Sensitivity to Dijet Resonances at Proton-Proton Colliders

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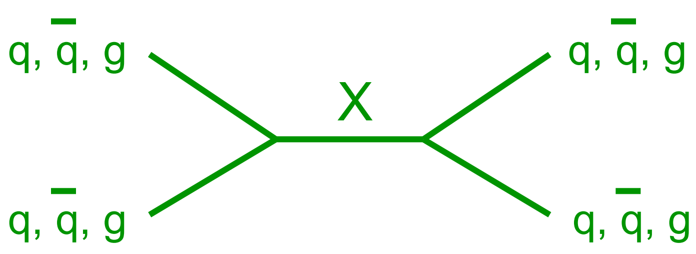
Outline

- Introduction to benchmark channel for discovery at pp colliders
- QCD background and models of dijet resonance signals
- 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
- √s: eight collision energies
  - LHC & HL-LHC: 13 & 14 TeV
  - FNAL-SF: 27 TeV (Fermilab site filler pp option, formerly HE-LHC)
  - FCC–hh: 75 (SPPC option), 100 (default), 150 TeV (higher energy option)
  - VLHC: 300 TeV (**NEW**: proposed by Liantao Wang & Meena Narrain at EF workshop)
  - 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 baseline 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 √s & ∫L dt

Narrow Resonance Models

- Multiple benchmark models
  - Exploring ALL of the parton-parton initial states available at pp colliders
  - Spanning a range of cross sections from various interaction strengths & PDF
- Strongly produced (σ ~ QCD)
  - Scalar diquarks (valence quark PDFs)
  - Colorons in model of extra color force
  - Excited states of composite quarks

Model	Spin	Partons	Coupling
Diquark	0	qq	EM Strength
Coloron	1	$q\bar{q}$	QCD-like
q*	½	qg	QCD-like

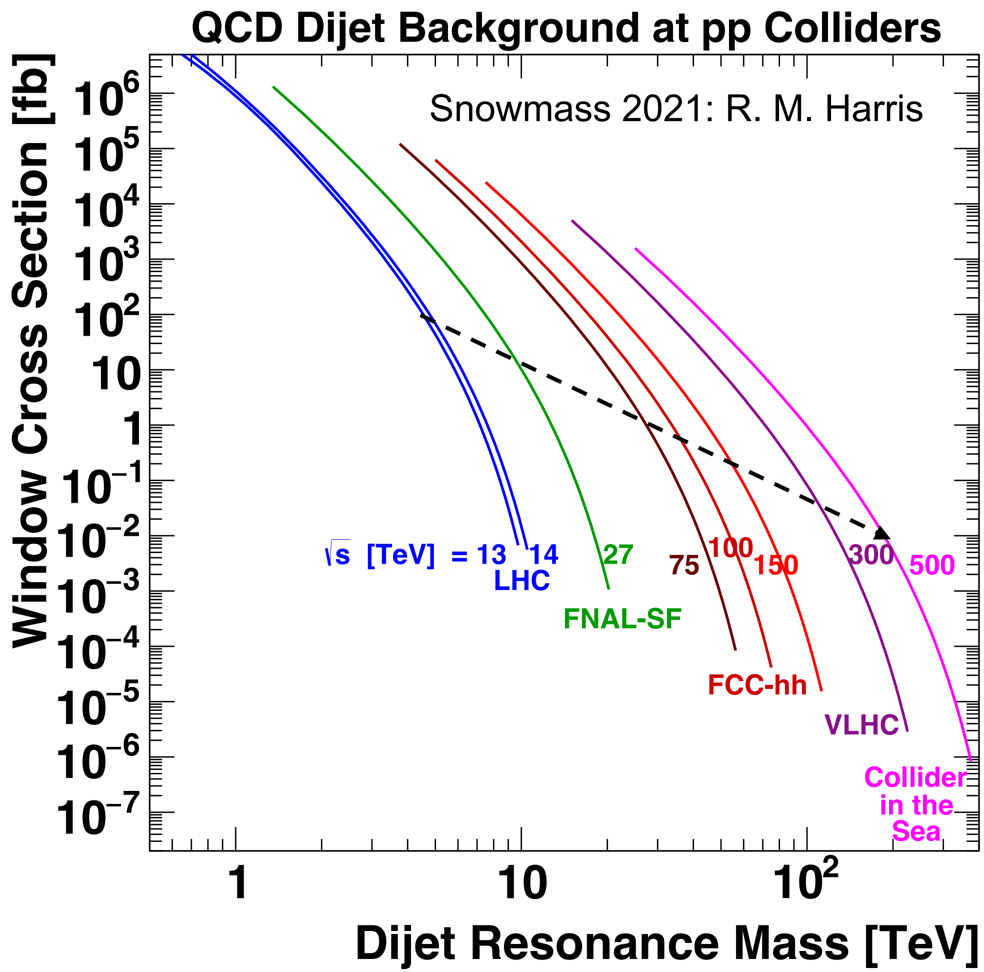
- Weakly produced (σ ~ Electroweak)
  - W' from EWK-like sequential SM.
  - Z' from EWK-like sequential SM.
  - Randall-Sundrum graviton in extra-dim.

Model	Spin	Partons	Coupling
W' SSM	1	$q\bar{q}'$	EWK-like
Z' SSM	1	$q\bar{q}$	EWK-like
RS grav	2	gg, $q\bar{q}$	$\kappa / M_{PL}=0.1$

- Lowest order calculations of total signal cross section (CTEQ6L1, μ=M)
  - Multiplied by signal acceptance in dijet mass window

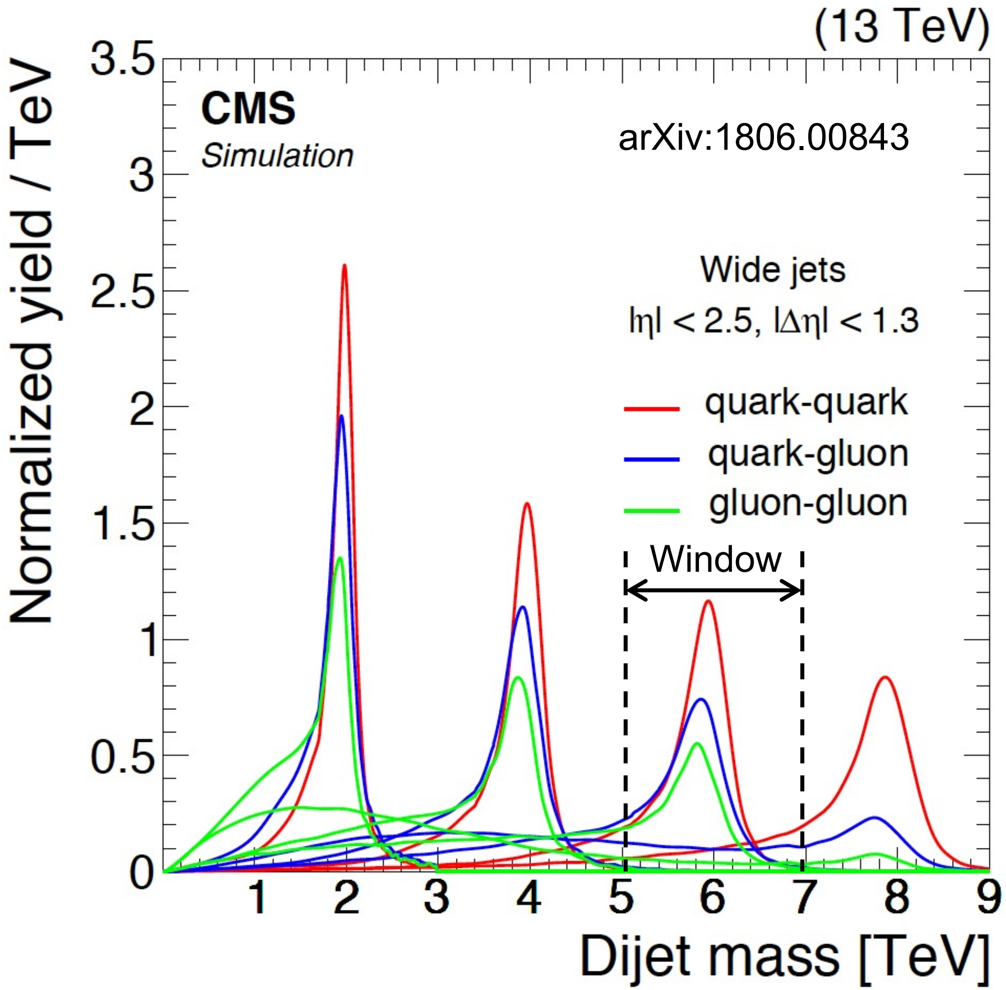
QCD Background at pp Colliders

- QCD background
  - Lowest order parton level calculation of cross section in 16.4% mass window centered on resonance pole
  - CTEQ6L1, $\mu=P_T/2$
- 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



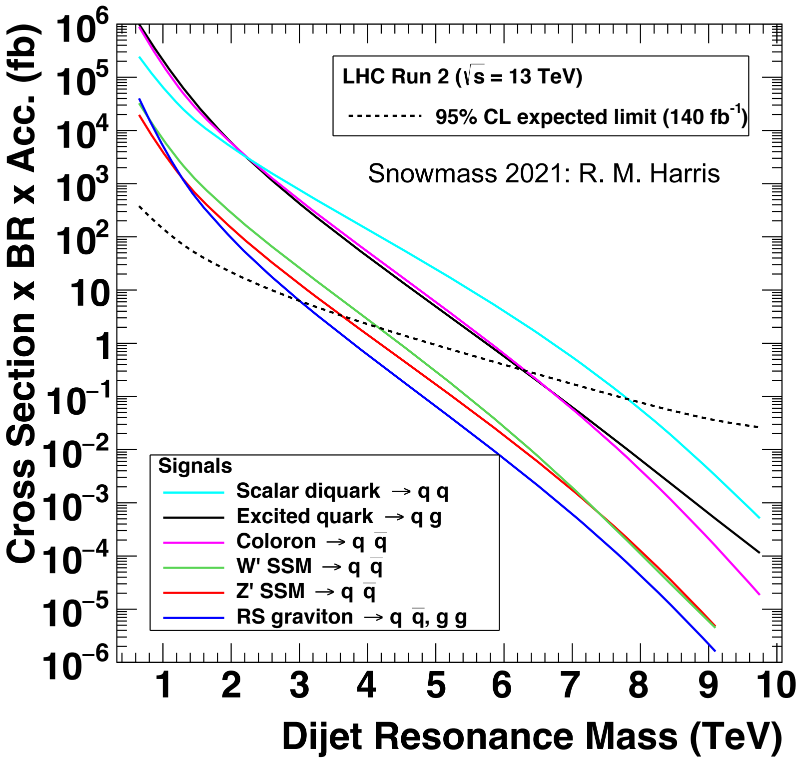
Signal Acceptance

- 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 √s
- Checked acceptance scaling with MC simulations of signals at each collision energy.



Check: Limits for LHC Run II

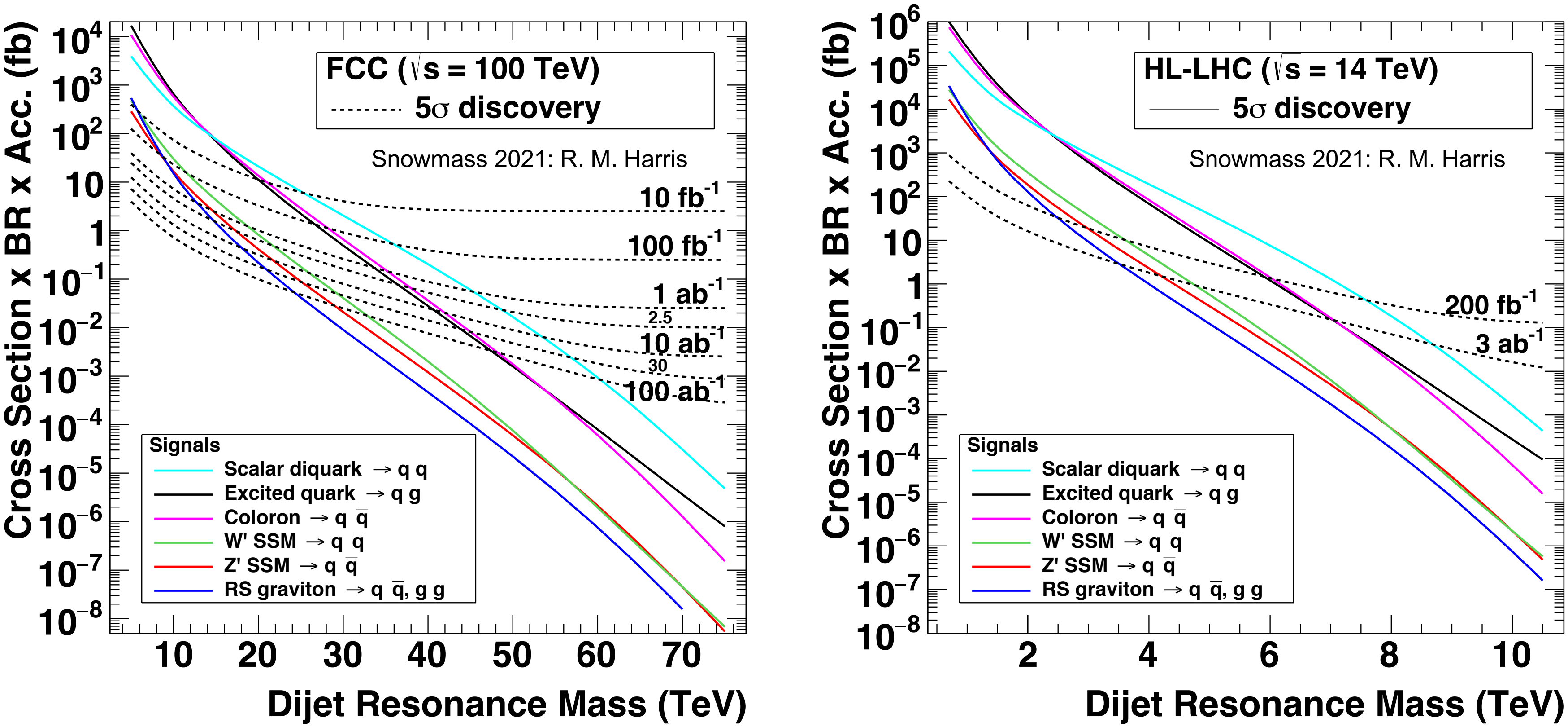
- Expected cross section upper limits compared to signals models in mass window
  - Gives snowmass 2021 expected mass limits on models where curves cross
- Snowmass limits at 13 TeV agree with CMS (1911.03947) & ATLAS (1910.08447)
  - Estimating sensitivity from LO calculation of events in a window works well enough ✓



95% CL Expected Limits ($\sqrt{s}$ = 13 TeV, $\int L dt$ = 140 fb^{-1})				
Snowmass 2021 R. M. Harris 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%

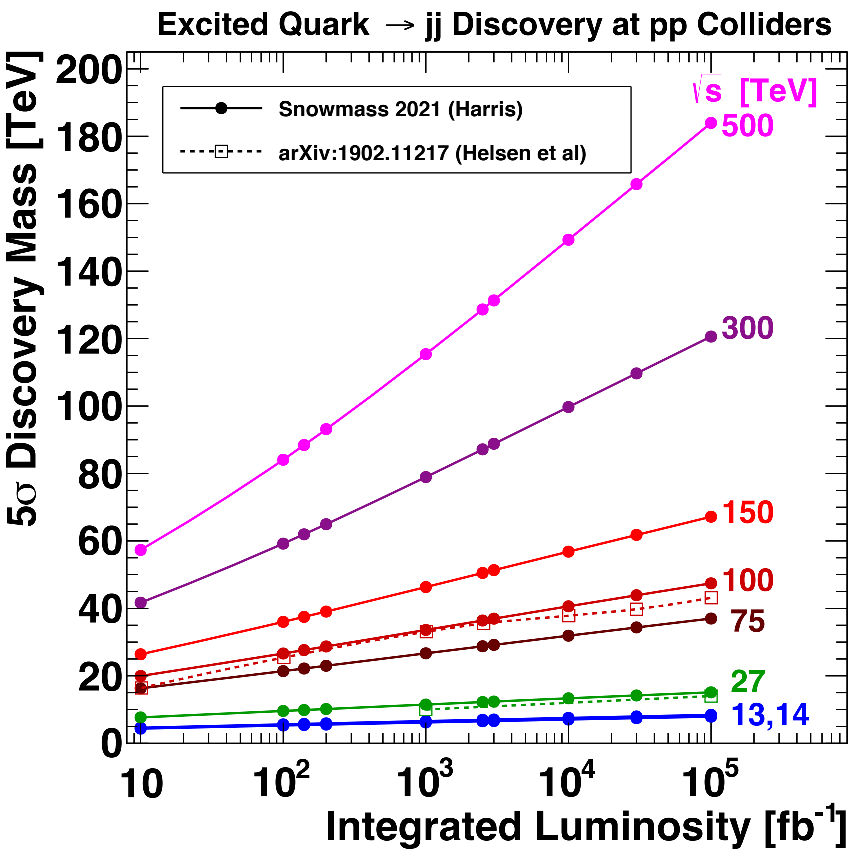
5σ Discovery Projections

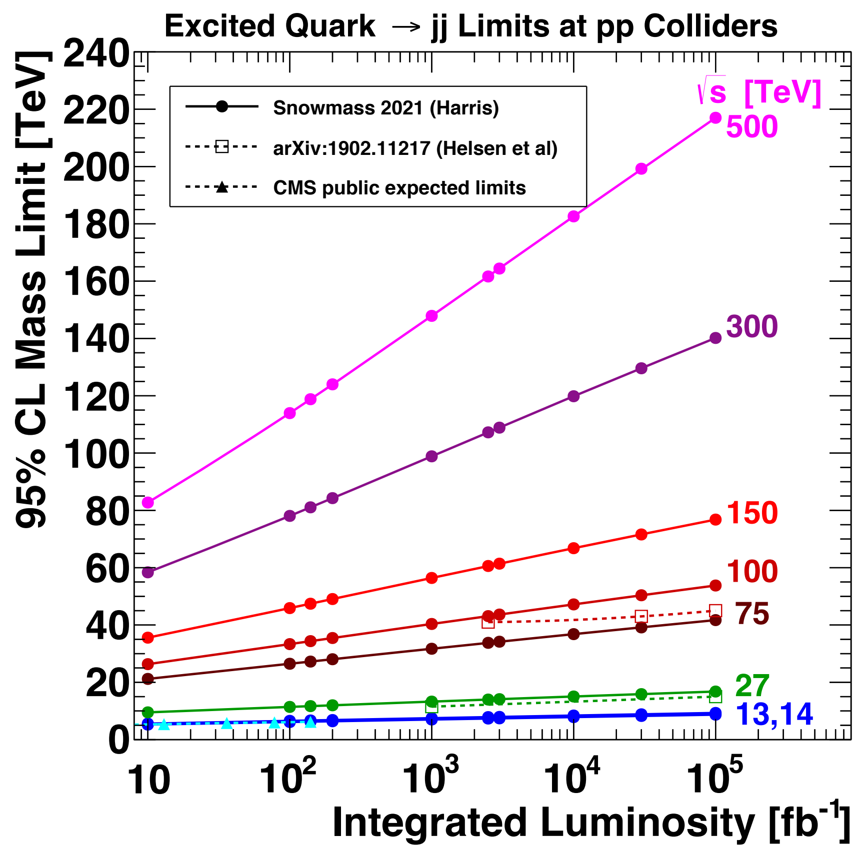
- Preliminary plots for FCC-hh (100 TeV) and HL-LHC (14 TeV)
  - Discovery cross section is inversely proportional to:
    - $\left(\int \mathcal{L}\, dt\right)^{1/2}$ (large background) ✓
    - $\int \mathcal{L}\, dt$ (no background) ✓



Excited Quark Results

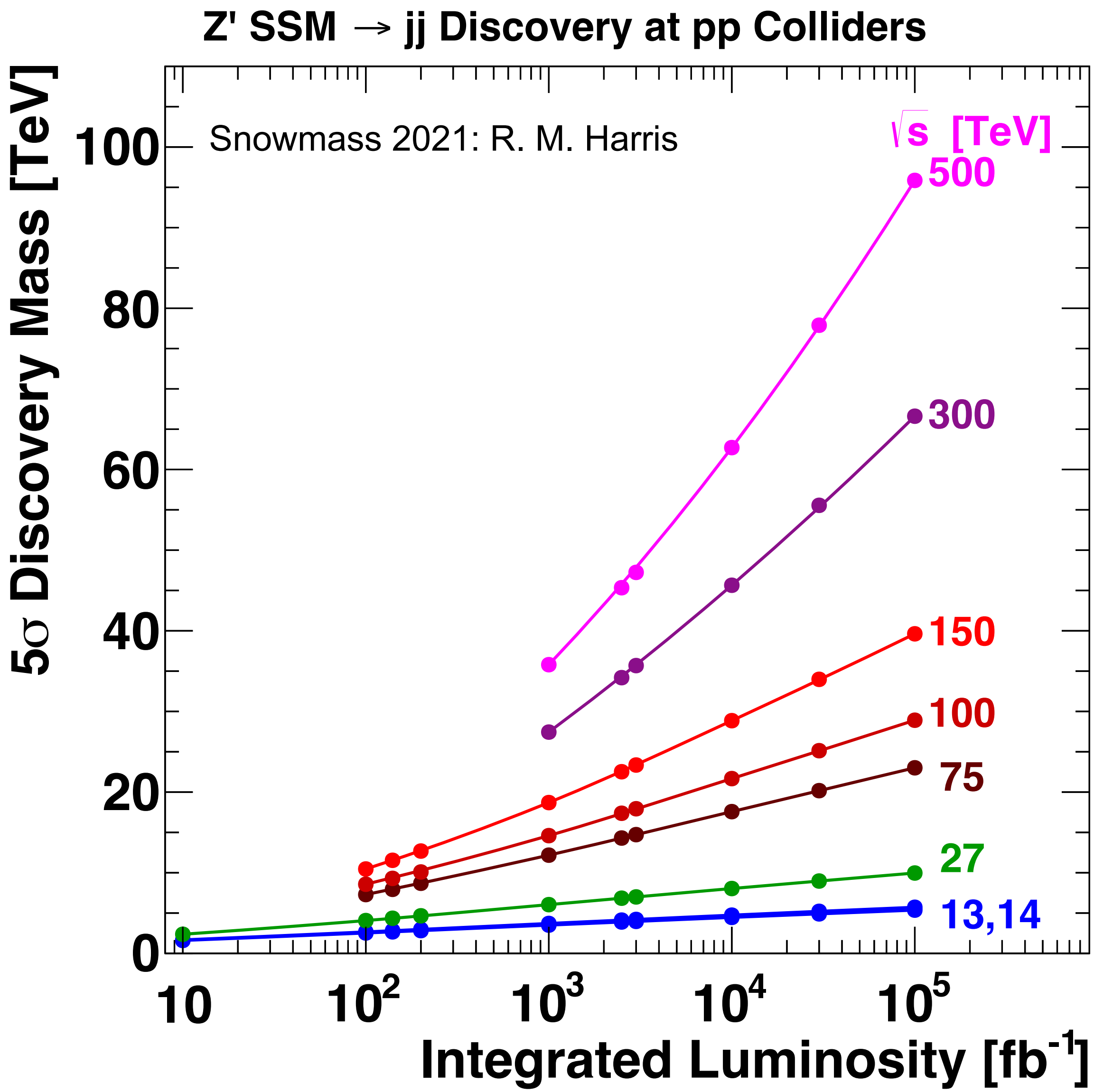
- 5σ Discovery and 95% CL Expected Exclusion of Heavy Fermion
  - Increases roughly linearly with √s & logarithmically with ∫ℒ dt ✓
  - Close to previous studies, and excellent agreement with all CMS results





Z' Discovery

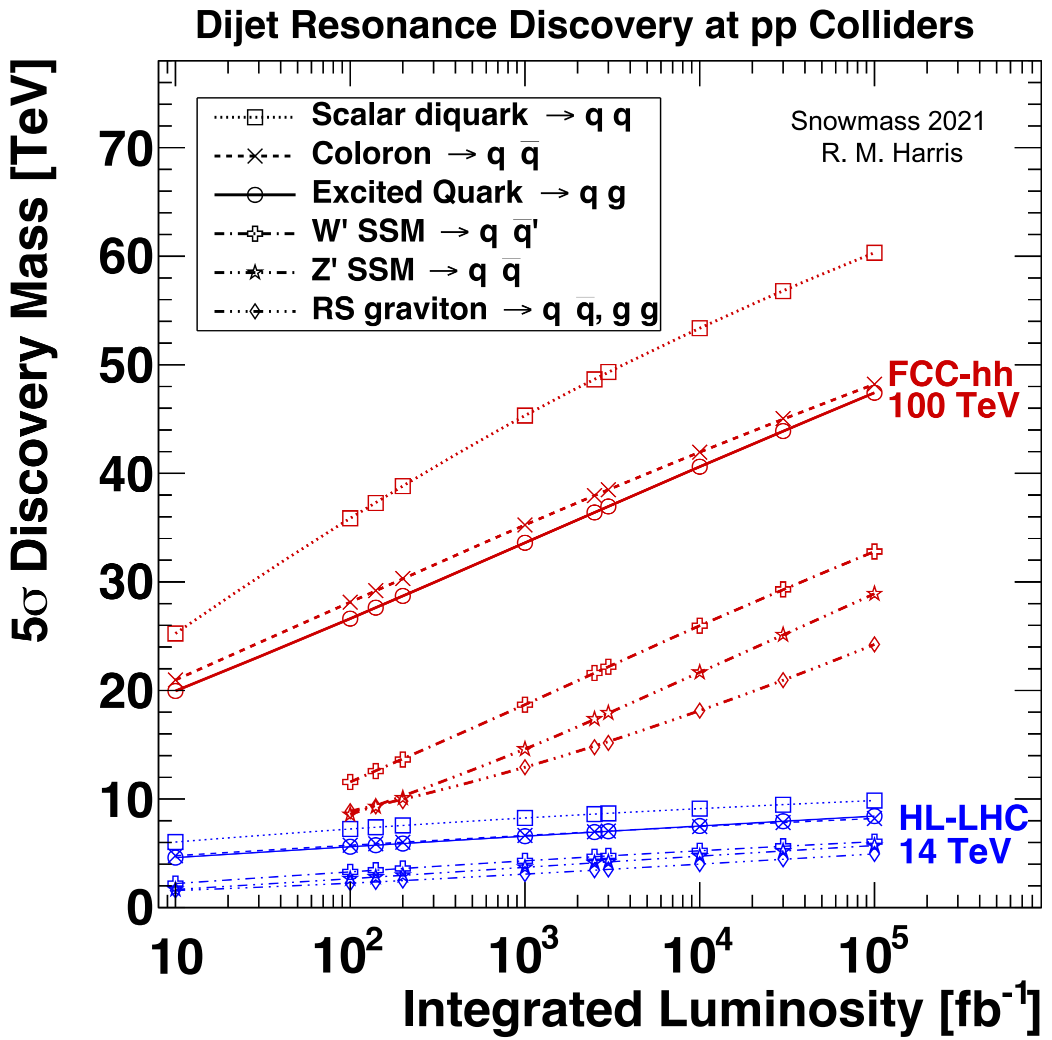
- Most frequently used benchmark of heavy boson
  - Weakly produced
- Decays to 5 light flavors of quarks
  - Conservative
- Results are for high mass search
  - M > 0.06 √s
  - Increases roughly linearly with √s & logarithmically with ∫ℒ dt ✓



All Models at HL-LHC & FCC-hh

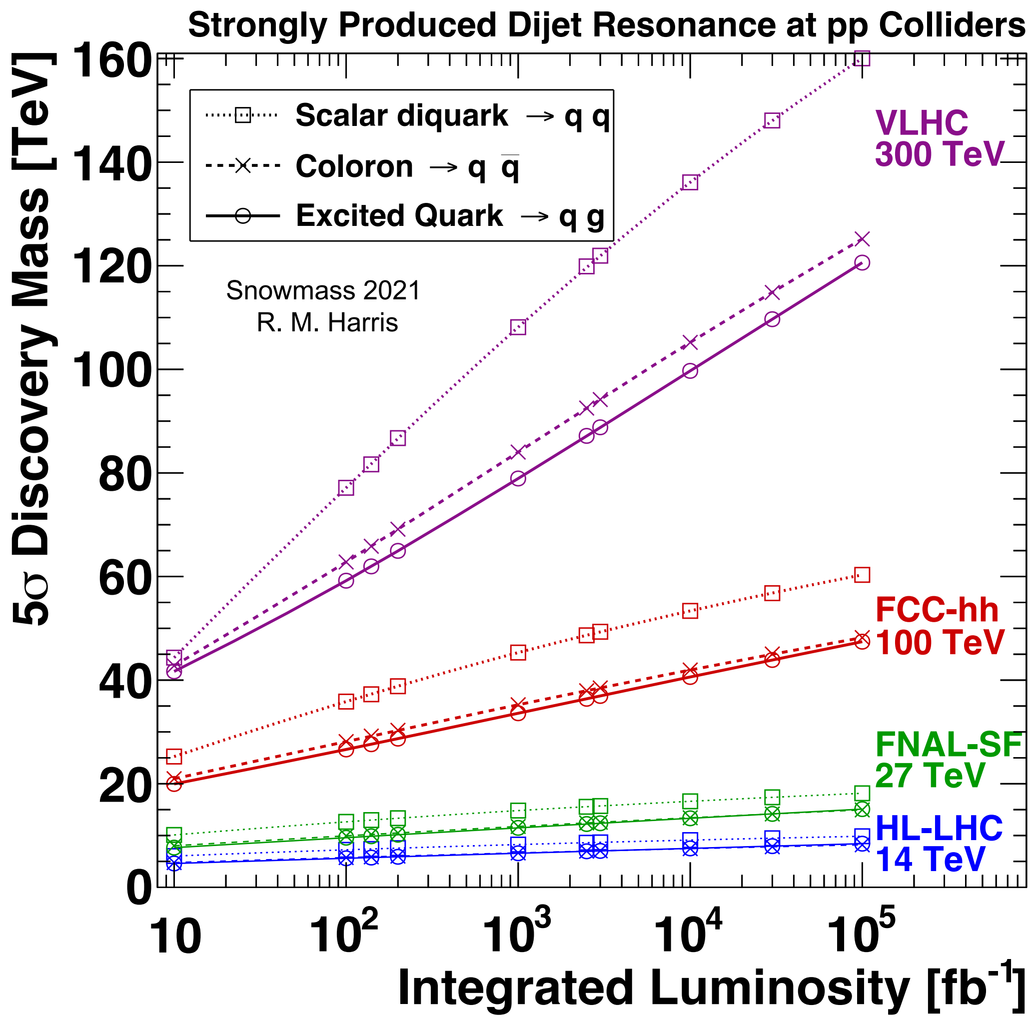
- Sensitivity highly dependent on production strength

Snowmass 2021 R. M. Harris **Model**	**HL-LHC** $\sqrt{s}$ = 14 TeV, $\int Ldt$ = 3 ab^{-1} **5σ** [TeV]	**95% CL** [TeV]	**FCC-hh** $\sqrt{s}$ = 100 TeV, $\int Ldt$ = 30 ab^{-1} **5σ** [TeV]	**95% CL** [TeV]
Strongly Produced Models				
Diquark	8.7	9.4	57	63
Coloron	7.1	7.8	45	51
q*	7.0	7.9	44	50
Weakly Produced Models				
W'	4.8	5.6	29	36
Z'	4.2	5.2	25	32
RS Grav.	3.5	4.4	21	27



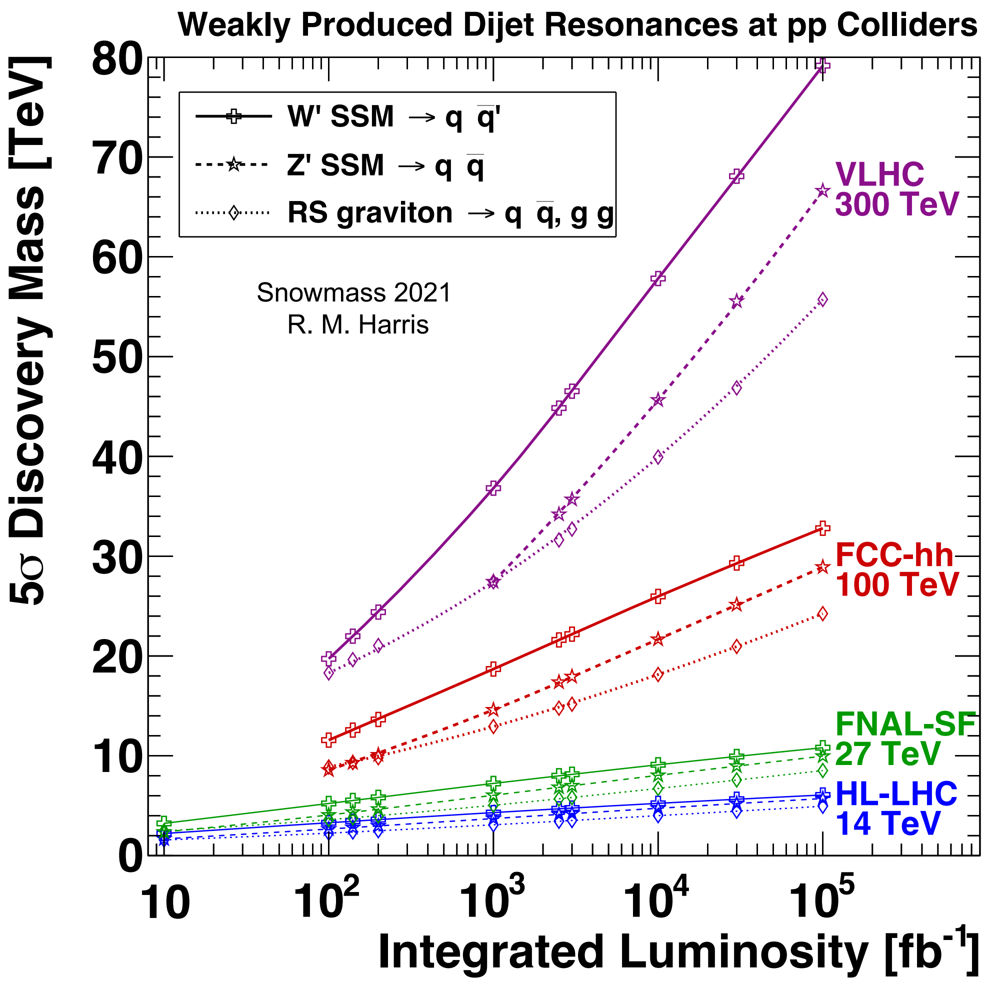
Strong Production Models

- Diquark model dominates with sufficient luminosity
  - Valence PDFs large when $x = M/\sqrt{s} \rightarrow 1/3$
- Coloron and q* models depend on anti-quark and gluon PDFs.
  - Relatively small when x is large.
- We don’t include decays of the coloron to top quarks



Weak Production Models

- W' and Z' sensitivities reflect relative SM coupling strengths.
  - We don't include decays of either W' or Z' to top quarks.
  - NLO k-factor included
- RS Graviton production via gg is significant at low mass.
  - Becomes negligible at very high mass, giving two slopes vs $\mathcal{L}$ dt
  - Near turn-on of $q\bar{q}$ process there is faster than logarithmic increase with $\int\mathcal{L}$ dt



Baseline Results

- 5σ Discovery and 95% CL exclusion for all models at all collider baselines
  - Exploring the highest masses of multiple models of new physics in one channel

Snowmass 2021 R. M. Harris **Model**	**HL-LHC** $\sqrt{s}$ = 14 TeV, $\int Ldt$ = 3 ab^{-1} **5σ** [TeV]	 **95% CL** [TeV]	**FNAL-SF** $\sqrt{s}$ = 27 TeV, $\int Ldt$ = 3 ab^{-1} **5σ** [TeV]	 **95% CL** [TeV]	**FCC-hh** $\sqrt{s}$ = 100 TeV, $\int Ldt$ = 30 ab^{-1} **5σ** [TeV]	 **95% CL** [TeV]	**VLHC** $\sqrt{s}$ = 300 TeV, $\int Ldt$ = 100 ab^{-1} **5σ** [TeV]	 **95% CL** [TeV]	**Collider in the Sea** $\sqrt{s}$ = 500 TeV, $\int Ldt$ = 100 ab^{-1} **5σ** [TeV]	 **95% CL** [TeV]
Strongly Produced Models of Dijet Resonances										
Diquark	8.7	9.4	16	17	57	63	160	180	249	284
Coloron	7.1	7.8	13	14	45	51	125	143	193	224
q*	7.0	7.9	12	14	44	50	121	140	184	217
Weakly Produced Models of Dijet Resonances										
W' (SSM)	4.8	5.6	8.2	9.9	29	36	79	99	117	150
Z' (SSM)	4.2	5.2	7.0	8.9	25	32	67	87	96	130
RS Grav.	3.5	4.4	5.8	7.5	21	27	56	73	81	109

Conclusions

- Dijet resonance process is a powerful channel for discovery at pp colliders.
  - Sensitive to highest mass scales of new physics in parton-parton collisions
  - Models of heavy bosons and fermions, strongly or weakly produced.
- We've estimated sensitivity to multiple models of dijet resonances across a wide range of pp collision energy ($\sqrt{s}$) and integrated luminosity ($\int\mathcal{L}\,dt$)
- Sensitivity to every sub-process of dijet resonance production at pp colliders scales as expected
  - Increases roughly linearly with $\sqrt{s}$ and logarithmically with $\int\mathcal{L}\,dt$.
- Preliminary results may be compared with other options for future colliders
- Future plans
  - Working on signal shape studies and refining mass-window acceptance
  - Will writeup for archive and publication

Backup

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

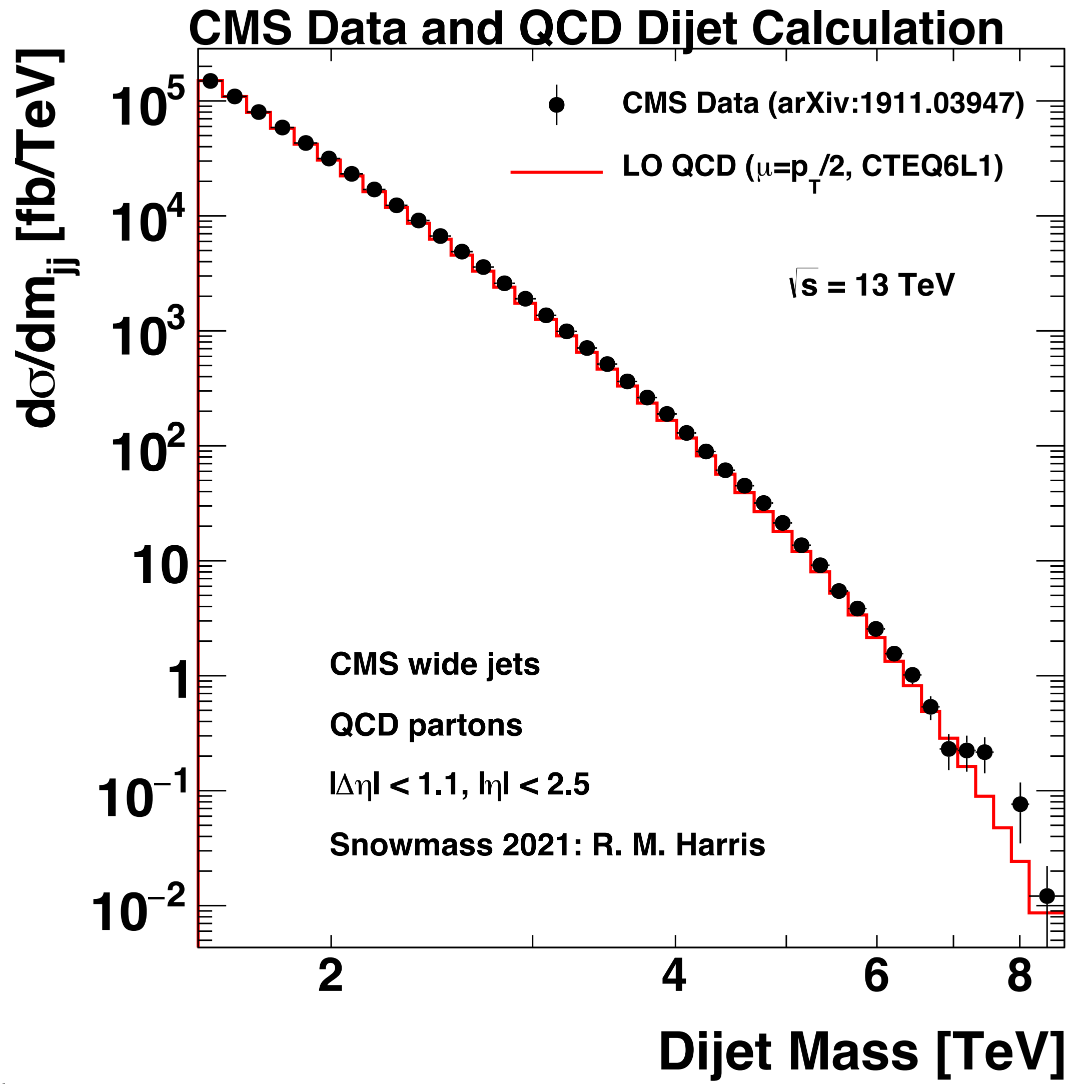
- Selection cuts similar to publications from LHC
  - Two final state partons have $|\eta|<2.5$
  - Angular cut $|\Delta\eta|<1.1$ (same as $|\cos\theta^*|< 0.5$) to suppress QCD t-channel pole

- 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

- 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



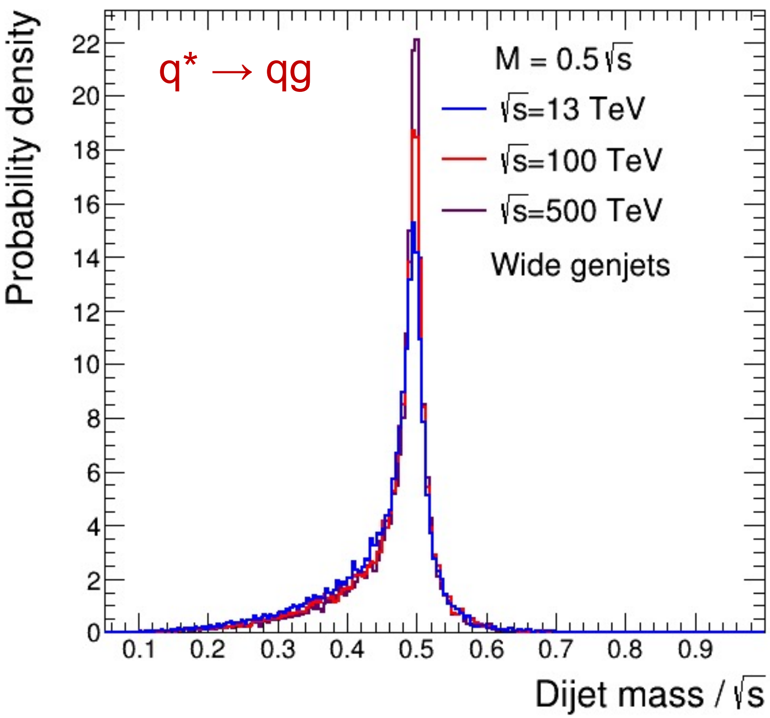
Rc

Scaling of Resonance Shape

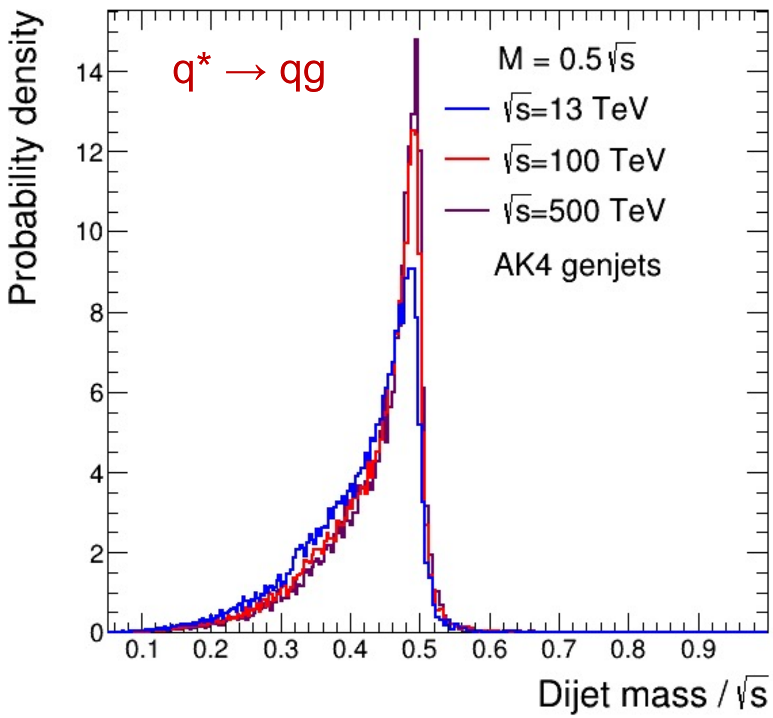
RMH, Emine Gurpinar Guler & Yalcin Guler

- 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)



Example Results: q* Discovery

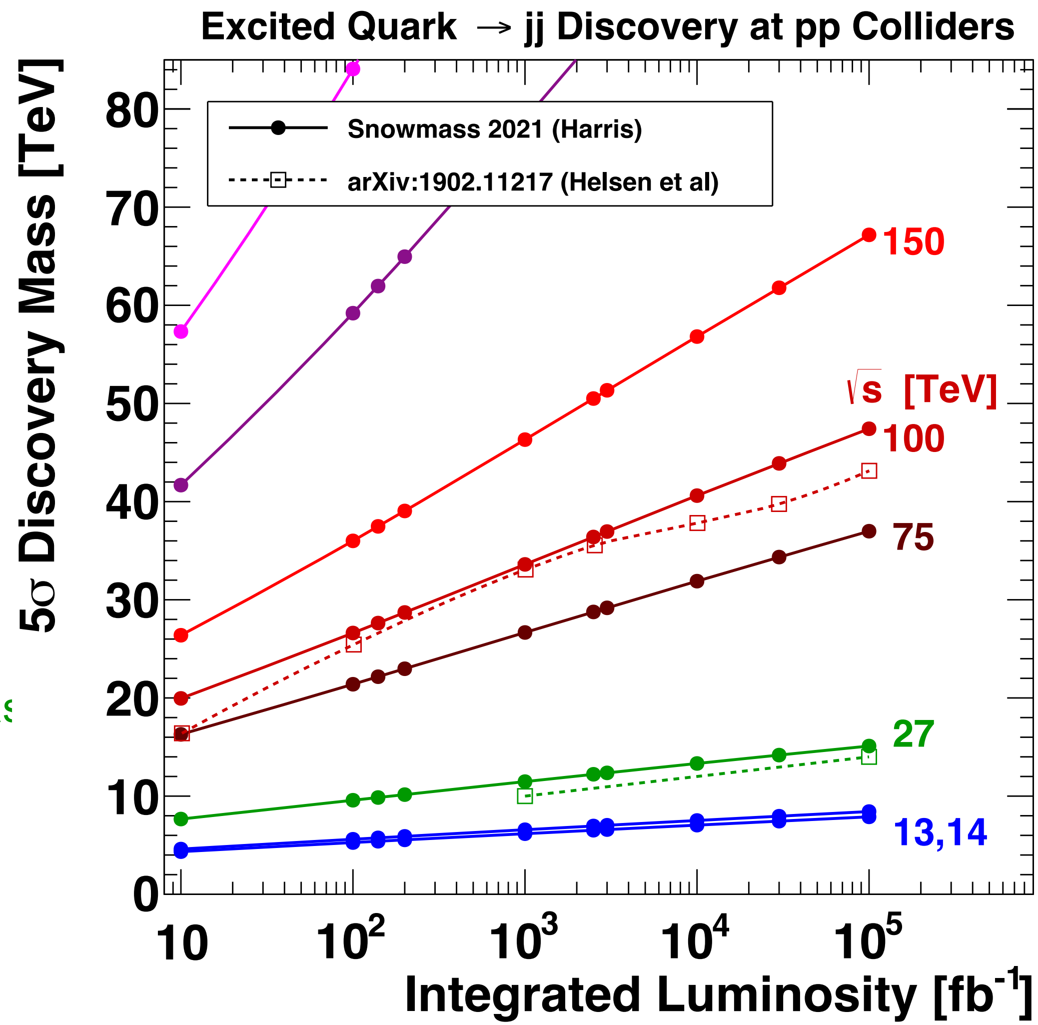
- 5σ discovery reach
  - Increases linearly with √s, and logarithmically with ∫ℒ dt ✓
  - Within ~10% of previous studies

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 Mas

∫ 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