Supersymmetry and how to search for it

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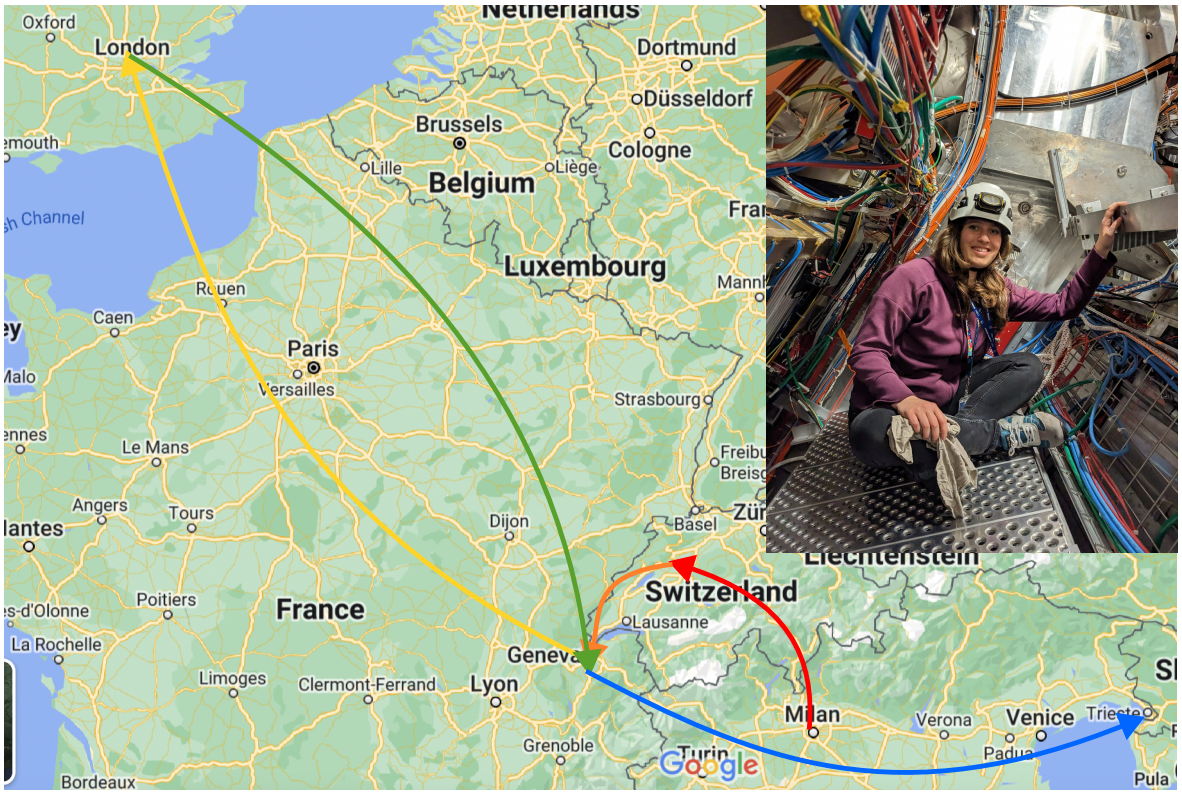
INFN Trieste

July 20^{th} 2023

A short presentation



- experimental physicist working in ATLAS
- searches for new physics, especially SUSY and dark matter
- operation of the trigger system
- just started as a researcher at INFN Trieste

Symmetries in the SM

Spacetime symmetries

- spacetime translations
- rotations and boosts

$\rightarrow$ Poincare group

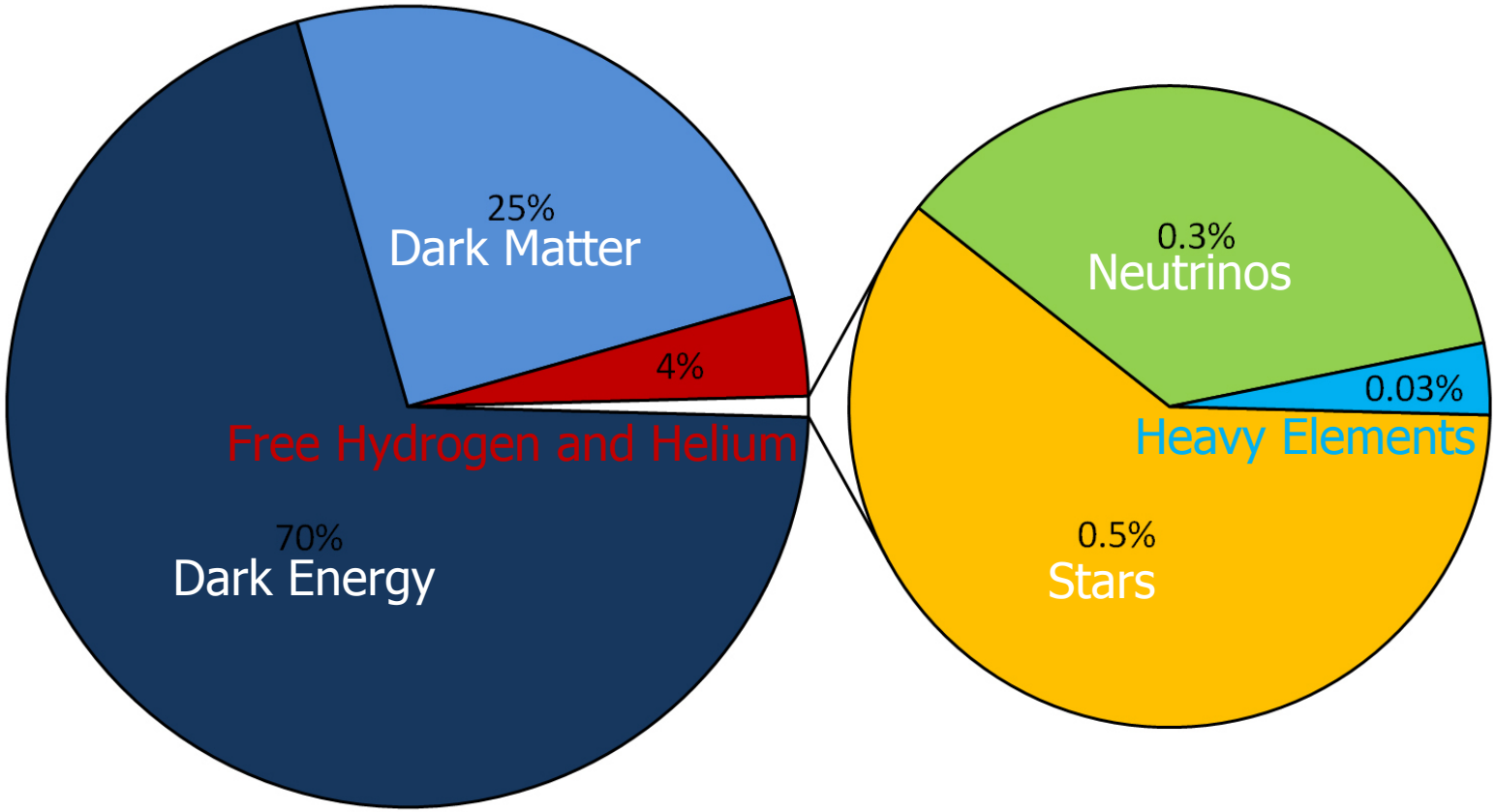
Internal symmetries

- Gauge symmetries: $SU(3)_{\text{QCD}} \times SU(2)_L \times U(1)_Y$
- Global symmetries: isospin, baryon number, lepton number...

Going beyond the Standard Model

Standard Model open questions:

- neutrino masses
- matter-antimatter imbalance
- nature of Dark Matter
- on the theoretical side: mass hierarchy problem



Extending the symmetry

Supersymmetry is the only possible extension of Poincare algebra

New symmetry relating fermions and bosons

$$Q\,|fermion\rangle = |boson\rangle \qquad Q\,|boson\rangle = |fermion\rangle$$

Representation of SUSY are "multiplets" of particles with:

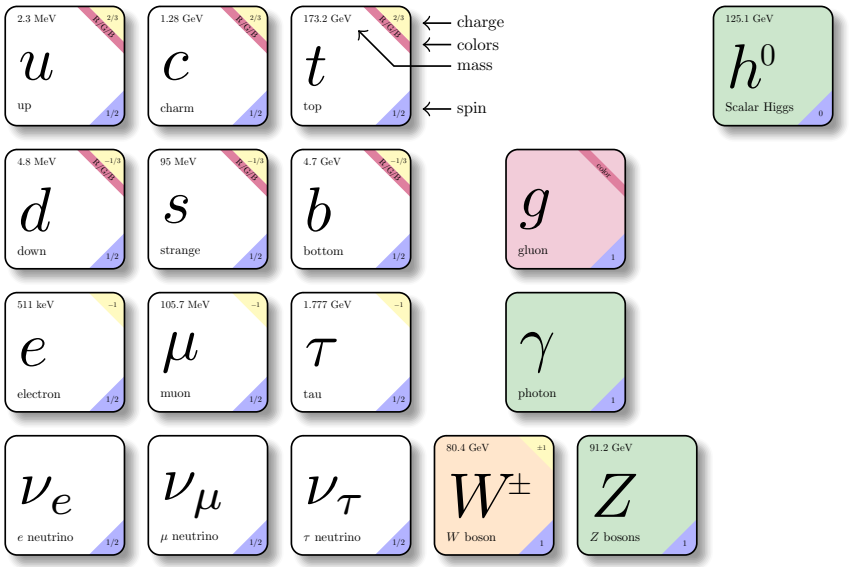
- Different spin
- Same mass
- Same quantum numbers

$\rightarrow$ we can't create those multiplets with particles available in the SM

Double the SM particle content!

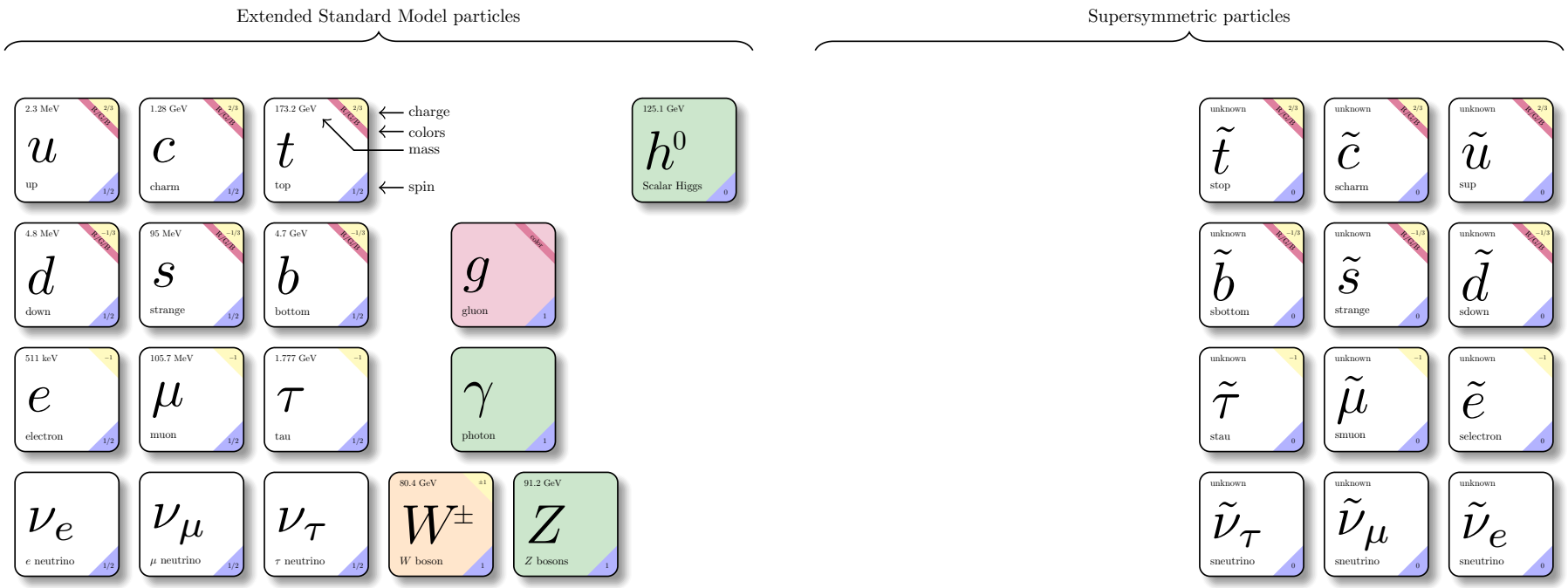
Supersymmetric particles

Extended Standard Model particles



Supersymmetric particles

Supersymmetric particles



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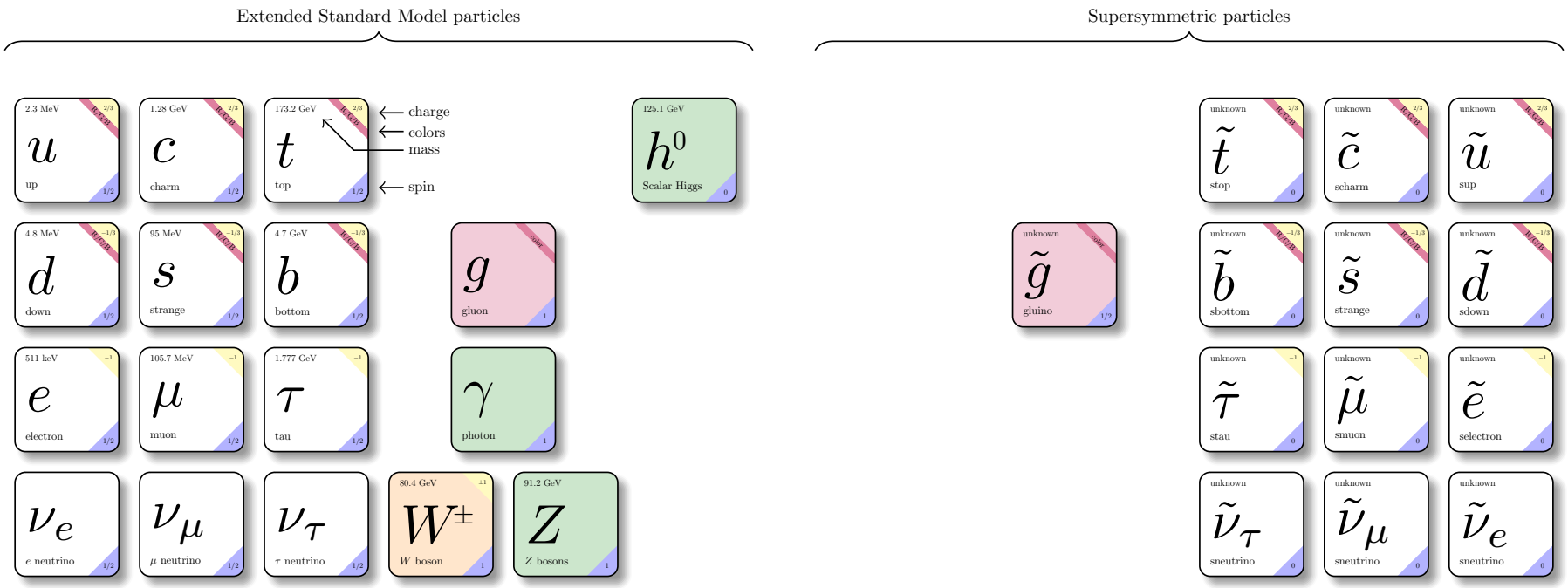

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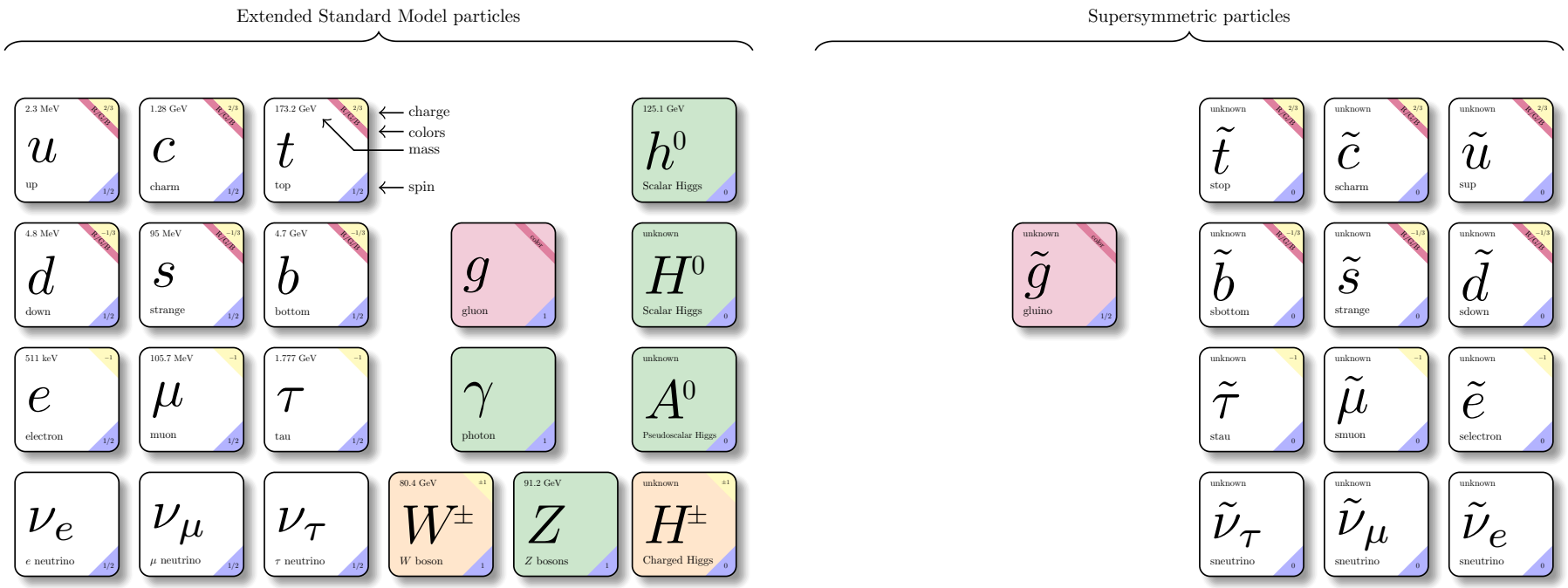

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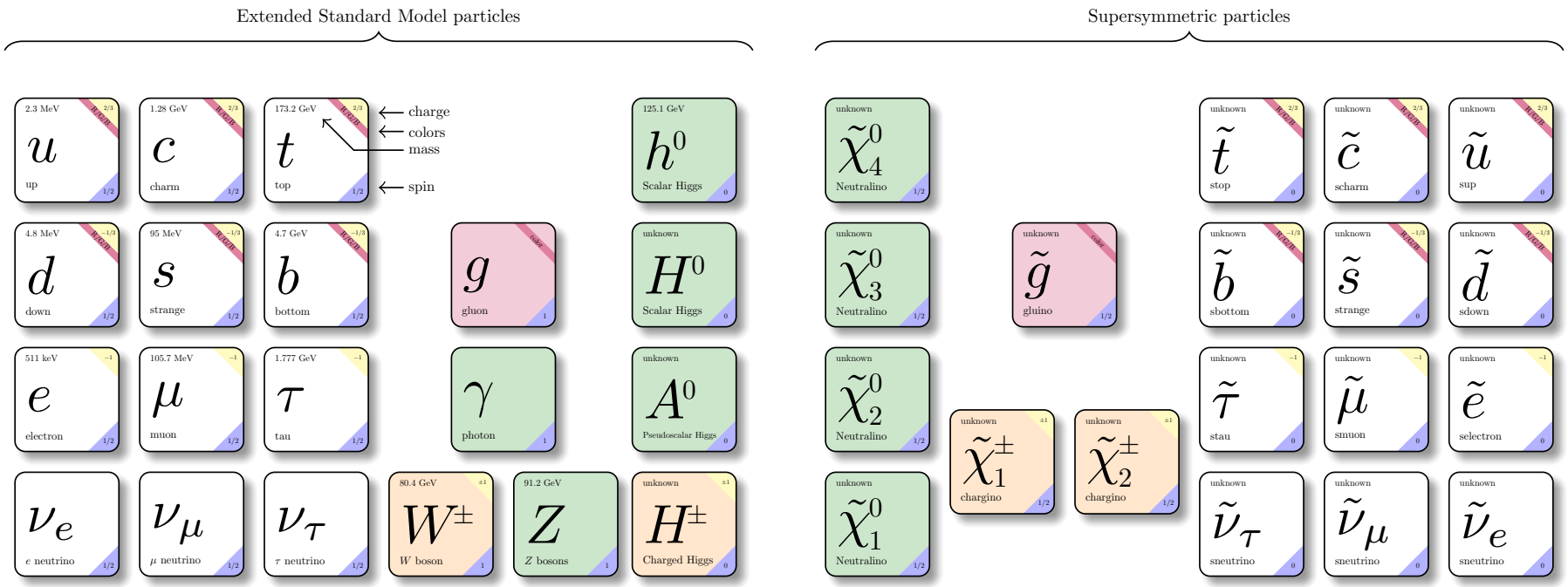

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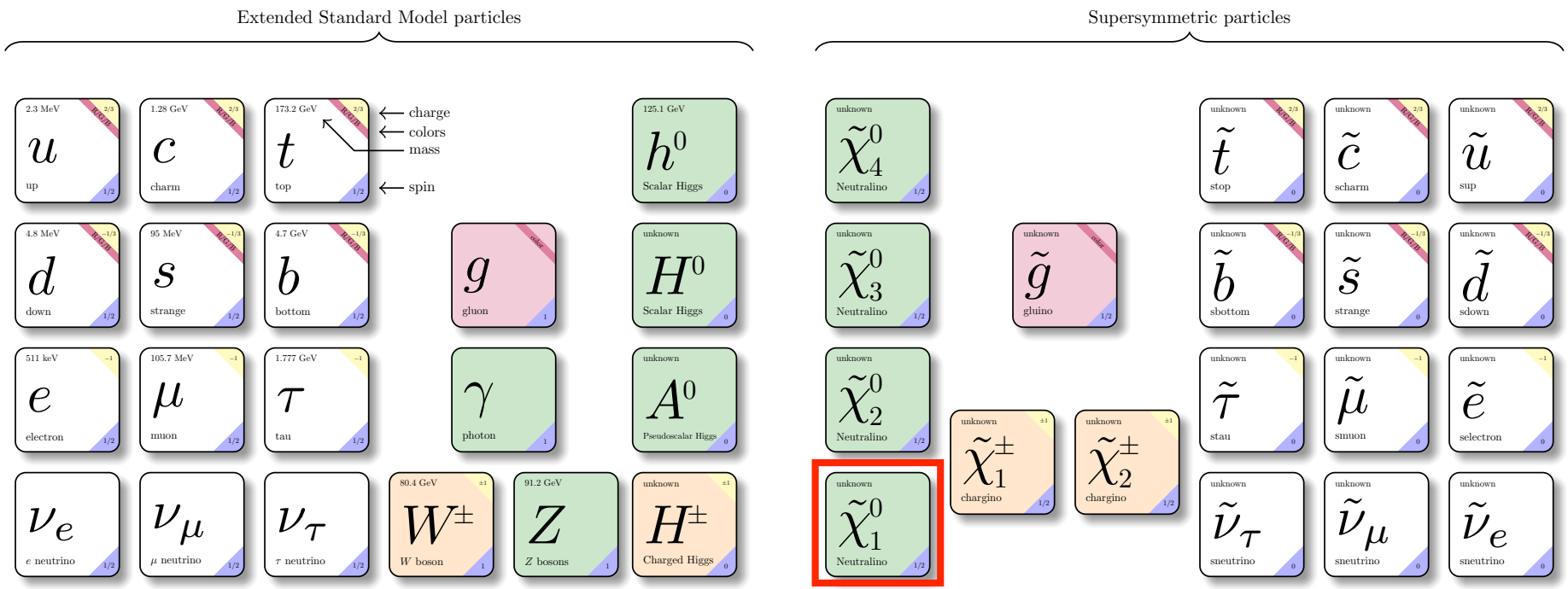

Heavy, stable and weakly interacting, good DM candidate!

SUSY and naturalness

$$m_H^2 \approx m_{H0}^2 - \frac{|\lambda_f|^2}{8\pi^2}\Lambda^2 + \dots$$

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If SM up to the Planck scale,

↓

correction term of the order of $(10^{19}\text{GeV})^2$

↓

the bare term has to be equally as big to result in the experimentally measured value

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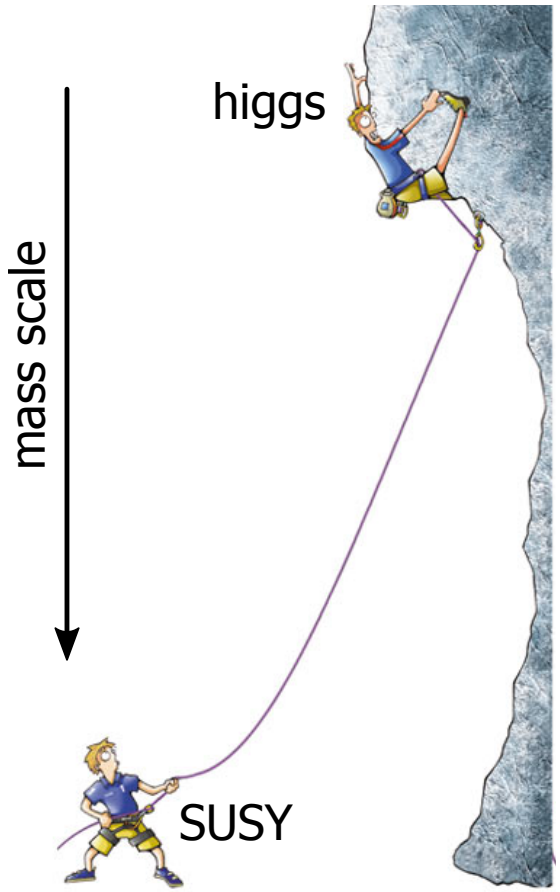
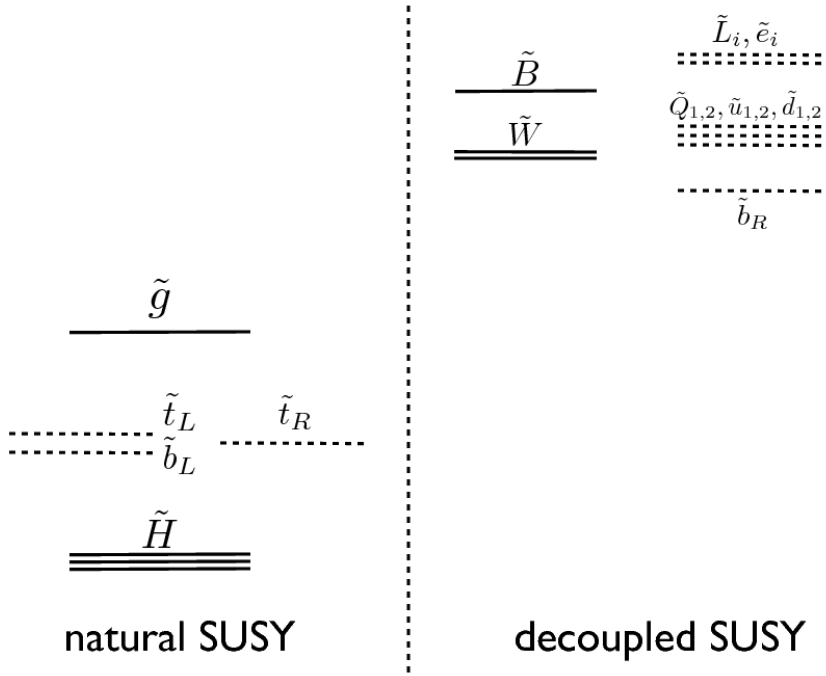


SUSY can balance the SM corrections and reduce the level of fine-tuning

SUSY mass spectrum

We haven't seen these particles yet $\rightarrow$ the symmetry must be broken!

Minimising the fine-tuning, constraints the mass spectrum



The LHC, with its high energy, is the perfect place where to search

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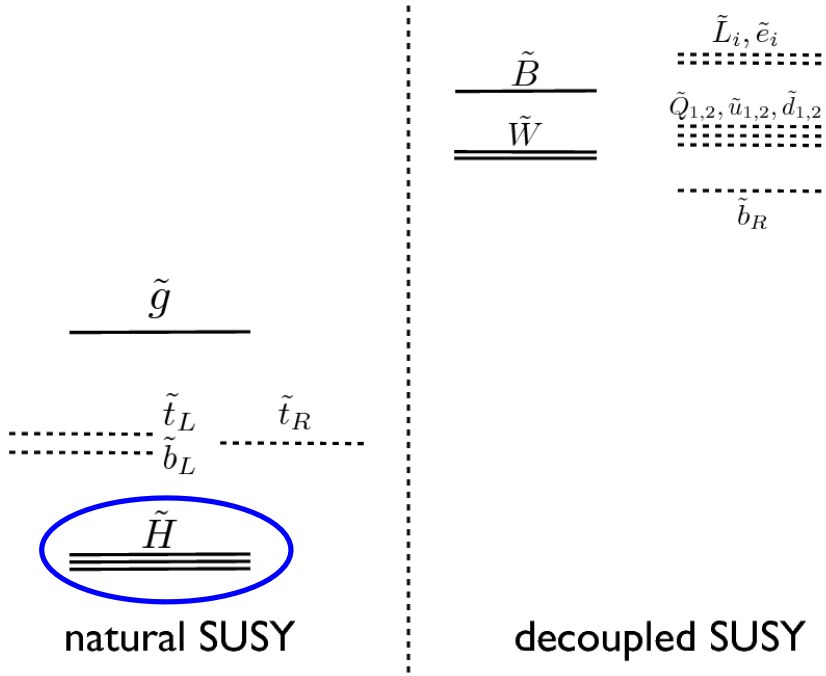
- m_h includes higgsinos term at tree level



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SUSY mass spectrum

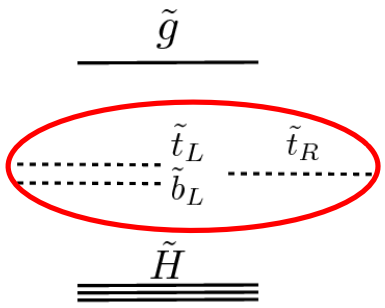
We haven't seen these particles yet $\rightarrow$ the symmetry must be broken!

Minimising the fine-tuning, constraints the mass spectrum

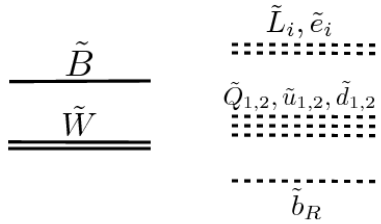
- m_h includes higgsinos term at tree level
- largest 1-loop contribution arising from top and stops

$\downarrow$

main focus of today's lecture



natural SUSY



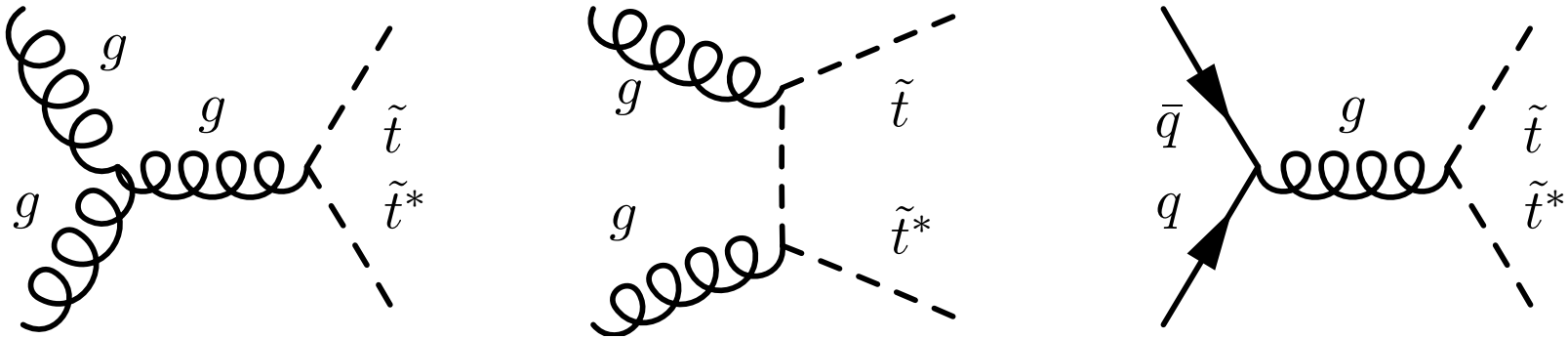
decoupled SUSY

The LHC, with its high energy, is the perfect place where to search

SUSY production at the LHC

Direct production's diagrams can be derived by the SM ones, replacing two particle lines with the respective SUSY partners

Example: stop pair production



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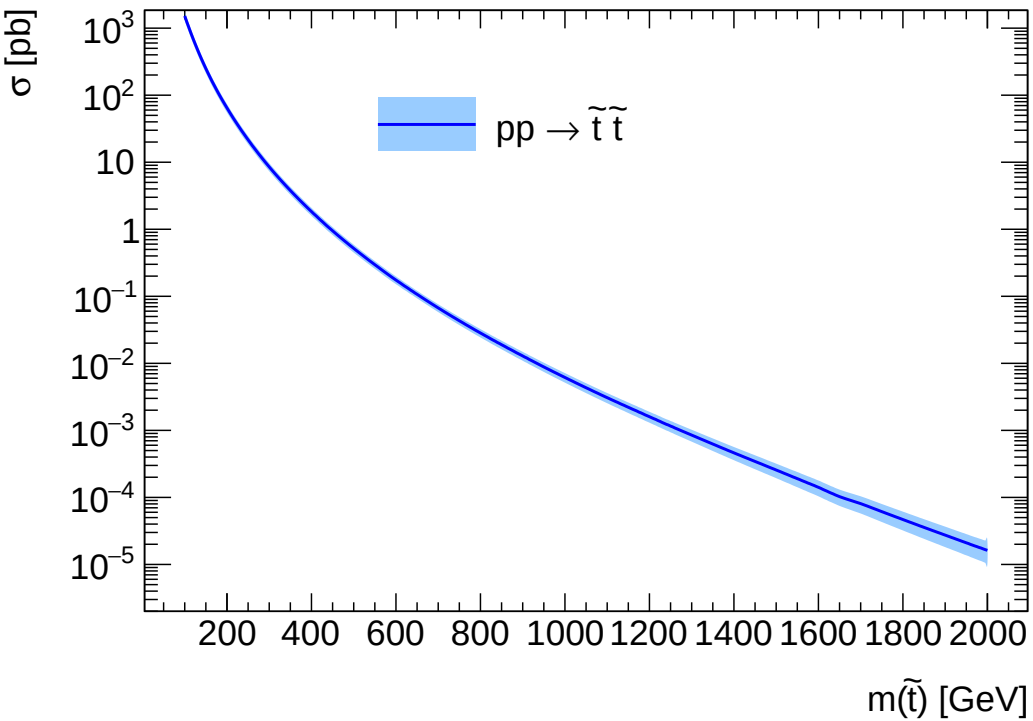
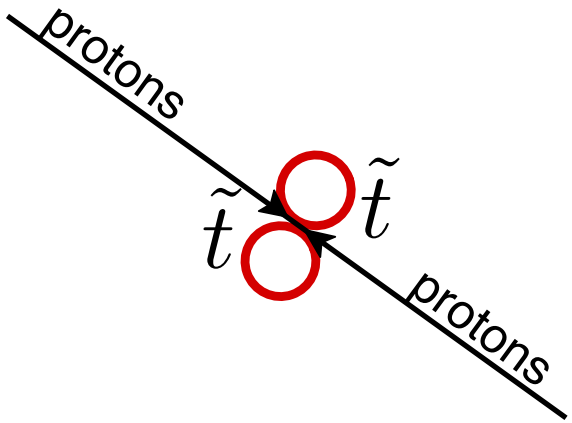


The cross-section depends on the top squark mass

SUSY production at the LHC

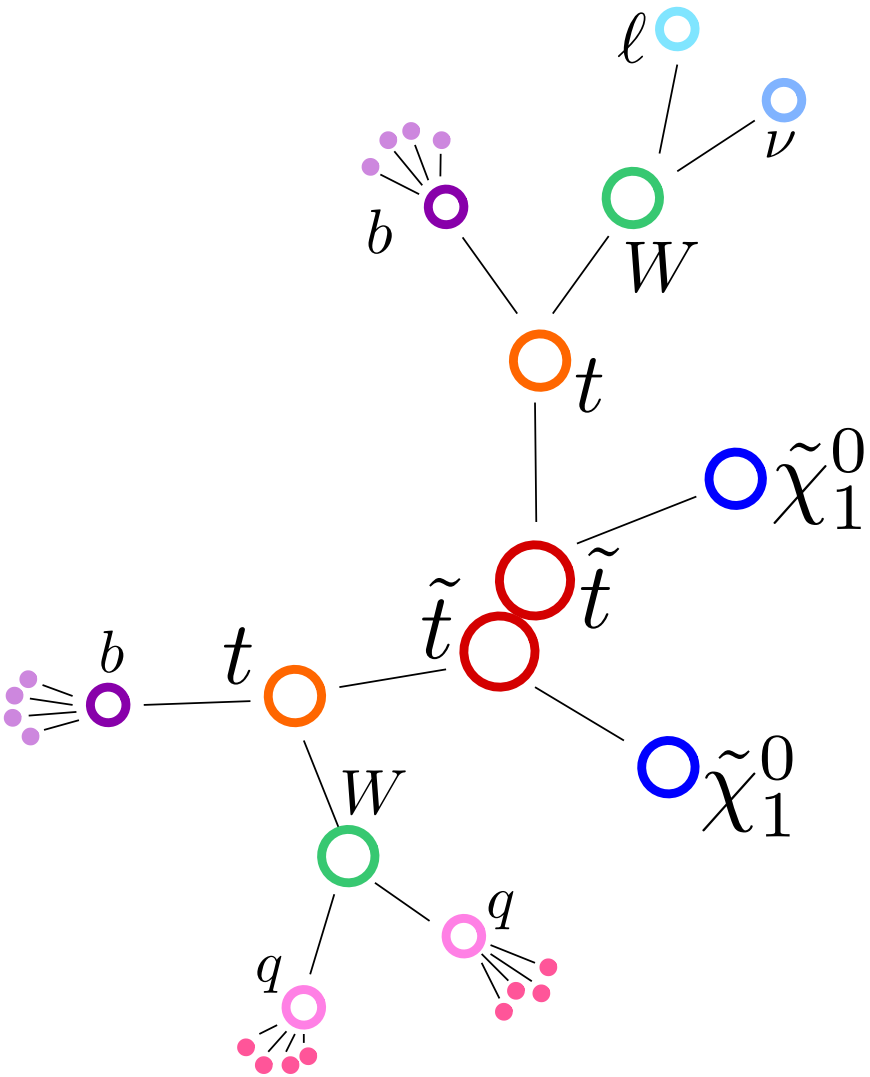


In models were the top squark is not the LSP it decays promptly

creating SM bosons, leptons and quarks, and other SUSY particles

Detectors like ATLAS and CMS are used for the identification of these particles

SUSY production at the LHC



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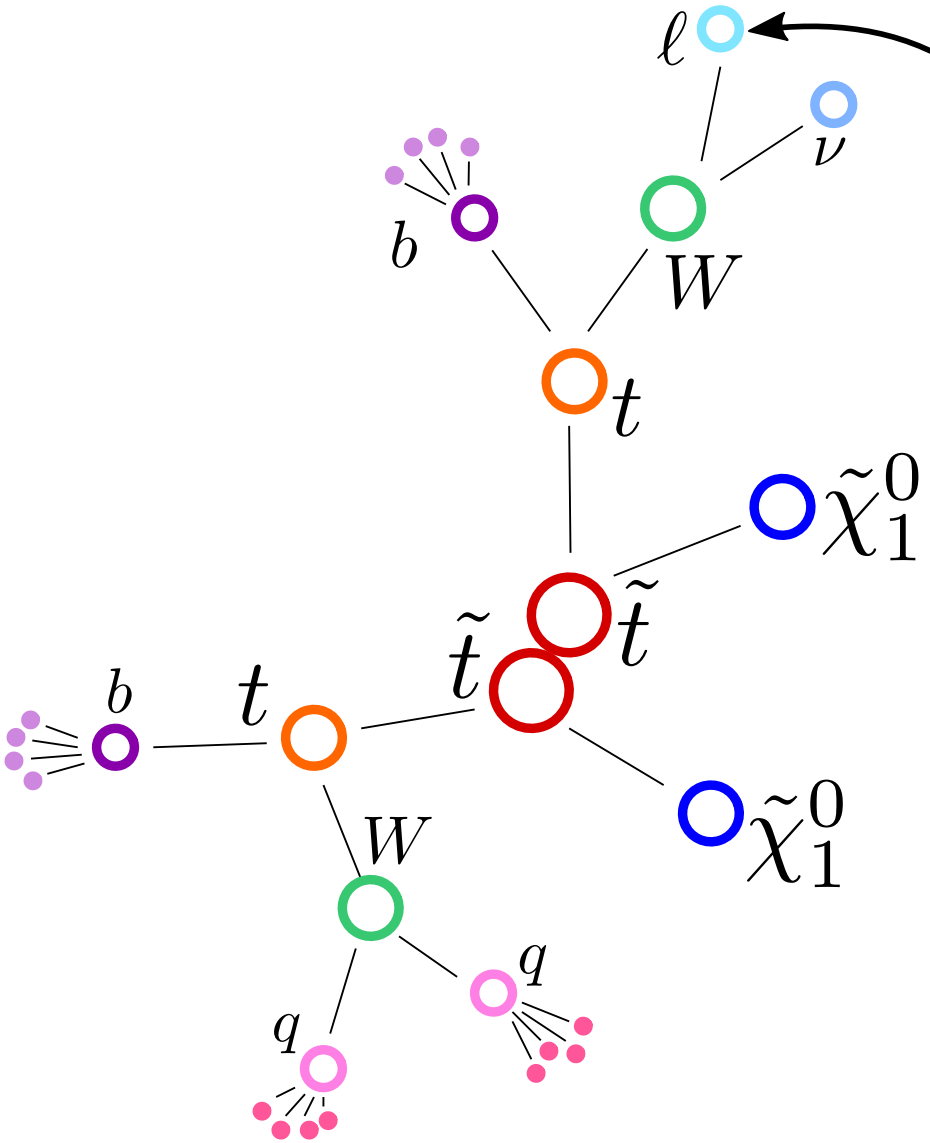
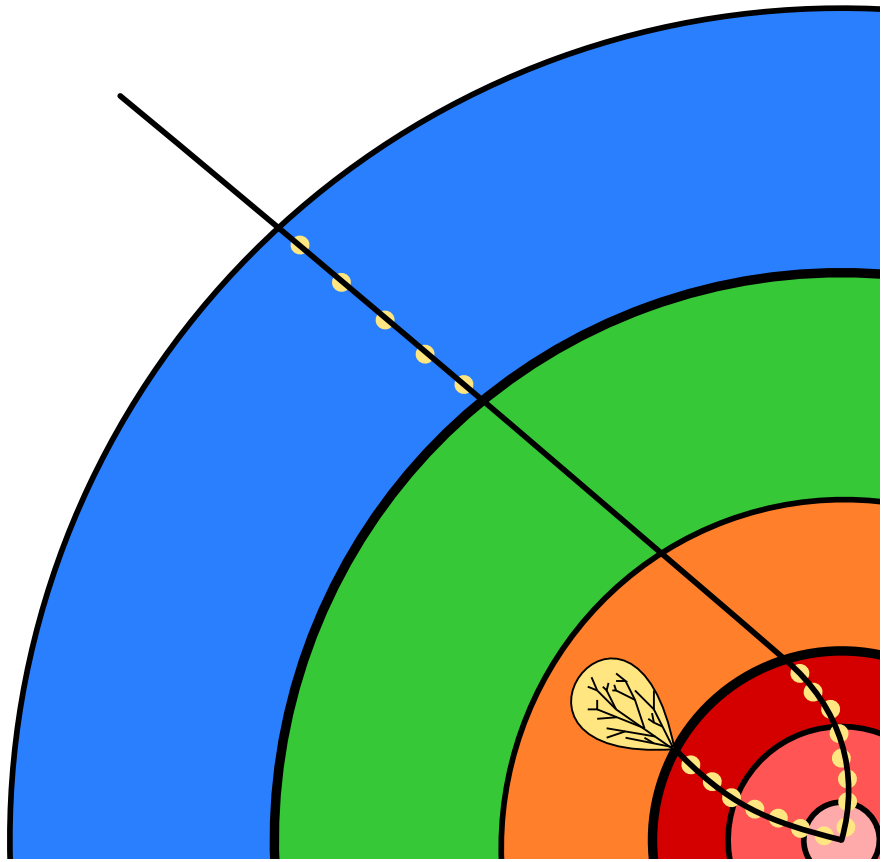
The top squark in the ATLAS detector



Electrons and muons

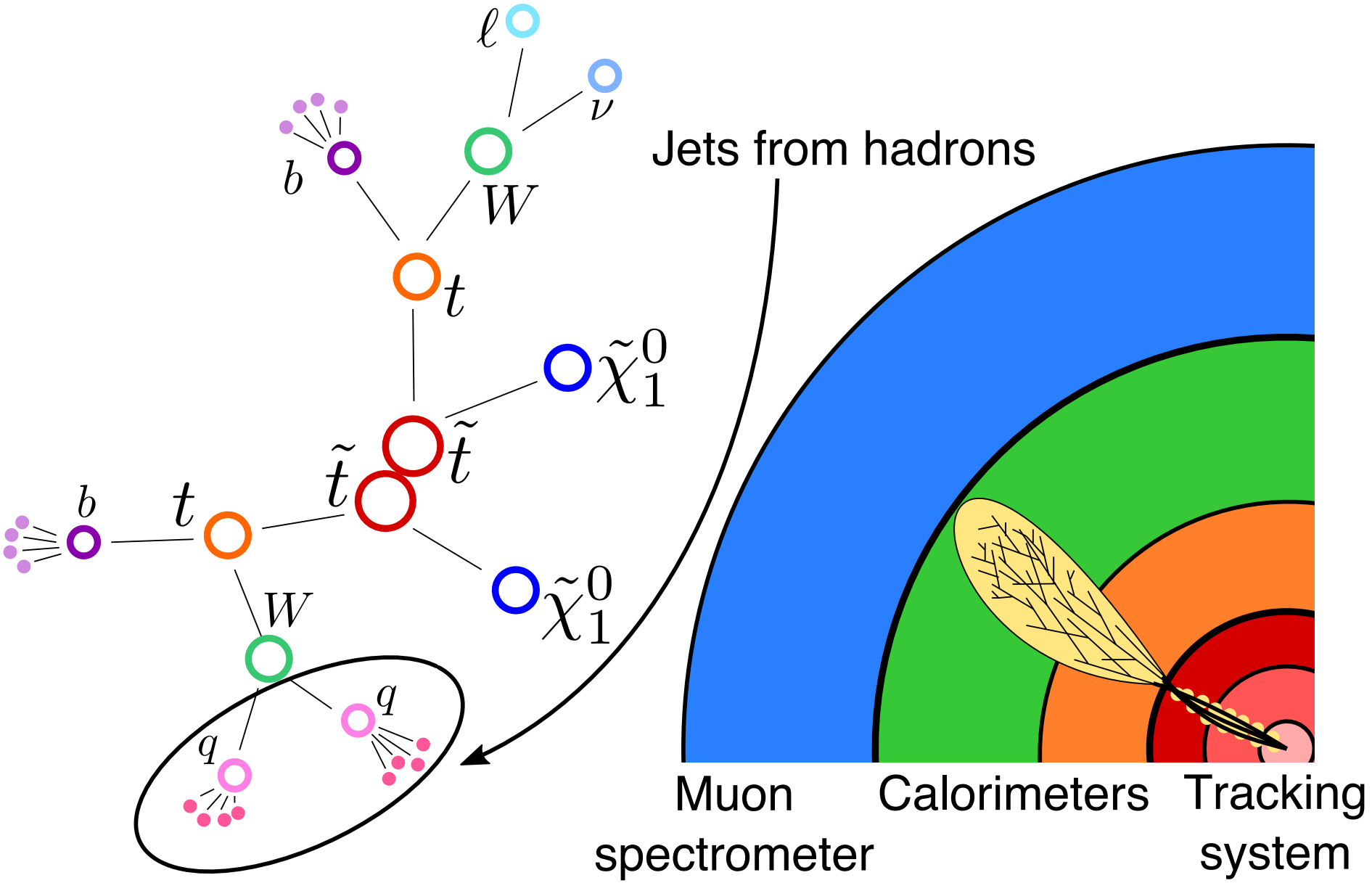


Muon spectrometer

Calorimeters

Tracking system

The top squark in the ATLAS detector



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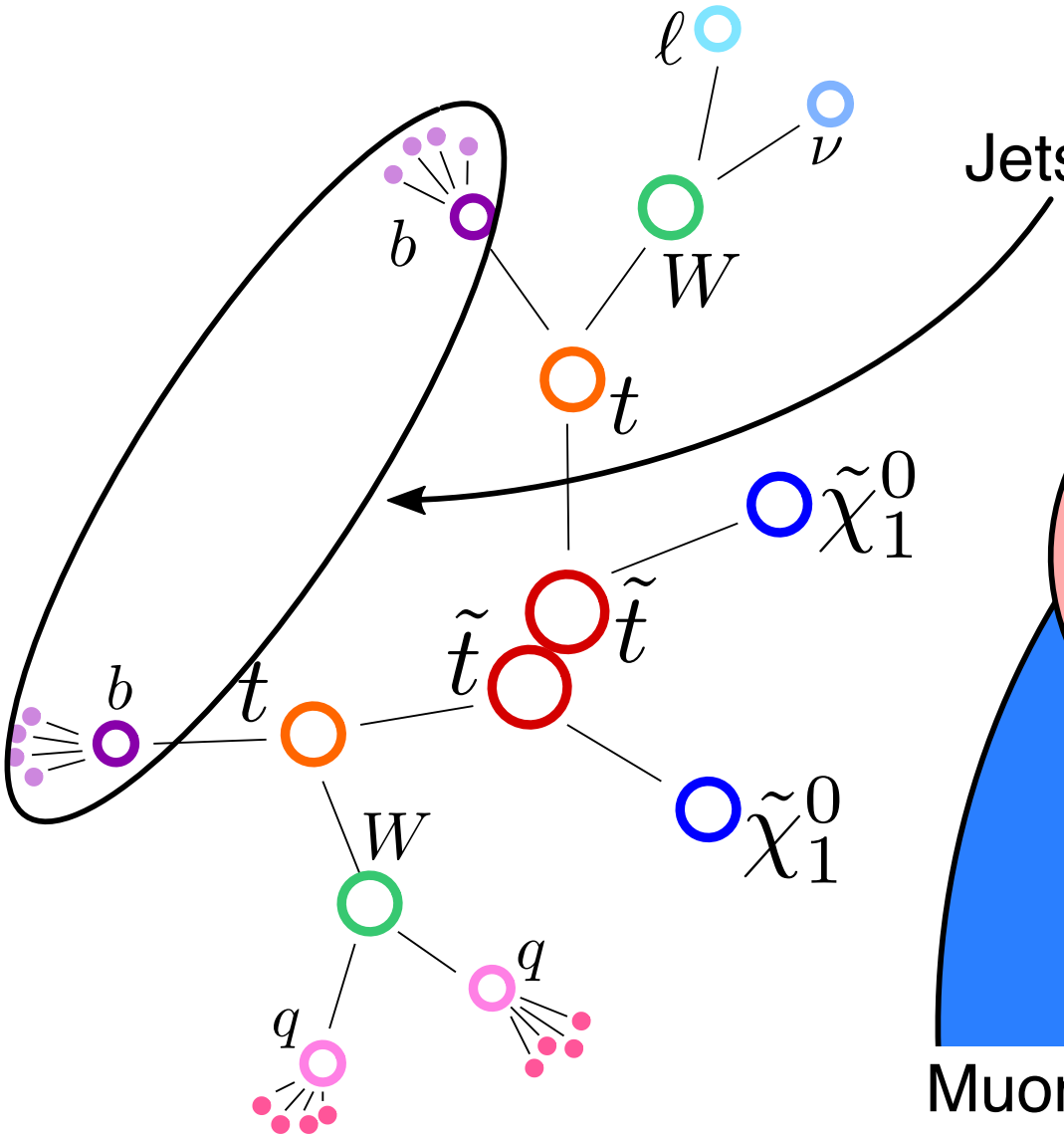

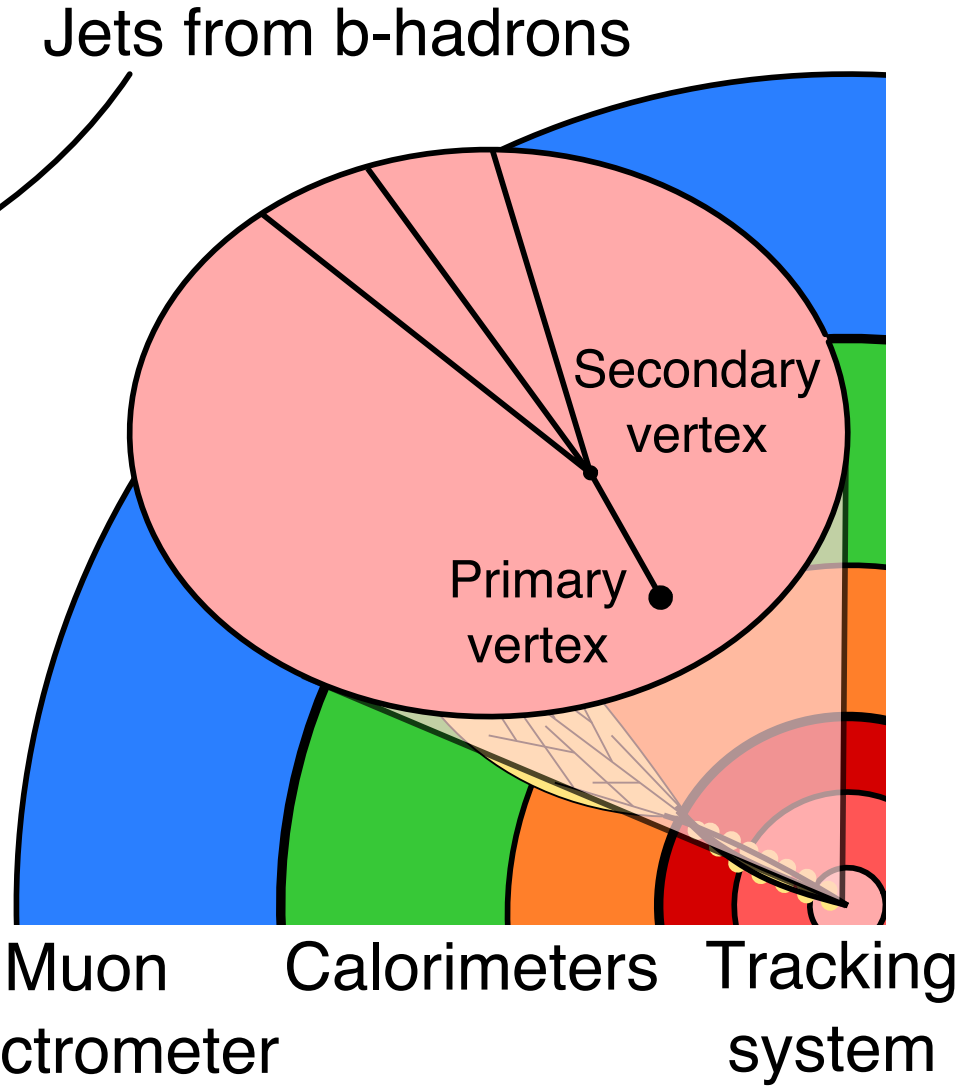

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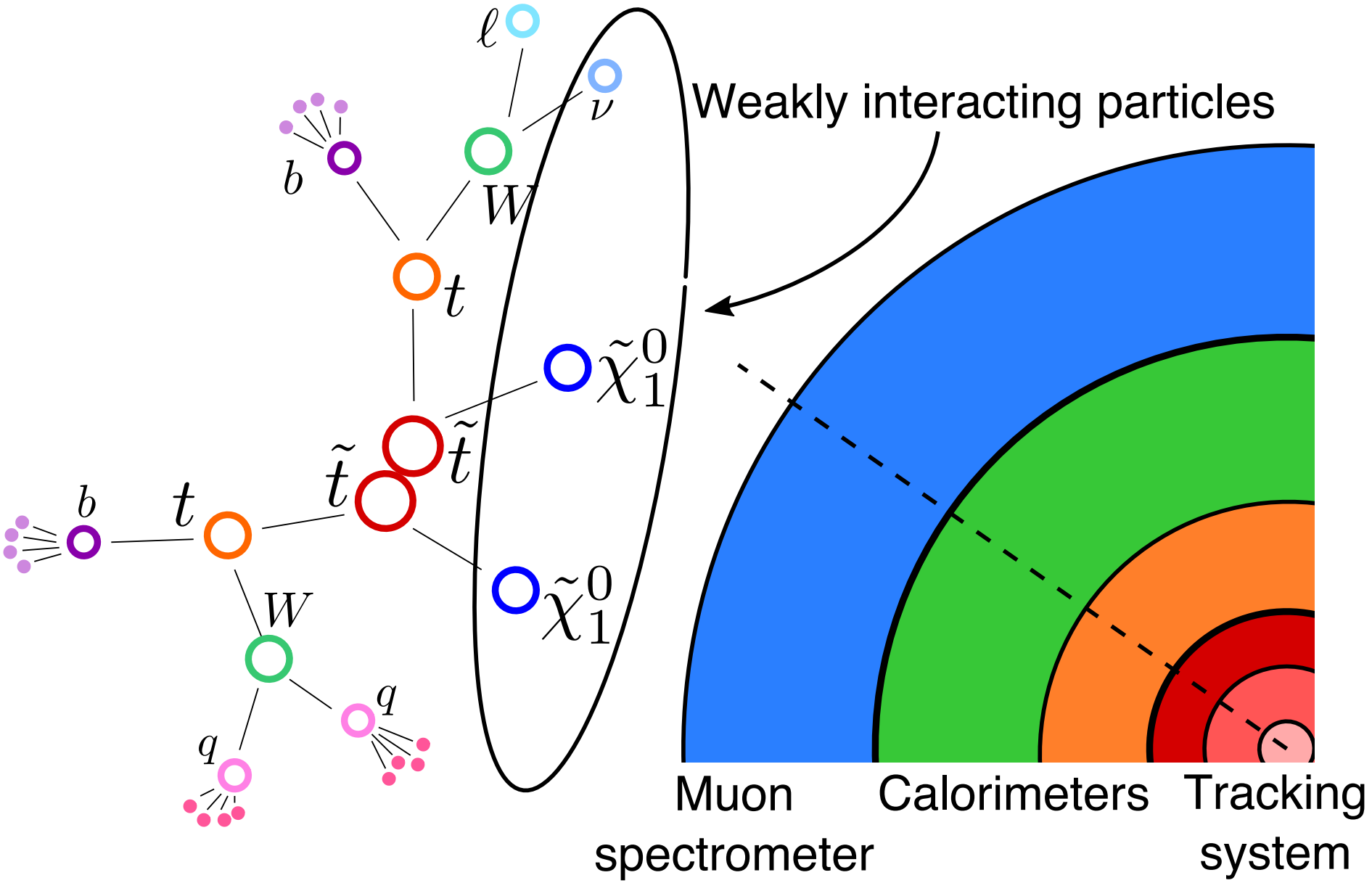

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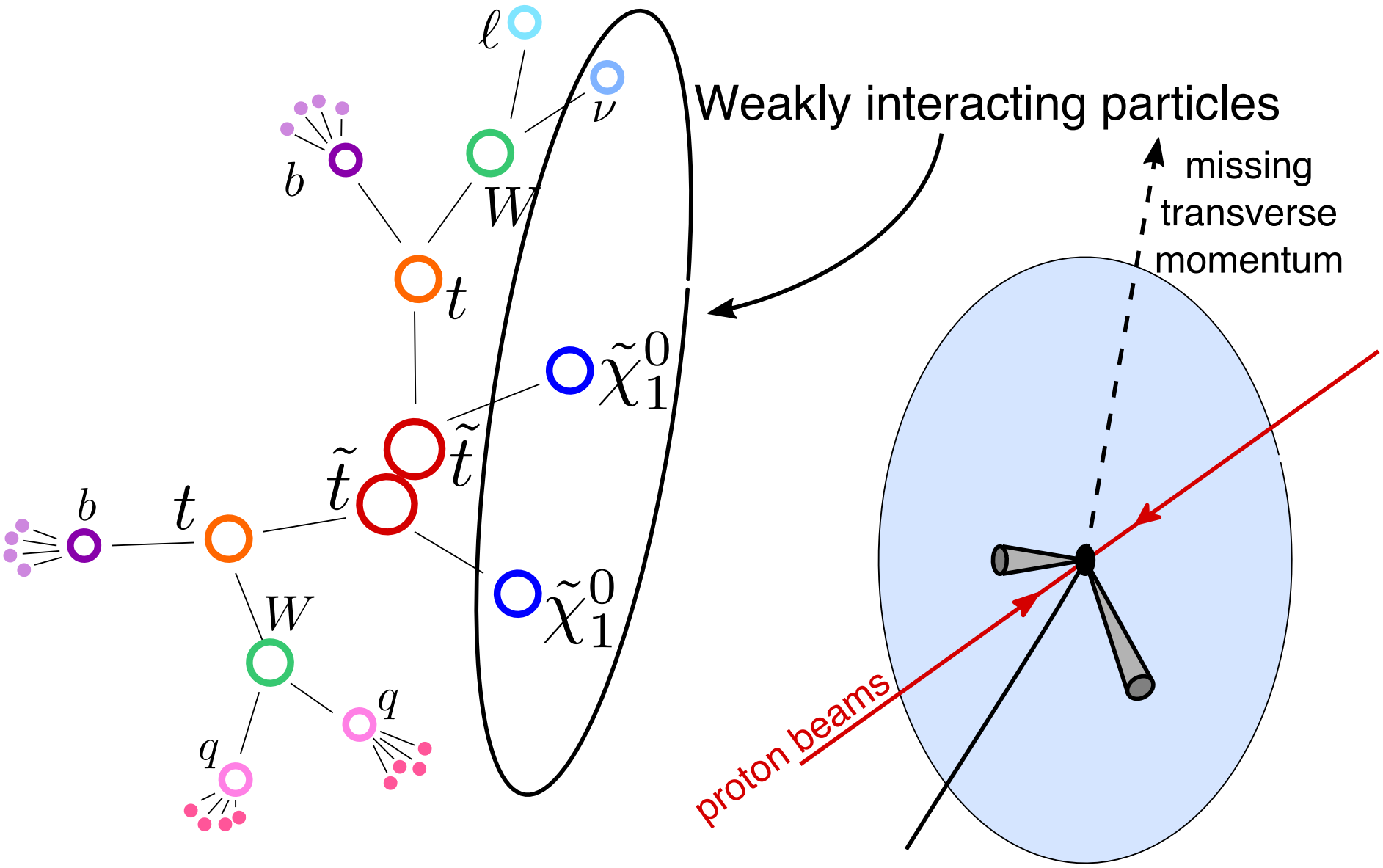
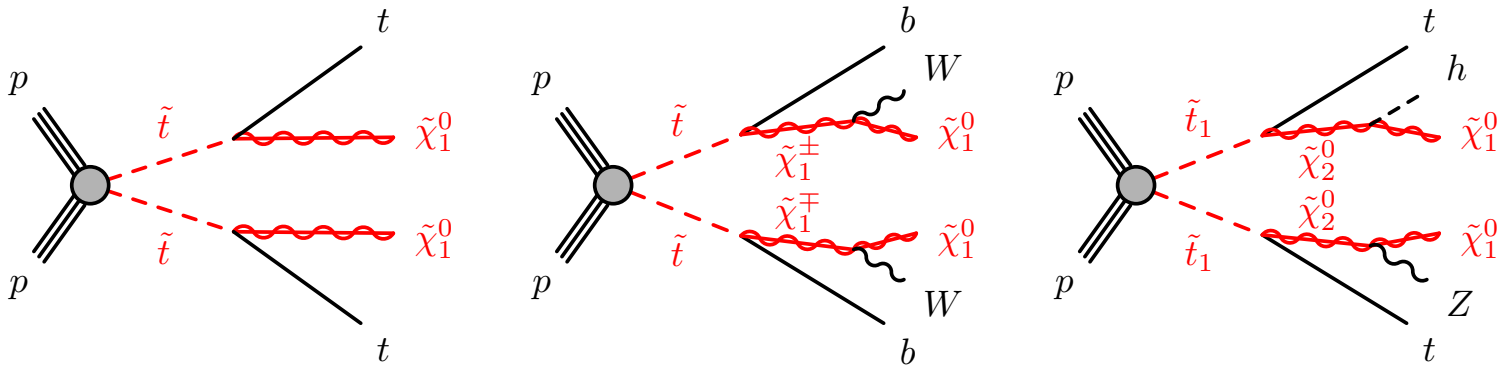


Stop decay modes

Possible stop decay modes depend on the SUSY mass spectrum



+ more...

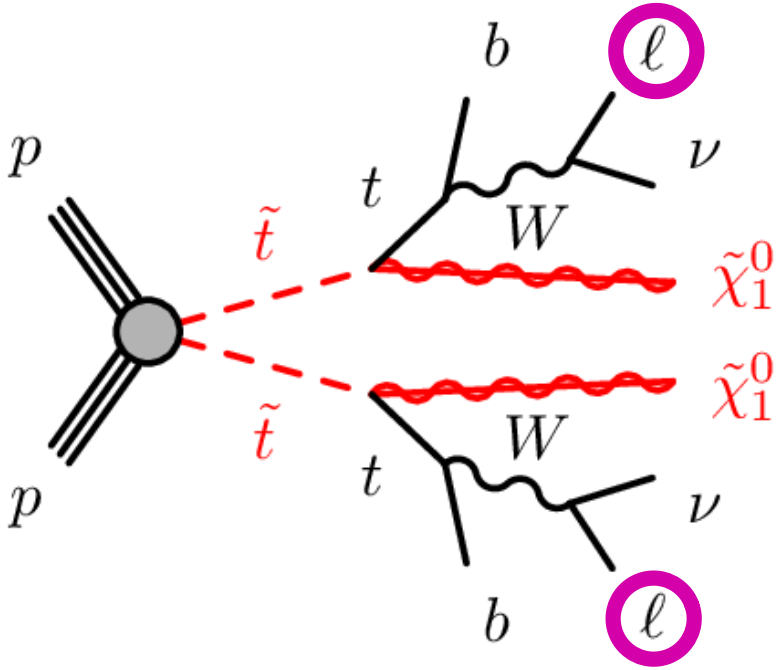
increasingly complex final states $\longrightarrow$

Searches are guided by simplified models

- fixed number of sparticles considered
- fixed branching fractions
- scan of the mass values

$\rightarrow$ reduced number of parameter
good guess of what could show up in the detector

2 leptons channel



Final state with:

- 2 leptons
- at least one b-jet (why just one?)
- large $E_{\mathrm{T}}^{\mathrm{miss}}$

How to isolate the signal

Major SM backgrounds with similar final state?

How to isolate the signal

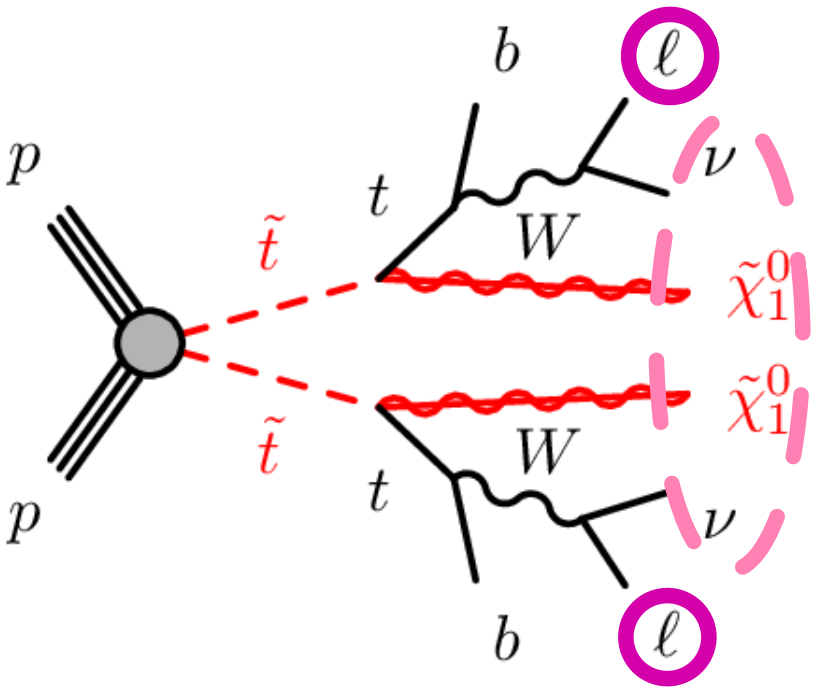
Major SM backgrounds with similar final state?

- $t\bar{t}$ pair production
- diboson production, such as WW and WZ
- $t\bar{t}$ production in association with Z boson

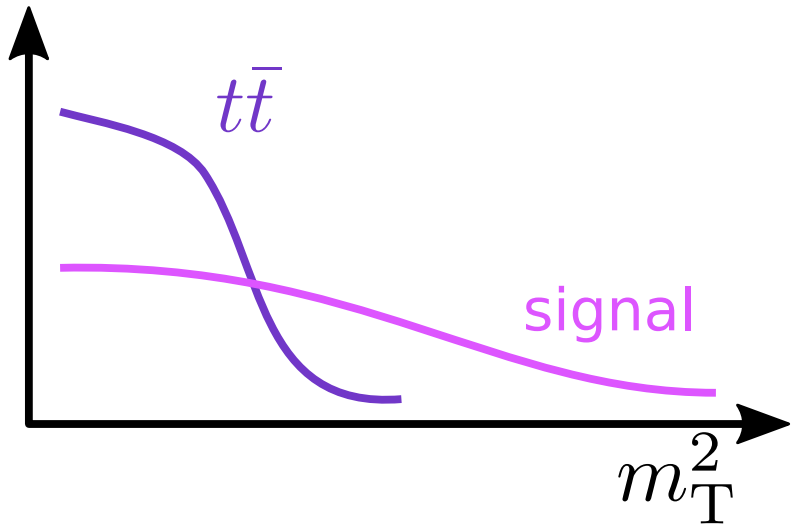
2 leptons channel

Main discriminating variable:

$$m_{\mathrm{T2}}(\boldsymbol{p}_{\mathrm{T}}^{\alpha}, \boldsymbol{p}_{T}^{\beta}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}) = \min_{\boldsymbol{q}_{\mathrm{T}}^{1}+\boldsymbol{q}_{\mathrm{T}}^{2}=\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}} \max(m_{\mathrm{T}}^{2}(\boldsymbol{p}_{\mathrm{T}}^{\alpha}, \boldsymbol{q}_{\mathrm{T}}^{1}), m_{\mathrm{T}}^{2}(\boldsymbol{p}_{\mathrm{T}}^{\beta}, \boldsymbol{q}_{T}^{2}))$$



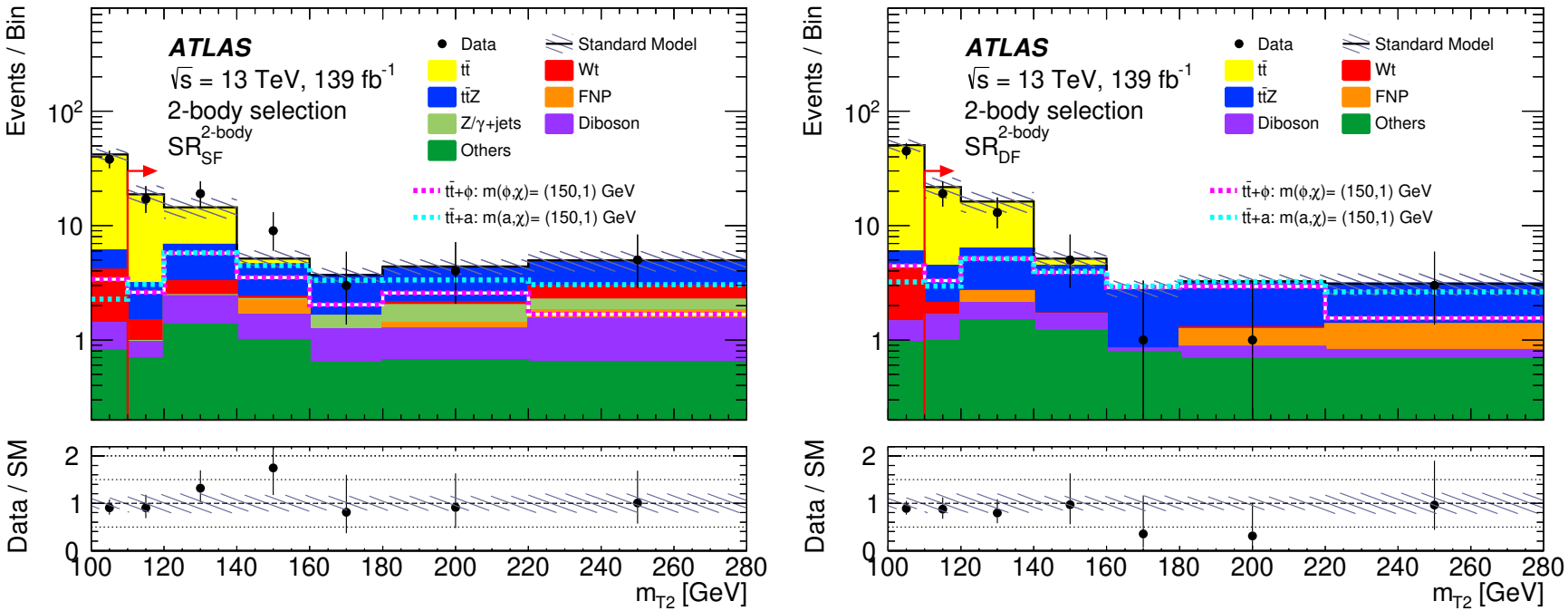
used to bound the masses of a pair of particles which both decay into a visible and an invisible particle



$\rightarrow$ after m_{T2} cut, $t\bar{t}Z$ becomes dominant bkg for this search

2 leptons channel

Example of Signal Region for ATLAS search

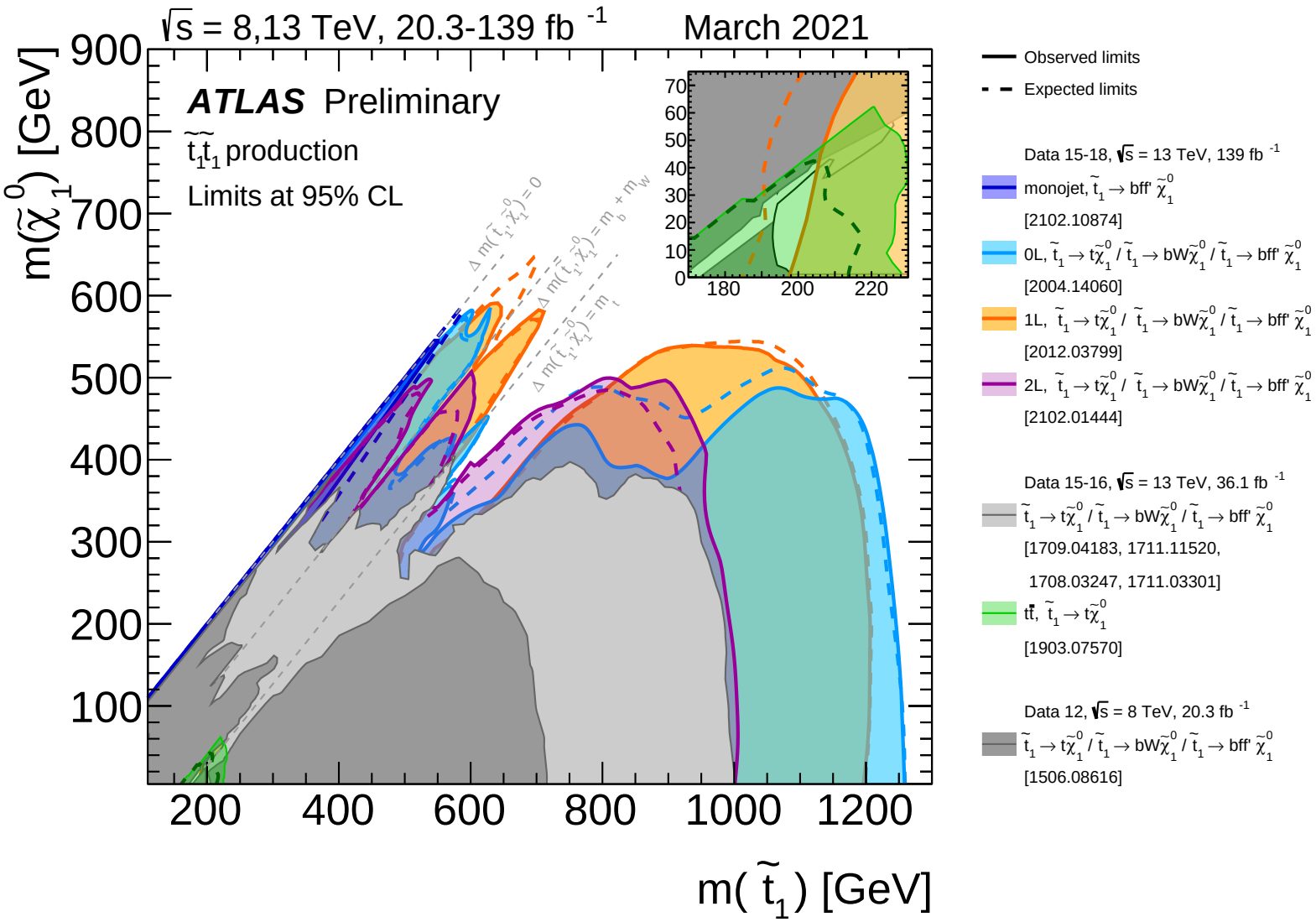


Very good agreement found with the SM predictions :(

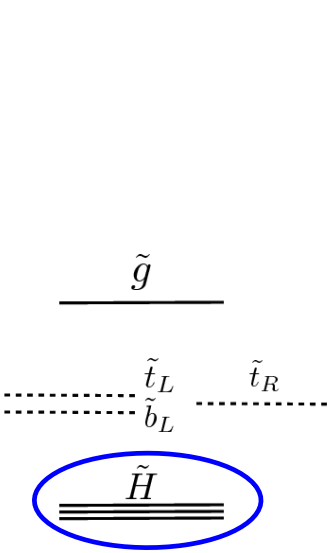
$\rightarrow$ signal models under test excluded

Looking for top squarks with ATLAS data

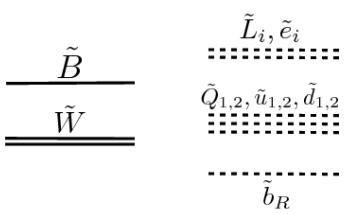
Many analysis looking at different final states



More challenging signatures



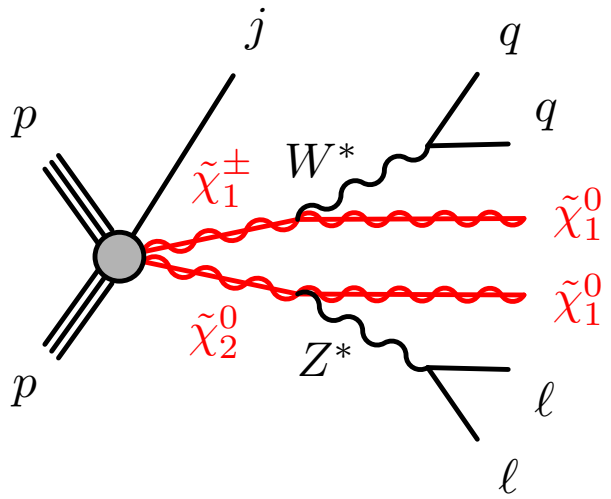
natural SUSY



decoupled SUSY

Light states higgsinos:

- electroweakinos very close in mass $\rightarrow$ chargino nearly mass degenerate with the neutralino
- very low cross-sections



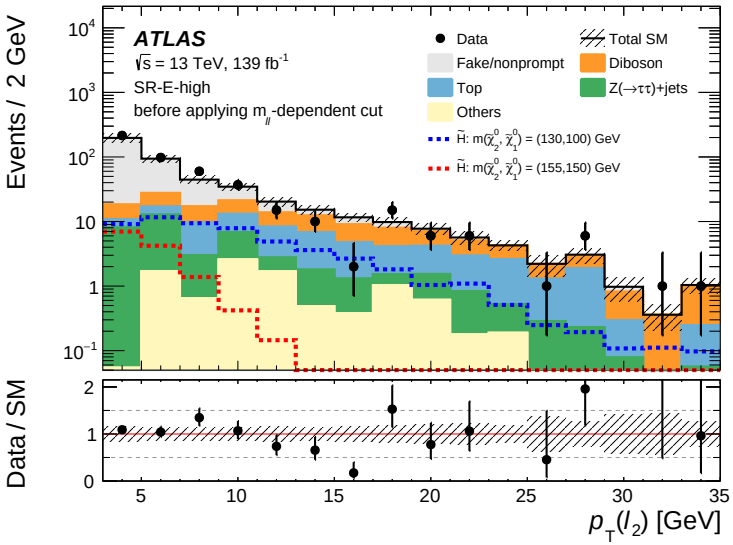
How to trigger?

LHC collides protons every 25ns
$\rightarrow$ we can afford to save events at a average rate of 1kHz

- two level of algorithms running at hardware and software level to select events with interesting features
- several searches relay on leptons triggers
- in our case few GeV of mass gap between SUSY particles, not reconstructed by trigger algorithms!

Solution: triggering on missing energy!

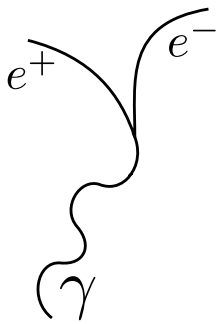
Soft leptons

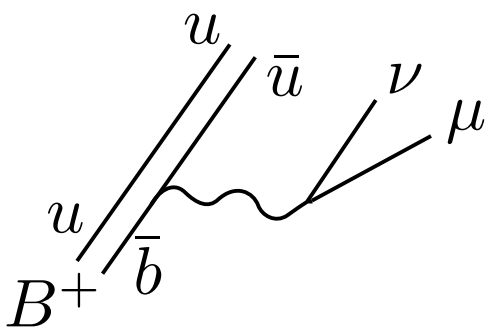


- dedicated reconstruction optimised for low energy electrons and muons
- relevant background arising from detector measmeasurement!

Background arising from events with at least one "fake" lepton:

- misidentified hadrons
- photon conversions
- leptons coming from hadronic decays

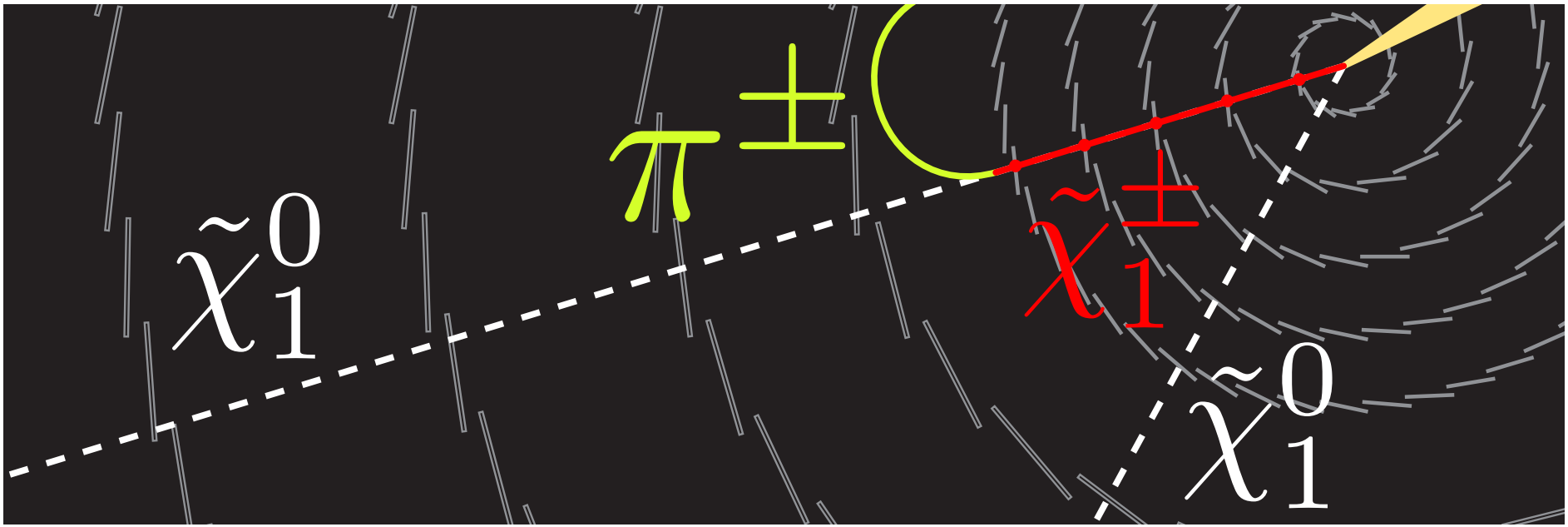




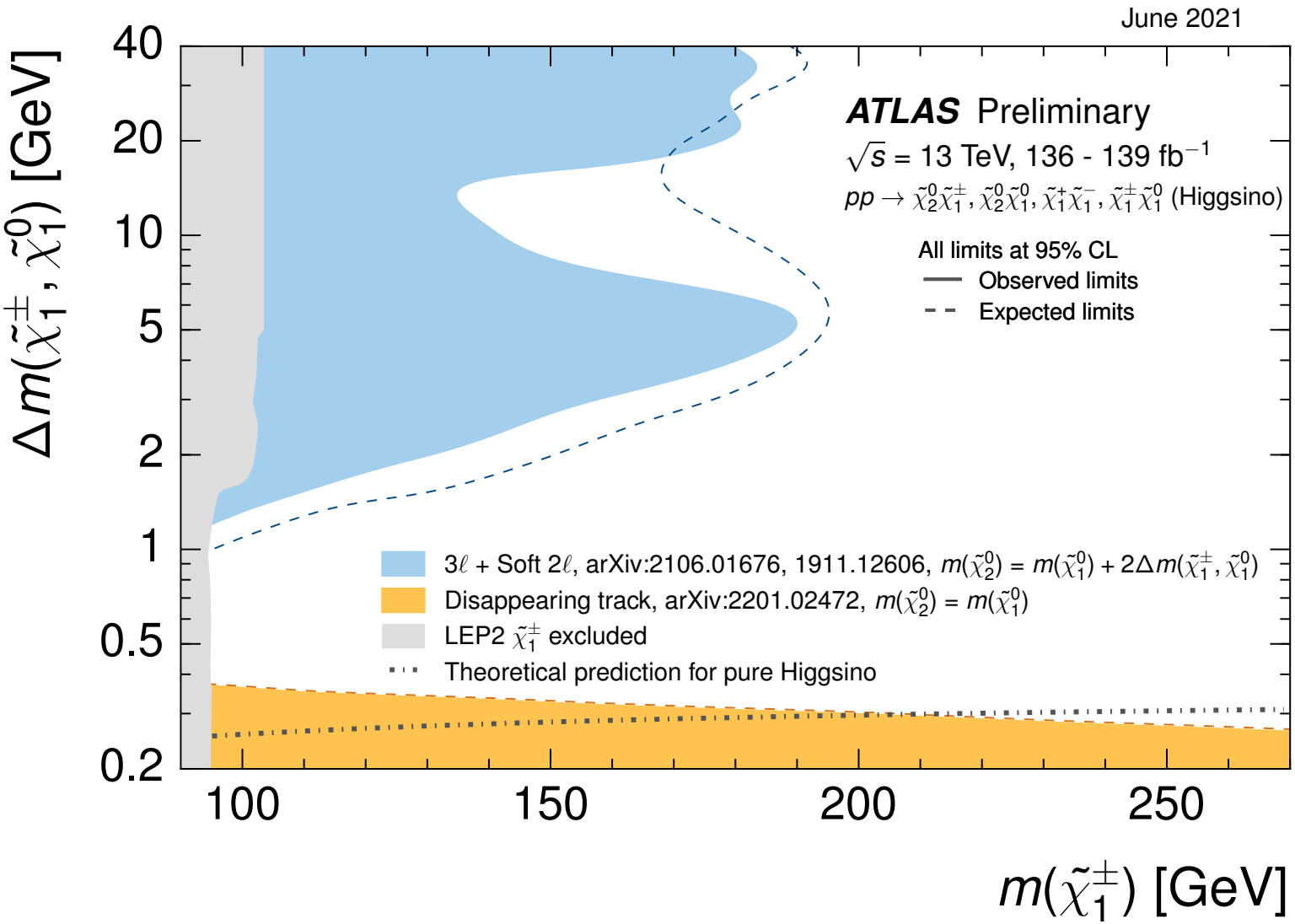
Disappearing tracks

Even more compressed spectra!

- long life-time
- chargino decays inside the ITk $\rightarrow$ very short visible track
- invisible decay products



Filling the gaps



Conclusions

Continuous effort to search for new particle at colliders

- the SM as it is needs to be extended to explain all our observations
- SUSY is still considered one of the most promising way to do so
- results from the first years of LHC data constrain several models
- but the phenomenology is very diverse
  $\rightarrow$ still many unexplored areas of parameter space

Backup slides

pMSSM

Parameters	Description
M_1, M_2, M_3	gaugino masses
$\tan\beta$	ratio of the VEVs of the two Higgs doublets
M_A	pseudoscalar Higgs boson mass
μ	higgsino mass
A_t, A_b, A_τ	trlinear couplings for third generation sfermions
$m_{\tilde{q}L}$, $m_{\tilde{u}R}$, $m_{\tilde{d}R}$, $m_{\tilde{\ell}L}$, $m_{\tilde{e}-\tilde{\mu}R}$	first and second generation sfermion masses
$m_{\tilde{q}3L}$, $m_{\tilde{t}R}$, $m_{\tilde{b}R}$, $m_{\tilde{\ell}3L}$, $m_{\tilde{\tau}R}$	third generation sfermion masses