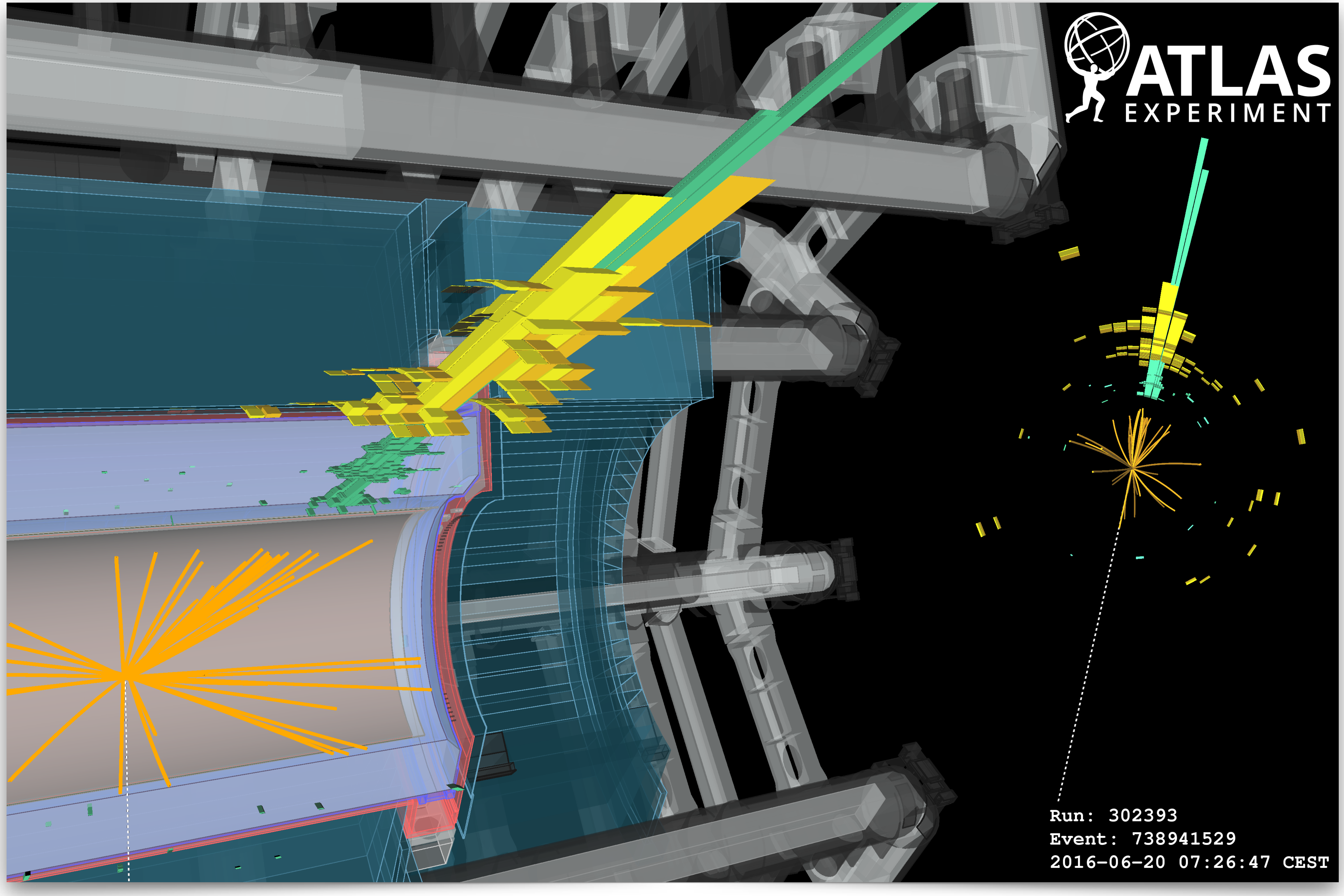
Experimental Physics at Hadron Collider

Lecture 4 - *Searches for new physics and outlook*



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CERN Summer Students
July 16-19, 2018

Outline

Lecture 1: Basic concepts, cross sections and QCD results

- Preamble
- Context and mission of the LHC
- Fundamentals of hadron collisions
- Luminosity and total cross section
- Cross sections measurements
- Jet production measurements
- Measurement of the strong coupling constant

Lecture 2: SM Measurements

- The electroweak sector in a tiny nutshell
- Measurement of the weak mixing angle
- W mass measurement
- Top mass measurement
- Diboson production
- Global fit of the Standard Model

Lecture 3: Higgs physics

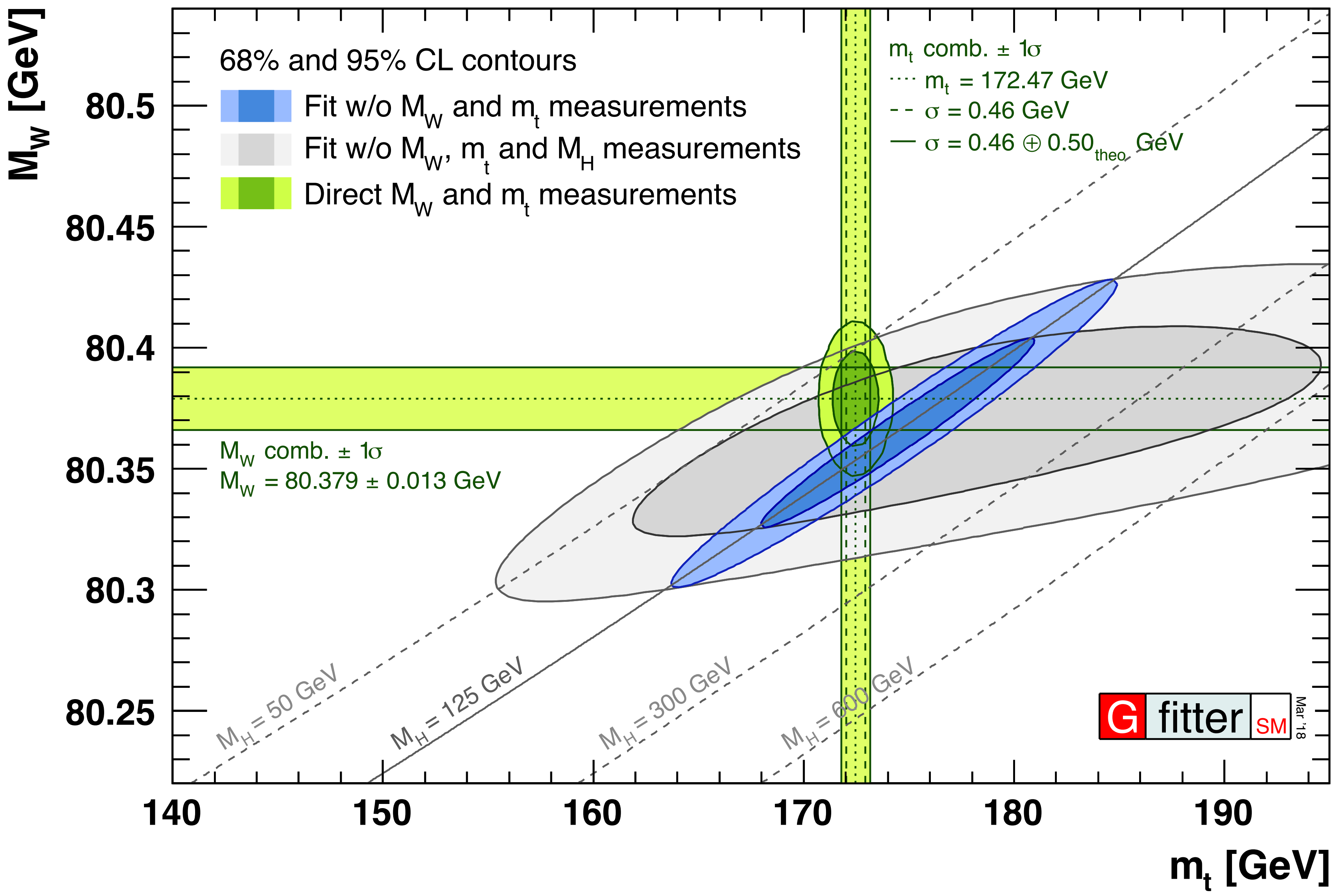
- The Higgs mechanism and Higgs production
- The discovery of the Higgs boson
- Precision Higgs physics with diboson channels
- Measuring the Yukawa couplings
- Measurement of Higgs properties
- Rare production and decays
- Global fit of the Standard Model (revisited)

Lecture 4: Searching for new physics BSM and future Hadron Colliders

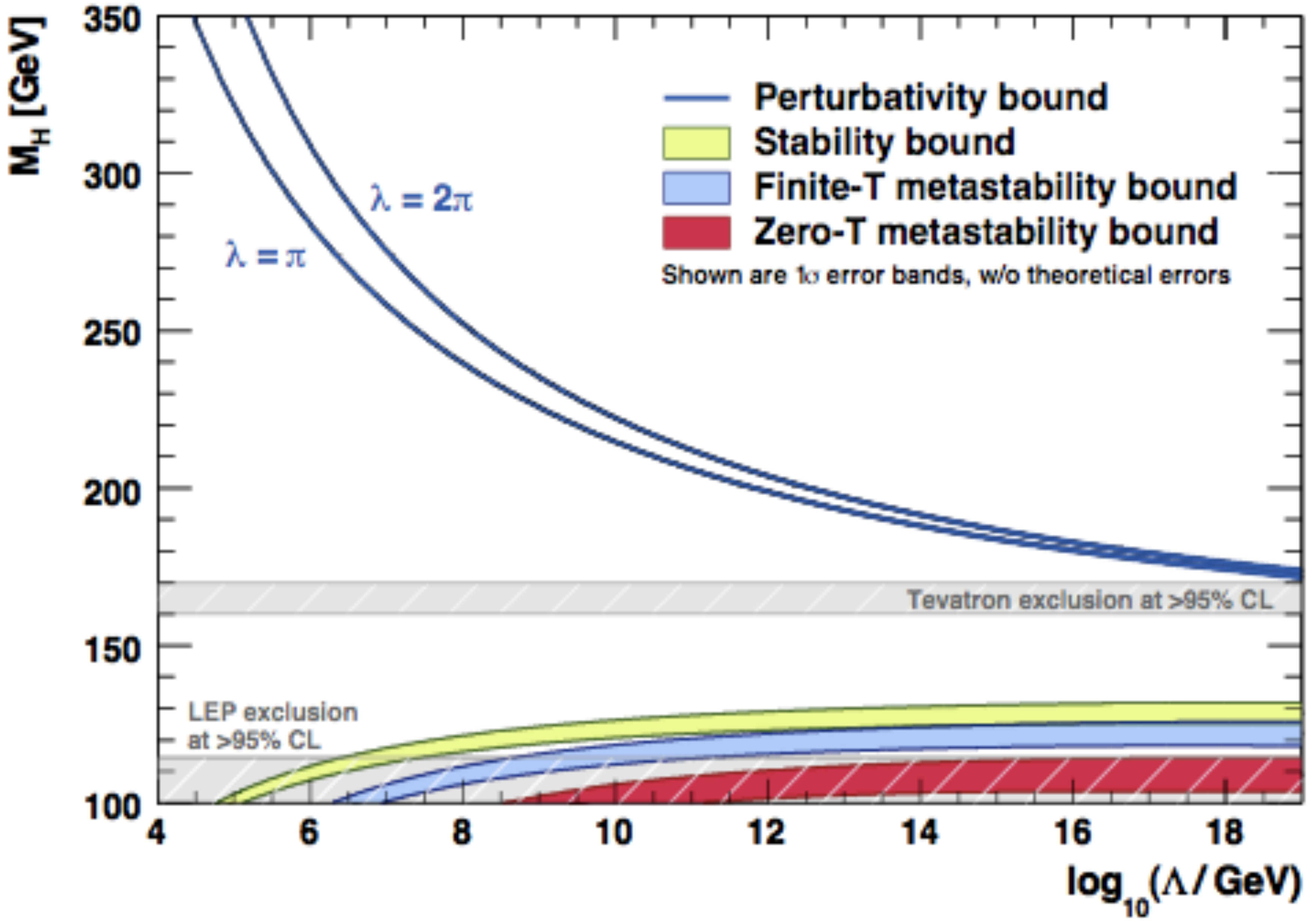
- Introduction
- Searches for supersymmetry and Dark Matter
- Searches in non SUSY theories
- Searches for unconventional signatures
- EFT and high energy observables
- Outlook on future colliders
- Conclusions

Triumph of the Standard Model?

From Lectures 2 and 3:



Global fit of the Standard Model: fully consistent!



No indication of new physics scale.

With the discovery of the Higgs, for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.

Nima Arkani Hamed

The *Unsatisfactory* Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\Psi} \not{D} \psi \quad + h.c.$$

The elegant gauge sector (tree parameters for EWK and one parameter for QCD)

$$\theta \frac{\alpha_s}{8\pi} F^{A}_{\mu\nu} \tilde{F}^{A\mu\nu}$$

$$\theta < 10^{-10}$$

From neutron electric dipole moment measurements

The strong CP problem

$$+ \bar{\Psi}_i y_{ij} \psi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

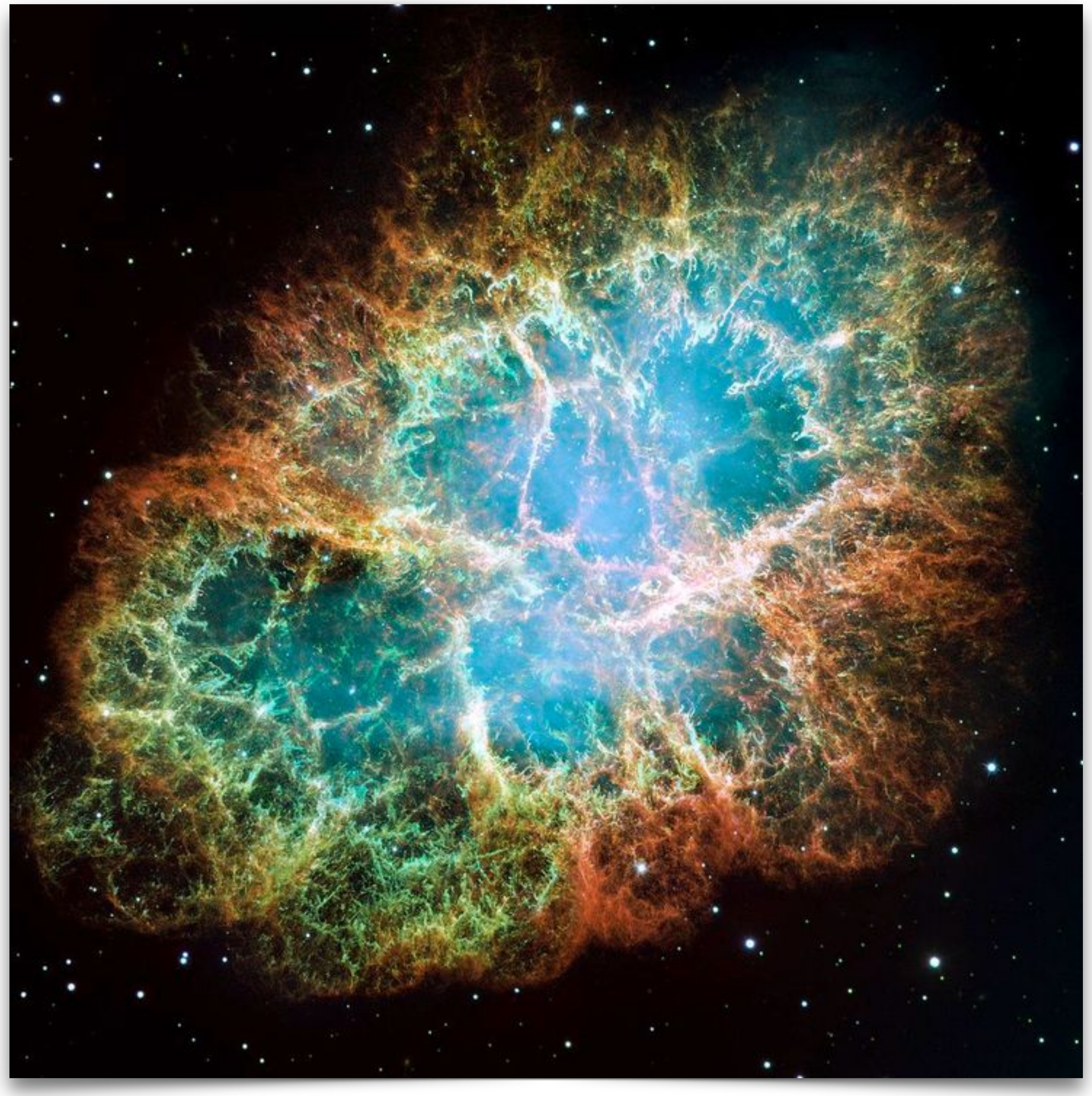
The less elegant Higgs sector:

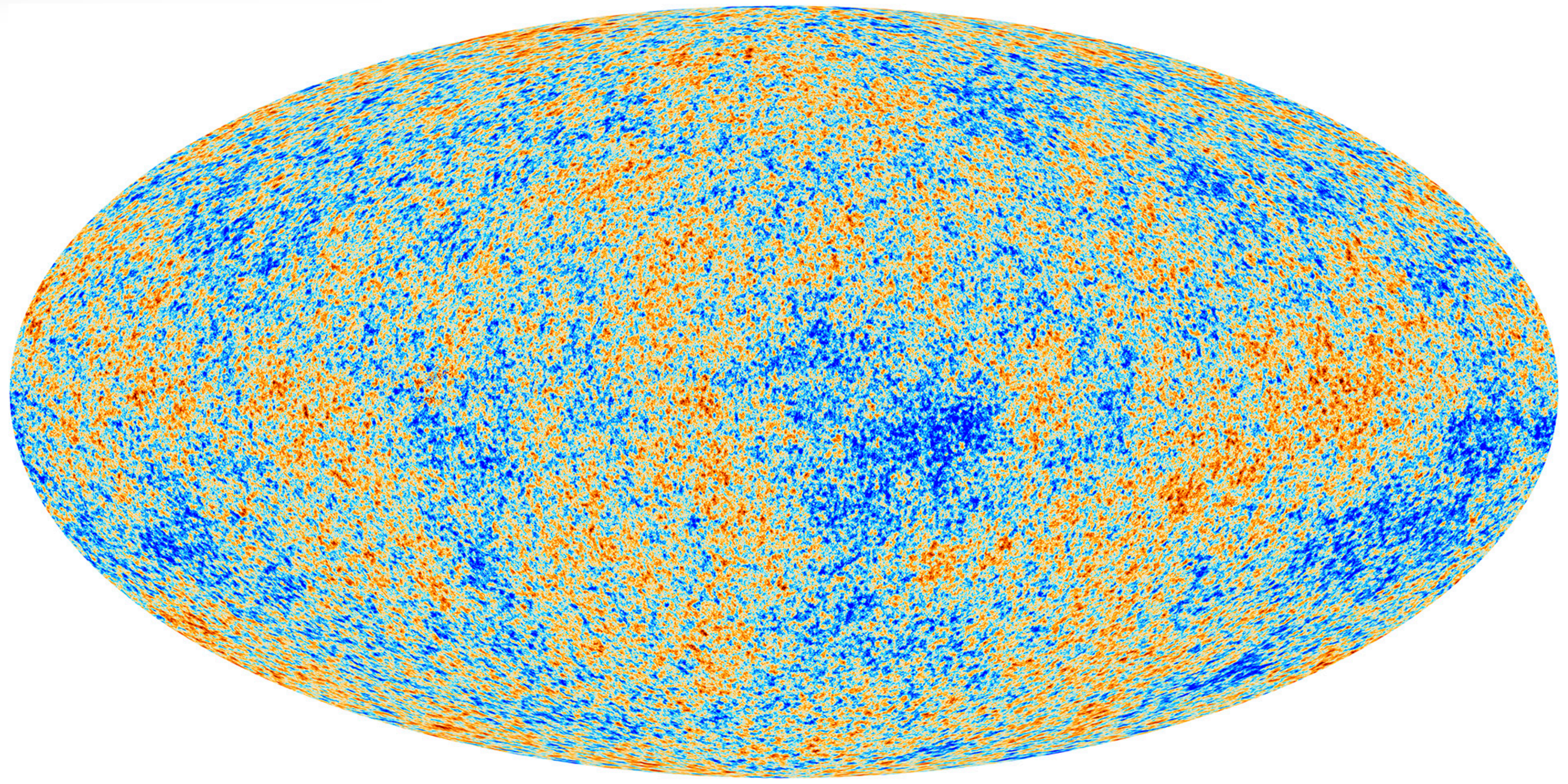
- Carries the largest number of parameters of the theory
- Not governed by symmetries
- Gauge Hierarchy (and Naturalness)
- Flavour hierarchy (includes neutrino masses)

Open questions (not explained by the Standard Model):

- Why is the charge of the electron matching the charge of the proton?
- Why is the mu parameter negative in the Higgs potential?
- Description of gravity at small distant scales?
- Many more…

Unexplained Observed Phenomena





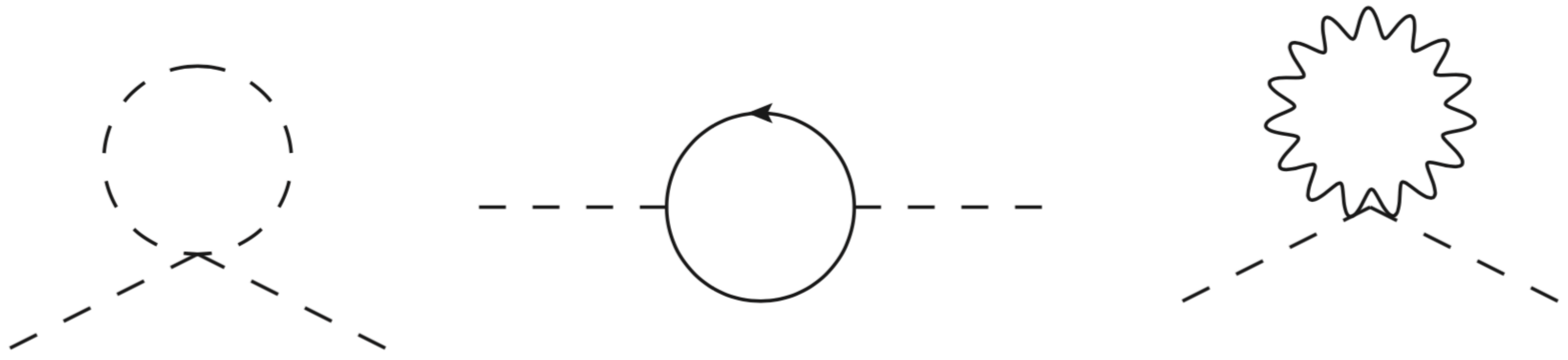
Astrophysical and cosmological observations:

- The mere existence of the universe and the matter/anti-matter balance?
- The nature of Dark Matter?
- The nature of Dark Energy?

Why is the Hierarchy an Issue?

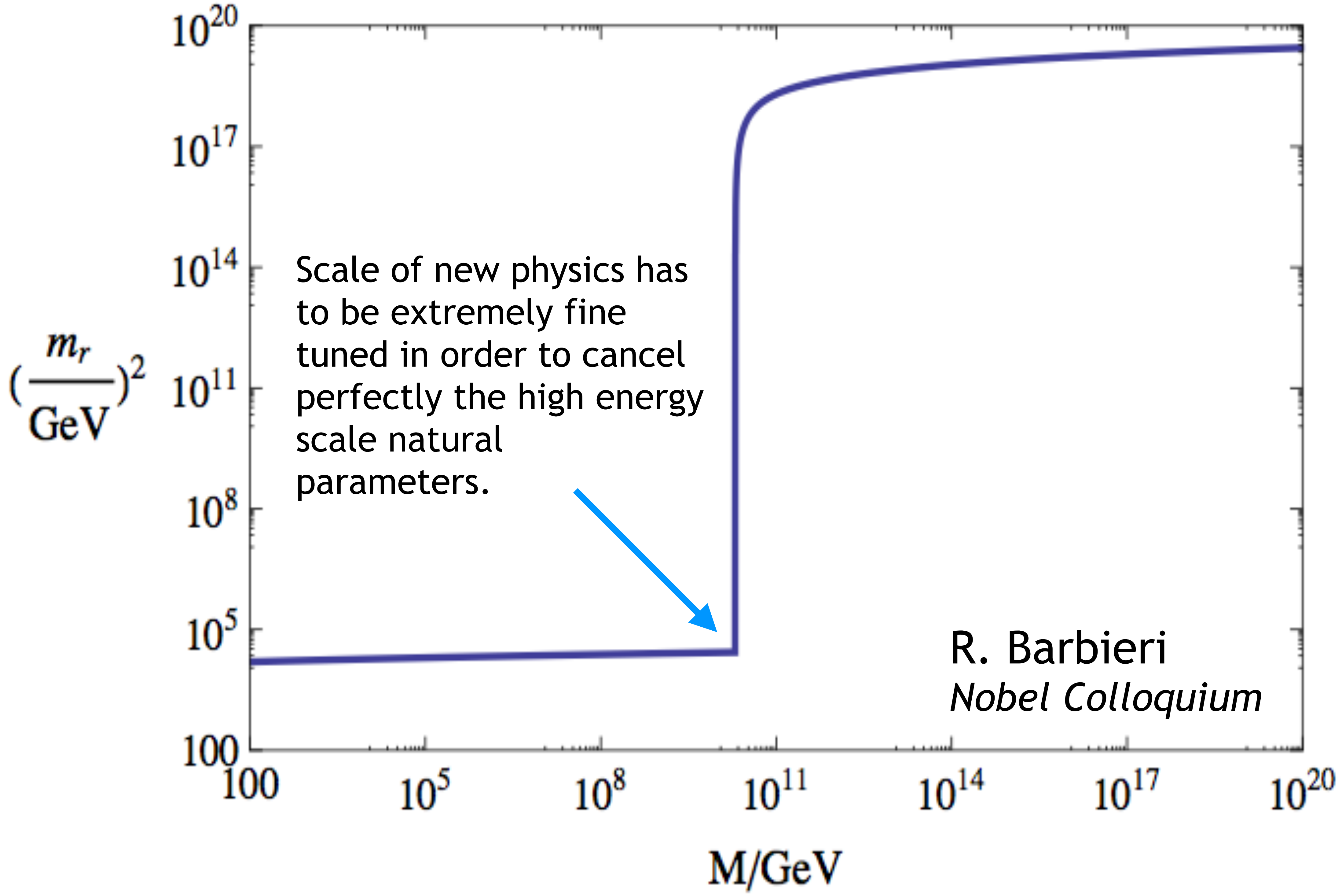
Naturalness

If the Higgs boson is an elementary scalar, loop corrections to its mass are quadratically divergent:



$$\Delta m^2 \propto \int^{\Lambda} \frac{d^4k}{(2\pi)^4}\frac{1}{k^2} \sim \frac{\Lambda^2}{16\pi}$$

The Standard Model is a renormalisable theory quadratic divergences are not a problem per se, but if we look at the running of the Higgs boson mass:



Scale of new physics has to be extremely fine tuned in order to cancel perfectly the high energy scale natural parameters.

R. Barbieri
Nobel Colloquium

Solutions:

- **Weakly coupled:** introduce fields in the theory that can cancel the quadratic divergence and alleviate the fine tuning (e.g. SUSY)
- **Strongly coupled** (Composite): in this case the above does not apply. The Higgs could be either a generic bound state or a pseudo goldstone boson (similarly to the pion in Chiral perturbation theory).
- **Warped extra dimensions:** Difference between scales generated by warping.
- **Anthropic principle:** fine tuning is acceptable since it is a condition for existence of the universe as it is.

or accepting it as it is

Supersymmetry

Supersymmetry

An elegant, simple and complete solution…

Nutshell description:

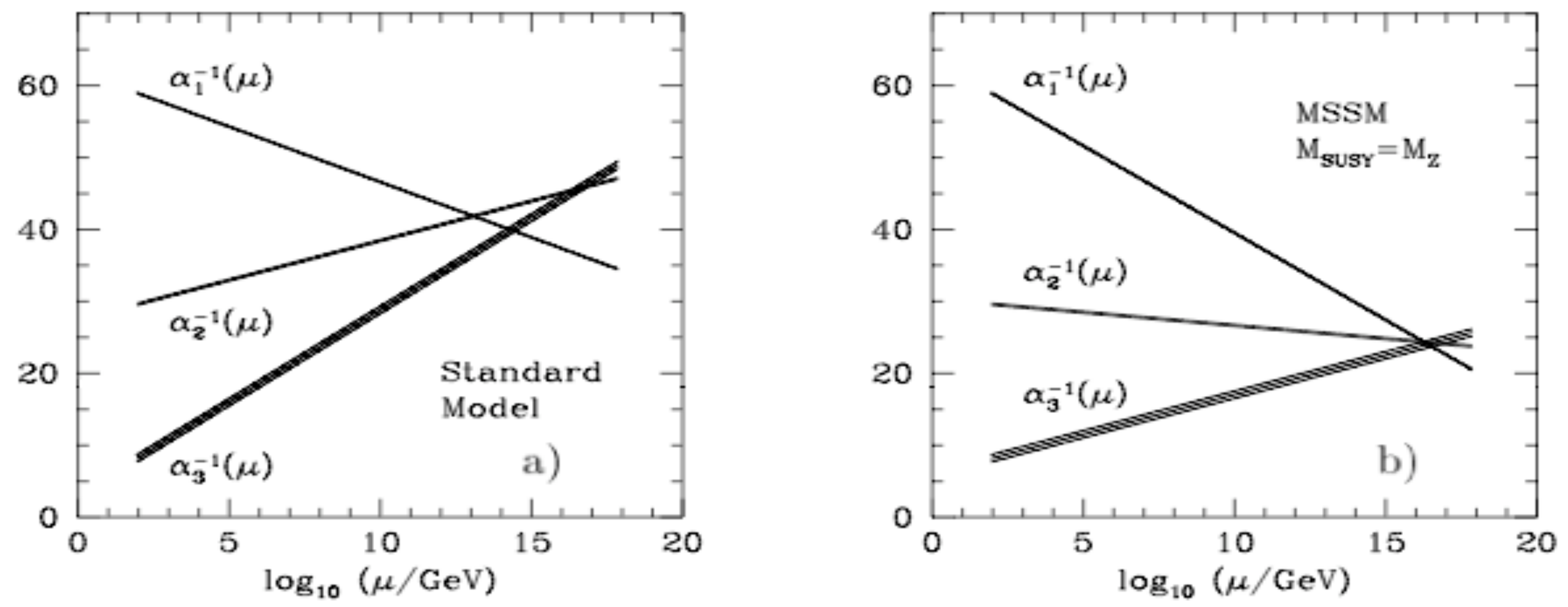
- For all fermions degree of freedom SUSY adds a boson degree of freedom
- To all bosons degree of freedom, SUSY adds a fermions

What SUSY addresses:

- It resolves the gauge hierarchy (naturaleness problem)
- It allows unification of gauge couplings
- Local SUSY requires gravitino and therefore via SUSY naturally brings the graviton and is an essential ingredient in string theory
- It provides a natural candidate for dark matter

The only few issues:

- It has not been found!
- If it exists it has to be broken
- If the super-partners are too heavy fine tuning re-emerges and one of the main issues (naturalness) reappears).
- With a much larger number of fields come a much larger number of parameters!

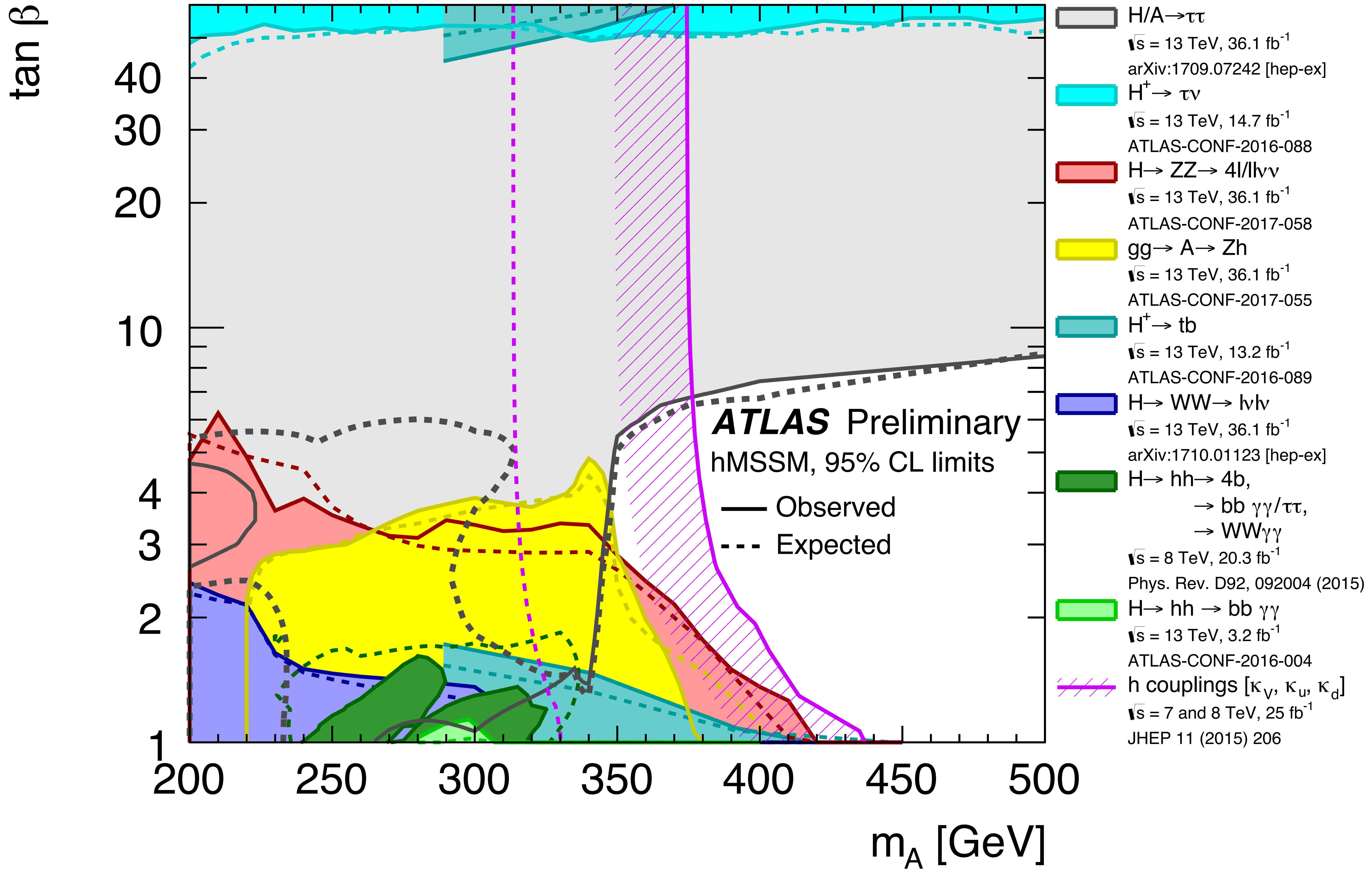


The main predictions of SUSY

- Superpartners that should be at a reachable scale!
- A candidate dark matter particle: the neutralino (typically).
- An extended Higgs sector. Its minimal realisation is the MSSM (2 Higgs doublets so 5 Higgs bosons, 3 neutral and 2 charged).

Reaching SUSY from an extended Higgs sector

The MSSM Higgs sector at tree level is governed by only two parameters (mA and tan β).



SUSY could modify the couplings of the Higgs

From the combination of all channels presented in Lecture 3, from constraints on up versus down Yukawa and coupling to vector bosons, limits in the MSSM parameter space can be set.

Direct searches for additional Higgs bosons (neutral and charged) have been performed:

- Neutral heavy Higgs to tau tau
- Charged Higgs to tau neutrino
- Heavy neutral Higgs to ZZ
- Charged Higgs to tb

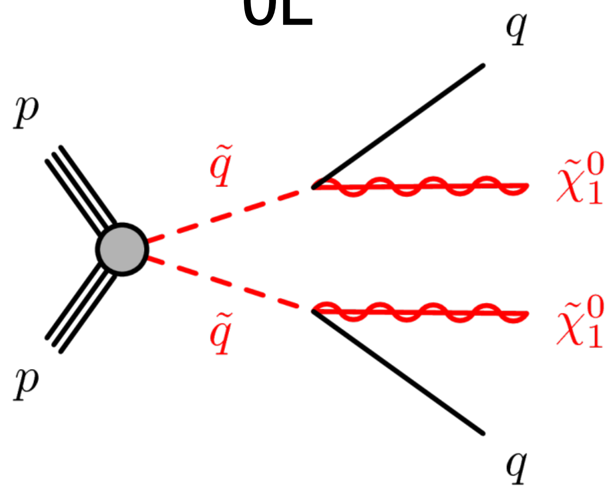
Using the Higgs boson as a tool for discovery:

- Heavy neutral Higgs to ZH
- Heavy Higgs boson to HH

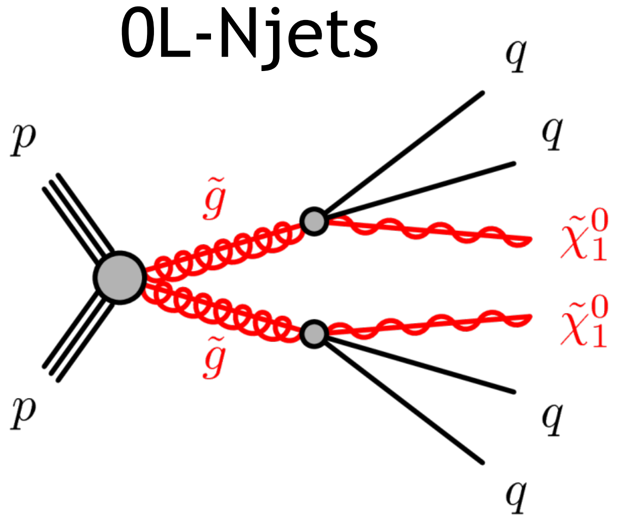
Strongly Produced SUSY Searches

Squarks and gluinos

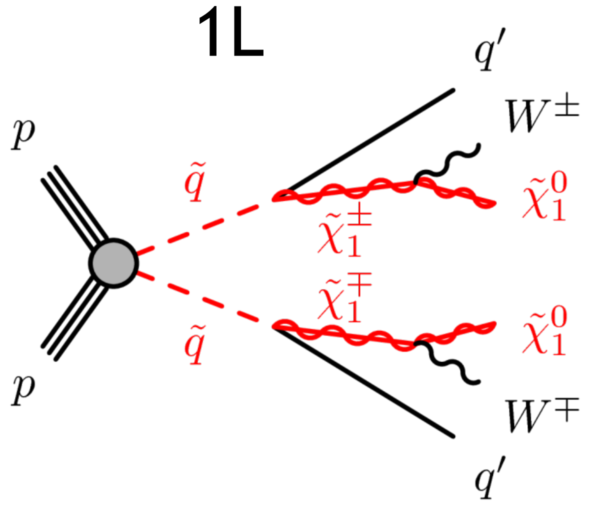
0L



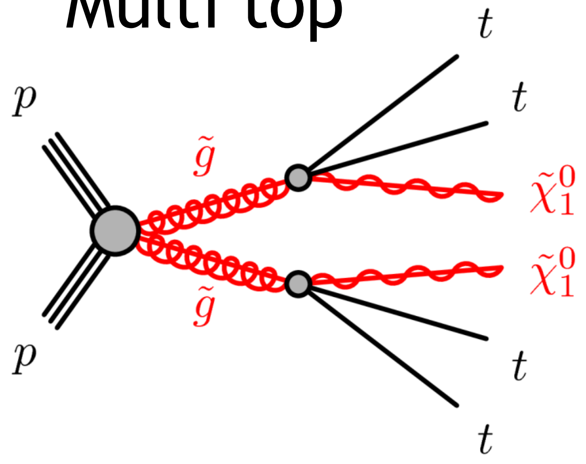
0L-Njets



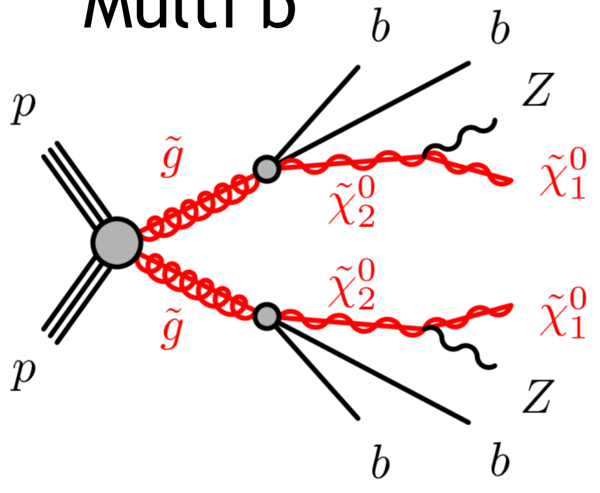
1L



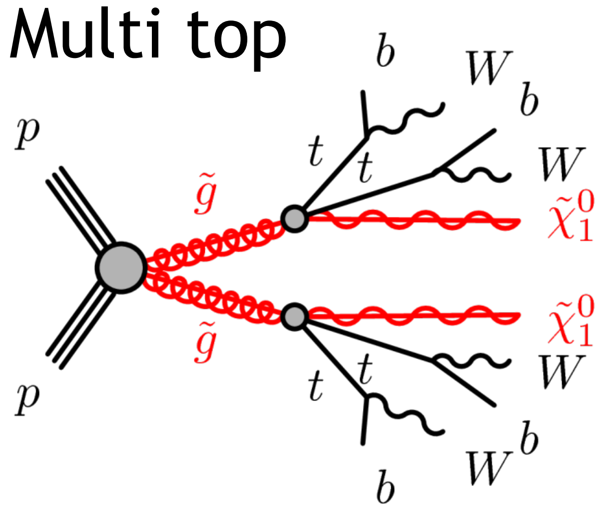
Multi top

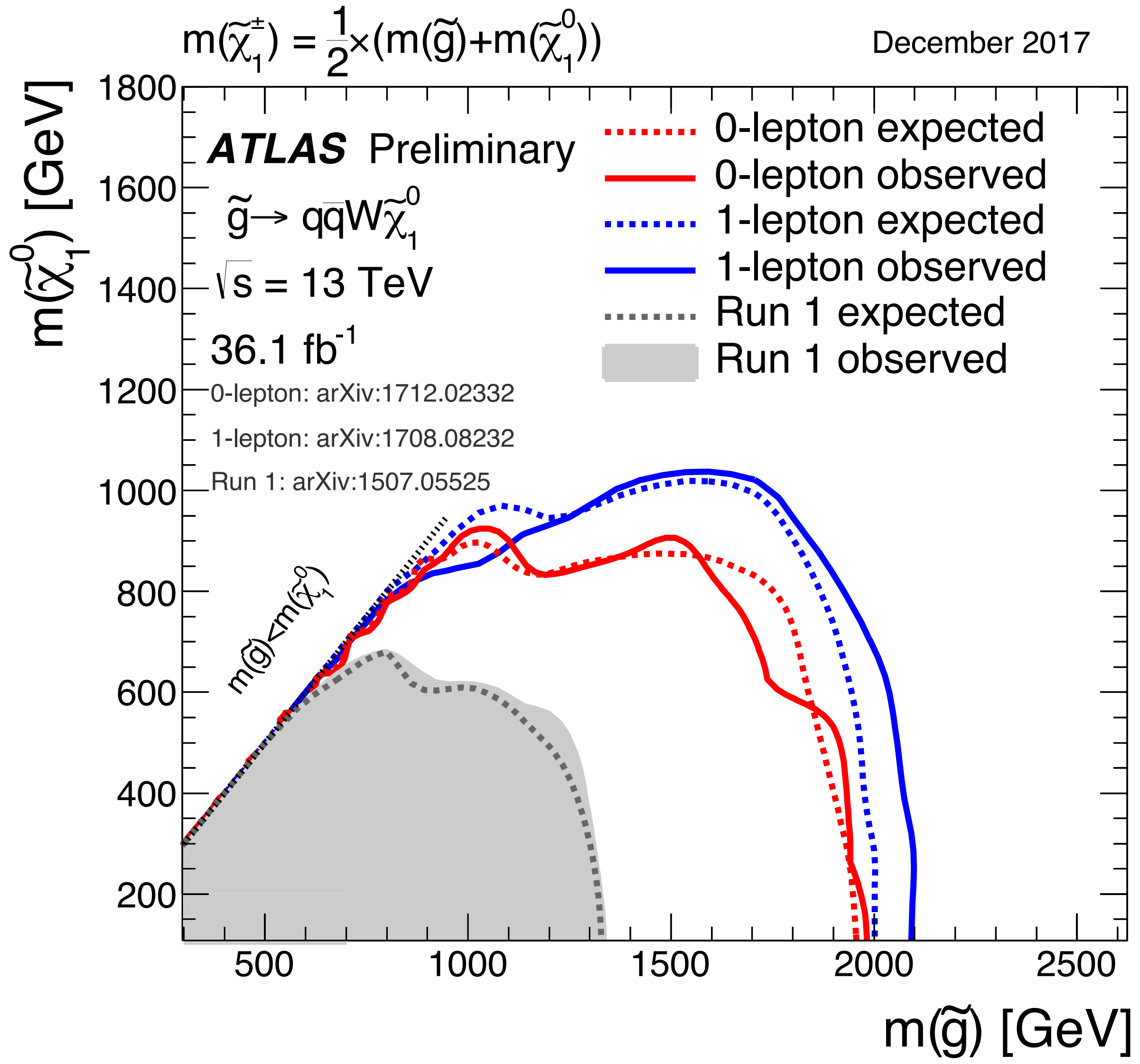


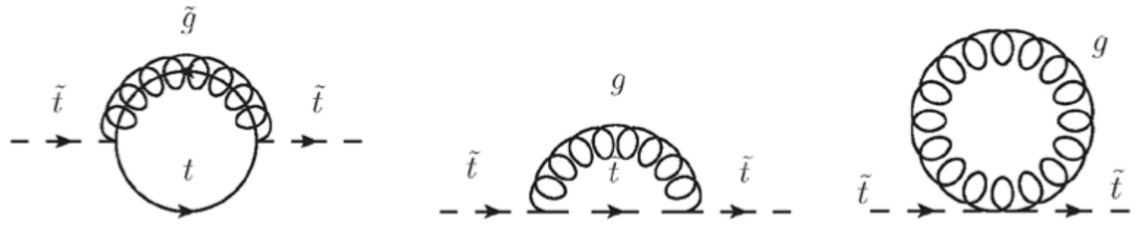
Multi b



Multi top



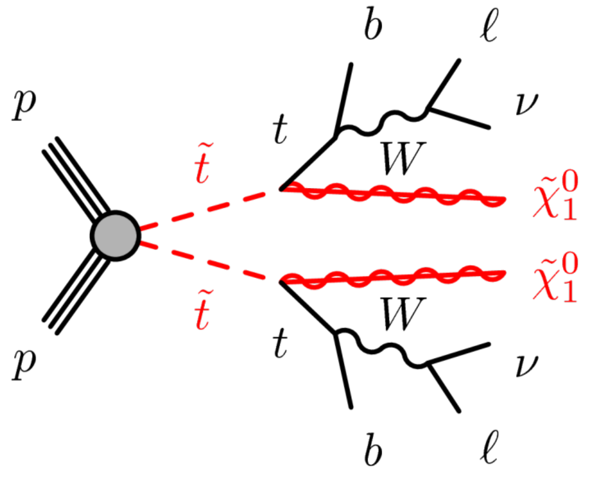




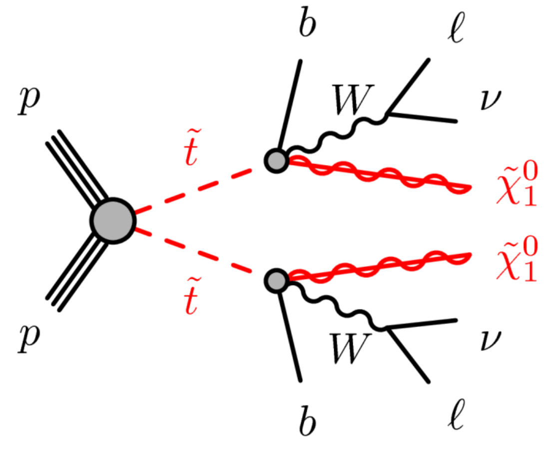
Stop also a scalar requires light gluinos to be light enough: for gluinos > 1.8 TeV ~tuning of Factor of 30

Stop

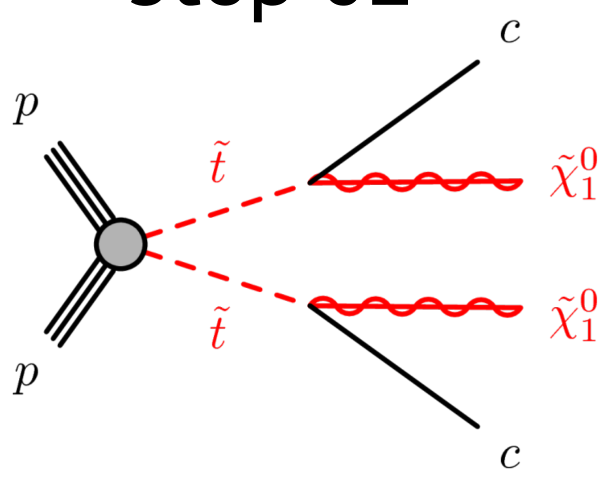
Stop 2L



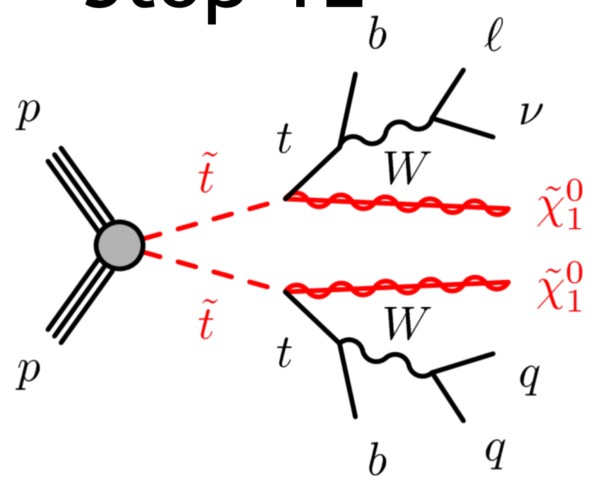
Stop 1,2-L



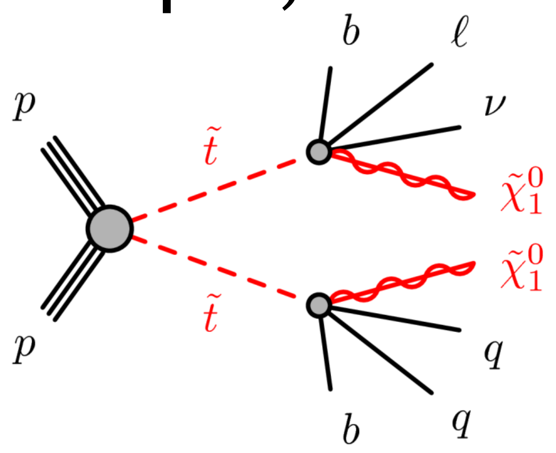
Stop 0L



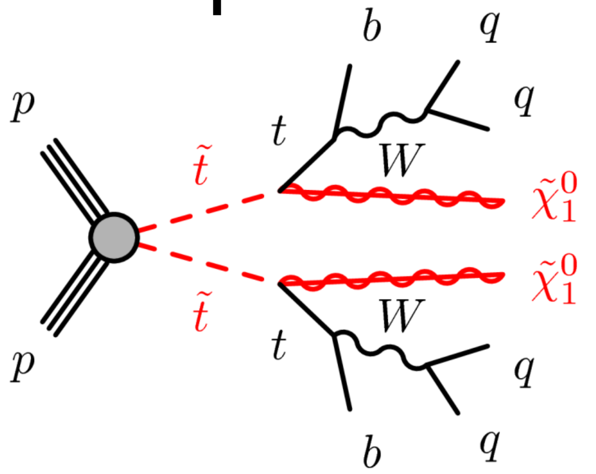
Stop 1L

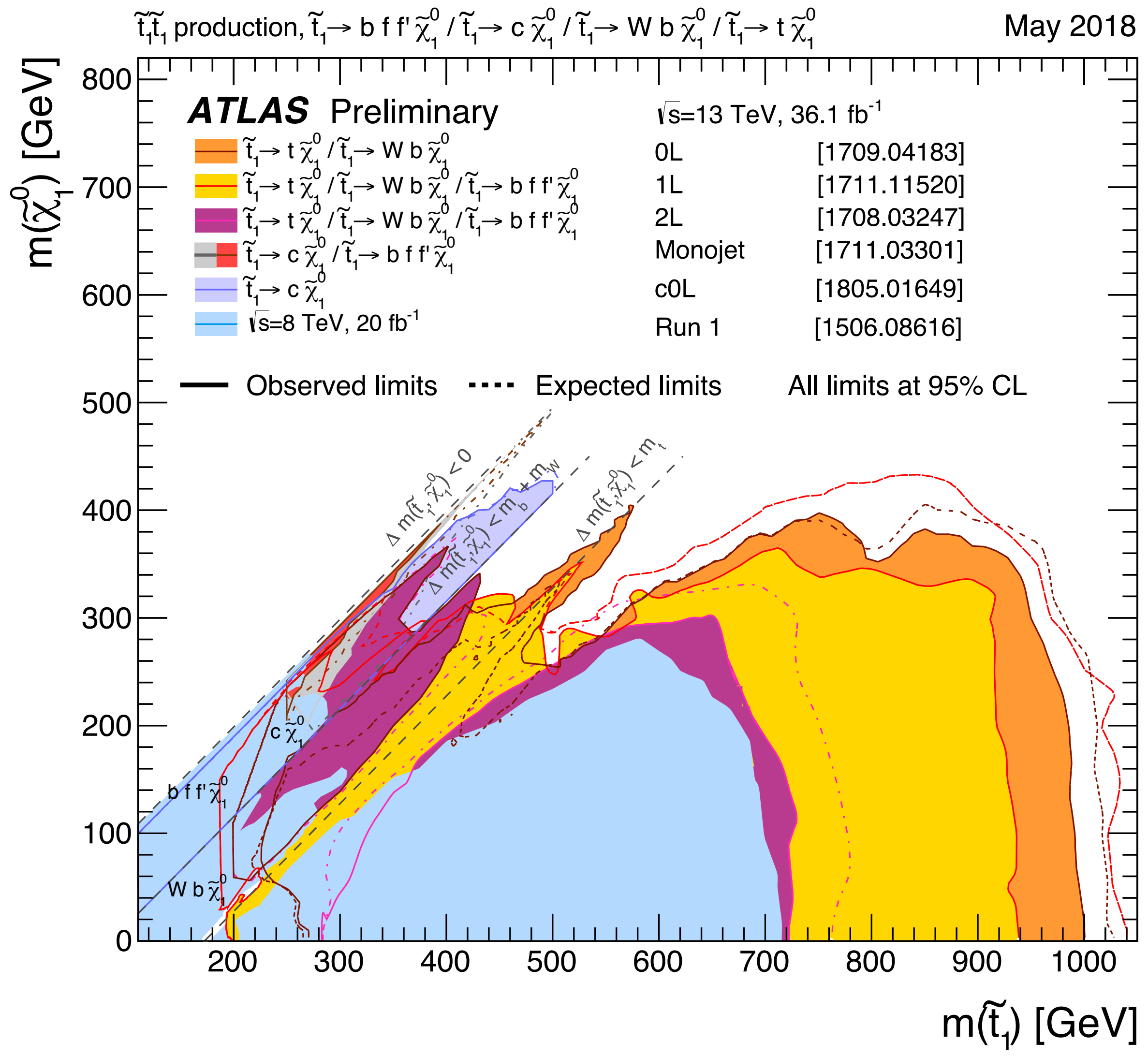


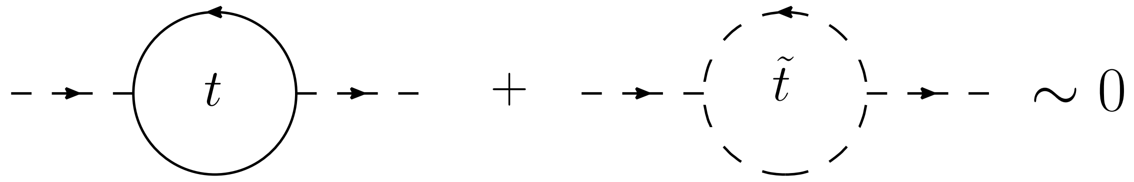
Stop 1,2-L



Stop 0L





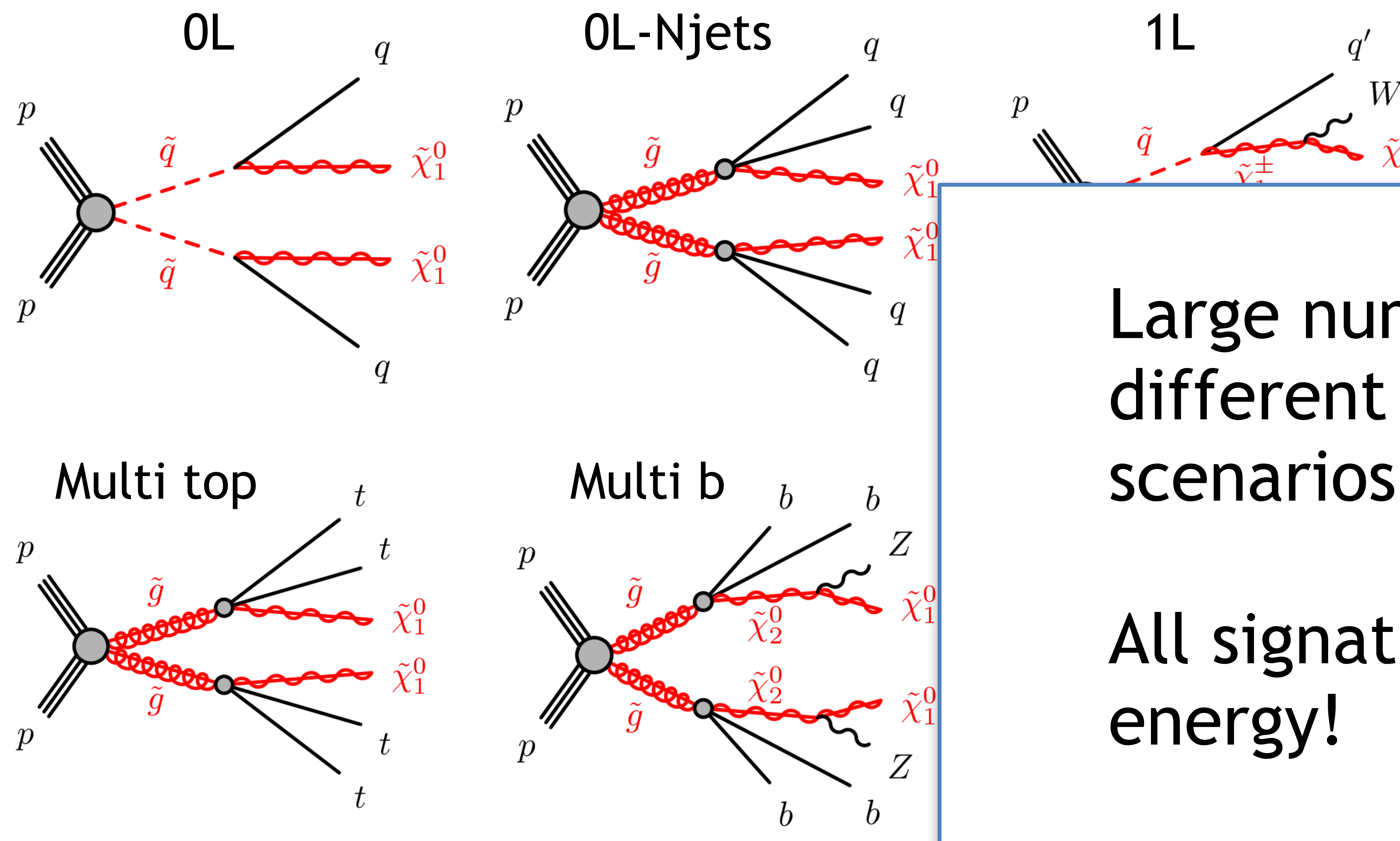


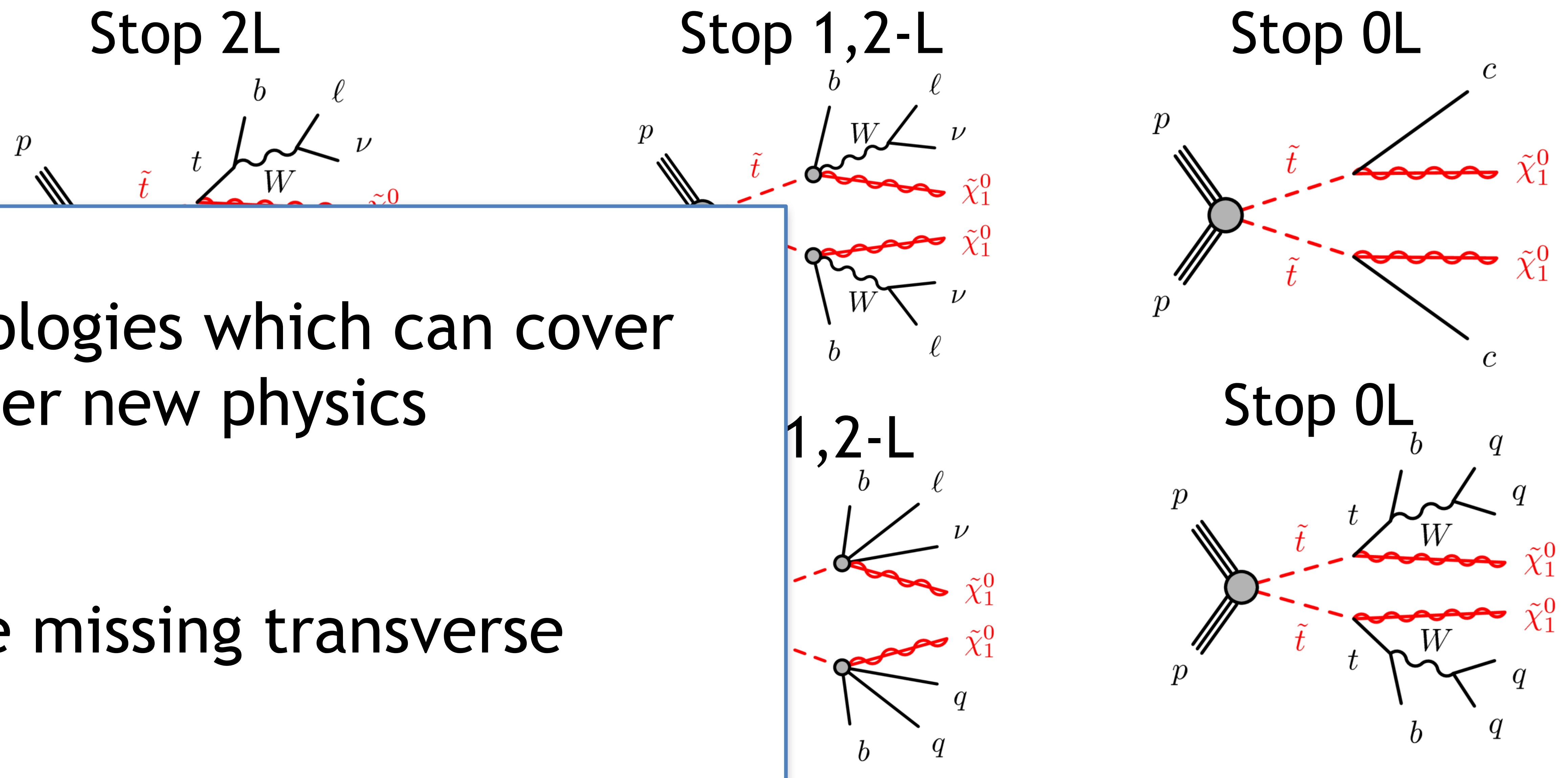
Not so natural SUSY: Stops > 800 GeV ~Tuning of factor 20, but these exclusions are under specific conditions, and there are unexcluded corridors.

Strongly Produced SUSY Searches

Stop

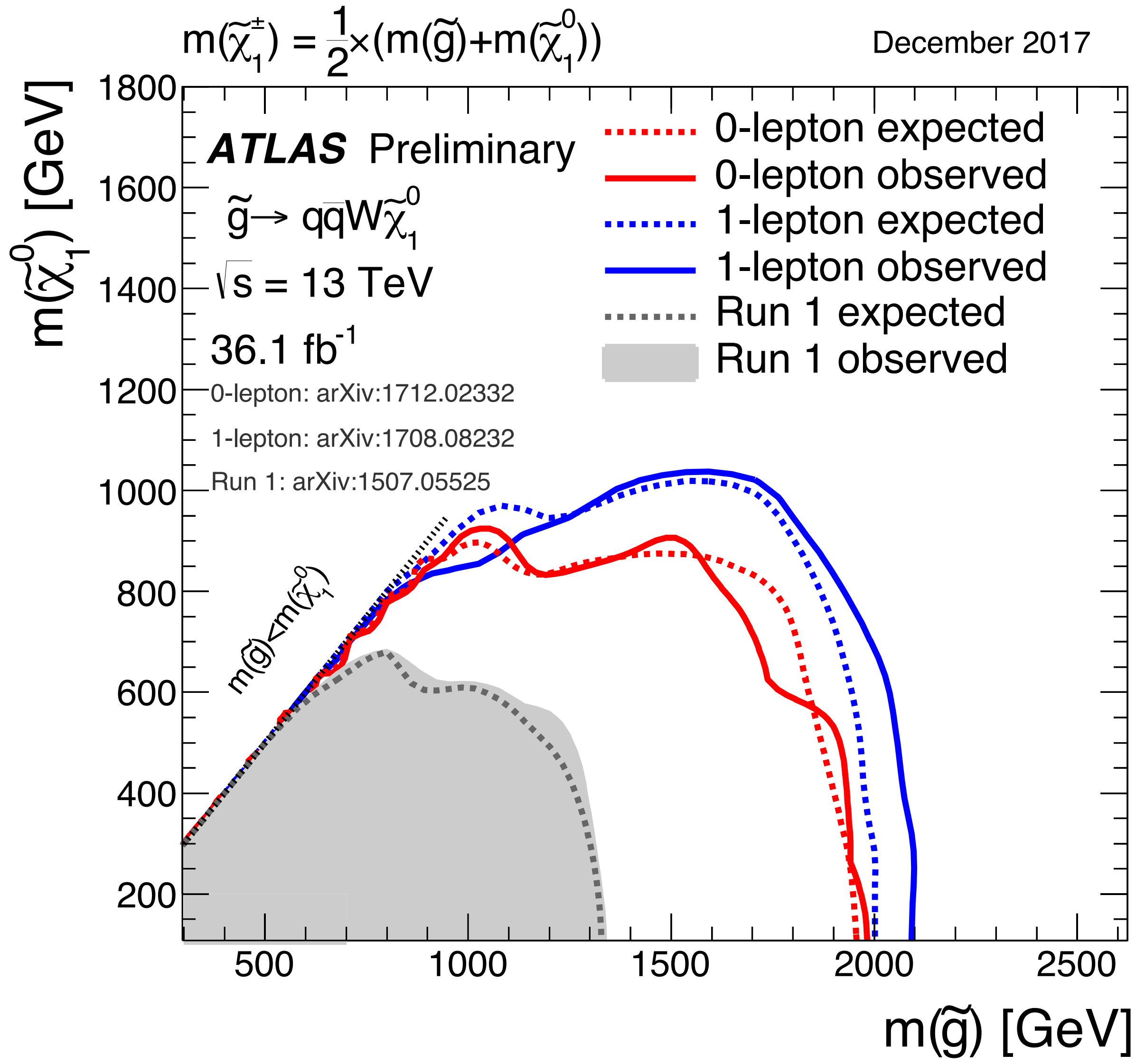
Squarks and gluinos

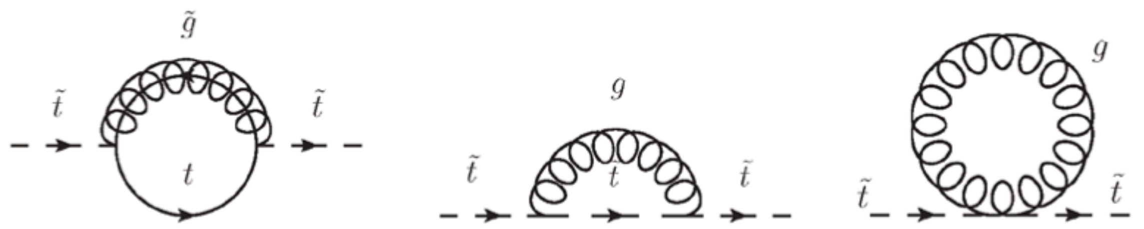




Large number of topologies which can cover different SUSY or other new physics scenarios

All signatures feature missing transverse energy!





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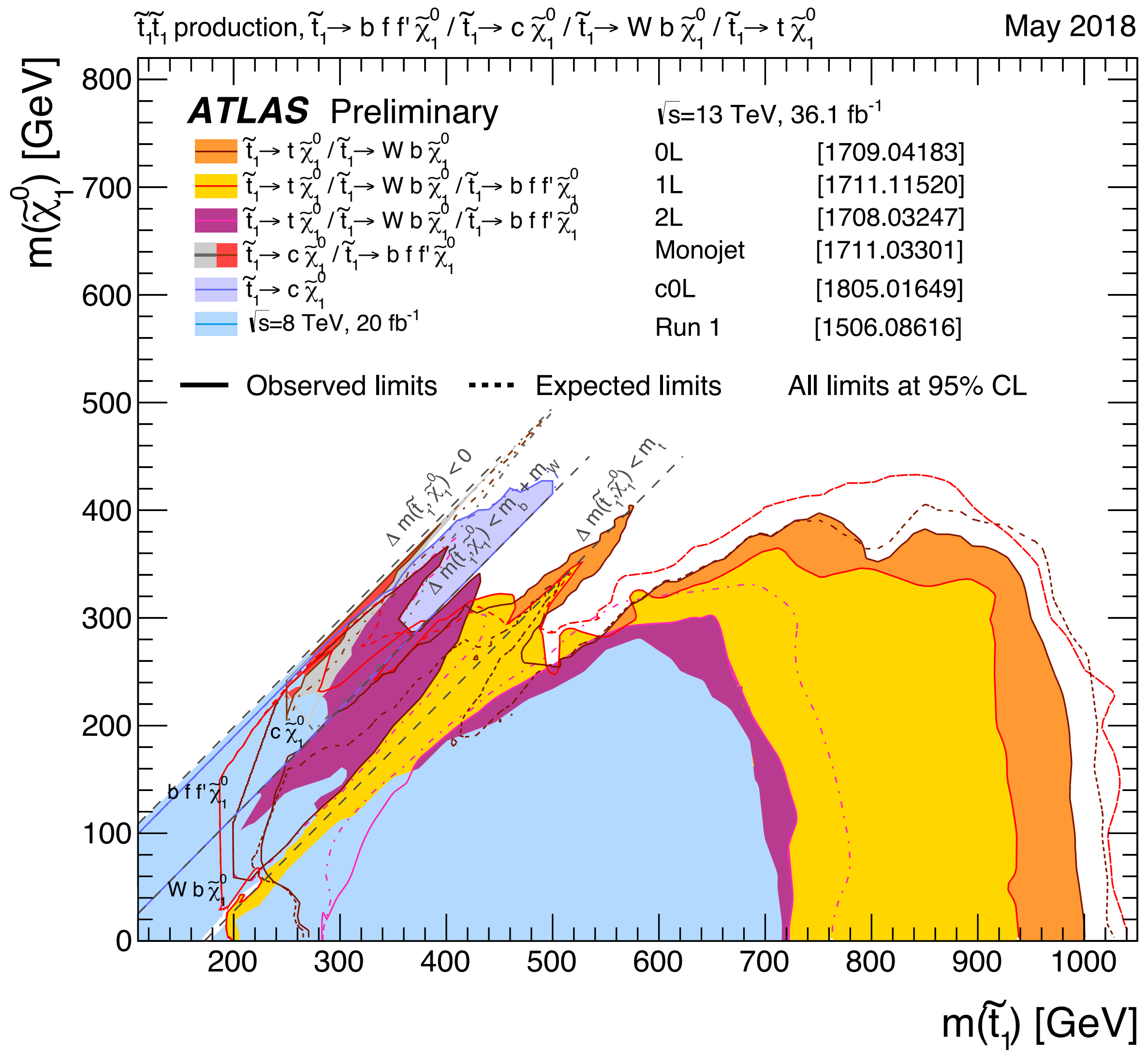
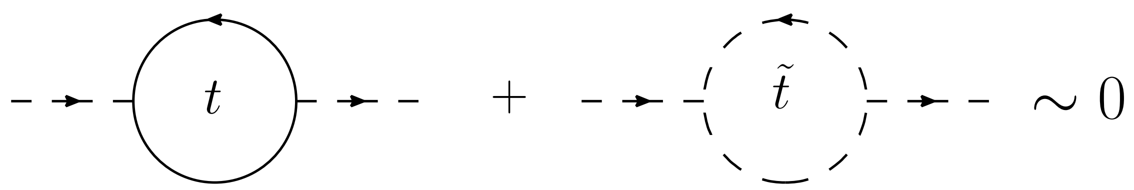
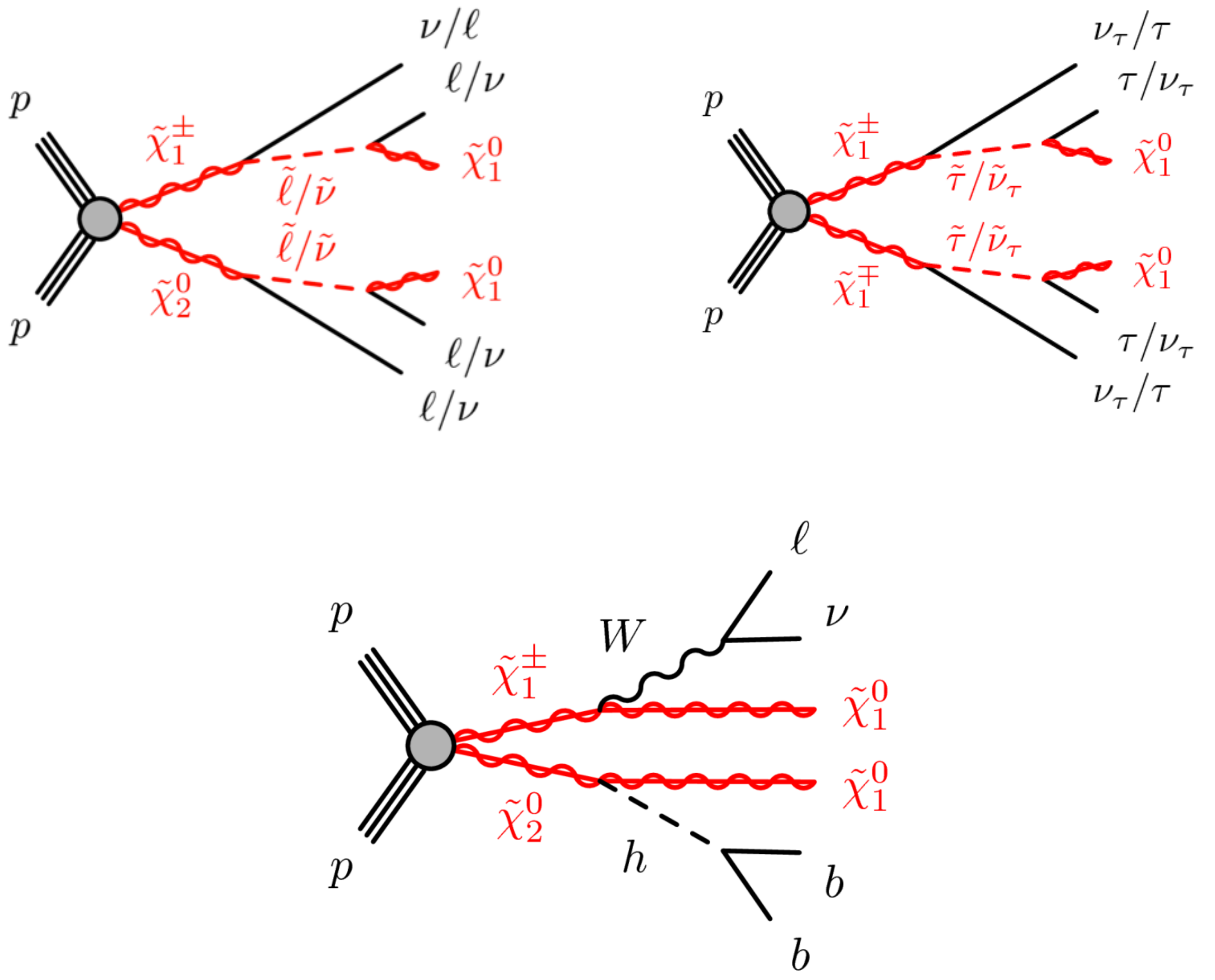




Not so natural SUSY: Stops > 800 GeV ~Tuning of factor 20, but these exclusions are under specific conditions, and there are unexcluded corridors.

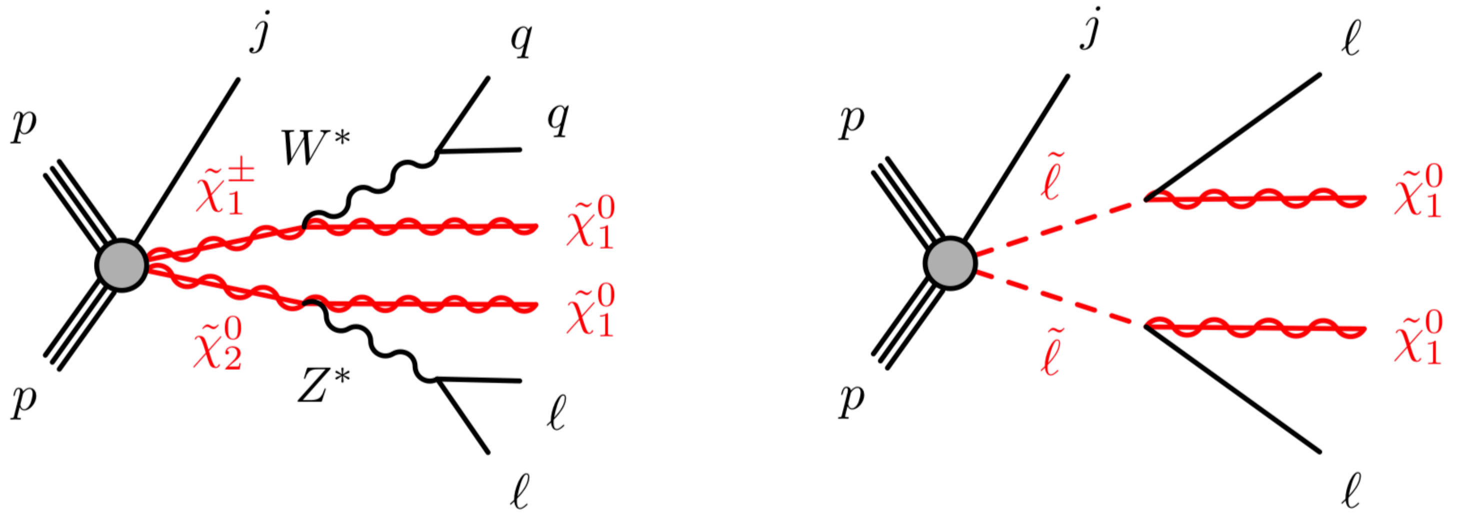
More intricate scenarios

Weak production of chagrinos, neutralinos and sleptons



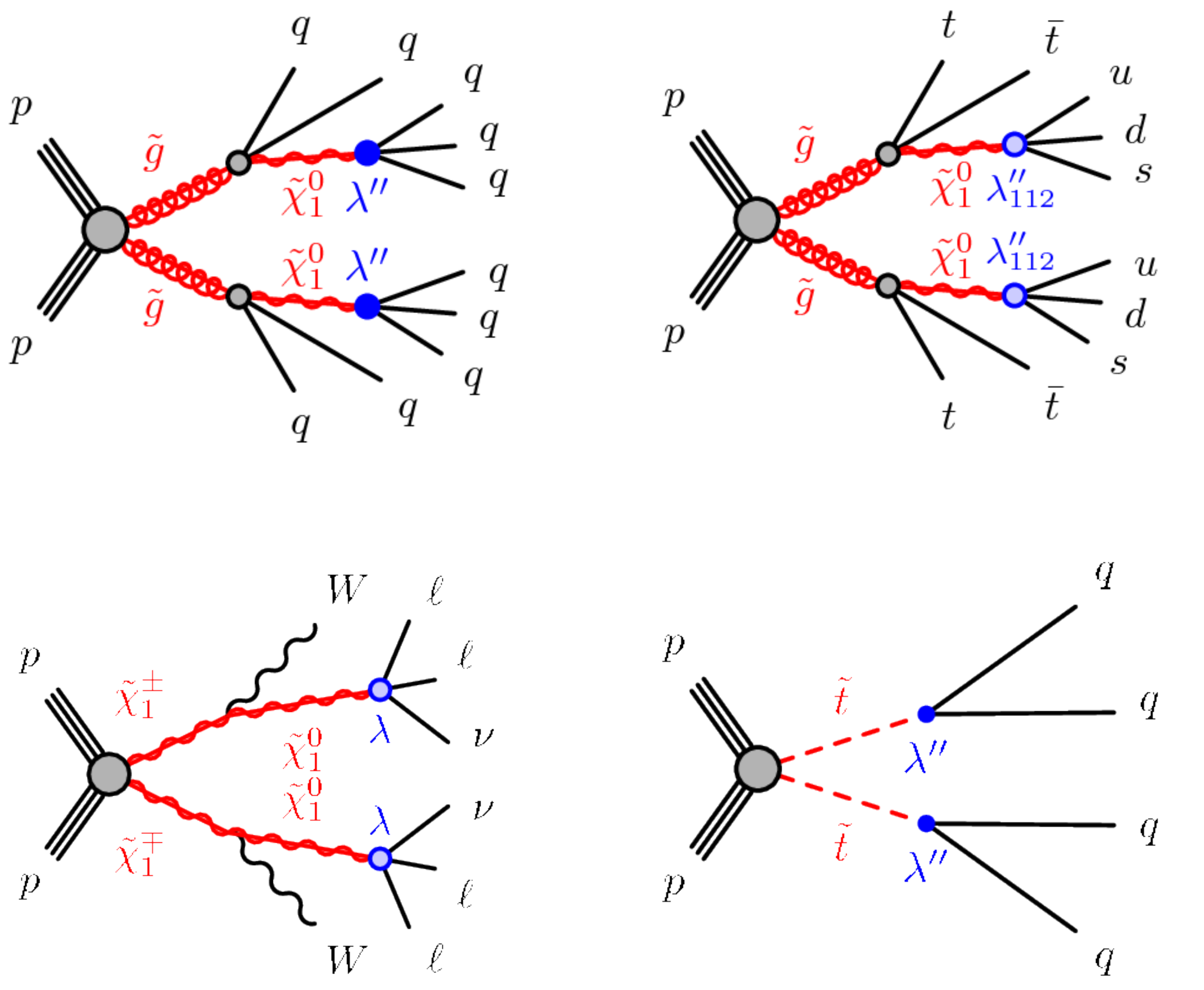
1 to 4 leptons (including taus) in the final state. Including decays to electroweak bosons.

Weak production in compressed scenarios



Scenarios where the charginos, neutralinos or sleptons are close to mass degenerate with the lightest SUSY particle (LSP).

R-Parity violating SUSY

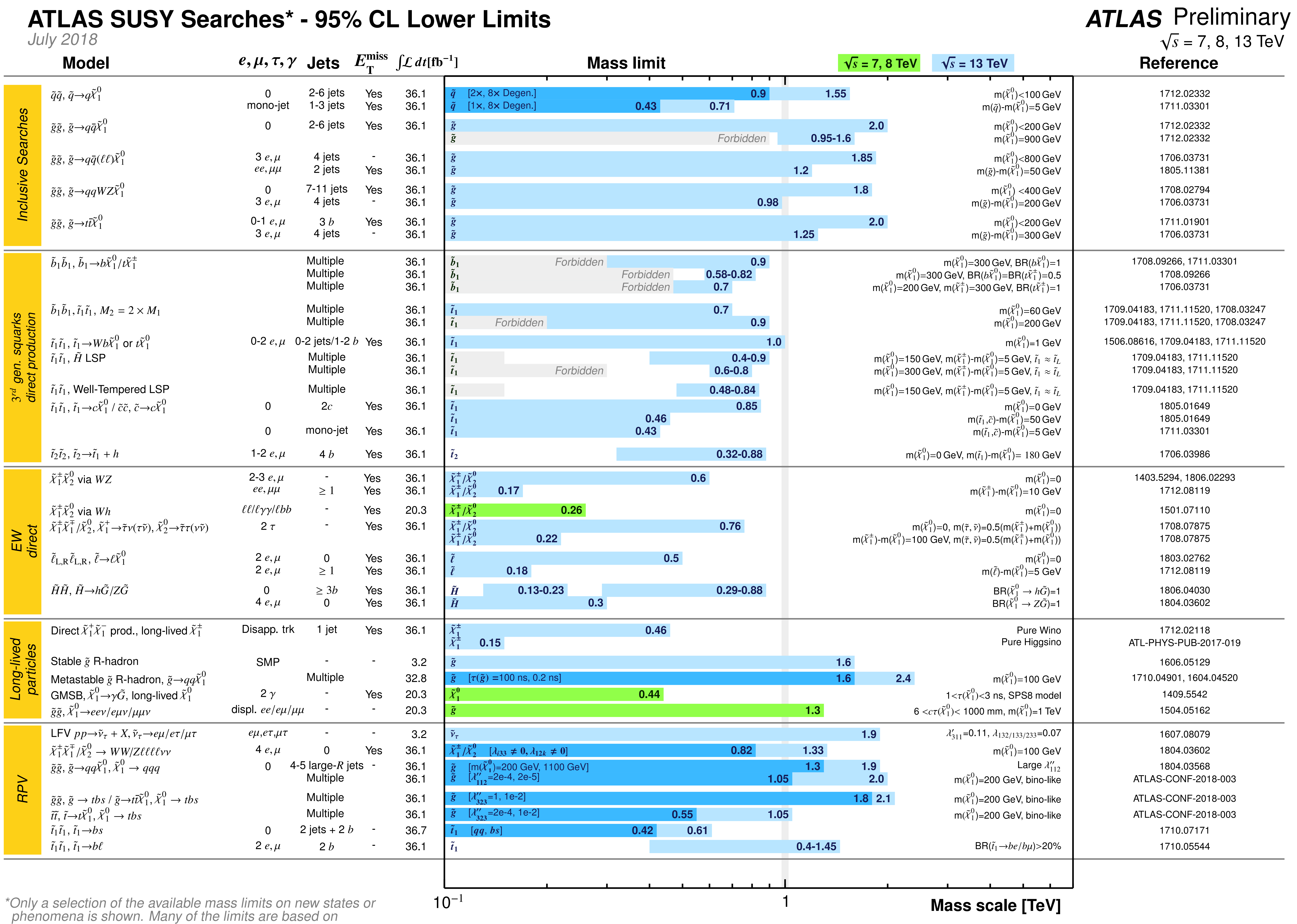


Resulting in topologies without LSP in the final state and therefore no MET.

$$\frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_i L_i H_2$$

RPV components of superpotential

SUSY Searches Overview (similar in CMS)



ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

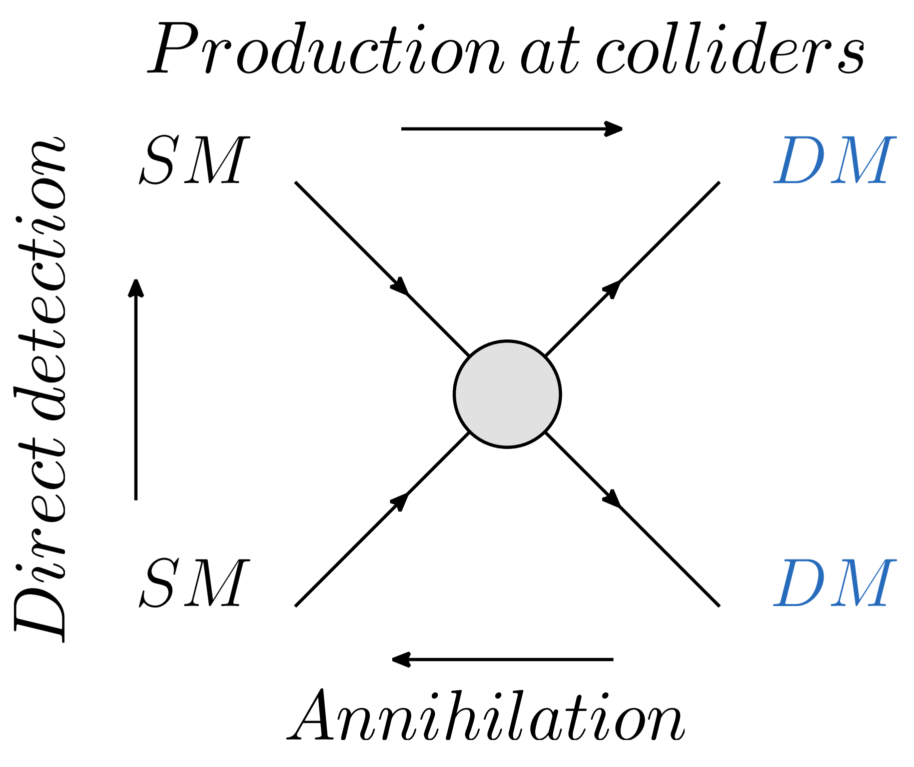
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$ [2×, 8× Degen.] 0.9 1.55	m($\tilde{\chi}_1^0$)<100 GeV	1712.02332
		mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ [1×, 8× Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.0	m($\tilde{\chi}_1^0$)<200 GeV	1712.02332
						$\tilde{g}$ Forbidden 0.95-1.6	m($\tilde{\chi}_1^0$)=900 GeV	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	$\tilde{g}$ 1.85	m($\tilde{\chi}_1^0$)<800 GeV	1706.03731
		$ee, \mu\mu$	2 jets	Yes	36.1	$\tilde{g}$ 1.2	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 1.8	m($\tilde{\chi}_1^0$) <400 GeV	1708.02794
		3 e, μ	4 jets	-	36.1	$\tilde{g}$ 0.98	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	1706.03731
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	$\tilde{g}$ 2.0	m($\tilde{\chi}_1^0$)<200 GeV	1711.01901
		3 e, μ	4 jets	-	36.1	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1706.03731
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.58-0.82	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($t\tilde{\chi}_1^\pm$)=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.7	m($\tilde{\chi}_1^0$)=200 GeV, m($\tilde{\chi}_1^\pm$)=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1	1706.03731
	$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1$, $M_2 = 2\times M_1$		Multiple		36.1	$\tilde{t}_1$ 0.7	m($\tilde{\chi}_1^0$)=60 GeV	1709.04183, 1711.11520, 1708.03247
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.9	m($\tilde{\chi}_1^0$)=200 GeV	1709.04183, 1711.11520, 1708.03247
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	36.1	$\tilde{t}_1$ 1.0	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{H}$ LSP		Multiple		36.1	$\tilde{t}_1$ 0.4-0.9	m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.6-0.8	m($\tilde{\chi}_1^0$)=300 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$ 0.48-0.84	m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2c	Yes	36.1	$\tilde{t}_1$ 0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.01649
		0	mono-jet	Yes	36.1	$\tilde{t}_1$ 0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	$\tilde{t}_2$ 0.32-0.88	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 180 GeV	1706.03986
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2-3 e, μ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.6	m($\tilde{\chi}_1^0$)=0	1403.5294, 1806.02293
		$ee, \mu\mu$	≥ 1	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.17	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=10 GeV	1712.08119
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.26	m($\tilde{\chi}_1^0$)=0	1501.07110
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.76	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
						$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.22	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=100 GeV, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1708.07875
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1	$\tilde{\ell}$ 0.5	m($\tilde{\chi}_1^0$)=0	1803.02762
		2 e, μ	≥ 1	Yes	36.1	$\tilde{\ell}$ 0.18	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=5 GeV	1712.08119
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0	$\geq 3b$	Yes	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}_1^0 \to h\tilde{G}$)=1	1806.04030
		4 e, μ	0	Yes	36.1	$\tilde{H}$ 0.3	BR($\tilde{\chi}_1^0 \to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$ 0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^\pm$ 0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron	SMP	-	-	3.2	$\tilde{g}$ 1.6		1606.05129
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		32.8	$\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns] 1.6 2.4	m($\tilde{\chi}_1^0$)=100 GeV	1710.04901, 1604.04520
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 0.44	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{g}$ 1.3	6 <$c\tau(\tilde{\chi}_1^0)$< 1000 mm, m($\tilde{\chi}_1^0$)=1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0 \to WW/Z\ell\ell\ell\ell\nu\nu$	4 e, μ	0	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33} \neq 0, \lambda_{12k} \neq 0$] 0.82 1.33	m($\tilde{\chi}_1^0$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ [m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}$, $\tilde{g} \to tbs$ / $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=1, 1e-2] 1.8 2.1	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e, μ	2 b	-	36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544

*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.

Generic Search for Dark Matter Searches and Dark Matter Mediator

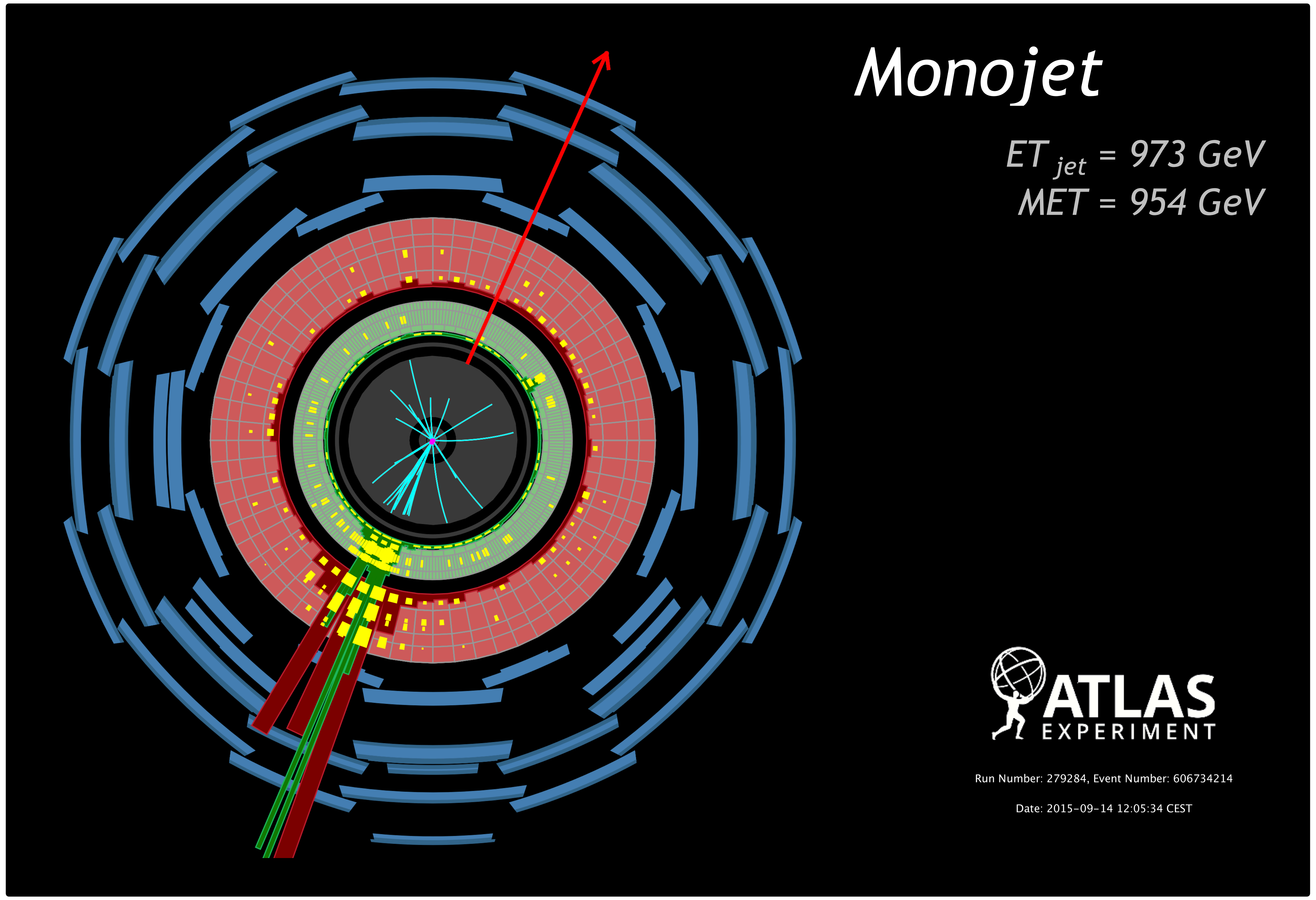
Complementarity with direct detection

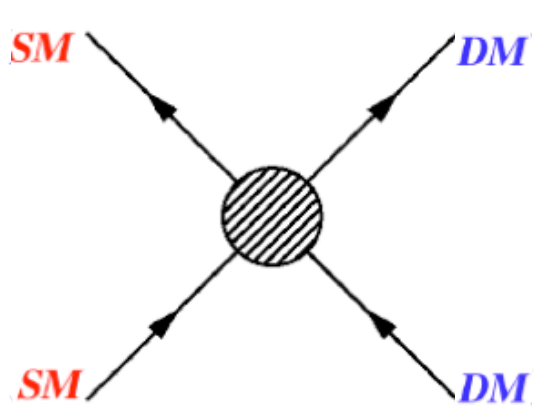
Of course outstanding if seen in a lab!

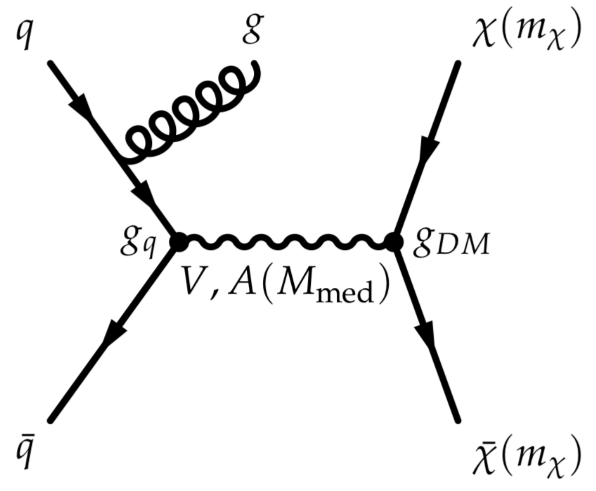


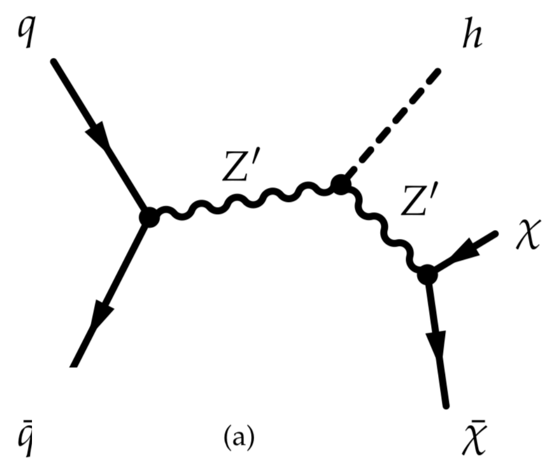
Direct searches for Dark Matter

- Invisible Higgs searches (Lecture 3).
- Mono-anything searches: Mono-jet, mono-V (leptonic and hadronic), Mono-Higgs (various modes), Mono-photon, Mono-top.



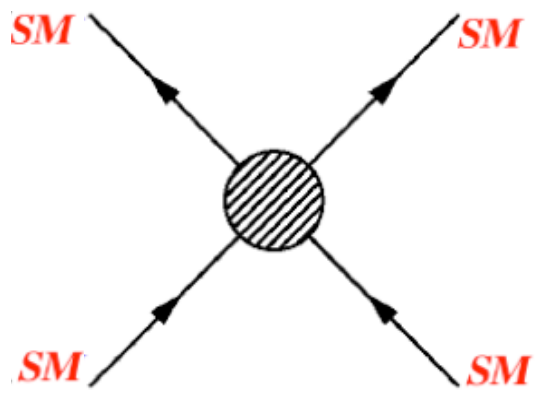






Searches for the dark matter mediator

in e.g. in dijet events extending at low masses



Searches for new Physics Beyond the Standard Model in non SUSY theories

Panorama of Searches for Conventional Signatures

Searches for Vector Like Quarks

Fermions that are not Chiral

- Their L and R components transform the same way under SM symmetries.
- Interact with SM through mixing with SM quarks.
- Present in models where the Higgs is a pseudo Goldstone boson (e.g. in Composite Higgs and little Higgs models).
- Present in Warped Extra dimension models.

Large variety of possible states and complex channels

- Heavy quark partners with charges -1/3, 2/3, 4/3 and 5/3.
- Complex channels looking for T(2/3), B(1/3): Ht+X, Wt+X, Wb+X, Zb+X, Zt+X (Performed at Run 2) so far and T(5/3) 4tops final state.

Any still many more !!

Searches for W'and Z'

High mass states motivated in many theories e.g. Grand Unified and additional gauge symmetries.

- electrons, muons, taus, jets, b-jets and tops.
- di-bosons including vector bosons and Higgs bosons

Searches for high mass states of spin 0 and 2

Motivate in Randall Sundrum models (Graviton and radion)

Searches in various channels dijet, diphoton and di-leptons

Any many more

- **Quark compositness**
- **Leptoquarks**: predicted in grand unified theories and interest raised by lepton flavor universality anomalies
- **Heavy neutrinos**: produced in theories for neutrino masses (e.g. Seesaw)
- **High mass and high activity events**: strong gravity (from extra dimension theories), mini black holes, quantum black holes…
- **Searches for low mass states.**

Panorama of Searches for Conventional Signatures

Searches for Vector Like Quarks

Fermions that are not Ch

- Their L and R componen under SM symmetries.
- Interact with SM throug
- Present in models wher boson (e.g. in Composit
- Present in Warped Extra

Large variety of possible

- Heavy quark partners w 5/3.
- Complex channels looki Wt+X, Wb+X, Zb+X, Zt+ T(5/3) 4tops final state

Searches for W’and Z’

High mass states motivated in many theories e.g.

symmetries.

s and tops.

nd Higgs bosons

es of spin 0 and 2

s (Graviton and radion)

iphoton and di-leptons

fied theories and interest

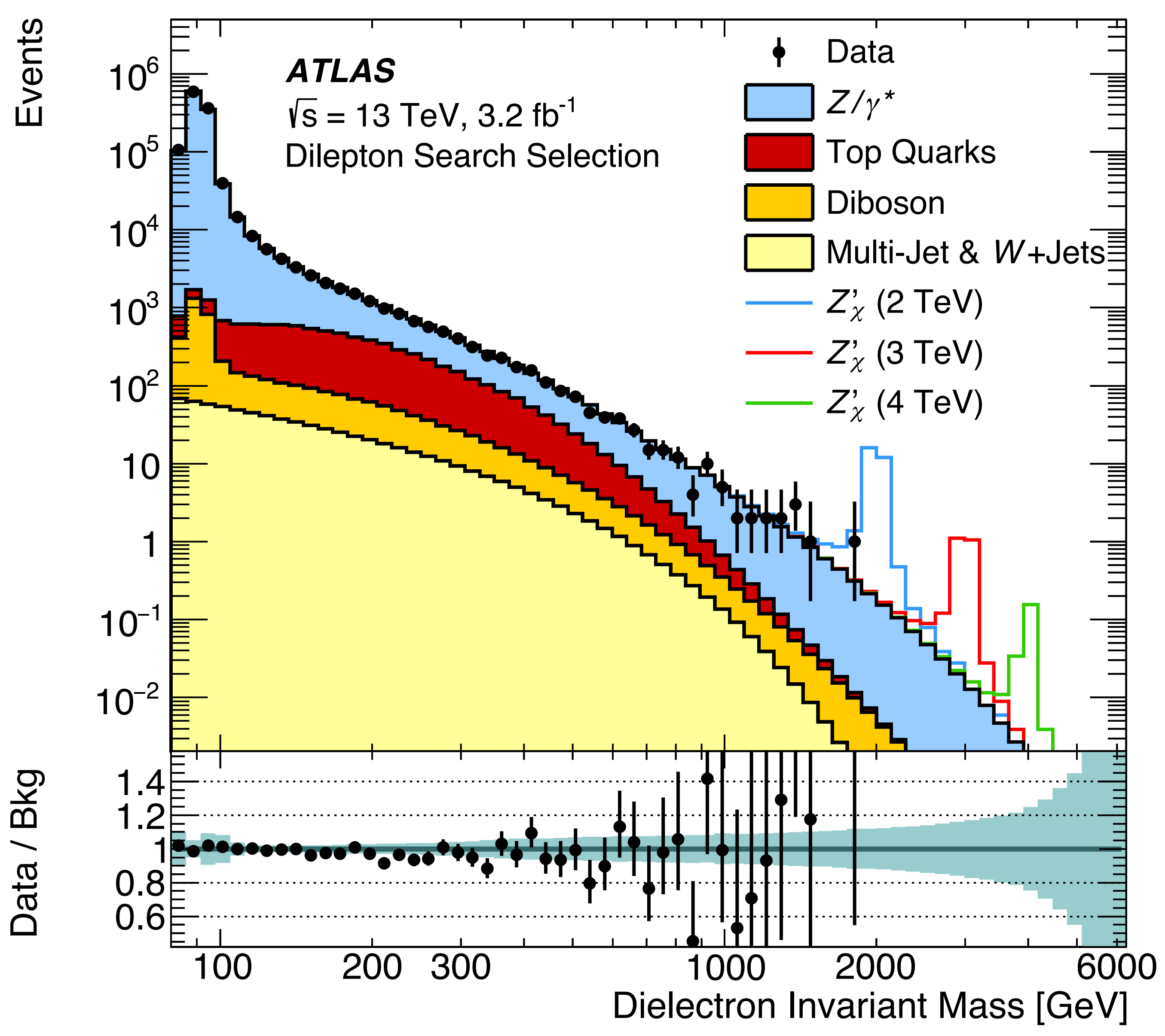
nomalies

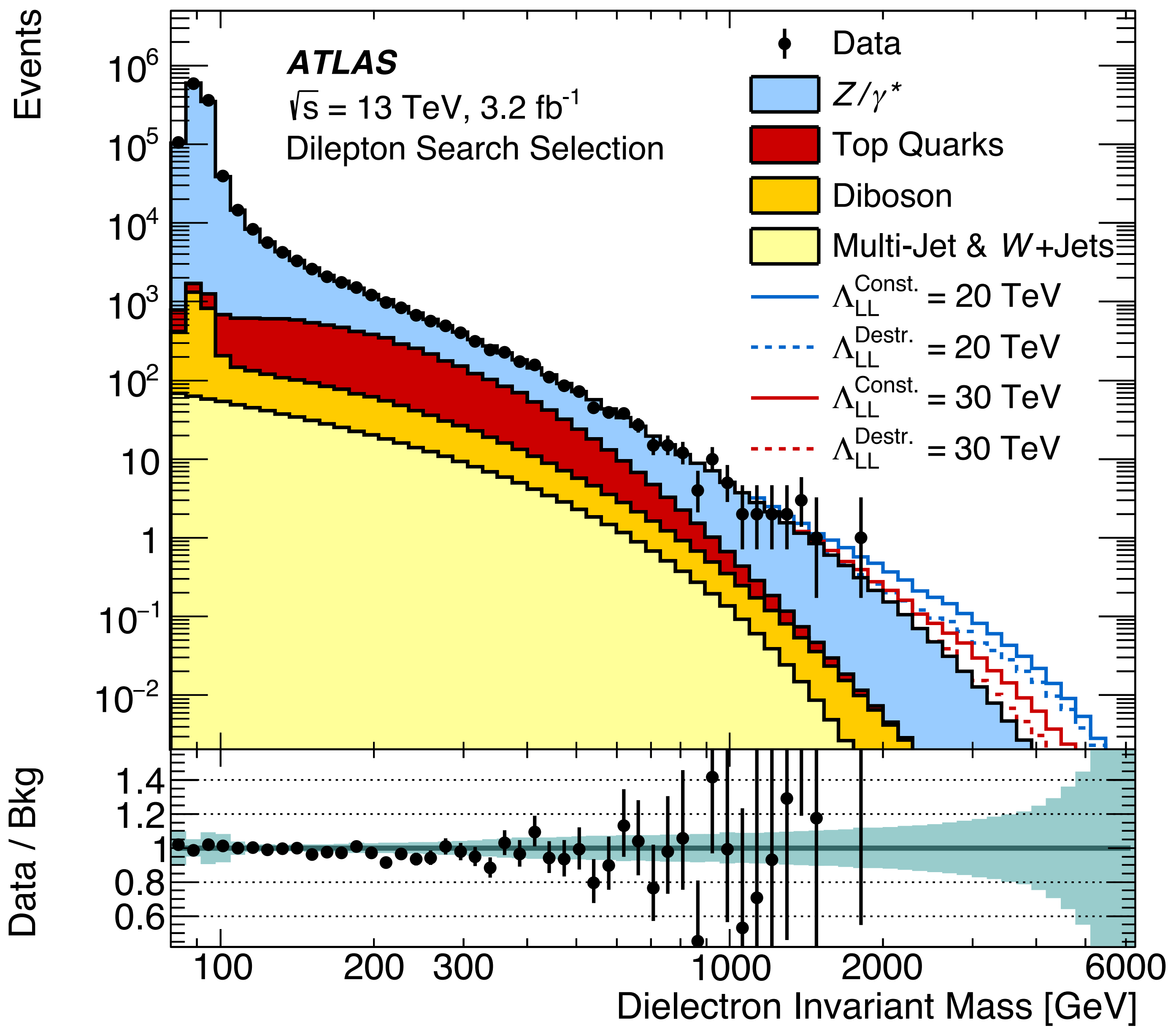
es for neutrino masses

- **High mass and high activity events:** strong gravity (from extra dimension theories), mini black holes, quantum black holes…
- **Searches for low mass states.**

Not only searches for resonances also deviations in tails

In this case predictions are key

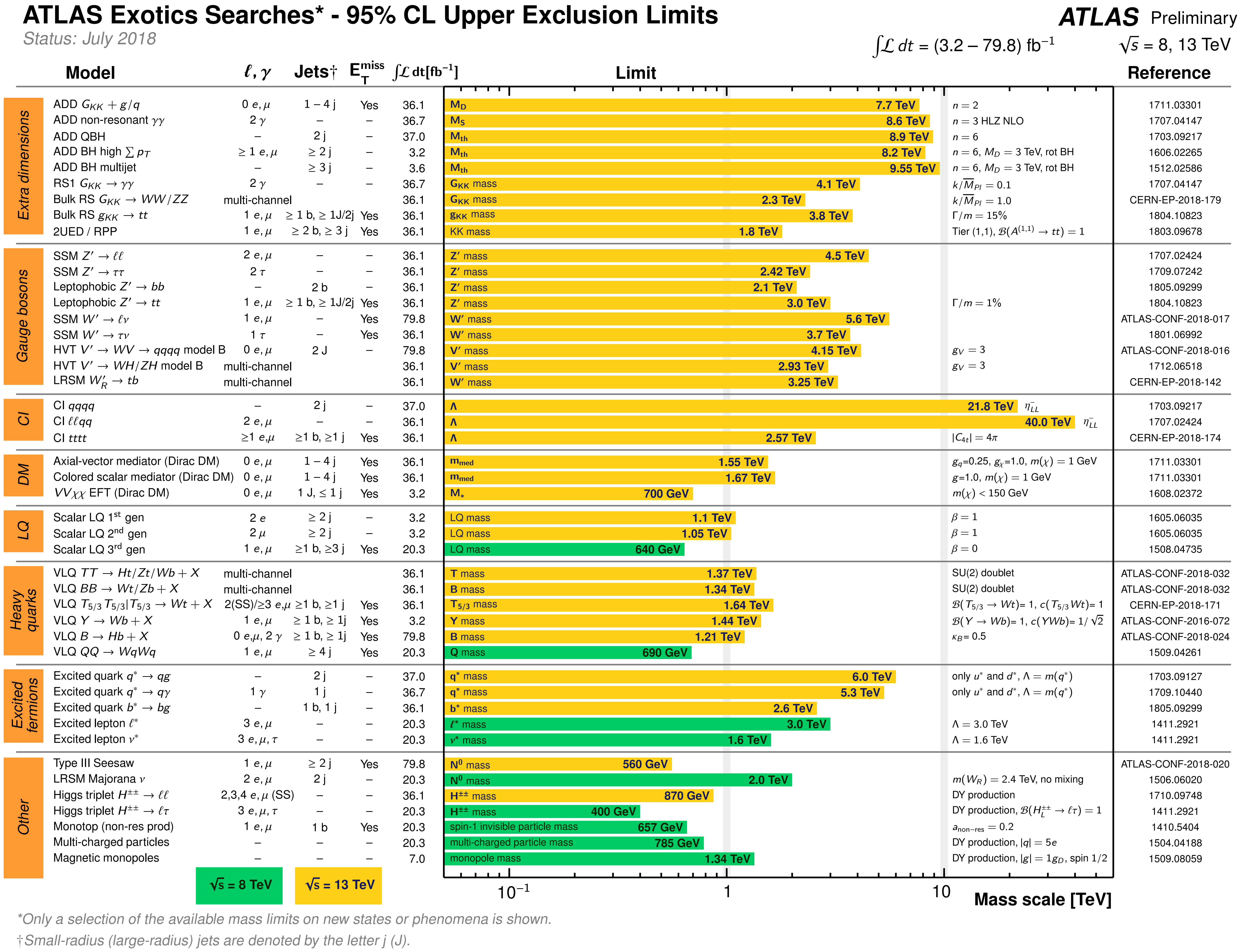




Contact interaction model

Any still many more !!

Exotics Searches Overview (similar in CMS)



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 79.8)\ \text{fb}^{-1}$

$\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	🟨 M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	🟨 M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	🟨 M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	🟨 M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	🟨 G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	🟨 G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	CERN-EP-2018-179
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	🟨 KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	🟨 Z' mass 4.5 TeV		1707.02424
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	🟨 Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	🟨 Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 Z' mass 3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	79.8	🟨 W' mass 5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	🟨 W' mass 3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	79.8	🟨 V' mass 4.15 TeV	$g_V = 3$	ATLAS-CONF-2018-016
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	🟨 V' mass 2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	🟨 W' mass 3.25 TeV		CERN-EP-2018-142
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ 21.8 TeV	η_{LL}^{-}	1703.09217
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	🟨 Λ 40.0 TeV	η_{LL}^{-}	1707.02424
	CI $tttt$	$\geq$1 e,μ	$\geq$1 b, $\geq$1 j	Yes	36.1	🟨 Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	🟨 m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	🟨 m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	🟨 M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	🟨 LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	🟨 LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	$\geq$1 b, $\geq$3 j	Yes	20.3	🟩 LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	🟨 T mass 1.37 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	🟨 B mass 1.34 TeV	SU(2) doublet	ATLAS-CONF-2018-032
	VLQ $T_{5/3}T_{5/3} \vert T_{5/3} \to Wt + X$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	36.1	🟨 $T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	CERN-EP-2018-171
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	3.2	🟨 Y mass 1.44 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c(YWb)$= $1/\sqrt{2}$	ATLAS-CONF-2016-072
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	🟨 B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	🟩 Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	🟨 q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	🟨 q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	🟨 b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	🟨 N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	🟩 N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	🟨 $H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	🟩 spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s}$ = 8 TeV

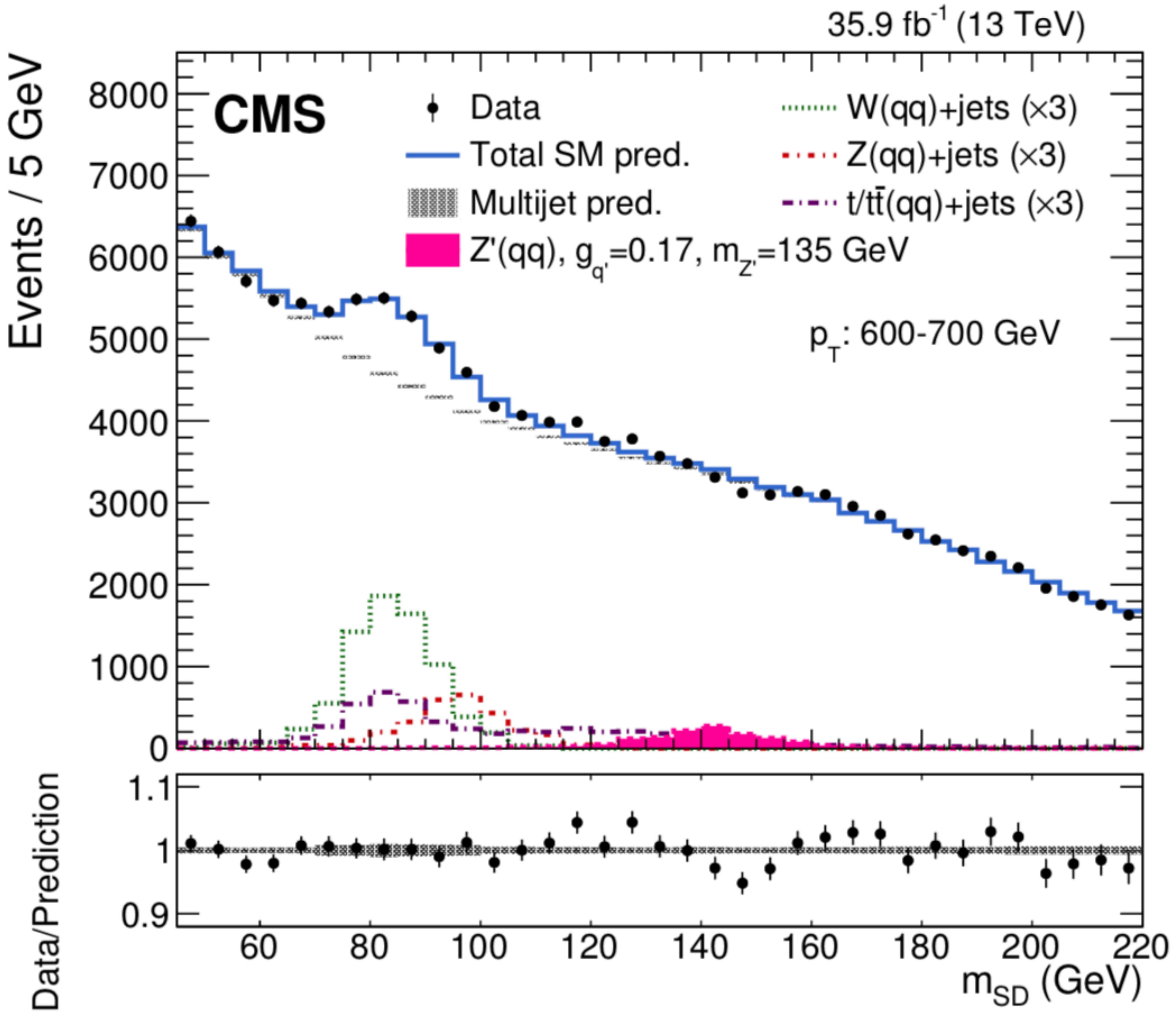
🟨 $\sqrt{s}$ = 13 TeV

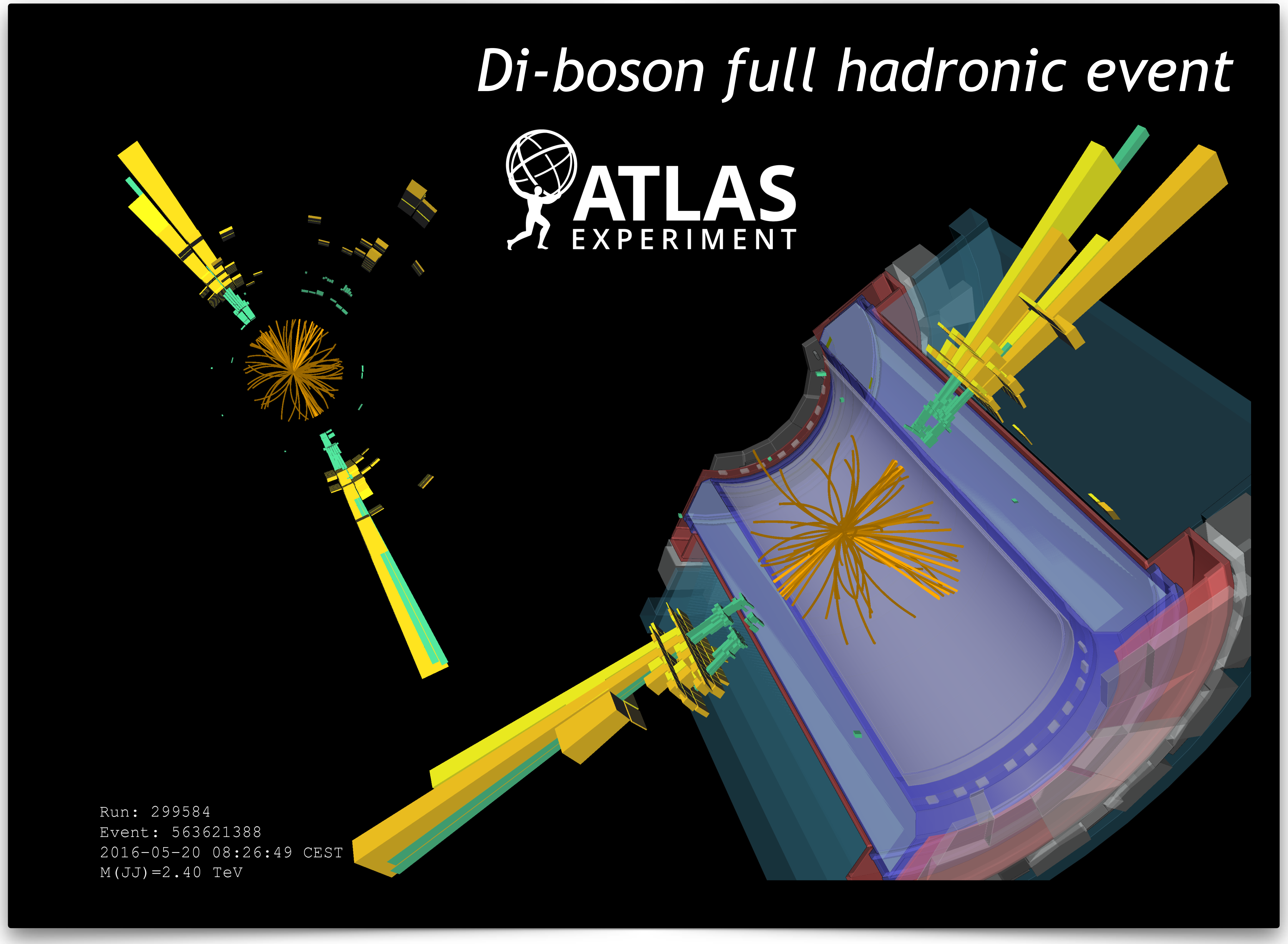
*Only a selection of the available mass limits on new states or phenomena is shown.

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

Comment (I): Improving Reconstruction Techniques

Jet substructure reconstruction improvements (reconstructing a vector boson as a single jet and investigating its structure to identify the vector boson).

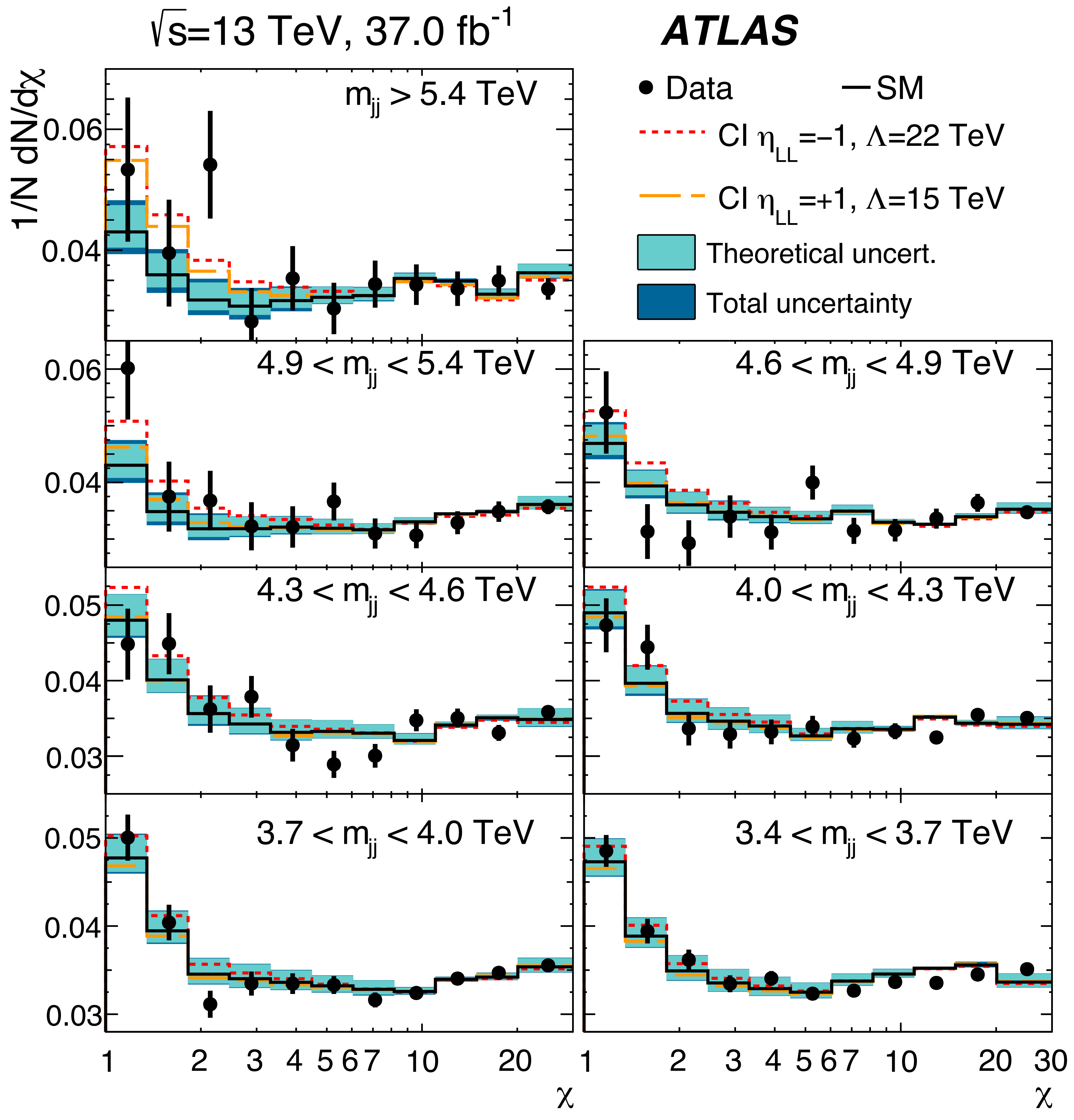




Di boson candidate event in a fully hadronic search, each jet has a mass compatible with a vector boson (W or Z).

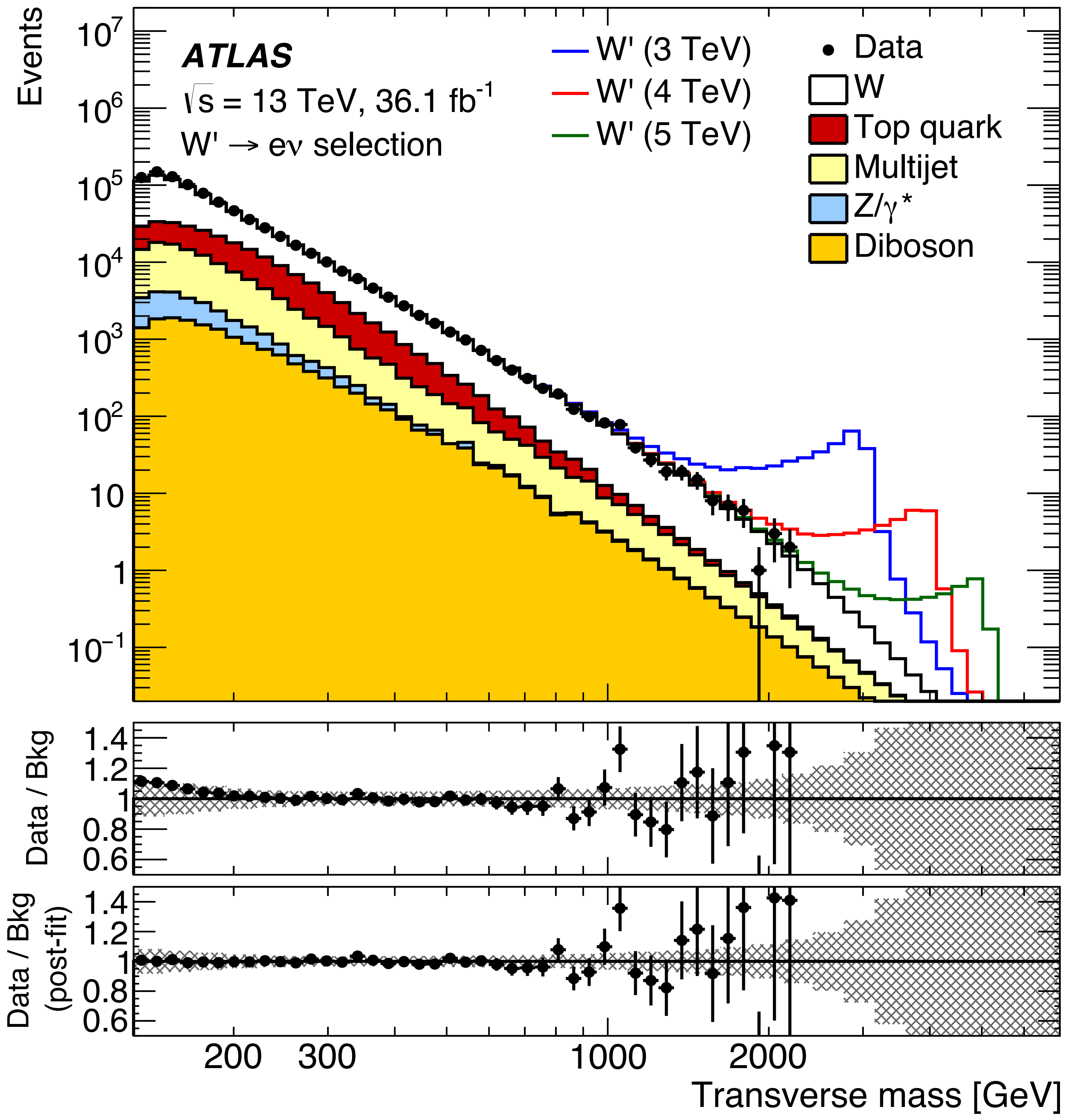
Comment (II): Examples of challenges in reconstruction, trigger and precision in difficult regions of phase space

Dijet angular distributions



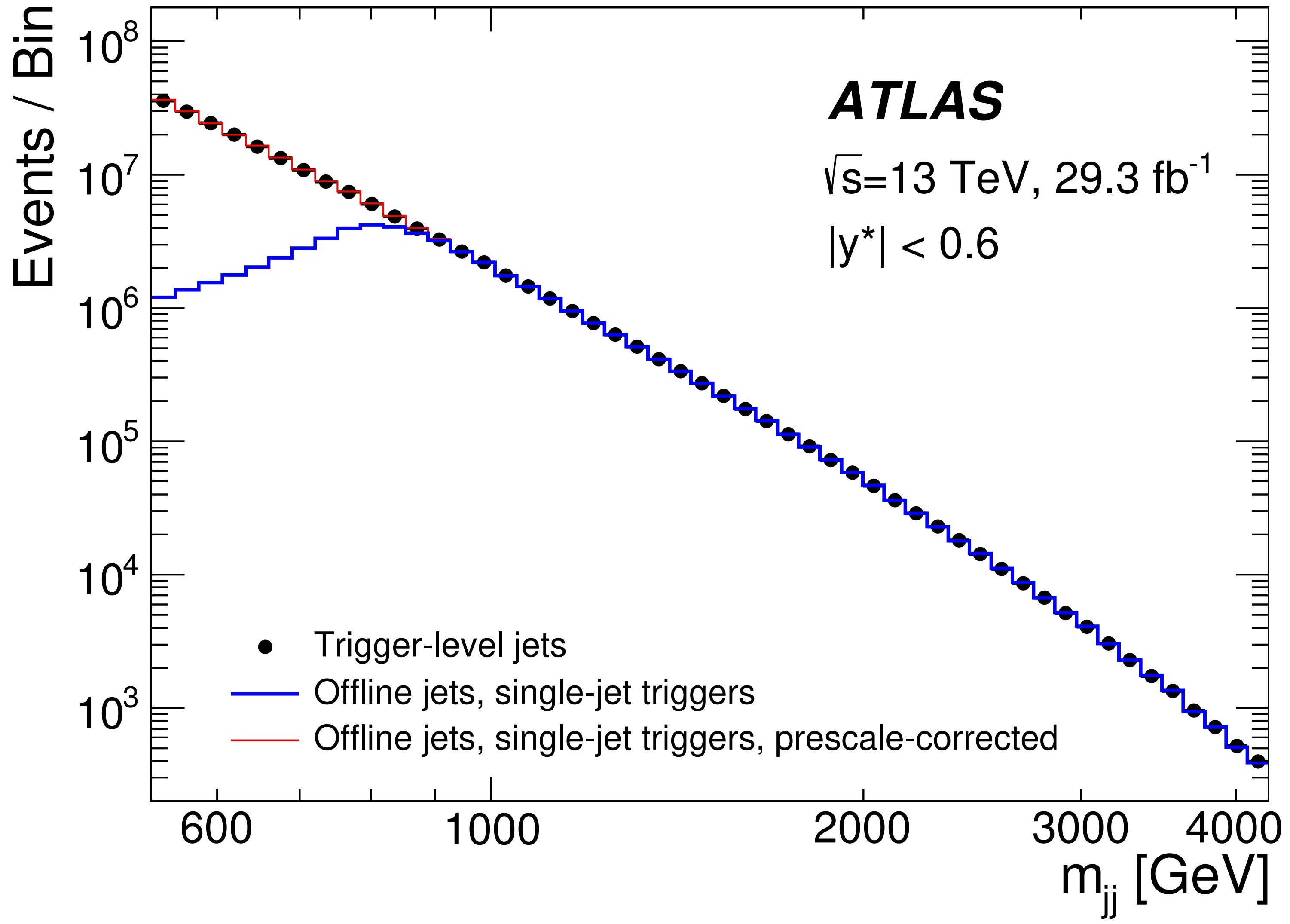
Jet cross sections predictions and jet calibration with multi TeV jets

Transverse mass (in lepton-MET search)



Drell Yan (and other processes) predictions and lepton calibration in the TeV energy range.

Dijet Trigger level analysis



Challenges to perform analysis at trigger level.

Unconventional Signatures

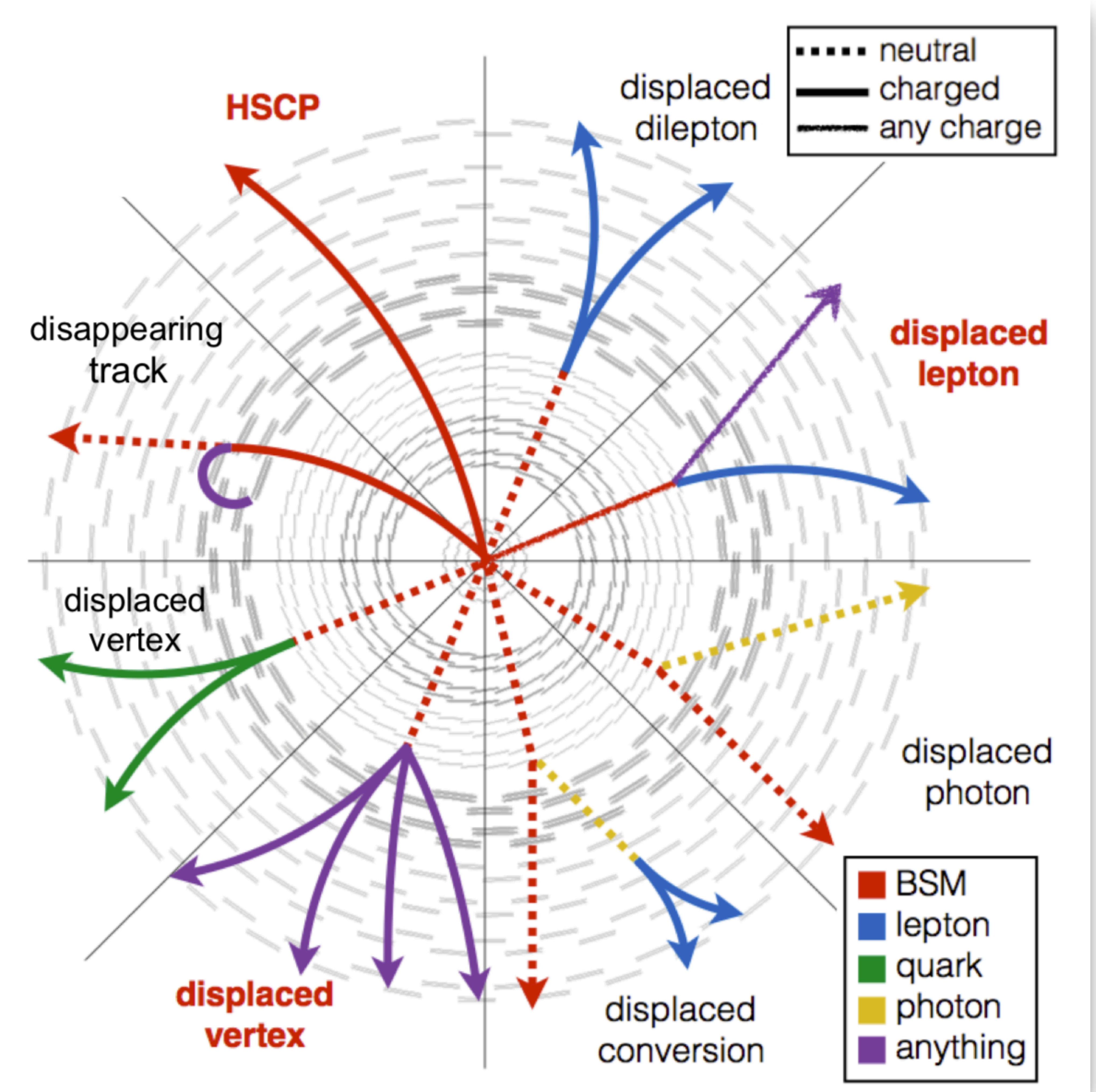
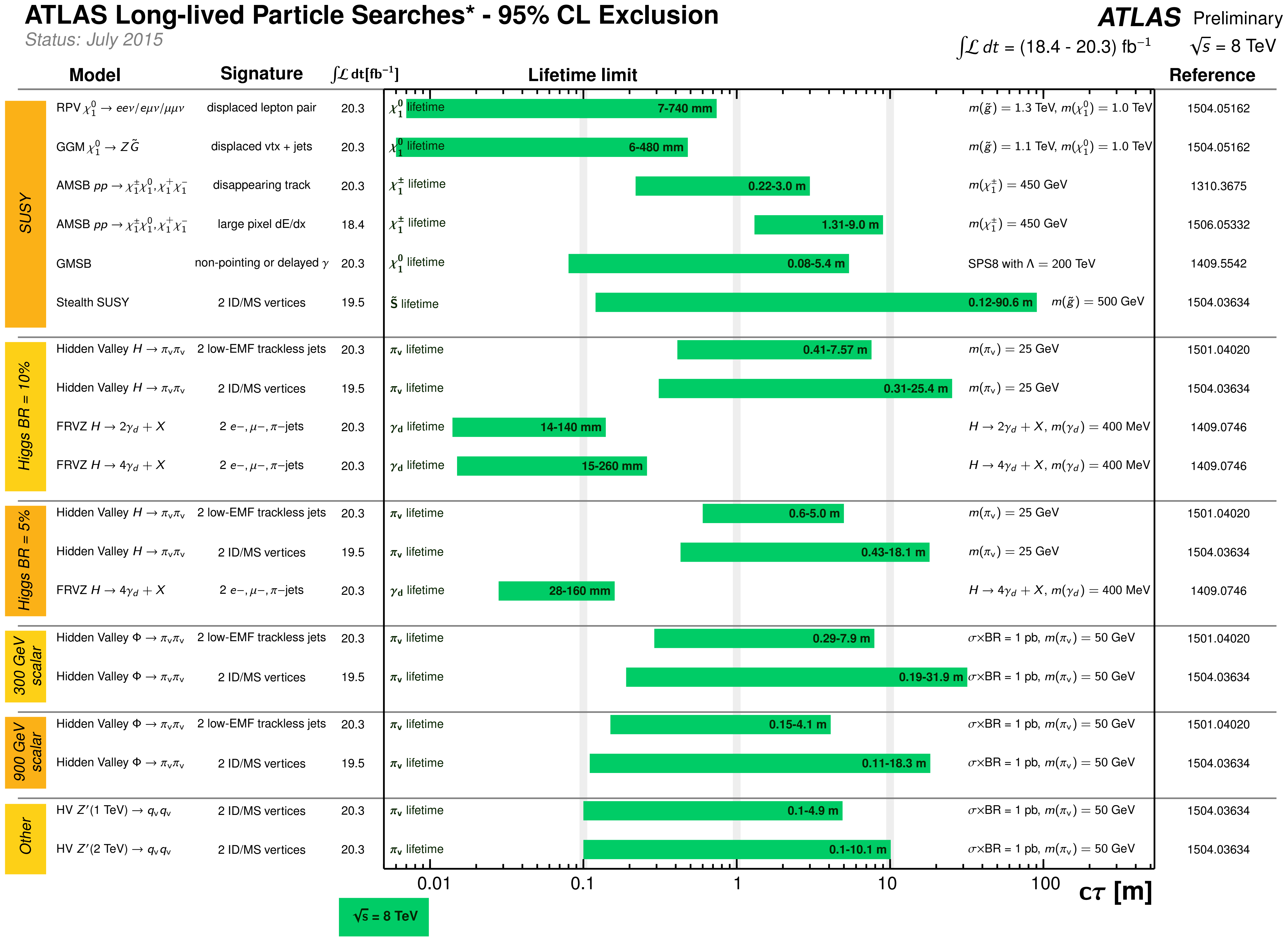


Image from J. Antonelli@ICHEP 2016

Many extensions of the Standard Model predict new particles that are long lived heavy (neutral and charged) and can decay after several cm or even meters.



*Only a selection of the available lifetime limits on new states is shown.

Difficult signatures requiring specific reconstruction and trigger!

Complementarity between searches and precision

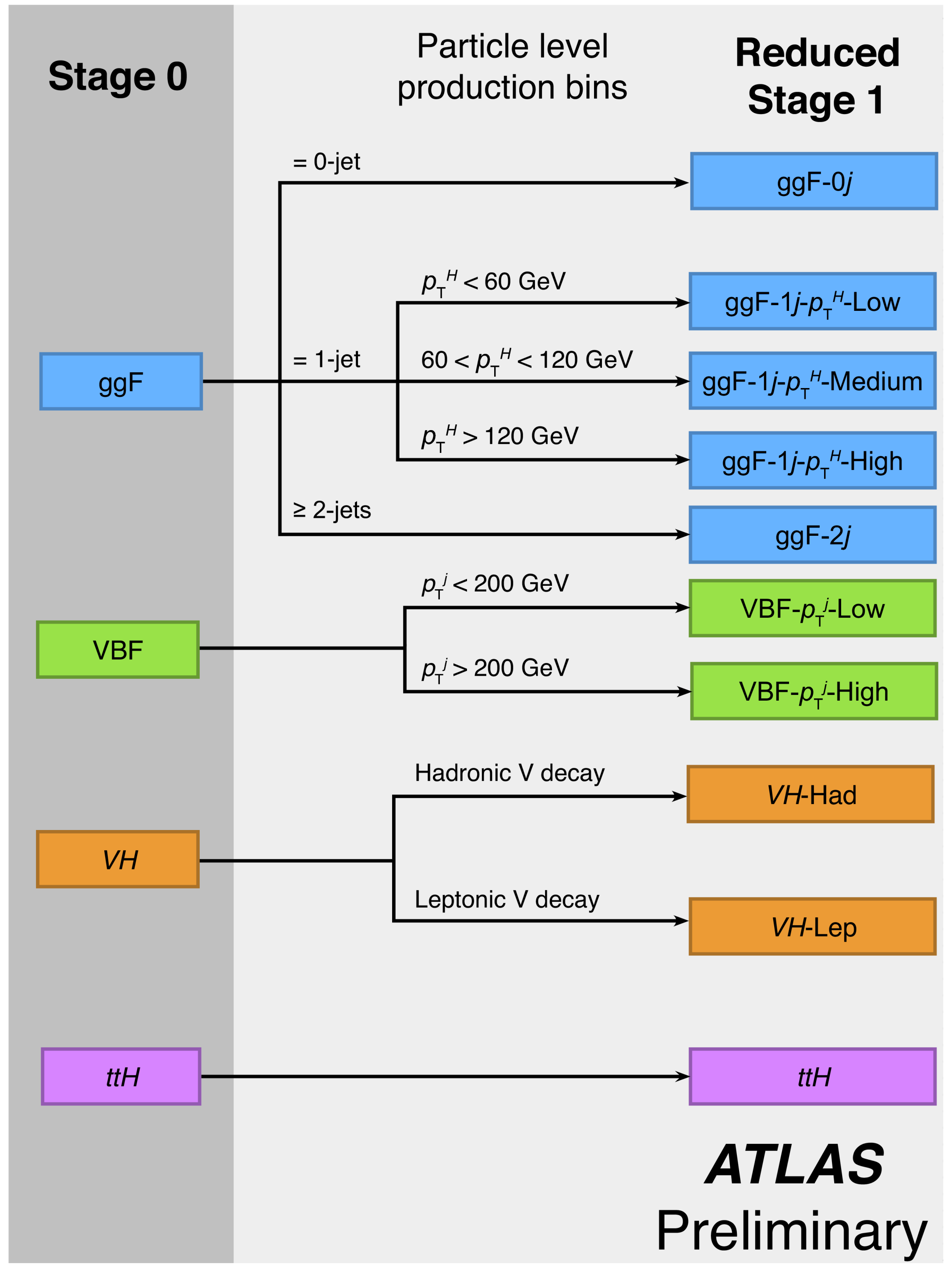
Measurement of SM processes in the high energy domain

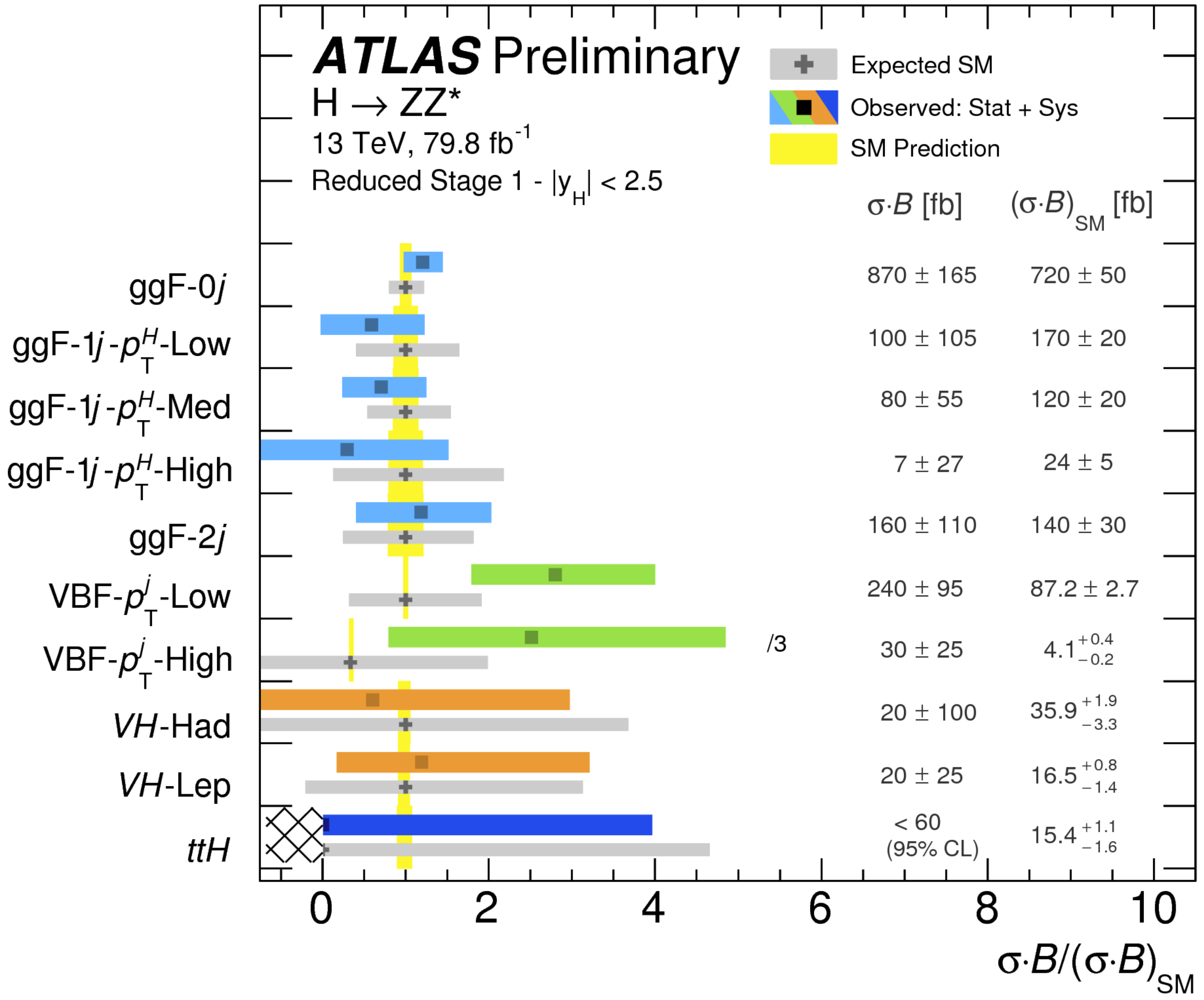
Effective field theory and measurements of non resonant processes at higher energy

$$\frac{\delta c}{c} \sim \frac{g_*^2}{g_{SM}^2}\frac{m_h^2}{\Lambda^2}$$

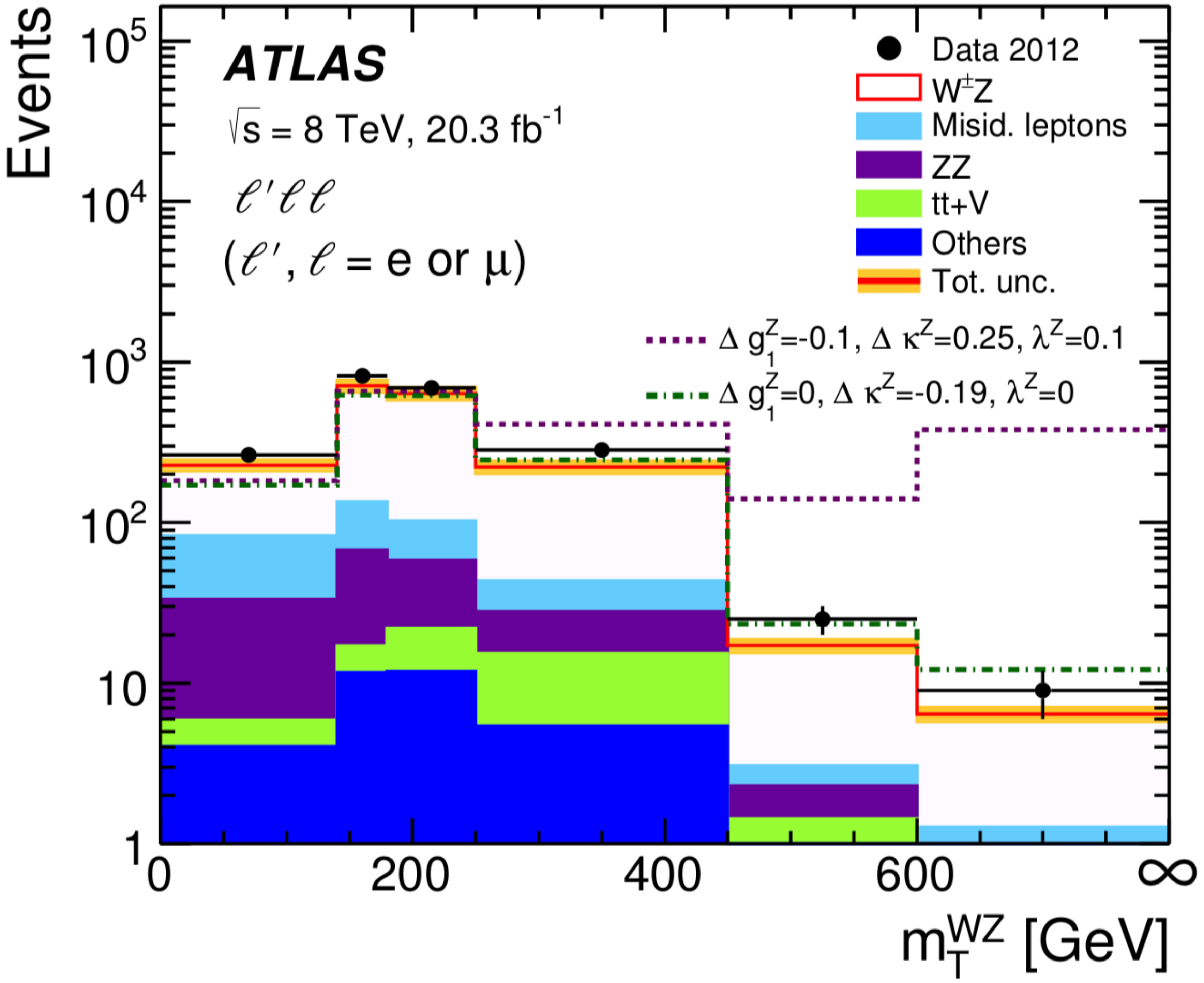
$$\frac{\delta \mathcal{A}}{\mathcal{A}} \sim \frac{g_*^2}{g_{SM}^2}\frac{E^2}{\Lambda^2}$$

Can reach similar or better sensitivity with less precision





Measurement of Higgs production cross sections in high transverse momentum regime



Measurement of di-boson in the high mass regime

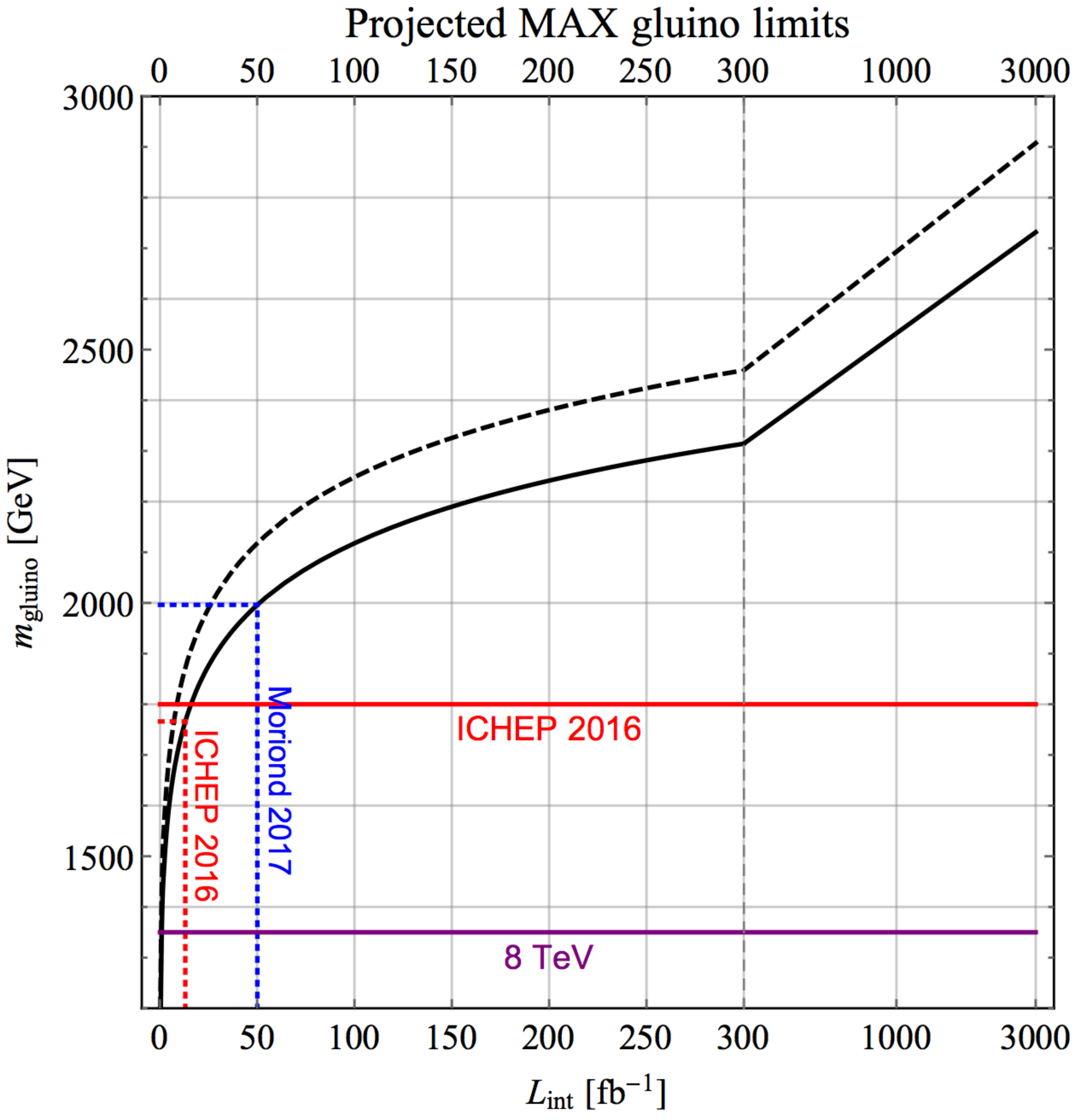
Conclusions on Searches

Nothing new!

- One of the main goals of the LHC as a hadron collider at the energy frontier is the direct searches for new phenomena.
- After the discovery of the Higgs boson, there is no « **no loose** » theorem anymore!
- TH guidance is crucial (see Lecture 3) the TH community has been actively providing it, addressing the large number of open questions, in particular naturalness (see talk by Christophe).
- An extensive program of direct searches has been carried out at the LHC following this guidance.
- So far no significant deviation in direct searches has been observed.

Where do we stand in the LHC program?

- So far only ~1% of the data of the entire LHC program has been analysed.



From D. Shih (from G. Salam)

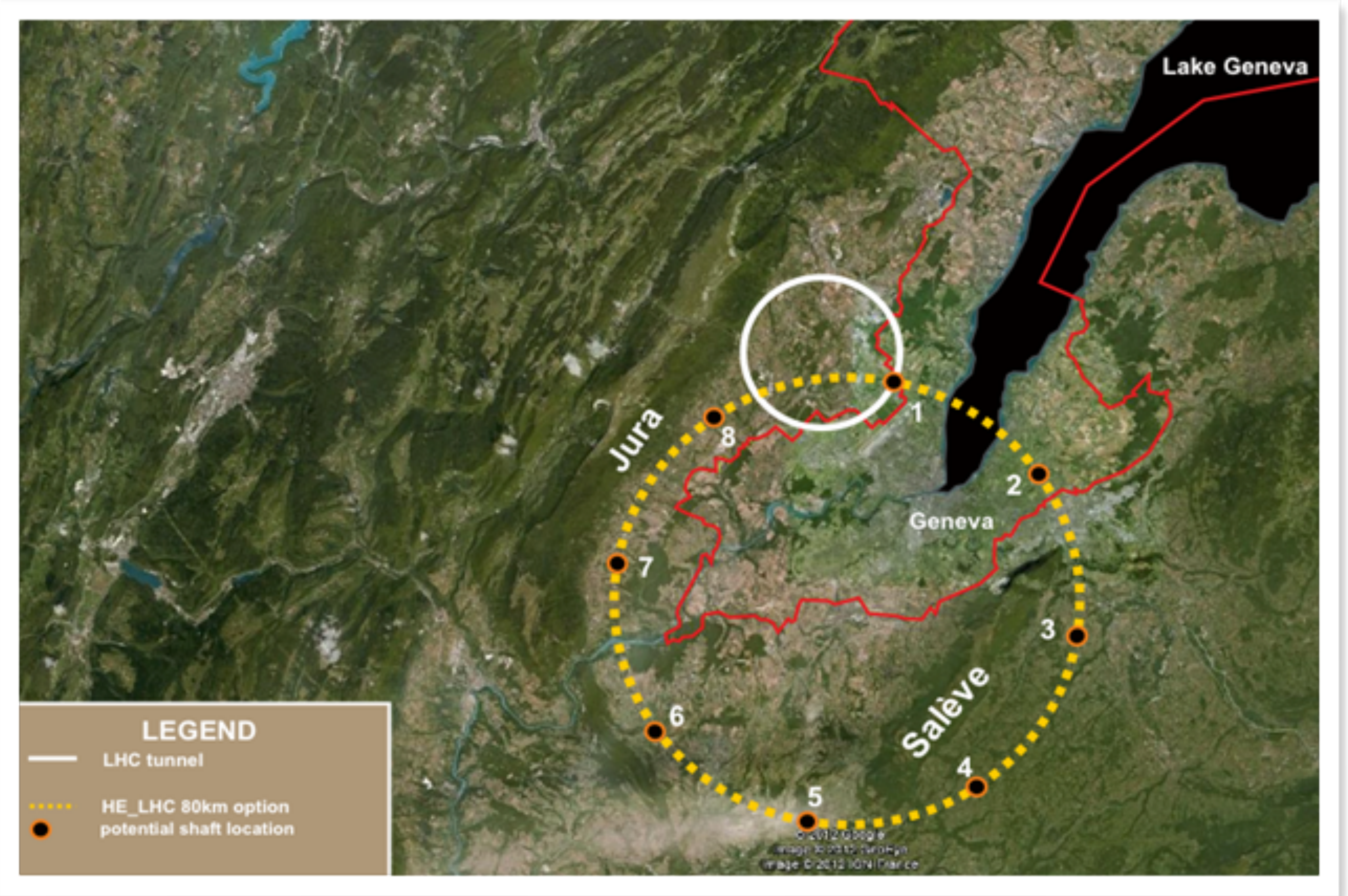
- The doubling time of the luminosity should now be counted in years.
- The time for spectacular discoveries (at this energy) is gone.
- **There is however plenty of room for discoveries!!**

Outlook on Future Hadron Colliders

Glimpse at Future Hadron Colliders

The candidate machines in a tiny nutshell

Project	HL-LHC	HE-LHC	FCC-hh	SppC
Location	CERN	CERN	CERN	China TBD
Circ.	27 km	27 km	100 km	55 - 100 km
COM energy	14 (15?) TeV	27 TeV	100 TeV	70 -140 TeV
Luminosity	3 ab-1	15 ab-1	20-30 ab-1	TBD
PU	up to 200	up to 800	up to 1000	TBS
Bunch sp.	25 ns	25 ns	25 ns	25 ns
Field	8T	16T	16T	20T
When?	Until 2037	After 2037?	After 2037	TBS



Much much more in Lecture by R. Corsini

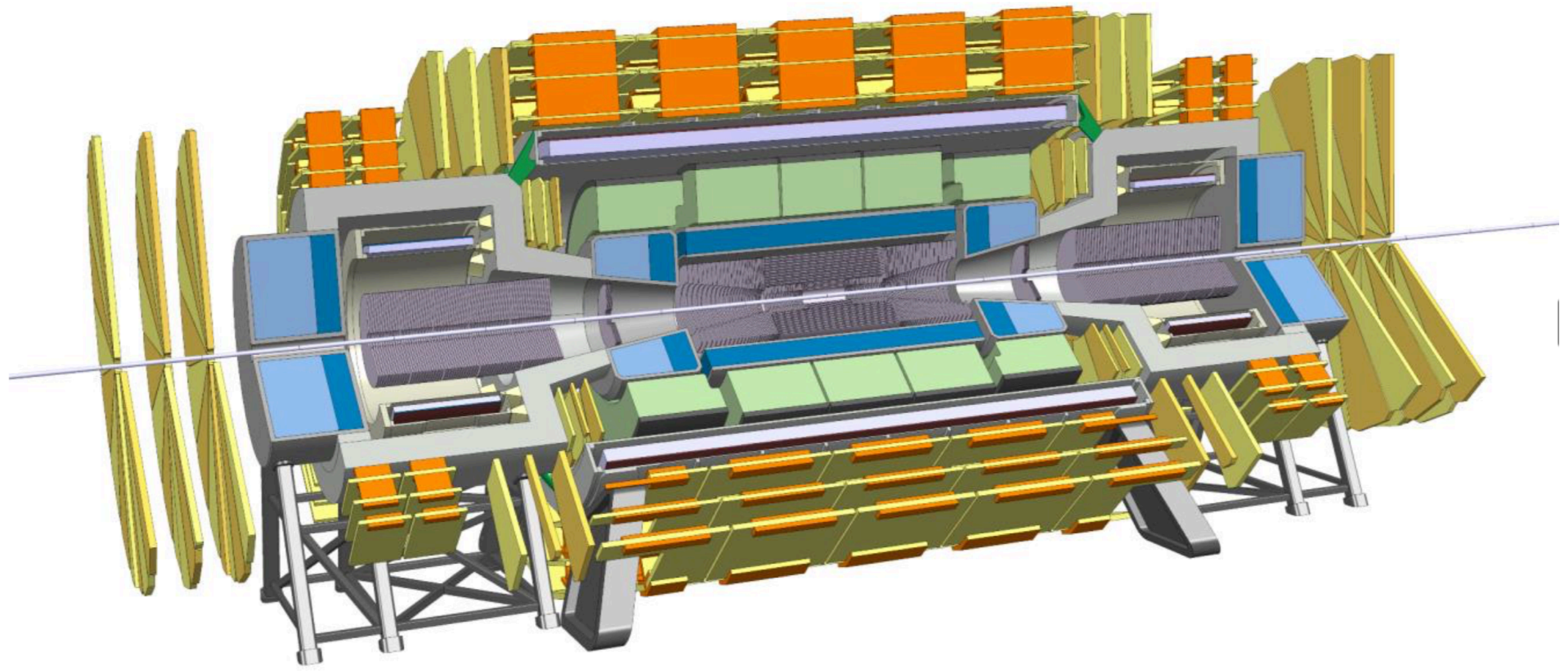
Detector, Trigger DAQ, Reconstruction challenges

Two challenges: higher PU (1000) higher pT

Answer: granularity and resolution

Decay products of a Z at 10 TeV are separated by $\Delta R = 0.01$

A b at 5 TeV can travel 50cm and a tau 10 cm



Outlook on Future Hadron Colliders

Preliminary remarks:

- The LHC program is only at its start with about only 1% of the data collected so far.

- Although no signals of physics beyond the Standard Model have been found so far despite the vast number of motivations, **does not preclude whatsoever future discoveries at the LHC**.

- In absence of new guidance either from the experiments or the TH community, and in the absence of **no loose theorem**, the complementarity between precision measurements and direct searches is essential.

- In case something new is found at the LHC the entire strategy has to be revisited.

The guaranteed potential:

- The detailed study of the Higgs boson couplings and further probing the consistency of the Standard Model with precision EW measurements is essential.

- The measurement of Standard Model production observables at high energy (di boson, Higgs, etc…)

The opportunities:

- Physics motivations are very similar to those we currently have at the LHC

- The direct search signatures are similar (taking into account the scaling of backgrounds at higher energy and different detector constraints)

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Numbers given here for FCC-hh and HL-LHC physics potential of HE-LHC is under study, however rule of thumbs scaling can give a fair estimate.

Direct searches

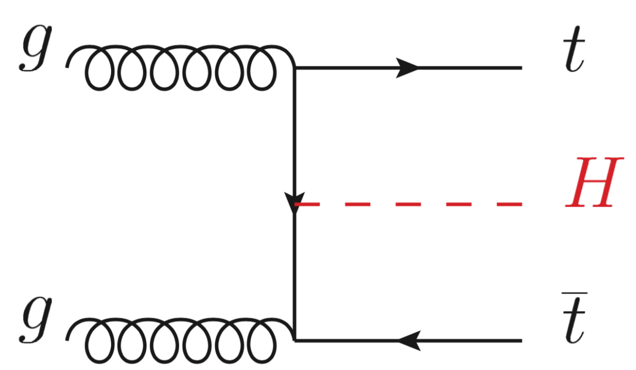
The reach in searches will range typically between a few TeV for weakly produced particles and **reach 20 TeV** for strongly interacting new particles as gluinos.

Precision SM and Higgs

- Precision EW measurements could reach unprecedented levels of accuracy with very high luminosity programs at the Z peak, the WW threshold and the tt threshold (MeV precision on the W mass, and tens of MeV on the top mass).

- Precision Higgs measurements will rely on a very complementary electron-positron collider which should reach sub percent level precision on most couplings (as well as measuring the total width of the Higgs boson)

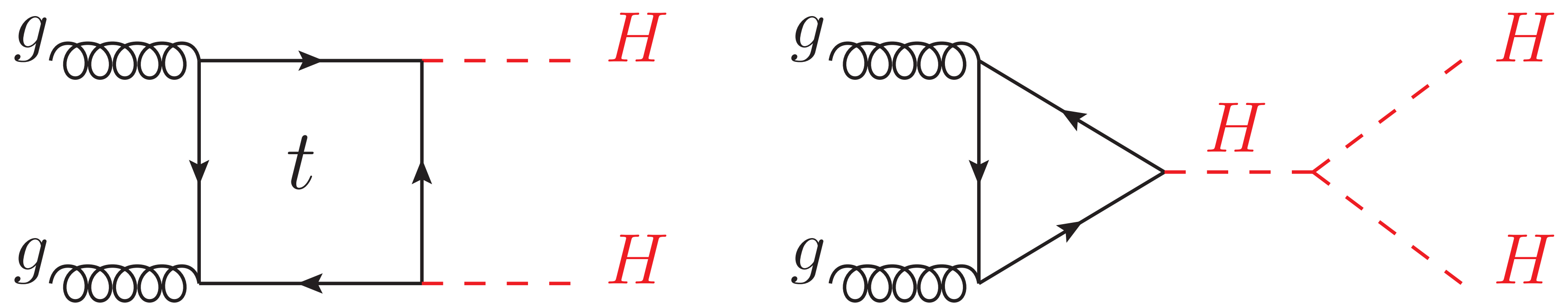
- Complementarity with the ee collider program



A production cross section 400 times larger than at LHC

O(5%) at HL-LHC

O(1%) at FCC-HH



Precision reach at HL-LHC O(100%)   O(3%) at FCC-HH

Precision SM and Higgs

High energy FCC is a natural environment for measurements of SM processes, which will have first been measured at the HL-LHC.

Conclusions of the Lectures

- Hadron colliders have been extremely successful to unveil the many of the secrets of nature at the smallest scales.

- The LHC has been extremely successful at Run 1 both in machine performance and in results of fundamental importance:
  - The discovery of the Higgs boson!
  - Nothing else!!
  - Precision measurements

- The LHC is also entering a new phase where the doubling time of the luminosity is now already as large as one year.

- However only 1% of the data has been collected so far, there is therefore a vast potential for discoveries!

- The level of precision reached in reconstruction and measurements is outstanding, but we should continue pushing the limit. It will be a common effort with the TH/MC community.

- **Exciting program ahead with great opportunities for you!**