Searches with unusual jet substructure in CMS

EPS-HEP 2019

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Alberto Orso Maria Iorio, for the CMS collaboration

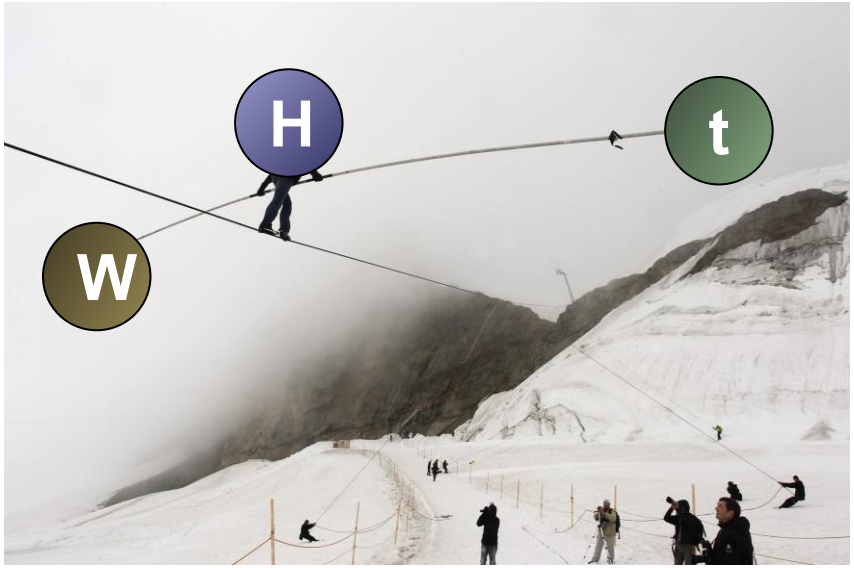
Particle physics after the Higgs: Non plus ultra?

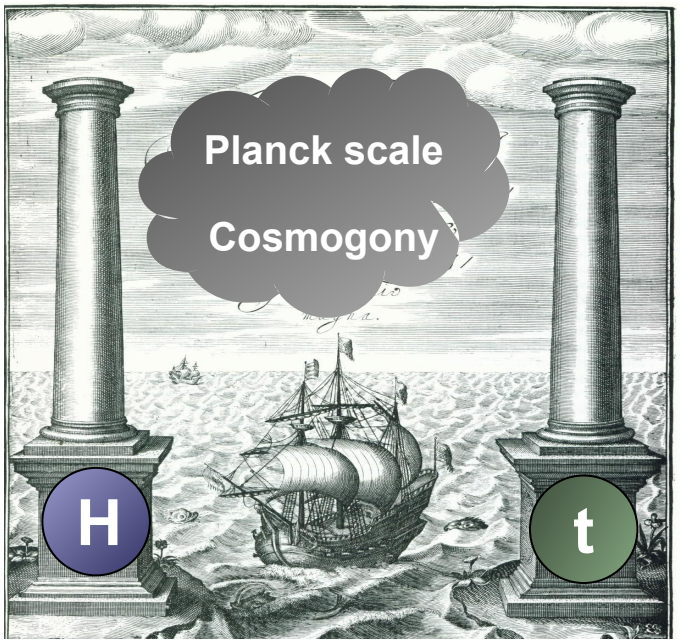
Going beyond: missing pieces

→ The inclusion of gravity

→ Dark matter, Dark energy

→ Matter-antimatter asymmetry





The SM "effective field theory vibe"

→ Origin of EWK symmetry breaking

→ Why does the Higgs stay so light

→ Why so many free parameters?

Particle physics after the Higgs: Non plus ultra?

New physics has eluded us so far! But **why could we have missed it?**

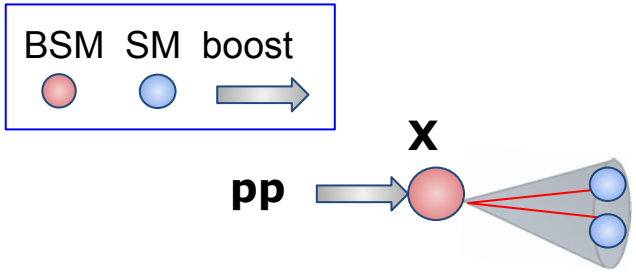
- **Energy range:** in a phase space not explored so far
- **Triggers:** not included in standard triggers
- **Signature:** in the detector not sought after

... or a combination of the above!

It is crucial to stay open-minded and go beyond our "comfort zone" for what concerns models and also technologies!

Examples are creative uses of jet substructure for searches.

Exotic jets and where to find them



1) **Light new physics objects X**:

- Relatively low energies can give large lorentz boost
- Collimated decay products → appear in single jet
- Typically detected in states exploiting ISR

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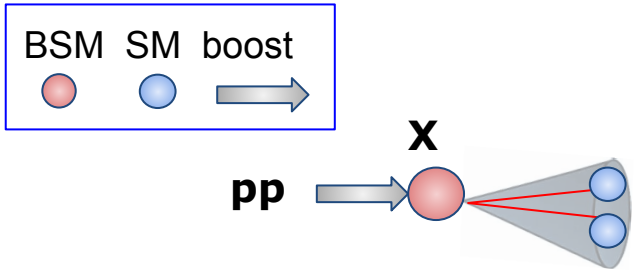
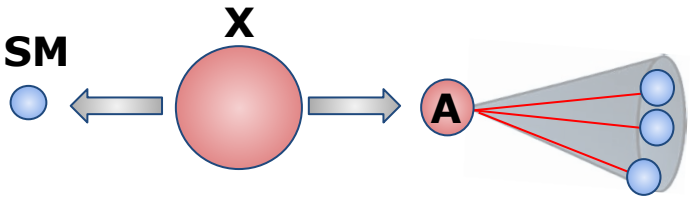
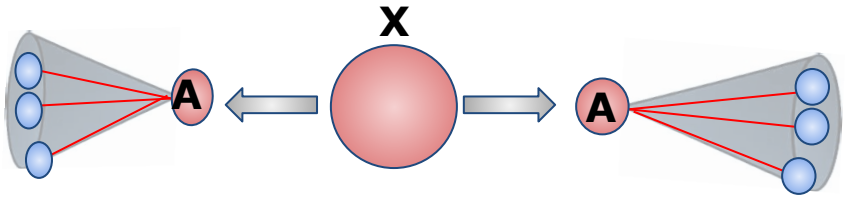


2) **Heavy final states** with **decay cascades**:

X → AA; A→ Multiple-SM particles
X → A+ SM; A→ Multiple-SM particles

- Large energy from original X mass
- Cascades of objects clustered together-





Z' resonances at LHC

Leptophobic Z' → qq:

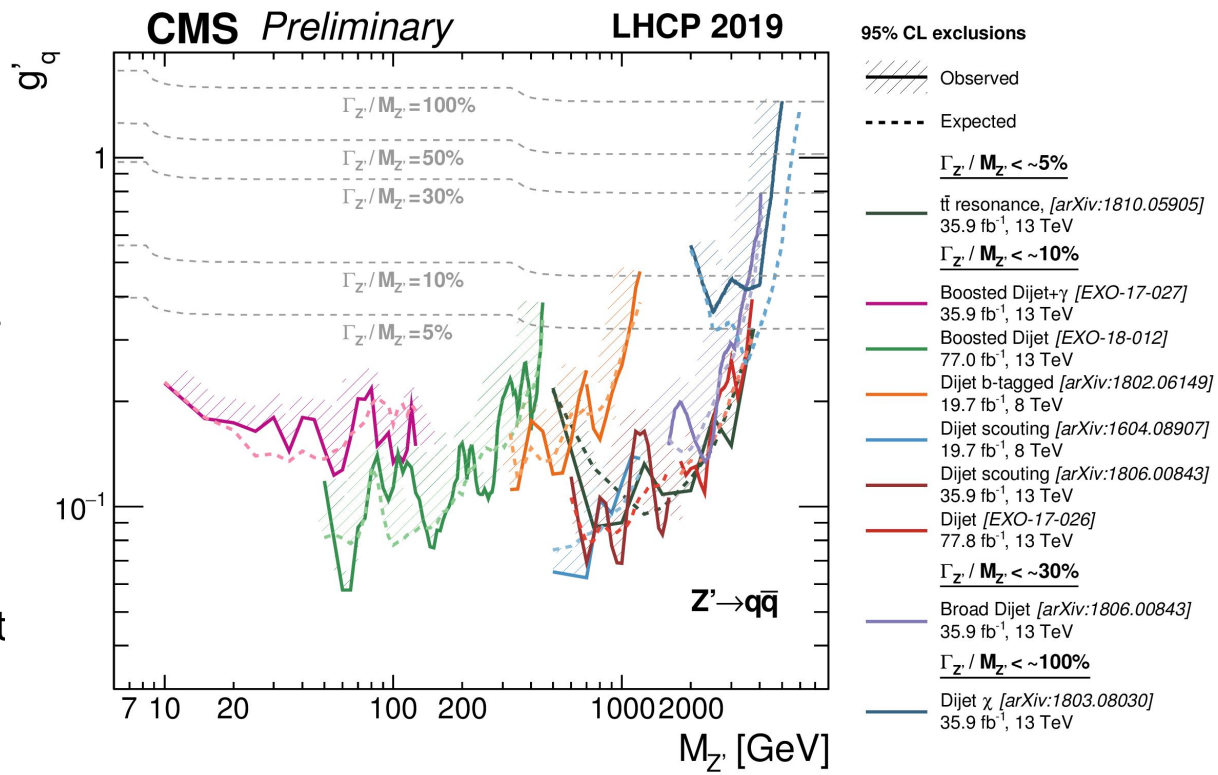
- Appear in extra dimensions, Dark matter, etc.

- Spans across several orders of magnitude in $\mathbf{m_Z}$

- Low-mass case **challenges**:

→ **High background** cross sect

→ **Tight trigger** requirements

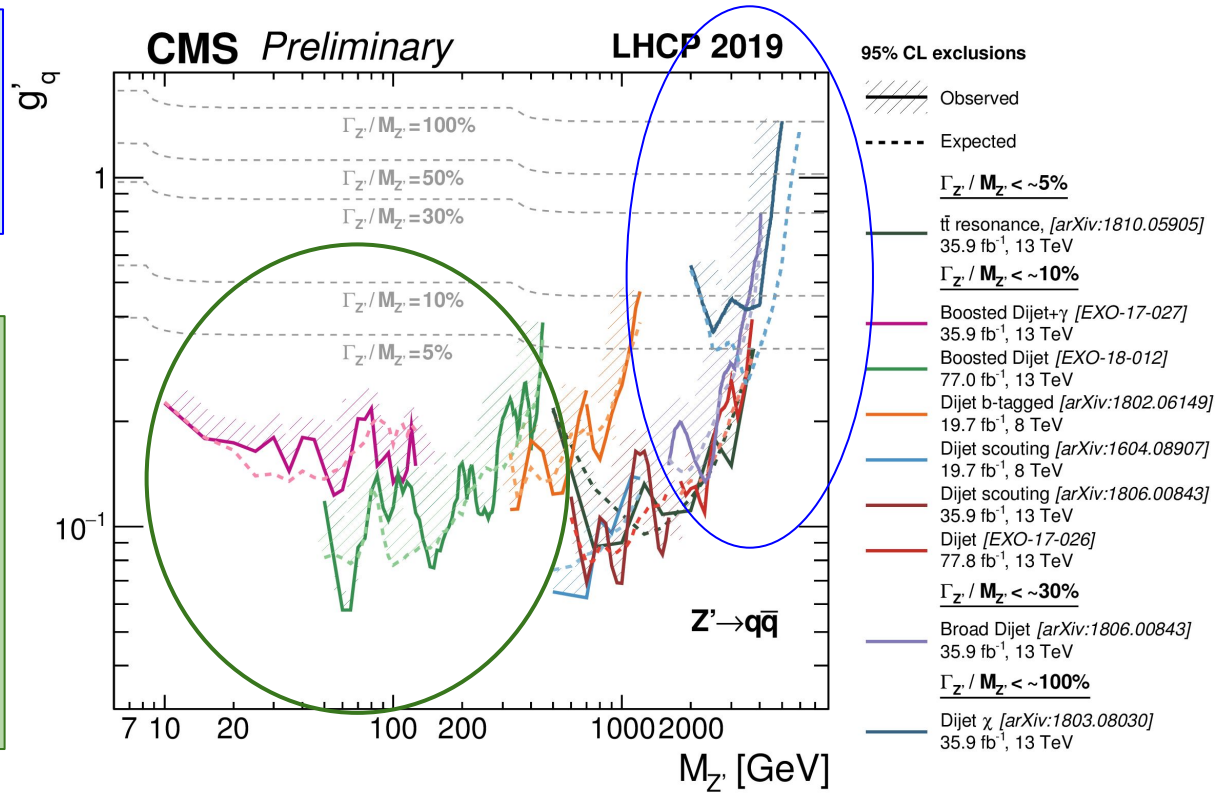


Z' search regimes

Heavy Z': bump hunts in di-jet mass spectrum
- see also this [talk yesterday from Beghin]

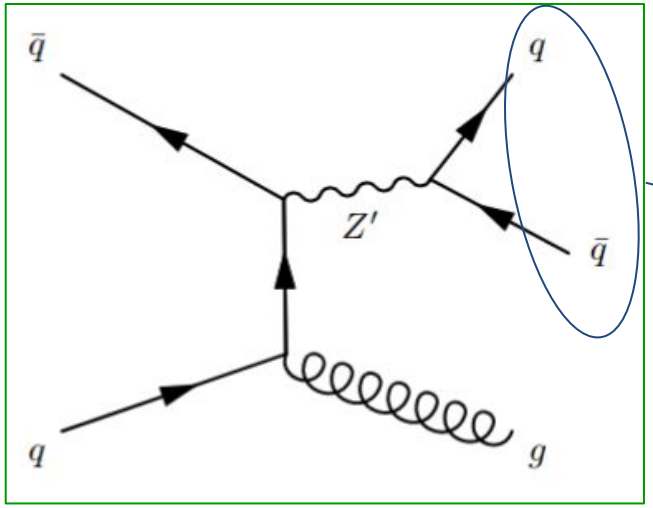
Light Z':

- qq + Initial state radiation
- Studies in Run II: Z' + gluon or photon



Z’ + ISR gluon

EXO-18-012



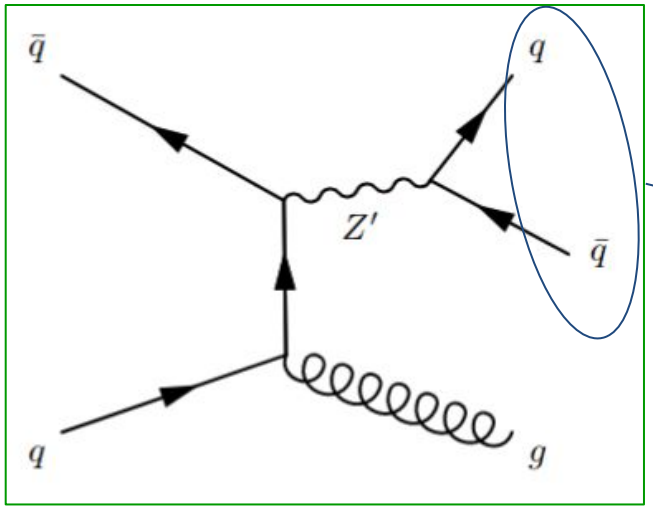
Quarks merged in one jet:
- reduces background combinatorics
- Can identify jet-substructure with ad hoc variables

Jet mass = Z’ mass

Additional ISR:
- Helps trigger efficiency using overall hadronic transverse energy

Z’ + ISR gluon

EXO-18-012



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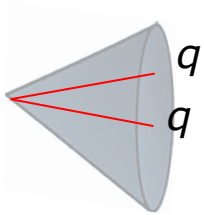
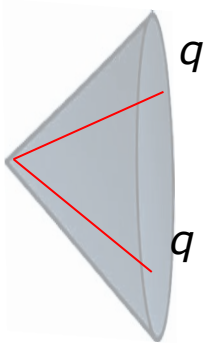
Different jets depending on mass range:



40 < mZ < 175 GeV
Anti-Kt
Radius 0.8



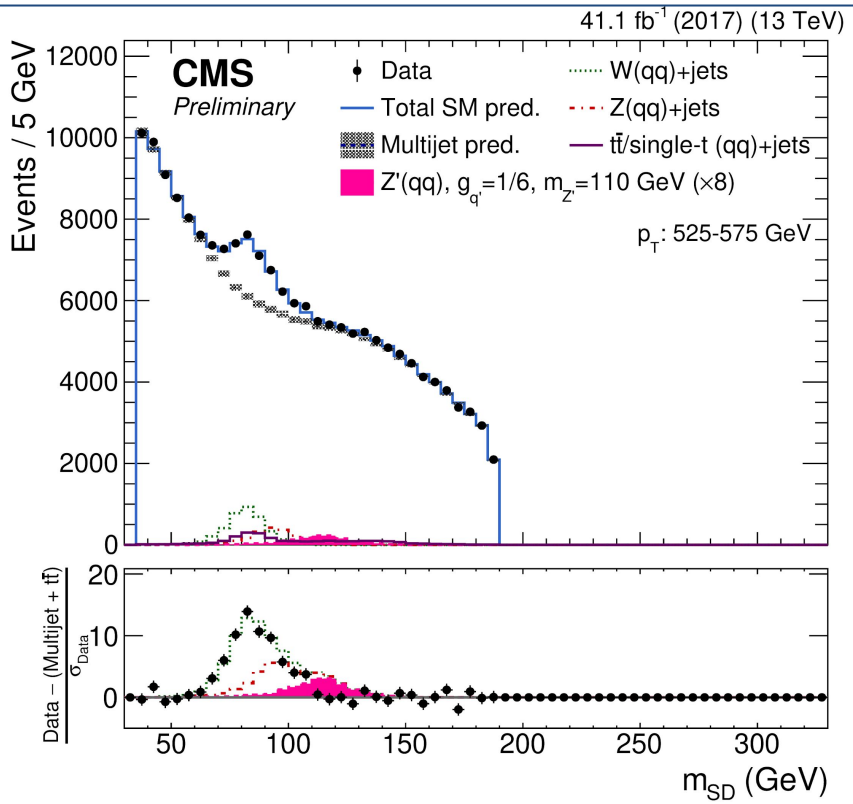
175 < mZ < 500 GeV
Cambridge Aachen
Radius 1.5

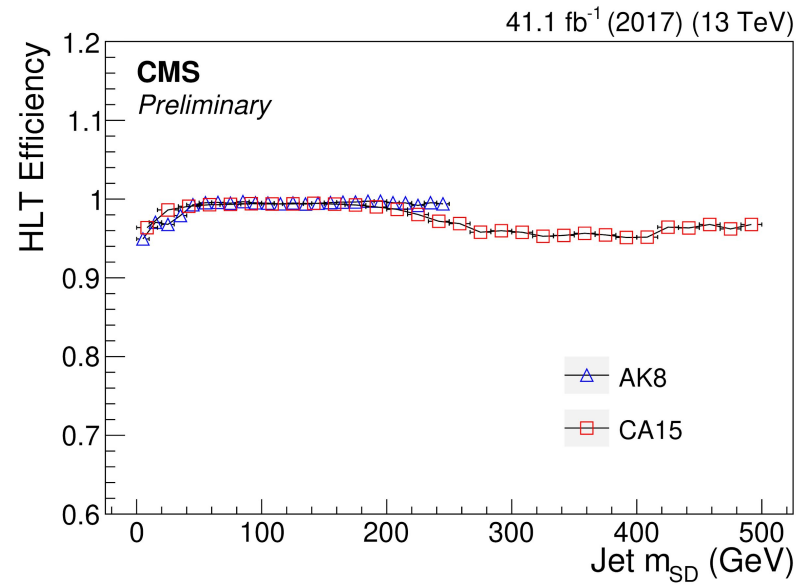
Z' + gluon: the analysis

EXO-18-012

Trigger: Efficiency as function of jet mass
Jet selection:
- 1 Anti-Kt8(Cambridge-Aachen) jet
- PT > 525 (575) GeV
- -5.5(4) < r = 2log(m/PT) < - 2.5(1)
- Cut on substructure variable N2, energy correlation functions

Veto on loose leptons



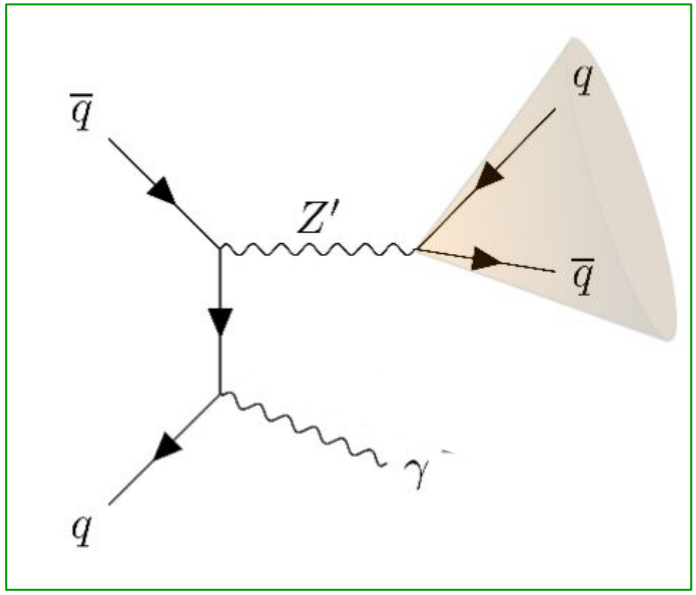


Mass reconstruction:

- **Soft-drop** algorithm to remove soft QCD components in jet
- **QCD dijet** from data in CR

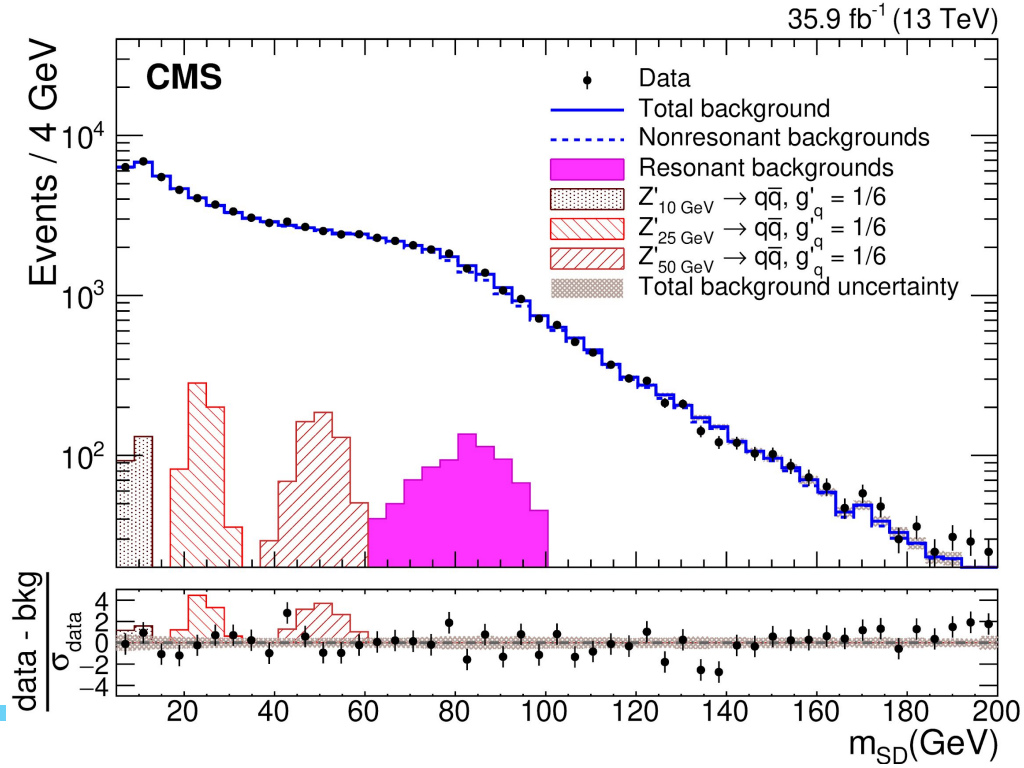
Z' + ISR photon

EXO-17-027



Similar strategy, but + photons:

- Photon present → easier trigger → lower mZ!
- Background **Gamma + jets**, **QCD multijet,** from Data in jet eta sideband

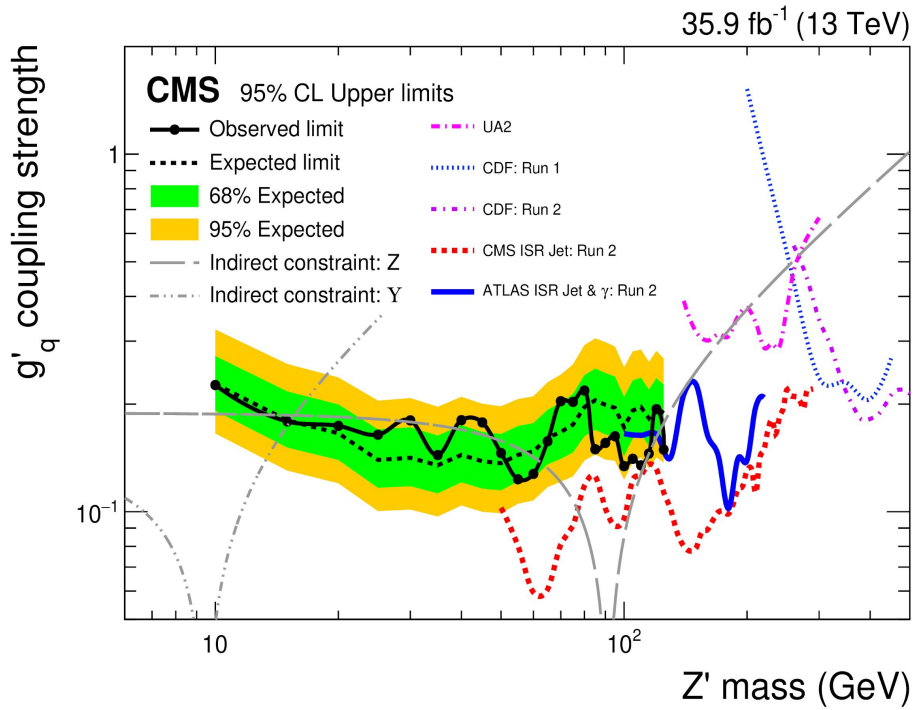


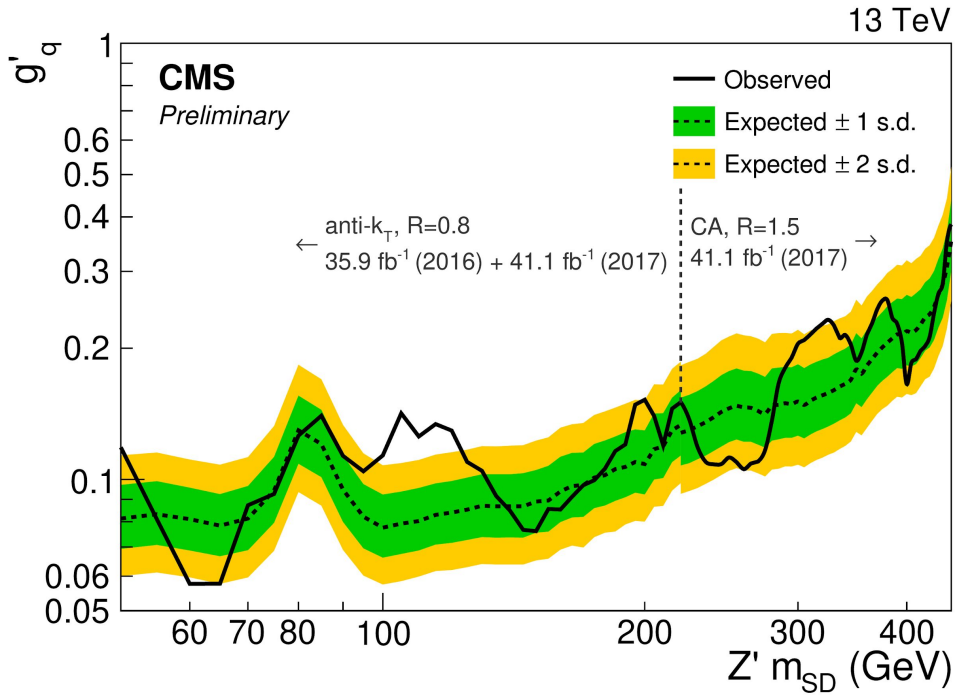
One AK8 jet:
- Pt > 200 GeV
- -7 < ϱ = 2log(m/PT) < - 2)
- N2 decorrelated wrt mass

One photon:
- Pt > 200 GeV
- ΔR(γ,jet) >2.2

EXO-17-027 EXO-18-012

Results Z' + ISR





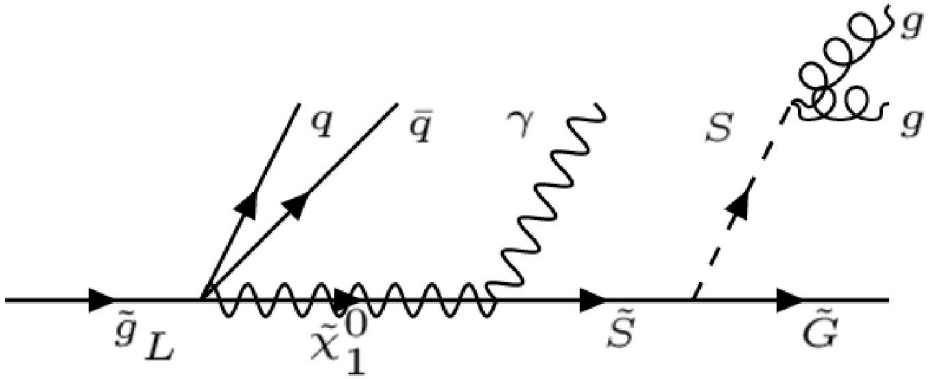
Z' + photons:
→ Results down to **10 GeV!**

→ Reach improves on indirect limits from Z and Υ widths

Z' + gluons:
→ Result in range **40-450 GeV**
→ Local excess of 2.9 sigma in 2016 ~110 GeV,
not confirmed in 2017
→ Keep looking at the full Run-II!
Note: similar analysis with pseudoscalar to ***bb***, see also EXO-17-024

New physics in photon - jets

B2G-18-007



Susy: scenario with **gluinos** much heavier than **neutralinos**

Low sensitivity by looking at angularly separated gluons and photons

→ **Clustering in a new "Photon-jet"**

New physics in photon - jets

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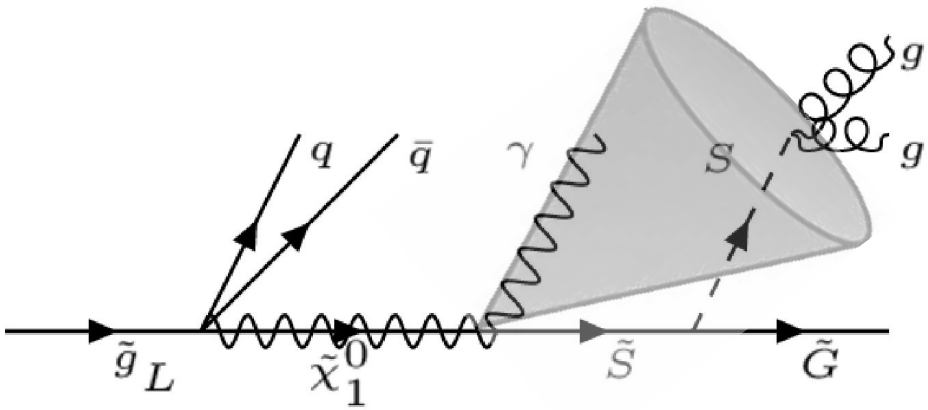


Susy: scenario with **gluinos** much heavier than **neutralinos**

Low sensitivity by looking at angularly separated gluons and photons

→ **Clustering in a new "Photon-jet"**

Jet reconstruction:

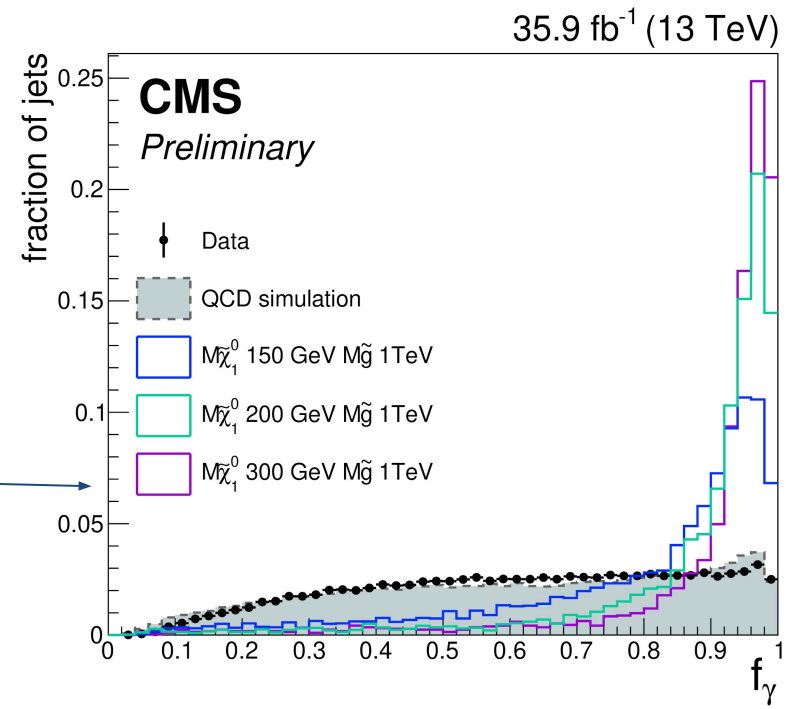
1 - Find photon footprint in jet

2 - Replace it with calibrated photon

3 - Recluster jet with calibrated photon

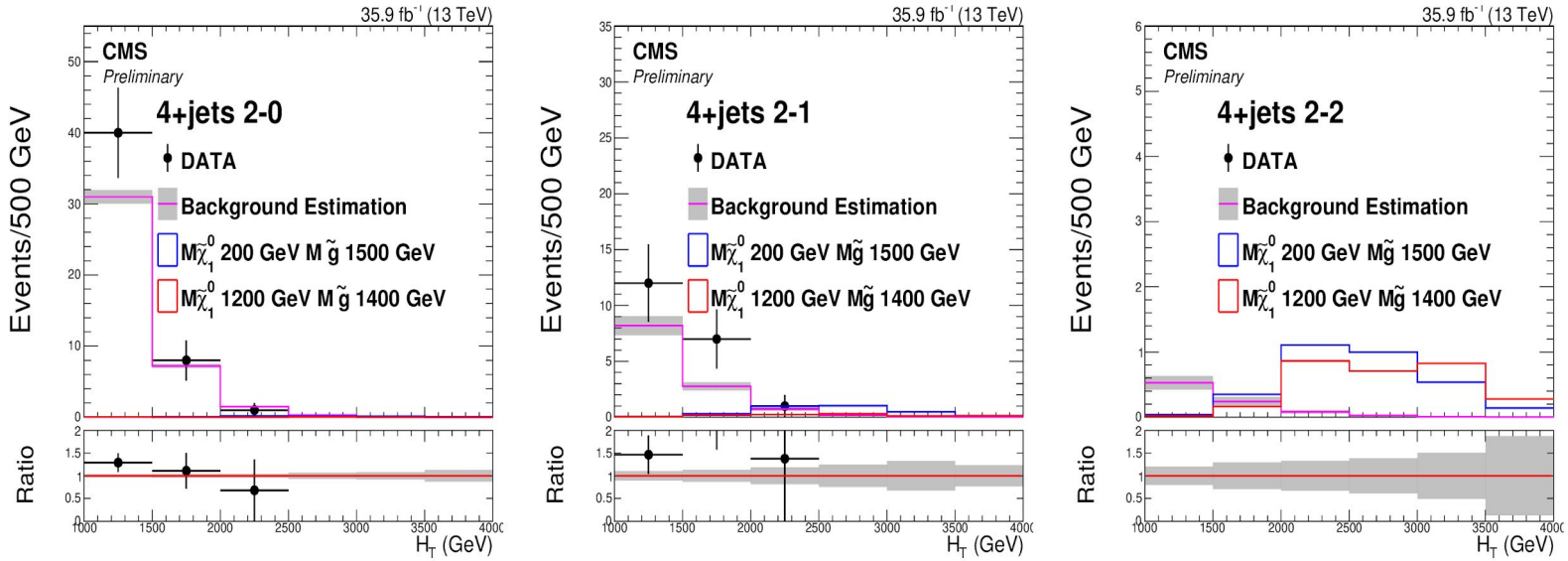
Photon subjet energy fraction:

4 - Acts as "isolation" requirement



Photon - jets analysis

B2G-18-007



Categories counting "loose" and "tight" photon-jets amongst 3 or 4 AK8 jets:

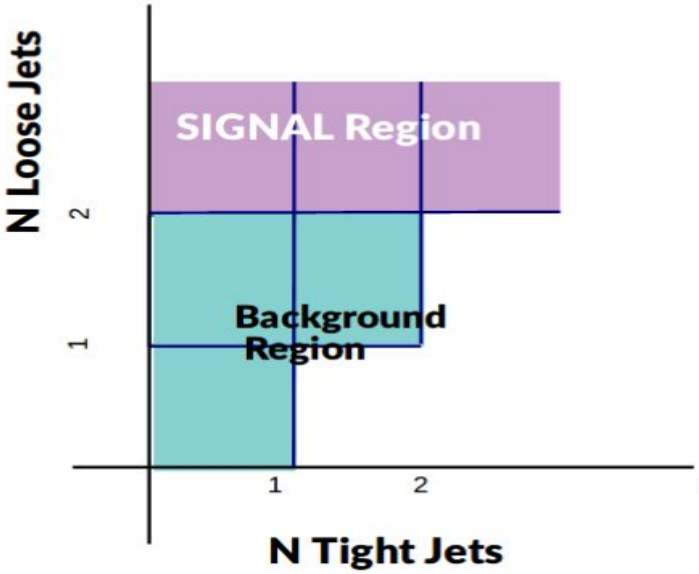
Loose:

- Pt > 200 GeV
- Substructure variable tau3/ tau1 <0.4
- 3 sub-jets with Pt > 10 GeV

Tight:

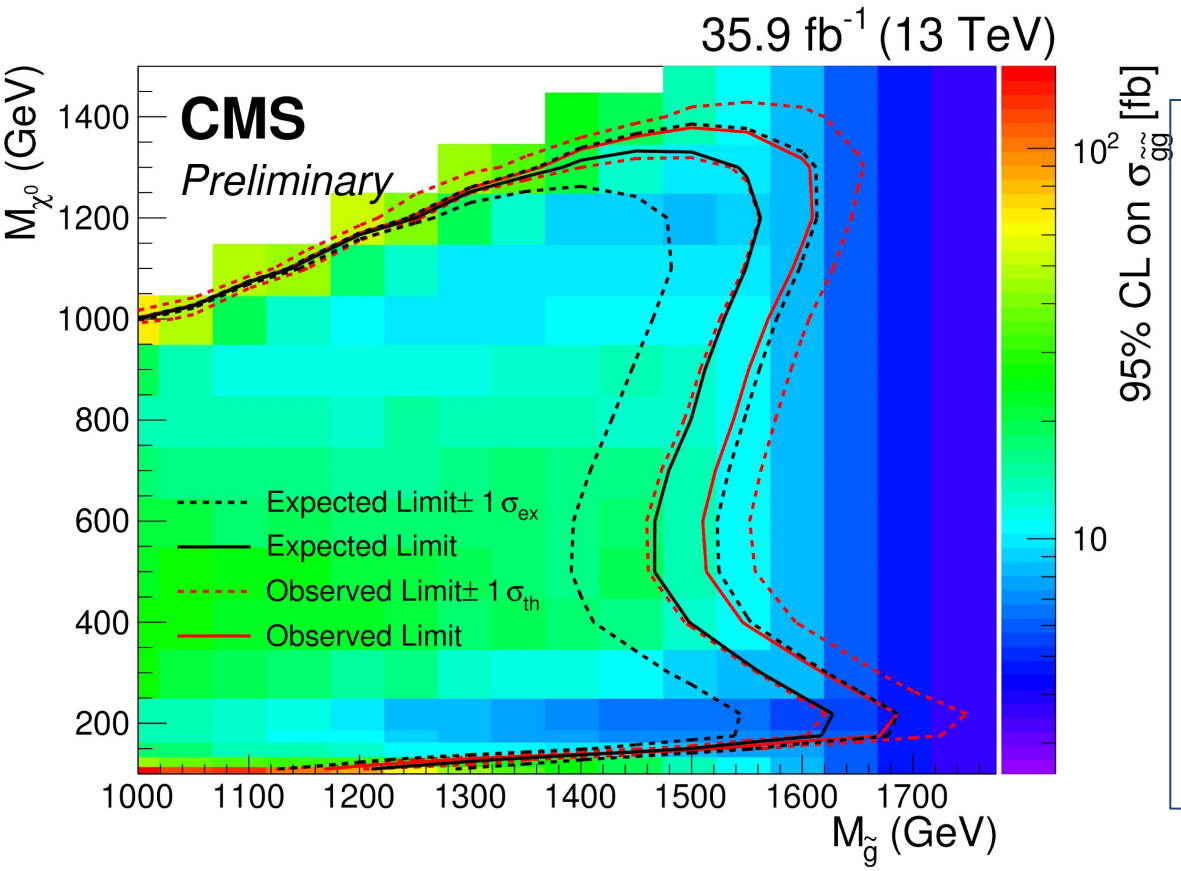
- Photon subjet fraction >0.9

Background extracted from remaining regions



Photon - jets results

B2G-18-007



New region of phase space probed:

→ Limits up to **1.8 TeV in gluino mass**

→ Up to **1 TeV in neutralino mass**.

Technology can be exploited also in final states with similar cascades!

E.g. photons + quarks pairs.

Conclusion: New physics ↔ new final states?

Use of **jet substructure** in **innovative ways** already helped us push the boundaries of our searches at LHC.

Implementations possible both at **high mass** and at **low mass!**

This is the tip of the iceberg for this kind of studies, several searches could have space for application of similar techniques.

With this great promise come great challenges as well, but with the reward of opening **exciting new scenarios** for our physics investigations!

Backup

Substructure variables

Energy correlation functions:

$$N_2(\beta) = \frac{2e_3^\beta}{(e_2^\beta)^2}$$

$${}_1e_2^\beta = e_2^\beta = \sum_{1\le i<j\le n_J} z_i z_j \Delta R_{ij}^\beta$$

$${}_2e_3^\beta = \sum_{1\le i<j<k\le n_J} z_i z_j z_k \min\{\Delta R_{ij}^\beta \Delta R_{ik}^\beta, \Delta R_{ij}^\beta \Delta R_{jk}^\beta, \Delta R_{ik}^\beta \Delta R_{jk}^\beta\}$$

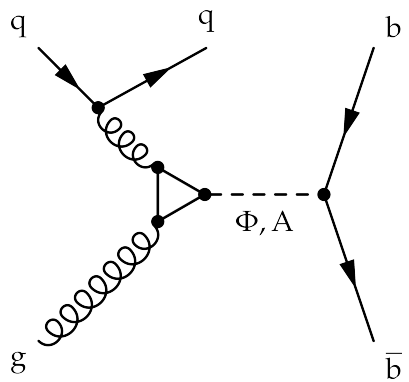
$$z_i \equiv \frac{p_{Ti}}{\sum_{j\in\text{jet}} p_{Tj}}$$

N-subjettiness:

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

Pseudoscalar to bb

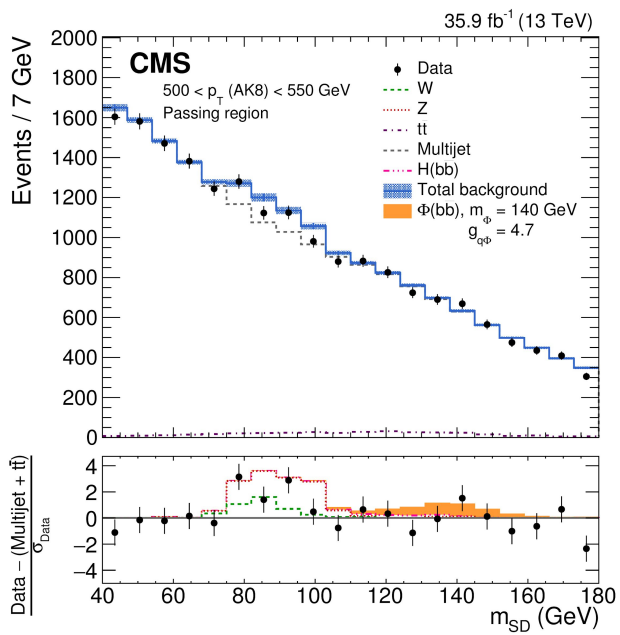
EXO-17-024

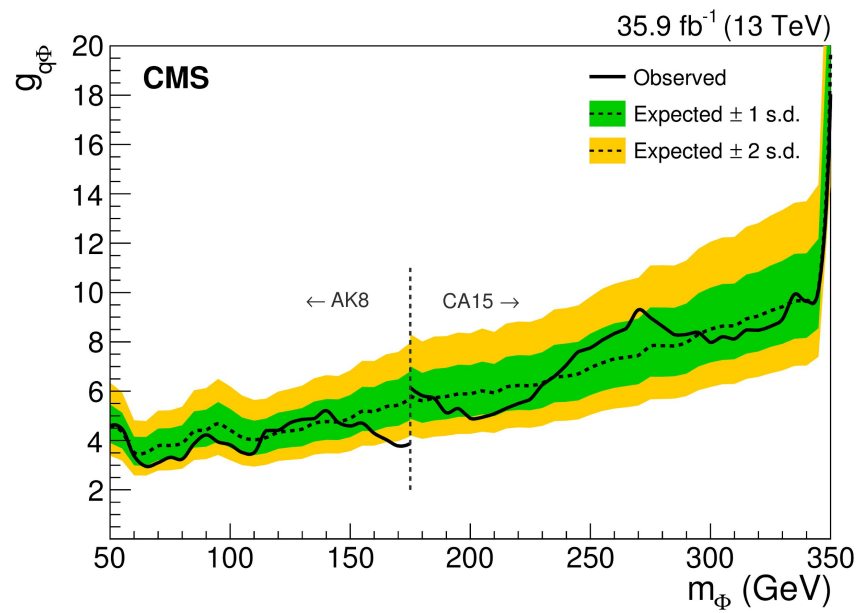


Similar to ISR + gluon:

→ Trigger with help of ISR

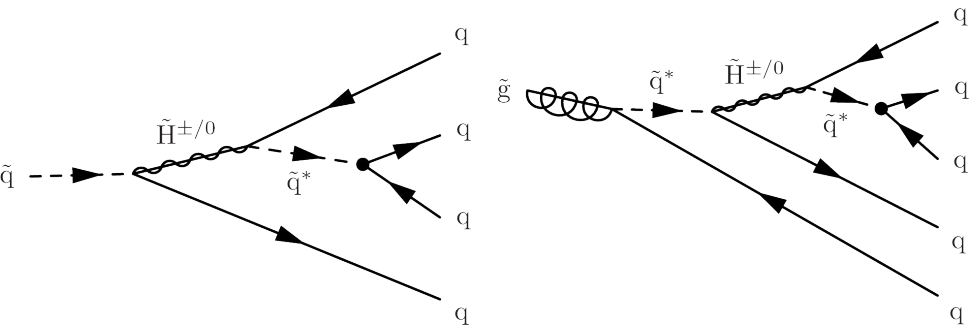
→ Bottom quark-antiquark resonance might be preferred by pseudoscalar mediator





Squark into multi-prong jets

EXO-17-022



Great mass difference between cascade particles

→ boosted decay products

→ Up to 4-pronged structure of jet.