Searches for dark matter mediators at LHC

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*on behalf of the **CMS** and **ATLAS** Collaborations*

Collider Physics and the Cosmos
Galileo Galilei Institute, 9-13 October 2017, Arcetri (Italy)

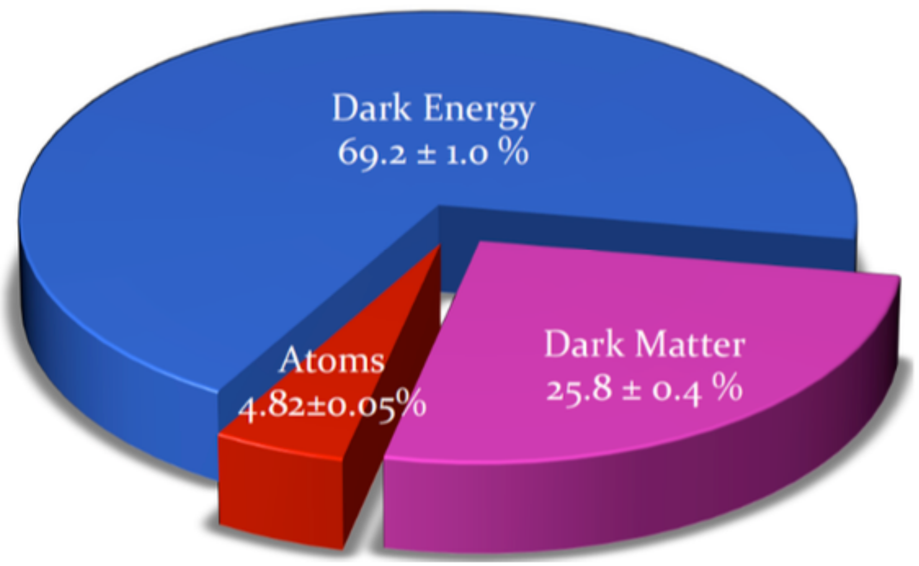
Dark Matter (DM) in Cosmology

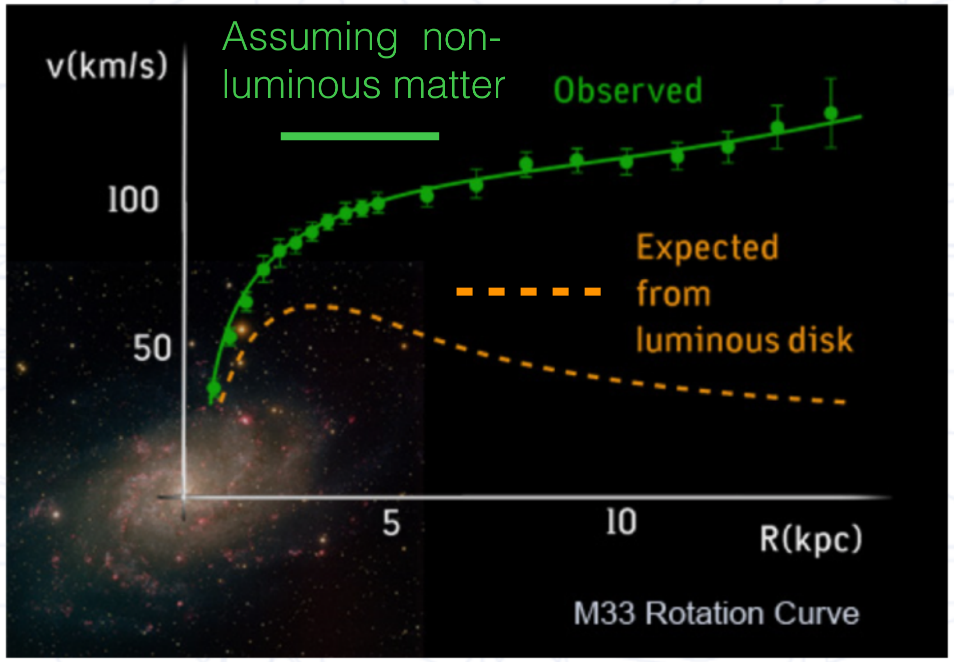
- Cosmological observations support that **85% of the matter component of the universe is dark matter (DM)**

- Key properties of DM particles
  - massive (gravitational interaction)
  - dark (no color and no electric charge)
  - stable (or very long-lived)
  - weakly interacting with SM particles

- The **hunt of Dark Matter** particles is an **interdisciplinary effort**
  - from cosmology to particle physics
  - potentially accessible by different experiments
  - potentially accessible by precision standard model measurements

Composition Of The Universe
arXiv: 1502.01589

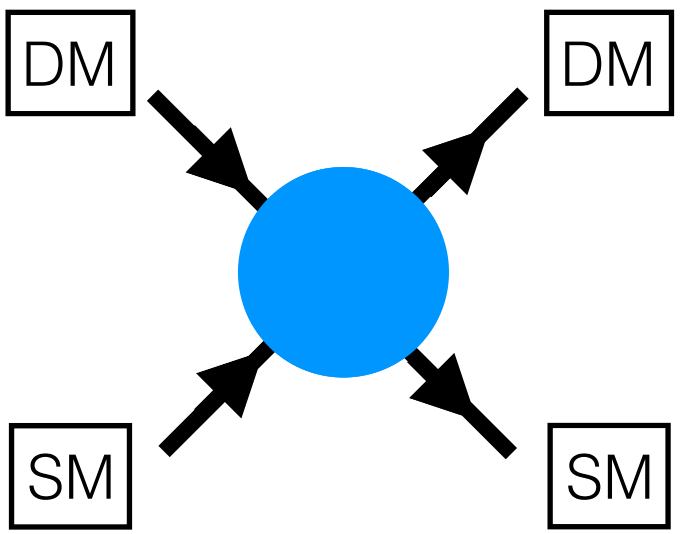




Dark Matter Detection

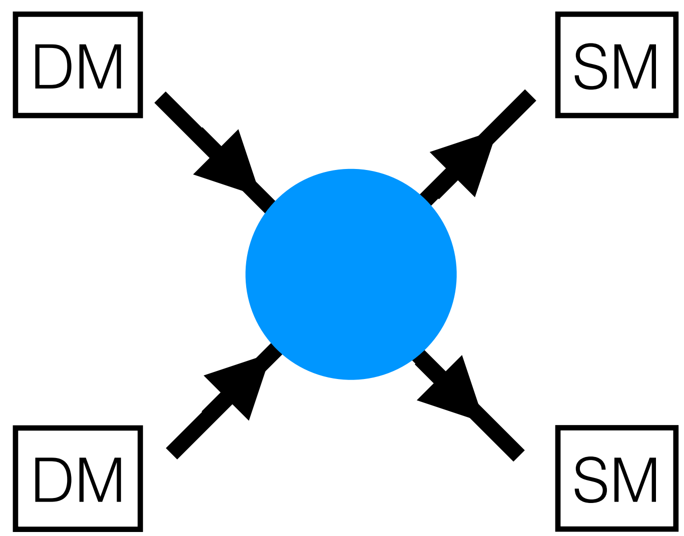
Direct Detection

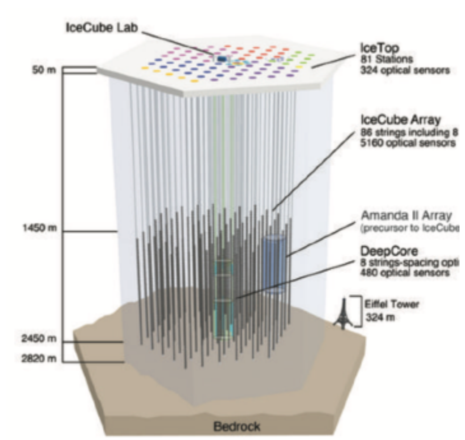
DM-nucleon scattering



Indirect Detection

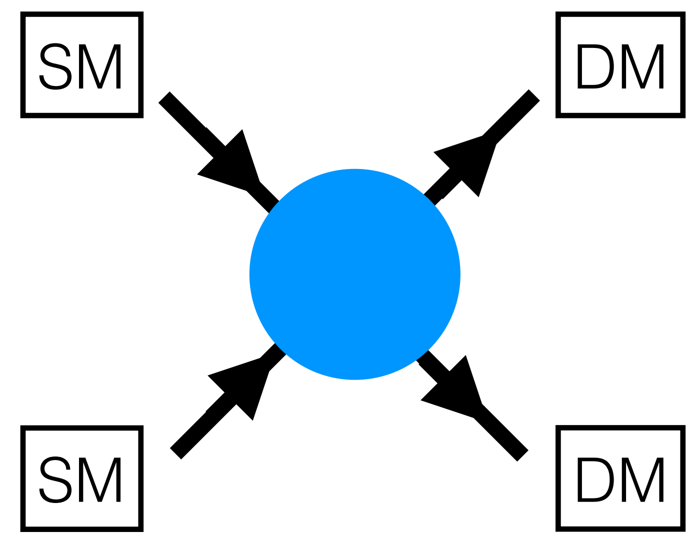
DM annihilation





Collider Experiments

DM annihilation



Dark Matter Models for Collider Searches

less complete → more complete

CONTACT INTERACTIONS

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Dark Matter Effective Field Theory

Dark photons

Z' boson

Higgs portal

Simplified Dark Matter Models

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UED

SUSY

Complete Dark Matter Models

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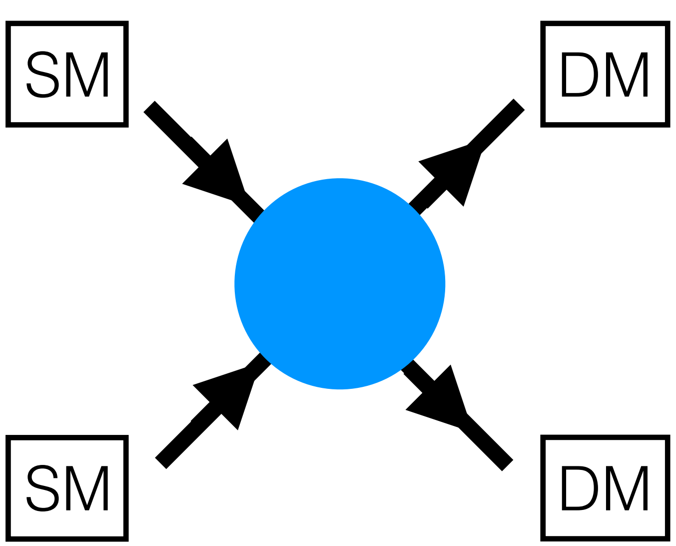
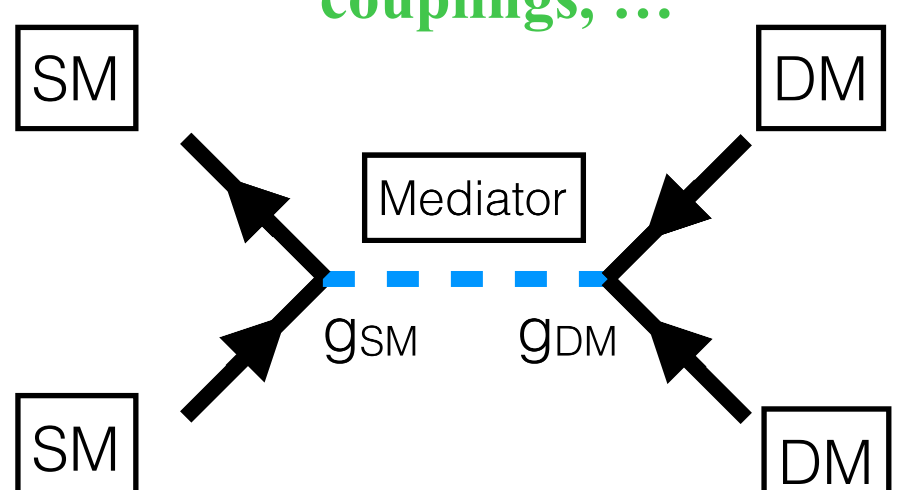
Ex. Contact interaction
Energy Scale Λ
Run1 results based on this model

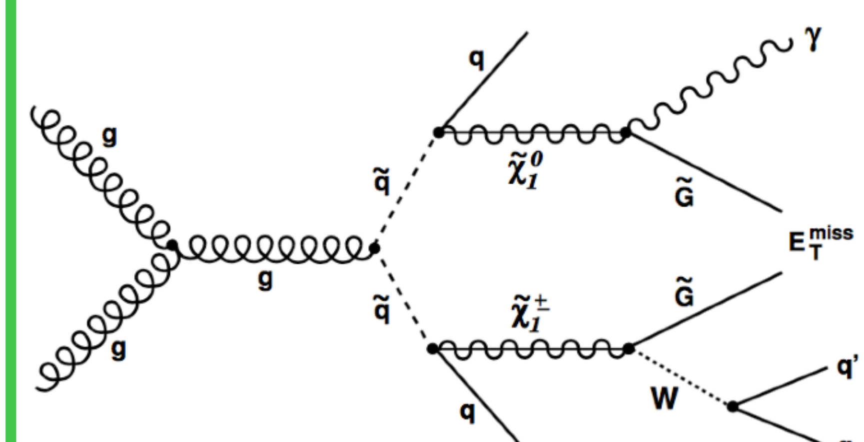


Ex. Z' mediator
Parameters: DM mass, mediator mass/spin, couplings, …



LHCDMWG - arXiv:1603.04156

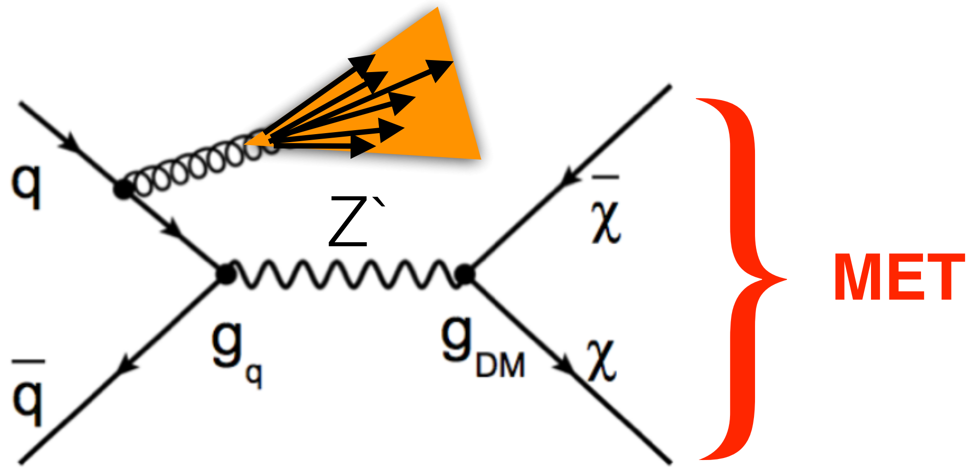
Ex. Decay chain in SUSY GMSB models
DM = gravitino

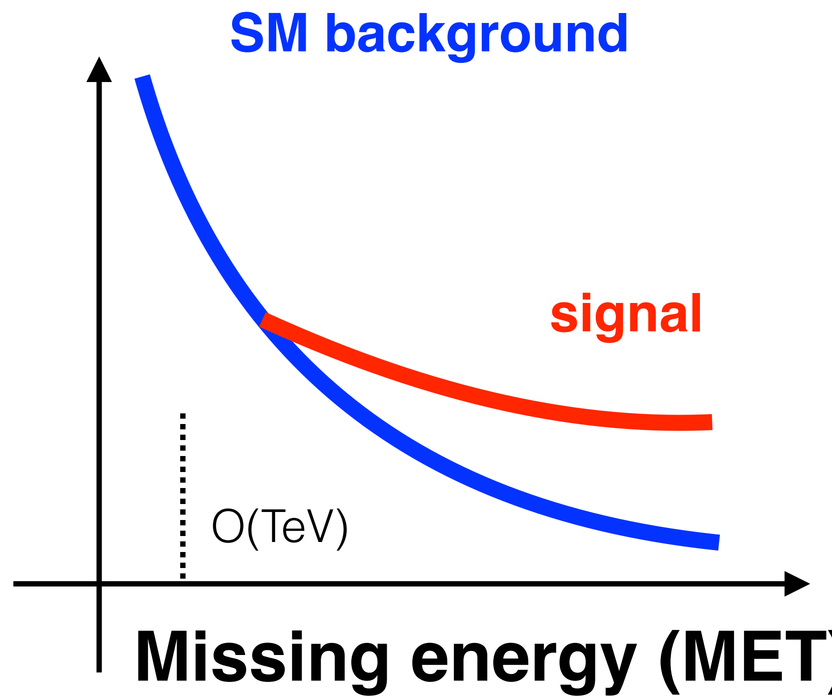


DM Searches at LHC

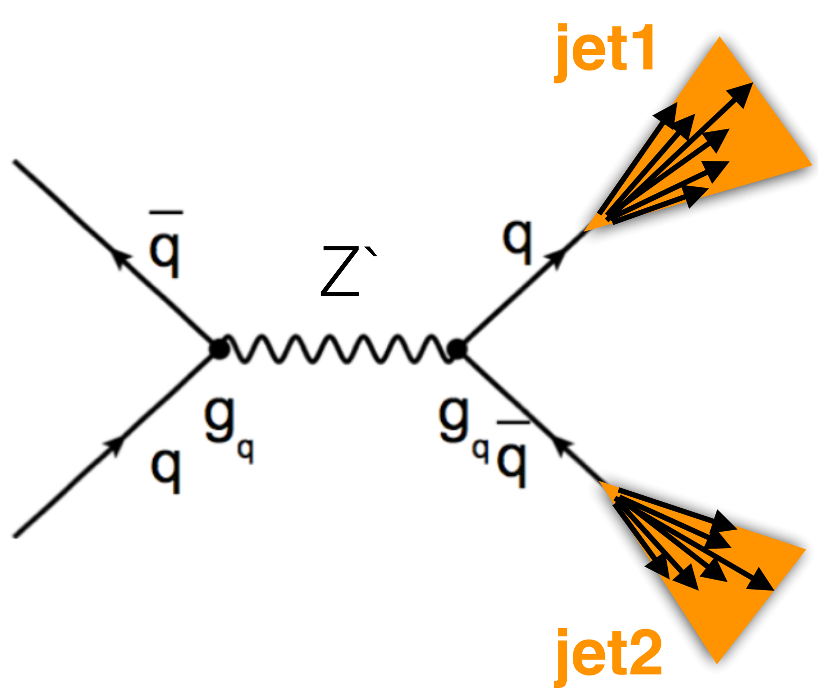
- Mono-X searches
  - DM recoils against initial state radiation (jet, photon, Z/W …)
  - *see Adish Vartak's talk tomorrow*

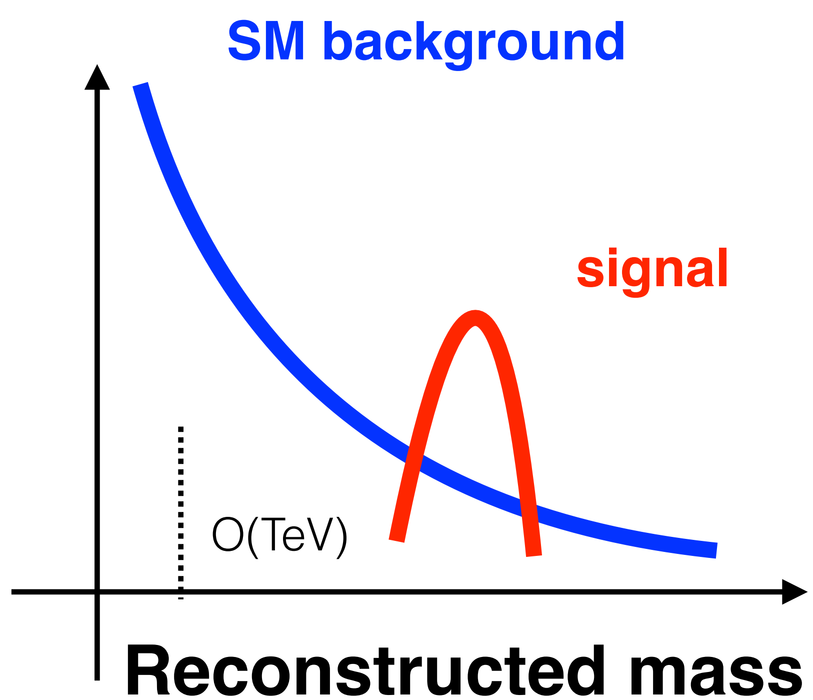
X = jet, γ, Z/W …





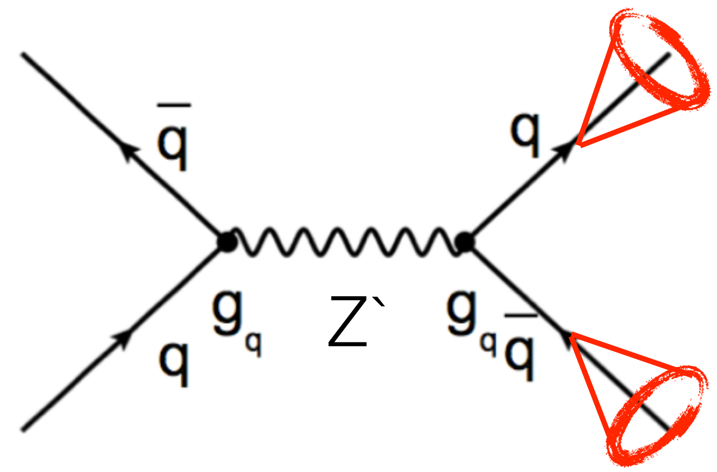
- Mediator searches
  - full reconstruction of mediator mass from decay products (bump search)
  - minimal model: **dijet final state**





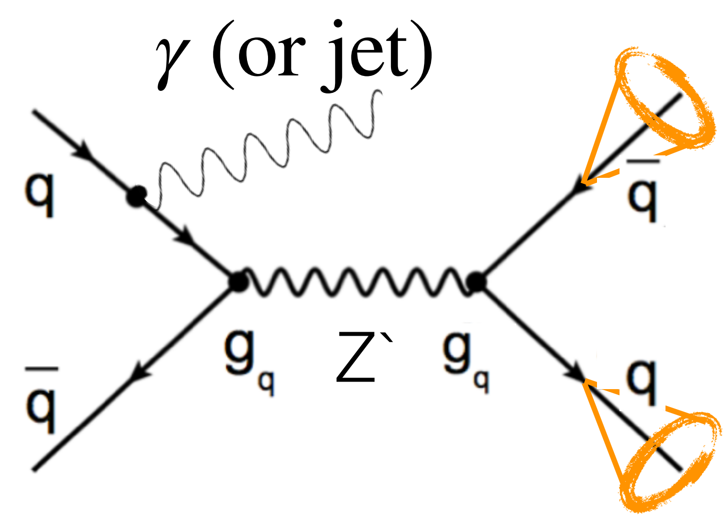
Dijet Analyses

- High-mass ($M>1.5$ TeV)
  - resonance produced almost at rest
  - trigger on high p_T jets from resonance decay
- Intermediate-mass ($0.5<M<1.5$ TeV)
  - lower jet p_T trigger thresholds
  - analysis with reduced data format
    - "data scouting" for CMS
    - "trigger-level analysis" for ATLAS
- Low-mass ($0.2<M<0.5$ TeV)
  - trigger on high p_T photon or jet from initial state radiation (ISR)
- Very low-mass ($M<0.2$ TeV)
  - decay products of boosted Z` within single wide-jet + ISR jet



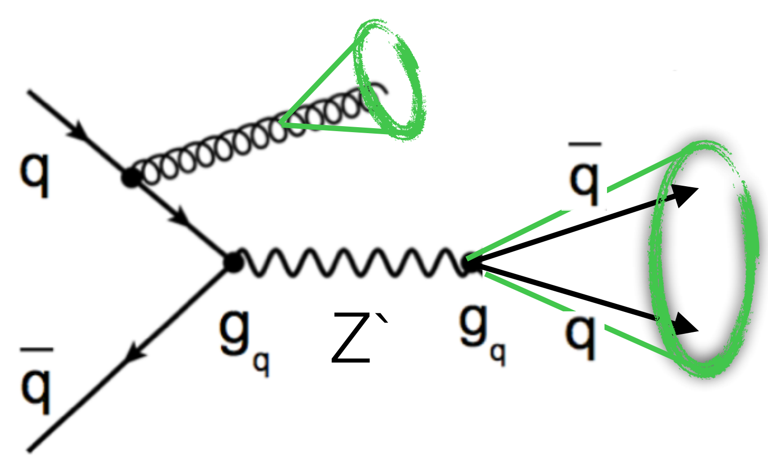
High-Mass

2 resolved jets



Low-Mass

1 ISR γ or jet
+
2 resolved jets

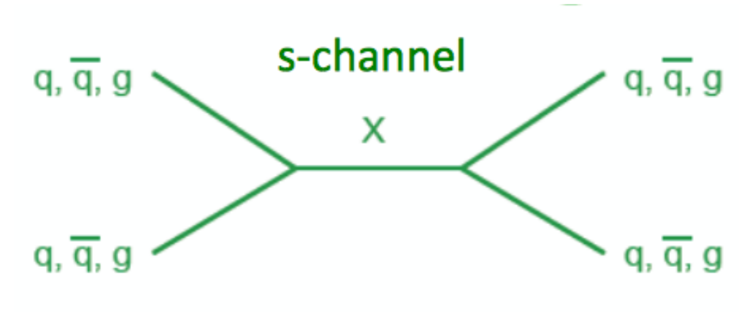


Very Low-Mass

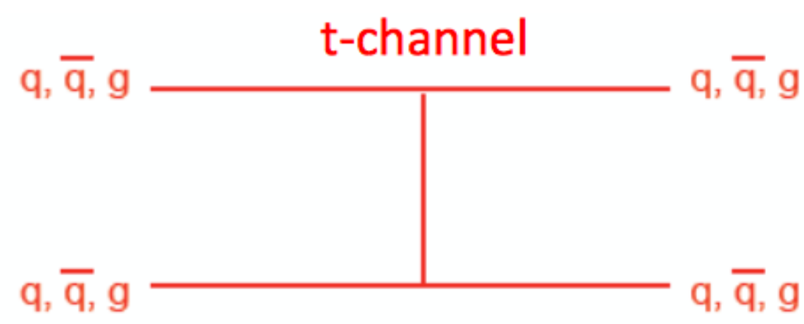
1 ISR jet
+
1 wide-jet

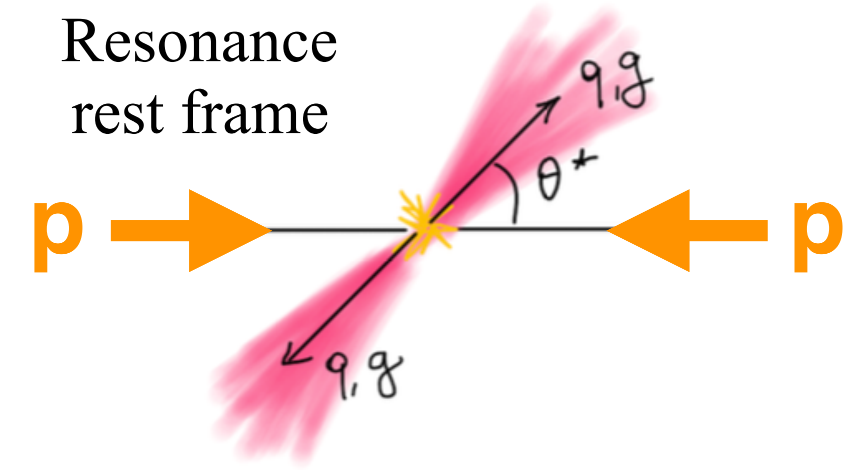
Kinematics of Dijet Resonances

Resonance signal



QCD background

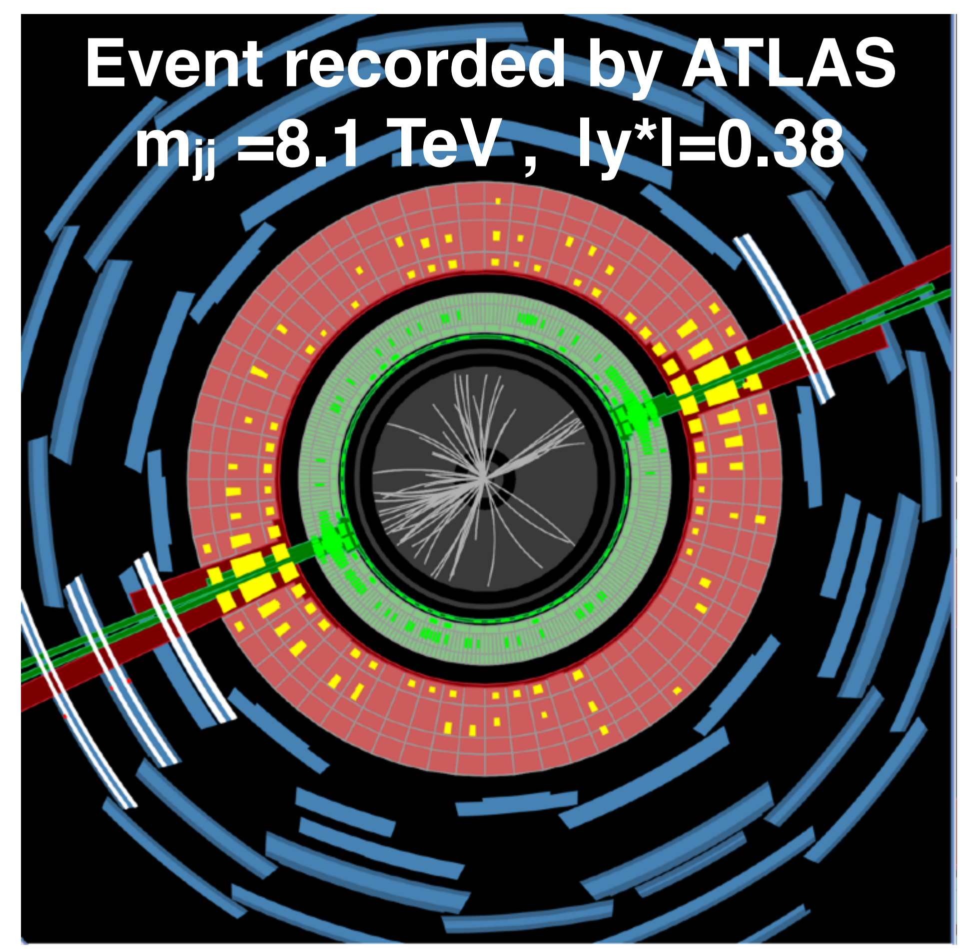




$$\cos\theta^* = \tanh y^* = \tanh\left[(\eta_{jet1} - \eta_{jet2})/2\right]$$

- Reconstructed **mass of dijet system (m_{jj})**
  - related to resonance mass

- Scattering angle (θ^*) in resonance rest frame
  - related to resonance spin
  - require small $\cos\theta^*$ to suppress QCD t-channel



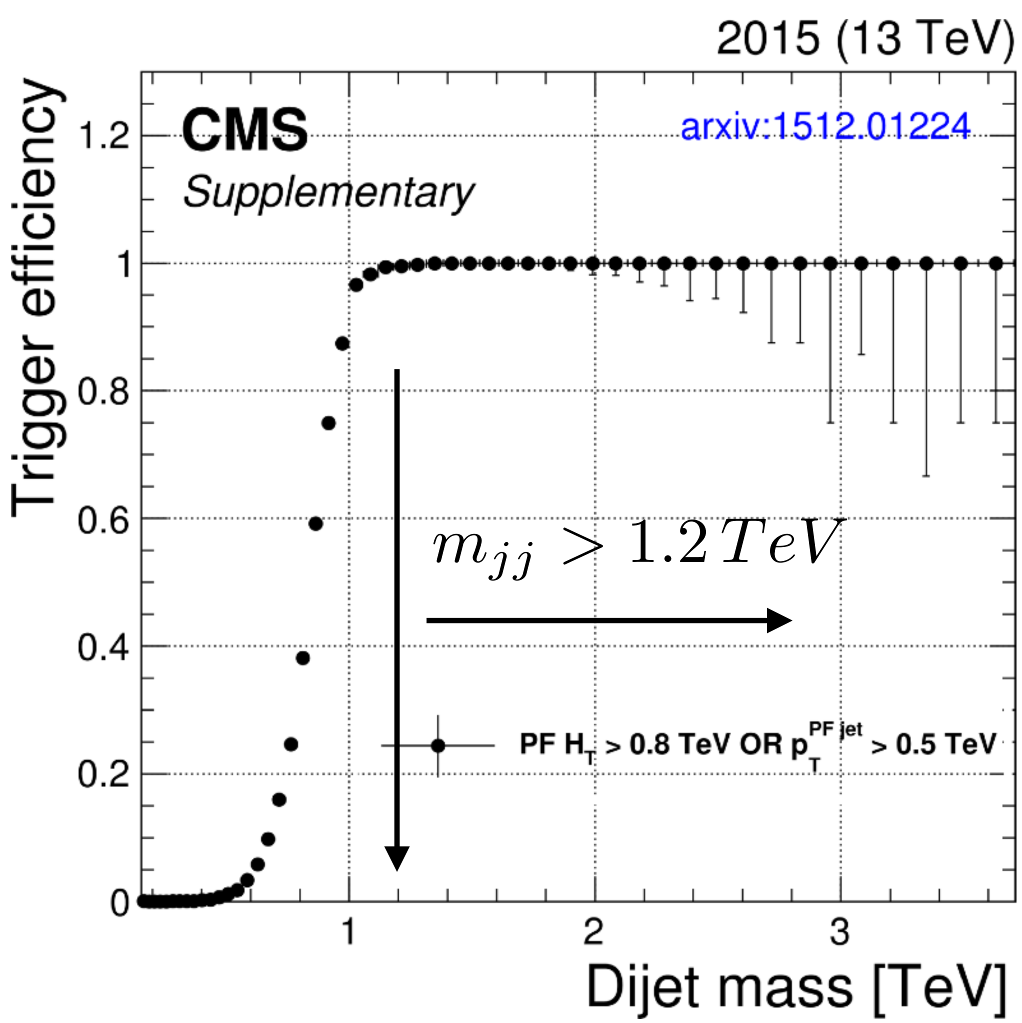
Trigger Challenge

- Experimental challenge
  - large dijet cross section at LHC
  - limited resources to process and store data (total CMS/ATLAS budget ~1KHz)

$\sigma_{jet}(p_T^{jet} > 100GeV)$	10^3 nb
Inst. Luminosity	10^{34} cm^{-2} s^{-1}
Event Rate	10 KHz

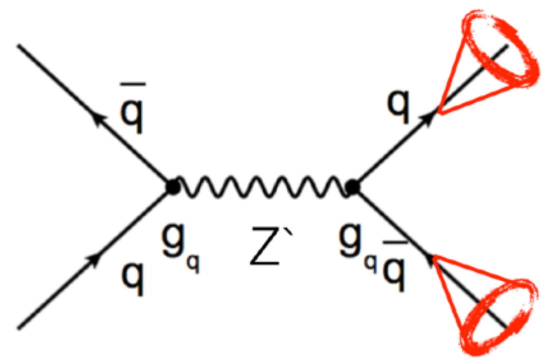
- About 10 Hz allocated for dijet searches
  - need to apply tight trigger selection
  - $H_T = \sum_{jets} p_T^i > 800\text{GeV}$
  - $p_T(\text{single jet}) > 500\text{GeV}$

- Search for resonances above **minimum dijet mass** where **trigger is fully efficient**
  - avoid trigger turn-on since difficult to model it with sufficient statistical precision



Dijet Mass Spectrum

- Search resonances with mass >1.5 TeV
  - dijet mass resolution ~10%
  - look for bumps in the mass spectrum



High-Mass

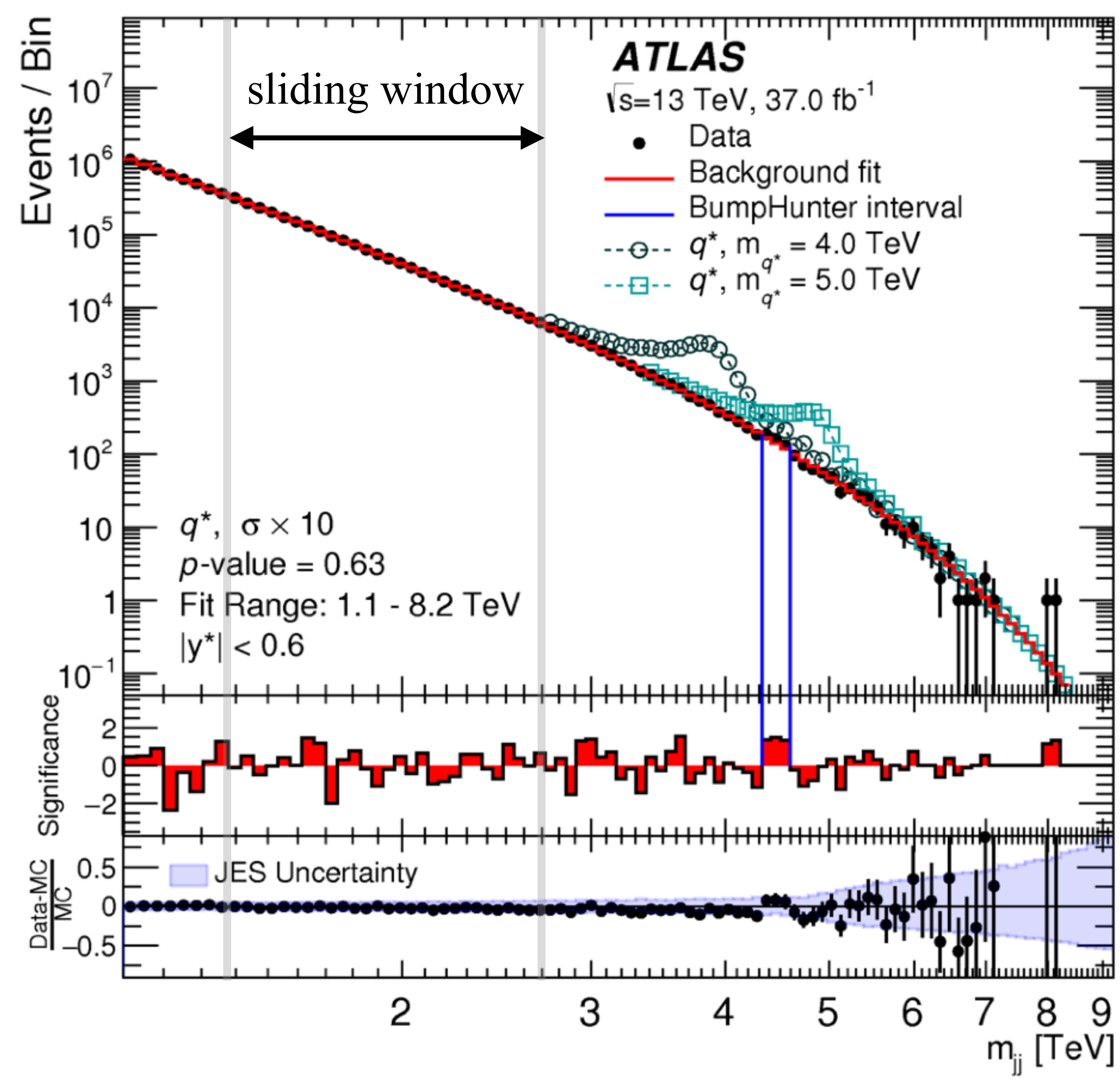
2 resolved jets

- Background estimated by fit to data using smoothly falling function
  - do not rely on QCD simulation

$$\frac{d\sigma}{dm_{jj}} = \frac{p_0(1-x)^{p_1}}{x^{p_2}} \qquad x = \frac{m_{jj}}{13000}$$

- Sliding window fit technique (ATLAS)
  - more robust than global fit with higher integrated luminosity expected in future

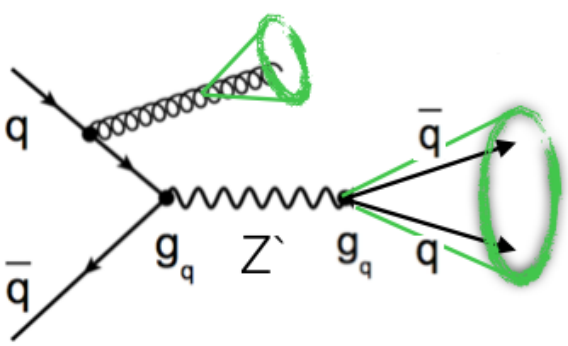
- **No sign of new resonances**

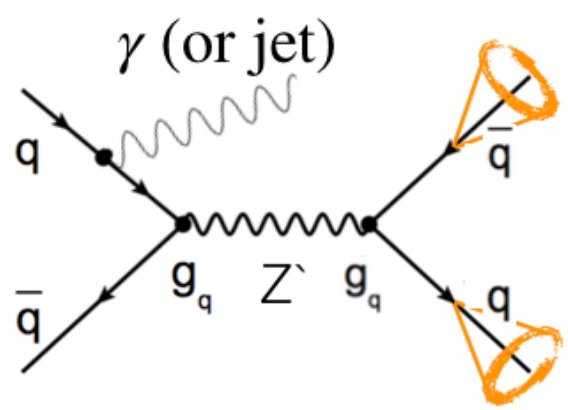


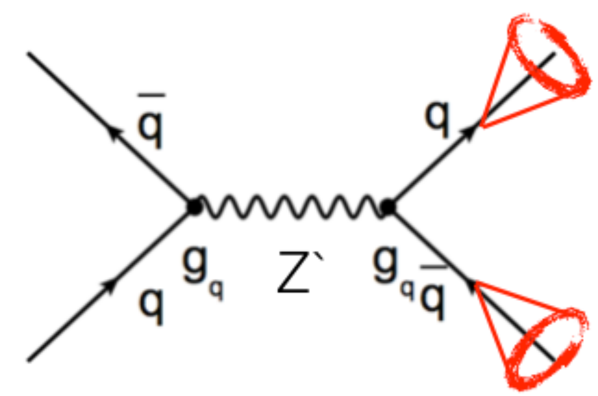
PhysRevD.96.052004

Resonance Mass Ranges

Associated Production (ISR)		Inclusive Analysis	
Boosted dijet	Resolved jets	Trigger Level Analysis	Standard Triggers
1 ISR jet + 1 widejet	1 ISR jet or γ + 2 jets	2 jets	2 jets





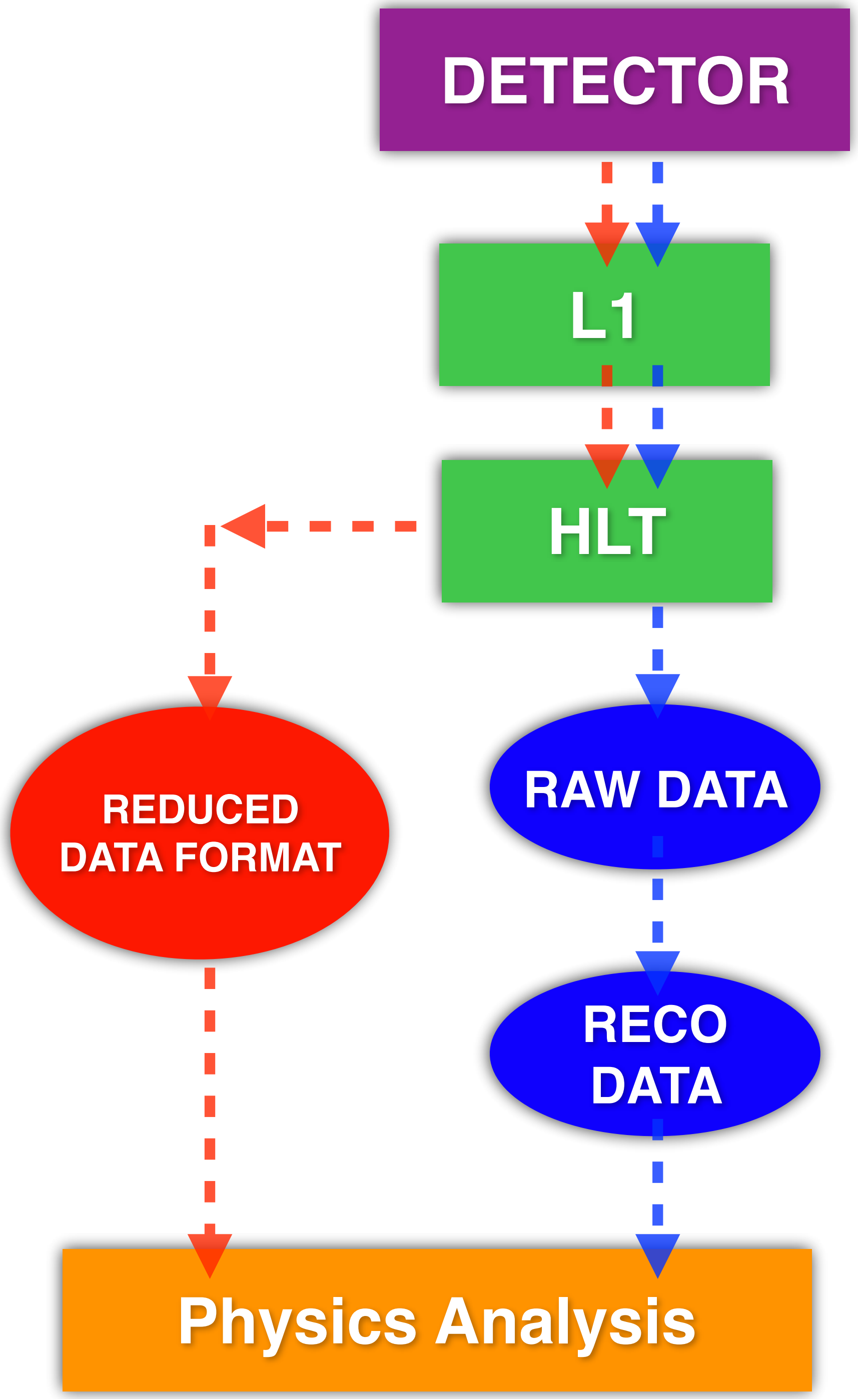


50 GeV | 200 GeV | 500 GeV | 1.5 TeV | 8.0 TeV

Resonance mass ranges

- High-mass search with the standard triggers starts at ~1.5 TeV
- In order to go to lower resonance masses we **need different trigger strategy**
  - trigger level analysis
  - initial state radiation (ISR) trigger

“Data Scouting” (CMS) , “Trigger Level Analysis” (ATLAS)



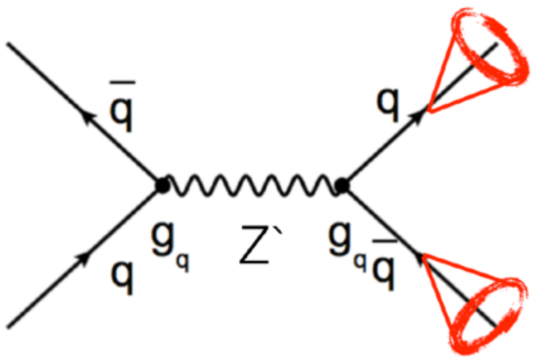
- Trigger strategy to probe lower resonance masses
  - lower trigger thresholds —> higher event rate
  - store reduce event content —> lower event size

	Main data stream	Data scouting
Trigger selection	All triggers (*ex. for CMS dijet* H_T>900 GeV)	Low-p_T jet triggers (H_T>250 GeV)
Event rate	~1 KHz	~4 KHz
Event content	FULL (RAW data + offline reconstruction)	REDUCED (store only jets reconstructed at trigger level)
Event size	~1 MB/event	~2-3 KB/event
Bandwidth	~1 GB/s	~0.01 GB/s

** Example from CMS Data Scouting, similar for ATLAS*

Dijet Analysis at Trigger Level

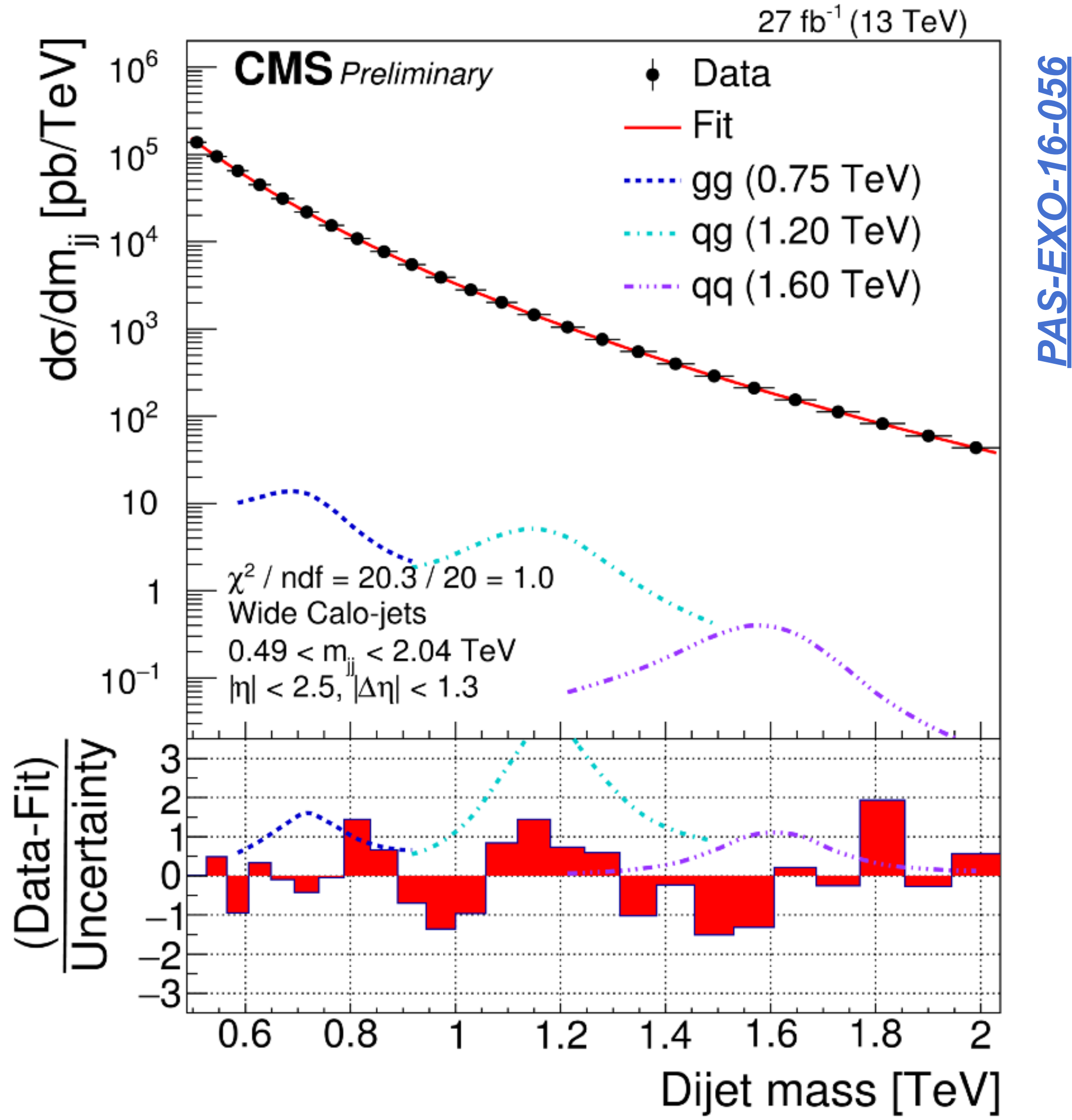
- Explore intermediate resonance mass range
  - 500 GeV < mass < 1500 GeV



- **Calorimeter jets at trigger level** (calo scouting)
  - fast online reconstruction (no tracking) allows lowest possible jet trigger thresholds
  - dijet mass resolution ~ 20% worse compared to offline reconstructed jets
- Background estimated by fit to data using smoothly falling function
  - same strategy of high-mass search

$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}} \qquad x = \frac{m_{jj}}{13000}$$

- No sign of new resonances



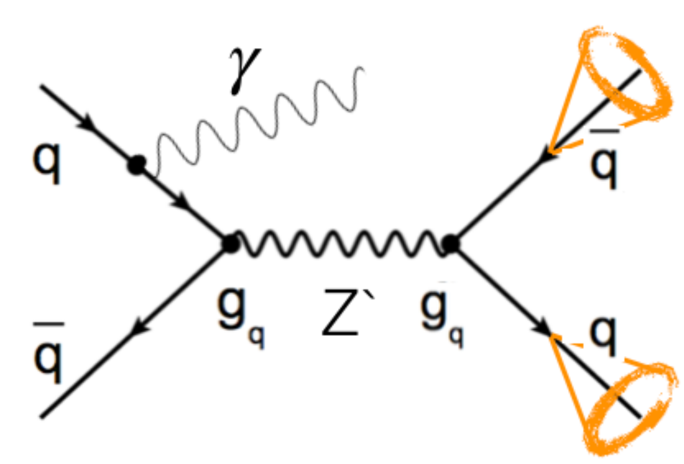
Probing Low-Mass with ISR Trigger

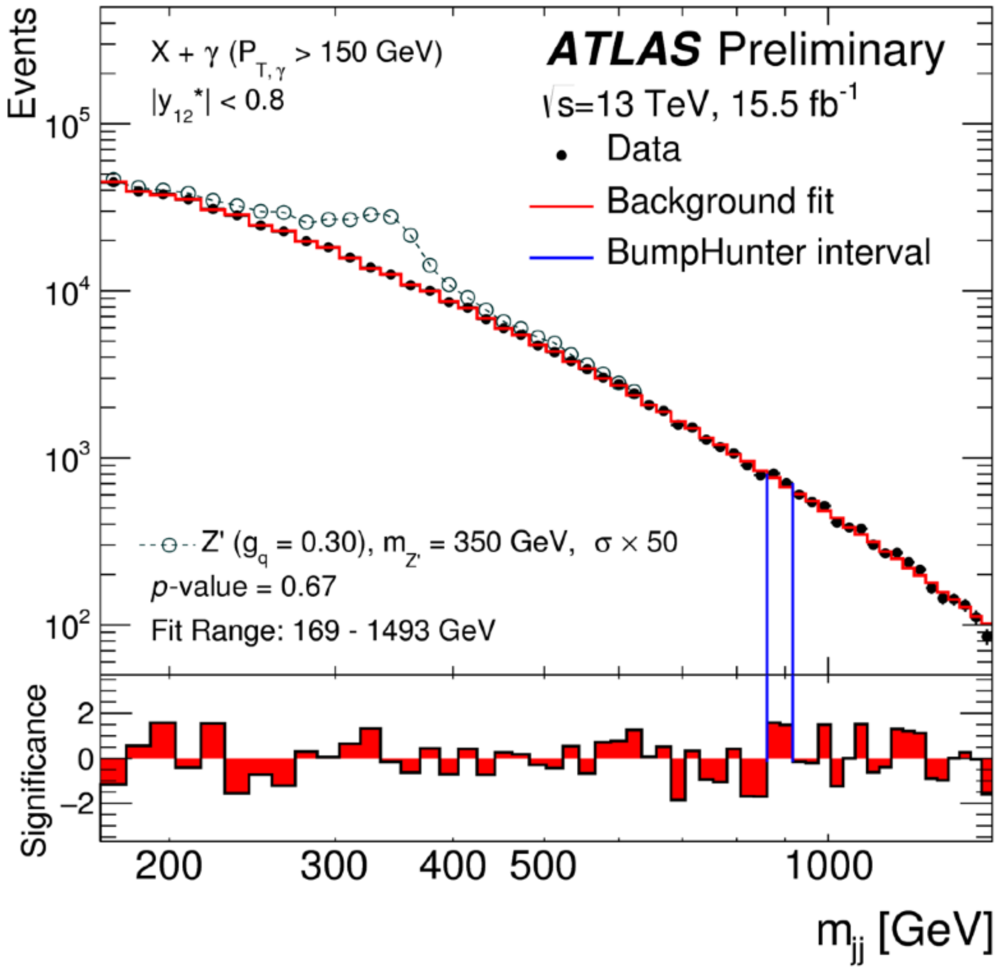
- Available jet triggers not efficient for low-mass resonances (mass <500 GeV) produced at rest
  - due to low energy of their decay products

- Search for **dijet resonances** produced **in association** with a **high-p_T initial state radiation (ISR)**
  - trigger on ISR object (jet or photon)
  - search for bump in m_{jj} spectrum of other 2 jets

- ATLAS analysis with ISR photon
  - trigger: pT photon > 150 GeV
  - extend search down to 200 GeV resonance mass
  - no sign of new resonances

high-p_T ISR photon

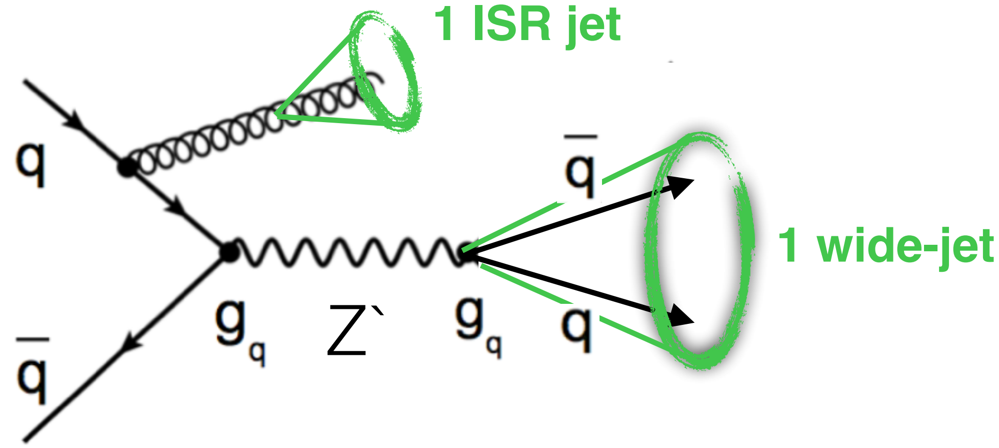




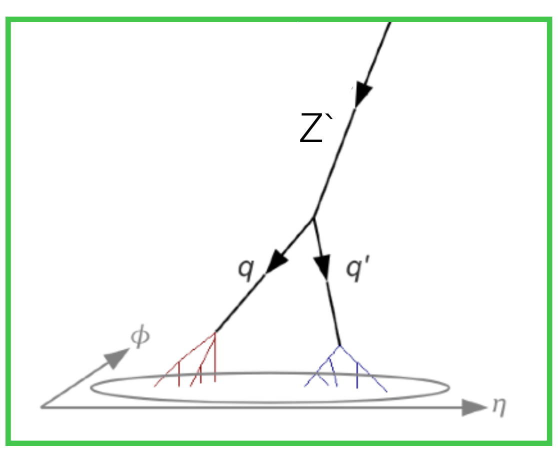
ATLAS-CONF-2016-070

Boosted Resonances

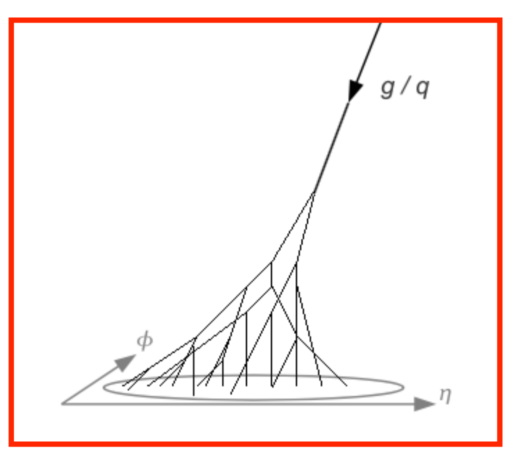
- Very-low mass resonances (<200 GeV) produced with large Lorentz boost
  - decay products collimated and reconstructed in single wide-jet
- Study **substructure** of **wide-jet**
  - jet mass (removing soft radiation) ⇒ resonance mass
  - observables to identify two-prong jet substructure (n-subjettiness, generalized energy correlation functions, …)

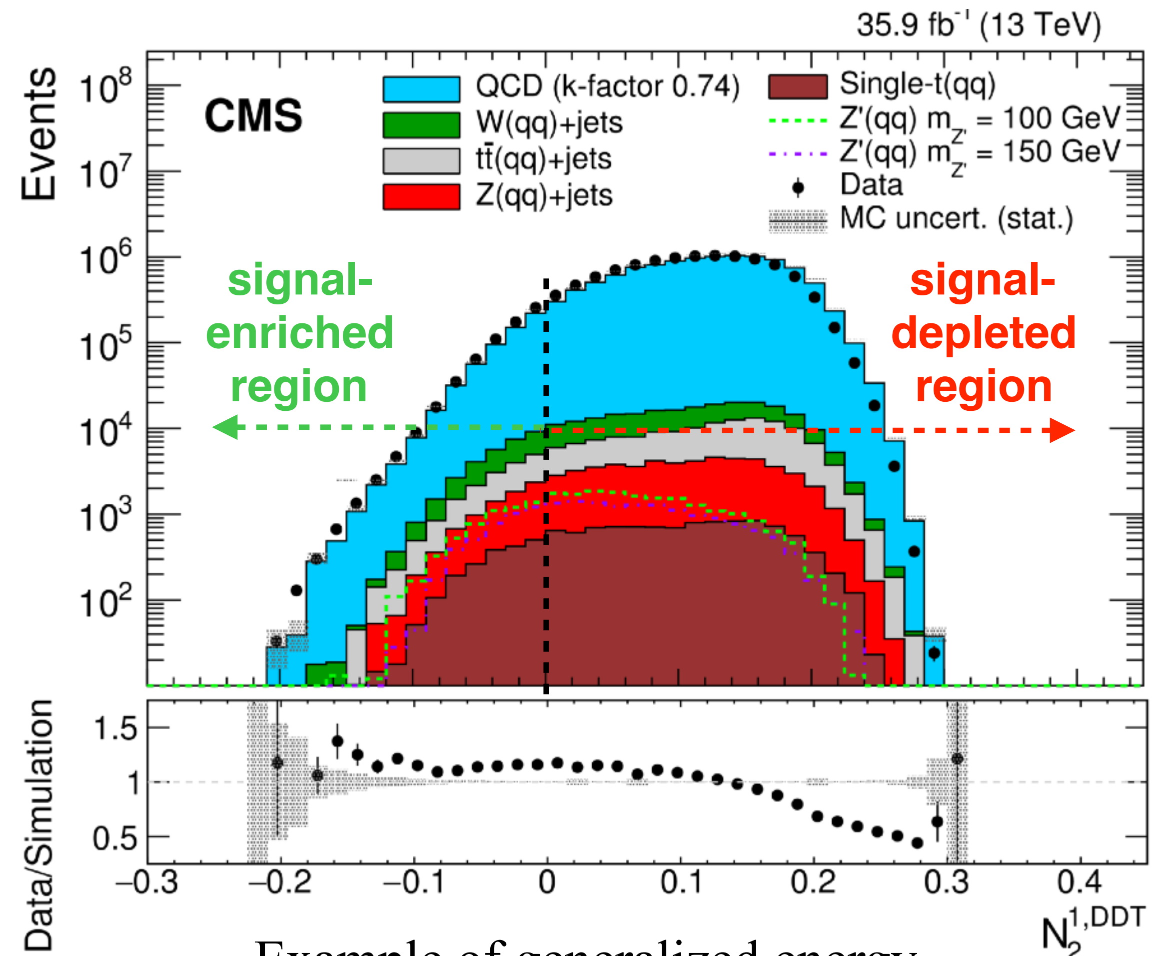


signal



QCD background

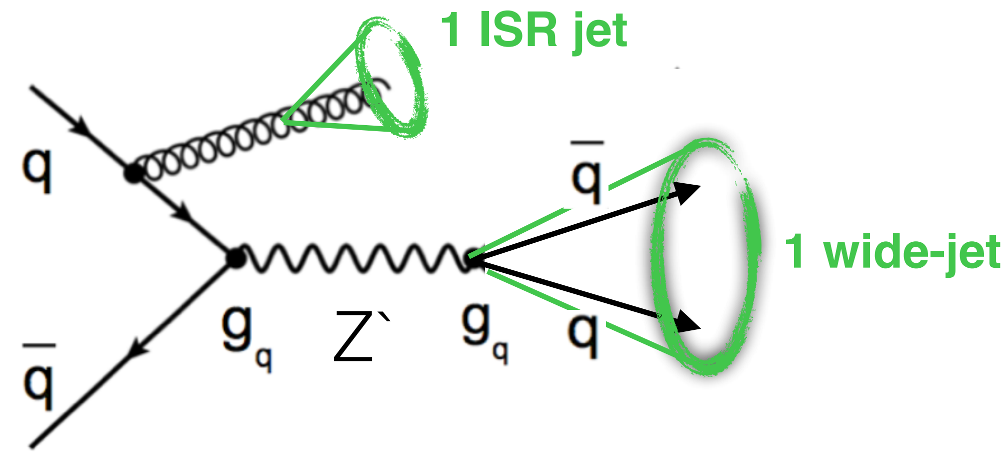




Example of generalized energy correlation variable (arXiv:1609.07483) to identify two-prong jet substructure

Boosted Dijet Analysis

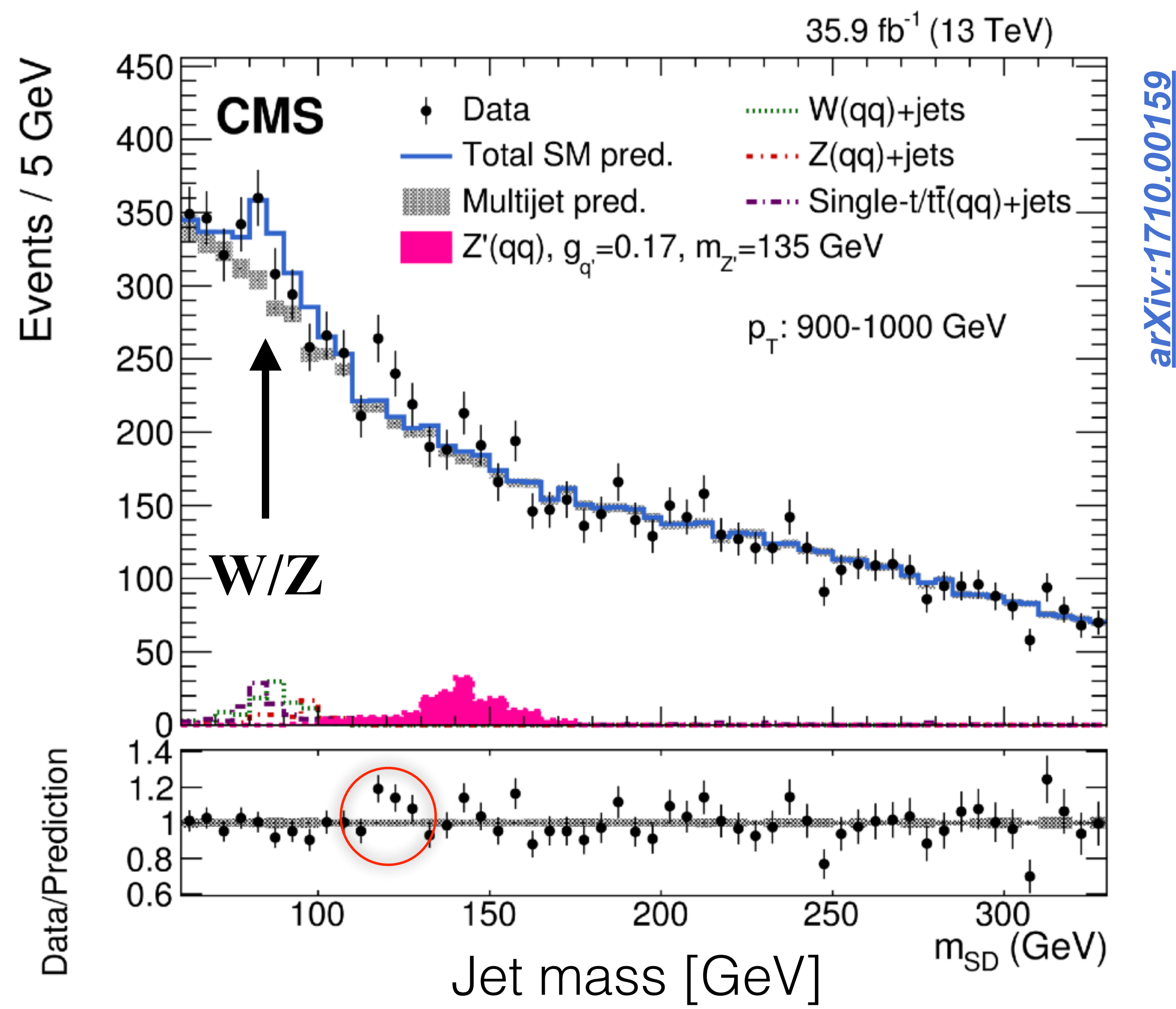
- CMS analysis strategy
  - trigger on single jet pT>500 GeV (anti-kt, R=0.8)
  - tight requirement on two-prong substructure of wide-jet
  - bump search in mass spectrum of the wide-jet



- QCD background estimated from data in signal-depleted control region, created by inverting the substructure selection
  - $n_{\rm pass}^{\rm QCD}(m_{\rm SD}, p_{\rm T}) = R_{\rm p/f}(\rho(m_{\rm SD}, p_{\rm T}), p_{\rm T})\, n_{\rm fail}^{\rm QCD}(m_{\rm SD}, p_{\rm T})$
  - transfer factor R = smooth function of jet mass and p_T

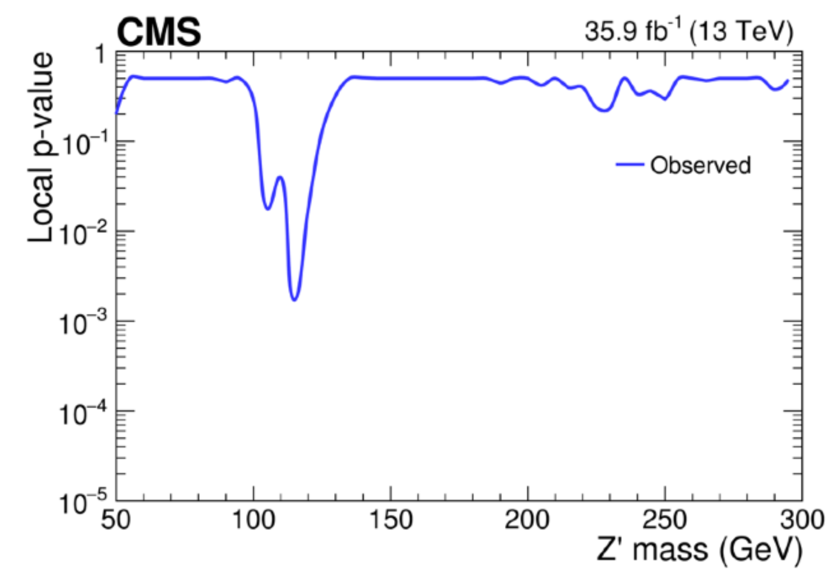
- Signal extracted from simultaneous fit to signal and control regions in 5 different jet p_T bins (from 500 to 1000 GeV)

- **W/Z boson peak well reconstructed**
  - standard candle to validate search for new resonances

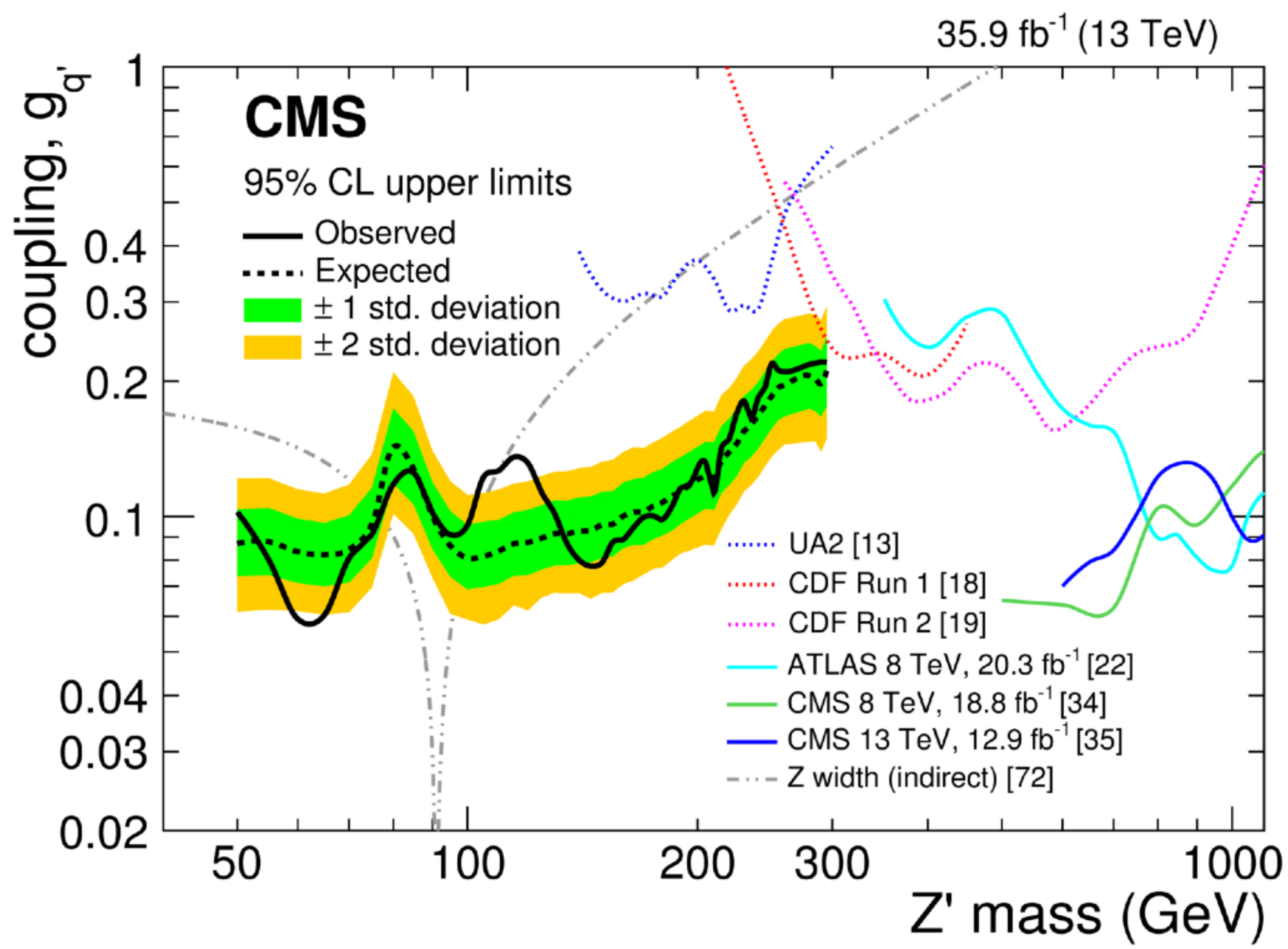


Results of Boosted Dijet Analysis

- Small fluctuation at resonance mass of 115 GeV
  - local significance = 2.9σ
  - global significance = 2.2σ
  - not sensitive to SM Higgs signal in this inclusive dijet channel



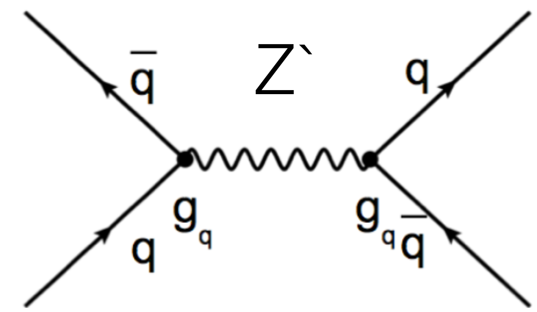
- Upper limits on coupling of Z` to quarks vs resonance mass
  - **probe new mass** and **coupling** regions, not explored by previous experiments



arXiv:1710.00159

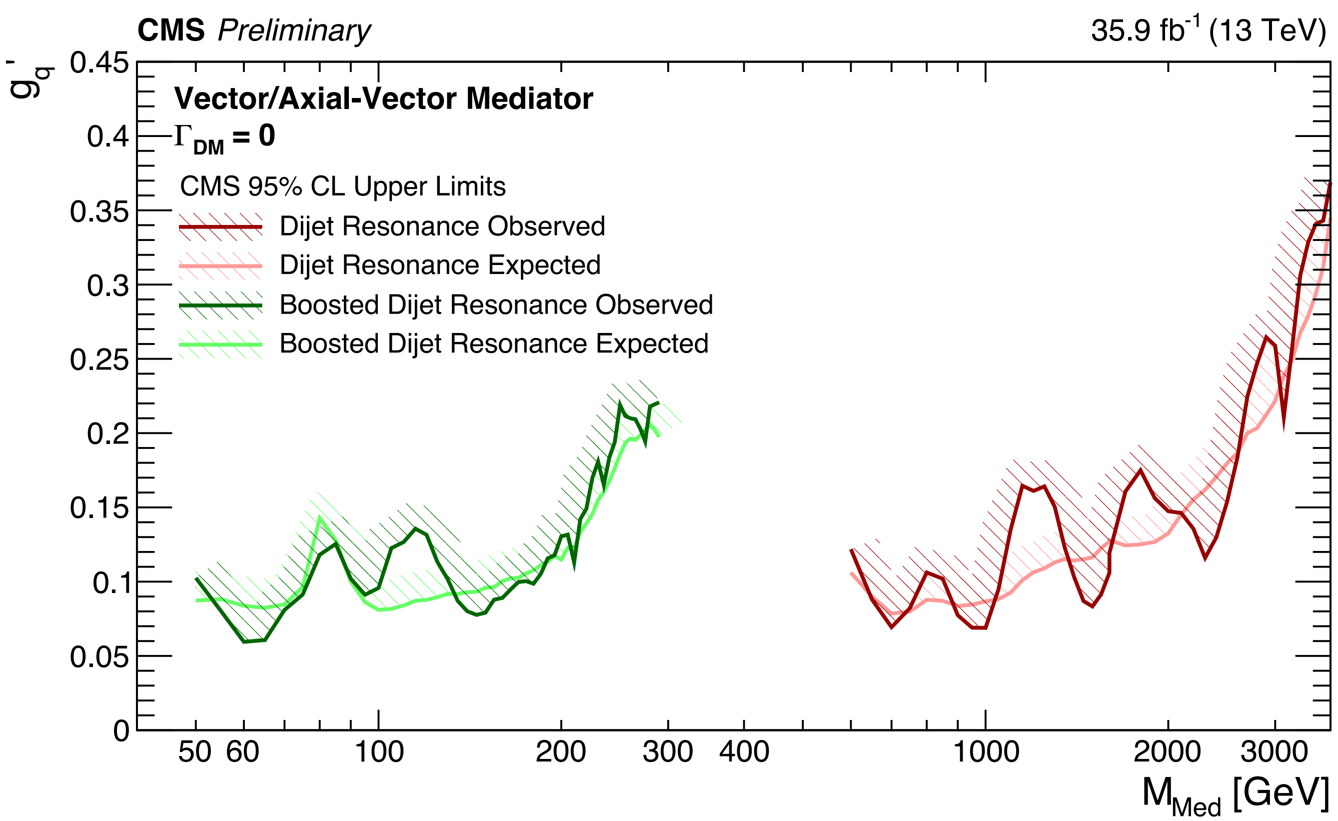
Summary of Dijet Searches

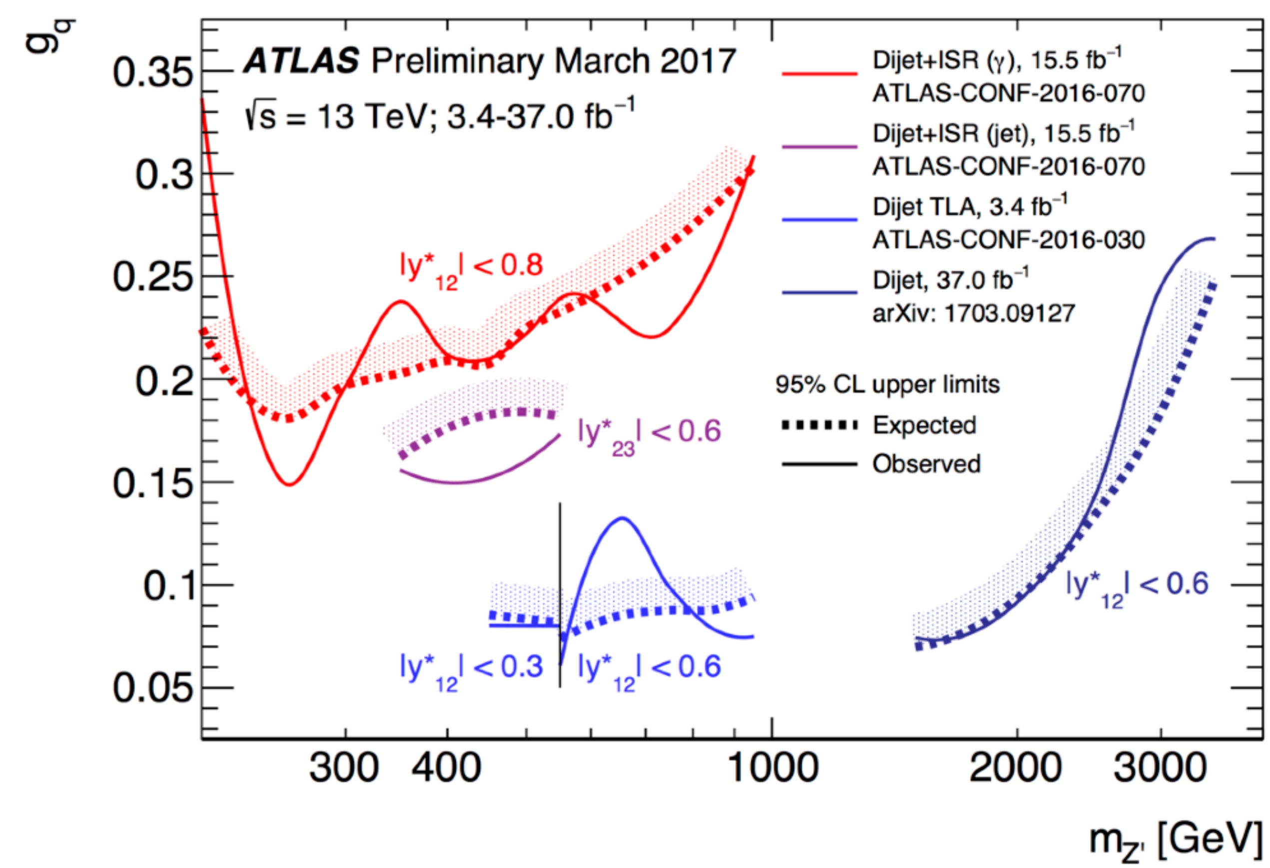
- Set limits on leptophobic Z`→qq benchmark model
  - 100% of decays to jets
  - limits valid for narrow resonance ($g_q \lesssim 0.5$)
- **ATLAS+CMS covers a wide mass range**
  - from 50 GeV to multi-TeV



$$\mathcal{L}_{\mathrm{axial-vector}} = g_q \sum_q Z'_\mu \bar{q}\gamma^\mu\gamma_5 q$$

$$\Gamma^{q\bar{q}}_{\mathrm{axial-vector}} = \frac{g_q^2 M_{\mathrm{med}}}{4\pi}\left(1 - 4\frac{m_q^2}{M_{\mathrm{med}}^2}\right)^{\frac{3}{2}}$$





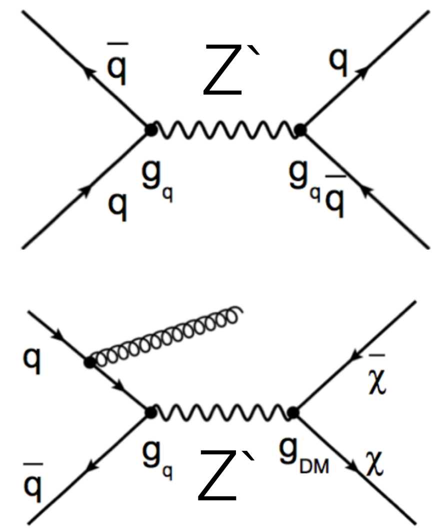
Dark Matter Interpretation

- **Dijet and mono-X searches exclude regions in DM-mass vs mediator-mass plane**

- $m_{DM} < M_{med} / 2$
  - mediator decays to DM → constraints from mono-X analyses
  - branching ratio to dijet increases with DM mass

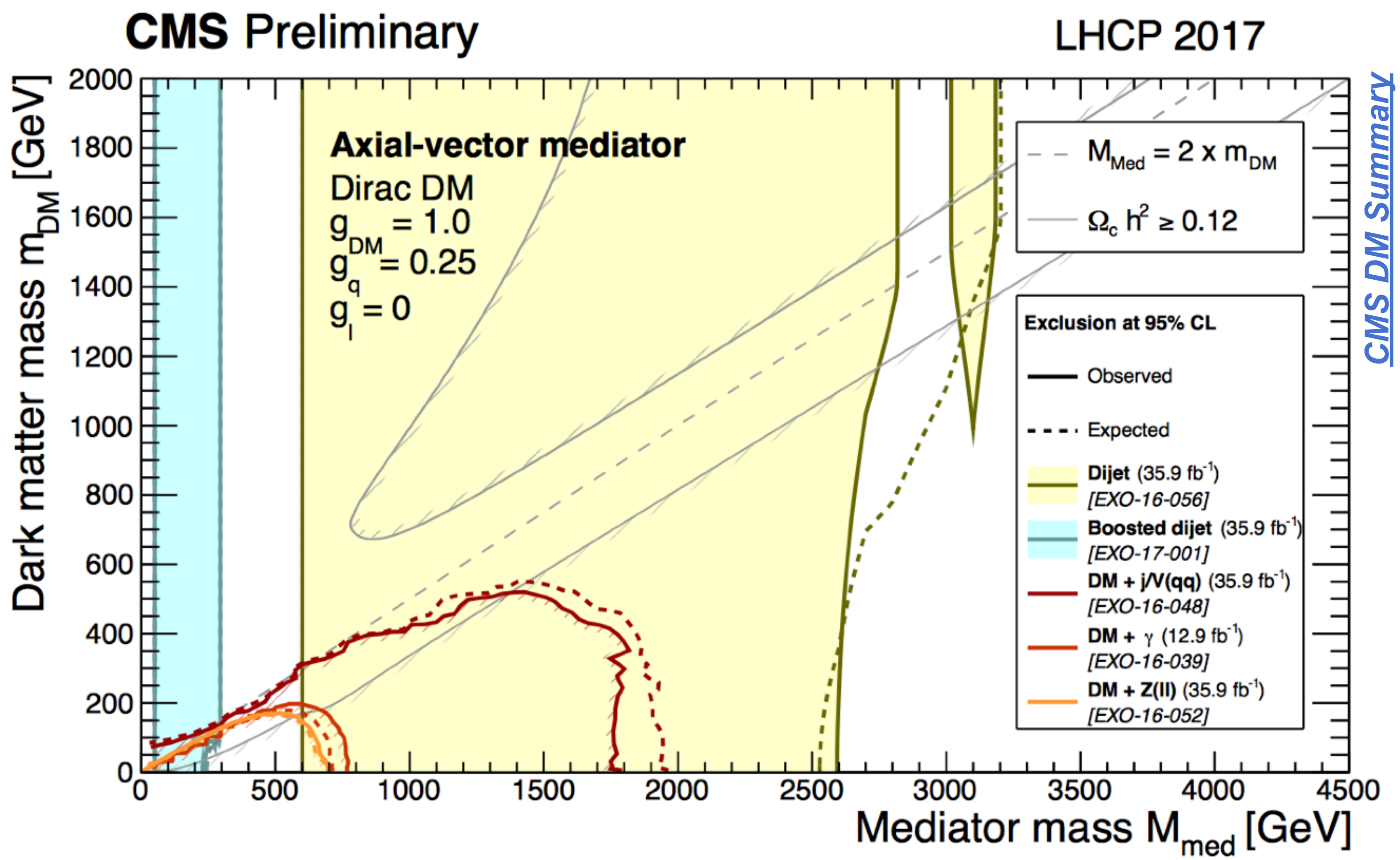
- $m_{DM} > M_{med} / 2$
  - on-shell mediator cannot decay to DM → no constraints from mono-X searches
  - 100% decays to jets → dijet limits independent on DM mass

Simplified DM model



$$\Gamma^{q\bar{q}}_{\mathrm{axial-vector}} = \frac{g_q^2 M_{\mathrm{med}}}{4\pi}\left(1 - 4\frac{m_q^2}{M_{\mathrm{med}}^2}\right)^{\frac{3}{2}}$$

$$\Gamma^{\chi\bar{\chi}}_{\mathrm{axial-vector}} = \frac{g_{DM}^2 M_{\mathrm{med}}}{12\pi}\left(1 - 4\frac{m_{DM}^2}{M_{\mathrm{med}}^2}\right)^{\frac{3}{2}}$$



Exclusion in Different Coupling Scenarios

- **Exclusion depends on coupling assumptions**
  - $g_q \ll g_{DM}$: dijet and mono-jet complementary

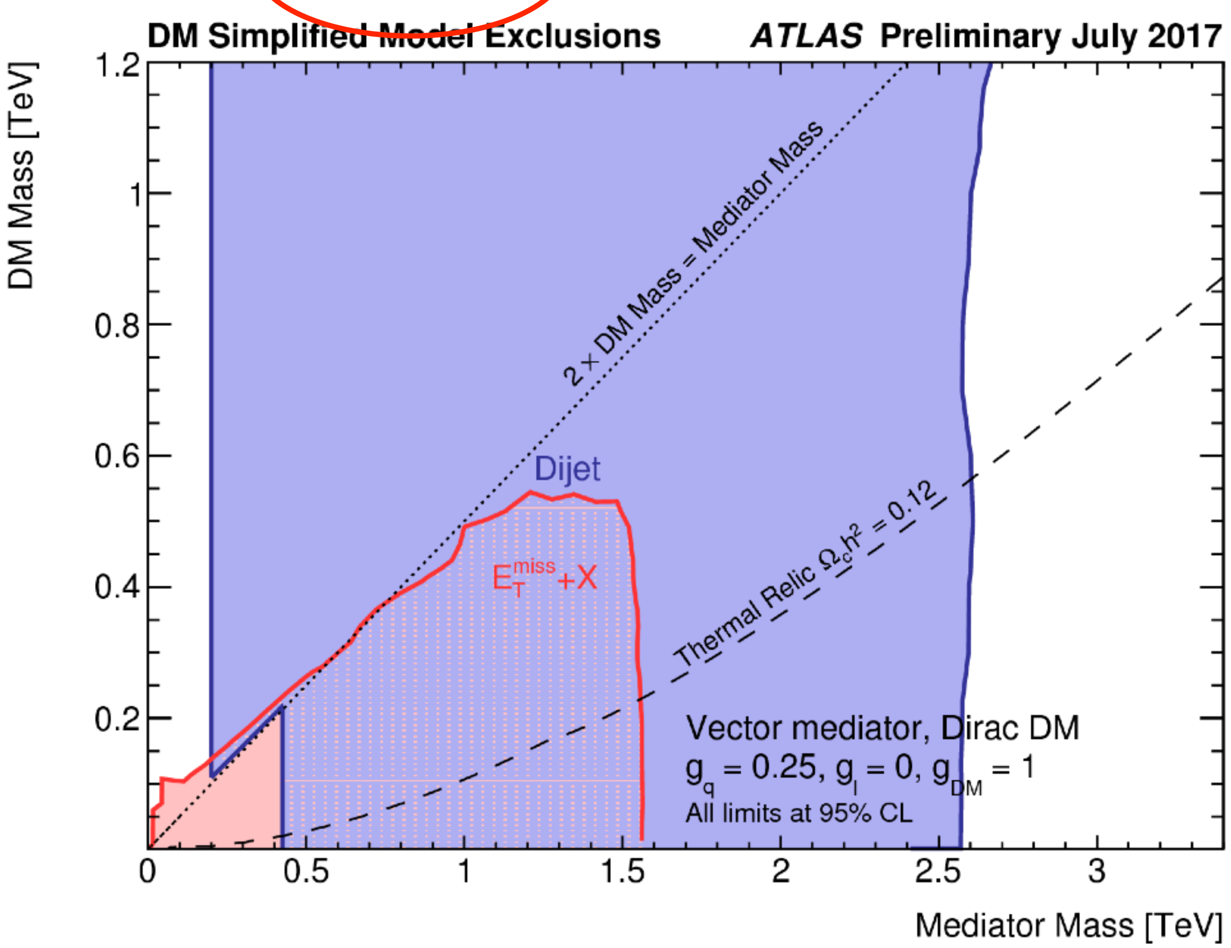
$$\sigma_{\mathrm{MET+X}} \propto \frac{g_q^2 \cdot g_{DM}^2}{\Gamma_{tot}} \qquad \sigma_{\mathrm{dijet}} \propto \frac{g_q^4}{\Gamma_{tot}}$$

Dijet
- Dijet 8 TeV $\sqrt{s}$ = 8 TeV, 20.3 fb^{-1} Phys. Rev. D. 91 052007 (2015)
- Dijet $\sqrt{s}$ = 13 TeV, 37.0 fb^{-1} arXiv:1703.09127 [hep-ex]
- Dijet TLA $\sqrt{s}$ = 13 TeV, 3.4 fb^{-1} ATLAS-CONF-2016-030
- Dijet + ISR $\sqrt{s}$ = 13 TeV, 15.5 fb^{-1} ATLAS-CONF-2016-070

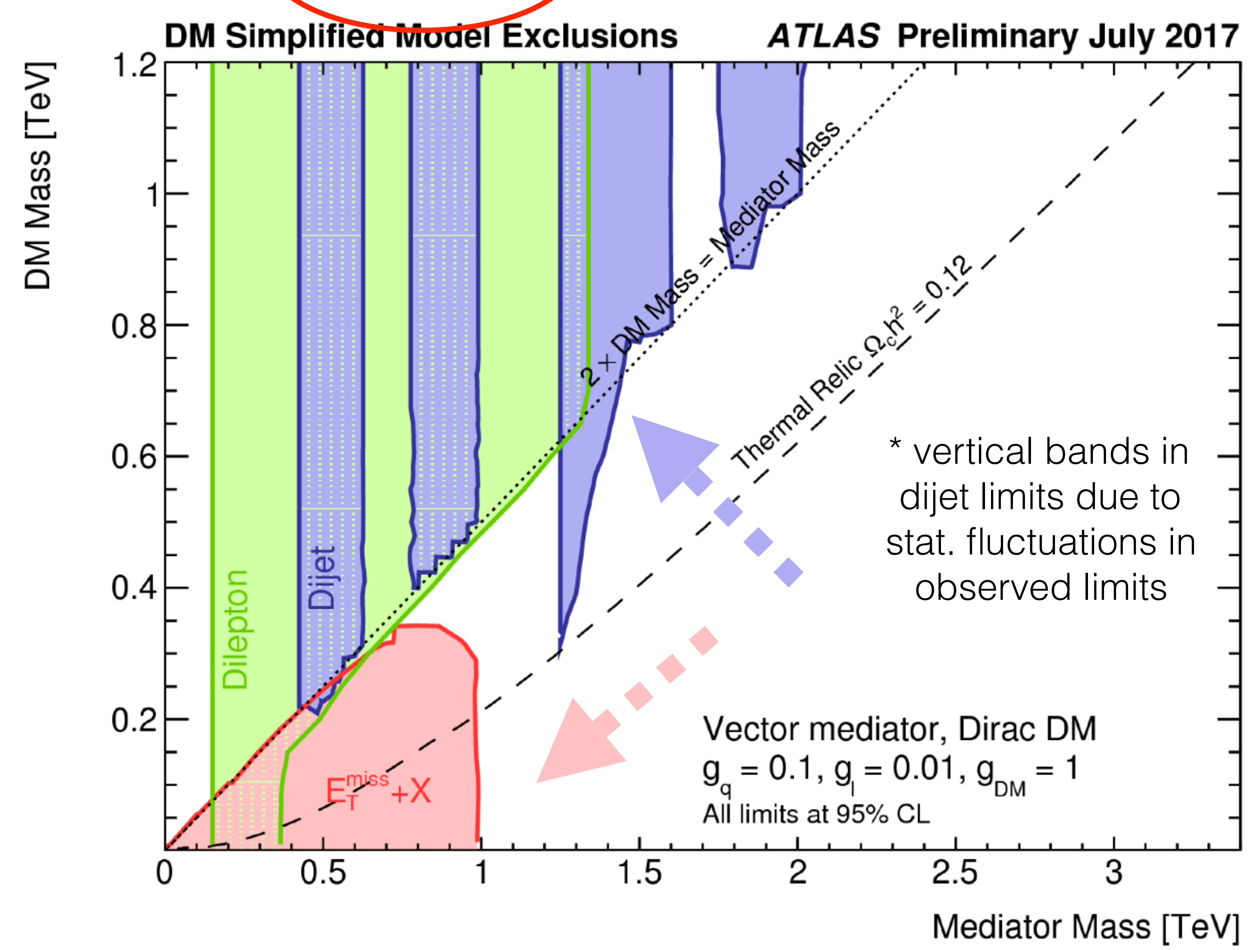
E_T^{miss}+X
- $E_T^{miss}+\gamma$ $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1} Eur. Phys. J. C 77 (2017) 393
- E_T^{miss}+jet $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1} ATLAS-CONF-2017-060

Dilepton
- $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1} CERN-EP-2017-119

$g_q = 0.25$, $g_{DM} = 1$, $g_\ell = 0$

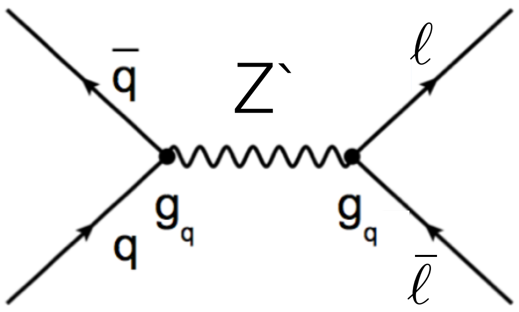


$g_q = 0.1$, $g_{DM} = 1$, $g_\ell = 0.01$



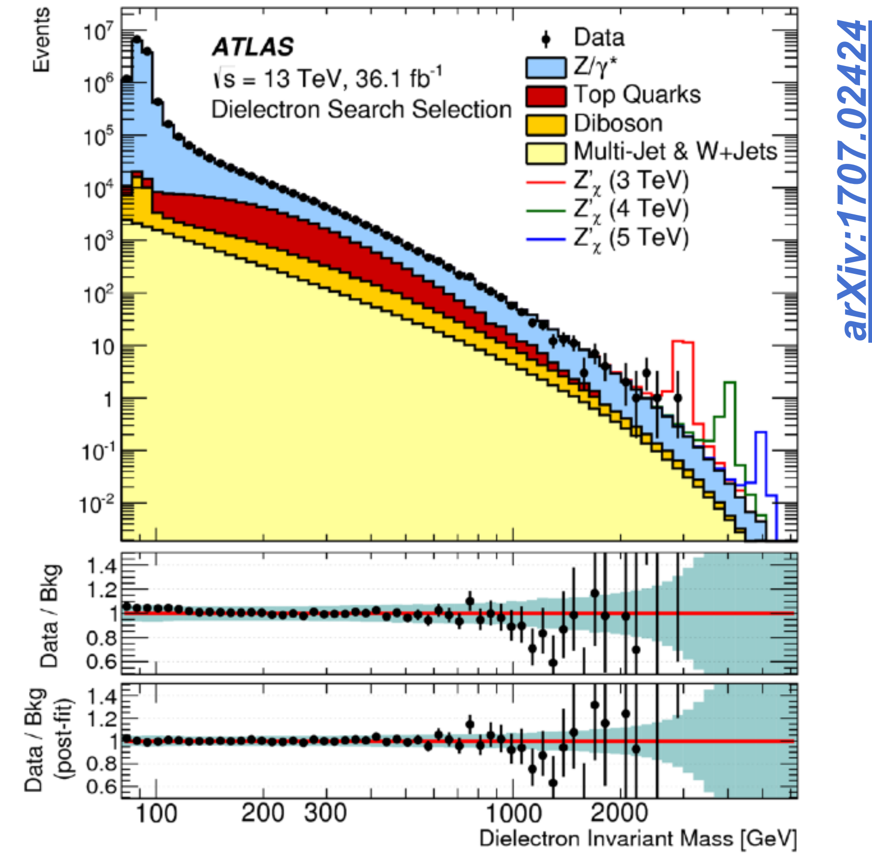
ATLAS EXOT summary

Dilepton Final State

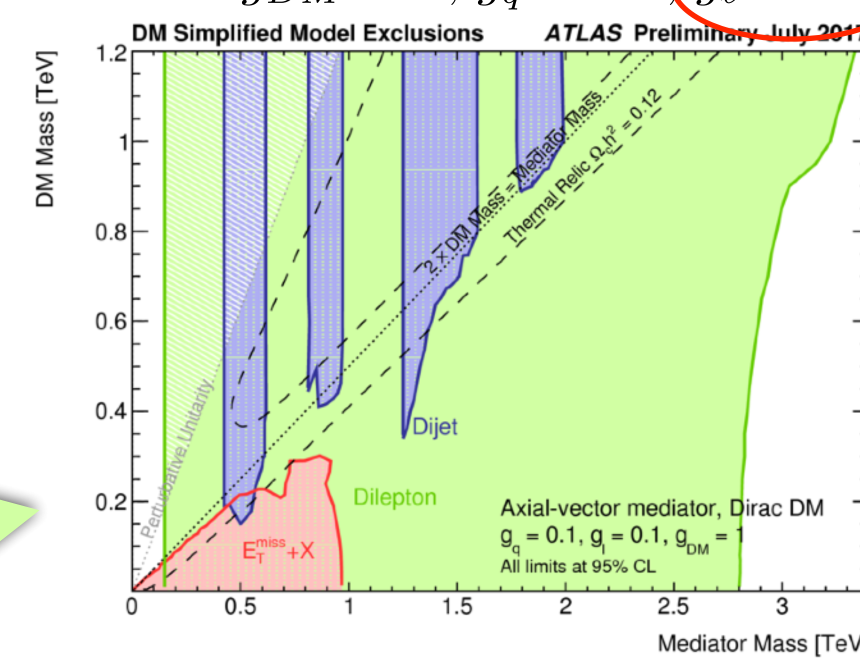


$$\Gamma^{\ell\bar{\ell}}_{\mathrm{axial-vector}} = \frac{g_\ell^2 M_{\mathrm{med}}}{12\pi}\left(1 - 4\frac{m_\ell^2}{M_{\mathrm{med}}^2}\right)^{3/2}$$

- DM mediators may also couple to leptons
- Search for new physics in **dilepton mass spectrum**
  - consider both ee and μμ final state
- Dominant Drell-Yan background estimated from NLO simulation
  - NNLO QCD and EW corrections applied as function of dilepton mass
- Data in very good agreement with SM prediction
  - set strong exclusion in DM-mediator mass plane



$g_{DM} = 1\,,\ g_q = 0.1\,,\ g_\ell = 0.1$



Comparison with Direct Detection (DD) Searches

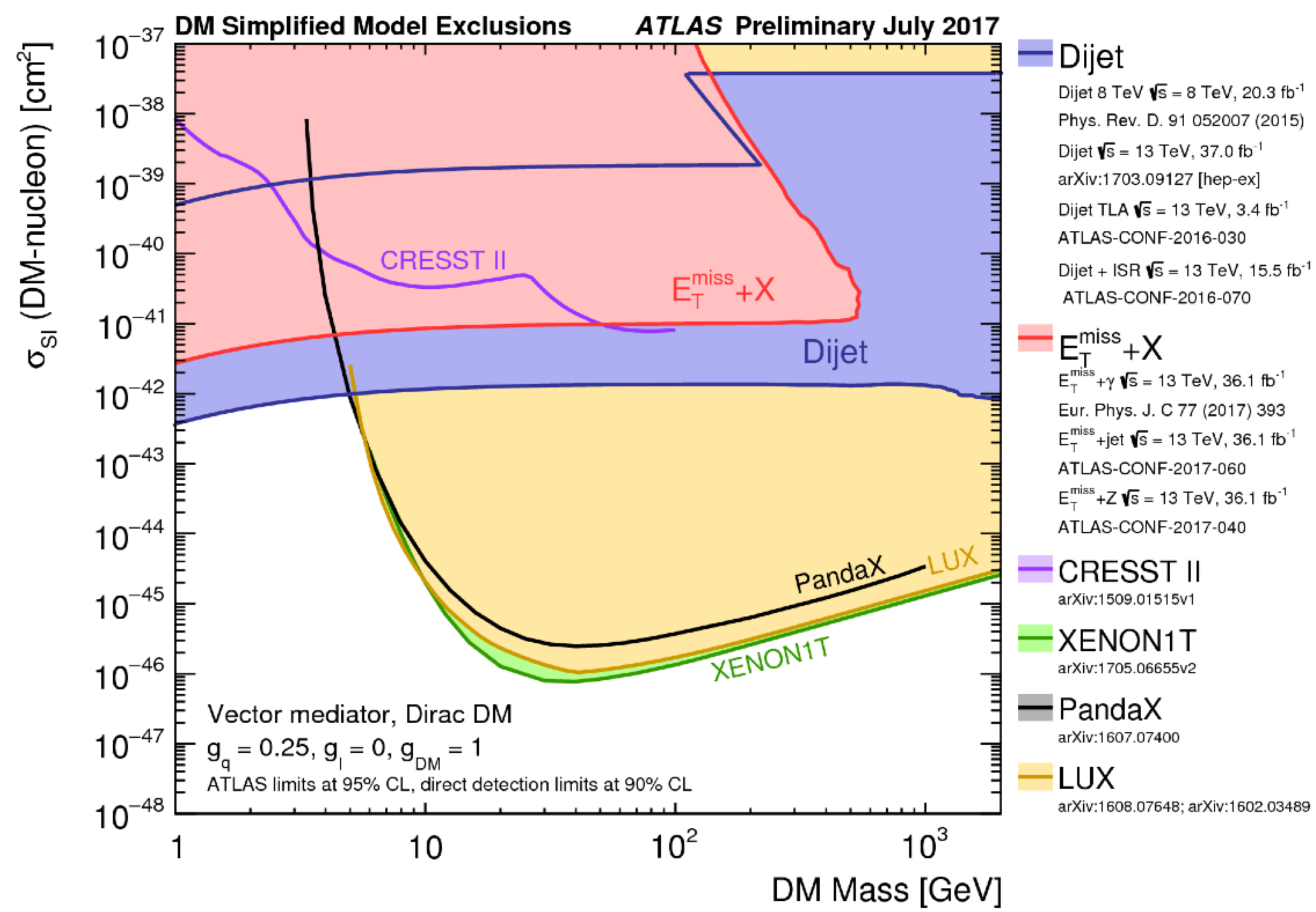
- Direct Detection (DD) experiments search for the recoil of a nucleus scattering off a DM particle traversing the detector
  - scattering cross sections depends on mediator mass and couplings
- Collider limits translated in cross section vs DM mass plane
  - collider searches **more sensitivity at low DM mass** ($m_{DM} < 10$ GeV)

Spin-Independent DM-nucleon scattering cross section

$$\sigma_{SI} = \frac{f^2(g_q) g_{DM}^2 \mu_{n\chi}^2}{\pi M_{med}^4}$$

mediator-nucleon coupling for vector Z`: $f(g_q) = 3g_q$

reduced DM-nucleon mass: $\mu_{n\chi} = \frac{m_n m_{DM}}{(m_n + m_{DM})}$



** Caveat: collider limits depends strongly on coupling assumptions

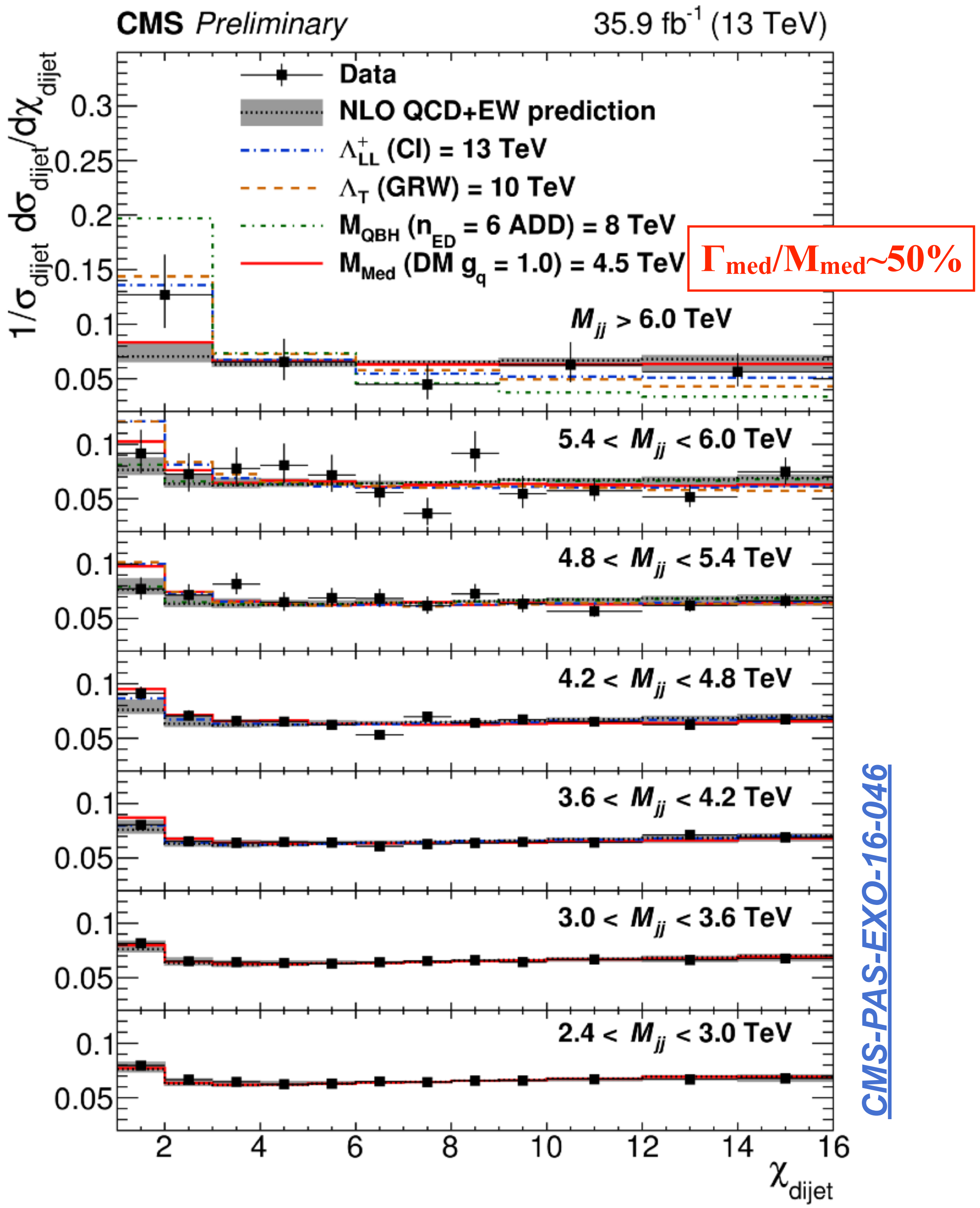
Future Analyses and DM Interpretations

- Wide resonances (Γ >> exp. resolution)
  - bump search ($\Gamma/M \lesssim 30\%$)
  - dijet angular analysis ($\Gamma/M \lesssim 100\%$) →
  - analyses sensitive to $0.5 \lesssim g_q \lesssim 1.5$
  - final results on DM interpretation to be released soon

- Final states with b-quarks
  - spin-0 mediators have larger coupling to b-quarks than light-quarks (as Higgs)
  - some results ready but DM interpretation in progress

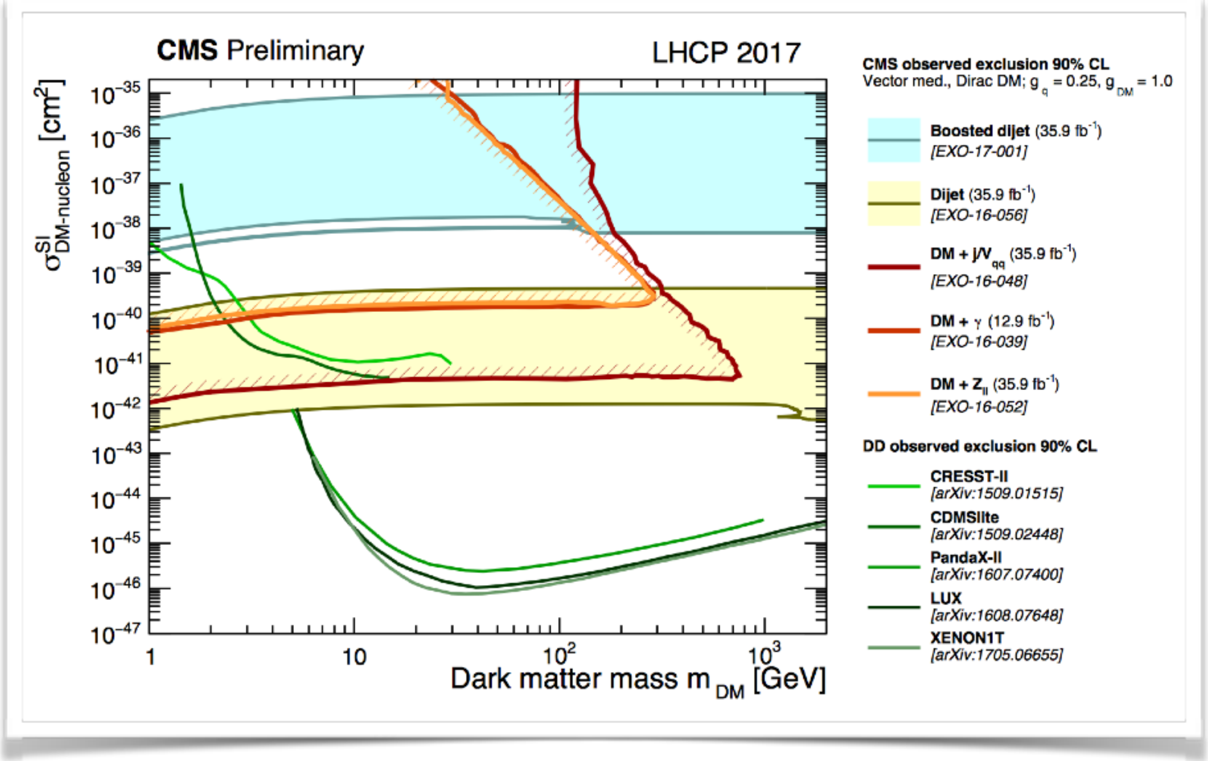
- Low-mass region (new experimental methods)
  - jet substructure in scouting / trigger level analysis

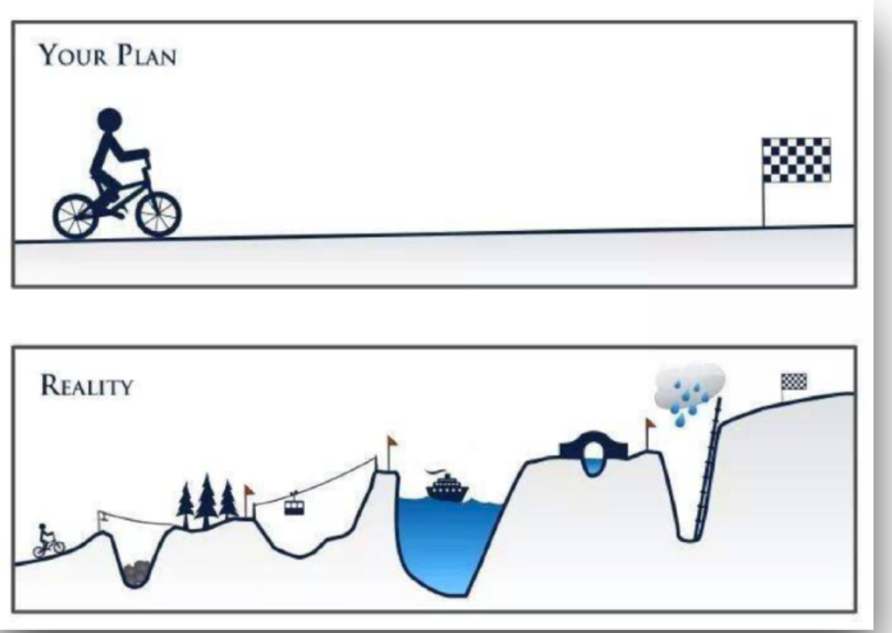
$$\chi_{\text{dijet}} = \exp\left(|\eta_{\text{jet1}} - \eta_{\text{jet2}}|\right)$$



Summary

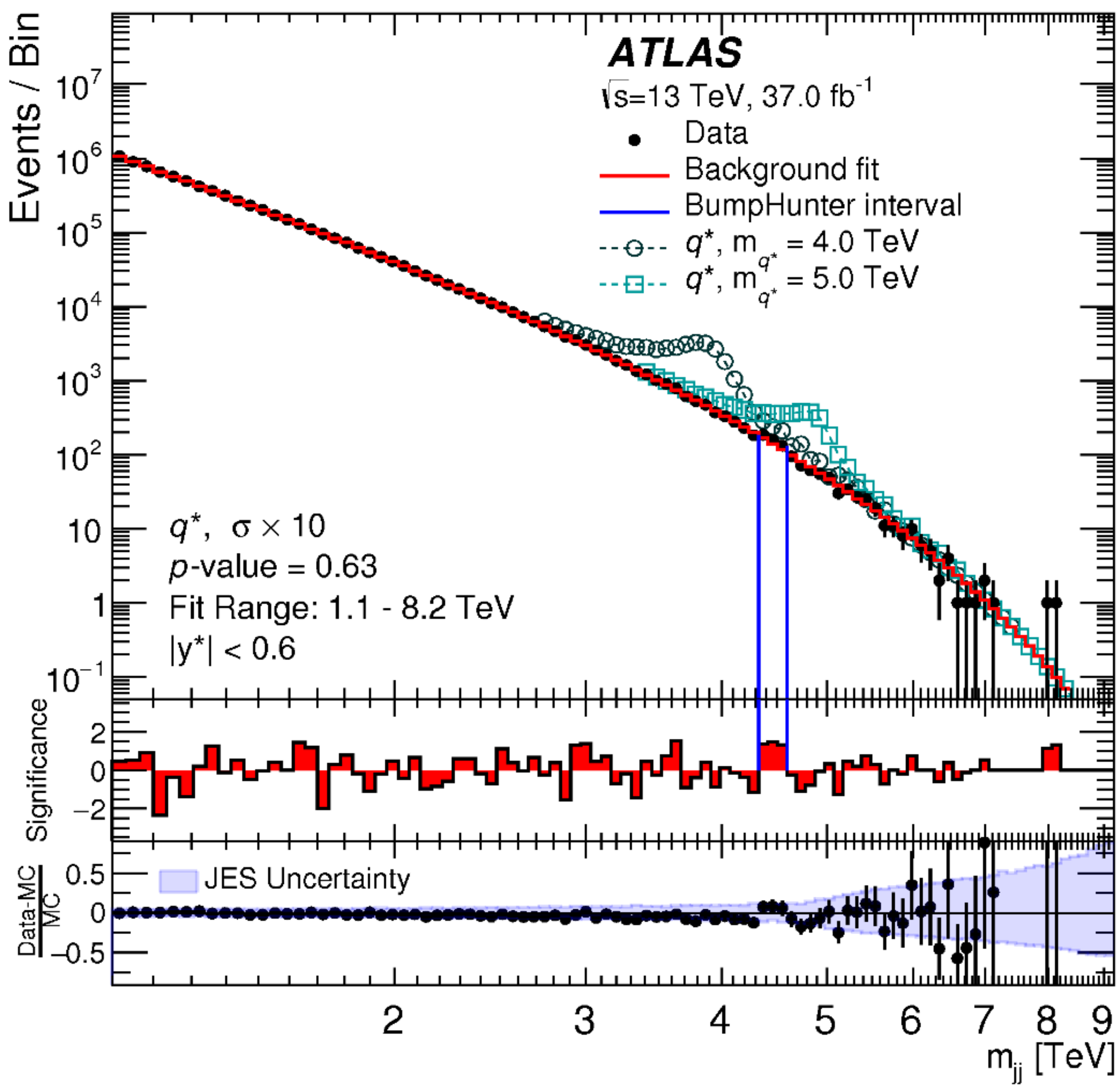
- Collider searches are complementary to direct and indirect dark matter detection experiments
- Searches for dijet resonances in ATLAS and CMS cover a wide range of mass and coupling
  - $M_{med} > 50$ GeV , $0.1 \lesssim g_q \lesssim 0.45$ (Z` model)
- Trigger strategy plays crucial role
  - different methods to probe low-mass region
  - trigger-level analysis and ISR tagging
- No discovery yet, but searches with more data and new experimental techniques can hold surprises
  - keep and eye on CMS excess at 115 GeV

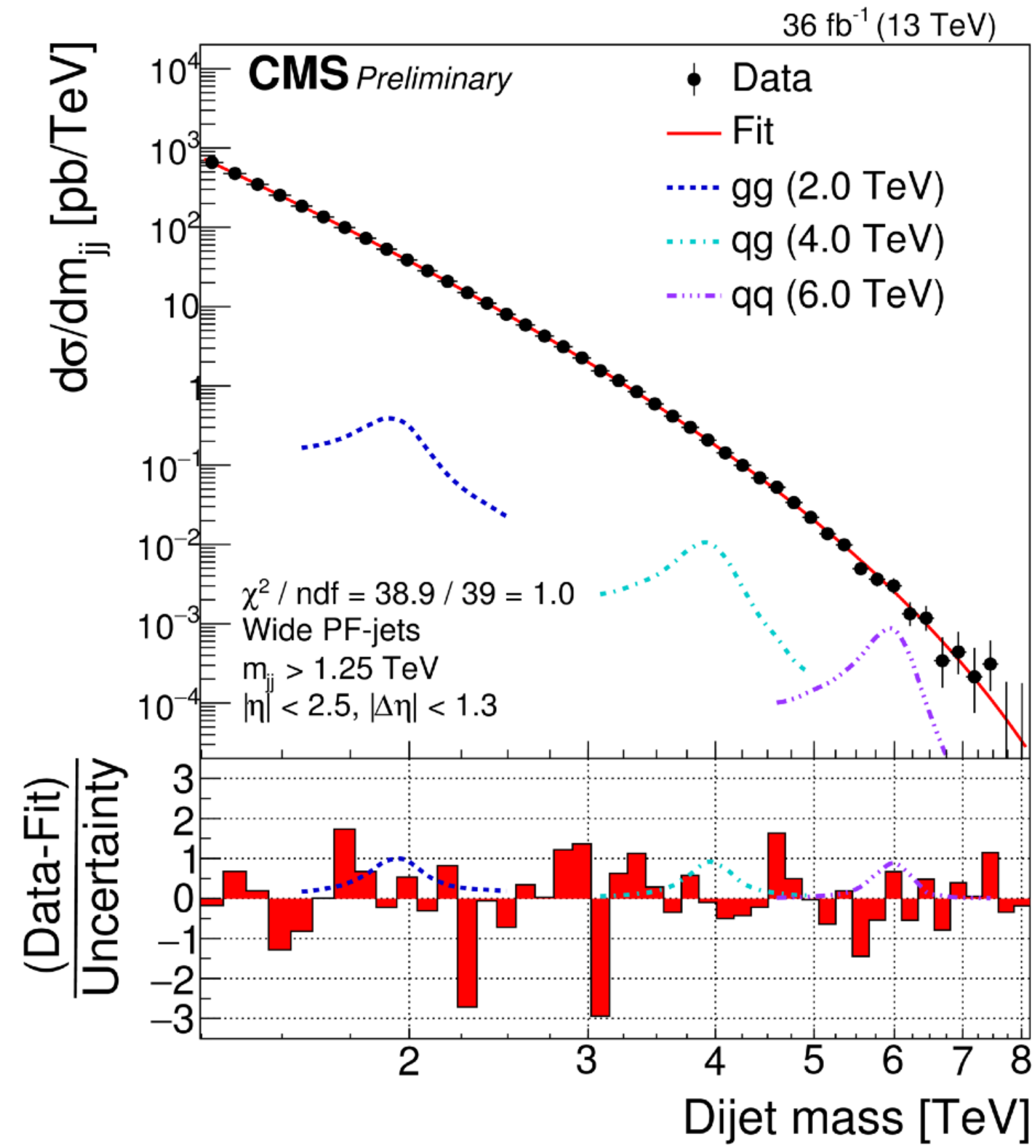




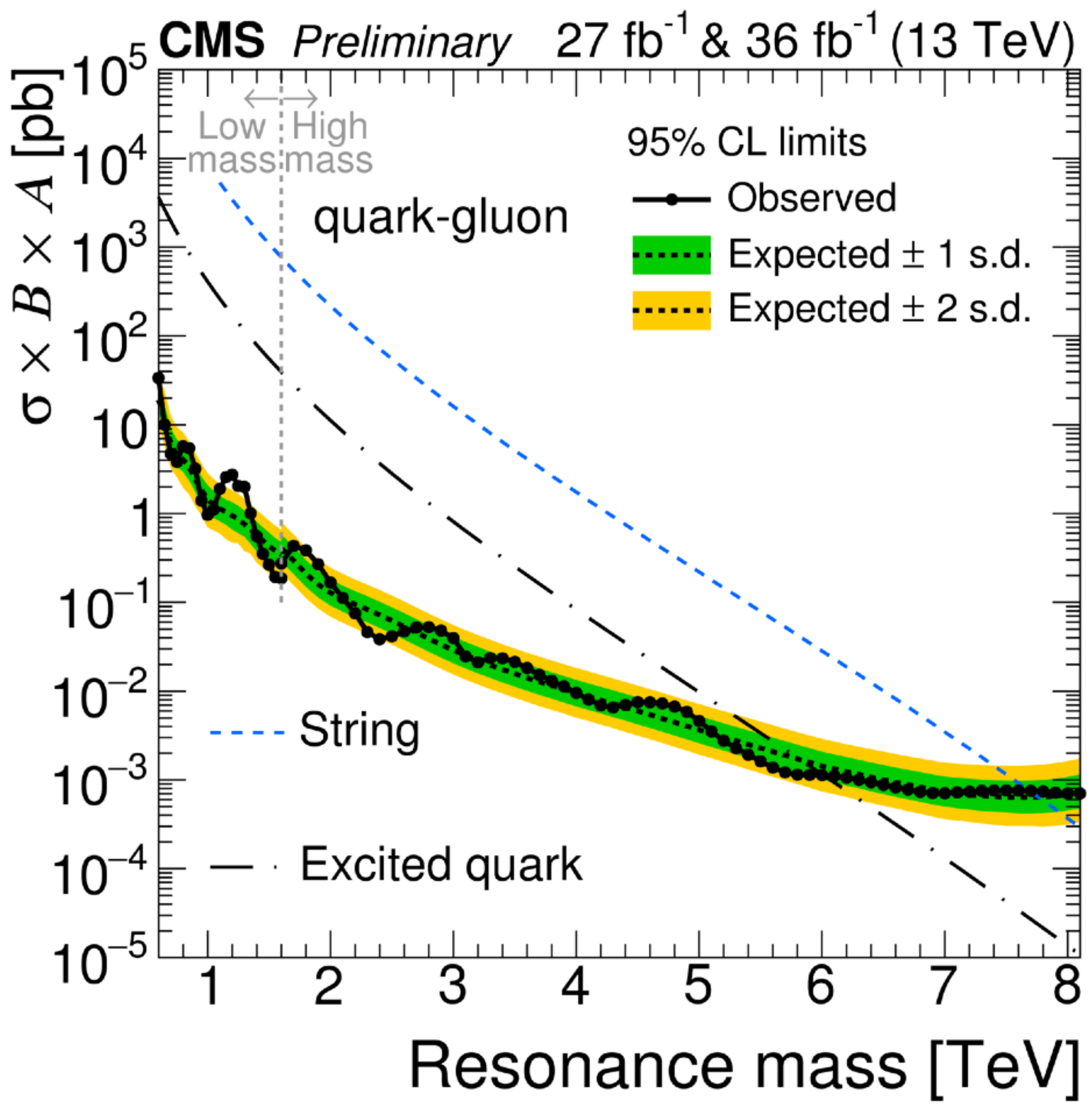
Backup

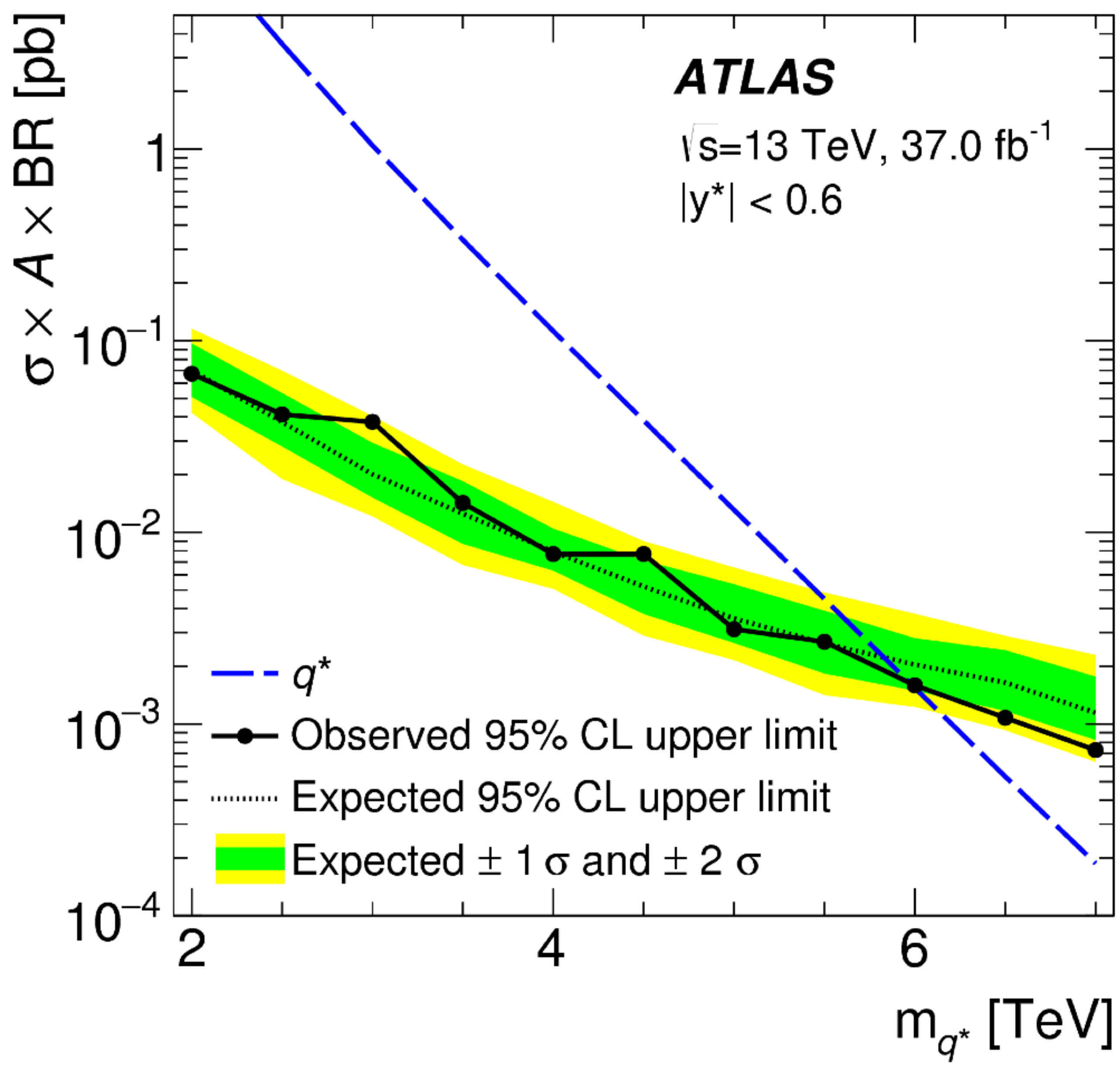
Dijet Mass Spectra





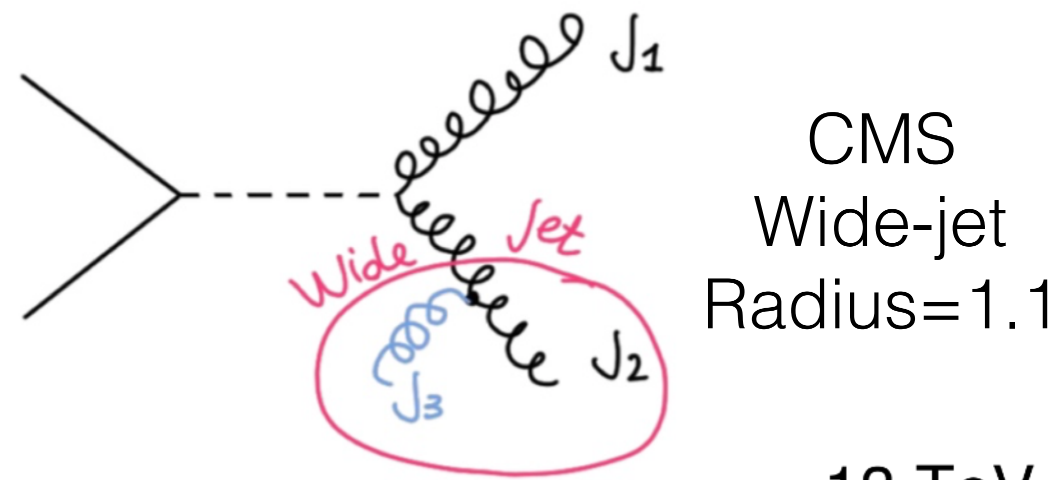
Dijet Cross Section Limits

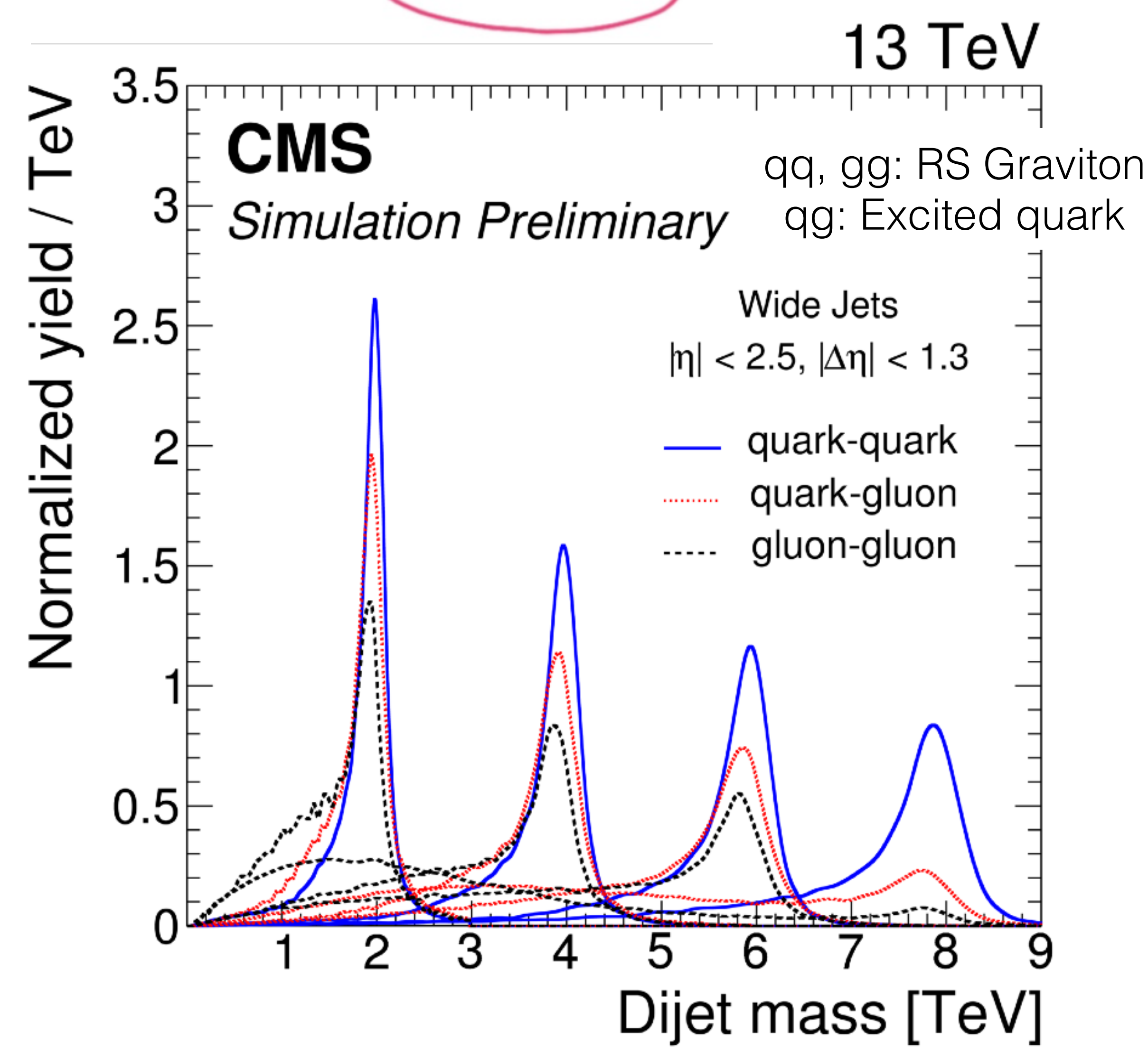




Dijet signal shapes

- Gaussian cores from the jet energy resolution, and tails towards lower mass values primarily from QCD radiation
  - Resonances containing gluons, which emit QCD radiation more strongly than quarks, have a more pronounced tail
- For the high-mass resonances, there is also a significant contribution that depends both on the PDF and on the natural width of the Breit–Wigner resonance
  - For resonances produced through interactions of non-valence partons in the proton, the low-mass component of the Breit–Wigner resonance distribution is amplified by the rise of the parton probability distribution at low fractional momentum.
- Neglecting the tails, the approximate value of the dijet mass resolution varies with resonance mass from 7% at 1.5 TeV to 4% at 7 TeV.

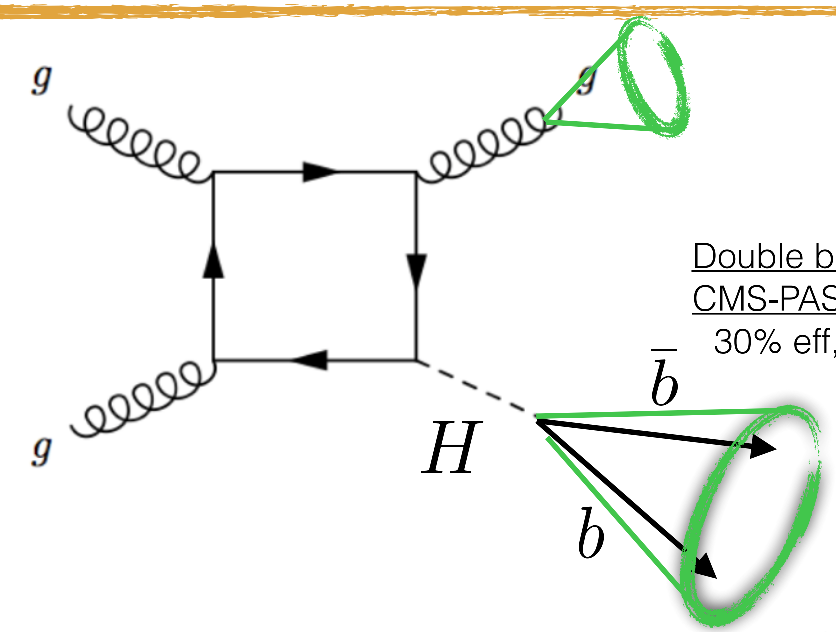




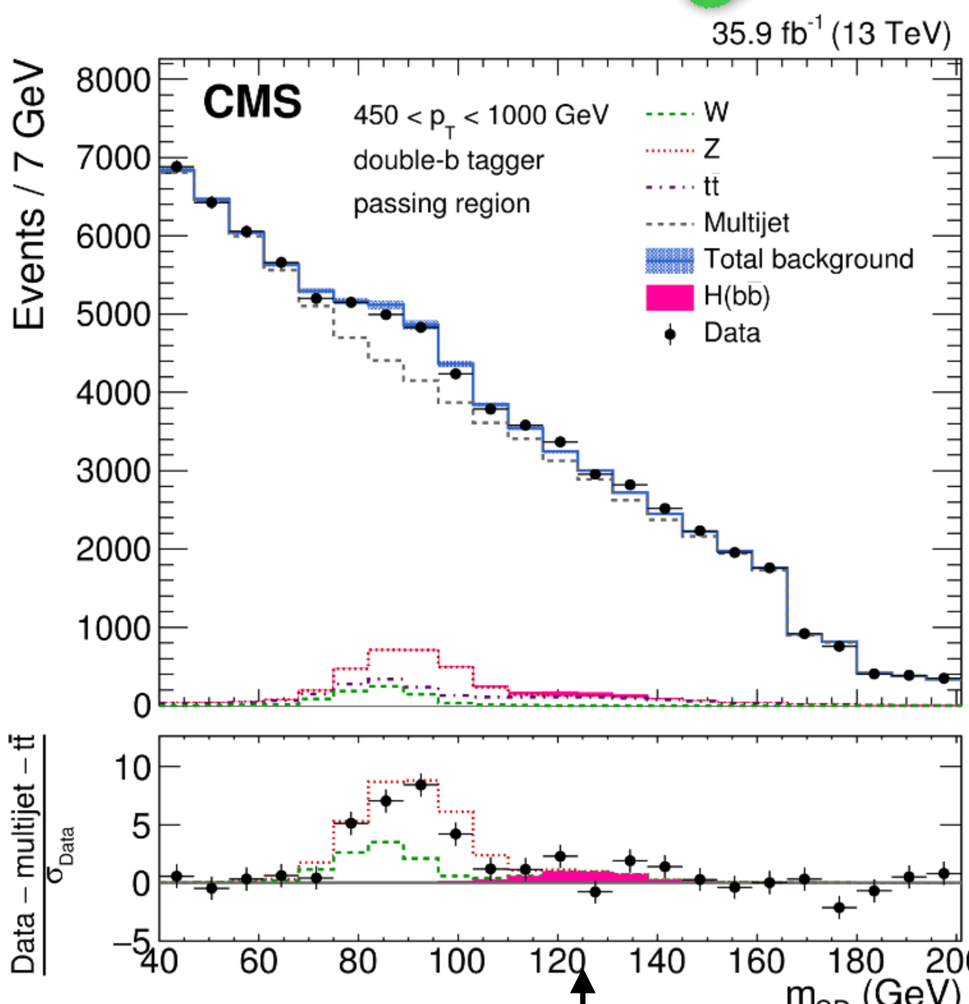
CMS Search for Boosted H→bb

- Search for boosted H(bb) + ISR jet
  - leading wide-jet (AK8) with pT>450 GeV and |η|<2.5, no MET, no leptons
  - H-jet candidate has requirement on two-prong substructure + b-tagging properties consistent with H(bb) signal
- QCD background estimated from data in signal-depleted control region, created by inverting the b-tag selection
  - $n_{\text{pass}}^{\text{QCD}}(m_{\text{SD}}, p_{\text{T}}) = R_{\text{p/f}}(\rho(m_{\text{SD}}, p_{\text{T}}), p_{\text{T}})\, n_{\text{fail}}^{\text{QCD}}(m_{\text{SD}}, p_{\text{T}})$
  - b-tag variable almost uncorrelated from jet mass and p_T
- Signal extracted from simultaneous fit to signal and control regions in 6 different jet p_T bins (from 450 to 1000 GeV)
- H signal generated with POWHEG (gluon-gluon fusion)
  - factorized pT dependent corrections to account for finite top mass effects and NNLO effects → 30% uncertainties on cross section in pT range considered
- Start being sensitive to H(bb) signal, observed Z(bb):

	H	H no p_T corr.	Z
Observed signal strength	$2.3^{+1.8}_{-1.6}$	$3.2^{+2.2}_{-2.0}$	$0.78^{+0.23}_{-0.19}$
Expected UL signal strength	< 3.3	< 4.1	—
Observed UL signal strength	< 5.8	< 7.2	—
Expected significance	0.7σ	0.5σ	5.8σ
Observed significance	1.5σ	1.6σ	5.1σ



Double b-tagger used
CMS-PAS-BTV-15-002
30% eff, 1% mistag

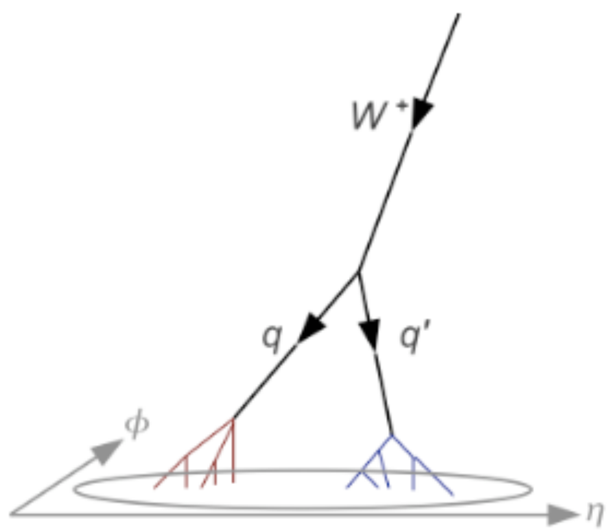


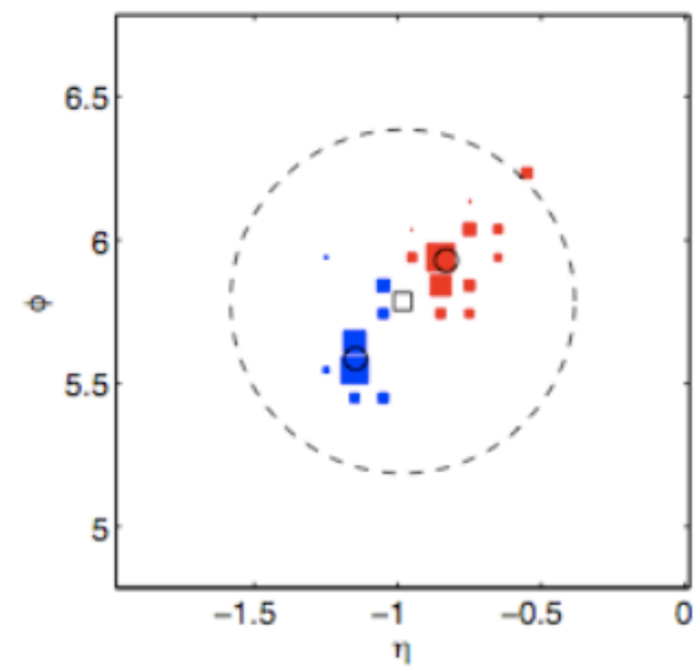
125 GeV

arXiv:1709.05543

Boosted signal identification

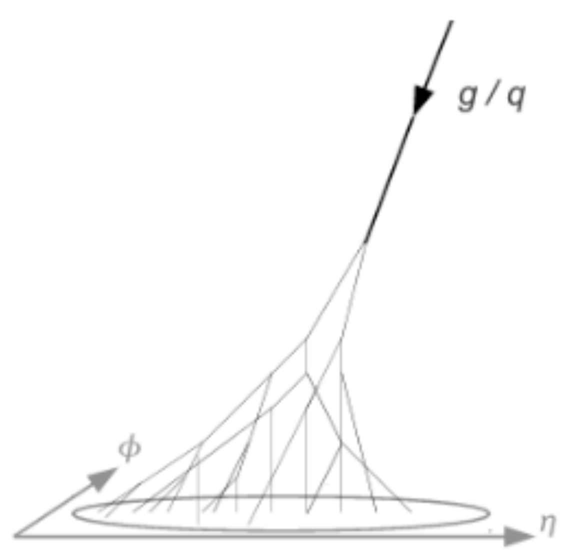
Signal

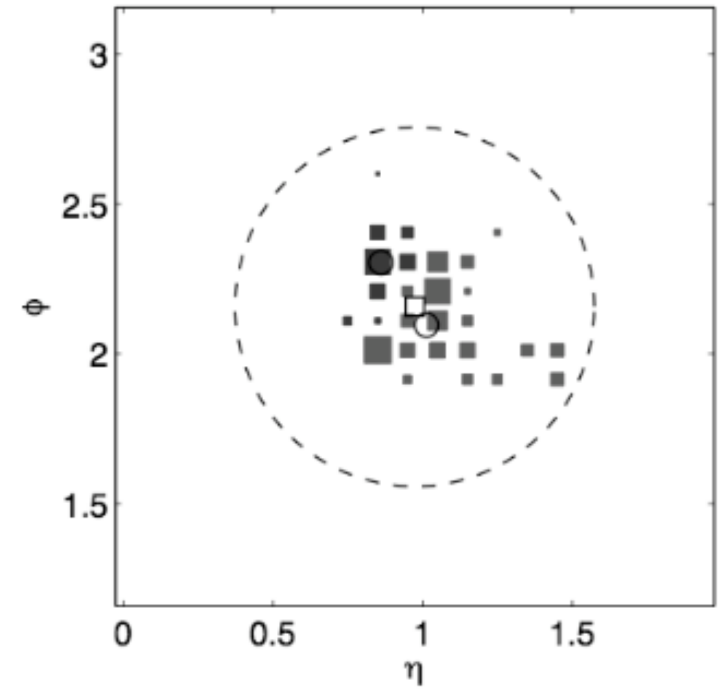




2D imprint of jet on calorimeter surface

Background

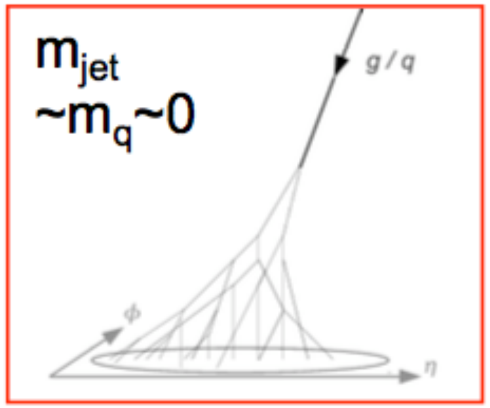


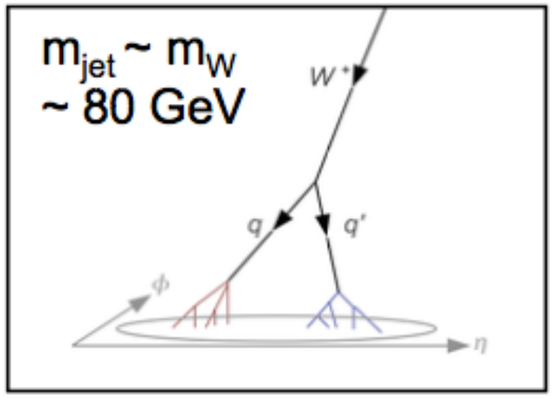


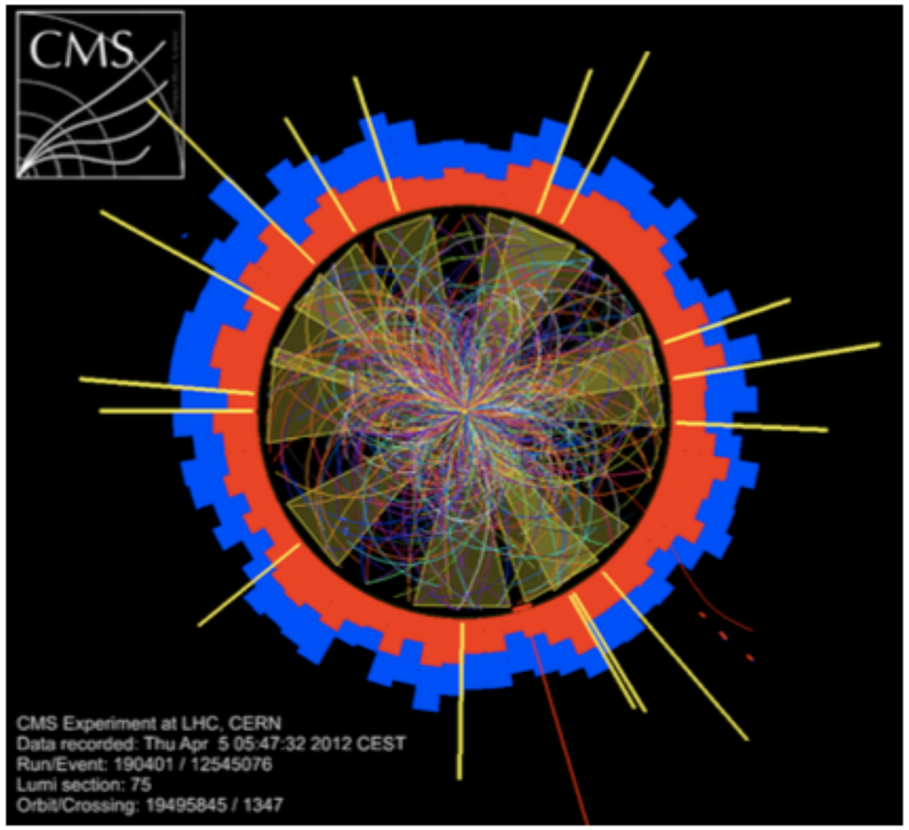
Background from jets is ~10^6 larger than signal

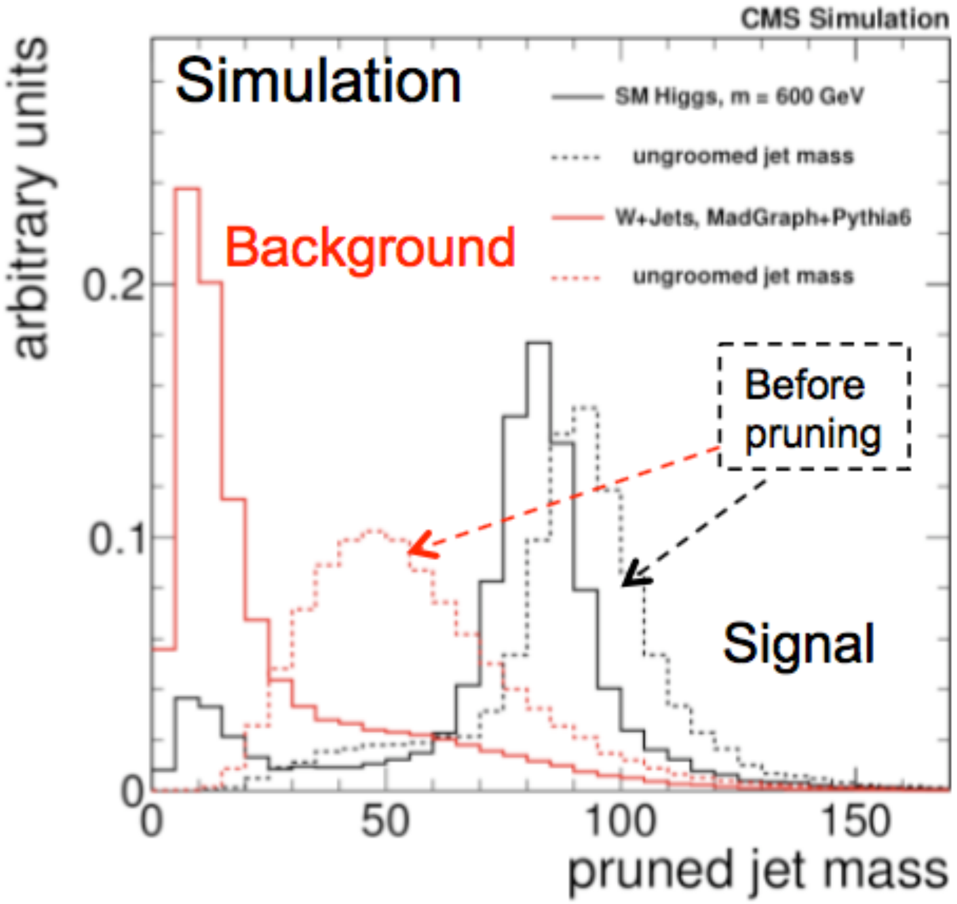
Jet substructure

- Jet invariant mass
  - QCD-jet → small mass
  - W-jet → $M_W \sim 80$ GeV
- Jet pruning
  - Clean jet from extra hadronic activity in event
  - Also remove soft part from hadron shower





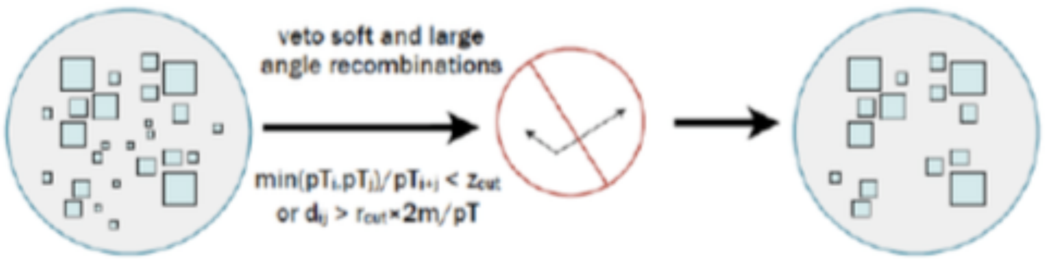




Jet pruning

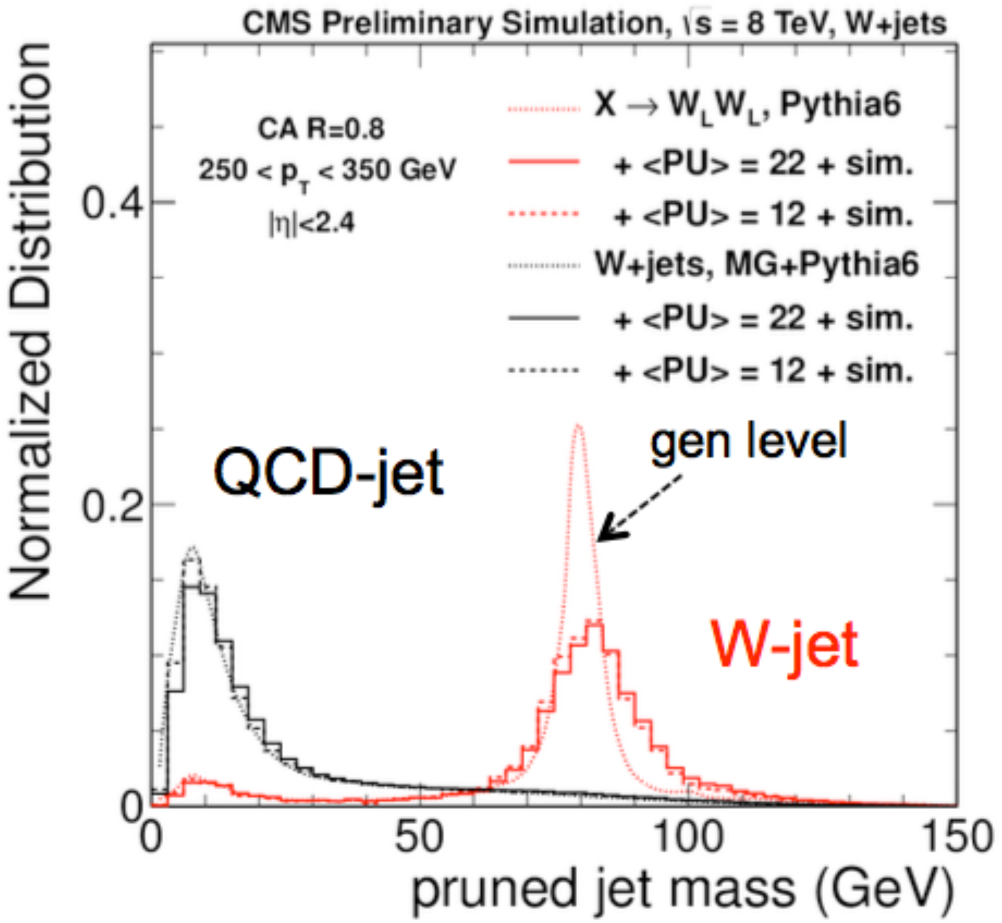
- Re-cluster jet constituents (using C/A or kt algorithm) applying additional requirements at each [i,j] recombination

$$z = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i+j}} > 0.1 \quad \text{OR} \quad \Delta R_{ij} < 0.5 \frac{M_{JET}}{p_{T,JET}}$$



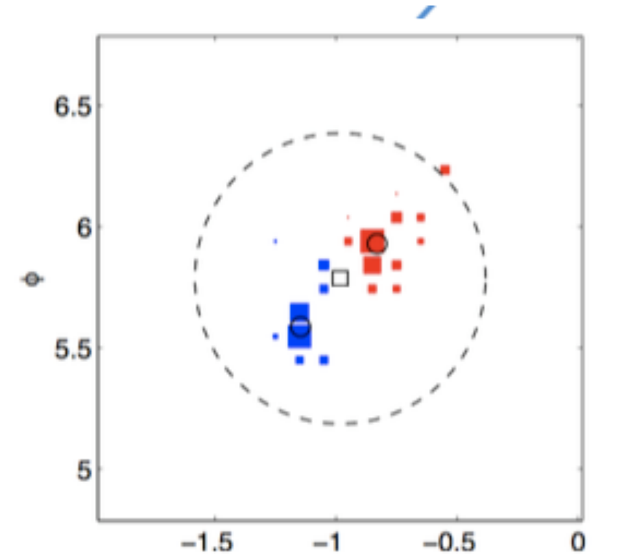
- Filter out soft and large-angle QCD emissions (i.e. pile-up)

- **Pruned jet mass**
  - Good separation between W-jet and QCD



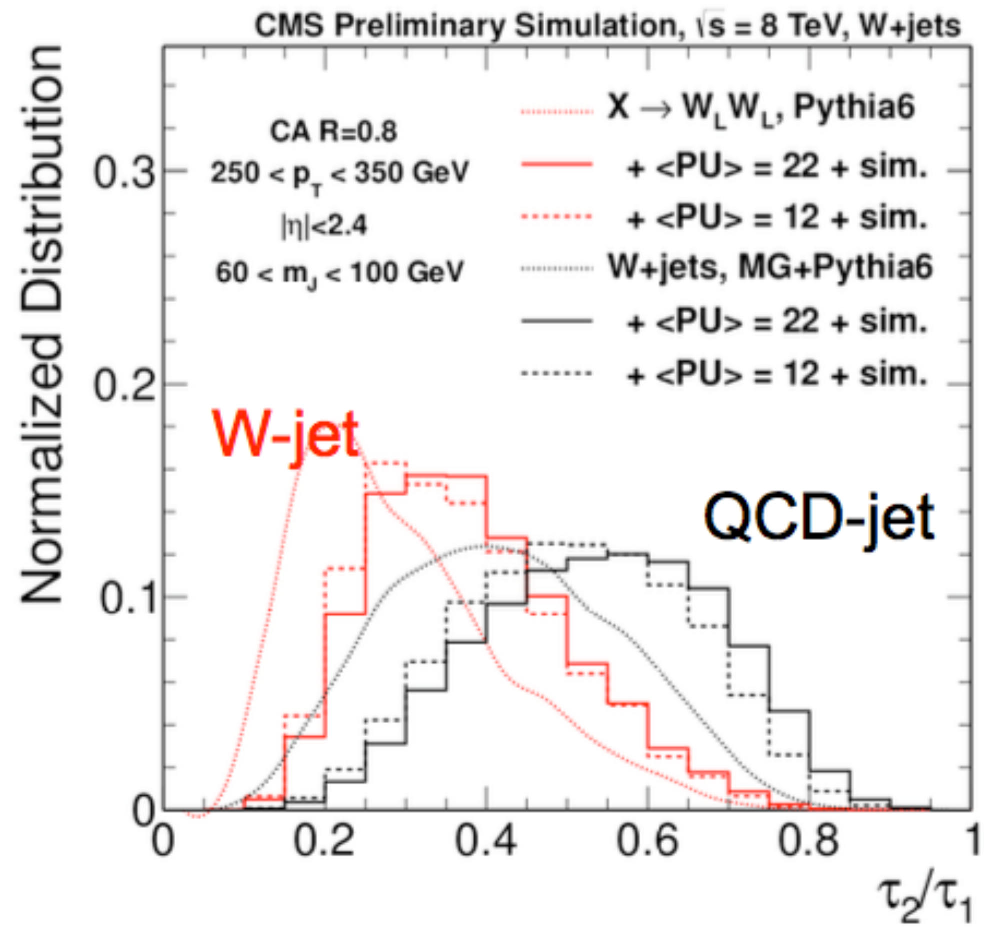
Nsubjettiness

- Topologial compatibility with hyp. of N subjets
- Re-cluster jet, halting once reached N subjets
- τ_N : p_T-weighted sum over jet constituents of distances from closest subjet axis



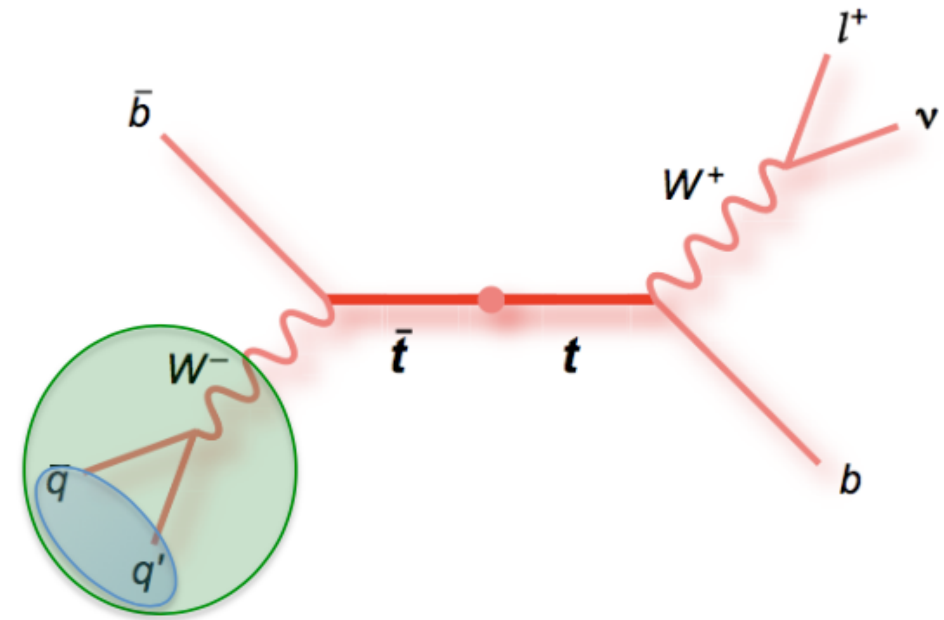
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\left[\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}\right]$$

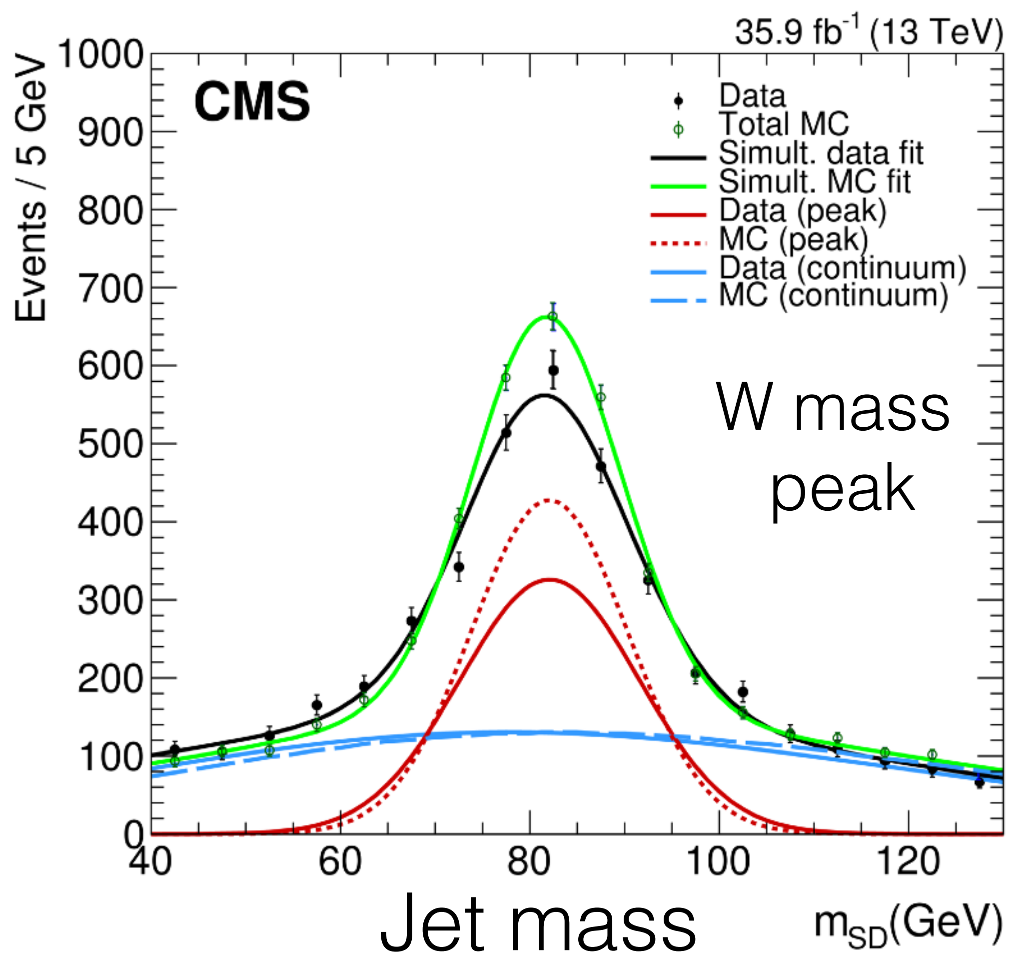
- **Di-polar structure: τ_2/τ_1 ratio**
  – Fairly good separation between W-jet and QCD after pruned jet mass cut



Calibration of Jet-substructure Observables

- Use known processes to calibrate and test jet substructure algorithms
  - W bosons from top pair production
- Measure data/MC scale factors
  - jet mass scale (few % uncert.)
  - jet mass resolution (~5% uncert.)
  - efficiency of two-prong substructure (~10% uncert.)
- Measurement extrapolated at higher pT (>500 GeV) than what measured in data (~200-300 GeV)
  - pT dependent corrections based on simulation studies (i.e. comparing different parton shower algorithms)

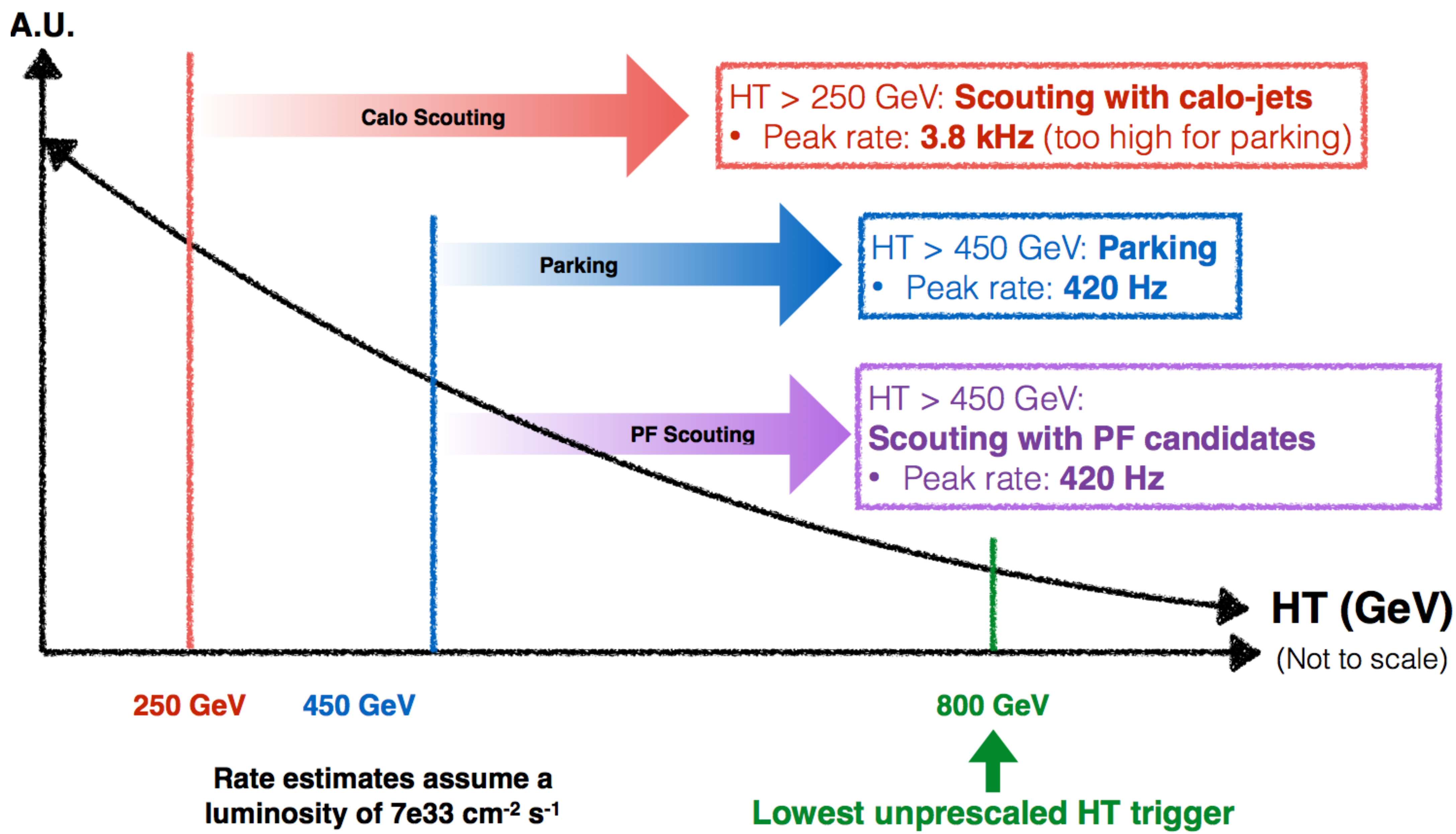




CMS Data Scouting (1)

2016 setup

EXAMPLE: The HT events



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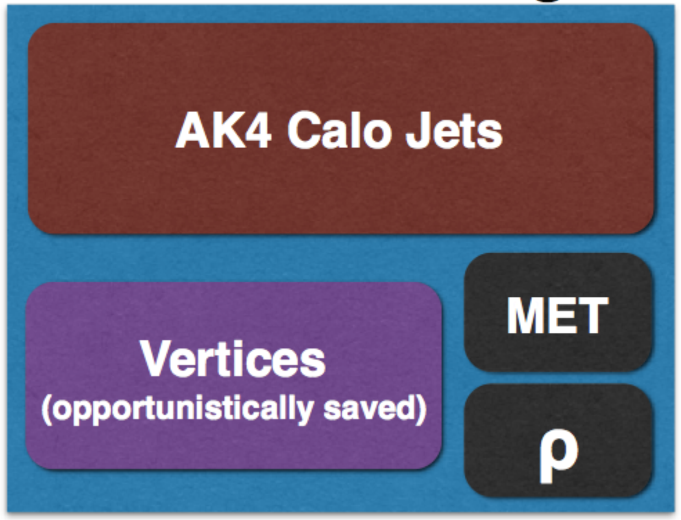
CMS Data Scouting (2)

2016 setup

Event Content

- **Calo Scouting**
  - Four-momenta of Calojets with pT>20 GeV
  - Vertices (when available), “opportunistically” from other paths in the trigger table
  - Event information
    - energy density ρ (for pile-up subtraction)
    - Missing transverse energy
- **PF Scouting**
  - Four-momenta of relevant physics objects
    - e, μ, γ, PFJets, PF candidates, vertices
  - Event information (as for Calo Scouting, but with tracking)

Calo Scouting



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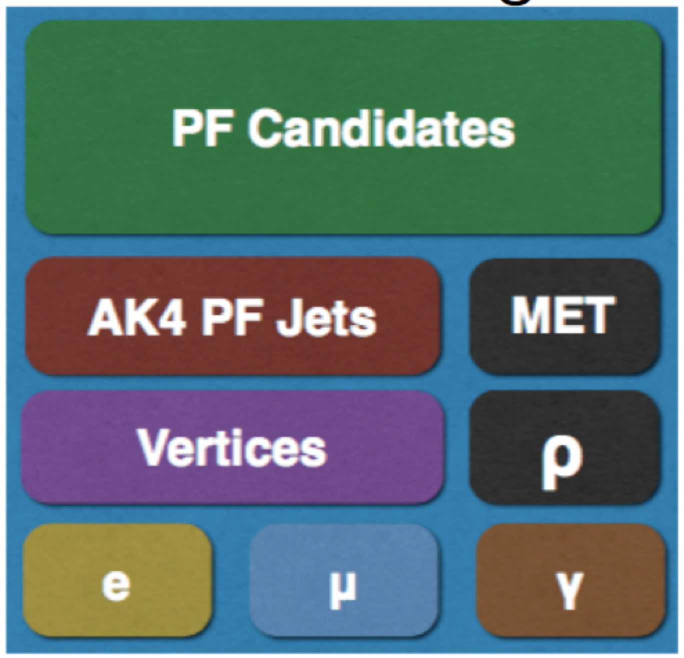
PF Scouting



Typical size: 10 kb

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Jets at Trigger Level

- Compare HLT jets vs offline reconstructed jets
  - jet energy scale agree at % level after corrections
  - jet energy scale uncertainties about factor 2 larger (still < few% in whole pT range)