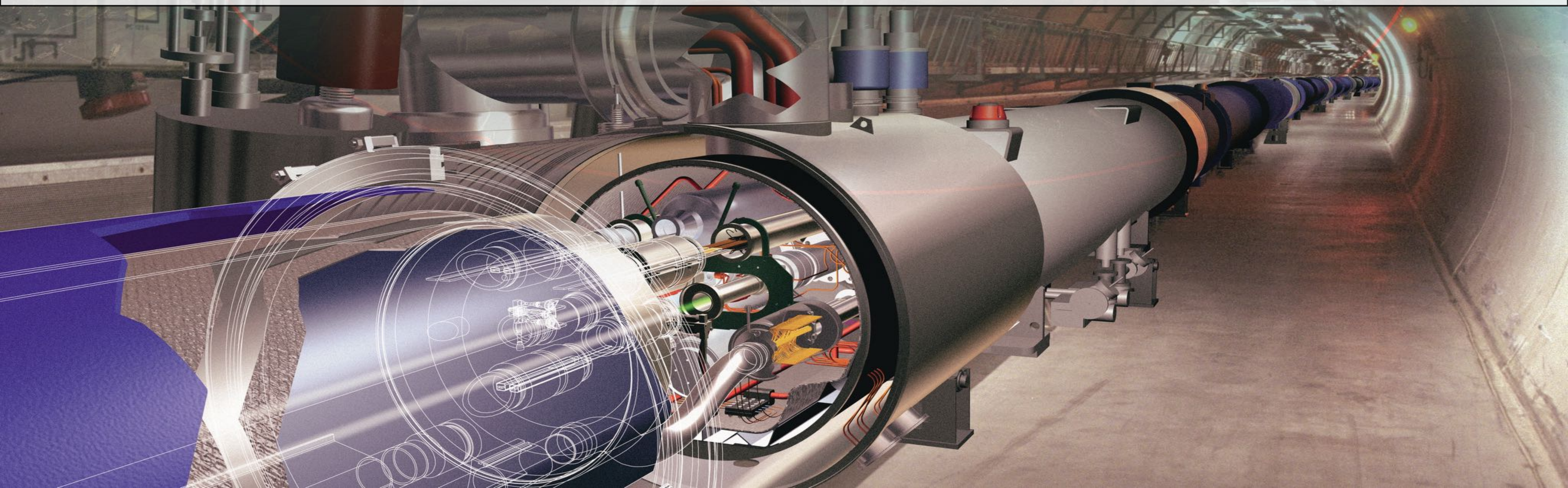
The importance and strategy of direct searches for LHC Run 3 and beyond

Till Eifert (U of Texas Arlington & CERN),
Workshop at Durham, UK, “Pushing the Boundaries — The SM and Beyond at the LHC.”, September 2019



Disclaimer & Acknowledgements

The organisers asked me to present "many personal and possibly original and provocative points”. Note that **I have a clear BSM bias towards SUSY**.

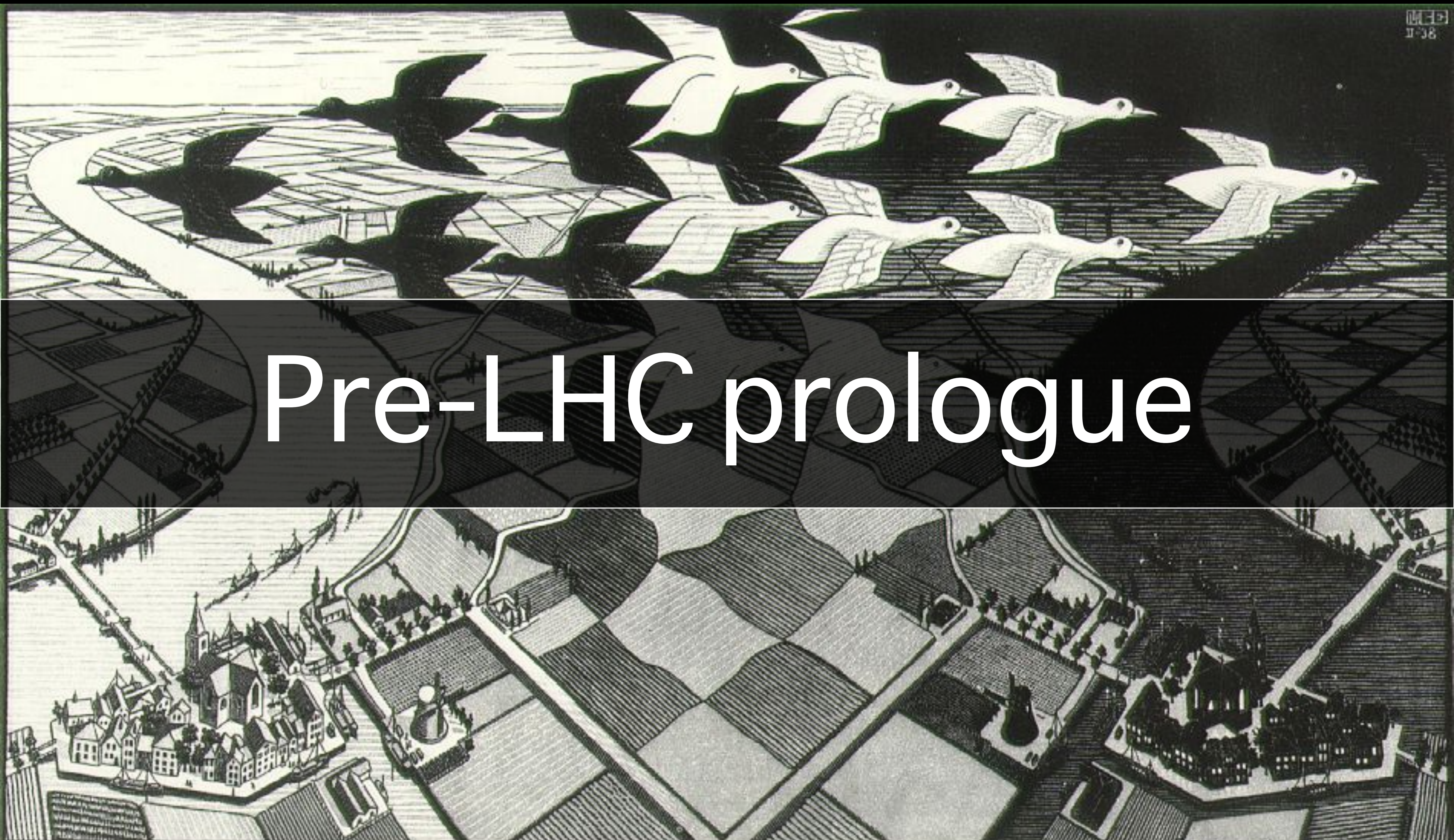
Thanks for input from: Federico Meloni, Klaus Mönig, Marie-Hélène Genest, Andreas Höcker.

The slides present my personal opinions. Any potential mistakes, oversights, etc. are on me!

Outline

- **Setting the scene**
  Selected SUSY impressions from pre-LHC to post-Run2.
- **Prospects of direct searches**
  What sensitivity gains can we expect with the HL-LHC?
- **Direct vs indirect searches**
  Should we all go and do measurements?
- **Strategy**

Pre-LHC prologue



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CERN — European Organization for Nuclear Research

LHCC Open SUSY Workshop

30 October 1996

Transparencies from the workshop are provisionally available here thanks to the CERN WWW service.

Agenda

- Introduction to supersymmetry phenomenology (C.Wagner)
- Supersymmetry searches at LEP (M.Schmitt)
- Supersymmetry searches at the TeVatron and HERA (H.Montgomery)
- Supersymmetry search by non-accelerator experiments: cosmological dark matter (M.Spiro)
- Precision SUSY measurements with ATLAS:
    - Simulation tools and inclusive analyses (F.Paige)
    - Reconstruction of exclusive final states Part I (F.Gianotti)
    - Reconstruction of exclusive final states Part II (G.Polesello)
    - Extraction of model parameters and conclusions (D.Froidevaux)
- SUSY studies in CMS:
    - Optimisation of CMS for SUSY searches (D.Denegri)
    - Squark and gluino searches in leptons + jets + missing Et final states (S.Abdullin)
    - Possibilities to observe sleptons (L.Rurua)
    - Chargino / neutralino study (I.Iashvili)
    - Search for next-to-lightest neutralino (A. Kharchilava)
    - Conclusions (D.Denegri)

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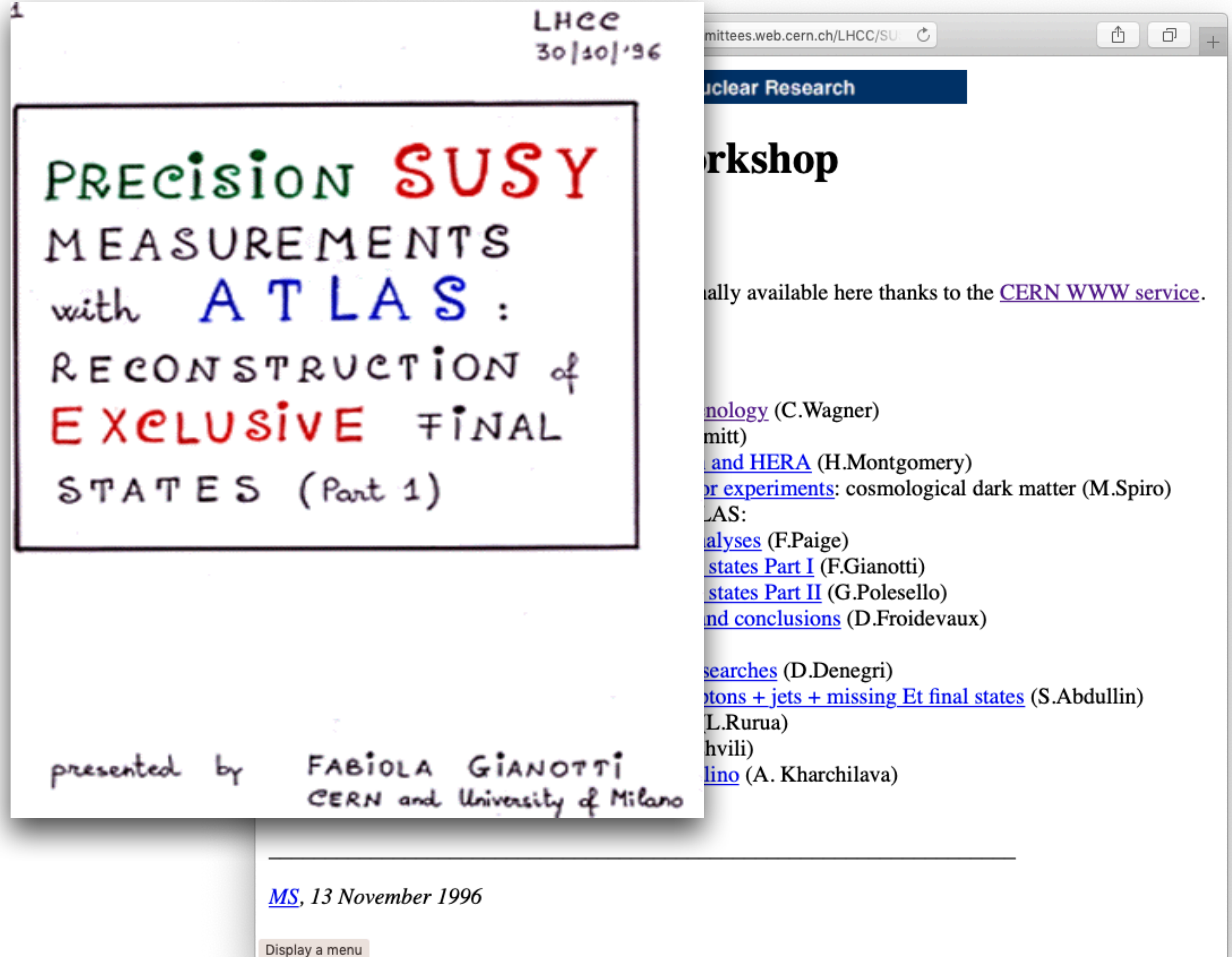
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PRECISION SUSY
MEASUREMENTS
with ATLAS:
RECONSTRUCTION of
EXCLUSIVE FINAL
STATES (Part 1)
presented by FABIOLA GIANOTTI
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PRECISION SUSY MEASUREMENTS with ATLAS: RECONSTRUCTION of EXCLUSIVE FINAL STATES (Part 1)

presented by FABIOLA GIANOTTI
CERN and University of Milano

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ATLAS-PHYS-No-107

Precision SUSY Measurements with ATLAS: Introduction and Inclusive Measurements*

I. Hinchliffe[a], F.E. Paige[b], G Polesello[c], E. Richter-Was[de]
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Abstract

If supersymmetry exists at the electroweak scale, then it should be discovered at the LHC. Determining masses, of supersymmetric particles however, is more difficult. In this paper, which serves as an introduction to a series of notes describing various SUSY studies within the ATLAS collaboration, the models used for simulation are discussed. A general method that can be applied to determine approximately the mass scale of the supersymmetric particles is described.

*This work was supported in part by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contracts DE-AC03-76SF00098 and DE-AC02-76CH00016 and by Polish Government grants 2P03B00212 and 2P03B17210

1996-1997

ATLAS-PHYS-No-107

Precision SUSY Measurements with ATLAS: Introduction and Inclusive Measurements*

The strategy developed within the ATLAS collaboration beginning at a meeting in Stockholm in January 1996 and culminating in the presentations to the LHC workshop in November 1996 [13] is reported in this series of papers [15]† involves three steps. First, we use a simple inclusive analysis to establish a deviation from the Standard Model. We select events with at least four jets and large missing energy and plot the distribution of

$$M_{\mathrm{eff}} = p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4} + \not{E}_T\,.$$

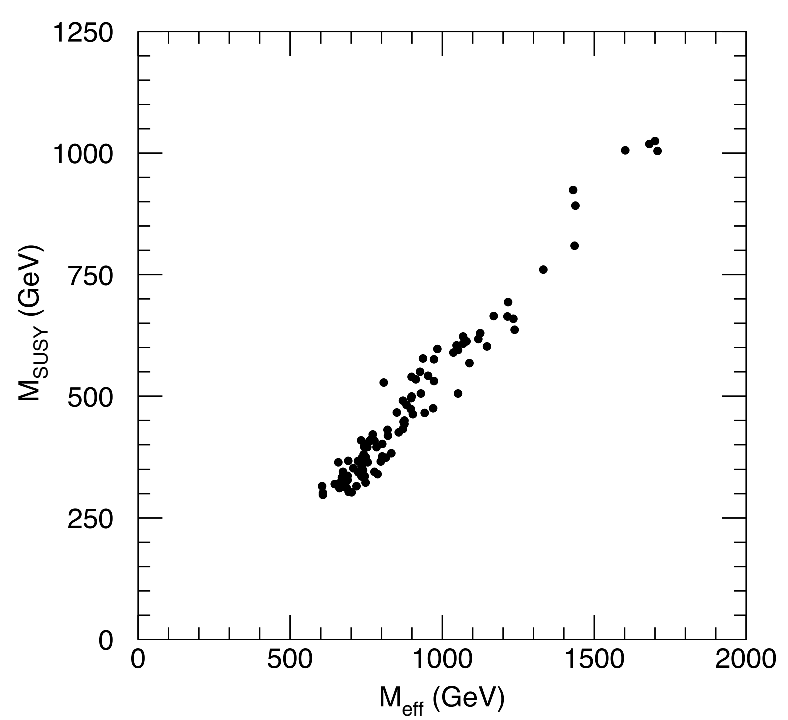
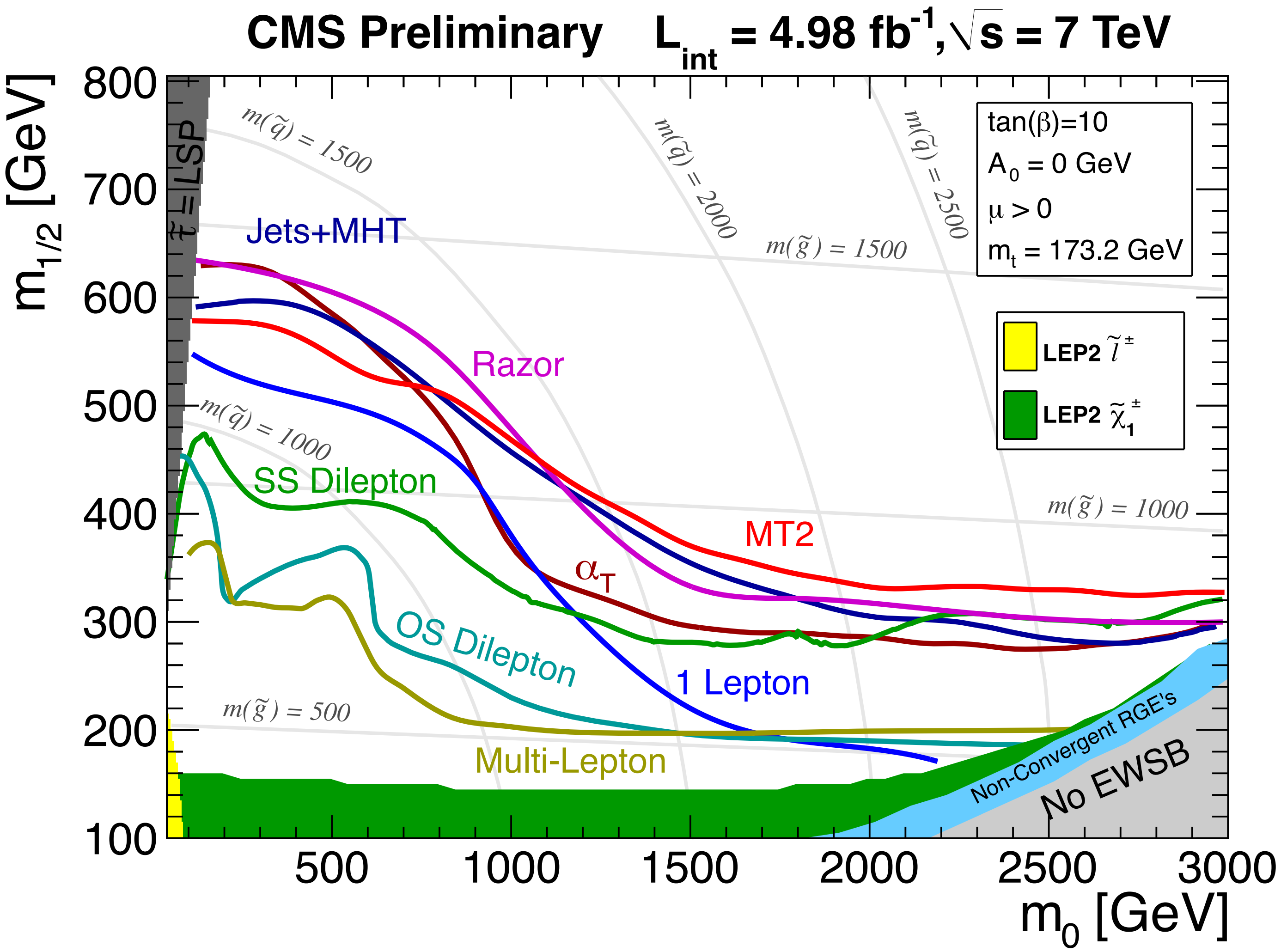
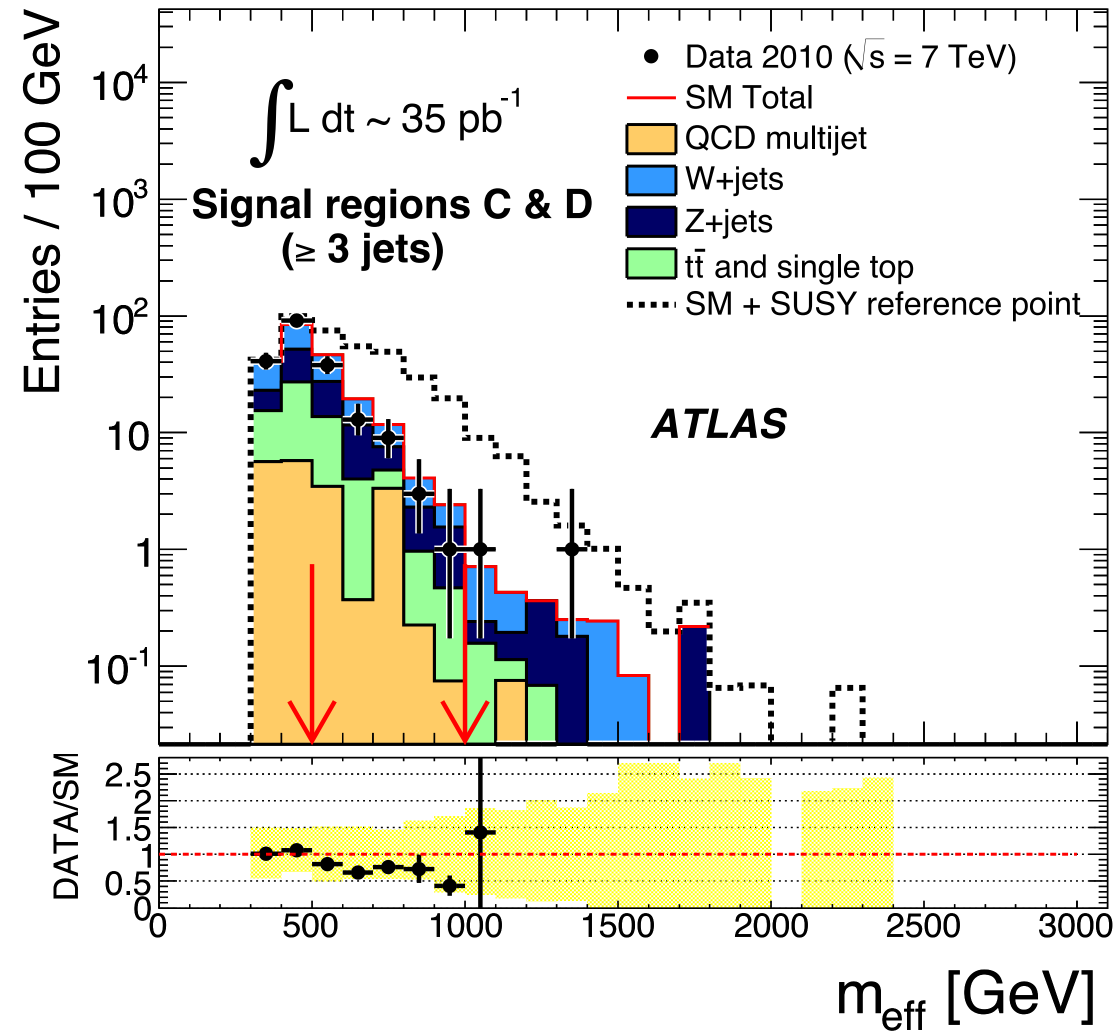


Figure 7: Scatterplot of $M_{\mathrm{SUSY}} = \min(M_{\tilde{g}}, M_{\tilde{u}})$ vs. M_{eff} for randomly chosen SUGRA models having the same light Higgs mass within $\pm 3\,\mathrm{GeV}$ as for LHC Point 5.

First act: LHC Run-1

LHC Run-1 2010-2012



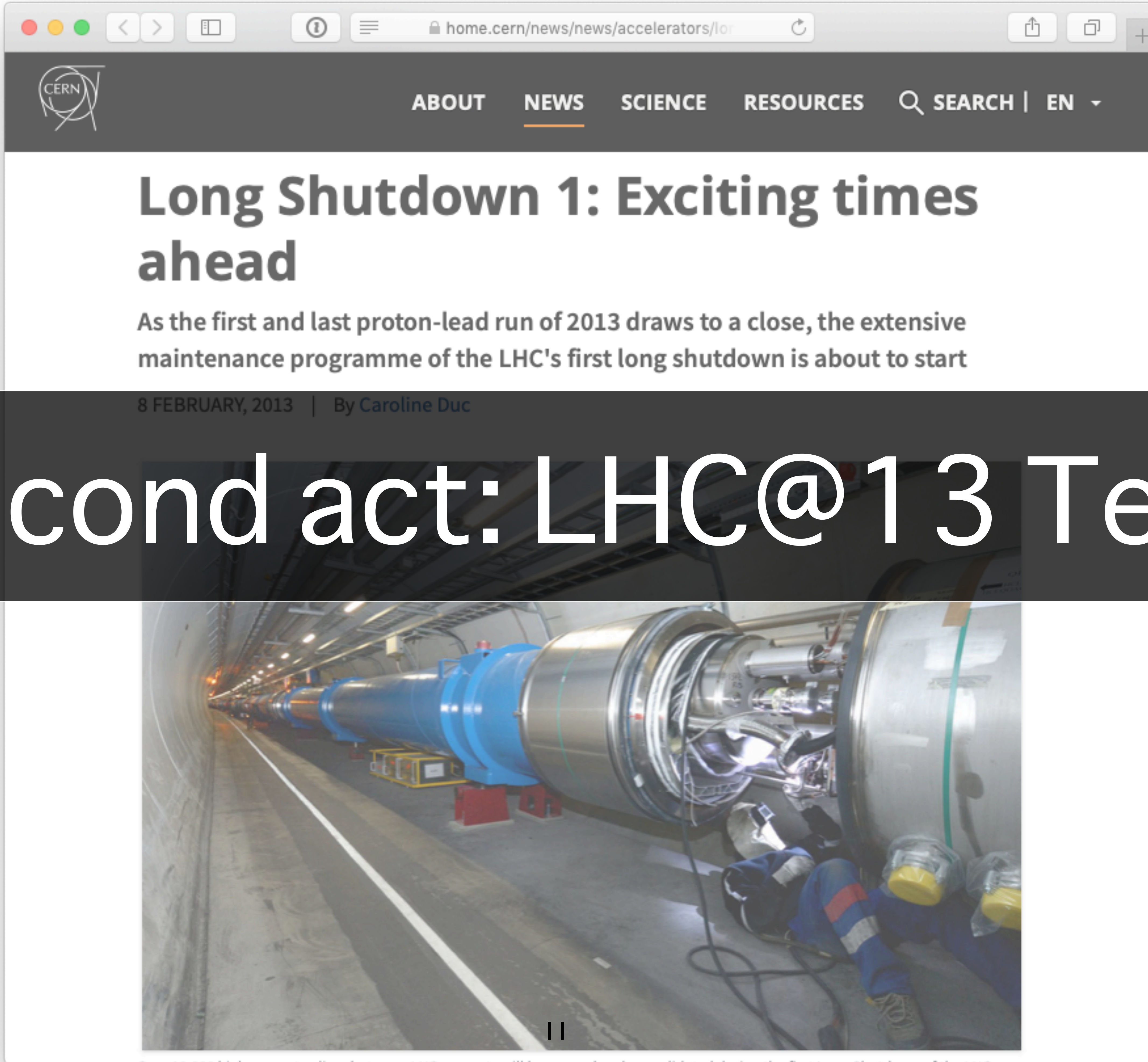


Pioneering data analyses: trigger, object reconstruction, tails, background estimation, …

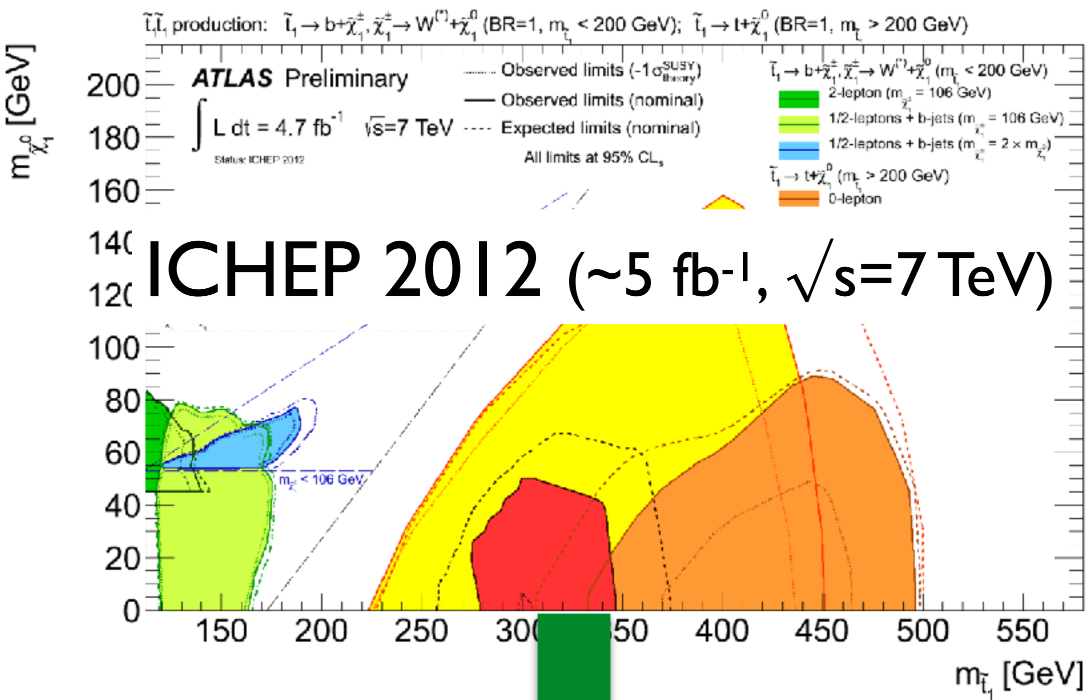
→ **exciting time**

We discovered the Higgs boson while not finding yet any evidence for new physics.
Before first LHC results, word on the street was that SUSY would show up first.

Second act: LHC@13 TeV



LHC Run-2 2015-2018

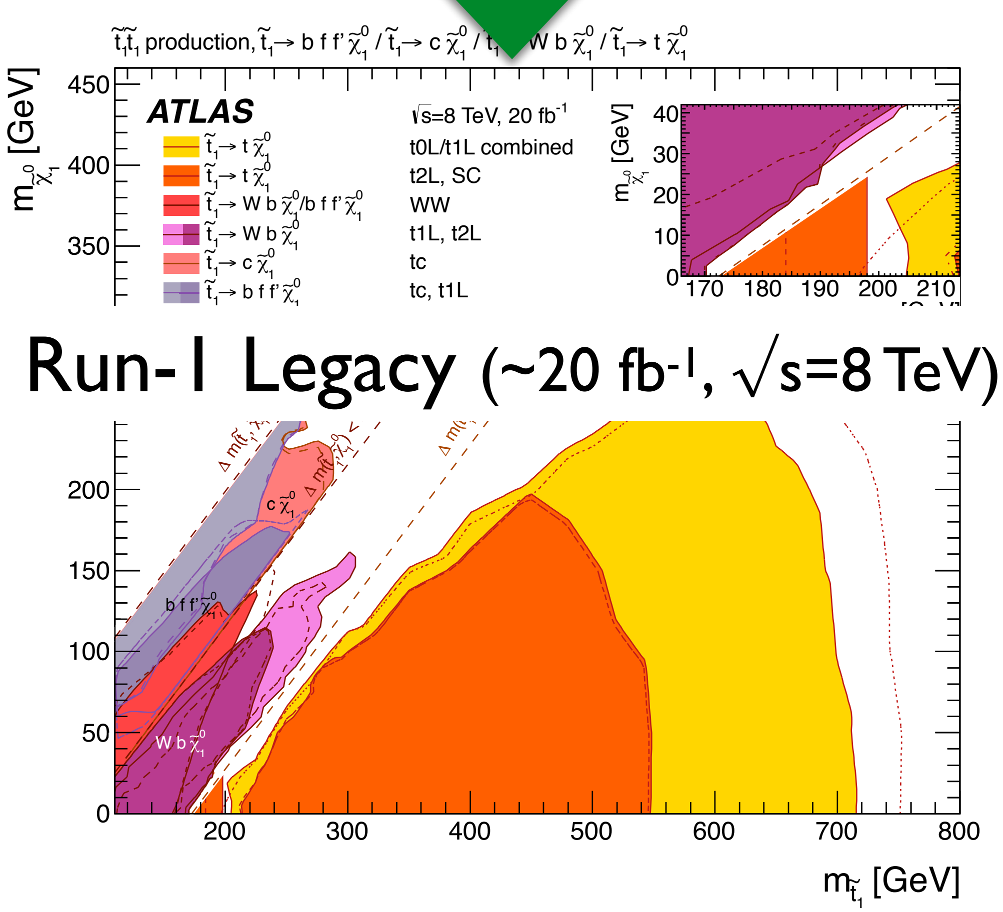


ICHEP 2012 (~5 fb^{-1}, $\sqrt{s}$=7 TeV)

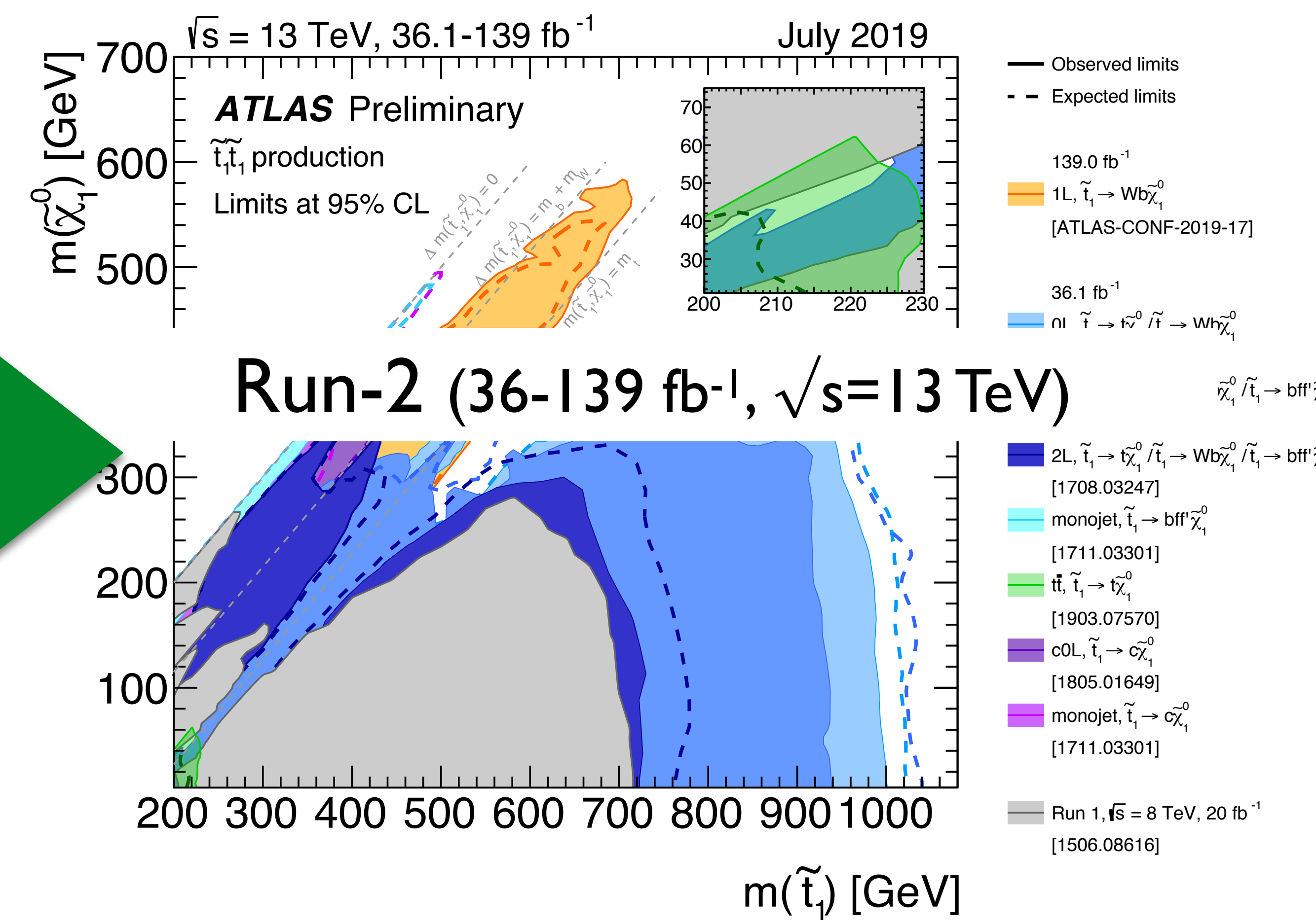
Significantly extended BSM reach

thanks to $\sqrt{s}$=13 TeV collisions and huge efforts.

Example: evolution of stop search program (similar in CMS)

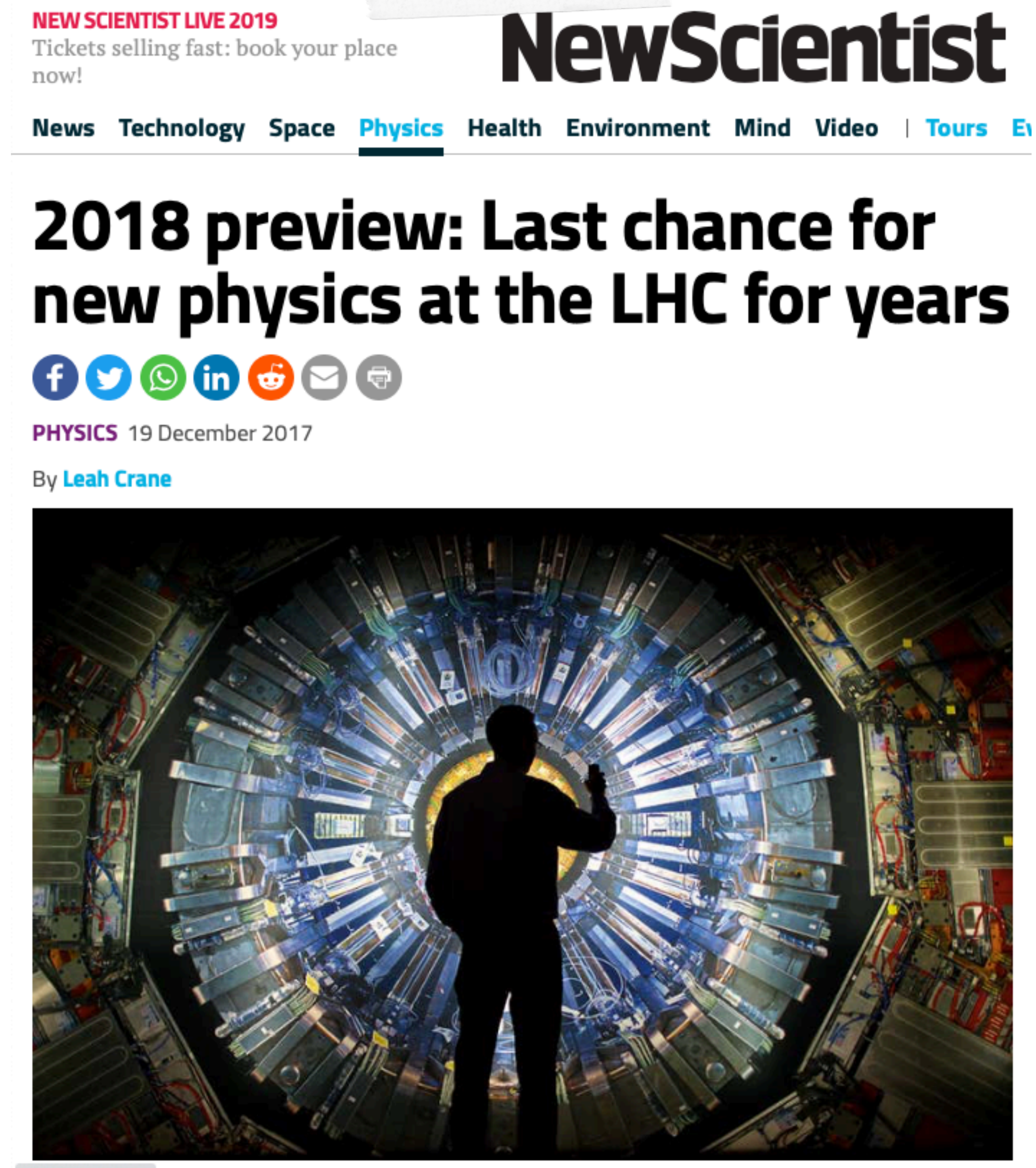


Run-1 Legacy (~20 fb^{-1}, $\sqrt{s}$=8 TeV)



Run-2 (36-139 fb^{-1}, $\sqrt{s}$=13 TeV)

Reactions …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2018 preview: Last chance for new physics at the LHC for years

PHYSICS 19 December 2017

By Leah Crane

Status today

- We learned that new physics was not around the corner.
- Naturalness: primary BSM guiding principle over the last decades.
  - key prediction: top quark partner (such as stop), mostly ruled out at the TeV level.
- Fundamental questions remain → puzzling time

What’s the importance and strategy of direct searches for LHC Run 3 and beyond?

What's next at (HL) LHC?

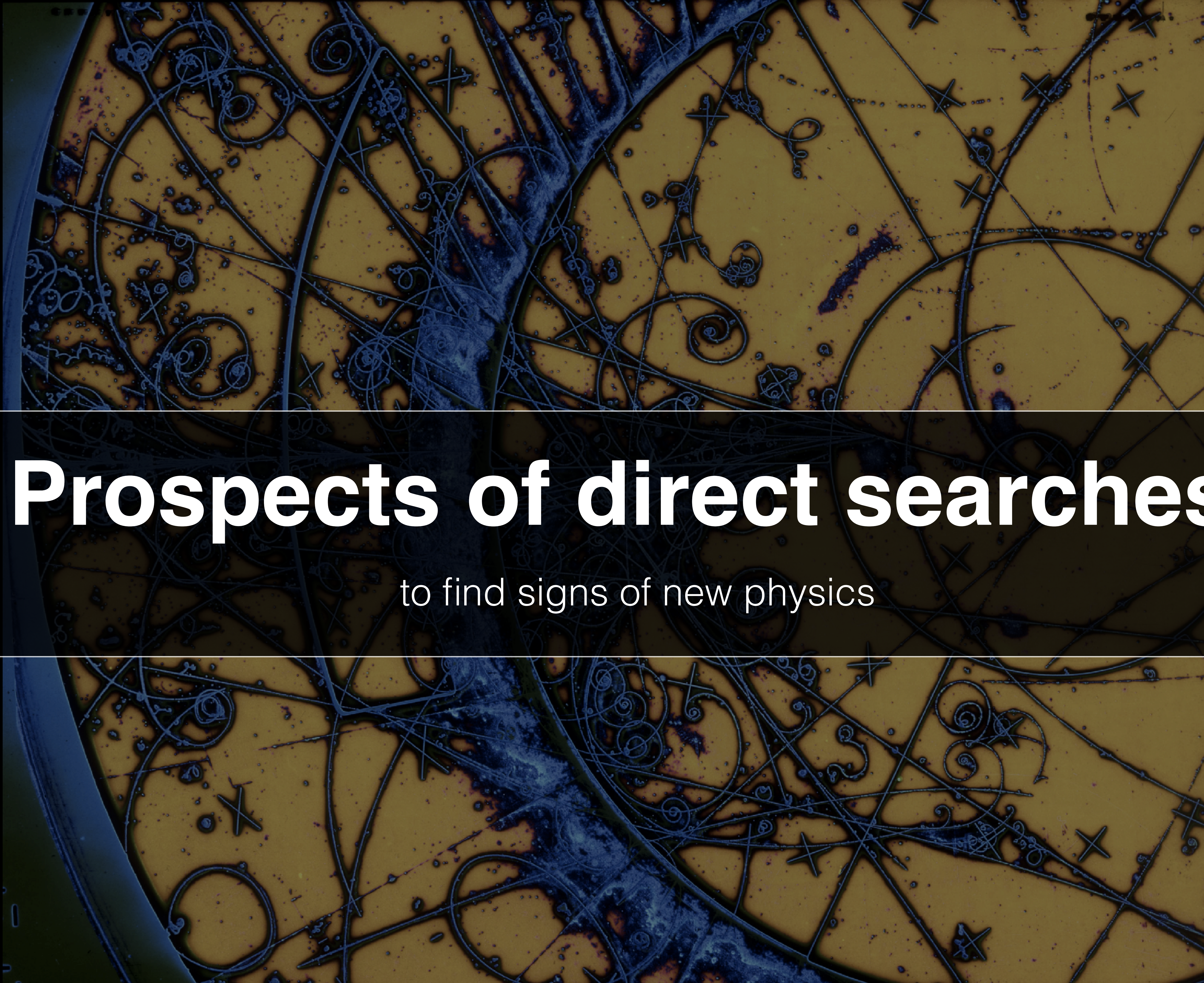
we're here

On the (HL) LHC menu for next ~20 years:

- small increase ~8% in $\sqrt{s}$,
- large increase x20-x30 in $\int \mathcal{L}dt$

Prospects of direct searches

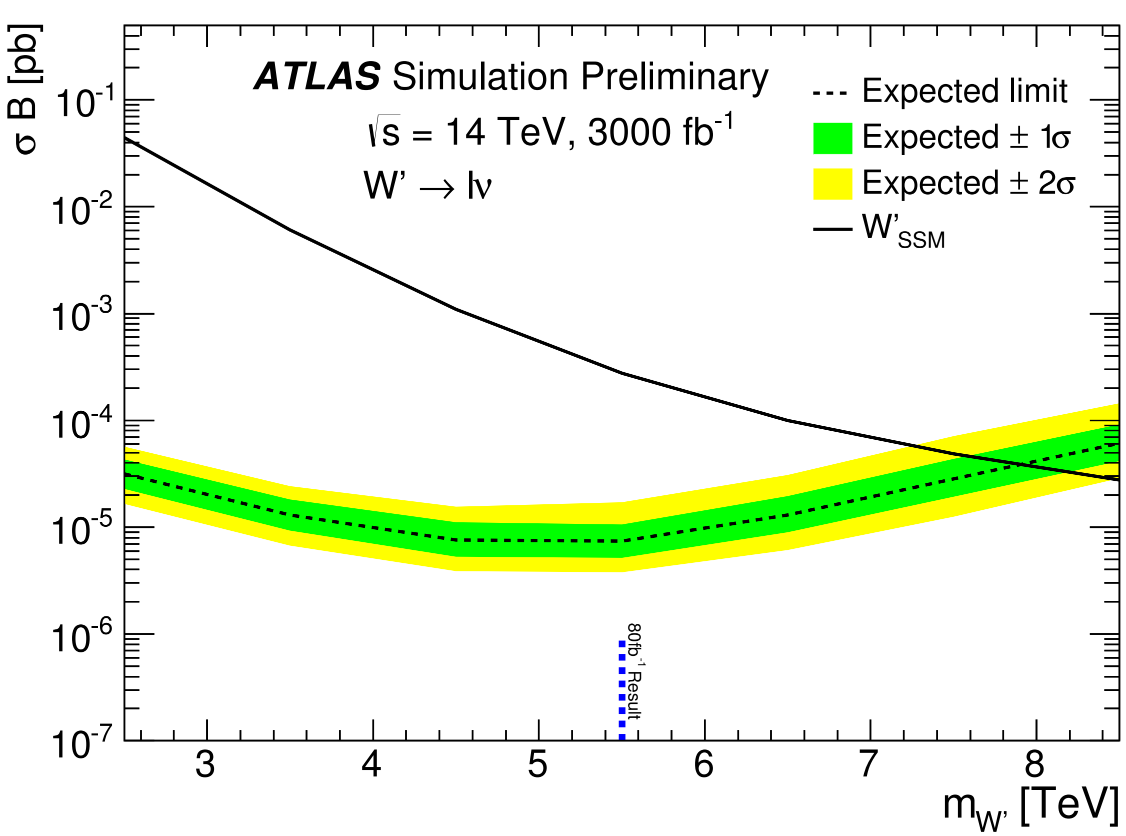
to find signs of new physics

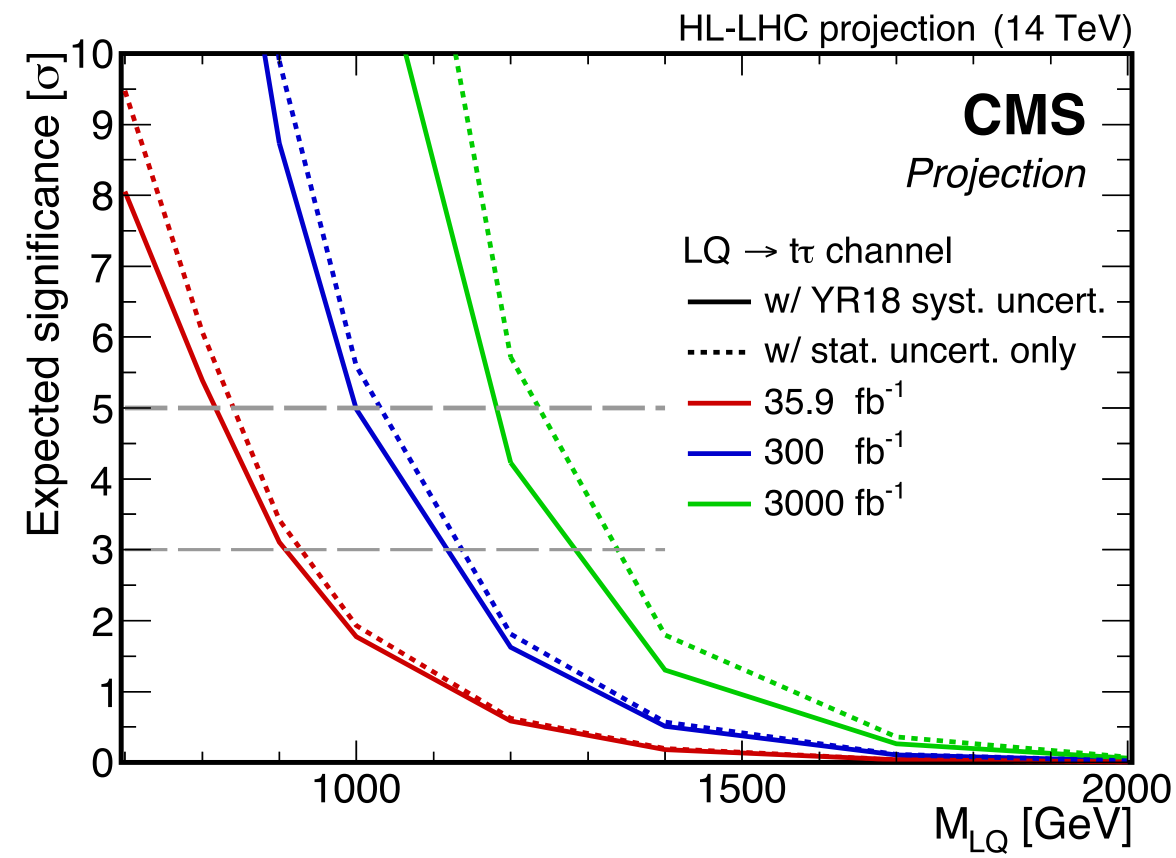


Prospects for finding NP at HL-LHC

[1812.07831]

Heavy resonances and Lepto-Quarks





Expect ~50% increase in mass reach

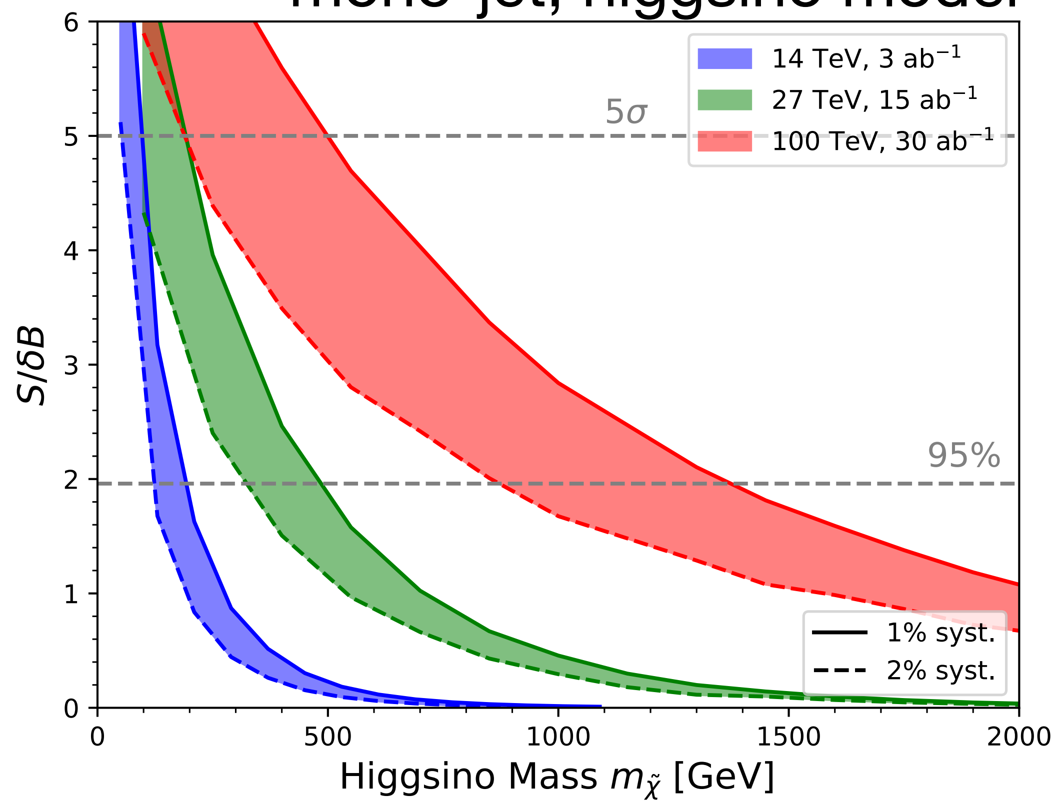
Opportunity: single production of LQs and VLQs

Prospects for finding NP at HL-LHC

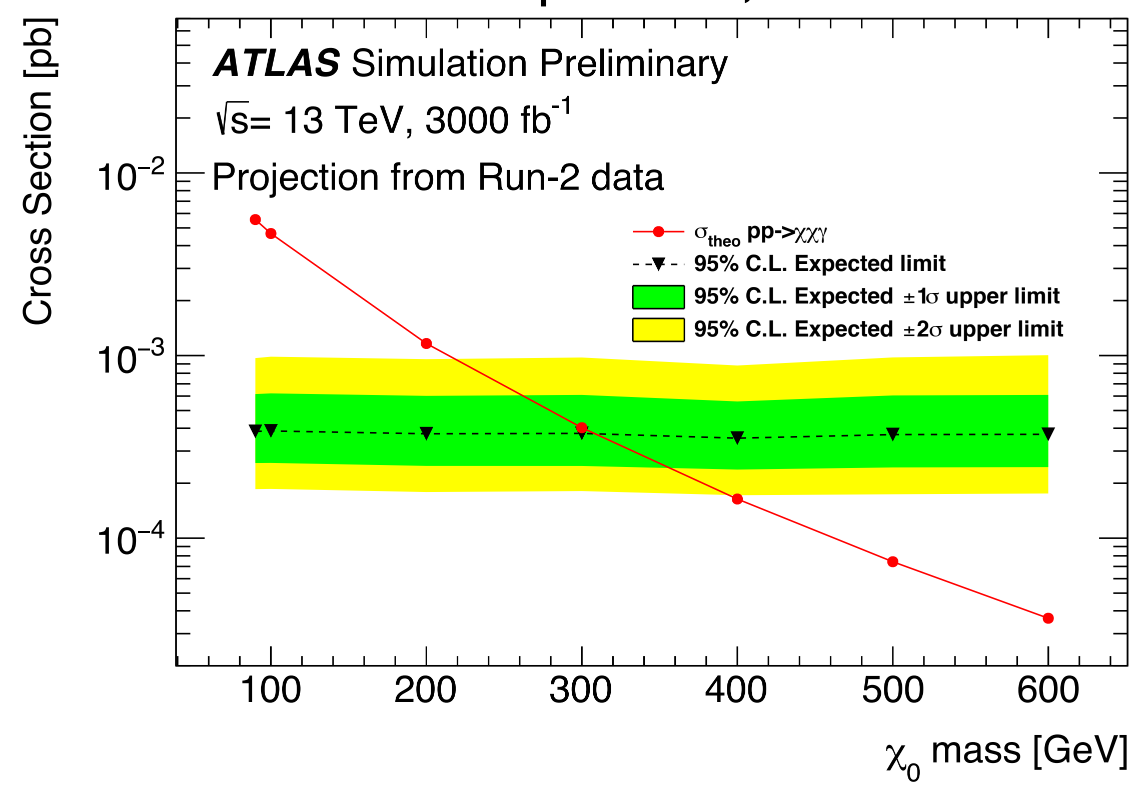
[1812.07831]

weakly coupled, DM

mono-jet, higgsino model

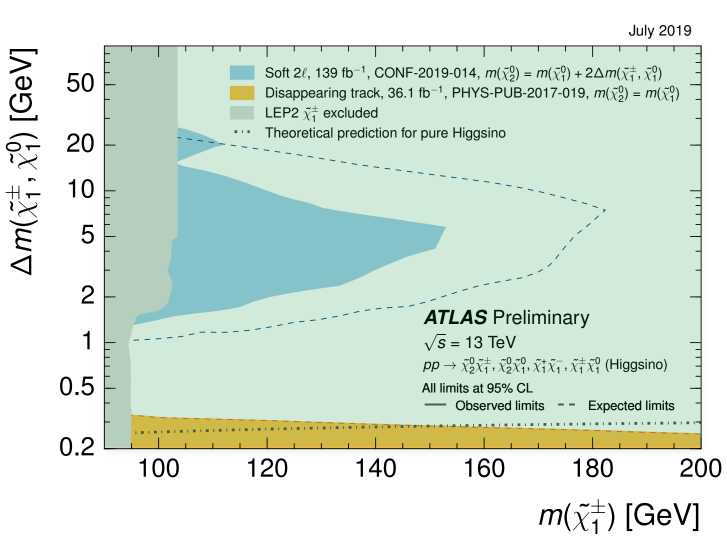


mono-photon, wino model

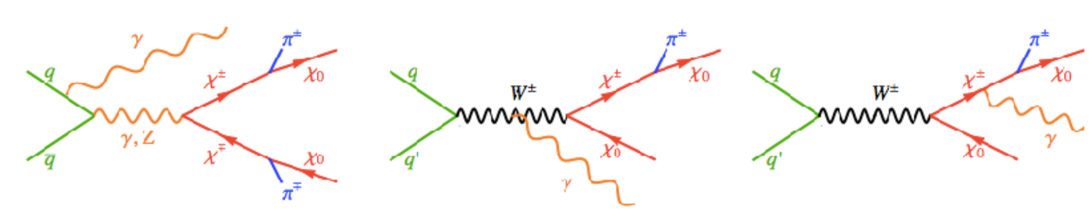


sys limited, assumed 2-7% (half of run2)

mono-jet search: from no sensitivity to higgsinos @ Run2, to 200 GeV at HL-LHC. (i.e. doubled wrt. LEP)



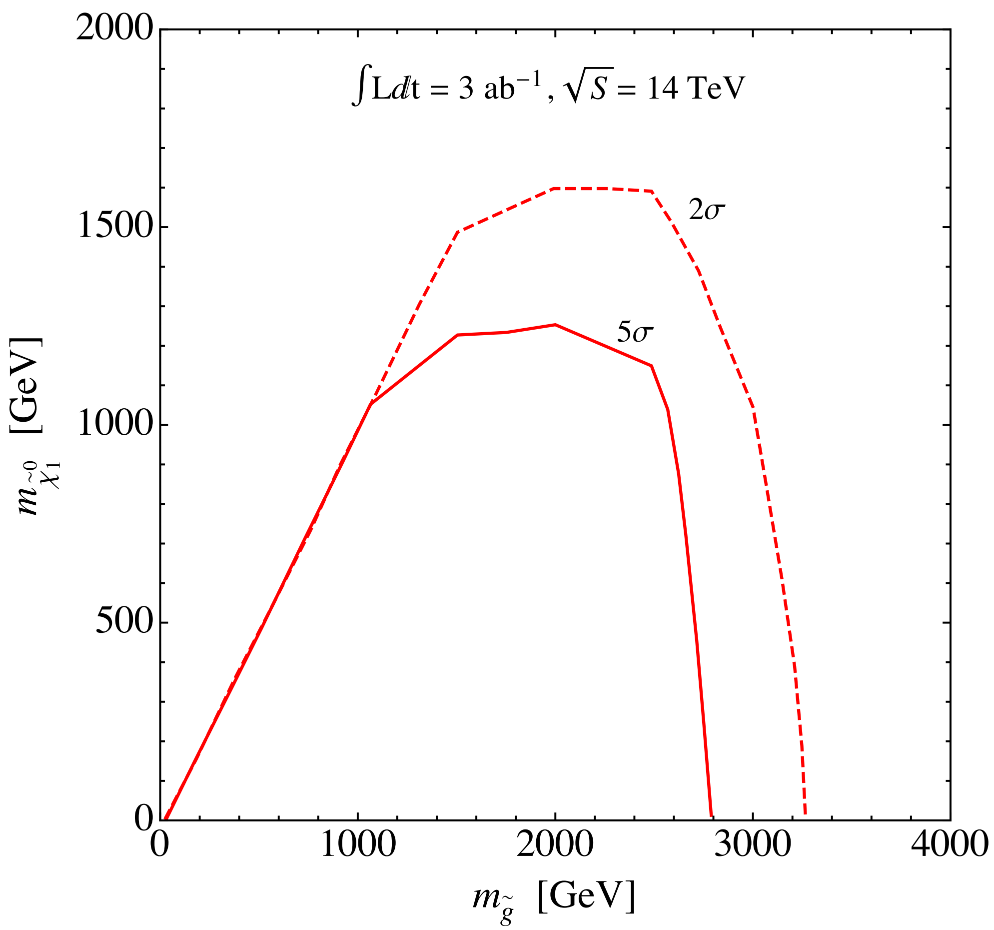
⇒ Δm ~independent limit (up to a few tens of GeV)

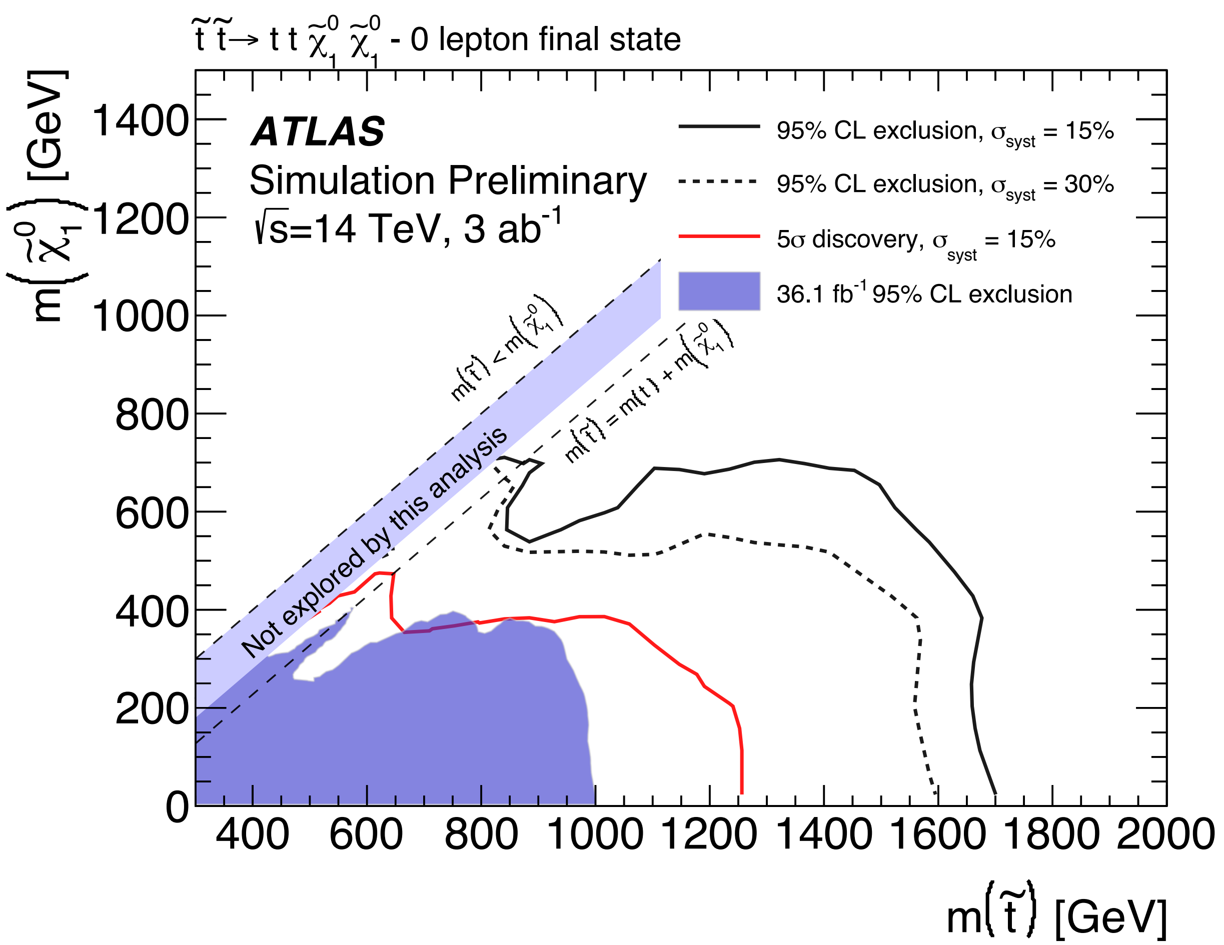


Prospects for finding NP at HL-LHC

[1812.07831]

strong s-particle pair production



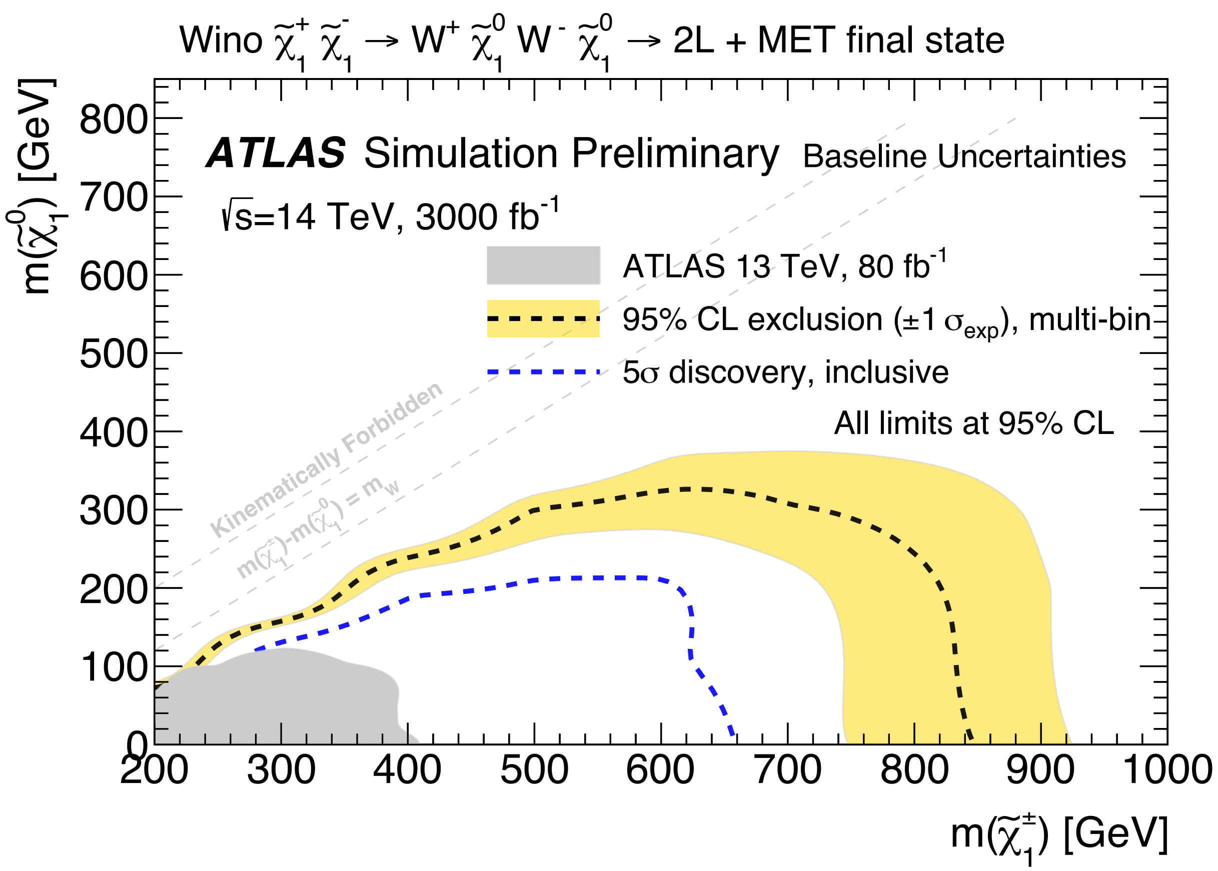


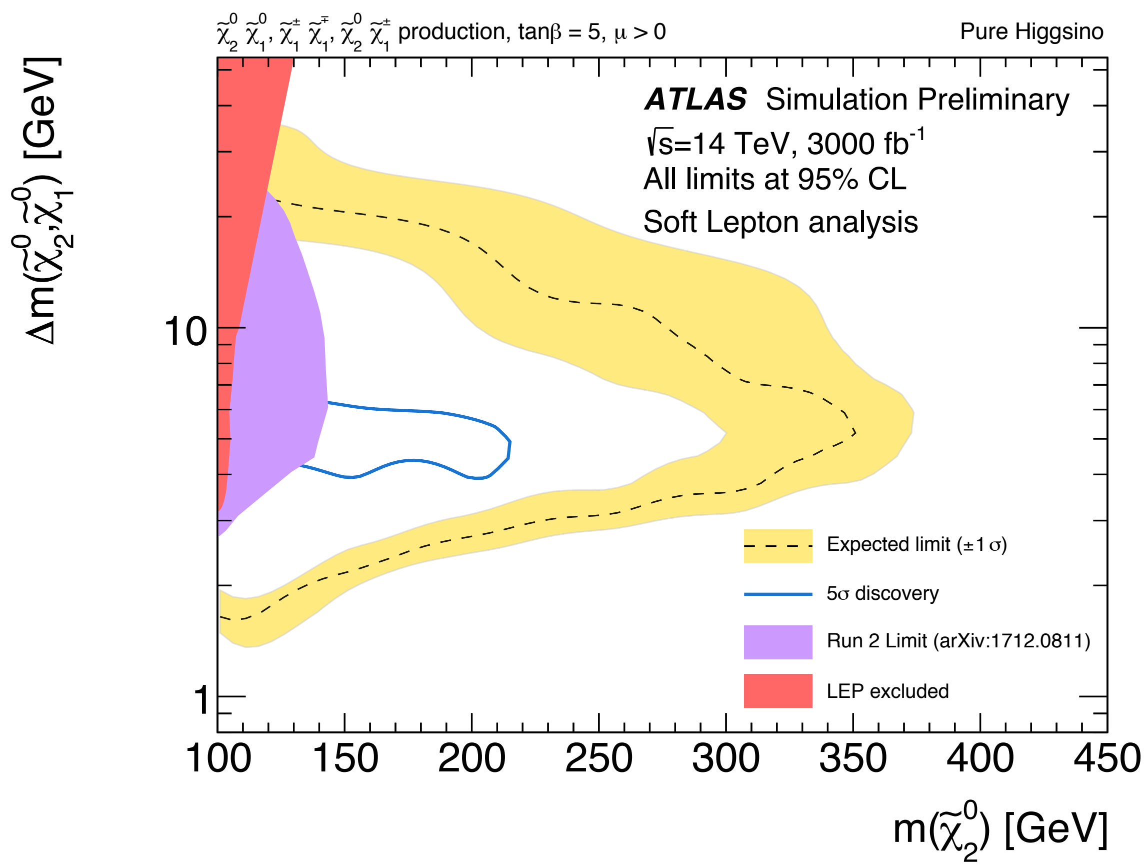
Expect ~50% increase in mass reach

Prospects for finding NP at HL-LHC

[1812.07831]

electroweak s-particle pair production

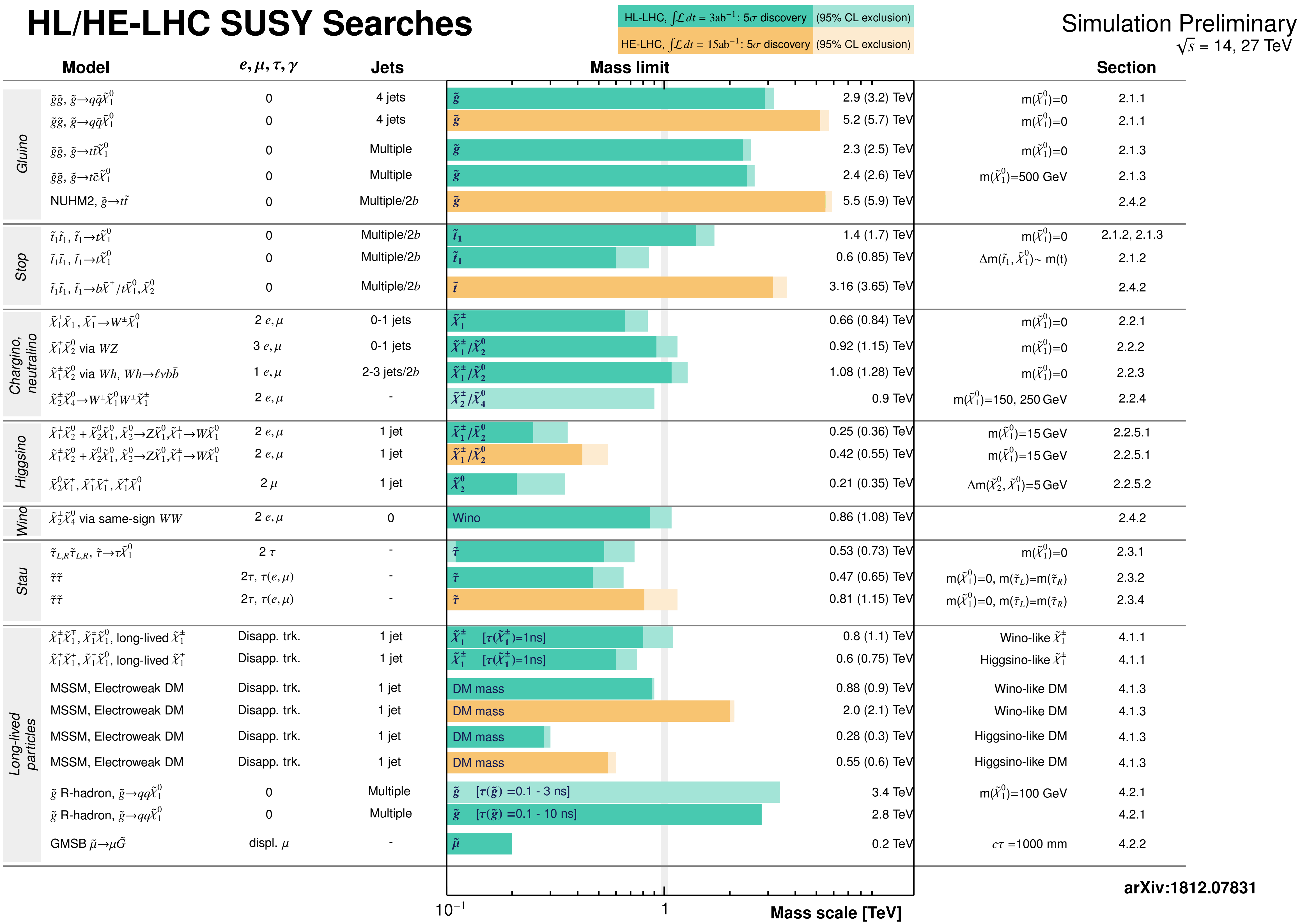




Expect to ~double the mass reach

Important to also "deepen" the sensitivity (σ can vary, BFs not 100% etc.)

Prospects for finding NP at HL-LHC



Opportunities

LHC phase-2 detector upgrades

Timing detectors (4D reconstruction, long-lived particles)

New trigger systems with more information (high granularity calorimeter, tracking information, global “view” at level-1)

Improved systematics (det. understanding, theory calc.)

Systematics limited searches, for example:

- low-mass resonances with tiny couplings
- monojet (to access higgsino/wino DM)

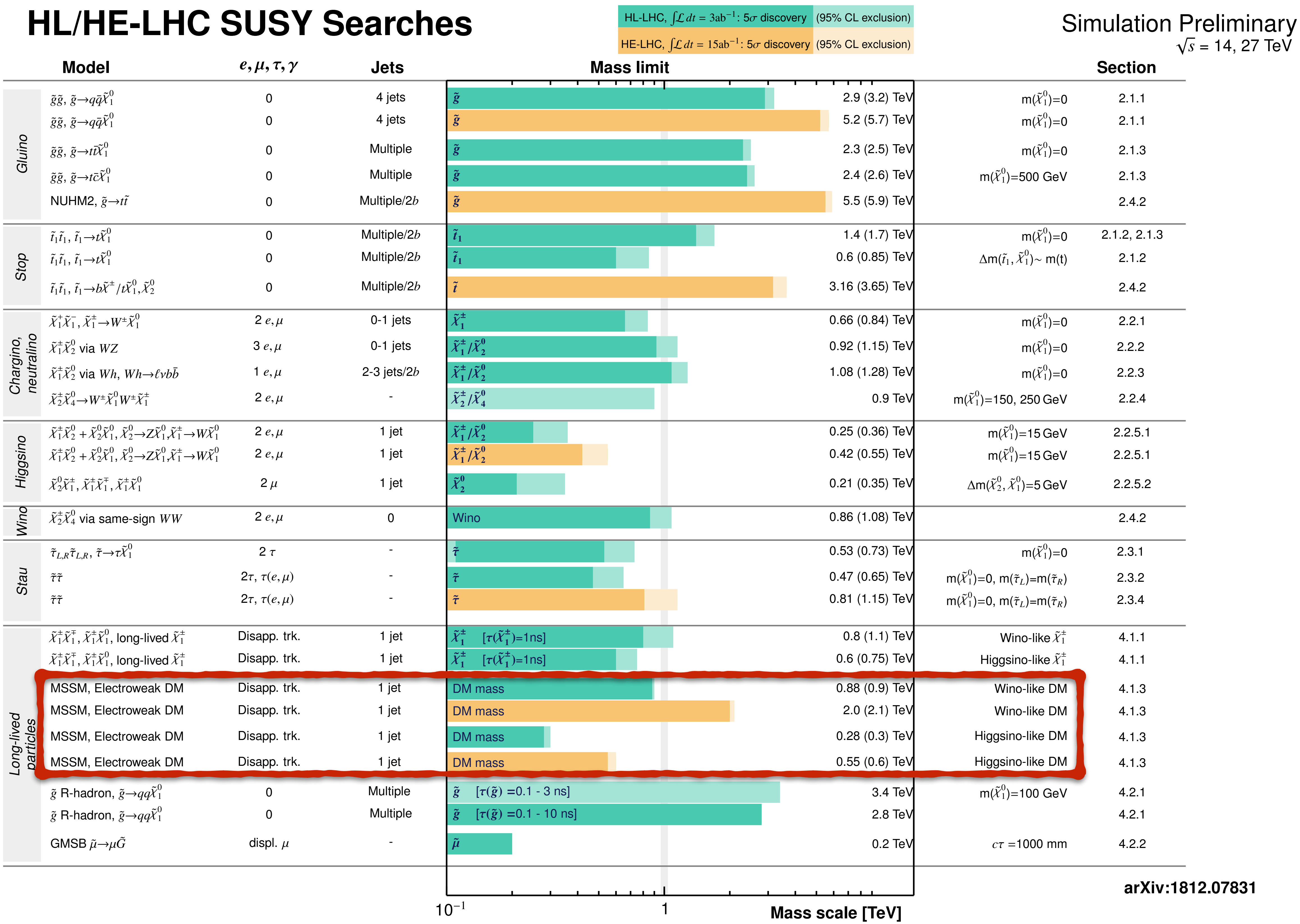
Measurements

Improved tools to discriminate signal from background

b-tagger, c-tagger, top-tagger, etc.

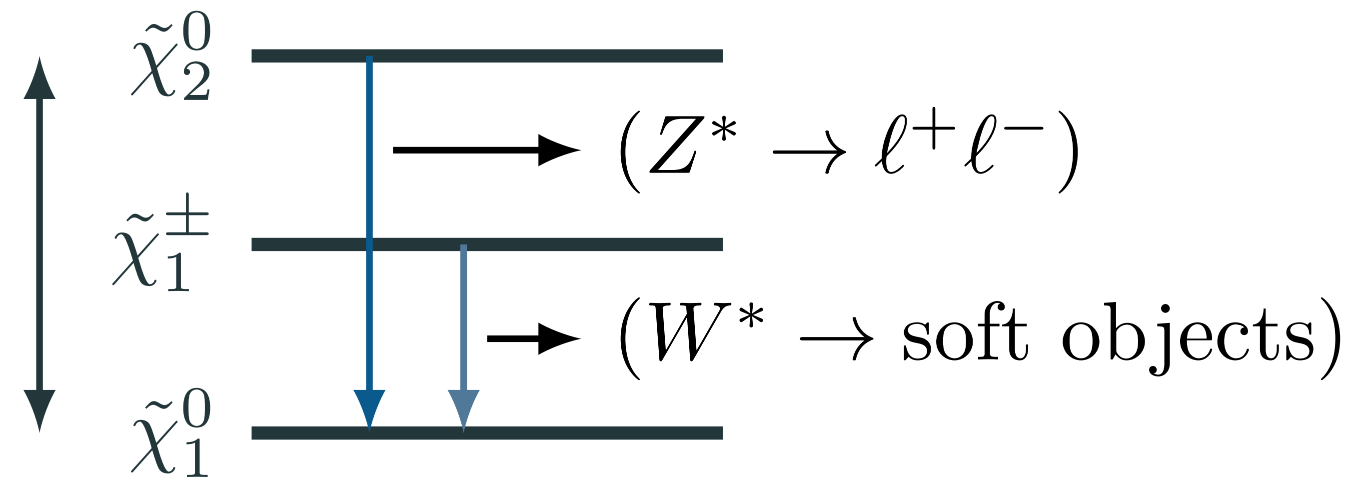
tau identification

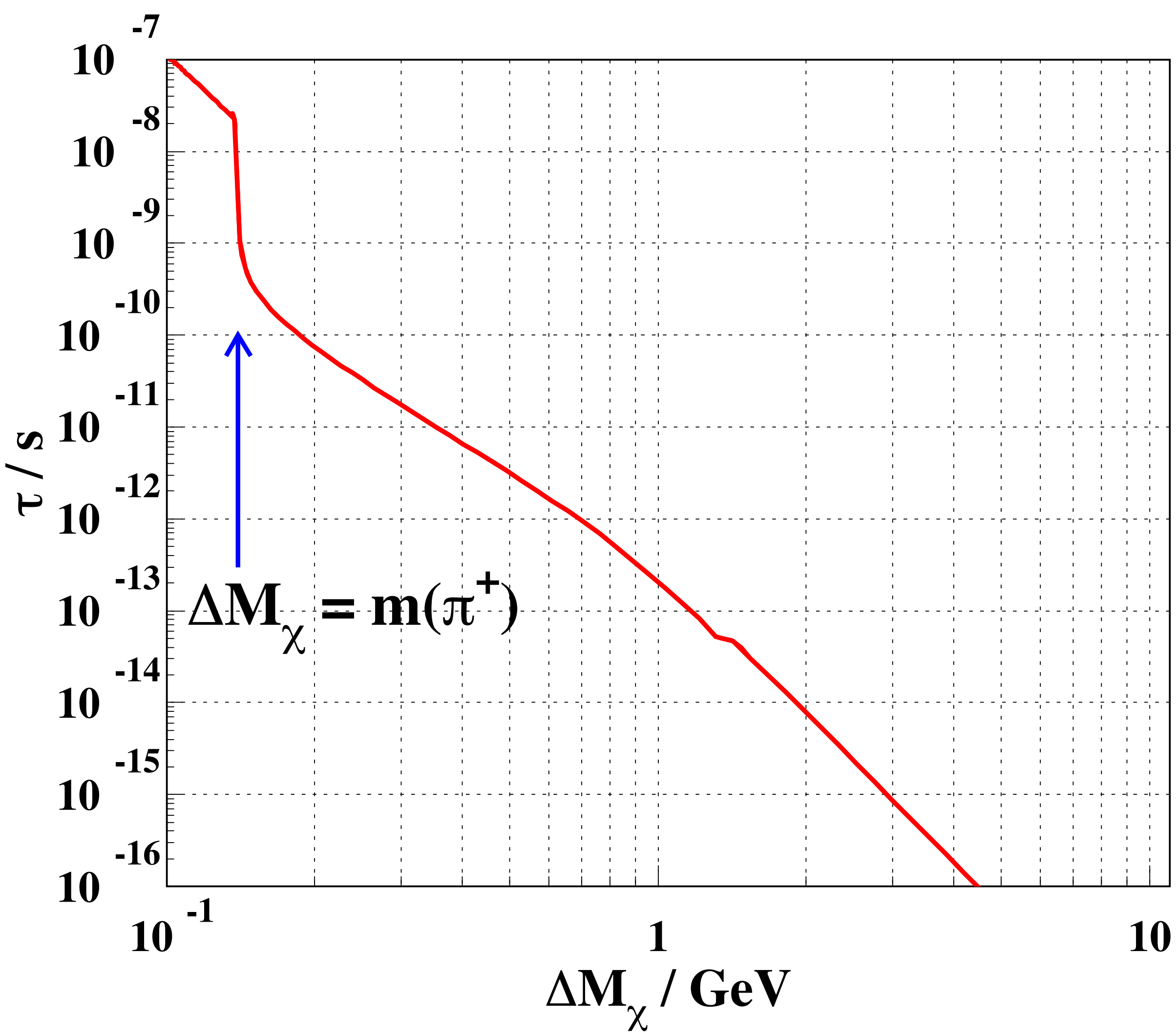
Prospects for finding NP at HL-LHC

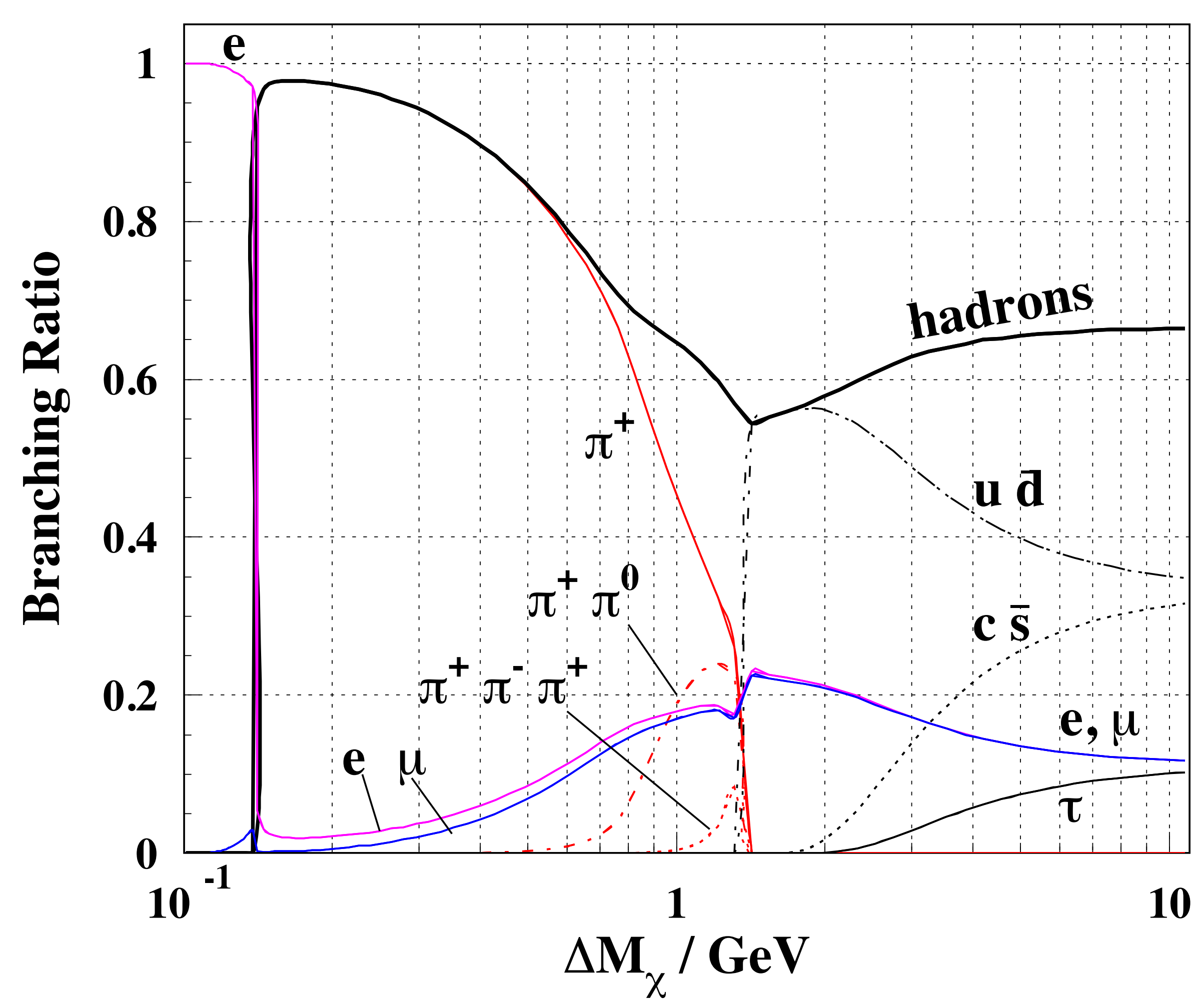


Ultra compressed spectrum

Δm = few hundred MeV



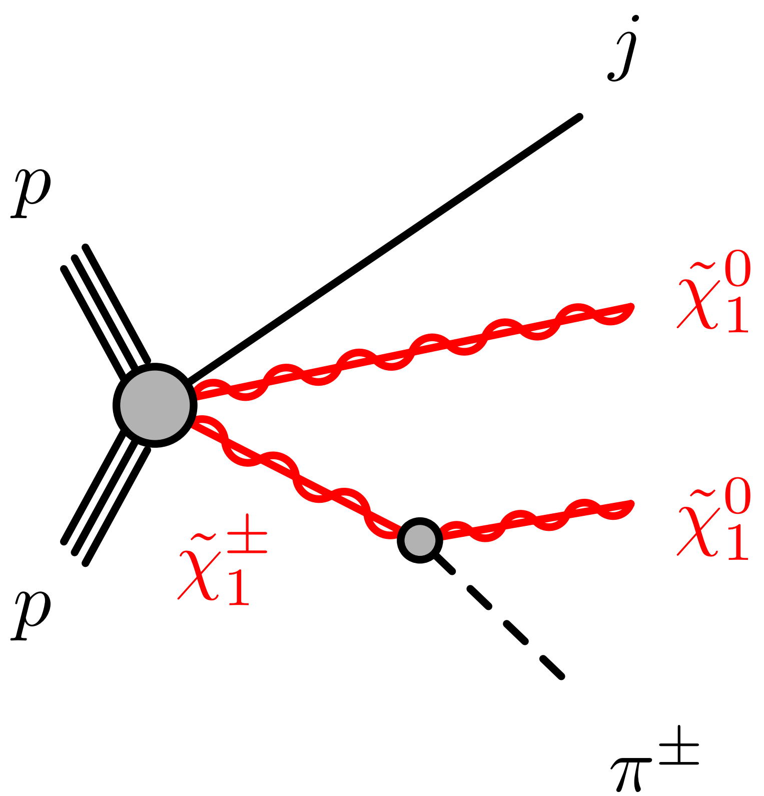


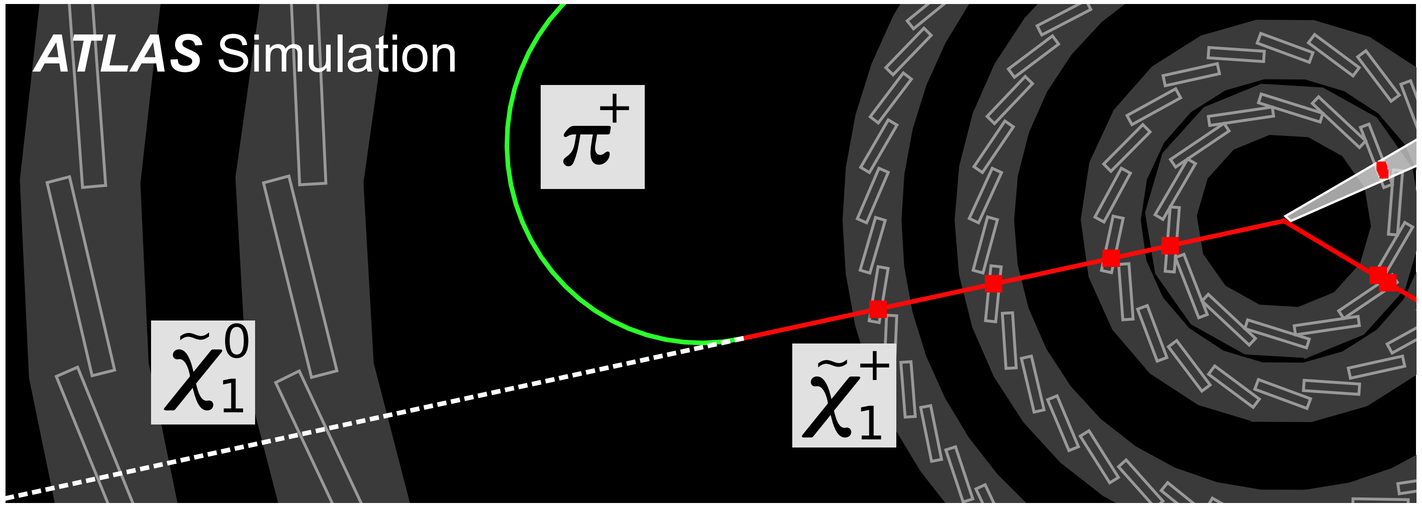


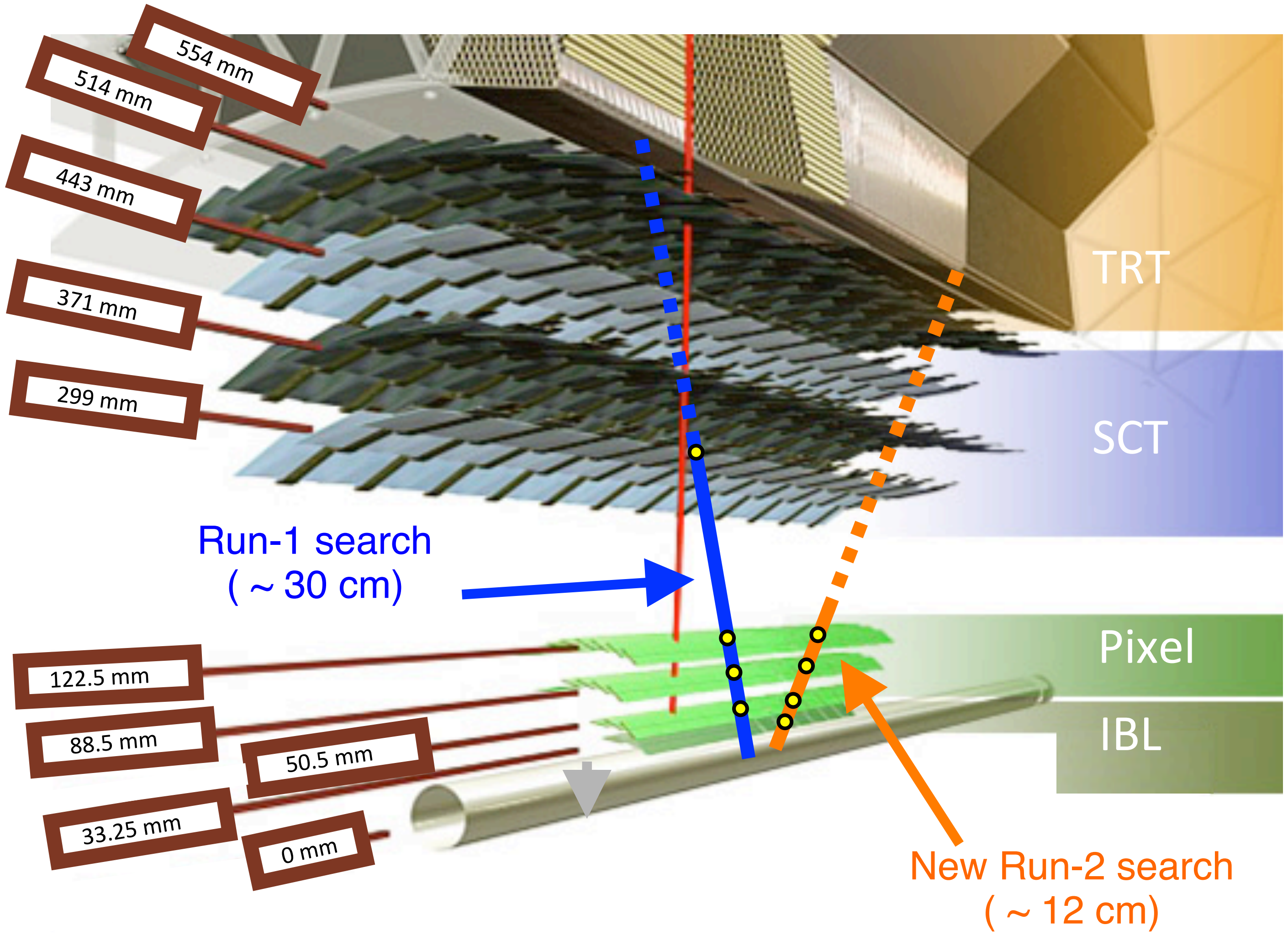
Journal of High Energy Physics, Volume 2003, JHEP03(2003)

Disappearing track

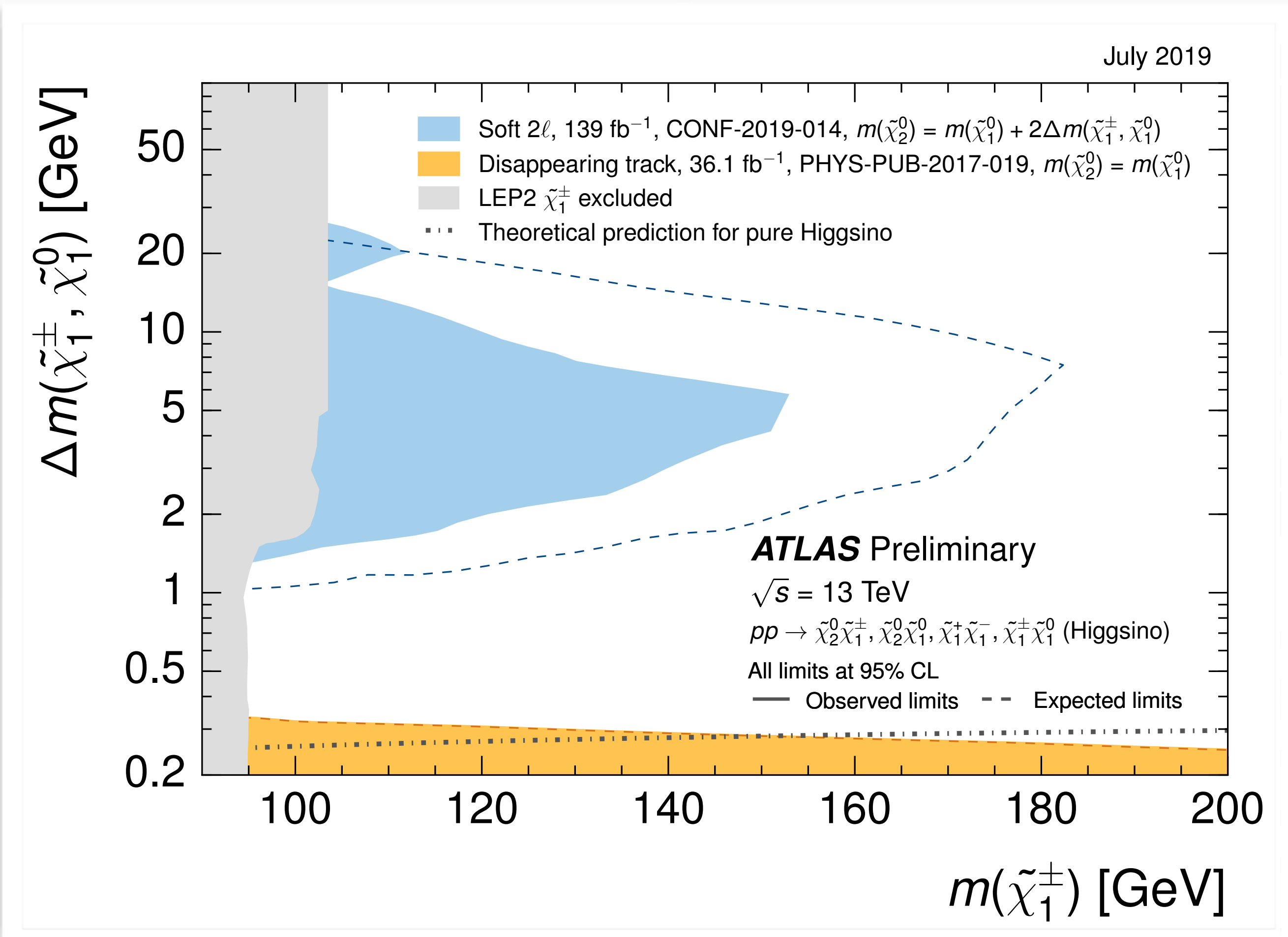
Hadronic recoil (ISR), trigger!

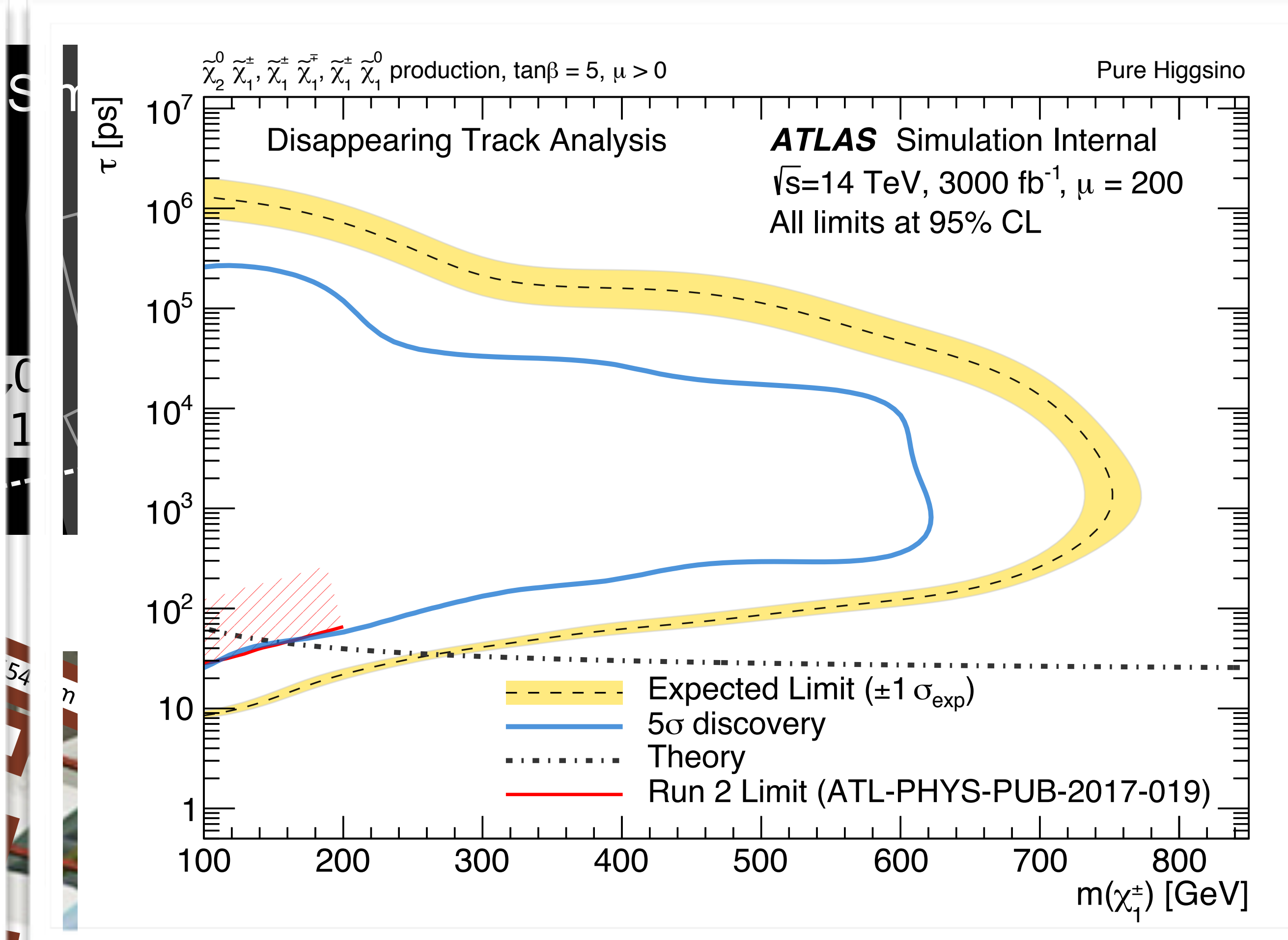


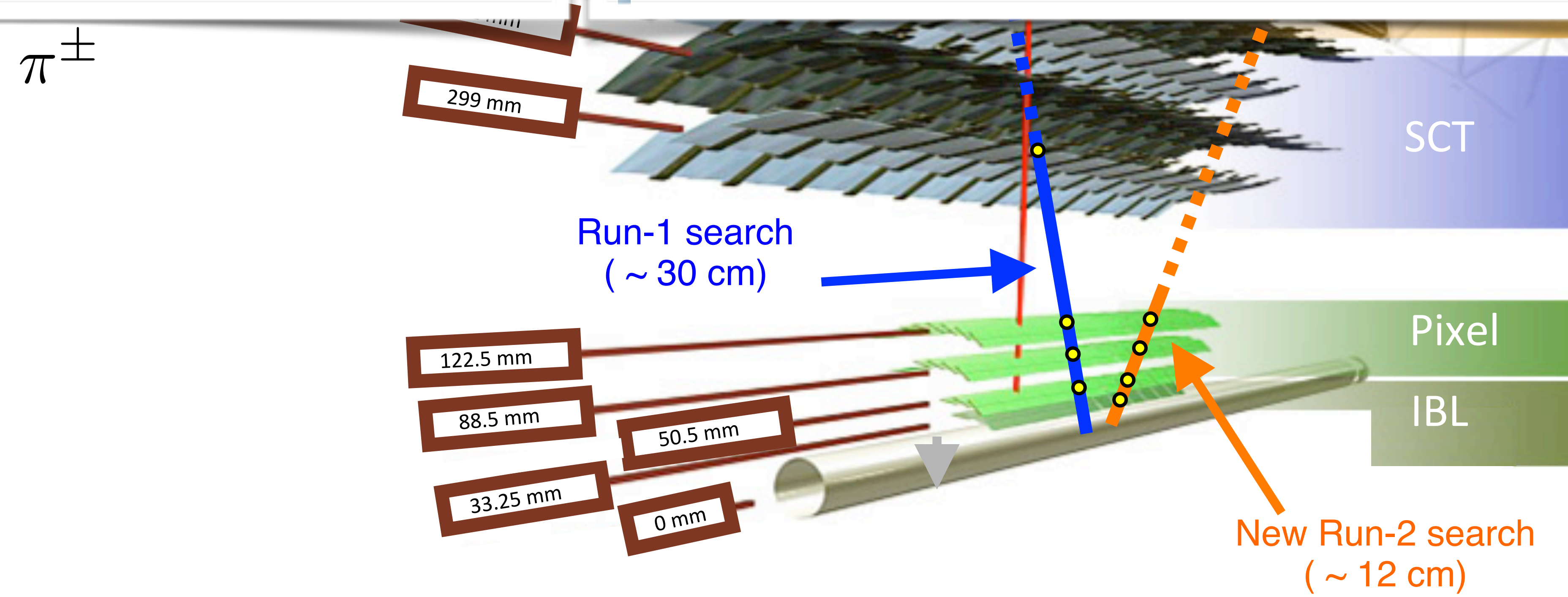




Disappearing track







Disappearing track with new Inner Tracker

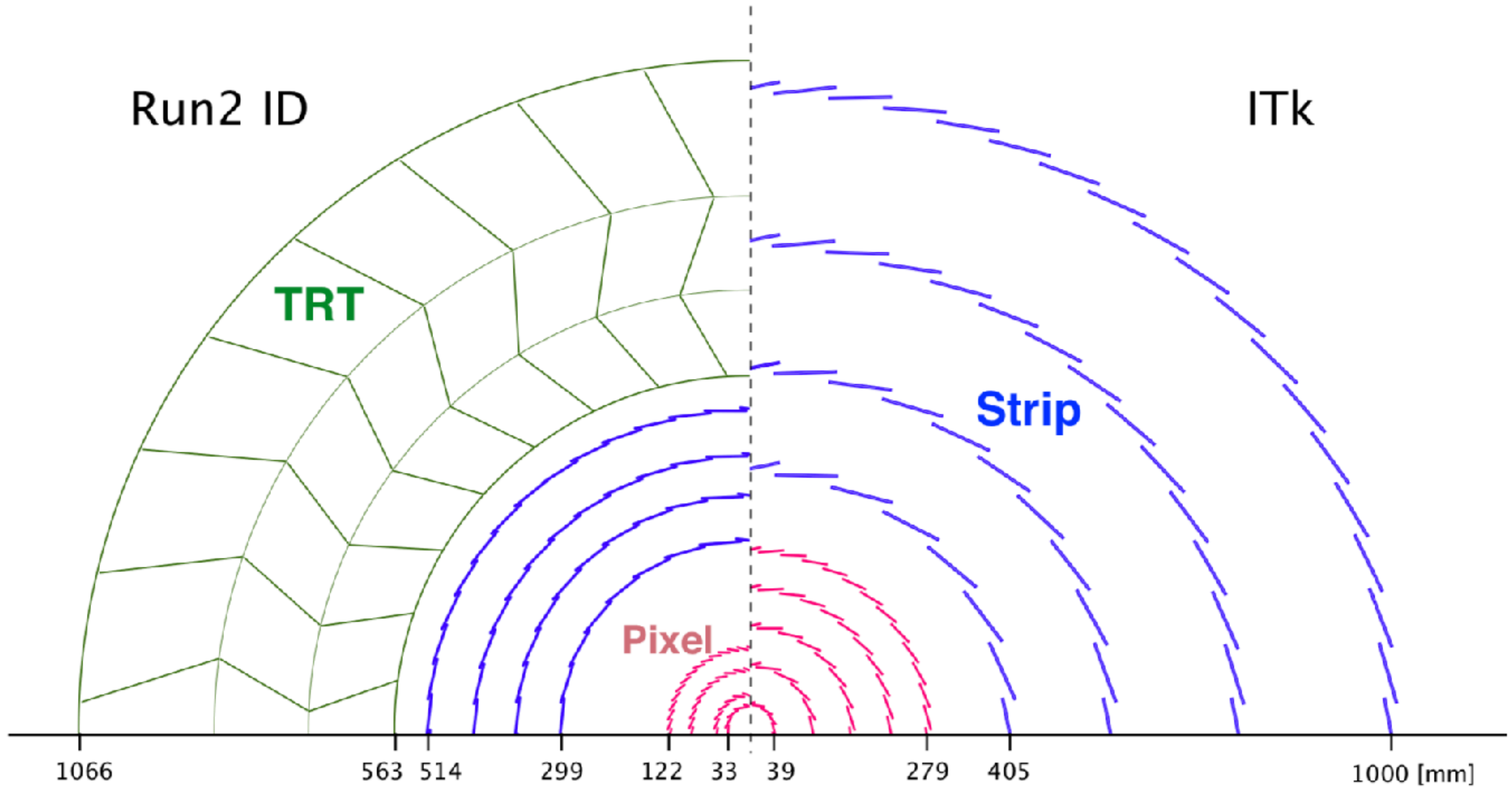


Figure 2: The radial layouts of the current ATLAS tracker and the proposed upgrade, the ITk.

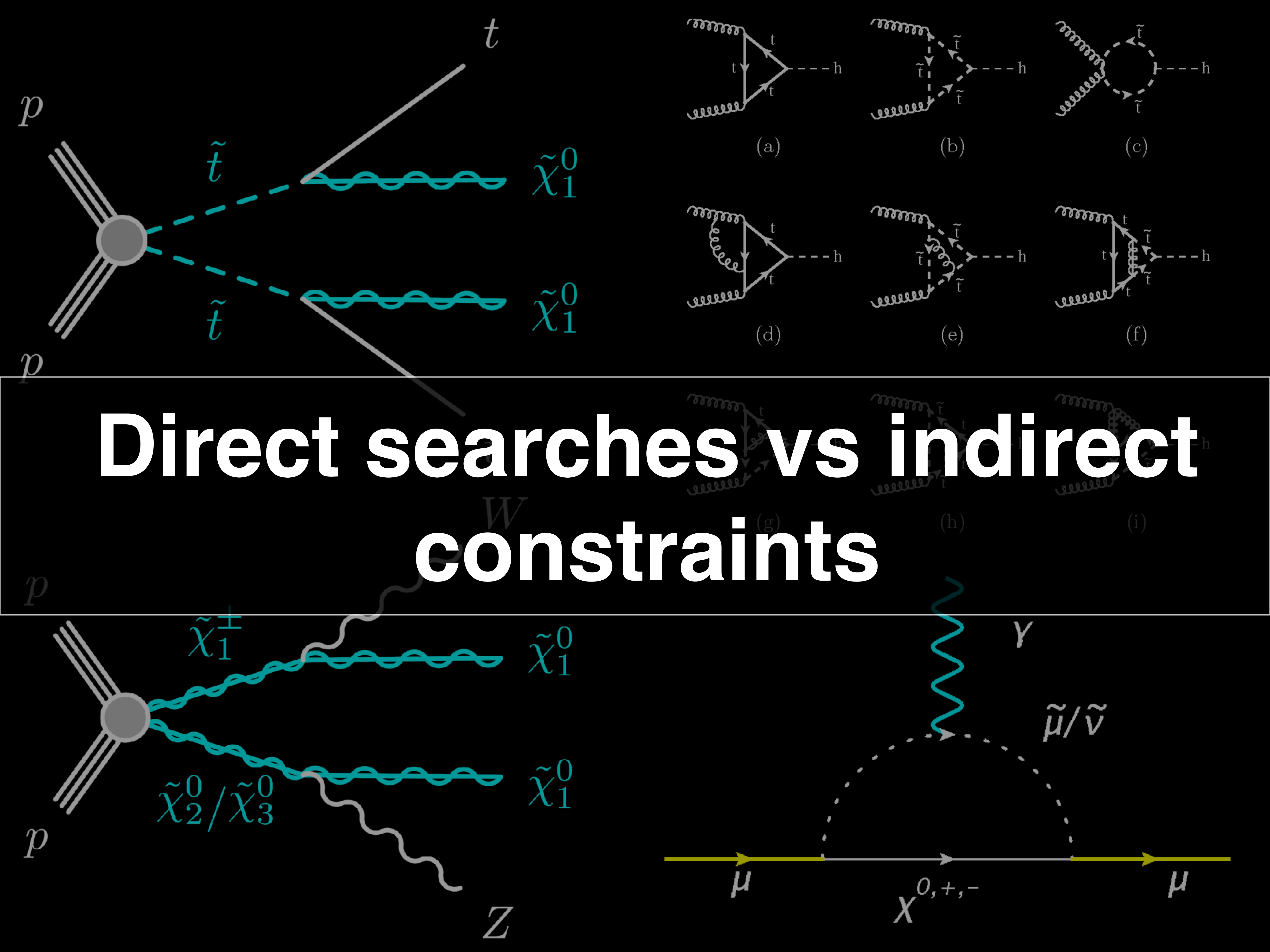
ATLAS Run2 ID gives x15 higher signal yield than ITK layout, for 4-hit tracklets (R ~ 12 cm vs 22 cm) and assuming a 400 GeV higgsino with τ = 0.05 ns.

While we expect x10 increase in int. luminosity when going from Run2+Run3 (300 fb^{-1}) to HL-LHC (3-4 ab^{-1})

Opportunity in ATLAS for Run3, should try to benefit from special trigger!

The lifetime of the higgsino chargino varies 0.03 to 0.07 ns
(the value decreases as the chargino mass increases).

Direct searches vs indirect constraints



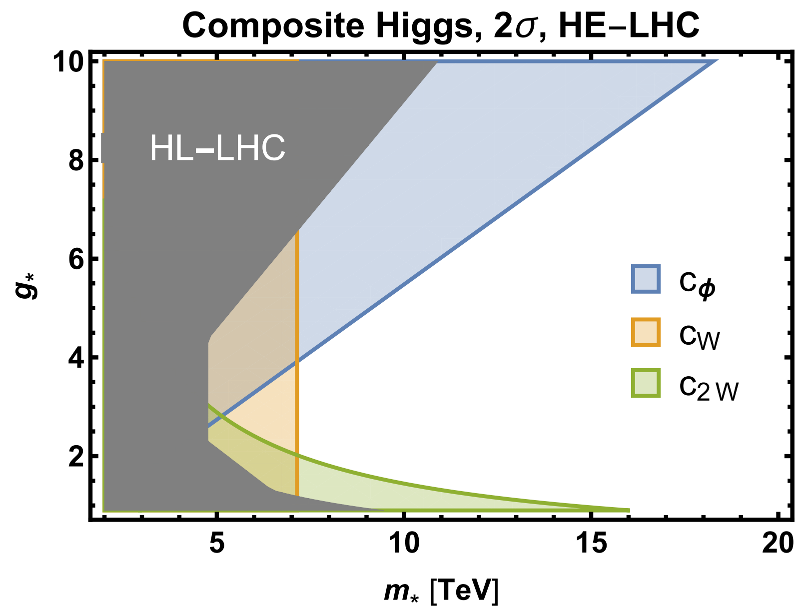
Direct searches vs indirect constraints

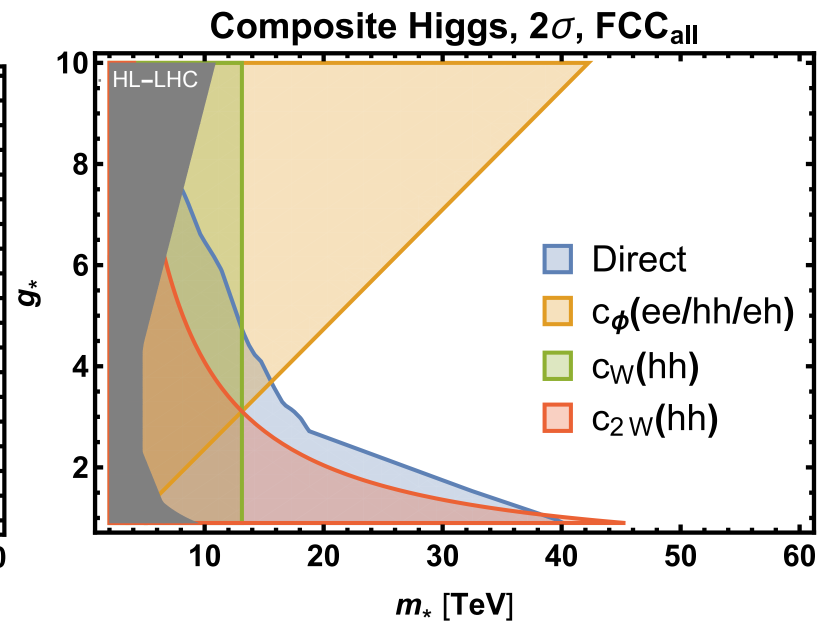
"Given the direct searches' null results and prospects, should we re-direct efforts to measurements?"

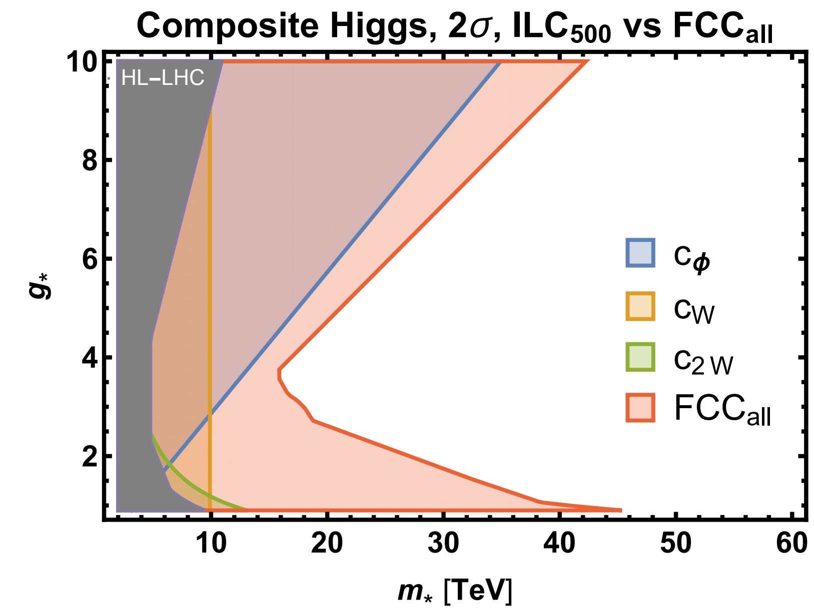
As the sensitivity of direct searches saturates, and the larger dataset and improved detector understanding lead to increasingly higher precision measurements, (that will cover more and more phase-space) will there be a point when NP is most stringently constrained by measurements?

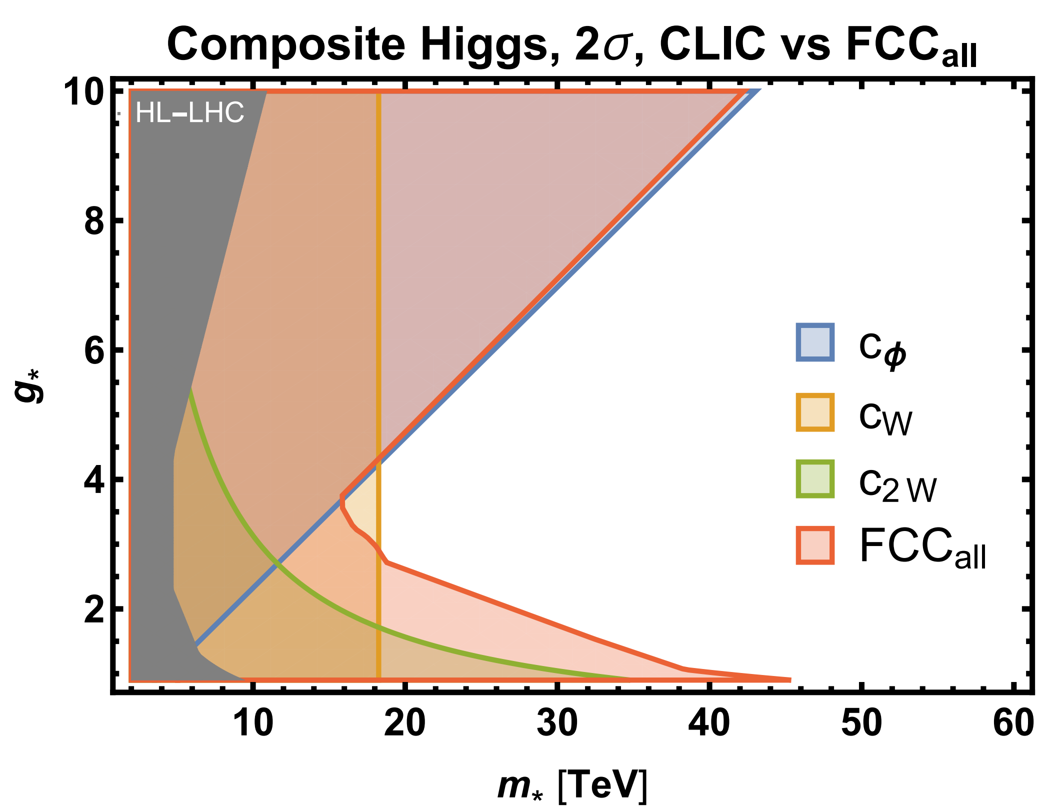
Giudice, Sphicas @ Granada workshop 2019

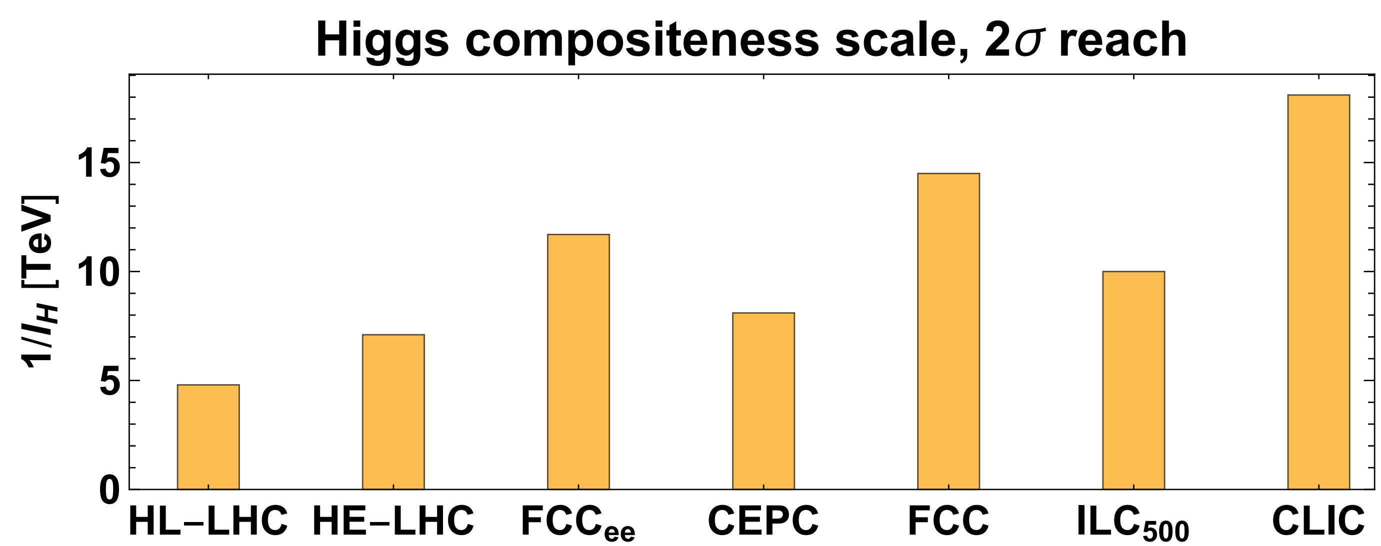
Higgs Compositeness?









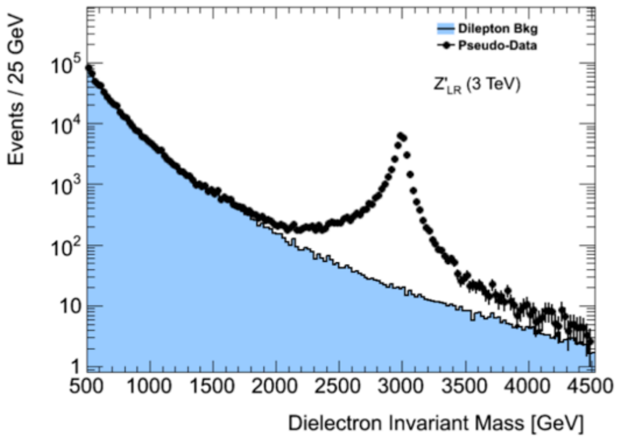


Giudice, Sphicas @ [Granada workshop 2019]

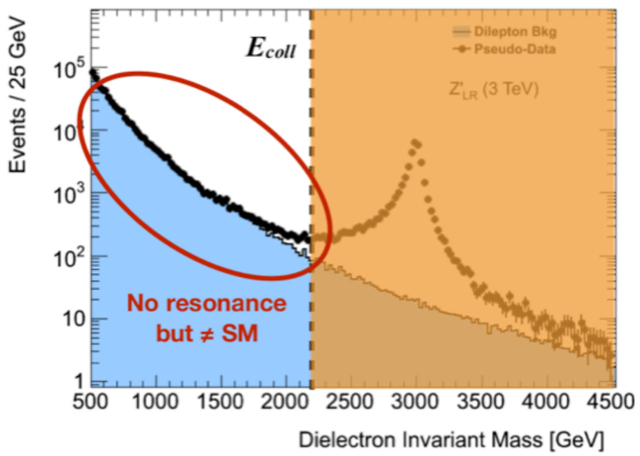
New resonances/particles/forces?

Seeing the peak. Reach:

- M < √s for lepton colliders
- M ≲ 0.3-0.5 √s in hadron colliders for couplings ~ weak couplings

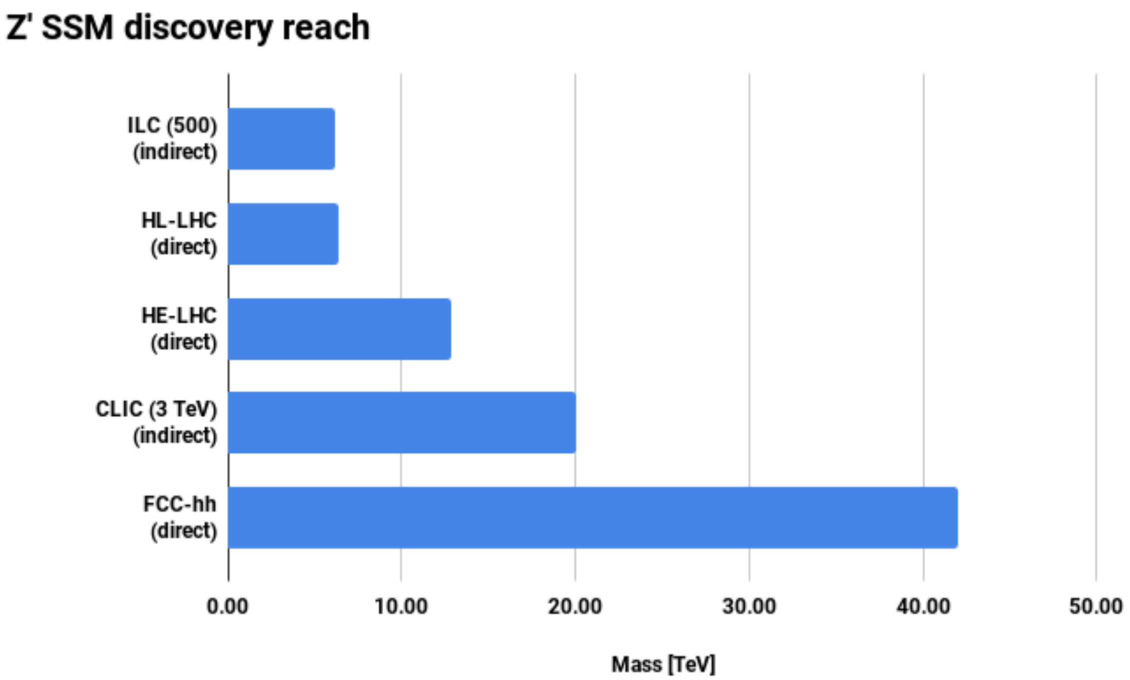


Courtesy: J. De Blas



Deviations in high-M tails:

- Better suited for lepton colliders; sensitive to [mass/coupling] ≫ √s
- Hadron colliders relevant for $g_{Z'} > g_{SM}$ couplings: [mass/coupling] ≫ 0.5√s



In what follows: using very simple model as example.
Universal Z'. Clearly, many models with flavor dependence etc.

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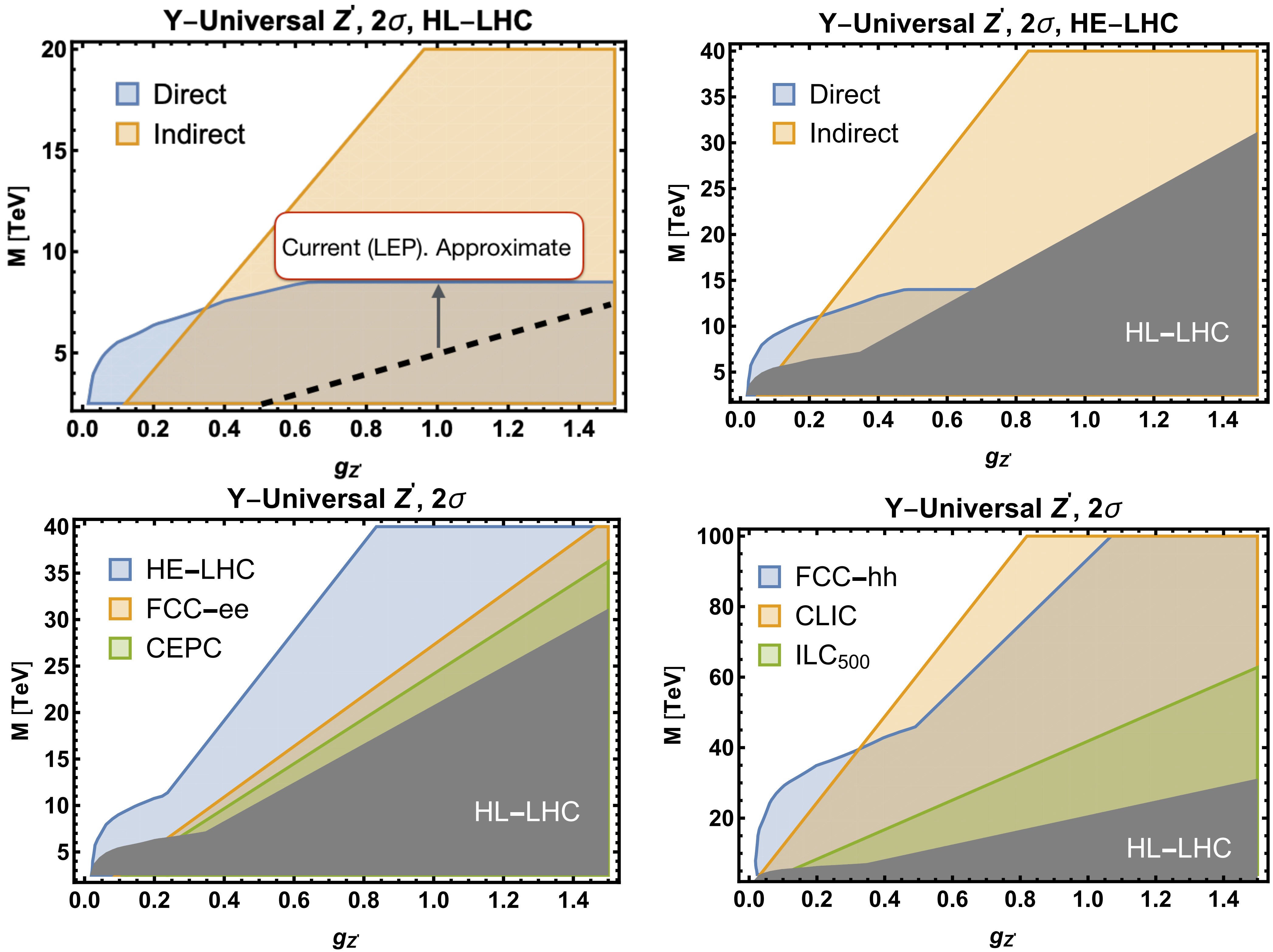
New resonances/particles/forces?



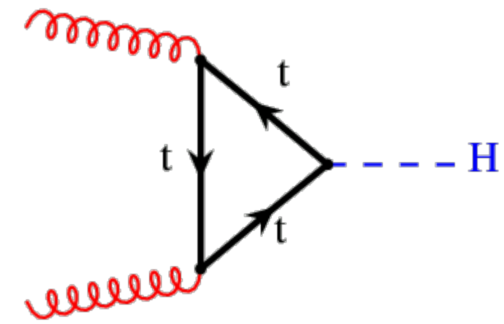
Indirect constraints

What are the indirect constraints assuming no additional flavor & CP violation?

SUSY is a **weakly** coupled theory:*

* coupling strength as in SM — if RPC: SM processes corrected @ 1-loop

$$\frac{\delta\mathcal{O}_{\mathrm{SUSY}}}{\mathcal{O}_{SM}} \sim \frac{m^2_{\mathrm{SM}}}{m^2_{\mathrm{SUSY}}}$$



Example: h -> gg

$$r_g = \frac{g_{hgg}}{g^{\mathrm{SM}}_{hgg}} \qquad r_g - 1 \approx \frac{1}{4}\frac{m_t^2}{m^2_{\tilde{t}_1}} \approx 0.7\% \left(\frac{1\ \mathrm{TeV}}{m^{\cancel{2}}_{\tilde{t}_1}}\right)^2$$

9

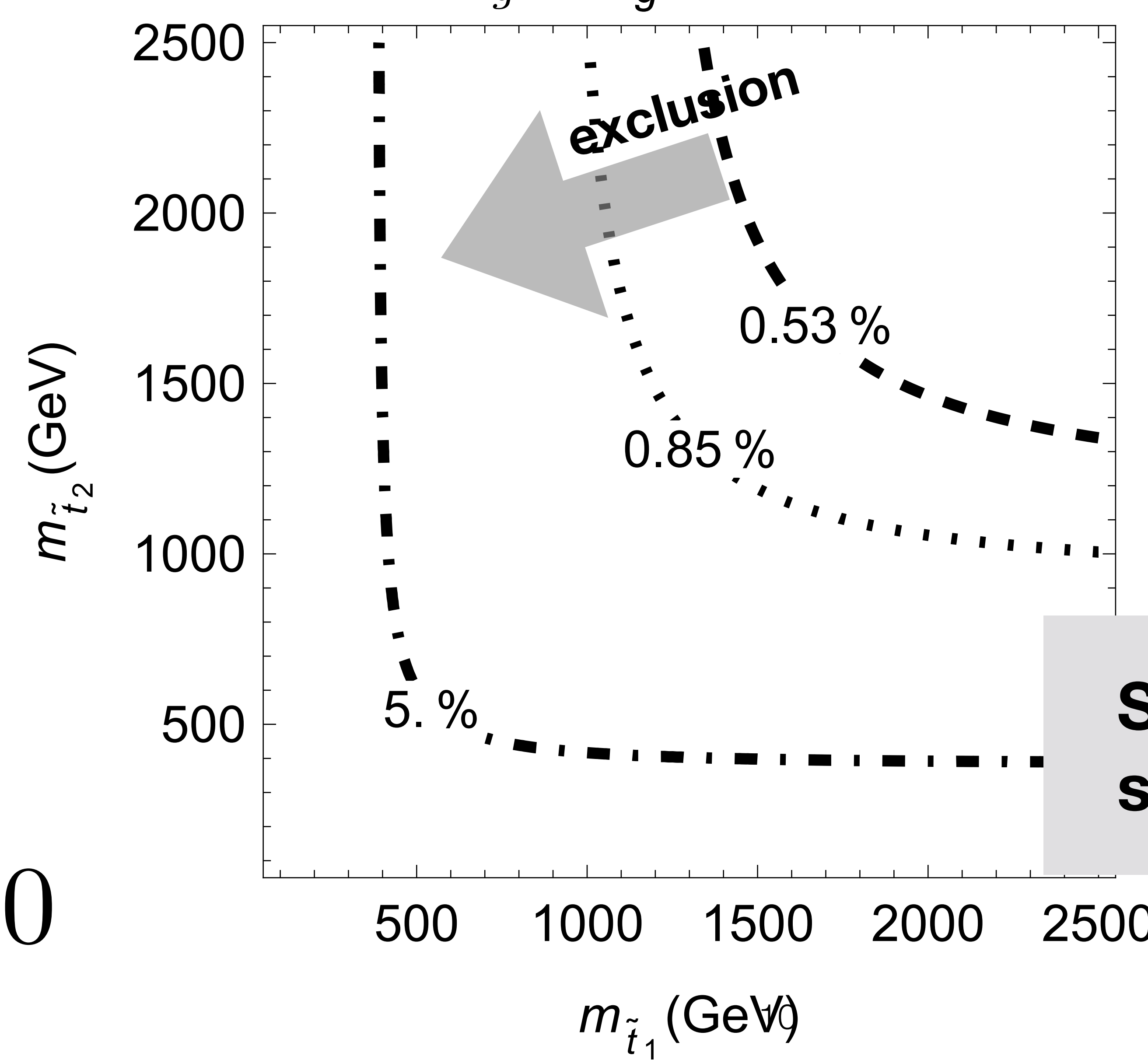
Weiler @ Granada workshop 2019

Indirect: Higgs precision

1905.03764

kappa-3 scenario	ILC$_{250}$	ILC$_{500}$	CLIC$_{380}$	CLIC$_{1500}$	HL-LHC+ CLIC$_{3000}$	CEPC	FCC-ee$_{240}$	FCC-ee$_{365}$	FCC-ee/eh/hh
$\kappa_g(\%)$	1.4	0.84	1.5	1.1	0.86	1.1	1.2	0.89	0.53

$$\kappa_g = r_g - 1$$



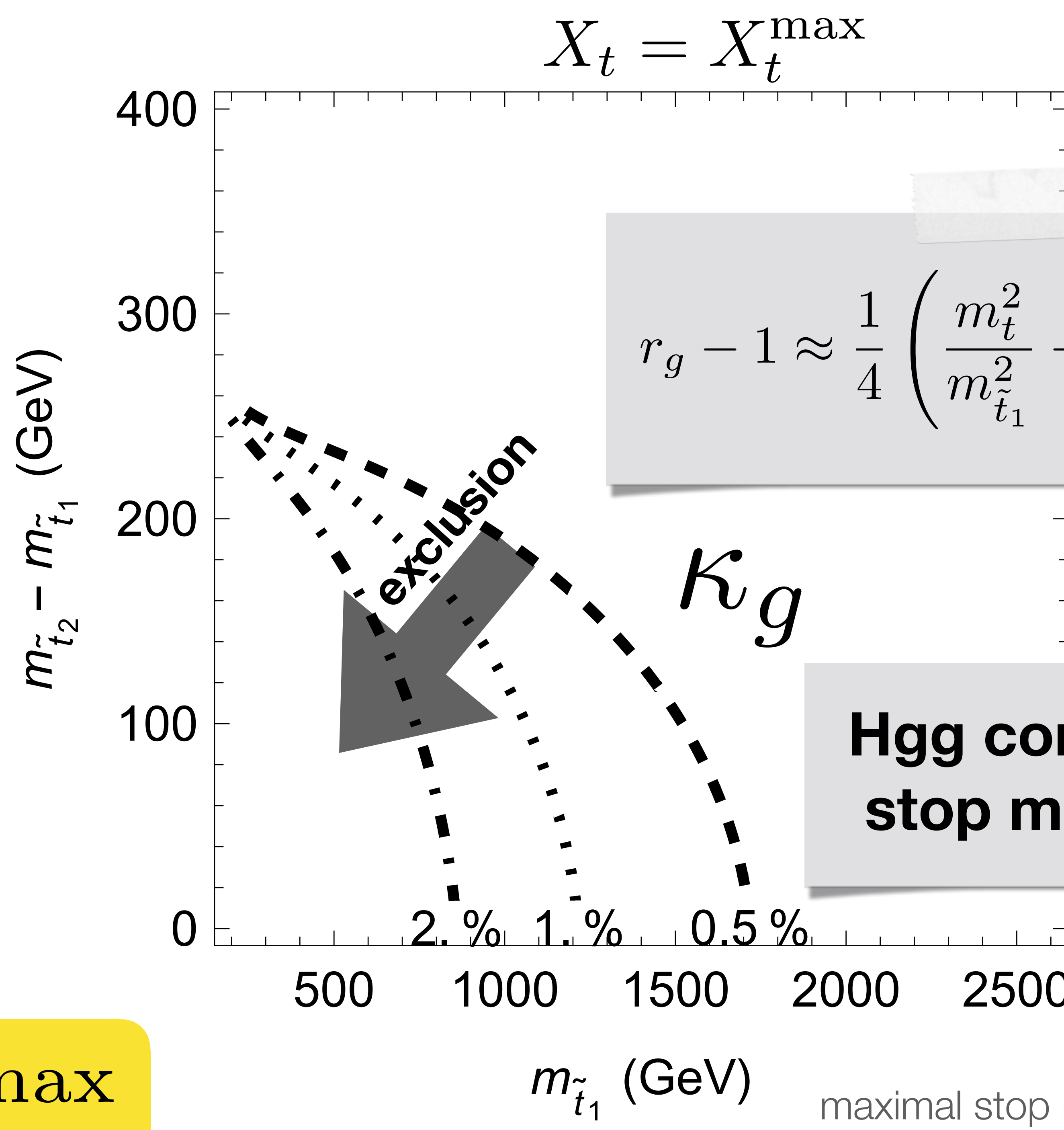
← FCC-ee/eh/hh

← CLIC$_{3000}$, ILC$_{500}$

Stringent limits for small X$_t$ stop mixing

$$X_t = 0$$

Indirect: Higgs precision



$$r_g - 1 \approx \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right)$$

Hgg contrib. cancels if stop mixing X_t is large.

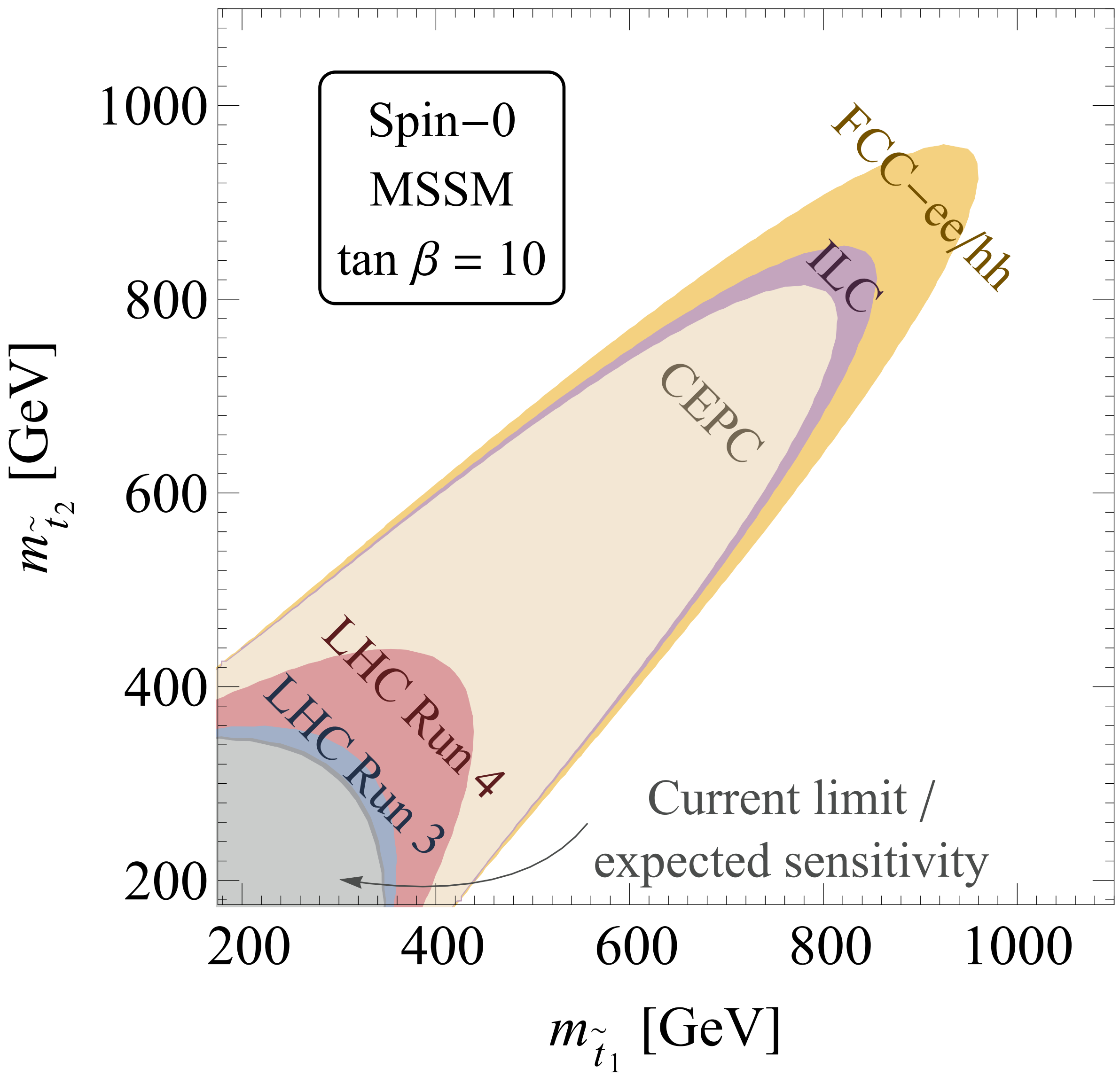
$$X_t = X_t^{\max}$$

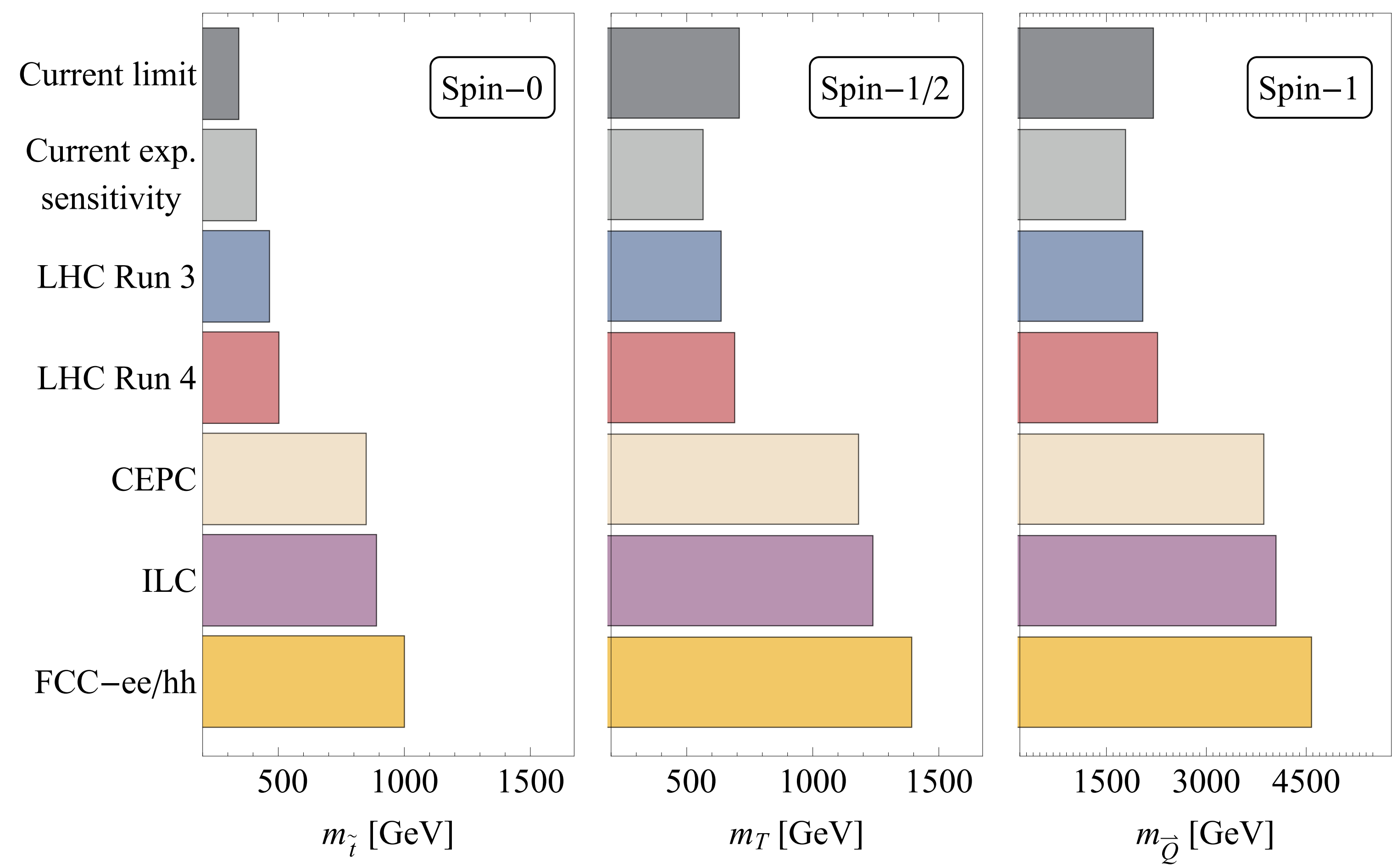
maximal stop mixing given the stop mass splitting: $\left|X_t^{\max}\right| = \frac{\left|m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2\right|}{2m_t}$

11

Similar picture in studies by

Essig, Meade, Ramani, Zhong, 1707.03399





Direct searches vs indirect constraints

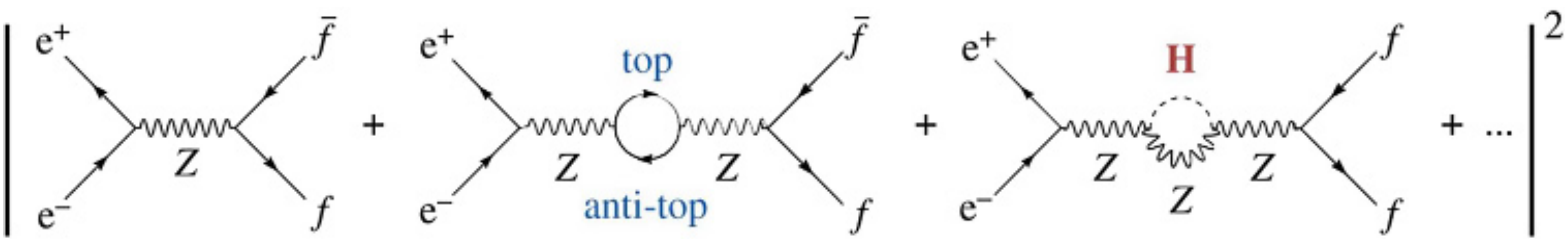
Direct searches and measurements (indirect constraints) complementary.

- (Higgs) measurements appear not competitive for SUSY.
- Measurement programme may reveal signs of NP at energy above directly accessible level ⇒ SM EFT.

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i + \cdots$$

LEP indirect prediction of Higgs mass,

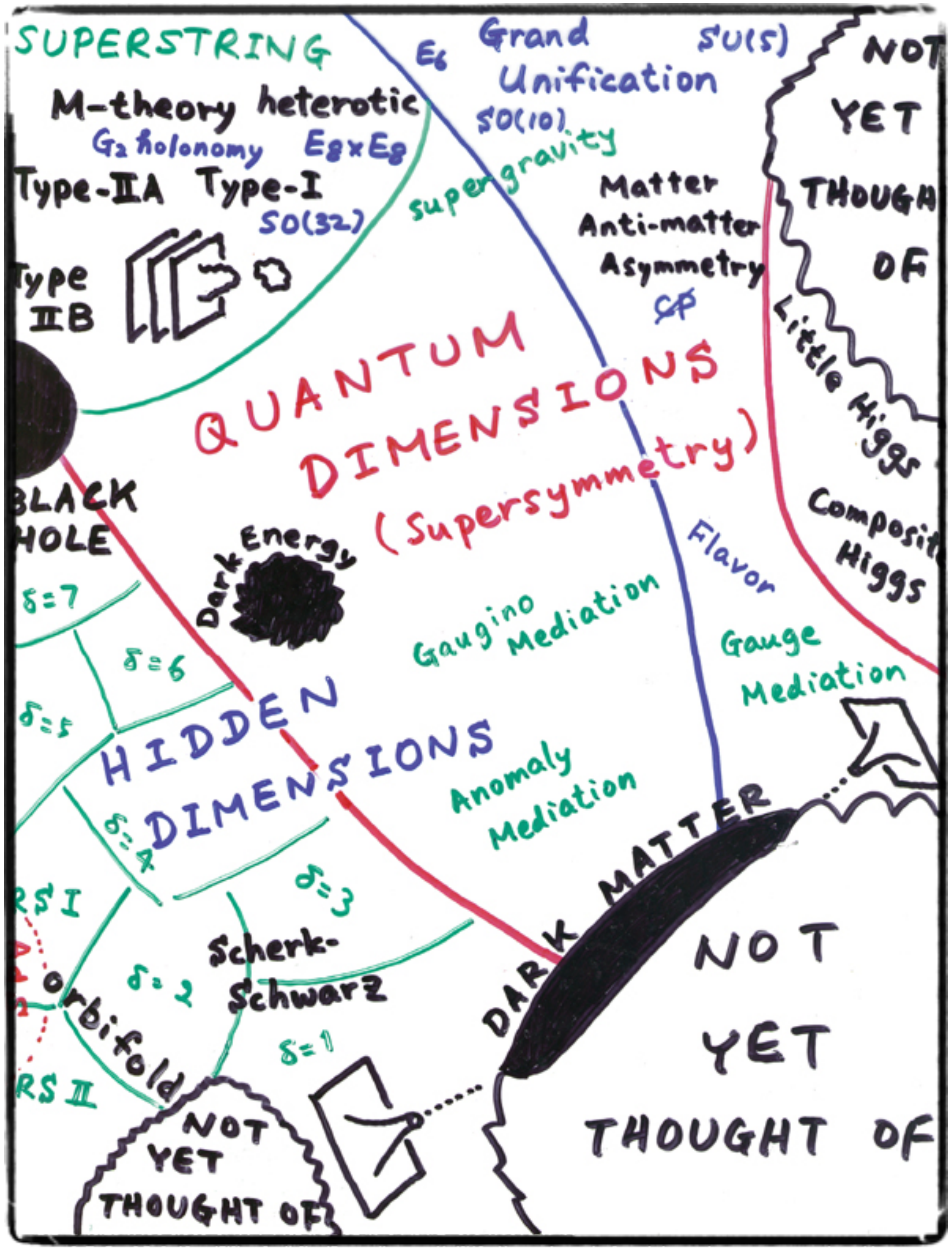
$$m_{\text{H}}^{\text{SM}} = 98^{+25}_{-21}\ \text{GeV}$$



- Higgs programme may reveal exotic decays, or invisible BF, or additional scalars (not sure these fall under direct or indirect searches).

Strategy for Run3 and beyond

Theory guidance?



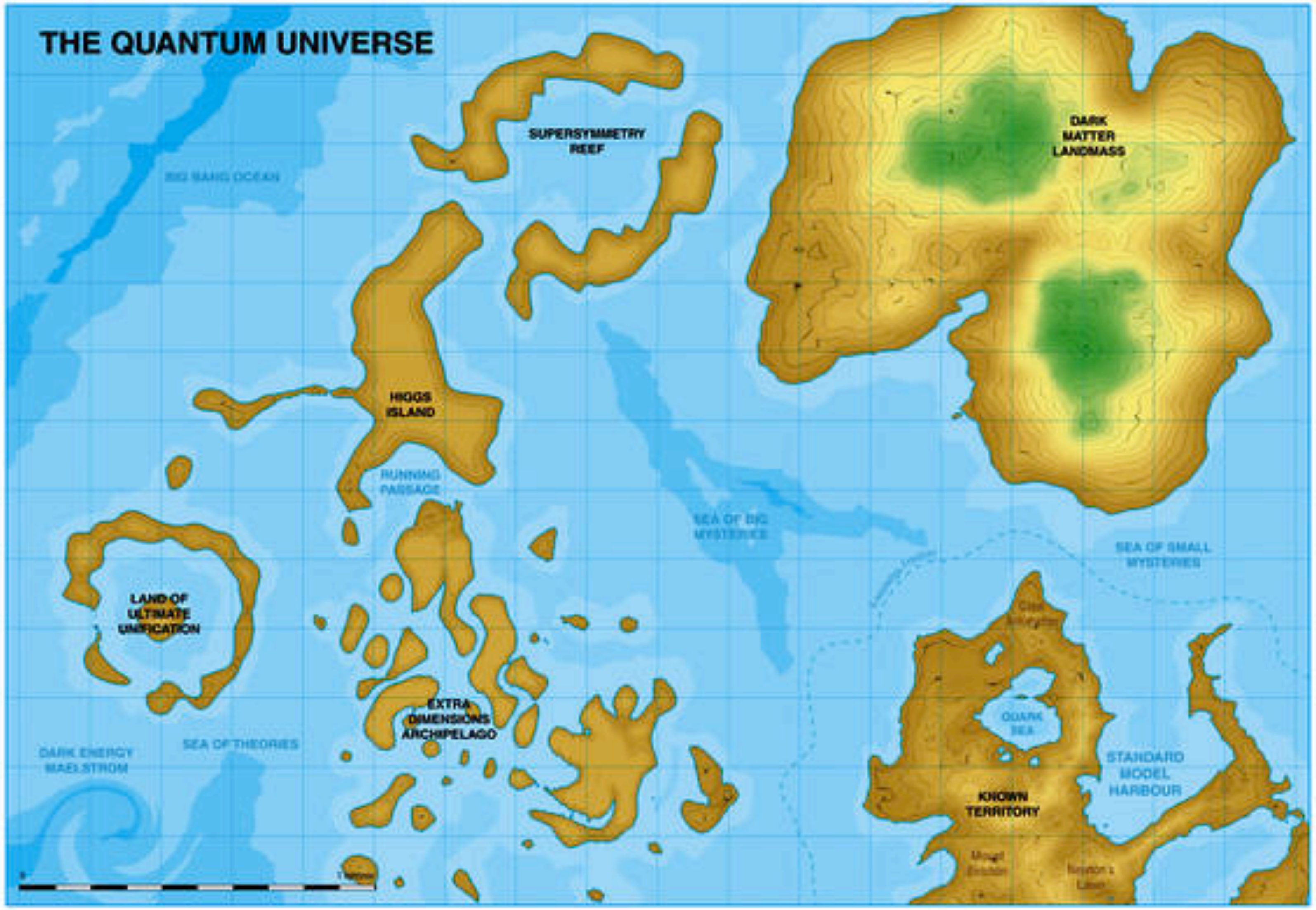
Some feel that a <u>paradigm change</u> is required, moving beyond the organising principles based on symmetry and separation of scales.

Exp.: waiting for guidance from new paradigm(s).

New theoretical directions: dark/hidden sectors with feebly interacting particles.

Strategy for Run3 and beyond

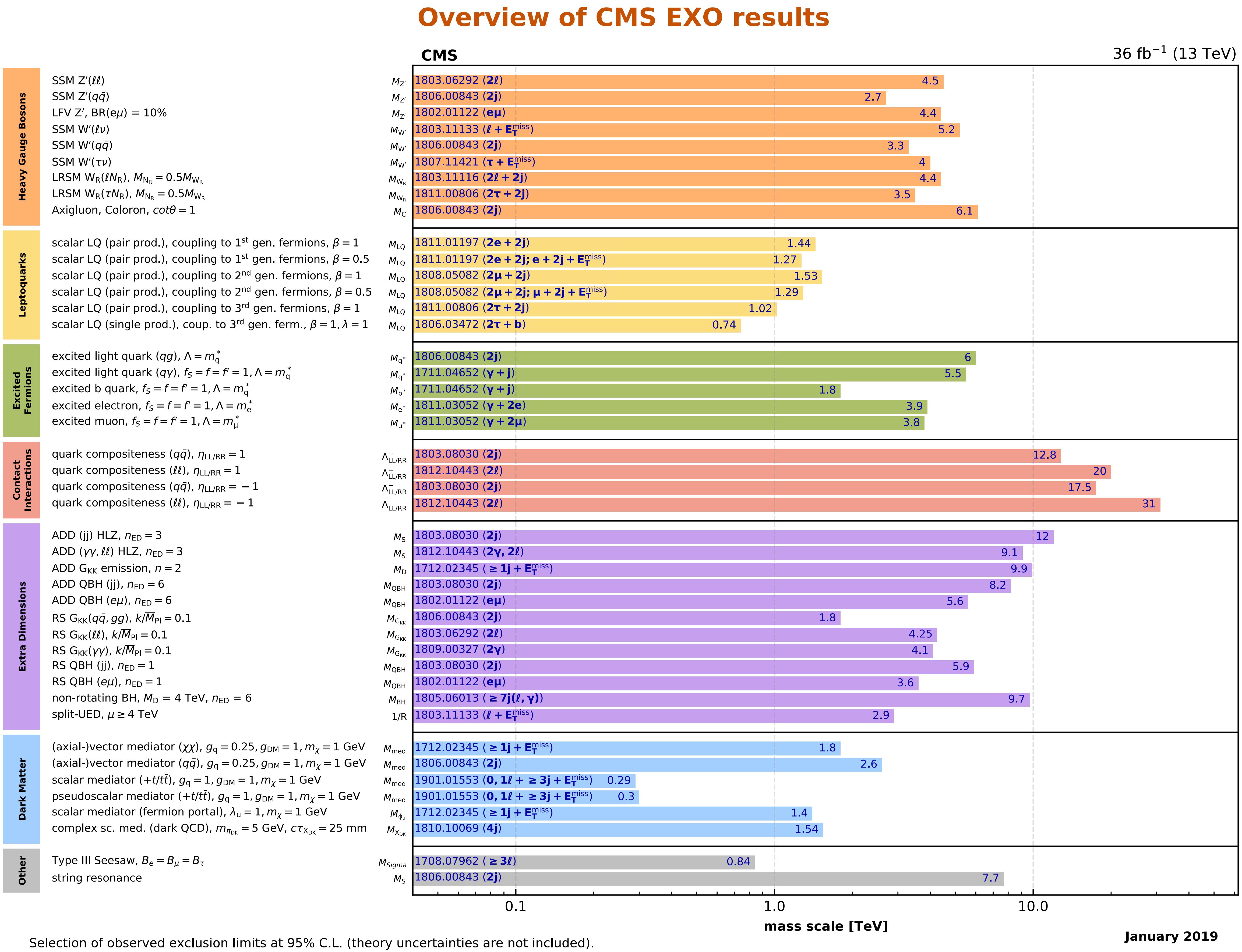
I think that our community is becoming more data-driven. Experimental results will have to guide the HEP community to the next stages of exploration.



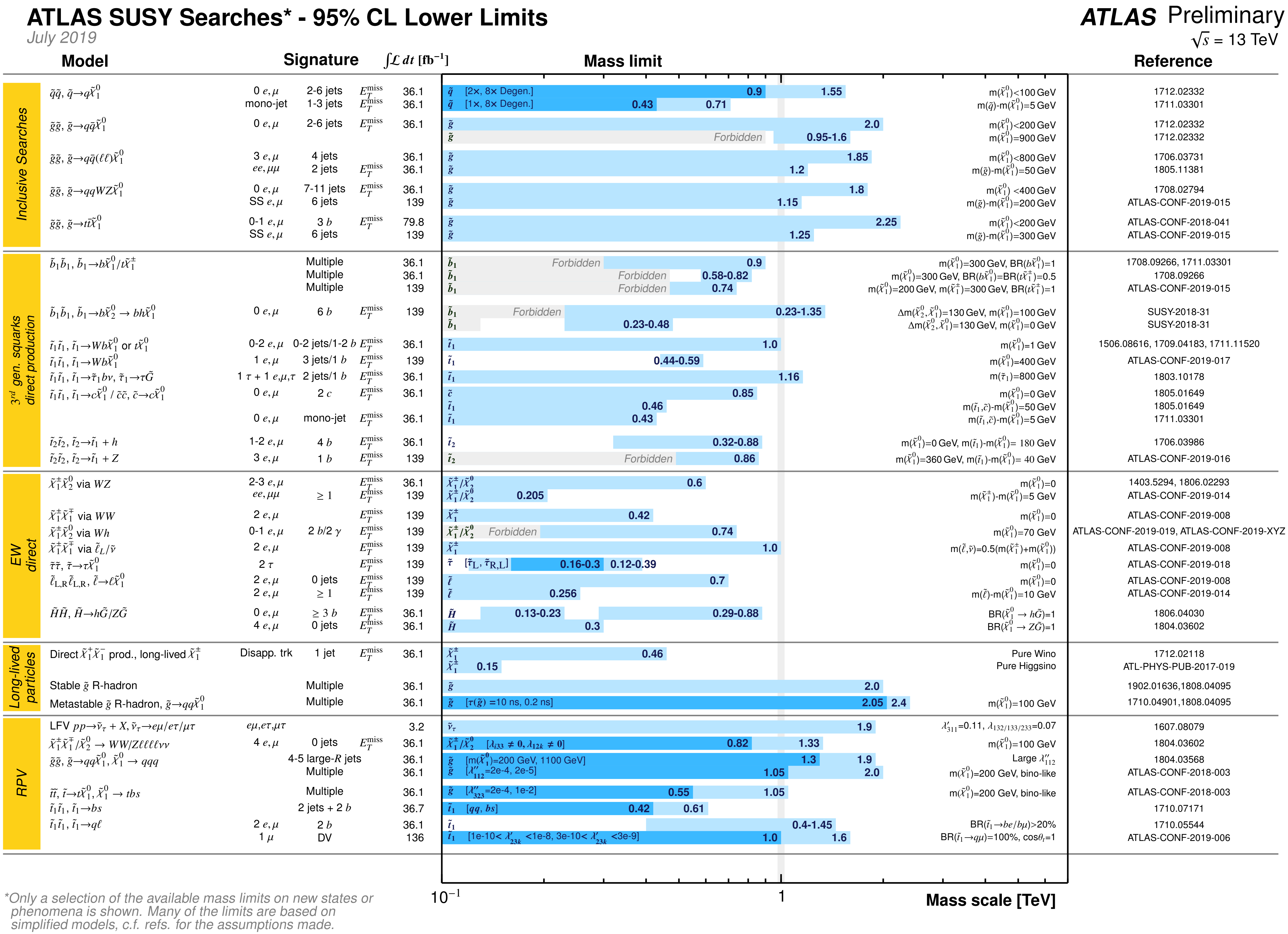
As long as no clear signs of NP ⇒

broad and diversified <u>search</u> and <u>measurement</u> programme.

Large Exotic(s/a) search programme



Large SUSY search programme @ LHC



Anything missing in search programmes?

- I am not aware of significant gaps in model / parameter space, perhaps not surprising given large community effort (~2 x 3000 exp physicists + th community) over past ~decade.
- New triggers for Run3 and beyond may create opportunities … requires good ideas and hard work!
- Long-lived particle searches:
  - I am a very excited about the LLP programme,
  - but I often hear: "There's still a lot of missing analyses / model space to be covered". I have not found many significant 'holes'.
  - For example, SUSY search coverage of LLP appears fairly robust. Example, study of sensitivity (gaps) between searches for prompt and long-lived particles in ATLAS-CONF-2018-003.
  - Exotica offers, as often, many crazy signatures. Are there signatures that we are not yet covering (i.e. completely uncovered ground)? Please let me know if you know one!
- New detectors (incl. LHC det. upgrades) can extend BSM reach.
- I haven't considered much FIPs …

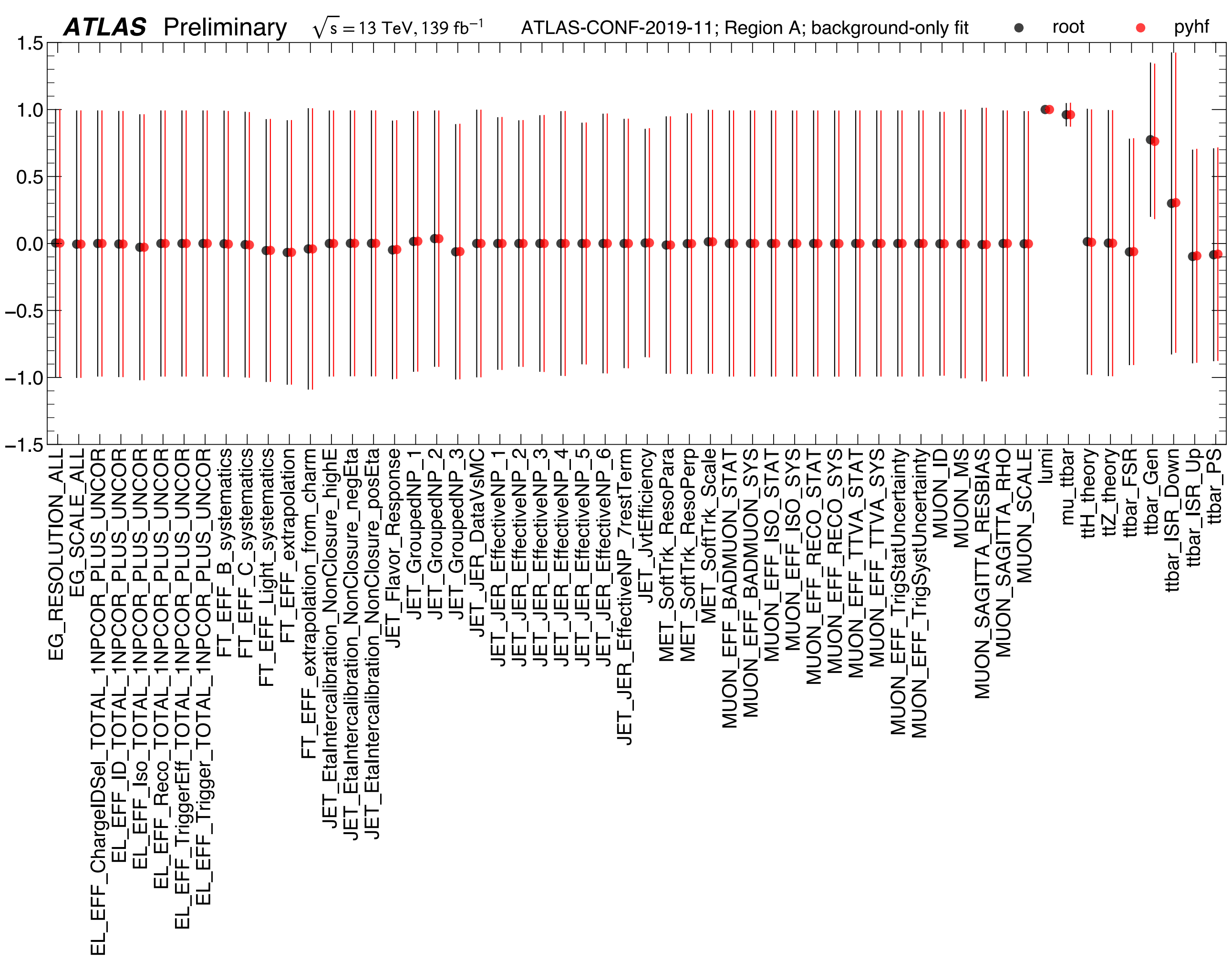
Publication cycle

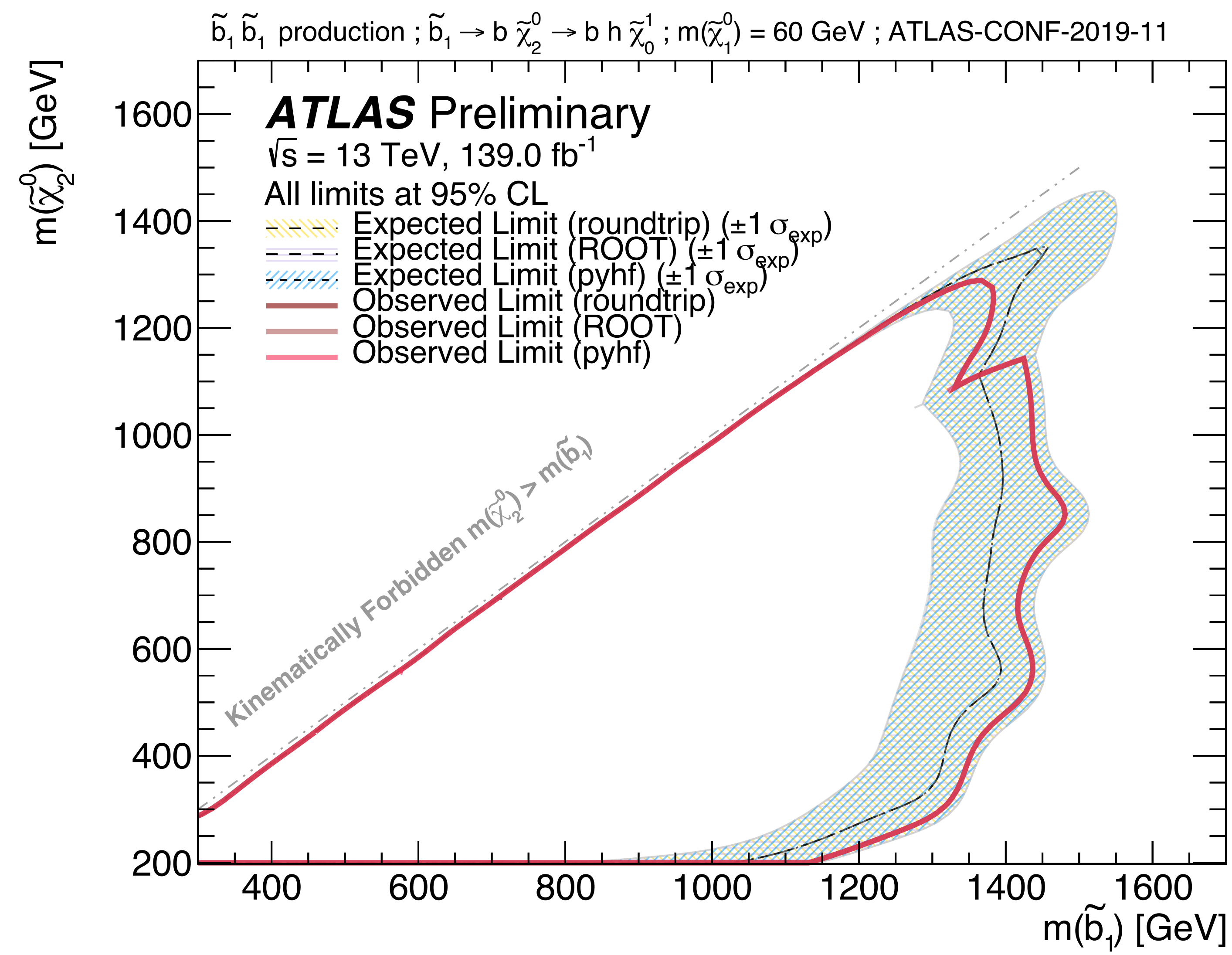
LHC Run1 & Run2: have published ~full search programmes x(2-3) per Run, justified by the quick increase in dataset size and step in $\sqrt{s}$.

LHC Run4 & beyond: I expect 1 round of search publications after Run3 (300 fb^{-1}), and then ~every time the dataset size increases by x2-3.

Reinterpretation: likelihood, unfolding,…

- Our duty to provide and maintain data, procedures and tools to facilitate the re-interpretation of the beautiful LHC results.
  - CMS began to provide “simplified” likelihoods
  - ATLAS SUSY publications come with analysis code-snippets, and new in 2019: full likelihood as json file (can be used directly by pyhf tool), ATL-PHYS-PUB-2019-029





Reinterpretation: likelihood, unfolding,…

- Measurements typically have Rivet routines.
- Should we begin to unfold the phase-space probed by direct searches?
  - Added-value but extra work, might not be straight forward in some search regions.
  - I’d like to see this for all control region, and then see how useful it is in practise.
- Measurements that extend to more extreme phase space (regime of searches), to provide input to EFT fits (e.g. indirect constraints on Z’) appears useful to me.

Summary

LHC + HL-LHC will continue to be the flagship machine for (at least) the next decade.

Privilege to harvest the rich physics from the (HL-)LHC dataset.

Direct searches and **indirect constraints** from measurements complementary in our quest to find hints of new physics.

Large increase of dataset x20-30:
will increase our current mass reach by 50%-100%

No magic bullet
⇒ We already have a powerful physics programme.

but opportunities for additional discovery potential may be obtained from:
new detectors, new triggers, improved systematics, new discrimination tools and new ideas!

Backup