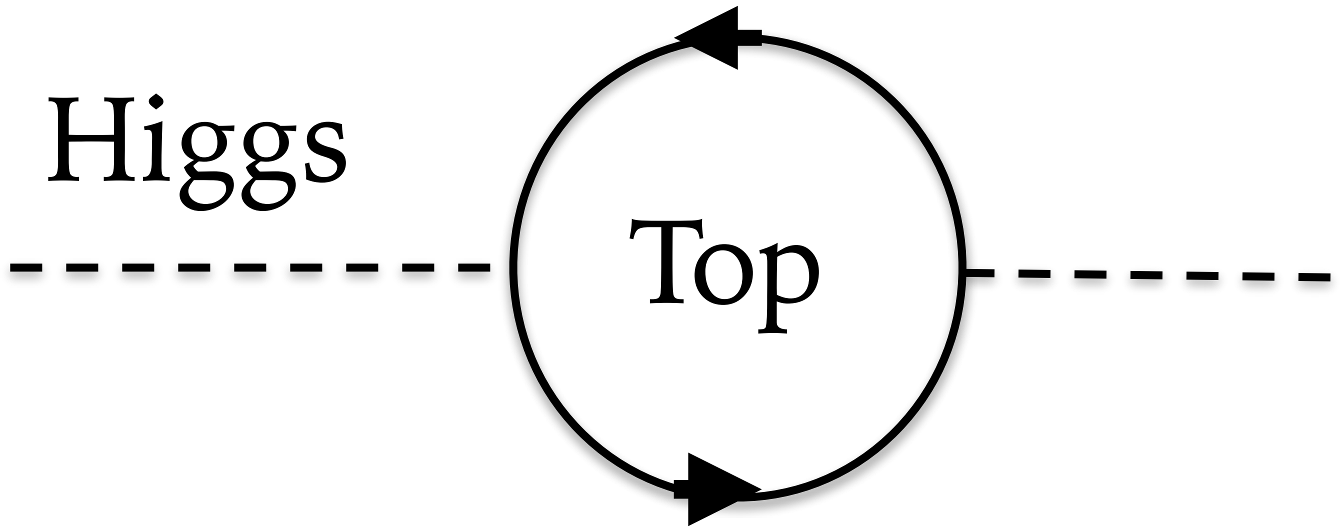
LHC Physics – BSM searches

DESY Summer Student Lectures, 16.08-17.08.2022

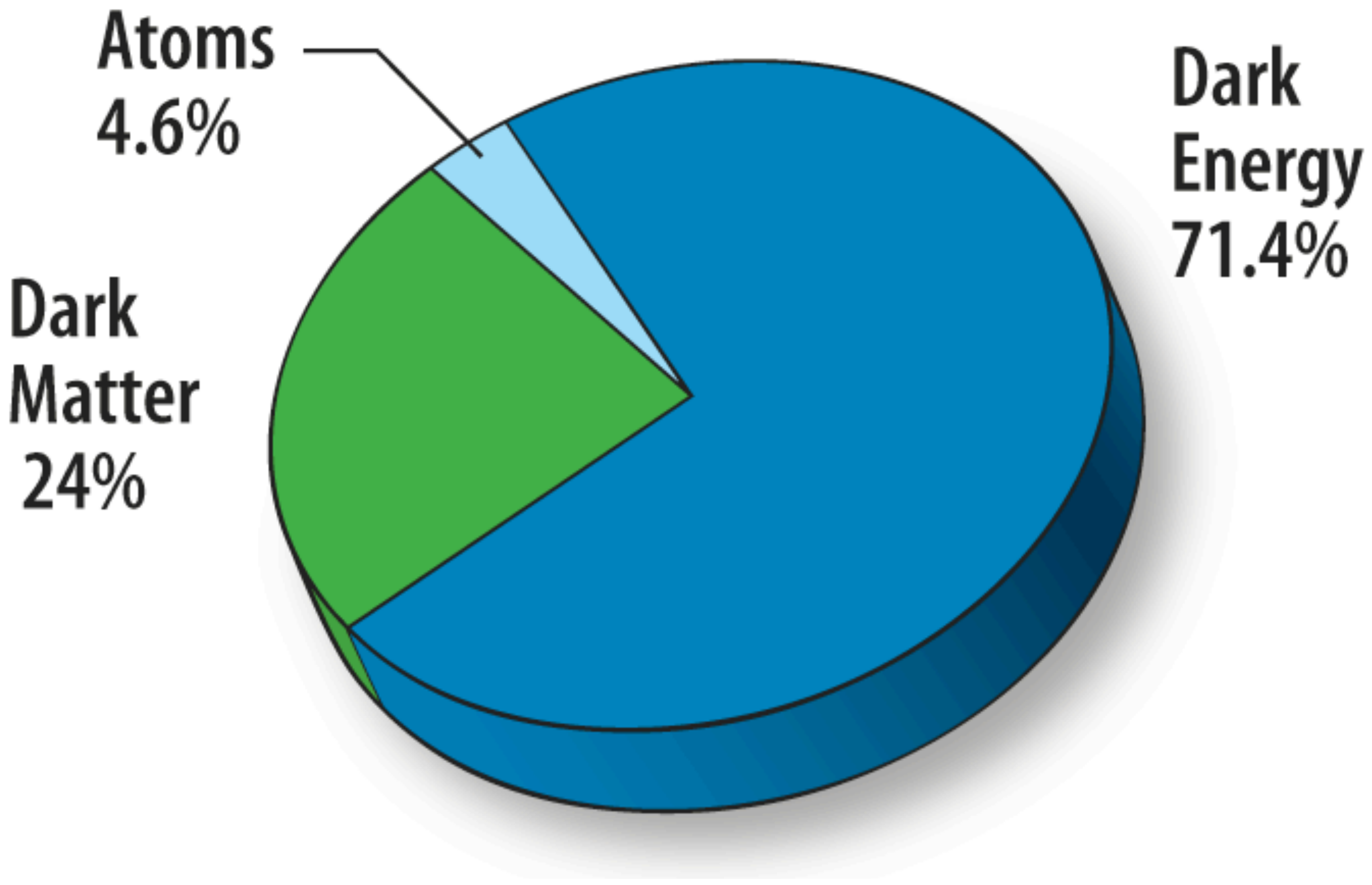
Claudia Seitz

Shortcomings of the Standard Model

- **Hierarchy problem**
  - Higgs mass should be at the Planck scale due to loop corrections from fermions to its mass

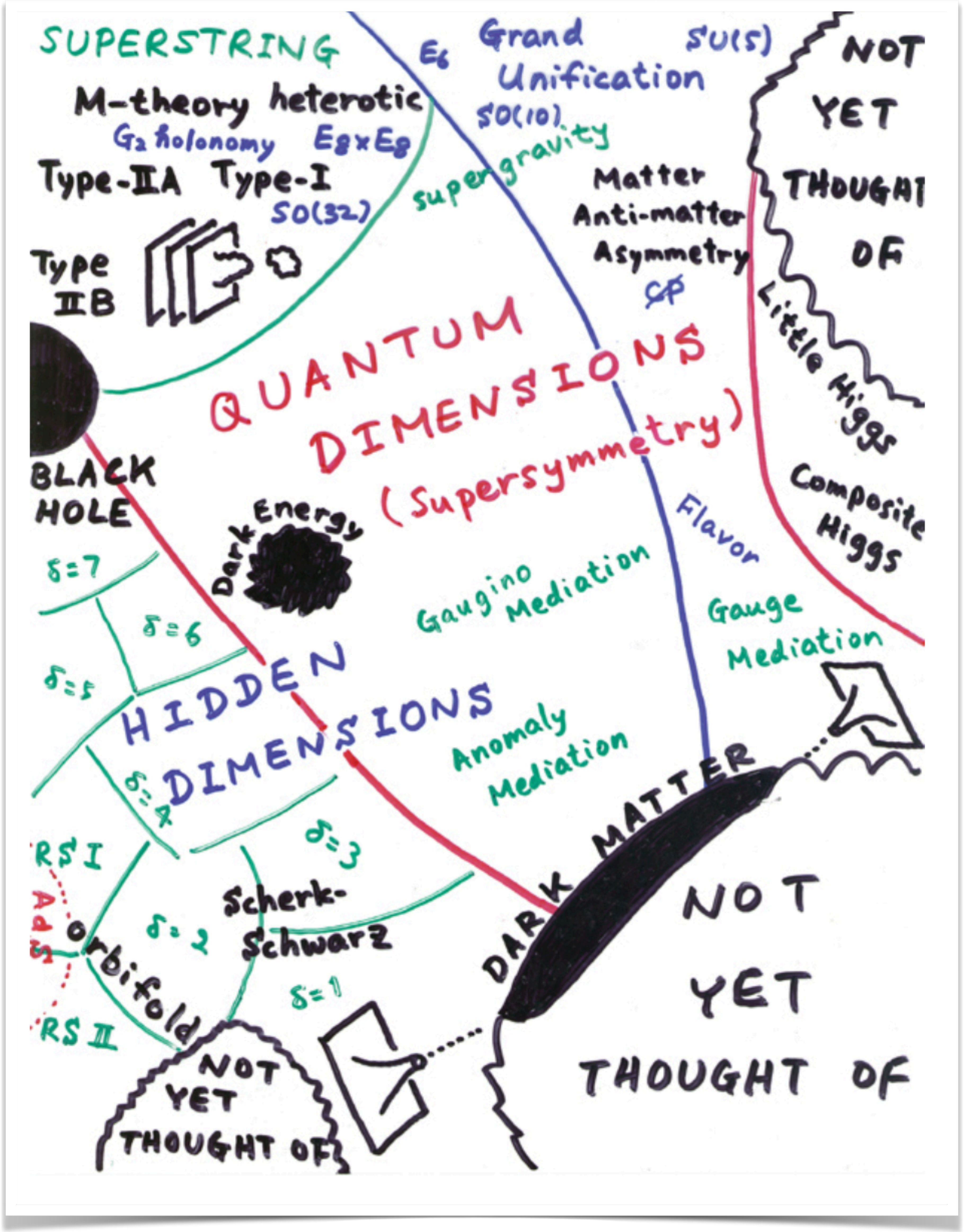


- **Gravity** is not included in the Standard Model
- No explanation for **Dark Matter** or Dark Energy



- **Neutrinos**
  - Assumed to be massless
  - Neutrino oscillations were discovered indicating a non-zero mass

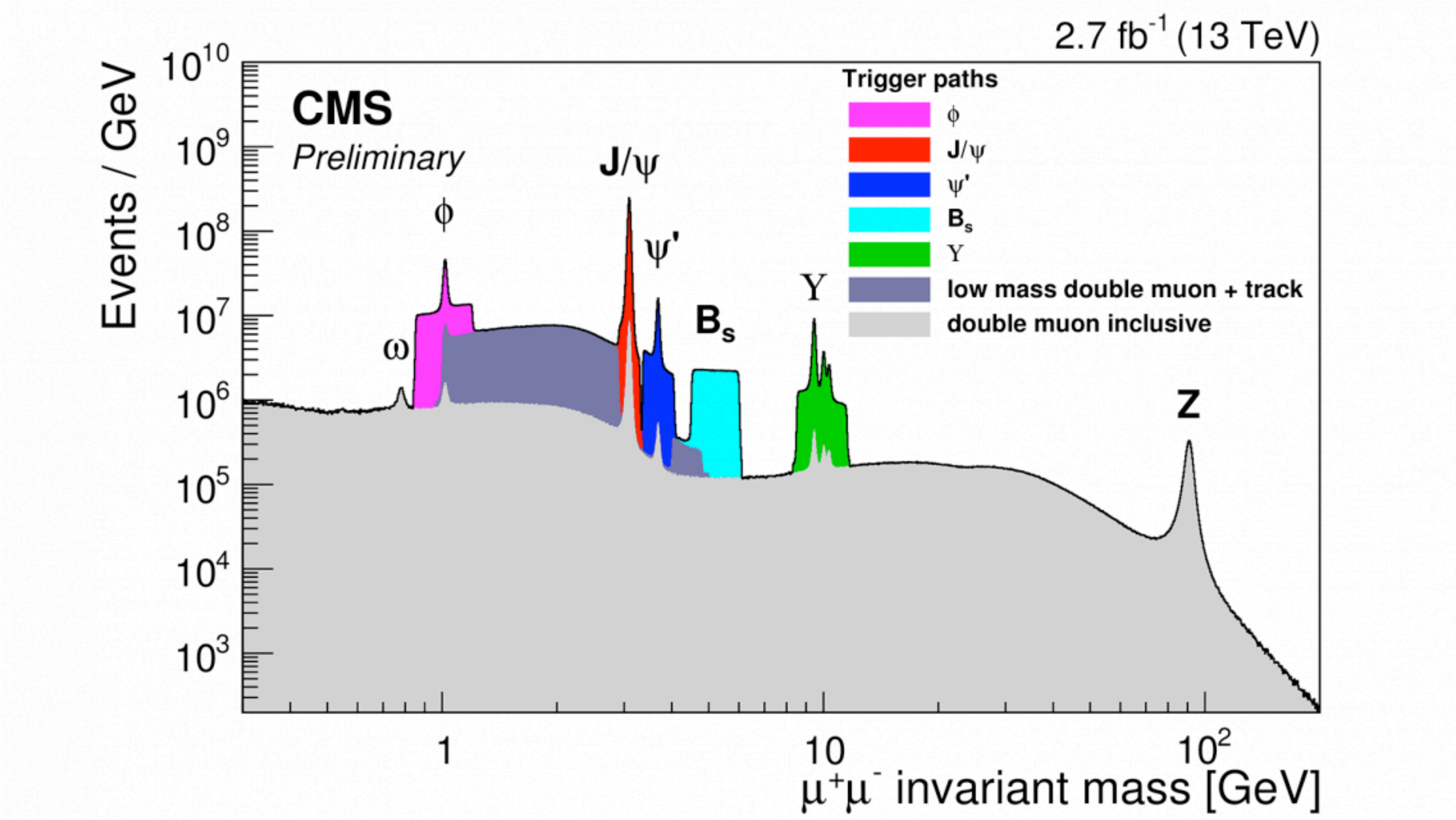
Landscape of proposed New Physics scenarios is vast!



- ➤ Two ways of approaching this issue
  - ➤ **Model driven**
    - ➤ start from a specific theory prediction
      ⇒ design and optimize for that specific signal
  - ➤ **Signature driven**
    - ➤ look for deviation from the SM anywhere
      ⇒ look at specific final states (dijet, high MET)
  - ➤ Both strategies are followed at the LHC
  - ➤ Crucial: excellent understanding of Standard Model backgrounds is needed!

Resonance searches

- Many models predict the existence of additional, so-far undiscovered particles
  $\Rightarrow$ would likely find them through their decay products



Resonance searches

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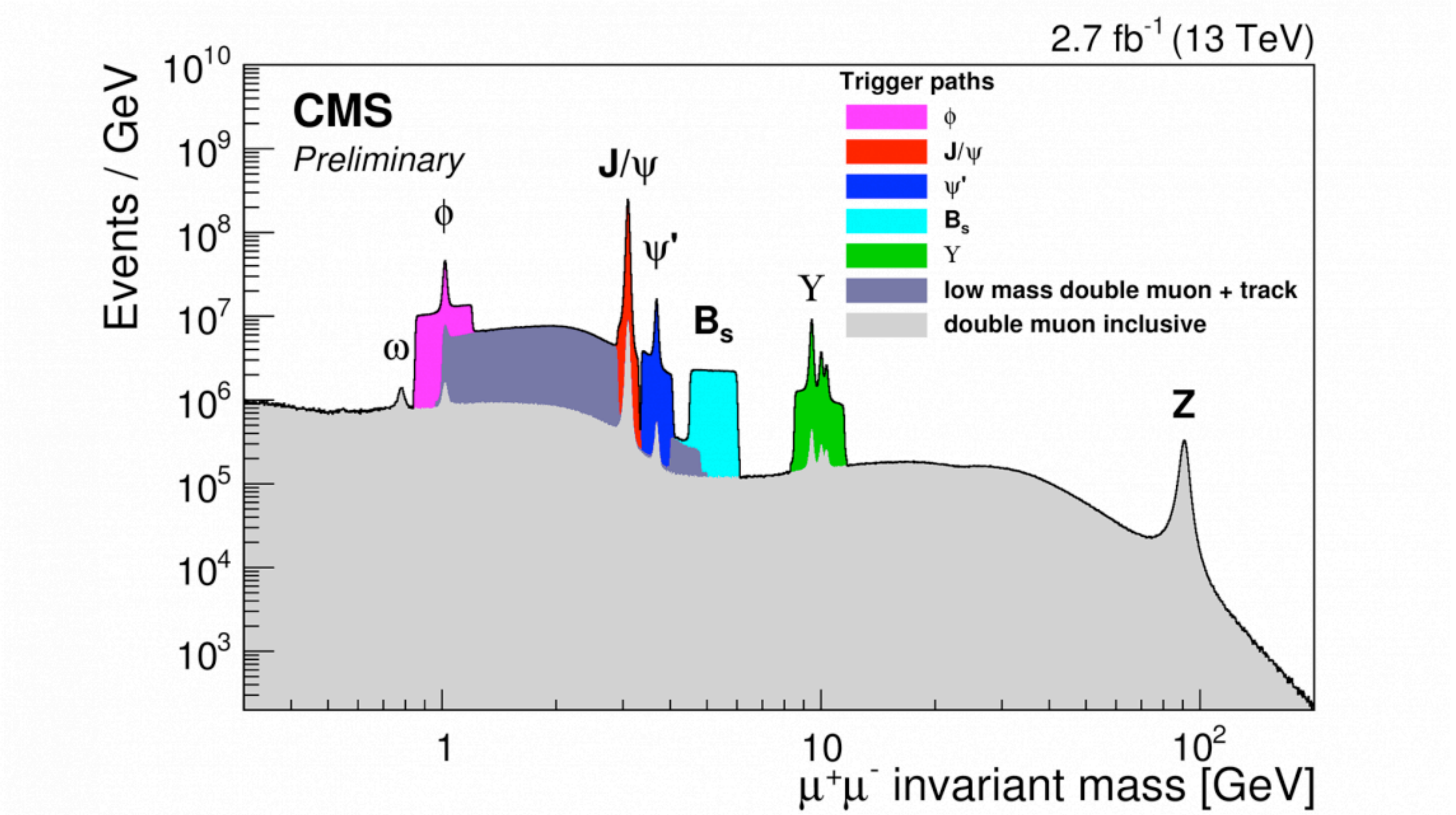
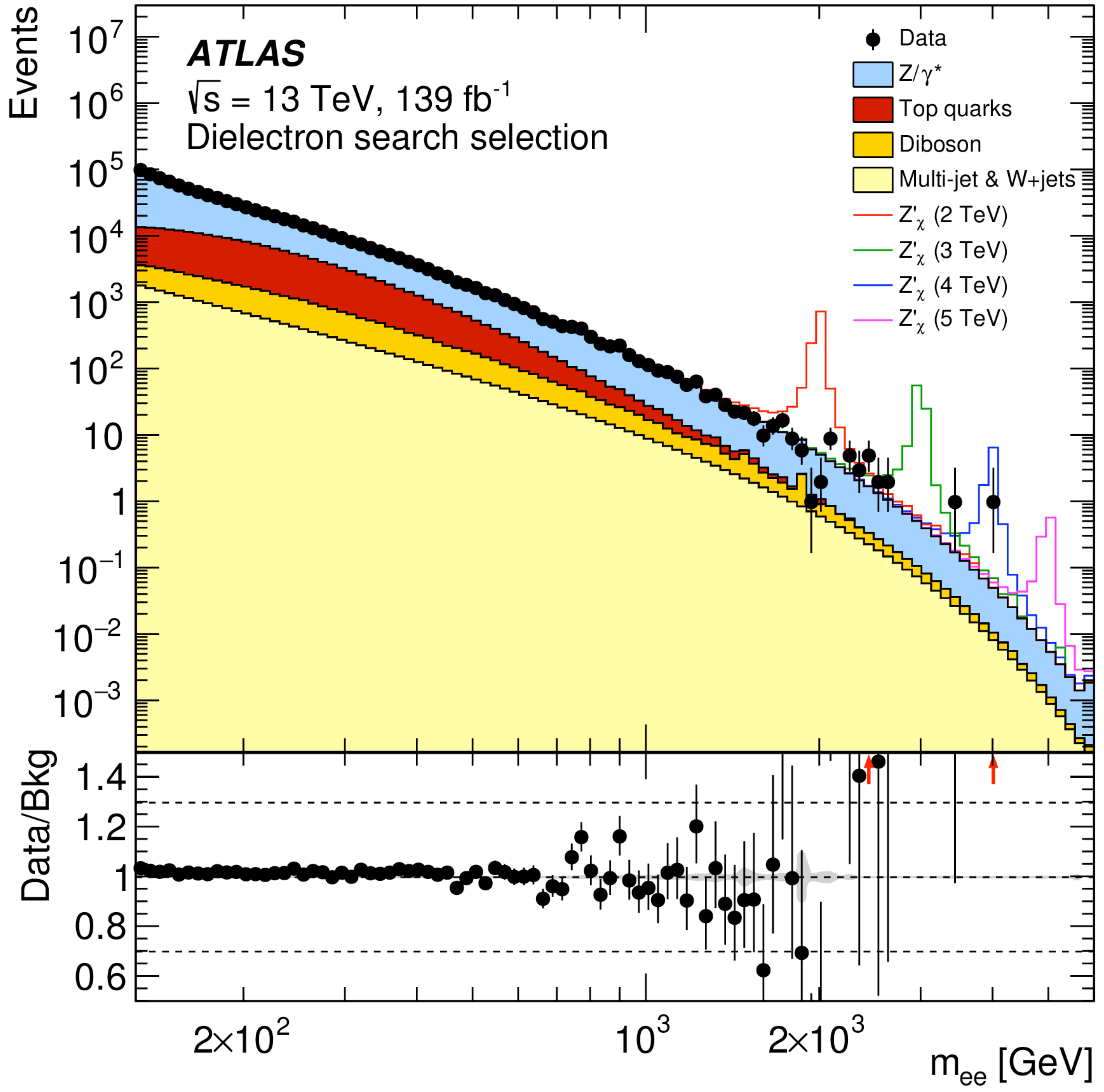


Z mass ~ 90 GeV



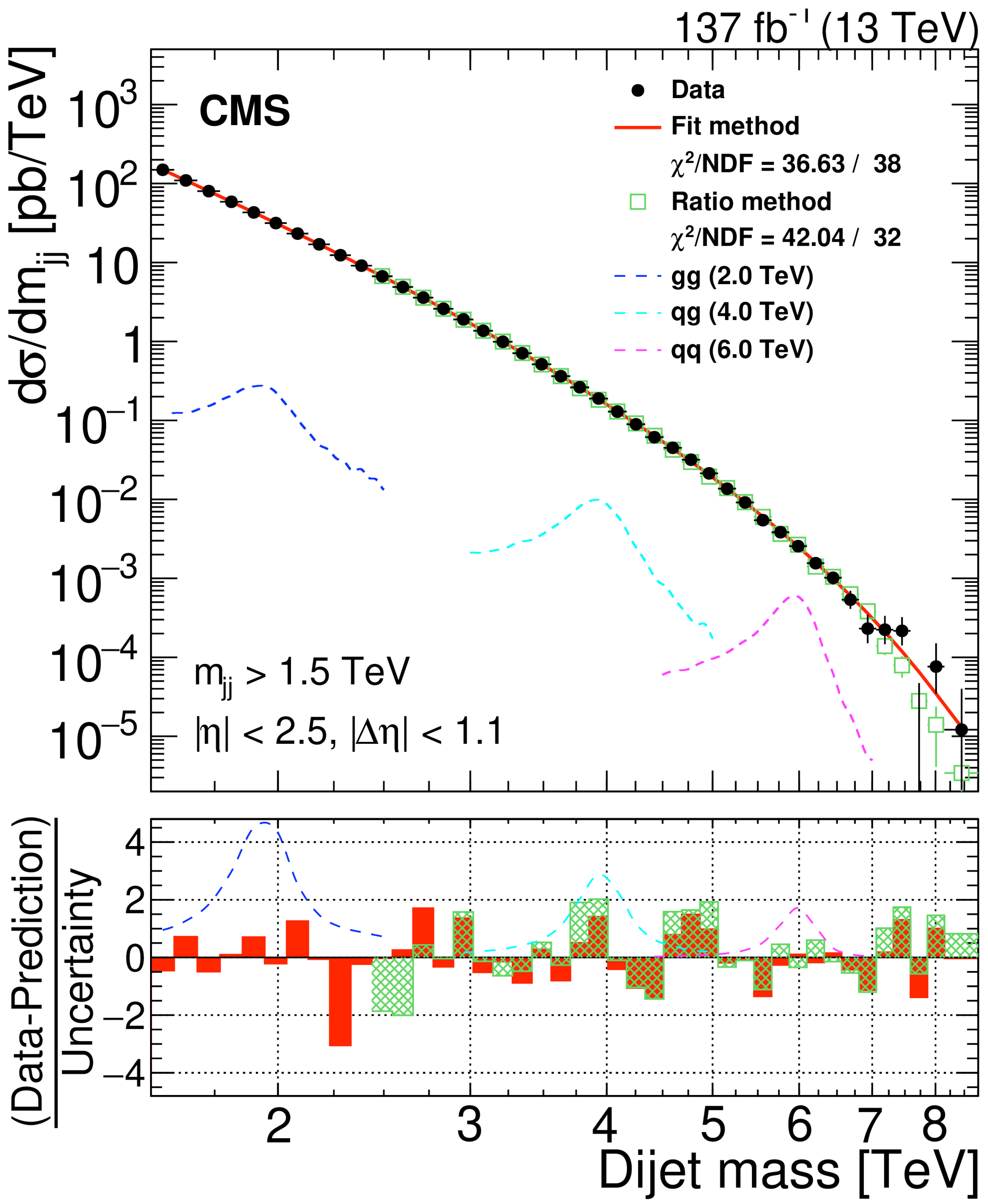
Heavy partners of the known bosons
Z' → ll

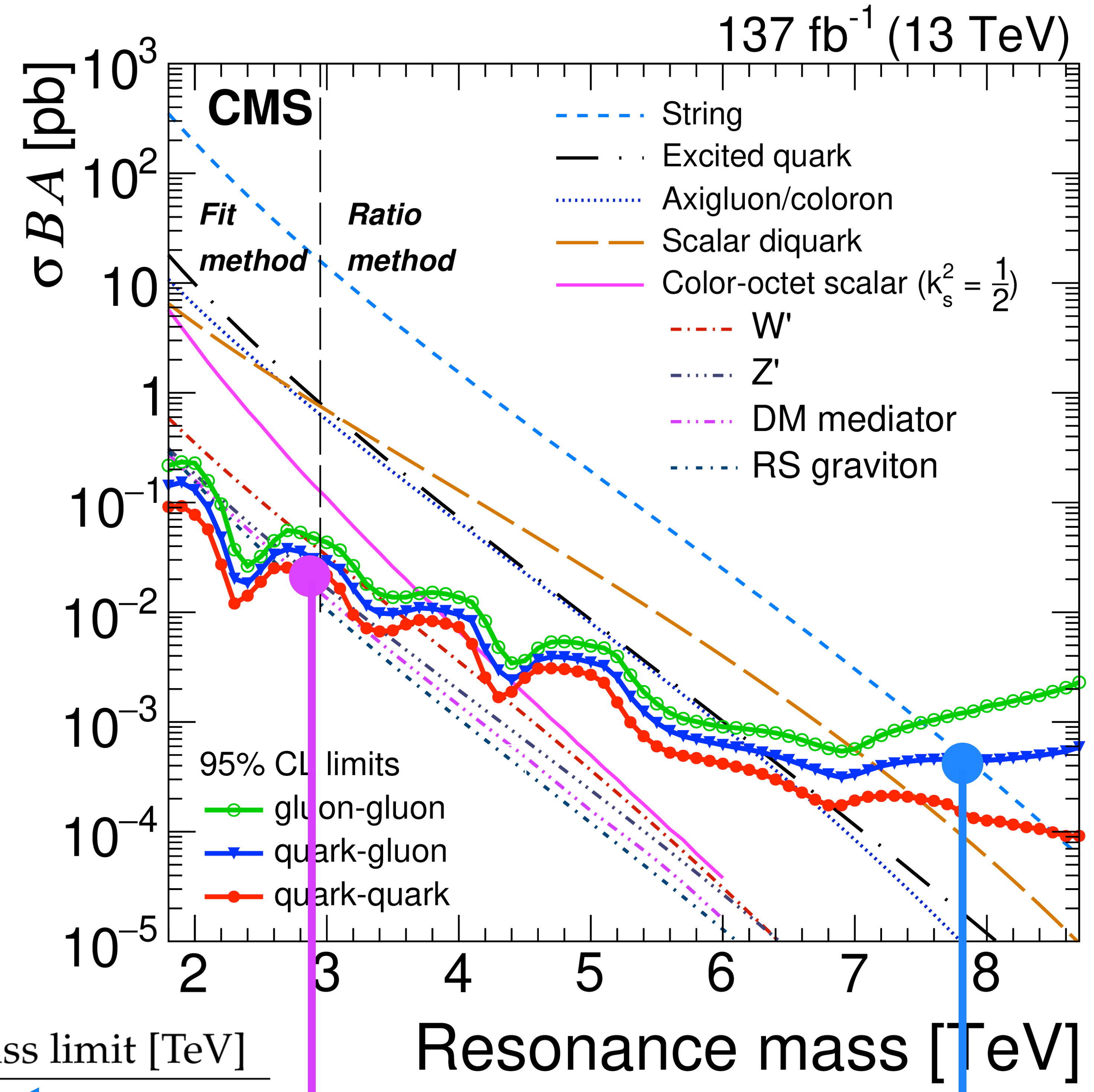
Now probing masses up to 4 TeV

- ➤ LHC strength: high CM energy => sensitivity to so far un-probed high masses!

Di-jet resonances

- Several new physics models predict heavy resonances that decay into dijets (qq, qg or gg)
- Result presented as model independent limits on σ×BR×A
- Limit differs depending on the final state qq, qg or gg because of dependence of resonance shape on parton content





Model	Final state	Observed (expected) mass limit [TeV]
String	q g	7.9 (8.1)
Scalar diquark	q q	7.5 (7.9)
Axigluon/coloron	q $\bar{q}$	6.6 (6.4)
Excited quark	q g	6.3 (6.2)
Color-octet scalar ($k_s^2 = 1/2$)	g g	3.7 (3.9)
W′ SM-like	q $\bar{q}$	3.6 (3.9)
Z′ SM-like	q $\bar{q}$	2.9 (3.4)
RS graviton ($k/\overline{M}_{\rm Pl} = 0.1$)	q $\bar{q}$, g g	2.6 (2.6)
DM mediator ($m_{\rm DM} = 1\,$GeV)	q $\bar{q}$	2.8 (3.2)

Supersymmetry

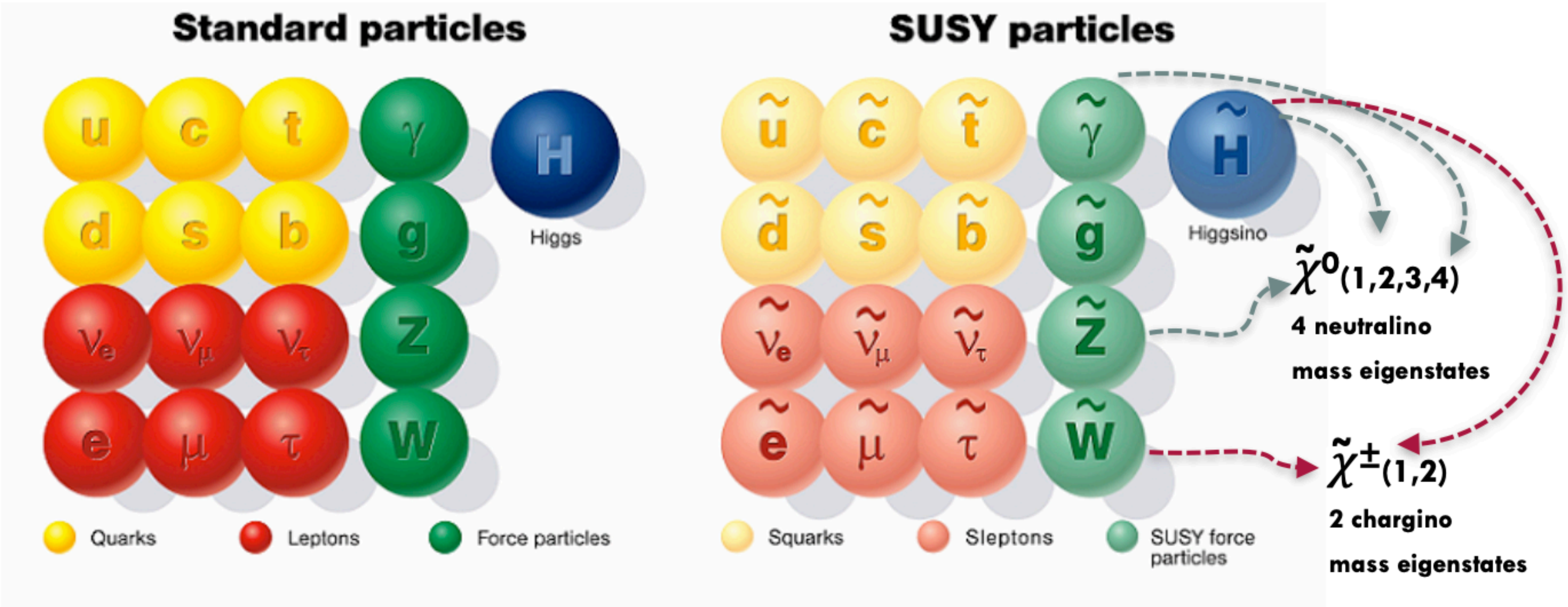
- Supersymmetry as possible extension of the Standard Model
- Assigns every SM particle a SUSY partner (sparticles)
  - R-parity to distinguish between SM and SUSY (B=Baryon number, L=Lepton number, s=Spin)

$$R = (-1)^{(2s+3B+L)} = \begin{cases} +1 & \textit{for SM particles} \\ -1 & \textit{for SUSY particles} \end{cases}$$

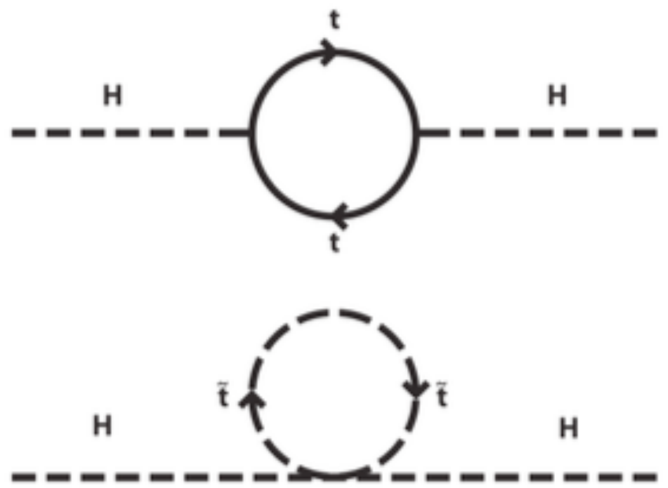
- **R-parity conservation (RPC)**
  - Always pairs of sparticles
  - Lightest supersymmetric particle (**LSP**) is stable and escapes detection
  - Final state decay has at least one LSP
- **R-parity violation (RPV)**
  - Either lepton or baryon number violation
  - Sparticles can decay exclusively to SM particles
  - Low missing energy in the final state

Supersymmetry

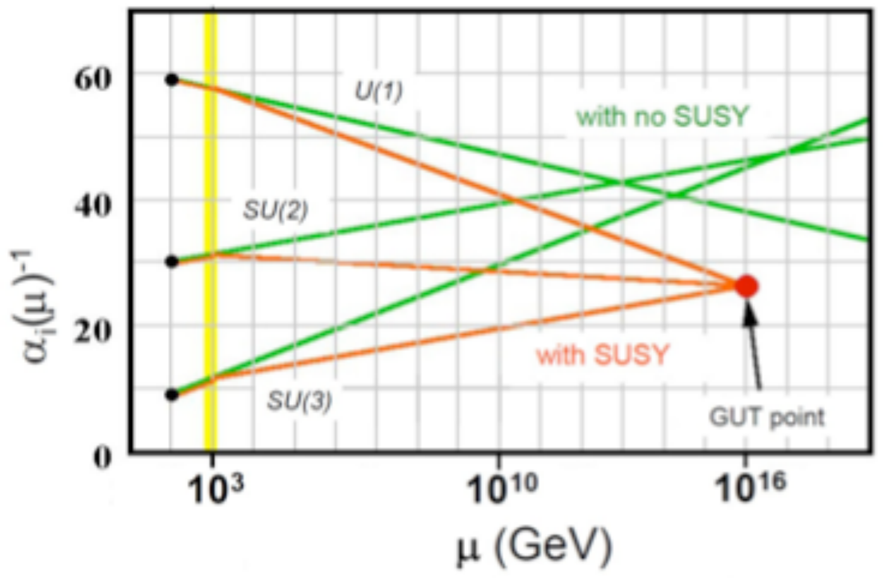
- SUSY predicts a plethora of new particles
- Potential parameter space is huge
  MSSM : ~ 100, pMSSM: 19, cMSSM: 4 + 1



MSSM = Minimal Supersymmetric Standard Model



Sparticle loops cancel corrections to Higgs mass



Possible unification of the gauge couplings at GUT scale

$$R = (-1)^{(2s+3B+L)} = \begin{cases} +1 & \text{SM} \\ -1 & \text{SUSY} \end{cases}$$

R-parity conservation implies the existence of a stable LSP as a dark matter candidate

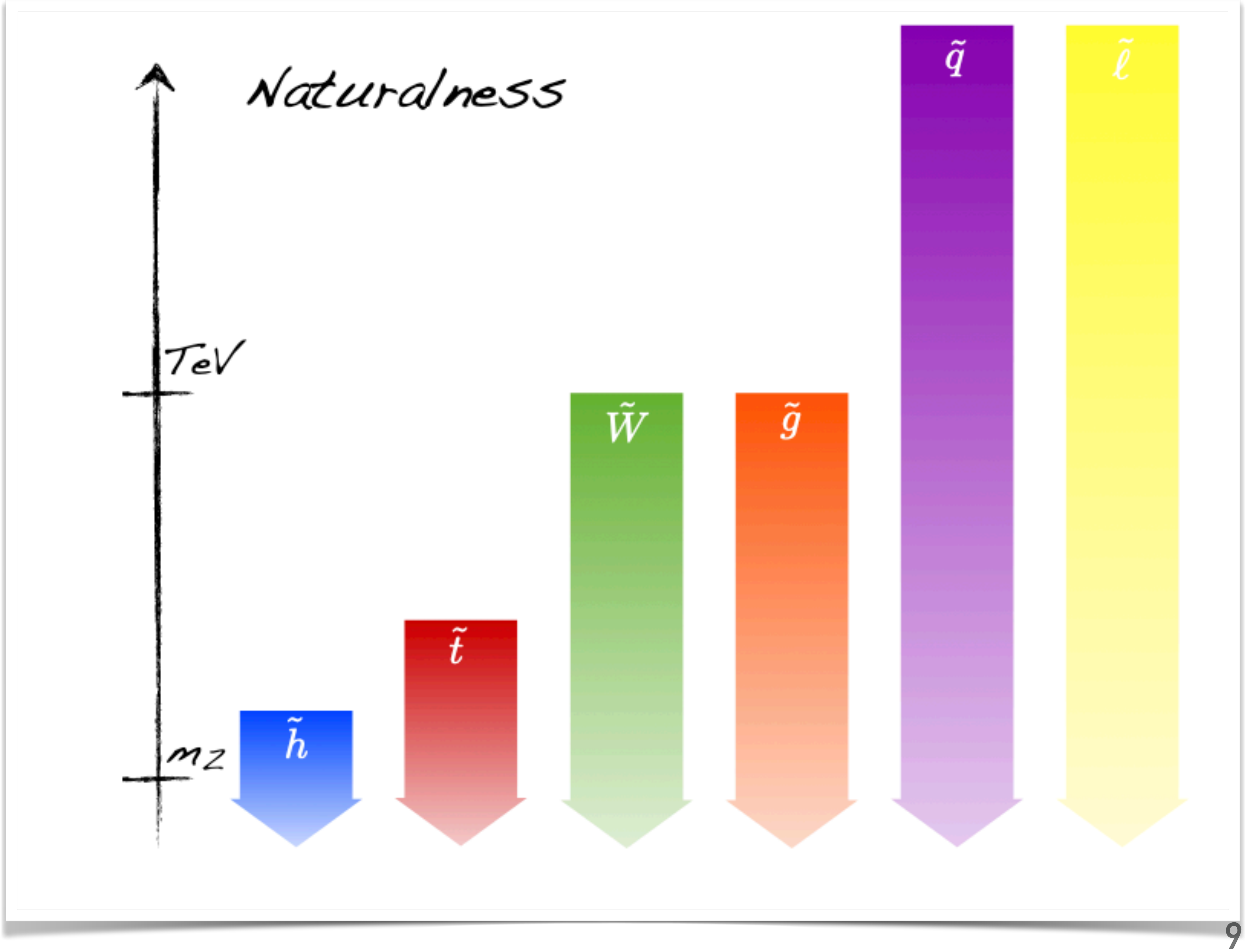
[N. Craig arXiv:1309.0528]

A natural SUSY spectrum?

$$\Delta[a_i] = \frac{\partial \ln m_Z^2}{\partial \ln a_i^2}, \Delta \equiv \max_i \Delta[a_i]$$

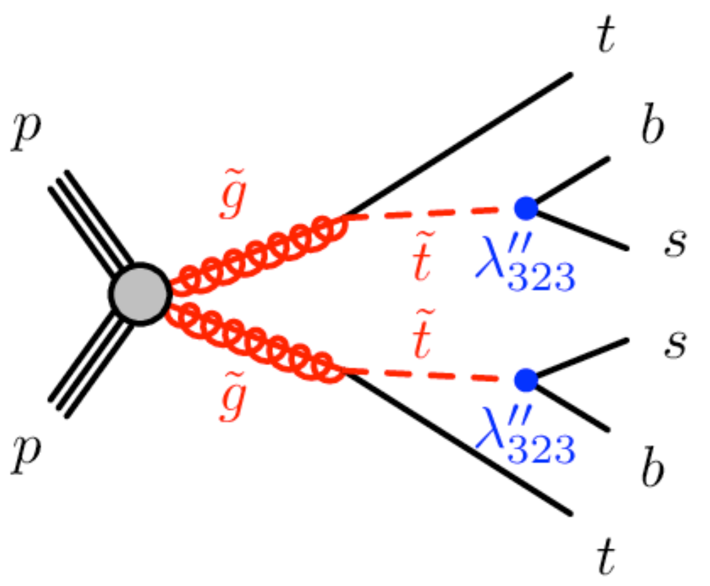
- Naturalness: one of the driving paradigms for SUSY searches at the LHC
  - However not entirely well defined: ratios between free parameters of a theory are "of order 1"
  - How much fine tuning can you live with?
- Implications
  - Tree-level: $m_Z^2 = -2(m_{H_u}^2 + |\mu|^2) + \ldots$
    - Light higgsinos
  - One-loop:
    - Light stops (few hundred GeV) to stabilize the Higgs mass
  - Two-loops
    - Not too heavy gluinos (TeV scale)
    - Loop corrections to the stop mass

Δ as a parameter for tuning ~ 10 → few % fine tuning

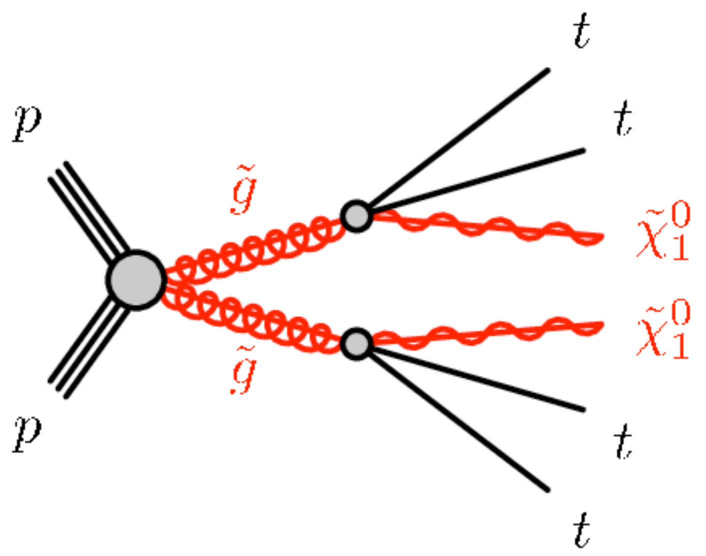


Simplified models in SUSY searches

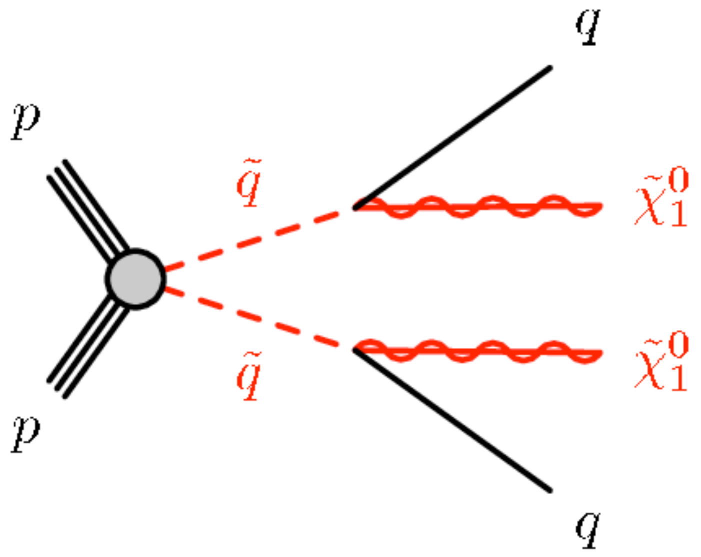
RPV gluino decay



RPC gluino decay



RPC squark decay



Decoupled mass spectrum

RPC or RPV

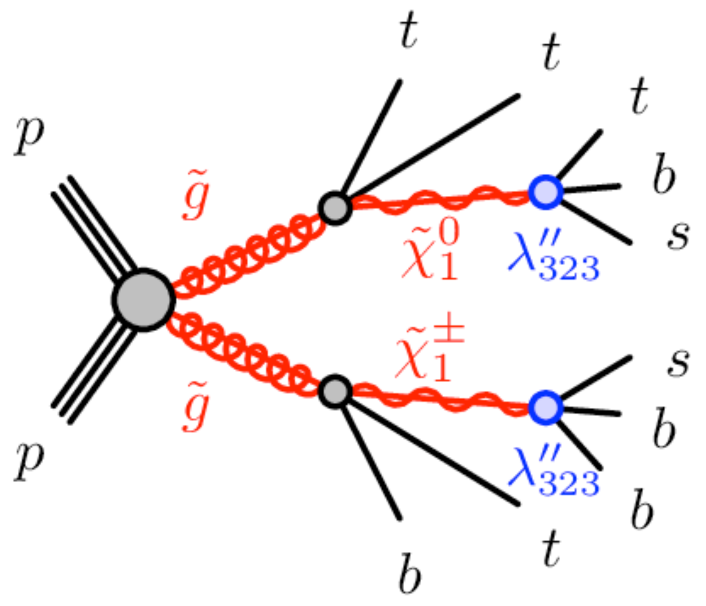
Few parameters

$\Delta M = \Delta M(\text{Sparticle,LSP})$

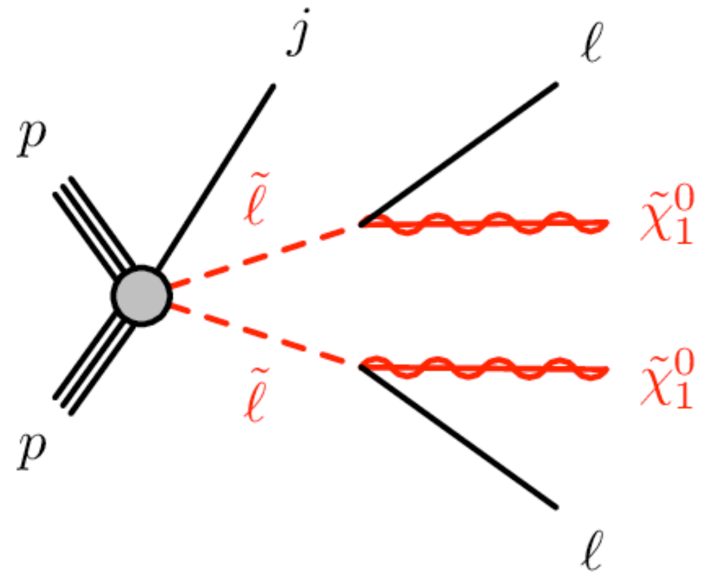
Mostly 100% BR

Not a complete story,
but a useful tool

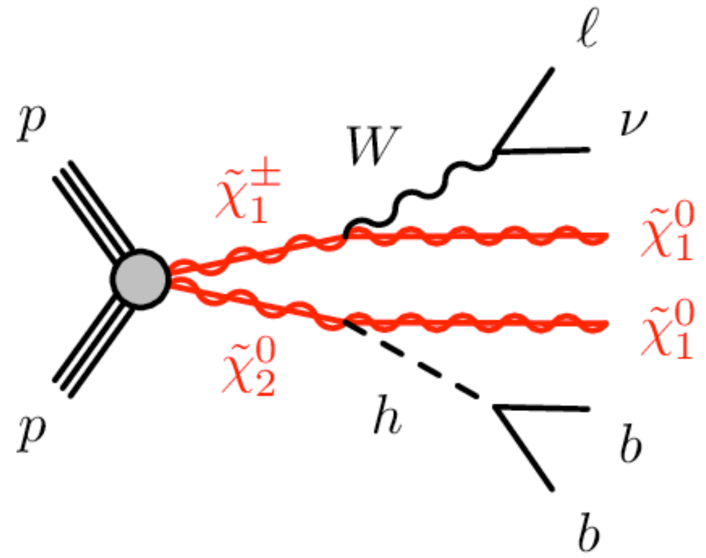
RPV gluino cascade decays



RPC slepton with ISR jet

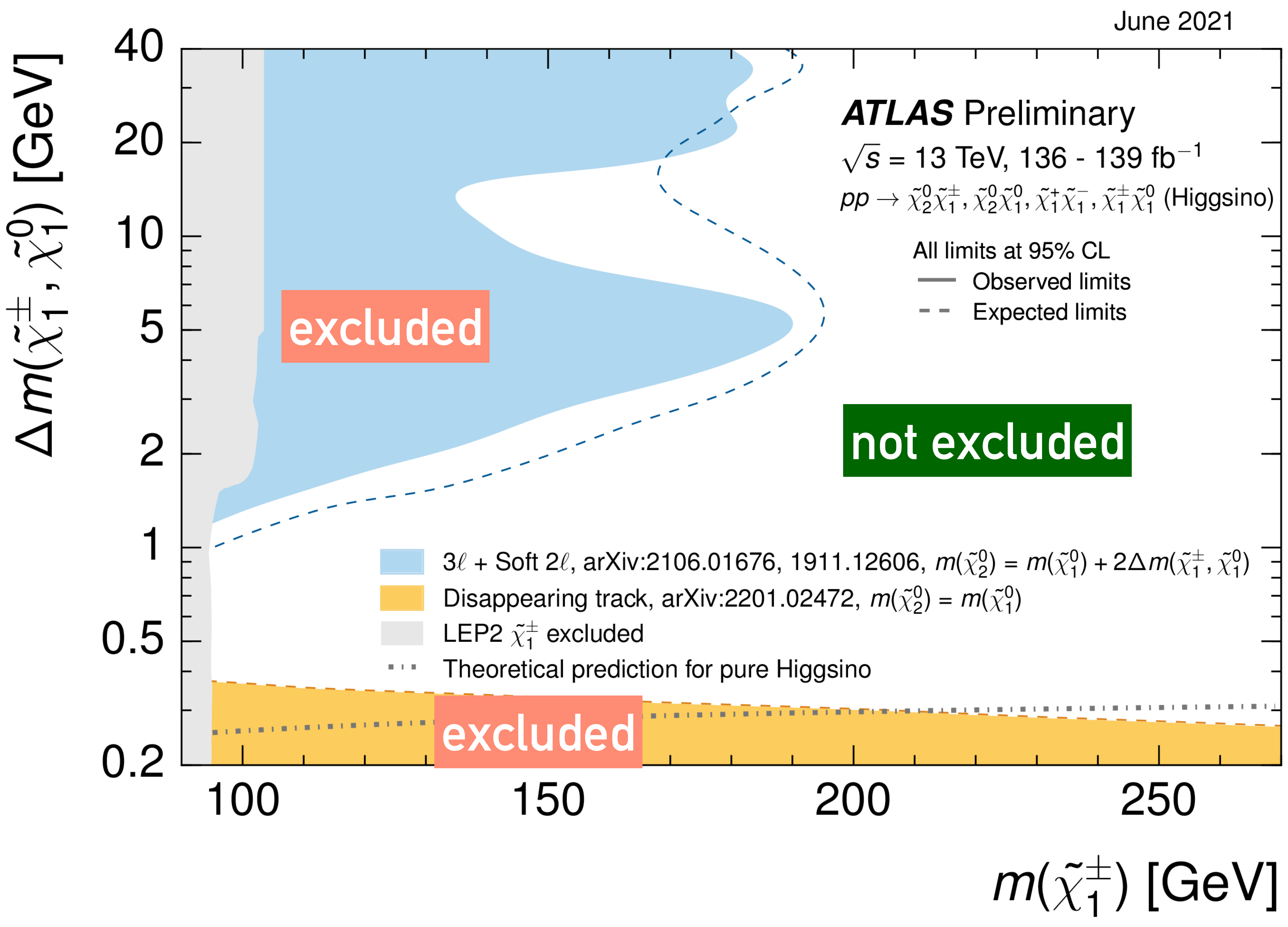


RPC chargino neutralino

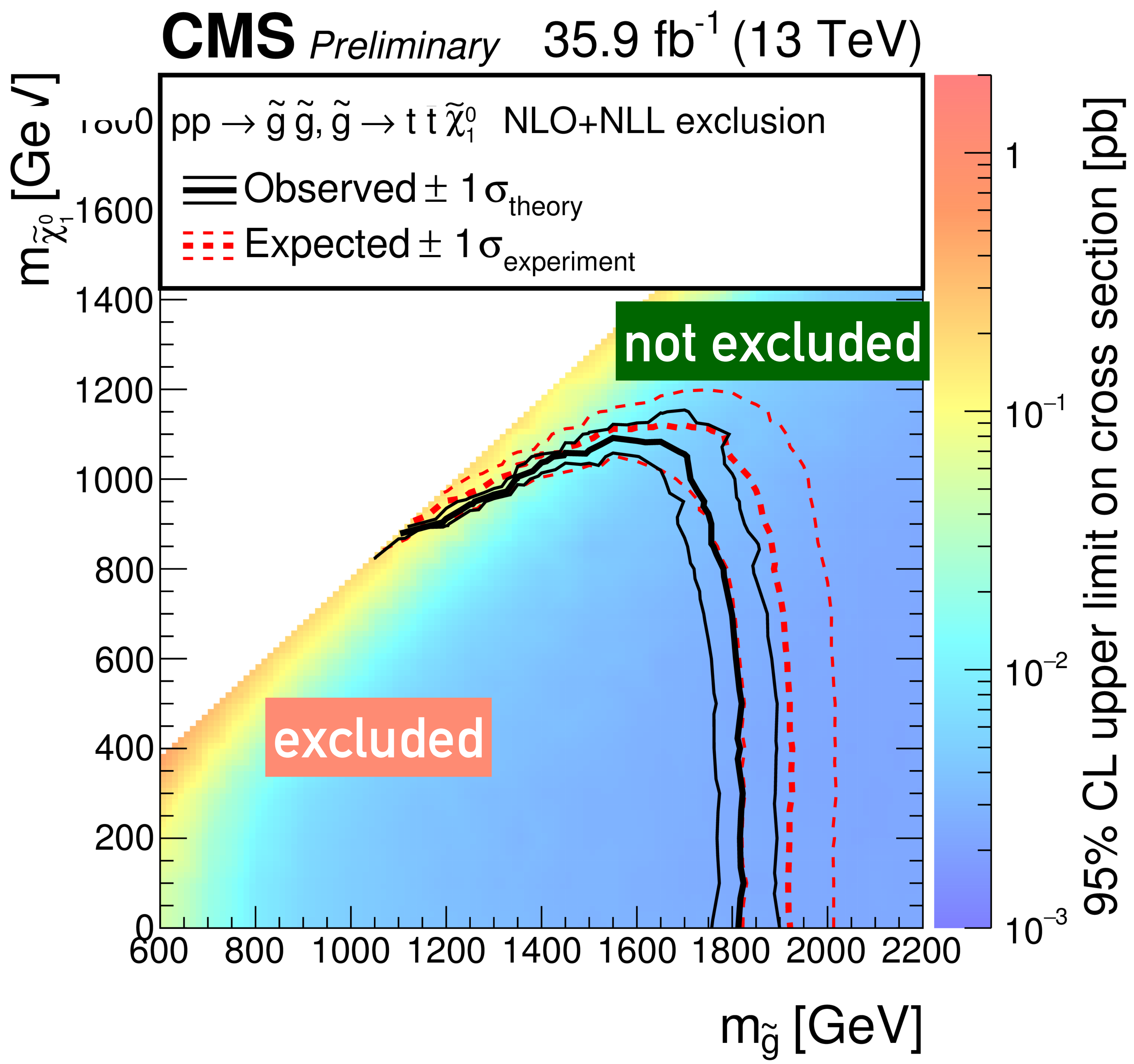


Interpretation: 2D limit plots

ΔM = ΔM(Sparticle,LSP) vs M(sparticle)



M(Sparticle) vs M(LSP)

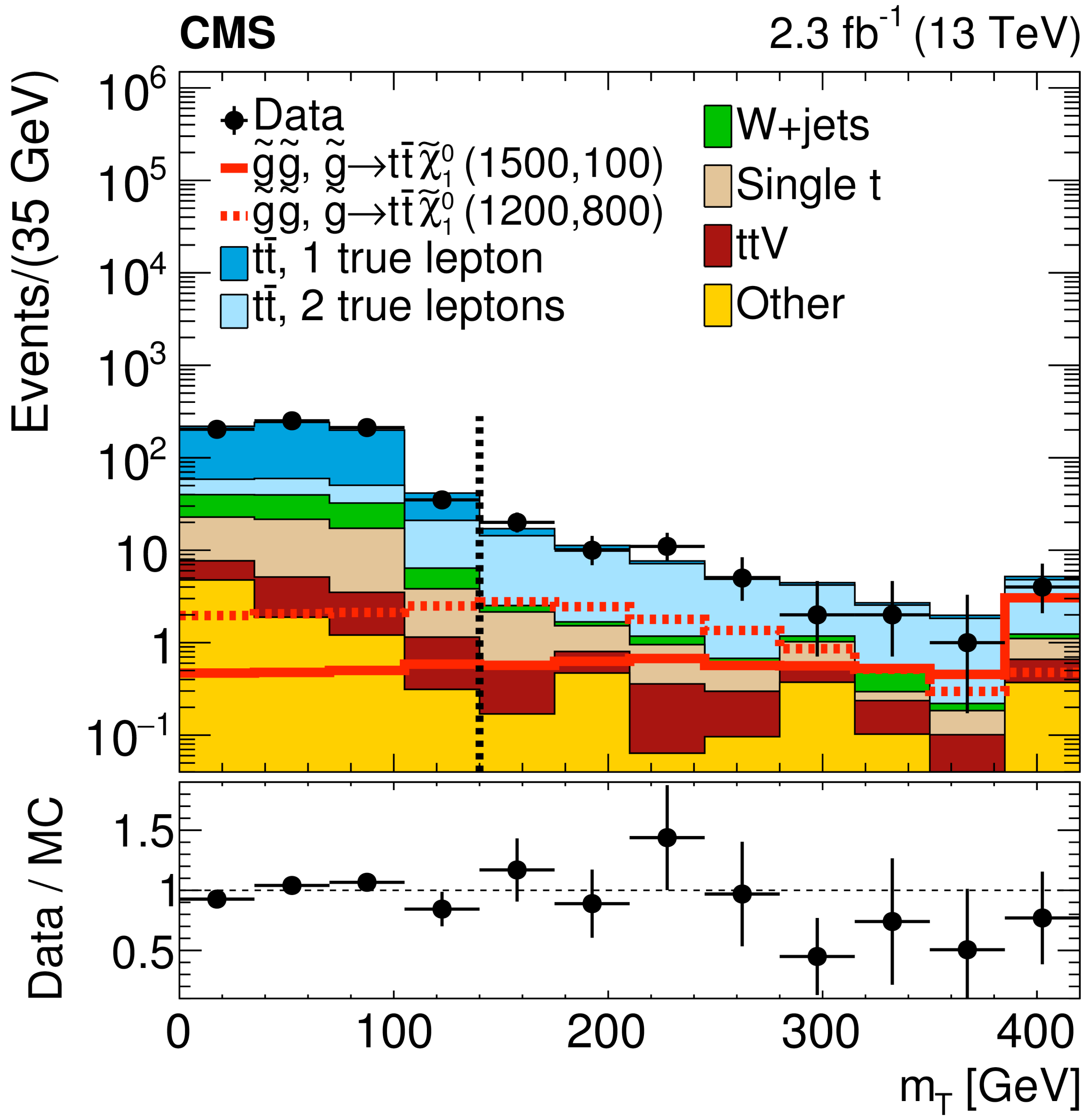


Z-axis = upper limit on cross section

How are we trying to find SUSY?

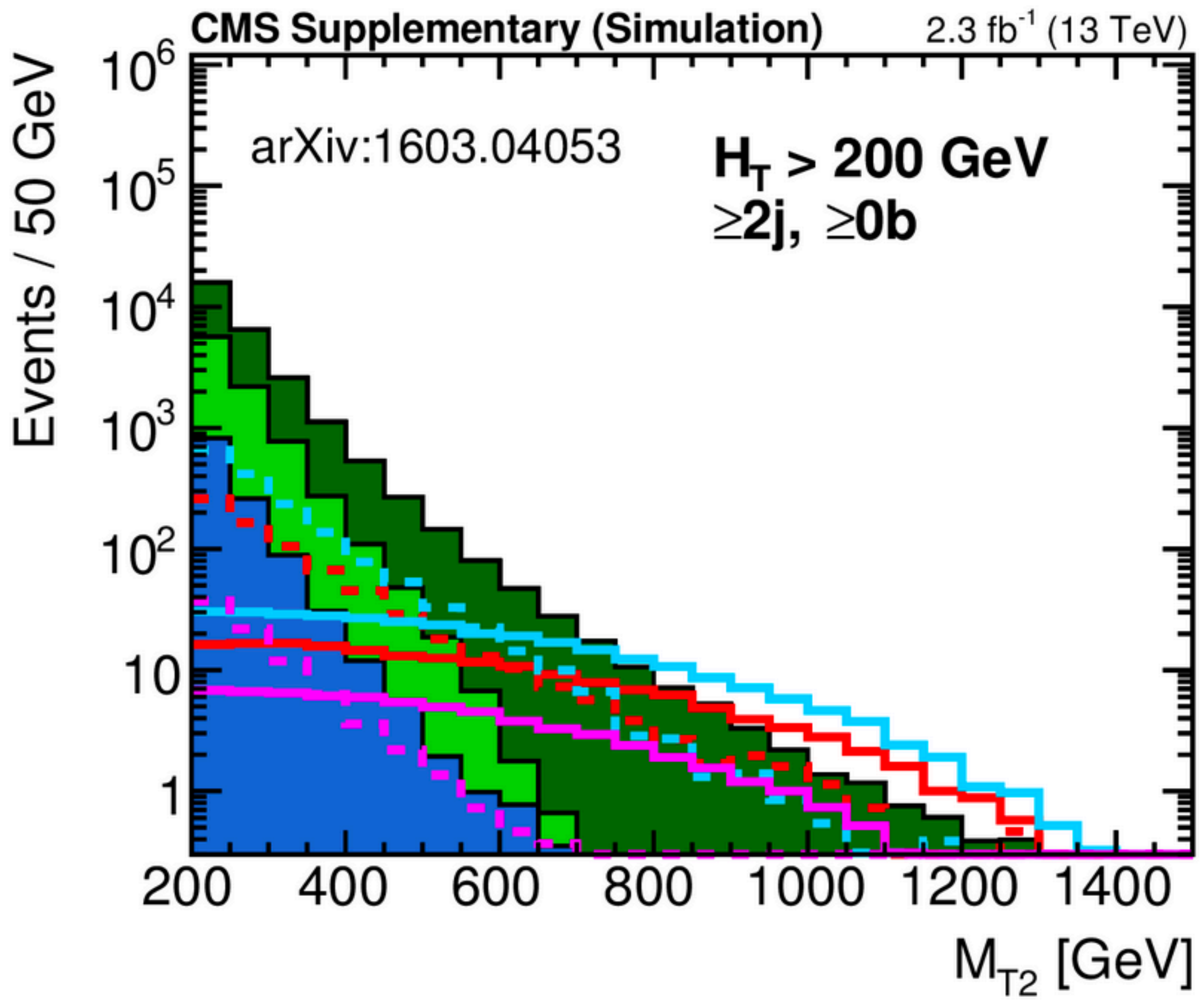
- Many SUSY searches in CMS and ATLAS are signature based
  - (b)Jets + MET + Leptons + photons + **dedicated search variables**

$$m_{\mathrm{T}}^{\mathrm{lep}} = \sqrt{2 p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} \left(1 - \cos \Delta\phi(\vec{p}_{\mathrm{T}}^{\ell}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})\right)}$$



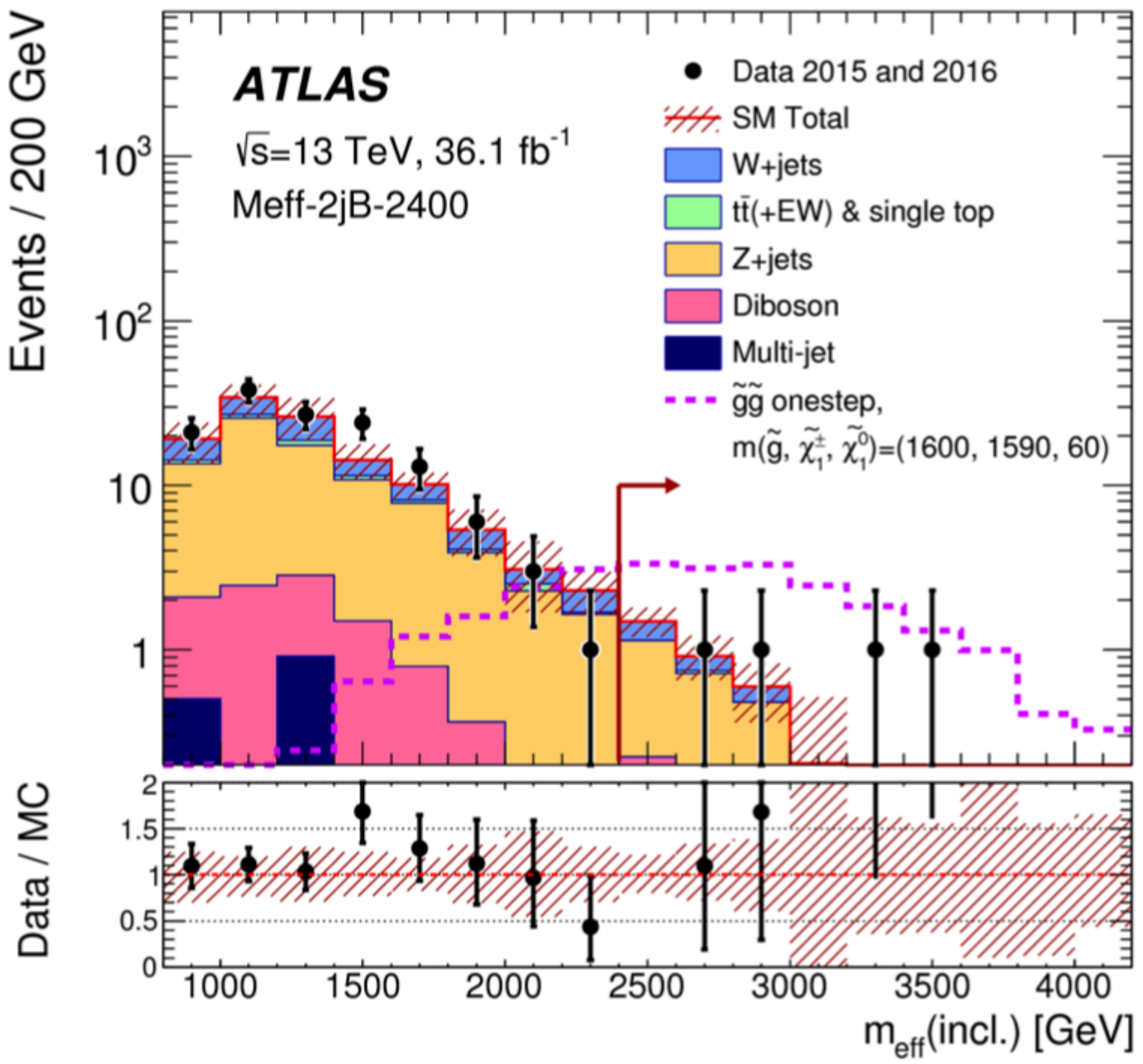
Endpoint around W mass for background

$$M_{\mathrm{T2}} = \min_{\vec{p}_{\mathrm{T}}^{\mathrm{miss}X(1)} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}X(2)} = \vec{p}_{\mathrm{T}}^{\mathrm{miss}}} \left[\max\left(M_{\mathrm{T}}^{(1)}, M_{\mathrm{T}}^{(2)}\right)\right]$$



Extension of transverse mass m_T
for decay chains with 2 invisible particles

$$m_{eff} = \sum p_T + E_T^{miss}$$



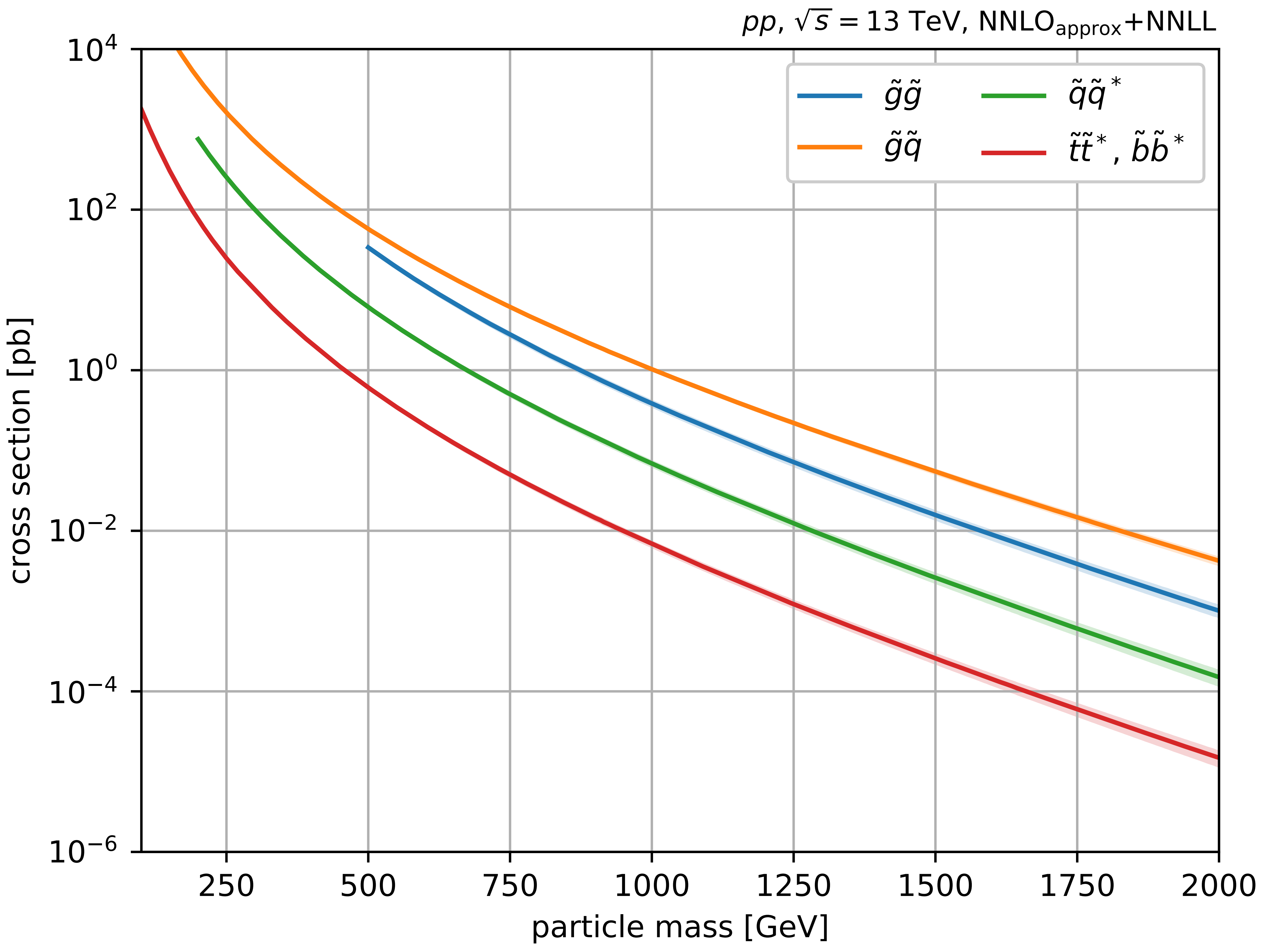
Squark and Gluino searches

- Assuming pair production of squarks and gluinos, decays to LSP + various SM quarks (light and heavy flavor) → highes production cross sections

$$\tilde{g} \to b\bar{b}\ \tilde{\chi}_1^0$$

$$\tilde{g} \to q\bar{q}\ \tilde{\chi}_1^0$$

$$\tilde{g} \to t\bar{t}\ \tilde{\chi}_1^0$$



$$\tilde{t} \to t\ \tilde{\chi}_1^0$$

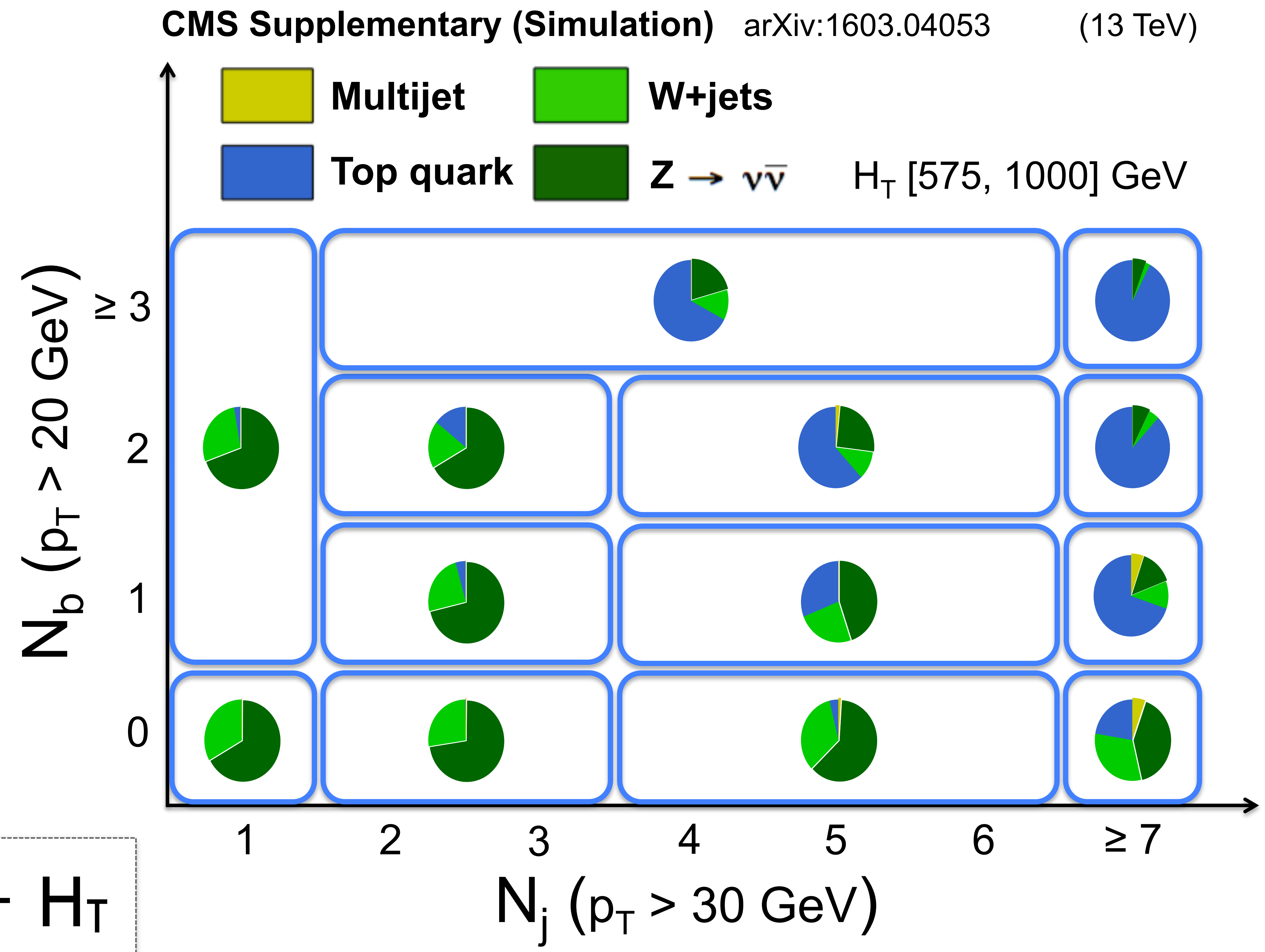
$$\tilde{q} \to q\ \tilde{\chi}_1^0$$

$$\tilde{b} \to b\ \tilde{\chi}_1^0$$

- Let's go through one analysis example in some more detail: the "inclusive" approach

Example: all-hadronic CMS search

- ➤ = 0 leptons in the final state
- ➤ Multijet bkg reduced through cut on $\Delta\phi$(jets, MET/MHT) > 0.3 - 0.5
- ➤ Many search regions covering a wide variety of models
  - ➤ Example "Binning" in M_{T2} + n(b)Jets + H_T
- ➤ Many different bkg sources

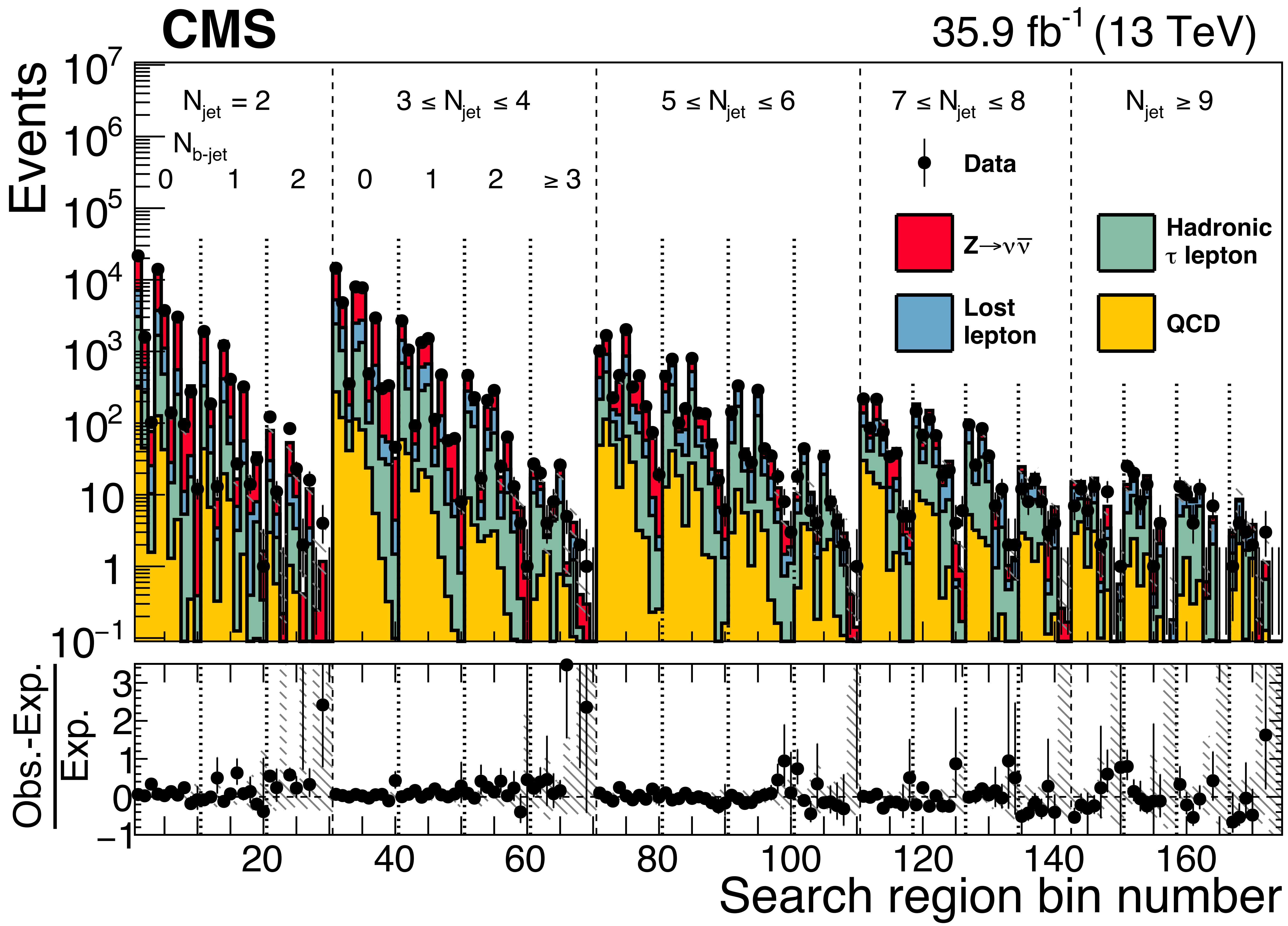


Data driven background estimates from CR by inverting event selection criteria:

- **W+jets, tt+jets** (lost lepton, hadronic tau): Isolated e/μ, with low M_T(l,MET)
- **Z→νν:** Use γ+jets or Z→ll events as proxy
- **Multijet:** Estimate $r_\phi = \frac{\Delta\phi(jets, MET) > x}{\Delta\phi(jets, MET) < x}$ multijet enriched control region

Results: Unrolled search regions or bins

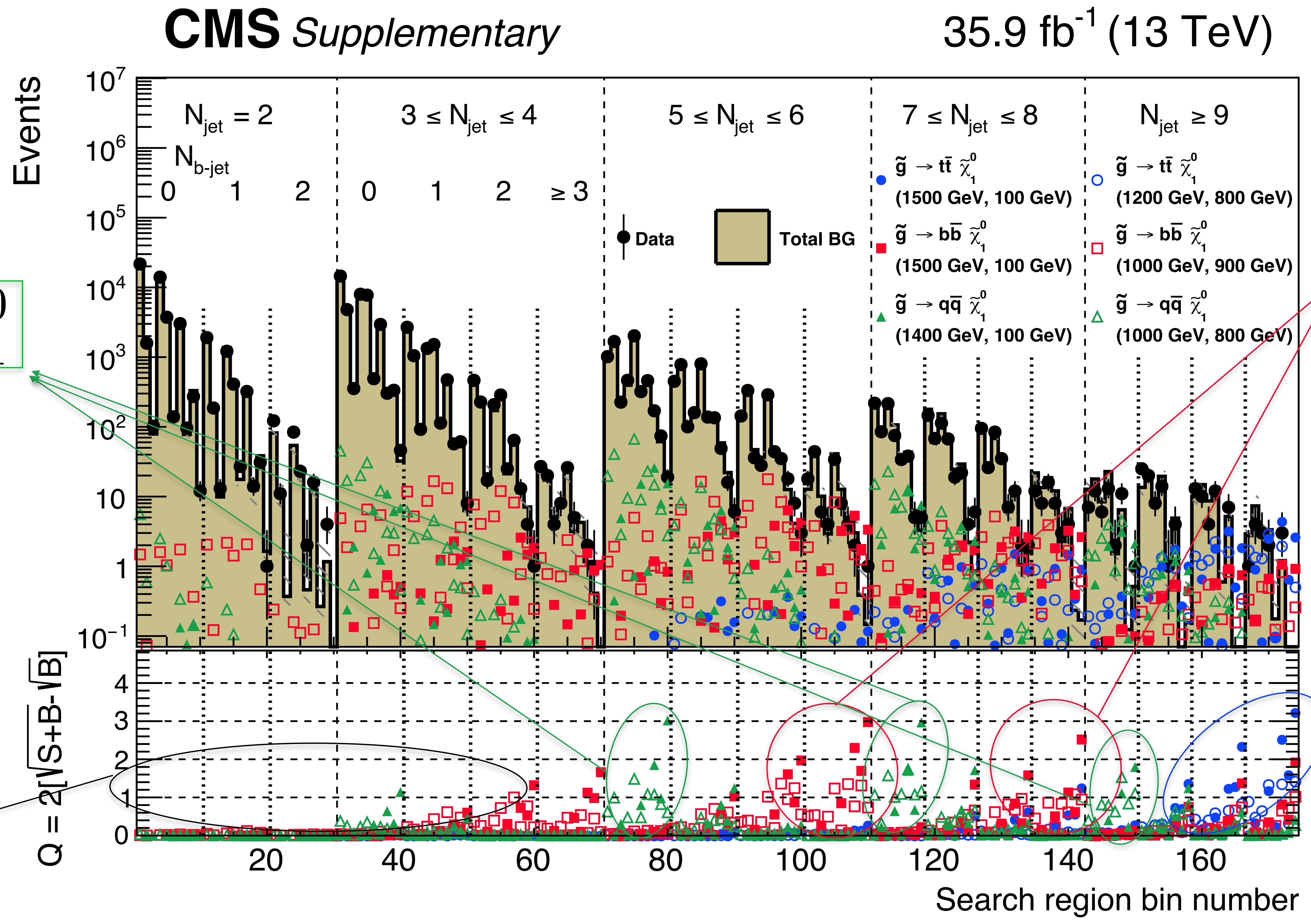
Many bins, but where does the sensitivity come from?



[Full Run2 at: JHEP 10 (2019) 244]

Which regions are sensitive to what?

$\tilde{g} \rightarrow q\bar{q}\ \tilde{\chi}_1^0$



$\tilde{g} \rightarrow b\bar{b}\ \tilde{\chi}_1^0$

$\tilde{g} \rightarrow t\bar{t}\ \tilde{\chi}_1^0$

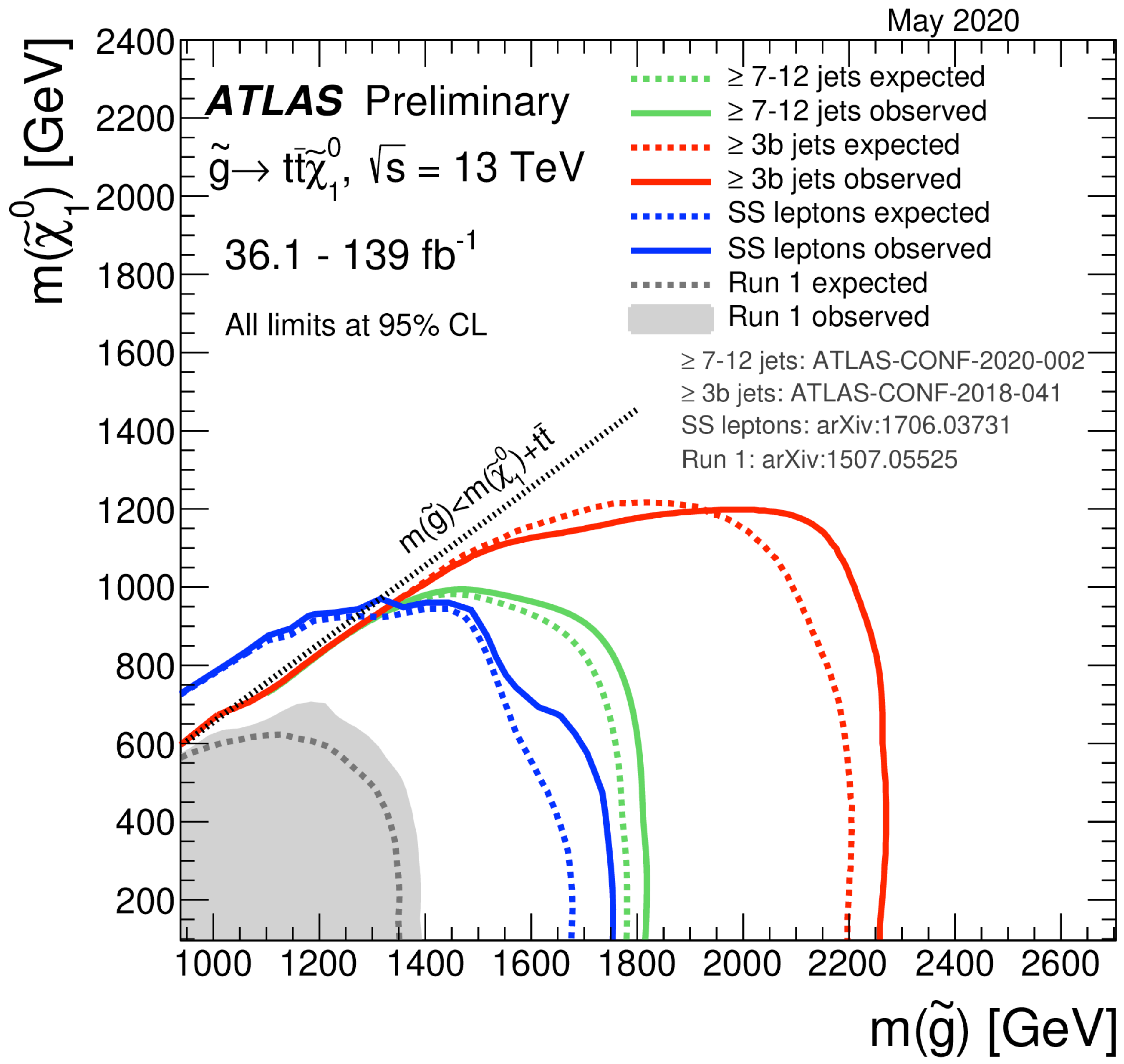
Not in the plot, low nJet regions cover:

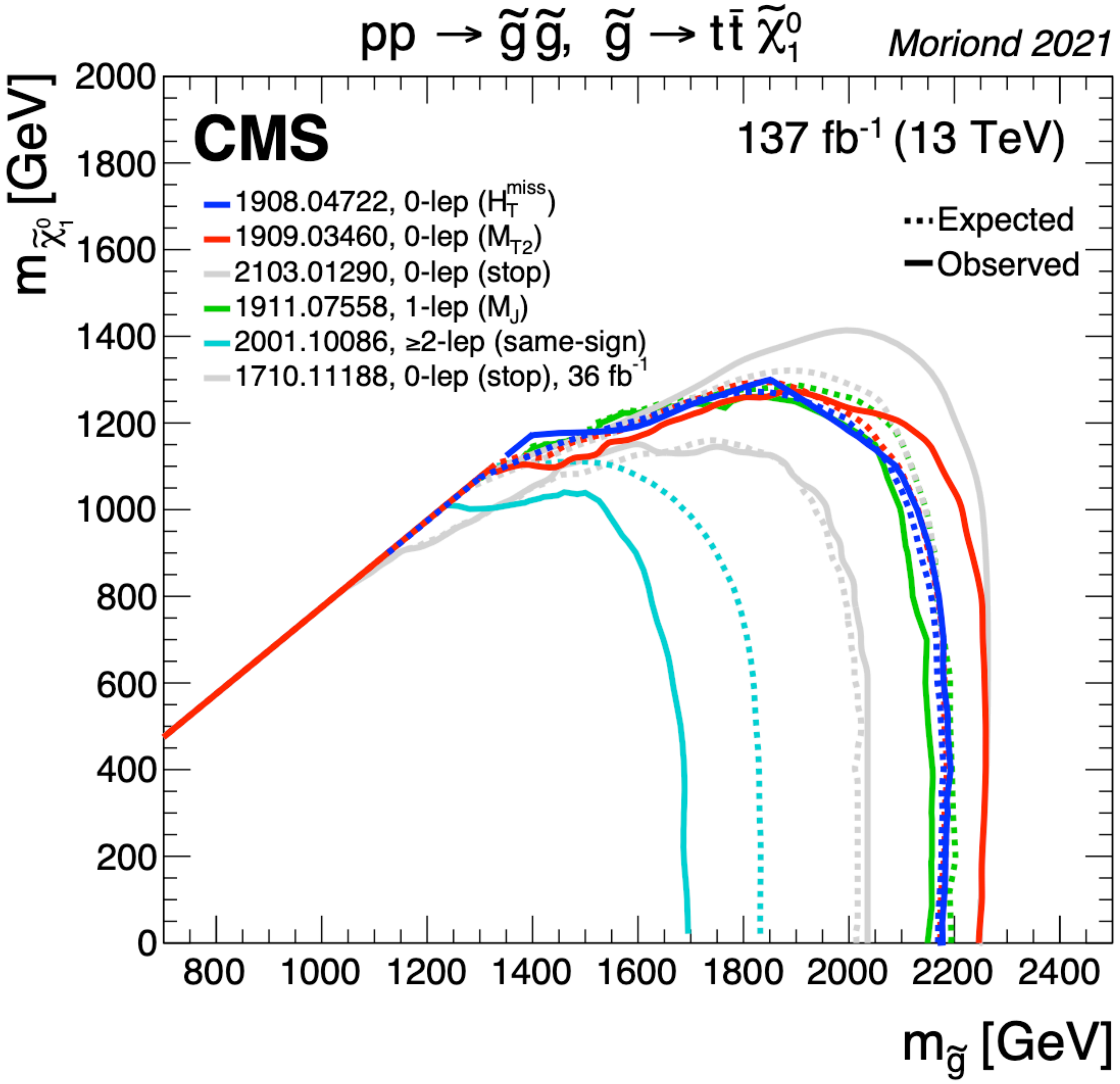
$\tilde{q} \rightarrow q\ \tilde{\chi}_1^0$

$\tilde{t} \rightarrow t\ \tilde{\chi}_1^0$

$\tilde{b} \rightarrow b\ \tilde{\chi}_1^0$

Results for squarks and gluinos

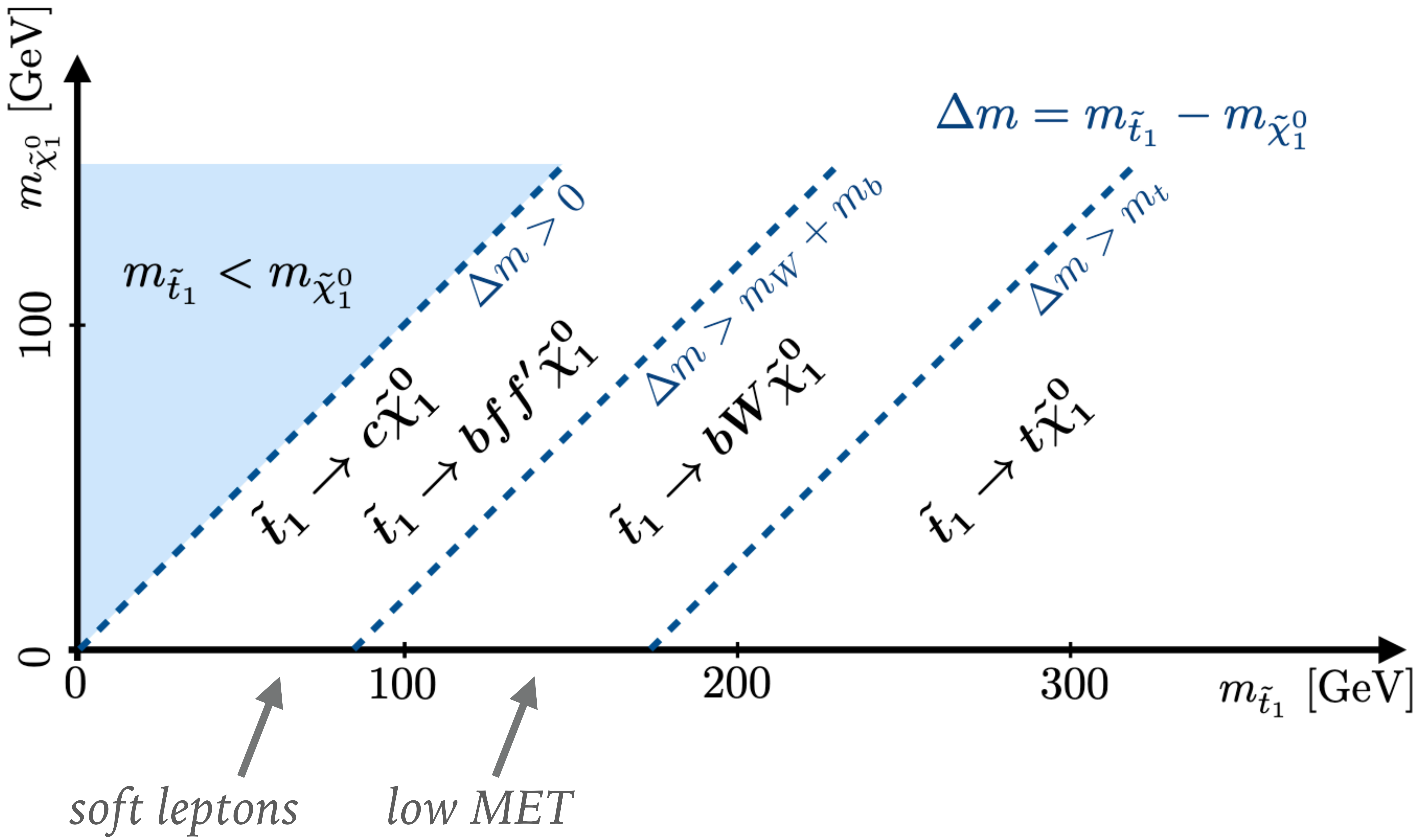




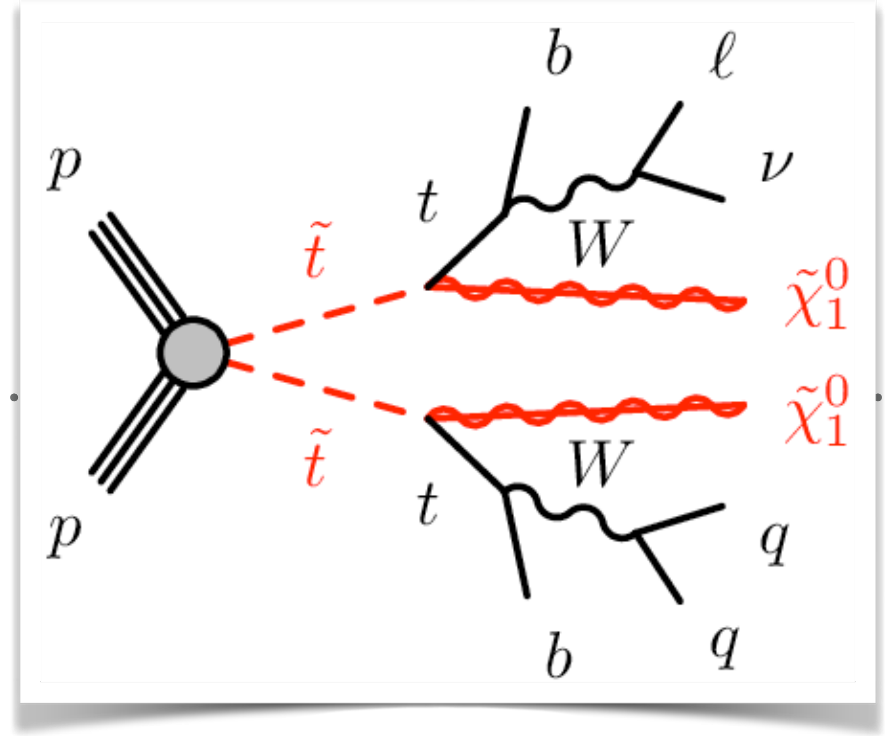
- Limits on Gluino mass pushing 2200 GeV in simplified models

Dedicated searches for stops

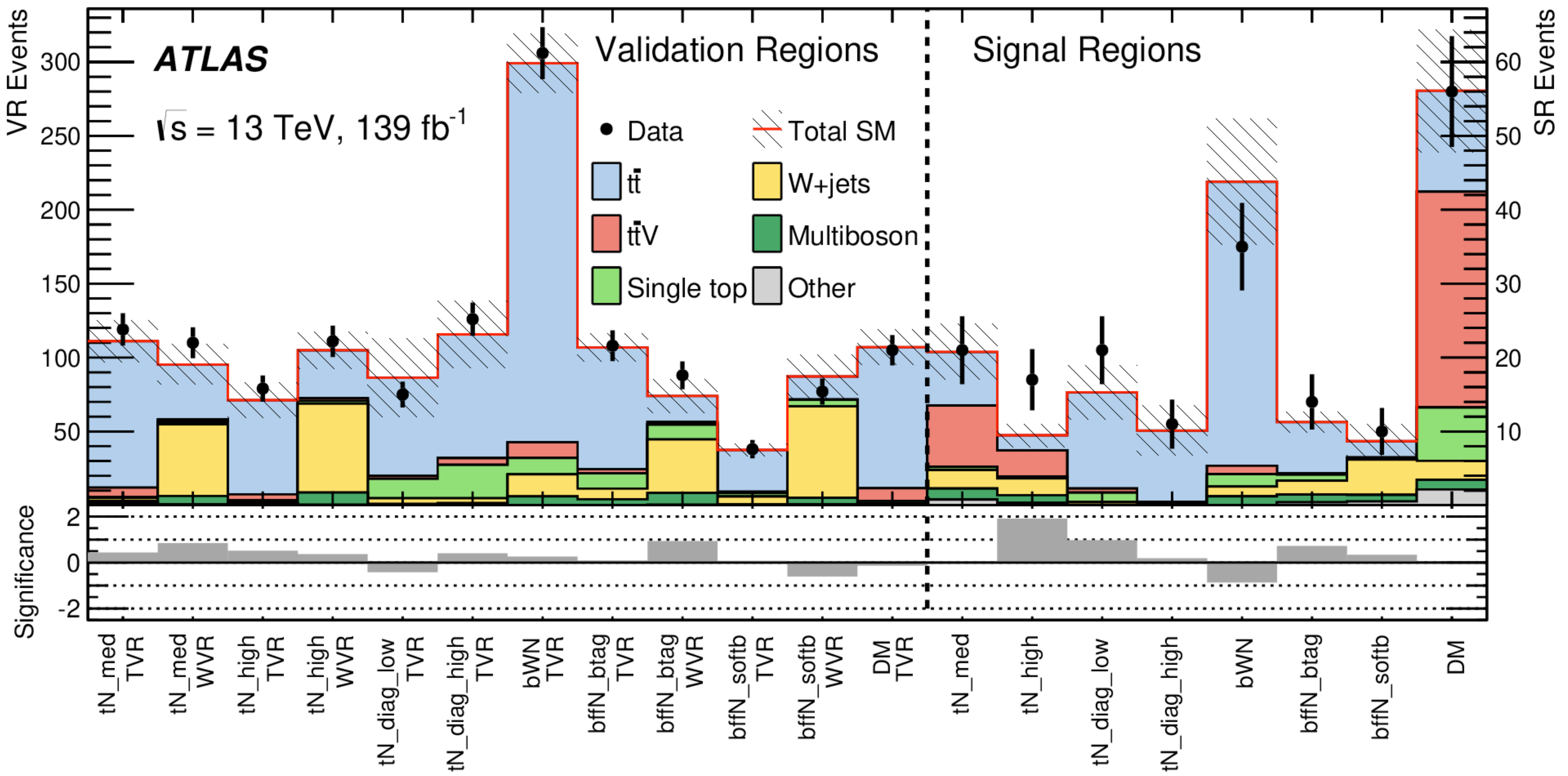
- Stops play important role in stabilizing the Higgs mass
- Dedicated search strategies are also employed
  - "Optimize" dedicated regions to make sure difficult corners of phase space aren't missed

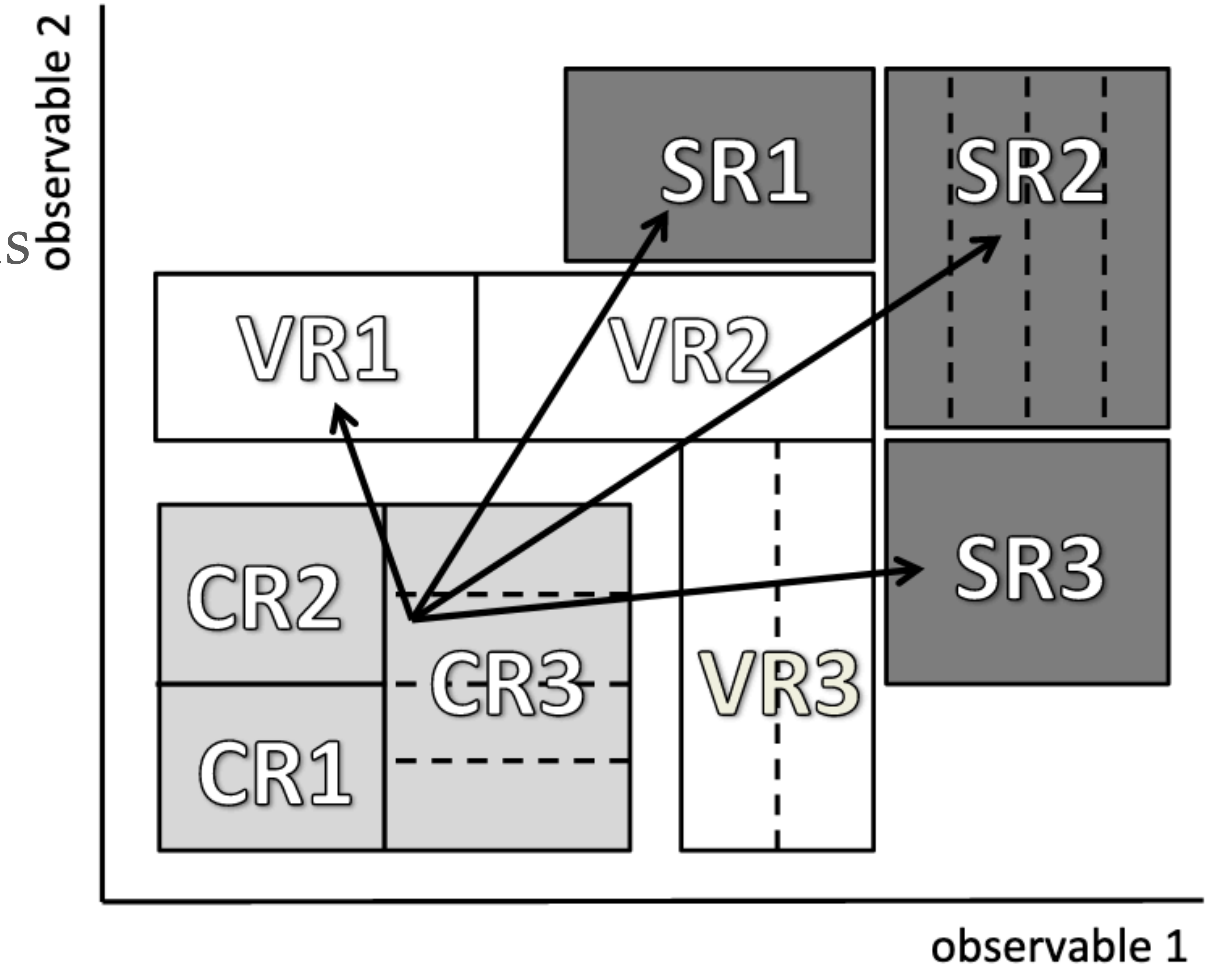


Dedicated searches for stops



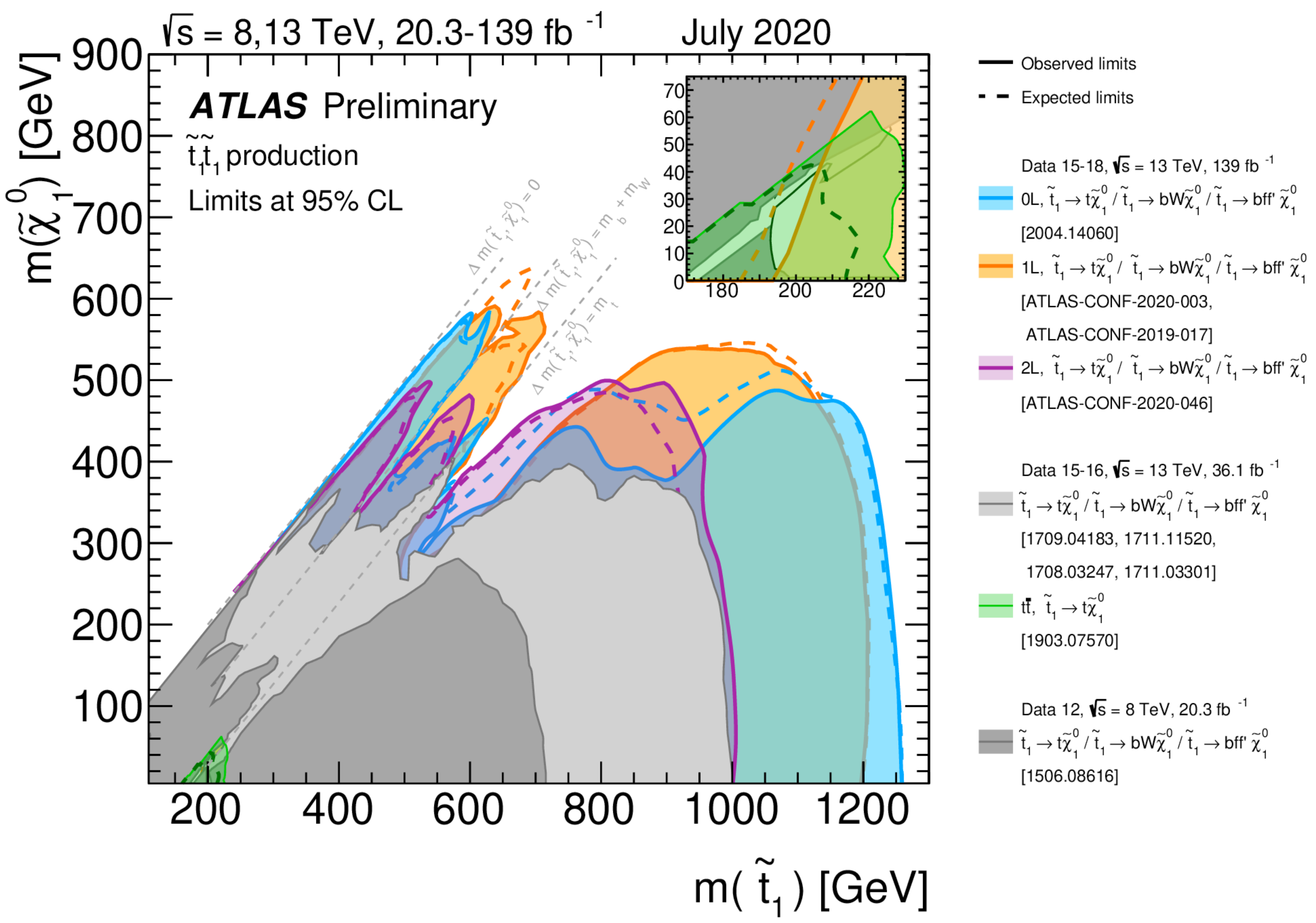
- 0, 1, and 2 lepton channels → remember ttbar decay modes + extra MET
- Strategy:
  - Design dedicated signal regions for specific signal topologies:
    - low MET, medium MET
  - Estimate SM backgrounds from simulation and data control regions
  - Extrapolate and Test in validation regions

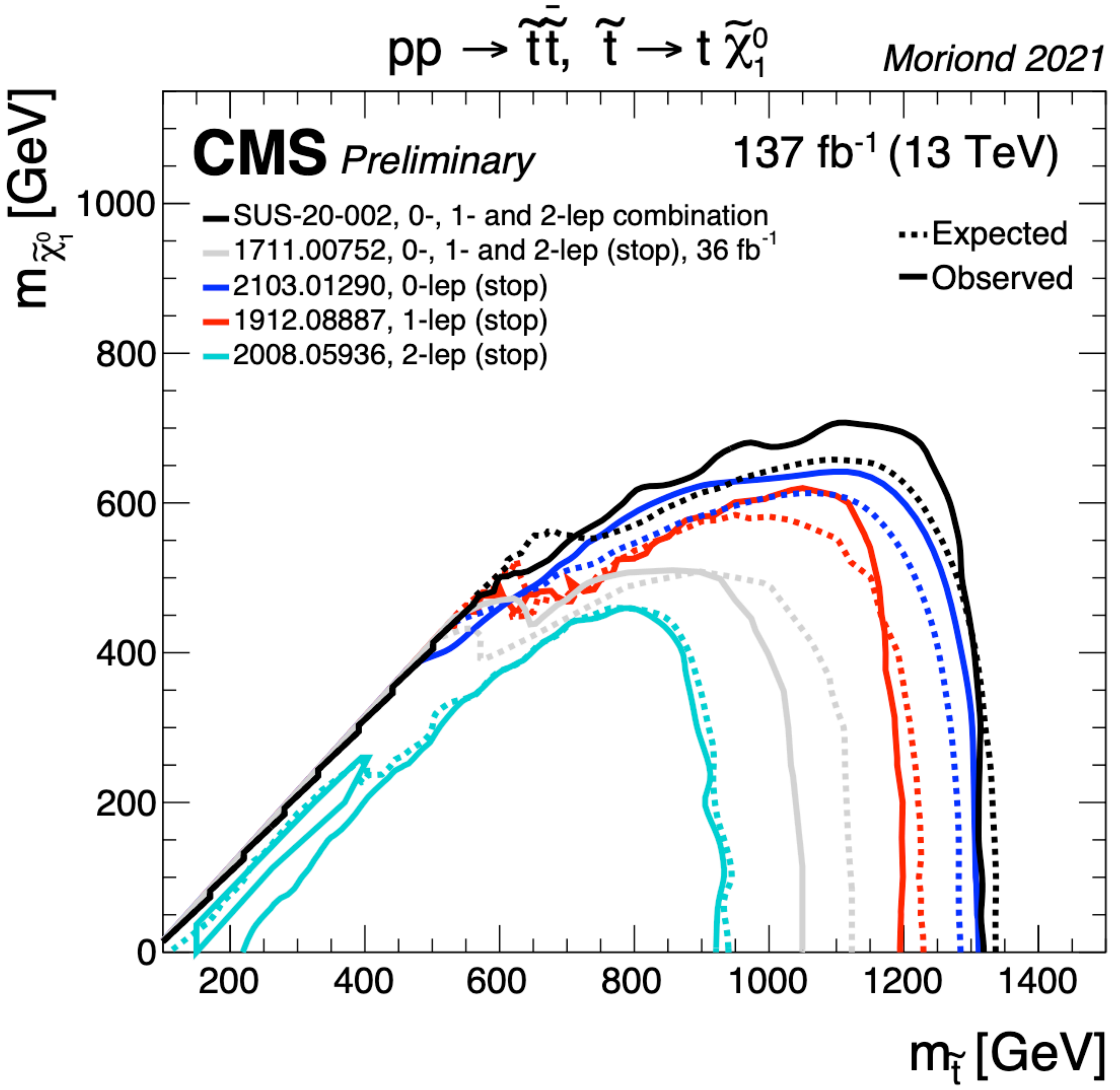




HistFitter: arXiv:1410.1280

Results on stop



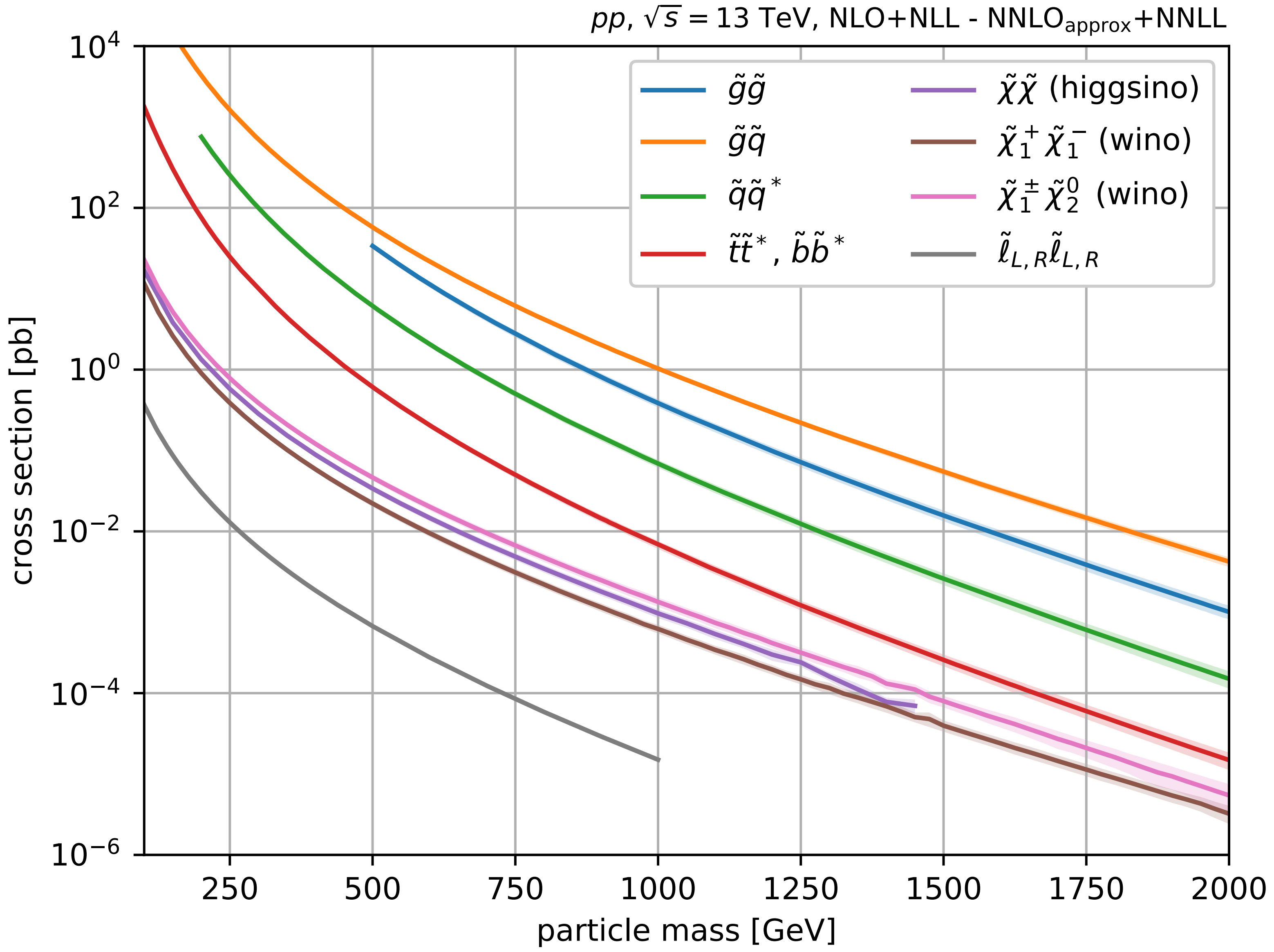


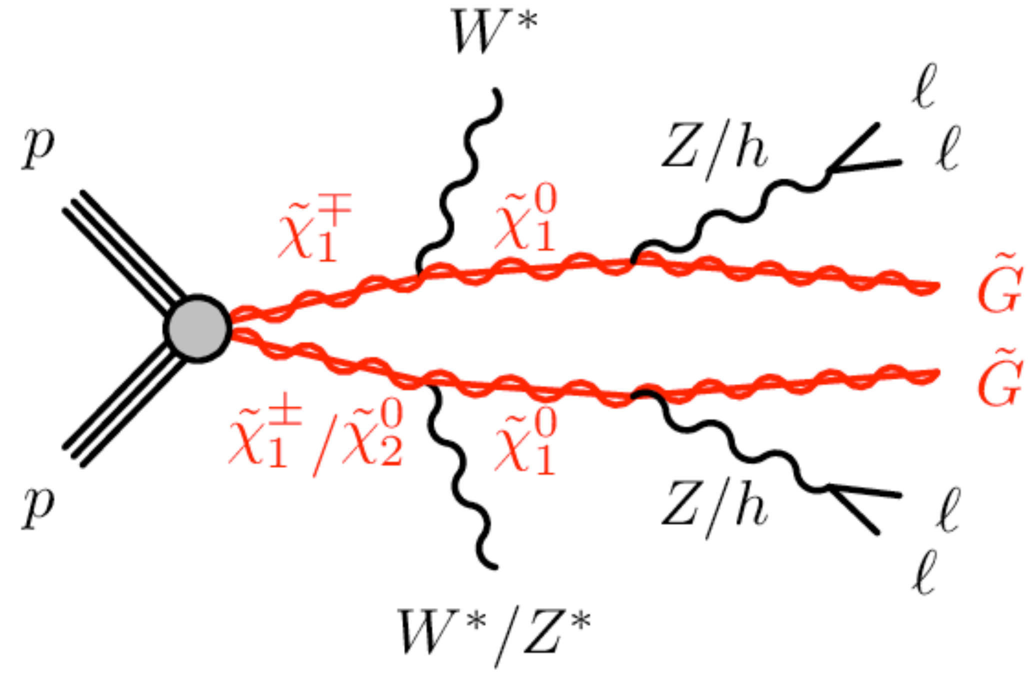
➤ Limits on Stop quark mass pushing 1200 GeV in simplified models

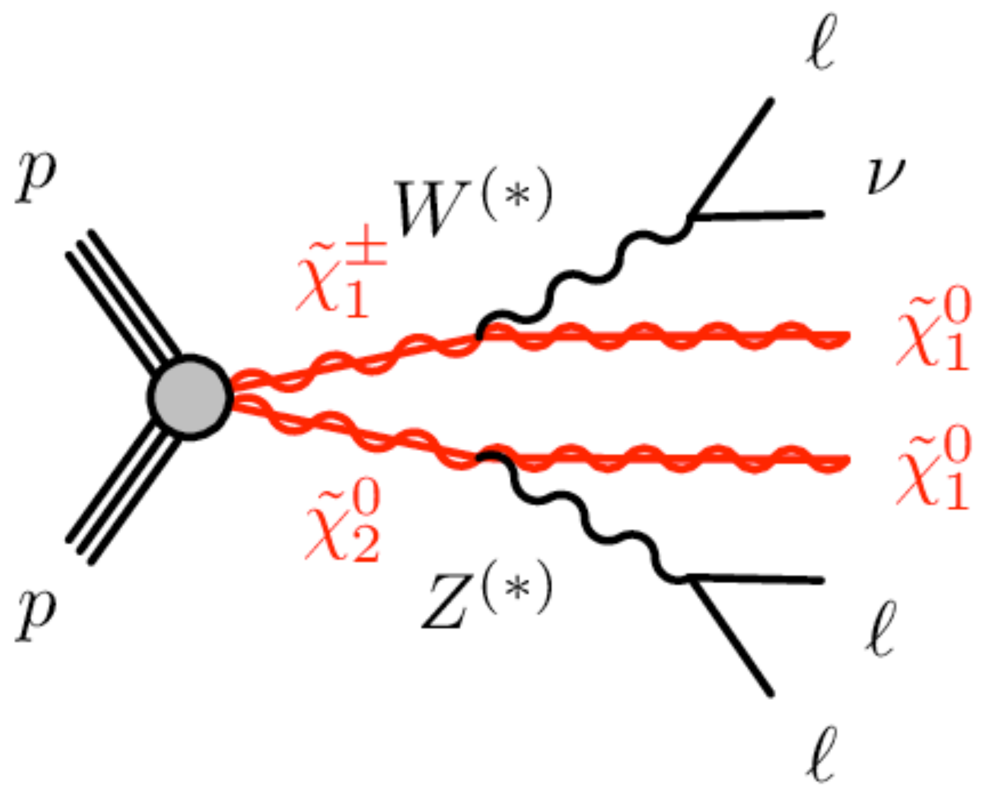
[JHEP 07 (2021) 167]
[Eur. Phys. J. C 81 (2021) 1118]

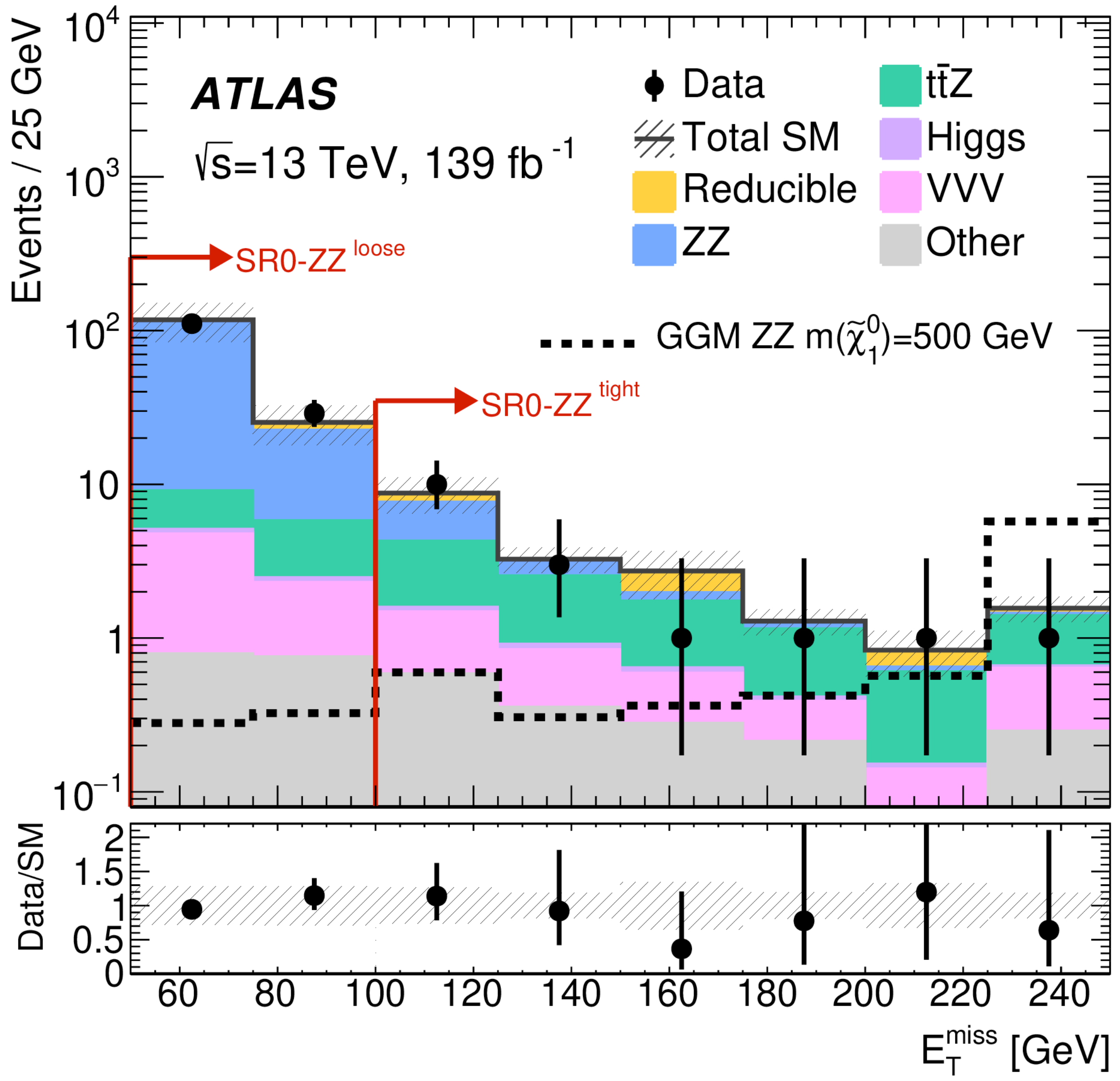
Electroweak searches

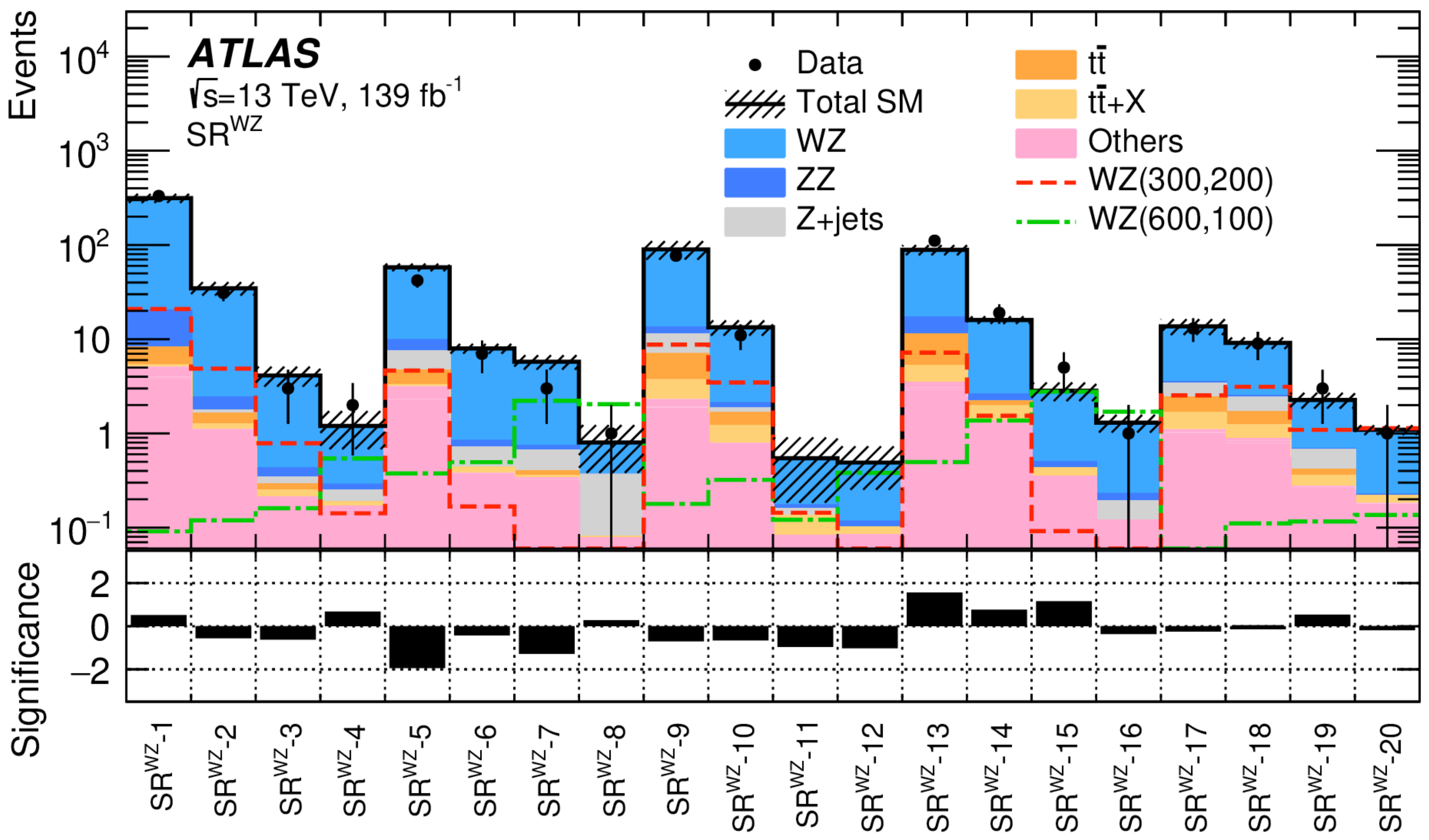
- Production cross section much lower for Higgsinos, winos and sleptons, than for squarks and gluinos









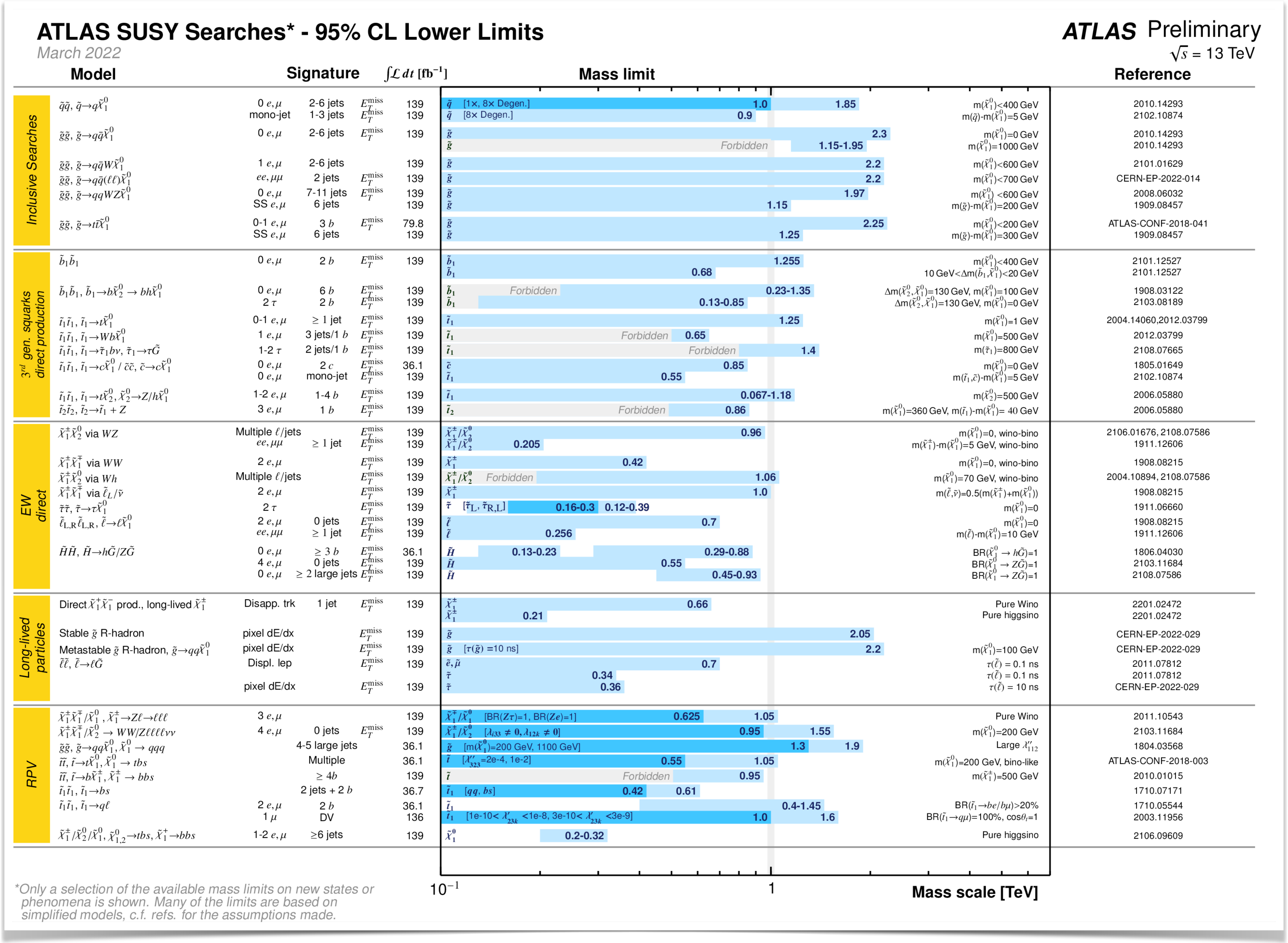


- Rare SM processes become main backgrounds

*4 lepton, bkg: **ZZ, ttZ, VVV***

*3 lepton bkg: **WZ, ZZ***

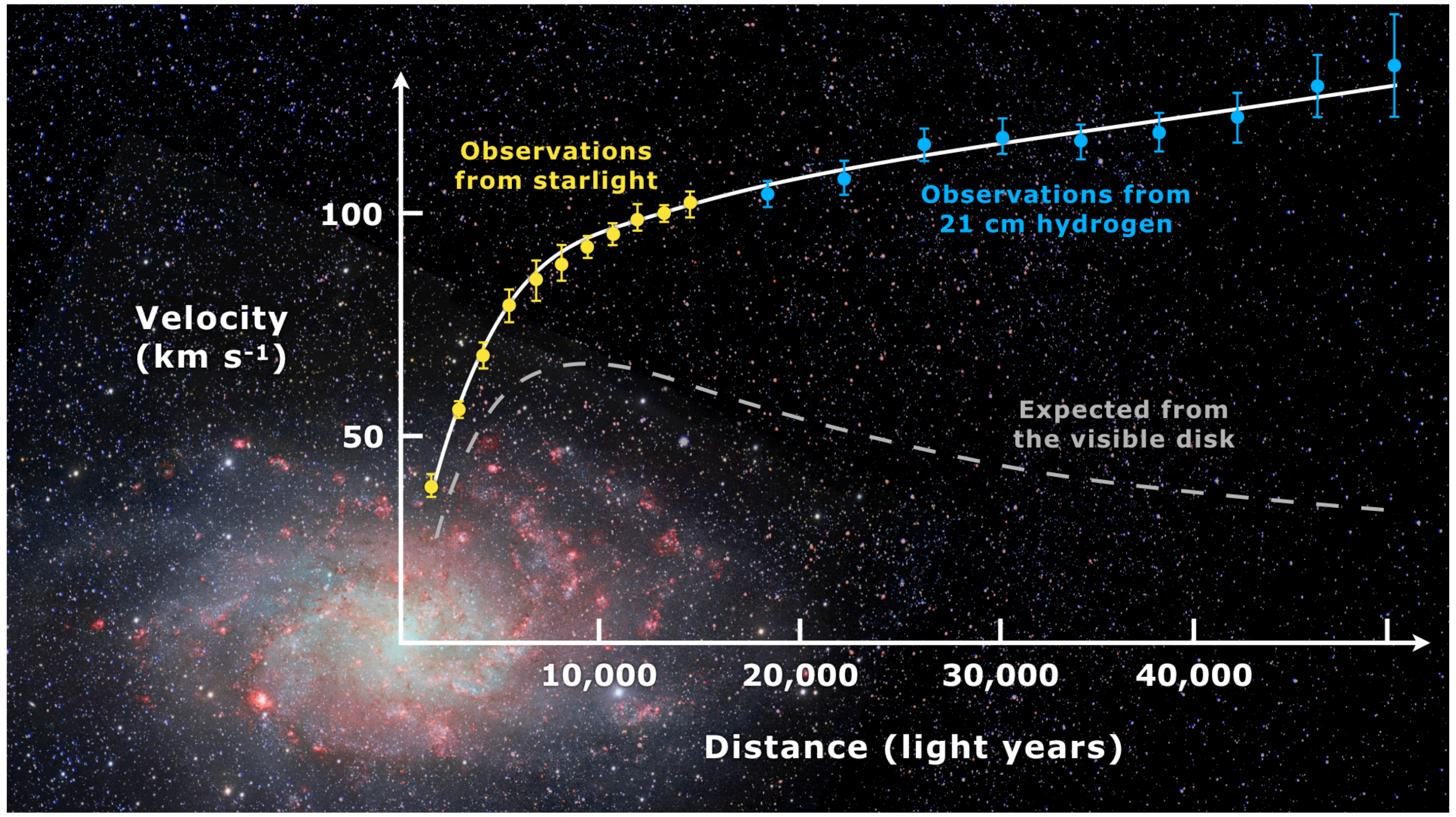
Where do we stand after Run2?



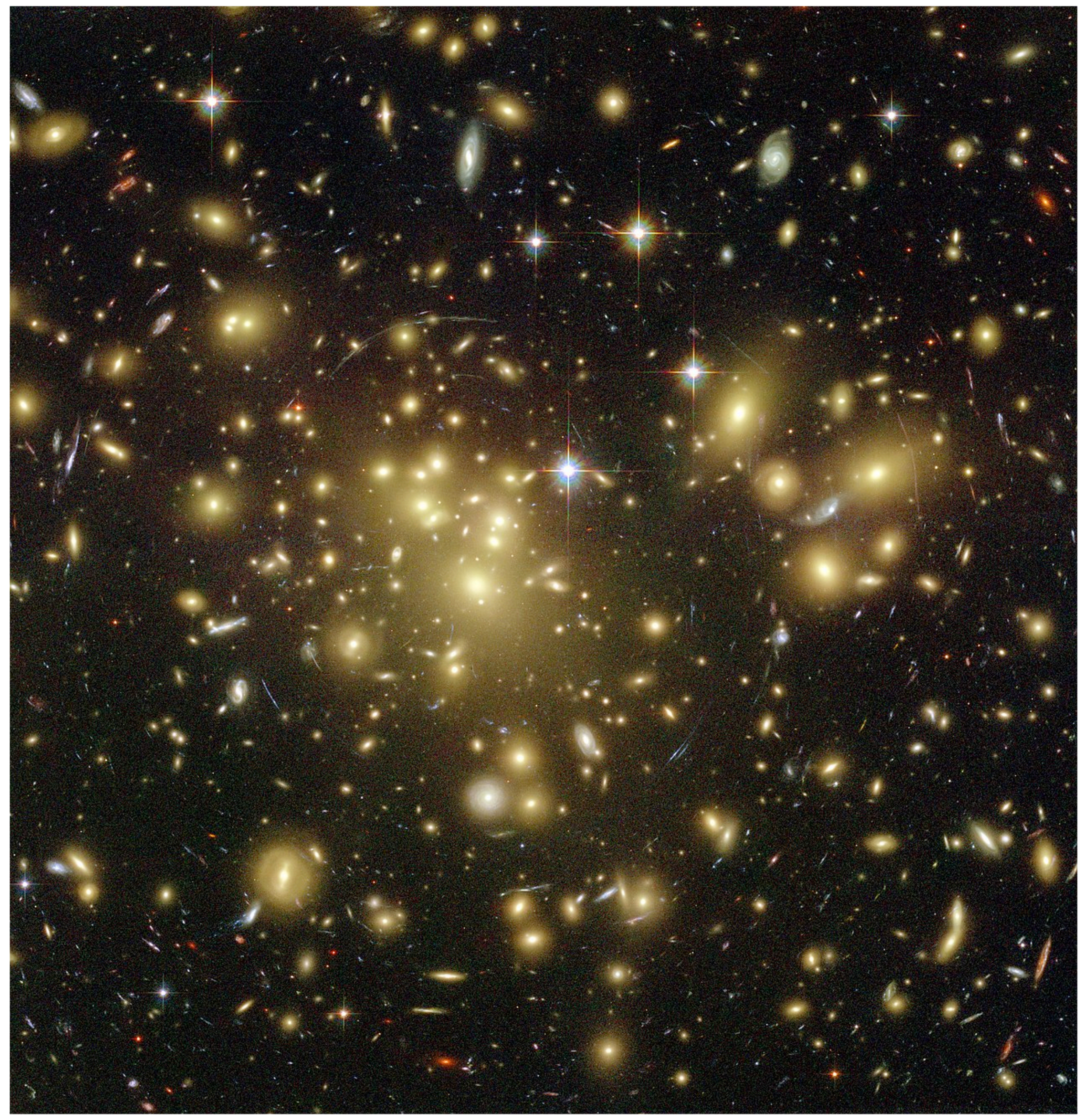
- ➤ The air is getting thin for natural SUSY
  - ➤ Gluinos ~ 2.2 TeV
  - ➤ Stops ~ 1.2 TeV
  - ➤ Elektroweakinos ~ 800 GeV
- ➤ However
  - ➤ Simplified models are only part of the story
  - ➤ always check assumptions in the model and how it fits with the bigger picture

Dark Matter

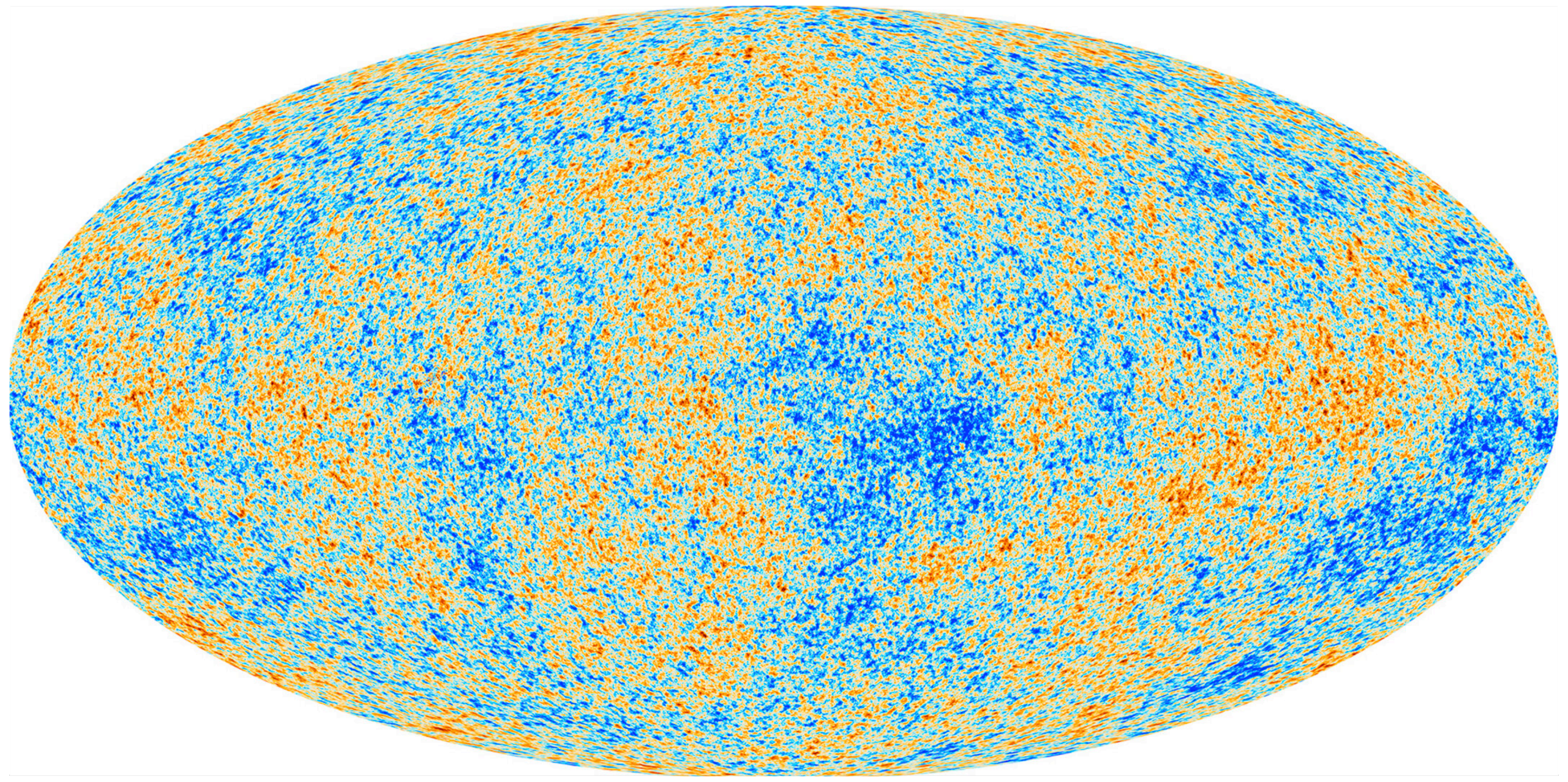
- Astrophysical observations show that a new kind of matter exists, that interacts gravitationally



Rotational curves of galaxies



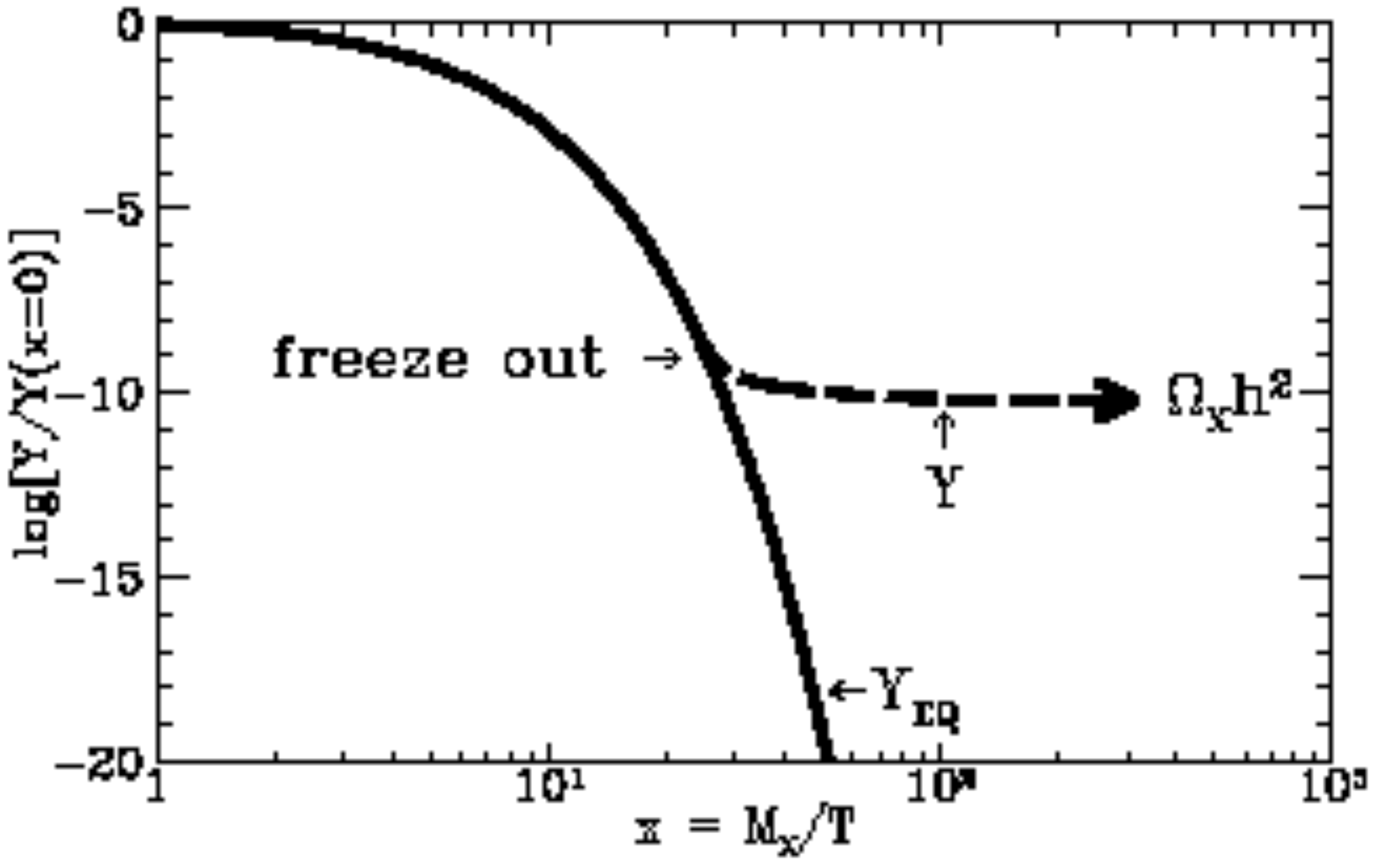
Strong gravitational lensing as observed by the [Hubble Space Telescope]() in [Abell 1689]()



Cosmic microwave background

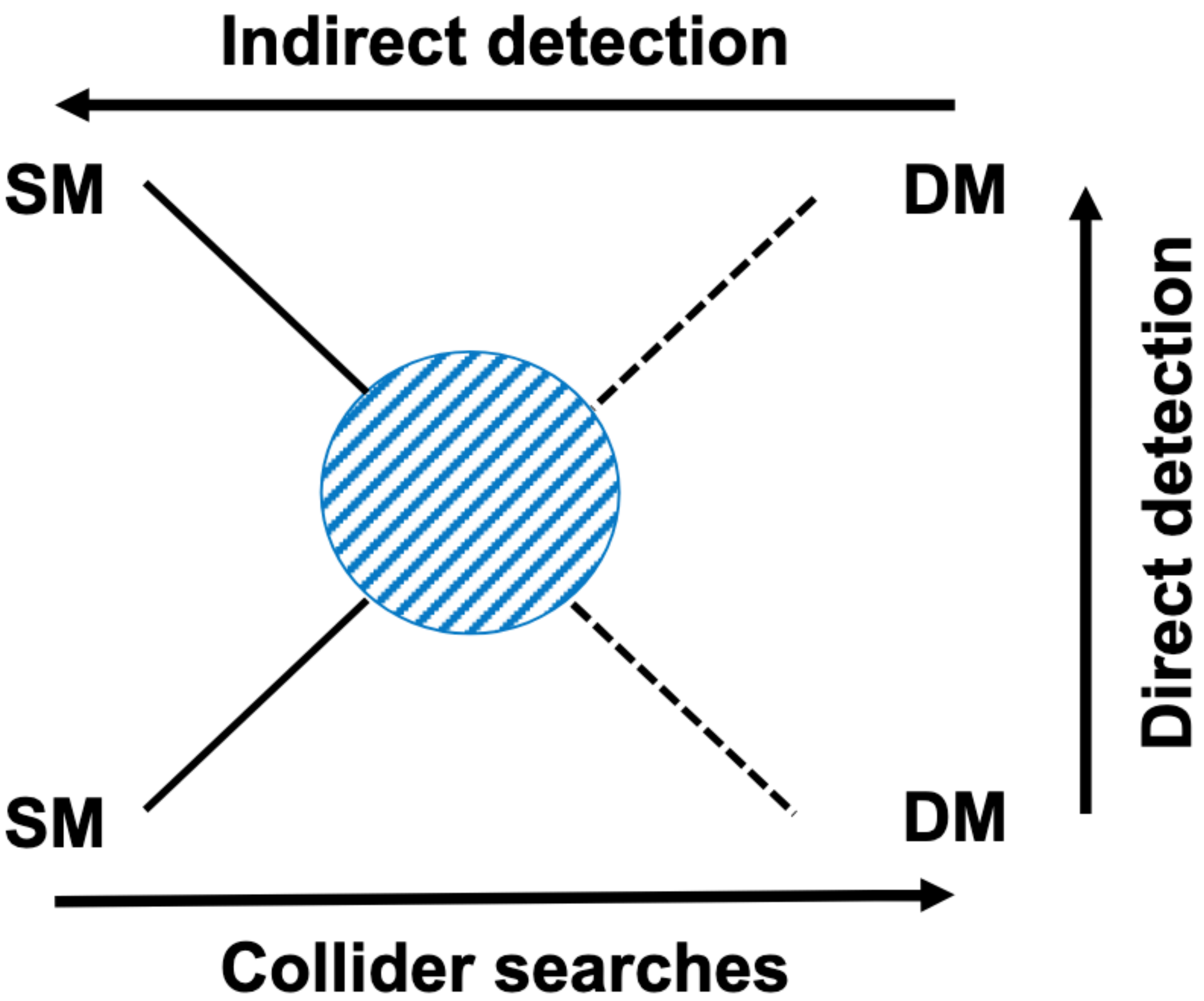
WIMP miracle

- In the early universe dark matter and SM particles were in a thermal equilibrium
  - Constant production and annihilation of dark matter $\chi\chi \rightleftarrows ff$
- Freeze out:
  - universe cools
  - WIMP mass too high for production $\chi\chi \rightarrow ff$
  - particles don't meet anymore
  - can obtain relic density from Boltzmann equation
  - compare with observation (CMB)



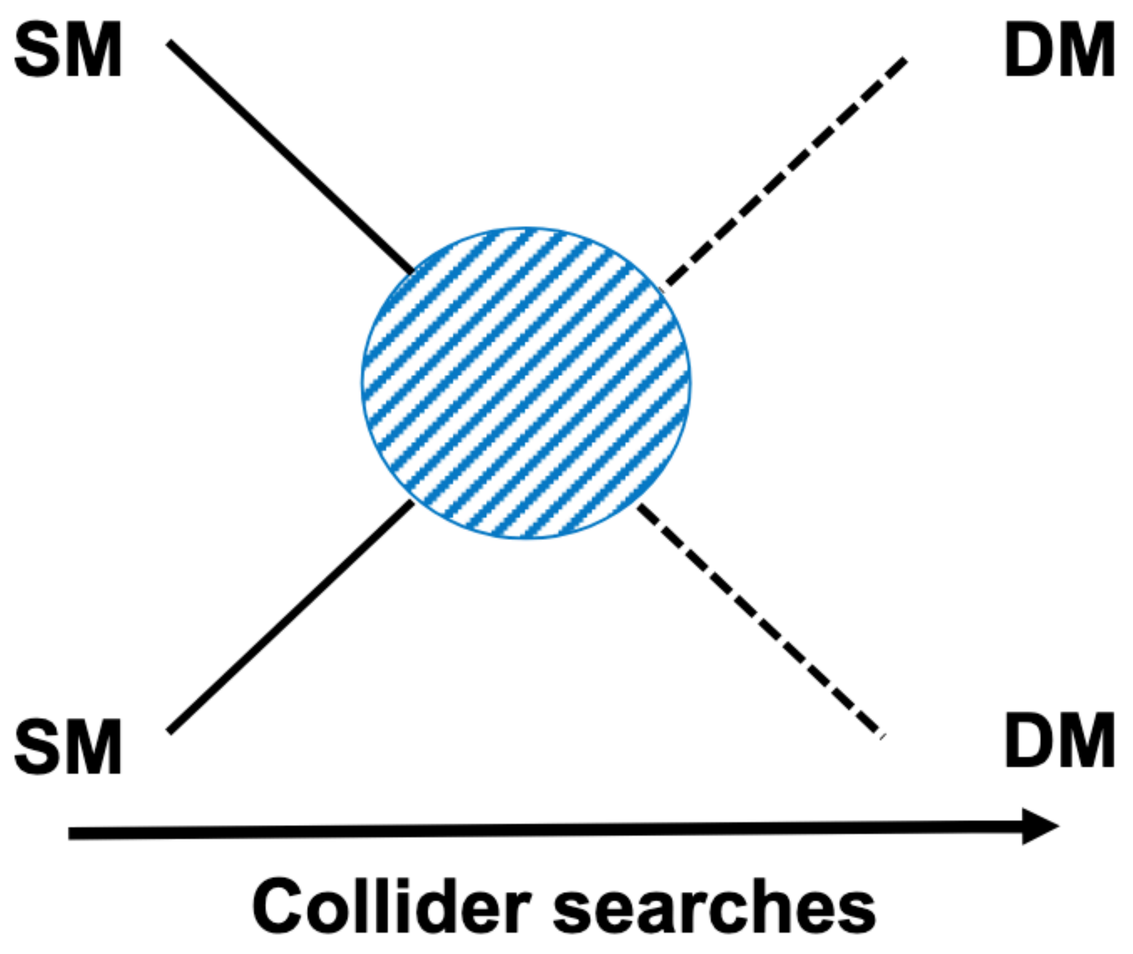
- **Corresponds to ~100 GeV particle interacting with the weak force**
  -

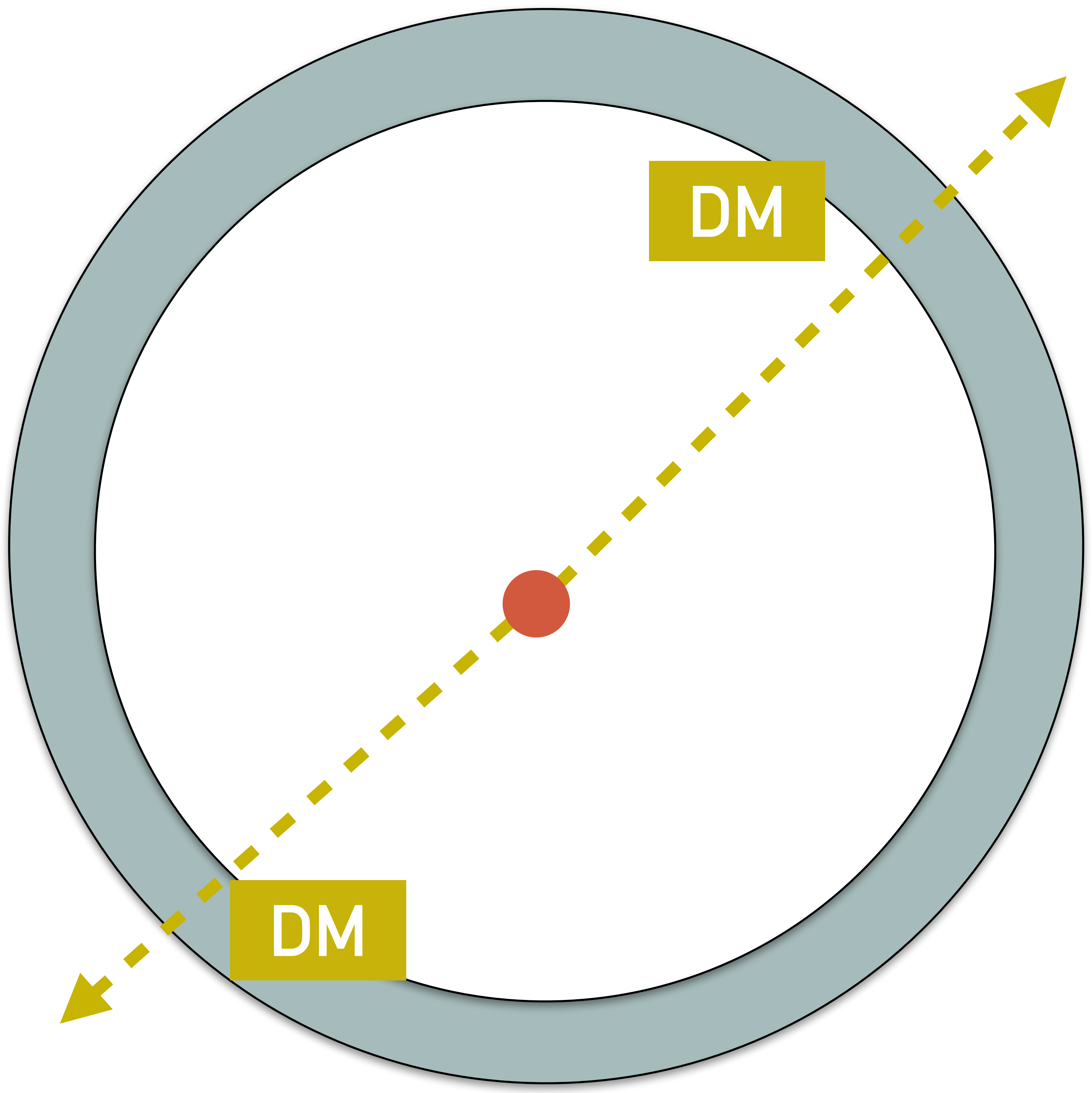
Searching for Dark Matter

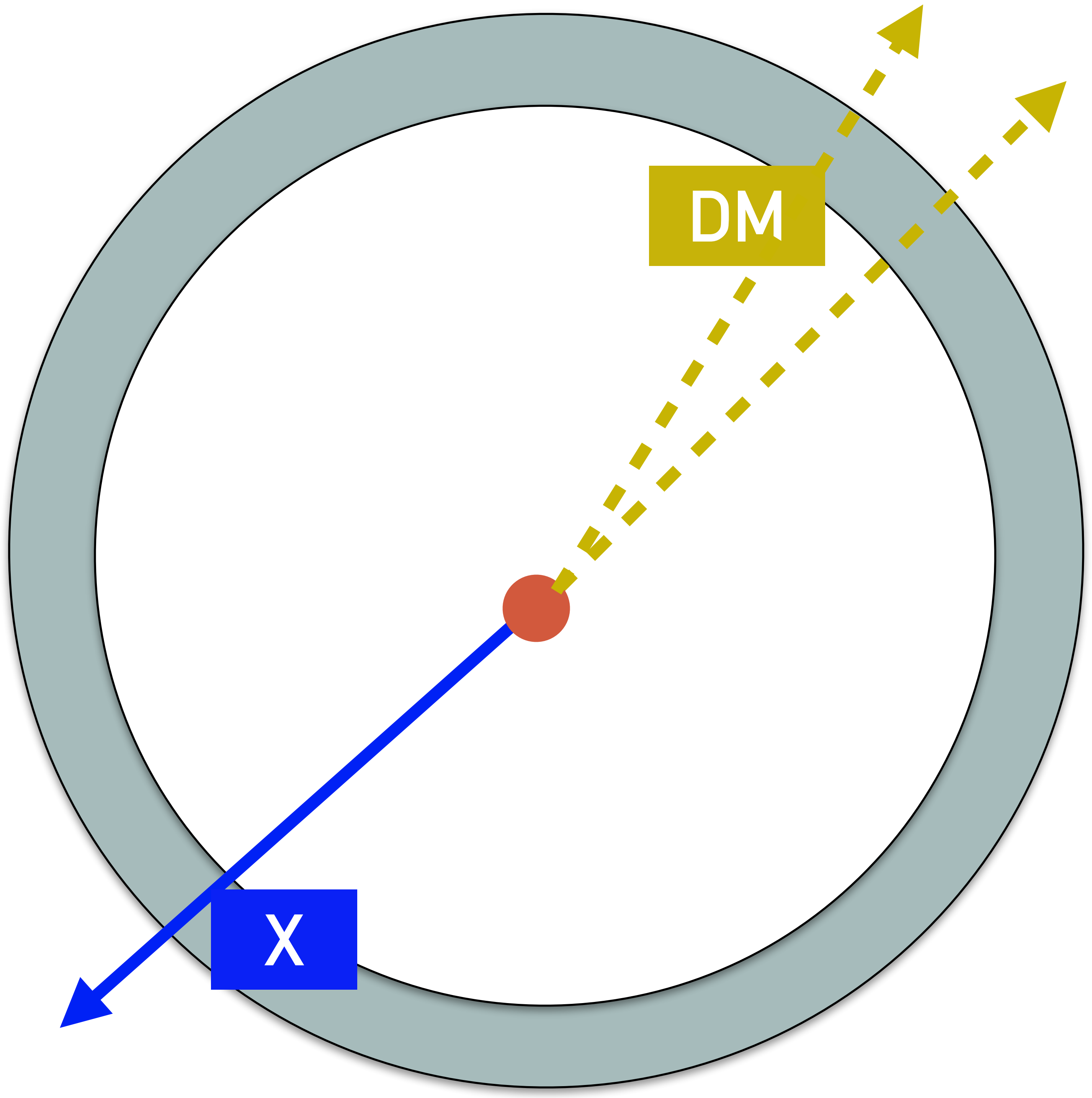


Dark Matter searches at colliders

- DM can be produced in proton-proton collisions
  - DM does not interact with the detector
  - Can be inferred due to a momentum imbalance when produced in association with particle “X”
    $\Longrightarrow$ mono-X (can also be several particles)



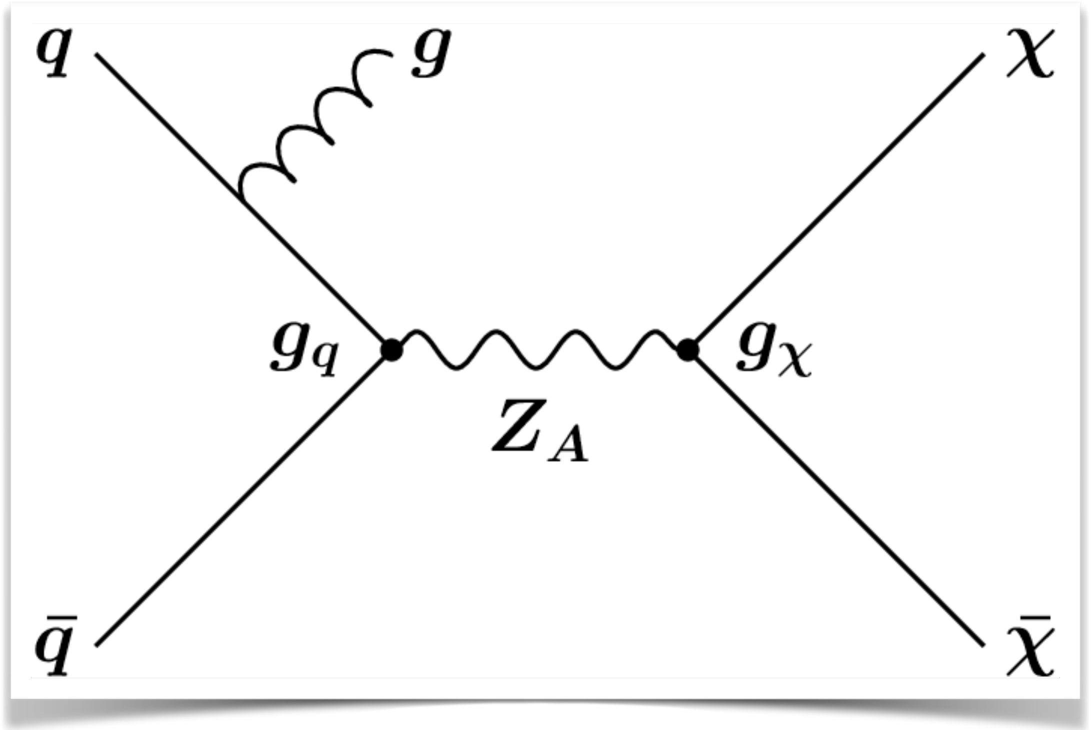




[Phys. Rev. D 103 (2021) 112006]

Mono-X signature

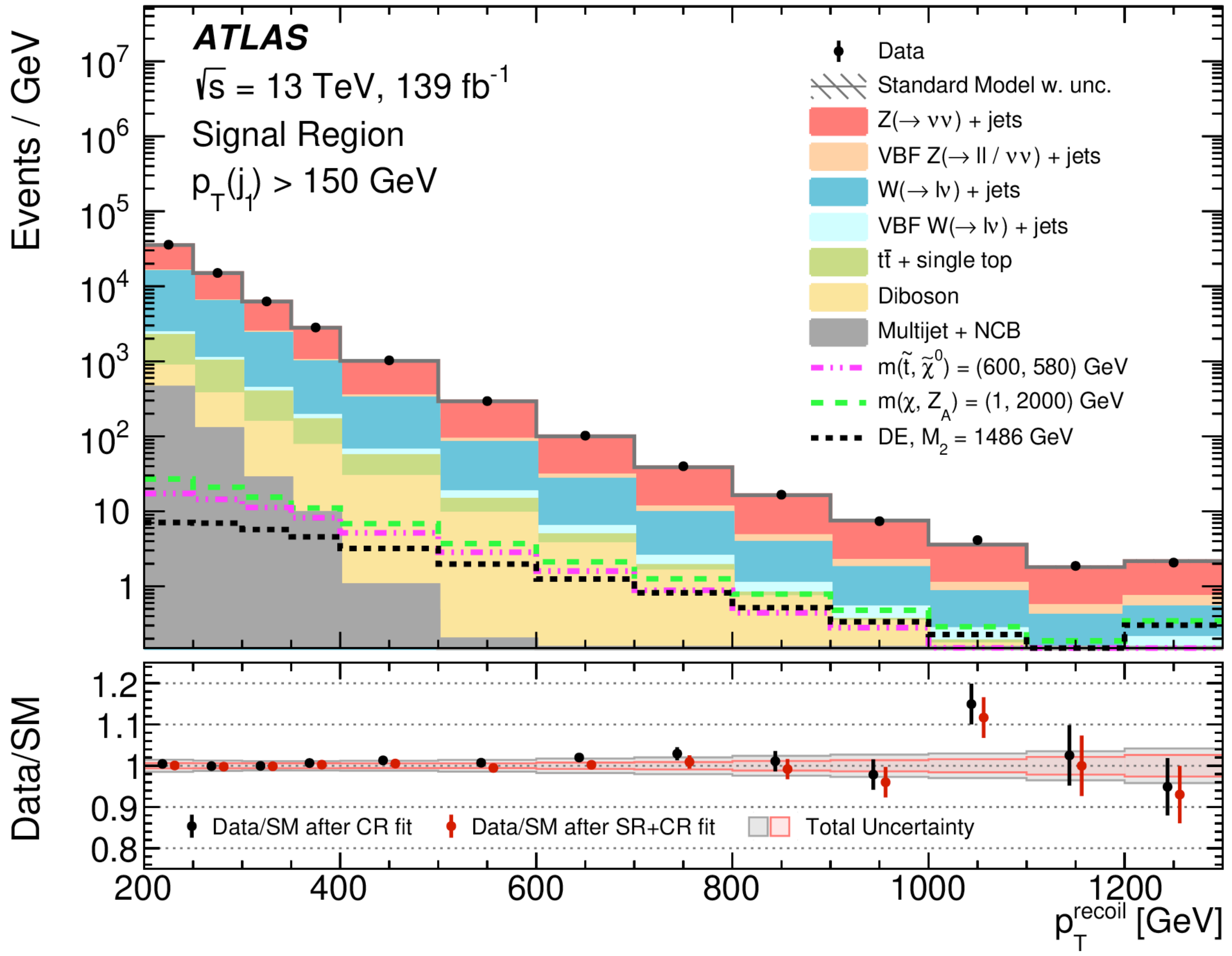
➤ ATLAS and CMS cannot detect what they cannot see → if DM is produced at the LHC need some X to trigger on

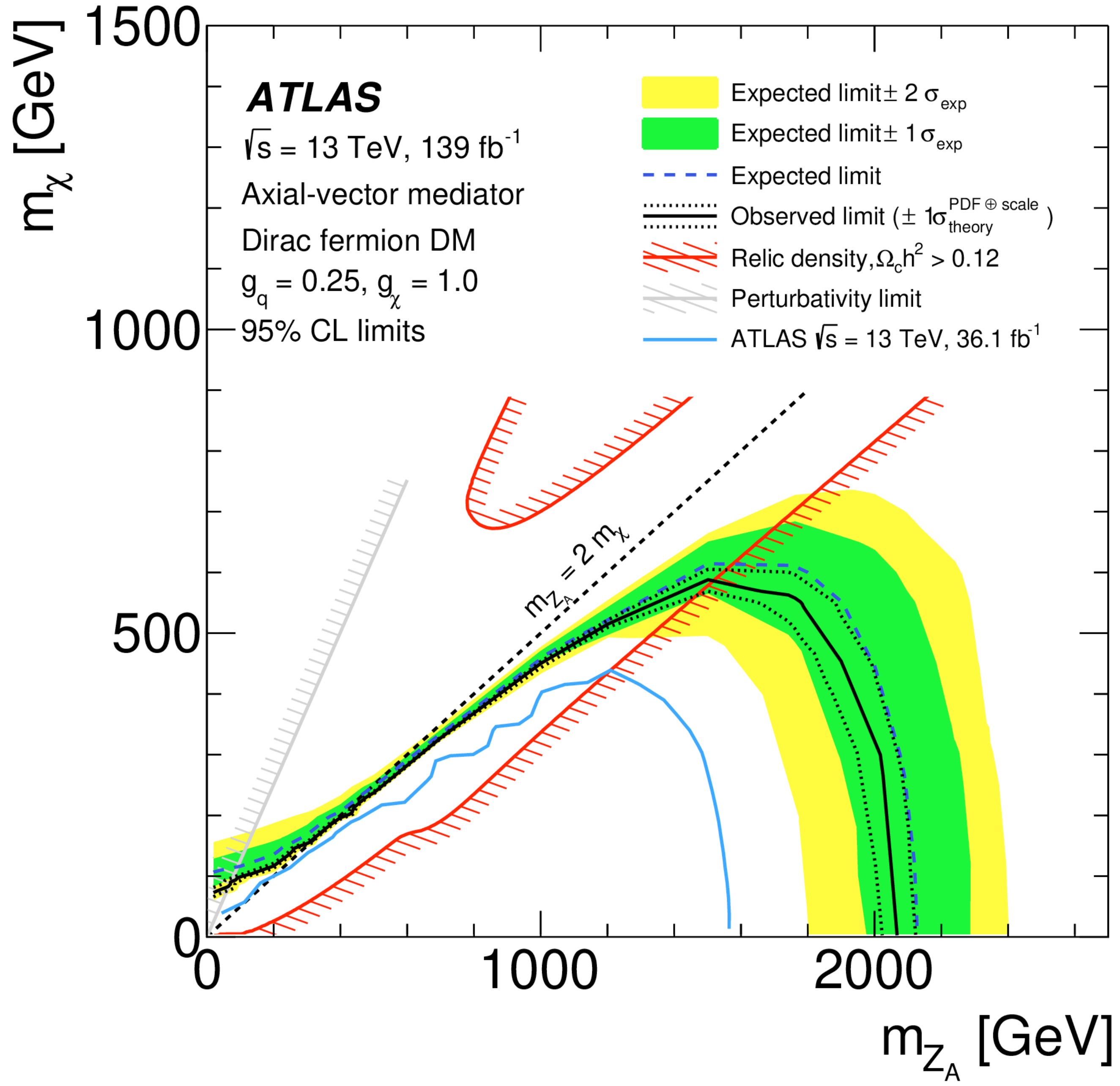


Simplified model

*ISR **jet** with (axial-)vector Z exchanged in s-channel*

Could also be:
photon, W, Z





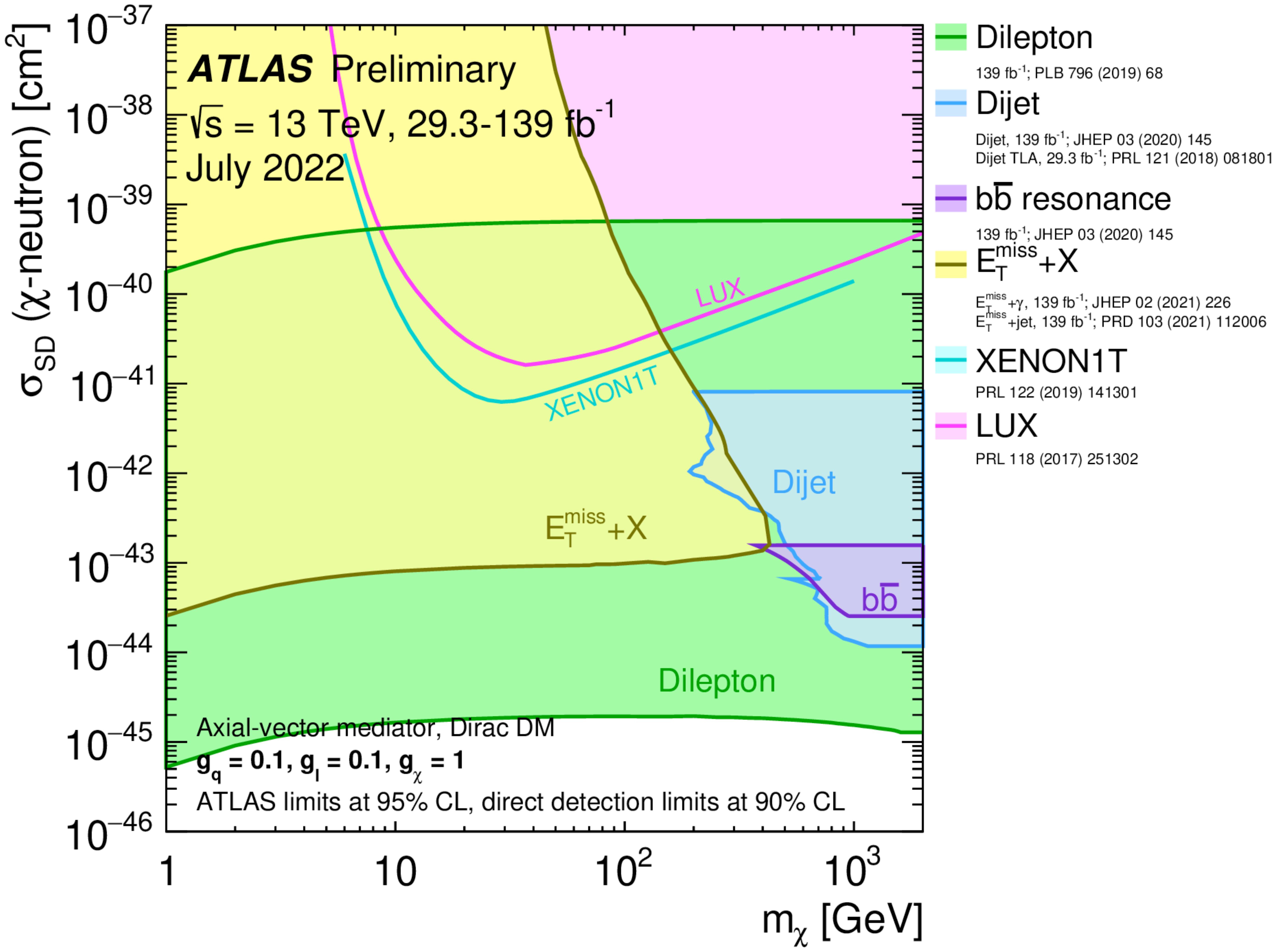
Comparing LHC results with direct detection

Axial-vector mediator

DM coupling $g_\chi = 1$

quark coupling $g_q = 0.1$

lepton coupling $g_l = 0.1$



Can only compare results for a given model and set of parameters

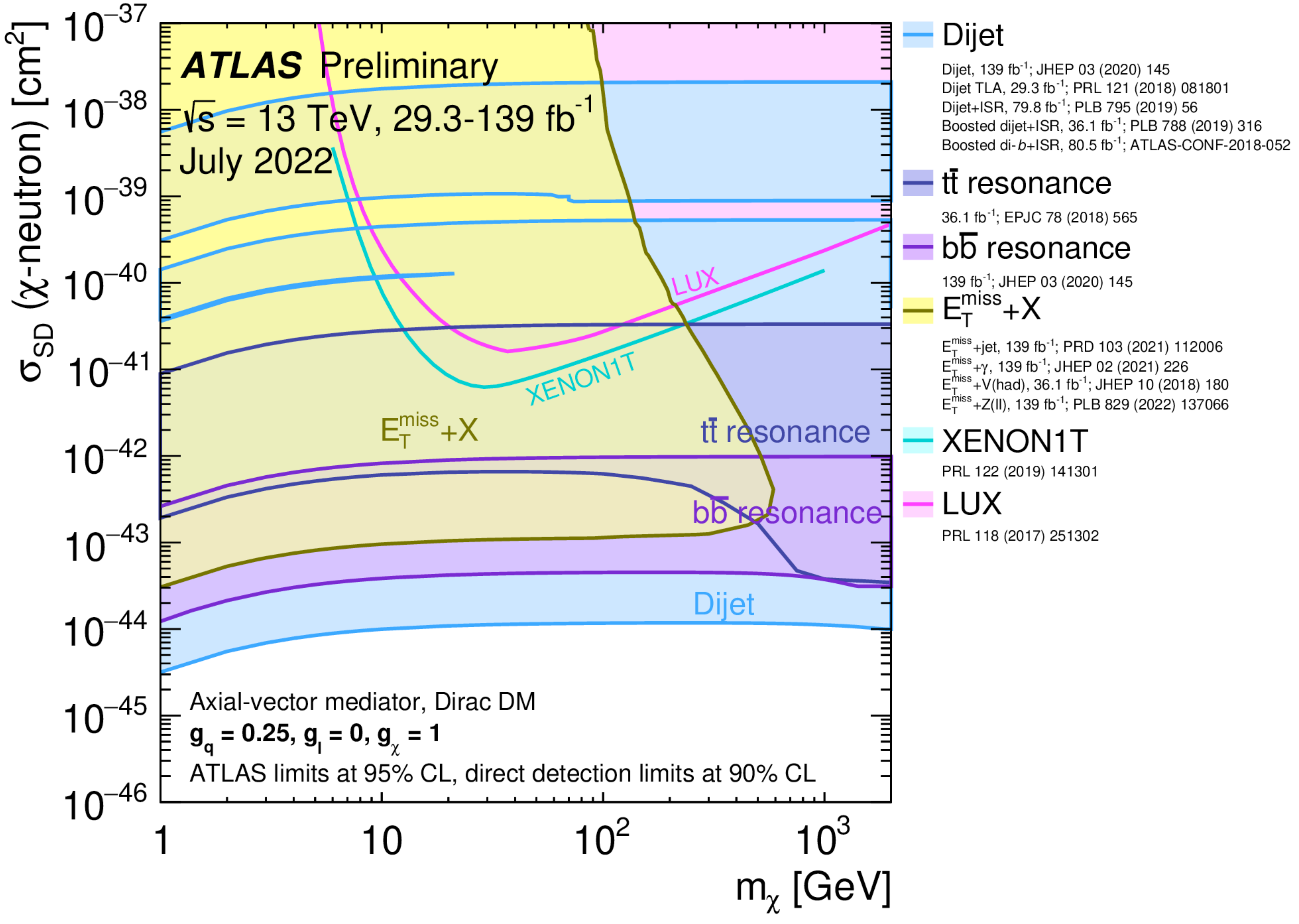
Comparing LHC results with direct detection

Axial-vector mediator

DM coupling $g_\chi = 1$

quark coupling $g_q = 0.25$

lepton coupling $g_l = 0$



Can only compare results for a given model and set of parameters

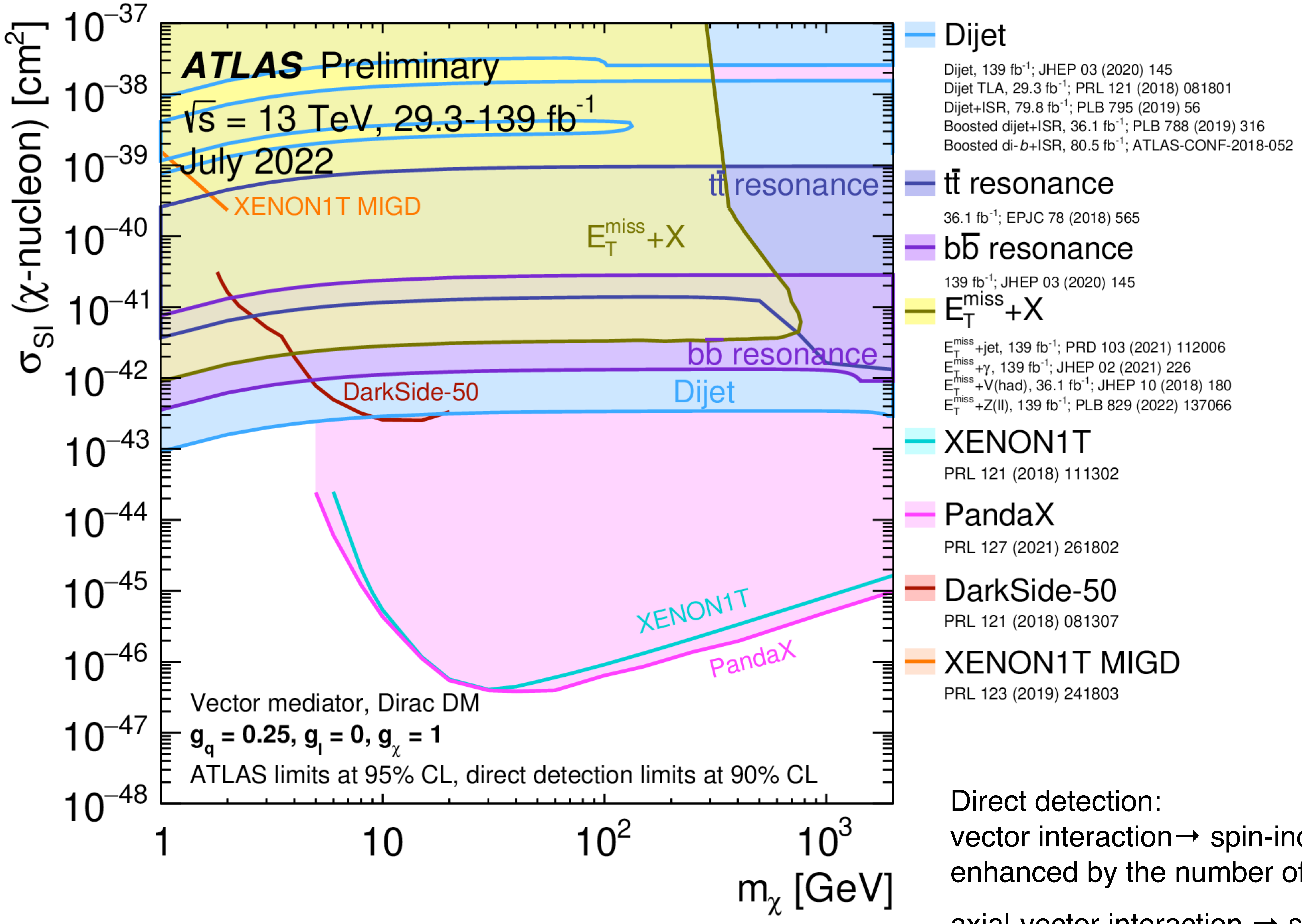
Comparing LHC results with direct detection

Vector mediator

DM coupling $g_\chi = 1$

quark coupling $g_q = 0.25$

lepton coupling $g_l = 0$



Direct detection:
vector interaction → spin-independent → enhanced by the number of nucleons

axial-vector interaction → spin-dependent → no enhancement

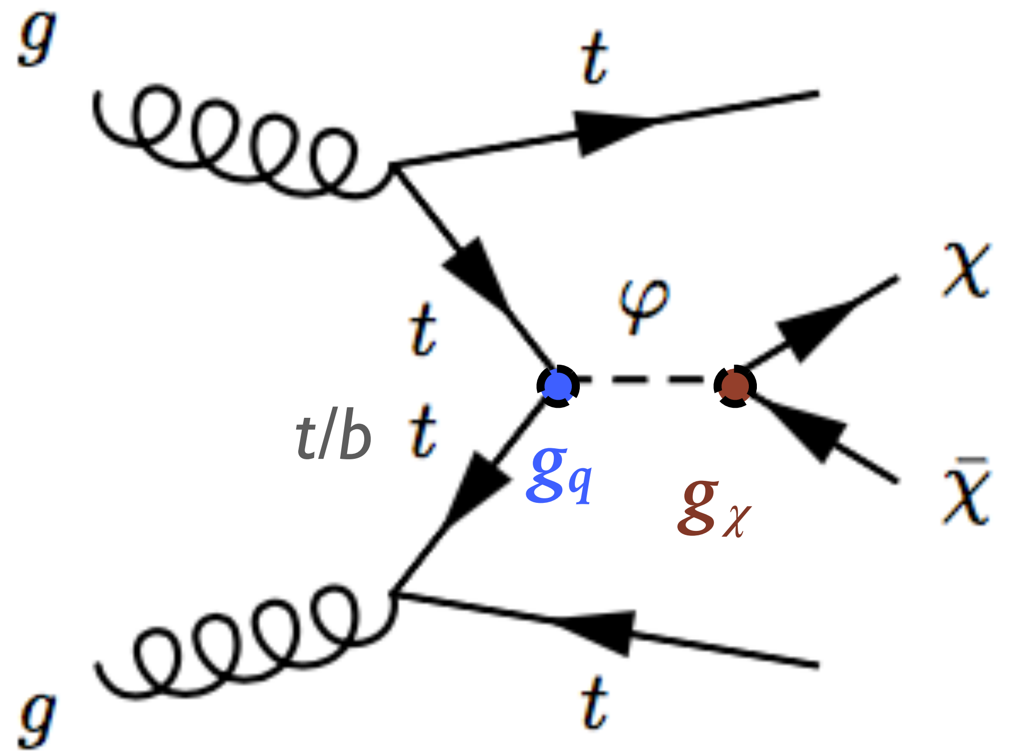
Can only compare results for a given model and set of parameters

Dark Matter + heavy flavor

- WIMP model for DM produced at colliders

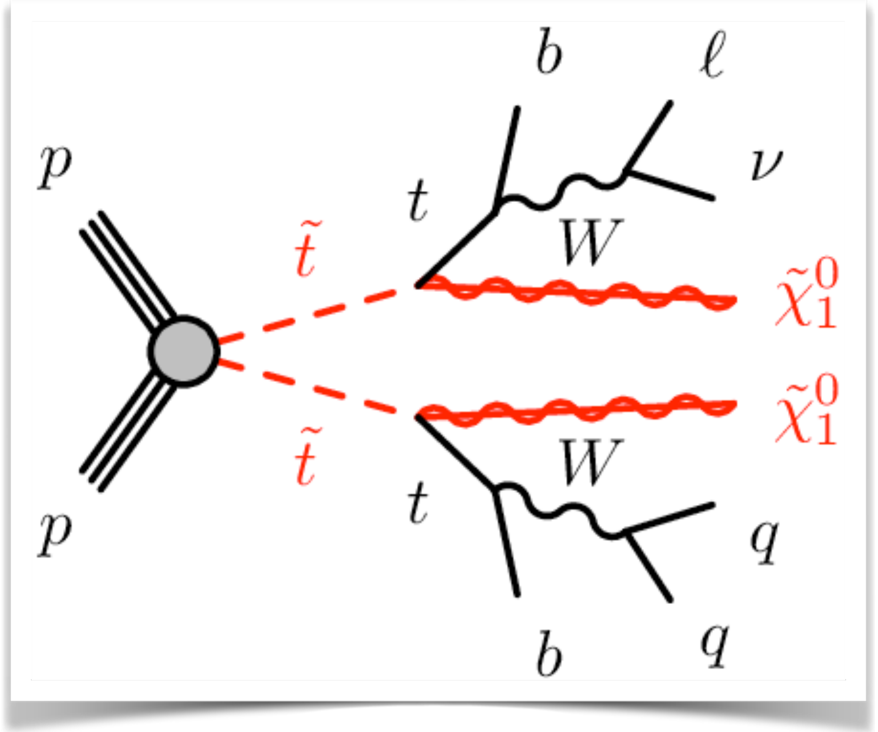
  Phys. Rev. D91 015017, arXiv:1507.00966

- Minimal flavor violation
  - Same flavor structure as in the SM
  - Yukawa couplings to spin-0 mediator



- **DM production via (pseudo)scalar most compelling for heavy flavor +DM**
  - **Parameters: m_φ, m_χ, g_q, g_χ Benchmark: $g_q = g_\chi = 1$**

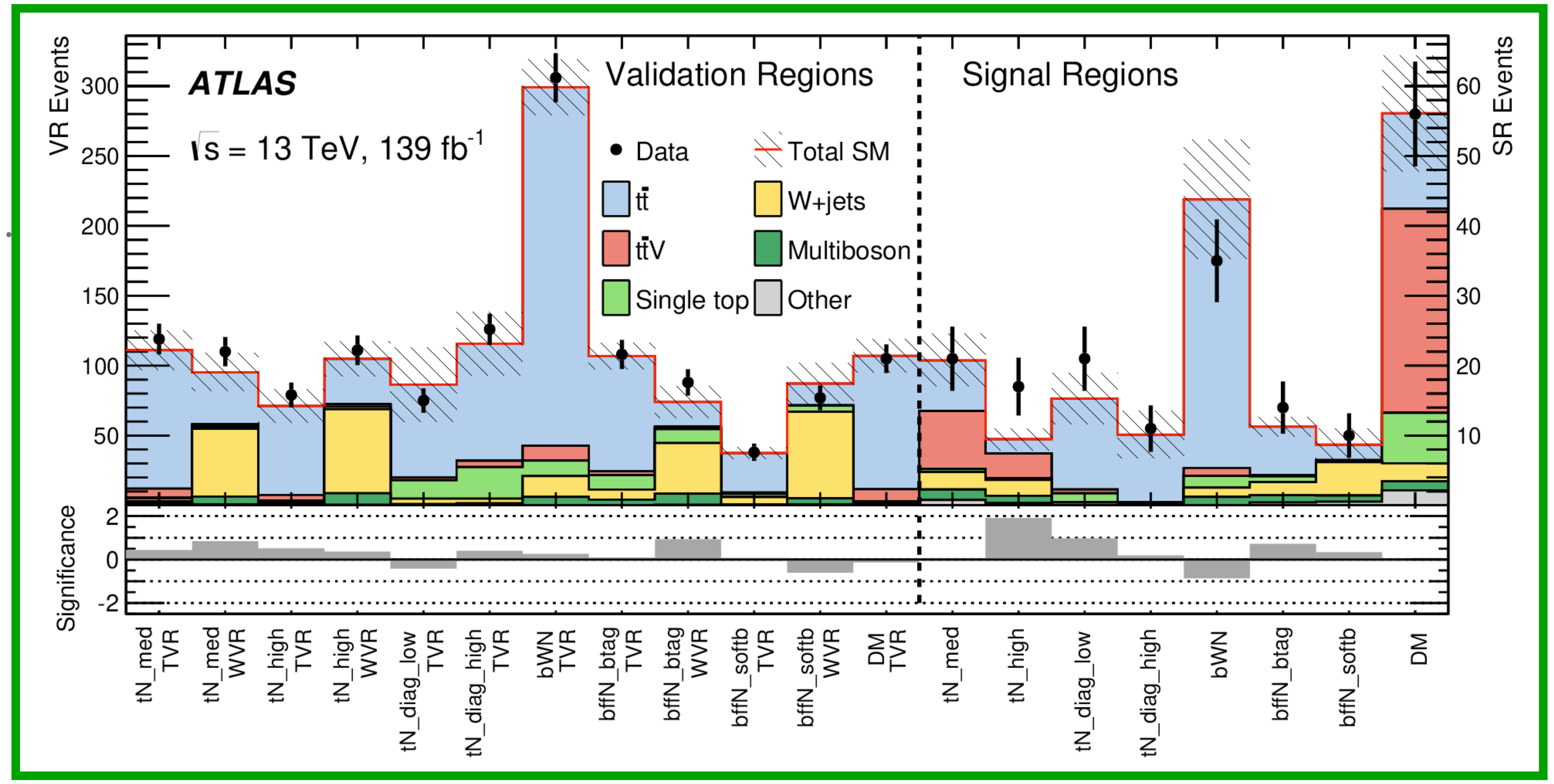
- Mediator decays into two dirac fermion dark matter particles χ, which escape detection
  → Missing energy is the main signature
  → Amount depends on mediator and its mass

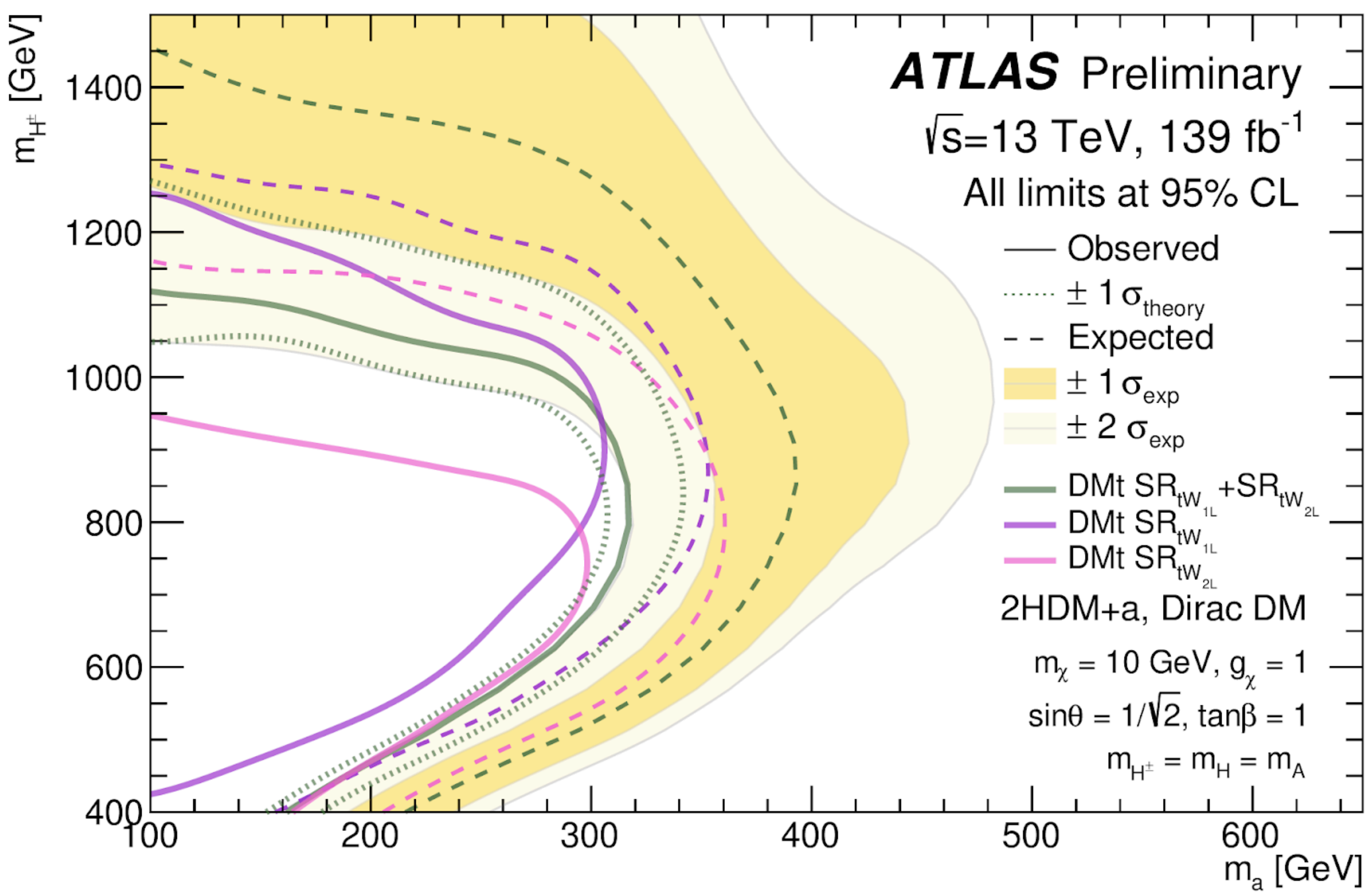


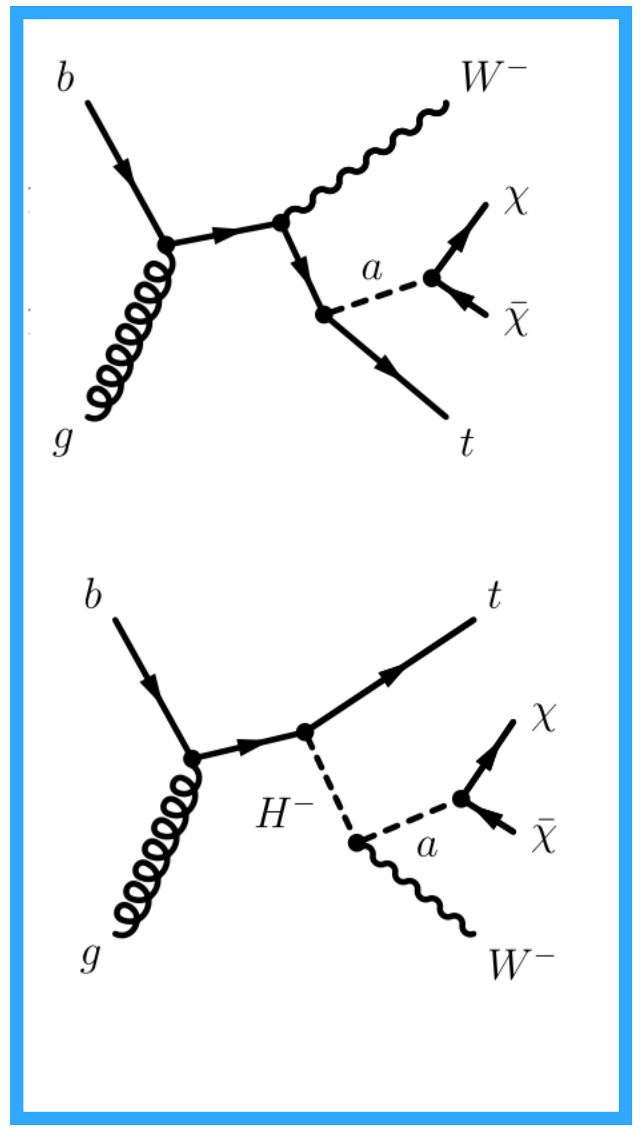
Very similar signature to stop searches

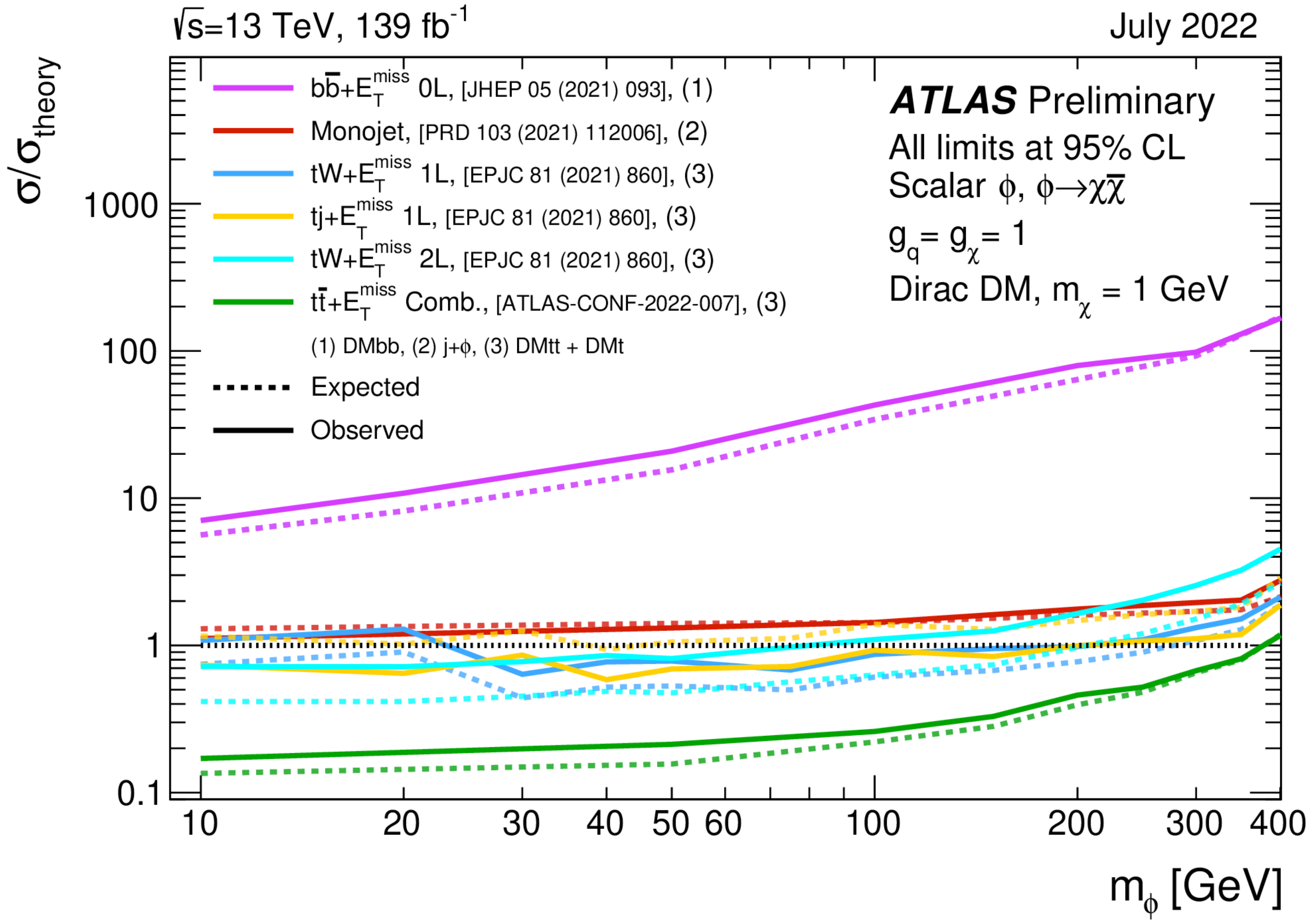
Dark Matter + heavy flavor

- Sometimes existing results can be reinterpreted for new models
  - ATLAS SUSY stop searches contained a dedicated “Dark Matter” signal region
  - Search for a 2 Higgs doublet (2HDM+a) model with an additional pseudo scalar predicting tW+MET final states is also sensitive





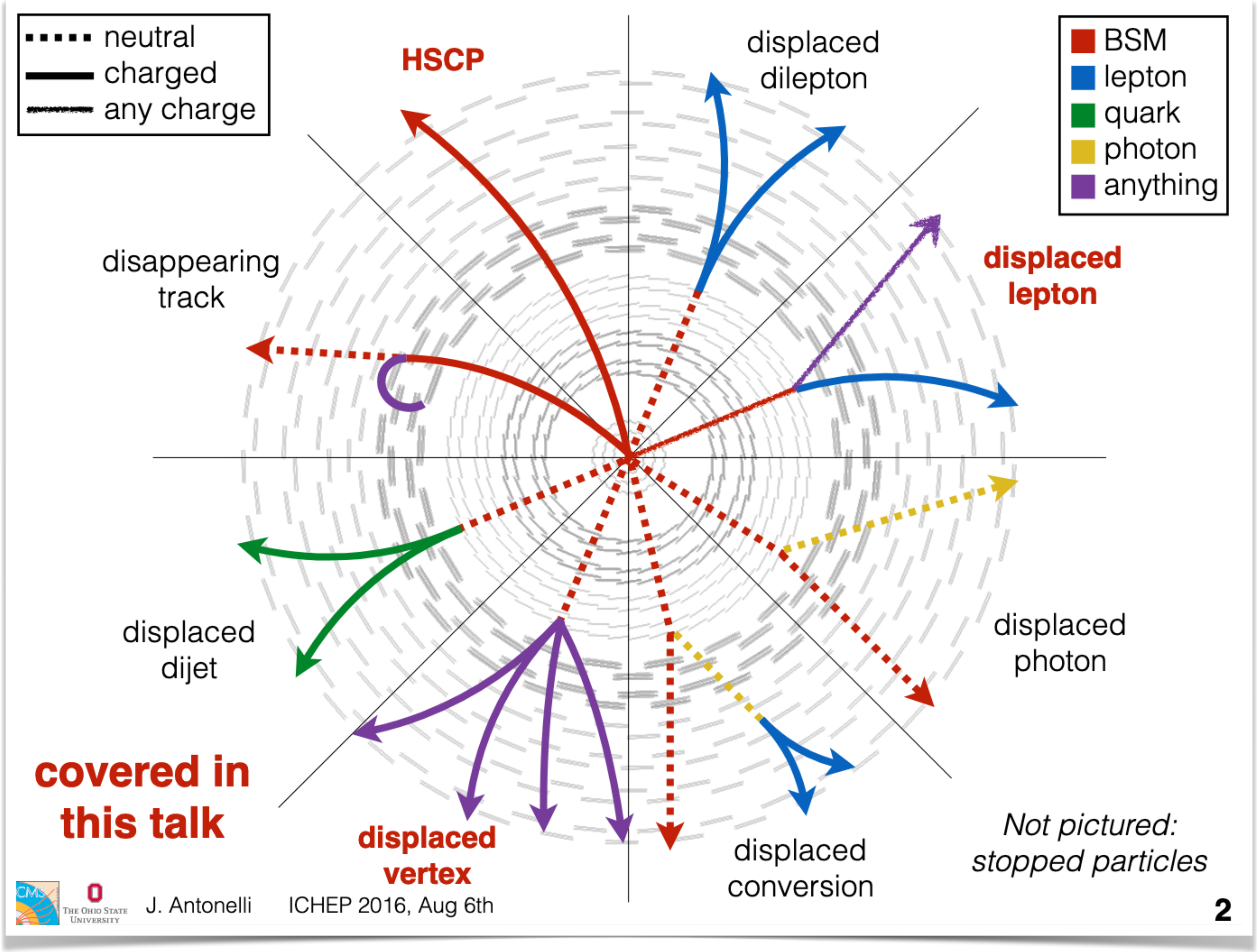




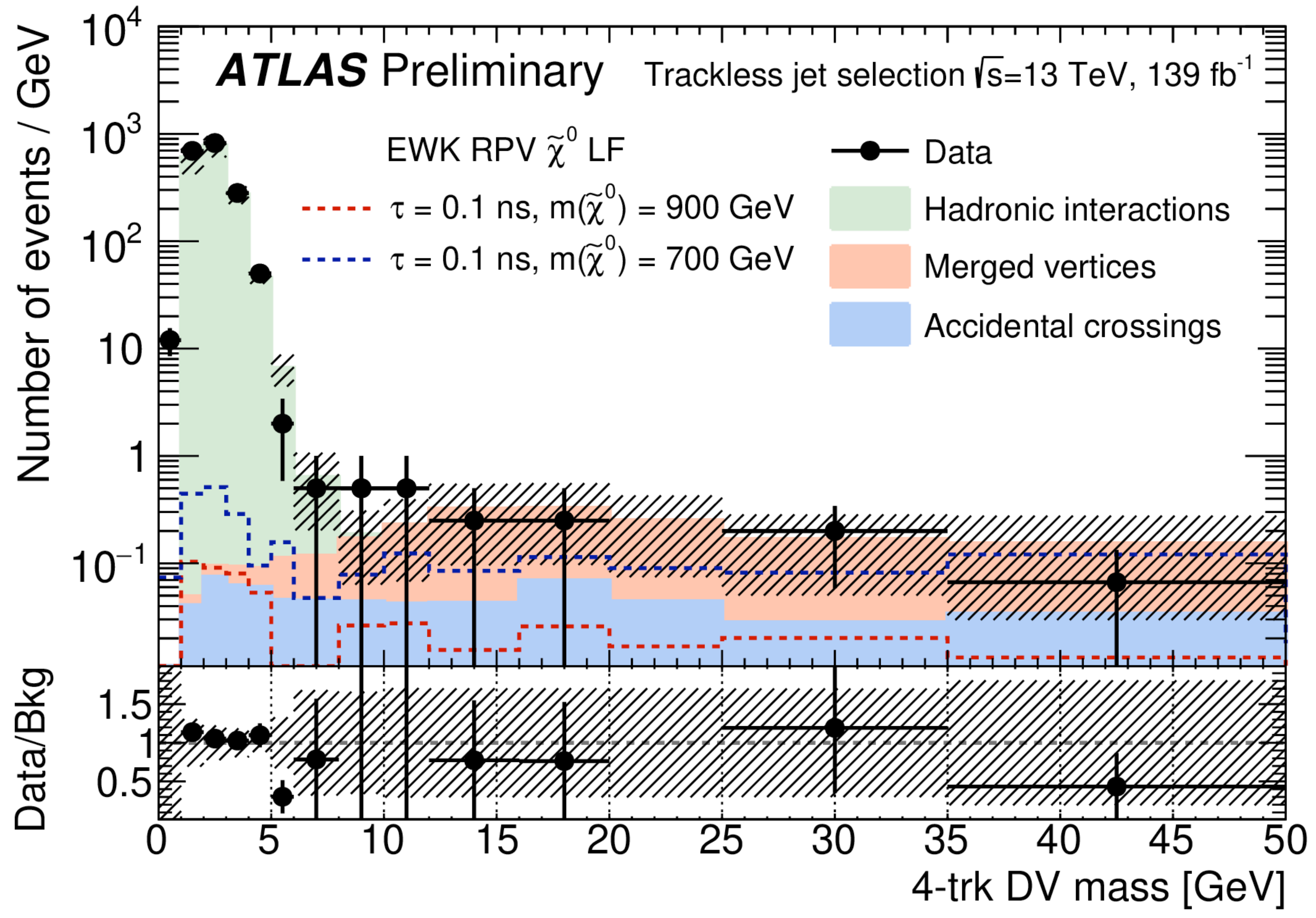
[Eur. Phys. J. C 81 (2021) 860]

Unconventional signatures

- So far the models were BSM but the signatures contained “known” SM particles
  → what if also the decay products are “BSM”?



- Often “long lived” new particles
- Backgrounds very different from other searches
  - data driven approaches to estimate them
- Often dedicated data reconstruction algorithms needed



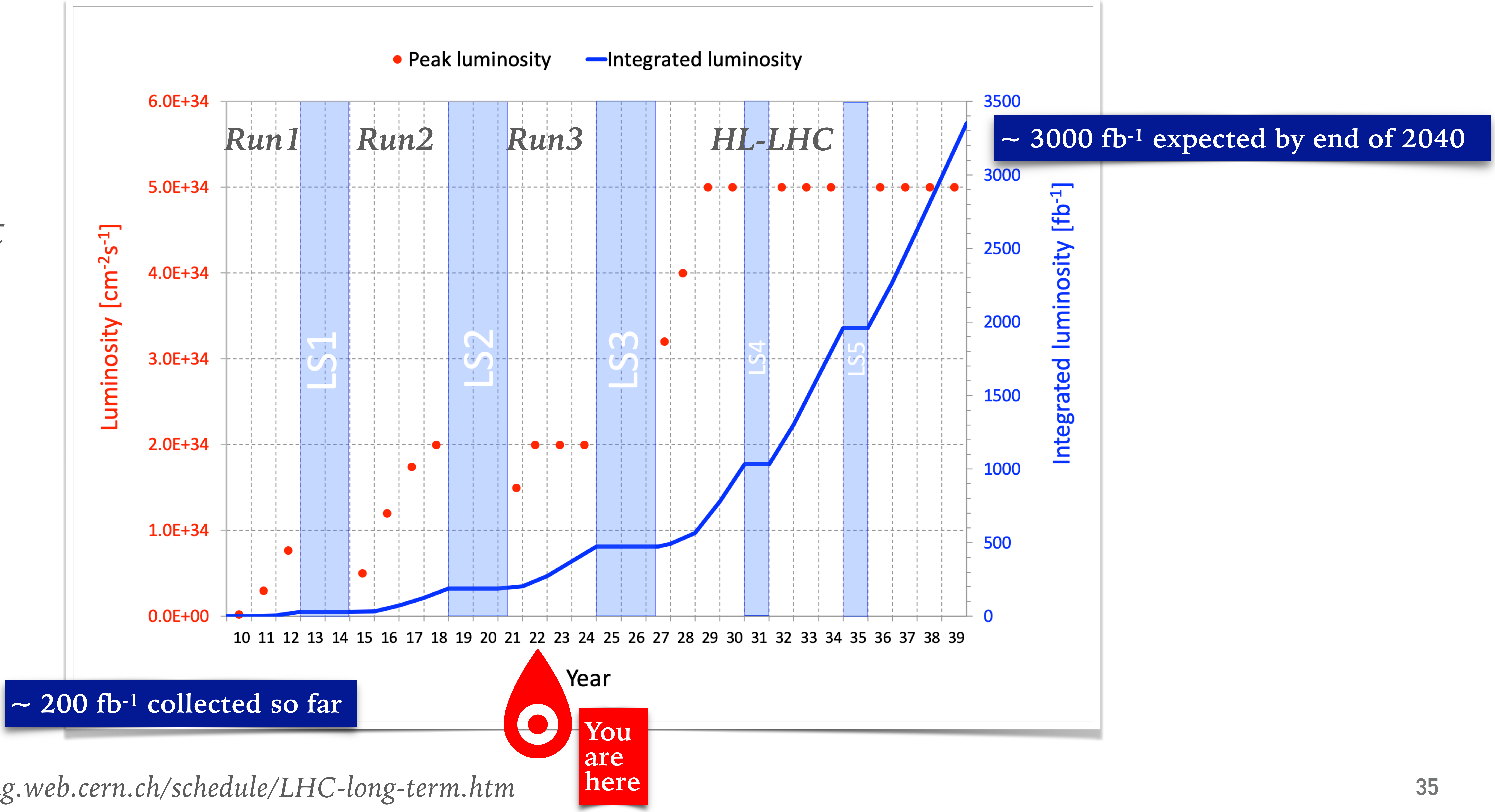
Searches for new physics at the LHC

- So far no smoking gun for signs of new physics
  - Flavor anomalies will be covered in b-physics lecture
- Here and there local 2-3 sigma excesses → important to follow up
  - However luminosity will now double only every couple of years

- NEW IDEAS?
  - Make sure we didn't miss something → what we didn't trigger on is lost forever
  - Maybe something super long lived is produced in ATLAS/CMS but can only be detected with other experiments → Proposals FASER, MATHUSLA etc.

Where do we go next?

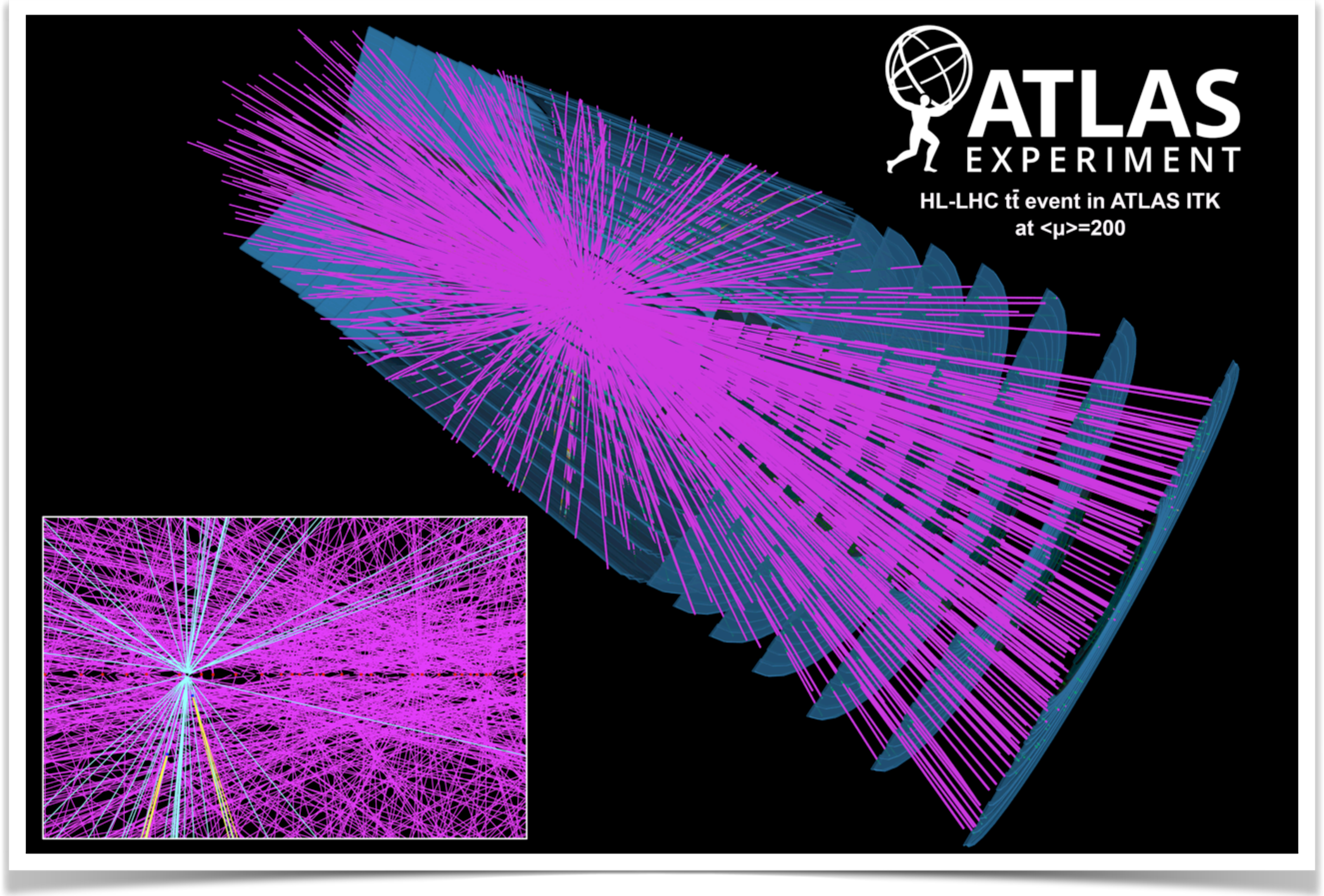
We will still collect 15 times more data



http://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

HL-LHC

- Major detector upgrades underway
  - expected pile up of ~200 poses an immense challenge
- Precision measurements of the Higgs boson
  - Establish Higgs self coupling at the 5 sigma level
- Push the boundaries of SM precision measurements
  - Find deviations that could hint at new physics
  - Watch out for exciting LHCb results
- Pursue dedicated searches for new physics
  - Your new crazy idea!



Thank you very much for your attention!

Measure

Standard Model

parameters with high precision

Search for the

Higgs boson

and measure it's properties

Search for

New Physics

Beyond the Standard Model

Large Hadron Collider

Questions?