EF09 New Bosons and Heavy Resonances

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Introduction

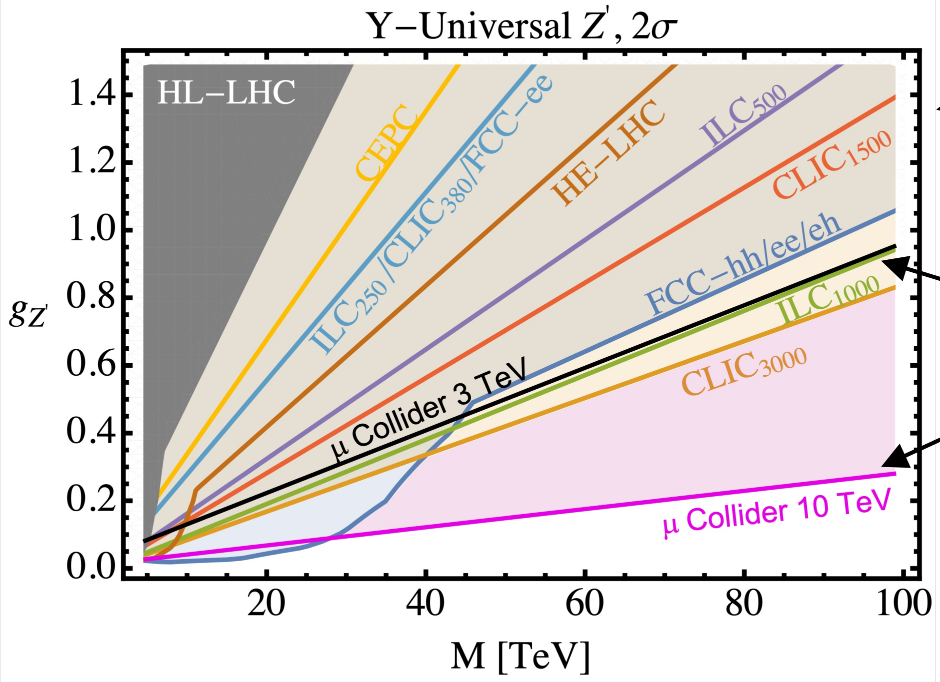
- Our report evaluates prospects for new bosons and heavy resonances
  - Synthesizing results from a dozen snowmass whitepapers on BSM physics

- We utilize **Z' bosons** as a standard candle to rank colliders by mass reach
  - A widely used benchmark of a new boson, ubiquitous within BSM physics
  - Searched for by all colliders at arbitrary mass and coupling

- We also discuss other models and channels evaluated at Snowmass
  - **W' bosons**: charged cousins to the Z', produced in s-channel at pp colliders
  - **Axion-like particles**: pseudo-scalars produced at all colliders
  - **Dijet resonances**: model-independent channel produced at pp colliders

- We make observations about the relative sensitivity of the colliders
  - Conclusions about the best experimental path towards new discovery

Universal Z'



European Strategy Briefing Book
arXiv:1910.11775

μ Collider Physics Summary
arXiv:2203.07526

95%CL at all colliders

- Z' with universal coupling $g_{Z'}$ to all SM fermions, ideal for collider comparisons.
  - Lepton colliders have an edge at large masses where only indirect effects can be measured
  - Hadron colliders provide best sensitivity at lower masses via direct observation of bumps.
- Muon collider results, new for Snowmass 2021, show impressive sensitivity
  - 3 TeV μ collider competitive with indirect searches using contact interactions at FCC-hh
  - 10 TeV μ collider most sensitive for $M_{Z'}$ > 28 TeV, uniquely probes $M_{Z'}$ > 100 TeV.

SSM Z'

- Z' with SM couplings to fermions is model most often used by searches
  - Sensitivity widely available: HL-LHC, ILC, and all pp colliders, but not μ collider.

SSM Z' at HL-LHC (14 TeV, $3ab^{-1}$)			
Source	Channel	5σ (TeV)	95% CL (TeV)
R.H.	$Z' \to$ dijet	4.2	5.2
ATLAS	$Z' \to \mu^+ \mu^-$	5.7	5.8
	$Z' \to e^+ e^-$	6.3	6.4
	$Z' \to l^+ l^-$	6.4	6.5
CMS	$Z' \to l^+ l^-$	6.3	6.8

Z' Model	ILC 250 excl.	ILC 250 disc.	ILC 500 excl.	ILC 500 disc.	ILC 1000 excl.	ILC 1000 disc.
SSM	7.7	4.9	13	8.3	22	14

Whitepapers:
CMS-PAS-FTR-21-005
ATL-PHYS-PUB-2018-044
arXiv:1902.11217
arXiv:2203.07272
arXiv:2202.03389

Dijets at pp Colliders	HL-LHC $\sqrt{s}$ = 14 TeV, $\int Ldt$ = 3 ab^{-1}		FNAL-SF $\sqrt{s}$ = 27 TeV, $\int Ldt$ = 3 ab^{-1}		FCC-hh $\sqrt{s}$ = 100 TeV, $\int Ldt$ = 30 ab^{-1}		VLHC $\sqrt{s}$ = 300 TeV, $\int Ldt$ = 100 ab^{-1}		Coll. in the Sea $\sqrt{s}$ = 500 TeV, $\int Ldt$ = 100 ab^{-1}	
	5σ	**95% CL**	**5σ**	**95% CL**	**5σ**	**95% CL**	**5σ**	**95% CL**	**5σ**	**95% CL**
Z' (SSM)	4.2	5.2	7.0	8.9	25	32	67	87	96	130

Machines Ordered by Z' Sensitivity

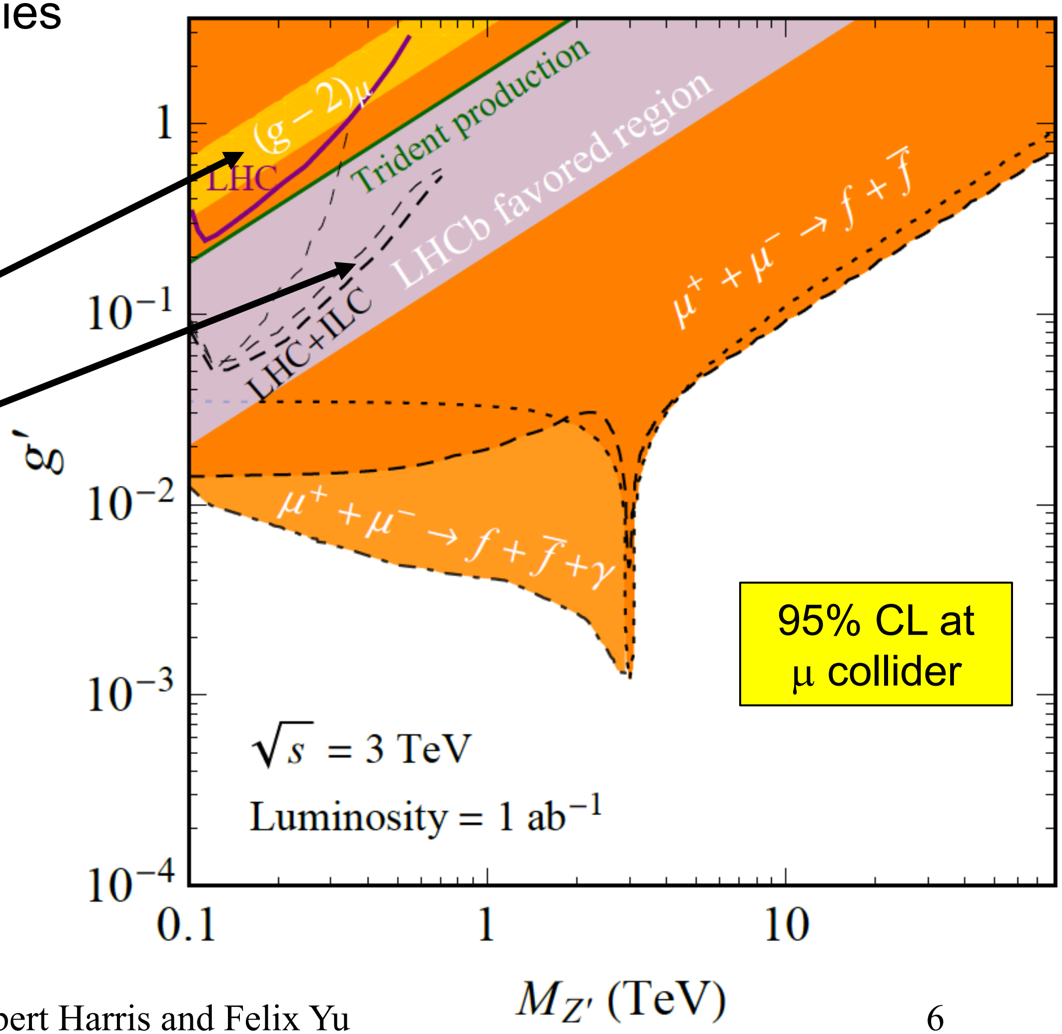
- SSM and Universal Z' provide a ranking of all colliders
  - Similar sensitivity for $g_{Z'} = 0.2$
- Lepton colliders are indirectly sensitive to Z' mass >> √s via difermion angular distributions
  - Would see early evidence of Z'
  - But large SM background
  - 5σ reach < 95% CL
- Hadron colliders directly produce Z' for mass < √s, clear discovery
  - No SM background with dileptons
  - 5σ reach ≈ 95% CL
- A lepton collider followed by a hadron collider is needed for early evidence and clear discovery.

Machine	Type	√s (TeV)	∫L dt (ab^{-1})	Source	Z' Model	5σ (TeV)	95% CL (TeV)
HL-LHC	p p	14	3	R.H.	$Z'_{SSM} \to$ dijet	4.2	5.2
				ATLAS	$Z'_{SSM} \to l^+ l^-$	6.4	6.5
				CMS	$Z'_{SSM} \to l^+ l^-$	6.3	6.8
				EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	6
ILC250/ CLIC380/ FCC-ee	$e^+ e^-$	0.25	2	ILC	$Z'_{SSM} \to f^+ f^-$	4.9	7.7
				EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	7
HE-LHC/ FNAL-SF	p p	27	15	EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	11
				ATLAS	$Z'_{SSM} \to e^+ e^-$	12.8	12.8
ILC	$e^+ e^-$	0.5	4	ILC	$Z'_{SSM} \to f^+ f^-$	8.3	13
				EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	13
CLIC	$e^+ e^-$	1.5	2.5	EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	19
Muon Collider	$\mu^+ \mu^-$	3	1	IMCC	$Z'_{Univ}(g_{Z'}=0.2)$	10	20
ILC	$e^+ e^-$	1	8	ILC	$Z'_{SSM} \to f^+ f^-$	14	22
				EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	21
CLIC	$e^+ e^-$	3	5	EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	24
FCC-hh	p p	100	30	R.H.	$Z'_{SSM} \to$ dijet	25	32
				EPPSU*	$Z'_{Univ}(g_{Z'}=0.2)$	--	35
				EPPSU	$Z'_{SSM} \to l^+ l^-$	43	43
Muon Collider	$\mu^+ \mu^-$	10	10	IMCC	$Z'_{Univ}(g_{Z'}=0.2)$	42	70
VLHC	p p	300	100	R.H.	$Z'_{SSM} \to$ dijet	67	87
Coll. In the Sea	p p	500	100	R.H.	$Z'_{SSM} \to$ dijet	96	130

Increasing Z' Sensitivity

Z' and Lepton Universality Violation

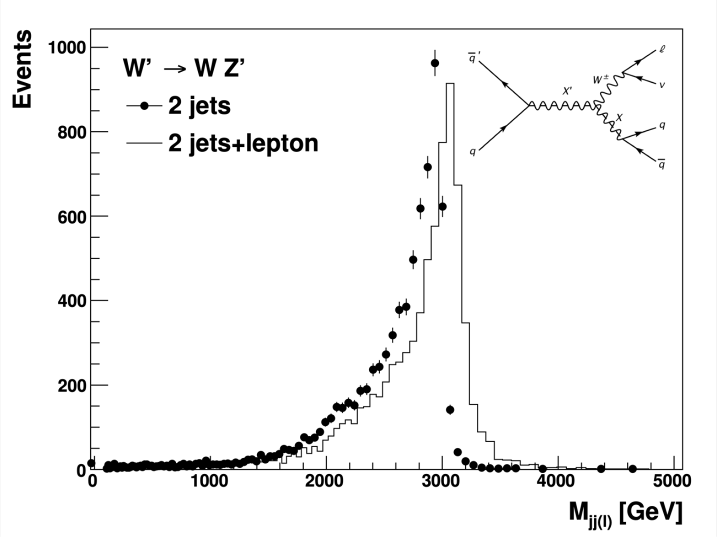
- A scenario where a particular type of machine may be advantageous
  - Motivated by current anomalies
- 3 TeV **μ Collider** can see a Z' from a model of
  - Gauged Lμ – Lτ number
  - Produces the (g- 2)μ anomaly
  - Produces the B-physics anomalies
  - Observation of this Z' could establish new physics as a source of these anomalies
  - Whitepaper: arXiv:2203.07261



W’

- SSM W’ and W’$_R$ (right-handed) are popular models of new charged currents
  - Three pp collider studies for di-fermions, mass reach > Z’, one study of di-bosons

W’ at HL-LHC (14 TeV, 3 ab^{-1})			
Source	Model & Channel	5σ (TeV)	95% CL (TeV)
ATLAS	$W'_R \to tb$	4.3	4.9
R.H.	$W'_{SSM} \to$ dijet	4.8	5.6
CMS	$W'_{SSM} \to \tau\,\nu$	--	7.2
ATLAS	$W'_{SSM} \to \mu\,\nu$	7.1	7.3
	$W'_{SSM} \to e\,\nu$	7.5	7.6
	$W'_{SSM} \to l\,\nu$	7.7	7.9

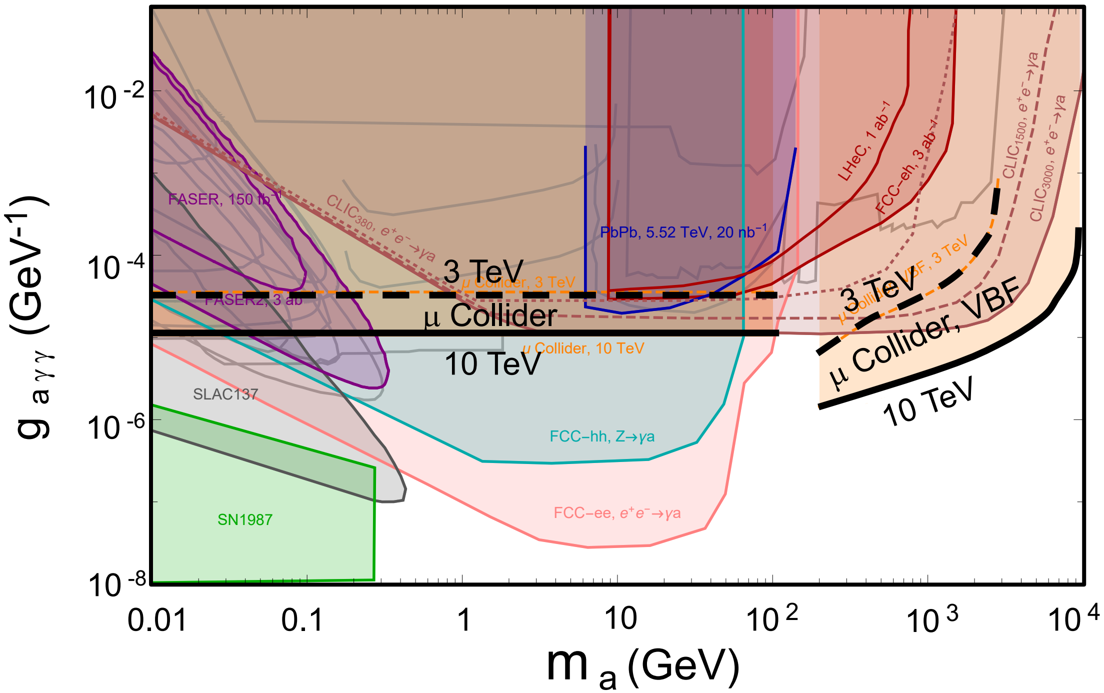


Dijets at pp Colliders	HL-LHC $\sqrt{s}$ = 14 TeV, $\int Ldt$ = 3 ab^{-1}		FNAL-SF $\sqrt{s}$ = 27 TeV, $\int Ldt$ = 3 ab^{-1}		FCC-hh $\sqrt{s}$ = 100 TeV, $\int Ldt$ = 30 ab^{-1}		VLHC $\sqrt{s}$ = 300 TeV, $\int Ldt$ = 100 ab^{-1}		Coll. in the Sea $\sqrt{s}$ = 500 TeV, $\int Ldt$ = 100 ab^{-1}	
	5σ	95% CL	5σ	95% CL	5σ	95% CL	5σ	95% CL	5σ	95% CL
W’ (SSM)	4.8	5.6	8.2	9.9	29	36	79	99	117	150

Whitepapers: ATL-PHYS-PUB-2018-044, CMS-PAS-FTR-18-030, arXiv:2202.03389, arXiv:2103.10217

Axion-Like Particles (ALPs)

- New pseudo-scalars "a" from a broken symmetry, like QCD axion or pion.
  - ALP produced in association or via VBF decays to diphotons with coupling $g_{a\gamma\gamma}$
  - For m_a < 100 GeV, FCC is best, but HL-LHC heavy-ions will explore first.
  - For m_a > 200 GeV, 10 TeV μ Collider is best

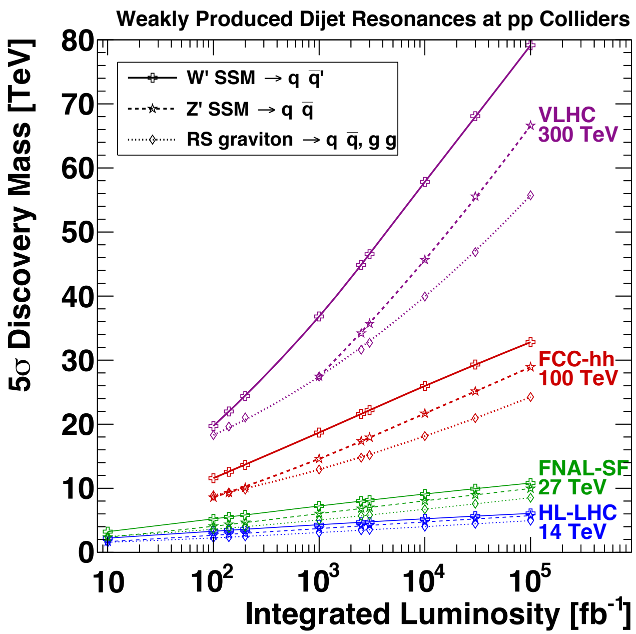


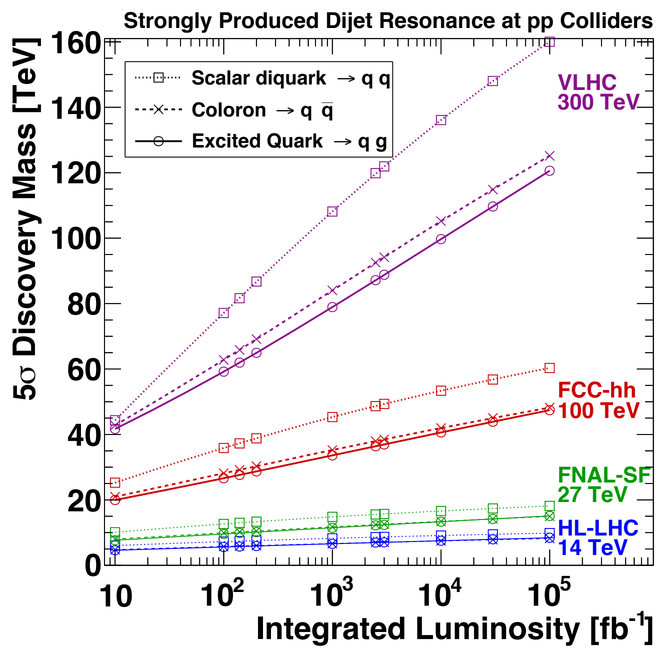
95% CL at all colliders

Whitepapers: FCC arXiv:2203.06520, μCollider: arXiv:2203.07261, arXiv:2203.05484

Dijet Resonances at pp Colliders

- Essential benchmark of discovery capability of pp colliders
- Sensitive to weakly produced models, to make discoveries from prior hints
  - An earlier lepton-collider could see first signs of a W', Z' or RS graviton
- Sensitive to strongly produced physics not accessible at lepton colliders
  - pp is only way to observe models like diquarks, colorons or excited quarks at high mass





Sensitivity:
$\propto \sqrt{s}$
$\propto \log \int \mathcal{L}\, dt$

Whitepapers:
All arXiv:2202.03389
FCC arXiv:2203.06520
DM arXiv:2206.03456

Dijet Resonance Sensitivity

- Direct discovery capability for a wide range of masses and models
  - Very roughly √s/2 for strongly and √s/4 for weakly produced dijet resonances

Snowmass 2021 R. M. Harris **Model**	**HL-LHC** √s = 14 TeV, ∫Ldt = 3 ab^{-1} **5σ** [TeV]	**95% CL** [TeV]	**FNAL-SF** √s = 27 TeV, ∫Ldt = 3 ab^{-1} **5σ** [TeV]	**95% CL** [TeV]	**FCC-hh** √s = 100 TeV, ∫Ldt = 30 ab^{-1} **5σ** [TeV]	**95% CL** [TeV]	**VLHC** √s = 300 TeV, ∫Ldt = 100 ab^{-1} **5σ** [TeV]	**95% CL** [TeV]	**Collider in the Sea** √s = 500 TeV, ∫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

Whitepapers: ALL arXiv:2202.03389, FCC arXiv:2203.06520, DM arXiv:2206.03456

Conclusions

- Snowmass 2021 has explored new bosons and heavy resonances
  - Multiple models and channels at many future colliders
- **Z' bosons** are our standard candle for BSM sensitivity at all colliders
  - Early indirect evidence for Z' at a lepton collider should be followed by clear direct discovery in the difermion channels at a hadron collider
  - μ collider has good mass reach and sensitivity to lepton universality violation
- Other models and channels also favor a future with multiple colliders
  - **W' bosons**: large mass reach at HL-LHC and higher energy pp colliders
  - **Axion-like particles**: μ collider most sensitive at high mass, FCC at low mass
  - **Dijet resonances**: pp colliders can discover physics that lepton colliders cannot
- New bosons and heavy resonances favors high energy multi-collider future
  - A hadron collider following a lepton collider, favoring μ collider due to its energy