International Workshop on Boosted Object Phenomenology, Reconstruction and Searches in HEP

July 24th, 2019

New Results from Searches with Uncommon Jet Substructure

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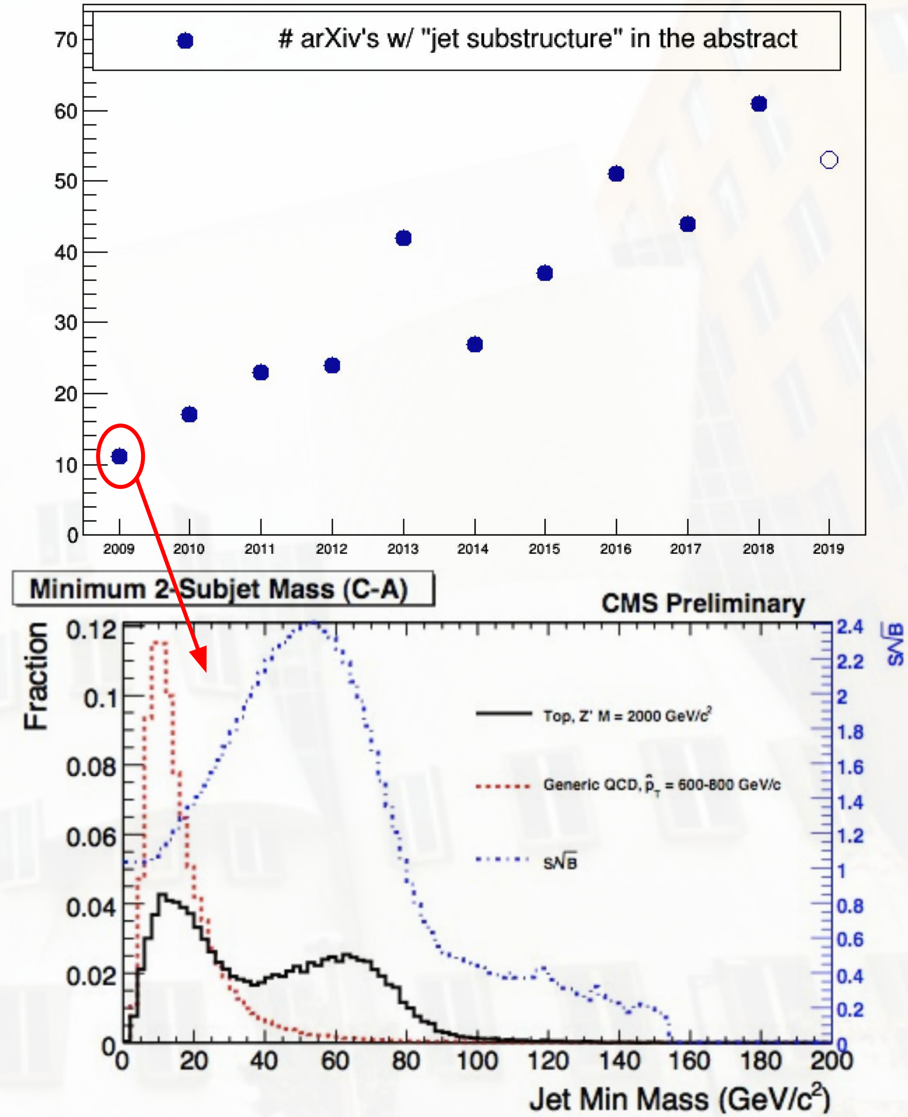
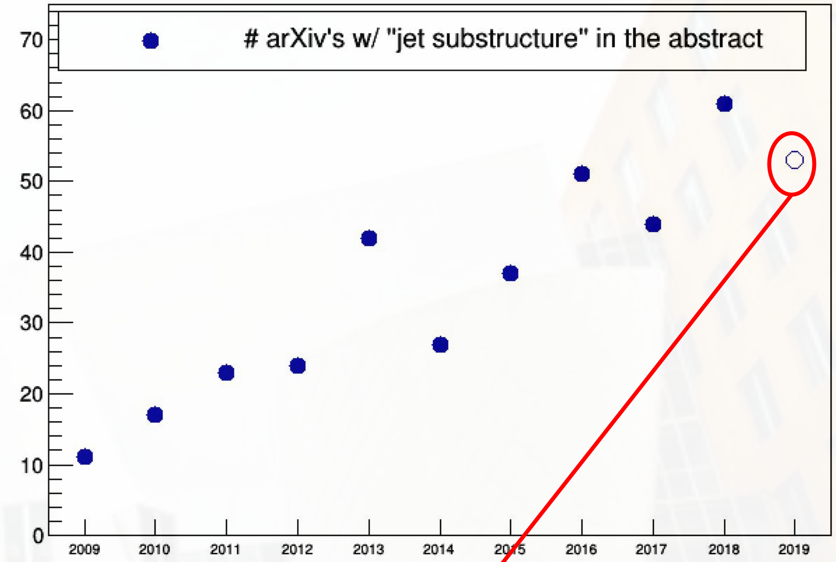
on behalf of

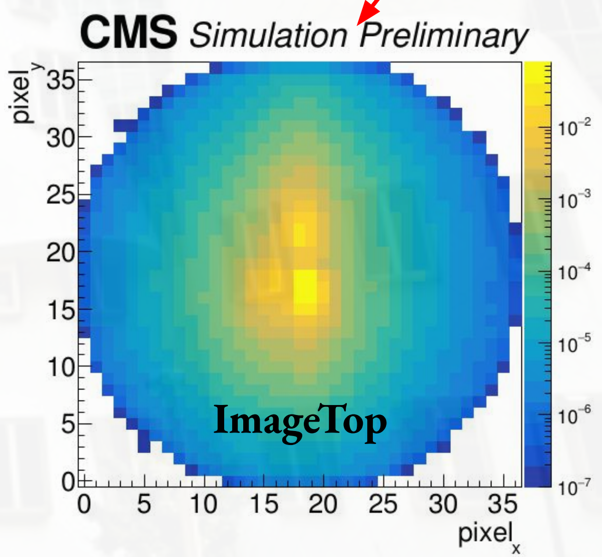
CMS

- Jet Substructure is no longer uncommon!
  - Huge improvements in tagging for standard objects like tops, Ws, Zs, h, etc
  - These common object seriously validated in large datasets



- Jet Substructure is no longer uncommon!
  - Huge improvements in tagging for standard objects like tops, Ws, Zs, h, etc
  - These common object seriously validated in large datasets
- **Today:** Two searches using jet substructure in uncommon ways:
  - [1]Z' → qq at low masses, which uses common substructure in an unusual way
  - [2]SUSY decays with photons in jets, which uses entirely new substructure variables



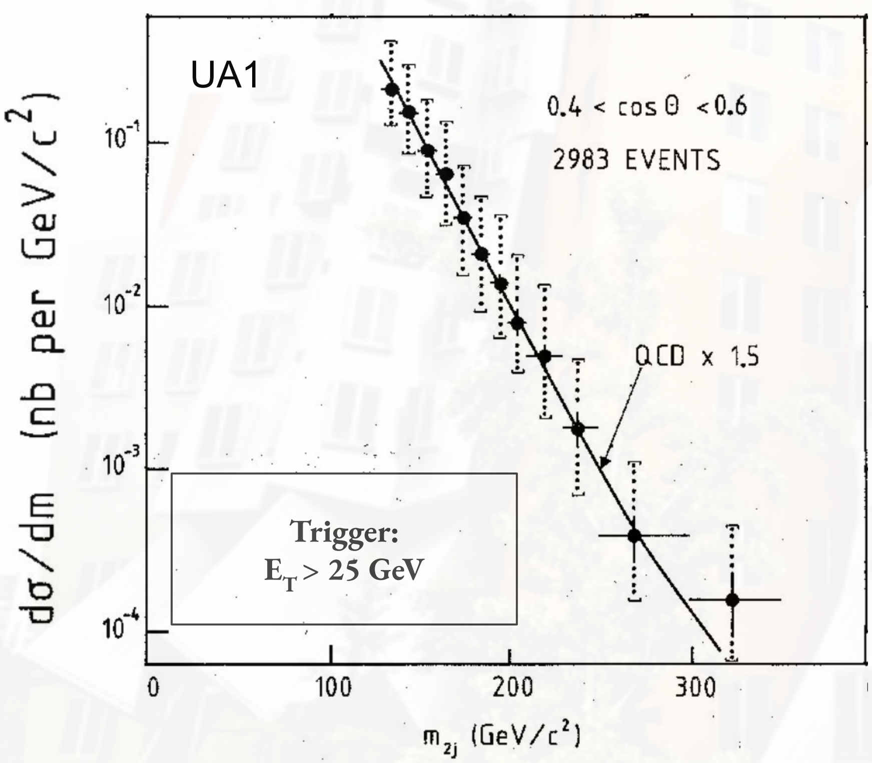


1: http://cds.cern.ch/record/2674921?ln=en & http://cds.cern.ch/record/2667276?ln=en
2: http://cds.cern.ch/record/2667271?ln=en

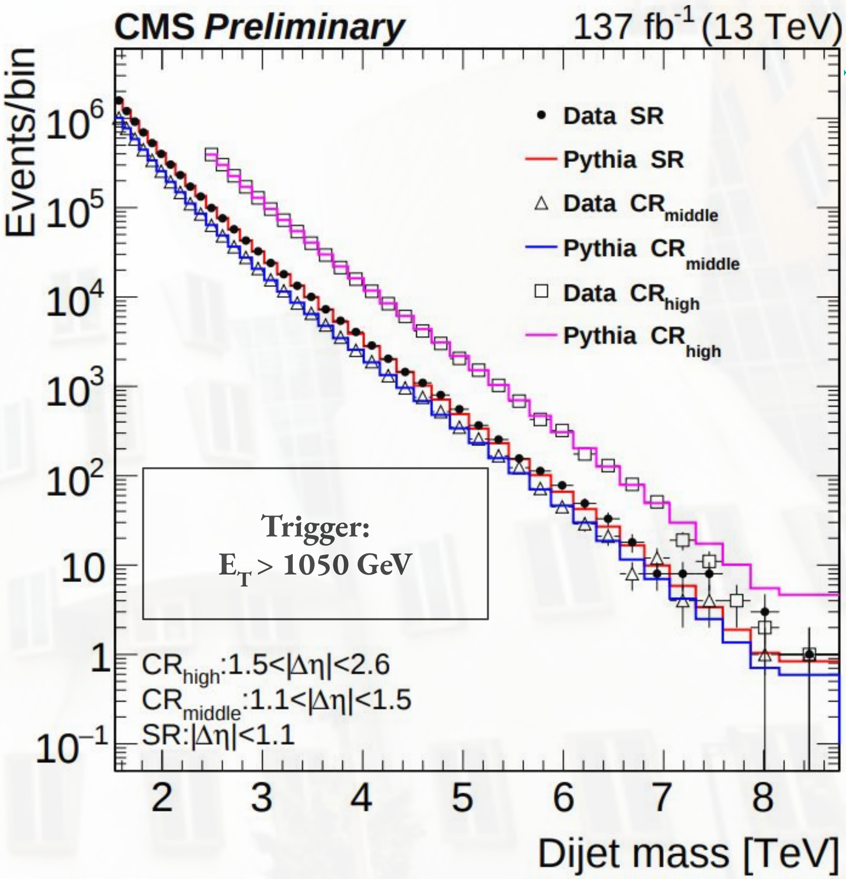
- Obvious signal to look for at a collider:

$$Z' \rightarrow qq$$

  - Many applicable new physics models.

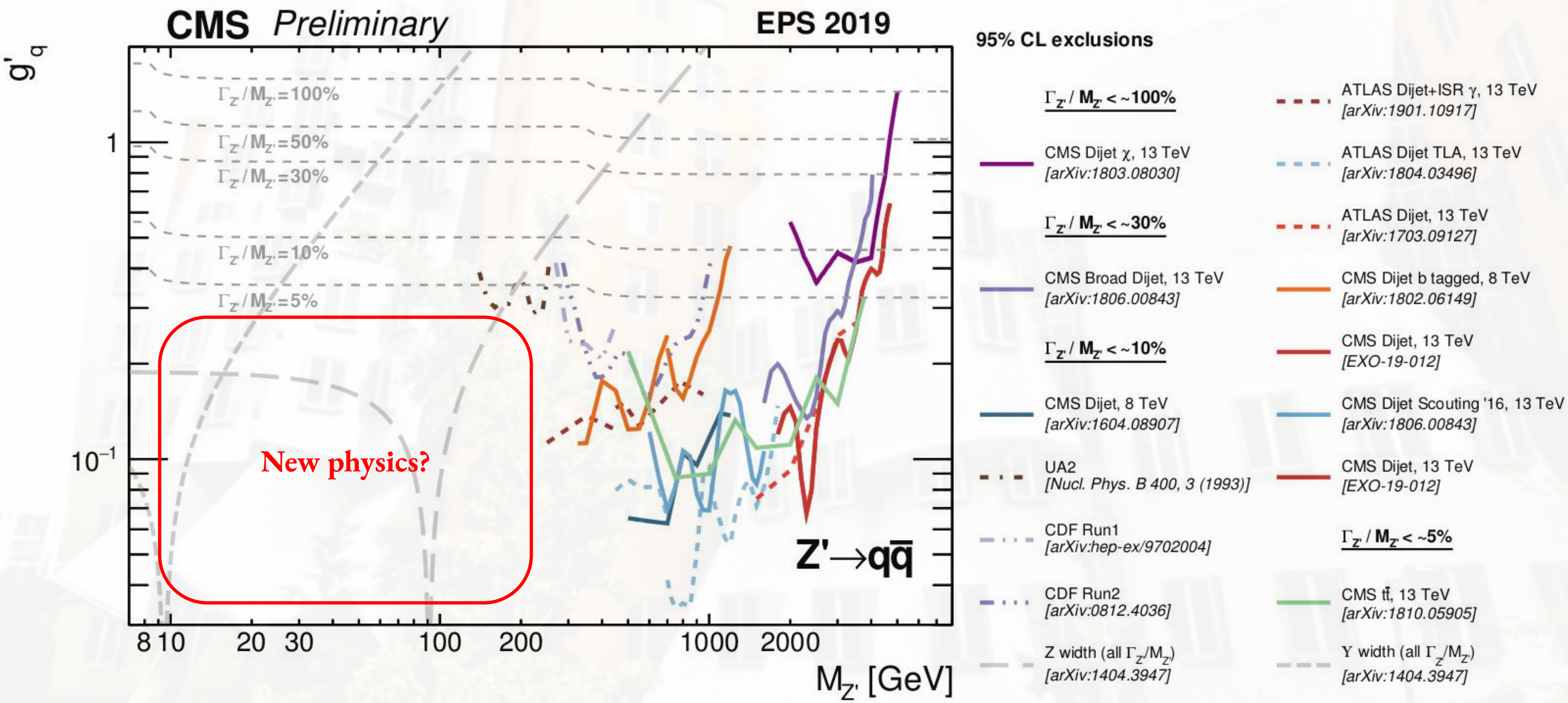


10.1016/0370-2693(88)91843-6

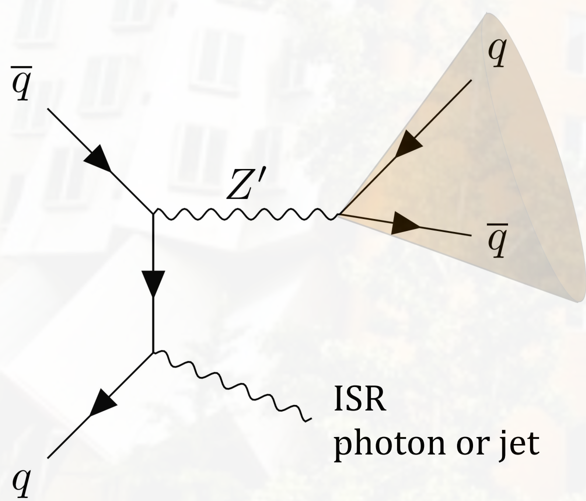


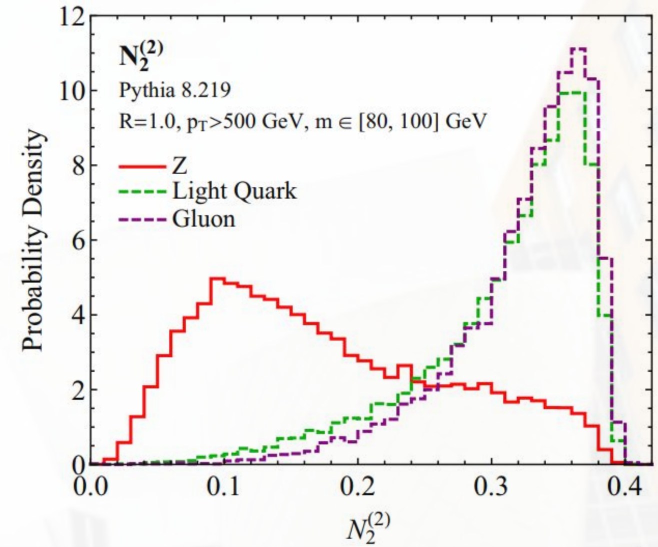
http://cds.cern.ch/record/2682120?ln=en

- As collider energies have increased, limits have steadily been set at higher mass, but not at lower coupling
- No limits from resolved dijet searches on Z' with mass below 100 GeV

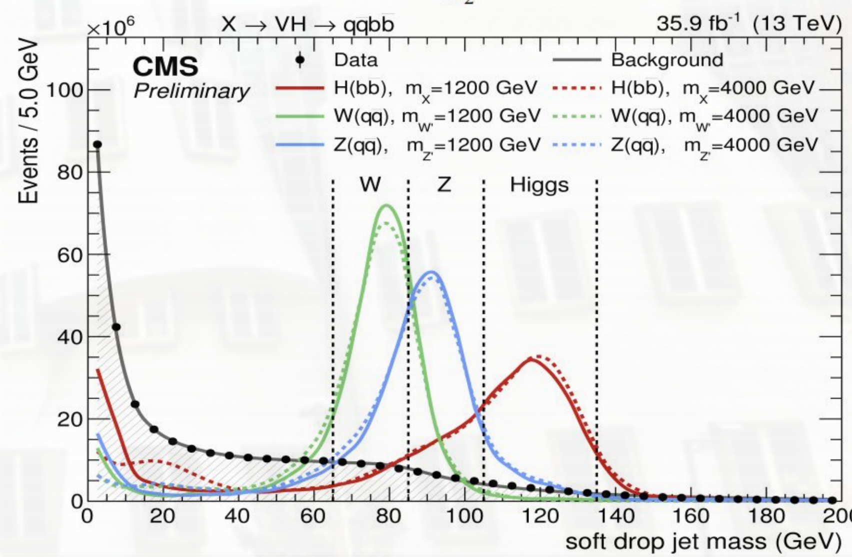


- To get around the trigger requirement, look for Z' produced with large ISR
  - Loss in cross-section
- Resulting merged object has useful substructure properties to be exploited!



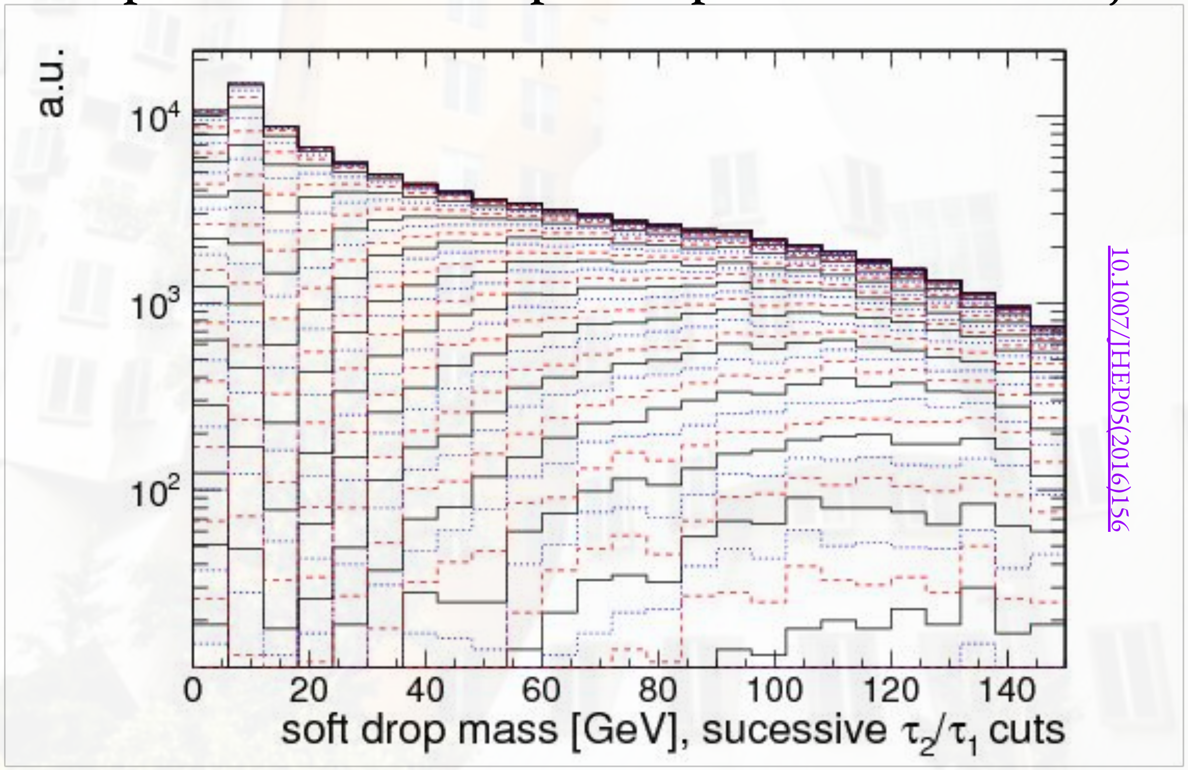


10.1007/JHEP12(2016)153



10.1140/epjc/s10052-017-5192-z

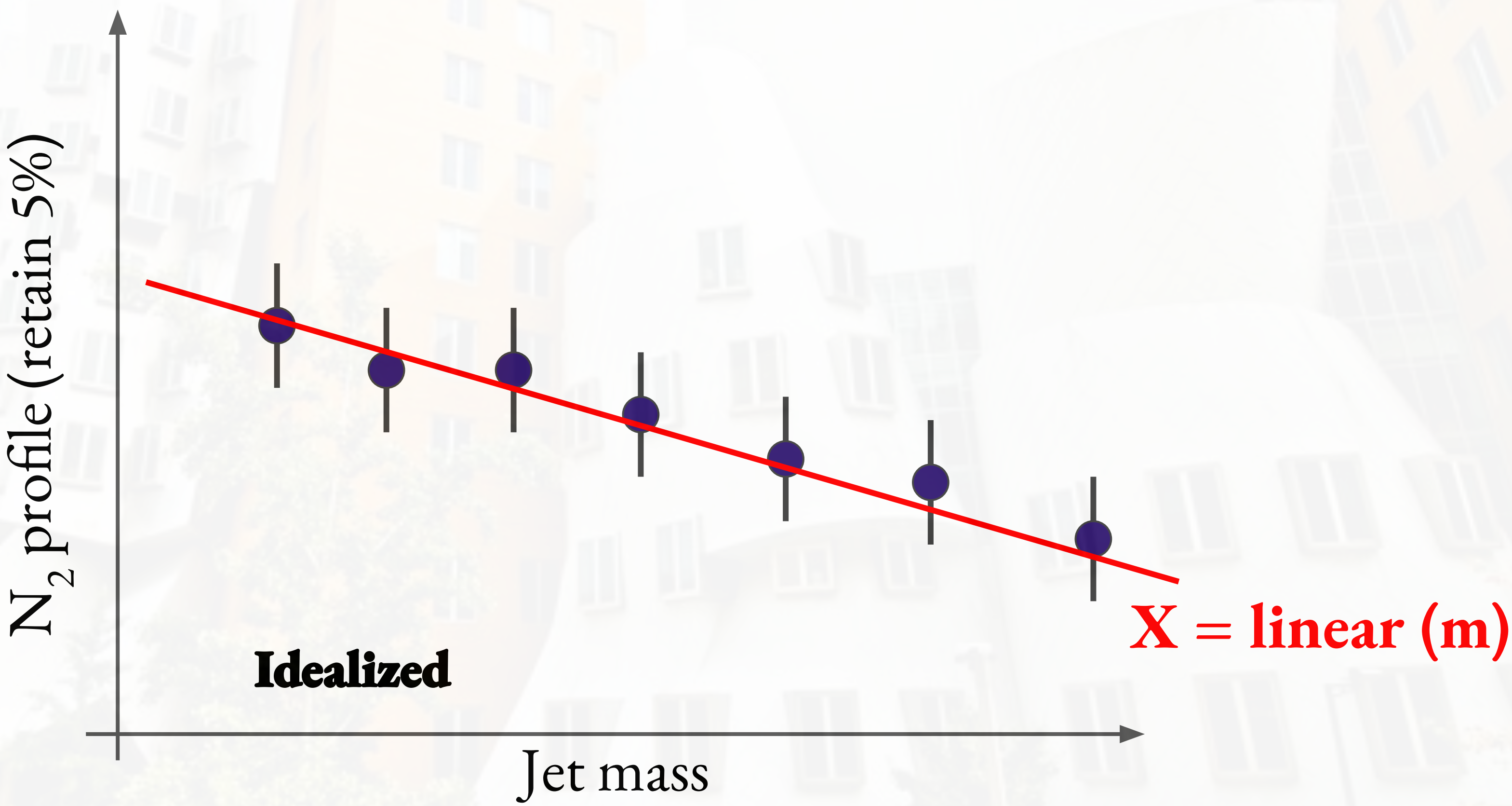
- Jet mass and "two-prongedness" are correlated. Cuts on one will sculpt the other:
  - Complicated a search for a localized resonance in the jet mass spectrum
- Even decorrelated variables may not be safe:
  - MC assumptions? Different phase space? Different object?



10.1007/JHEP05(2016)156

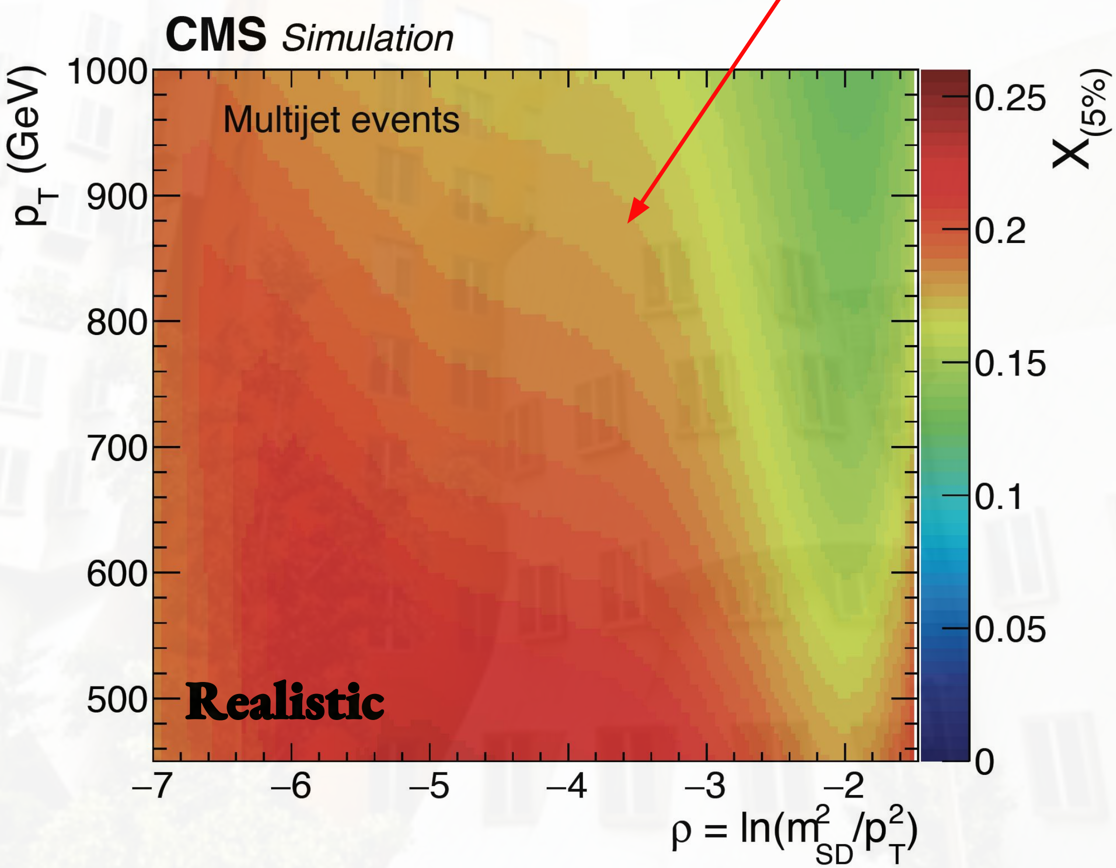
- We can create a custom variable, N2DDT, specific to our analysis which is decorrelated from the mass:

$$N_2^{DDT} = N_2 - X(m)$$



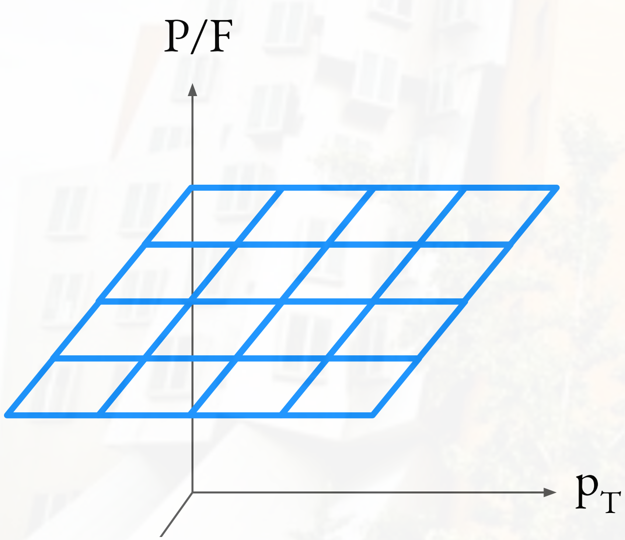
- We can create a custom variable, N2DDT, specific to our analysis which is decorrelated from the kinematic variables:

$$N_2^{DDT} = N_2 - X(pT, \rho)$$



- The background estimate is now simple (in theory):
- Shape and normalization for events passing N_2^{DDT} cut is exactly related to the distribution of events failing that cut
- Unless our original function **X** needs some correction
  - Can allow the pass-fail ratio to float as a functional in a simultaneous fit:

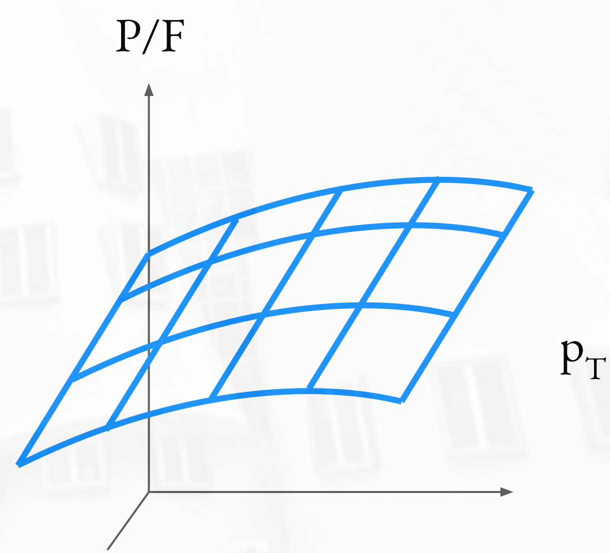
IDEAL



$$N_{\texttt{pass}} = \frac{\epsilon}{1-\epsilon} \times N_{\texttt{fail}}$$

ρ

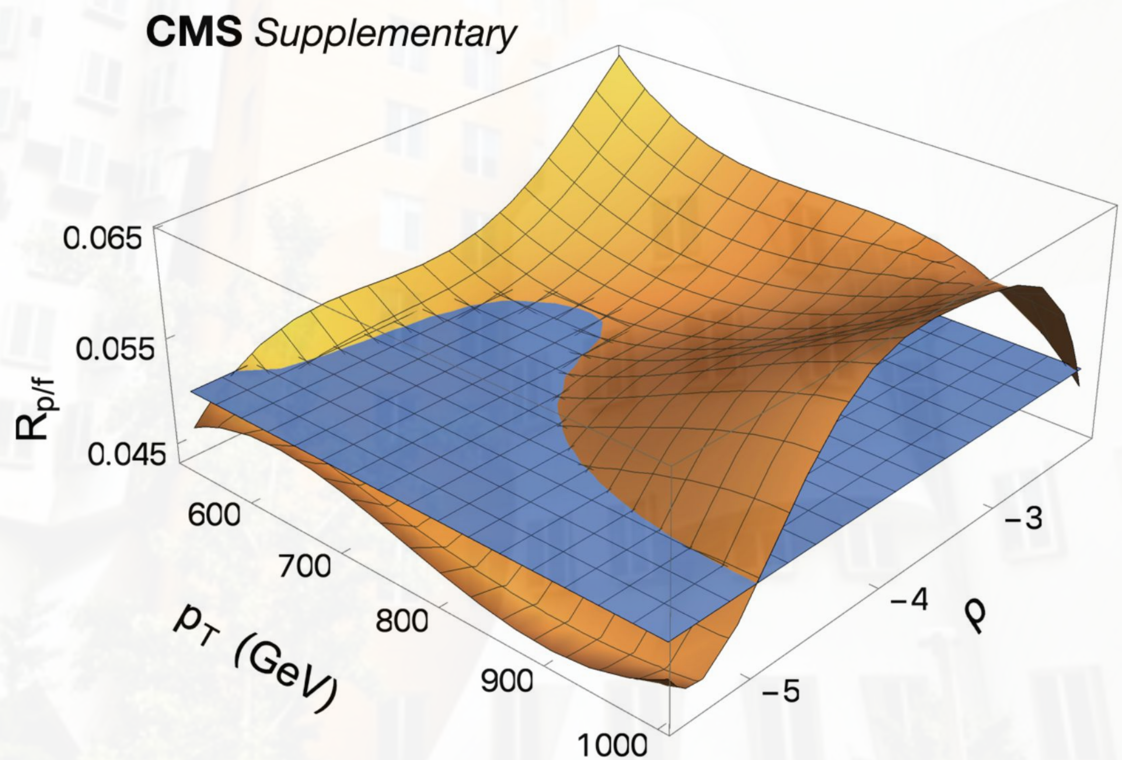
REALISTIC



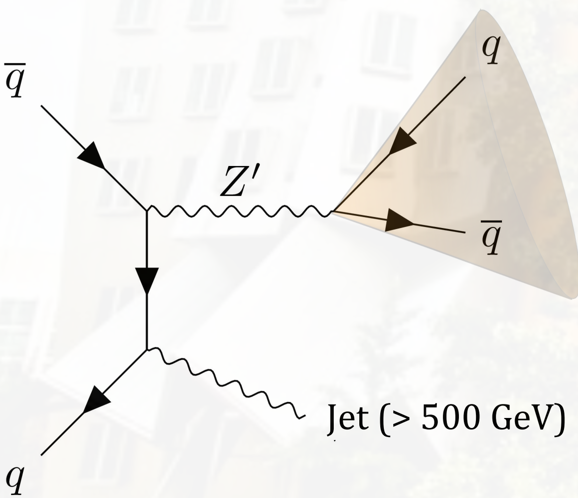
$$N_{\texttt{pass}}(m, p_T) = F(m, p_T) \times N_{\texttt{fail}}(m, p_T)$$

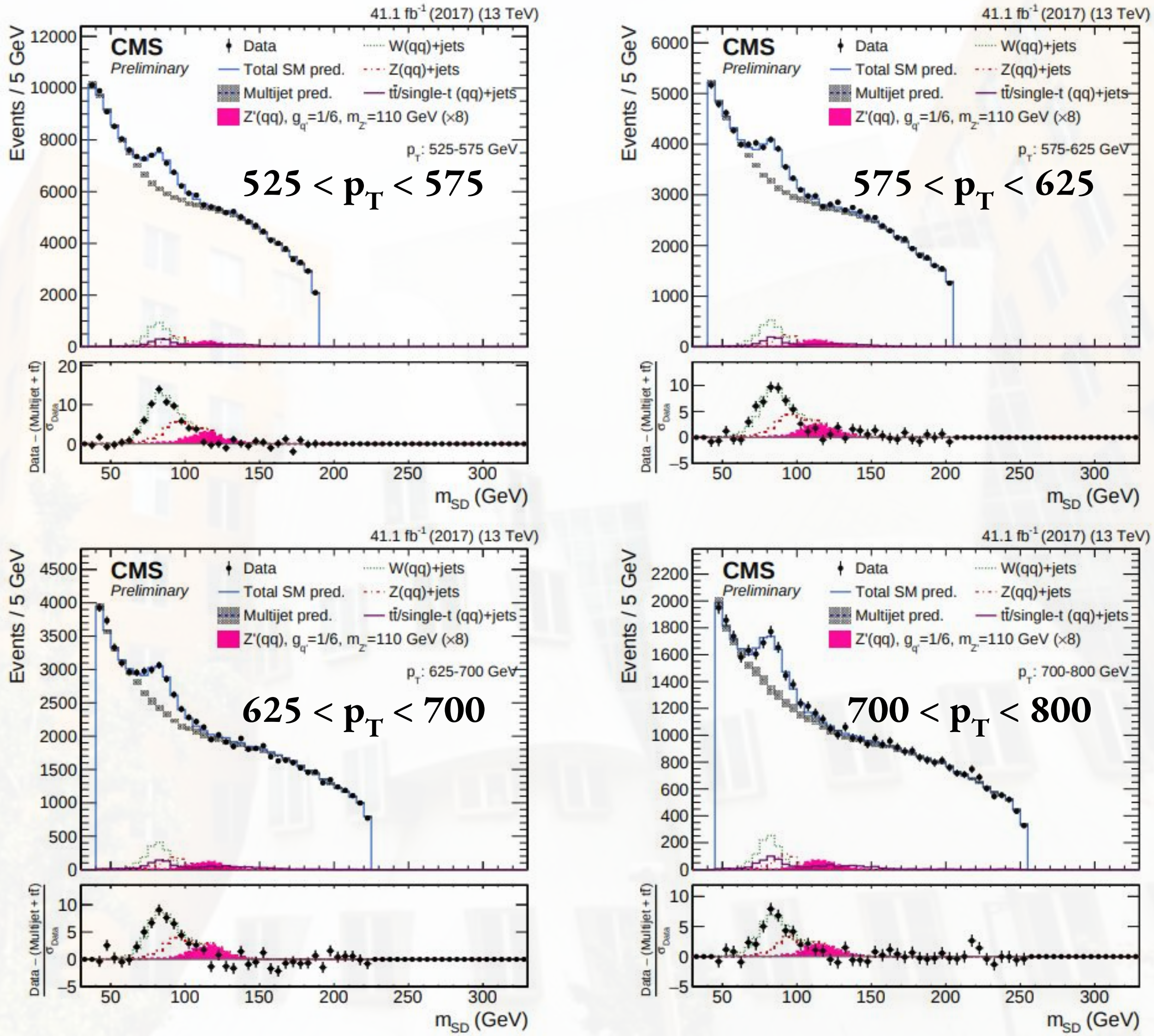
ρ

- The background estimate is now simple (in theory):
- Shape and normalization for events passing N_2^{DDT} cut is exactly related to the distribution of events failing that cut
- Unless our original function **X** needs some correction
  - Can allow the pass-fail ratio to float as a functional in a simultaneous fit:

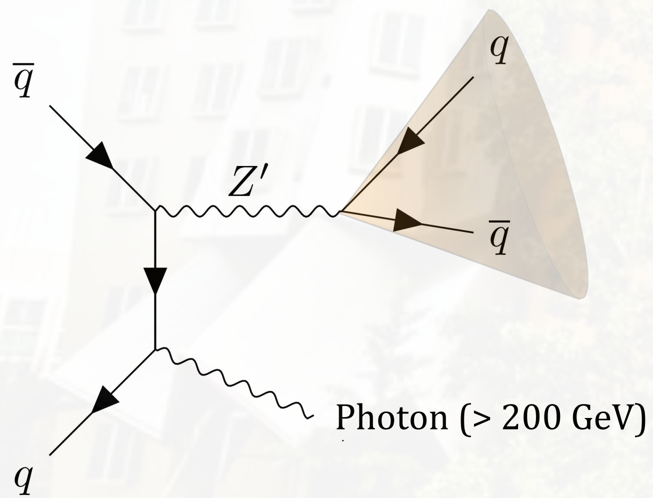


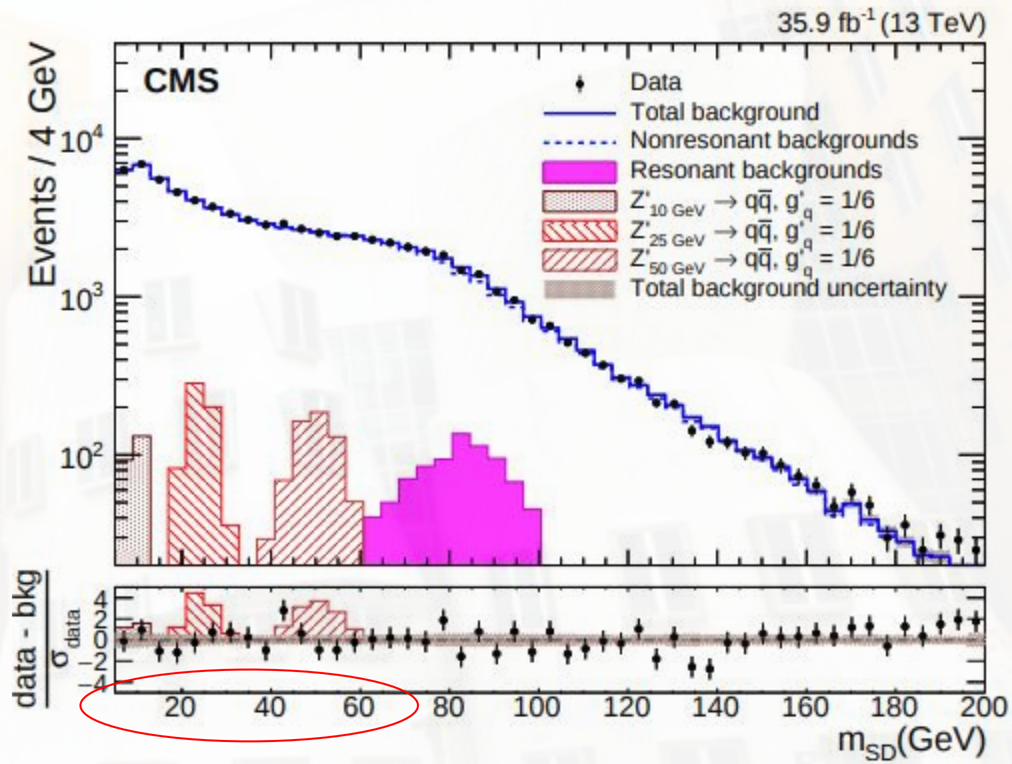
- Analysis with **ISR jet** first to set limits down to 50 GeV
- W/Z as standard candle
- Good performance of simultaneous fit!
- But… how to go lower?



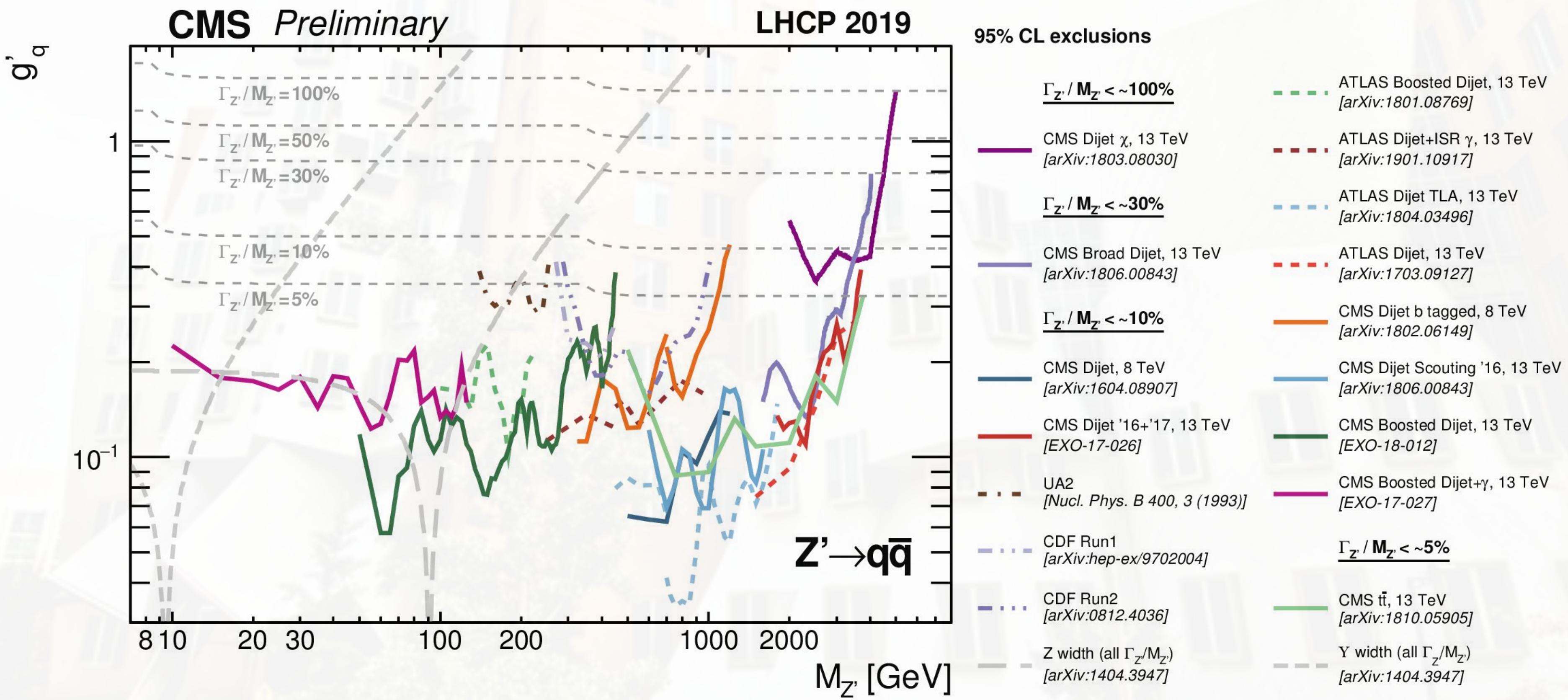


- Single **photon** trigger has much lower threshold than hadronic counterpart!
- Allows us to lower Z' p_T threshold to 200 GeV
- First limits to reach 10 GeV in Z' mass!





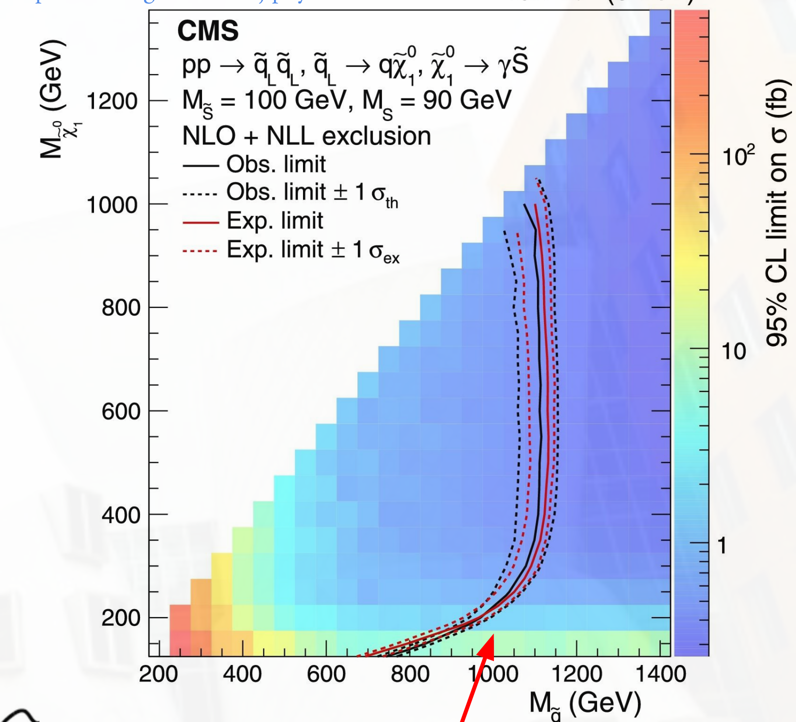
- Limits can now be set over 4 orders of magnitude in Z' mass!
- Improvements in two-pronged variables expected to help:
  - Better S/B rates
  - Less complex correlations easier to remove with DDT methods



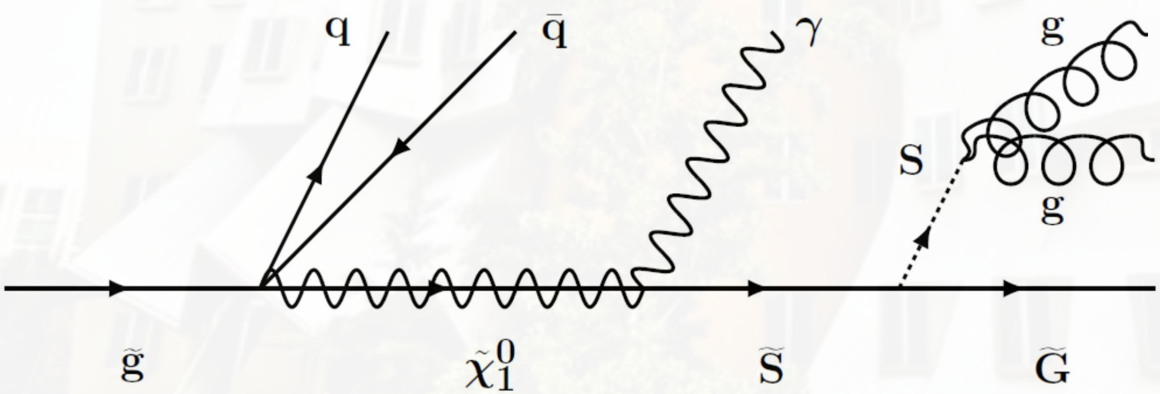
Not uncommon enough?

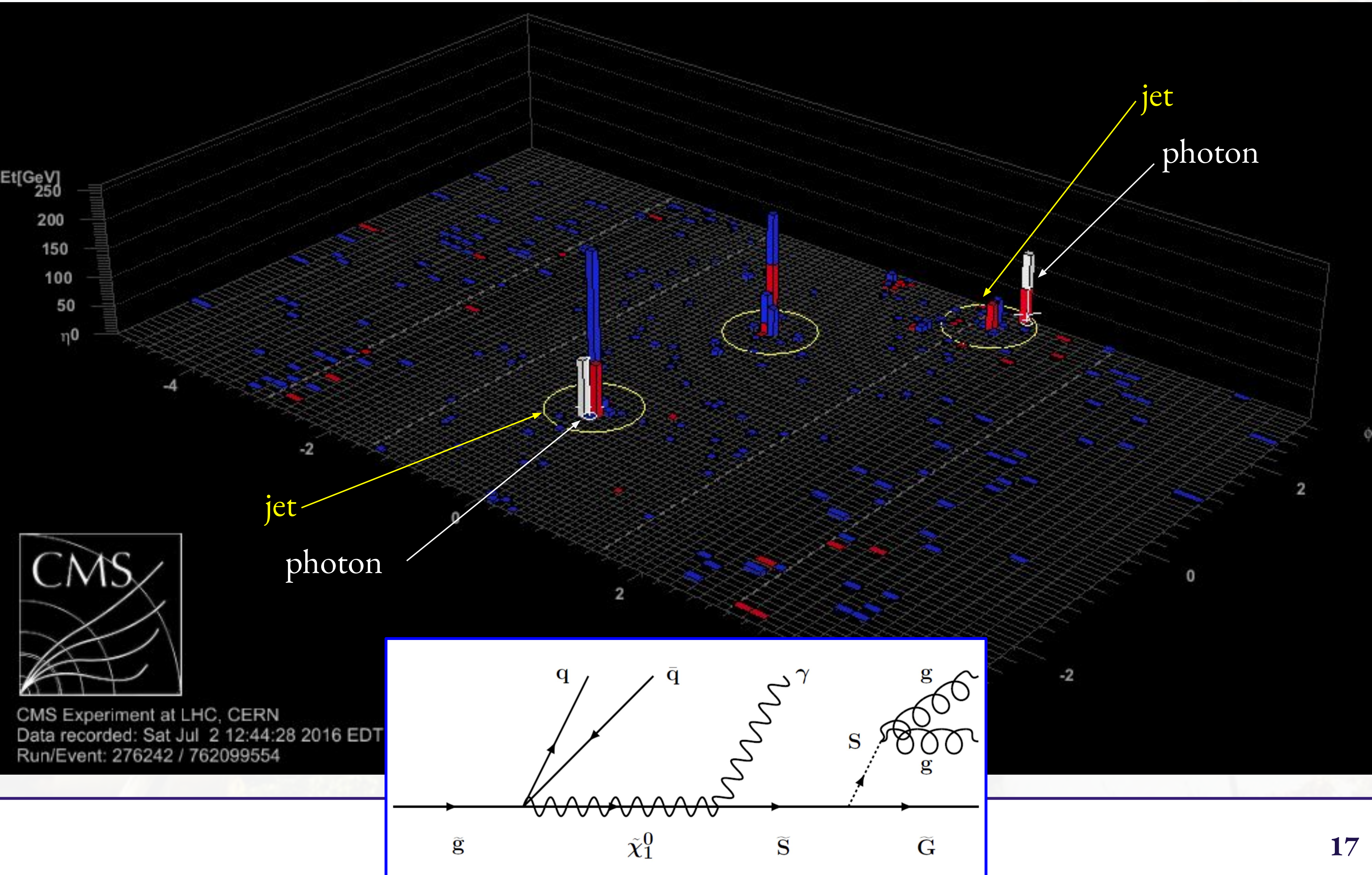
- Consider the complicated Stealth SUSY model below:
  - In stealth model, very little MET
  - Final state for neutralino is essentially a photon and two gluons
  - Gluinos pair produced:
    - Complex final state with many objects

https://doi.org/10.1016/j.physletb.2015.03.017

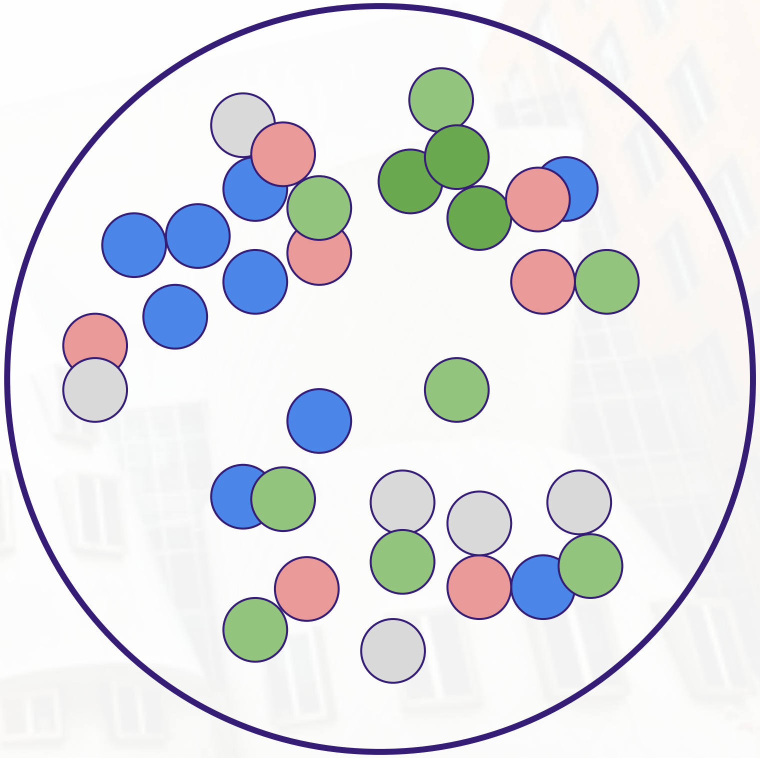


Kinematically unobtainable if isolated photon is required!

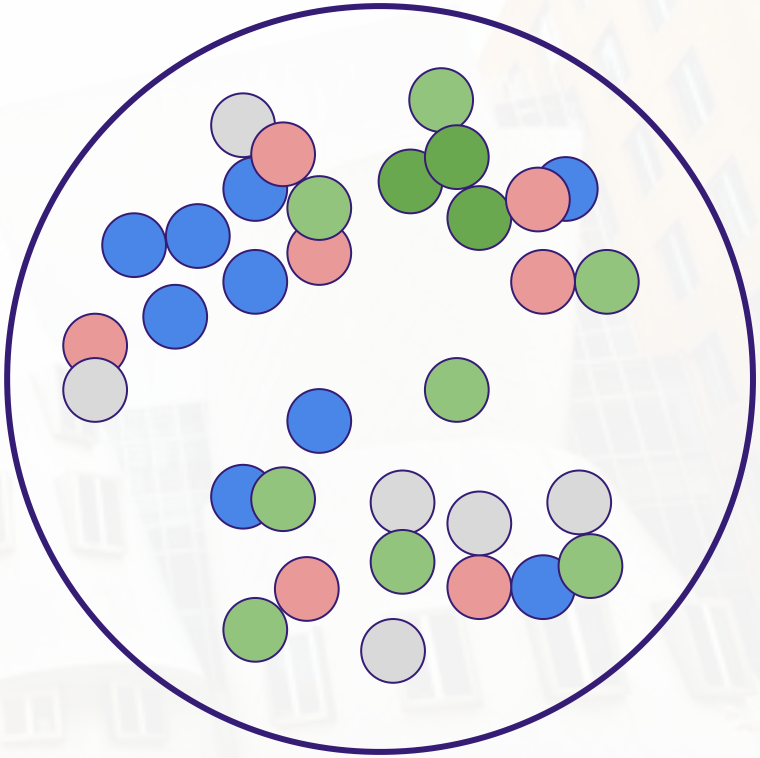


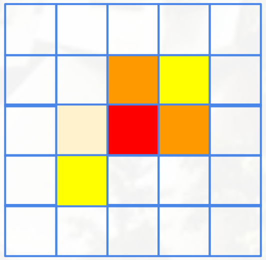

Et[GeV]
250
200
150
100
50
η0
-4
-2
0
2
2
0
-2
jet
photon
jet
photon
CMS
CMS Experiment at LHC, CERN
Data recorded: Sat Jul 2 12:44:28 2016 EDT
Run/Event: 276242 / 762099554
q
q̄
γ
g
S
g
g̃
$\tilde{\chi}_1^0$
S̃
G̃

- We will need an altogether new strategy to separate jets with real photons in them from jets which simply radiate photons/electrons
- Let's build a new variables, starting with the PF candidates in a jet

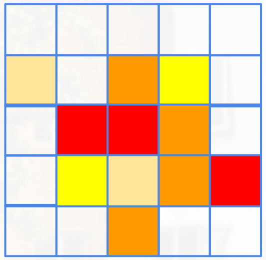


- We will need an altogether new strategy to separate jets with real photons in them from jets which simply radiate photons/electrons
- Let's build a new variables, starting with the PF candidates in a jet
  - Find a photon: use $\sigma_{i\eta i\eta}$: a measure of the shower shape. Essentially the second moment of energy in η



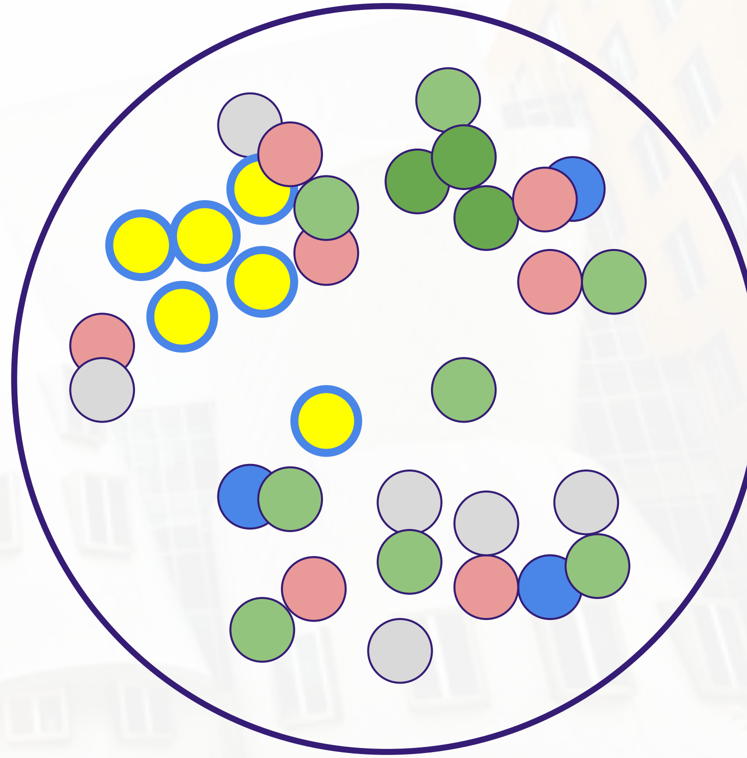


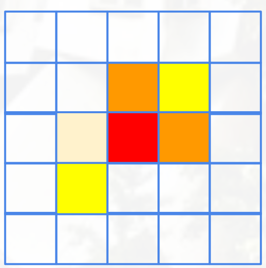
photon-like

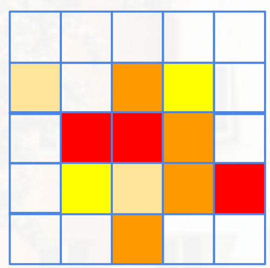


not photon-like

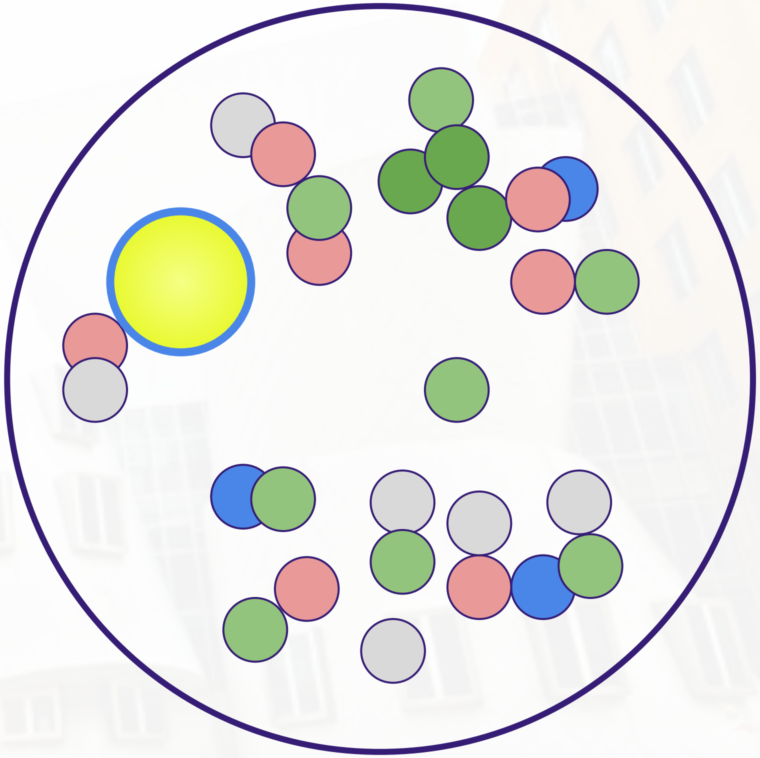
- We will need an altogether new strategy to separate jets with real photons in them from jets which simply radiate photons/electrons
- Let's build a new variables, starting with the PF candidates in a jet
    - Define photon: if $\sigma_{i\eta i\eta}$ < some cut




photon-like

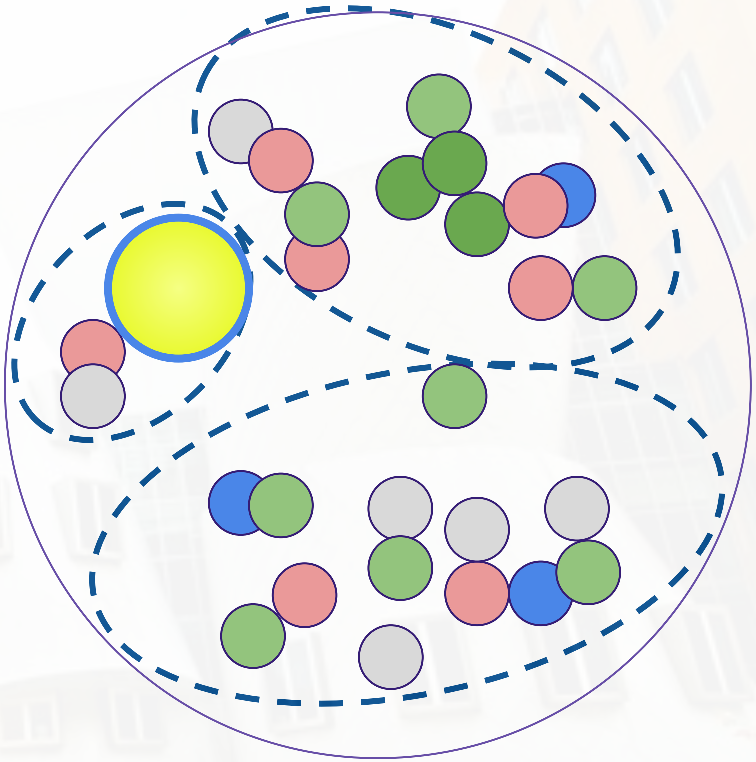

not photon-like

- We will need an altogether new strategy to separate jets with real photons in them from jets which simply radiate photons/electrons
- Let's build a new variables, starting with the PF candidates in a jet
    - Recluster jet with single photon object replacing its shower

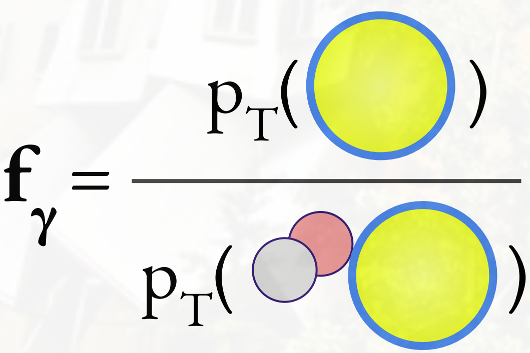


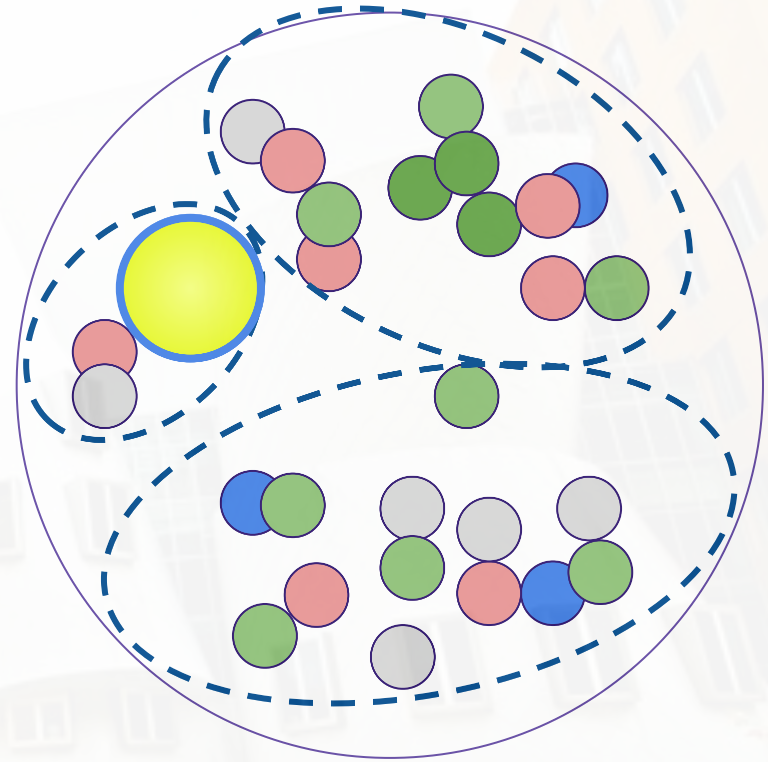
Rare in QCD: ~0.5% rate
> 80% of signal survives

- We will need an altogether new strategy to separate jets with real photons in them from jets which simply radiate photons/electrons
- Let's build a new variables, starting with the PF candidates in a jet
    - Cluster jet into 3 subjets using the KT algorithm

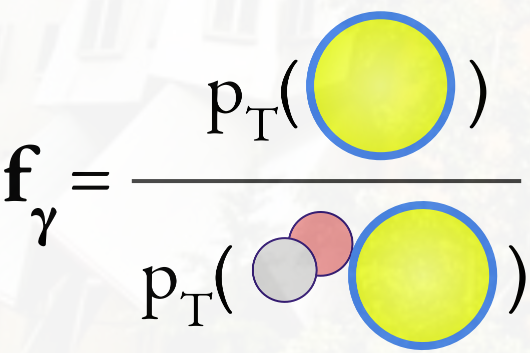


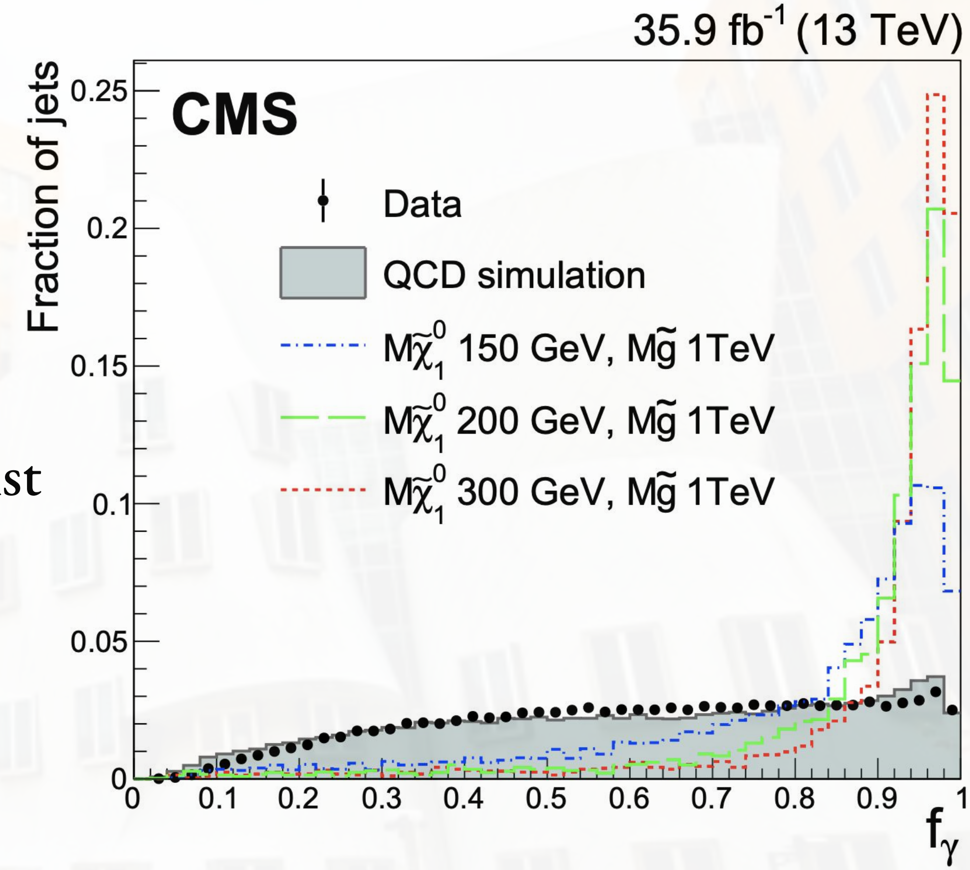
- We will need an altogether new strategy to separate jets with real photons in them from jets which simply radiate photons/electrons
- Let's build a new variables, starting with the PF candidates in a jet
  - Compute the **photon-subjet fraction:**



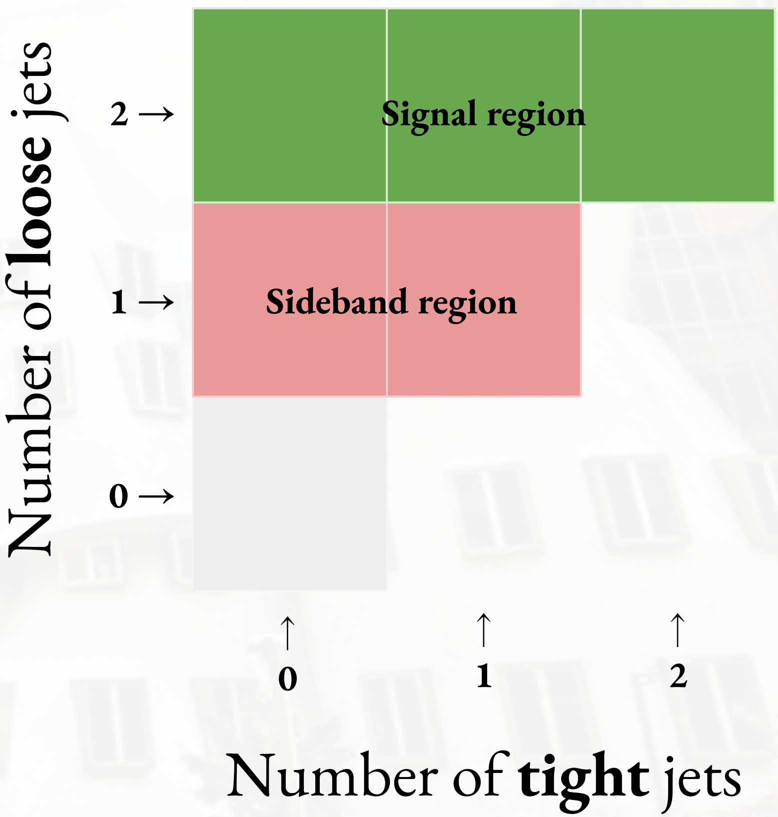


- We will need an altogether new strategy to separate jets with real photons in them from jets which simply radiate photons/electrons
- Let’s build a new variables, starting with the PF candidates in a jet
  - Compute the **photon-subjet fraction**
  - Very good discrimination against jets from QCD!

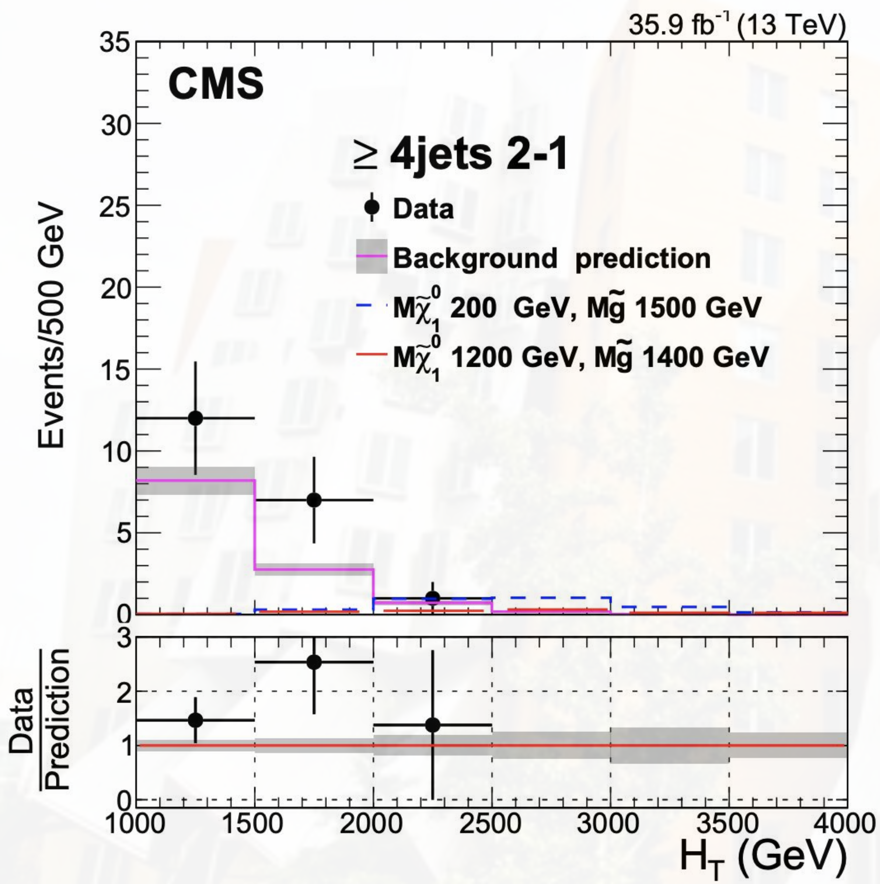


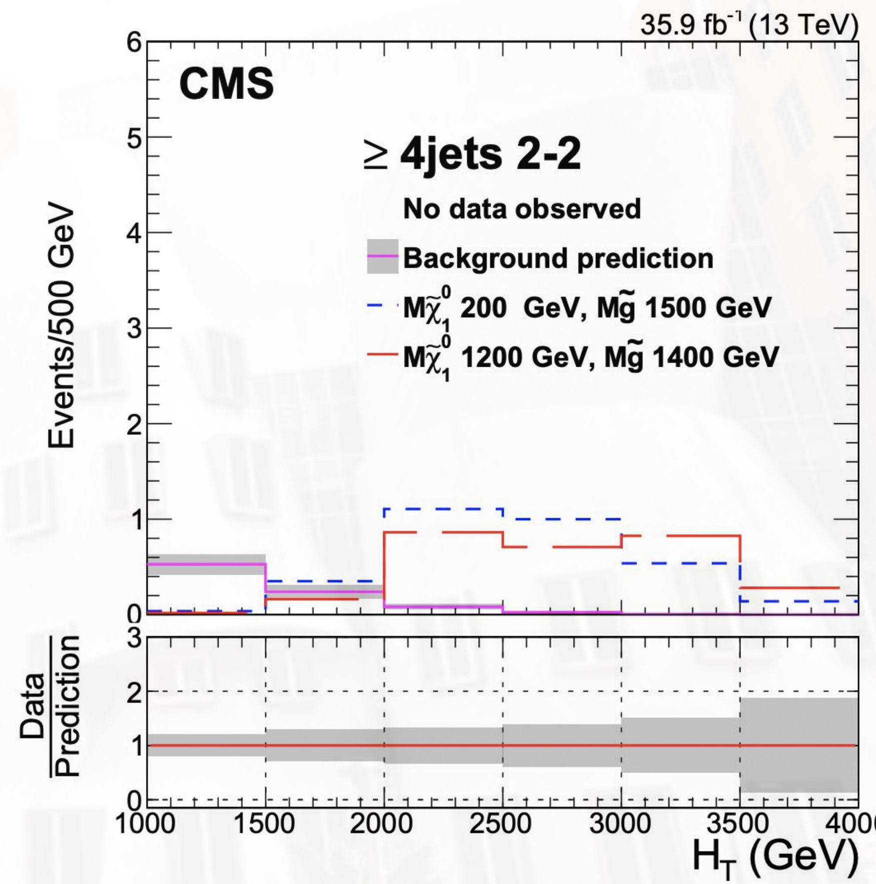


- Loose jet:
  - $p_T > 200$ GeV
  - $\tau_3/\tau_1 < 0.4$
  - has good photon
  - has 3 subjets ($p_T > 10$ GeV)
- Tight jet:
  - Loose + $f_\gamma > 0.9$
- Measure **loose-to-tight** rate (as a function of p_T and η) in the one-loose-jet sideband.
- Signal region required two loose jets.
- Use loose-to-tight rate to estimate background in signal region



- Large signal to background expected
- Can set limits on new phase space!

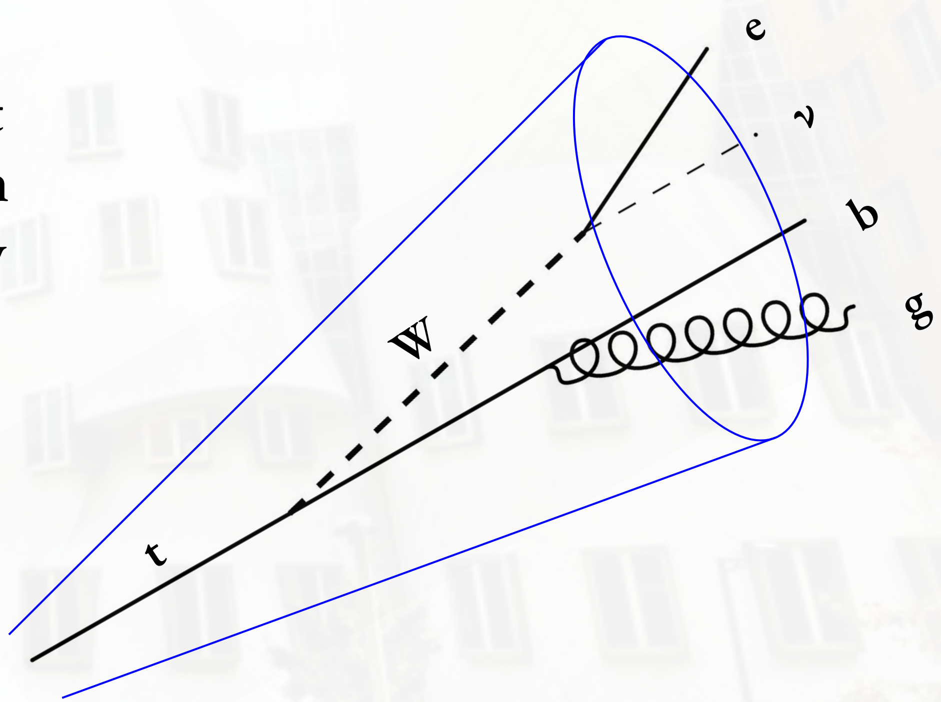




One issue:

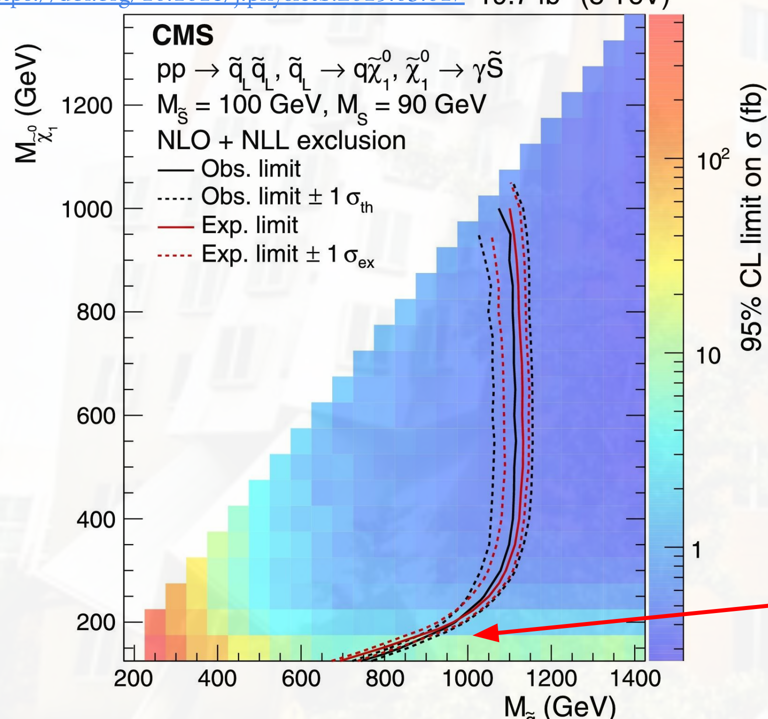
- How do we calibrate this object?
  - Z' → not exactly represented in the data, but W/Z resonances serve as standard candles
  - No photon+jet activity expected
- No perfect solution:
  - Analysis calibrated photon-subjet fraction on ttbar events with high three-pronged activity: nominally from FSR
  - Resulting Data-to-MC scale factors come with large uncertainties
- Nonetheless ...

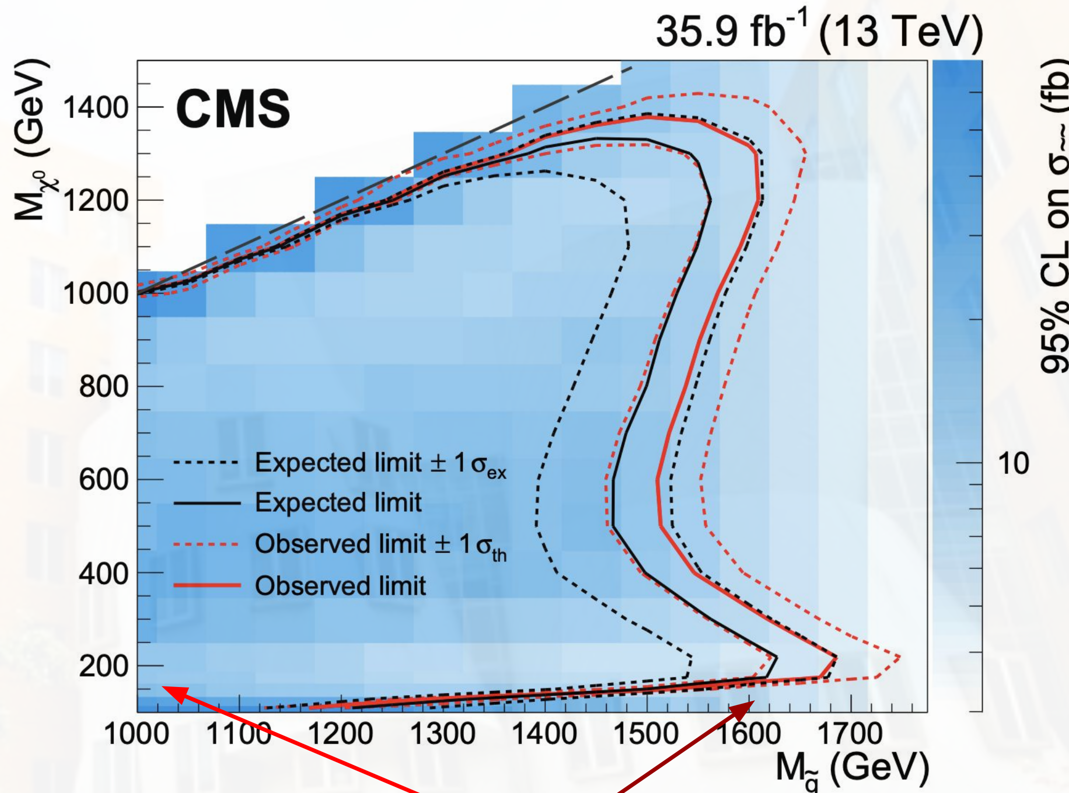
Source	Impact
Simulation-to-data signal efficiency correction ^{*s}	30–50%
Background estimation ^{*b}	10%
Jet energy resolution ^{*sb}	<10%
Jet energy scale corrections ^{*sb}	<10%
Pileup re-weighting ^{*s}	<5%
Integrated luminosity^{s}	2.5%
Detector FULLSIM - FASTSIM^{s}	1–2%
PDF choice uncertainty^{s}	1%



- Large extension of limit into previously unexplored territory!

https://doi.org/10.1016/j.physletb.2015.03.017





Large extension in covered phase-space! New "unobtainable" range due to subjets merging

In summary:

- "Standard" tagging techniques increasing in sophistication!
- Uncommon substructures offer a unique way to attack hard problems
- Two strategies shown today (ISR boosting and custom substructure) can be married to pursue a large number of final states:
    - $H \to WW^*$, $H \to aa \to qqqq$
      SUSY (hadronic + ℓ/γ)
      $N \to W\ell\ell$, $X \to 3j$ ...
- ***Bottleneck:*** **validation of these substructures in real data. New ideas needed!**