

CERN + BSM



Carleton
University

Department of Physics

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TRISEP 2024

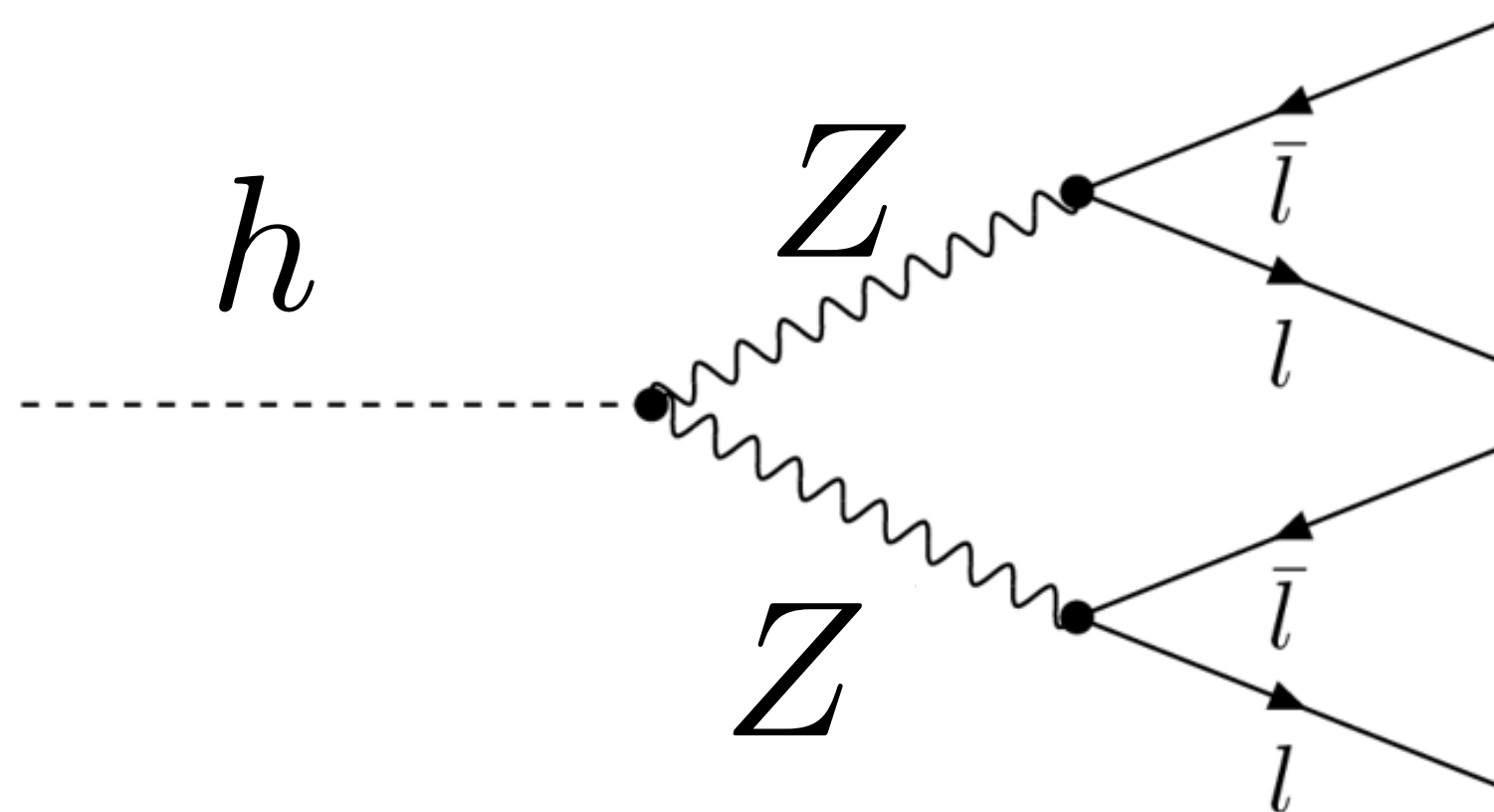
July 16-18, 2024

THE HIGGS

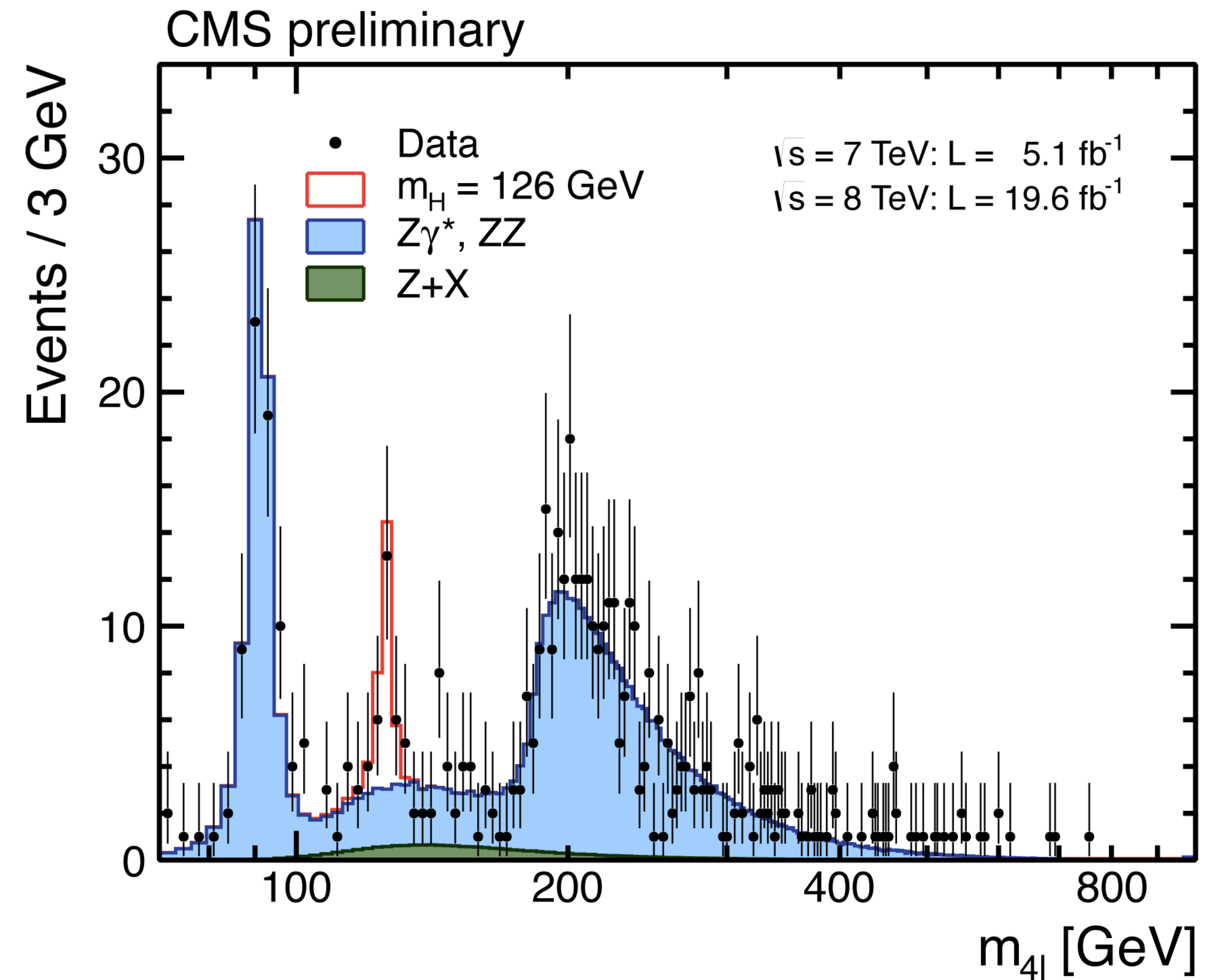


SPIN MEASUREMENT

Golden channel decay to 4 leptons.

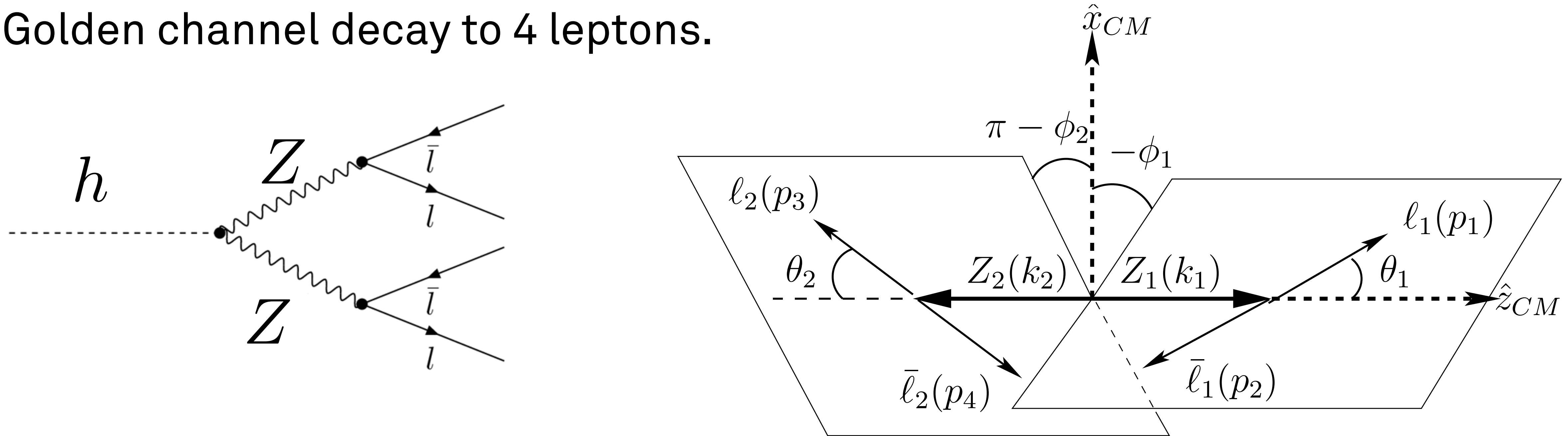


- Very low background
- Fully reconstructable final state



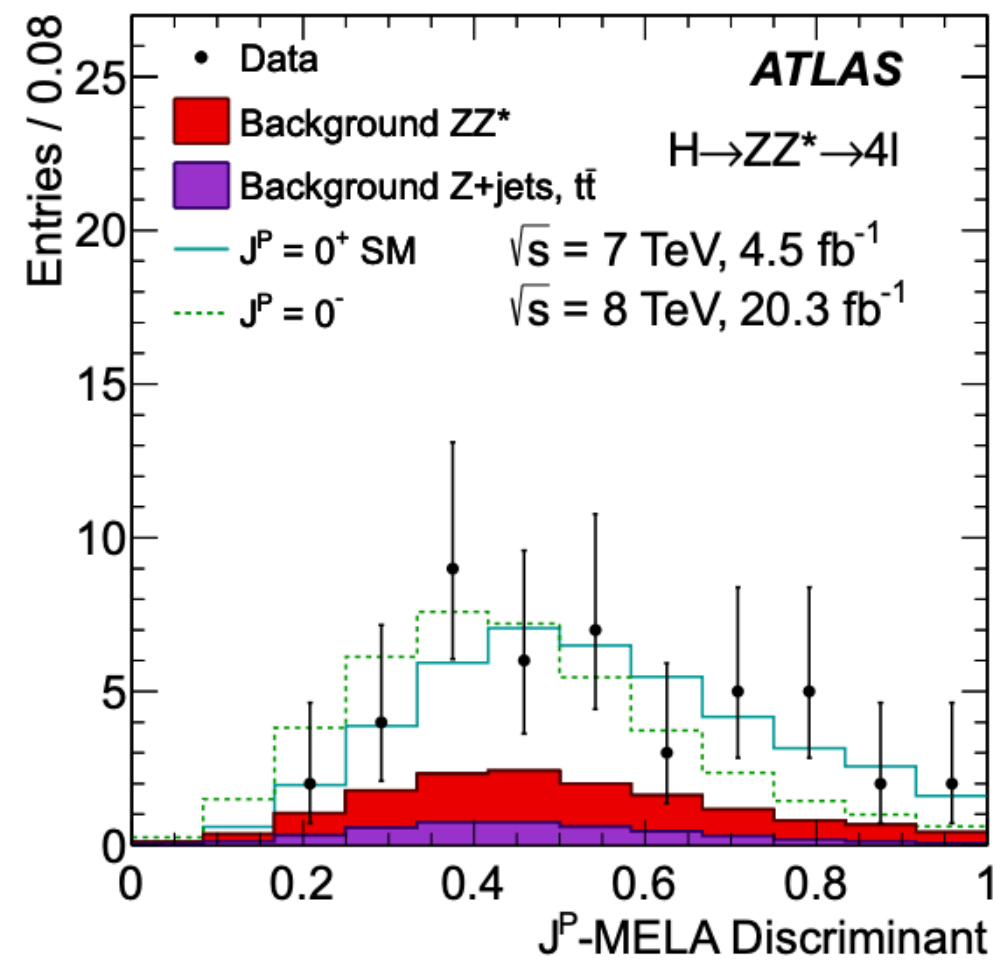
SPIN AND PARITY MEASUREMENT

Golden channel decay to 4 leptons.

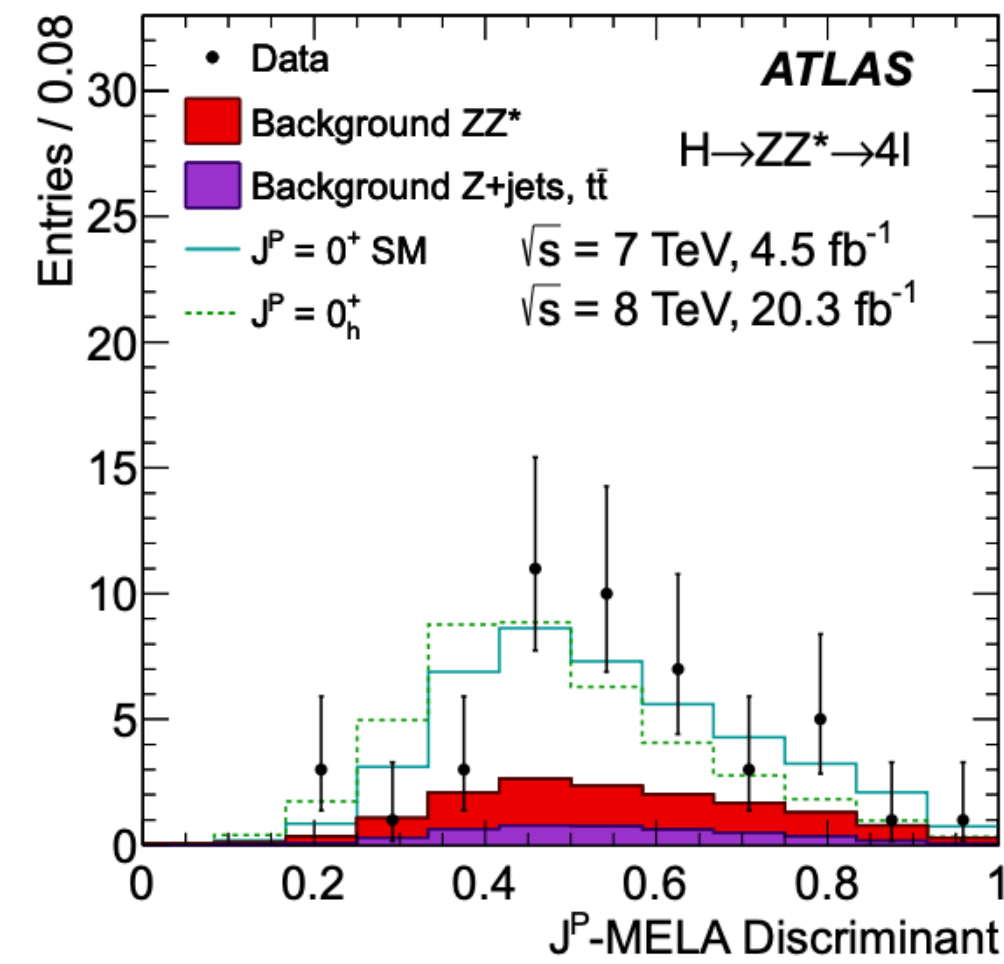


Each event described by 5 variables in Higgs rest frame.

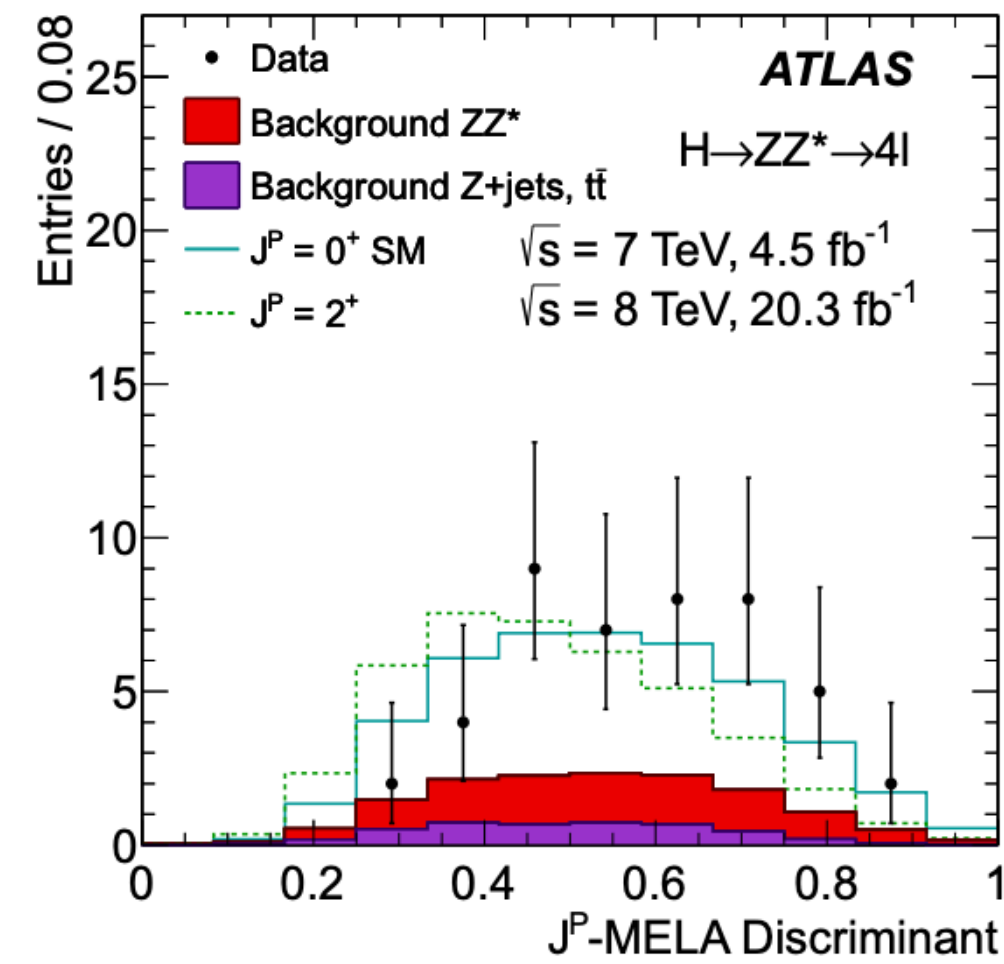
SPIN AND PARITY MEASUREMENT



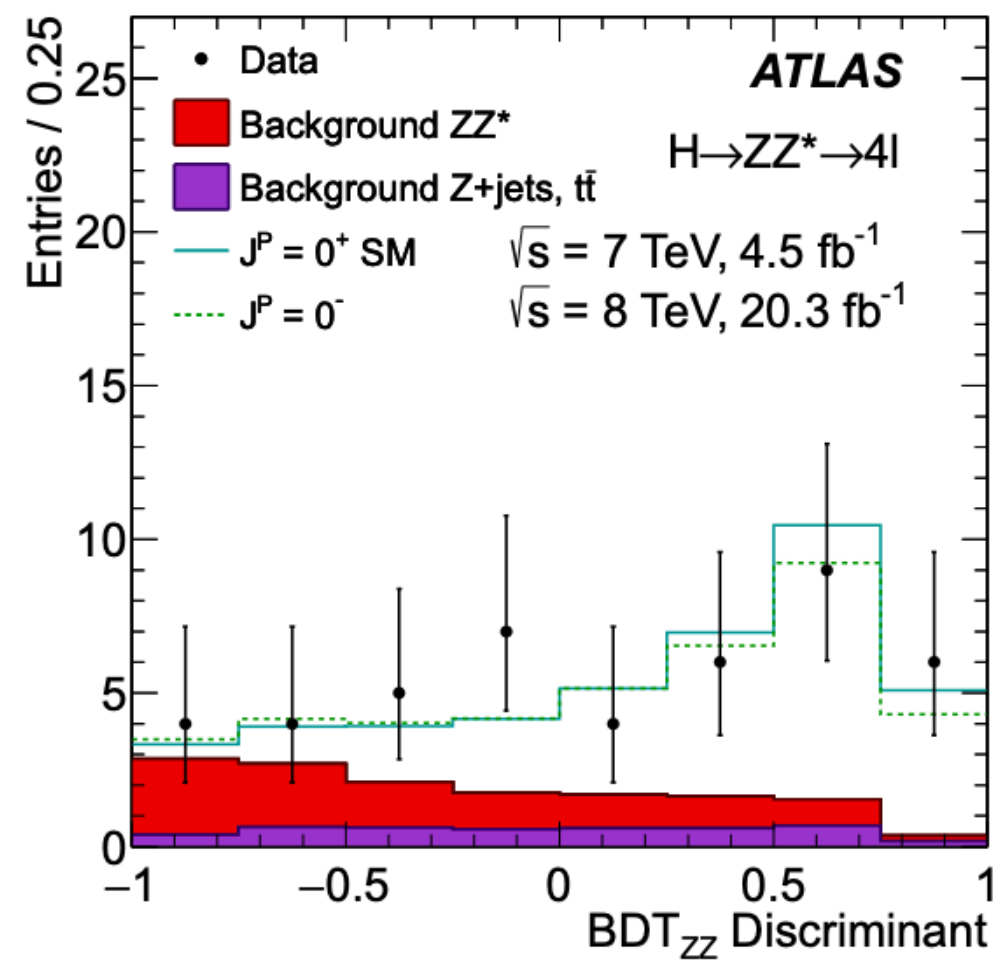
(a)



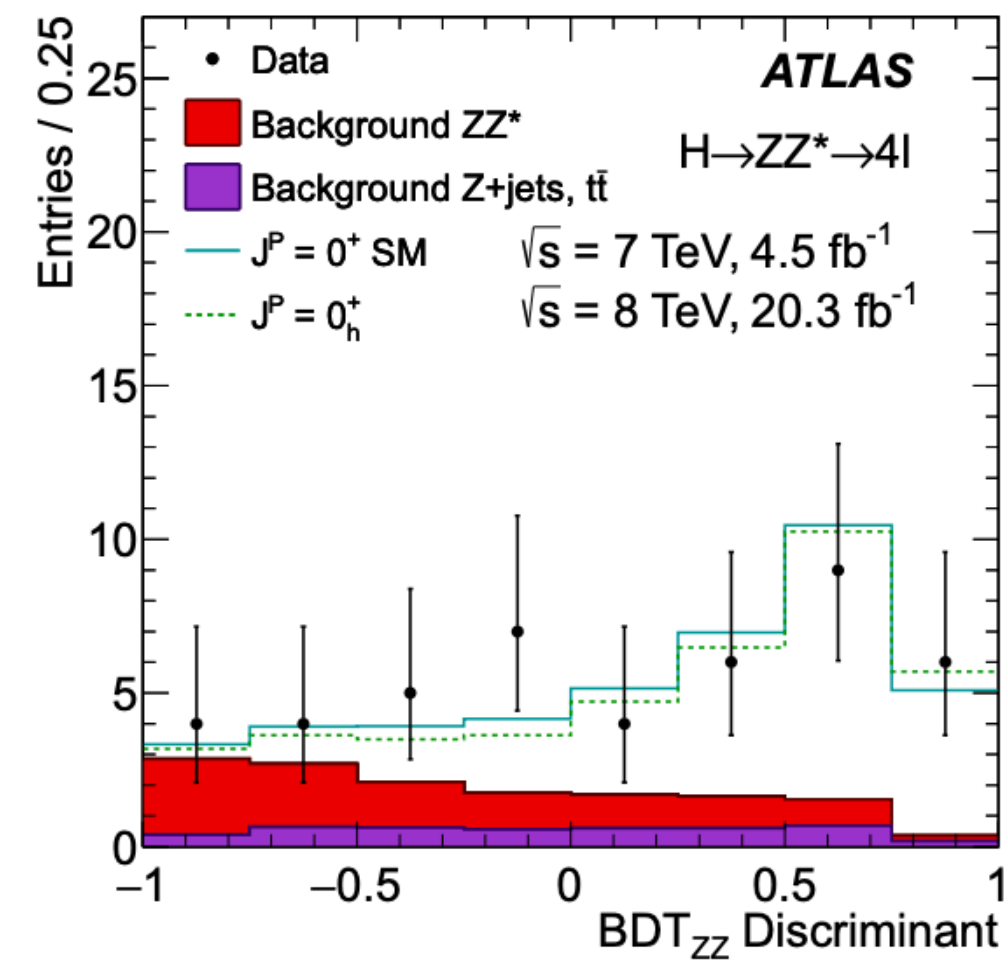
(b)



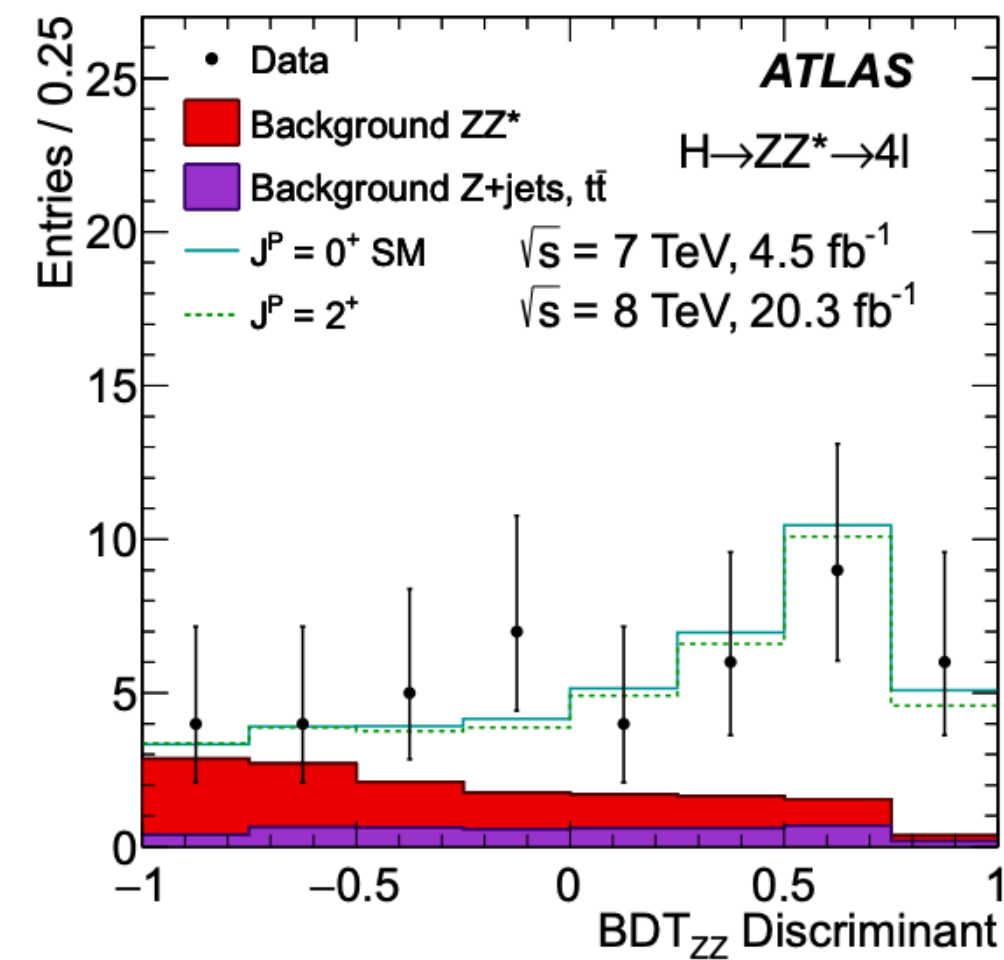
(c)



(d)



(e)



(f)

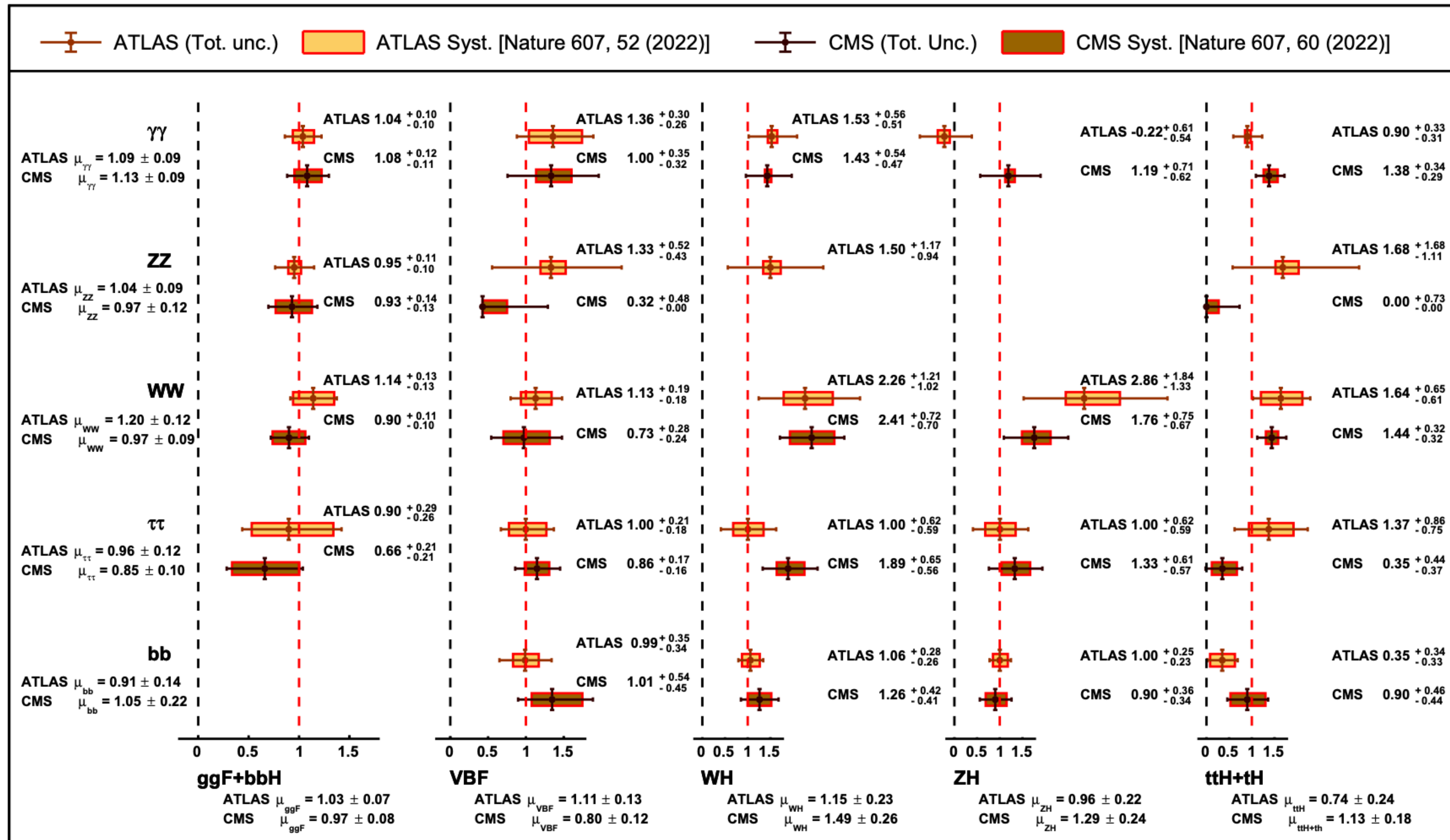
$$J^P = 0^+$$

is consistent with all data.

Agrees with SM prediction.

ATLAS, arXiv:1506.05669.

HIGGS RATE MEASUREMENTS

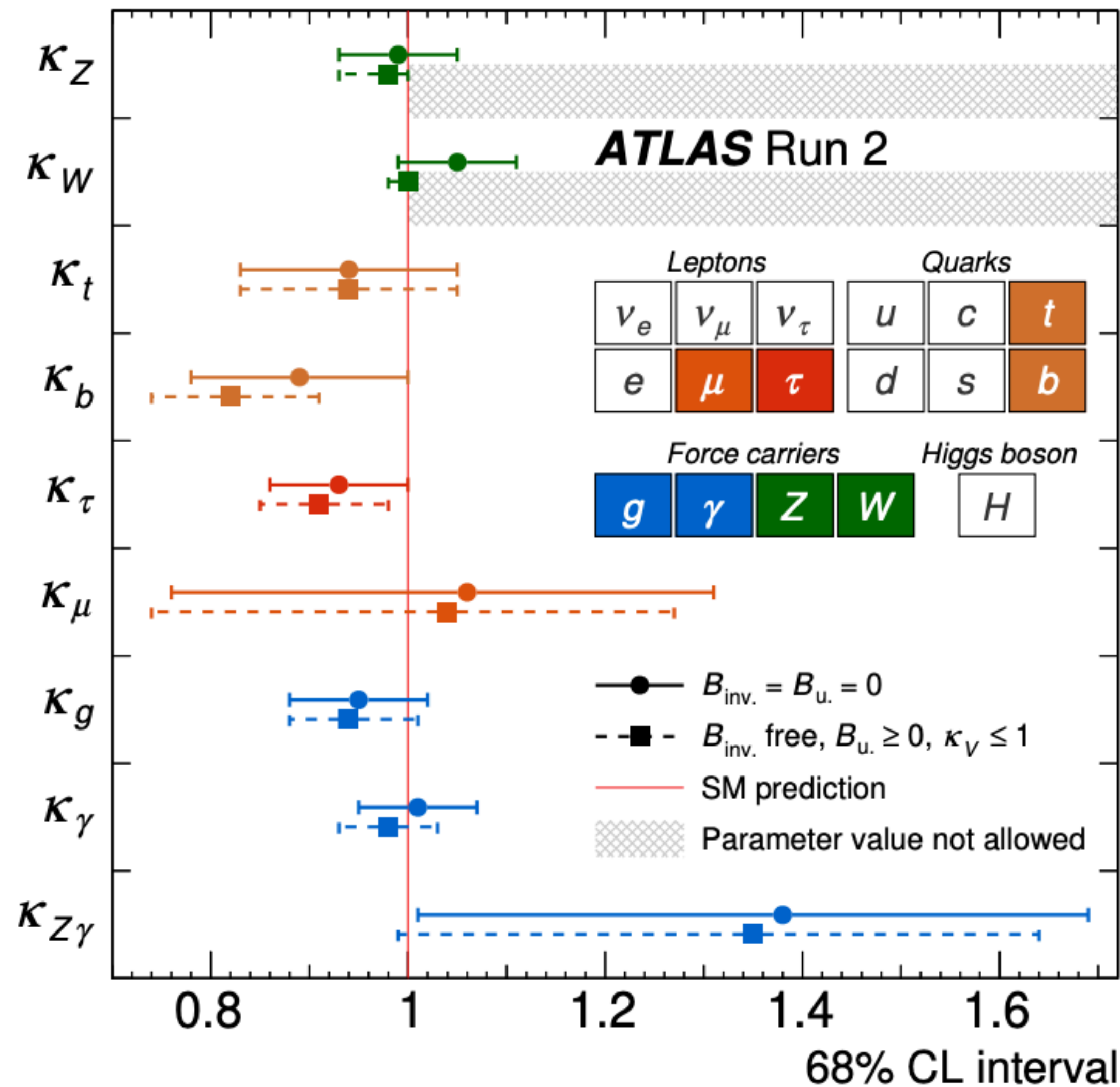


HIGGS COUPLING MEASUREMENTS

Convert rate measurement to coupling measurement.

Again normalize to SM ($\kappa_{SM} = 1$).

Precision ranges from 10 to 30%.



PDG

HIGGS COUPLING MEASUREMENTS

Convert rate measurement to coupling measurement.

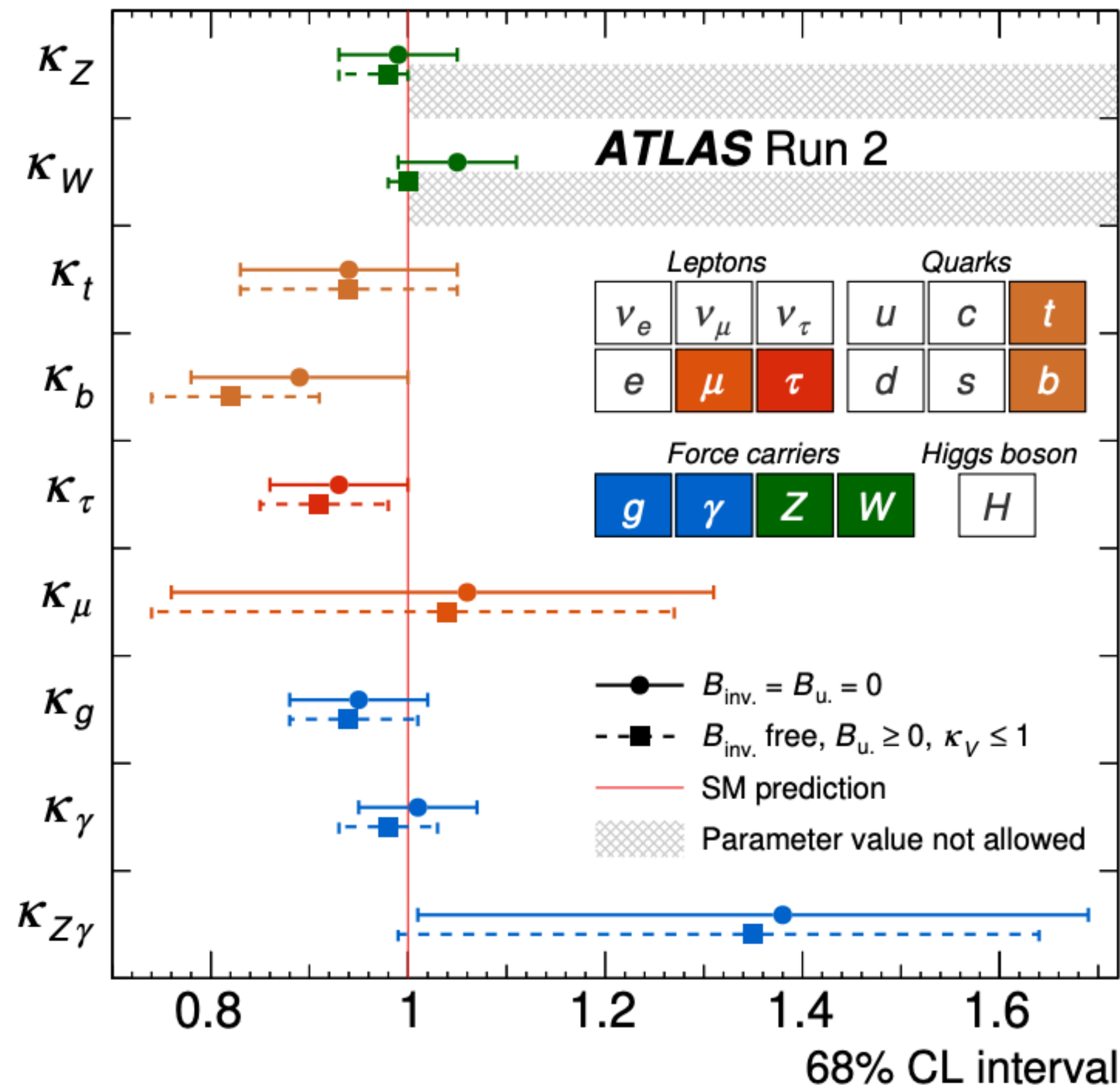
Again normalize to SM ($\kappa_{SM} = 1$).

Precision ranges from 10 to 30%.

Except Higgs self-coupling

(ATLAS) $-0.6 < \kappa_\lambda < 6.6$ (observed)

(CMS) $-1.2 < \kappa_\lambda < 6.5$ (observed),

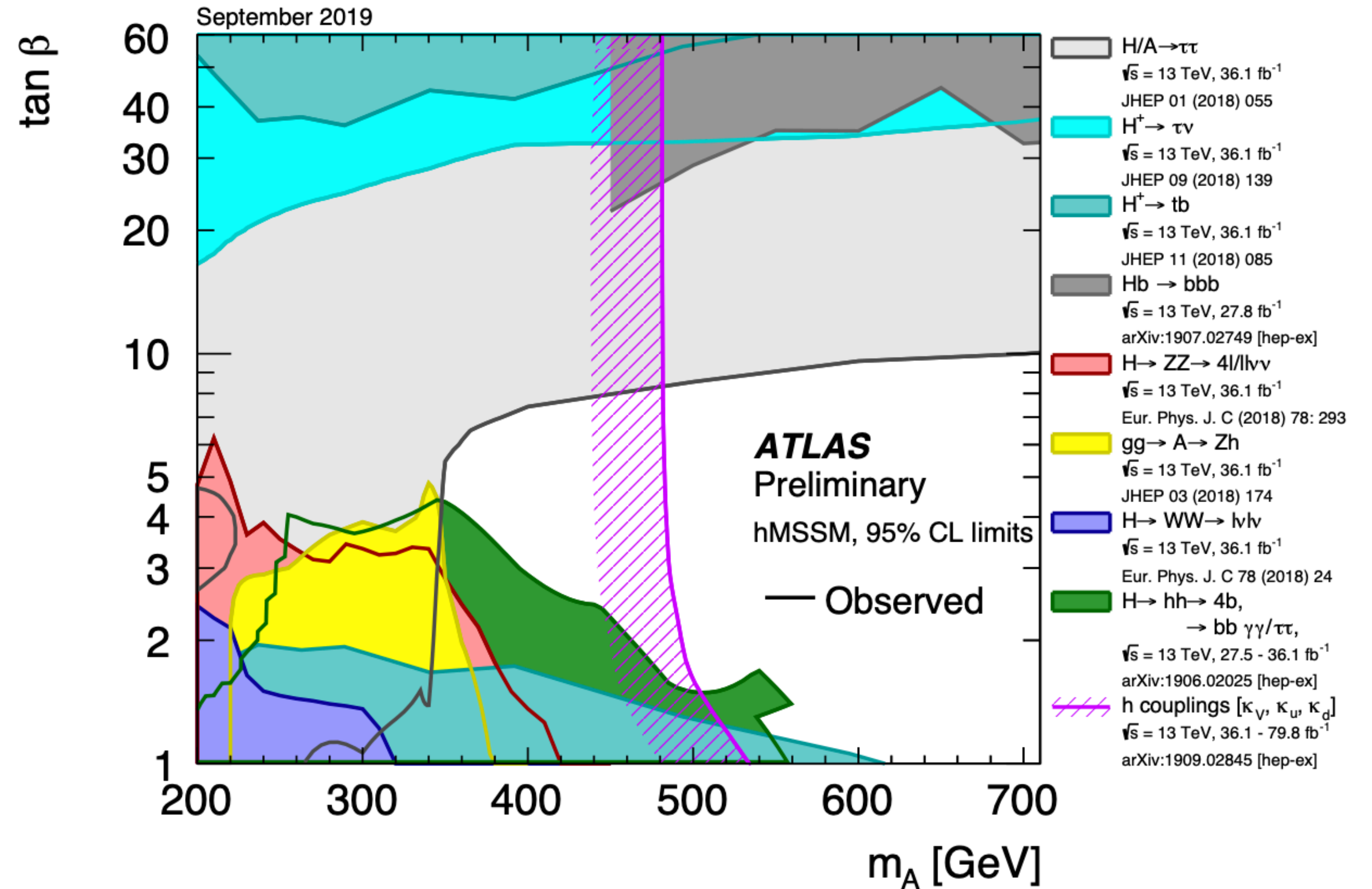


OTHER HIGGSES

SM has one Higgs because it is minimal.

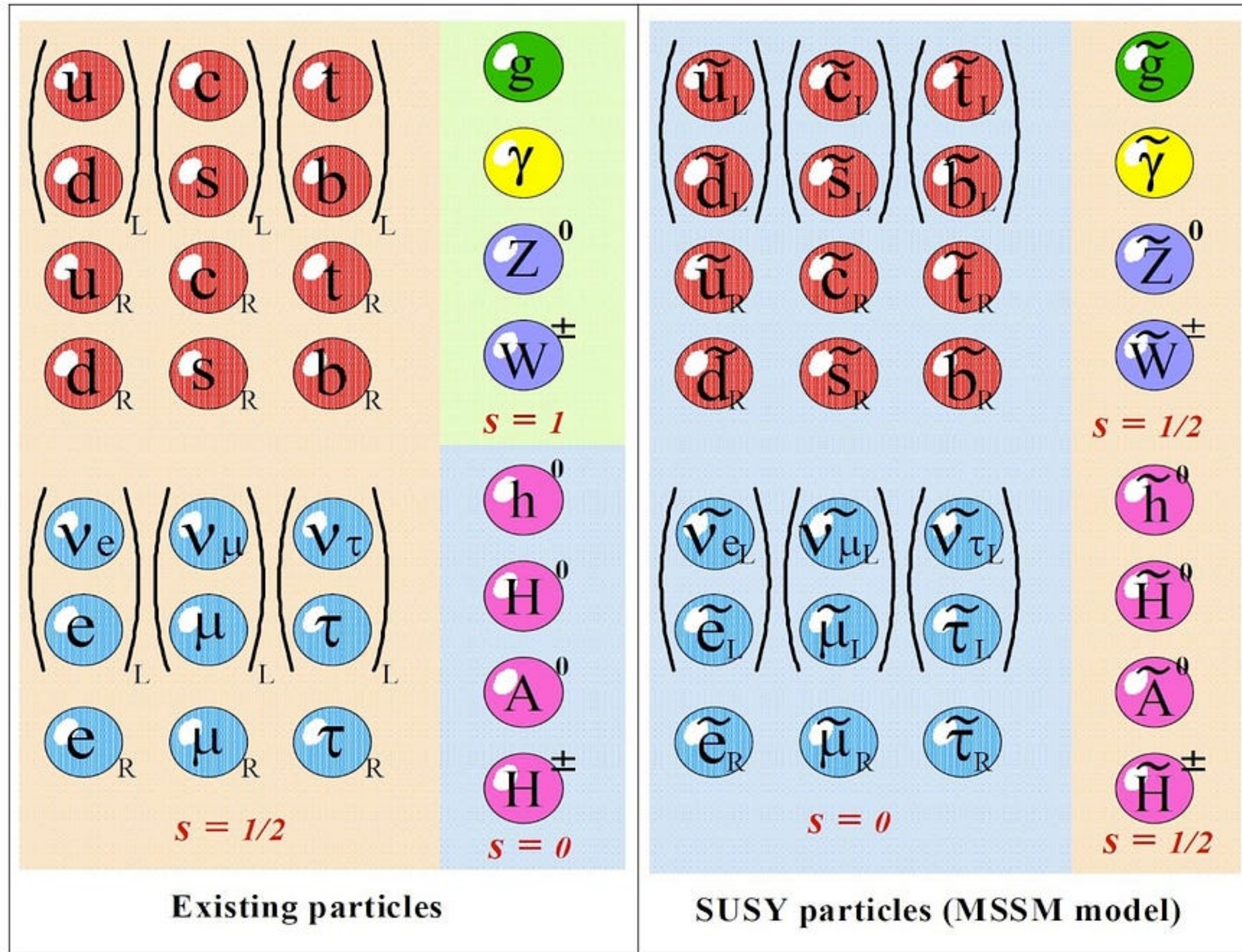
Can have additional Higgs states.

New Higgses can be charged (and doubly charged!).



SUPERSYMMETRY

MSSM

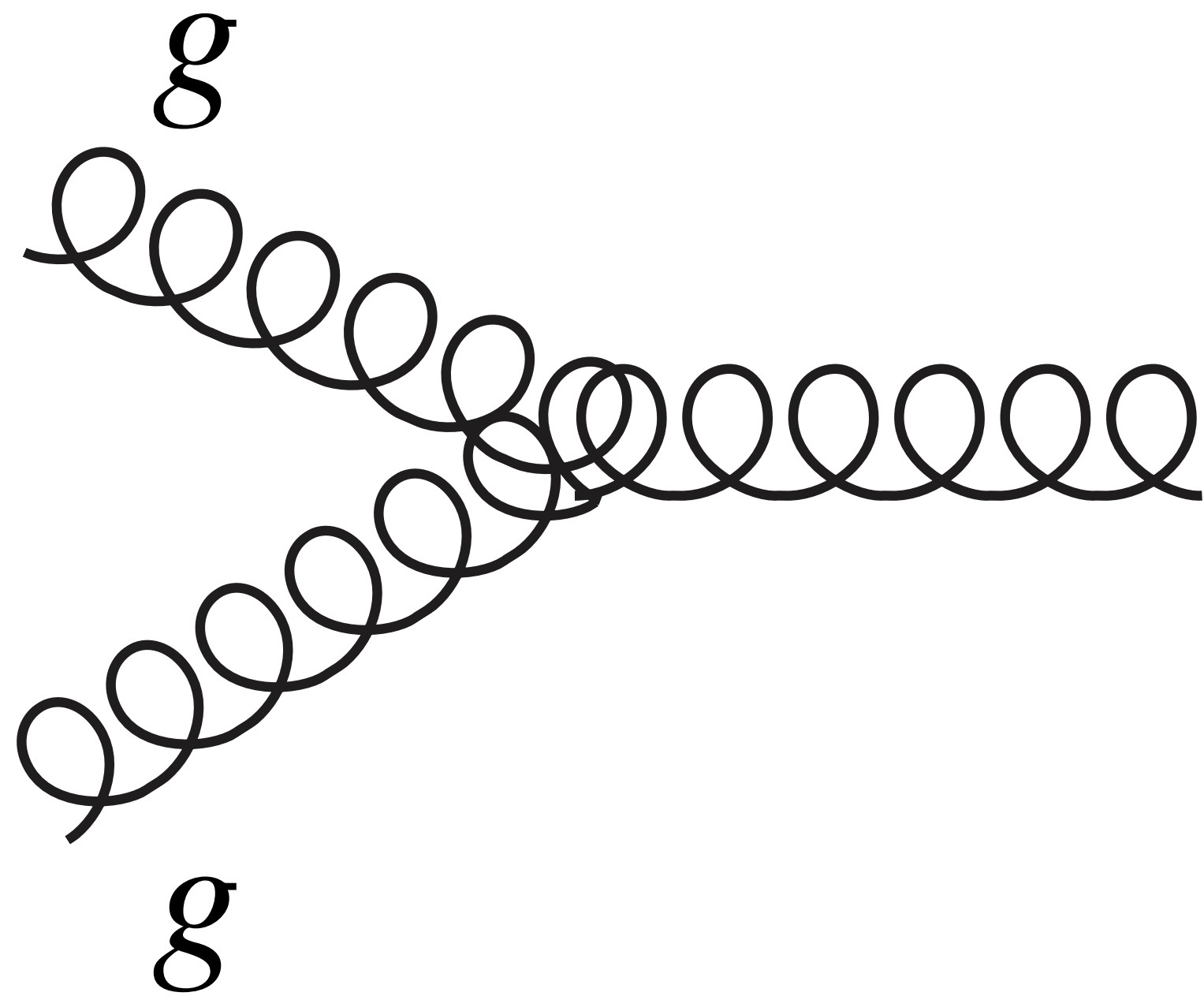


MSSM SIMPLIFICATIONS

Large number of parameters. Simplifying assumptions:

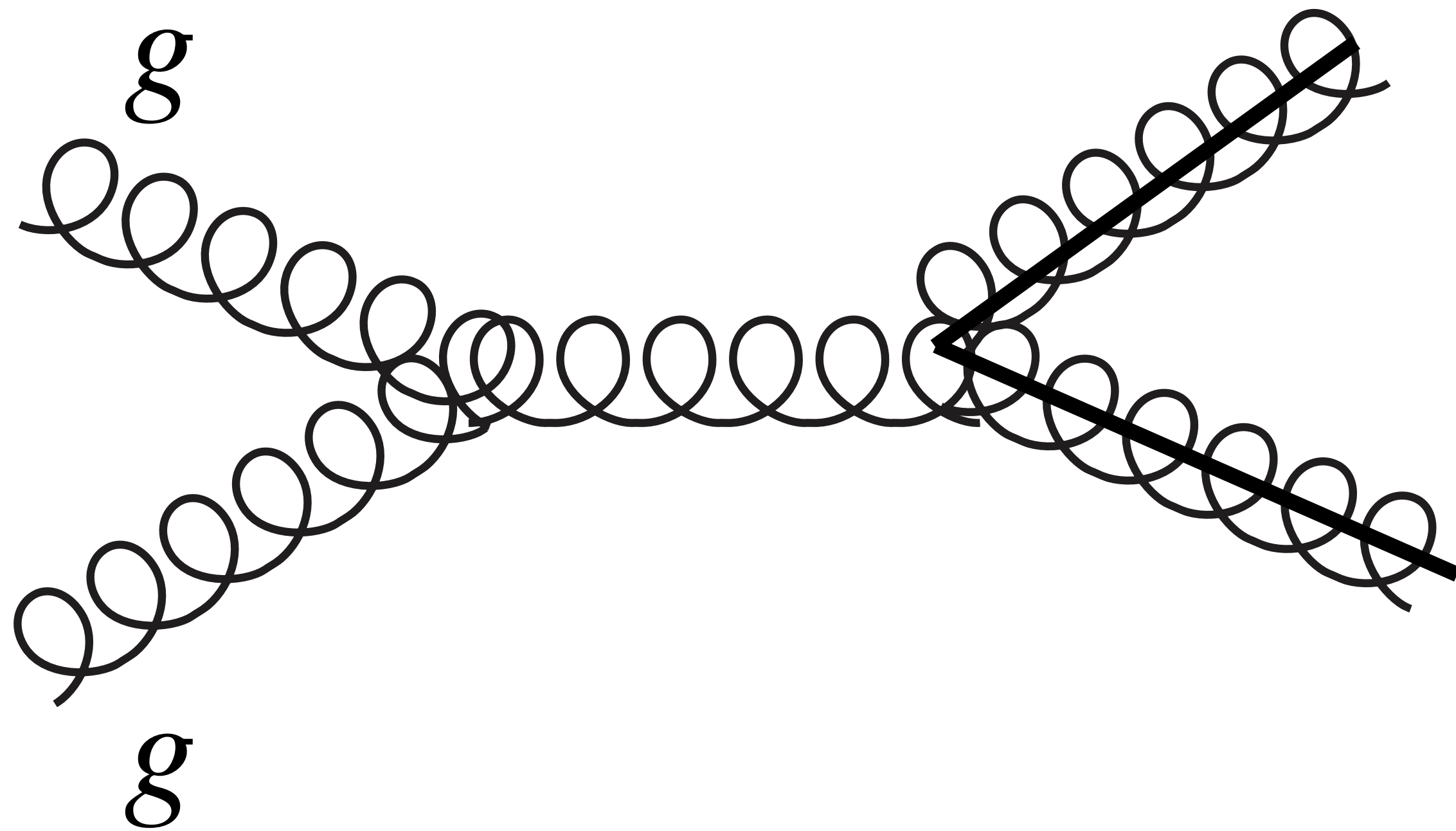
- R-parity conservation (save the proton)
- Neutralino LSP (WIMP miracle)

SEARCH FOR MSSM



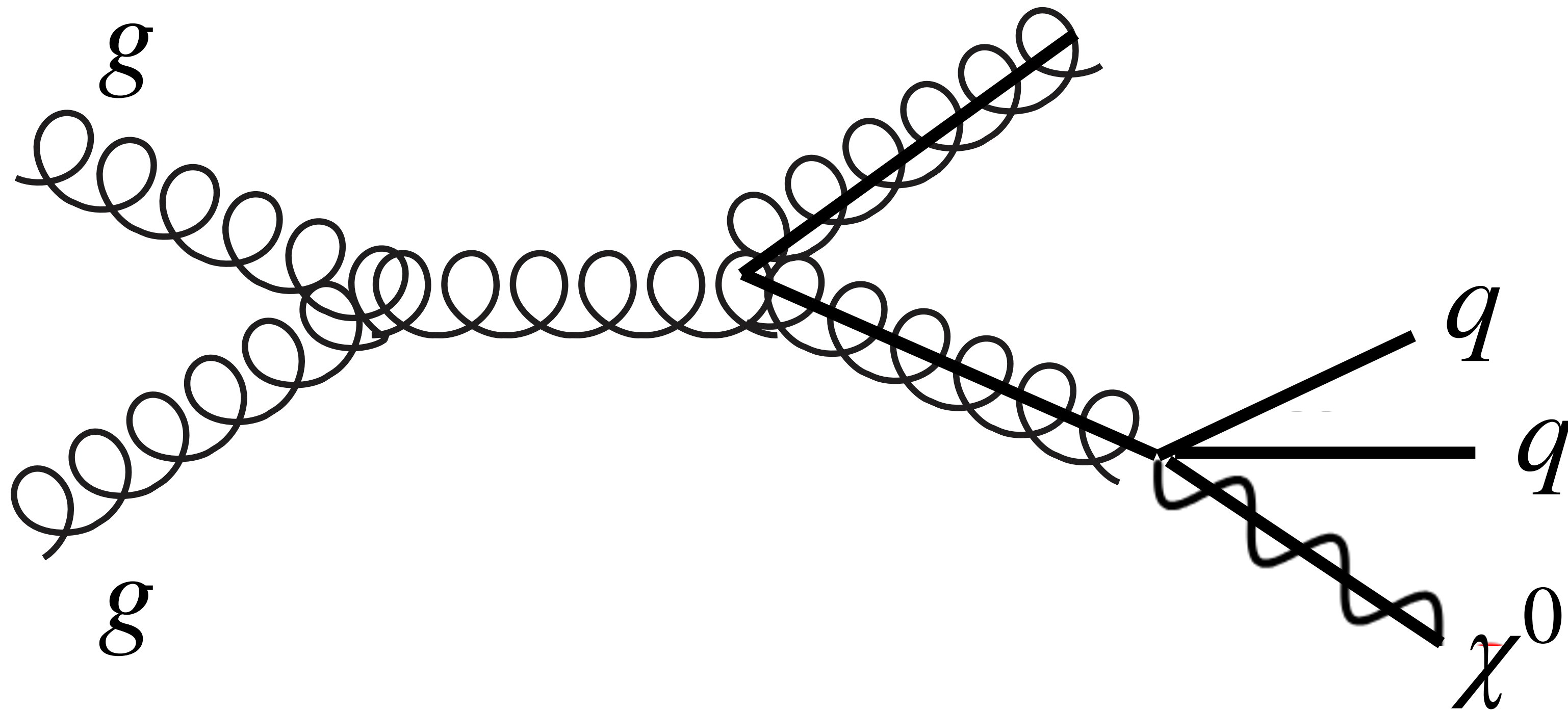
SEARCH FOR MSSM

Gluino pair
production



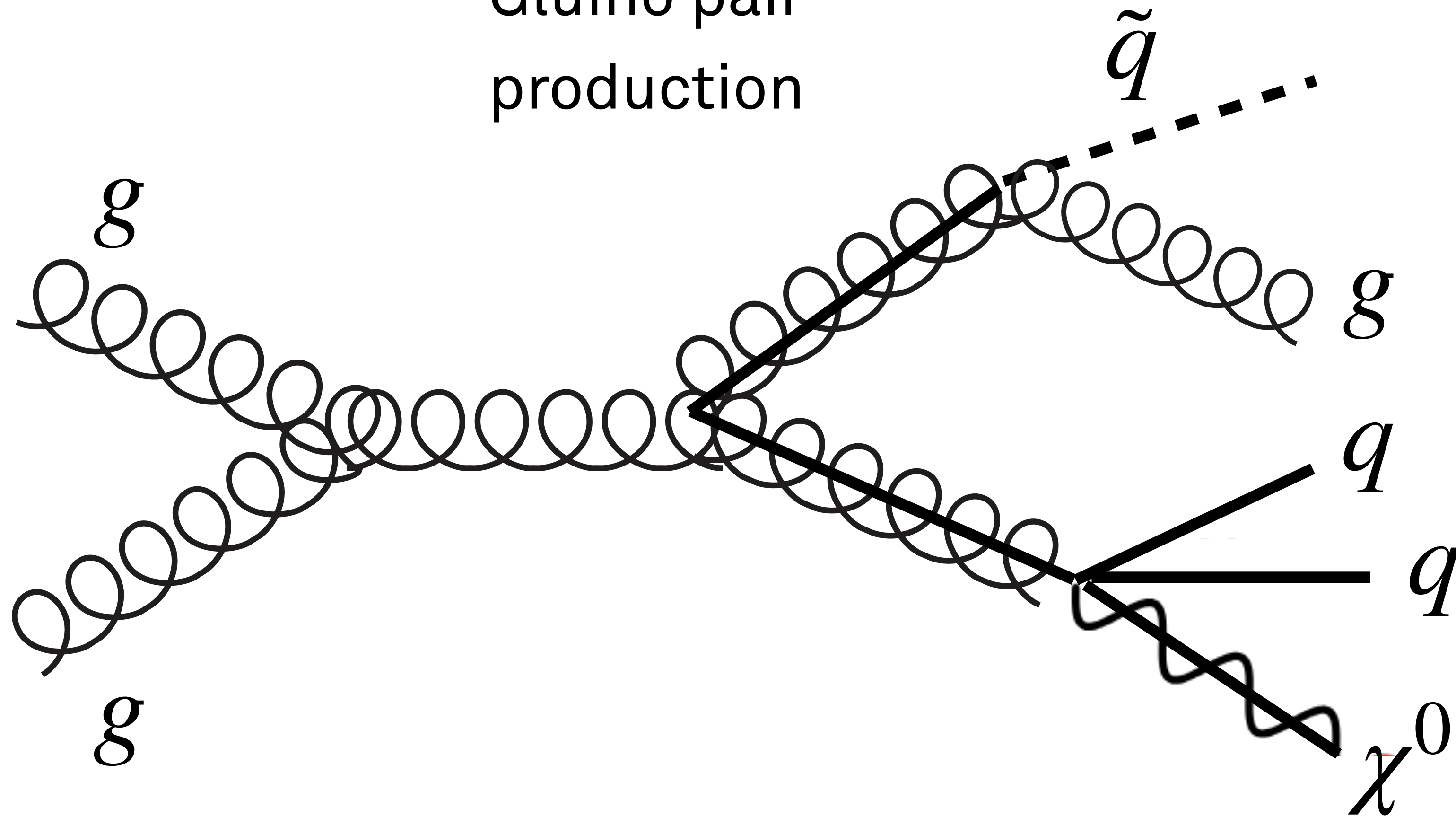
SEARCH FOR MSSM

Gluino pair
production

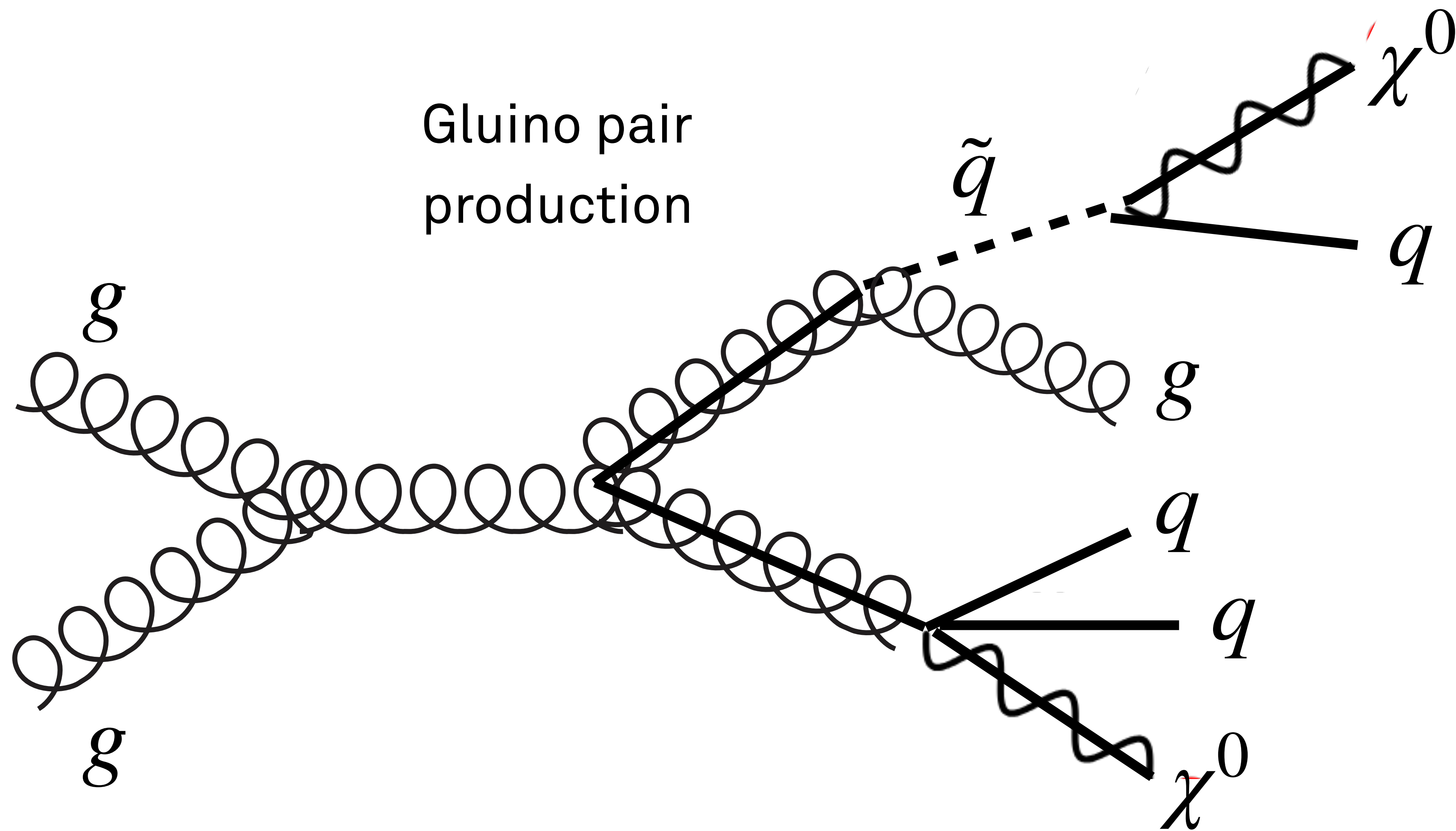


SEARCH FOR MSSM

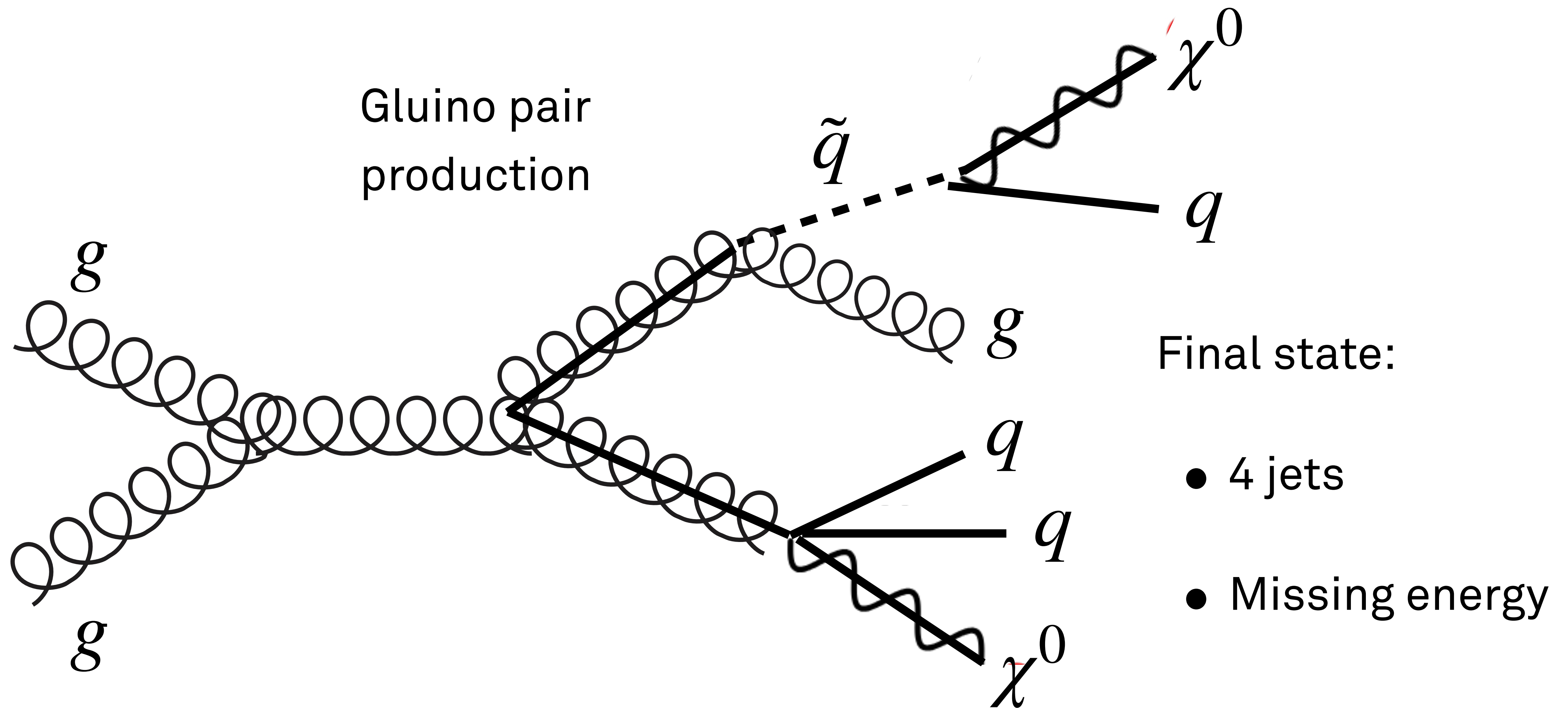
Gluino pair
production



SEARCH FOR MSSM



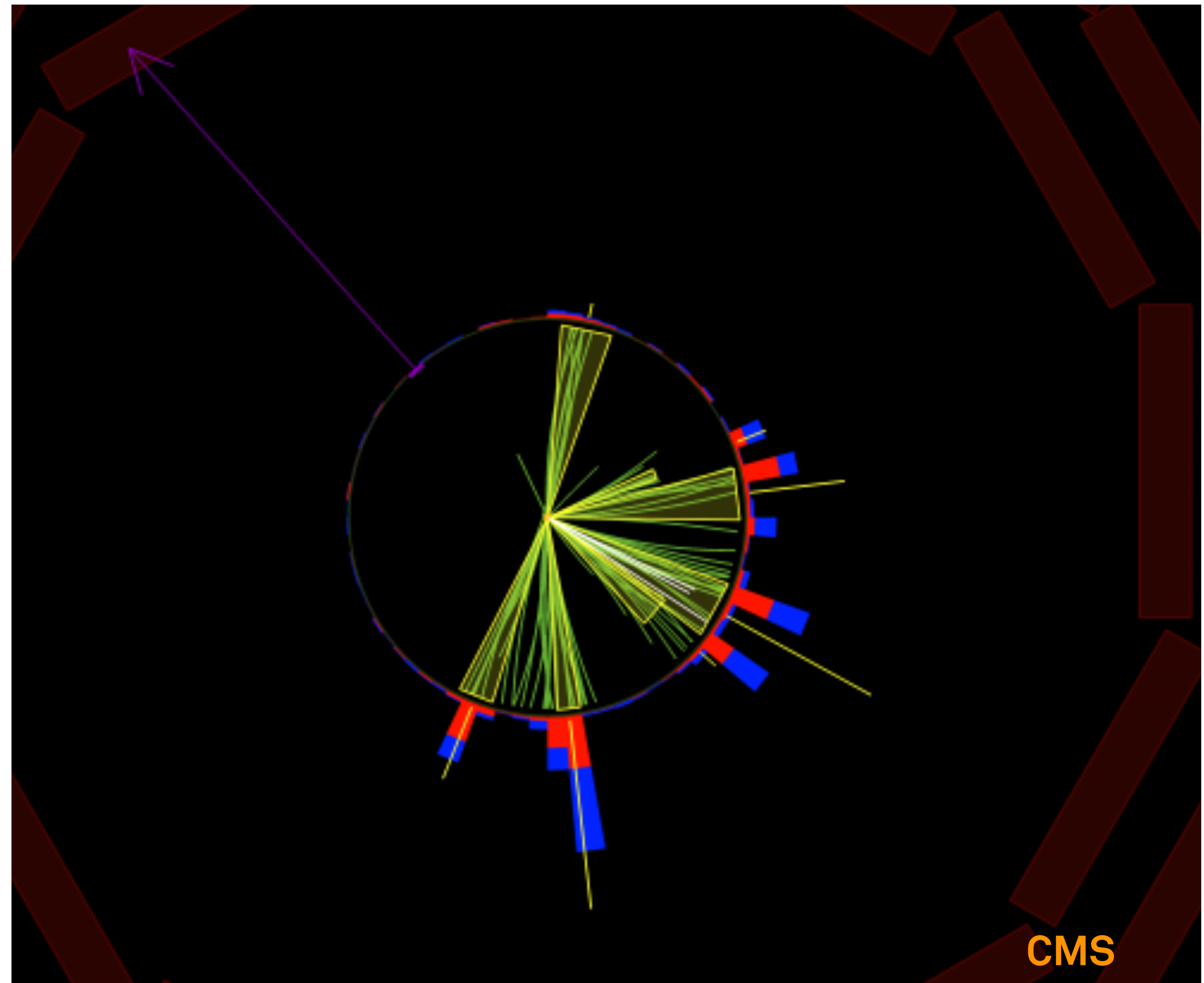
SEARCH FOR MSSM



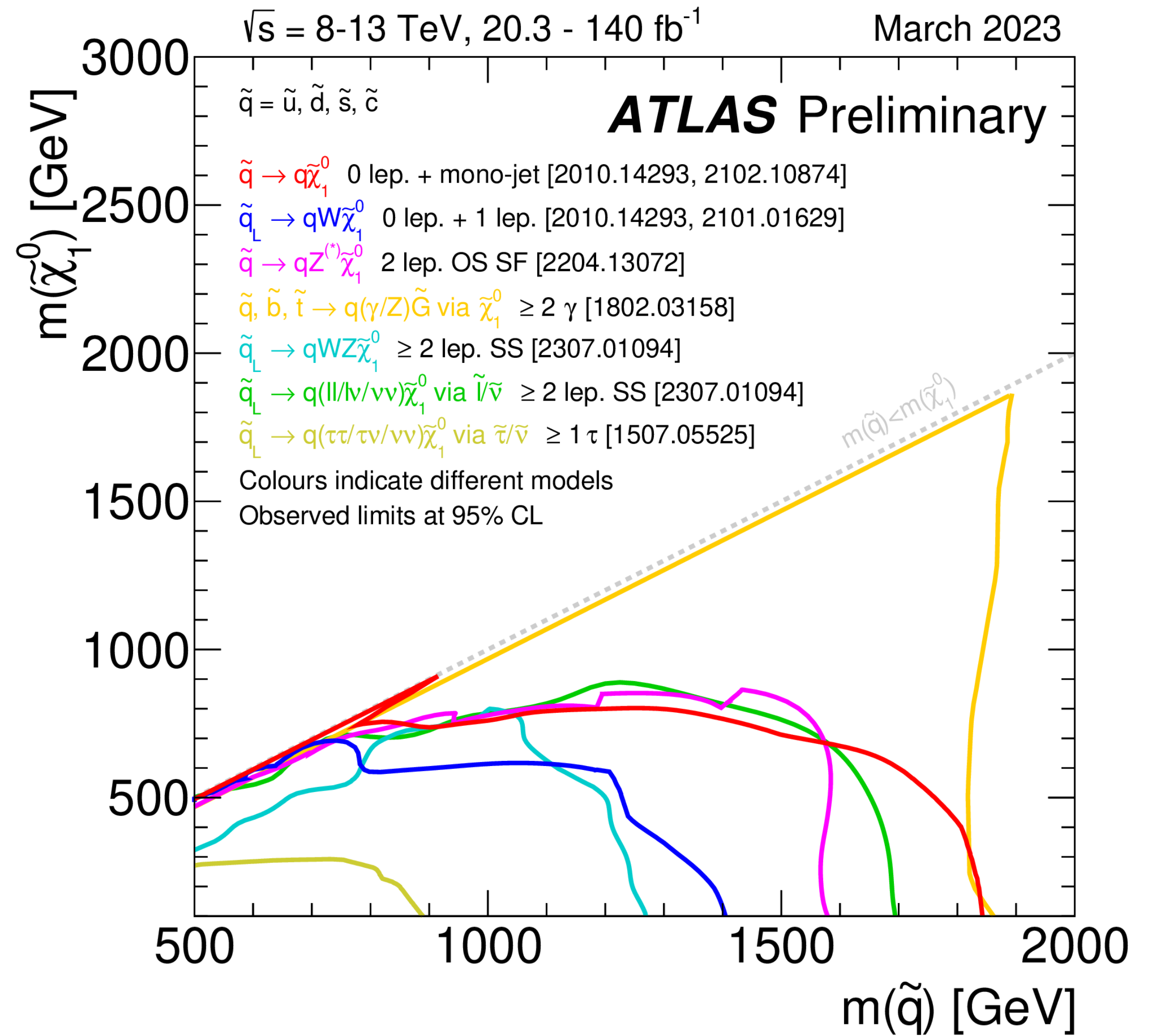
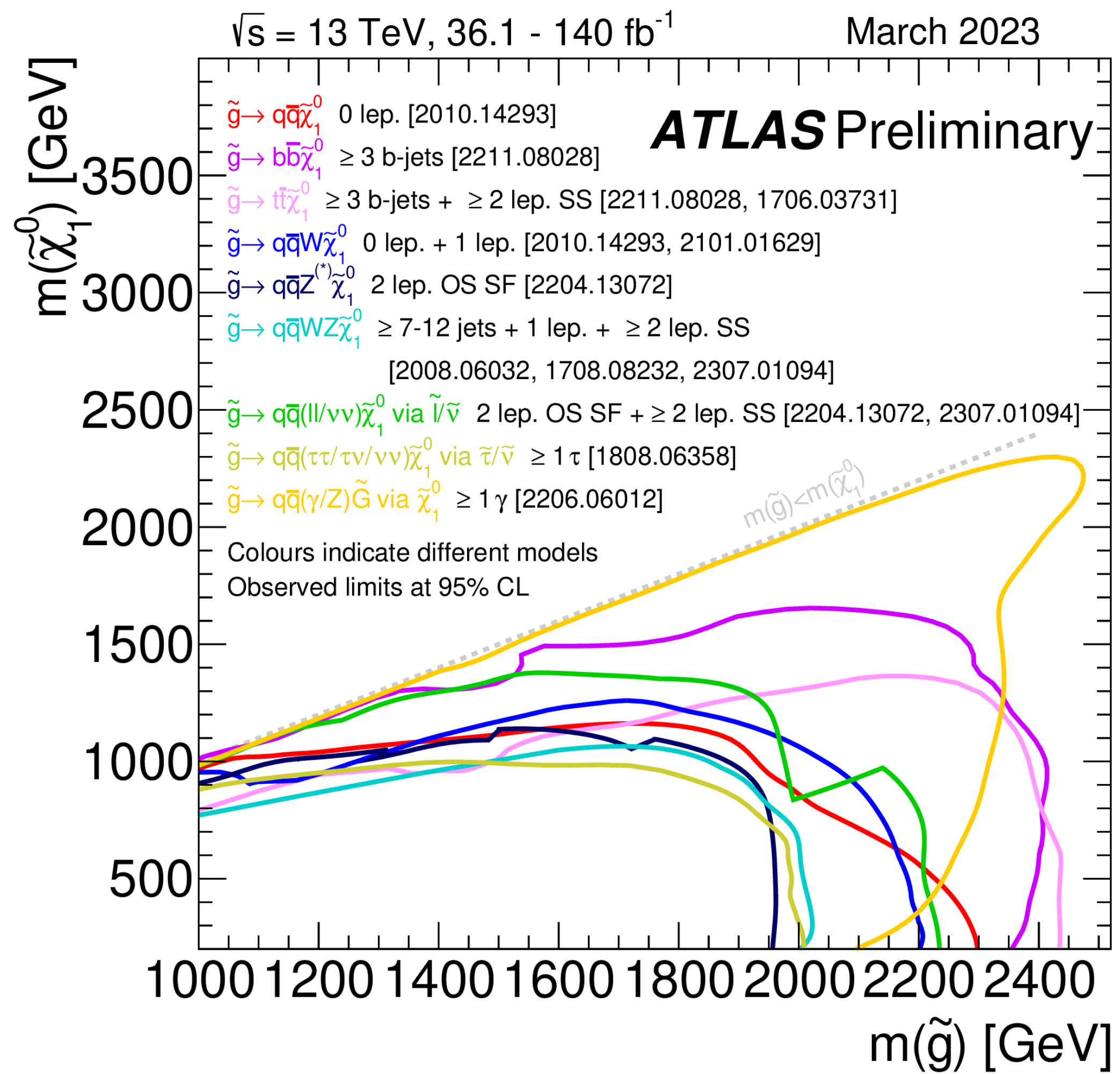
MISSING ENERGY

How do we detect something invisible?

Conservation of (transverse) momentum.



LIMITS

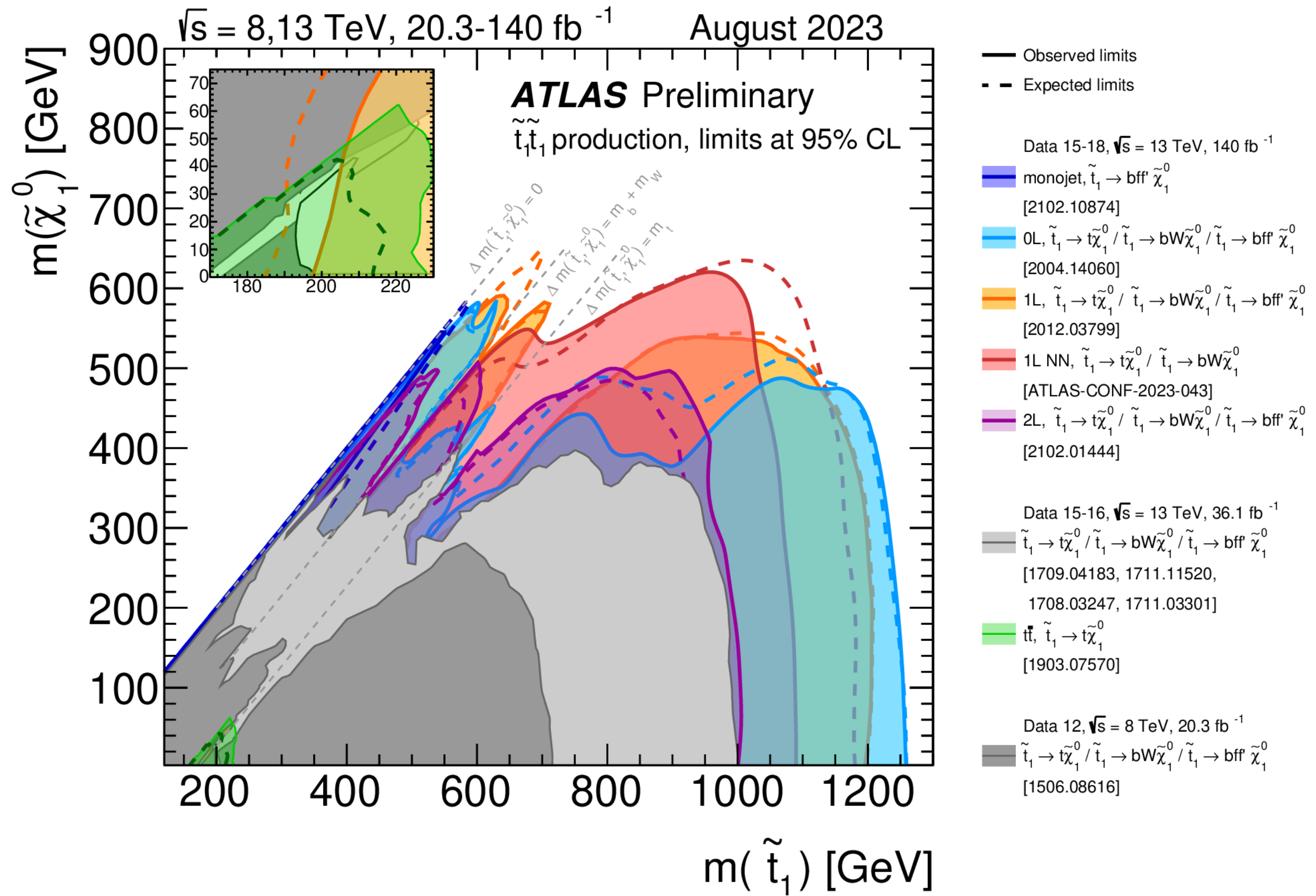


NATURAL SUSY

To solve hierarchy problem, mainly need top partner (stop) to be light.

Keep light WIMP for dark matter.

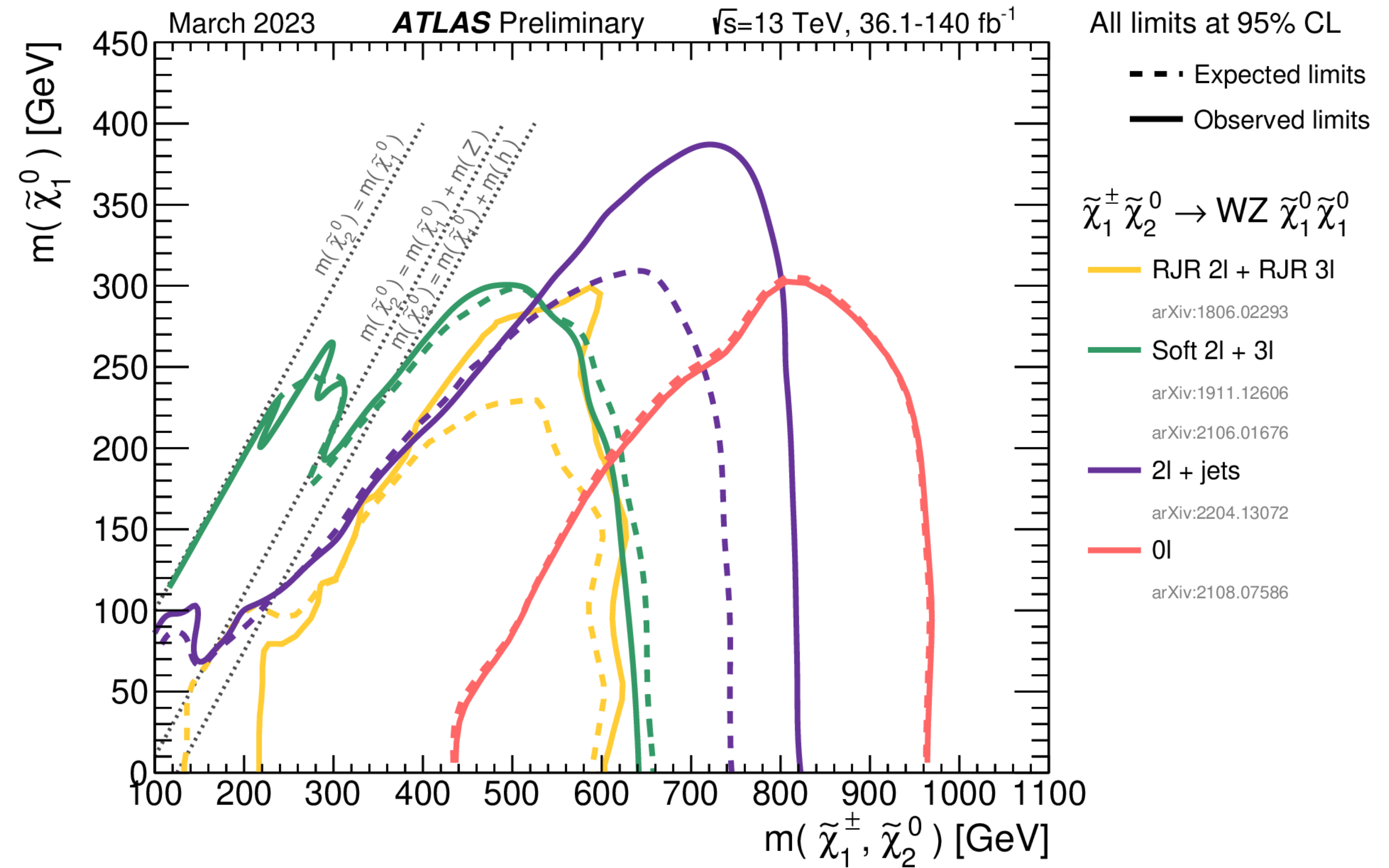
Final state is 2 tops + missing energy.



ELECTROWEAK SUSY

Forget naturalness, just dark matter.

Look for leptons and missing energy.



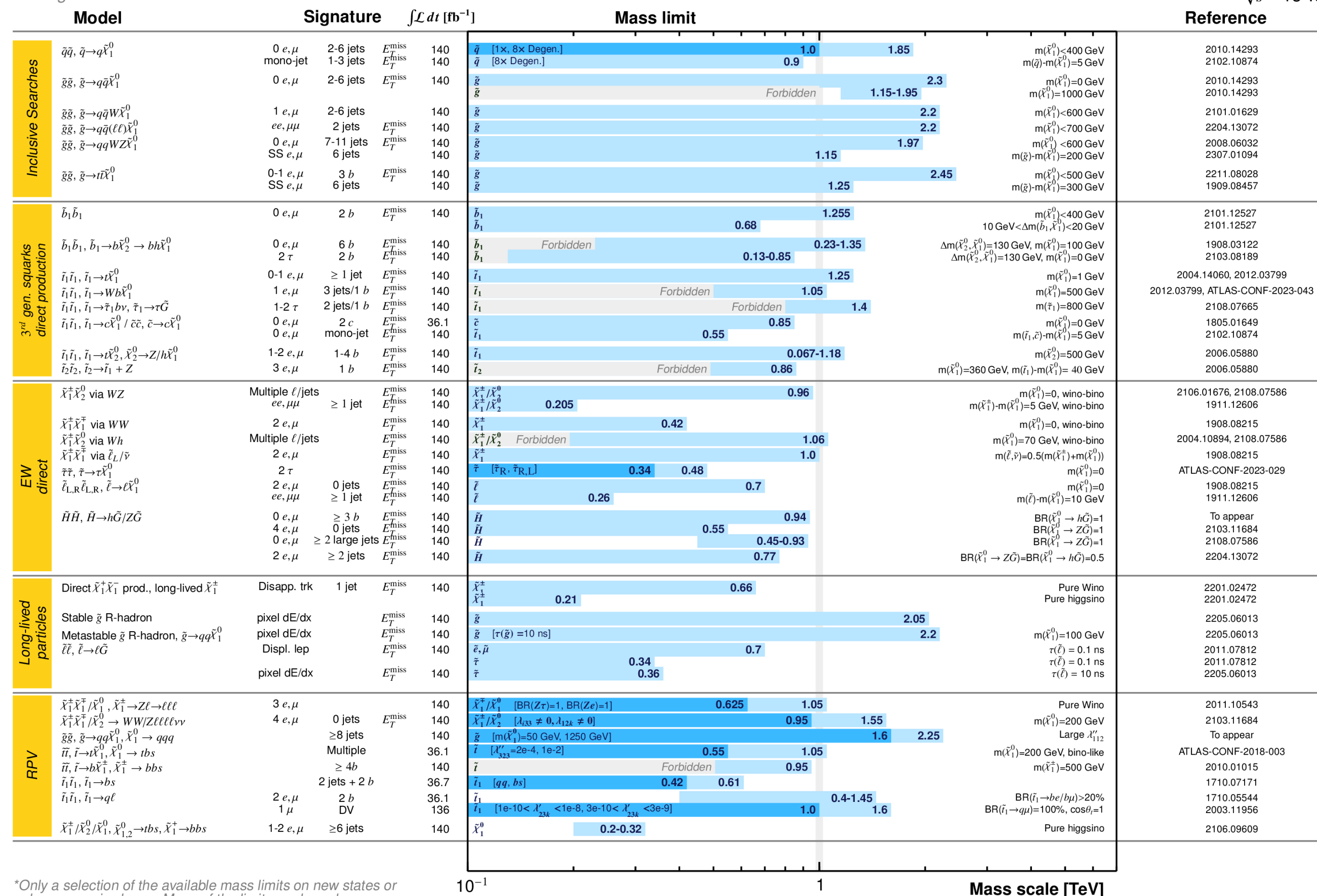
LOTS OF LIMITS

Hundreds of experimental searches constrain an enormous variety of SUSY scenarios.

Folk Theorem: any BSM scenario has the same pheno as a SUSY model.

ATLAS SUSY Searches* - 95% CL Lower Limits
August 2023

ATLAS Preliminary
 $\sqrt{s} = 13$ TeV



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

NON-SUSY (SORT OF)

Lots of other searches excluding things at the TeV scale.

Some searches sensitive to ~ 30 TeV.

ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

ATLAS Preliminary
 $\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$
 $\sqrt{s} = 13 \text{ TeV}$

Model	ℓ, γ	Jets [†]	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference	
Extra dimen.	ADD $G_{KK} + g/q$	$0 e, \mu, \tau, \gamma$	$1 - 4 j$	Yes	139	M_D 11.2 TeV $n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	M_S 8.6 TeV $n = 3$ HLZ NLO	1707.04147
	ADD QBH	-	$2 j$	-	139	M_{hh} 9.4 TeV $n = 6$	1910.08447
	ADD BH multijet	-	$\geq 3 j$	-	3.6	M_{th} 9.55 TeV $n = 6, M_D = 3 \text{ TeV, rot BH}$	1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	139	G_{KK} mass 4.5 TeV $k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	G_{KK} mass 2.3 TeV $k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $g_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2 j$	Yes	36.1	g_{KK} mass 3.8 TeV $\Gamma/m = 15\%$	1804.10823
2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$	1803.09678	
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	Z' mass 5.1 TeV	1903.06248
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	Z' mass 2.42 TeV	1709.07242
	Leptophobic $Z' \rightarrow bb$	-	$2 b$	-	36.1	Z' mass 2.1 TeV	1805.09299
	Leptophobic $Z' \rightarrow tt$	$0 e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	Z' mass 4.1 TeV $\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	139	W' mass 6.0 TeV	1906.05609
	SSM $W' \rightarrow \tau\nu$	1τ	-	Yes	139	W' mass 5.0 TeV	ATLAS-CONF-2021-025
	SSM $W' \rightarrow tb$	-	$\geq 1 b, \geq 1 J$	-	139	W' mass 4.4 TeV	ATLAS-CONF-2021-043
	HVT $W' \rightarrow WZ$ model B	$0-2 e, \mu$	$2 j / 1 J$	Yes	139	W' mass 4.3 TeV	2004.14636
HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell' \ell'$ model C	$3 e, \mu$	$2 j$ (VBF)	Yes	139	W' mass 340 GeV	2207.03925	
HVT $Z' \rightarrow WW$ model B	$1 e, \mu$	$2 j / 1 J$	Yes	139	Z' mass 3.9 TeV	2004.14636	
LRSM $W_R \rightarrow \mu N_R$	2μ	$1 J$	-	80	W_R mass 5.0 TeV $m(N_R) = 0.5 \text{ TeV, } g_L = g_R$	1904.12679	
CI	CI $qqqq$	-	$2 j$	-	37.0	Λ 21.8 TeV η_{LL}	1703.09127
	CI $\ell\ell qq$	$2 e, \mu$	-	-	139	Λ 35.8 TeV η_{LL}	2006.12946
	CI $e e b s$	$2 e$	$1 b$	-	139	Λ 1.8 TeV $g_s = 1$	2105.13847
	CI $\mu\mu b s$	2μ	$1 b$	-	139	Λ 2.0 TeV $g_s = 1$	2105.13847
	CI $t t t t$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Λ 2.57 TeV $ C_4 = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	-	$2 j$	-	139	m_{med} 3.8 TeV	ATL-PHYS-PUB-2022-036
	Pseudo-scalar med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	$1 - 4 j$	Yes	139	m_{med} 376 GeV	2102.10874
	Vector med. Z' -2HDM (Dirac DM)	$0 e, \mu$	$2 b$	Yes	139	$m_{Z'}$ 3.0 TeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	m_a 800 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1 st gen	$2 e$	$\geq 2 j$	Yes	139	LQ mass 1.8 TeV	$\beta = 1$ 2006.05872
	Scalar LQ 2 nd gen	2μ	$\geq 2 j$	Yes	139	LQ mass 1.7 TeV	$\beta = 1$ 2006.05872
	Scalar LQ 3 rd gen	1τ	$2 b$	Yes	139	LQ_3^u mass 1.49 TeV $\mathcal{B}(LQ_3^u \rightarrow b\tau) = 1$	2303.01294
	Scalar LQ 3 rd gen	$0 e, \mu$	$\geq 2 j, \geq 2 b$	Yes	139	LQ_3^d mass 1.24 TeV $\mathcal{B}(LQ_3^d \rightarrow t\nu) = 1$	2004.14060
	Scalar LQ 3 rd gen	$\geq 2 e, \mu, \geq 1 \tau, \geq 1 j, \geq 1 b$	-	-	139	LQ_3^d mass 1.43 TeV $\mathcal{B}(LQ_3^d \rightarrow t\tau) = 1$	2101.11582
	Scalar LQ 3 rd gen	$0 e, \mu, \geq 1 \tau, 0-2 j, 2 b$	Yes	139	LQ_3^d mass 1.26 TeV $\mathcal{B}(LQ_3^d \rightarrow b\nu) = 1$	2101.12527	
	Vector LQ mix gen	multi-channel	$\geq 1 j, \geq 1 b$	Yes	139	LQ_3^u mass 2.0 TeV $\mathcal{B}(\tilde{U}_1 \rightarrow t\mu) = 1, \text{ Y-M coupl.}$	ATLAS-CONF-2022-052
	Vector LQ 3 rd gen	$2 e, \mu, \tau$	$\geq 1 b$	Yes	139	LQ_3^d mass 1.96 TeV $\mathcal{B}(LQ_3^d \rightarrow b\tau) = 1, \text{ Y-M coupl.}$	2303.01294
Vector-like fermions	VLQ $TT \rightarrow Zt + X$	$2e/2\mu \geq 3e, \mu$	$\geq 1 b, \geq 1 j$	-	139	T mass 1.46 TeV	SU(2) doublet 2210.15413
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV	SU(2) doublet 1808.02343
	VLQ $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS) \geq 3 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$ 1807.11883
	VLQ $T \rightarrow Ht/Zt$	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	139	T mass 1.8 TeV	SU(2) singlet, $\kappa_T = 0.5$ ATLAS-CONF-2021-040
	VLQ $Y \rightarrow Wb$	$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$ 1812.07343
	VLQ $B \rightarrow Hb$	$0 e, \mu$	$\geq 2b, \geq 1 j, \geq 1 J$	-	139	B mass 2.0 TeV	SU(2) doublet, $\kappa_B = 0.3$ ATLAS-CONF-2021-018
VLL $\tau' \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1 j$	Yes	139	τ' mass 898 GeV	SU(2) doublet 2303.05441	
Excited ferm.	Excited quark $q^* \rightarrow qg$	-	$2 j$	-	139	q^* mass 6.7 TeV	only u^* and $d^*, \Lambda = m(q^*)$ 1910.08447
	Excited quark $q^* \rightarrow q\gamma$	1γ	$1 j$	-	36.7	q^* mass 5.3 TeV	only u^* and $d^*, \Lambda = m(q^*)$ 1709.10440
	Excited quark $b^* \rightarrow bg$	-	$1 b, 1 j$	-	139	b^* mass 3.2 TeV	1910.08447
	Excited lepton τ^*	2τ	$\geq 2 j$	-	139	τ^* mass 4.6 TeV	$\Lambda = 4.6 \text{ TeV}$ 2303.09444
Other	Type III Seesaw	$2, 3, 4 e, \mu$	$\geq 2 j$	Yes	139	N^0 mass 910 GeV	2202.02039
	LRSM Majorana ν	2μ	$2 j$	-	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1 \text{ TeV, } g_L = g_R$ 1809.11105
	Higgs triplet $H^{\pm\pm} \rightarrow W^\pm W^\pm$	$2, 3, 4 e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV	DY production 2101.11961
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4 e, \mu$ (SS)	-	-	139	$H^{\pm\pm}$ mass 1.08 TeV	DY production 2211.07505
	Multi-charged particles	-	-	-	139	multi-charged particle mass 1.59 TeV	DY production, $ q = 5e$ ATLAS-CONF-2022-034
	Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV	DY production, $ g = 1g_D, \text{ spin } 1/2$ 1905.10130

$\sqrt{s} = 13 \text{ TeV}$
 partial data $\sqrt{s} = 13 \text{ TeV}$
 full data

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).