Search For Low-Mass Quark-Antiquark Resonances Produced With an Initial State Photon at 13 TeV Using the CMS Detector

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On behalf of the CMS collaboration
Special thanks to the boosted dijet team at CMS

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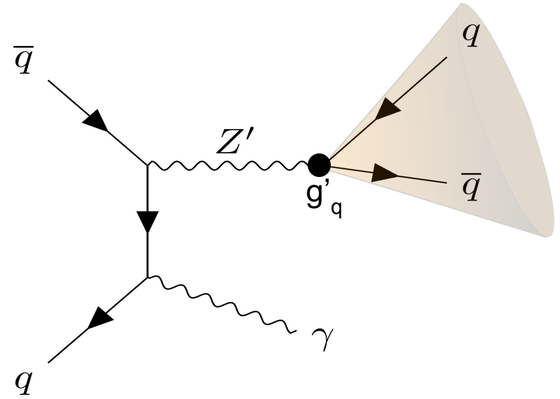
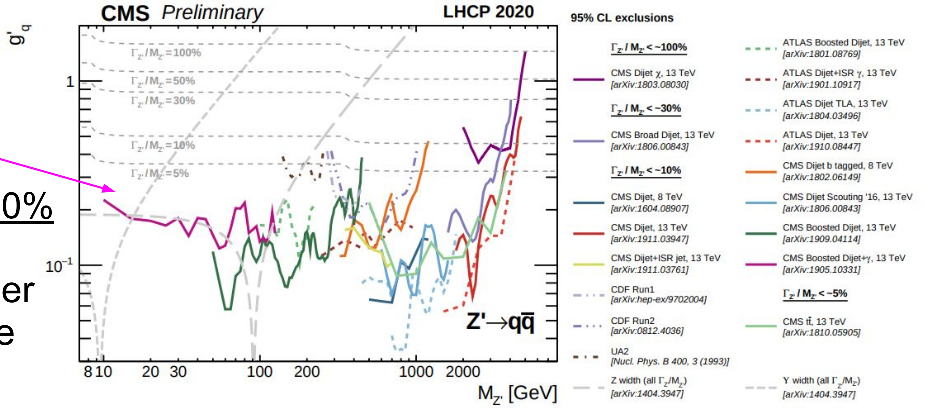
Introduction

- New resonances coupling to quark pairs are common in many **BSM** theories
  - e.g. leptophobic particle Z’, or dark matter mediator
- Analysis searches for low-mass quark-antiquark resonances recoiling against an initial state photon
- Previously published analysis ([PRL 123, 231803 (2019)]) used only 36fb^{-1} of Run 2 data (shown in pink)
- New analysis discussed today:
  - Full 137 fb^{-1} Run 2 CMS data
    - Current version of the analysis only uses 10% of Run2 Data
  - A lower transverse momentum (p_T) photon trigger implemented in 2018 allowing for more sensitive probe of the low mass region
  - Improved two-prong jet tagger



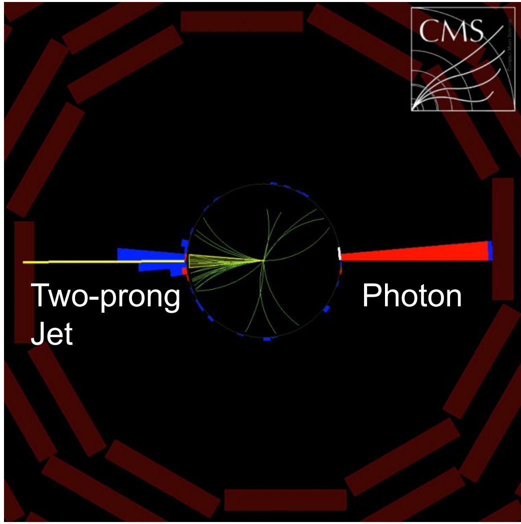


https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV

Analysis Strategy

- For low mass Z' decays to quark pairs that have sufficient p_T, the resulting two jets tend to collimate and merge into a single large ($\Delta R=0.8$) cone jet with two-pronged substructure
- Search looks for an excess in the **two-pronged jet** mass distribution
- Consider two possible two-pronged substructure variables, both decorrelated from mass:
  - **N2DDT** (https://arxiv.org/abs/1603.00027)
  - **ParticleNet** tagger (https://arxiv.org/abs/1902.08570) using ML
- Data-driven Background Estimate created using a fitted polynomial Transfer Factor between events which pass and fail the two-pronged requirement

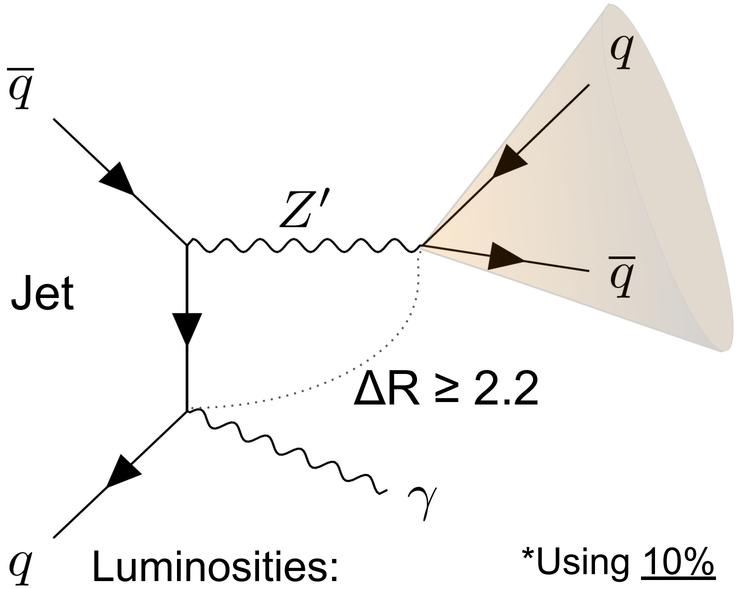
2016 Data Event Display:



https://cms.cern/news/casting-light-dark-sector

Event Selection

- Photon and jet must have p_T above a minimum threshold determined by trigger
  - 2016/2017: 200 GeV
  - 2018: 120 GeV
  - Lowered 2018 threshold due to added trigger
- Additional ID requirements applied to Photon and Jet
- Jet must be sufficiently boosted, measured using variable $\rho \equiv \ln(m^2/p_T^2)$
- Separation of photon and jet by $\Delta R \geq 2.2$
- Two-pronged substructure requirement



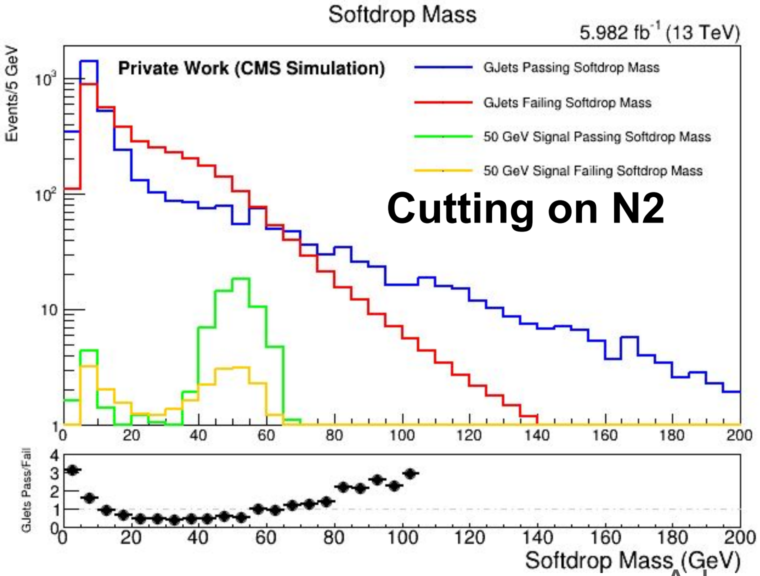
Luminosities:
2016: 36.31 fb^{-1}
2017: 41.48 fb^{-1}
2018: 59.82 fb^{-1}
Full Run 2: 137.61 fb^{-1}

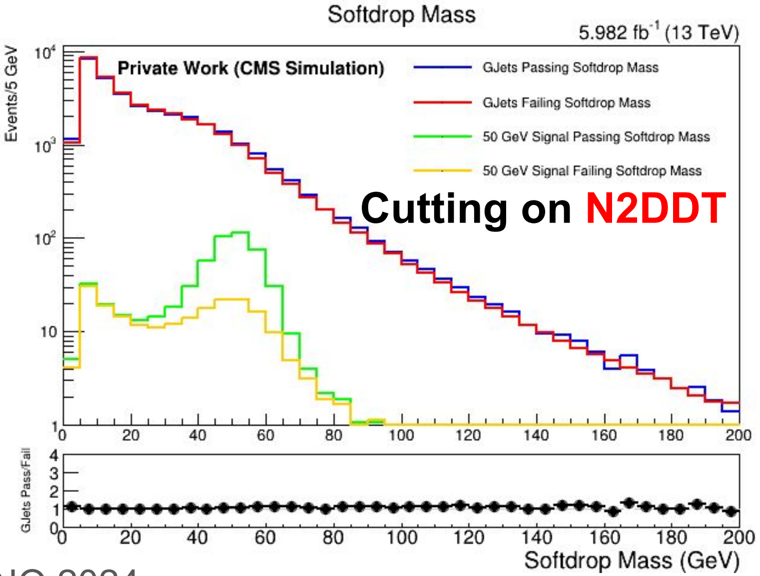
*Using 10% of data in today's presentation

N2DDT

- N2 variable measures two-pronginess of a jet
- Decorrelated **N2DDT** variable based on main background of photon+jet events allows for cutting on substructure variable N2 without shaping the background
  - Cutting on **N2DDT** maintains a fixed percentage of the background
- **N2DDT** = N2 - DDT(ρ, p_T)
- Current working point is 10% of background retained

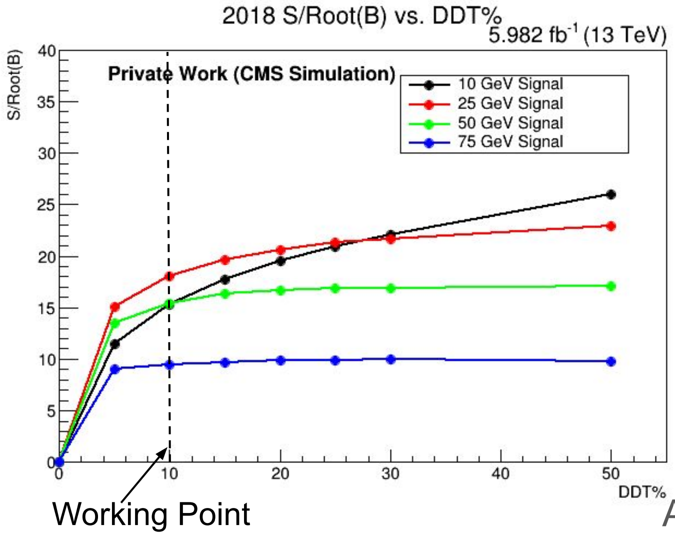
*DDT Method: https://arxiv.org/abs/1603.00027





ParticleNet Tagging

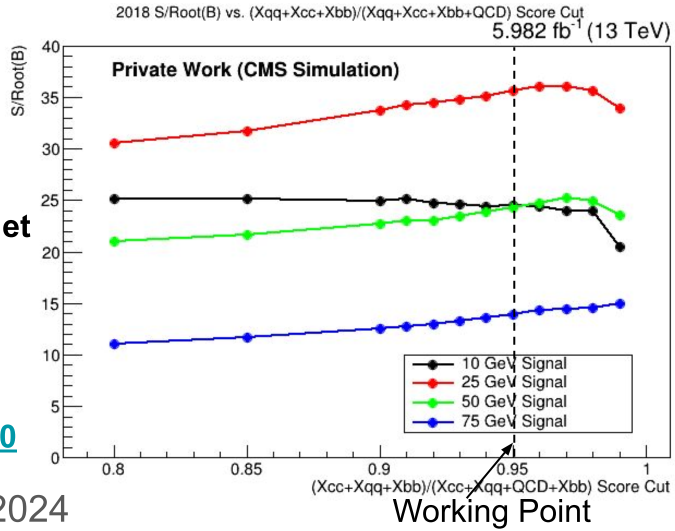
- Considering the use of ML tagger **ParticleNet** for selecting two-pronged jets
- **ParticleNet** tagger gives mass decorrelated classification scores for X→di-quark pairs of various flavors as well as QCD events
- Testing shows that we see improvement in signal significance test when cutting on this score vs. cutting on **N2DDT** for all years
  - ParticleNet is not yet trained in the 120-200 GeV region added by 2018 lower threshold photon trigger



Signal Significance vs. N2DDT% Background

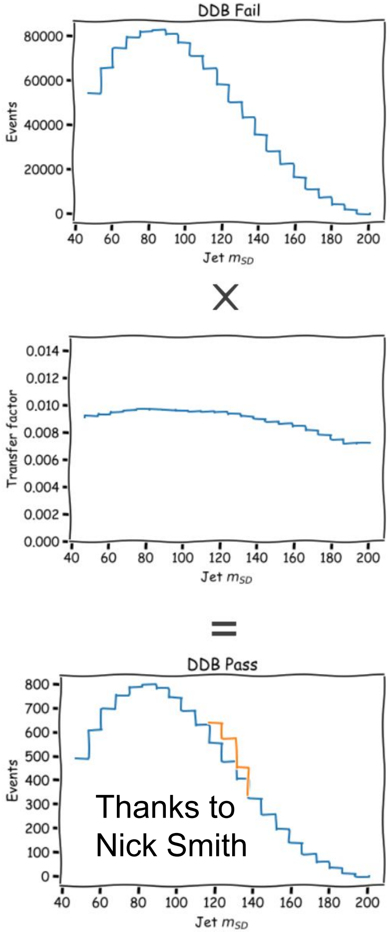
Signal Significance vs. ParticleNet Score Cut

*ParticleNet: https://arxiv.org/abs/1902.08570



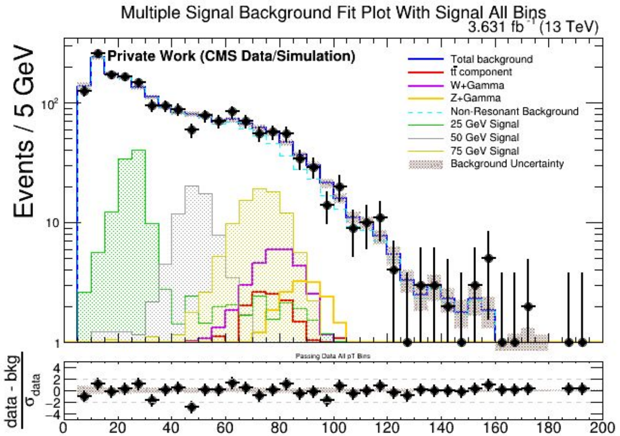
Data Driven Background Estimate

- Data Driven Non-Resonant Background
  - To estimate the background, we will measure a Transfer Factor (TF) between events that pass and fail the **N2DDT** or **ParticleNet** requirement
  - TF is a function of ρ and jet p_T
  - N_pass = TF(ρ, p_T)×N_fail
  - TF is based on a Bernstein Polynomial (order 2x2)
  - TF fits background well, while not fitting peaks associated with signal
- Resonant Backgrounds (taken from simulation)
  - TTBar, W+Gamma and Z+Gamma, allowed to float within 10% of their theory cross-sections

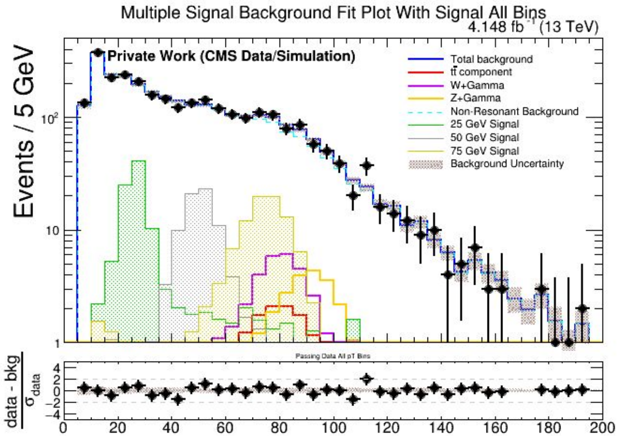


Background Estimate (N2DDT)

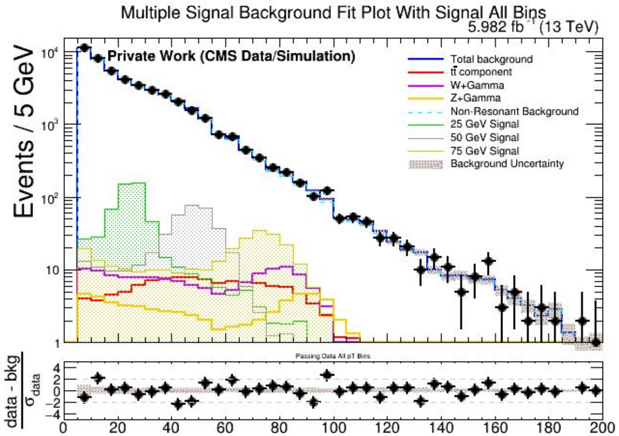
- Background estimation using **N2DDT** as the two-pronged jet identification
  - Several signal Monte Carlo are shown, scaled to their 95% CL expected limits
- These plots are the sum of the fits in all p_T bins, actual fit is done simultaneously over all p_T bins
- In 2018 signal and resonant background shape effect is expected, due to lower p_T thresholds



2016



2017

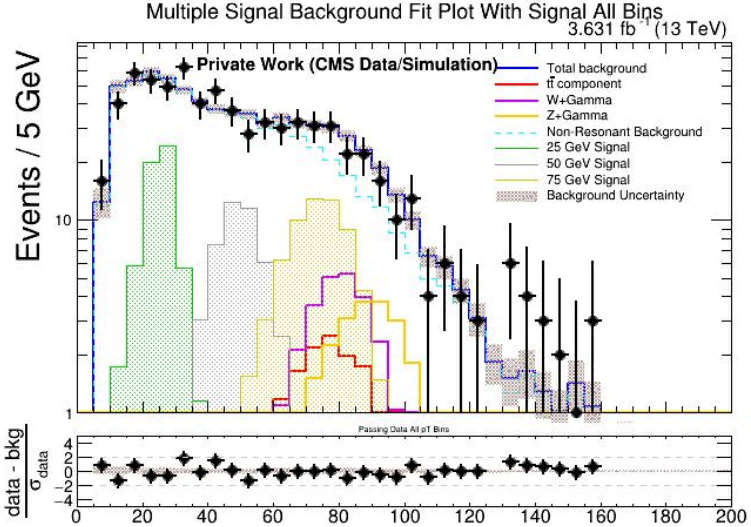


2018

*This is 10% of data for all years

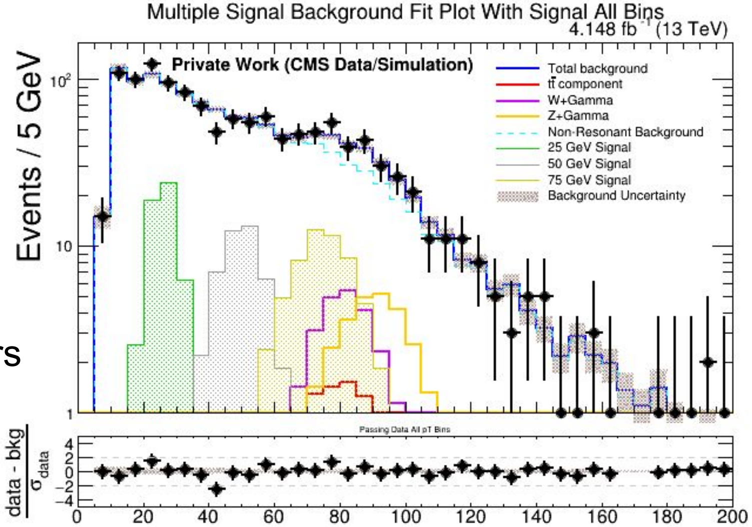
Background Estimate (ParticleNet)

- Background estimation using **ParticleNet** score as the two-pronged jet identification
  - Several signal Monte Carlo are shown, scaled to their 95% CL expected limits
- These plots are the sum of the fits in all p_T bins, actual fit is done simultaneously over all p_T bins
- 2018 not included, due to ongoing retraining of ParticleNet tagger for lower p_T jets



2016

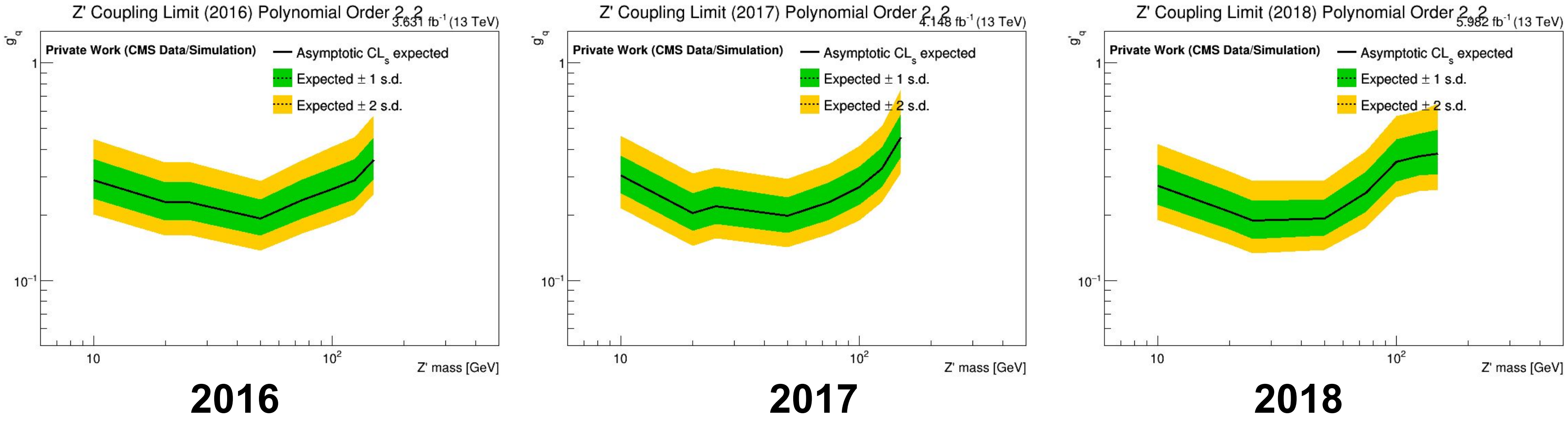
*This is 10% of data for all years



2017

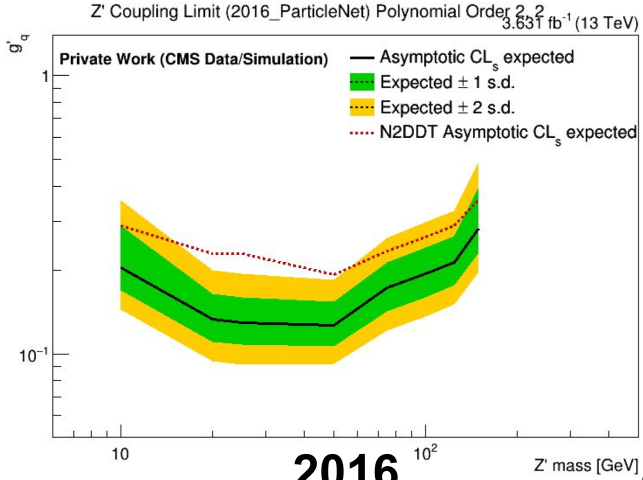
N2DDT Preliminary Limits (10% Data)

- 95% Confidence Level (CL) expected limits on $Z' \to q\bar{q}$ coupling strength (g'_q) for all Run 2 years using **N2DDT** as the two-pronged jet identifier
  - All experimental uncertainties accounted for in limits
  - Currently using only 10% of data for each year



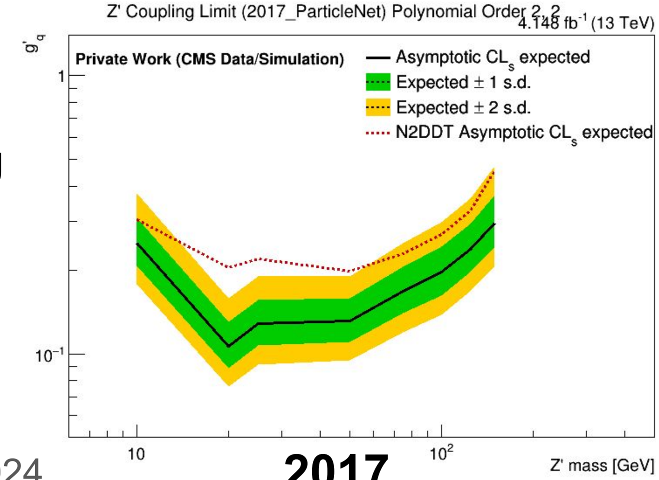
ParticleNet Preliminary Limits (10% Data)

- 95% Confidence Level (CL) expected limits on $Z' \to q\bar{q}$ coupling strength (g'_q) for 2016 and 2017 using **ParticleNet** as two-pronged jet identifier
  - All experimental uncertainties accounted for in limits
  - Currently using only 10% of data for each year
- **N2DDT** shown in red dashed line and **ParticleNet** shown in black
  - Significant improvement in limits due to switch to **ParticleNet**



2016

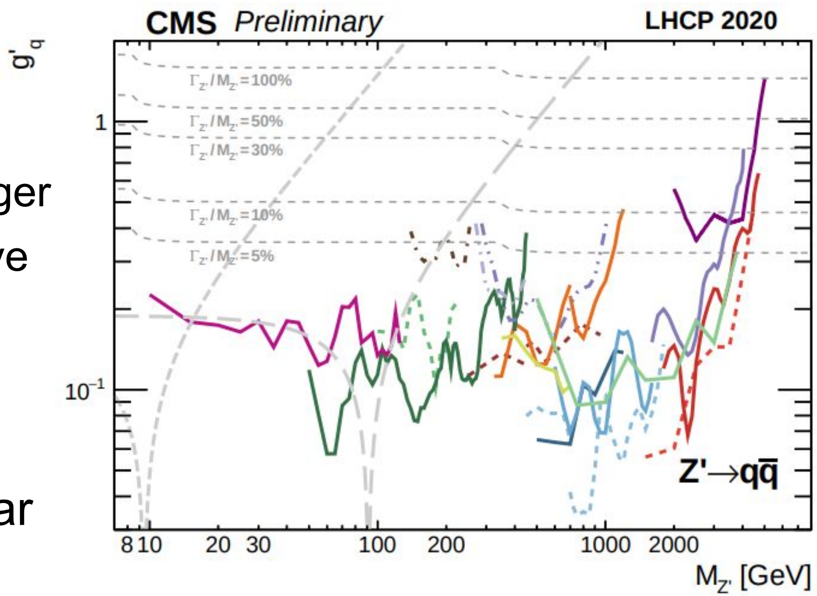
***ParticleNet** not shown for 2018 due to ongoing retraining on lower p_T jets



2017

Summary

- Presented an analysis searching for low-mass quark-antiquark resonances recoiling against an initial state photon using the Run 2 CMS data
- The following improvements are being implemented:
  - A lower transverse momentum (p_T) photon trigger implemented in 2018 allowing for more sensitive probe of the low mass region
  - New two-prong jet tagger with ML (ParticleNet) shows great improvement over N2DDT
- Stay tuned for final full Run 2 results in the near future which promise to improve sensitivity significantly

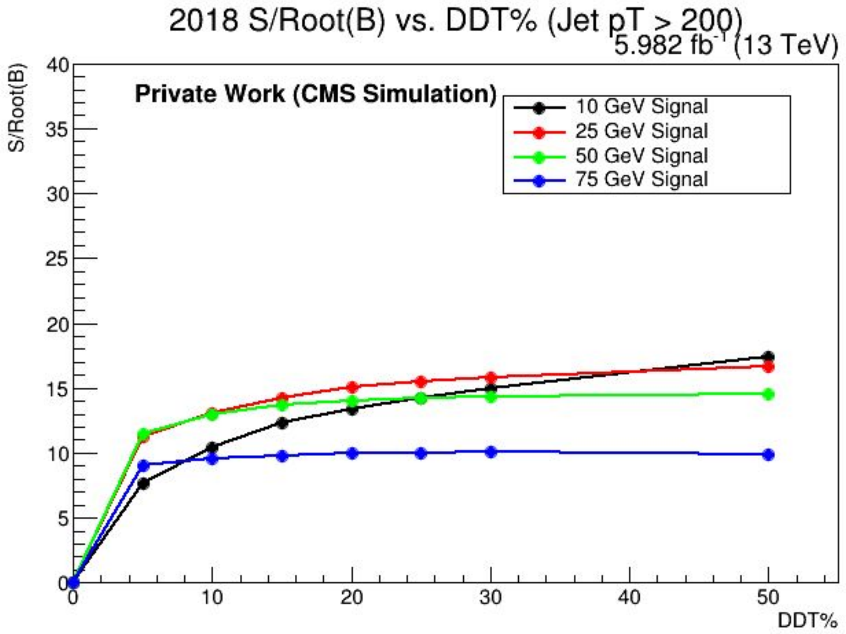


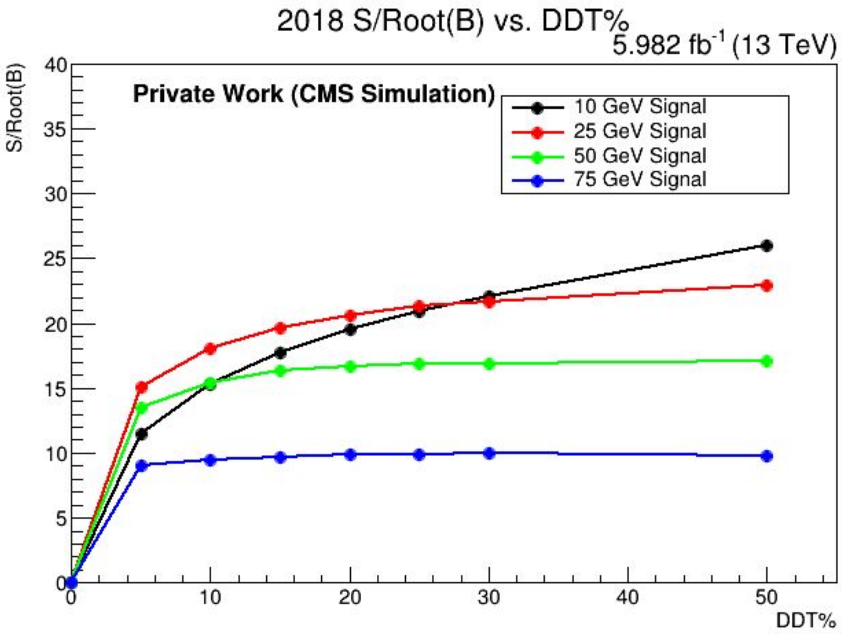
https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV

Backup Slides

Low p_T Significance

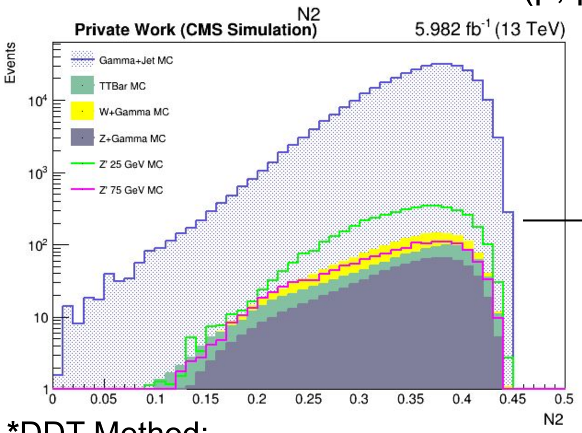
- Lowering jet p_T threshold in 2018 from 200 GeV to 120 GeV improves signal significance
- Improvement especially clear for low mass events, ~40% improvement

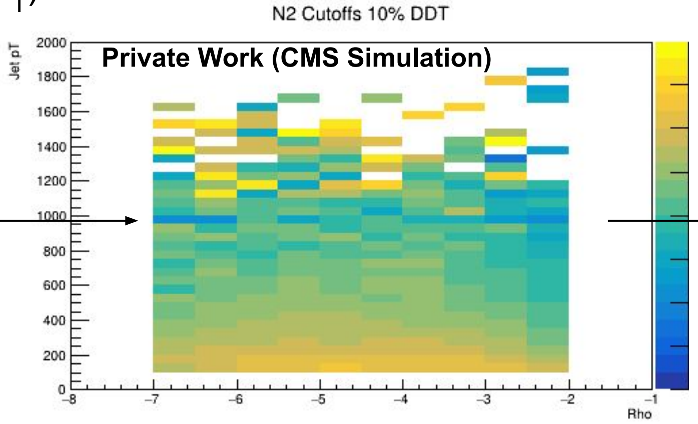


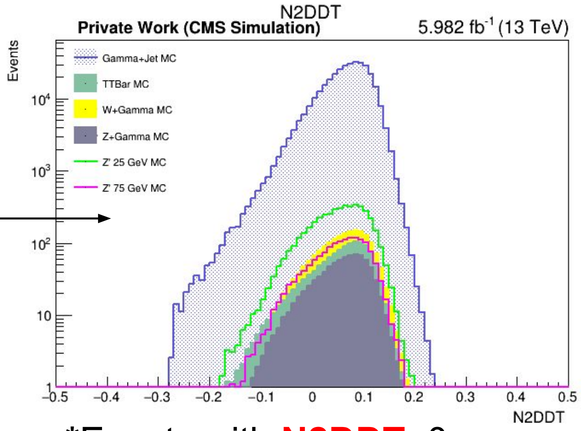


N2DDT Derivation

- N2 variable measures two-pronginess of a jet
- Decorrelated **N2DDT** variable based on main background of photon+jet events allows for cutting on substructure variable N2 without shaping the background
  - Cutting on **N2DDT** maintains a fixed percentage of the background
- DDT(ρ, p_T) map is calculated in bins of ρ and p_T
  - In each bin, the value below which a fixed percentage of the background is kept is calculated
  - This value is subtracted from the N2 value for events in that bin to calculate **N2DDT**
  - **N2DDT** = N2 - DDT(ρ, p_T)







*DDT Method:
https://arxiv.org/abs/1603.00027

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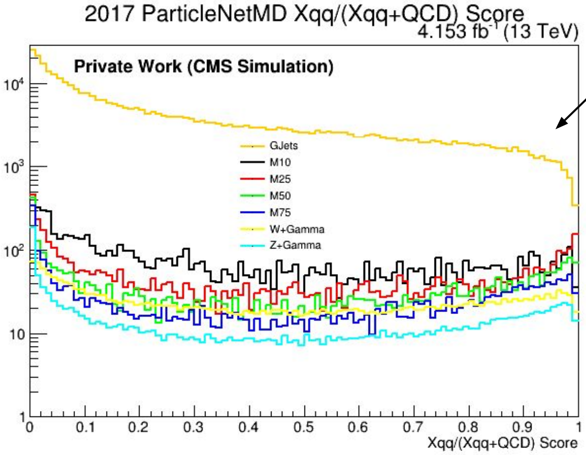
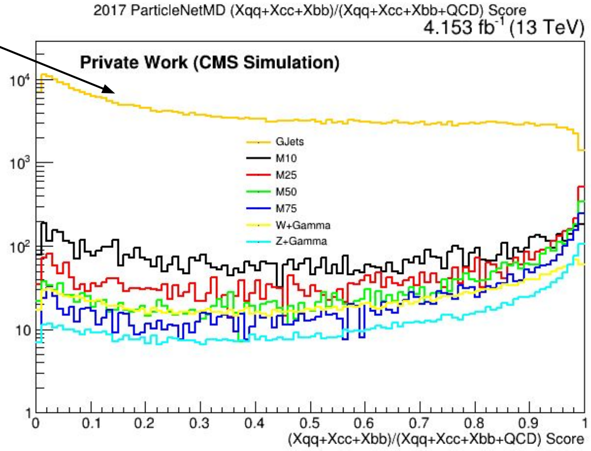
*Events with **N2DDT**<0 pass requirement

ParticleNet Score

- **ParticleNet** tagger gives mass decorrelated classification scores for X→di-quark pairs of various flavors as well as QCD events
  - Xqq is classification score to light flavor (up, down ,strange) pair
  - Xcc and Xbb are classification scores to charm pairs and bottom pairs respectively
  - QCD is classification score for QCD events
- (Xqq+Xcc+Xbb)/(Xqq+Xcc+Xbb+QCD) does better at distinguishing two-pronged jets than using only Xqq/(Xqq+QCD)

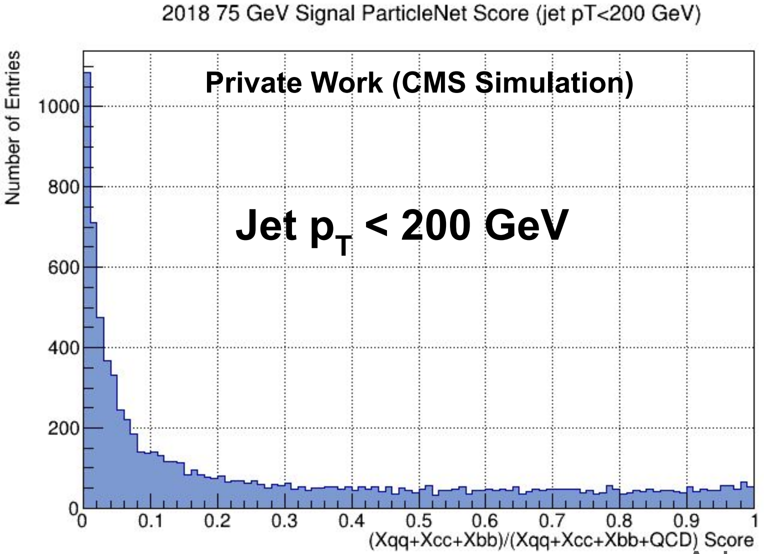


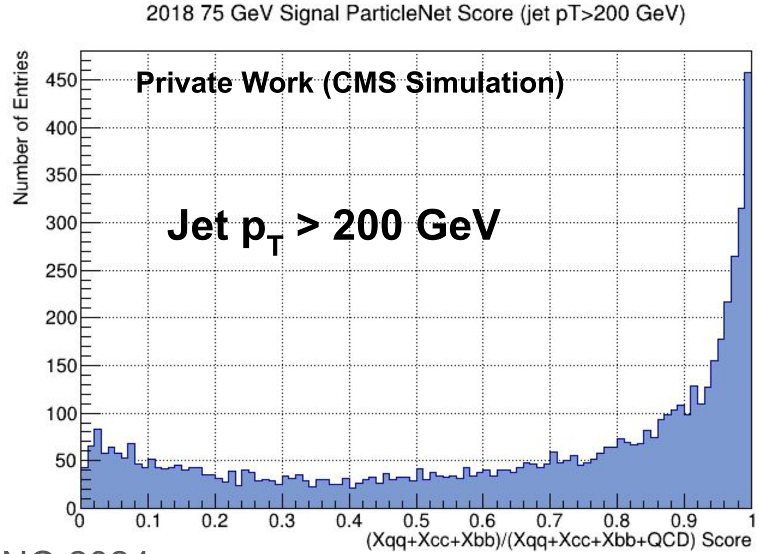


*ParticleNet: https://arxiv.org/abs/1902.08570

ParticleNet Tagging for Lower p_T Region

- **ParticleNet** score should peak at 1, but **ParticleNet** score for events below 200 GeV jet p_T peak at 0
  - The less than 200 GeV region is the region added to 2018 by new photon trigger
- **ParticleNet** has not yet been trained on jets in this p_T range, it will be necessary to retrain it if we want to use it in 2018





Systematics and Scale Factors

- List of all systematics and scale factors being used in the analysis

Systematics/Scale Factors	Source	Type	2016 Value	2017 Value	2018 Value
Lumi	Lumi POG	lnN	1.012	1.023	1.025
Trigger	Trigger Study	lnN	1.05	1.05	1.05
Photon ID	EGamma POG	lnN	1.05	1.05	1.05
JES	NanoAODTools	Shape	Varies By Sample	Varies By Sample	Varies By Sample
JER	NanoAODTools	Shape	Varies By Sample	Varies By Sample	Varies By Sample

Systematics and Scale Factors

Systematics/Scale Factors	Source	Type	2016 Value	2017 Value	2018 Value
N2DDT SF	TTBar Control Region Study	lnN	0.719 ± 0.156	0.762 ± 0.133	0.562 ± 0.153
JMS	TTBar Control Region Study	Shape	-2.706 ± 0.488 GeV	-1.764 ± 0.332 GeV	-3.764 ± 0.532
JMR	TTBar Control Region Study	Shape	6.2% ± 4.1%	-7.0% ± 2.0%	6.5% ± 4.1%
Pileup	Lumi POG	Shape	Varies By Sample	Varies By Sample	Varies By Sample

*TTBar Control Region Study examines shifting and smearing of semileptonic TTBar → W+muon peak between simulation and SingleMuon data