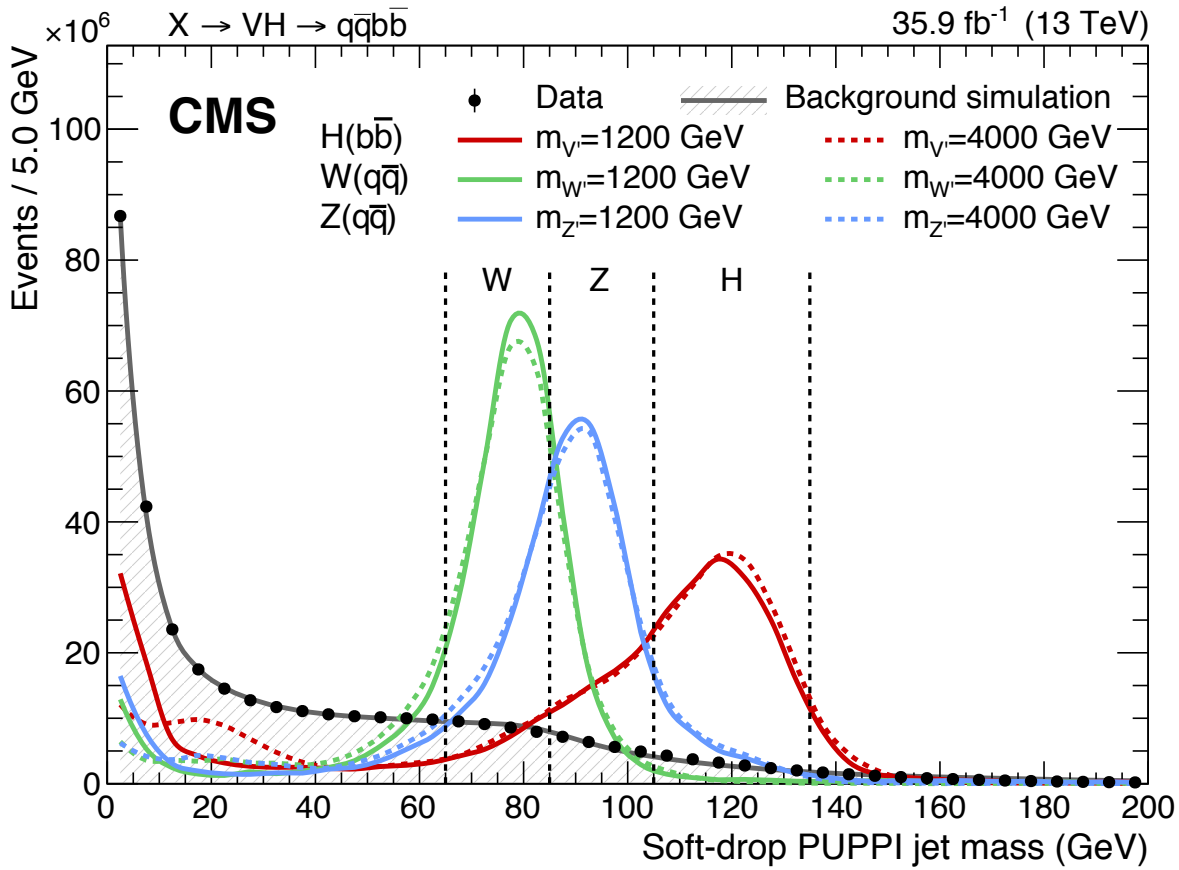




Jet Mass

Two main methods for jet grooming :**Pruning [Phys.Rev.D80, 05150 (2009)]** (recluster) and **Softdrop [JHEP05(2014),146]** (decluster).

Eur.Phys.J. C77 (2017) no.9, 636

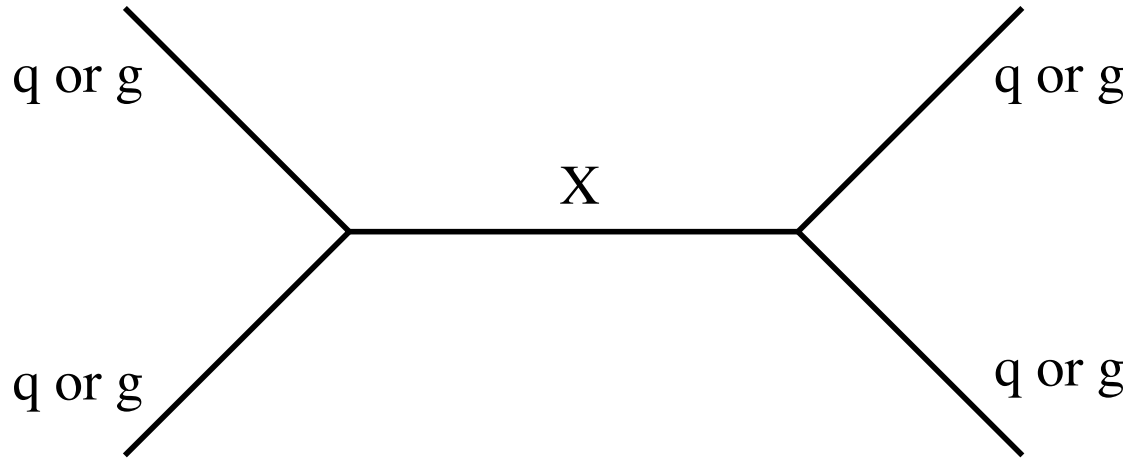


New Physics Searches with Jets

- **Dark Matter (*mono-X*, dijet, trijet)**
- **Compositeness (dijets)**
- **Flavour difference (dijets)**
- **Extra dimensions (dijets, *multijets*)**
- **Fourth generation (dijets)**
- RPV SUSY (multijets)
- **Lepto-quarks (dijet+X pair production, jet+X single-production) *Talk by Norbert Neumeister***
- Majorana Neutrinos (*dijet+X*)
- **Long-lived particles (displaced, delayed, disappearing, emerging jets) *Talk by Alberto Escalante Del Valle***

Dijets with/without ISR, Boosted or Resolved

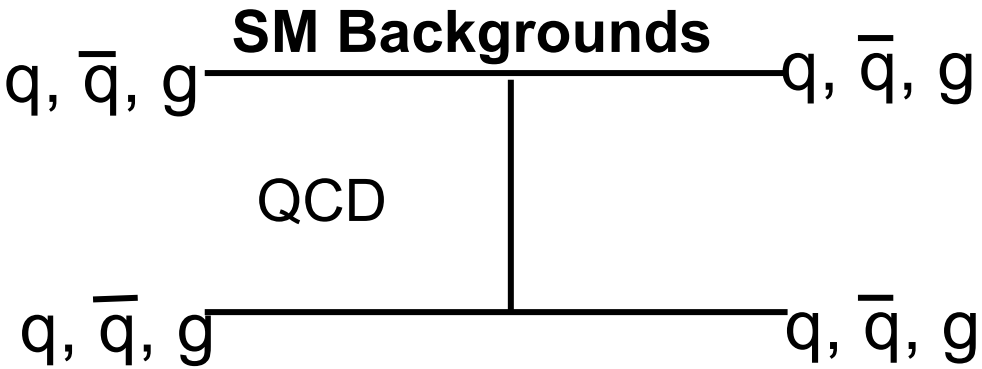
Access a broad range of new physics hypothesis

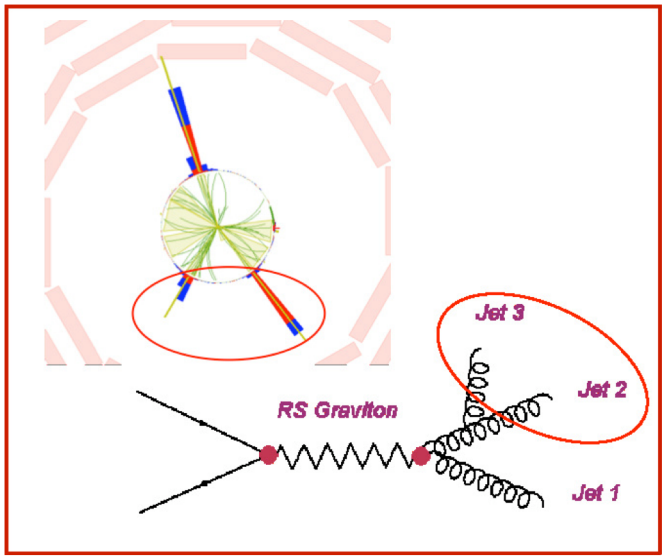


- **Decay Products can be:**
  - Highly boosted, merged in one jet : Access low X masses and utilize jet substructure techniques
  - Produced at medium or low boost : Access higher X masses and utilized resolved jets and scouting techniques.
- **Triggers** can be satisfied by final state particles or initial (final) state radiation **(ISR and FSR) jets or photons**

Resolved dijet in a nutshell

CMS-PAS-EXO-17-026





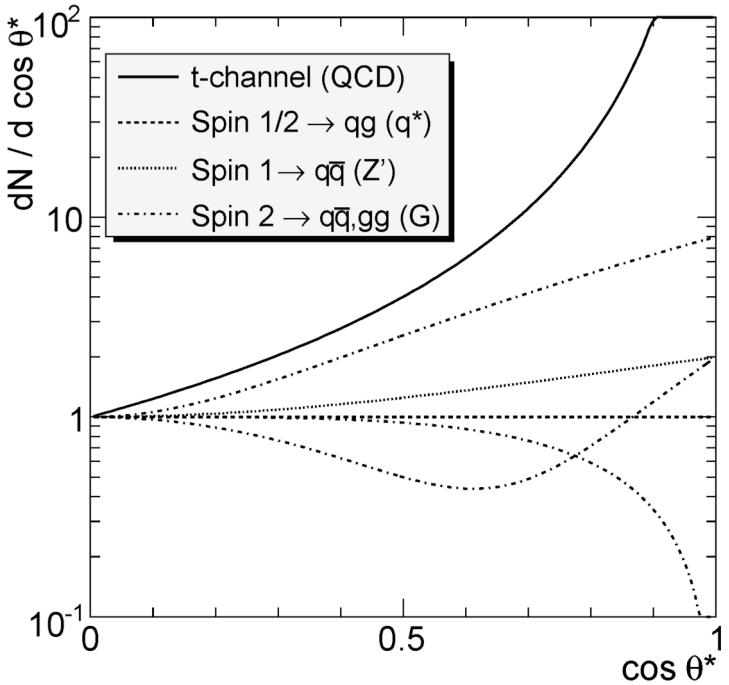
- **Reconstructed objects**

-Particle Flow Jets, Calorimeter Jets

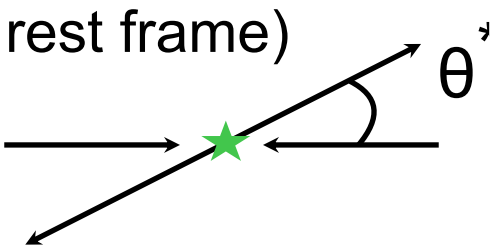
- **Physics observables**

M(jj) → Resonance Mass

Δη(jj) → Resonance Spin



$$\Delta\eta_{12} = |\eta_{jet1} - \eta_{jet2}| = \ln\frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$



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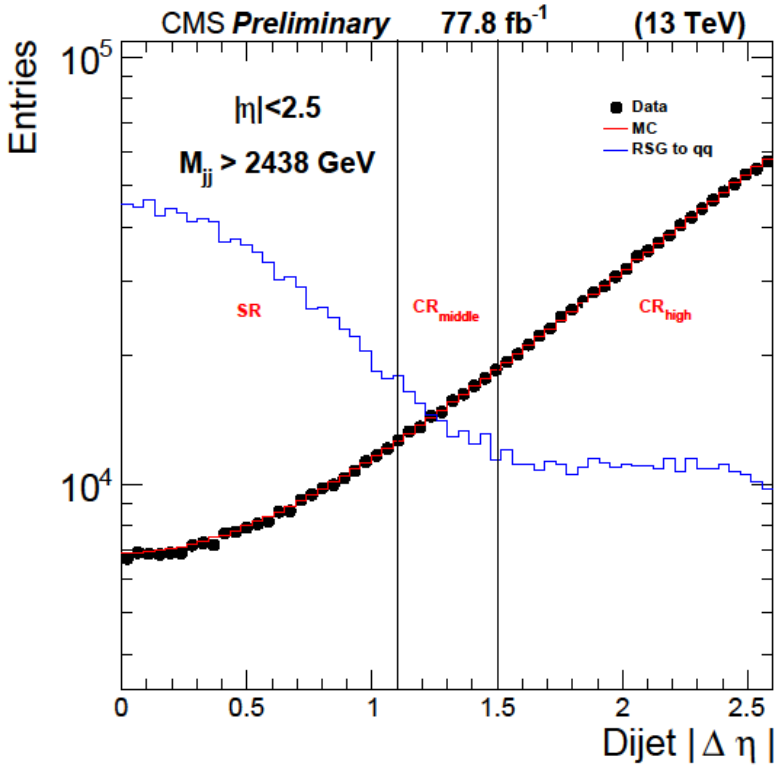
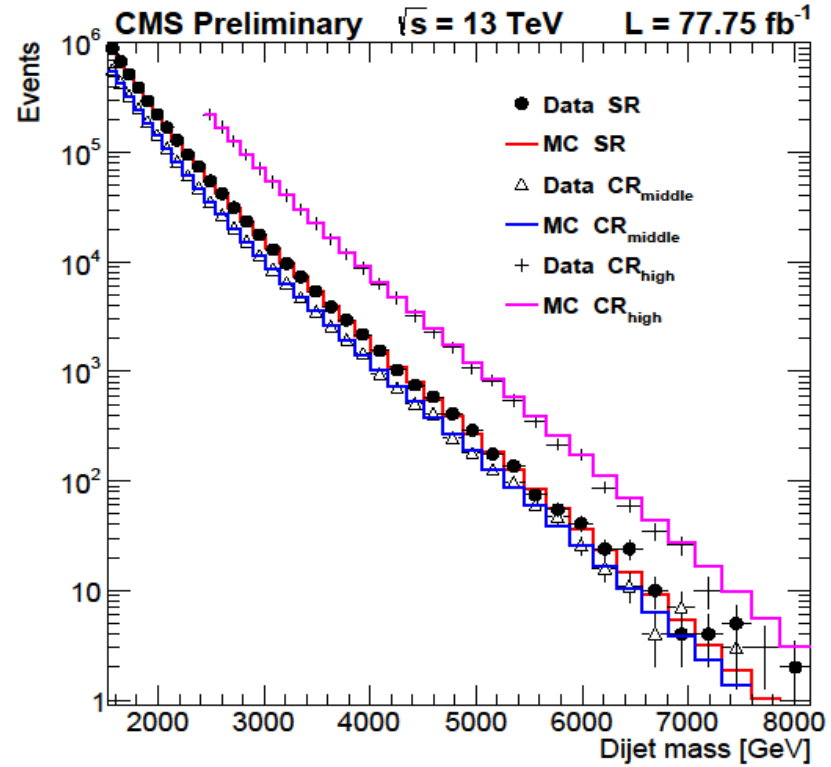
New Background Estimation

CMS-PAS-EXO-17-026





- New data driven background estimation technique:
  - Ratio Method uses data in the the control region at high | Δη | to estimate the background in the signal region at low | Δη |.
  - **Robust technique, complementary to the standard fit method, with less dependence on arbitrary parameterizations.**
- Data in the signal region extends to a new high dijet mass value of 8 TeV.

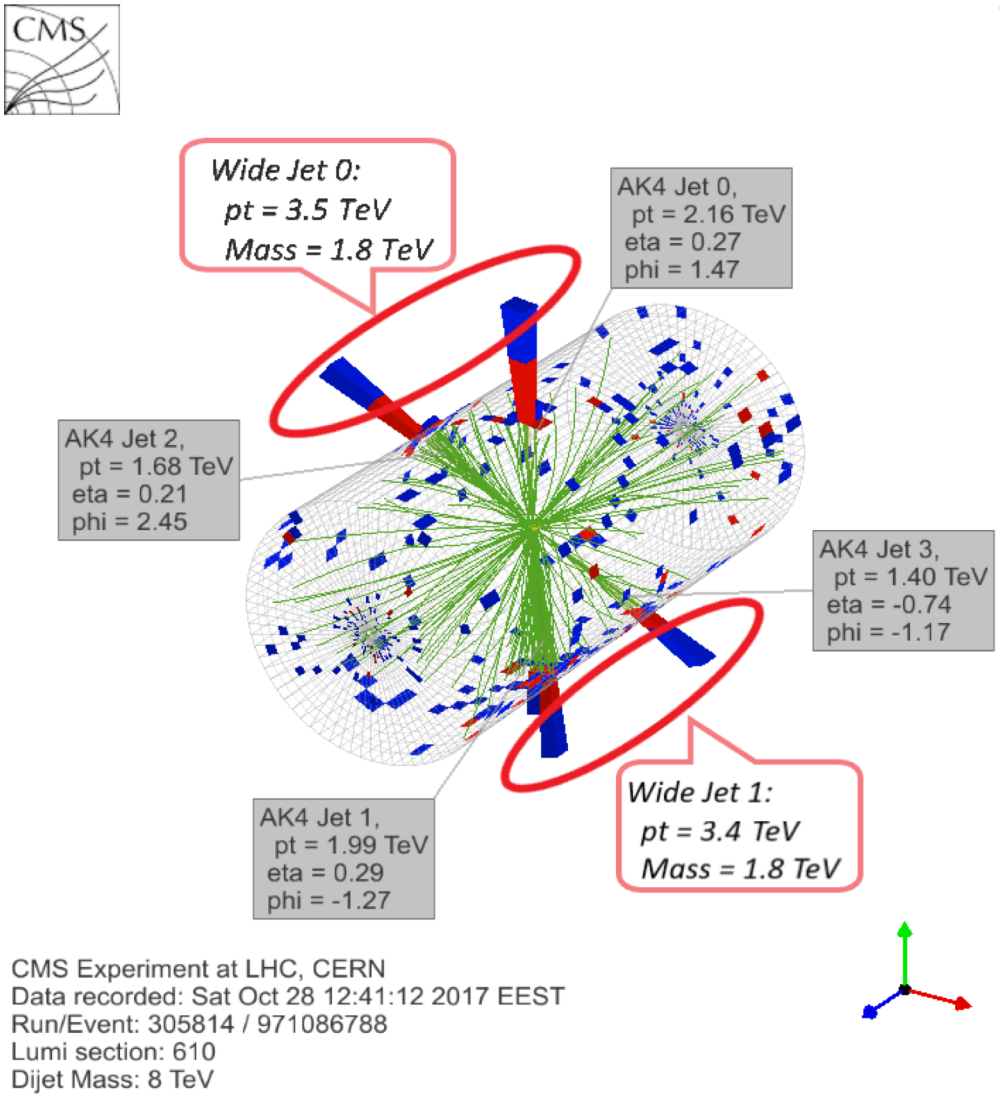
Highest Dijet Mass Event

CMS-PAS-EXO-17-026

- Highest dijet mass event at 8 TeV has unusual 4-jet topology.
  - Wide jets each have a mass of 1.8 TeV.
  - Probability of getting such a 4-jet event from QCD is approximately 10^{-4}.

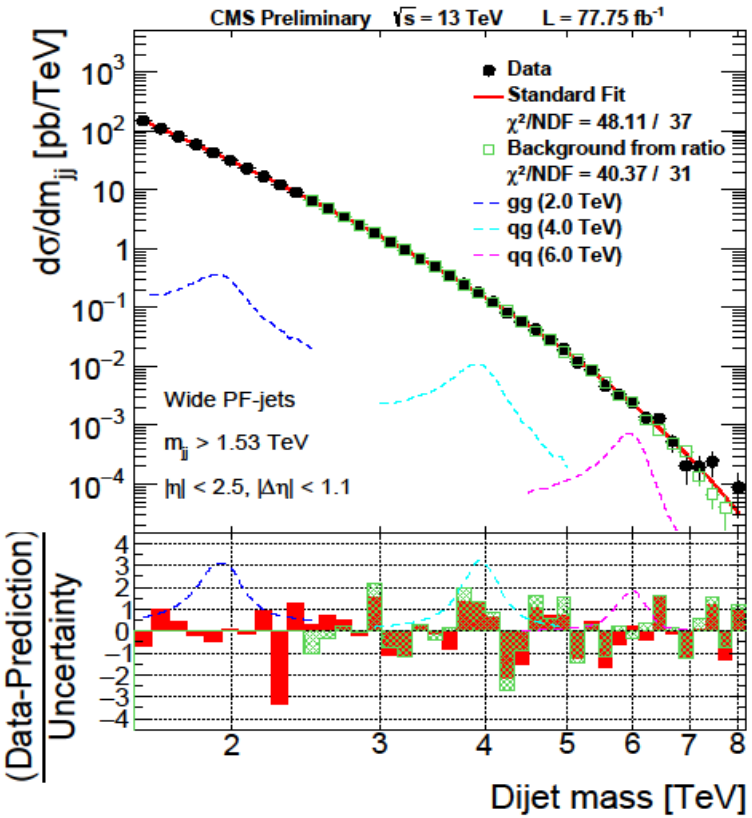
  [arXiv:1810.09429]

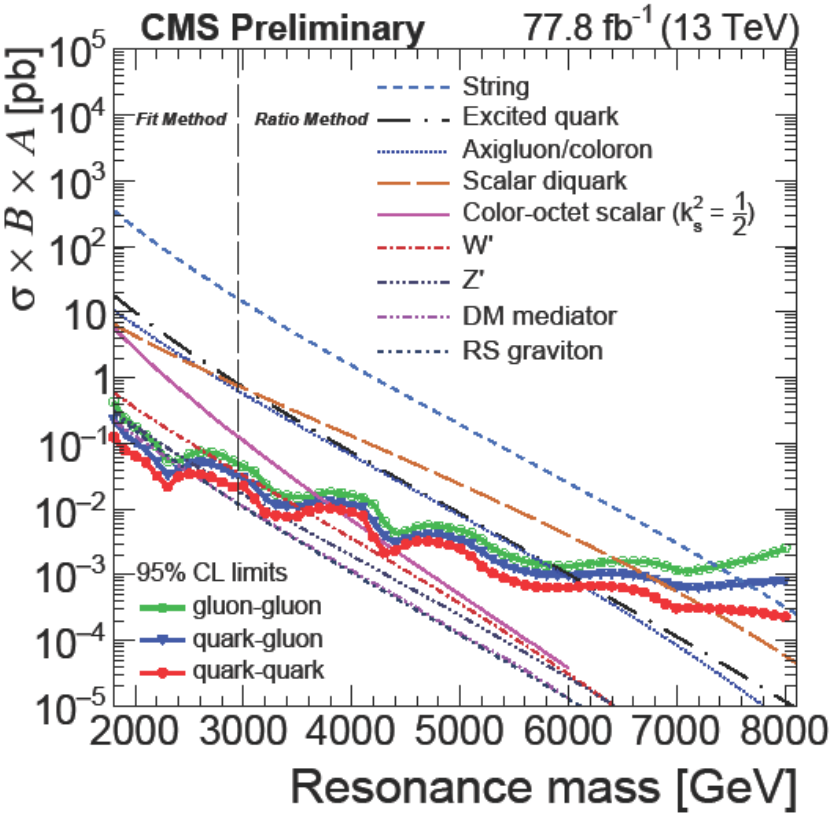
- Possible candidate for a massive resonance decaying to pairs of dijet resonances.



Dijet Mass & Limits

CMS-PAS-EXO-17-026



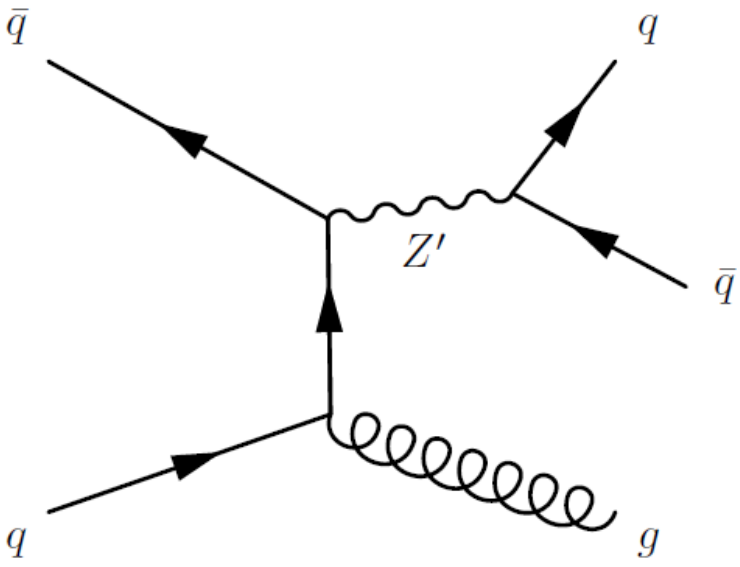


- Data is well modeled by both ratio method and the background fit.
  - No evidence for dijet resonances.
- **We set limits on 10 different models of dijet resonances including those of a DM mediators.**
  - Expected limits have improved by 0.2-0.3 TeV

Boosted dijet in a Nutshell

JHEP 01 (2018) 097

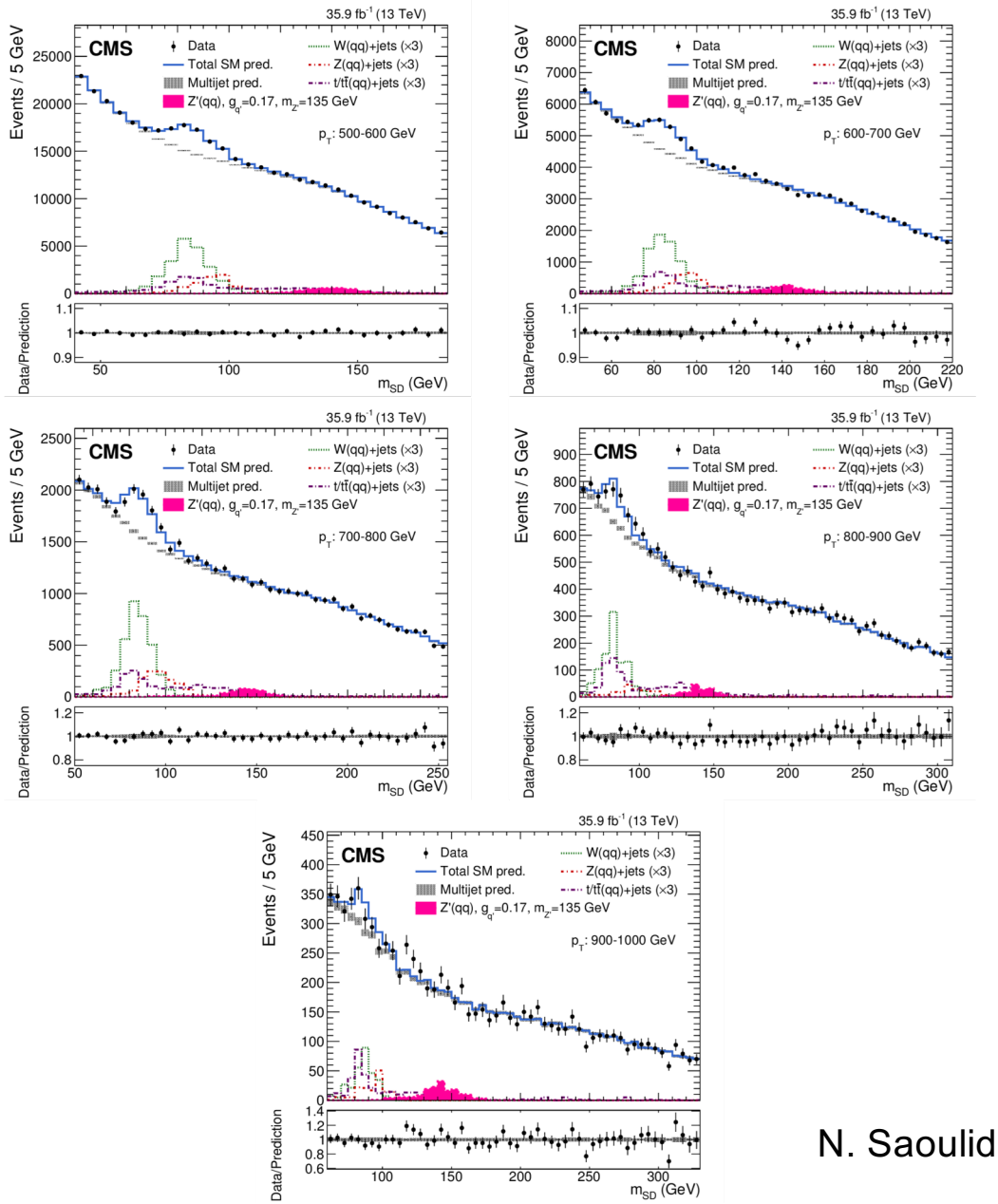
- Search for Z' resonance produced in association with a jet (m_{SD}:50-450 GeV).
- Uses **ISR jet** to overcome trigger requirements.
- Uses **jet substructure** techniques to identify 2 prong-signal.
- Background is estimated from data by inverting substructure requirement.
- Use **soft-drop mass** distribution to look for signal.



AK8 jets (pT>500 GeV) or
CA15 jets (pT>550 GeV)

Boosted dijet mass

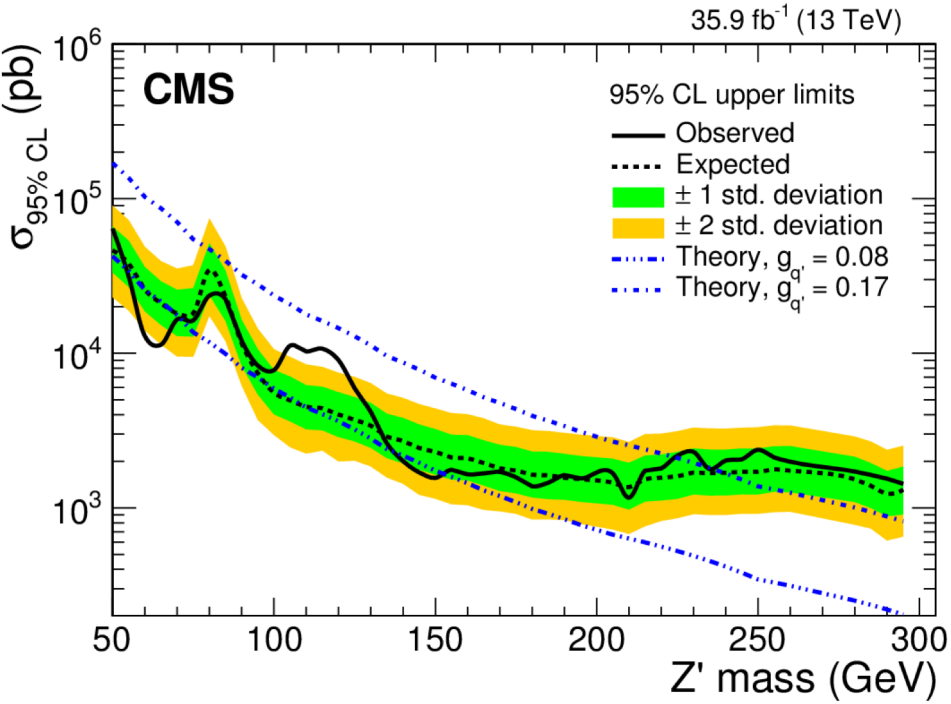
JHEP 01 (2018) 097

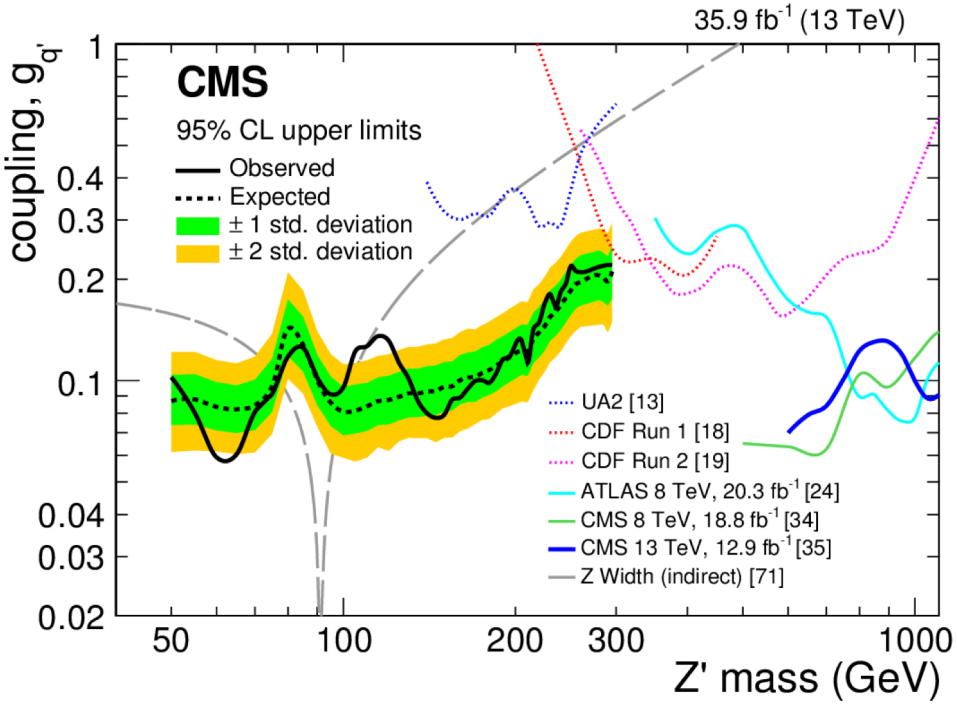


- The W and Z peaks clearly visible in an all hadronic final state.
- Sensitivity of search extended significantly to lower Z' masses

Boosted dijet limits

JHEP 01 (2018) 097



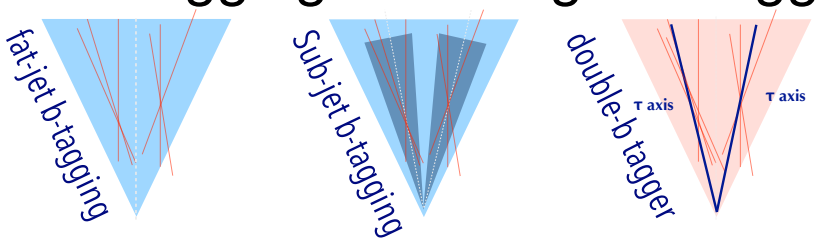


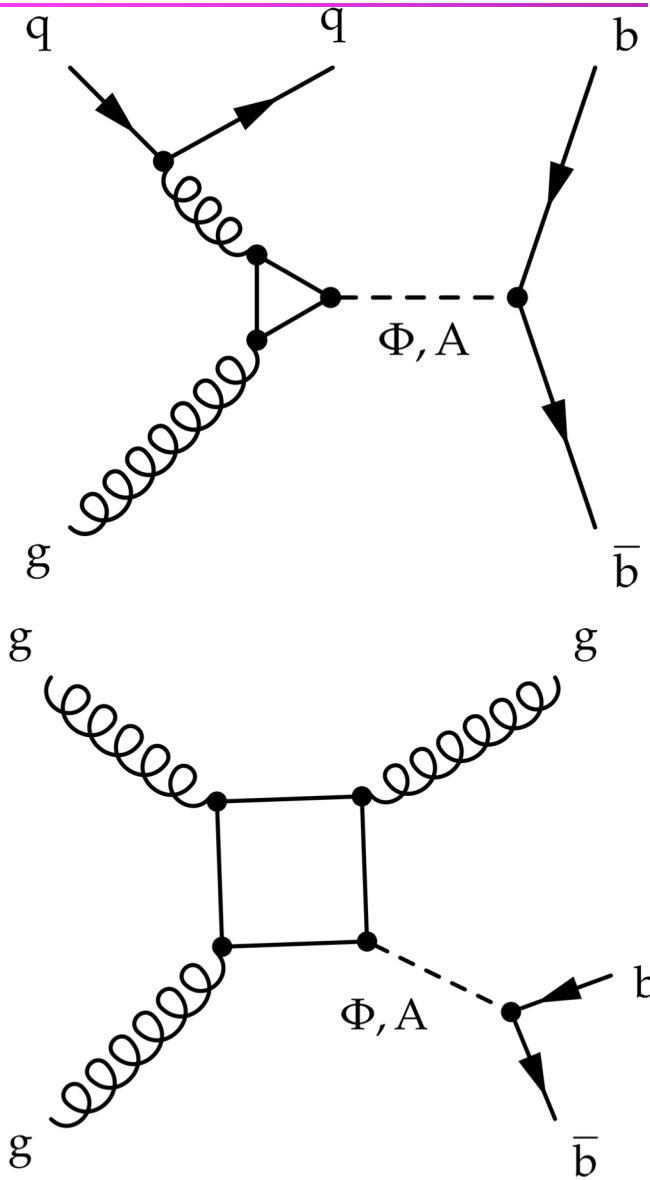
Z' limits in a previously unexplored region.

Boosted b-tagged dijet in a Nutshell

arXiv:1810.11822

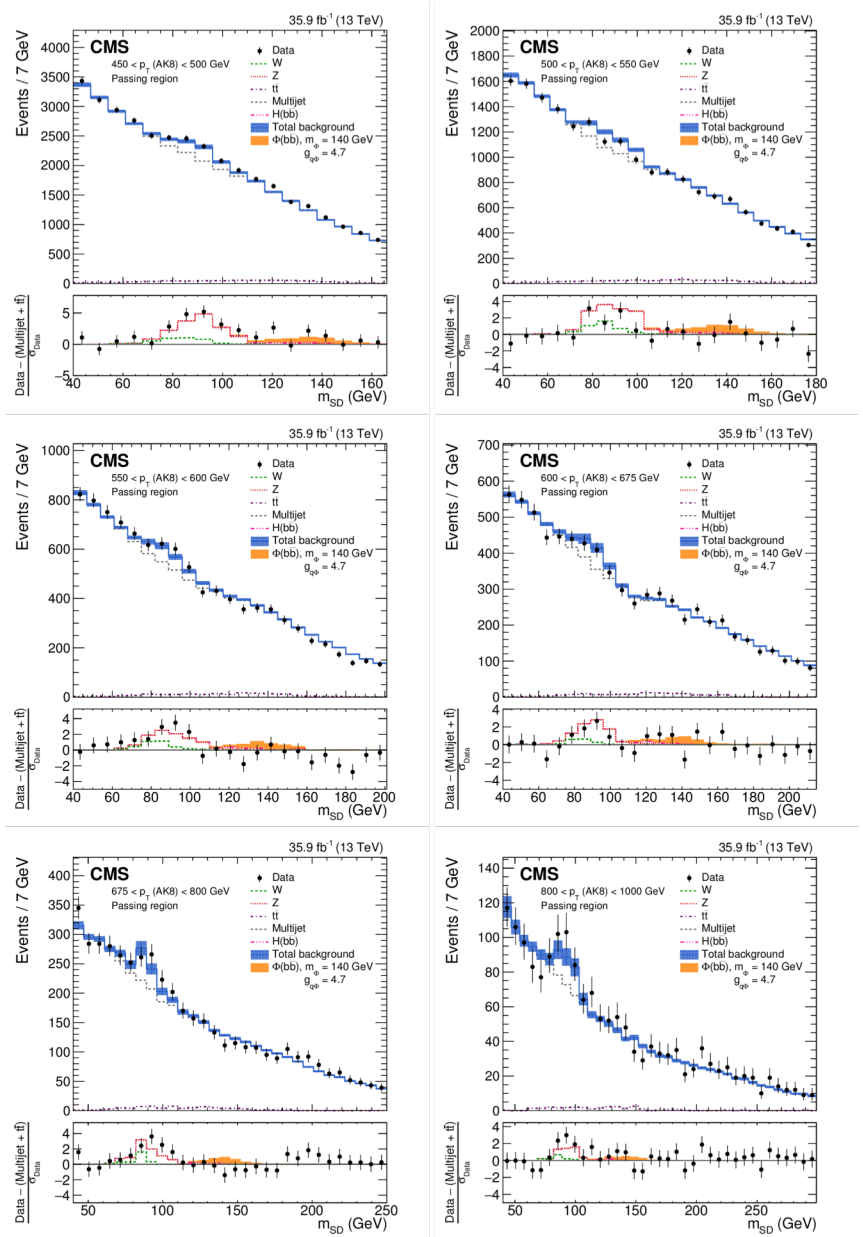
- Search for Φ resonance decaying to a bbbar pair produced in association with a jet using **two jet cone-sizes (AK8 0.8 and CA1.5) to probe lower and higher resonance masses.**
- Use **ISR jet** to overcome trigger requirements.
- Use **jet substructure and soft-drop mass** techniques to identify 2 prong-signal.
- Background is estimated from data by inverting the b-tagging requirement.
- Use double b-tagging and single b-tagging of sub-jets.





Boosted b-tagged dijet mass

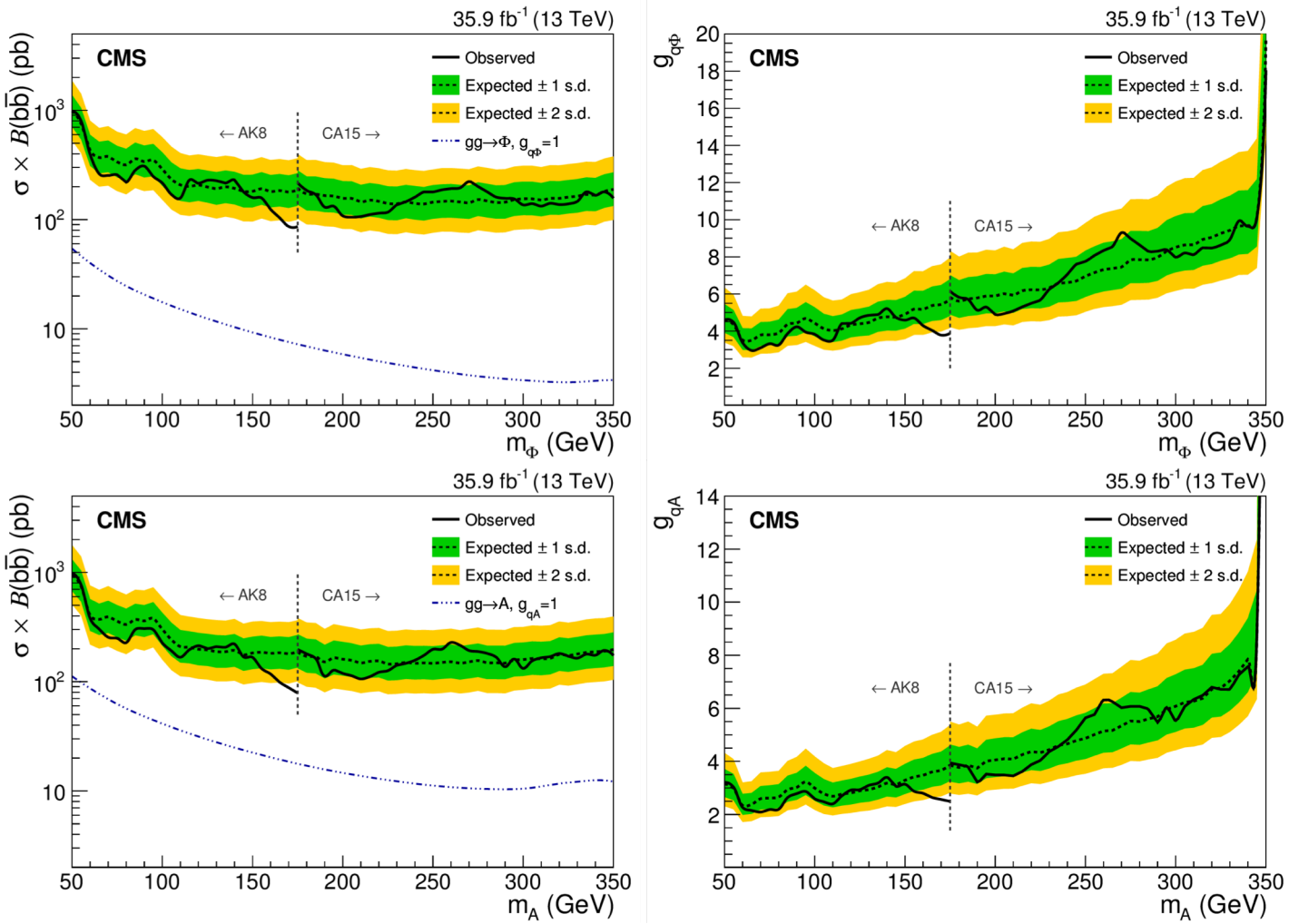
arXiv:1810.11822



- The Z peak clearly visible in an all hadronic final state with b-tagged jets.
- Sensitivity of search extended significantly to medium Z' masses

Boosted b-tagged dijet limits

arXiv:1810.11822

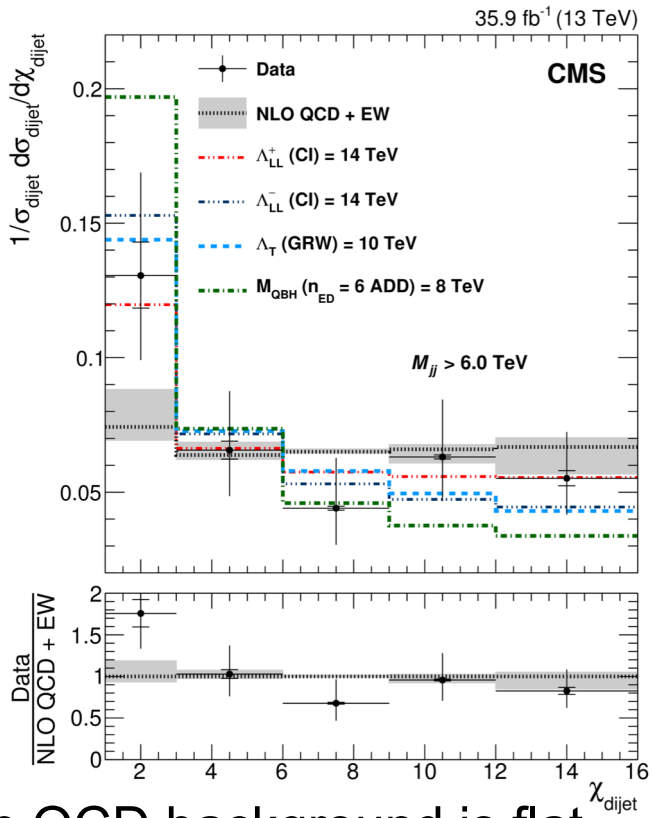


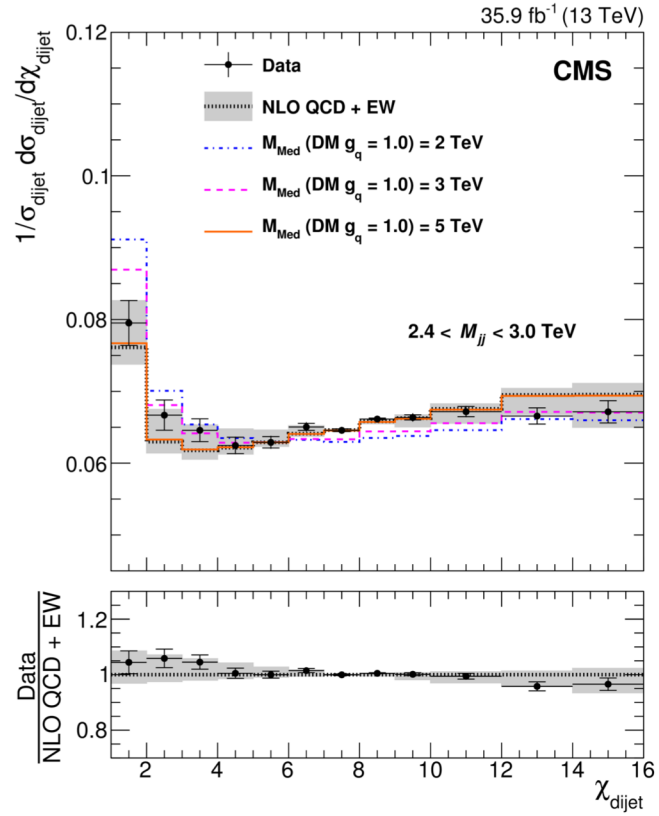
First constraints from the LHC on exotic bottom quark-antiquark resonances with masses below 325 GeV

Dijet χ Distributions

Eur. Phys. J. C 78 (2018) 789

$$\chi = e^{|y_1 - y_2|} \approx \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$



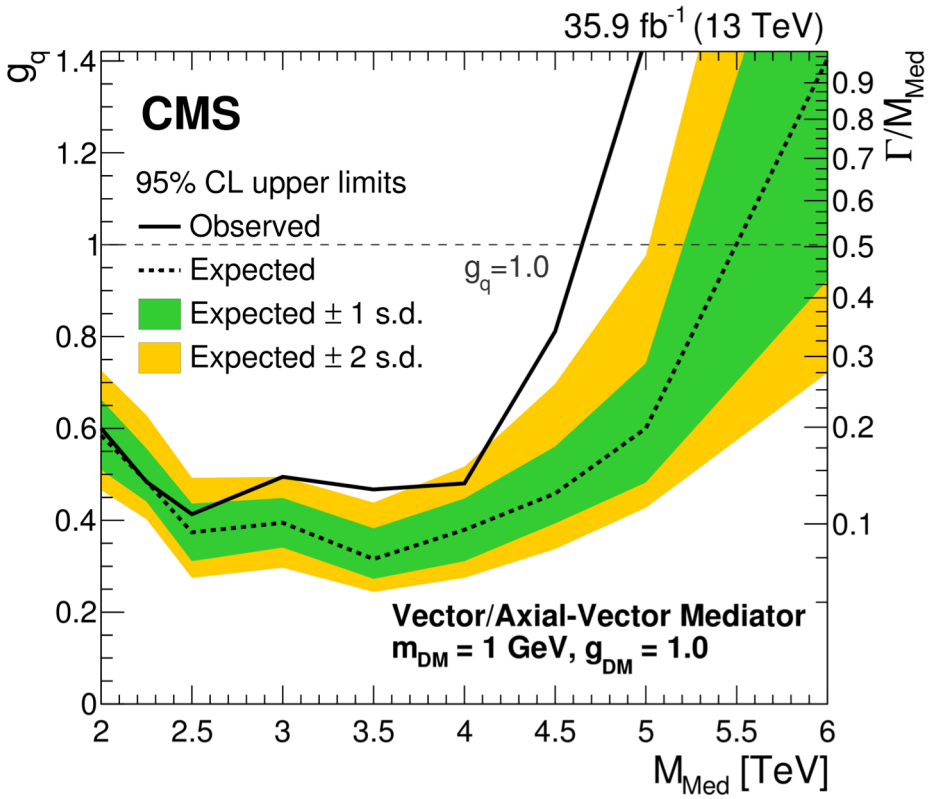


- χ chosen since main QCD background is flat.
- Experimental uncertainties dominated by jet resolution and relative (vs η) JES (absolute cancels)
- Theoretical uncertainties dominated by non perturbative corrections and renormalization scale.

Dijet x Limits

Eur. Phys. J. C 78 (2018) 789

	Model	Observed lower limit (TeV)	Expected lower limit (TeV)
CI	$\Lambda^{+}_{LL/RR}$	12.8	14.6 ± 0.8
	$\Lambda^{-}_{LL/RR}$	17.5	23.5 ± 3.0
	Λ^{+}_{VV}	14.6	16.4 ± 0.8
	Λ^{-}_{VV}	22.4	30.7 ± 3.7
	Λ^{+}_{AA}	14.7	16.5 ± 0.8
	Λ^{-}_{AA}	22.3	30.6 ± 3.8
	$\Lambda^{+}_{(V-A)}$	9.2	11.5 ± 1.0
	$\Lambda^{-}_{(V-A)}$	9.3	11.8 ± 1.1
ADD	Λ_T (GRW)	10.1	11.4 ± 0.9
	M_S (HLZ) $n_{ED} = 2$	10.7	12.4 ± 1.0
	M_S (HLZ) $n_{ED} = 3$	12.0	13.6 ± 1.1
	M_S (HLZ) $n_{ED} = 4$	10.1	11.4 ± 0.9
	M_S (HLZ) $n_{ED} = 5$	9.1	10.3 ± 0.8
	M_S (HLZ) $n_{ED} = 6$	8.5	9.6 ± 0.8
QBH	M_{QBH} (ADD $n_{ED} = 6$)	8.2	8.5 ± 0.4
	M_{QBH} (RS $n_{ED} = 1$)	5.9	6.3 ± 0.7
DM	Vector/Axial-vector M_{Med}	2.0 – 4.6	2.0 – 5.5



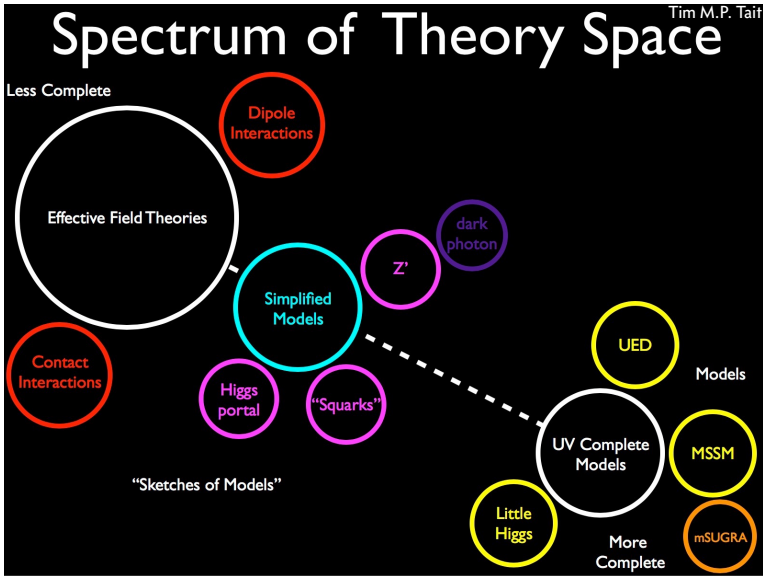
- **Unique analysis with coupling limits extending to higher DM mediator masses and larger DM mediator widths.**
- Additional **limits** are placed to **a variety of new physics models like quark contact interactions, extra spatial dimensions, quantum black holes.**

Where we stand , What is next

- Jets are a unique tool to search for new physics at the LHC.
- Recent significant improvements in:
  - Analysis methodologies
  - Substructure techniques
  - Triggering
  - Heavy flavor tagging

  allow us to probe lower particle masses and larger widths, thus significantly enhancing our physics discovery potential.
- **There are many more results in the pipeline aiming at legacy publications with the full 2016+2017+2018 dataset so stay tuned!**

Dark Matter Particles and Mediators

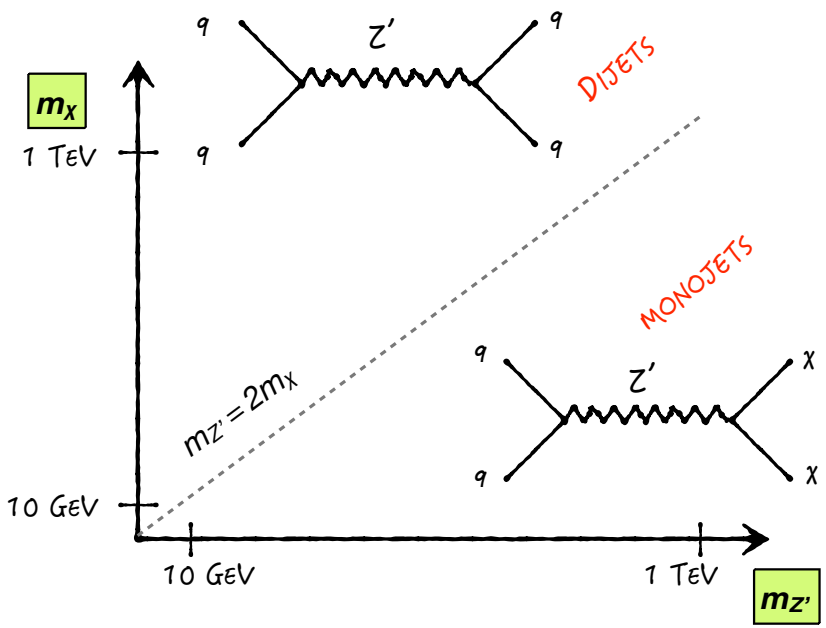


- There is plenty of evidence for the existence of Dark Matter which we have only seen so far gravitationally, and there are several ways to search for it.
- **Direct Dark Matter searches** : Detect interactions of DM particle (or particles) with terrestrial detectors
- **Indirect Dark Matter searches** : Detect DM-DM interactions in the cosmos, ie DM-DM interactions at the centre of the galaxy
- **Collider Searches : Produce DM and DM mediators in the Lab**

N. Saoulidou (Univ. of Athens, Greece)

Dark Matter Searches: Simplified Models

https://arxiv.org/pdf/1703.05703.pdf



$$\Gamma^{\rm tot}_{\rm AV} = \Gamma^{\chi\bar{\chi}}_{\rm AV} + 3 \times \sum_{q=u,d,s,c,b,t} \Gamma^{q\bar{q}}_{\rm AV}$$

$$\Gamma^{q\bar{q}}_{\text{axial-vector}} = \frac{g_q^2 M_{\rm med}}{4\pi} (1 - 4 z_q)^{3/2} ,$$

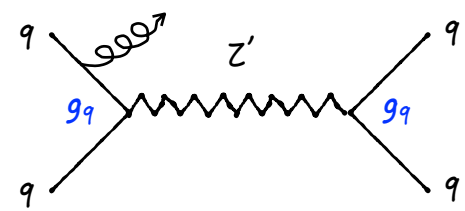
$$\Gamma^{q\bar{q}}_{\text{vector}} = \frac{g_q^2 M_{\rm med}}{4\pi} (1 - 4 z_q)^{1/2} (1 + 2 z_q) ,$$

$$z_i = m_i^2 / M_{\rm med}^2$$

- DM-nucleon scattering cross section:

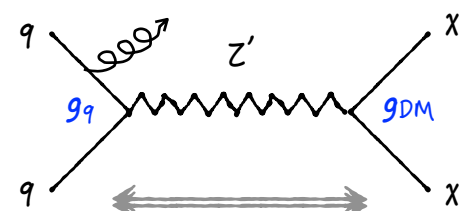
vector:

$$\sigma_{\rm SI} \simeq 6.9 \times 10^{-41}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$$

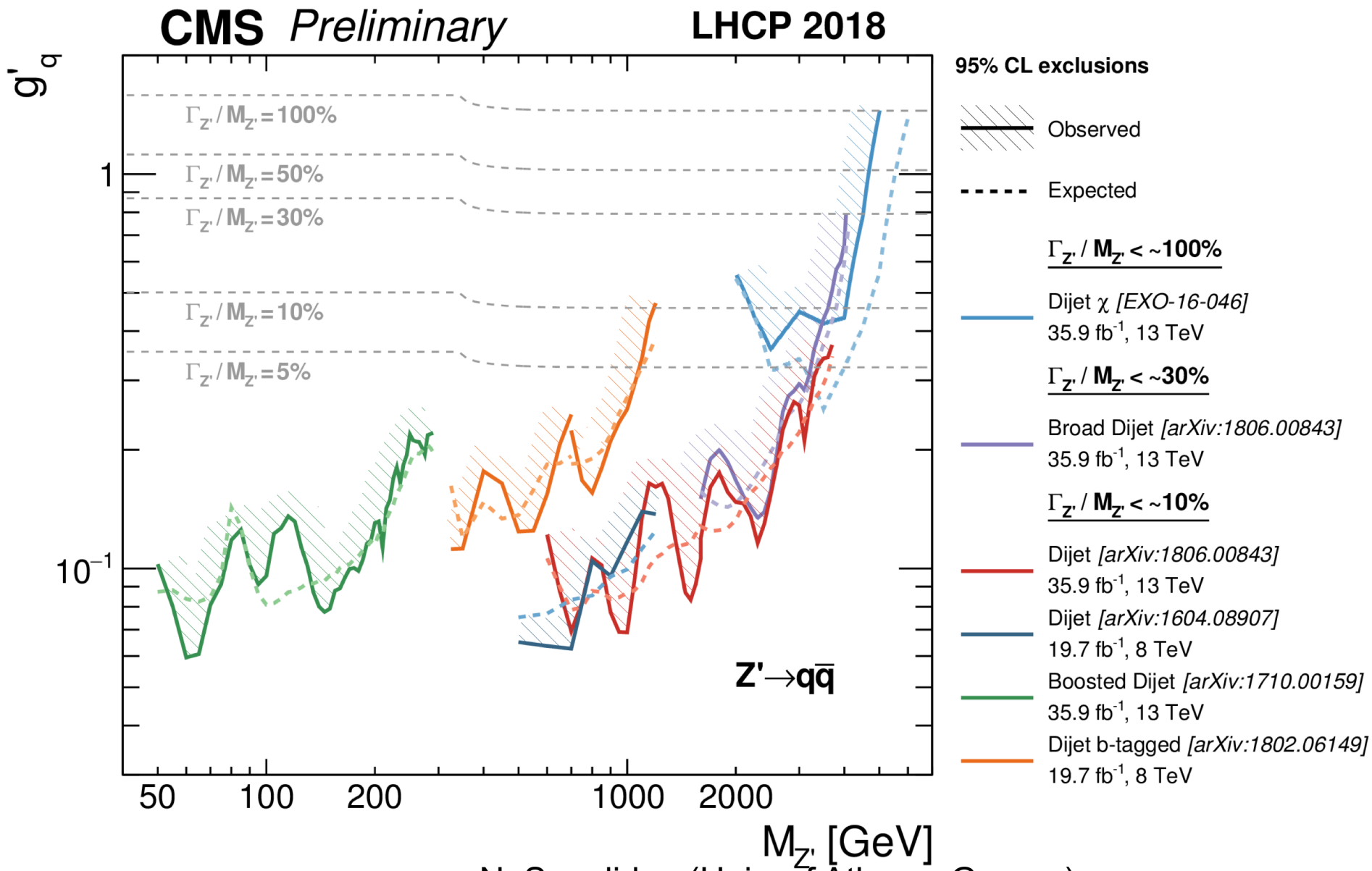


axial-vector:

$$\sigma^{\rm SD} \simeq 2.4 \times 10^{-42}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$$



Dark Matter Searches : g_q Coupling summary plot

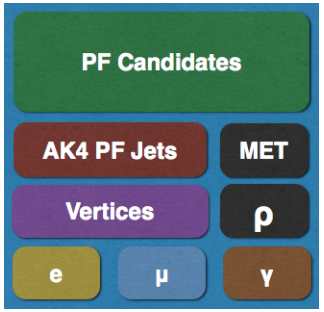


CMS Data Scouting

D. Anderson "Data Scouting at CMS" 2015 IEEE NSS/MIC

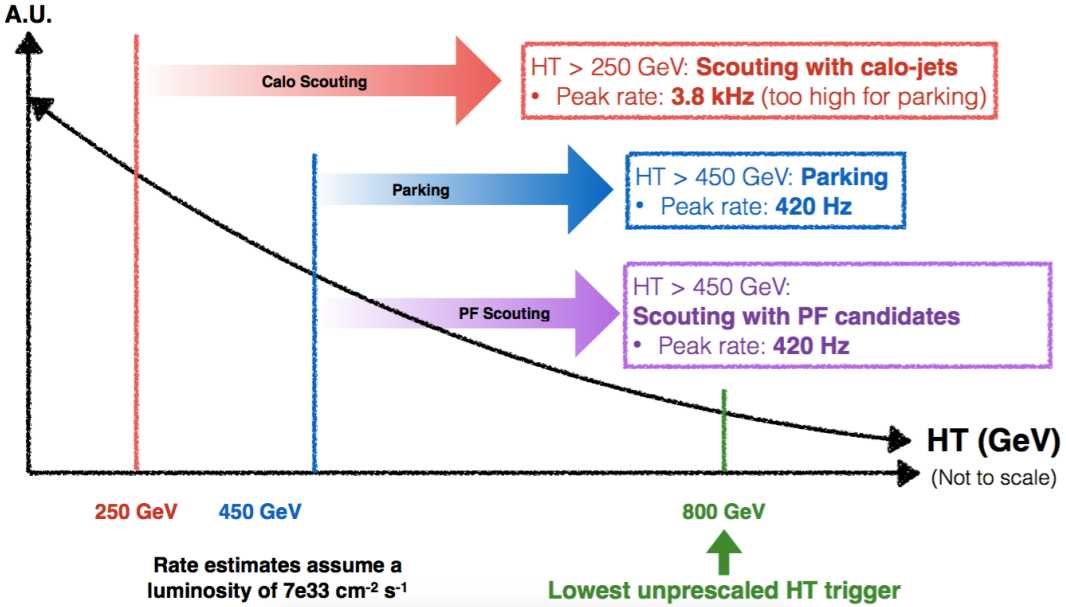
DATA SCOUTING

- Technique of data scouting
  - Reconstruct/save only necessary information to perform analysis → record more events
  - "**PF Scouting**" limited by CPU time: allows us to get down to **H_T > 450 GeV**
  - "**Calo Scouting**" allows us to get down to **H_T > 250 GeV** (L1 trigger limited)



Calo Scouting 4kHz × 1.5 kB

PF Scouting 500 Hz × 10 kB



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Model-less Motivation

Robert Harris (2006)

- **Theoretical Motivation**
  - The many models of dijet resonances are ample theoretical motivation.
  - But experimentalists should not be biased by theoretical motivations . . .

- **Experimental Motivation**
  - The LHC collides partons (quarks, antiquarks and gluons).
    - LHC is a parton-parton resonance factory in a previously unexplored region
    - Motivation to search for dijet resonances and contact interactions is obvious
      - We <u>must</u> do it.
  - We search for generic dijet resonances, not specific models.
    - Nature may surprise us with unexpected new particles.
    - One search encompasses ALL narrow dijet resonances.
  - We search for deviations in dijet angular distributions vs. dijet mass
    - Now the search is focused on a model of quark contact interactions.
    - It will also be applicable for generic parton contact interactions.
    - And essential for confirming and understanding any resonances seen.