SUSY RPV Multi-jet Search

Chiara

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3. Without the assumption of R-parity conservation (R-parity violation)

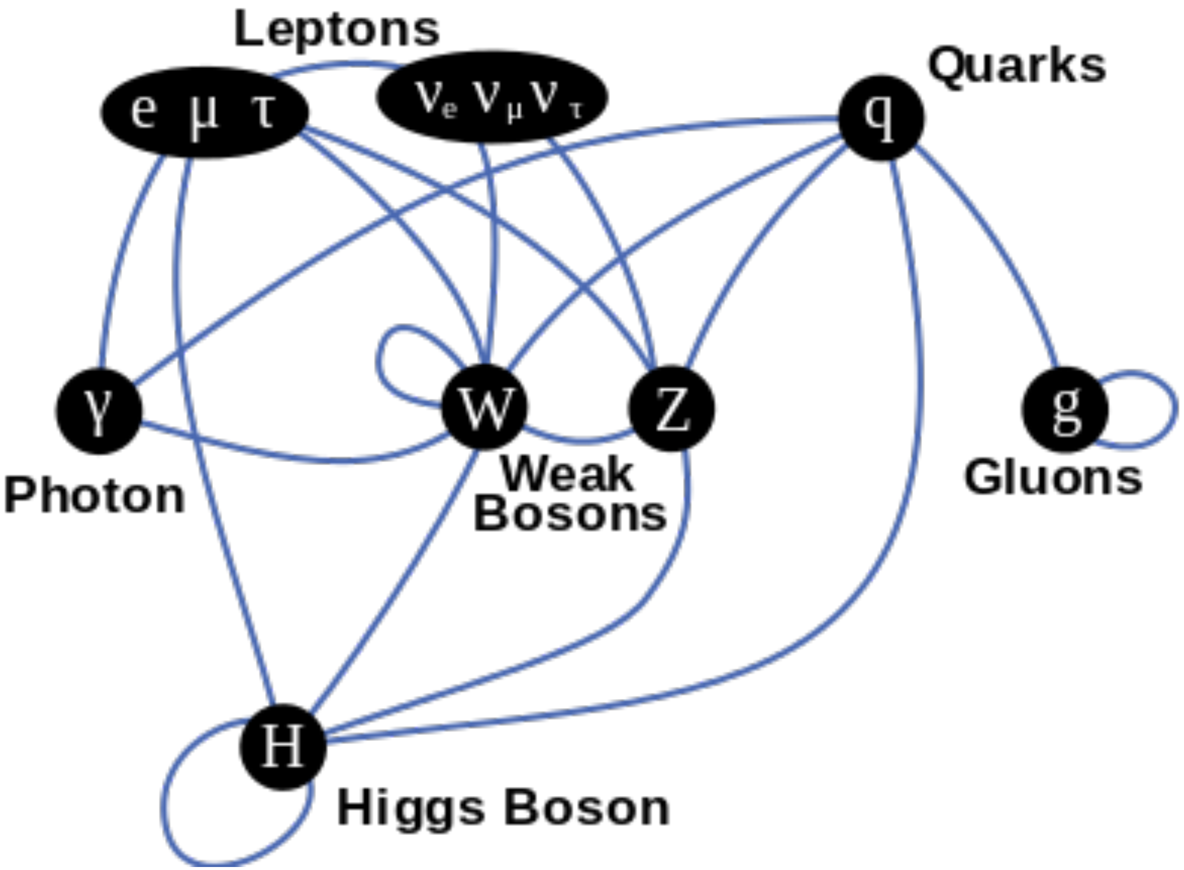
SUSY RPV Multi-jet Search

1. Search (we are looking for new phenomena)
2. For Supersymmetry
3. Without the assumption of R-parity conservation
4. In final states with several hadronic jets

Why Doing Searches?

Standard Model of Particle Physics

- Describes the interaction between all known elementary particles
- Verified to a high-level of accuracy



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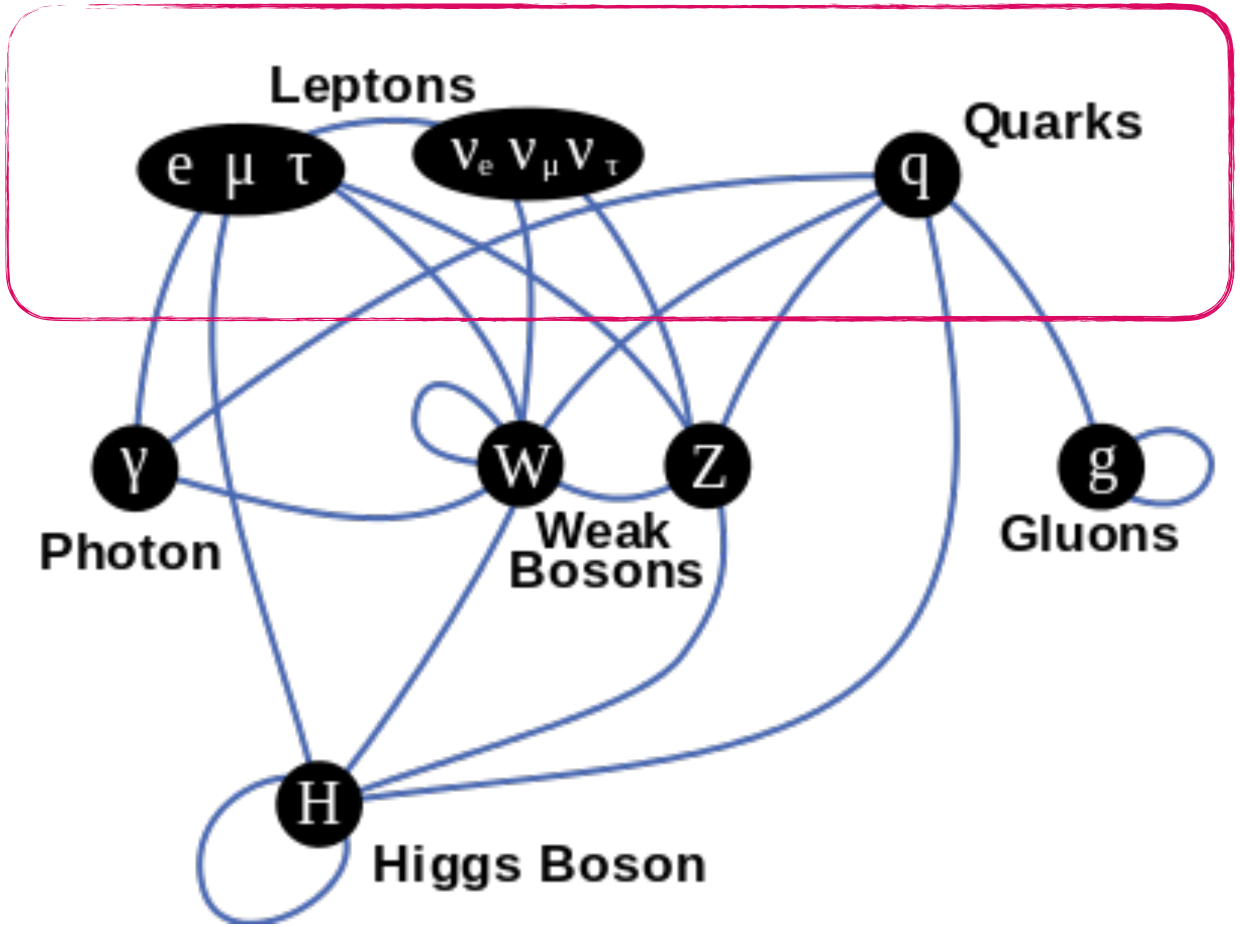
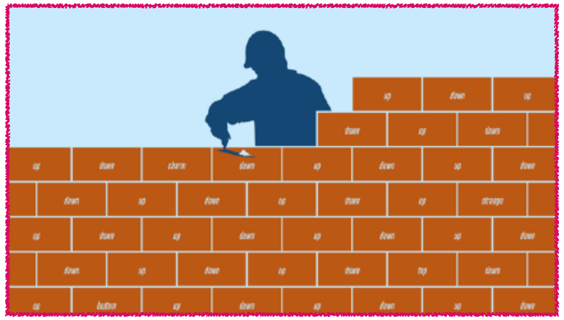
Click on the images for some more info from symmetrymagazine.org



12 fermions
(matter)



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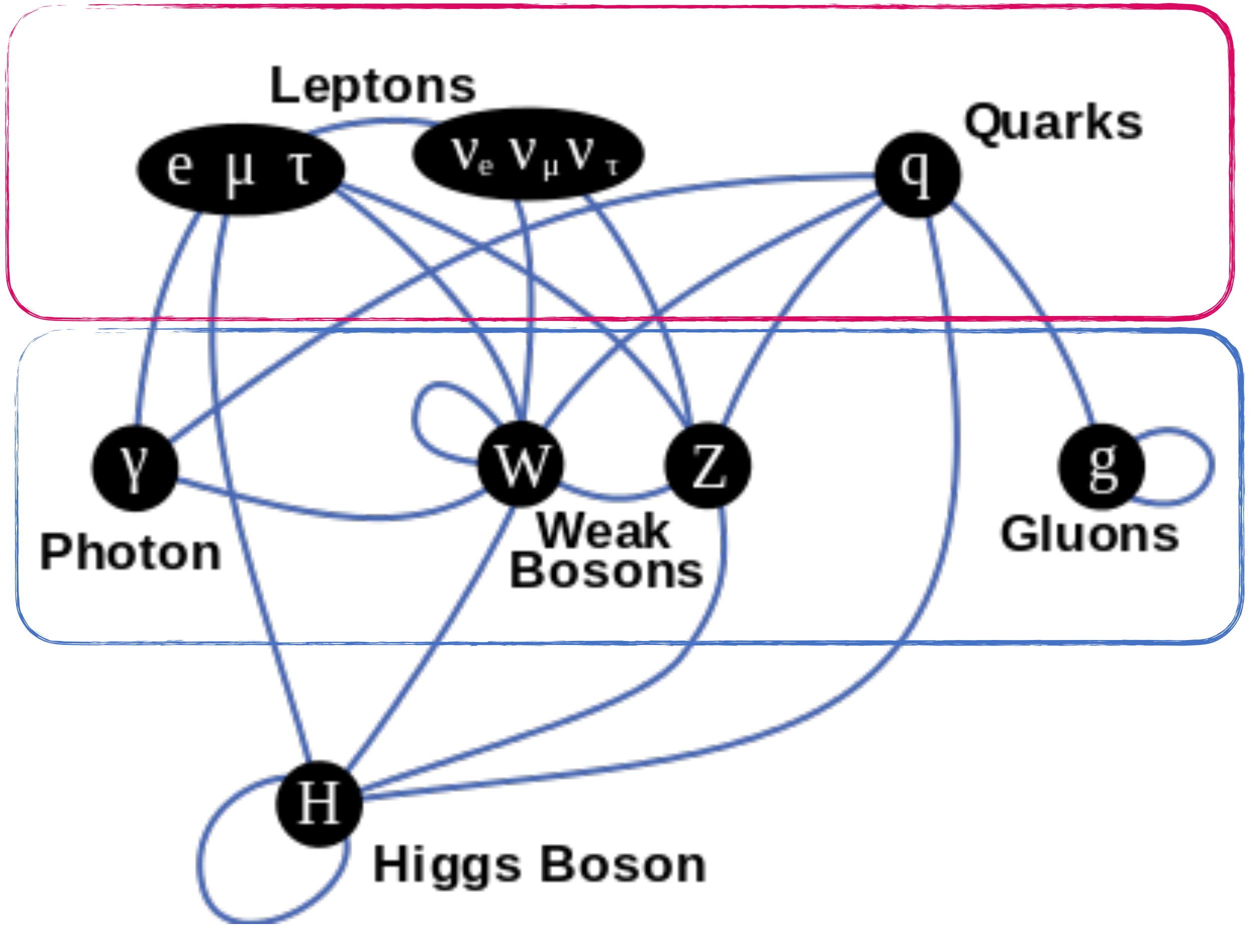

12 fermions
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4 spin-1 bosons
(force carriers)

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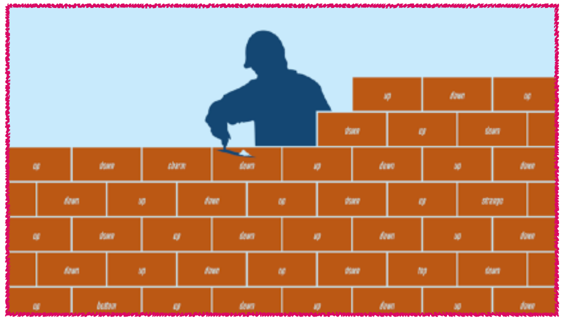

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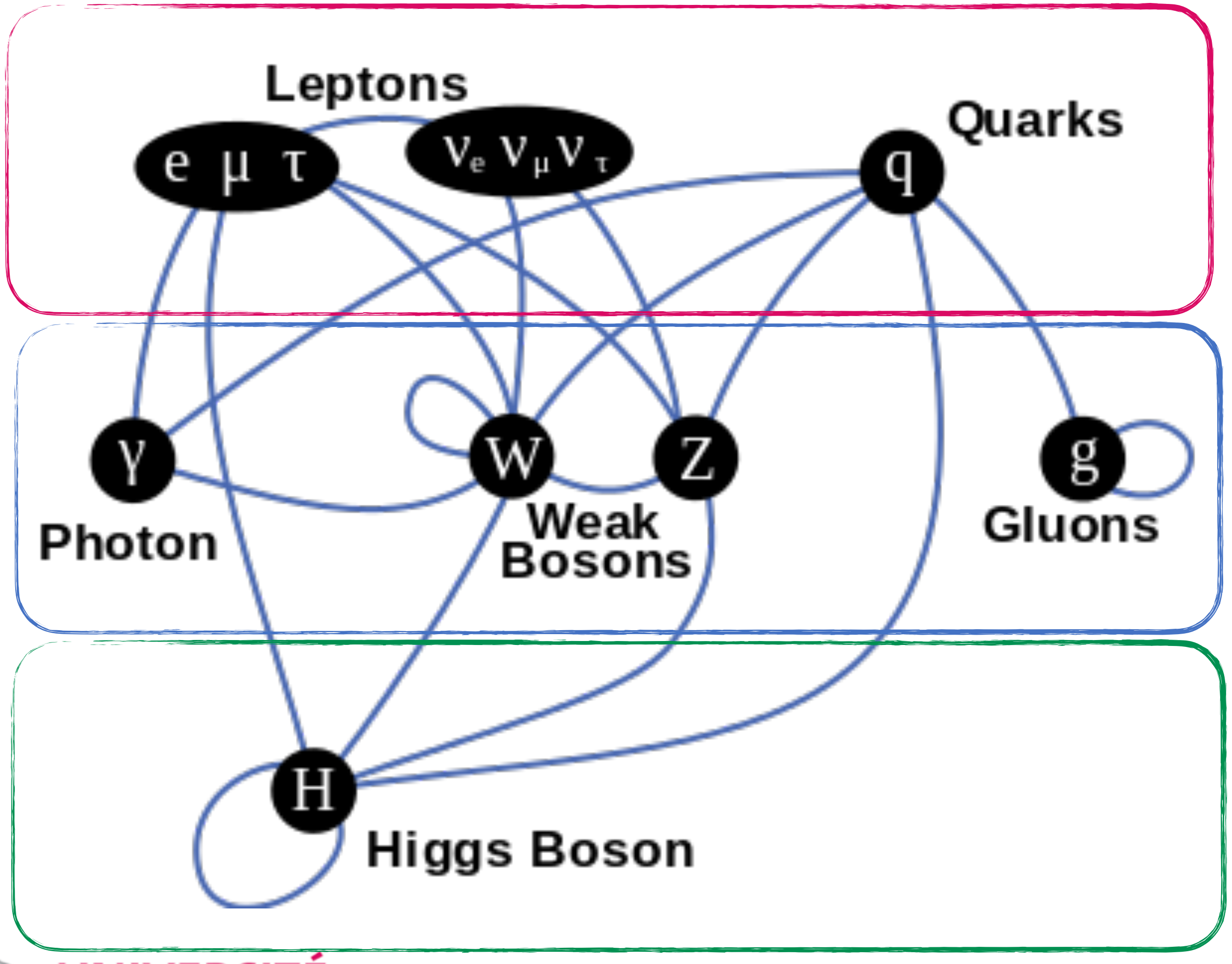

12 fermions (matter)

4 spin-1 bosons (force carriers)

1 spin-0 boson (Higgs boson)

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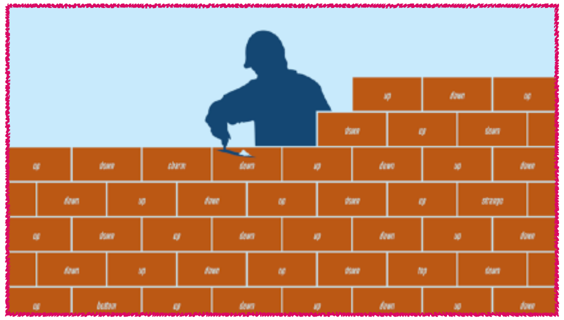
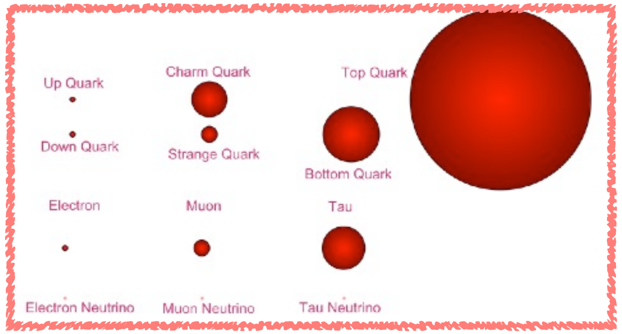


Limitations of the Standard Model

There are several reasons why we think the SM is the low-energy limit of a more general theory, e.g.:

Dark Matter

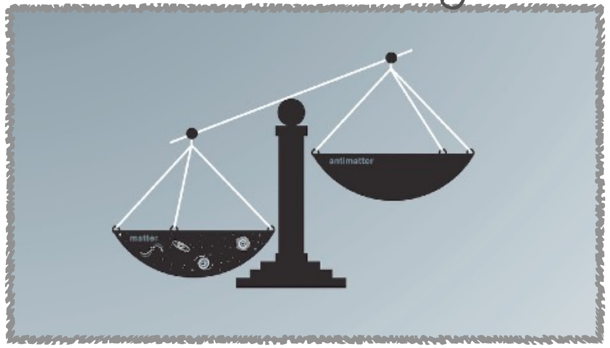
Flavour Puzzle



Naturalness

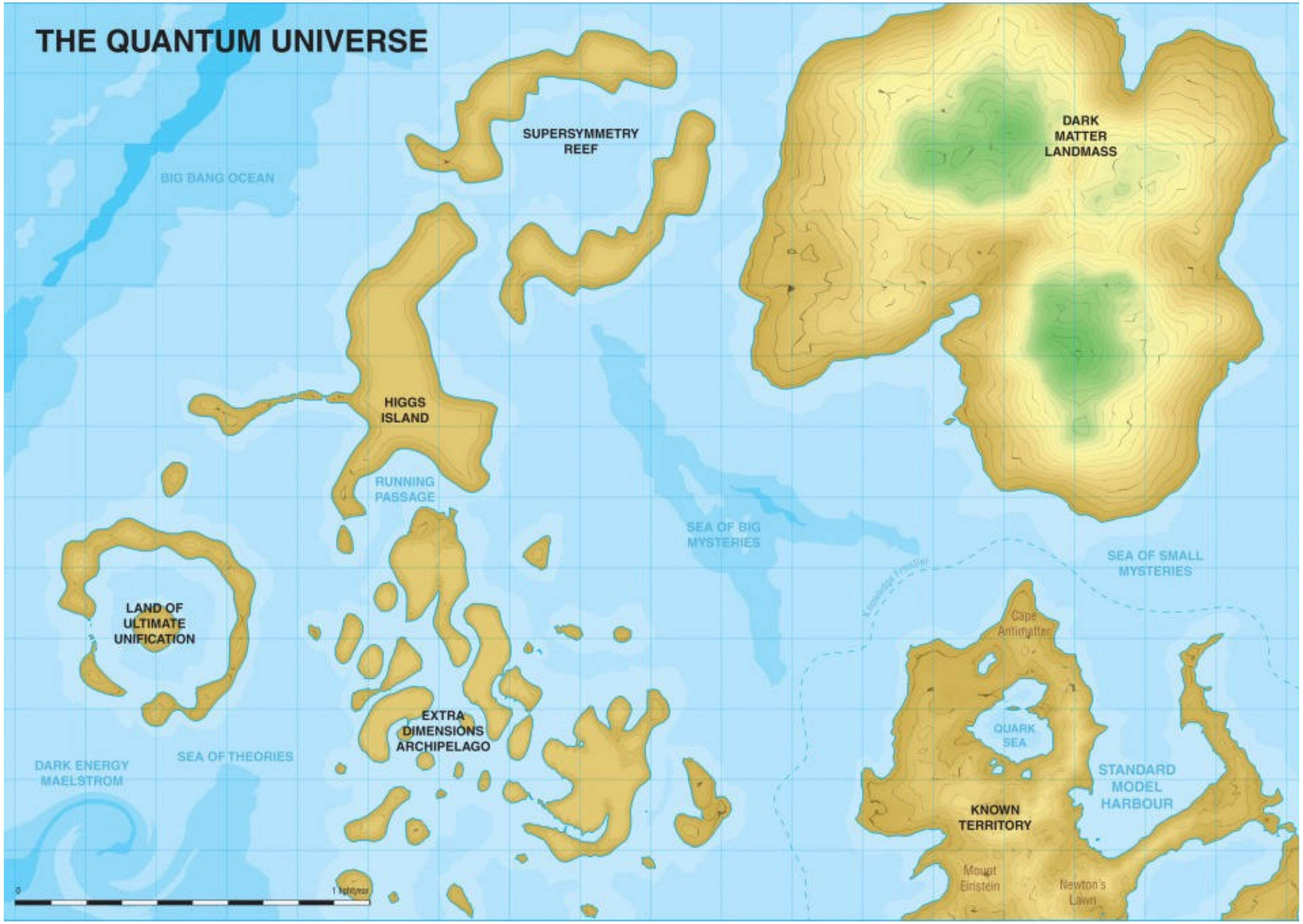
Neutrino masses

Matter-antimatter asymmetry



Gravity

Extensions of the Standard Model



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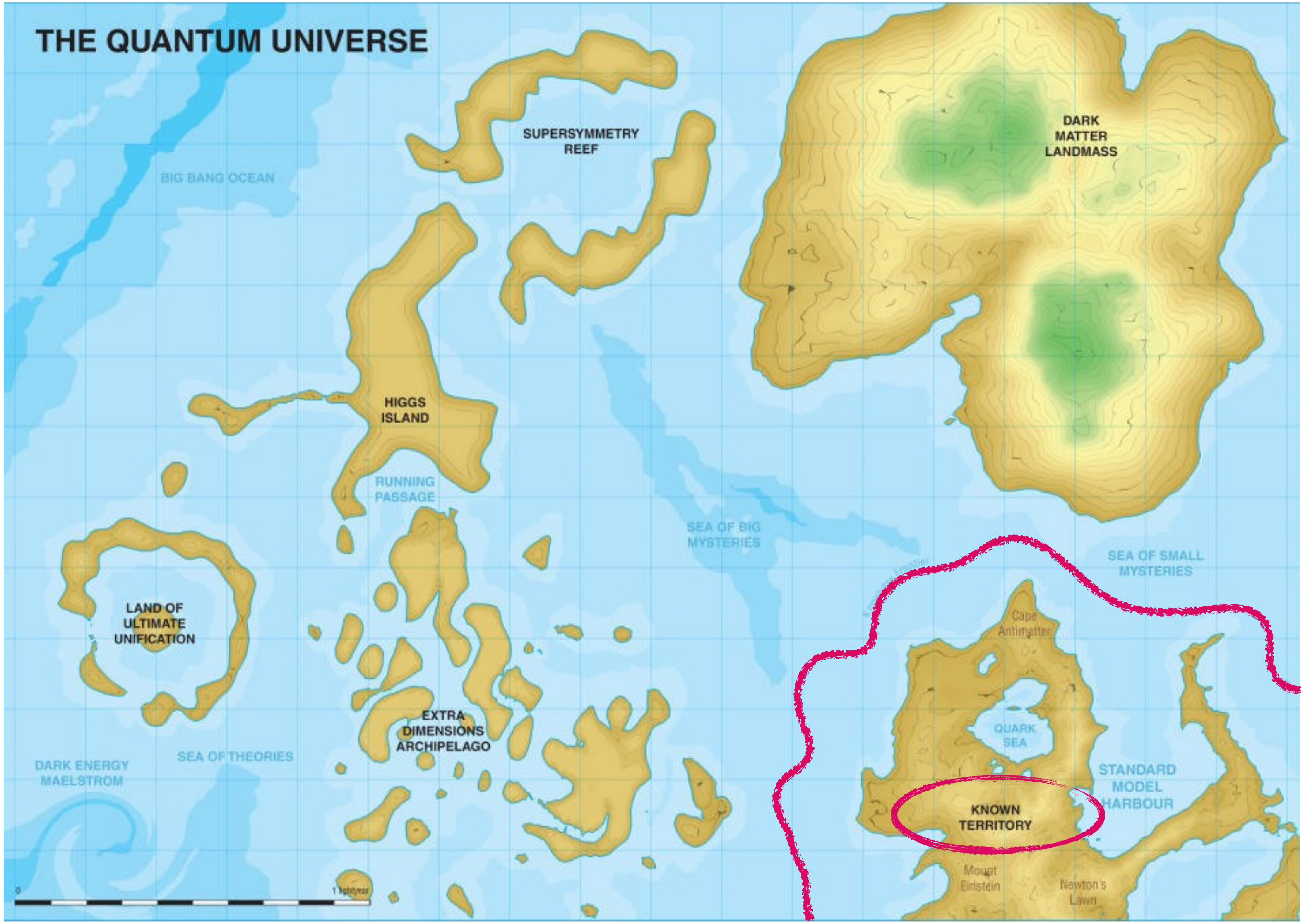

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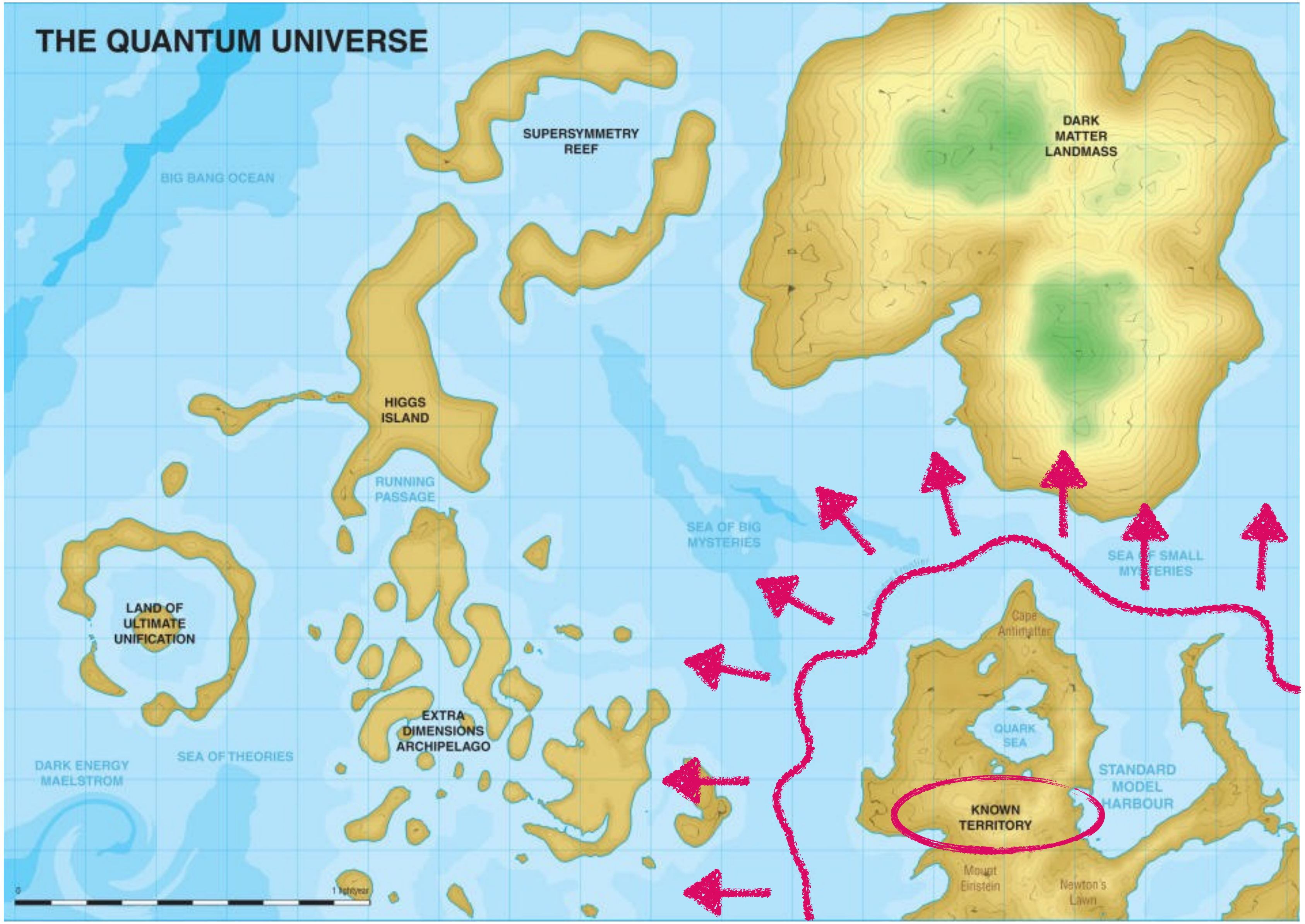

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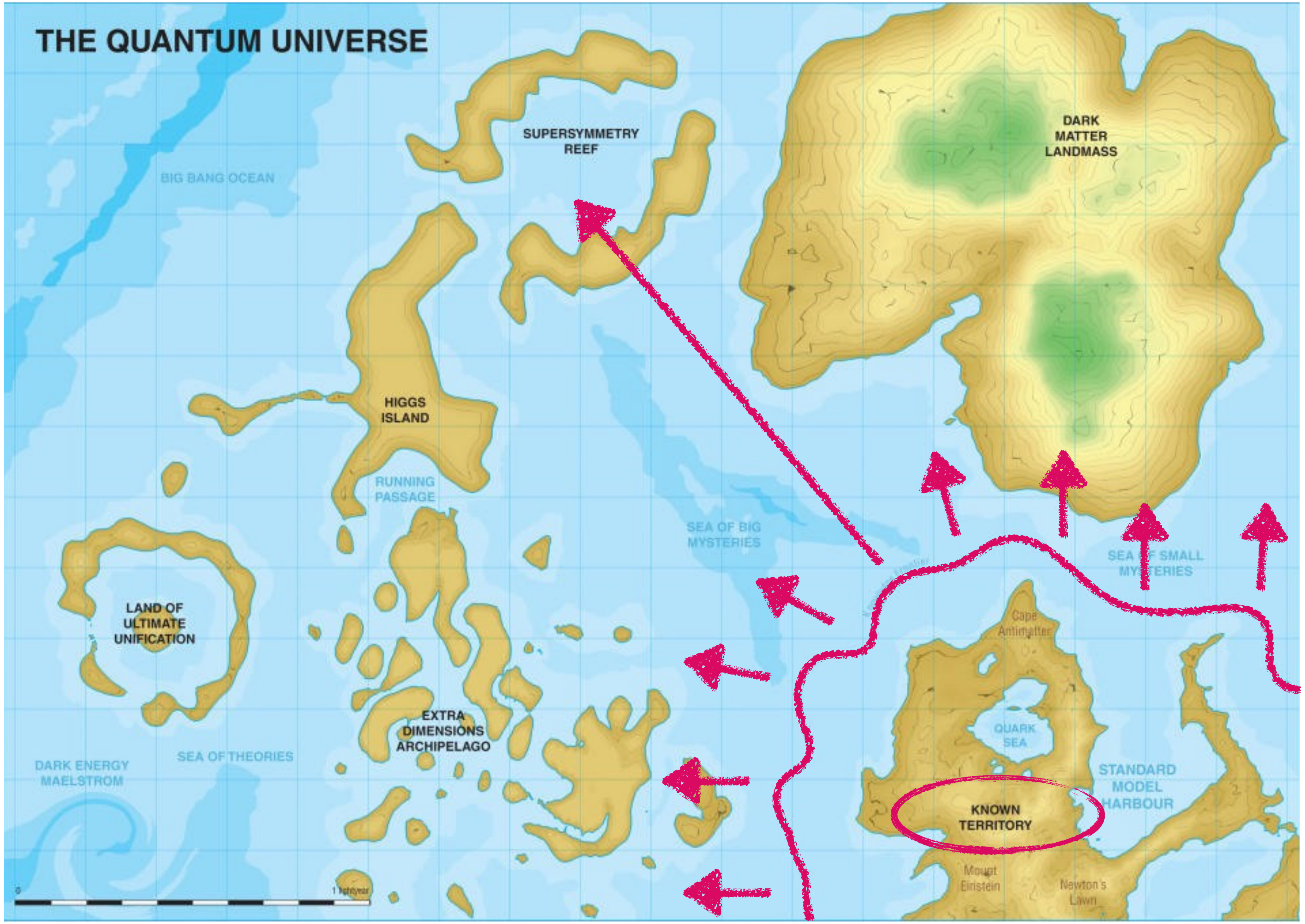

Supersymmetry

Super-Partners for the SM Particles

- Supersymmetry: extension of the Poincaré group that transforms bosons into fermions and vice versa
- Super-partners for all the degrees of freedom of the Standard Model
  - quarks → squarks
  - lepton → sleptons
  - gluon → gluinos
  - Higgs → higgsinos
  - W → winos
  - B → bino

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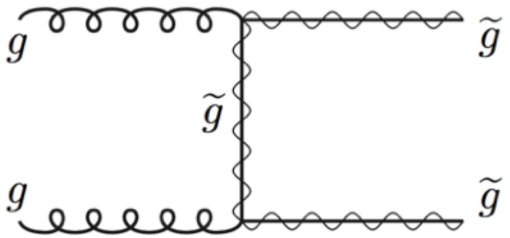
Two Higgs doublets

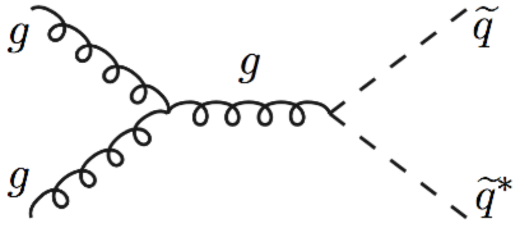
Mix to form charginos and neutralinos

Looking for SUSY

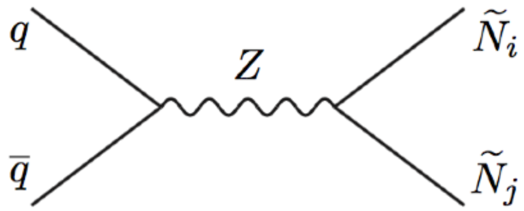
How are SUSY particles produced at the LHC? (*)



Gluino pair production



Direct production of third-generation squarks



Electroweak production of charginos and neutralinos

(*) Here showing only representative production diagrams, but there's more!

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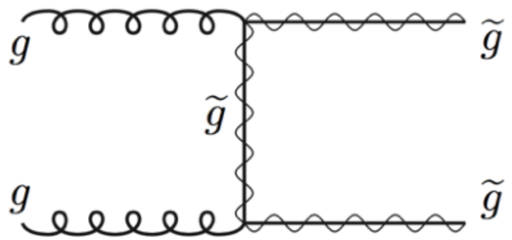

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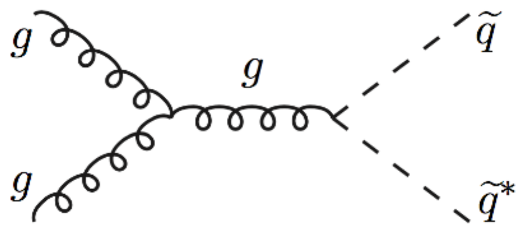

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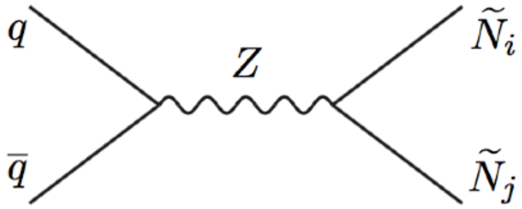

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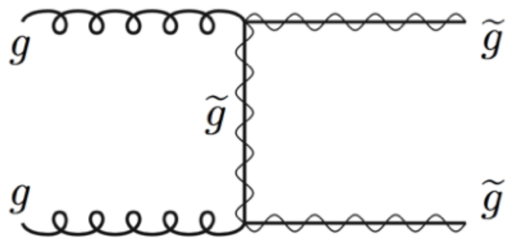

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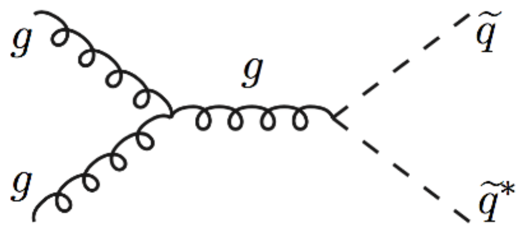

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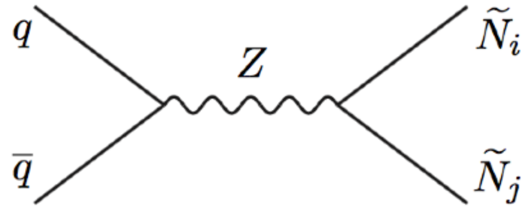

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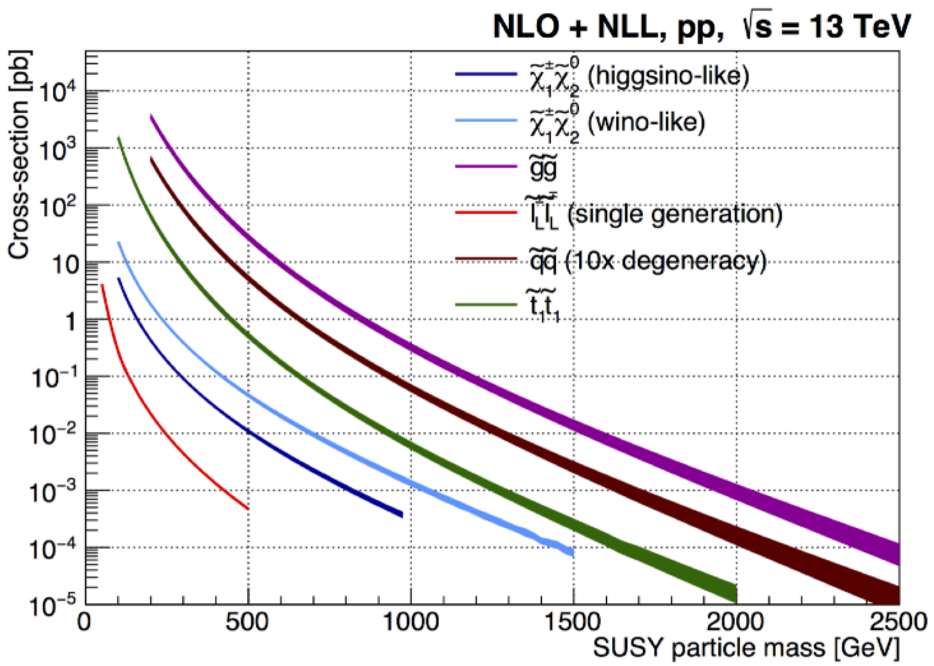

- Different processes have very different cross-sections
- For the same process, the cross-section depends strongly on the mass of the SUSY particle (unknown!)

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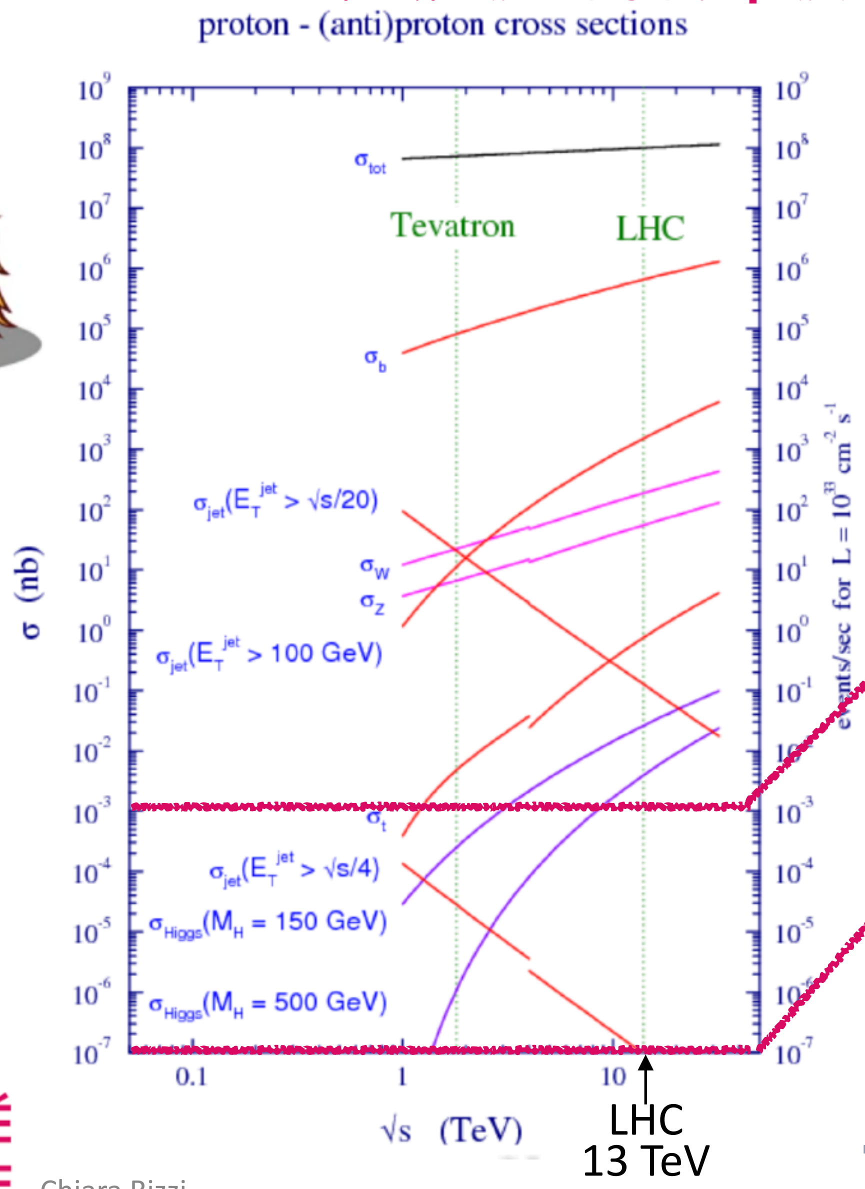

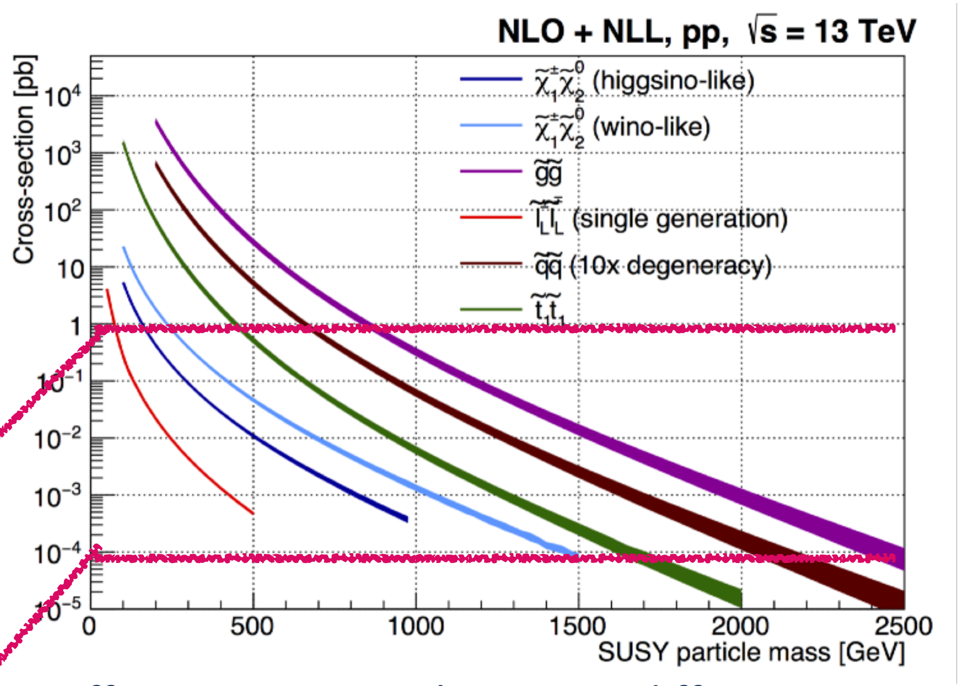

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$N^{events} = \mathscr{L} * \sigma$ Product of luminosity and cross section

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Looking for SUSY

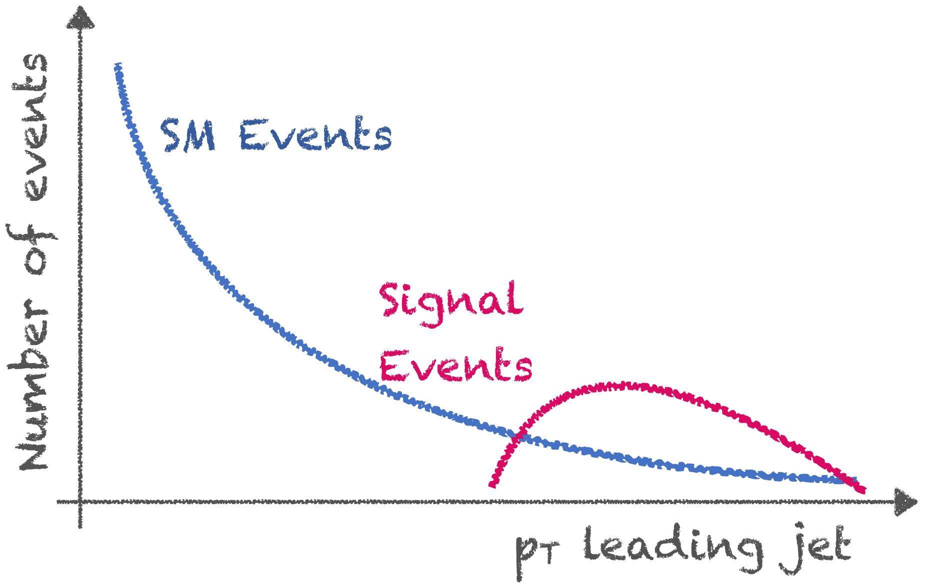
How do SUSY particles decay?

- The decay mode of SUSY particles depends on the parameters of the model
  - Several possible well motivated choices!
- Assumptions are needed to allow a search for SUSY particles
- **Simplified models** are simple models with only a few particles
  - Limit of more complex models where other particles are too heavy to be produced
- 100% BR: each decay chain can be considered as a different simplified model
- Used to optimise and interpret searches

Sensitivity is typically higher than for realistic models

General Search Strategy

- Identify characteristics of the signal (i.e. characteristics of the objects in the final state) that can distinguish it from the background (background = Standard Model events)



General Search Strategy

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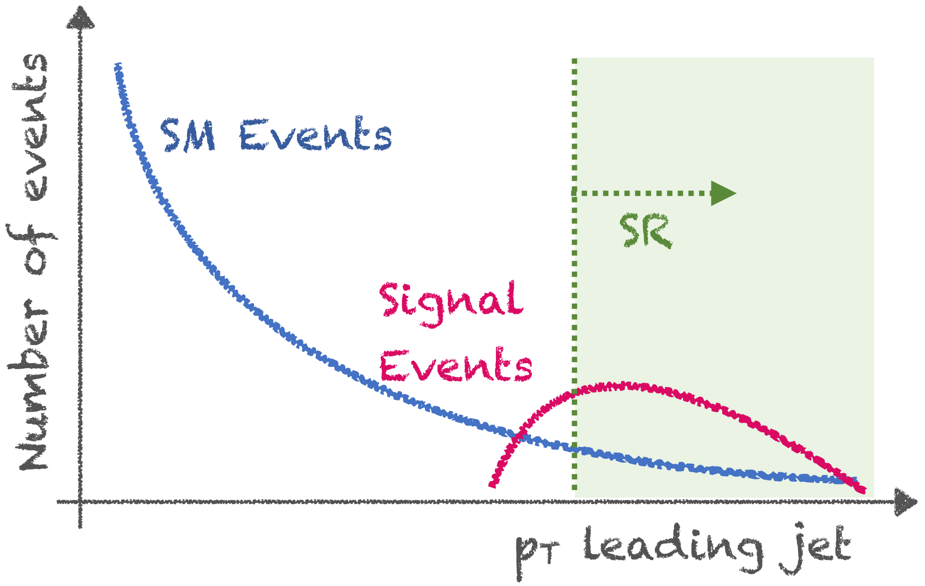
- Use these characteristics to define signal-enriched regions (**SR**)



Simplest option: just count the total number of events in the SR

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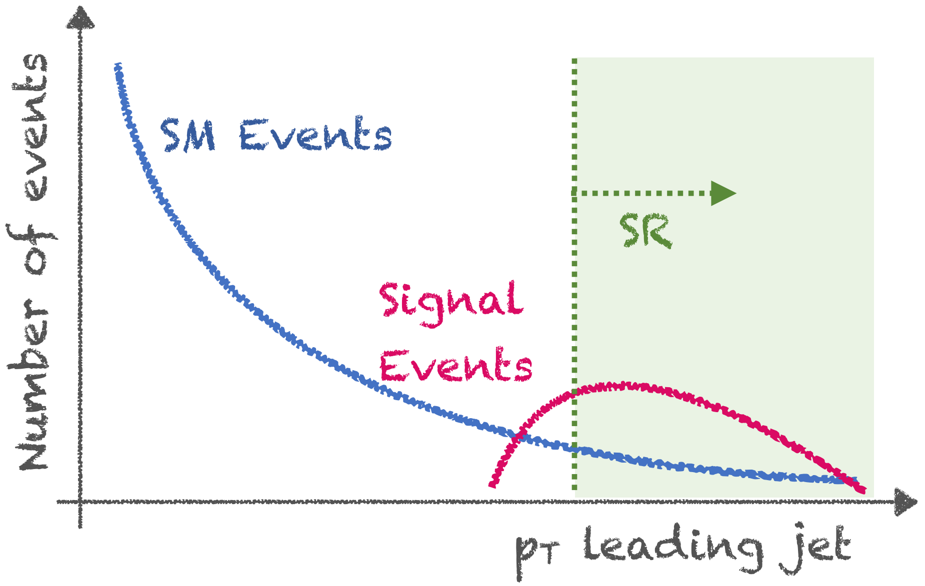


Often the most time-consuming step of the analysis!

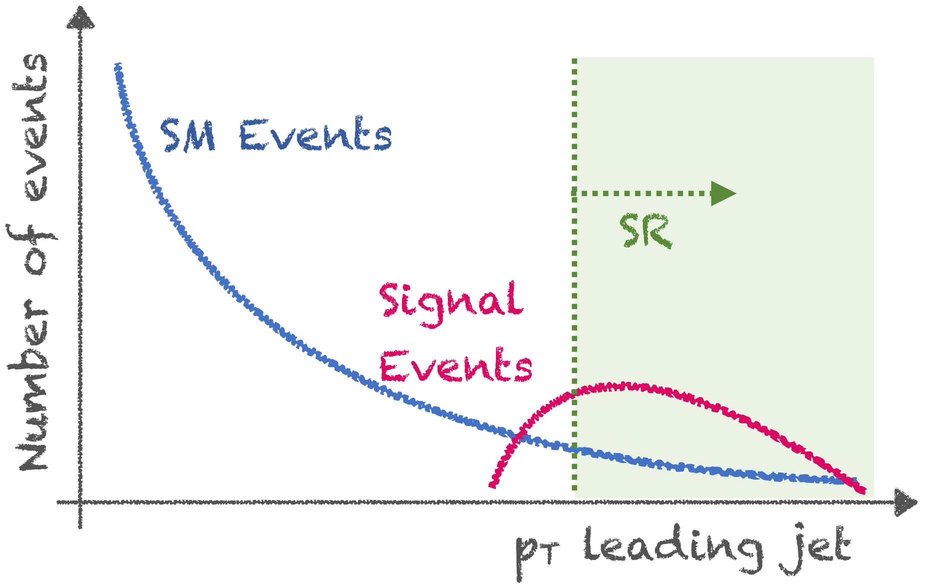
Simplest option: just count the total number of events in the SR

$N_{Sig} = X + \sigma X$

$N_{Bkg} = Y + \sigma Y$

General Search Strategy

- Identify characteristics of the signal (i.e. characteristics of the objects in the final state) that can distinguish it from the background (background = Standard Model events)
- Use these characteristics to define signal-enriched regions (**SR**)
- Derive an accurate **background estimate** in the SR (with an associated uncertainty)
- Compare the number of expected background events in the SR with the actual number of observed **data** events (statistical techniques)
  - **Blinding**: look at data in the SR only at the end, do avoid bias



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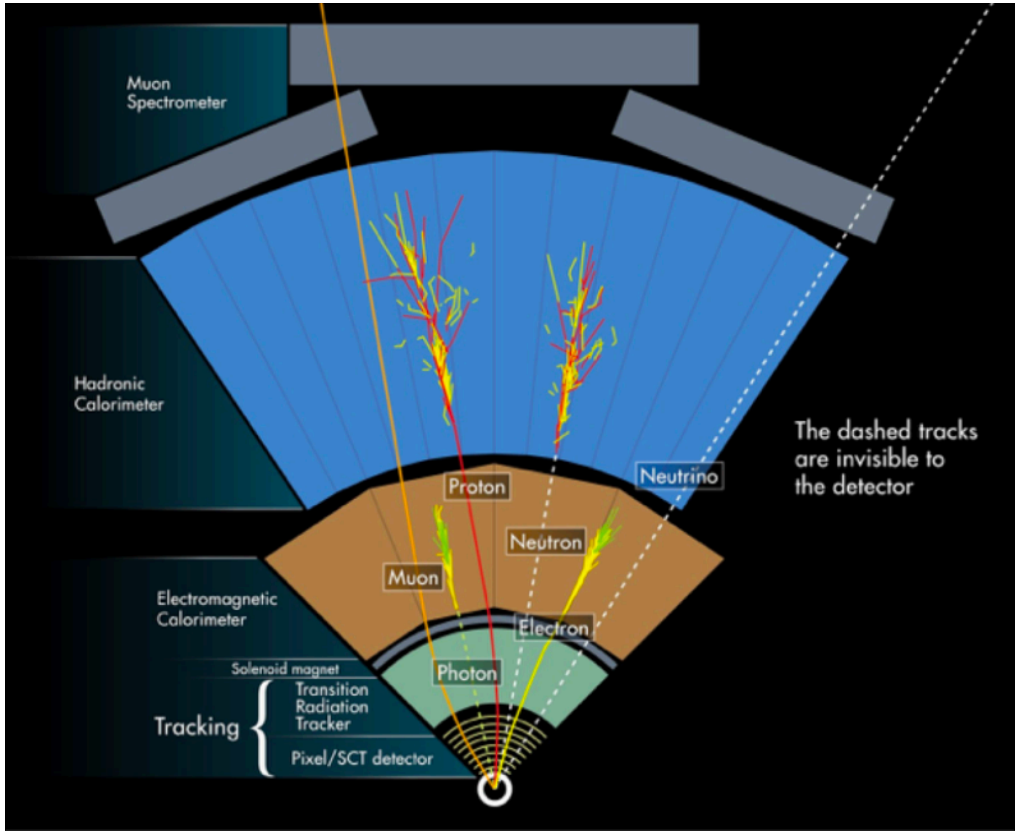
$N_{Sig} = X + \sigma X$

$N_{Bkg} = Y + \sigma Y$

$N_{Data} = ?$

Typical Handles to Isolate Signal

- All of the reconstructed objects that we can reconstruct and identify with our detector and their characteristics, e.g. the transverse momentum of:
    - Hadronic jets
    - Hadronic taus
    - Electrons
    - Muons
    - Photons

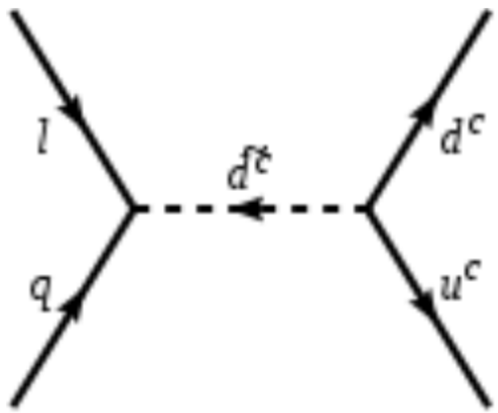


- Event-level variables, e.g.:
    - Multiplicity of all the objects mentioned above
    - Effective mass: sum of the transverse momentum of all the objects in the event
    - Hadronic energy: sum of the transverse momentum of the jets
    - Missing transverse momentum

R-parity
(and its violation)

R-parity

- The most general SUSY Lagrangian would contain also interactions leading to the proton decay
- R-parity: $P_R = (-1)^{3(B-L)+2s}$
- Multiplicative quantum number
- +1 for SM particles, -1 for SUSY particles
- If conserved, SUSY particles are **produced in pair** and have an **odd number of SUSY particles in their decay products**
- The lightest SUSY particle is stable
  - If neutral can be a **dark matter candidate**
  - Events with **missing transverse energy**
- R-parity also **forbids** the couplings that would lead to **proton decay**



R-parity Violation

- Do we really need R-parity conservation to have a physically motivated SUSY model?
- NO :)
- E.g. for the proton decay, we need simultaneous violation of both L and B
- We can add RPV terms to the SUSY Superpotential

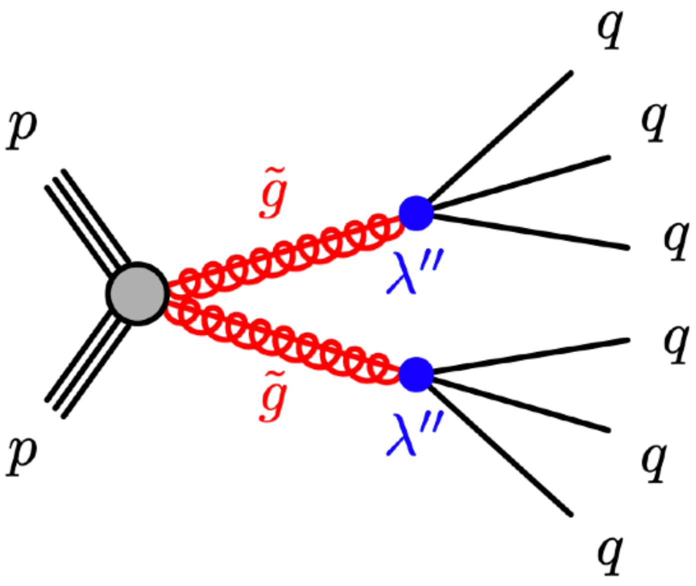
$$W_{\mathrm{RPV}} = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_i L_i H_2$$

- But, in general R-parity violating couplings have stronger experimental constraints —> are assumed to be weaker
- This is why in our RPV models we typically assume RPC production and RPV decay

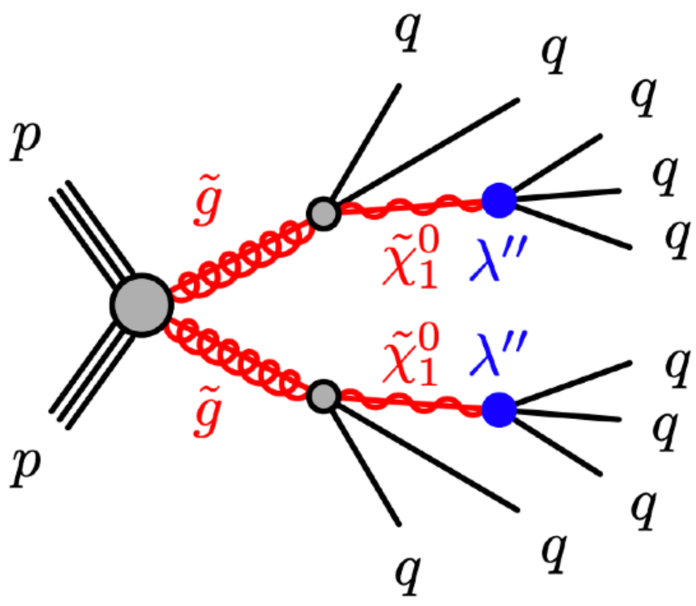
RPV Multi-jet Search

The Simplified Models We Look At

6-jets Model

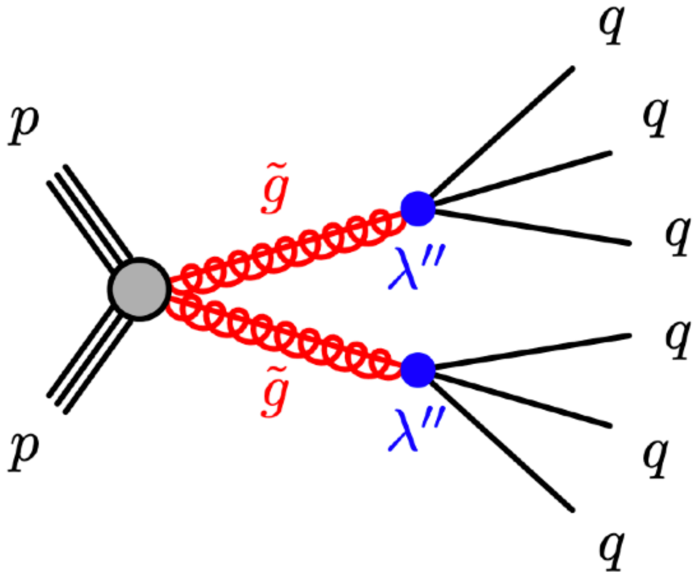


10-jets Model



Limits for these models from previous analyses in backup

More in Details: The 6-jets Model



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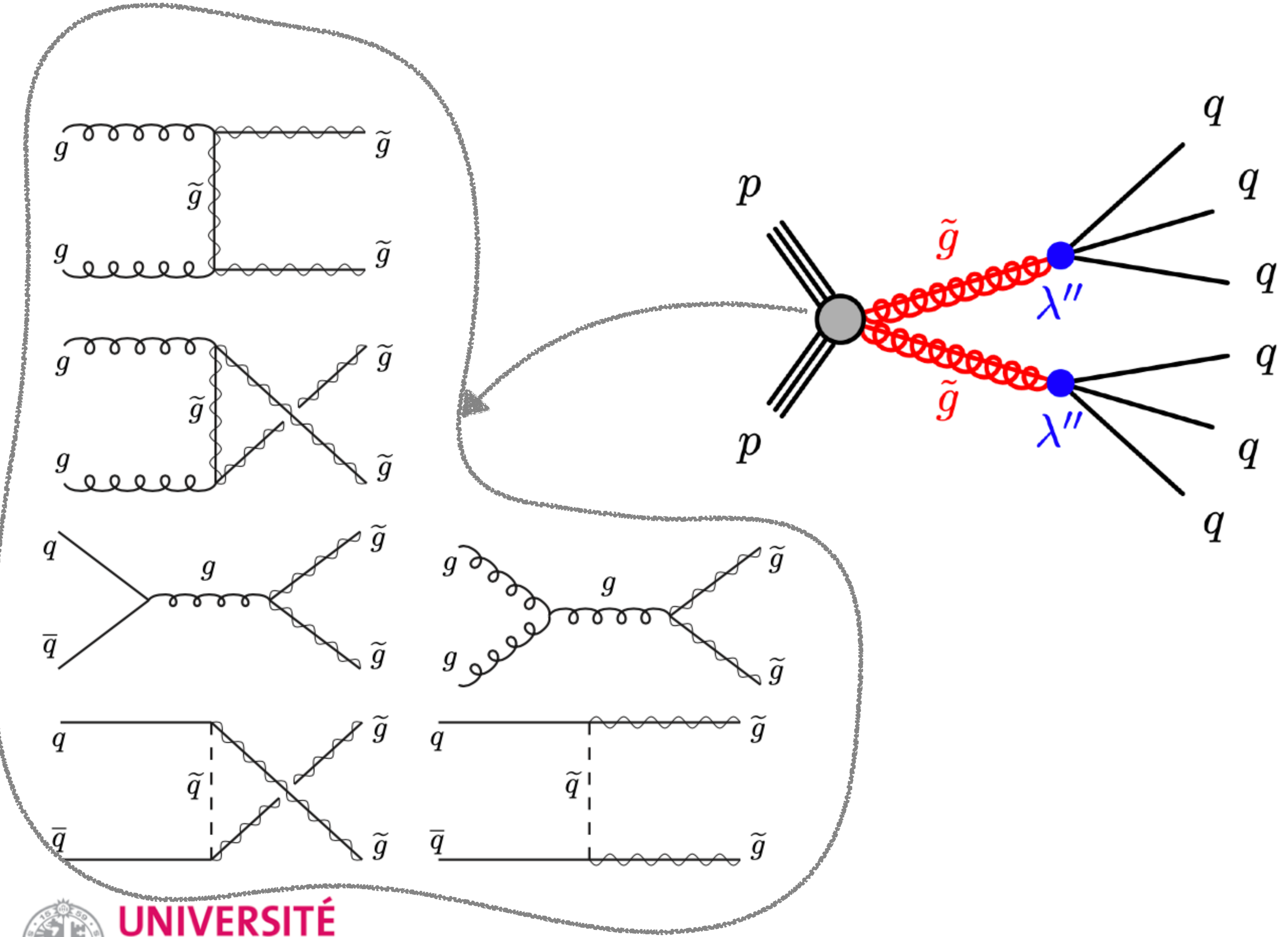

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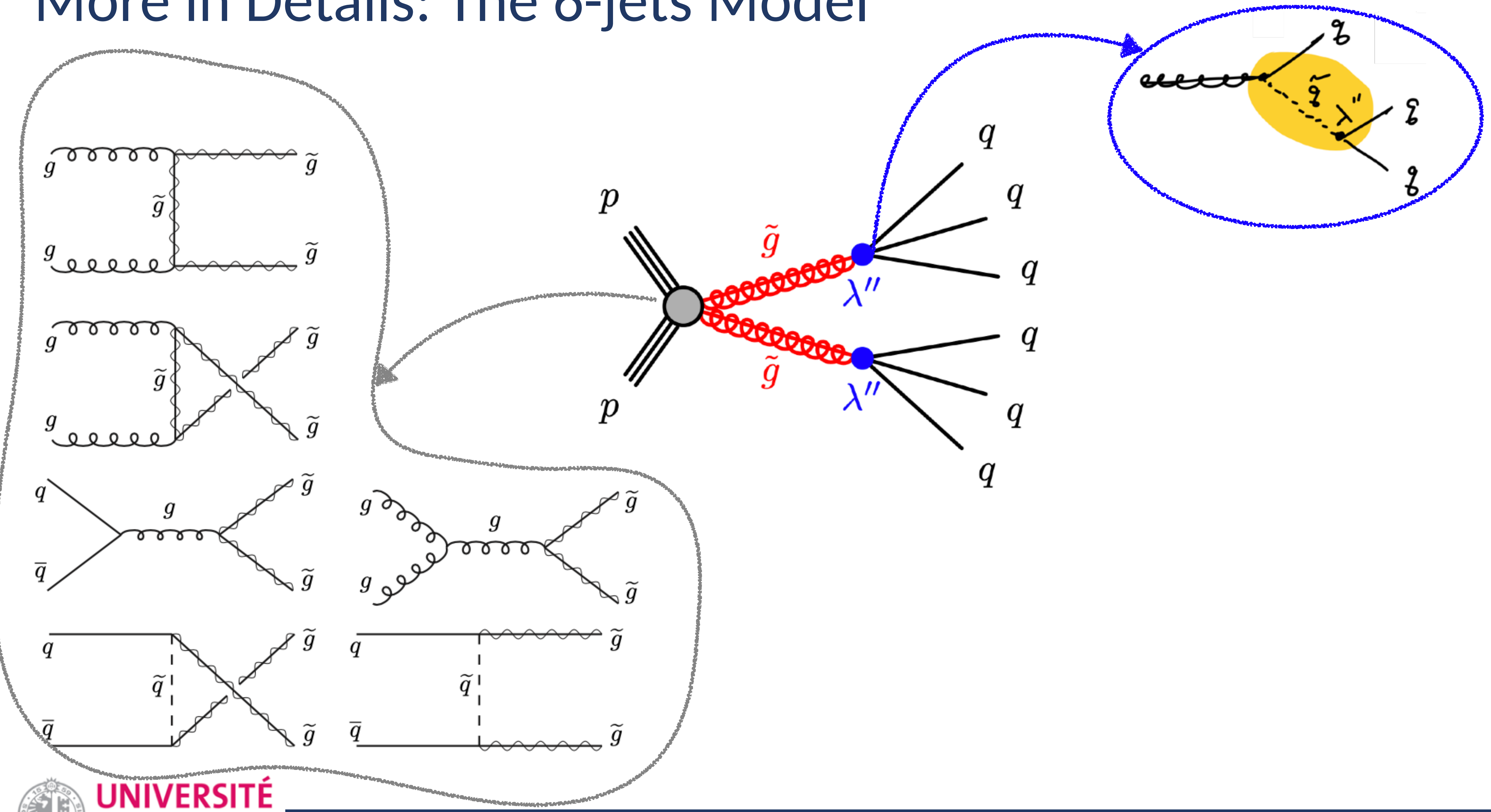

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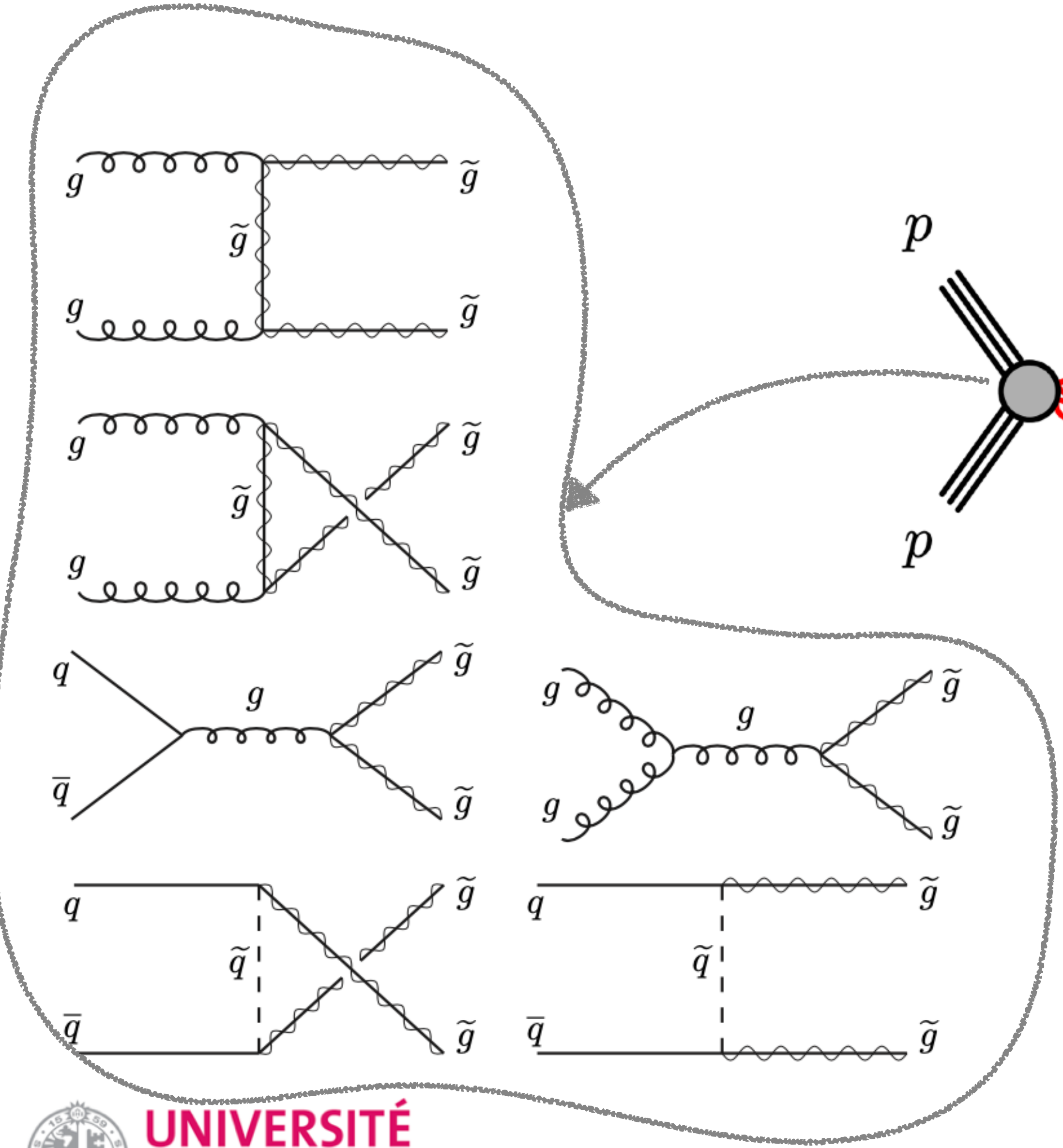
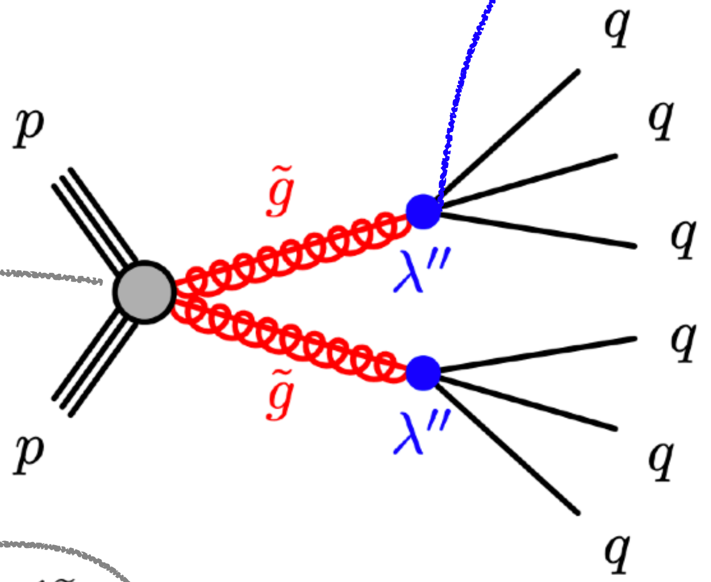
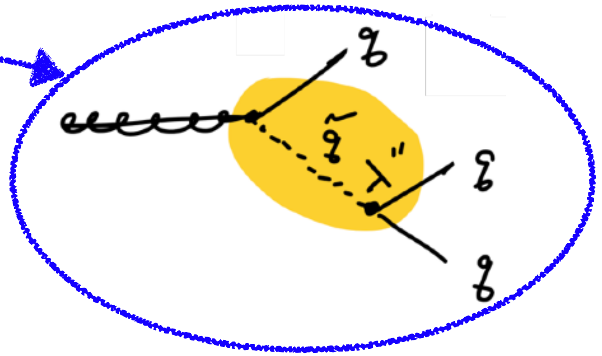


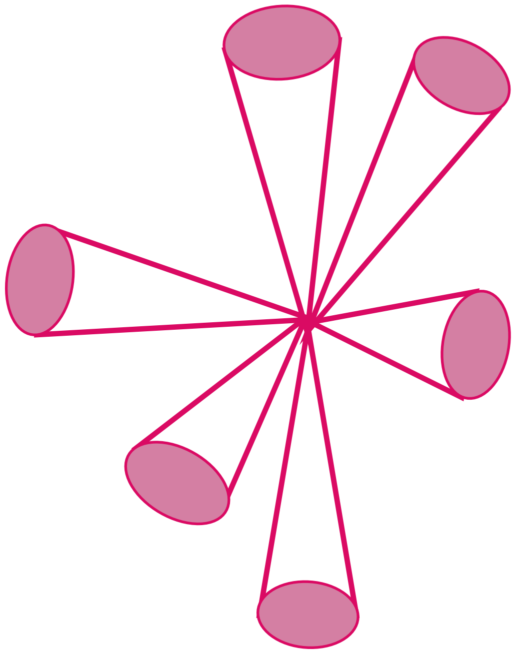




- What are the flavours of the final-state quarks?
- It's a simplified model! Consider two cases: **UDS, UDB**
- The gluino mass is a free parameter
- Higher gluino mass —> more energetic jets

What do the Events Look Like?

- Jets originating from the gluinos



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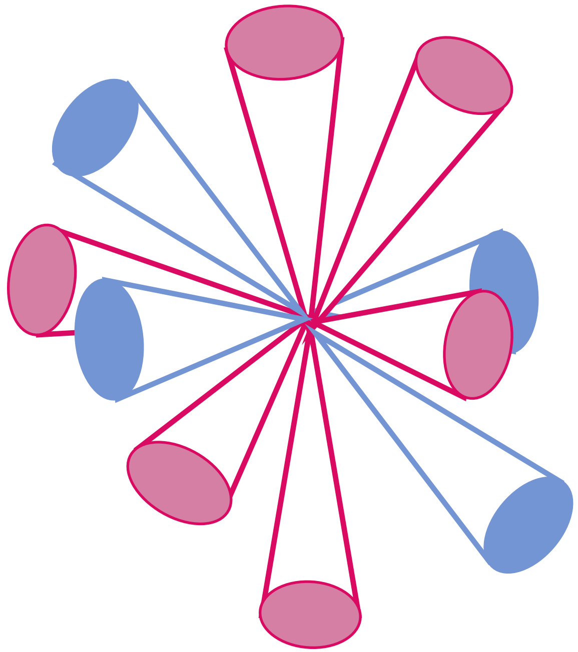
- Jets originating from the gluinos
- But also extra jets from radiation —> complicated events
- Signal events are simulated with Monte Carlo techniques



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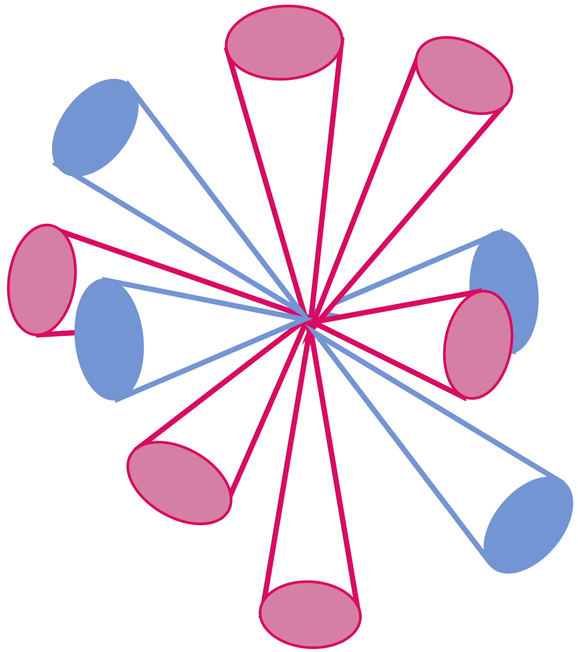

Challenge: very large background

- All-hadronic final states (i.e. only jets, no leptons) have extremely high background rates

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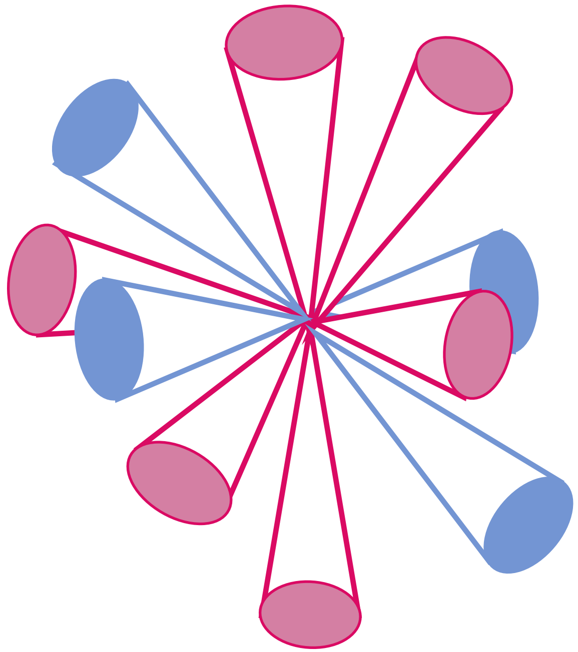

Challenge: event reconstruction

- How to distinguish jets from the gluinos from jets from extra radiation?
- Can we also distinguish the jets originating from each gluino?
  - The invariant mass of these three jets would peak at the gluino mass, giving us an extra handle to identify the signal

What do the Events Look Like?

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Challenge: event reconstruction

Ongoing analysis activities are addressing these challenges!

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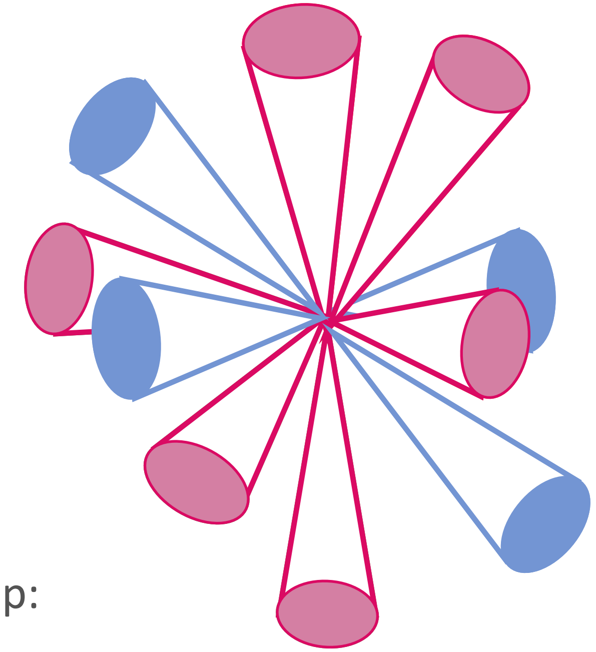
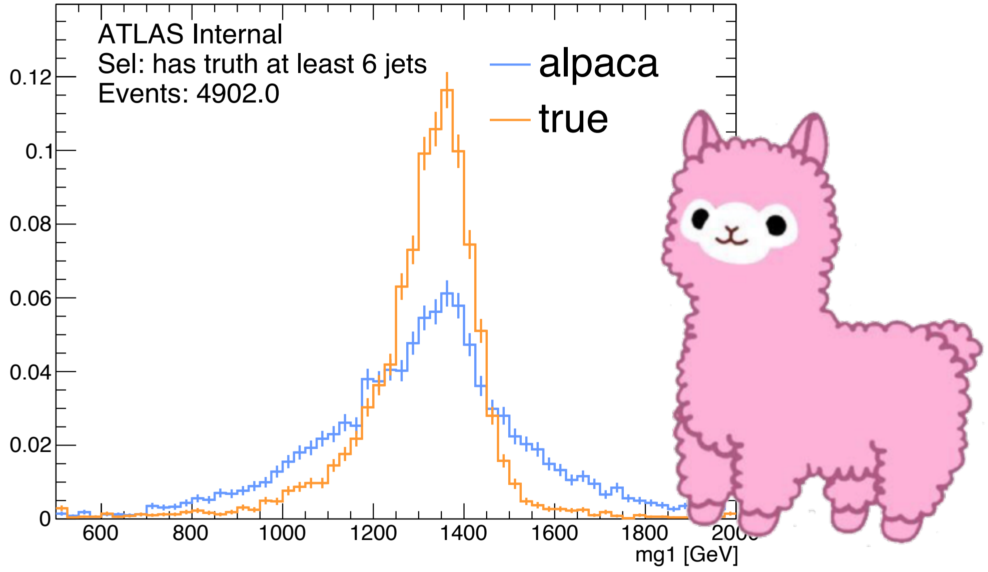
Analysis Activity — Alpaca

- ALPACA: machine learning tool to help us understand which jets are originating from the gluino decays, and how to group them into the two gluinos





Involved people from our group:
Anna, TJ, Riccardo, Chiara
But also from the analysis team:
CERN, Bern, Harvard and Cambridge groups

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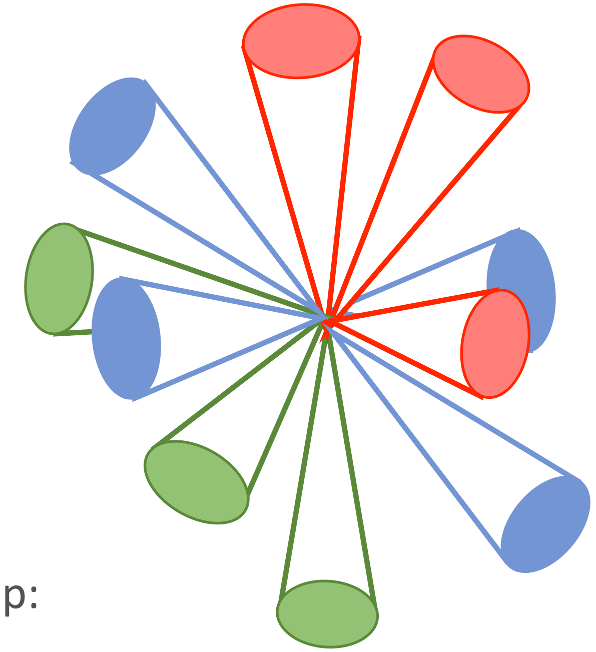

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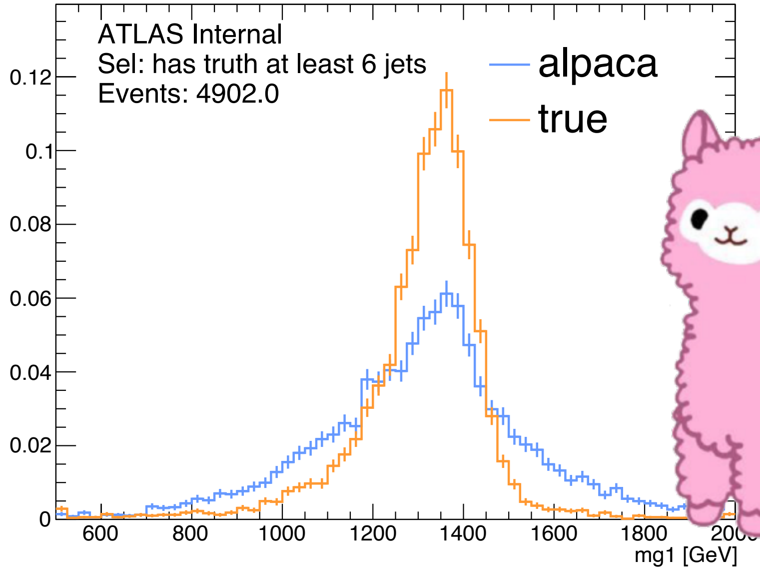
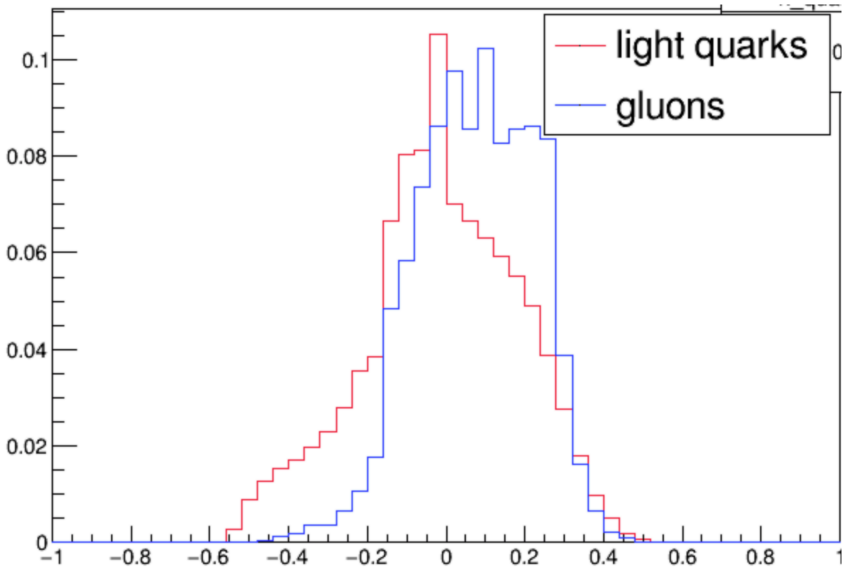


Analysis Activity — Quark-Gluon Tagging

- Jets originating from the hadronization of quarks and gluons have different substructure characteristics
- This is can be useful for the analysis!
  - Jets from the gluino —> hadronization of quarks
  - Extra jets from radiation —> can originate from gluons
- E.g. use as input to alpaca only quark-tagged jets
- Technically implemented through a boosted decision tree
  - More info in backup

UDS m(gluino)=1400 GeV

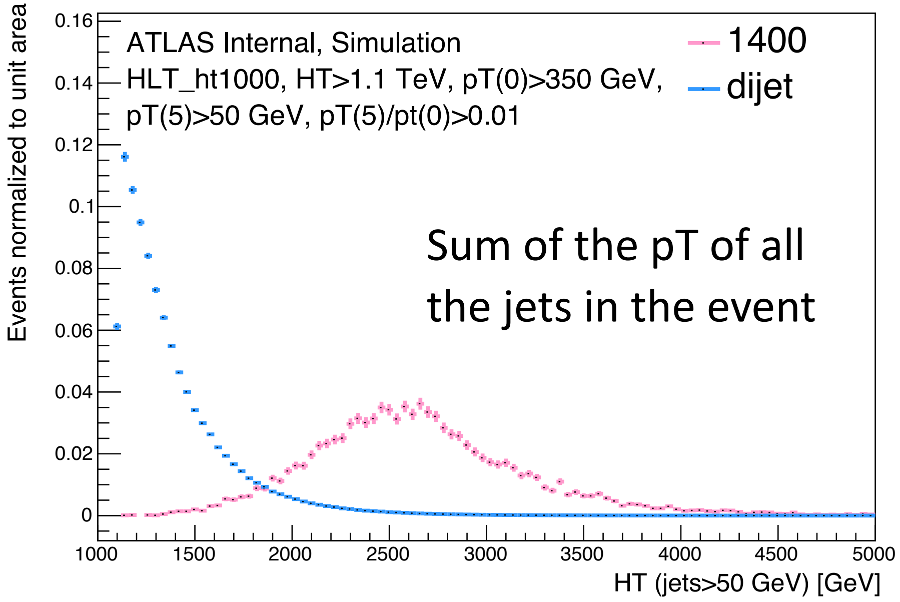


BDT score

Involved people from our group:
Anna, Chiara, Snigdho
But also from the analysis team:
Oxford group

Analysis Activity — Backgrounds

- Background estimate
  - We need to find ways to have a reliable background (QCD) estimate
  - With systematics
- Background suppression
  - We need to identify variables that allow us to reduce the background while having a good signal efficiency

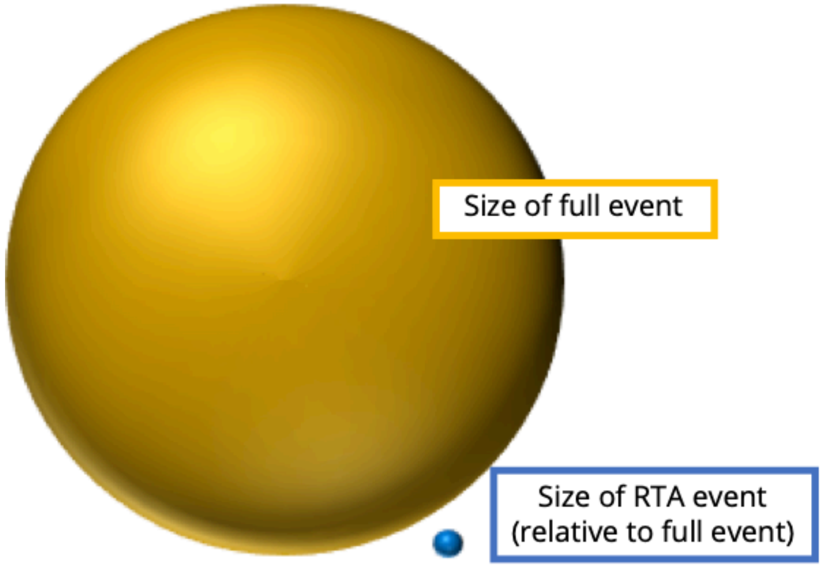


Sum of the pT of all the jets in the event

Involved people from our group:
Anna, Chiara
But also from the analysis team:
Oxford Group

Analysis Activity — TLA

- TLA: trigger-level analysis
  - Current trigger thresholds allow to select only events with extremely energetic jets —> low acceptance for low-mass gluinos
  - Reducing the amount of information that we store for each events, we can reduce the used bandwidth and have much lower trigger thresholds
- Talk from Claire last week!



Involved people from our group:
Anna, Claire
But also from the analysis team:
Lund group

Do You Want to Know More?

- Analysis twiki (ATLAS Internal)
- First steps into the analysis tutorial (quark/gluon-tagger oriented)
- 36 ifb ATLAS paper
- 36 ifb CMS paper, boosted
- 36 ifb CMS paper, resolved
- ALPACA presentation at the SUSY background forum from A. Badea
- ATLAS 2014 quark-gluon tagging paper

Backup

SUSY Particles

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\widetilde{G}$	(same)

Quark Gluon Tagger

- I've added to our FT analysis the output of the official quark-gluon tagger from JetEtMiss
- Tagger based on a BDT that takes as input:
  - Number of tracks in the jet

$$N_{\mathrm{trk}} = \sum_{\mathrm{trk} \in \mathrm{jet}}$$

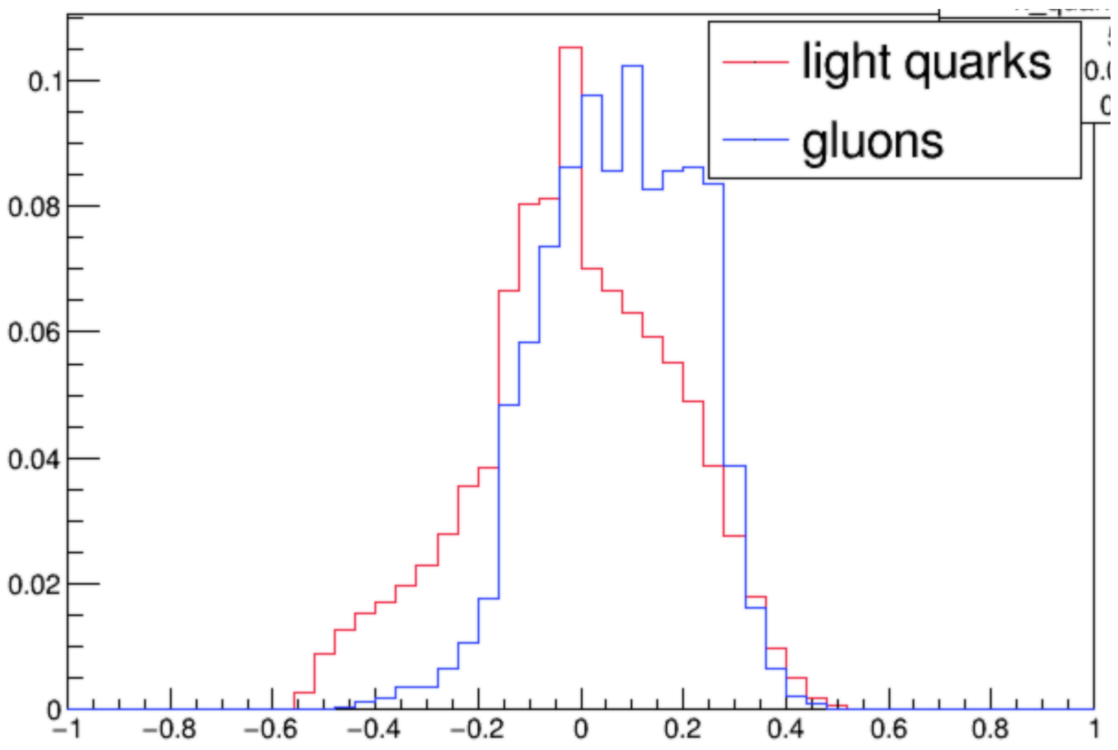
  - Rrack-pT weighted width of the jet

$$W_{\mathrm{trk}} = \frac{\sum_{\mathrm{trk}\in\mathrm{jet}} p_{\mathrm{T,trk}} \Delta R_{\mathrm{trk,jet}}}{\sum_{\mathrm{trk}\in\mathrm{jet}} p_{\mathrm{T,trk}}},$$

  - Two-point energy correlation function

$$C_1^{\beta=0.2} = \frac{\sum_{i,j\in\mathrm{jet}}^{i\neq j} p_{\mathrm{T},i} p_{\mathrm{T},j} \left(\Delta R_{i,j}\right)^{\beta=0.2}}{\left(\sum_{\mathrm{trk}\in\mathrm{jet}} p_{\mathrm{T,trk}}\right)^2},$$

UDS m(gluino)=1400 GeV



Previous ATLAS Limits