Status of
Sensitivity to Dijet Resonances at proton-proton Colliders

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Fermilab

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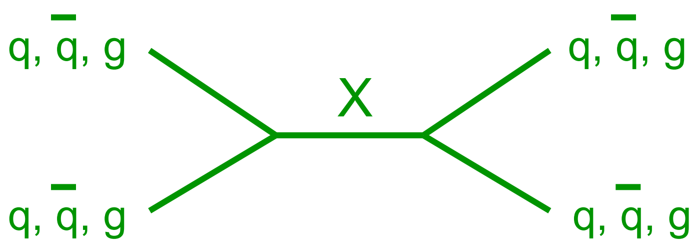
Outline

- Introduction to benchmark channel for discovery at pp colliders
- QCD background and dijet resonance signal
- Sensitivities: 5σ discovery and 95% CL exclusion
- Conclusions

Dijet Resonances

- Essential benchmark of discovery capability of proton-proton colliders
  - Discovery process sensitive to a variety of new physics at highest mass scales
  - Predicted by countless models proposed to address fundamental questions

- Proton-proton colliders are natural dijet resonance factories
  - Dijet resonances, X, produced by annihilation of partons in the colliding protons
  - Must decay to two partons giving dijets



- We estimate the sensitivity of pp colliders to this essential process
  - LOI: SNOWMASS21-EF9_EF8_RobertHarris-055.pdf

pp Colliders

- Comprehensive study of all scenarios for current and future pp colliders

- $\sqrt{s}$: eight collision energies
  - LHC & HL-LHC: 13 & 14 TeV
  - HE–LHC: 27 TeV
  - FCC–hh: 75, 100 (default), 150, 200 TeV
  - Collider in the sea: 500 TeV (why not . . .)

- $\int \mathcal{L}\, dt$: ten integrated luminosities
  - Five general values with logarithmic spacing: $10^1 – 10^5$ fb^{-1}
  - Five benchmark integrated luminosities previously used or recommended
    - LHC: 140 fb^{-1} (Run 2), 200 fb^{-1} (Run 3)
    - HL-HC: 3 ab^{-1}
    - FCC-hh: 2.5, 30 ab^{-1}

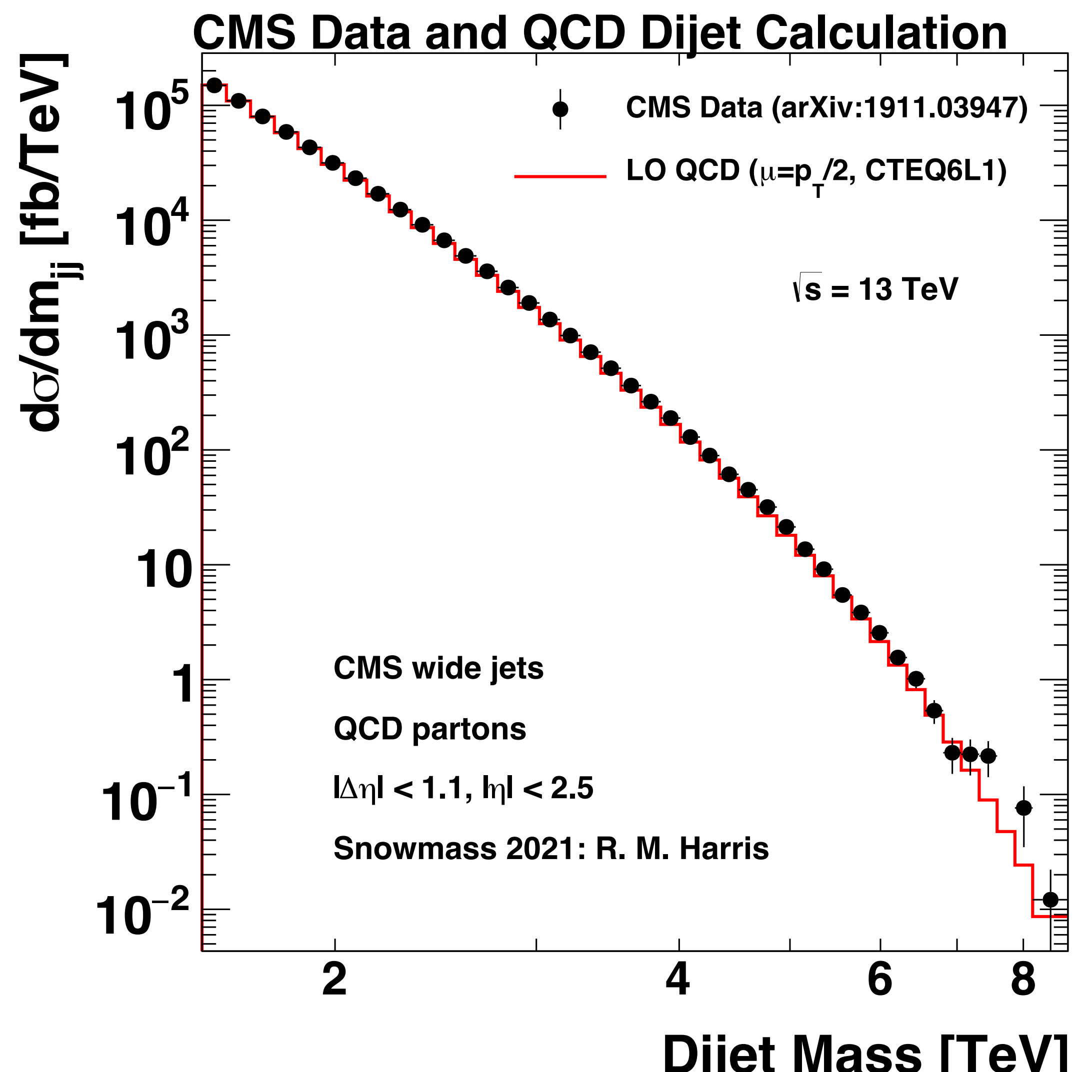
- Mass sensitivity for discovery/exclusion of dijet resonances at all $\sqrt{s}$ & $\int L\, dt$

Methodology

- Lowest order parton level calculations of QCD background and signals
  - Updating my study for Snowmass 1995: hep-ph/9609319 (time flies …)
  - Supplemented by more modern simulation estimates of signal acceptance
- Selection cuts similar to publications from LHC
  - Two final state partons have $|\eta|<2.5$
  - Angular cut $|\Delta\eta|<1.1$ (same as $|\cos\theta^*|< 0.5$) to suppress QCD t-channel pole
- Calculate signal and background inside a search window
  - Centered on pole mass M and 16.4% wide: 0.836 M < dijet mass < 1.164 M
  - Signal acceptance estimated from CMS resonance shapes (more on this later)
- Estimate number of events, and signal model masses, required for
  - 95% CL exclusion: 1.64σ on $N_{QCD}\rightarrow\infty$, 3 events when $N_{QCD}=0$.
  - 5s discovery: 5σ on $N_{QCD}\rightarrow\infty$, 25 events (conservative) when $N_{QCD}=0$.

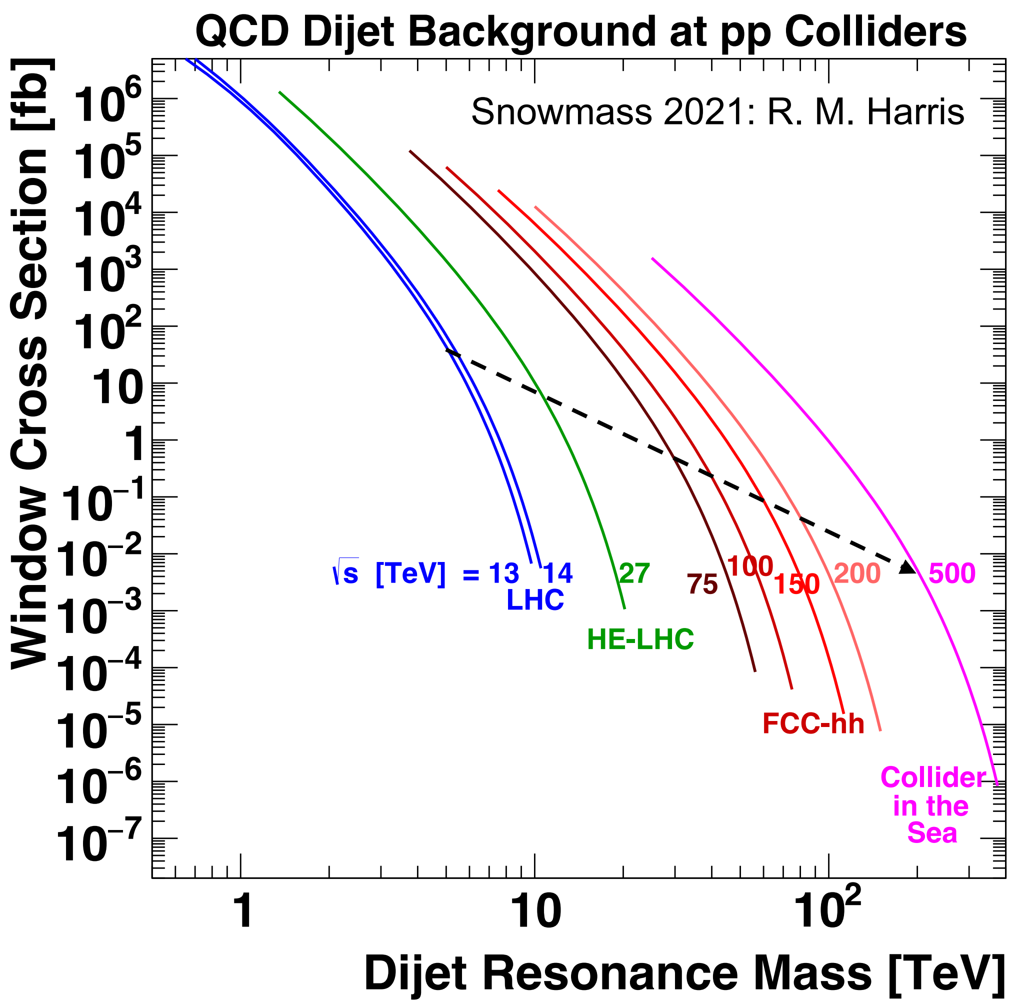
Check: QCD Background at LHC

- We check our lowest order QCD calculation of the background with LHC data
- It agrees to within ~10% with CMS data from Run 2.
  - CMS uses wide jets that correspond well to the partons in a 2→2 process
- We use the same choices for all pp collision energies
  - Renorm. scale $\mu = p_T/2$
  - CTEQ6L1 PDF



QCD Background at pp Colliders

- QCD background
  - Lowest order parton level calculation of cross section in 16.4% mass window centered on resonance pole
- QCD background, at a mass proportional to the collision energy, decreases gradually with increasing collision energy
- High mass searches use QCD data between about 5% and 75% of the collision energy

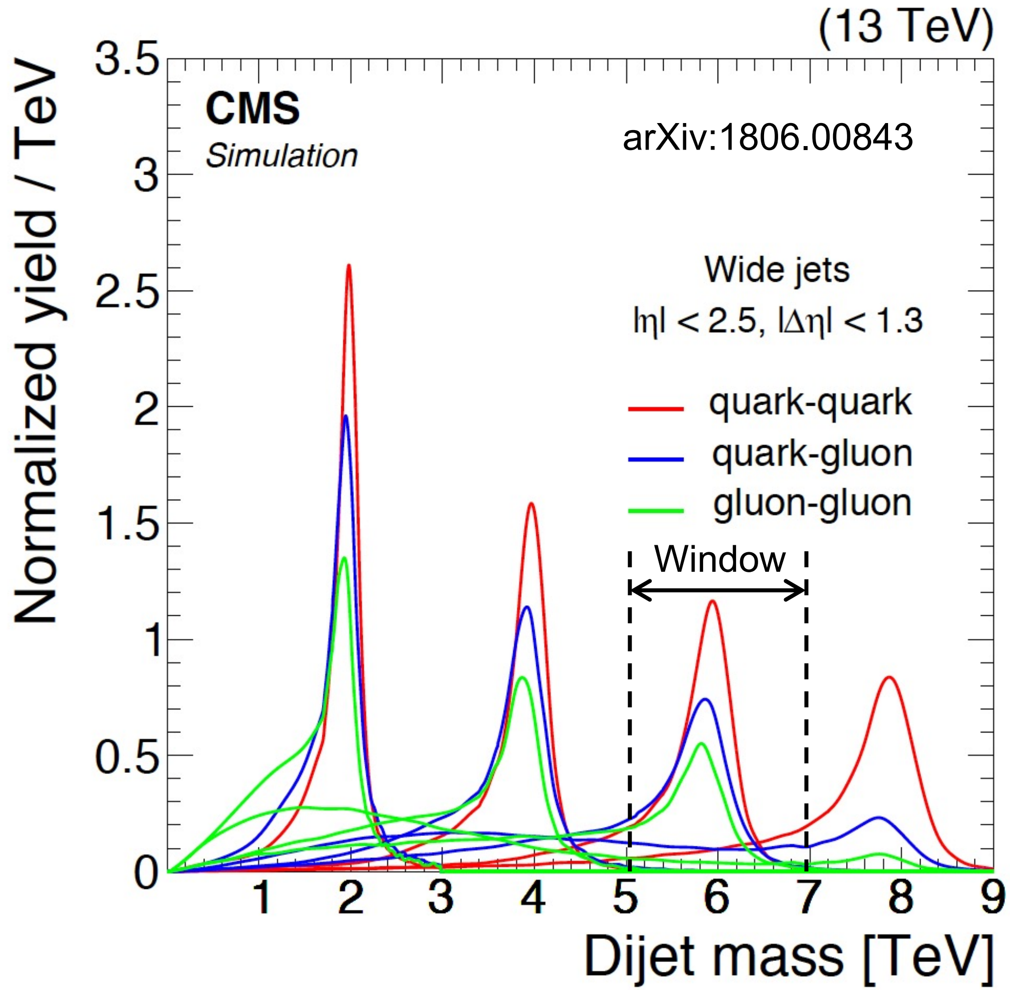


Narrow Resonance Models

- Multiple benchmark models
  - Spanning a range of cross sections from various interaction strengths
- Excited quarks ($qg \rightarrow q^* \rightarrow qg$), preliminary results now.
  - Earliest benchmark for searches at hadron colliders: S$p\bar{p}$S, Tevatron, LHC
  - Large cross section from strong production
- Other models we will explore fully later, a few preliminary results now
  - Scalar diquarks ($qq \rightarrow$ D $\rightarrow qq$): large cross sections from valence quark PDF
  - Colorons ($q\bar{q} \rightarrow$ C $\rightarrow q\bar{q}$): strong production of massive gluons
  - W' ($q\bar{q}' \rightarrow$ W' $\rightarrow q\bar{q}'$): electroweak-like production of a new W boson (SSM)
  - Z' ($q\bar{q} \rightarrow$ Z' $\rightarrow q\bar{q}$): electroweak-like production of a new Z boson (SSM)
  - Randall-Sundrum Graviton ($q\bar{q}$, $gg \rightarrow$ G $\rightarrow gg$, $q\bar{q}$): Warped extra-dimension
- Lowest order calculations of total signal cross section (CTEQ6L1, μ=M)
  - Multiplied by signal acceptance in dijet mass window

Signal Acceptance

- Resonance shape
  - Gaussian core from experimental resolution
  - Long tail to low mass from radiation and PDF
- Acceptance scaling
  - Window acceptance should be roughly independent of $\sqrt{s}$
- Check acceptance scaling with MC simulations of signals at each collision energy (next slide)

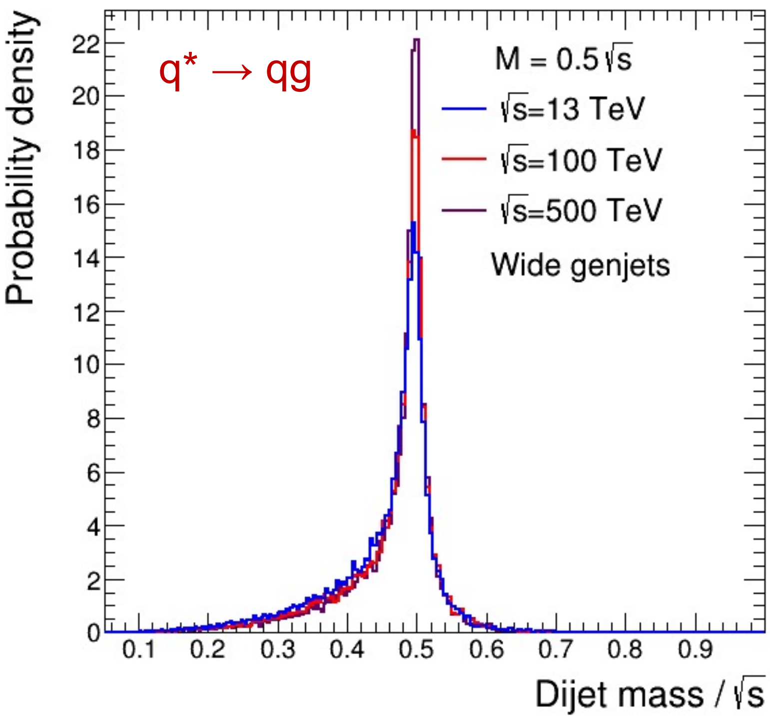


Scaling of Resonance Shape

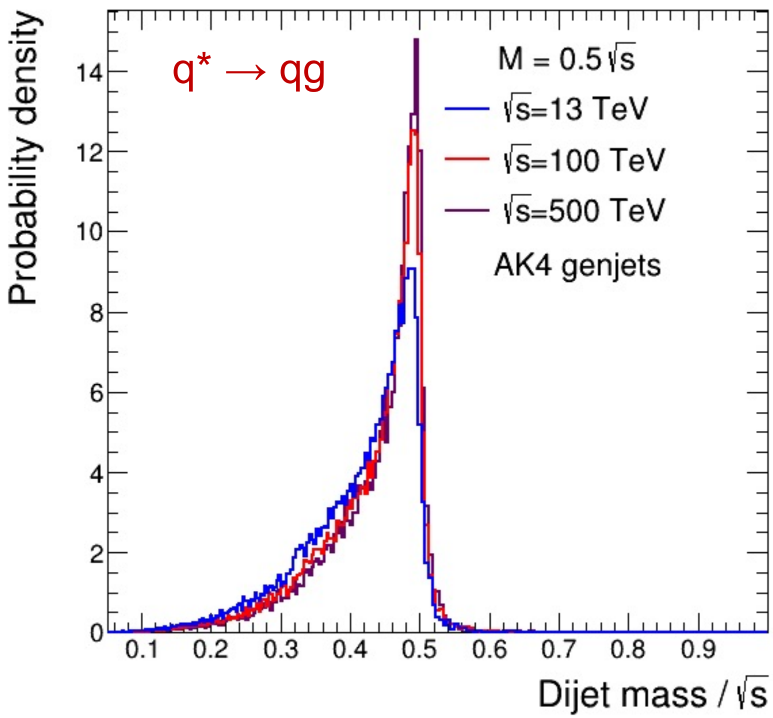
RMH, Emine Gurpinar Guler & Yalcin Guler

- q* shape for genjets scales when resonance mass is a fixed fraction of √s
  - Approximately invariant with increasing √s for wide genjets
  - Window acceptance should be invariant for fixed model & appropriate detector

Wide genjets (ΔR=1.1)

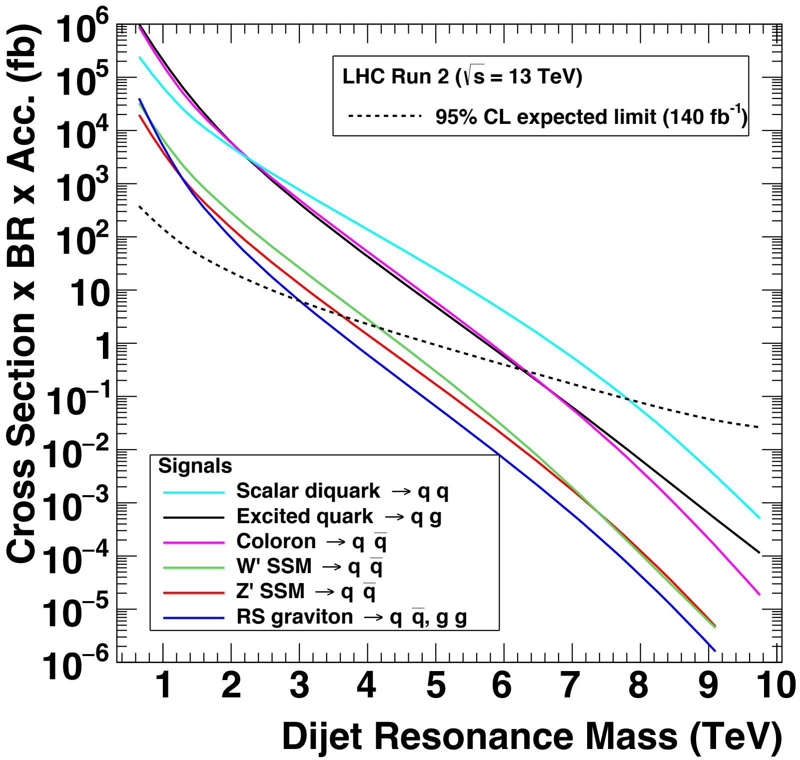


Narrow genjets (ΔR=0.4)



Check: Limits for LHC Run II

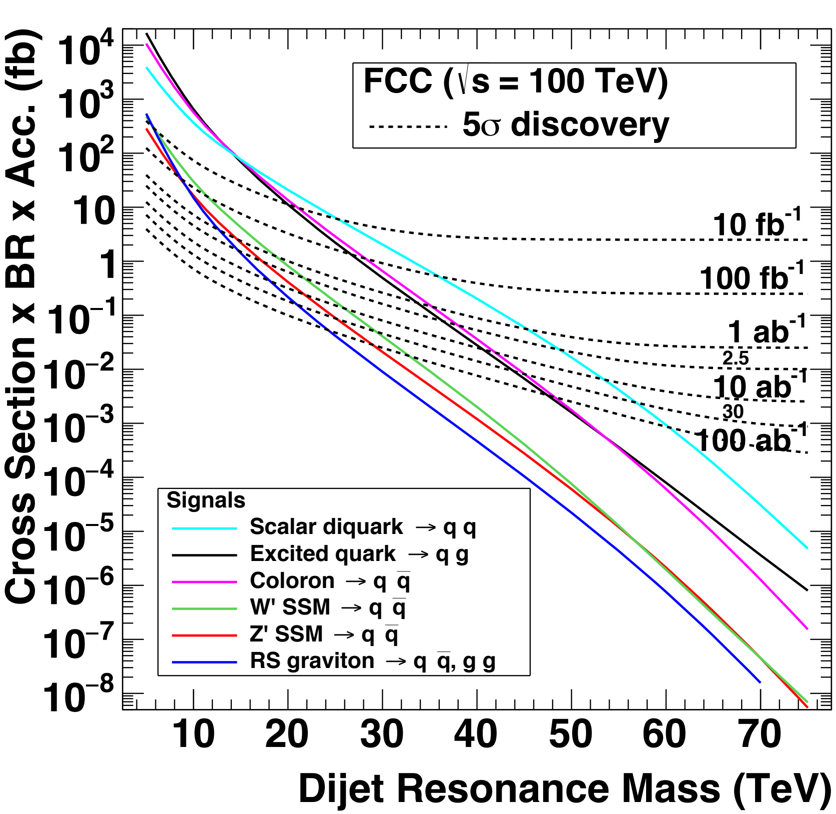
- Expected cross section upper limits compared to signals models in mass window
  - Gives snowmass expected mass limits on models where curves cross
- Snowmass limits at 13 TeV agree with CMS (1911.03947) & ATLAS (1910.08447)
  - Estimating sensitivity from LO calculation of events in a window works well enough ✓

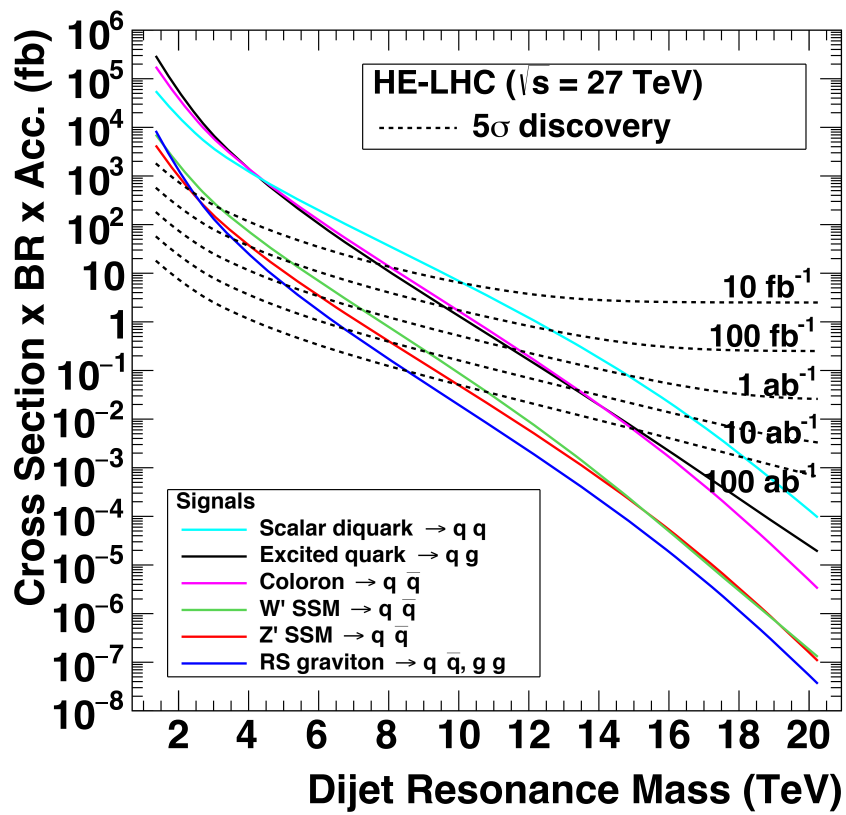


95% CL Expected Limits ($\sqrt{s}$ = 13 TeV, $\int Ldt$ = 140 fb^{-1})				
Model	CMS Pub. (TeV)	ATLAS Pub. (TeV)	Snow-mass (TeV)	Mass Window Accept. at Limit
Diquark	7.9	---	7.8	≈ 75%
Coloron	6.4	---	6.3	≈ 80%
q*	6.2	6.4	6.3	≈ 60%
W’	3.9	4.2	4.2	≈ 85%
Z’	3.4	---	3.6	≈ 85%
RS Graviton	2.6	---	3.0	≈ 65%

5σ Discovery Projections

- Preliminary plots for FCC-hh (100 TeV) and HE-LHC (27 TeV)
  - Discovery cross section is inversely proportional to:
    - $(\int \mathcal{L}\, dt)^{1/2}$ (large background) ✓
    - $\int \mathcal{L}\, dt$ (no background) ✓





Example Results: q* Discovery

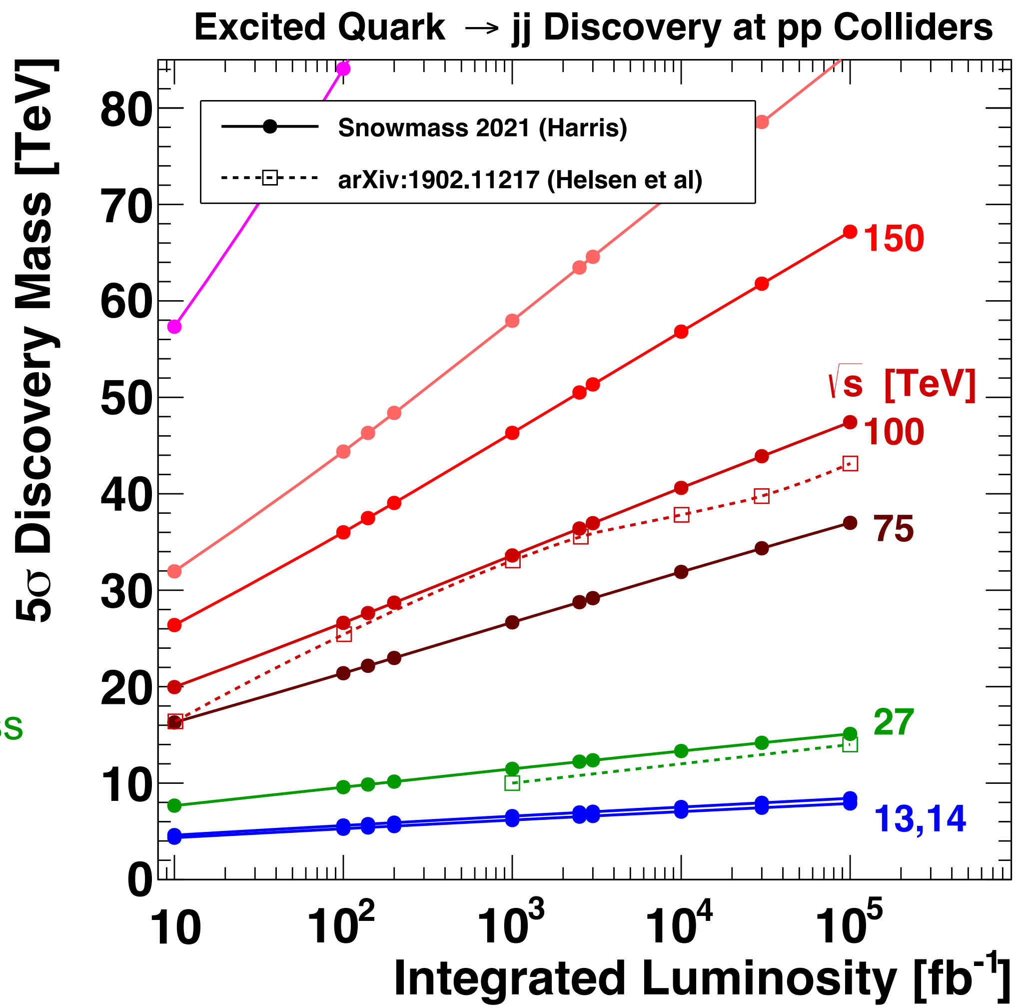
- 5σ discovery reach
  - Increases linearly with √s, and logarithmically with ∫ℒ dt ✓
  - Within ~10% of previous studies

FCC (100 TeV) q* Discovery Mass

∫ L dt [ab^{-1}]	Harris [TeV]	Helsen [TeV]
2.5	36	36
30	44	40
100	47	43

HE-LHC (27 TeV) q* Discovery Mass

∫ L dt [ab^{-1}]	Harris [TeV]	Helsen [TeV]
1	11.5	10
10	13.3	--
100	15.1	14



Example Results: q* Exclusion

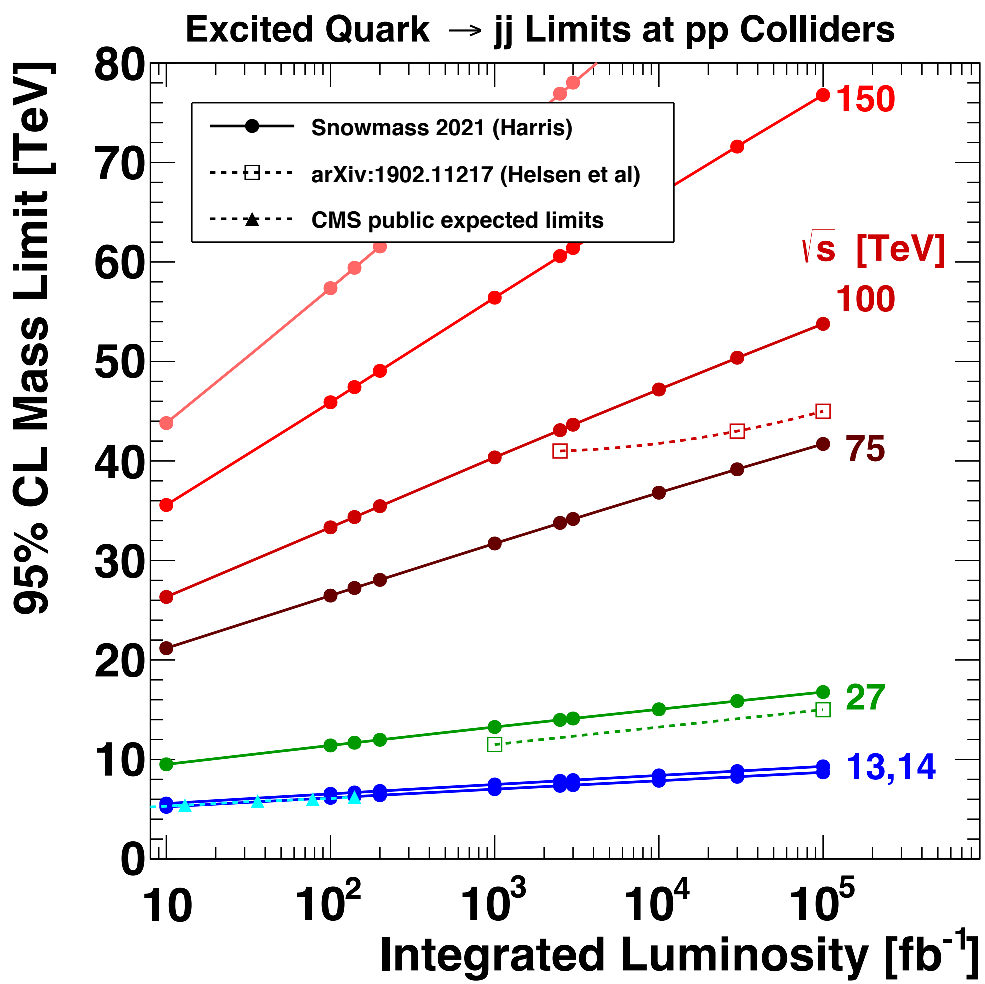
- 95% CL Expected Exclusion
  - Increases linearly with √s & logarithmically with ∫ℒ dt ✓
  - More significant differences with previous FCC studies.
  - Agrees with all CMS data

FCC (100 TeV) q* Expected 95% CL

∫ L dt [ab^{-1}]	Harris [TeV]	Helsen [TeV]
2.5	43	41
30	50	43
100	54	45

LHC (13 TeV) q* Expected 95% CL

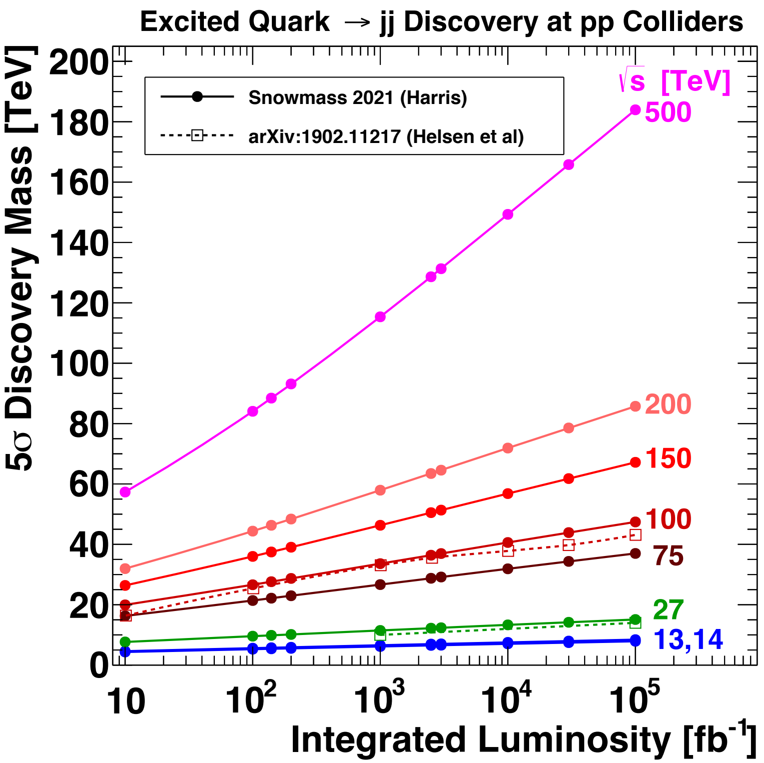
∫ L dt [fb^{-1}]	Harris [TeV]	CMS [TeV]
13	5.34	5.4
140	6.27	6.2



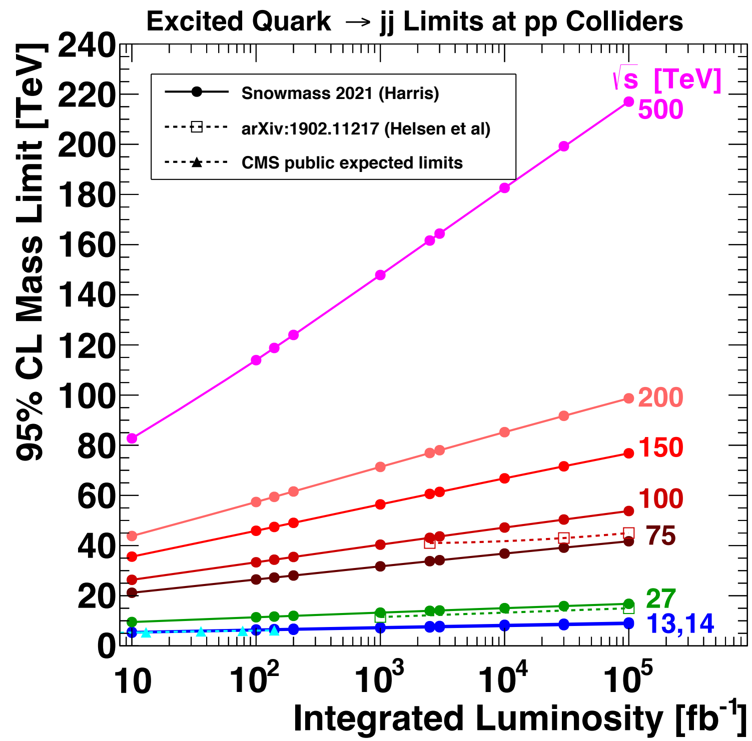
q* Results: All Scenarios

- Preliminary q* discovery and exclusion masses vs. integrated luminosity for all pp collision energies, from the LHC to the Collider in the Sea.

5σ Discovery



95% CL Limits



Conclusions

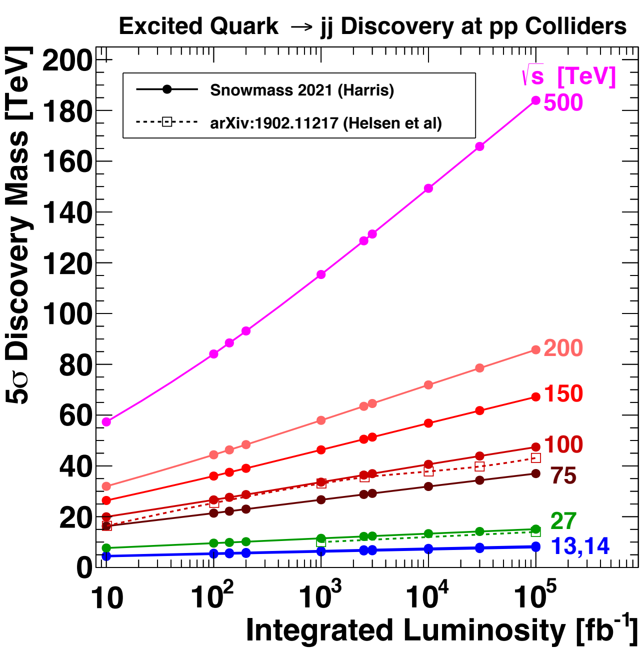
- We are estimating sensitivity to multiple models of dijet resonances across a wide range of pp collision energy ($\sqrt{s}$) and integrated luminosity ($\int\mathcal{L}\,dt$)
- Simple methodology gives robust predictions
  - Reproduces CMS Run 2 backgrounds and LHC expected limits for all models
- Shape of dijet resonances at fixed fraction of $\sqrt{s}$ is approximately invariant
  - When searches are conducted using wide jets that correspond well to partons
- Sensitivity to excited quarks (q*) at pp colliders scales as expected
  - Increases linearly with $\sqrt{s}$ and logarithmically with $\int\mathcal{L}\,dt$.
  - For HL-LHC (14 TeV, 3 ab^{-1}), q* limit at 8 TeV, discovery at 7 TeV
  - For HE-LHC (27 TeV, 10 ab^{-1}), q* limit at 15 TeV, discovery at 13 TeV
  - For FCC-hh (100 TeV, 30 ab^{-1}), q* limit at 50 TeV, discovery at 44 TeV
- Future plans include other benchmark models (diquarks, colorons, W', Z', RS gravitons) and more signal shape studies

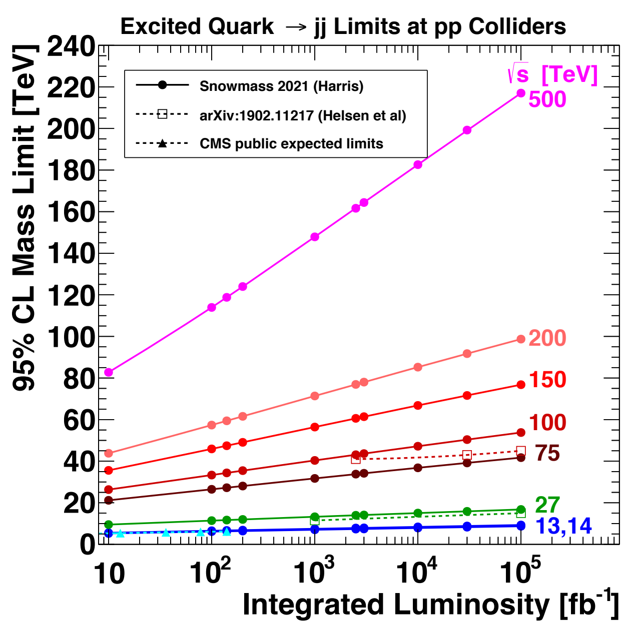
Backup

Summary Slide on Aug. 26

- Sensitivity to Dijet Resonances at proton-proton Colliders
  - **Collision Energies**: 13, 14, 27, 75, 100, 150, 200 & 500 TeV
  - **Luminosities**: 10 – 10^5 fb^{-1} and machine benchmarks in between.
  - **Models**: Excited Quarks (q*), Diquarks, Colorons, W', Z', RS gravitons
  - **Preliminary q* results below**, working on other models & signal shape studies

R. M. Harris with
E. Gurpinar Guler
Y. Guler





q* 5σ Discovery Mass

HL-LHC (14 TeV, 3 ab^{-1})
7 TeV

HE-LHC (27 TeV, 10 ab^{-1})
13 TeV

FCC-hh (100 TeV, 30 ab^{-1})
44 TeV