

SUSY RPV Multi-jet Search

Chiara

12/03/2021



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1. Search (we are looking for new phenomena)



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



SUSY RPV Multi-jet Search

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2. For Supersymmetry
3. Without the assumption of R-parity conservation
4. In final states with several hadronic jets

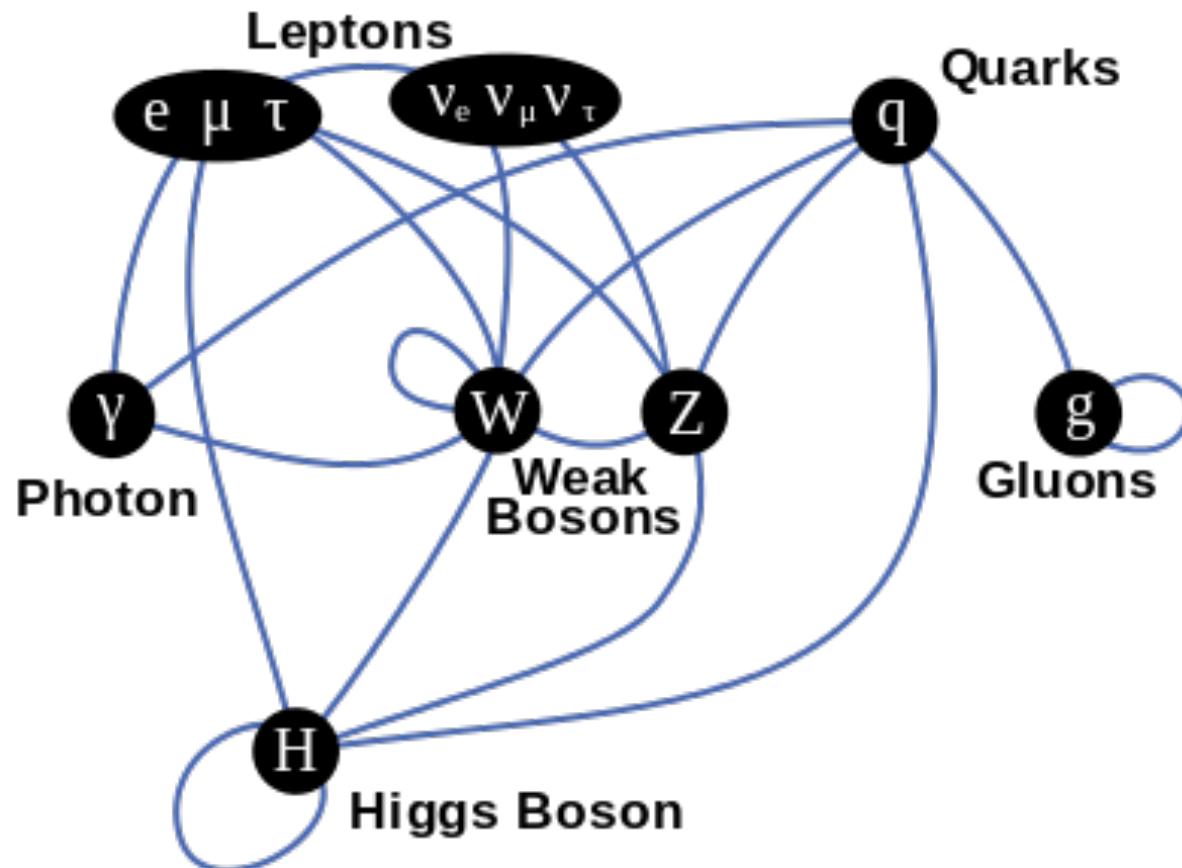


Why Doing Searches?



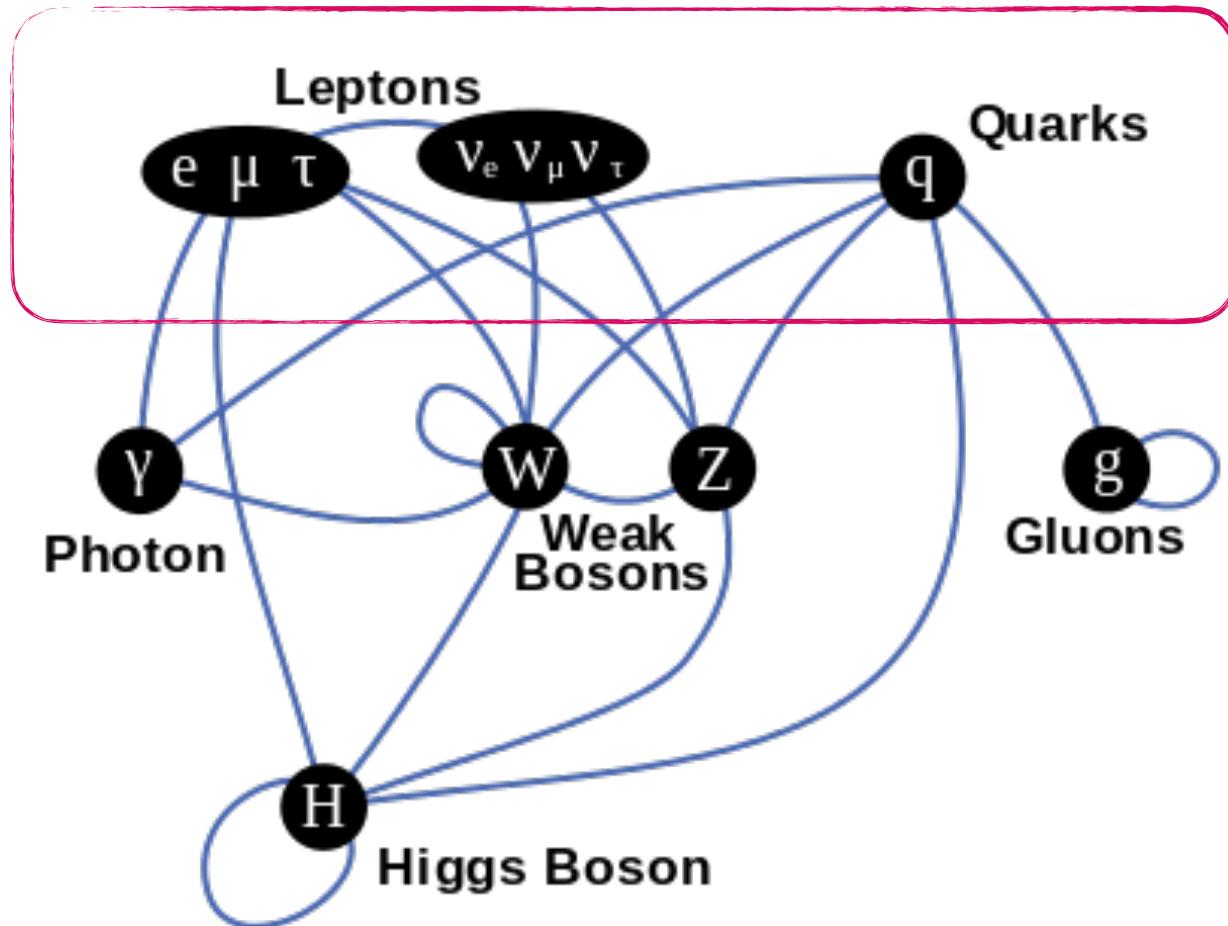
Standard Model of Particle Physics

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



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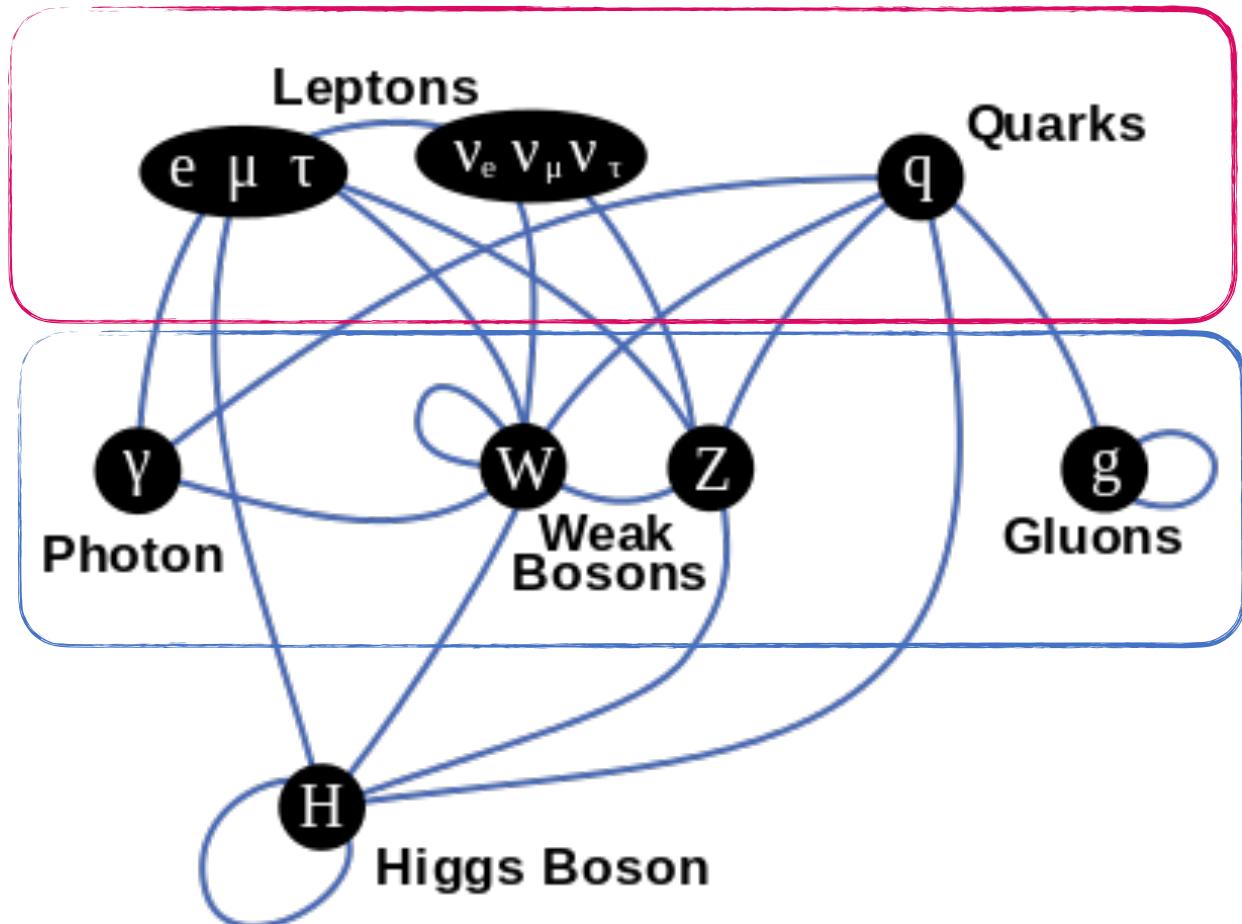
12 fermions
(matter)

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



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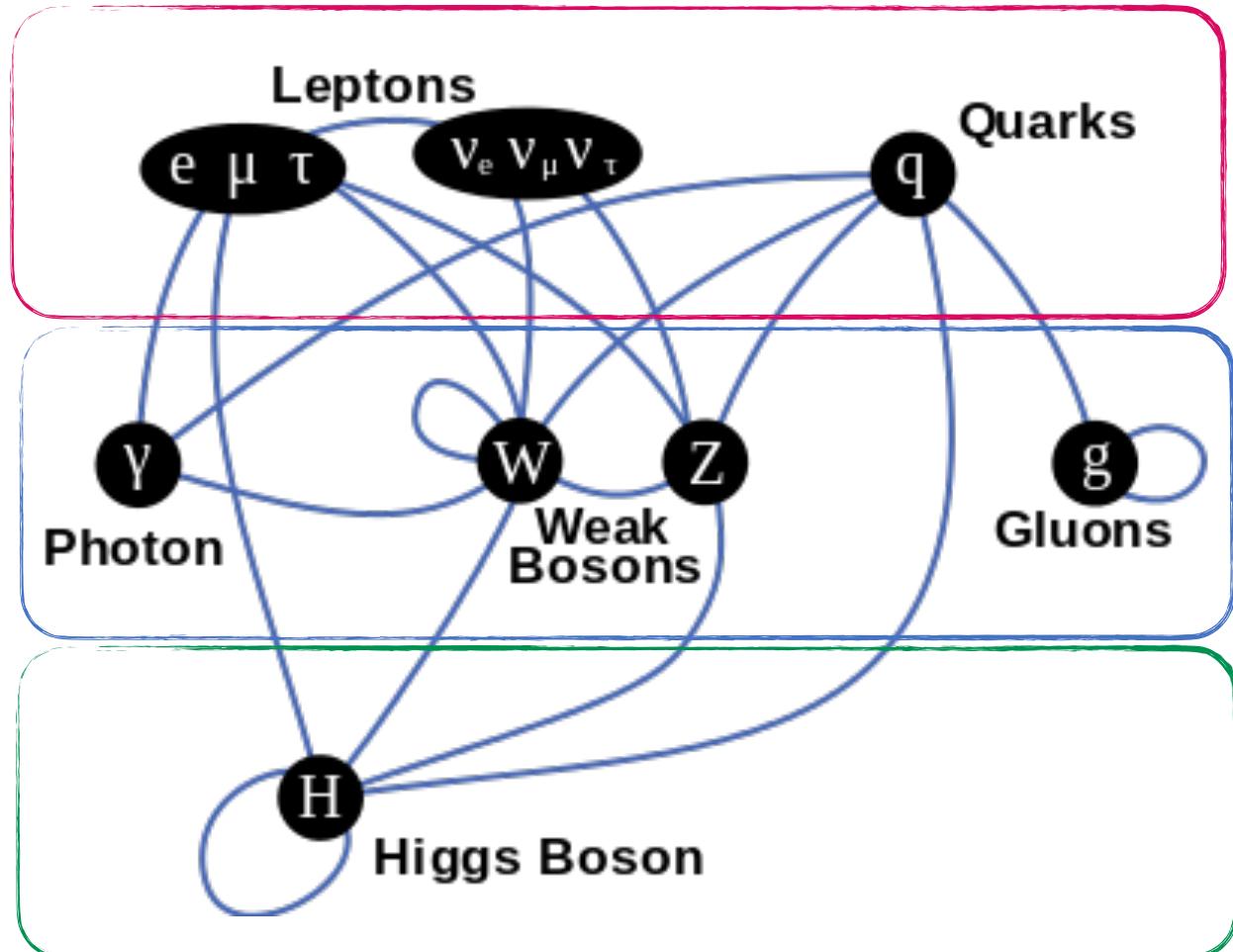
4 spin-1 bosons
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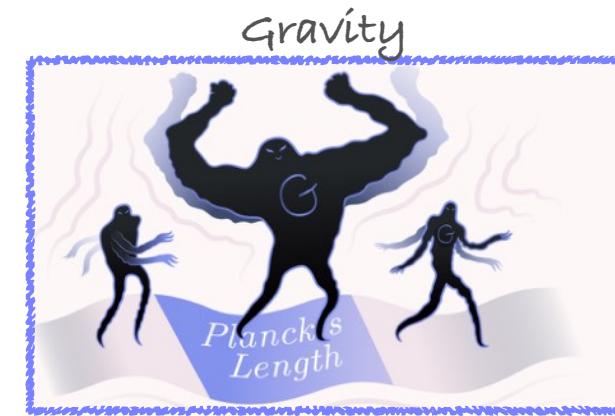
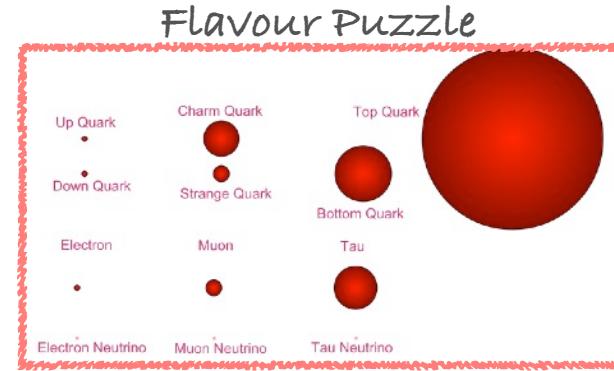
1 spin-0 boson
(Higgs boson)

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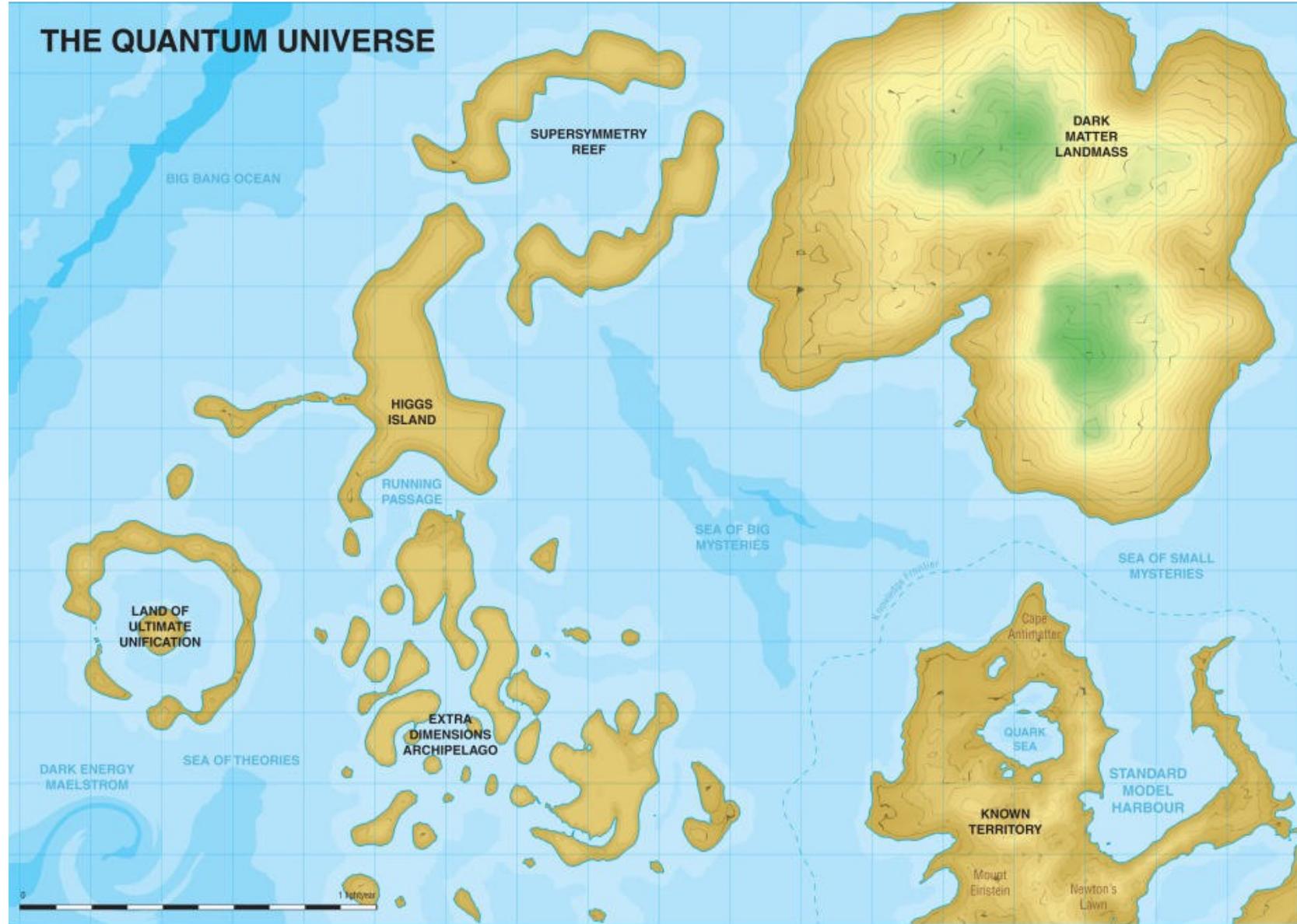


Limitations of the Standard Model

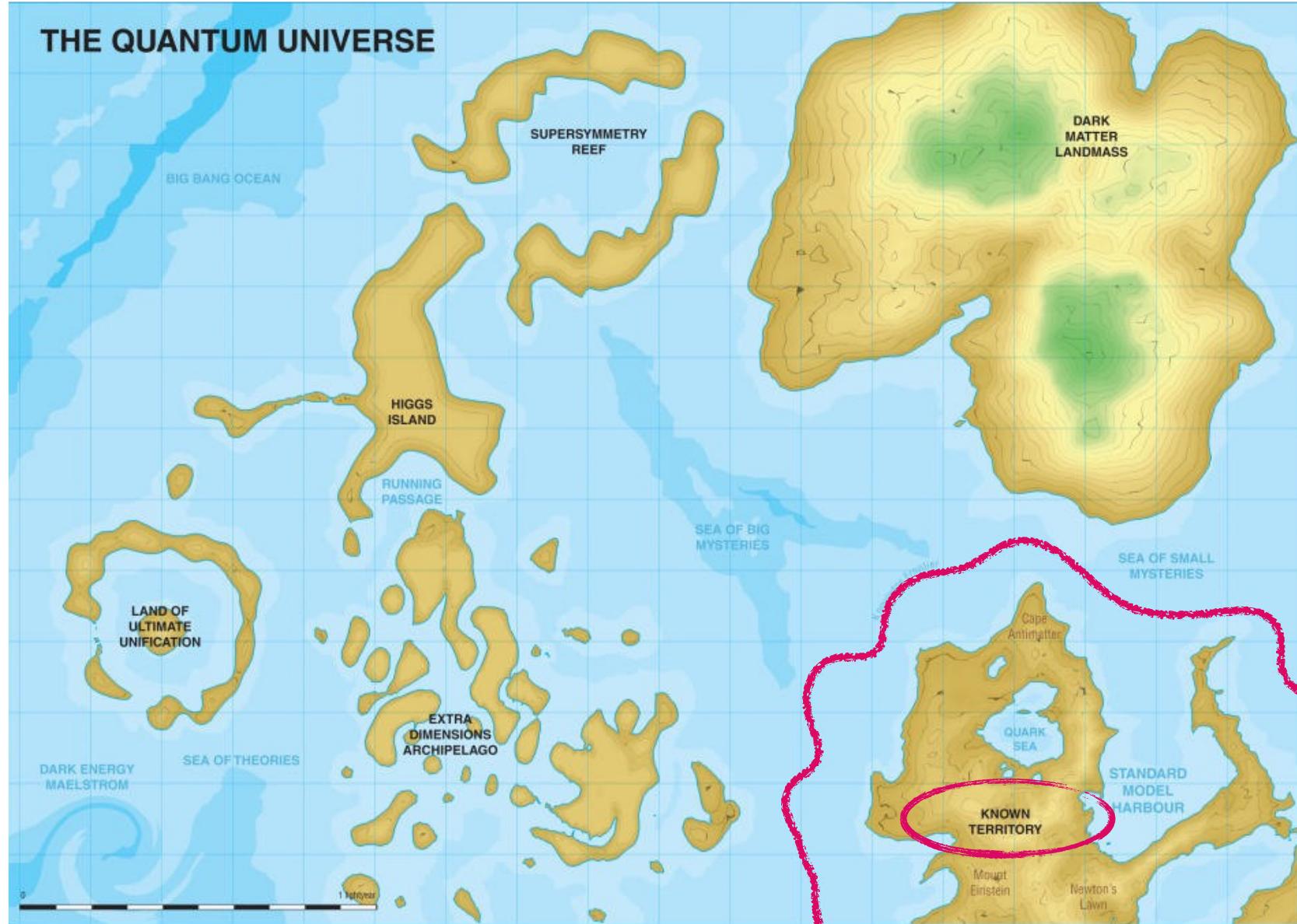
There are several reasons why we think the SM is the low-energy limit of a more general theory, e.g.:



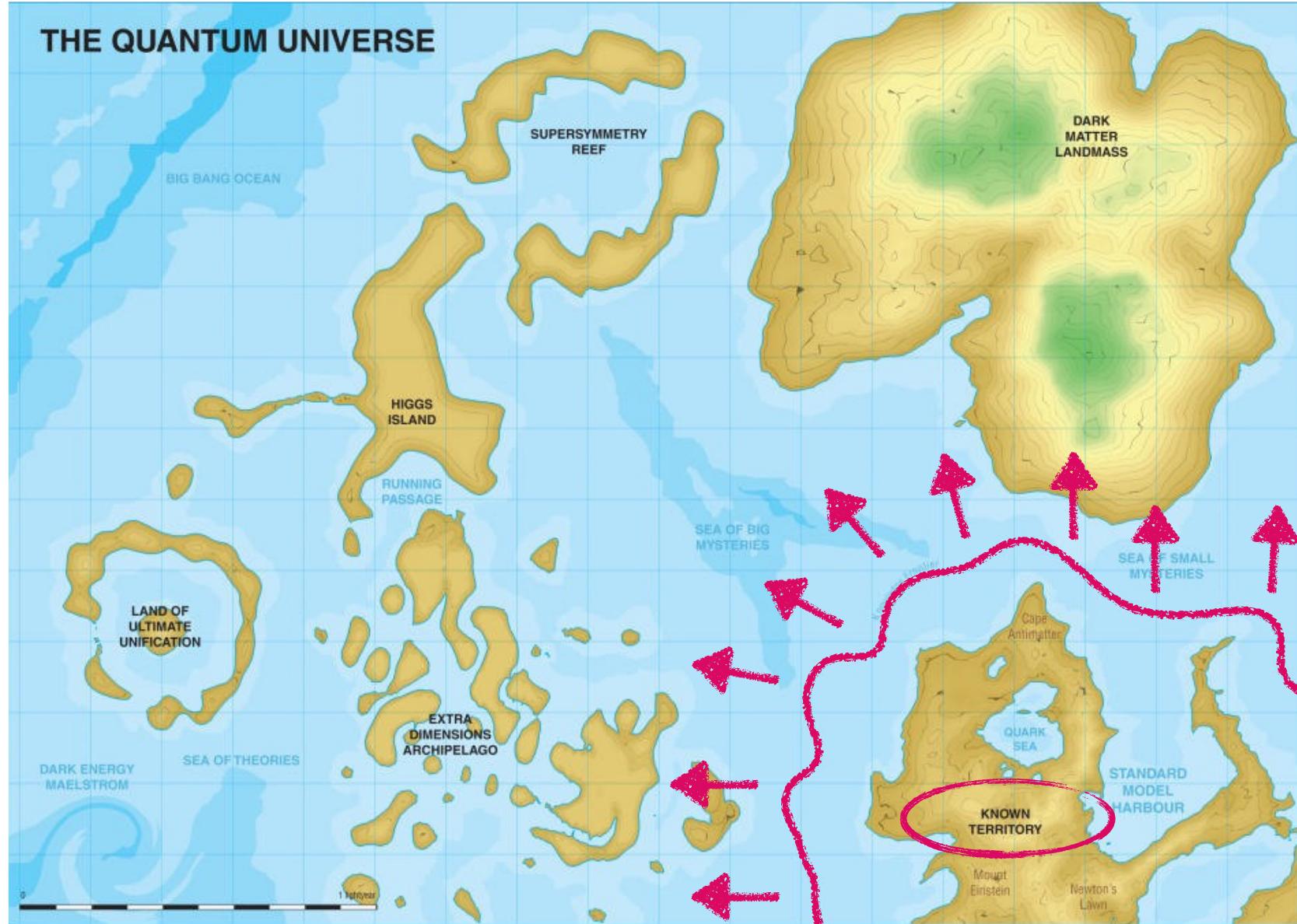
Extensions of the Standard Model



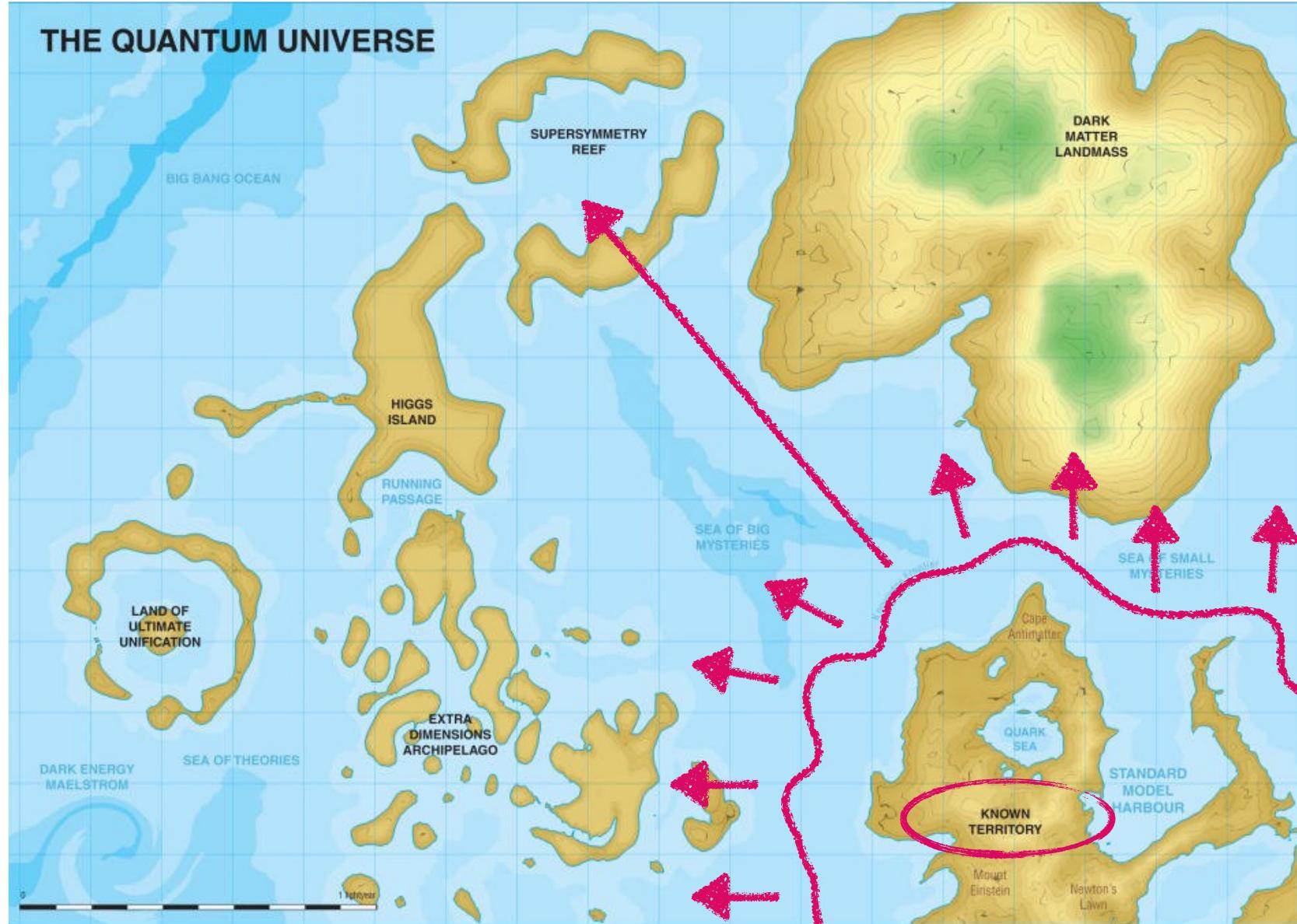
Extensions of the Standard Model



Extensions of the Standard Model



Extensions of the Standard Model



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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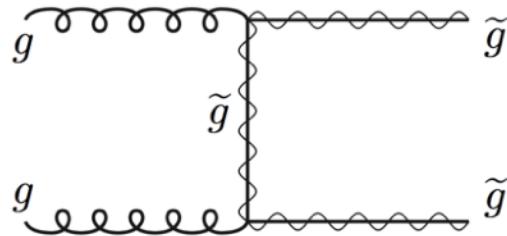
Two Higgs doublets

Mix to form charginos and neutralinos

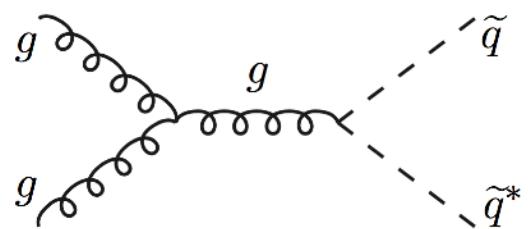


Looking for SUSY

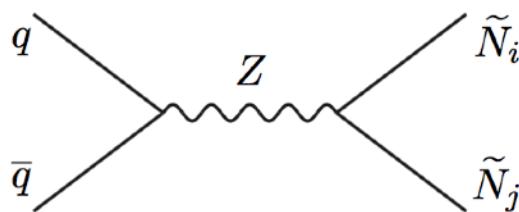
How are SUSY particles produced at the LHC? (*)



Gluino pair
production



Direct production
of third-generation
squarks

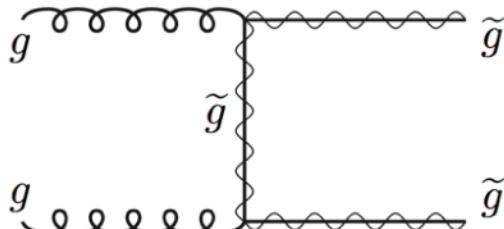


Electroweak
production of
charginos and
neutralinos

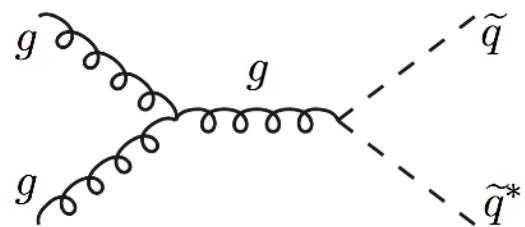


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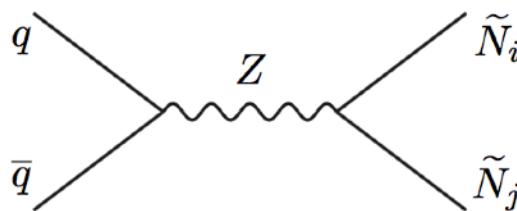
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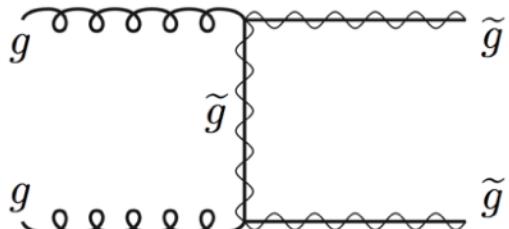


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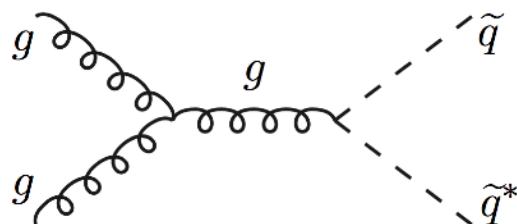


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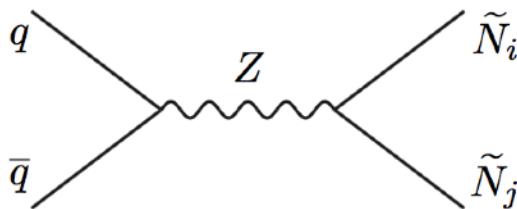
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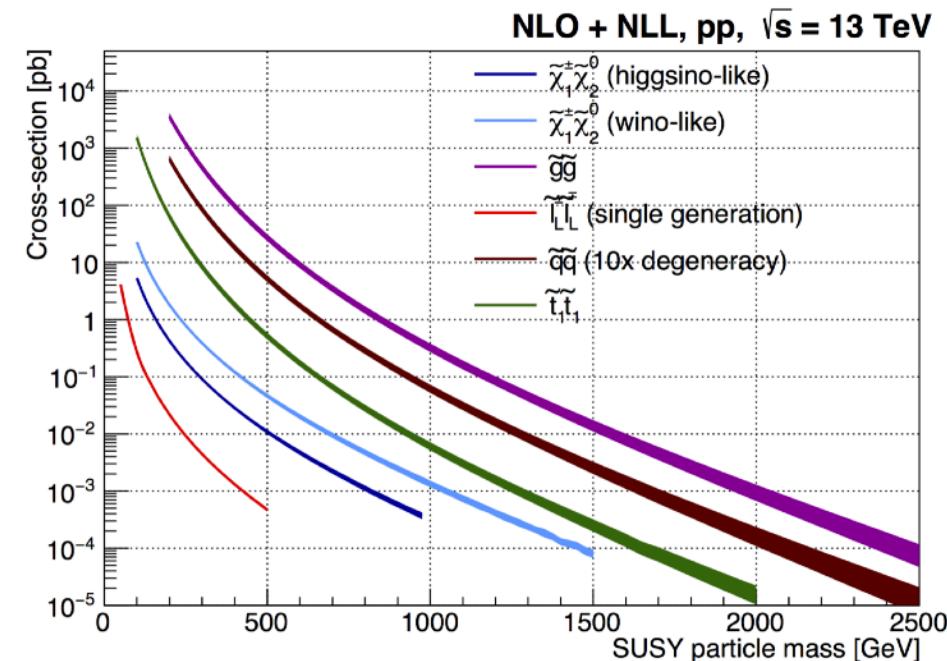
Gluino pair production



Direct production of third-generation squarks



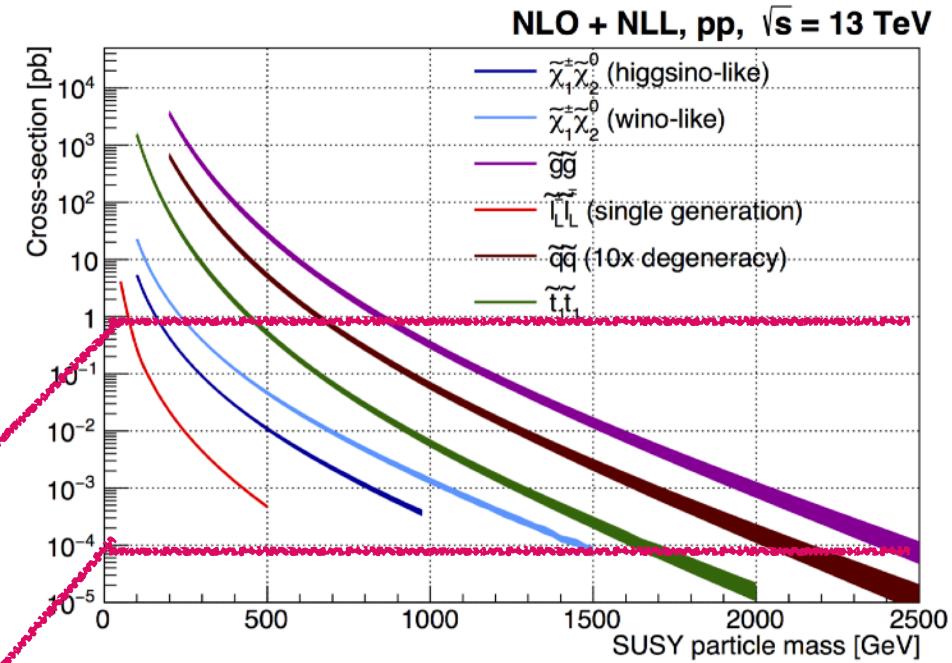
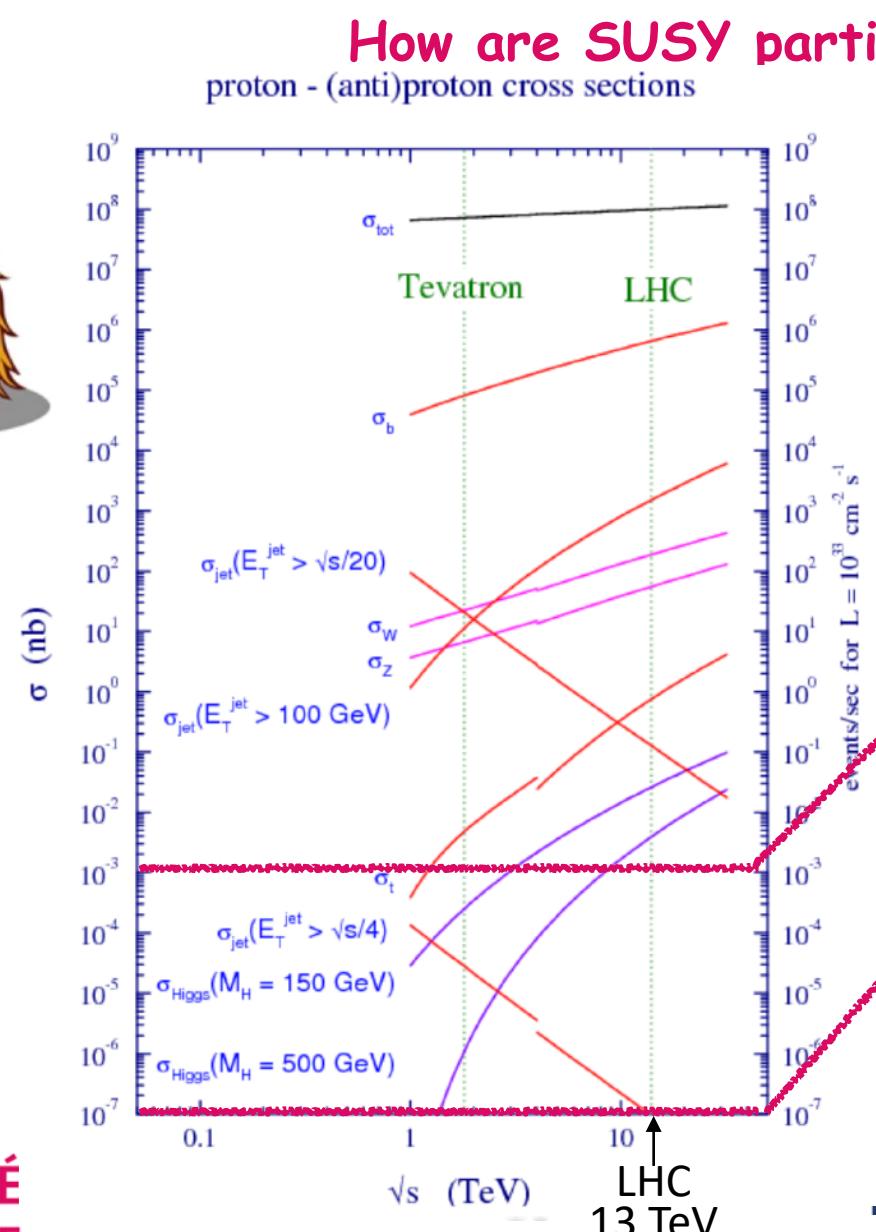
Electroweak production of charginos and neutralinos



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



Looking for SUSY



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

$$N_{\text{events}} = \mathcal{L} * \sigma$$

Product of luminosity and cross section



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

Looking for SUSY

How do SUSY particles decay?

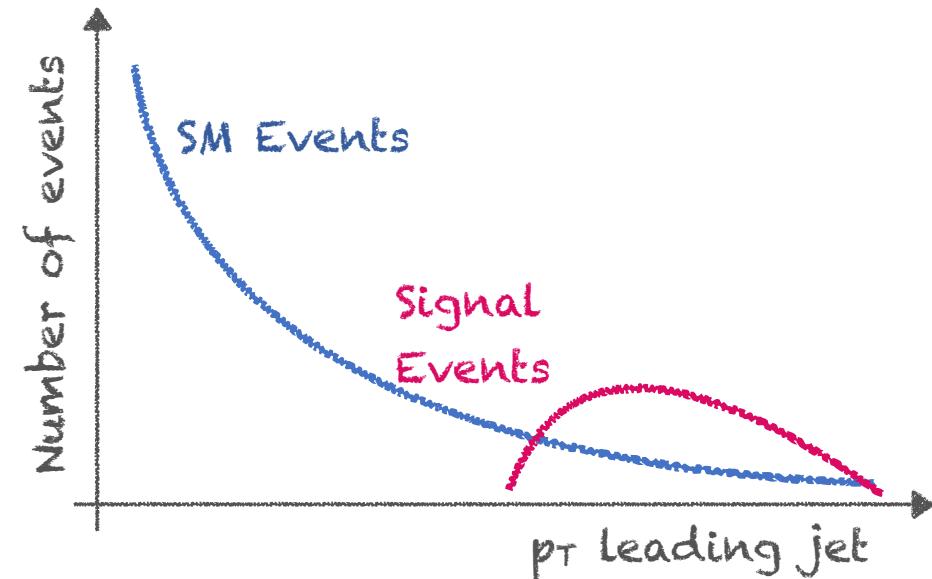
- The decay mode of SUSY particles depends on the parameters of the model
 - Several possible well motivated choices!
- Assumptions are needed to allow a search for SUSY particles
- **Simplified models** are simple models with only a few particles
 - Limit of more complex models where other particles 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

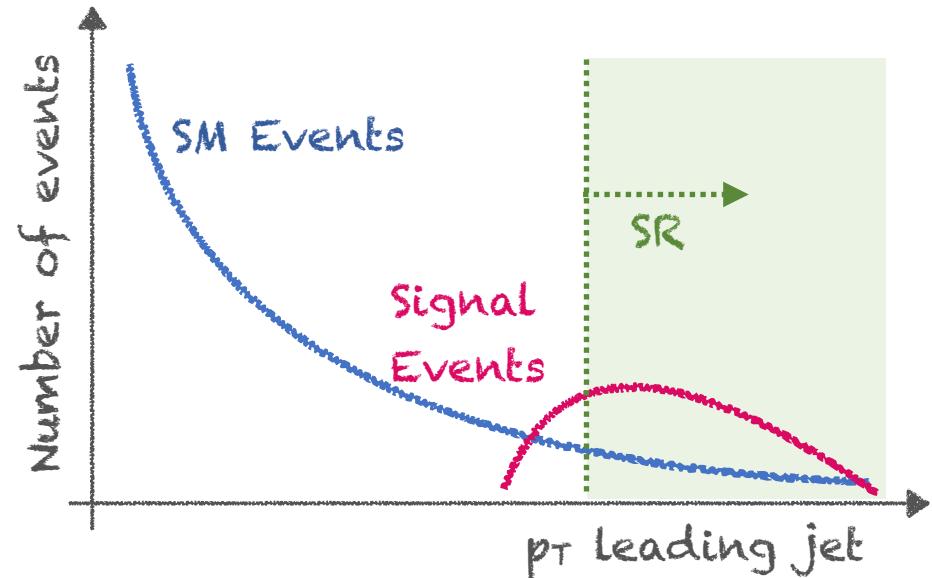
General Search Strategy

- 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)



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



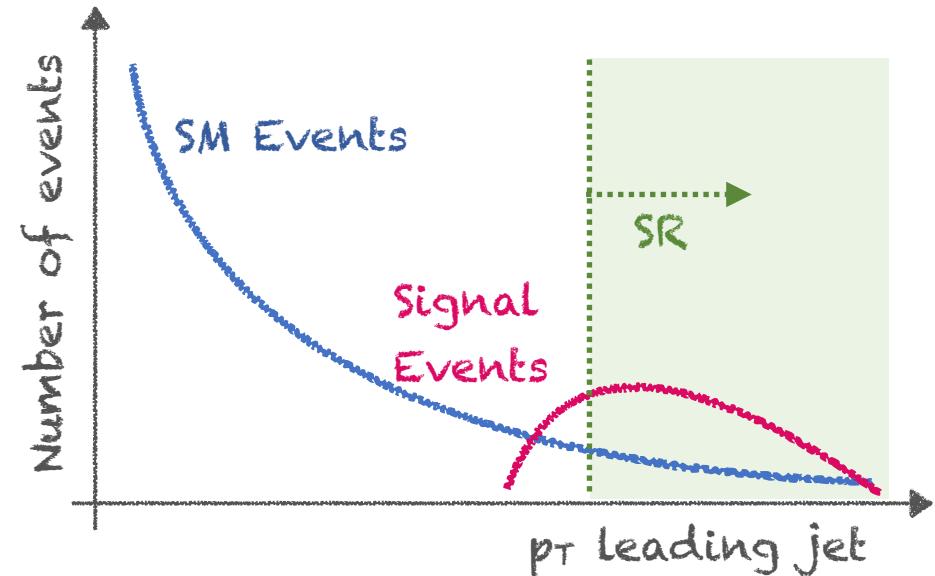
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General Search Strategy

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- Use these characteristics to define signal-enriched regions (SR)
- Derive an accurate **background estimate** in the SR (with an associated uncertainty)

Often the most time-consuming step of the analysis!

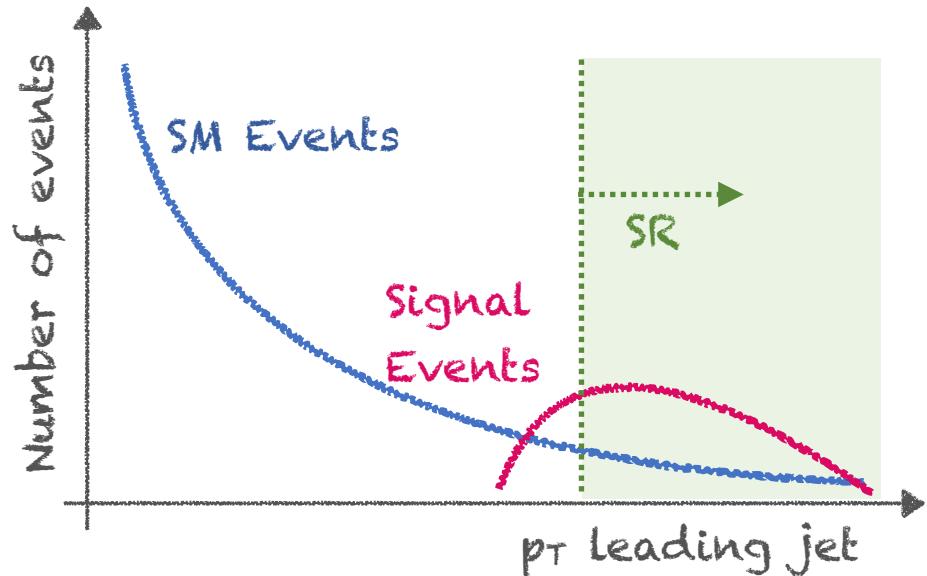


Simplest option: just count the total number of events in the SR

$$N_{\text{Bkg}} = X + \sigma X$$
$$N_{\text{sig}} = Y + \sigma Y$$

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



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

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

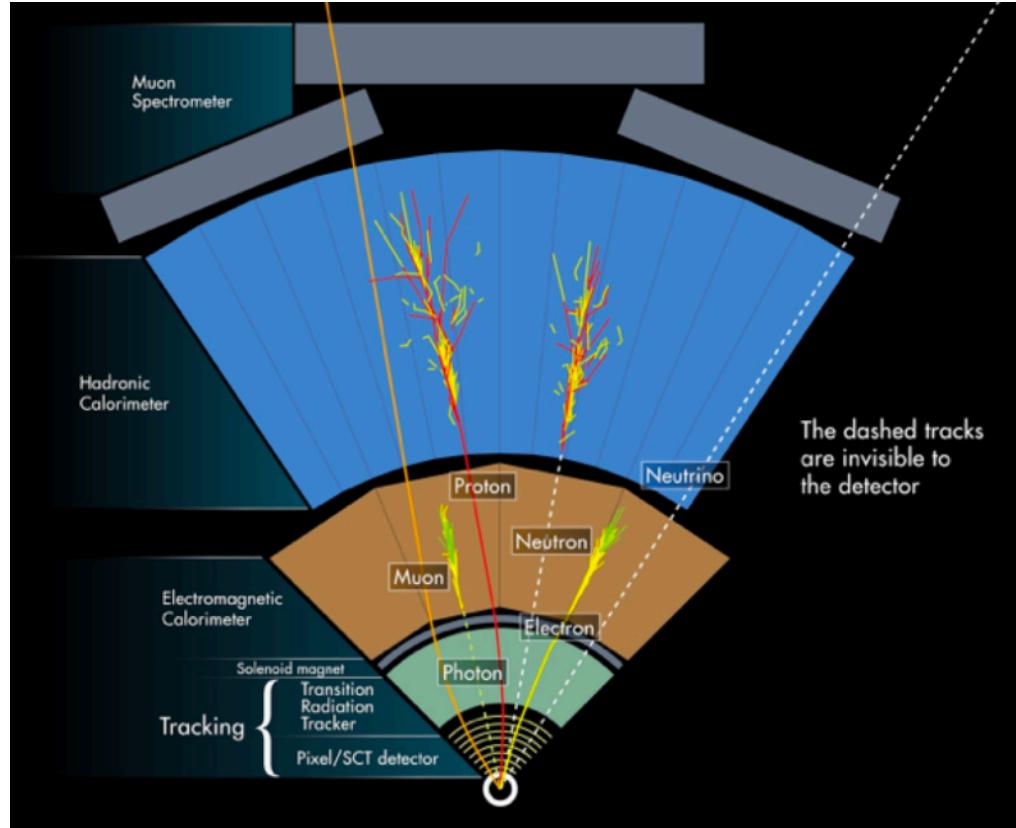
$$N_{sig} = Y + \sigma Y$$

$$N_{Data} = ?$$



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

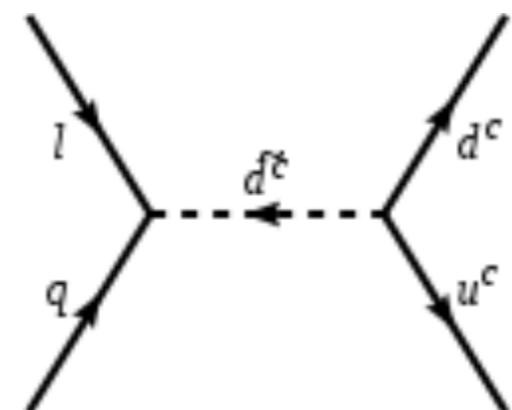


R-parity (and its violation)



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

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

- 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

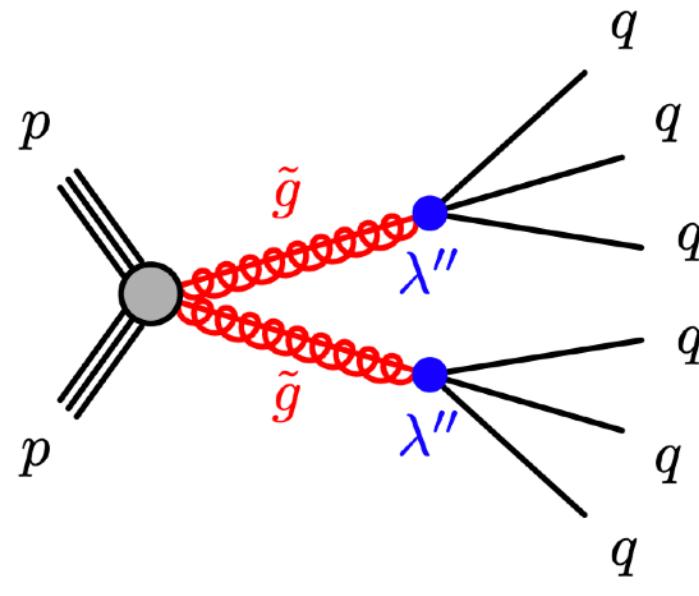


RPV Multi-jet Search

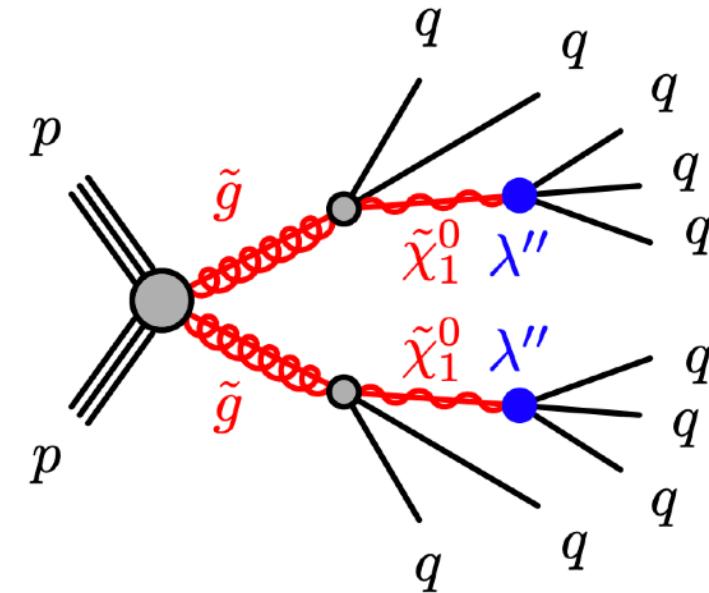


The Simplified Models We Look At

6-jets Model

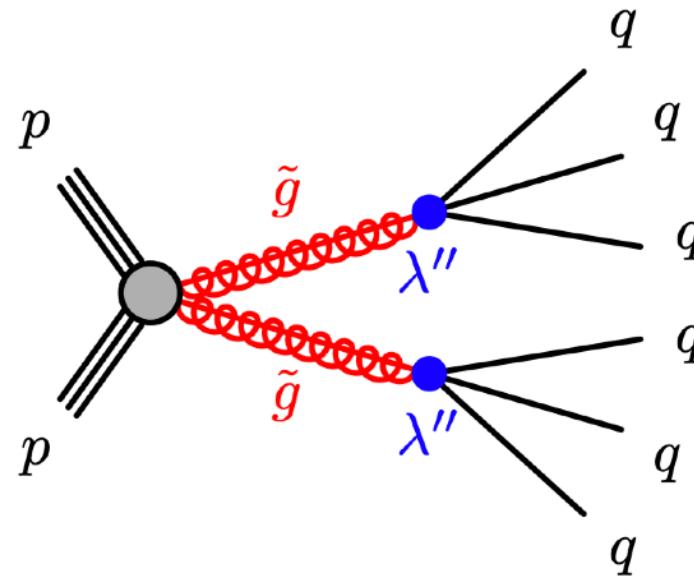


10-jets Model

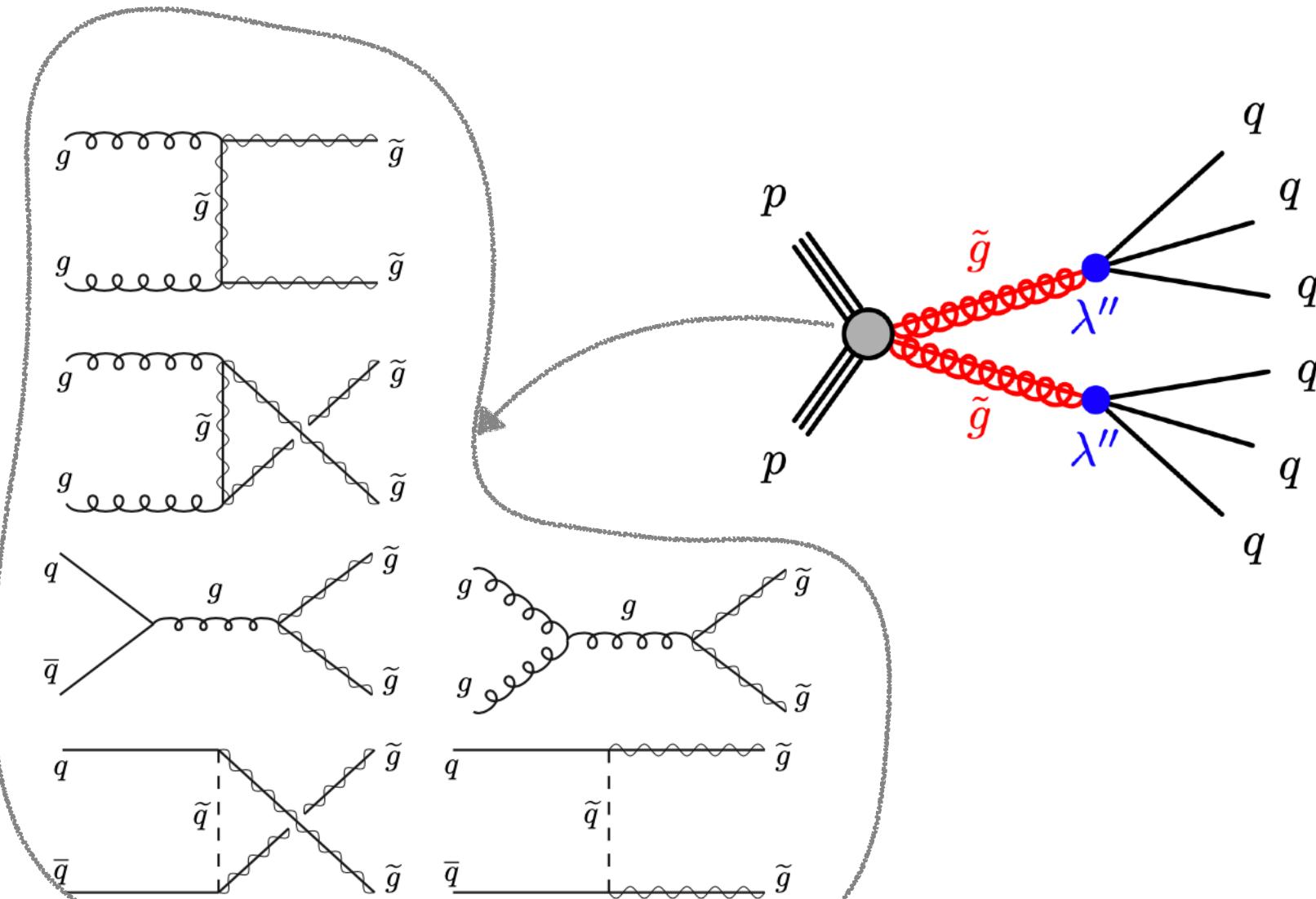


Limits for these models from previous analyses in backup

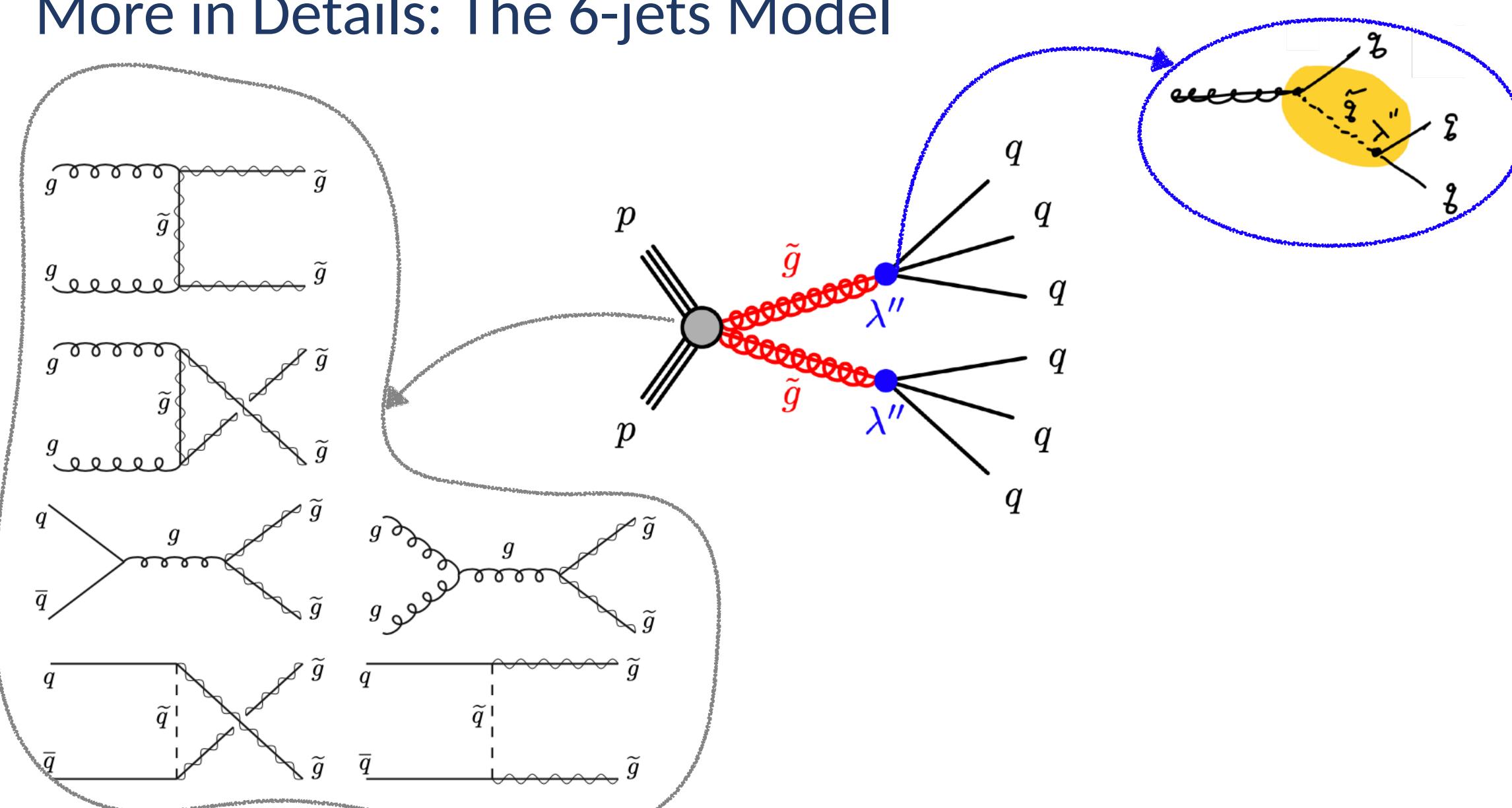
More in Details: The 6-jets Model



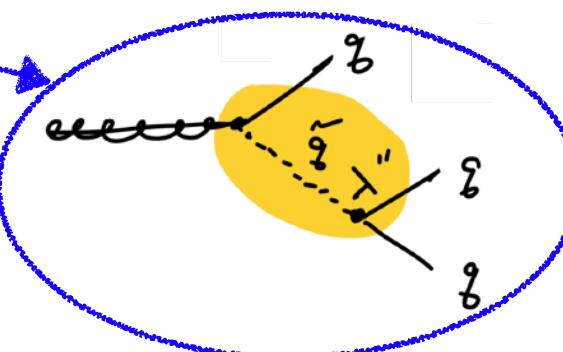
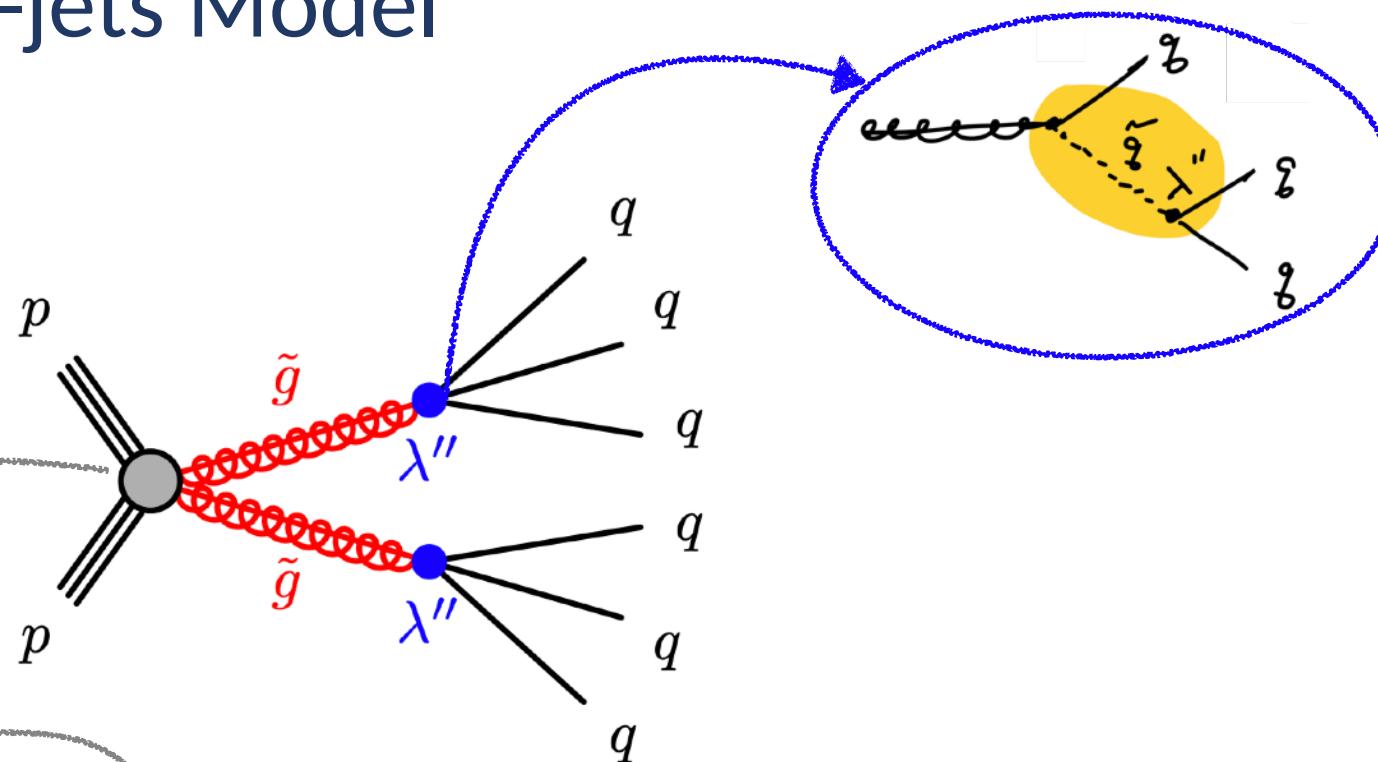
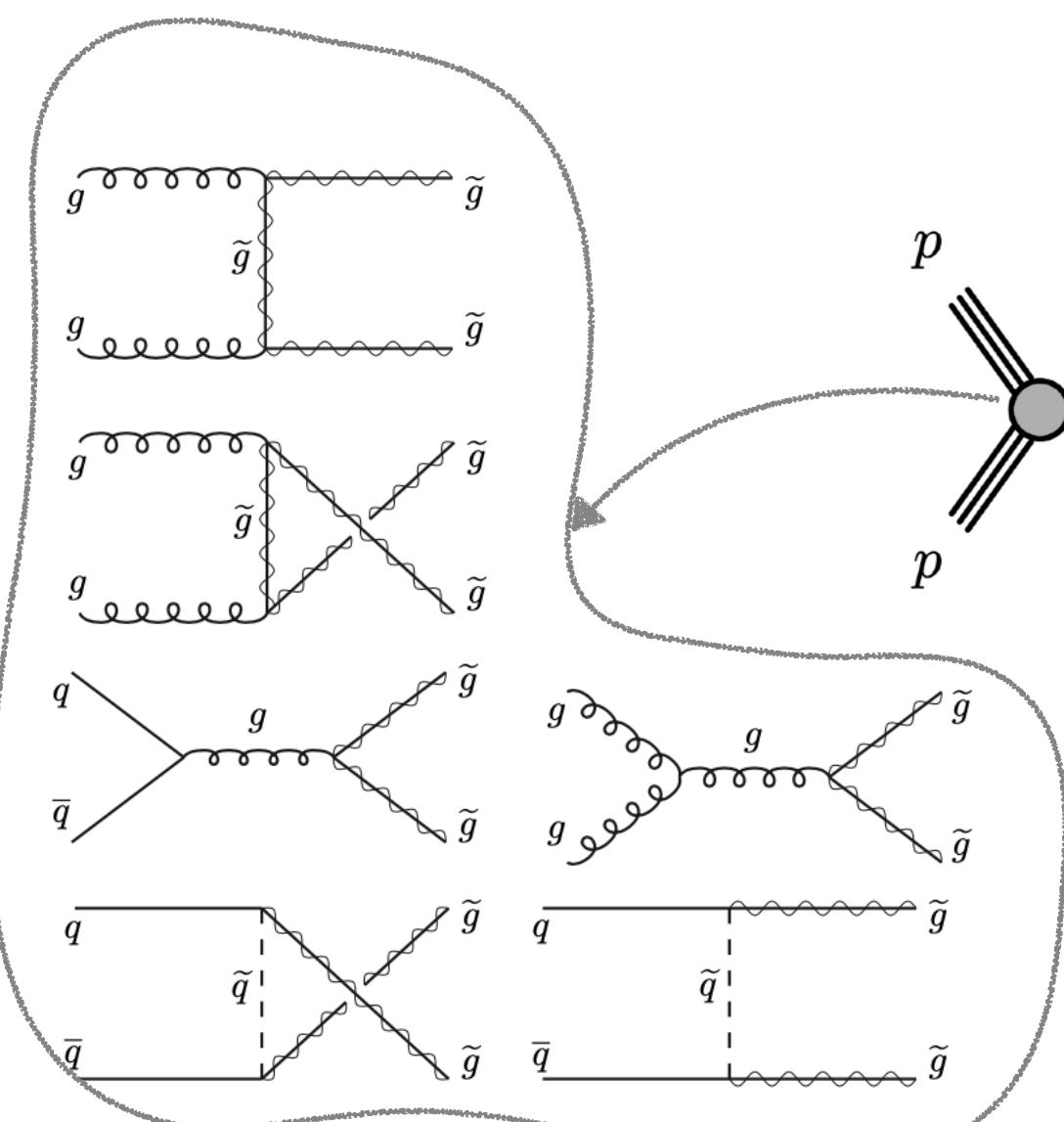
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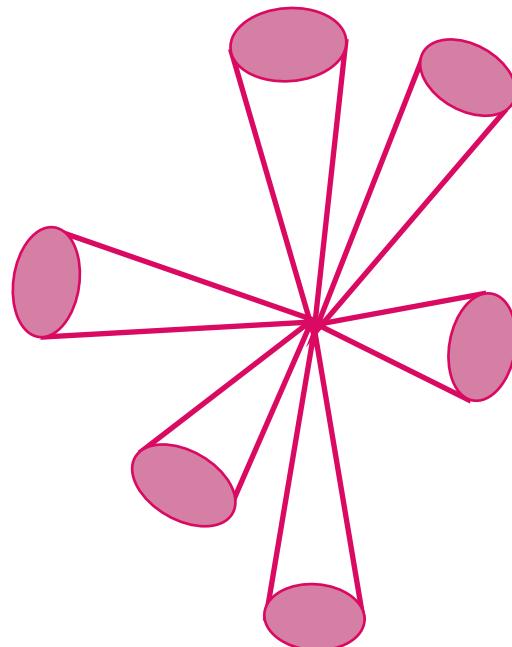
More in Details: The 6-jets Model



- 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

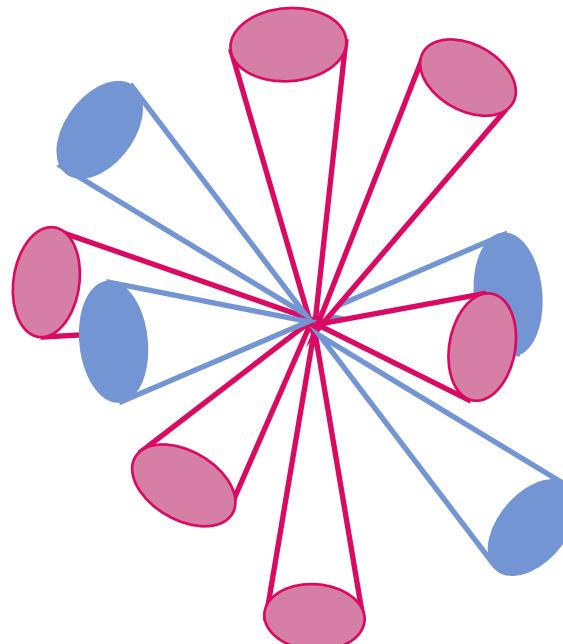
What do the Events Look Like?

- Jets originating from the gluinos



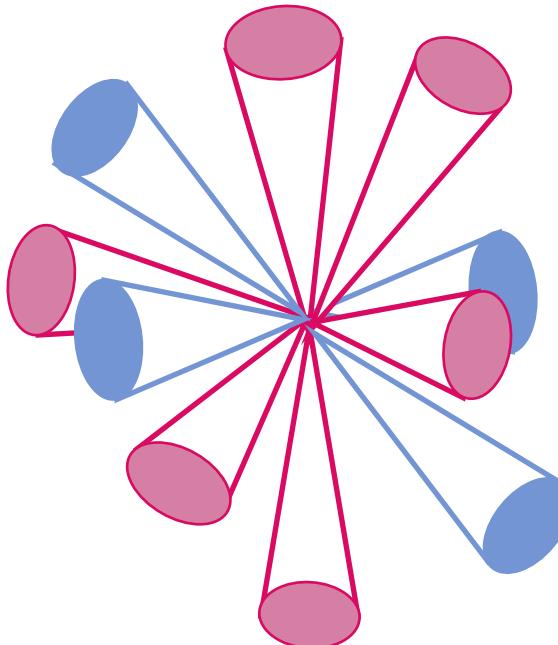
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- But also extra jets from radiation —> complicated events
- Signal events are simulated with Monte Carlo techniques



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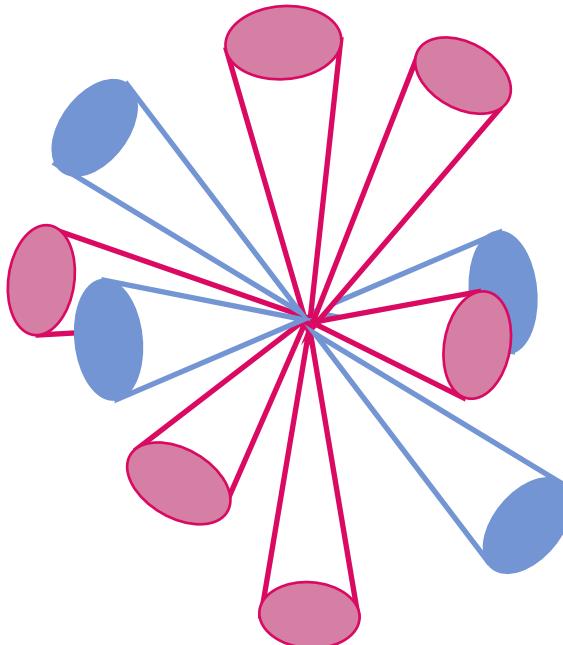


Challenge: very large background

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

What do the Events Look Like?

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



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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Ongoing analysis activities are addressing these challenges!

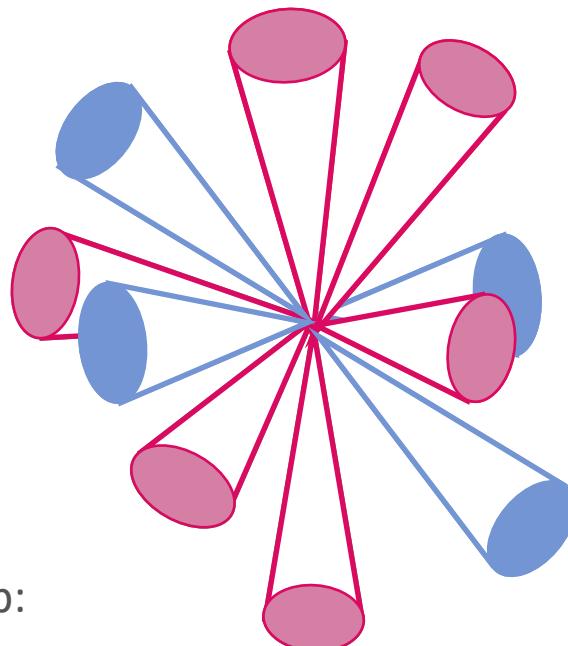
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Analysis Activity — Alpaca

- 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

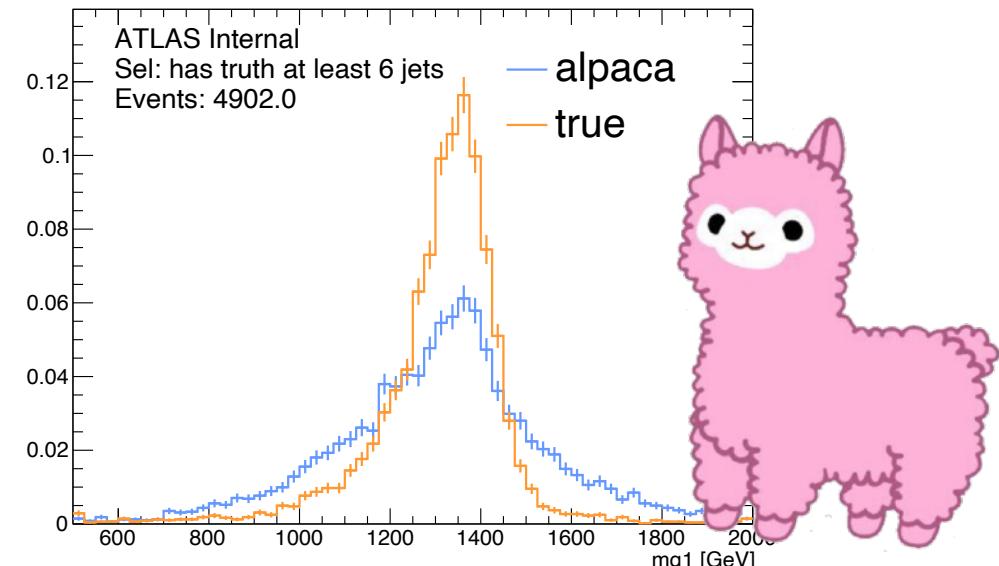


Involved people from our group:

Anna, TJ, Riccardo, Chiara

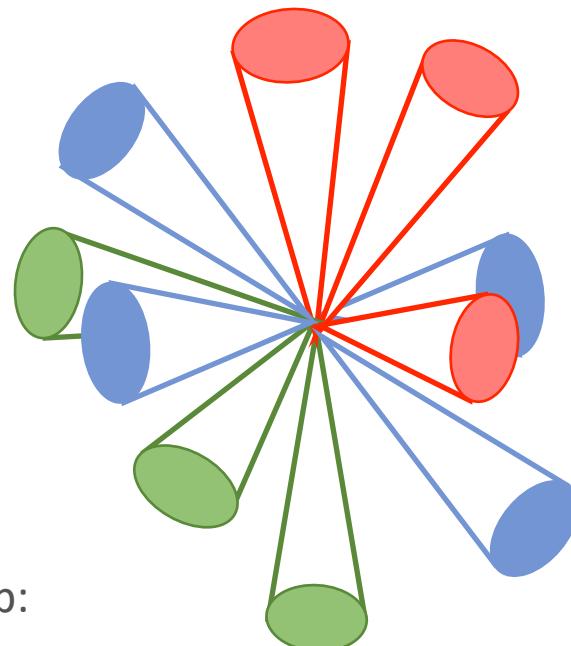
But also from the analysis team:

CERN, Bern, Harvard and Cambridge groups



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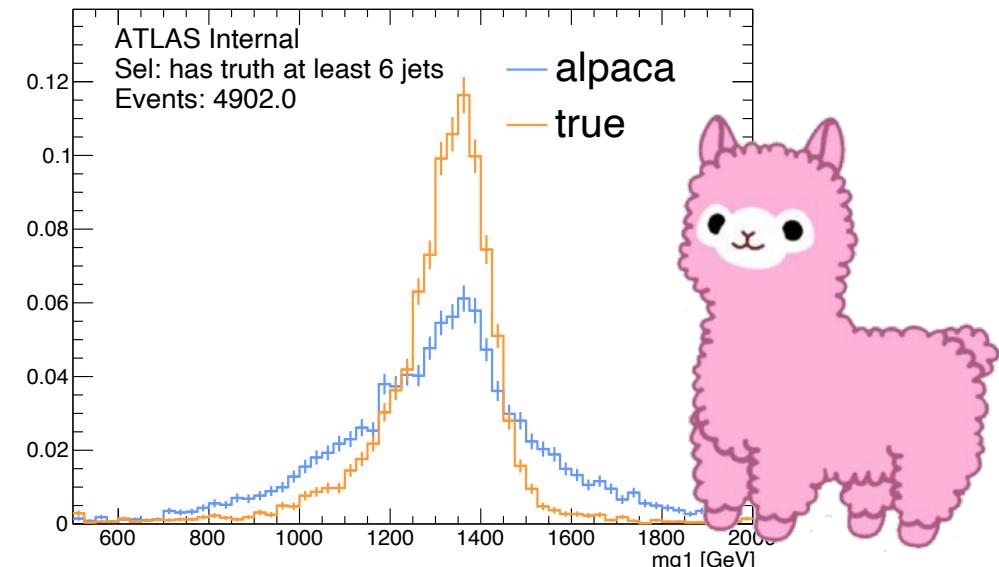


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Analysis Activity – Quark-Gluon Tagging

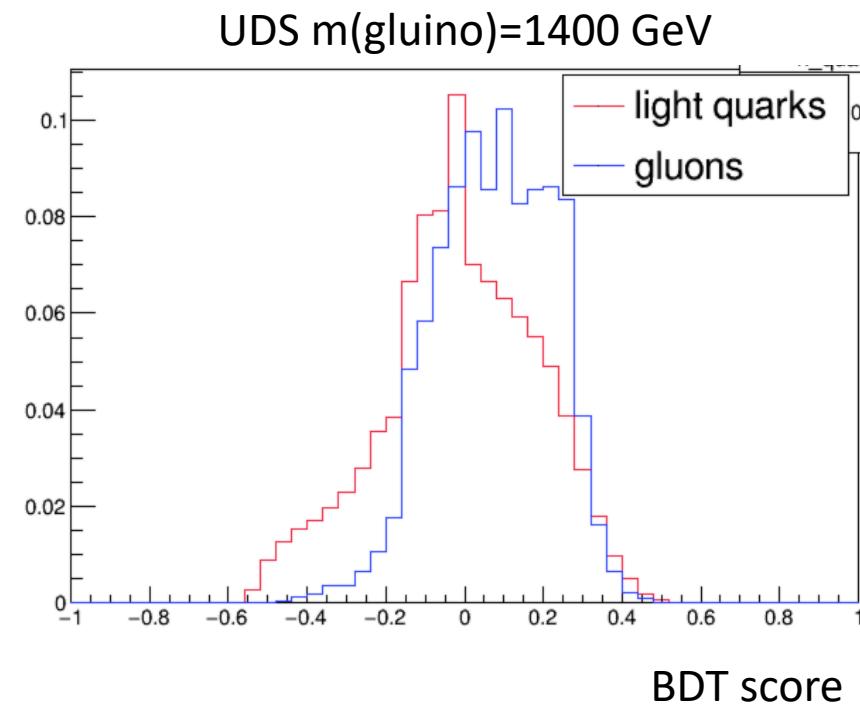
- Jets originating from the hadronization of quarks and gluons have different substructure characteristics
- This is can be useful for the analysis!
 - Jets from the gluino → hadronization of quarks
 - Extra jets from radiation → can originate from gluons
- E.g. use as input to alpaca only quark-tagged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

Involved people from our group:

Anna, Chiara, Snigdho

But also from the analysis team:

Oxford group



Analysis Activity — Backgrounds

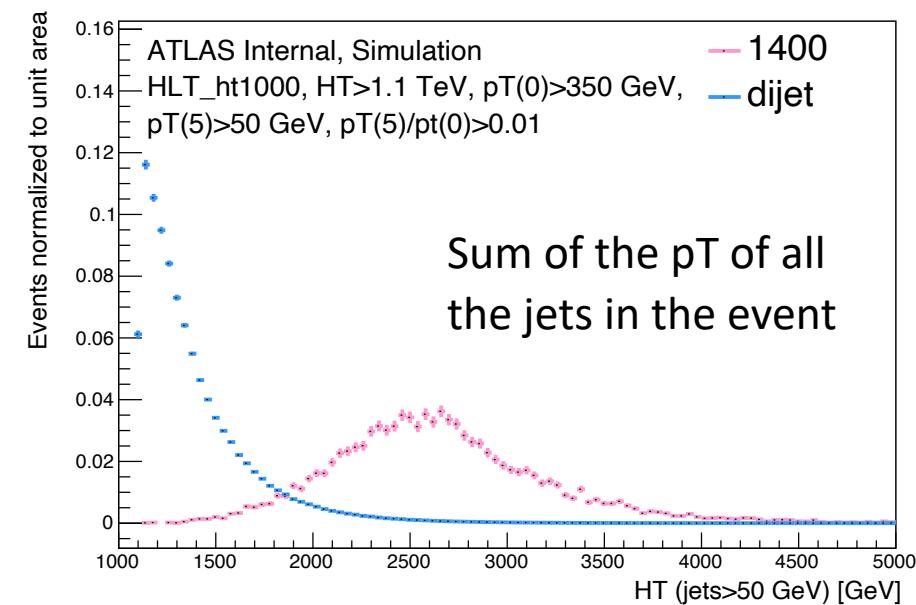
- Background estimate
 - We need to find ways to have a reliable background (QCD) estimate
 - With systematics
- Background suppression
 - We need to identify variables that allow us to reduce the background while having a good signal efficiency

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Oxford Group



Analysis Activity — TLA

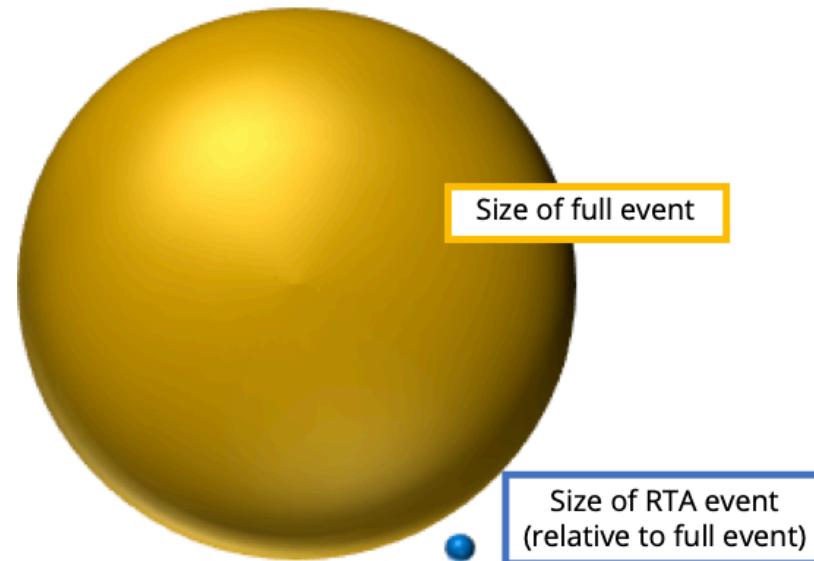
- TLA: trigger-level analysis
 - Current trigger thresholds allow to select only events with extremely energetic jets → low acceptance for low-mass gluinos
 - Reducing the amount of information that we store for each events, we can reduce the used bandwidth and have much lower trigger thresholds
- [Talk from Claire](#) (UniGe account required to open the link)

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	$\tilde{u}_L \ \tilde{u}_R \ \tilde{d}_L \ \tilde{d}_R$ $\tilde{s}_L \ \tilde{s}_R \ \tilde{c}_L \ \tilde{c}_R$ $\tilde{t}_L \ \tilde{t}_R \ \tilde{b}_L \ \tilde{b}_R$	(same) (same) $\tilde{t}_1 \ \tilde{t}_2 \ \tilde{b}_1 \ \tilde{b}_2$
sleptons	0	-1	$\tilde{e}_L \ \tilde{e}_R \ \tilde{\nu}_e$ $\tilde{\mu}_L \ \tilde{\mu}_R \ \tilde{\nu}_\mu$ $\tilde{\tau}_L \ \tilde{\tau}_R \ \tilde{\nu}_\tau$	(same) (same) $\tilde{\tau}_1 \ \tilde{\tau}_2 \ \tilde{\nu}_\tau$
neutralinos	1/2	-1	$\tilde{B}^0 \ \tilde{W}^0 \ \tilde{H}_u^0 \ \tilde{H}_d^0$	$\tilde{N}_1 \ \tilde{N}_2 \ \tilde{N}_3 \ \tilde{N}_4$
charginos	1/2	-1	$\tilde{W}^\pm \ \tilde{H}_u^+ \ \tilde{H}_d^-$	$\tilde{C}_1^\pm \ \tilde{C}_2^\pm$
gluino	1/2	-1	\tilde{g}	(same)
goldstino (gravitino)	1/2 (3/2)	-1	\tilde{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

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

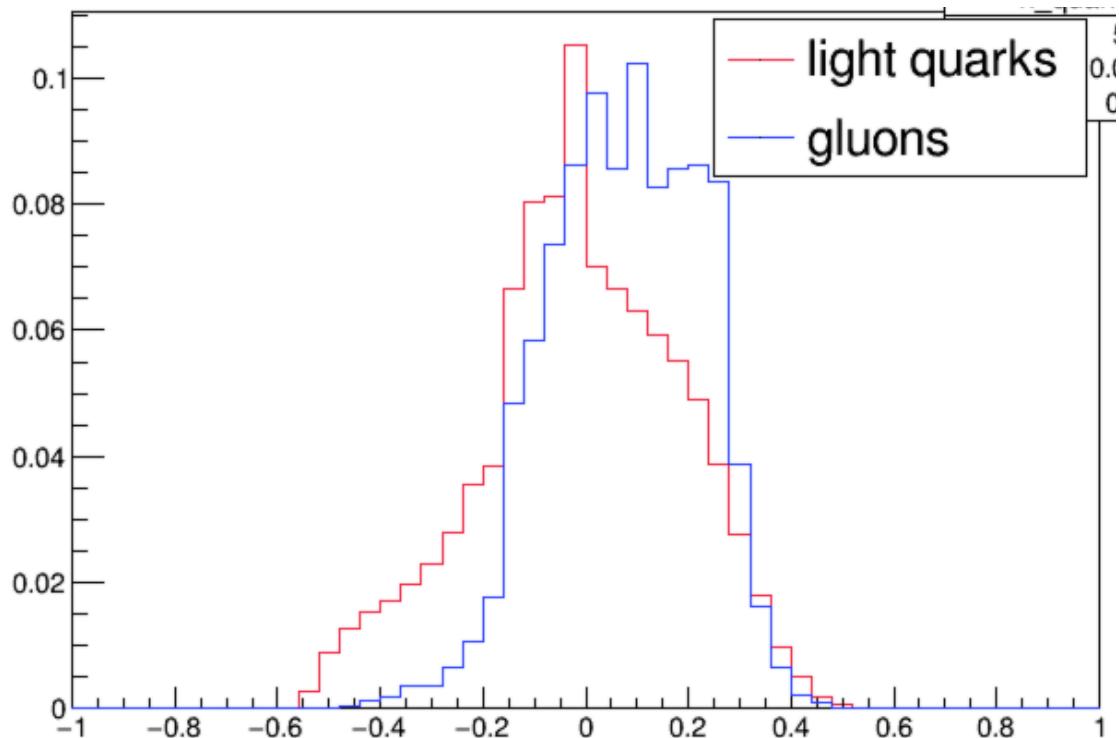
- Rrack-pT weighted width of the jet

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

- Two-point energy correlation function

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

UDS $m(\text{gluino})=1400 \text{ GeV}$



Previous ATLAS Limits

