Using ML to Break the Unnaturalness of Nature

Lawrence Lee

THE UNIVERSITY OF TENNESSEE KNOXVILLE

UTK CMS

Why is the Higgs so light?

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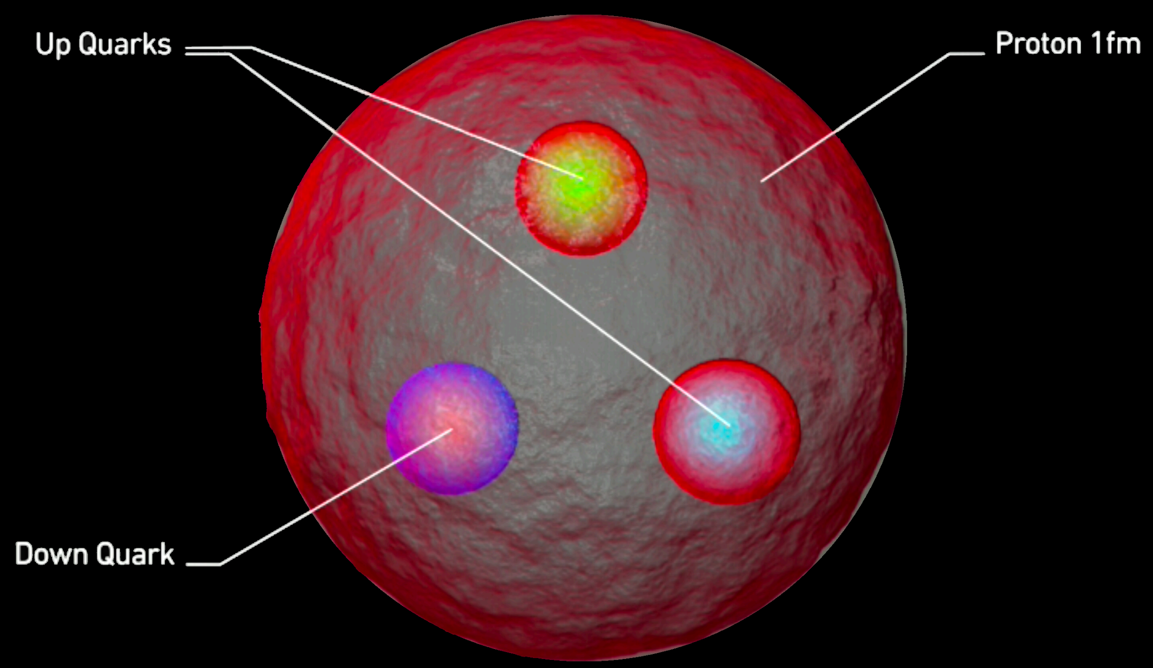

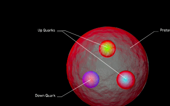

125 GeV

1 GeV

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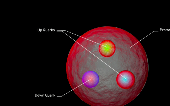

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IF WE TAKE STANDARD MODEL TOO SERIOUSLY...

Bare mass and quantum corrections need to cancel **34 decimal places** to match observations

34TH DIGIT OF PI

$\pi \cong 3.1415926535\ 8979323846\ 2643383279\ 5028841971\ 6939937510\ \ldots$

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χ ≅ 3.1415926535 8979323846 2643383279 5022431232 3654386221 ...

But the SM says this is truly a coincidence
in the Higgs mass calculation!

The Naturalness Problem

"Unnatural" if unrelated numbers just happen to cancel to **34 decimal places**

Why is the Higgs sector so *unnatural?*

Only a problem because $\mathbf{m_{Planck} >> m_H}$

i.e. Why is gravity so much weaker than the other forces?

The (Gauge) Hierarchy Problem

$$m_H^2 = m_{H,bare}^2 + \Delta m^2$$

$$\Delta m^2 = \sum_f \Delta m_f^2 + \sum_b \Delta m_b^2$$

REMEMBER:

Higgs likes to couple to **heavy** particles
(it's ~why they're heavy)

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Higgs likes to couple to **heavy** particles
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And these couplings give Δm^2!

So the **top quark**
(heaviest SM particle)
is the worst offender!

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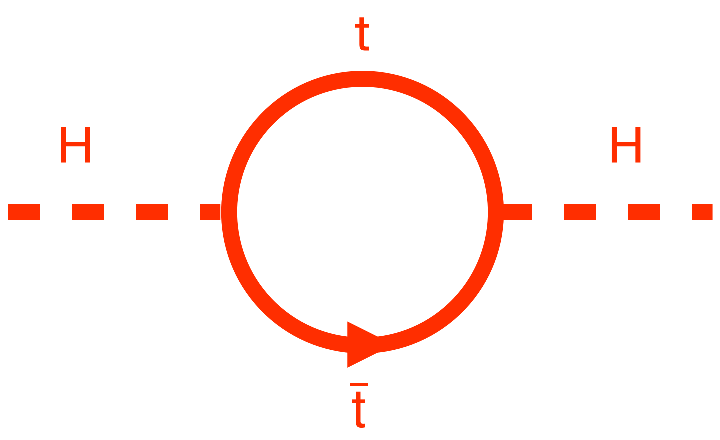

$$\Delta m^2 = \Delta m_t^2 \ + \ \ldots$$

$$\sim - c_t \, \Lambda_{UV}^2 + \ \ldots$$

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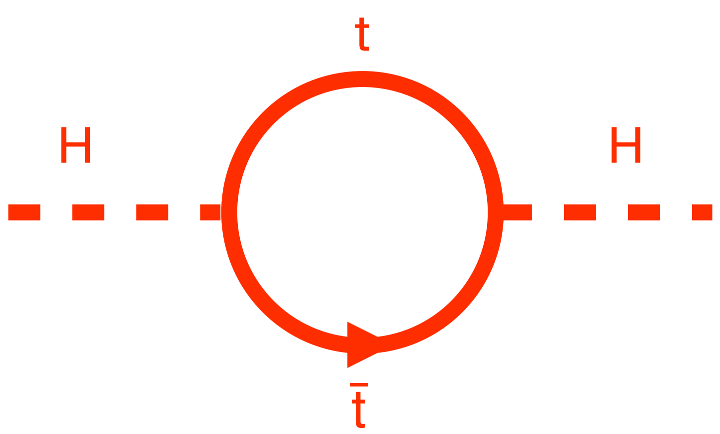

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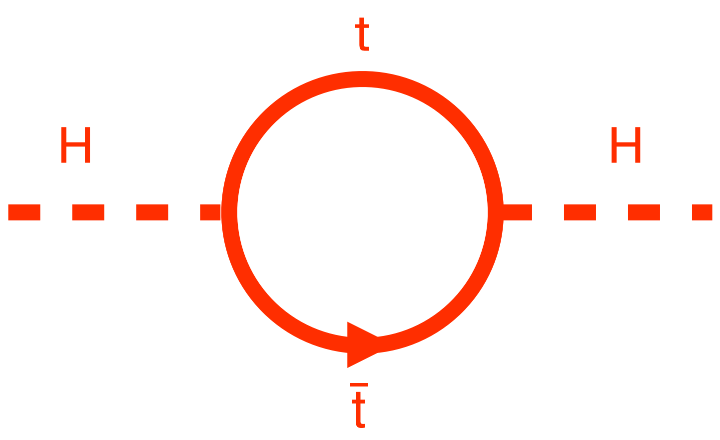

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Some constant given the quantum numbers of the top quark

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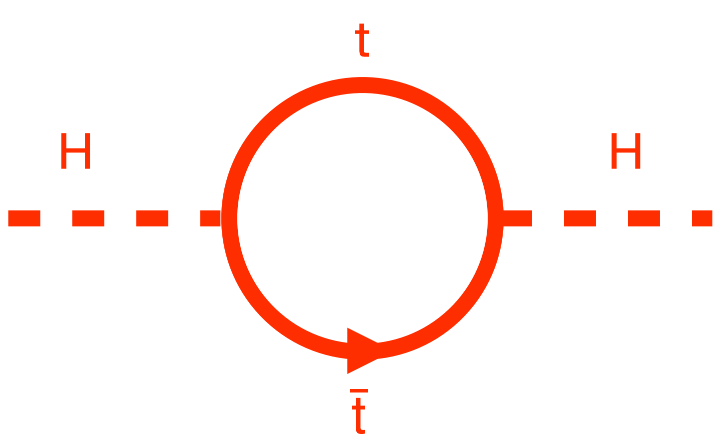

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That gross quad. divergence

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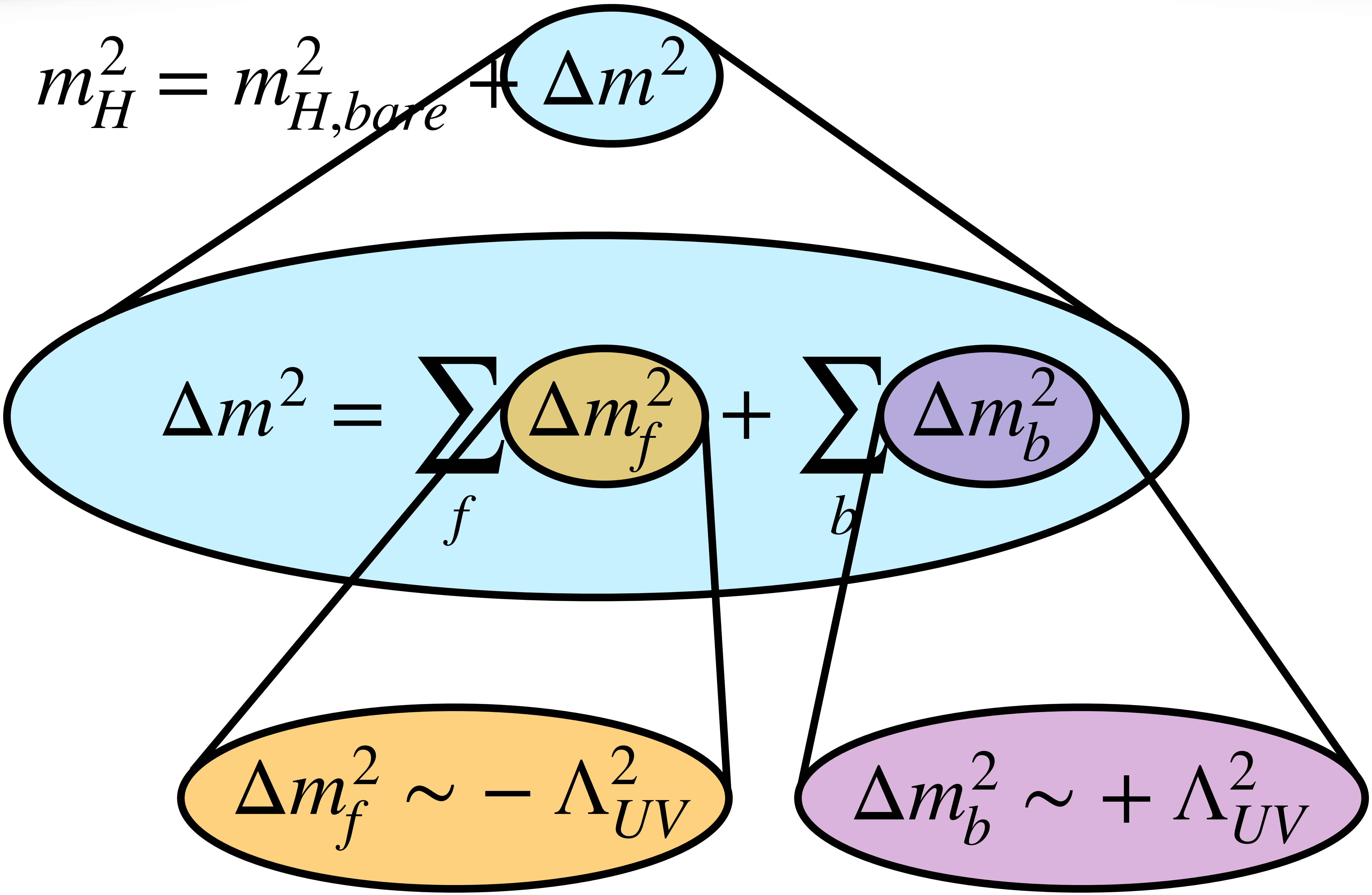

To leading order fermions and bosons contribute with opposite sign

Problem: Our issue is that Δm^2 is getting really big because it's so sensitive to the UV cutoff

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$$\Delta m_f^2 \sim -\Lambda_{UV}^2$$

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SUPERSYMMETRY (SUSY):

Fundamental relationship between fermions and bosons

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Fundamental relationship between fermions and bosons

1/2 Spin "Rotation"

s=1/2 fermions

SM Electron $e \longleftrightarrow \tilde{e}$ SUSY Selectron

SM Quarks $q \longleftrightarrow \tilde{q}$ SUSY Squarks

s=0 bosons

$$\Delta m_f^2 \sim -\Lambda_{UV}^2 \qquad \Delta m_b^2 \sim +\Lambda_{UV}^2$$

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If every SM particle had a SUSY partner
w/ same quantum numbers (except spin),
We could cancel off these quadratic divergences

$$m_H^2 = m_{H,bare}^2 - \Delta m^2$$

10^4 GeV^2

Λ_{UV}^2

$(1\ \text{TeV})^2$

$$O(10^4) = \,?\, - O(10^6)$$

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10^6 GeV^2 → $(1$ TeV$)^2$

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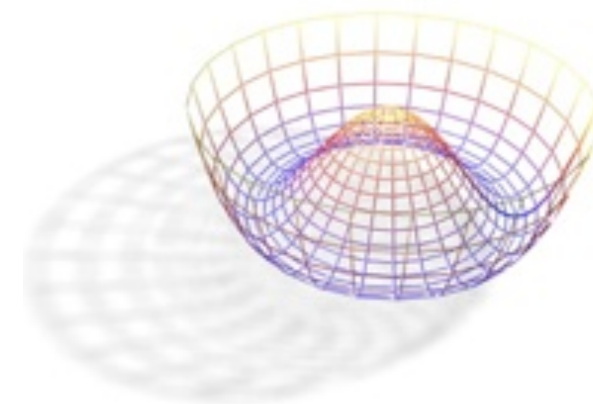
HINT FROM NATURE

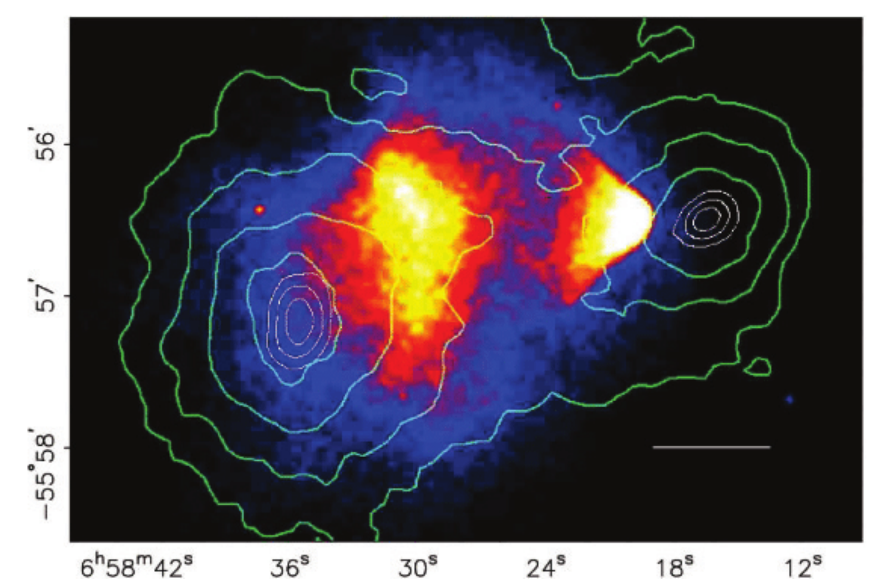
FOR WHERE TO LOOK!

Supersymmetry is pretty super

- **TeV-Scale SUSY can solve a lot of problems simultaneously**
  - **Deflates naturalness problem**
  - **Electroweak Symmetry Breaking just falls out**
  - Gives hope for **gauge coupling unification**
  - Convenient **WIMP DM candidate** in the lightest SUSY particle (LSP)
  - SUSY is the only mathematically possible extension of the Poincaré group. Why wouldn’t it be realized in nature? (HLS)

~~1 in 10^{34}~~





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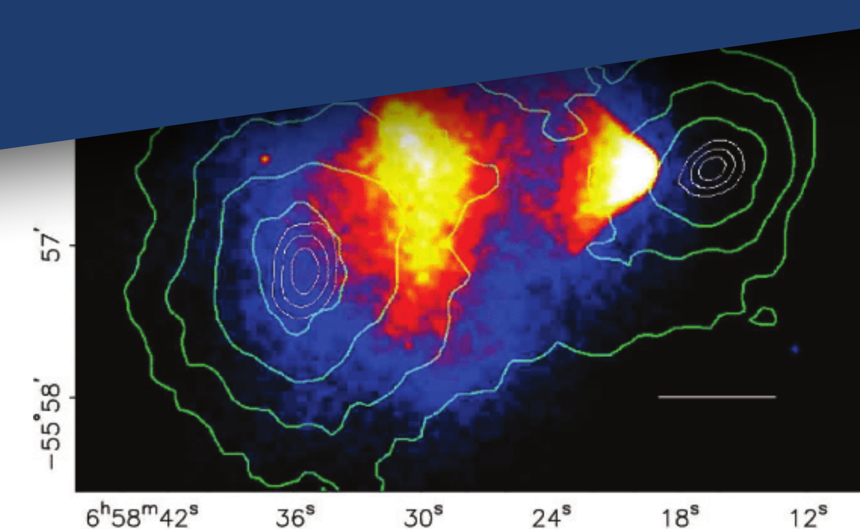

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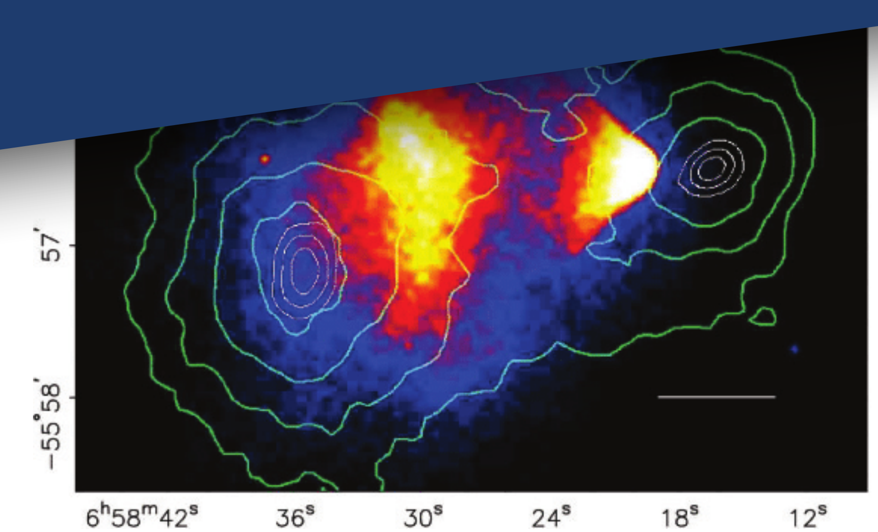

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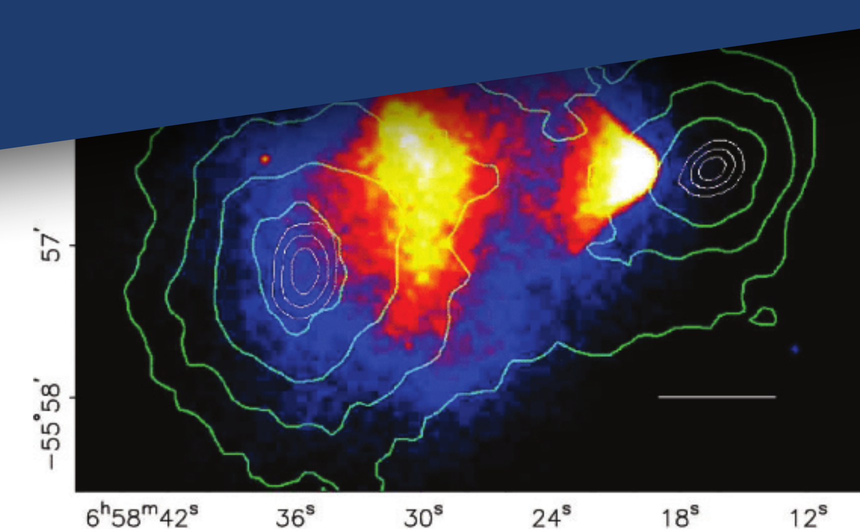
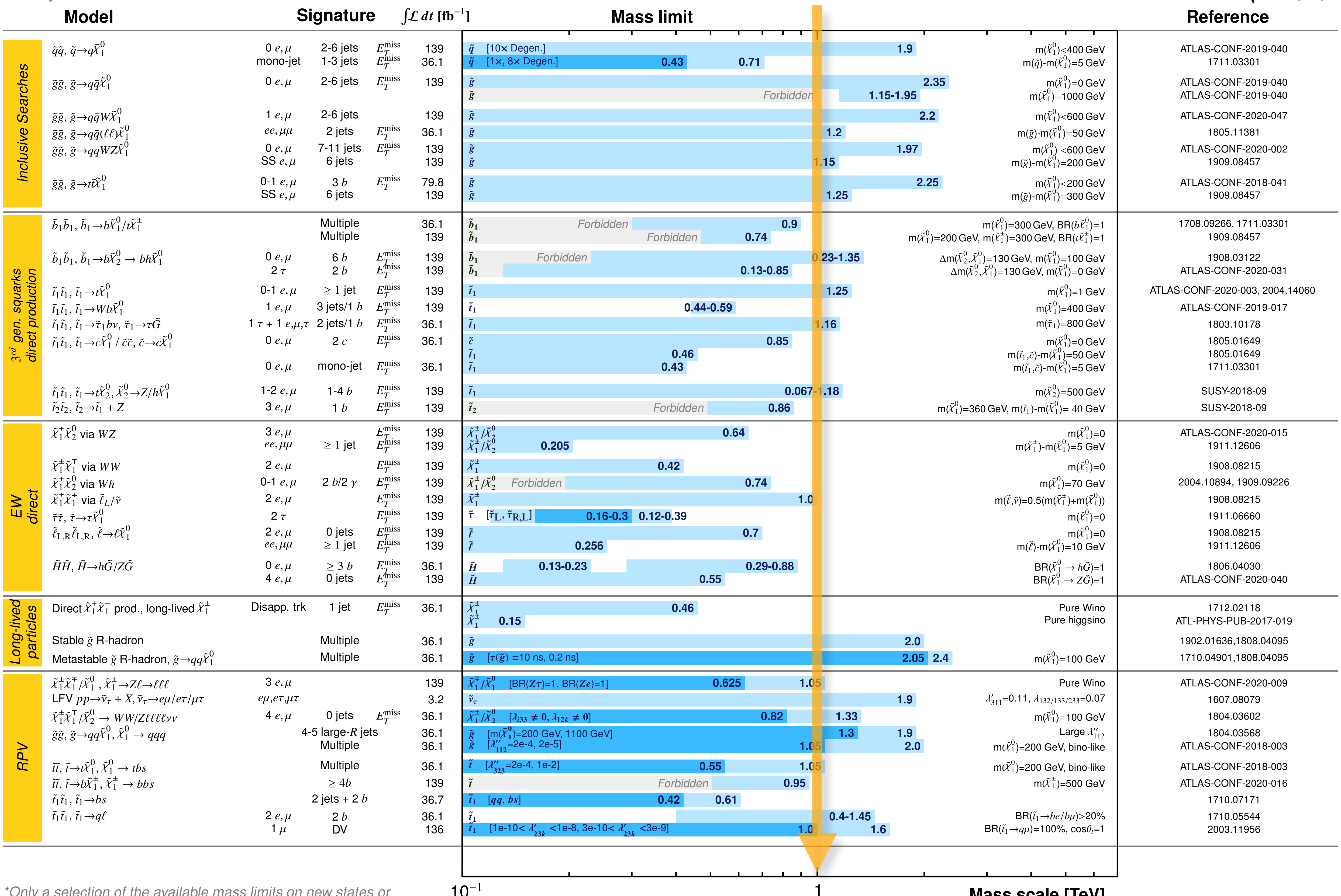


ATLAS SUSY Searches* - 95% CL Lower Limits

July 2020

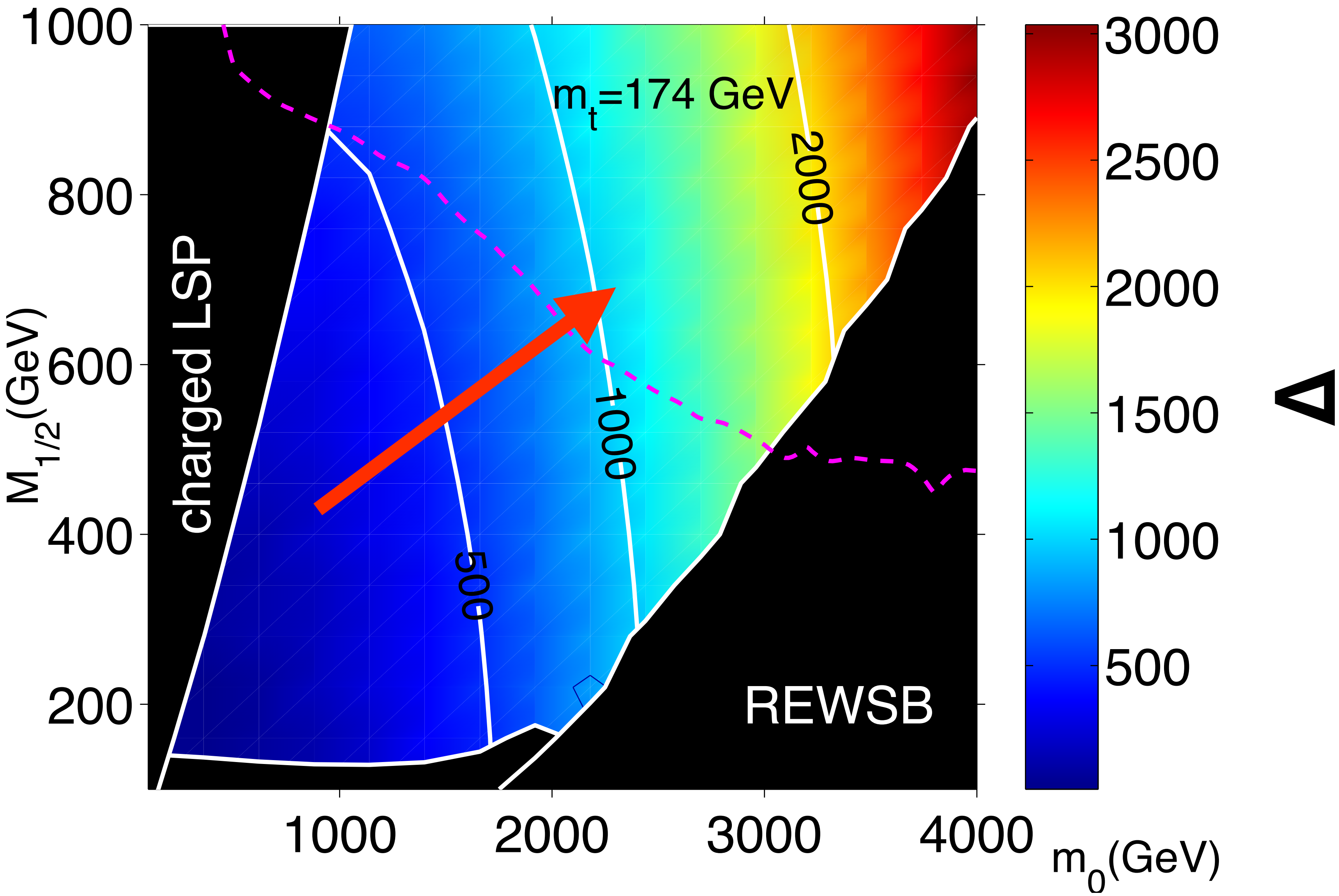
ATLAS Preliminary

$\sqrt{s}$ = 13 TeV



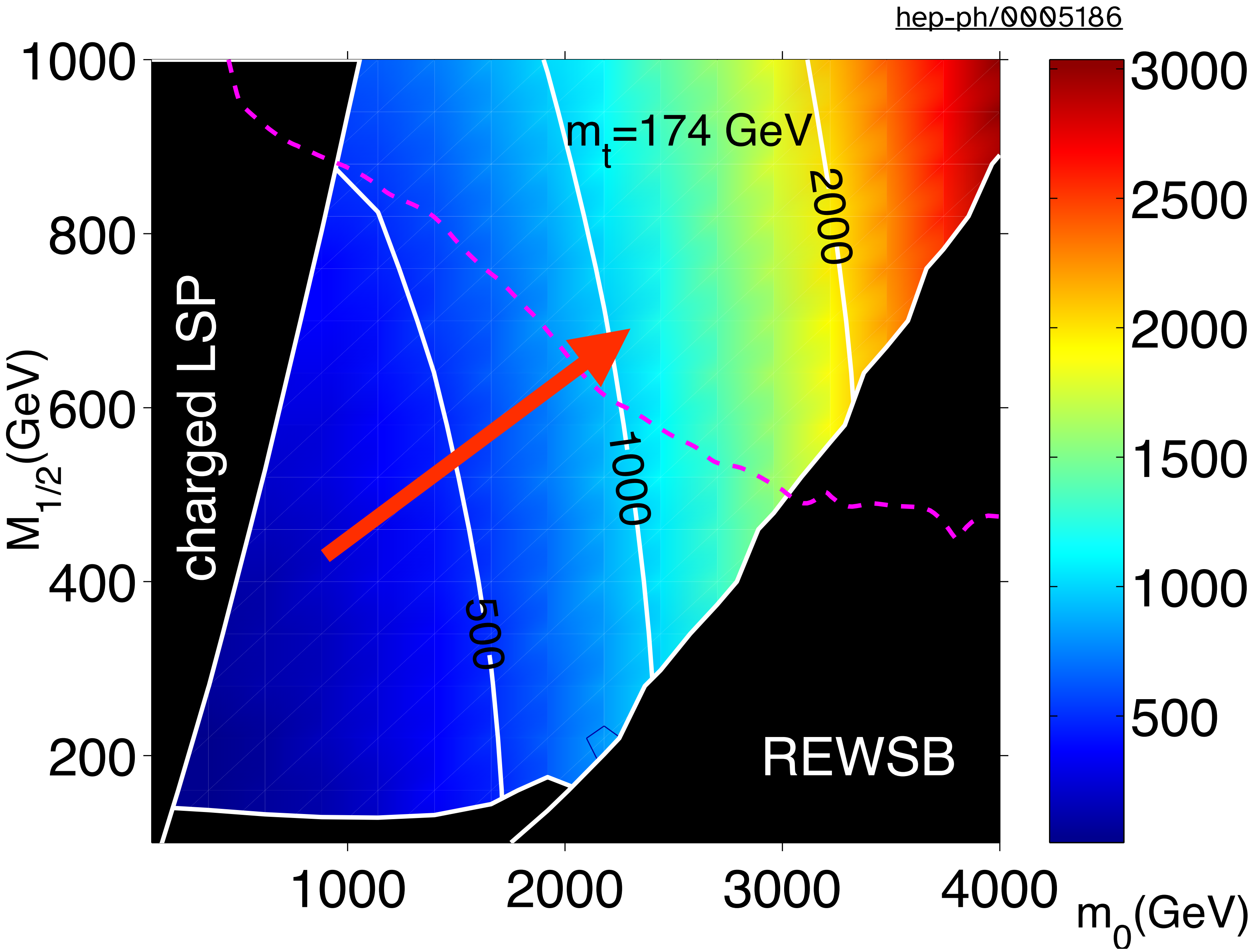
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

hep-ph/0005186



Universe is 1-in-Δ fine-tuned

If want small fine-tuning,
need low masses for new physics!



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- Are there any opportunities left to discover **≤TeV-scale BSM at the LHC**?
- Focus on scenarios where limits might be weak, because of **very large BGs**


$\exists$ >10 yrs of
LHC searches
Why haven't we
found anything?


HOPED FOR THIS...
LHC 8Gs


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LHC 8GS
NEW PHYSICS?

R-PARITY VIOLATION (RPV)

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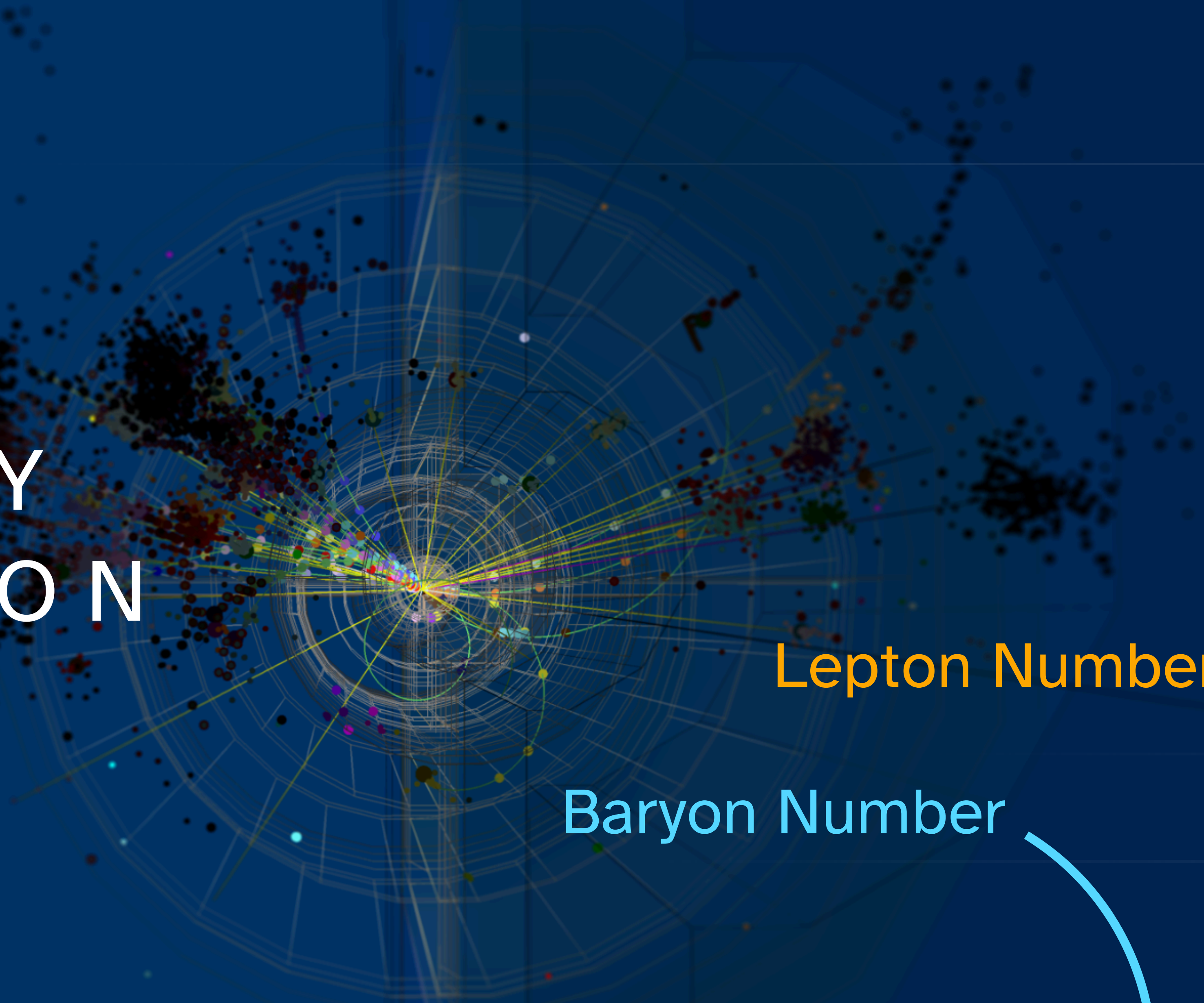

Lepton Number

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R-PARITY VIOLATION (RPV)

Lepton Number

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Spin

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  - +1 SM, -1 SUSY partner

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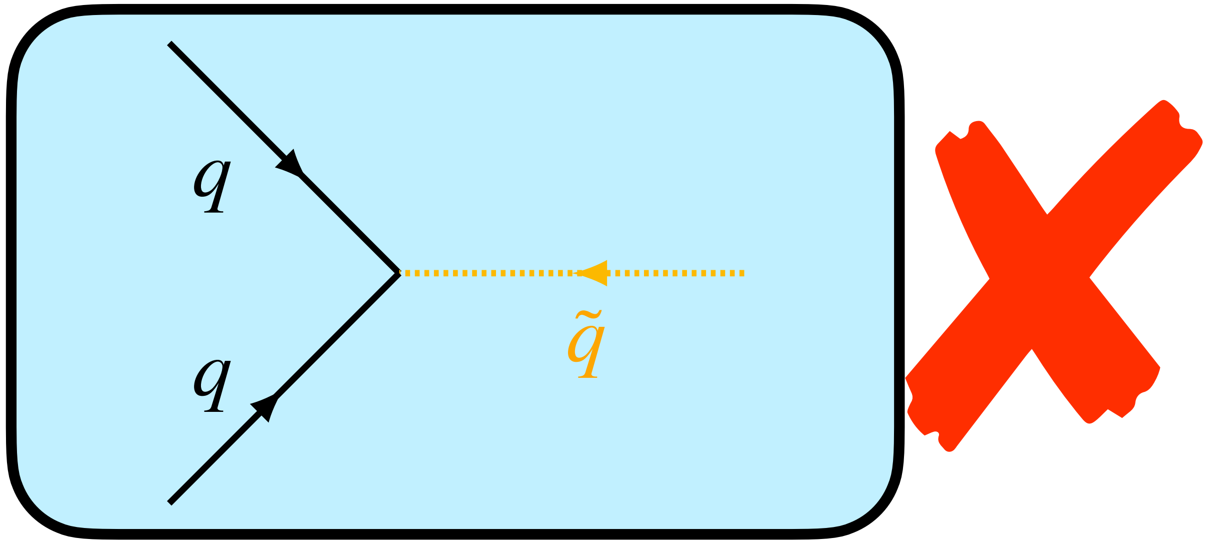
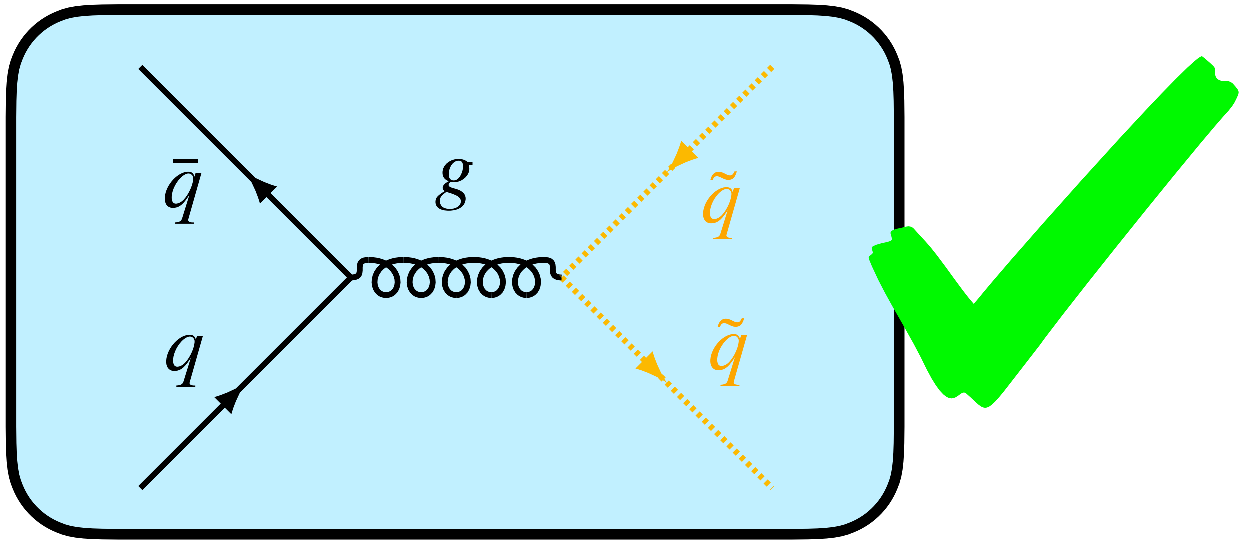
  - Sparticle **pair** production at colliders
  - Lightest sparticle (LSP) must be **stable** (and could be DM)





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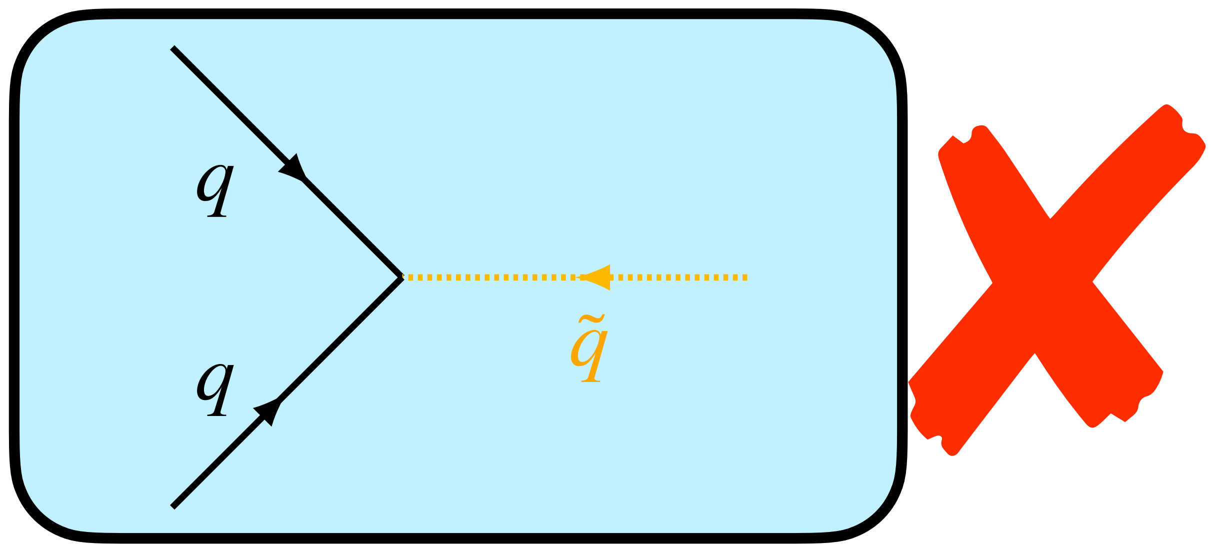

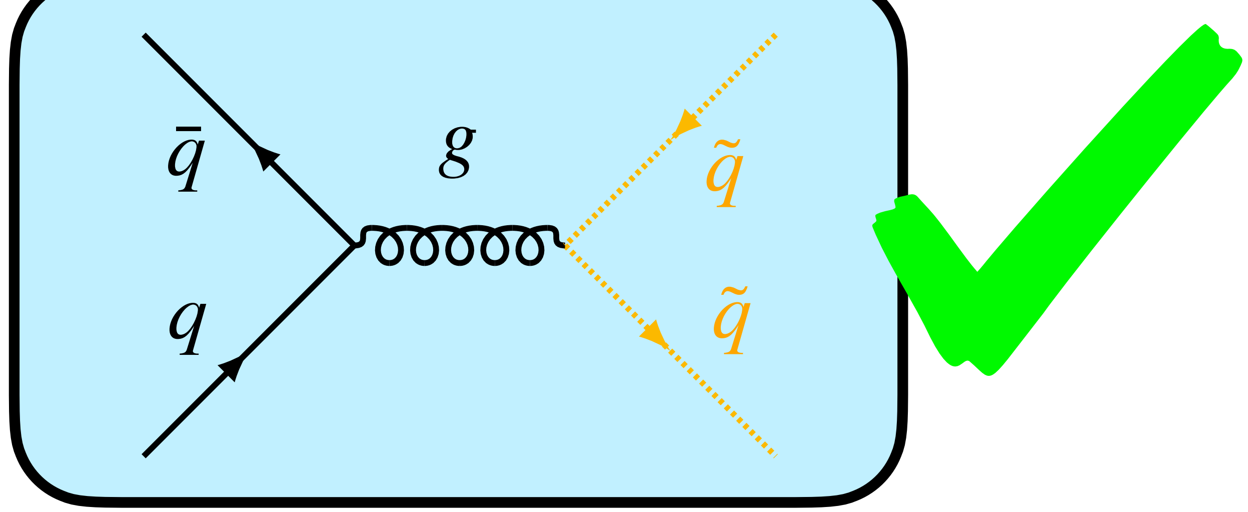

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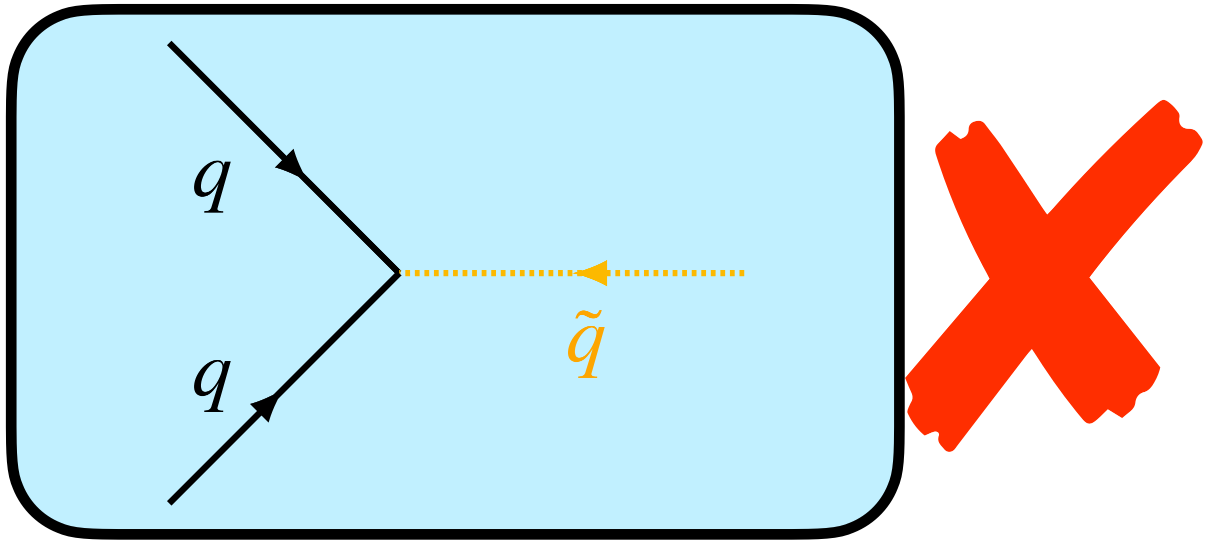
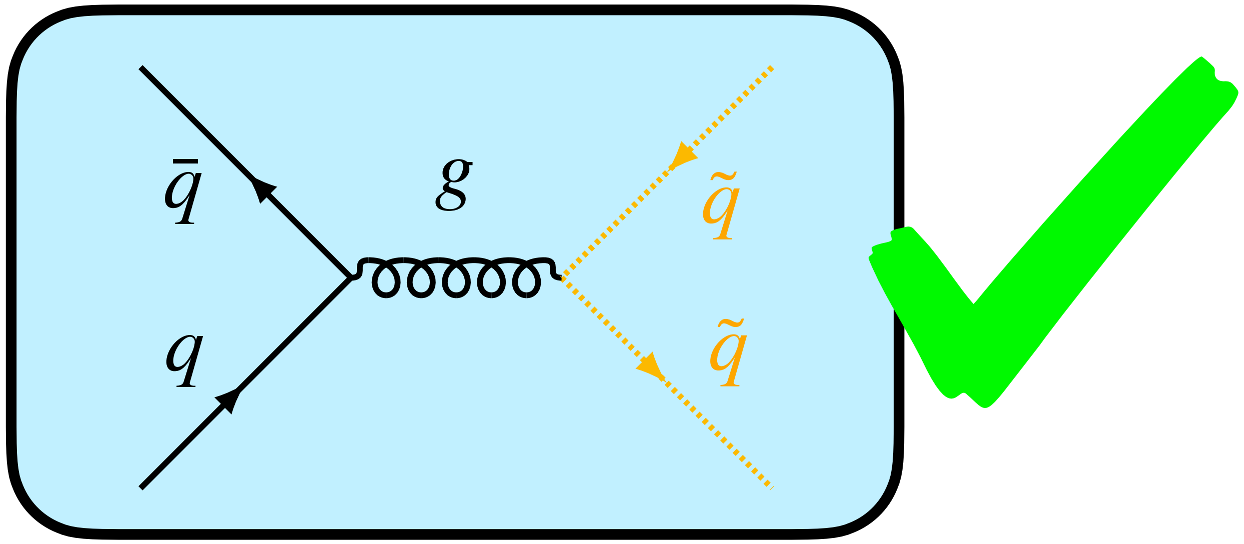
- The vast majority of SUSY searches assume this is conserved





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2.5 Throw away terms we didn’t like (in RPC)

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    - *Seems more contrived to manually forbid couplings*

R-Parity Violating SUSY

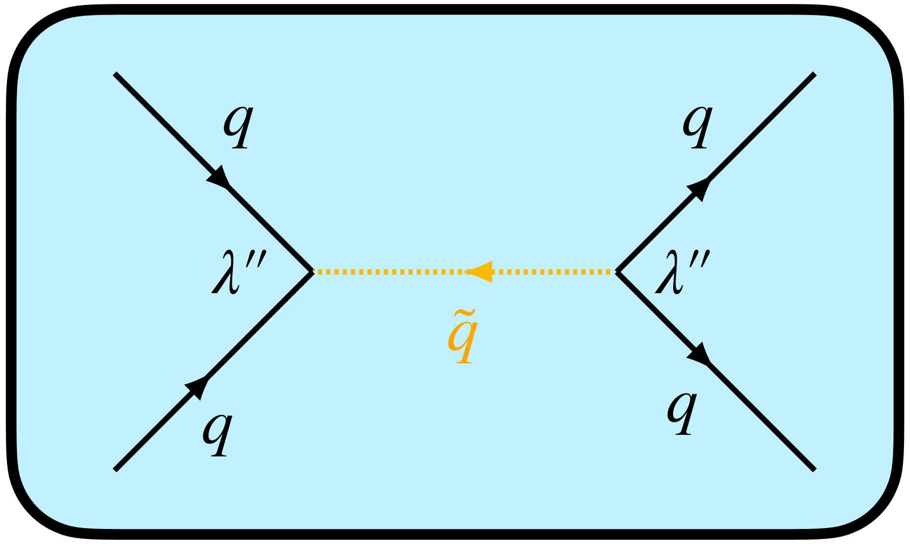
$$W_{RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \frac{1}{2}\lambda''_{ijk} U_i D_j D_k$$

L Violating

B Violating

- General RPV superpotential in MSSM
  - Signature-generating **machine**
- **At colliders:**
  - Allow for **single-production** of sparticles
  - Couplings allow LSP to **decay**

$$P_R = (-1)^{3(B-L)+2s}$$



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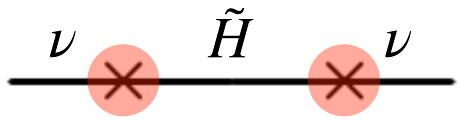
TREE LEVEL NEUTRINO MASSES+MIXING



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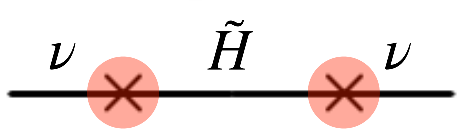
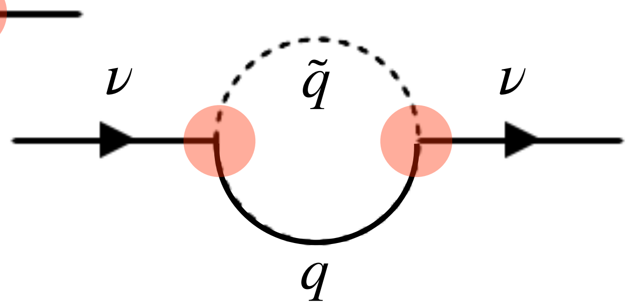
TREE LEVEL NEUTRINO MASSES+MIXING

1-LOOP NEUTRINO MASSES+MIXING





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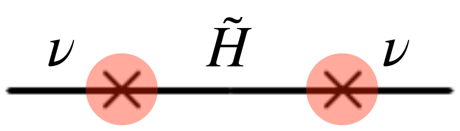
L Violating

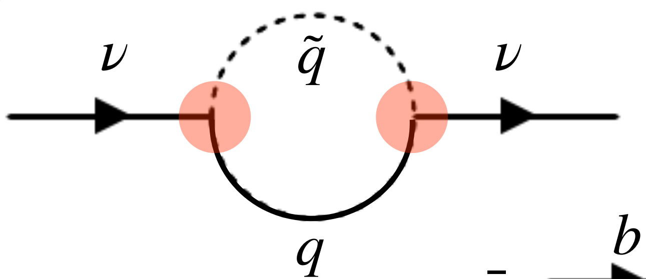
B Violating

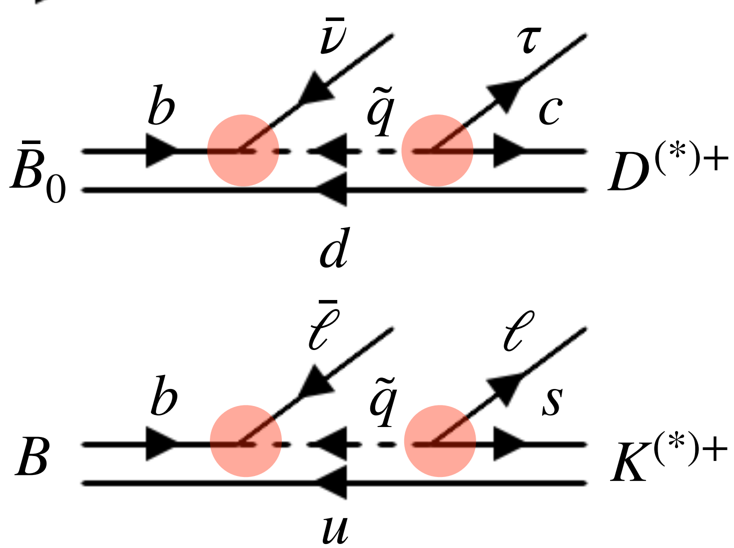
TREE LEVEL NEUTRINO MASSES+MIXING

1-LOOP NEUTRINO MASSES+MIXING

B-PHYSICS ANOMALIES







R-Parity Violating SUSY

$$W_{RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \frac{1}{2}\lambda''_{ijk} U_i D_j D_k$$

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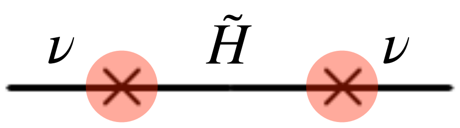
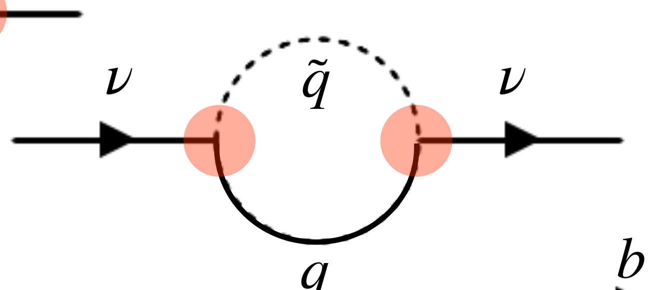
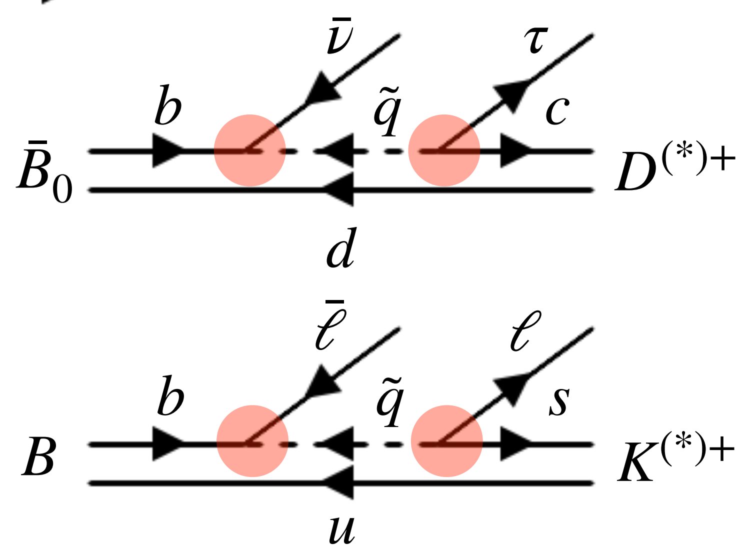
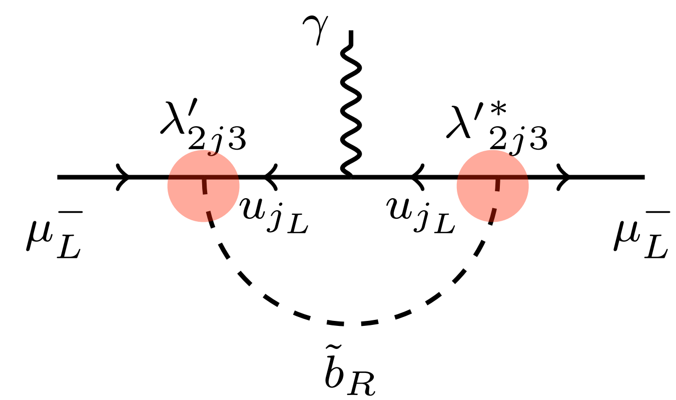
MUON G-2 ANOMALY









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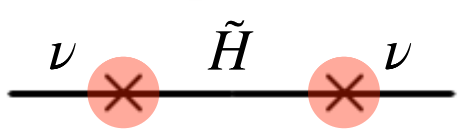
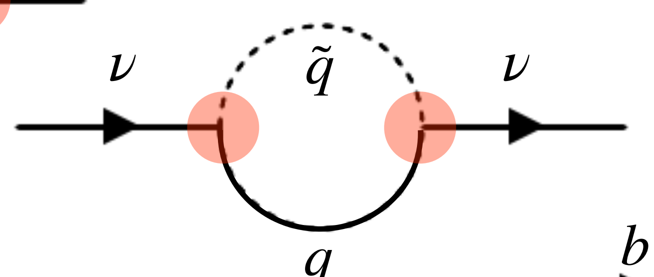
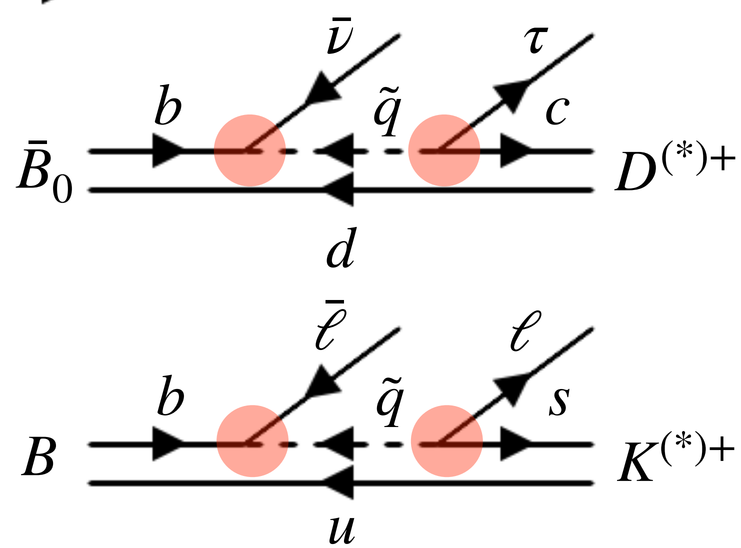
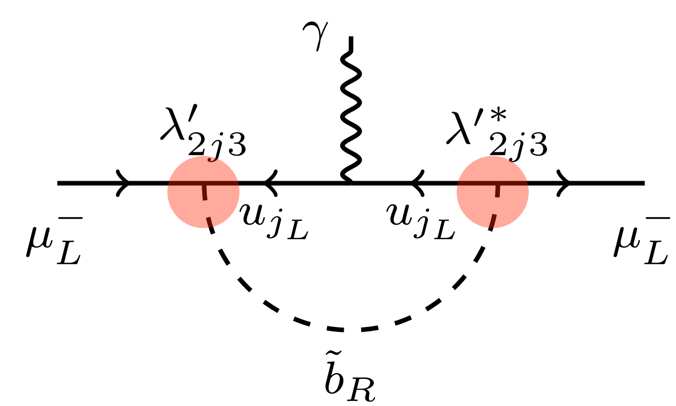
NEW ROOM FOR CP VIOLATION!









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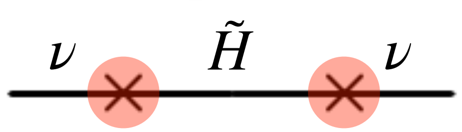

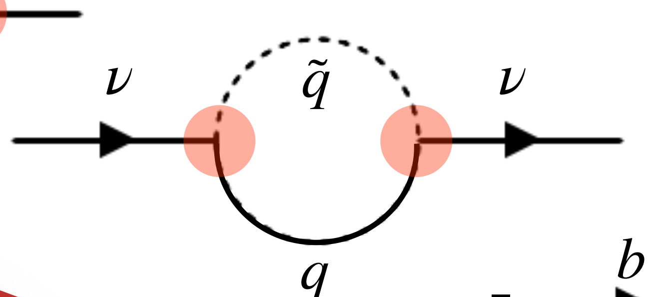

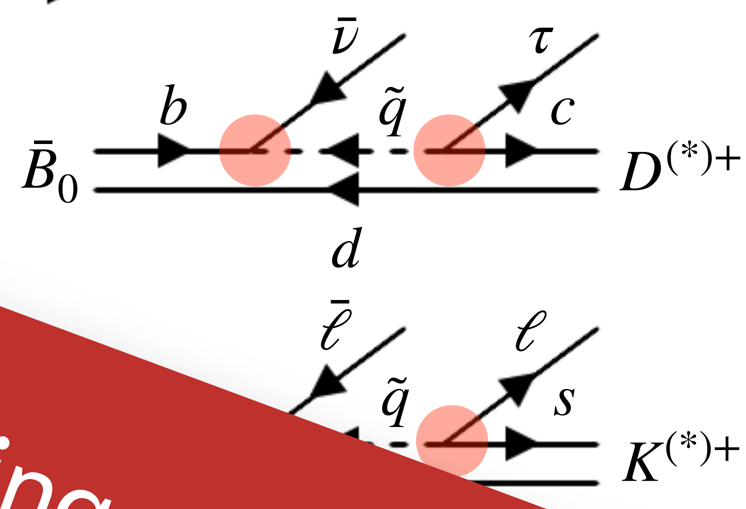

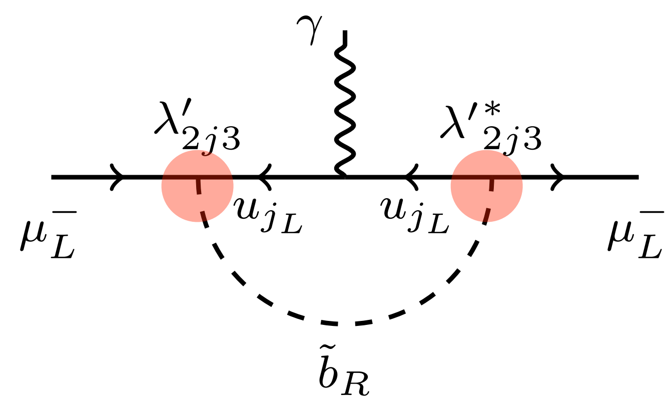

Nonzero RPV Couplings greatly weaken LHC Limits

R-Parity Violating SUSY

$$W_{RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \frac{1}{2}\lambda''_{ijk} U_i D_j D_k$$

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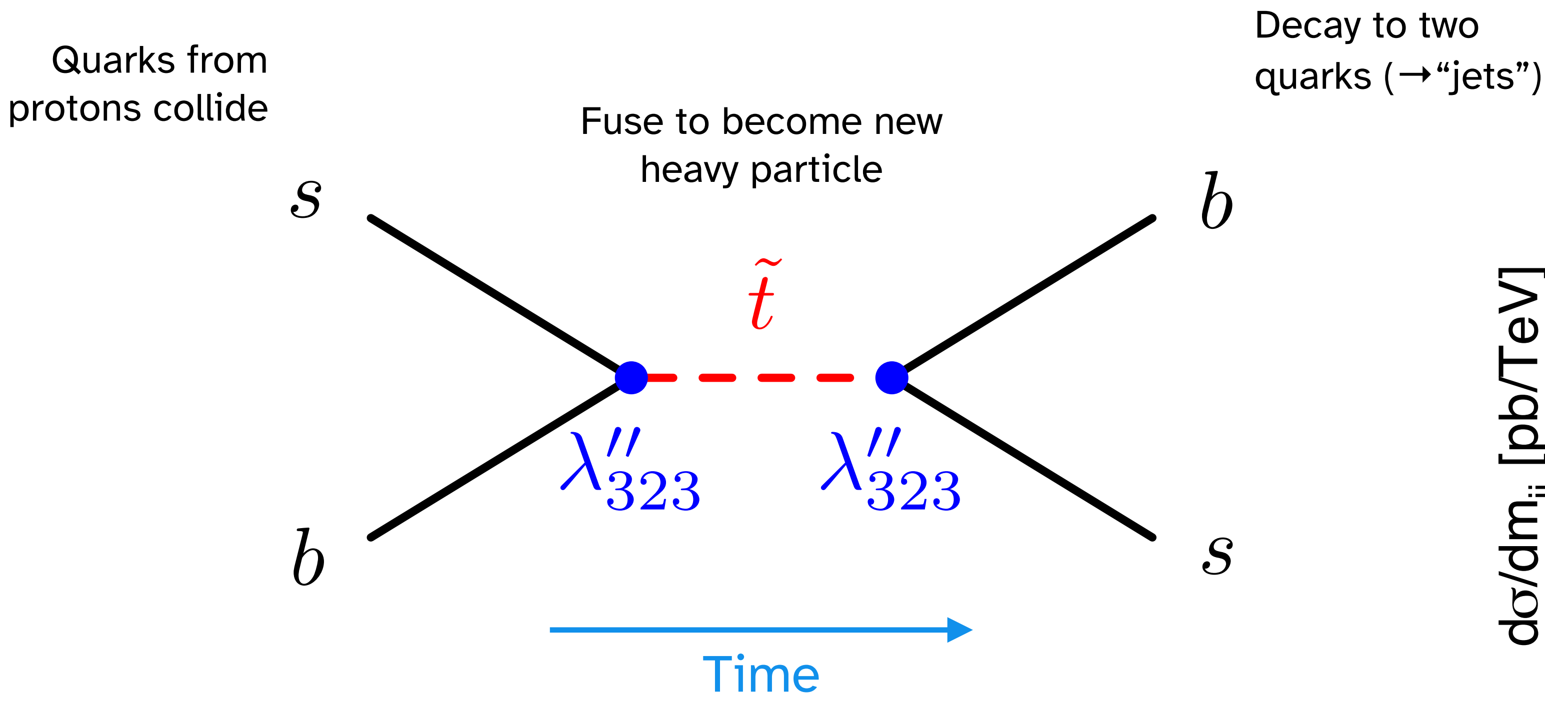
MUON G-2 ANOMALY

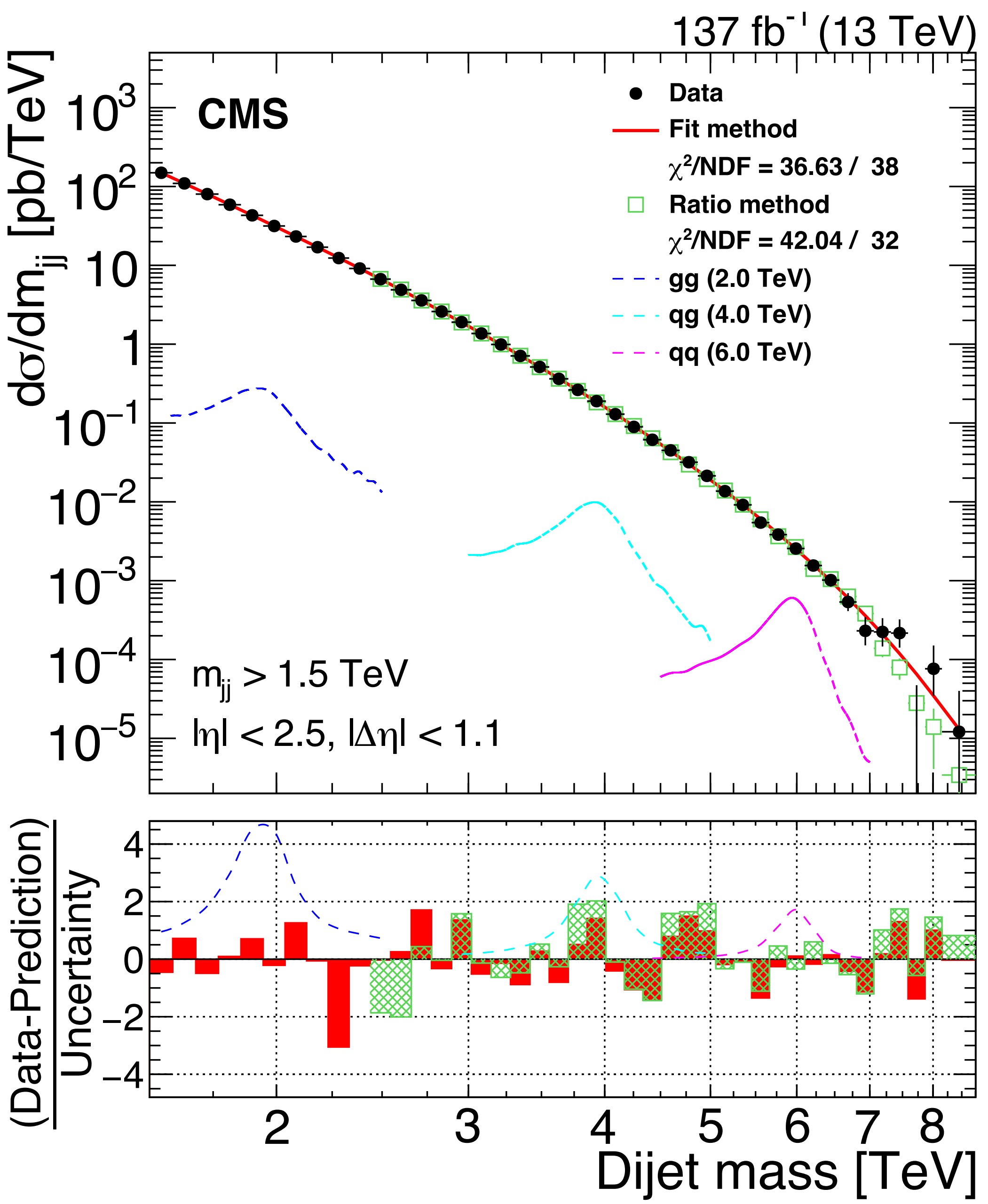
NEW ROOM FOR CP VIOLATION!

∃ so much explanatory power+discovery potential!

If your symmetries allow a coupling and you don't have a symmetry forbidding it — don't make one up!

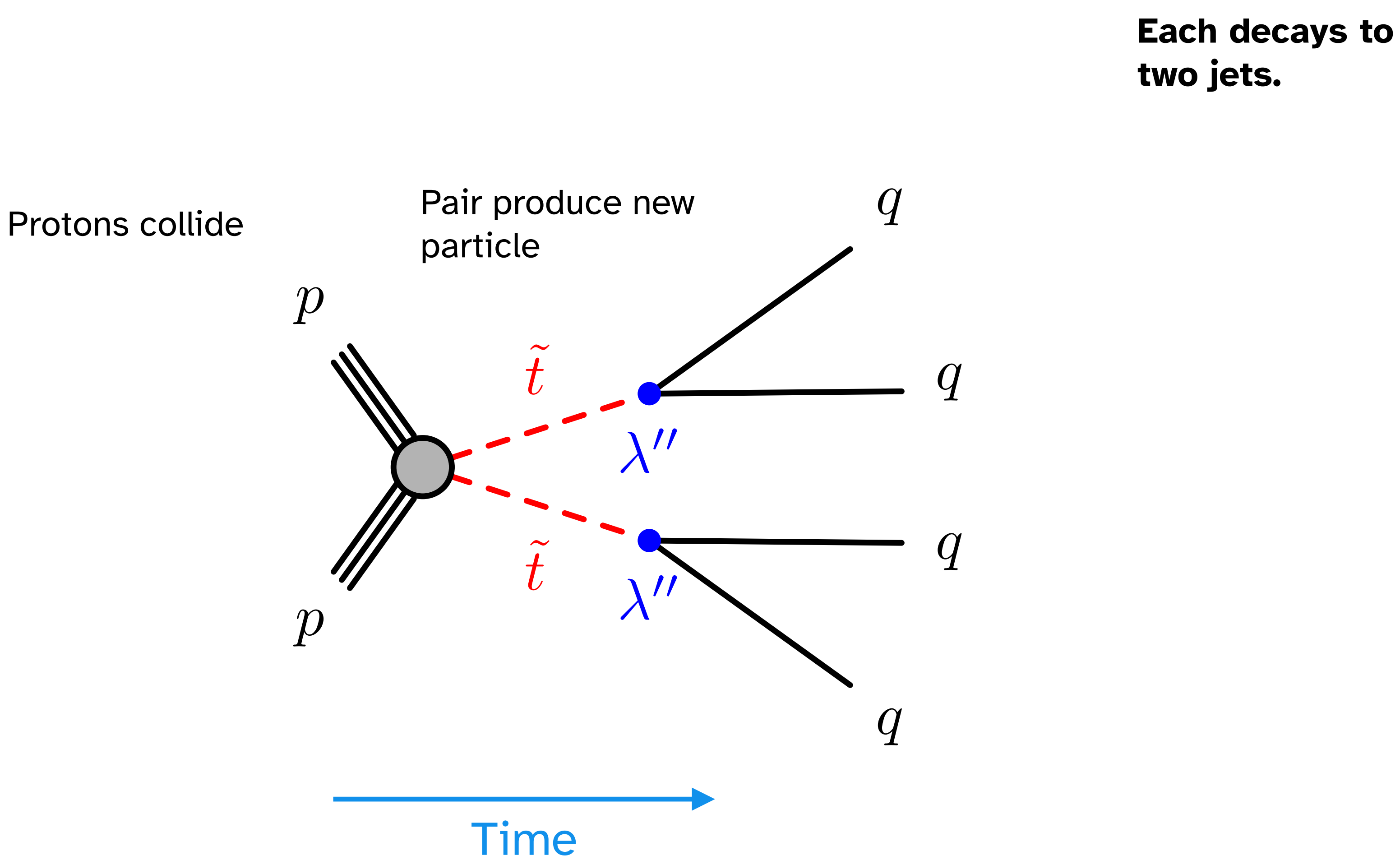
Simple Example





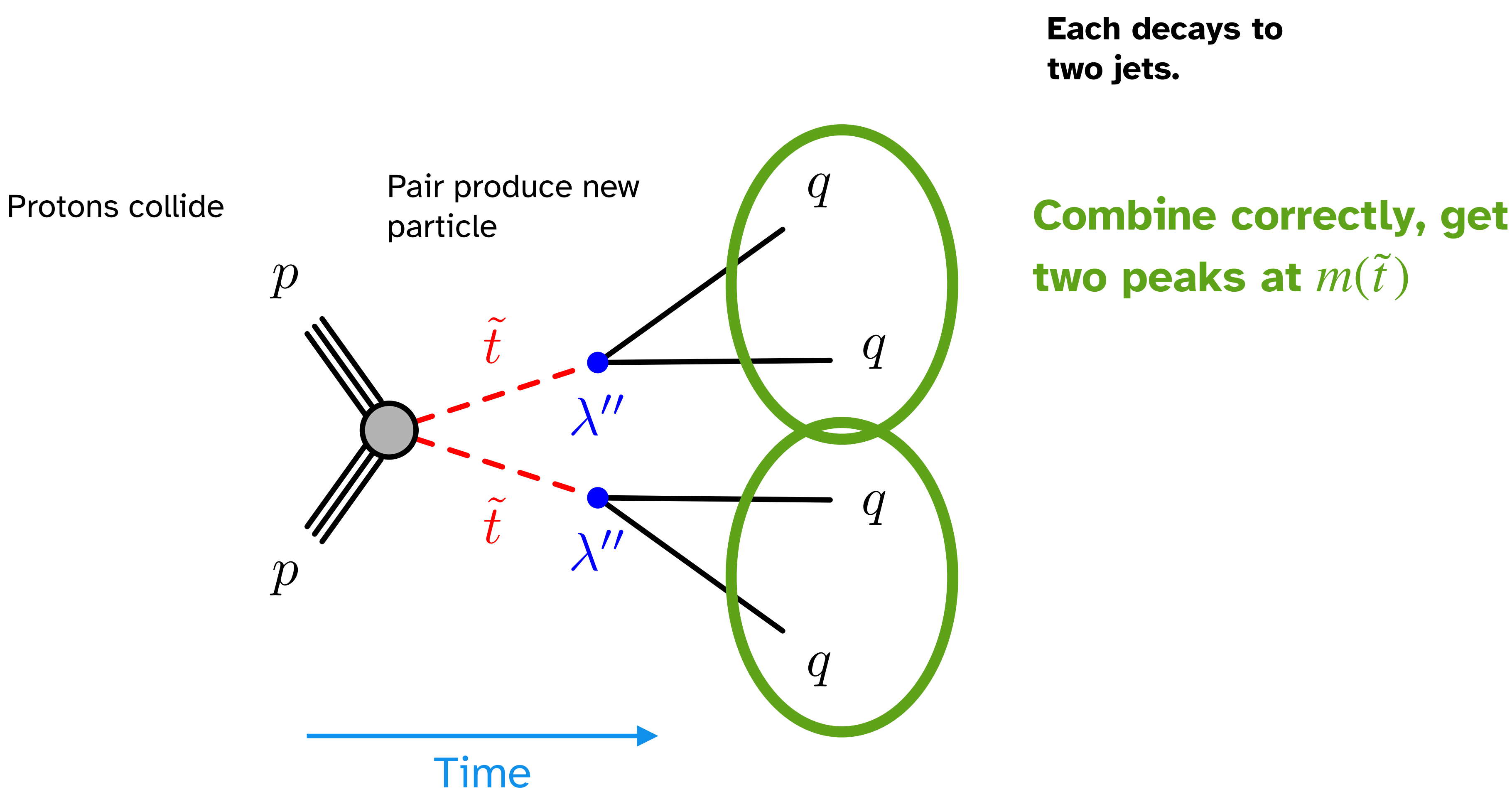
- We measure the four-momentum of each jet
- Sum them to get the four-momentum of the new particle
- Relativity tells us how to get the mass $(p \cdot p) = m^2$
- Plot this mass and our new physics signals will peak at the mass of the new thing
- Backgrounds steeply falling distribution

Less Simple Example



- Increasing multiplicity introduces combinatorial issues
- Wrong combinations don't contain peak-y mass variables → Make signal harder to find.
- Brute-force → Add **combinatorial** background

Less Simple Example



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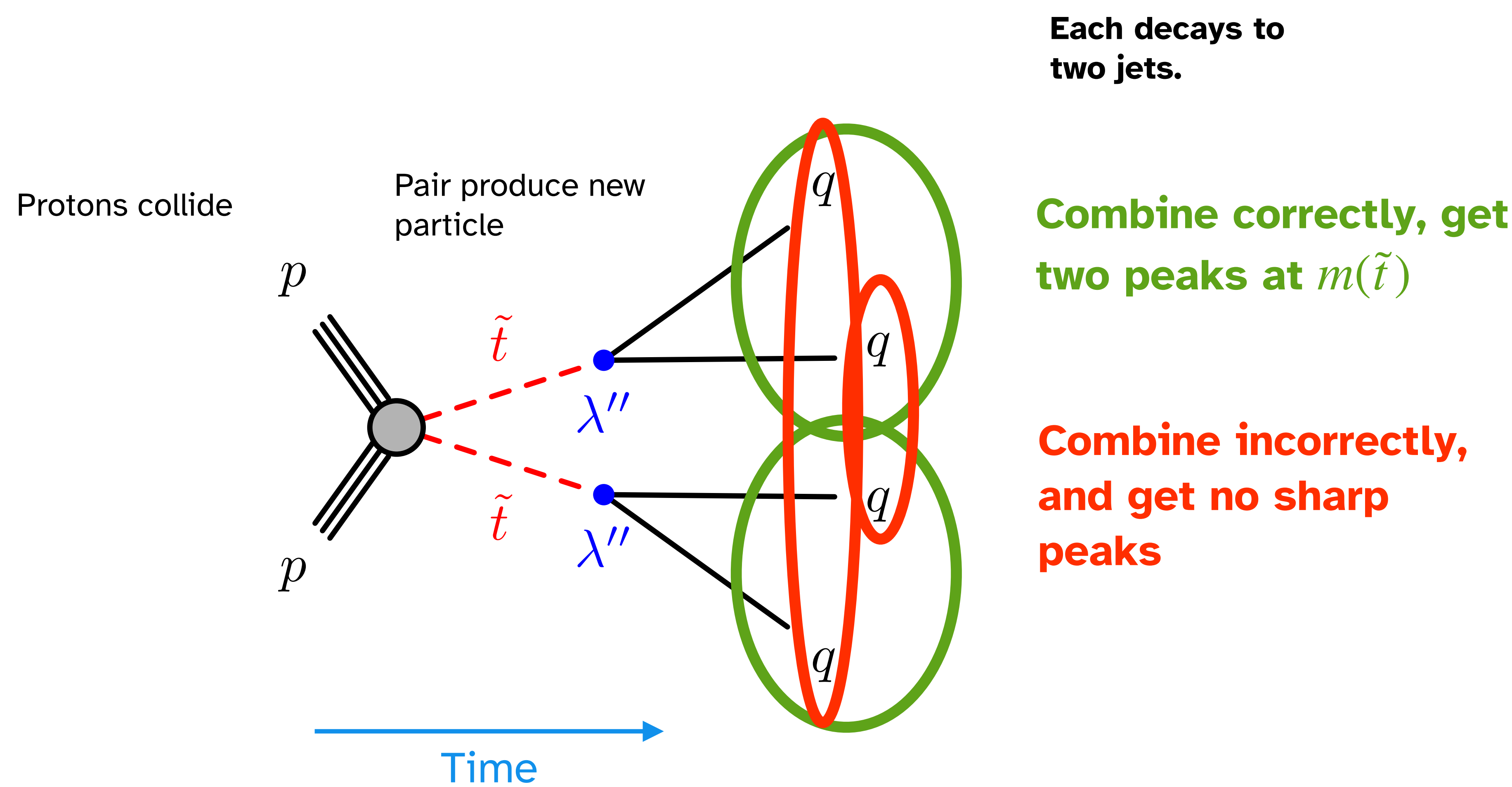

- Increasing multiplicity introduces combinatorial issues
- Wrong combinations don't contain peak-y mass variables → Make signal harder to find.
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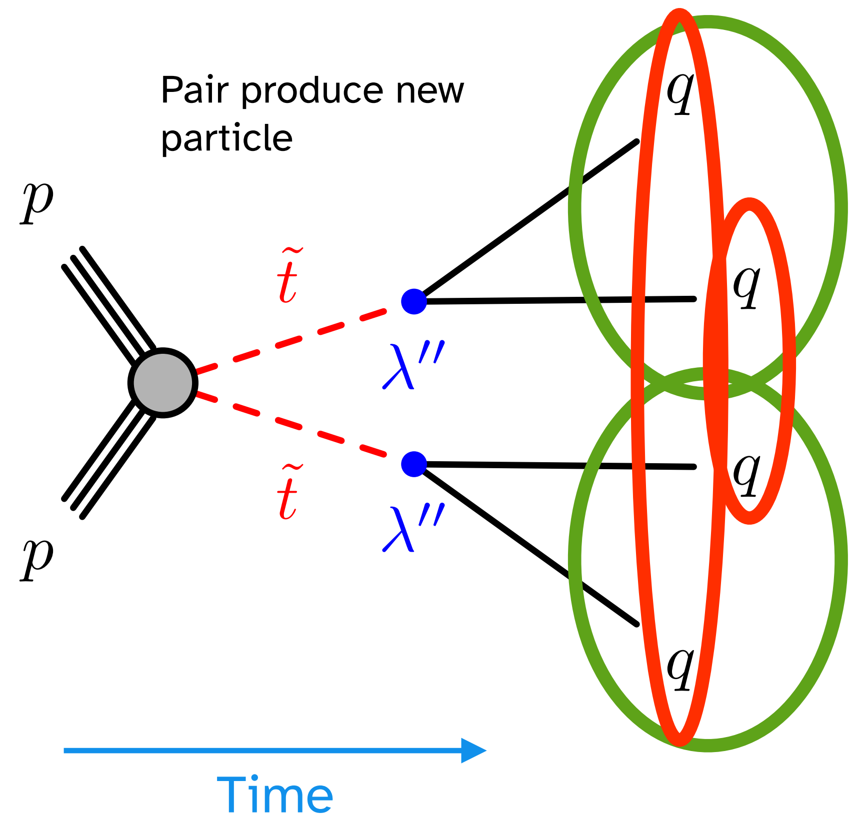
Less Simple Example

Each decays to two jets.

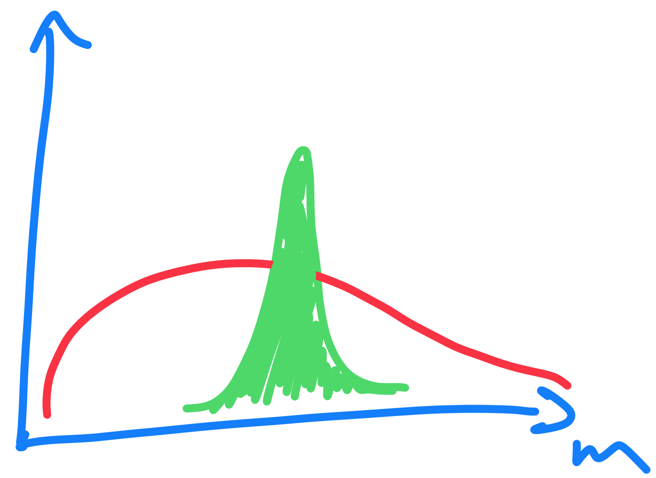
Protons collide

Pair produce new particle



Combine correctly, get two peaks at $m(\tilde{t})$

Combine incorrectly, and get no sharp peaks

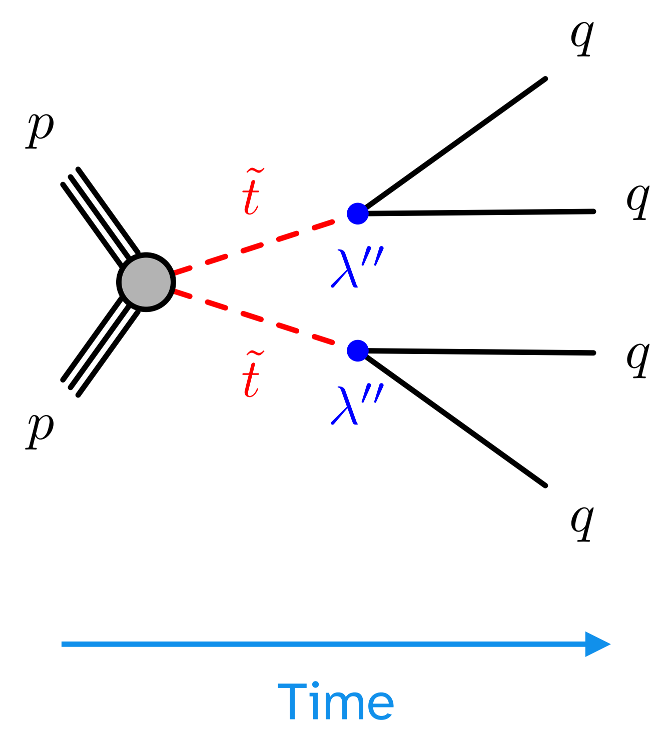


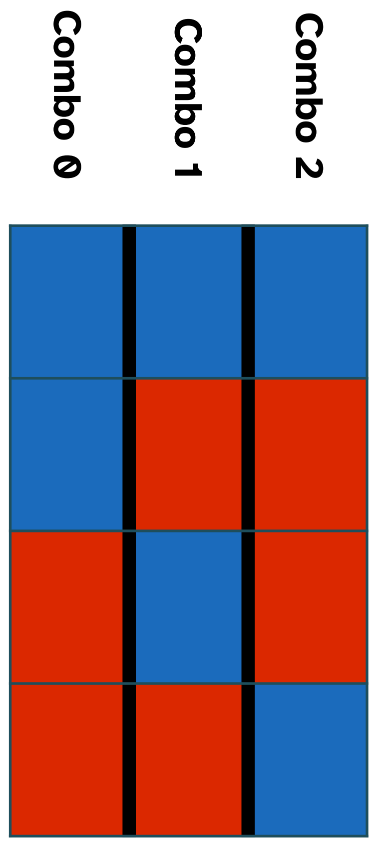
- Increasing multiplicity introduces combinatorial issues
- Wrong combinations don't contain peak-y mass variables → Make signal harder to find.
- Brute-force → Add **combinatorial** background

Less Simple Example

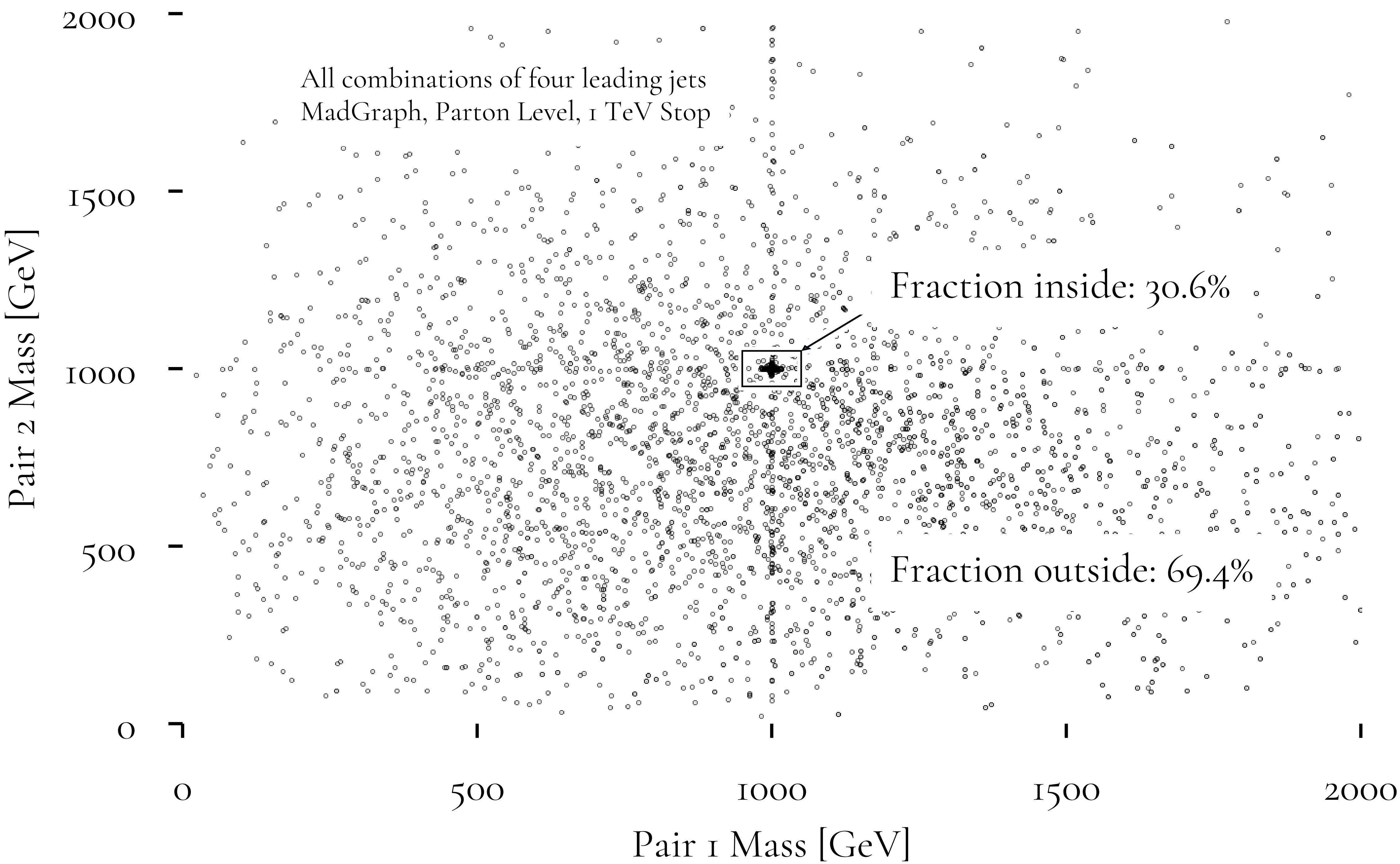
- Here — one of three possible configurations is correct
- → 200% combinatoric background!

- ∃ Prob of extra ~uncorrelated jets produced in the same event
    - Even harder!



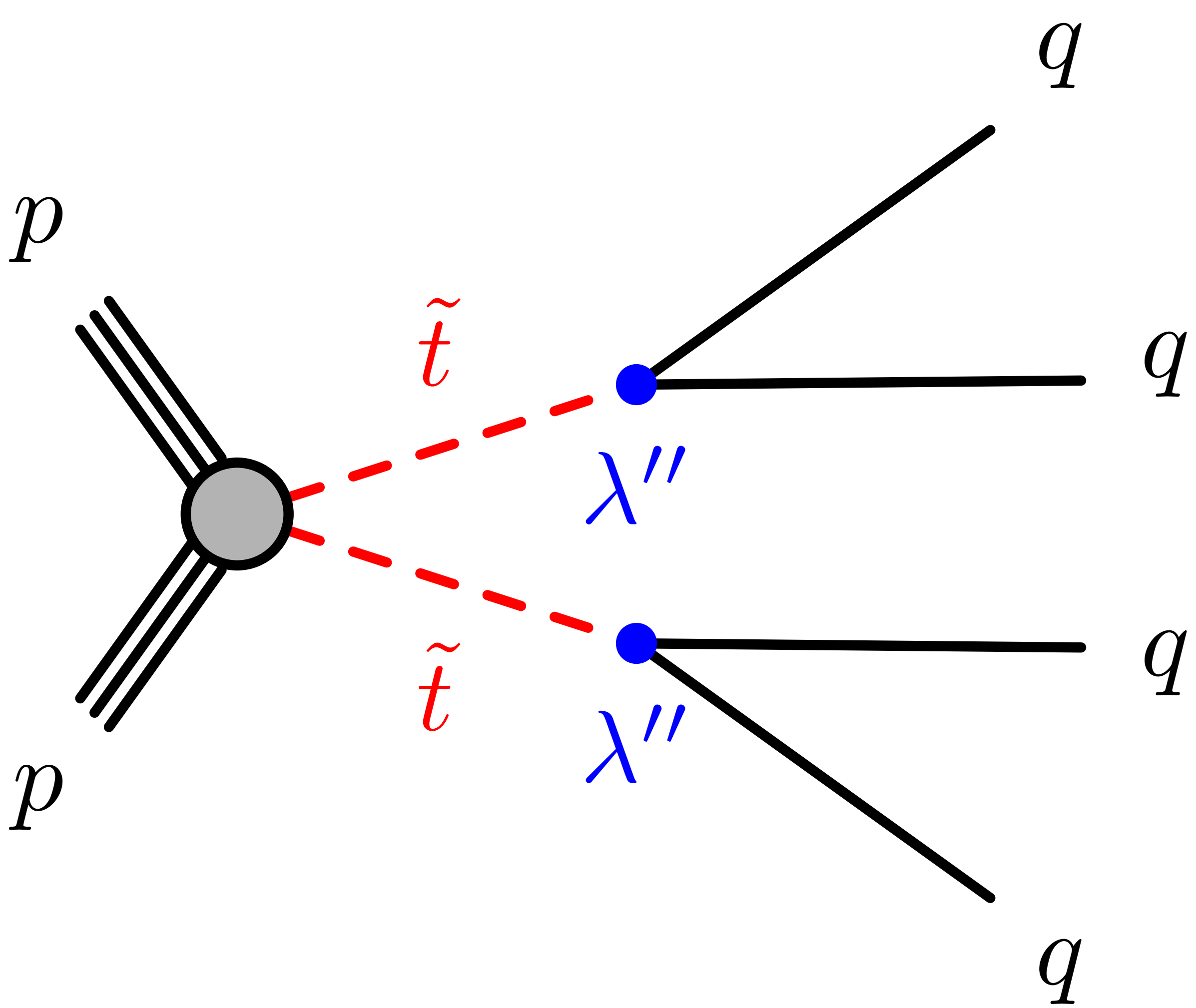


$$\binom{4}{2}/2 = 3$$

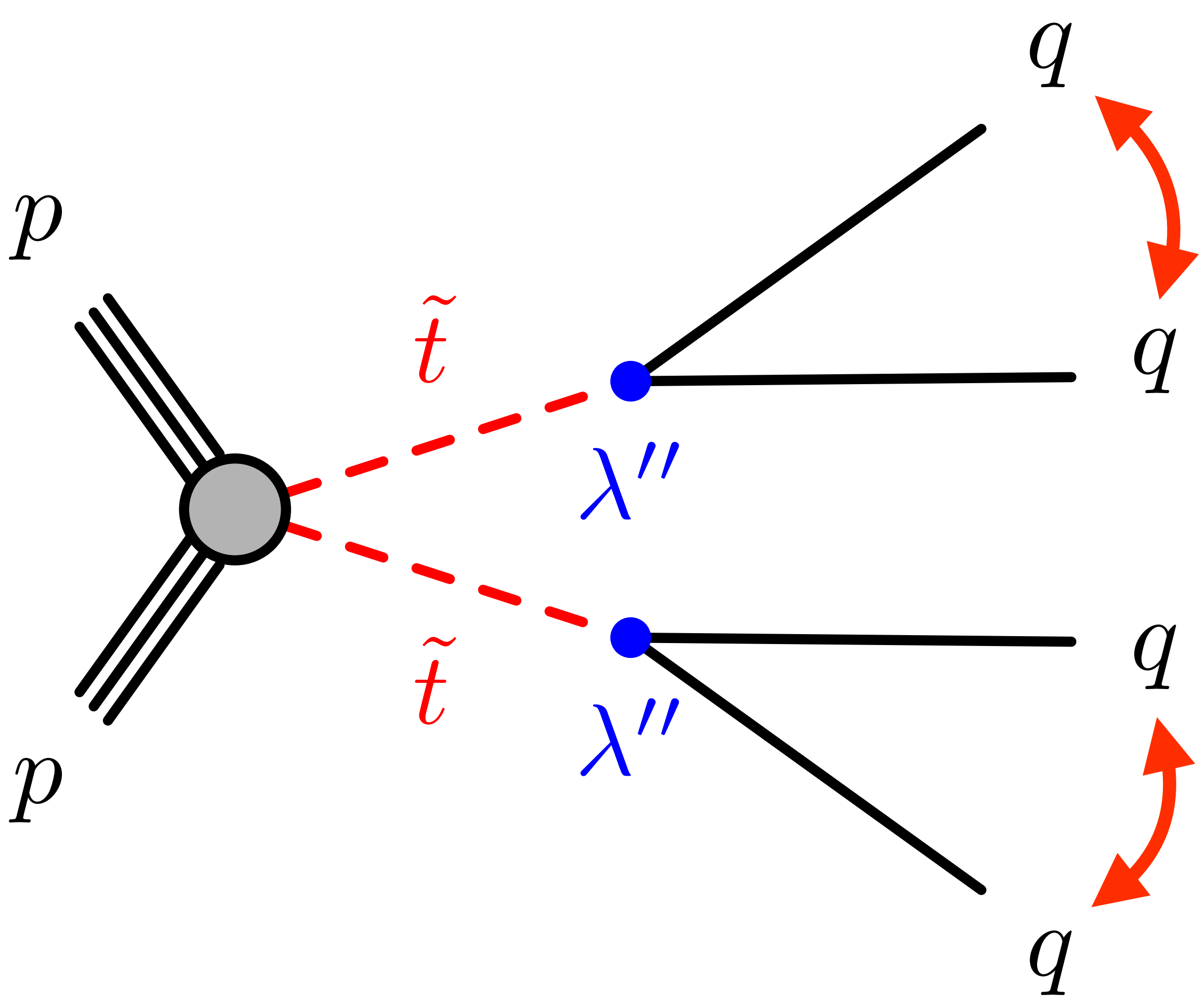


Combinatorics start to annoy us
but aren't the end of the world

“Classical” Combinatorial Soln's



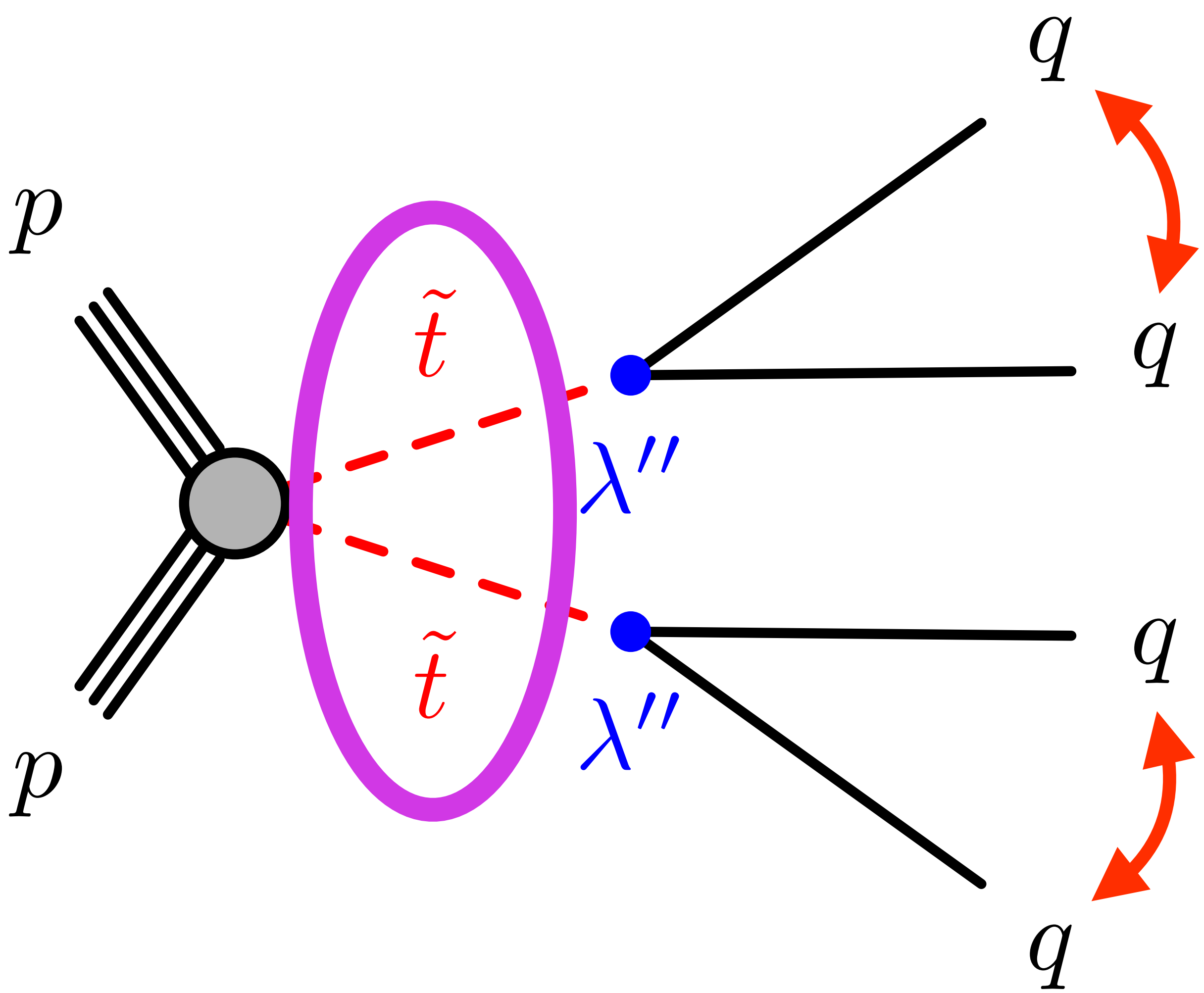
"Classical" Combinatorial Soln's



"ΔR^Σ Minimization"

$$\min_{\text{combs}} \left\{ \sum \Delta R_{\text{pair}} + C \right\}$$

"Classical" Combinatorial Soln's



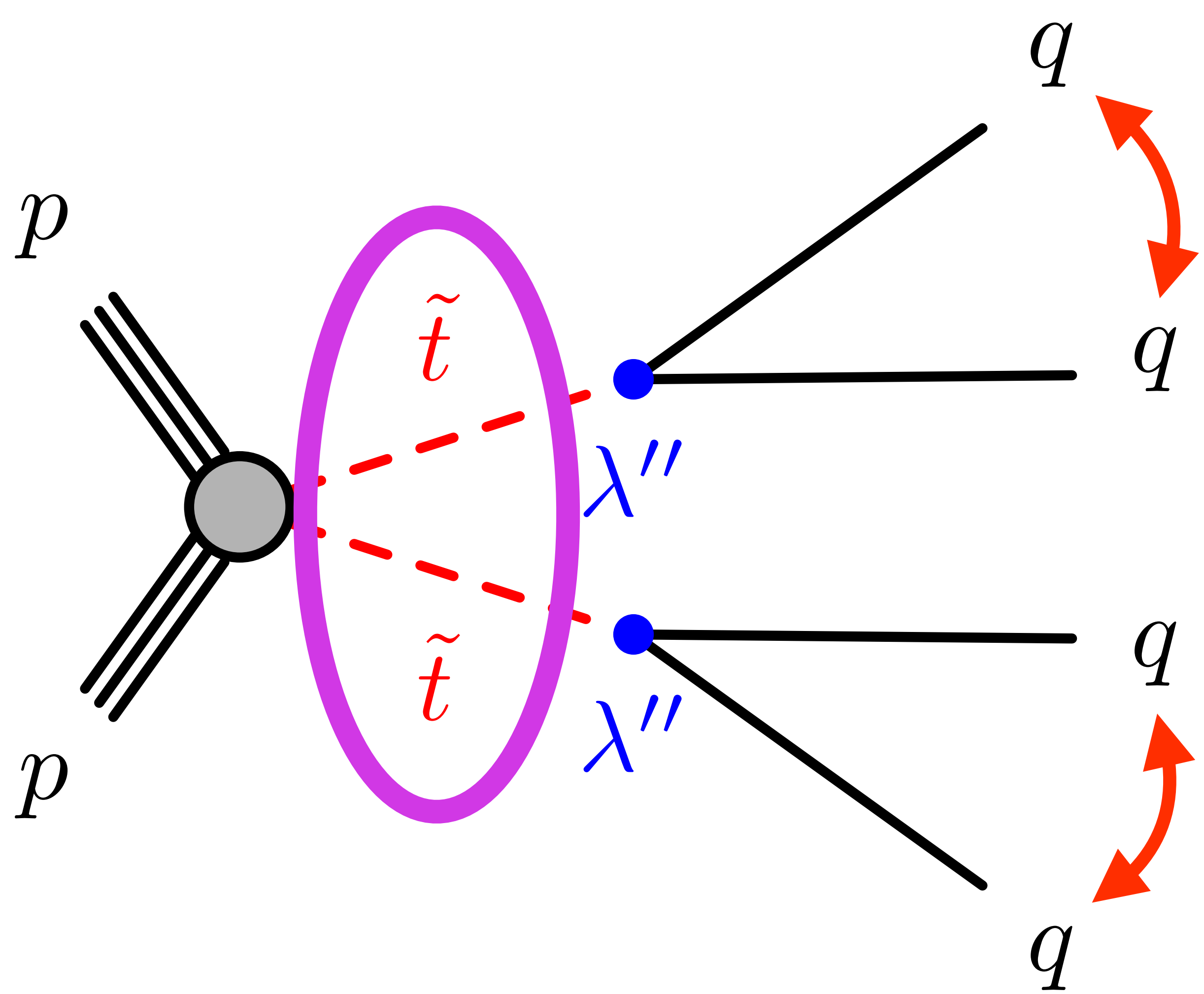
"ΔR^{Σ} Minimization"

$$\min_{\text{combs}} \left\{ \sum \Delta R_{\text{pair}} + C \right\}$$

"Mass Asymmetry Minimization"

$$\min_{\text{combs}} \left\{ \frac{|m_1 - m_2|}{m_1 - m_2} \right\}$$

"Classical" Combinatorial Soln's



"Mass Asymmetry Minimization"

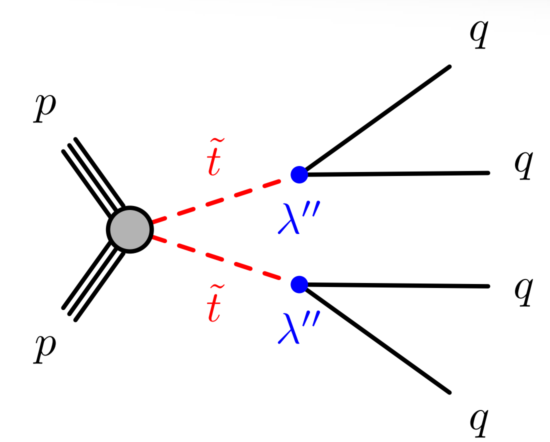
$$\min_{\text{combs}} \left\{ \frac{|m_1 - m_2|}{m_1 - m_2} \right\}$$

"ΔR$^{\Sigma}$ Minimization"

$$\min_{\text{combs}} \left\{ \sum \Delta R_{\text{pair}} + C \right\}$$

Possible because the multiplicity is low!

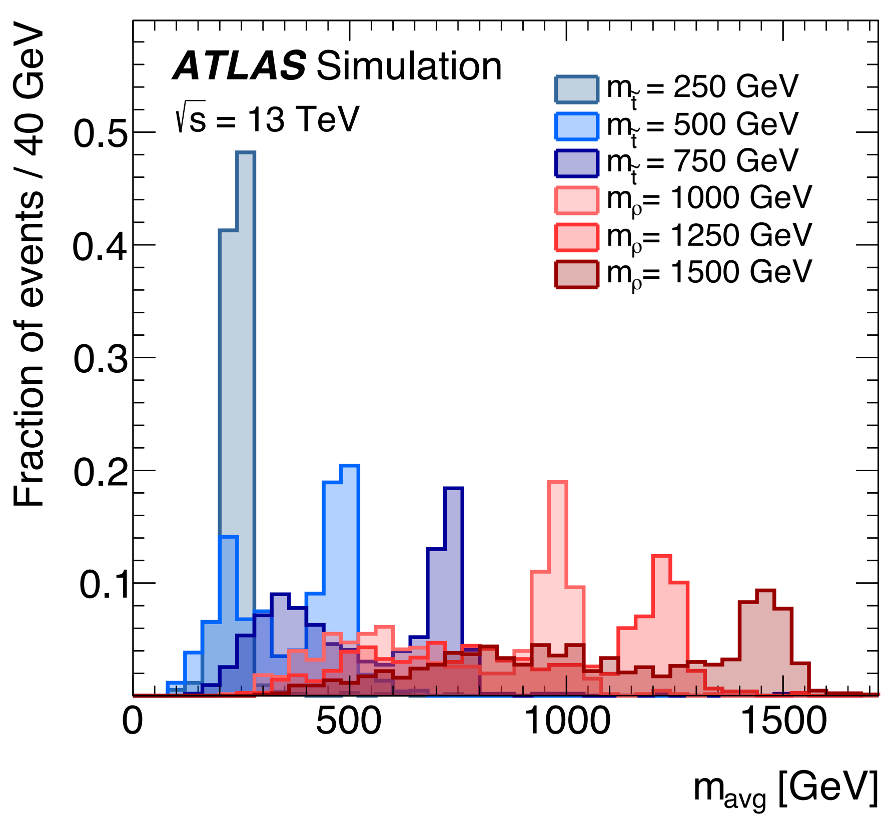
"CLASSICAL" 2X2

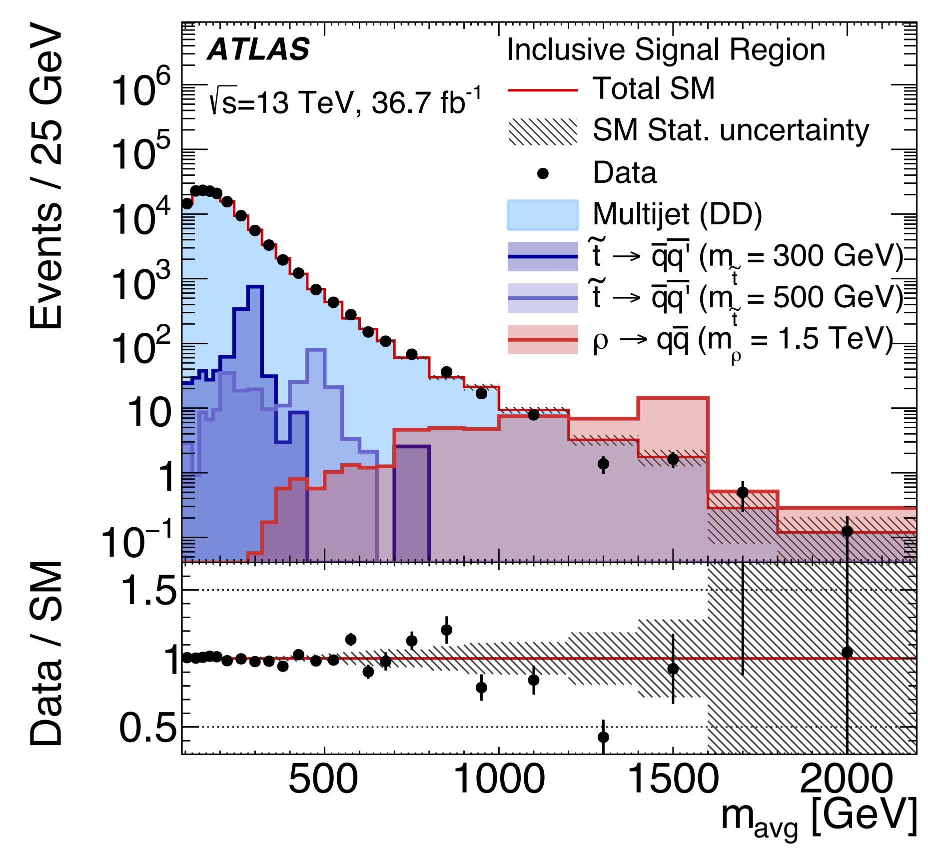


- Example of traditional analysis technique
- Use ΔR^{Σ} to try to get peaking mass
- Do a bump hunt in this mass

COMBINATORIAL SOLUTION → GET SIGNALS TO PEAK → COMPARE TO FALLING BG

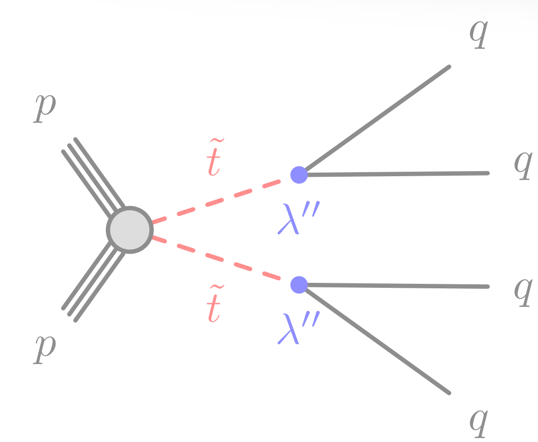
ΔR^{Σ} MINIMIZATION

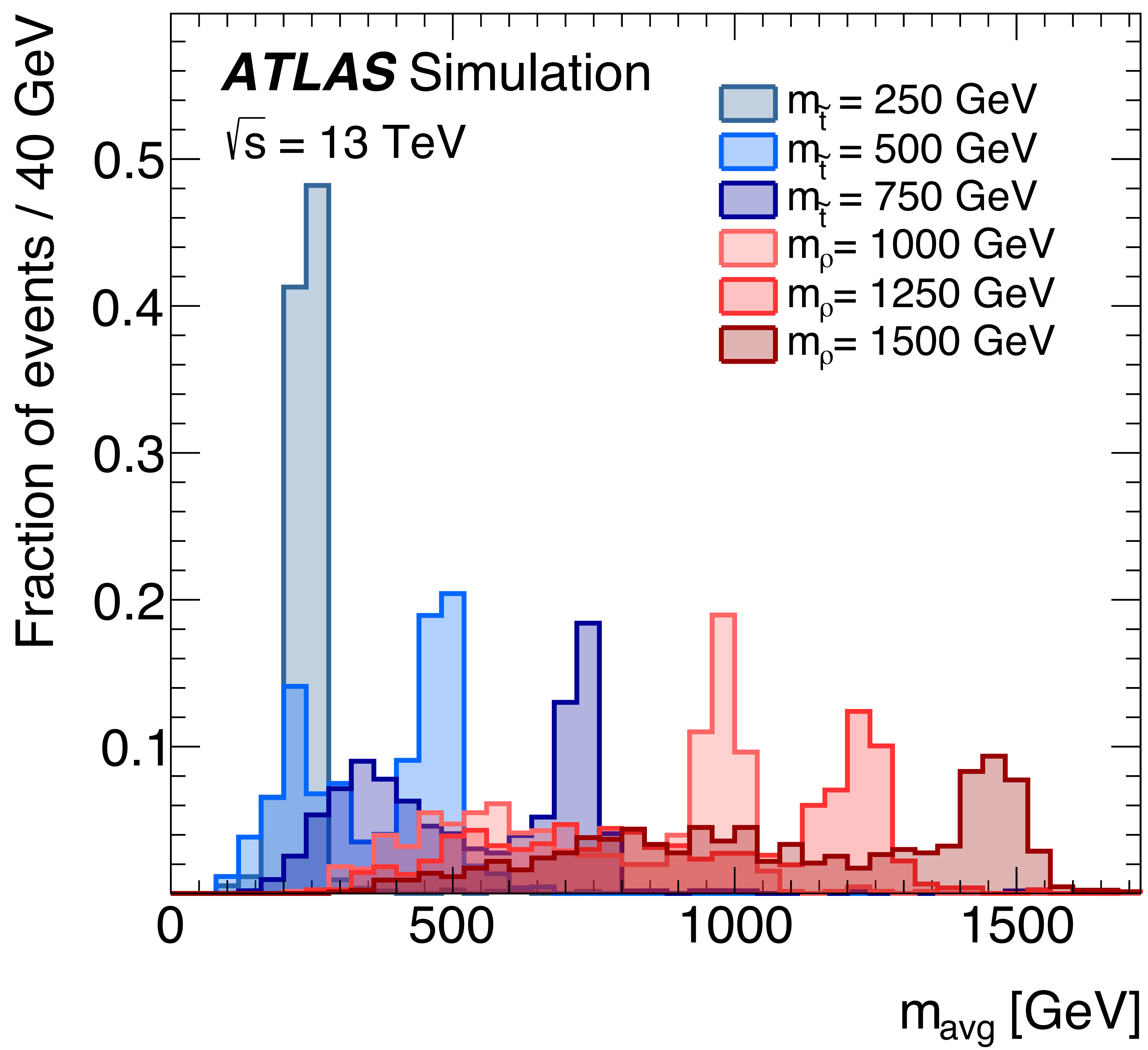




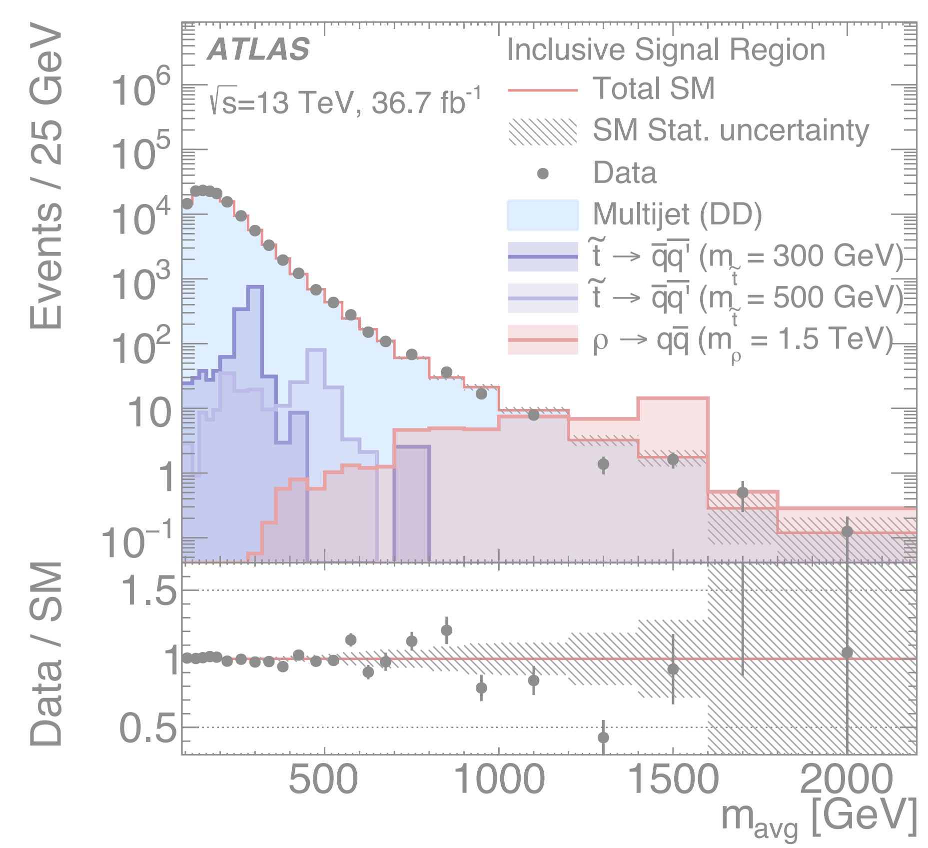
arXiv:1710.07171

"CLASSICAL" 2x2





COMPARE TO FALLING BG



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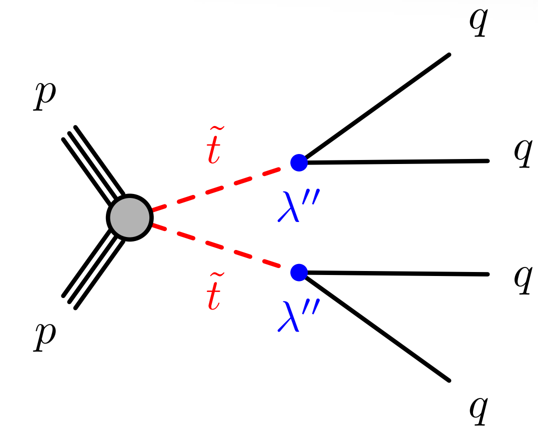
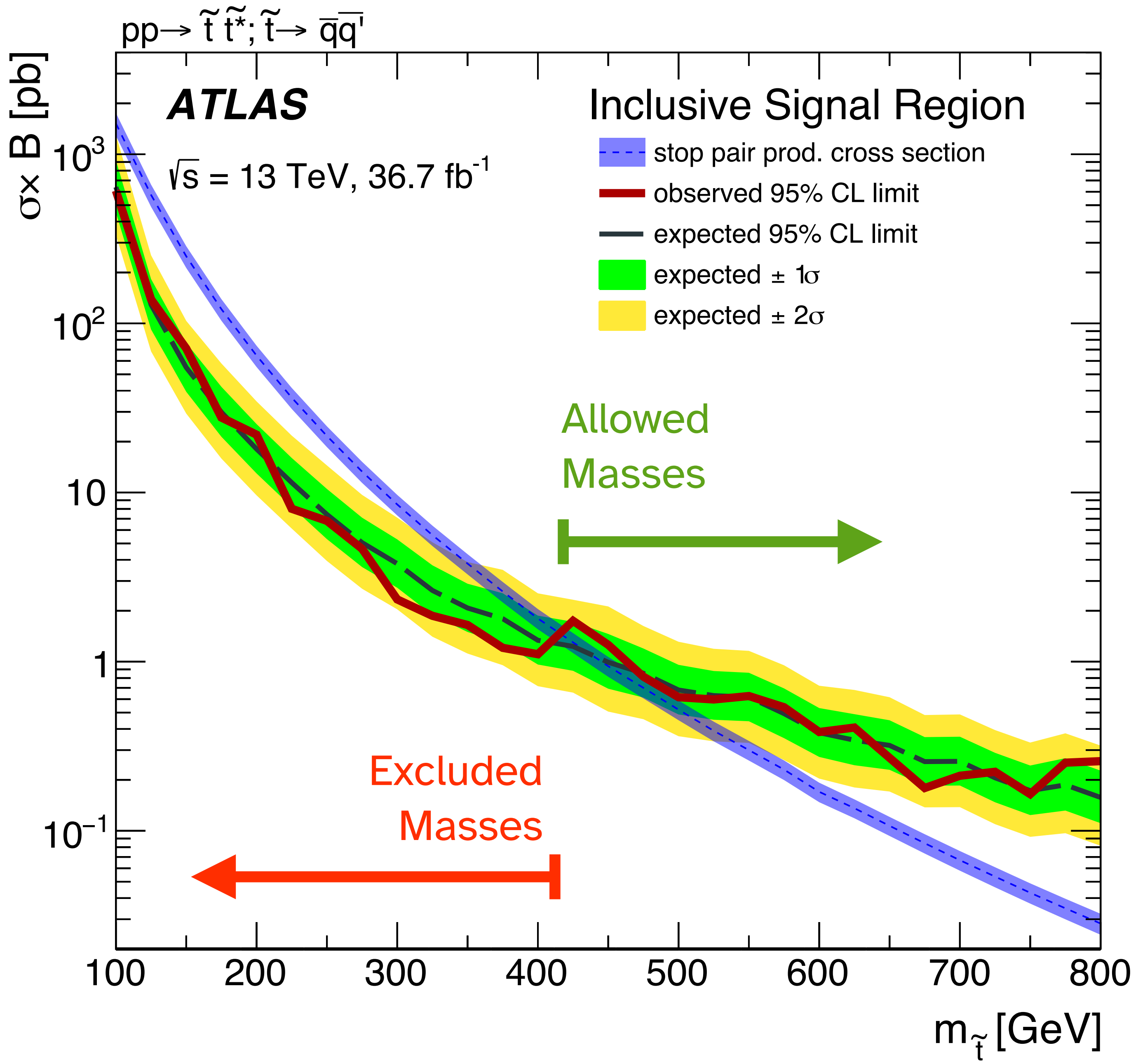


- We can do this search but…
- Sensitivity pretty bad!
- Limits run out at $m(\tilde{t}) \approx 400$ GeV
- If stop just out of reach, very natural theory
- [i.e. maybe RPV couplings have prevented the discovery of a natural BSM]



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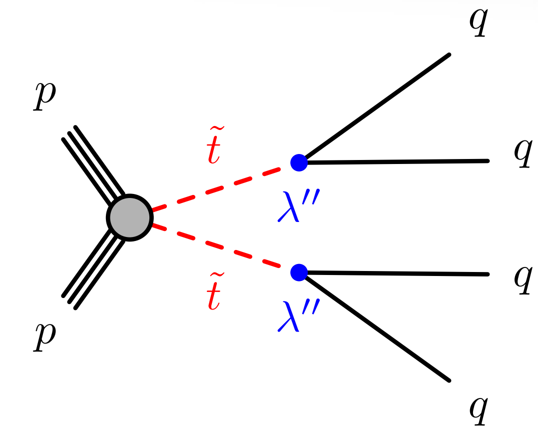
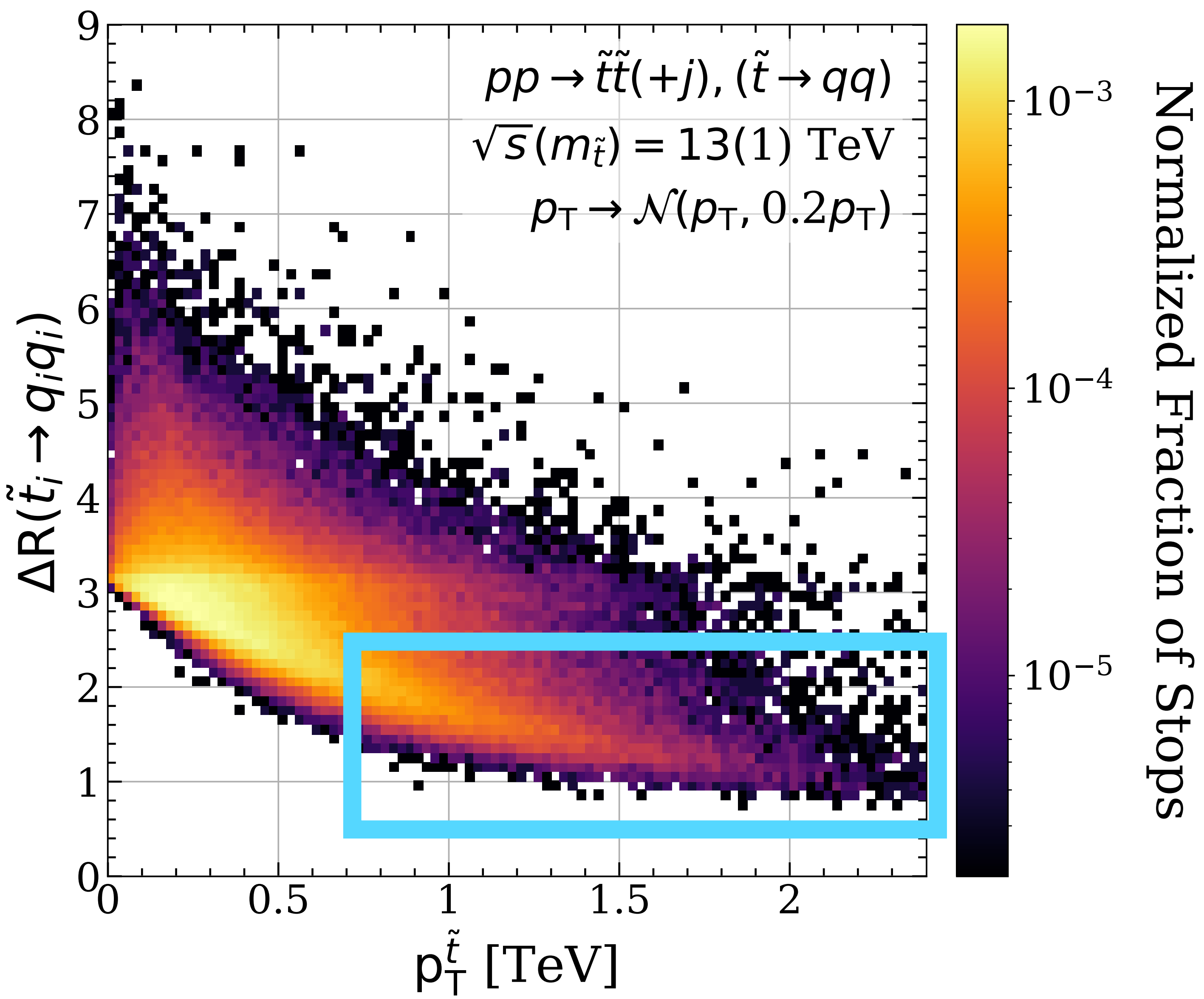
“Classical” 2x2



- But in order to get small ΔR^{Σ} values, stops need to be **highly boosted**
- **Low signal acceptance!**
  - Throwing away a lot of the signal…
- **Can we do better?**
- Can we scale this to **larger multiplicities?**



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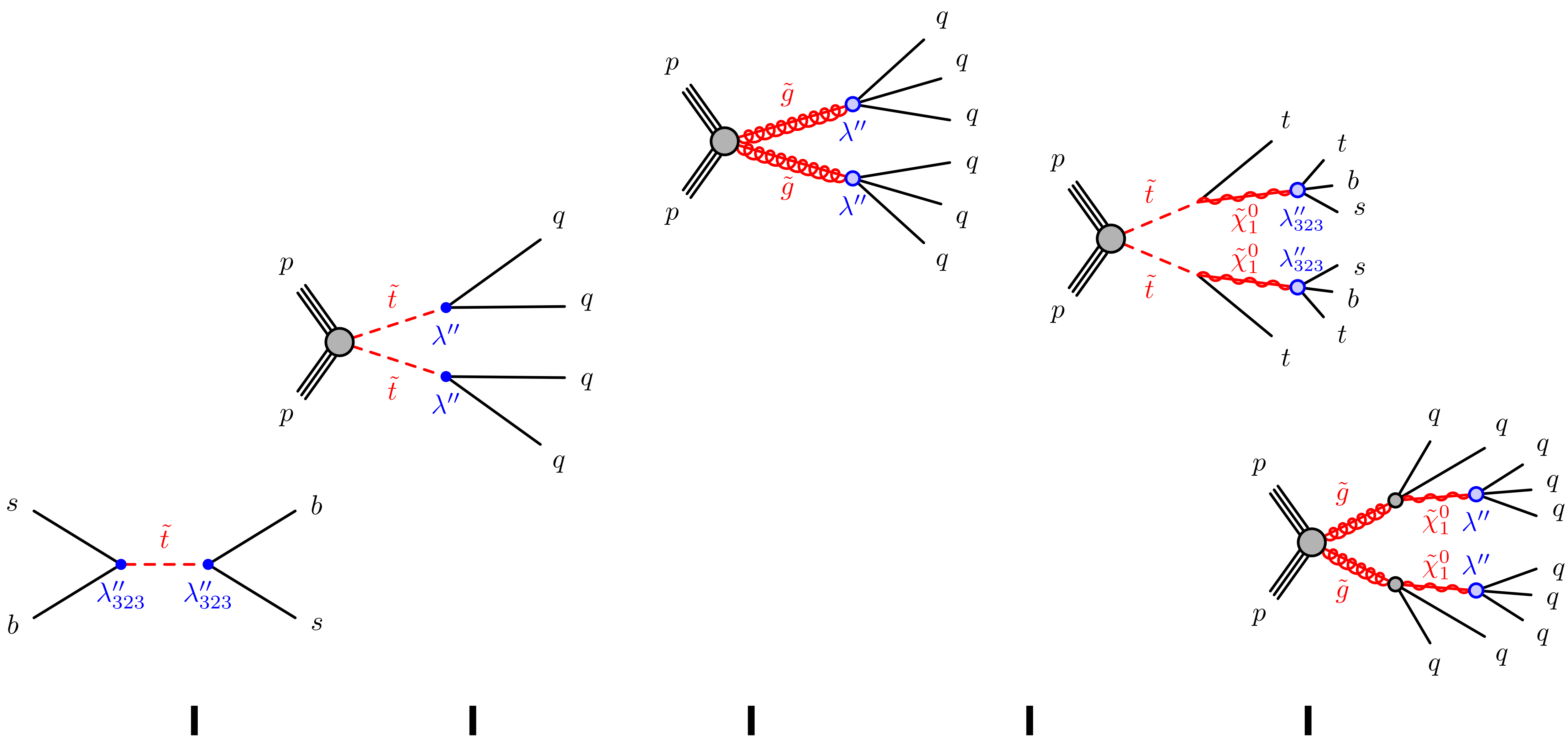
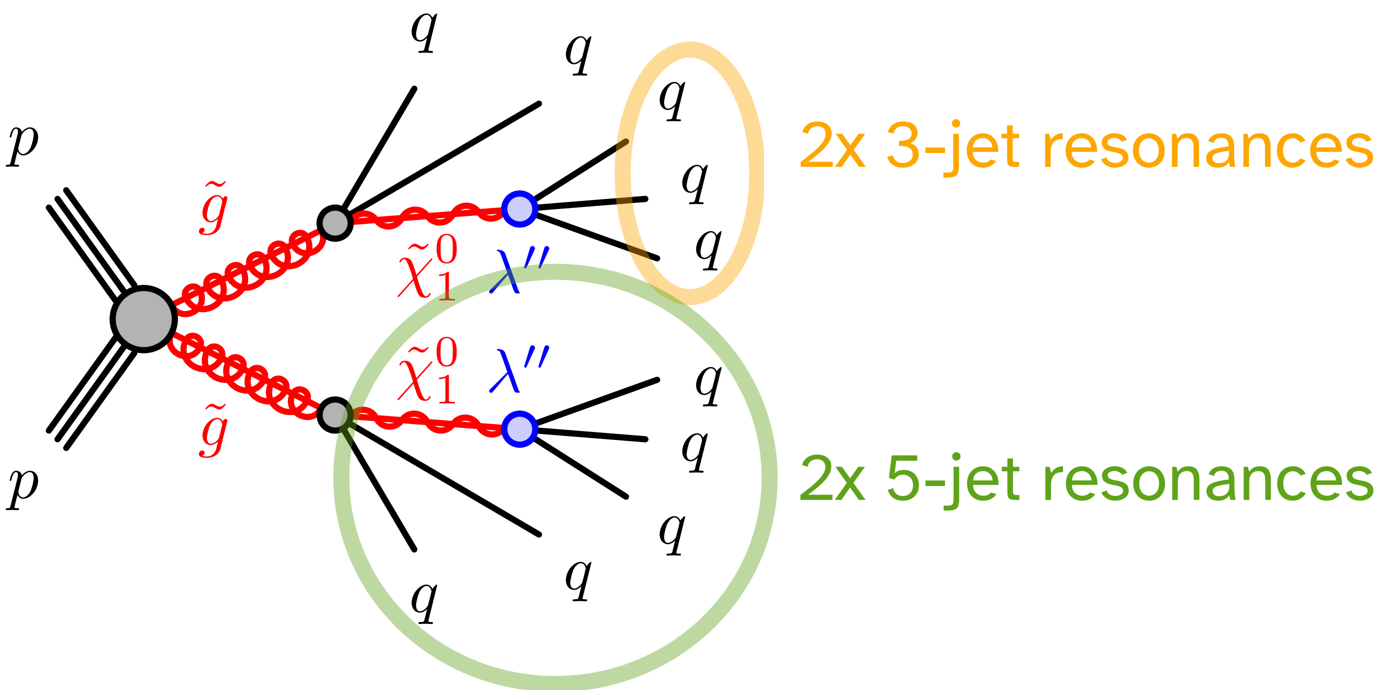


2×1 2×2 2×3 2×4 2×5

But it could easily be that new particles don’t produce 4-jet events.

The new particles might like to decay to many more jets!



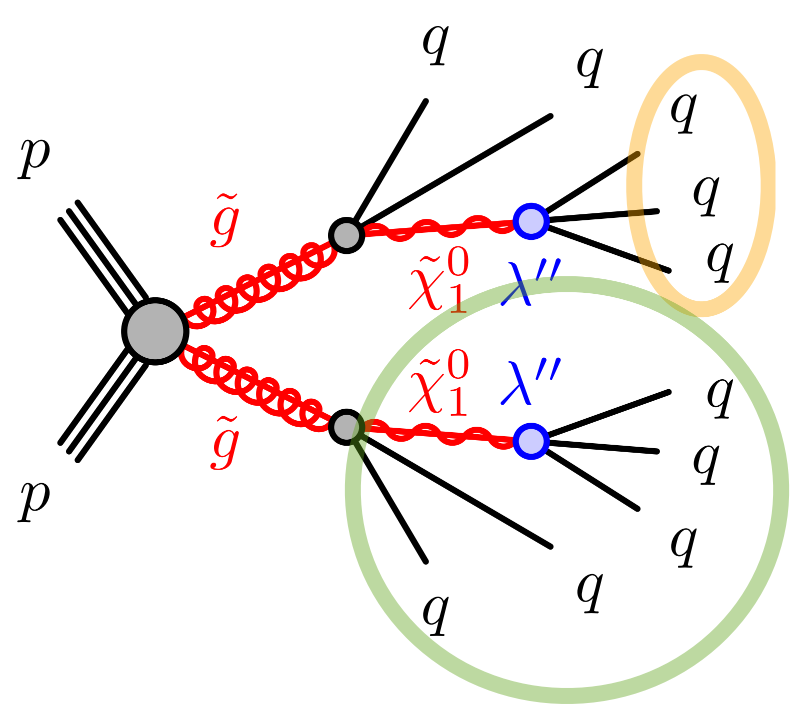
$$\binom{10}{5}/2 = 126$$

$$\binom{5}{3} = 10$$

- Focus on “10-jet”, “2x5-jet” signal
- 126 ways to find the 5-jet peak ($\tilde{g}$)
- **+ each contains extra 10 configs to find intermediate peak ($\tilde{\chi}$)**

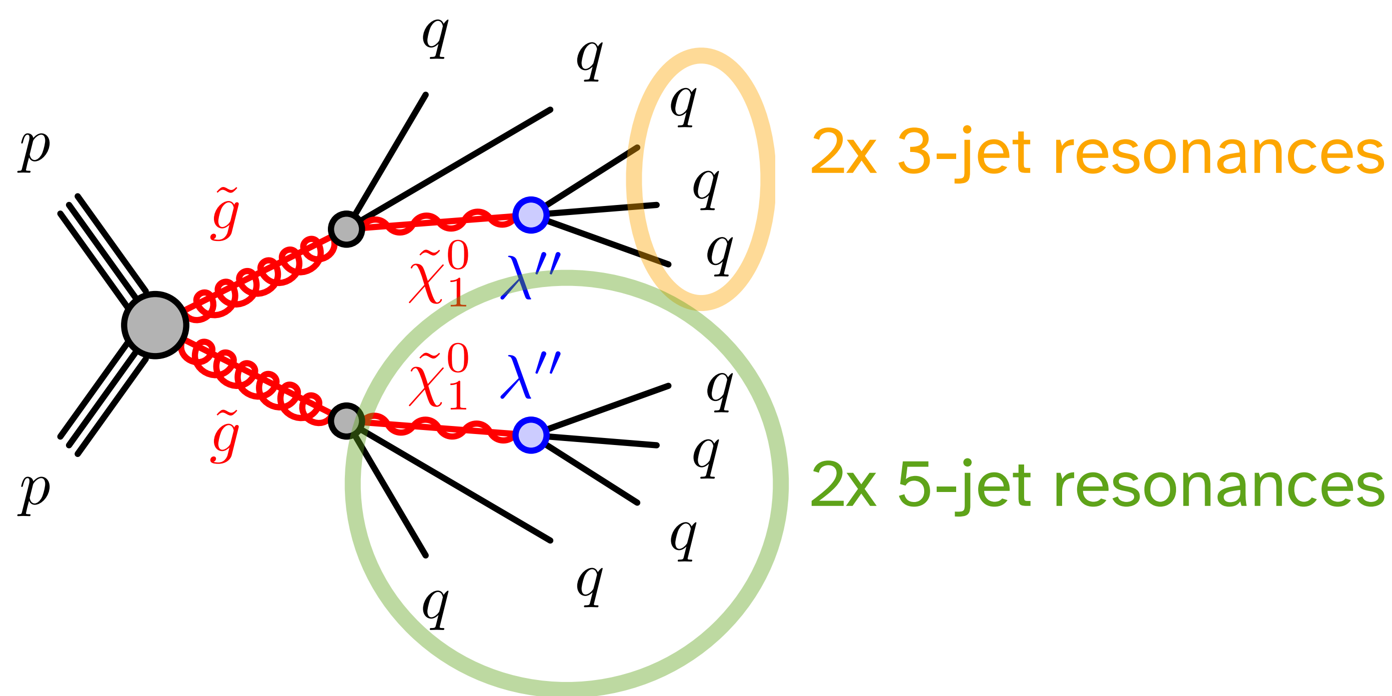
For the one “correct” view of this event,

there are >12k “wrong” views



- But lots of **kinematic information exists** shouldn't need to brute force problem...

- Yes, but have 10 four-vectors → **Info in 10x4=40D feature space!**
  - Can't construct useful variables by hand...

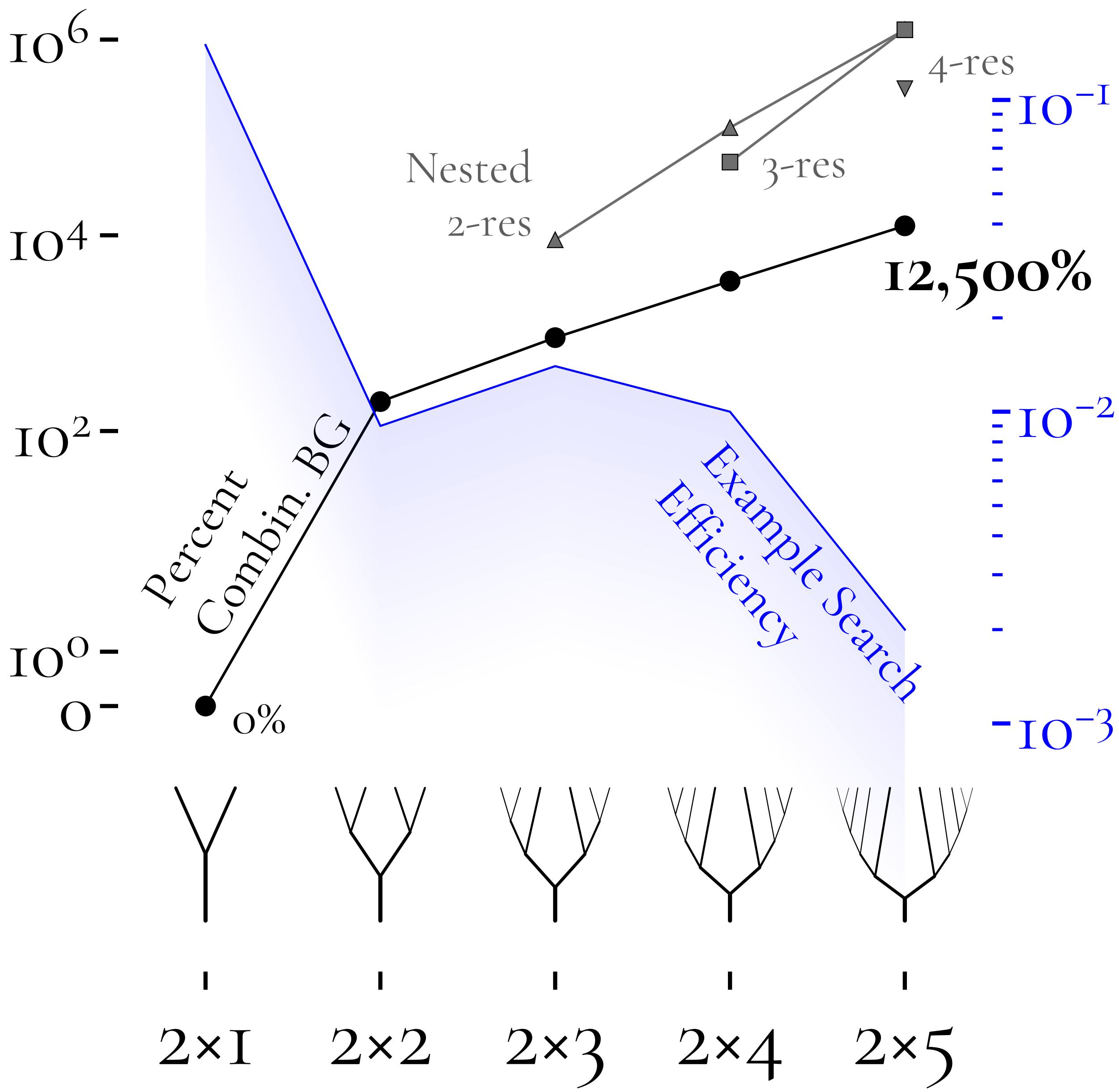


ML?

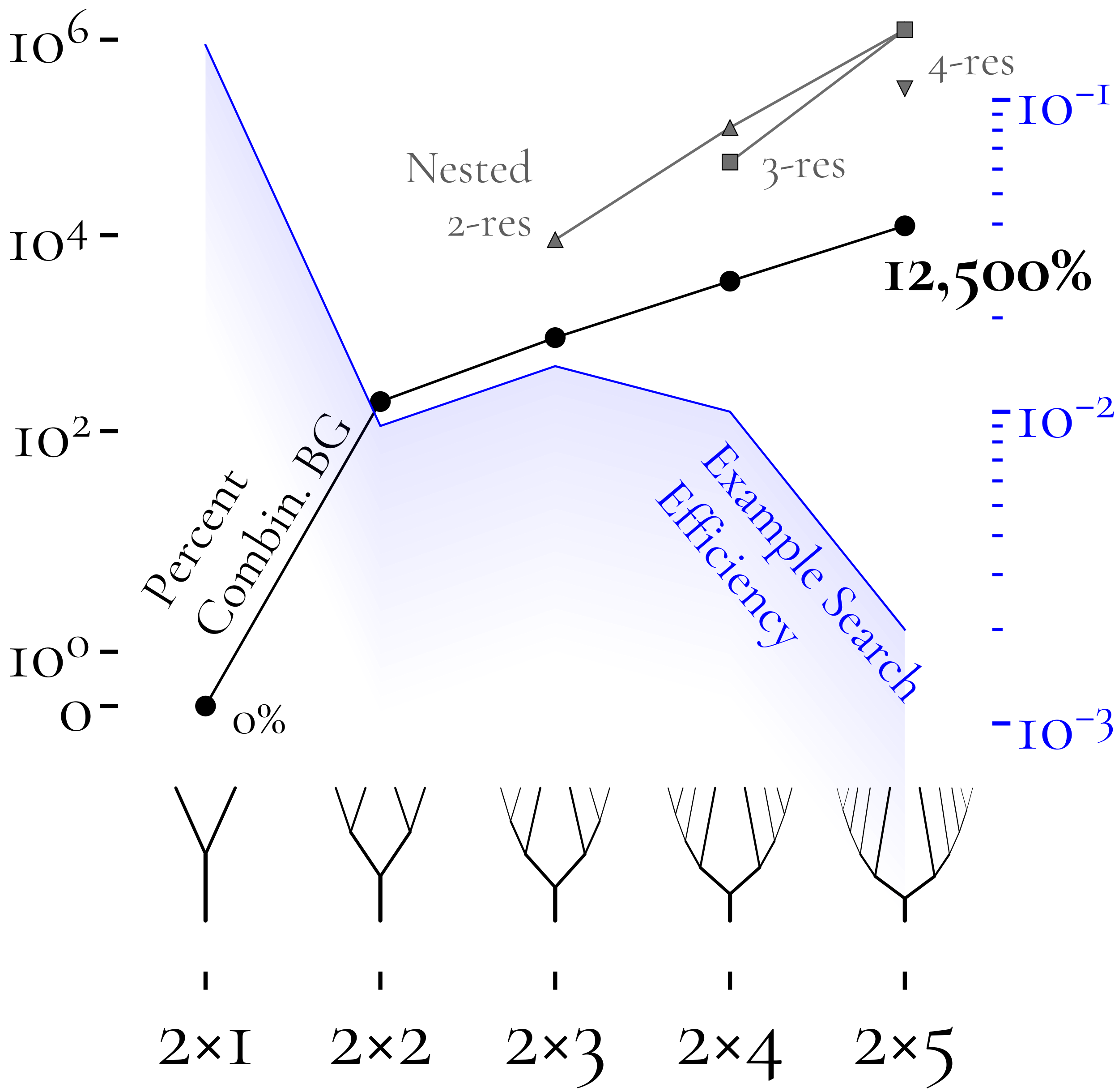
- Many HEP ML applications say “sig looks like BG. Let’s try a DNN.”
  - Always remember: **ML ≠ Magic.** Just a lot of Linear Alg

- **This is different: Sig and BG look very different.**
  - (It’s just that they look different in 40D)

- It’s not that we have little information
- We have **way too much** information!!! Large dim feature space.

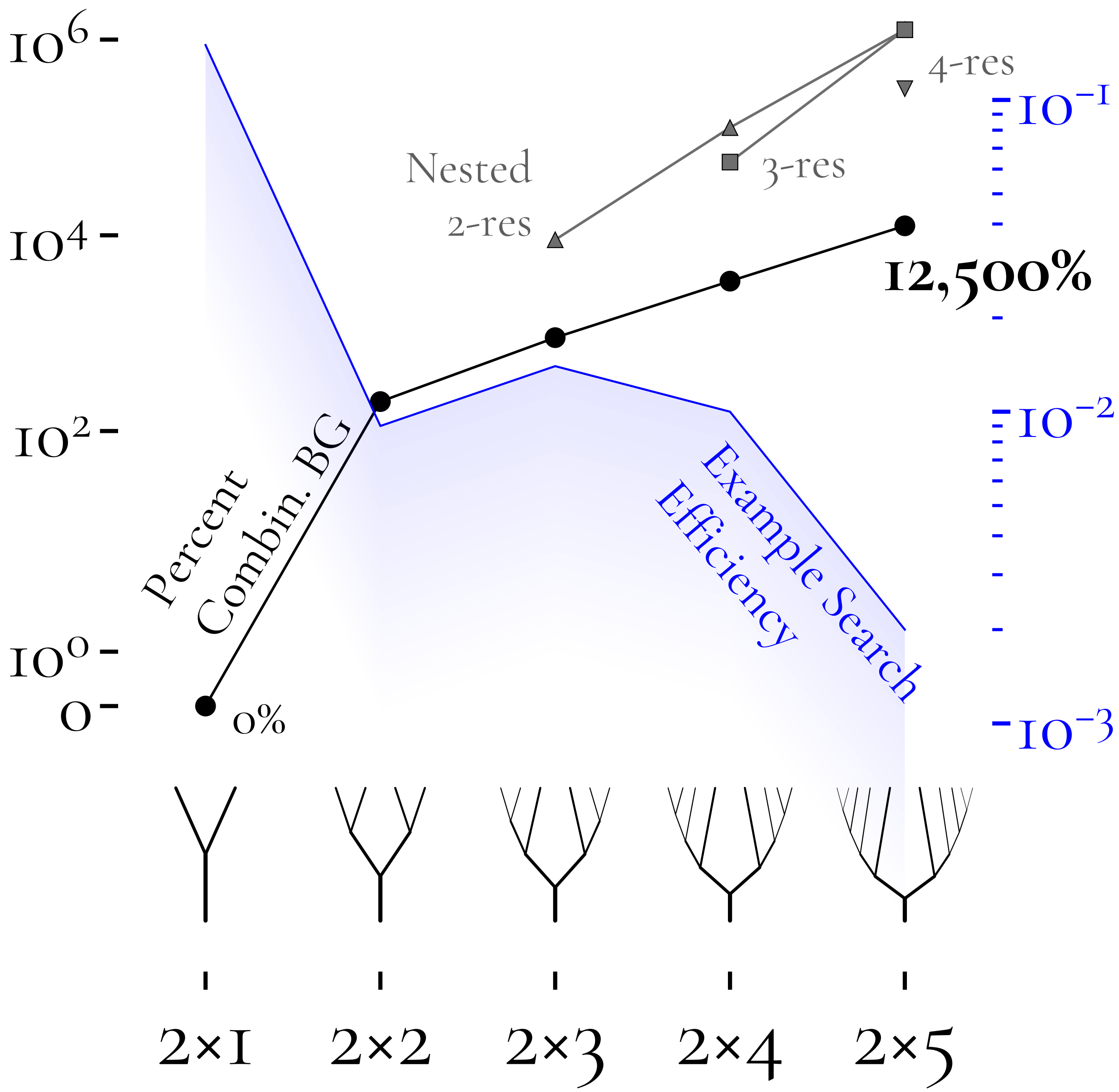


A Badea, W Fawcett, J Huth, TJ Khoo, R Poggi, LL — arXiv:2201.02205



In fact: LHC limits are pretty bad out here

A Badea, W Fawcett, J Huth, TJ Khoo, R Poggi, LL — arXiv:2201.02205

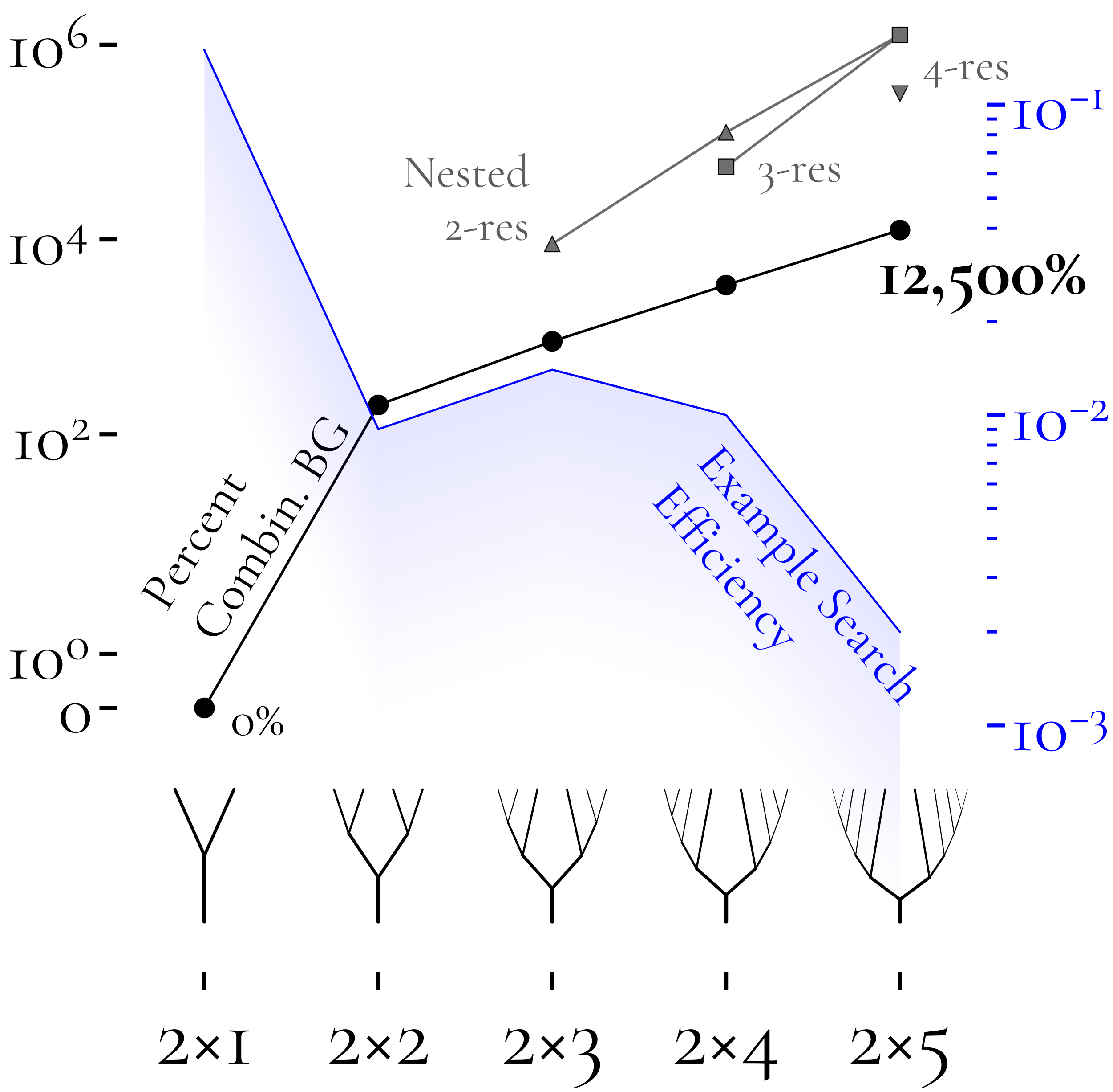


And it's a shame…

Because this is really well motivated…

In fact: LHC limits are pretty bad out here

A Badea, W Fawcett, J Huth, TJ Khoo, R Poggi, LL — arXiv:2201.02205



And it's a shame…

Because this is really well motivated…

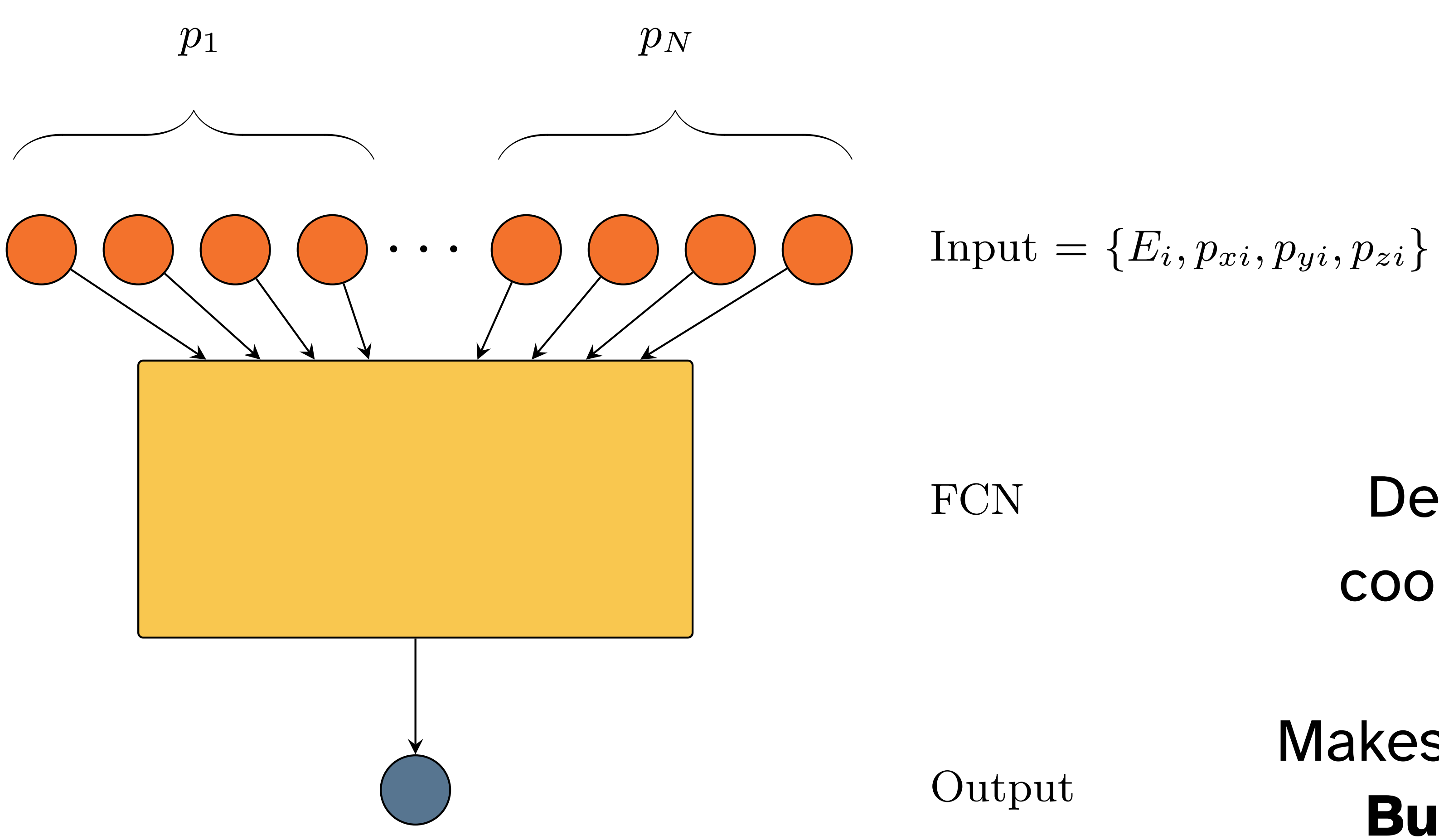
In fact: LHC limits are pretty bad out here

All still possible in RPV SUSY:
- 500 GeV stops
- 1.2 TeV gluinos
- 200 GeV Higgsinos

A Badea, W Fawcett, J Huth, TJ Khoo, R Poggi, LL — arXiv:2201.02205

Back to 2x2

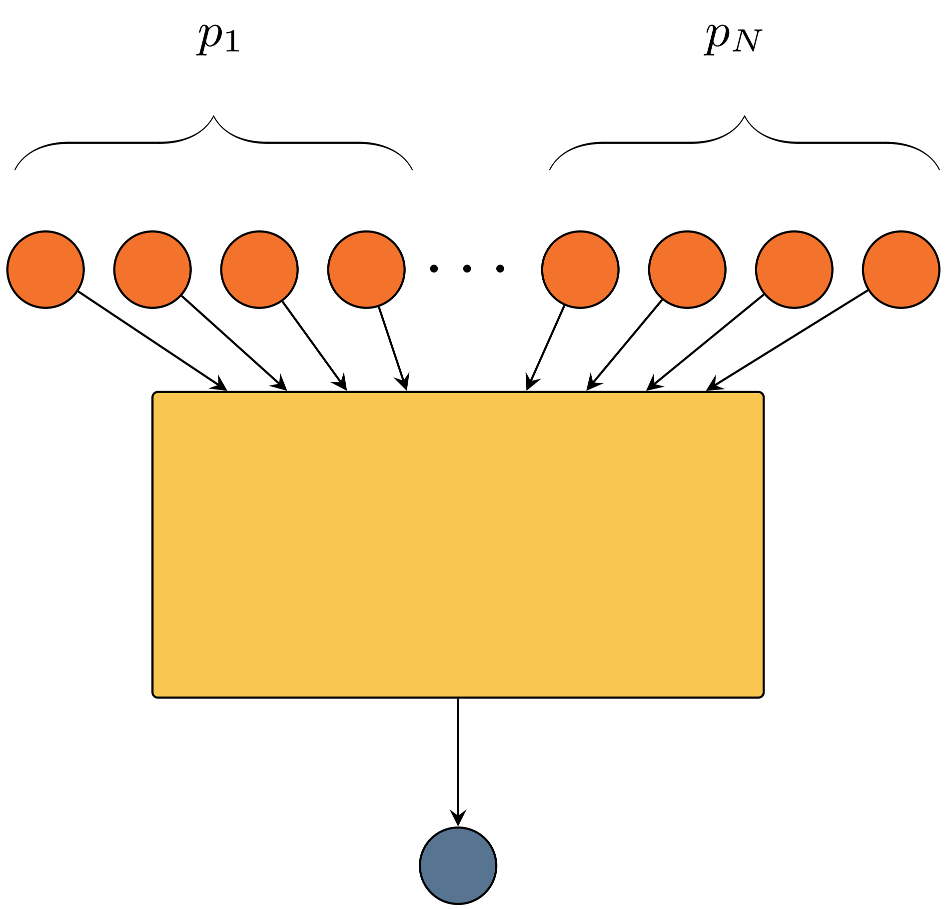
- Let's play with some Neural Nets to solve (relatively) simple problem
- What input structure?
- Some HEP applications use full 4-momenta:



Describing inputs in orthogonal coordinate system $\{E, p_x, p_y, p_z\}$

Makes it easy for NN to sum inputs
But NN needs to learn how to calculate masses!

Back to 2x2



$$\text{Input} = \{m_i, p_{Ti}, \eta_i, \phi_i\}$$

~~$\text{Input} = \{E_i, p_{xi}, p_{yi}, p_{zi}\}$~~

FCN

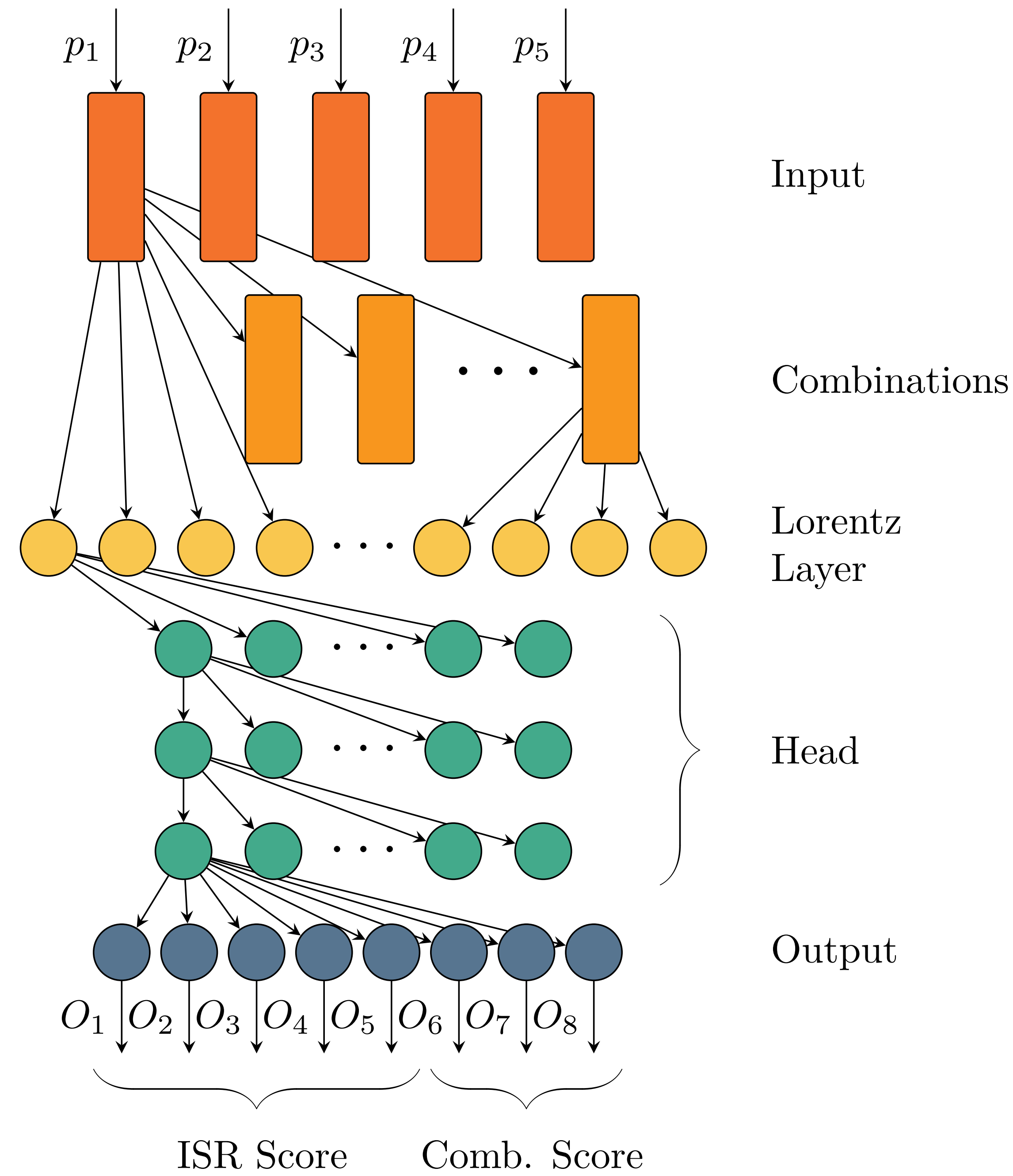
Output

Others might hand it $\{m, p_T, \eta, \phi\}$

NN is told about masses and angles
But it then needs to learn how to combine vectors!

NN w/ Lorentz Layer

- Construct a NN layer that **knows about relativity!**
- Input four-momenta → Knows how to do four-vector addition, calculate mass!
- **Don't need a network to learn physics we already know about!**
- NN is optimizing in physics basis
- Send into "traditional" feed-forward neural net to reduce dimensionality of problem



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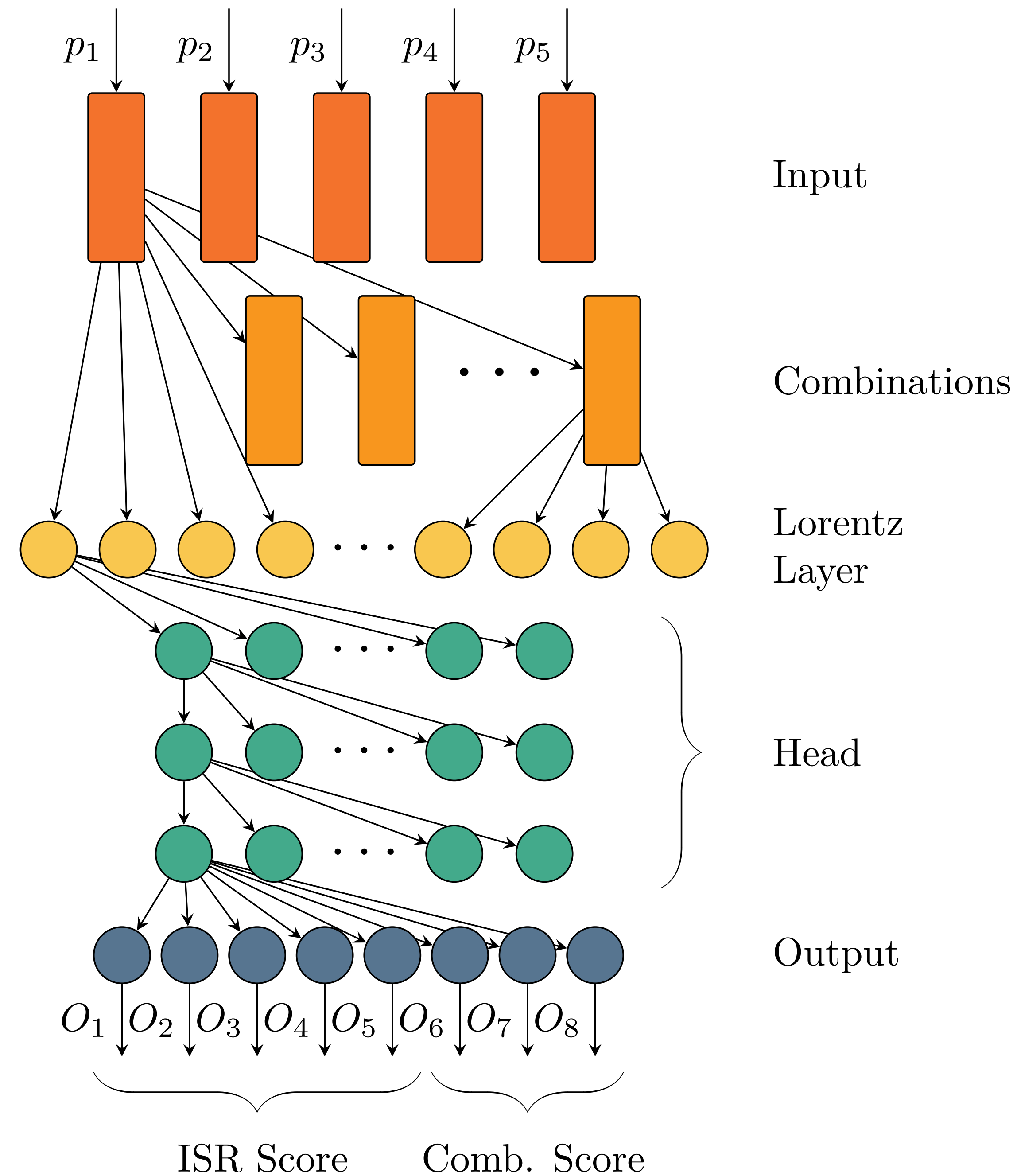
NN w/ Lorentz Layer

Cannonball:

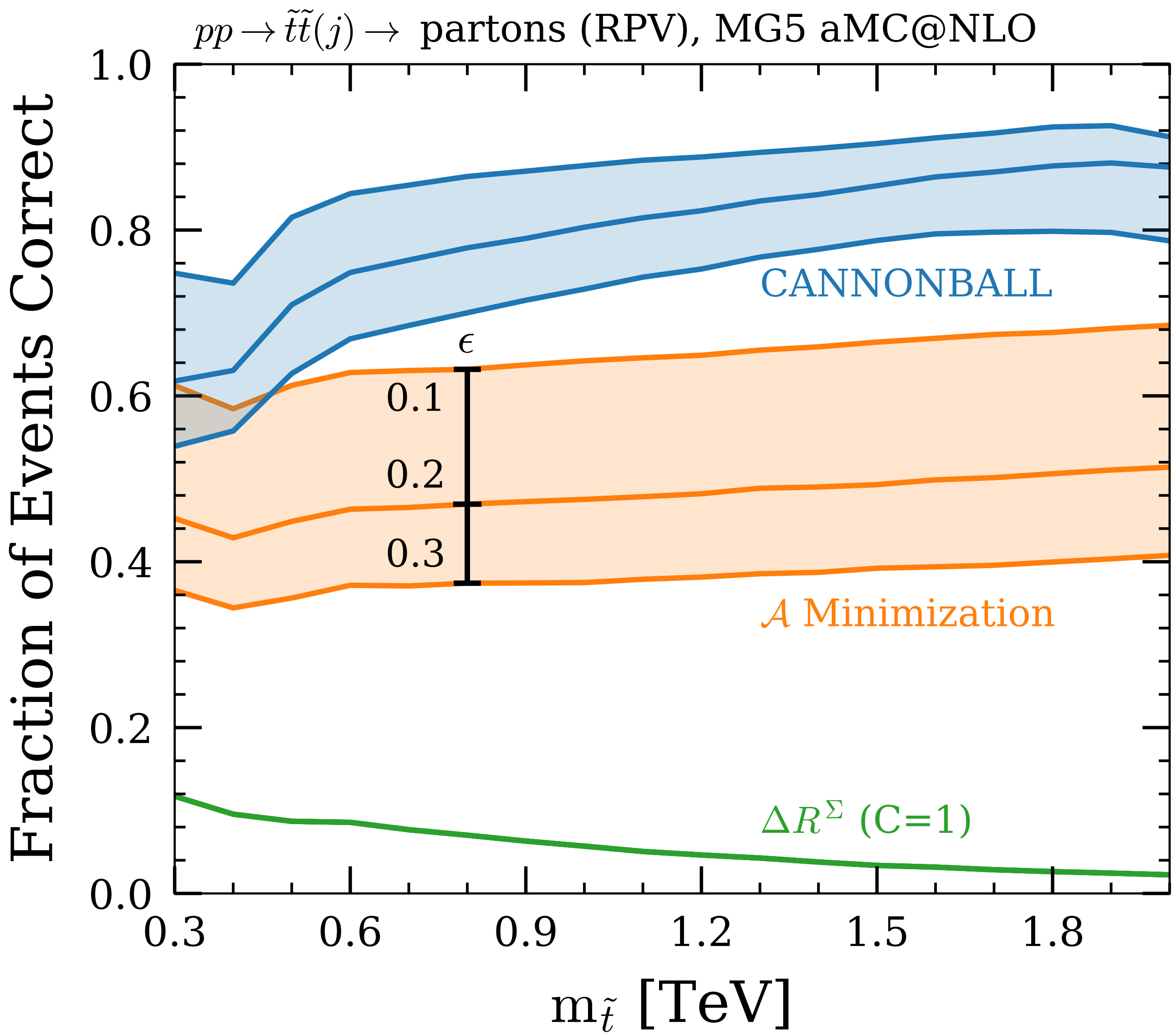
Combinatoric Artificial NN ON (BAckronym) Lorentz Layer

- Output not a single score.
- **Outputs *interpretation* of event** to choose the "best" combination for us
- Then traditional analysis methods come in!
    - [Including systematics]



A Badea, W Fawcett, J Huth, TJ Khoo, R Poggi, LL — arXiv:2201.02205

- ΔR^Σ minimization does terribly at getting the right pairing!
- **CANNONBALL performs ~30x better at large mass**
- And is fairly robust to mismeasurement of jets (ϵ)



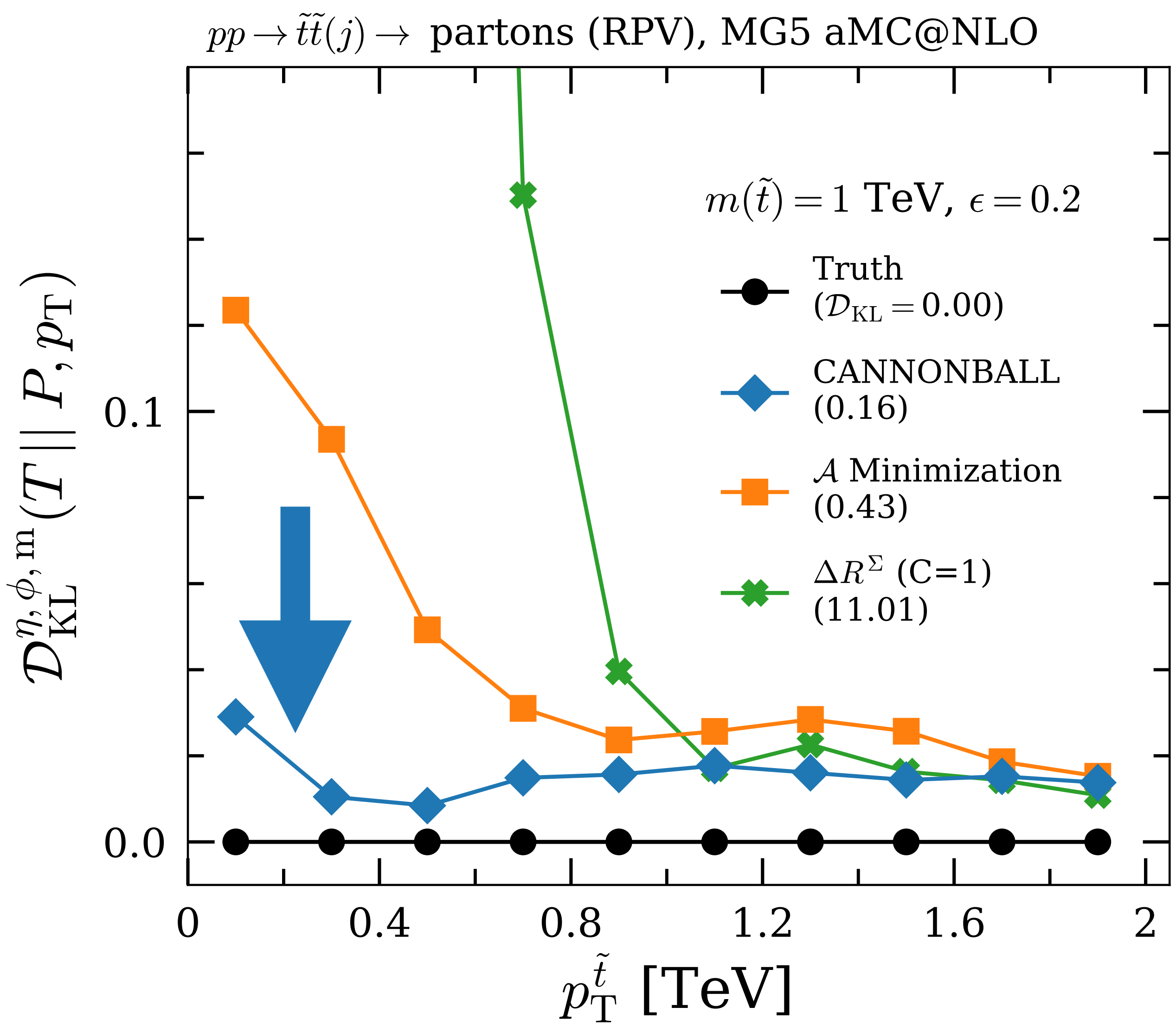
A Badea, W Fawcett, J Huth, TJ Khoo, R Poggi, LL — arXiv:2201.02205

- D_{KL}: A measure of how much two PDFs differ
- How well each method reconstructs full four-vec of the heavy resonances (i.e. getting the right comb. answer)
- **CANNONBALL's big advantage is at low stop p_T**

$$\mathcal{D}_{\mathrm{KL}}\left(T||P\right) = \int T \log\left(\frac{T}{P}\right) dp^{\mu}$$

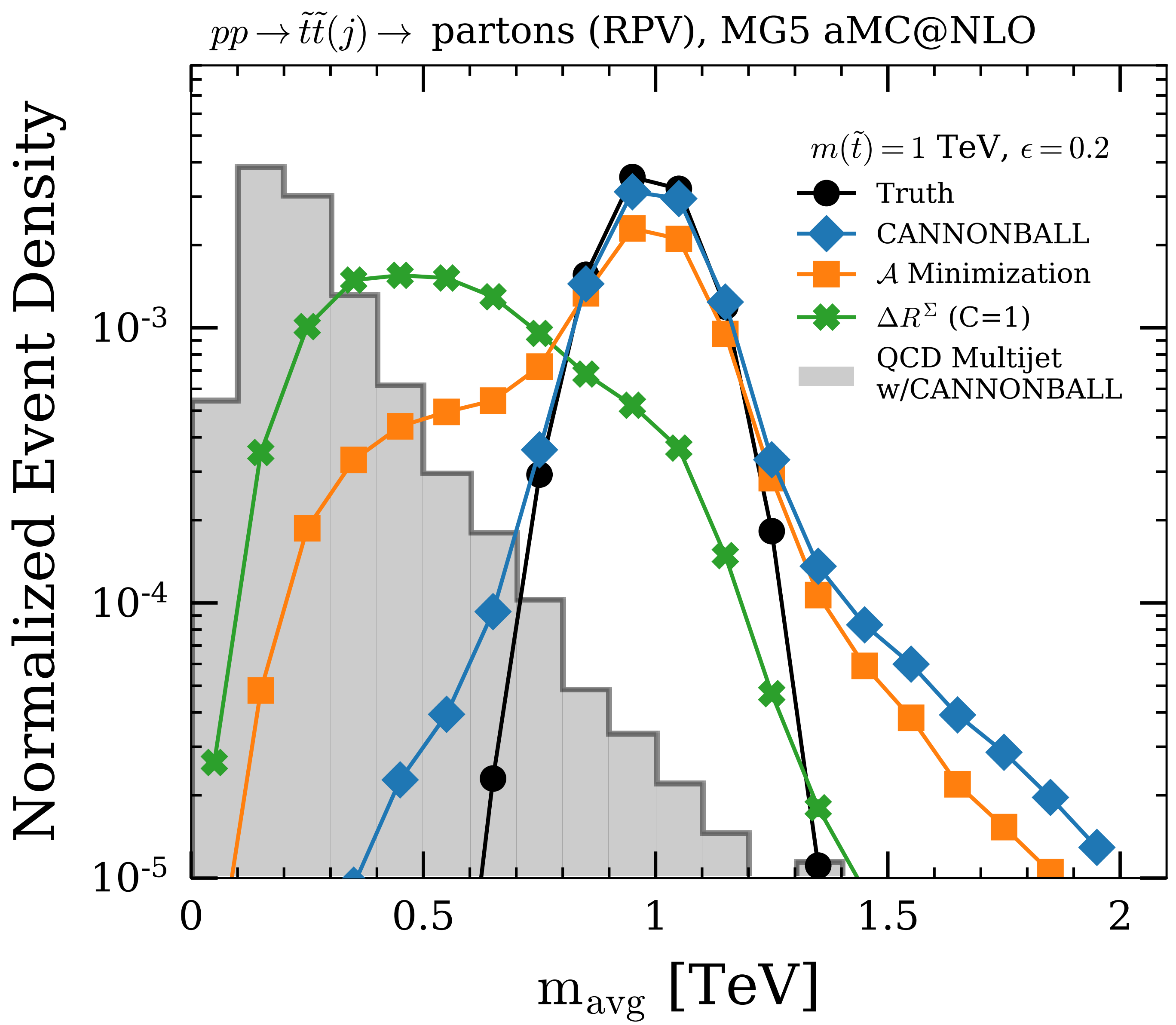
$$= \sum_{p_{\mathrm{T}}\ \mathrm{bins}} \sum_{\eta,\phi,\mathrm{m}\ \mathrm{bins}} T \log\left(\frac{T}{P}\right)$$

$$= \sum_{p_{\mathrm{T}}\ \mathrm{bins}} \mathcal{D}_{\mathrm{KL}}^{\eta,\phi,\mathrm{m}}\left(T||P, p_{\mathrm{T}}\right)$$



A Badea, W Fawcett, J Huth, TJ Khoo, R Poggi, LL — arXiv:2201.02205

- Better comb solns give peak-ier mass distributions
- Easier to distinguish from QCD+comb BGs
- **This should translate to more search sensitivity.**
  - Ongoing work



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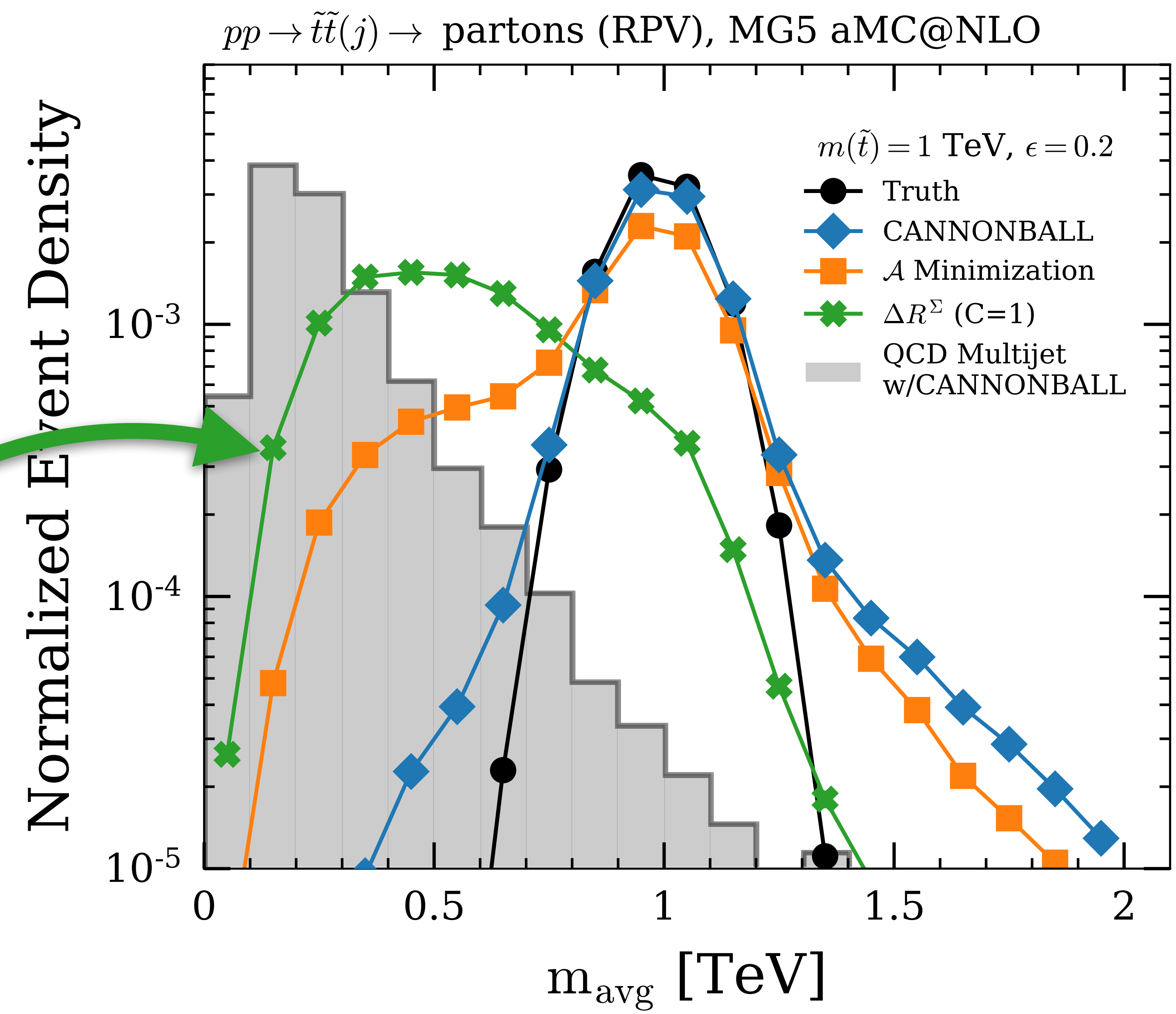
ΔR^Σ does terribly unless boosted.

To see peak, throw away low p_T



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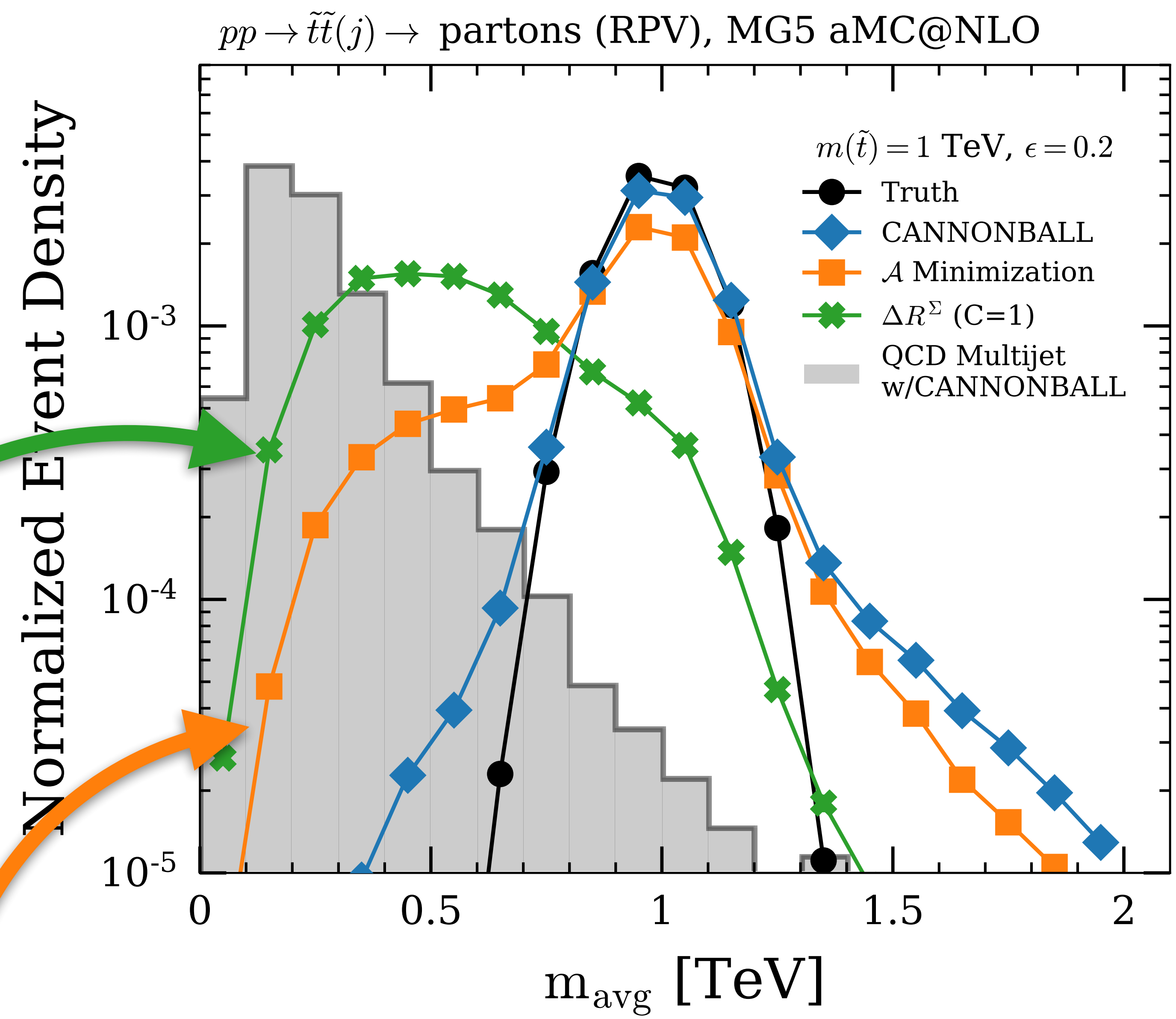

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Mass Asymmetry Min

Large off-peak contributions…

A Badea, W Fawcett, J Huth, TJ Khoo, R Poggi, LL — arXiv:2201.02205

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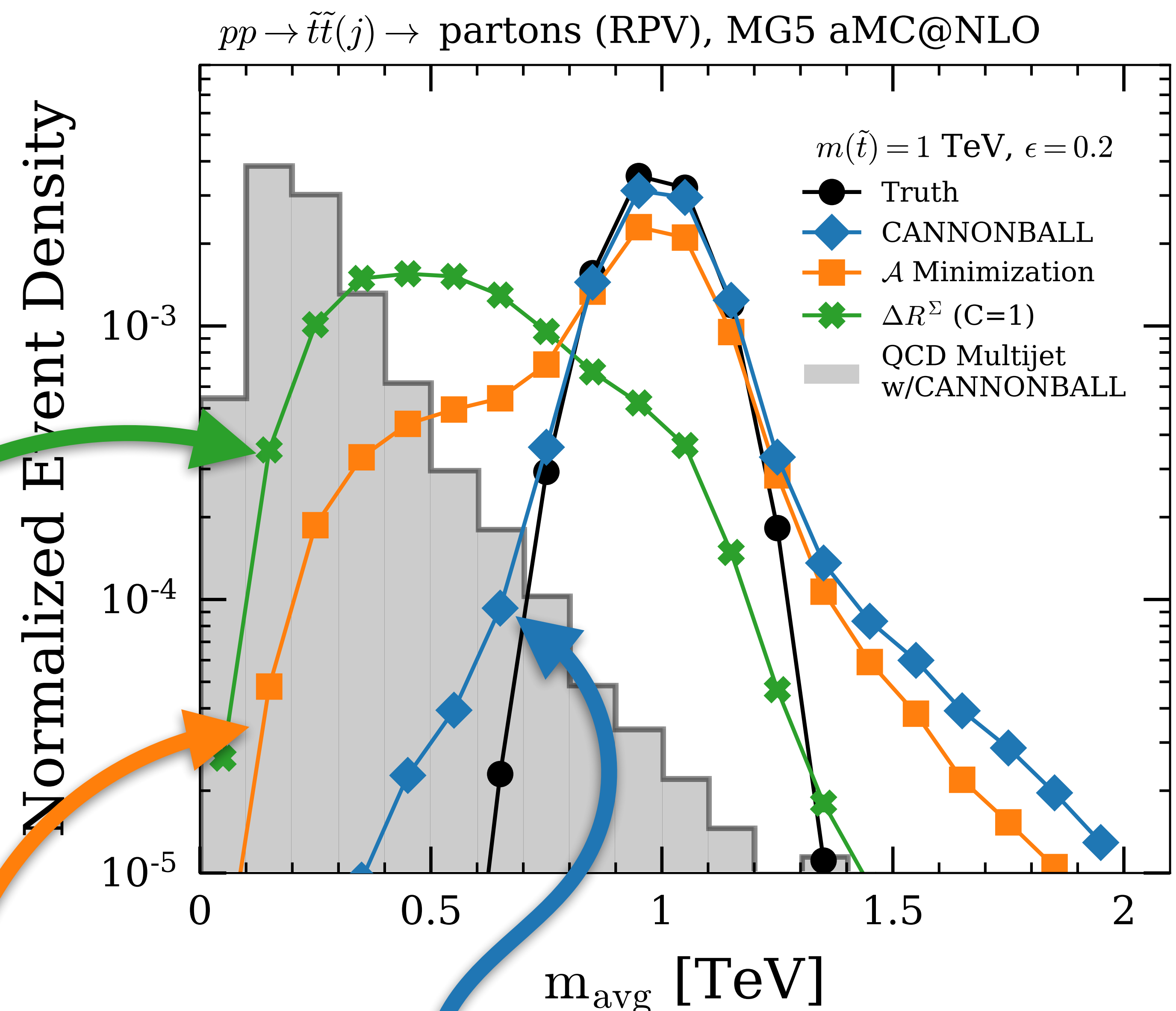

ΔR^{Σ} does terribly unless boosted.

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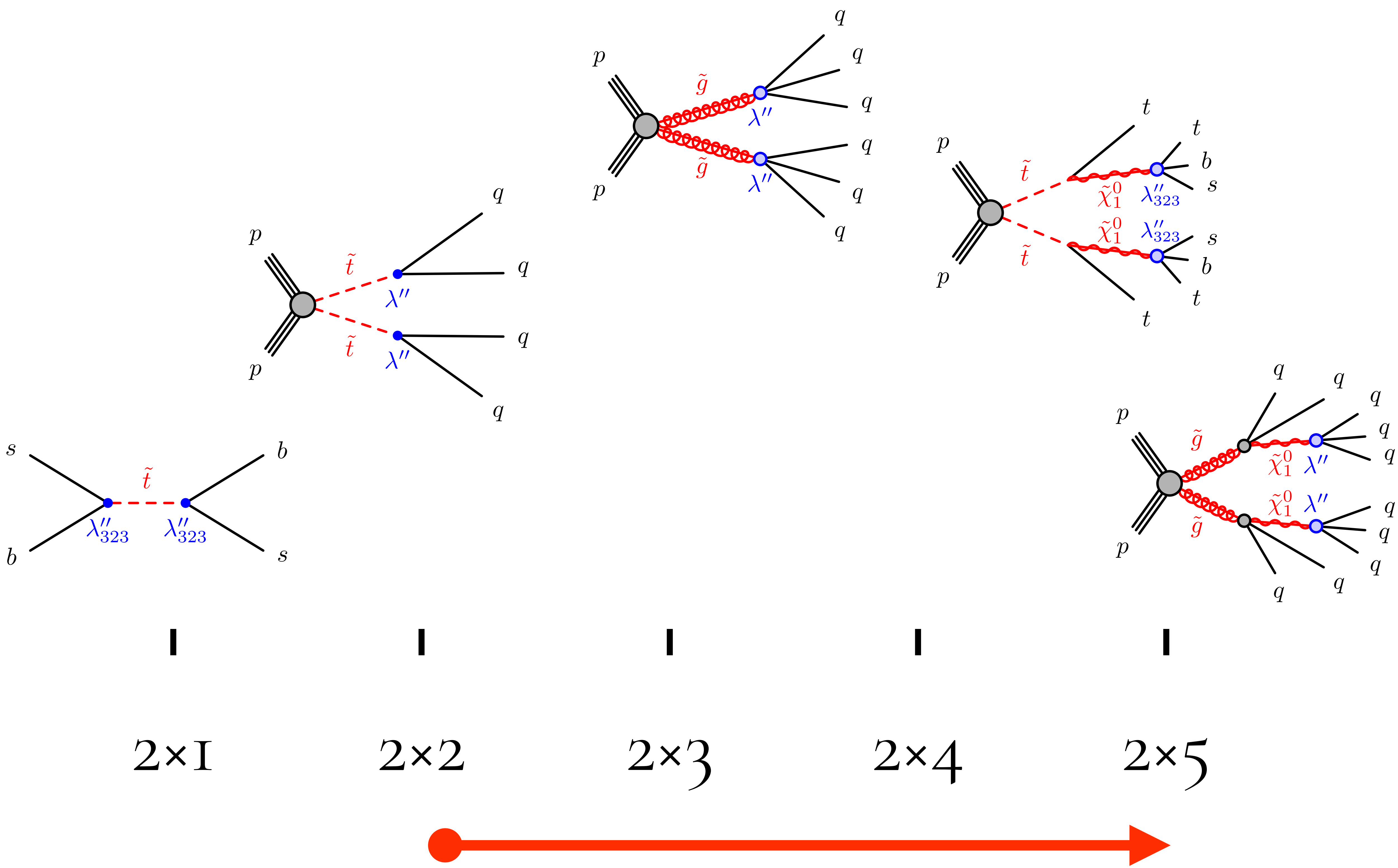
Mass Asymmetry Min

Large off-peak contributions…

CANNONBALL

Very close to best case scenario (truth)

A Badea, W Fawcett, J Huth, TJ Khoo, R Poggi, LL — arXiv:2201.02205

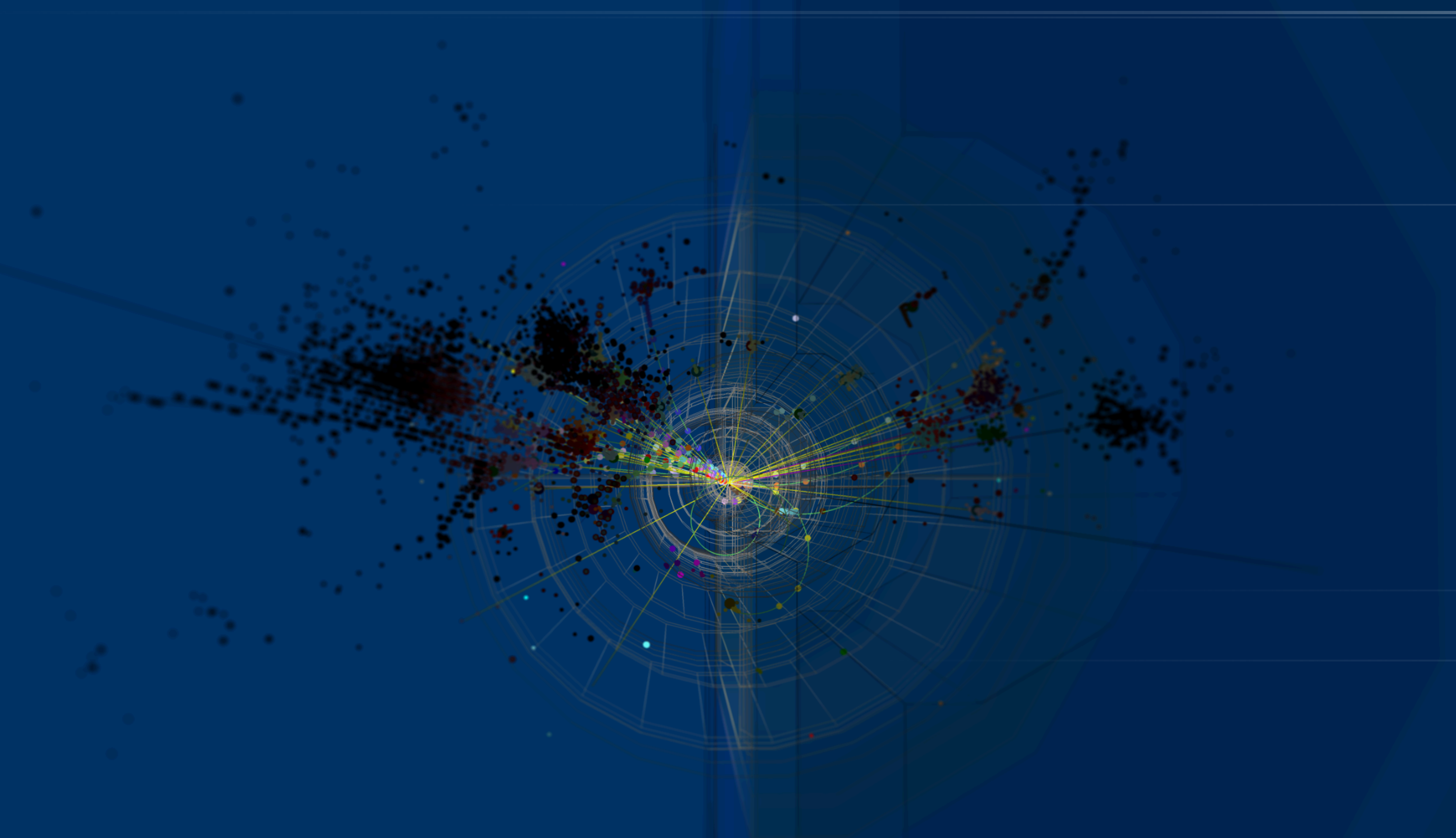


Does this approach scale?

- Attack large dim feature spaces
- If we think in this way, **realize lots of room for low mass new particles from natural theories!**
- Hidden under the SM BGs **and combinatorial BGs created by our lack of 40D tools**
- **Not using** ML to eke out a little more exclusion power

- Attack large dim feature spaces
- If we think in this way, **realize lots of room for low mass new particles from natural theories!**
- Hidden under the SM BGs **and combinatorial BGs created by our lack of 40D tools**
- **Not using** ML to eke out a little more exclusion power

Trying to enable searches that are really (really) hard that might actually **DISCOVER** something.



Thanks for your attention!

R-Parity Violating SUSY

$$W_{RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \frac{1}{2}\lambda''_{ijk} U_i D_j D_k$$

L Violating

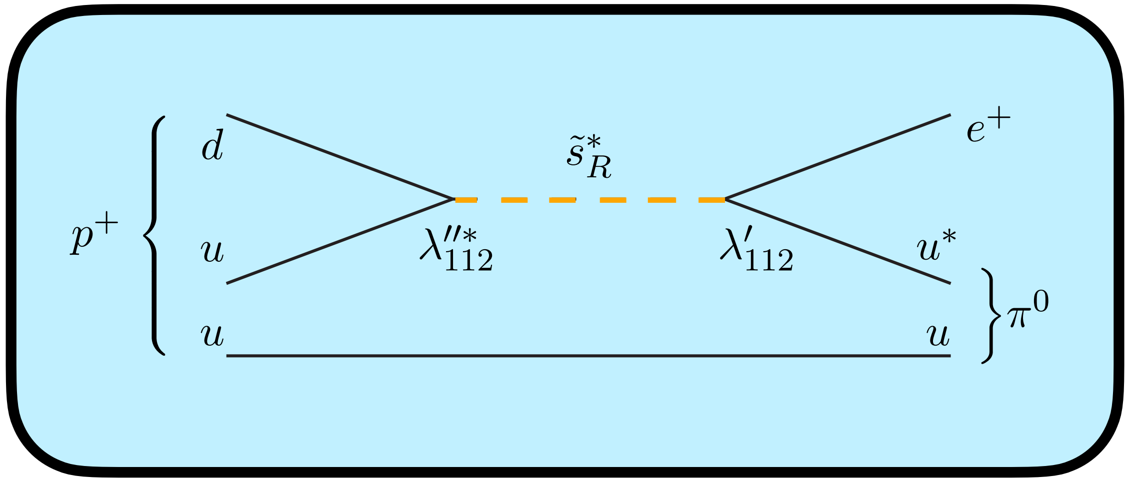
B Violating

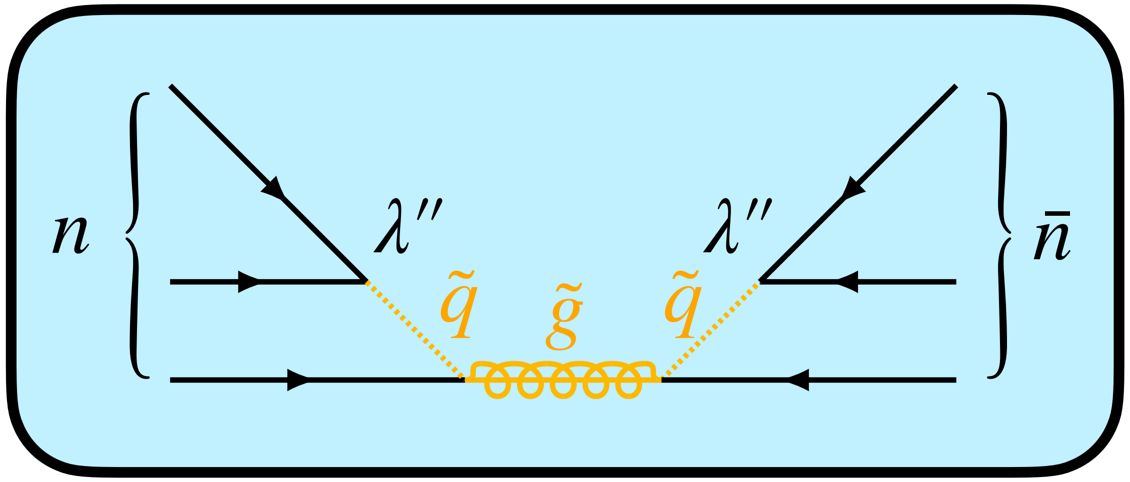
R-Parity Violating SUSY

$$W_{RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \frac{1}{2}\lambda''_{ijk} U_i D_j D_k$$

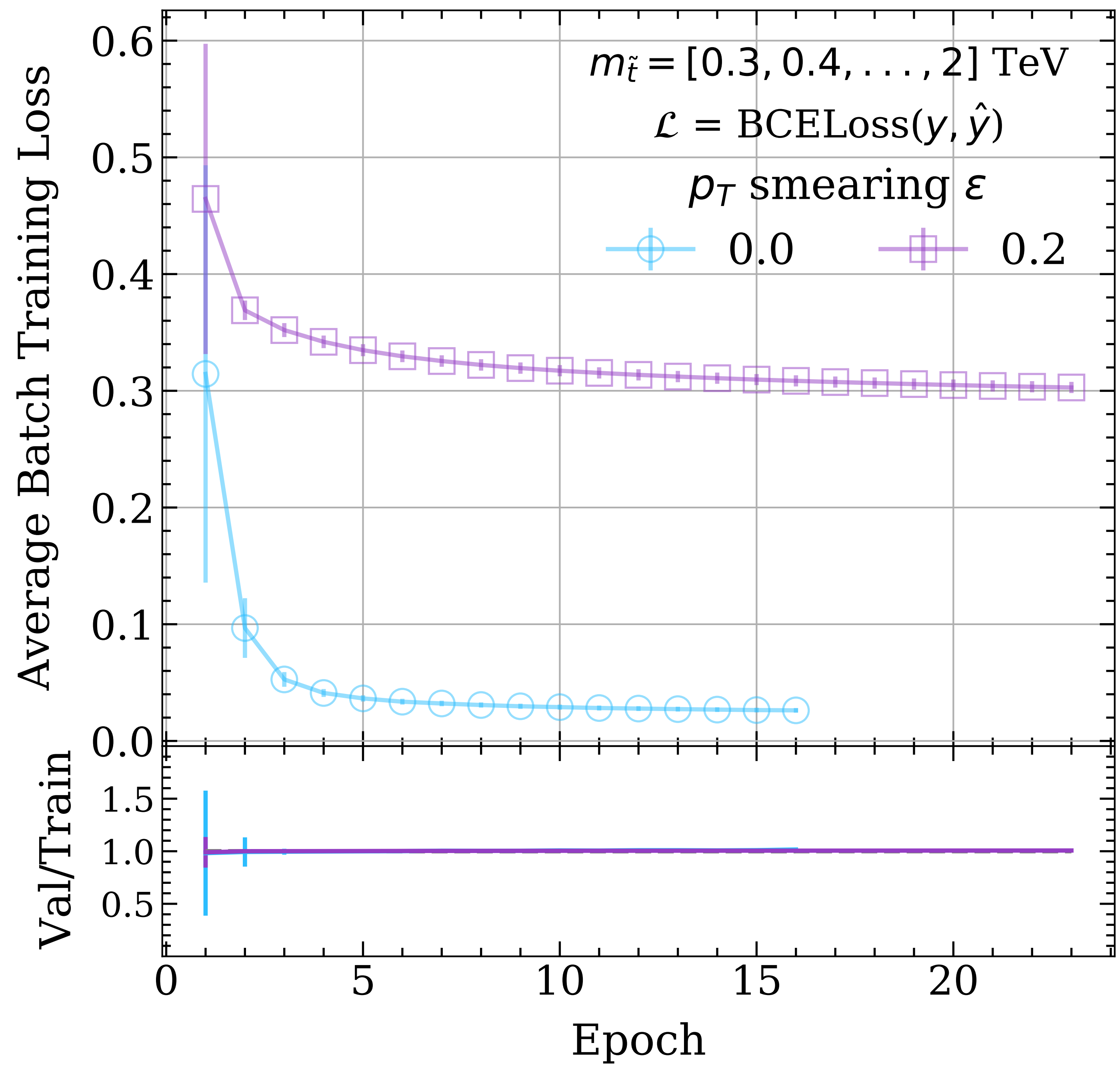
L Violating B Violating

- **Low energy/Electroweak constraints**
  - **Proton lifetime limits** set *very* strict bounds on simultaneous L- and B-violation here (for light flavor couplings)
  - **Z boson** line shape measurements set some limits on L-violation in RPV
  - Biggest constraints on (light flavor) λ″ come from **n-nbar oscillation** limits
  - **nEDM<<1** also constrains certain λ″





- Using pyTorch
  - Training on NVIDIA Quadro RTX w 8GB RAM using CUDA 11.5
- Enforcing mass invariance by mixing masses (democratically) in training sample
  - 180k events x 20 masses
- Loss fn: Binary cross entropy, minimized using Adam.
- Learning rate of 1e-3 — playing with dynamic learning rate
- Batch size of 10k
- 30 combination layer nodes
- 3 hidden layers in head (200 nodes)



$$m_H^2 = m_{H,bare}^2 + \Delta m_{SM}^2 + \Delta m_{BSM}^2$$

$q{=}{+}2/3$ $s{=}1/2$	u	c	t	W	±1 1
$-1/3$ $1/2$	d	s	b	Z	0 1
0 $1/2$	ν_e	ν_μ	ν_τ	γ	0 1
-1 $1/2$	e	μ	τ	g	0 1
$+2/3$ 0	$\tilde{u}_{R,L}$	$\tilde{c}_{R,L}$	$\tilde{t}_{1,2}$	$\tilde{\chi}_1^\pm$	±1 $1/2$
$-1/3$ 0	$\tilde{d}_{R,L}$	$\tilde{s}_{R,L}$	$\tilde{b}_{1,2}$	$\tilde{\chi}_2^\pm$	±1 $1/2$
0 0	$\tilde{\nu}_e$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$	$\tilde{\chi}_{1-4}^0$	0 $1/2$
-1 0	$\tilde{e}_{R,L}$	$\tilde{\mu}_{R,L}$	$\tilde{\tau}_{1,2}$	$\tilde{g}$	0 $1/2$
0 0	h^0	A^0	H^0	$H^\pm$	±1 0

What if we say each particle has a *partner* *("sparticle")* that cancels off corrections

SUPERSYMMETRY

(SUSY)

$$m_H^2 = m_{H,bare}^2 + \Delta m_{SM}^2 + \Delta m_{BSM}^2$$

$q=+2/3$ $s=1/2$	u	c	t	W	± 1 1
$-1/3$ $1/2$	d	s	b	Z	0 1
0 $1/2$	ν_e	ν_μ	ν_τ	γ	0 1
-1 $1/2$	e	μ	τ	g	0 1
$+2/3$ 0	$\tilde{u}_{R,L}$	$\tilde{c}_{R,L}$	$\tilde{t}_{1,2}$	$\tilde{\chi}_1^\pm$	± 1 $1/2$
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0 0	$\tilde{\nu}_e$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$	$\tilde{\chi}_{1-4}^0$	0 $1/2$
-1 0	$\tilde{e}_{R,L}$	$\tilde{\mu}_{R,L}$	$\tilde{\tau}_{1,2}$	$\tilde{g}$	0 $1/2$
0 0	h^0	A^0	H^0	$H^\pm$	± 1 0

Minimally Supersymmetric Extension to the SM

(MSSM)

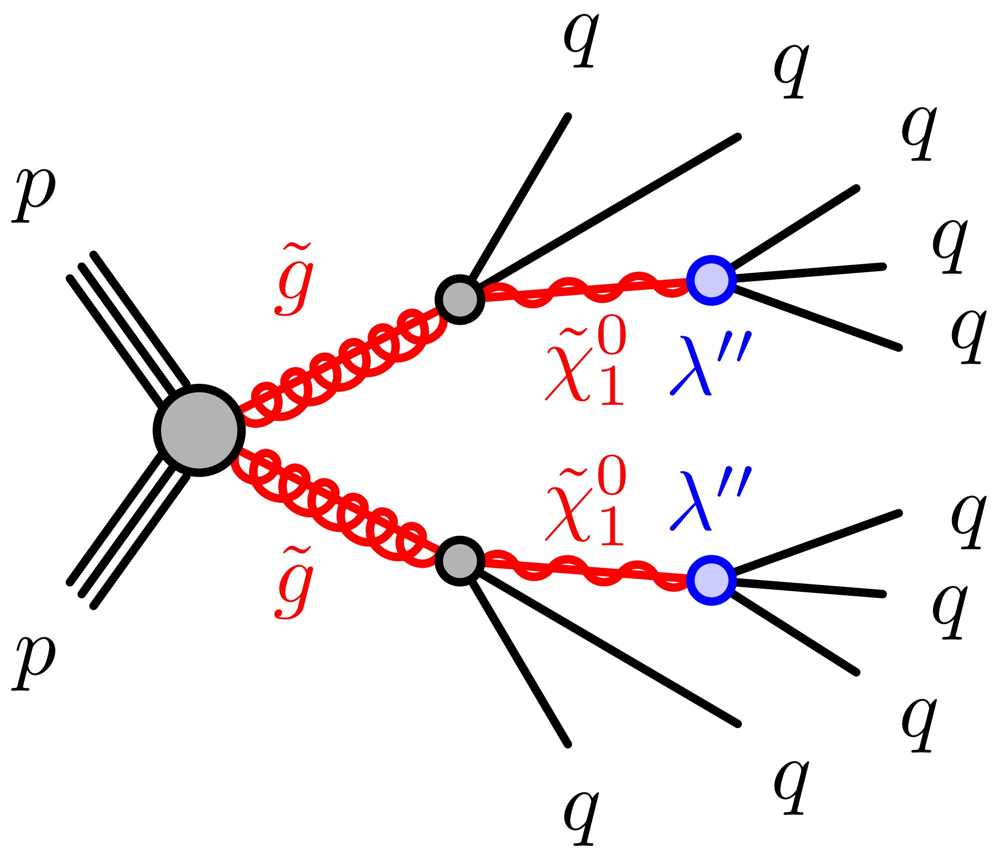
R-Parity Violating SUSY

$$W_{RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \frac{1}{2}\lambda''_{ijk} U_i D_j D_k$$

L Violating

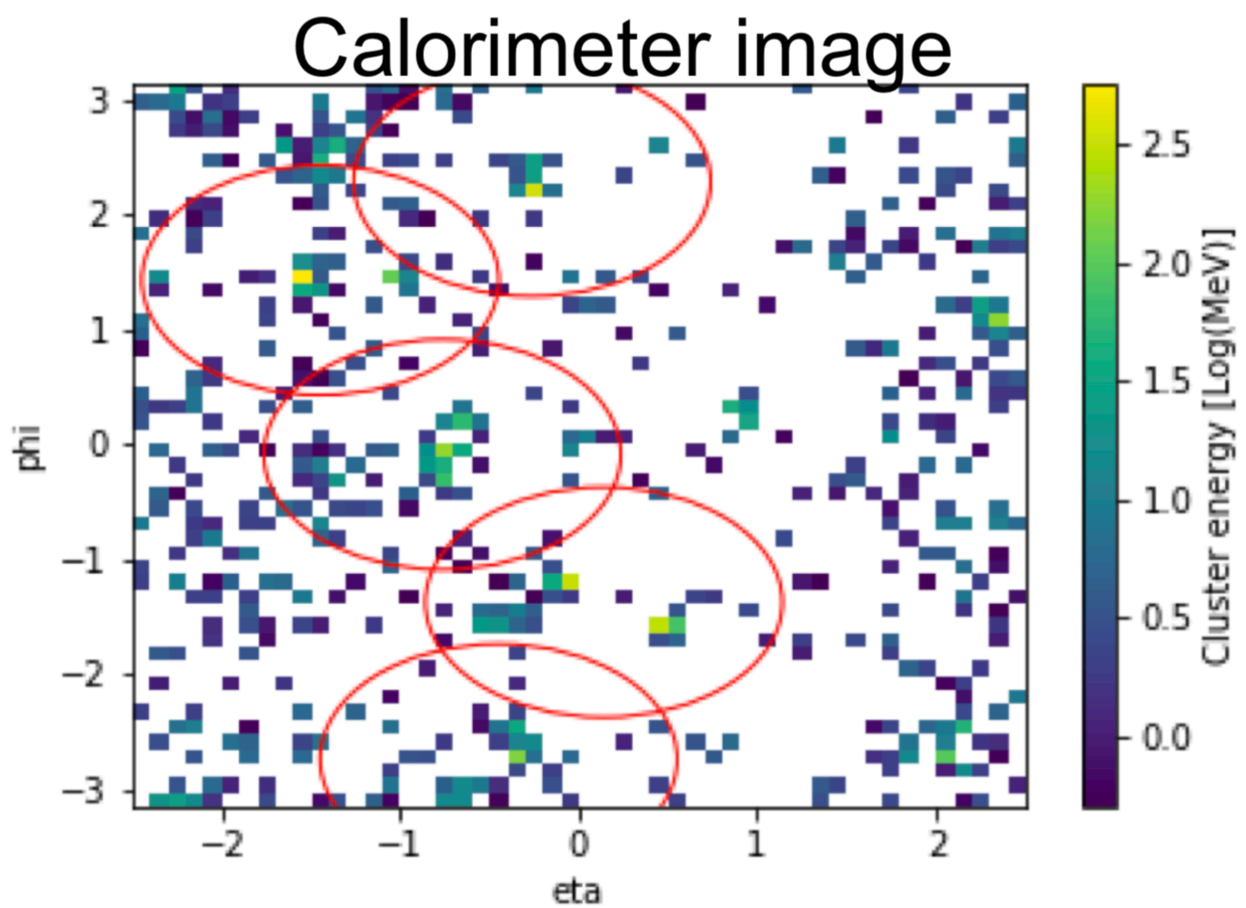
B Violating

- λ″ gives rise to **all-hadronic final states** at LHC
- B-Violating SUSY could **easily hide** at LHC



- Papers have argued for low-level calo images → CNN: 1805.10730 1711.03573

- Could work, but overly complicates…
  - Most of the detector is empty! Inefficient!
  - Throw away all jet physics (*) and tries to rediscover it.
  - That's not the problem I'm interested in solving…



50x50 x 3 layers ~ 7.5k Dimensions!

(*) The work it takes to go from raw detector info to calibrated four-vector

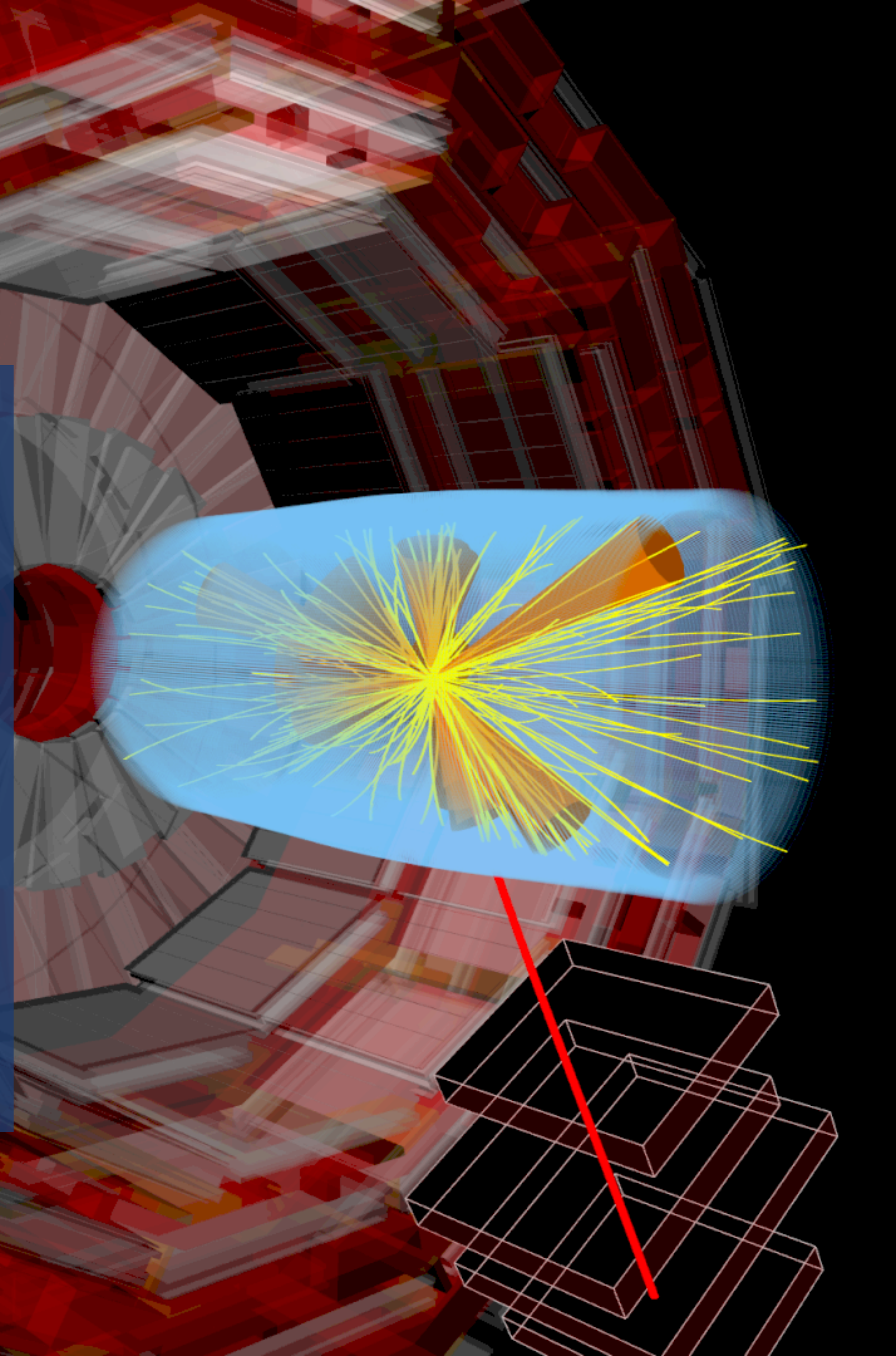
Talk by SFarrell at SUSY Mini-workshop on ML

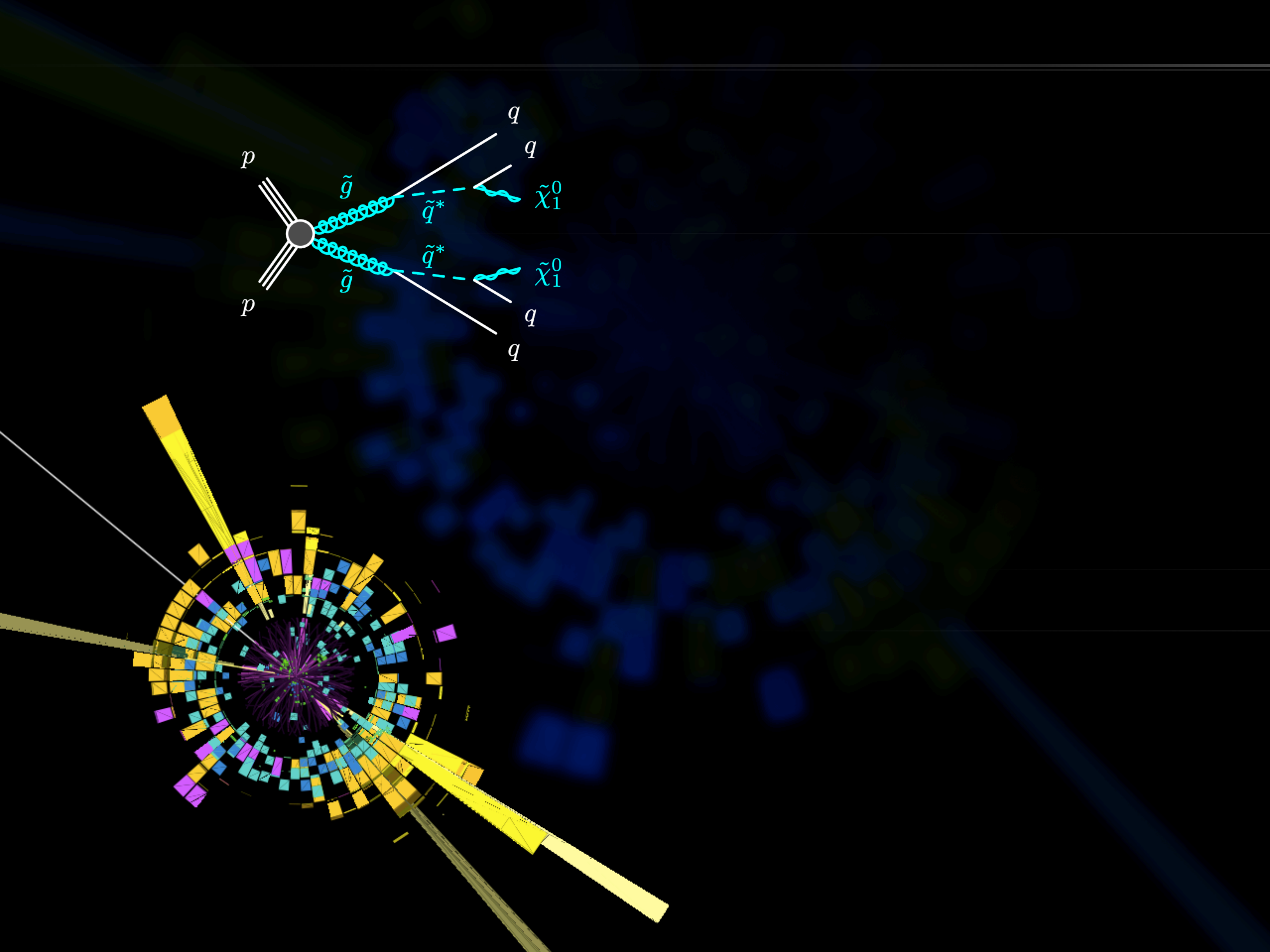
Instead, use huge jet physics industry…

Distill calo inputs to **well-understood,** calibrated 4-vectors.

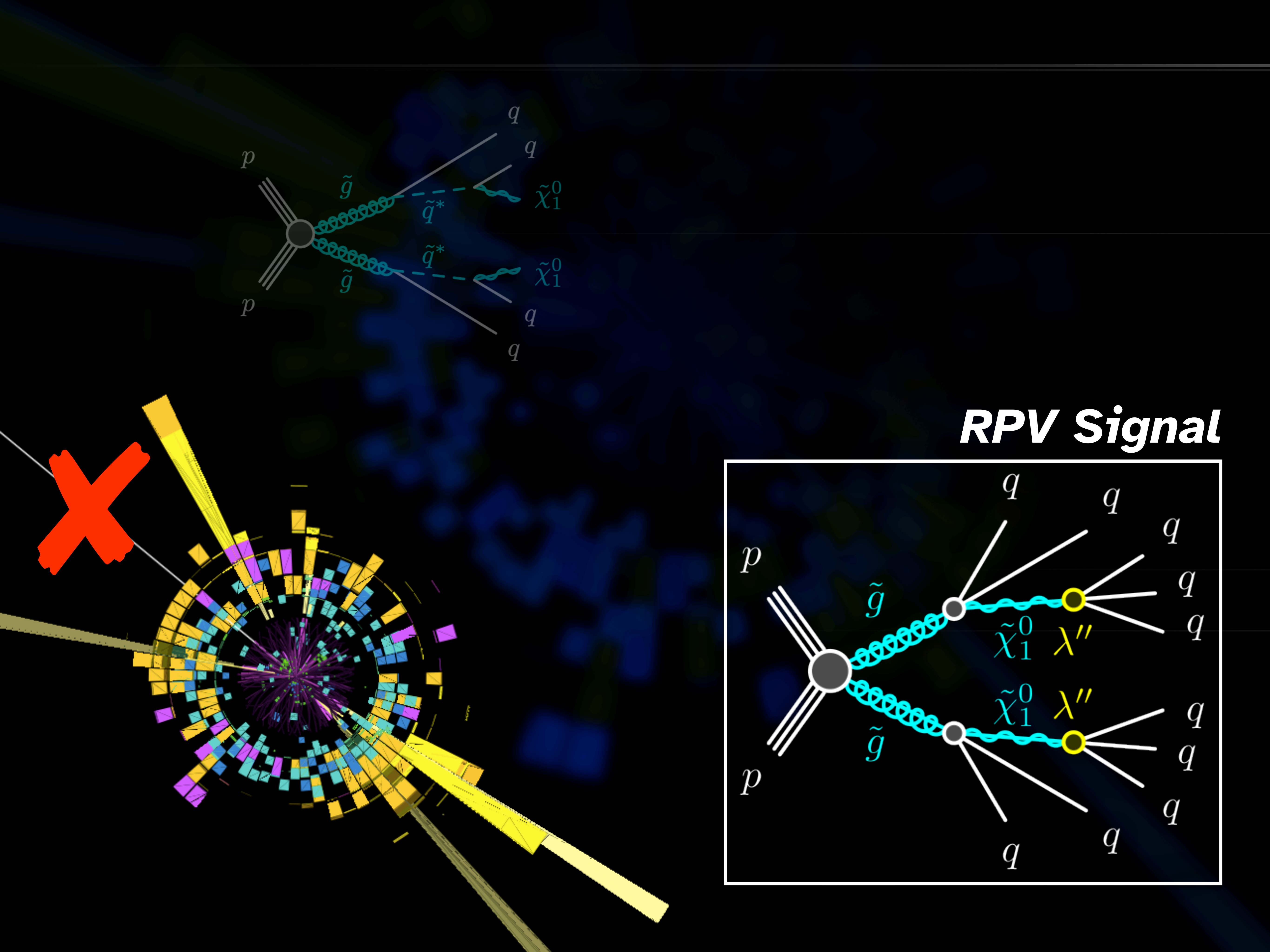
Problem "only" 40D

Hand those 4-vectors to a NN
→ **Huge head start**



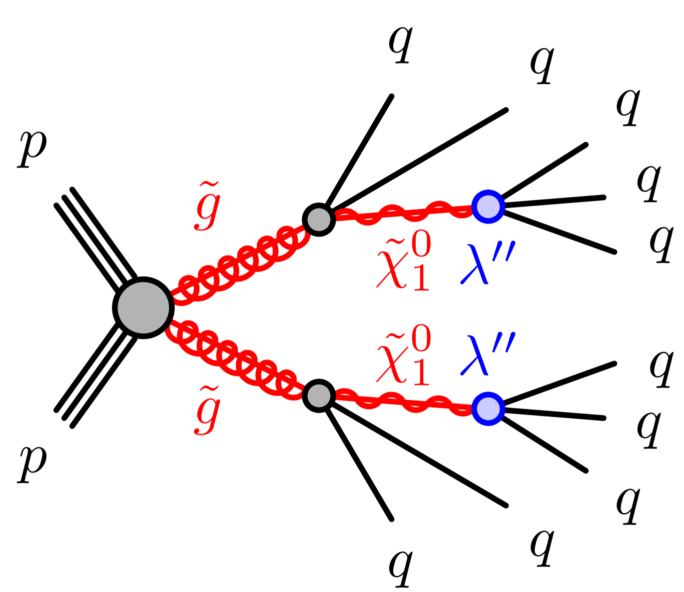


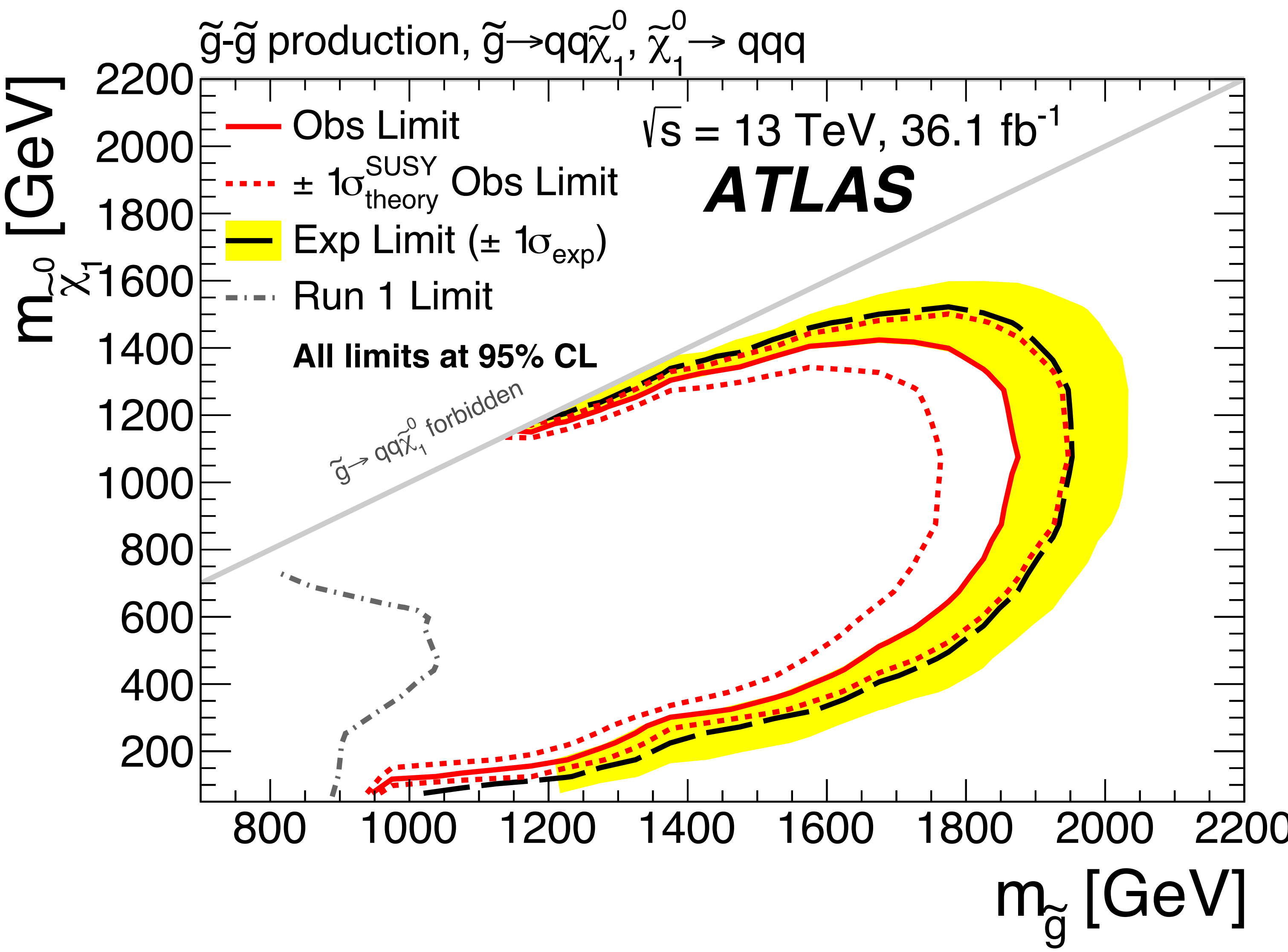
p
p
$\tilde{g}$
$\tilde{g}$
$\tilde{q}^*$
$\tilde{q}^*$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
q
q
q
q



RPV Signal
p
p
$\tilde{g}$
$\tilde{g}$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
λ''
λ''
q

RPV MULTIJET

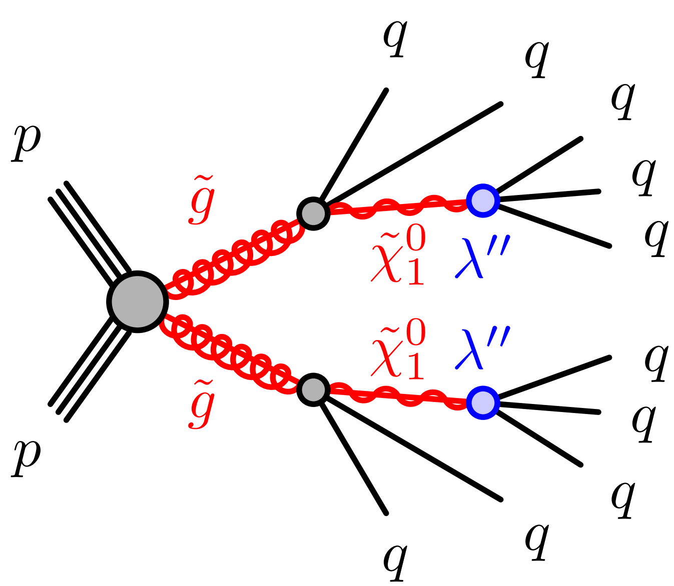


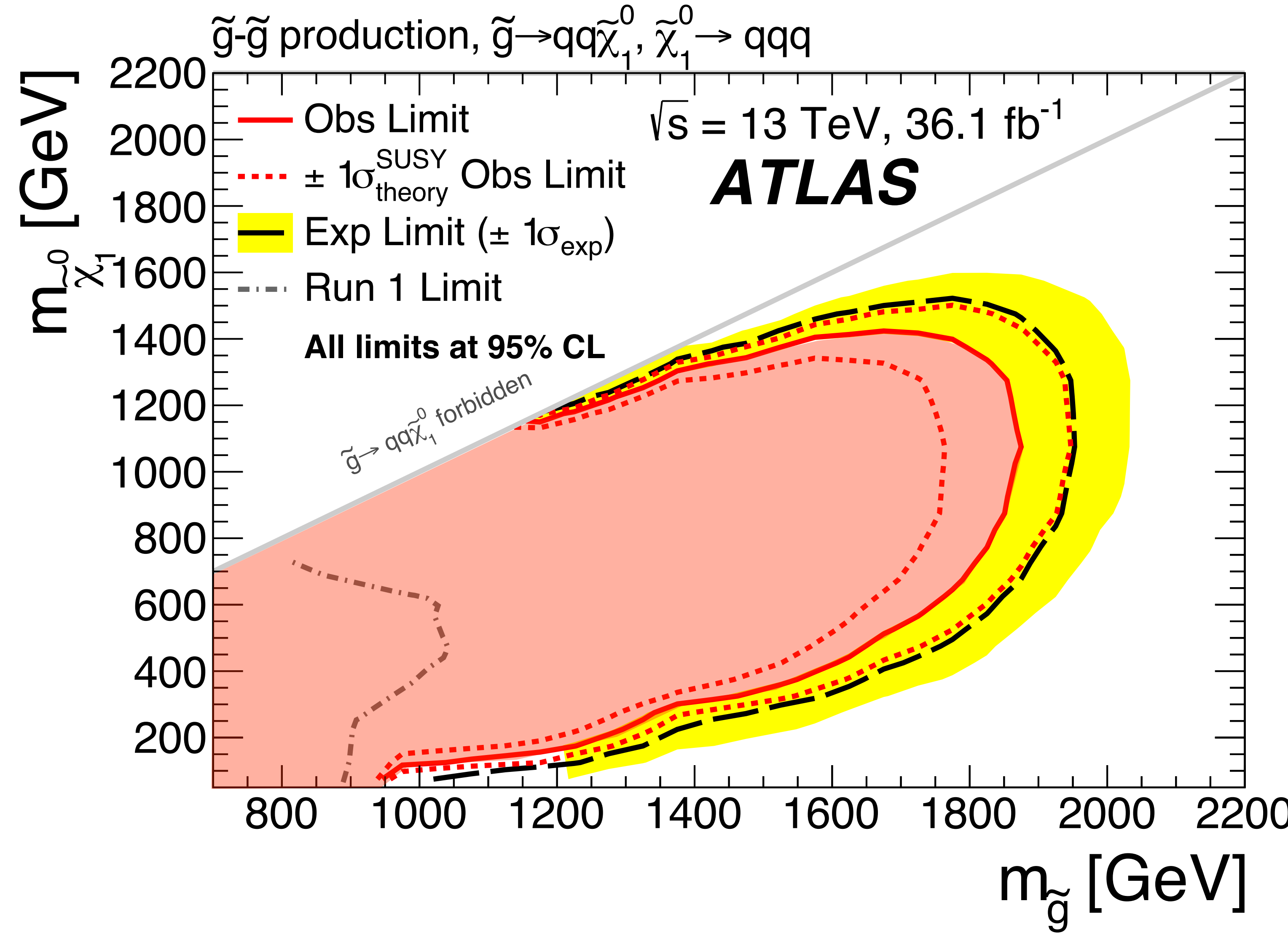


- Look in the tails, see no disagreement with background hypothesis
- Limits up to ~1.9 TeV in gluino mass
  - (But also as weak as ~1 TeV!)

SUSY-2016-22

RPV MULTIJET





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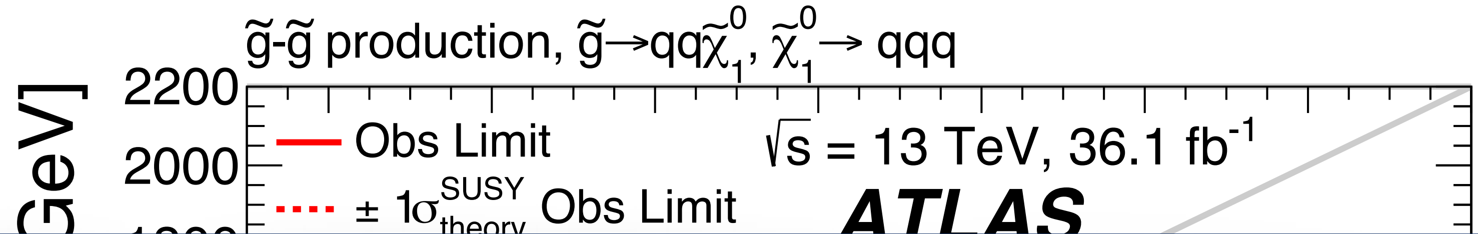
SUSY-2016-22

RPV Multijet



COULD BE A GLUINO SITTING THERE AT 1 TEV

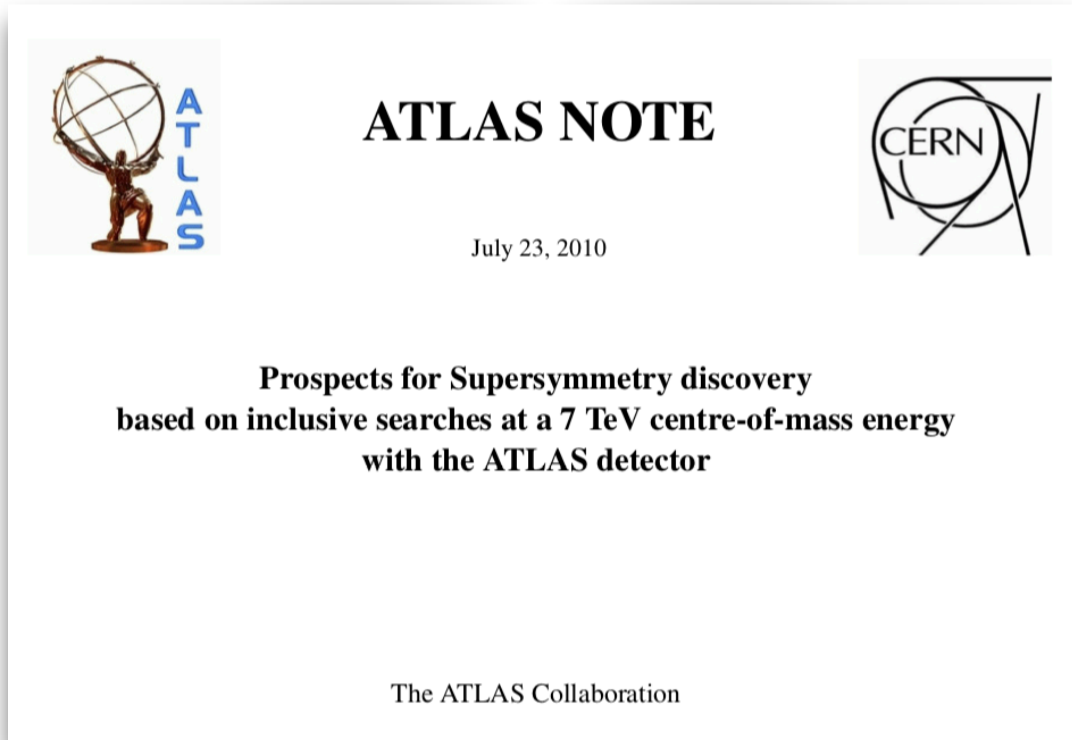
THE LHC DREAM

(JUST HAS THIS RPV TERM ON!)

- Limits up to ~1.9 TeV in gluino mass
  - (But also as weak as ~1 TeV!)

SUSY-2016-22

We were a bit optimistic…

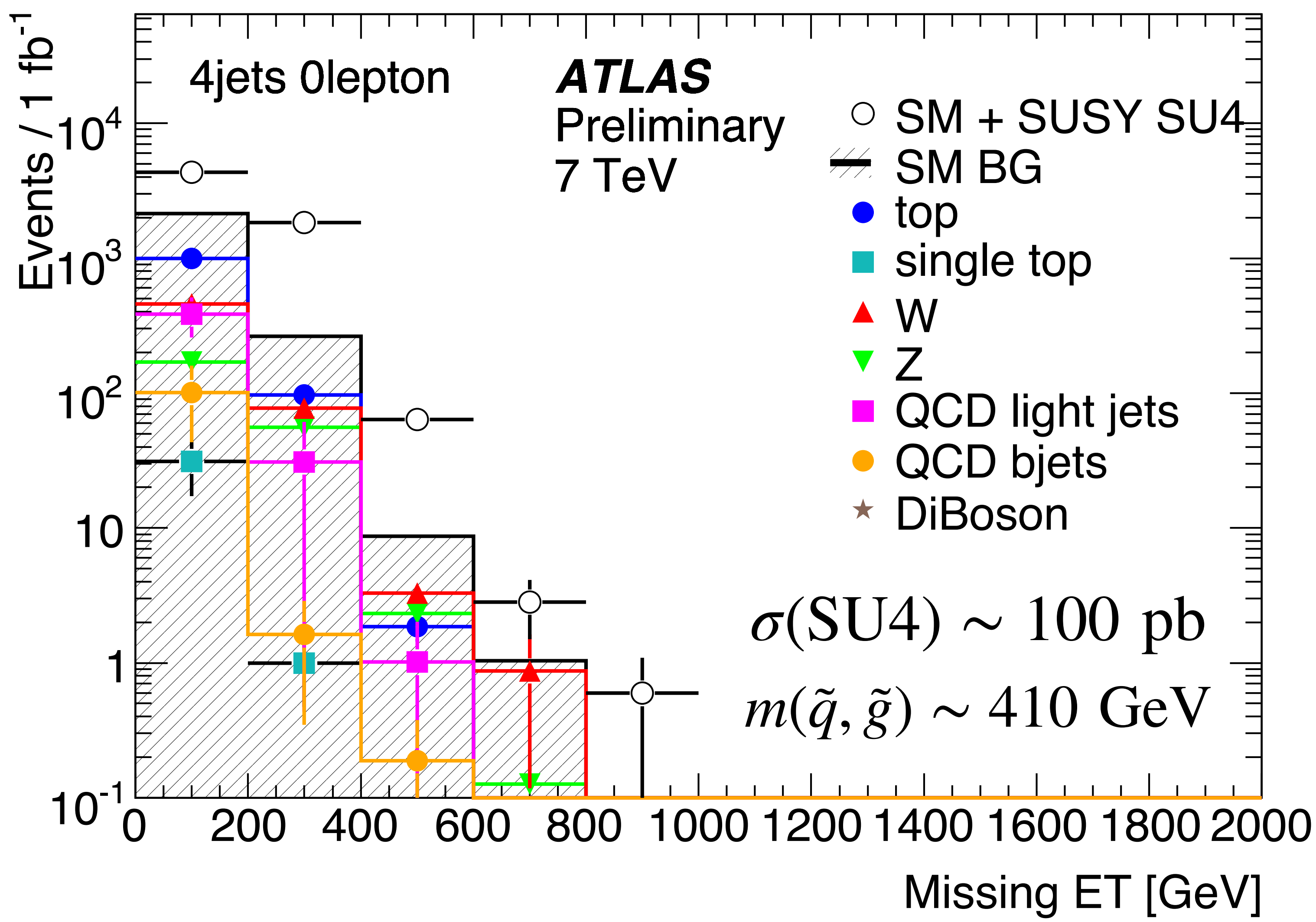


ATLAS NOTE

July 23, 2010

Prospects for Supersymmetry discovery based on inclusive searches at a 7 TeV centre-of-mass energy with the ATLAS detector

The ATLAS Collaboration

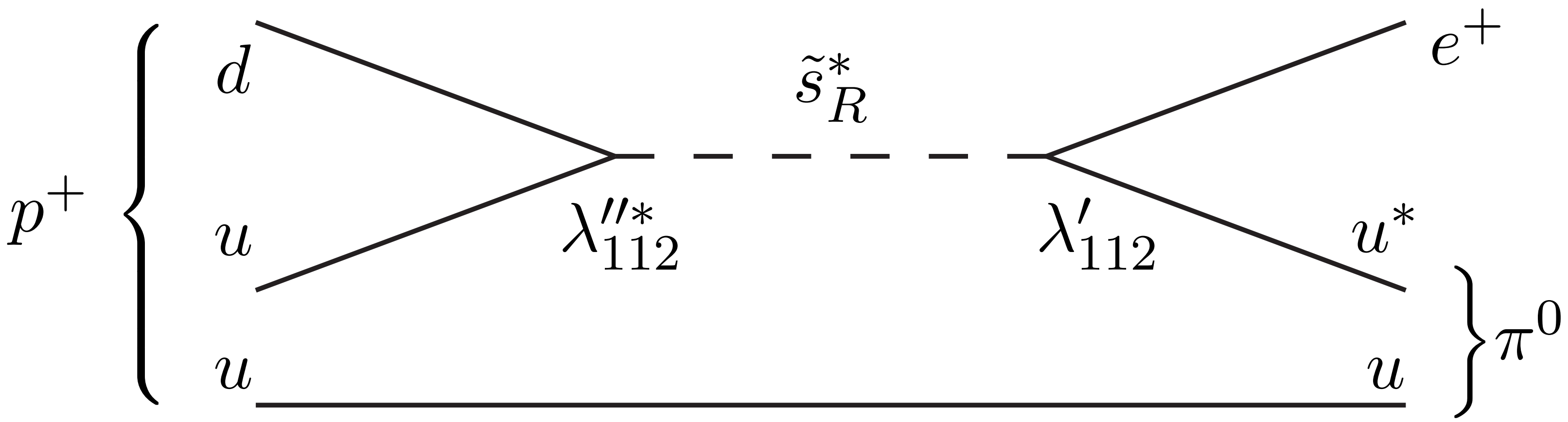


ATL-PHYS-PUB-2010-010

Proton decay

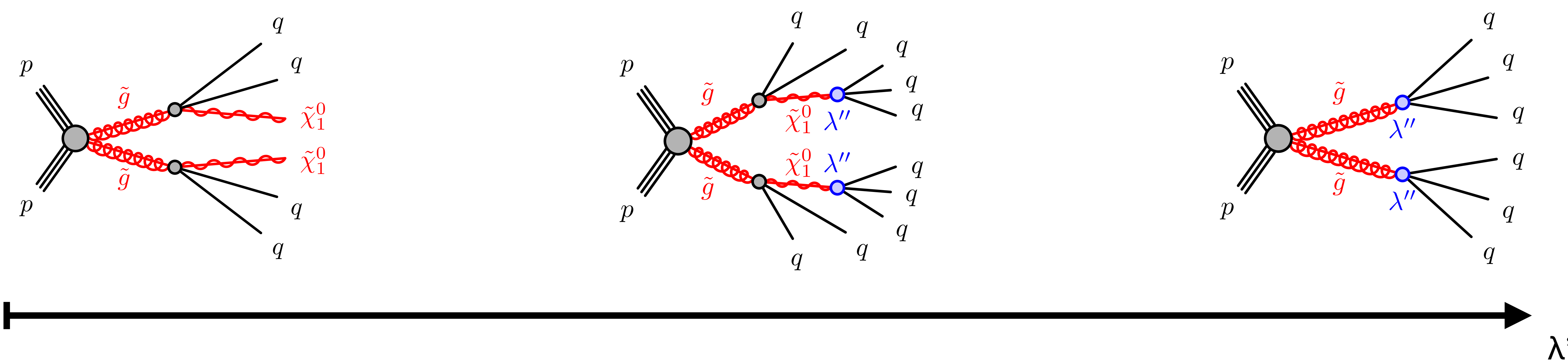
$$W_{RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \frac{1}{2}\lambda''_{ijk} U_i D_j D_k$$

L Violating B Violating



$$\Gamma_{p\to e^+\pi^0} \sim m^5_{\text{proton}} \sum_{i=2,3} |\lambda'^{11i}\lambda''^{11i}|^2 / m^4_{\tilde{d}_i}$$

Scanning RPV Strength



Zero RPV coupling
= RPC case

Moderate coupling:
Diagrams still dominated by gauge couplings

LSP at end of RPC decay chain then **decays** (potentially displaced)

Large coupling:
Direct decays if RPV coupling dominates over RPC vertices

ATLAS-CONF-2018-003

Scanning RPV Strength

IS THERE ANY REGION OF THIS SIGNATURE SPACE WE HAVEN'T COVERED YET?

λ''

Zero RPV coupling
= RPC case

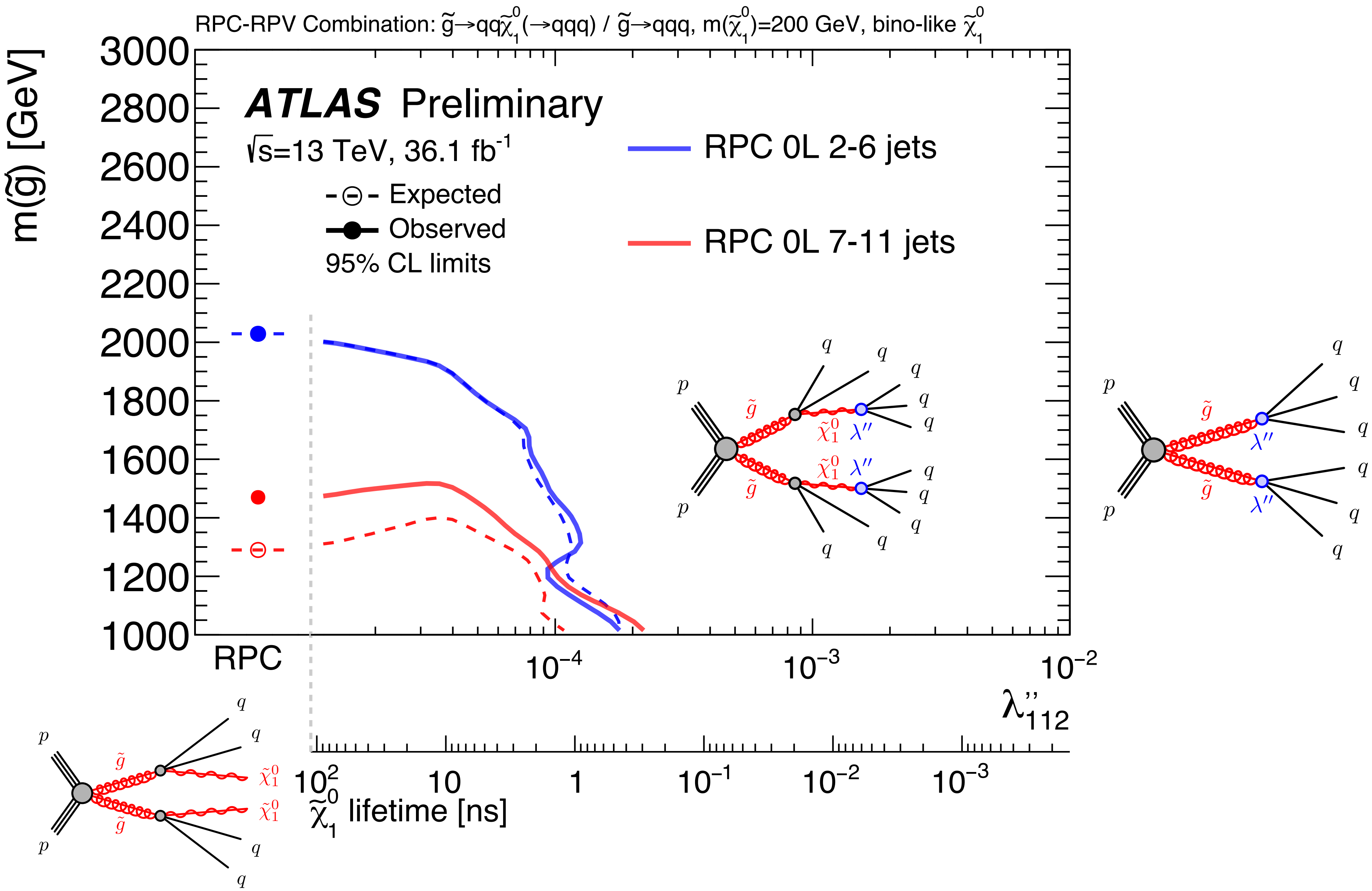
Moderate coupling:
Diagrams still dominated by gauge couplings

LSP at end of RPC decay chain then **decays** (potentially displaced)

Large coupling:
Direct decays if RPV coupling dominates over RPC vertices

ATLAS-CONF-2018-003

SCANNING RPV STRENGTH



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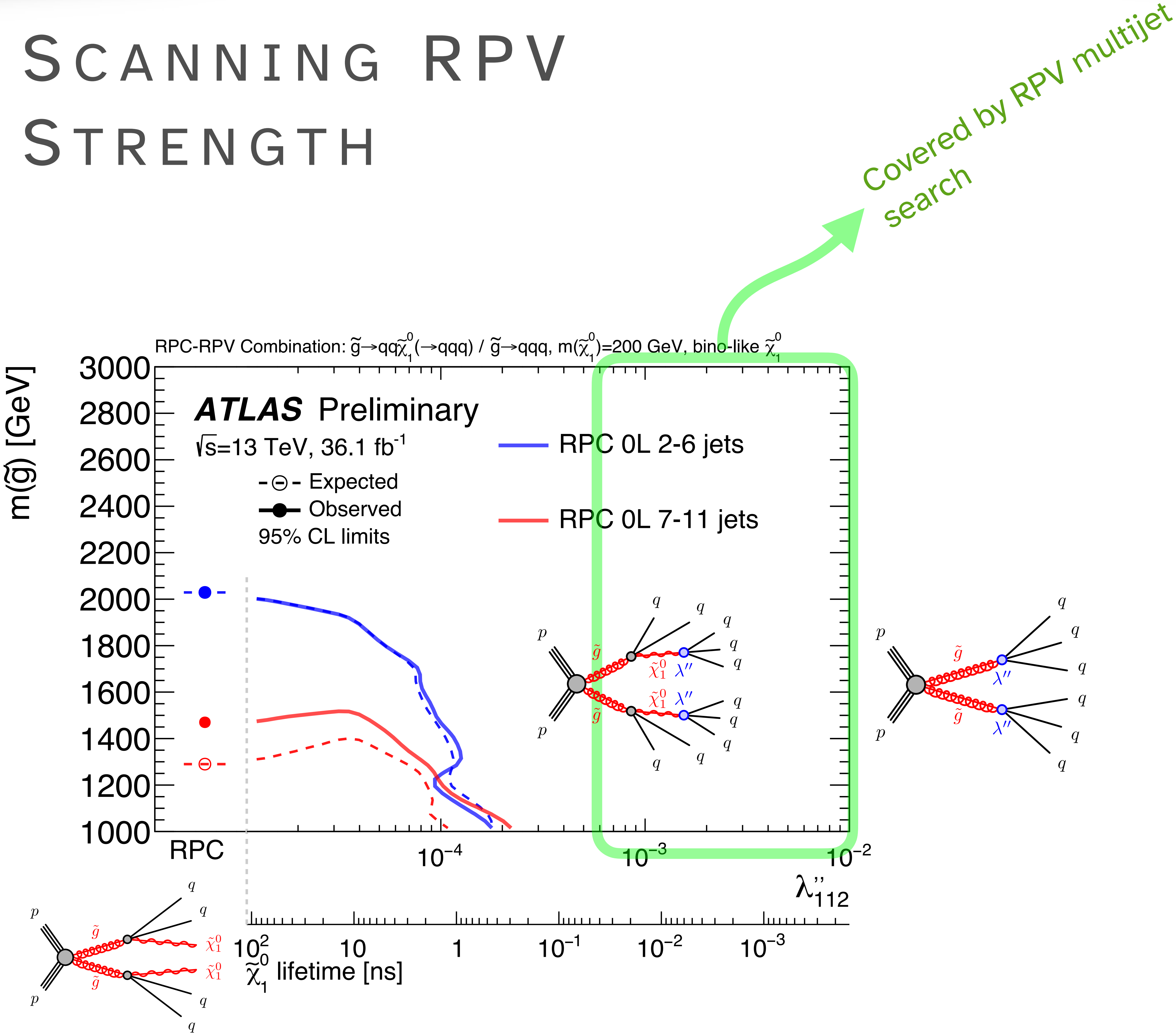
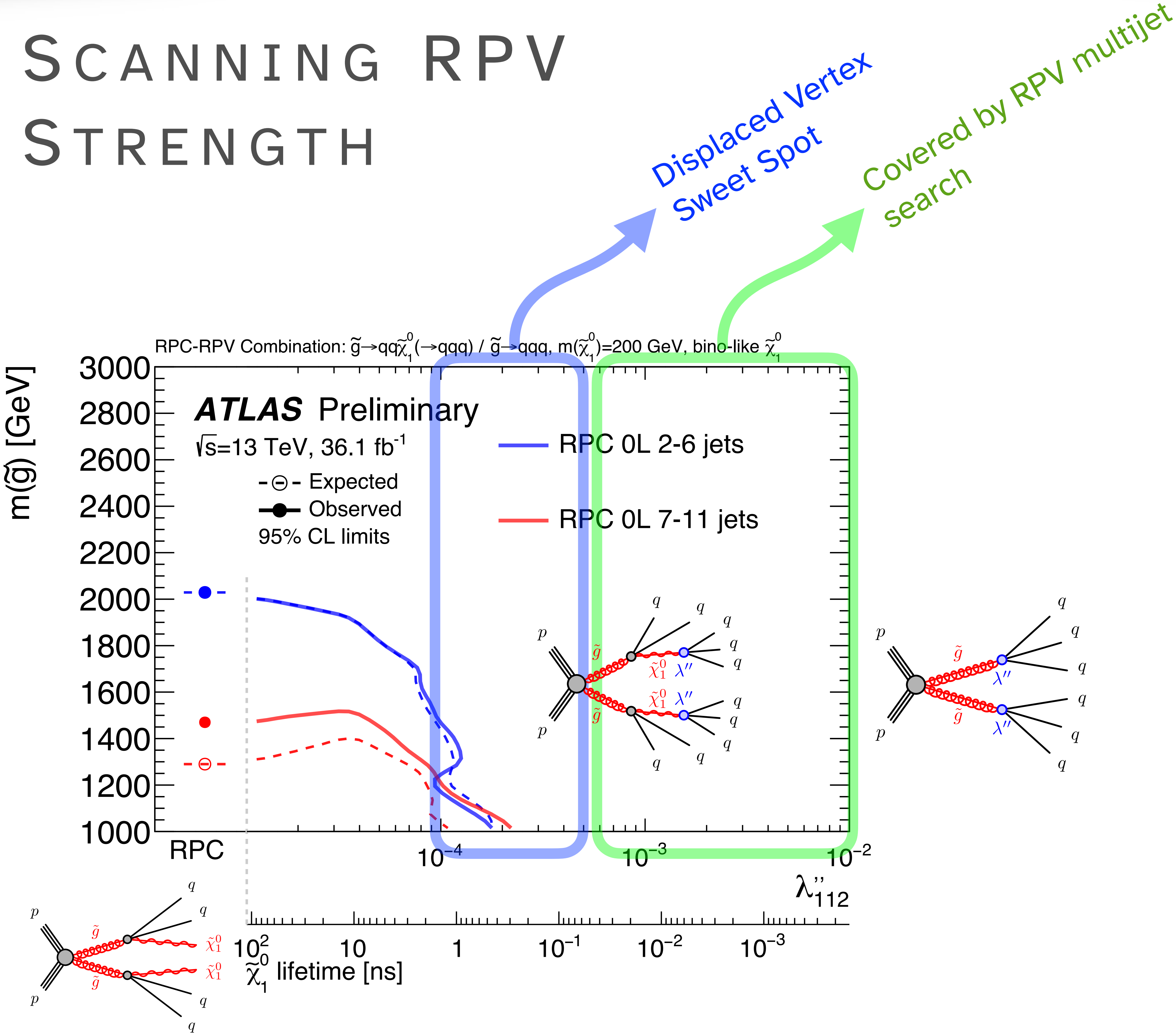
SCANNING RPV STRENGTH



ATLAS-CONF-2018-003

Scanning RPV Strength



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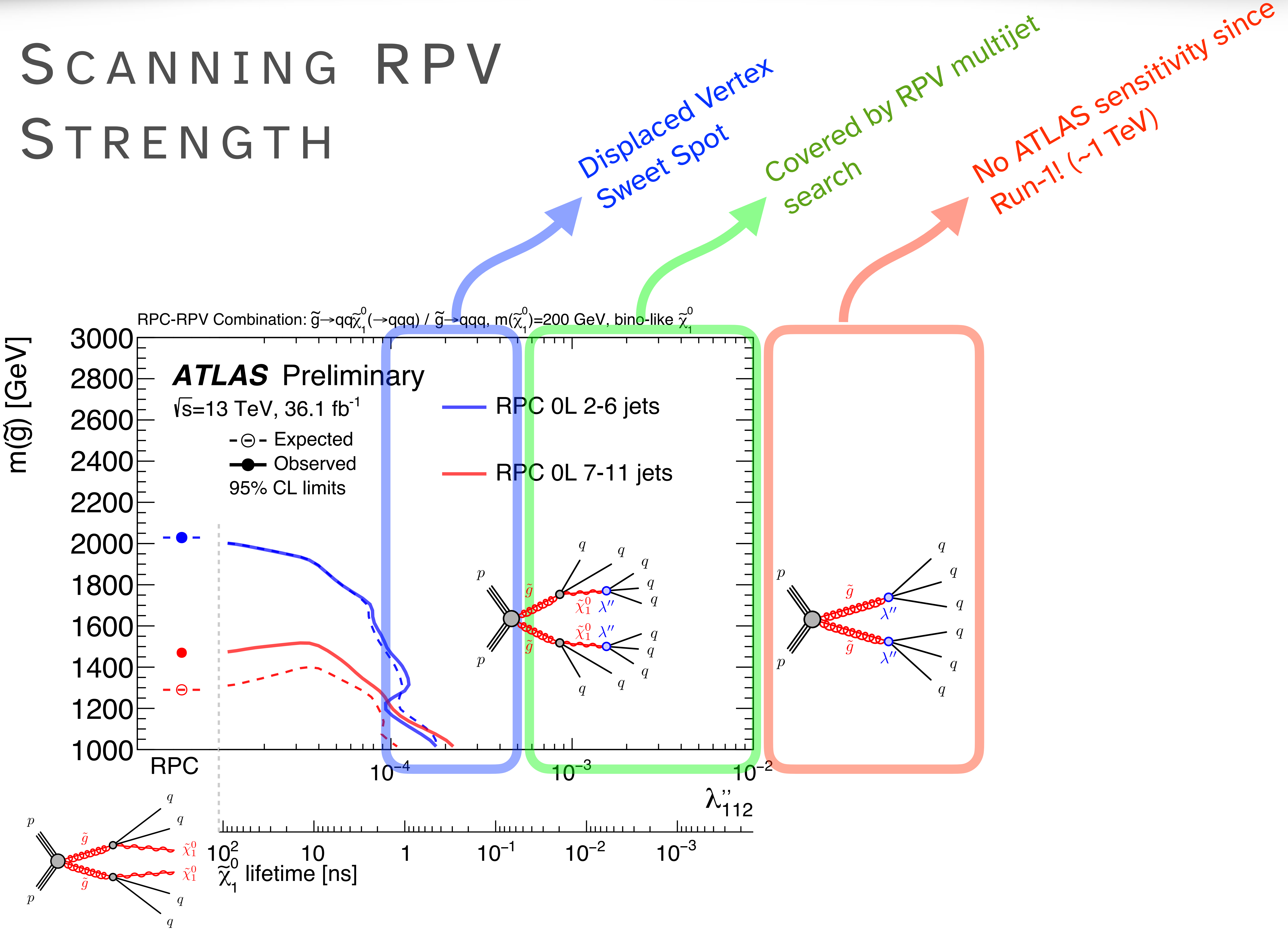
Scanning RPV Strength



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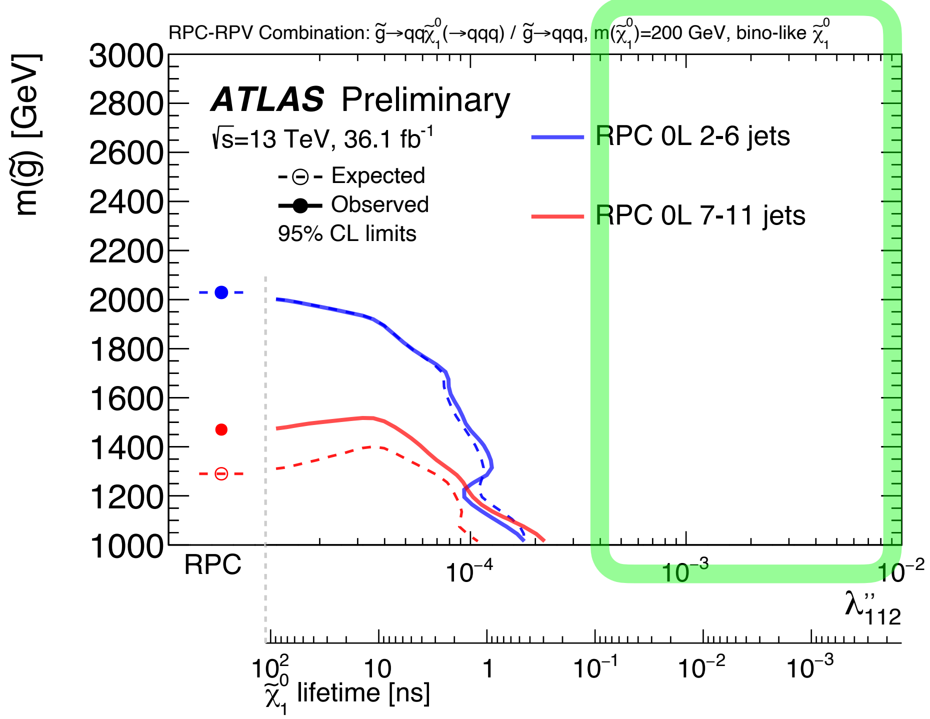
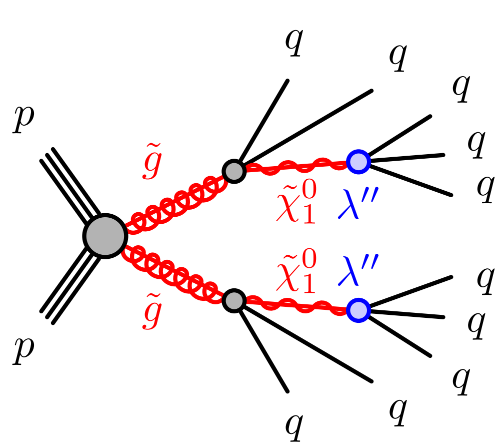
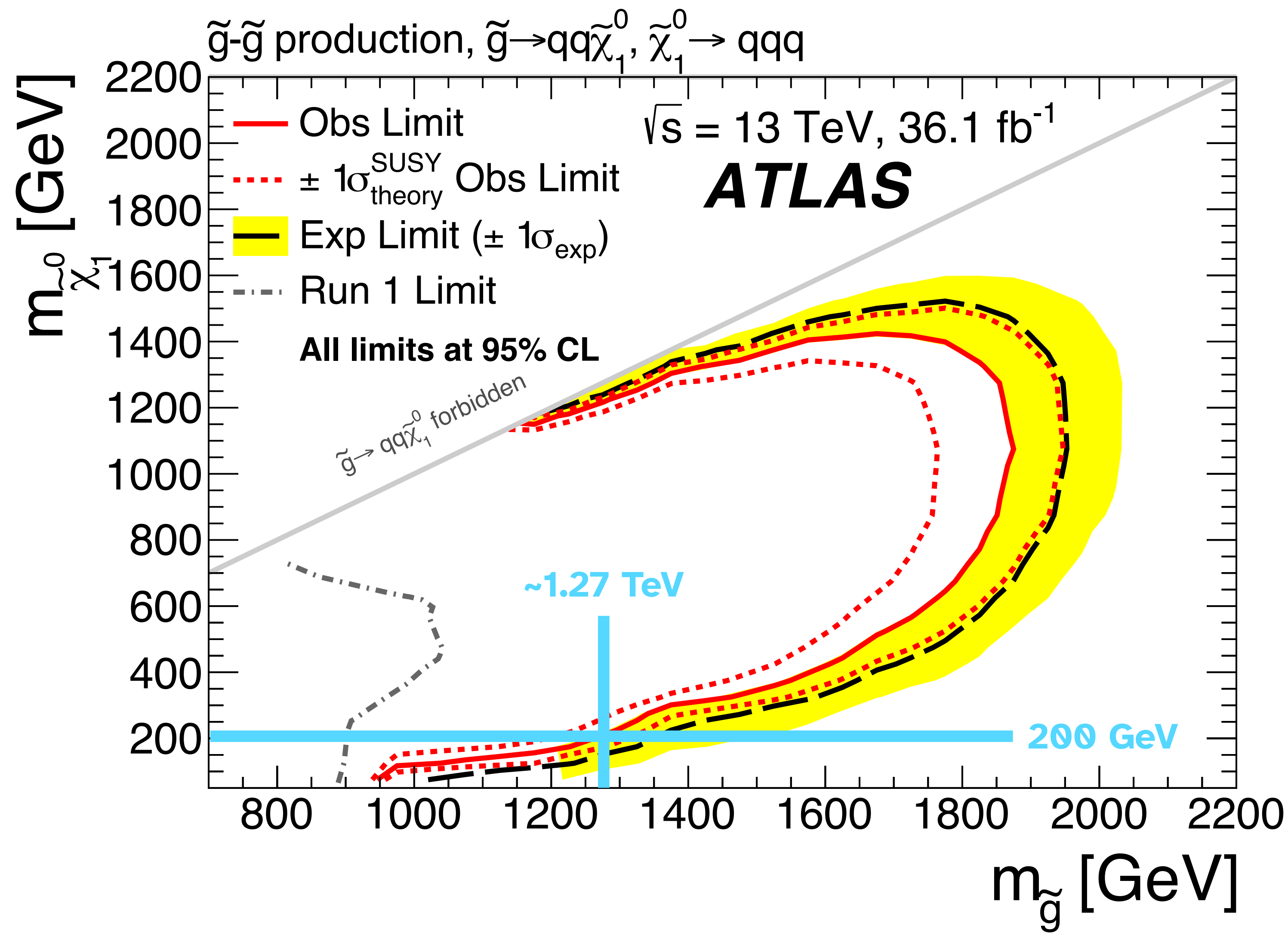
RPV Survey

Covered by RPV multijet?



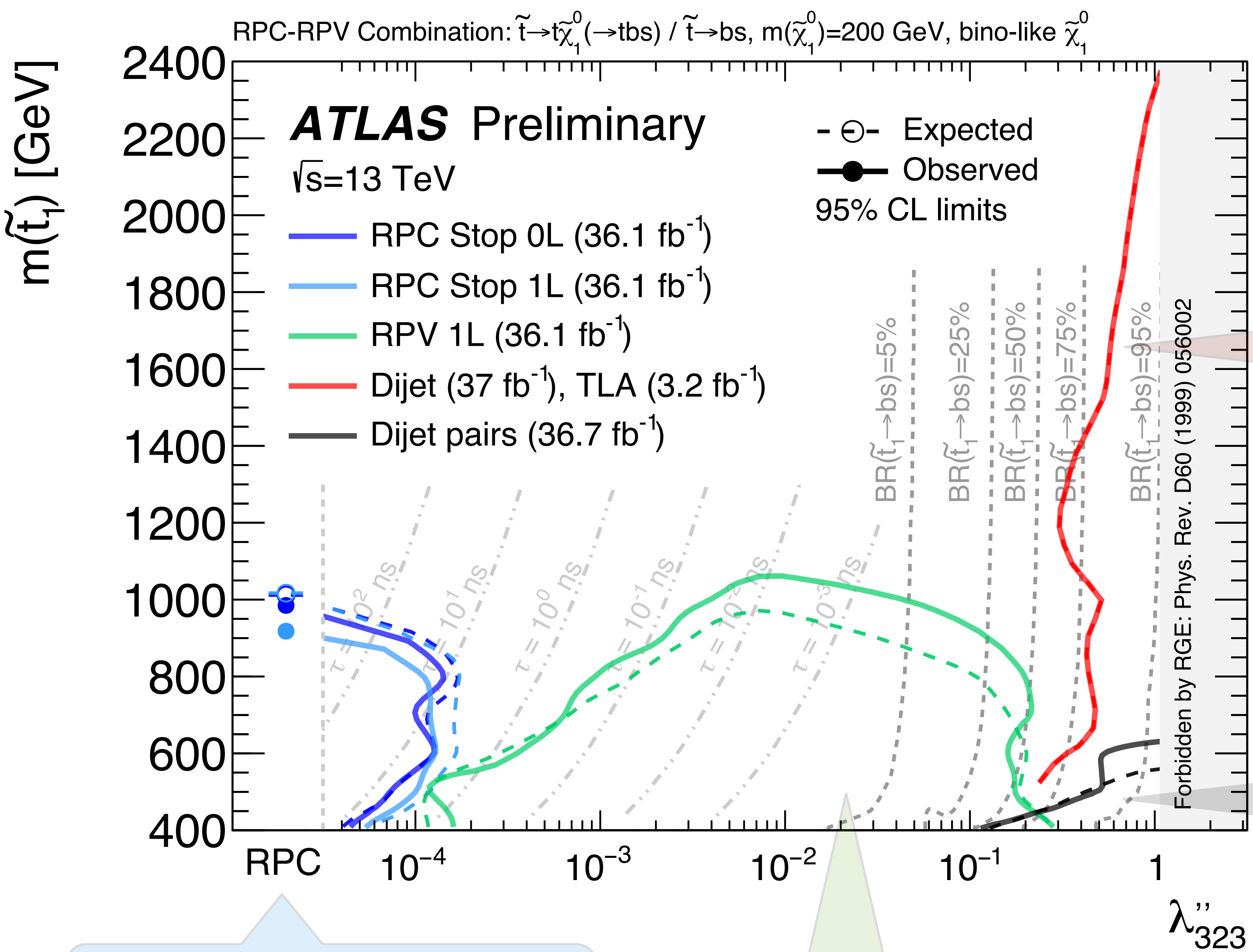


But not looking great...

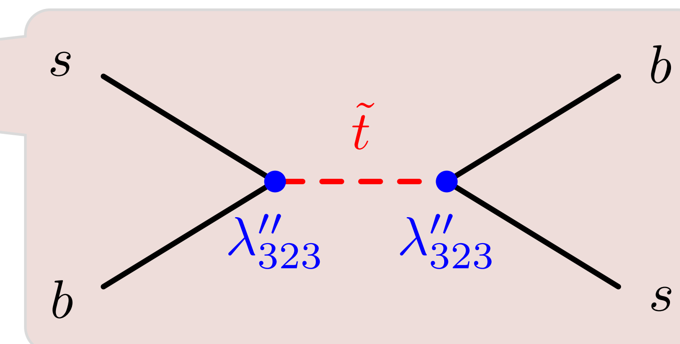


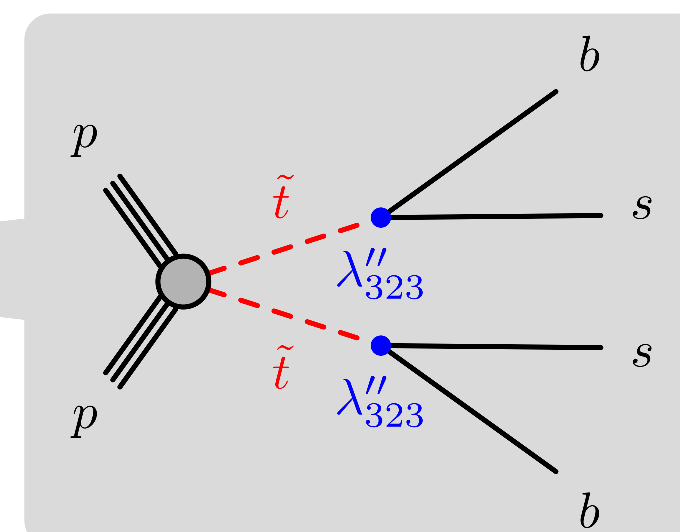
SUSY-2016-22 ATLAS-CONF-2018-003

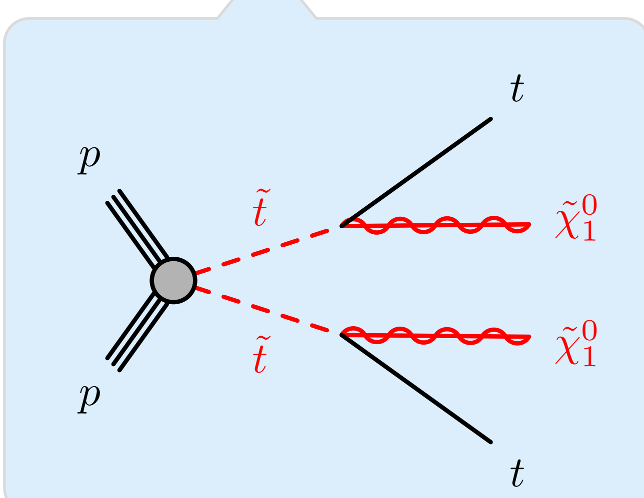
SCANNING RPV STRENGTH

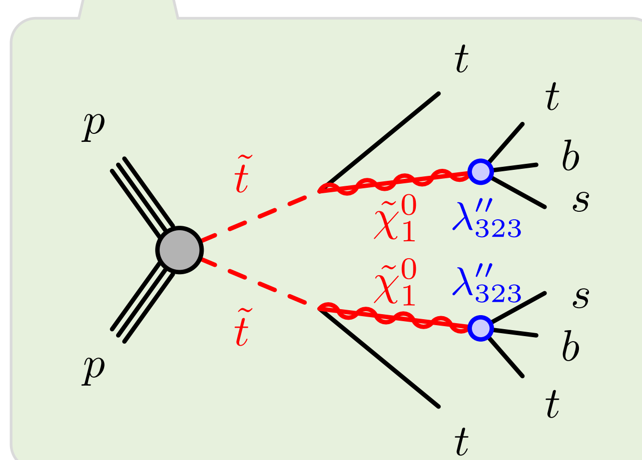


Reinterpret many searches for varying lifetime / BRs





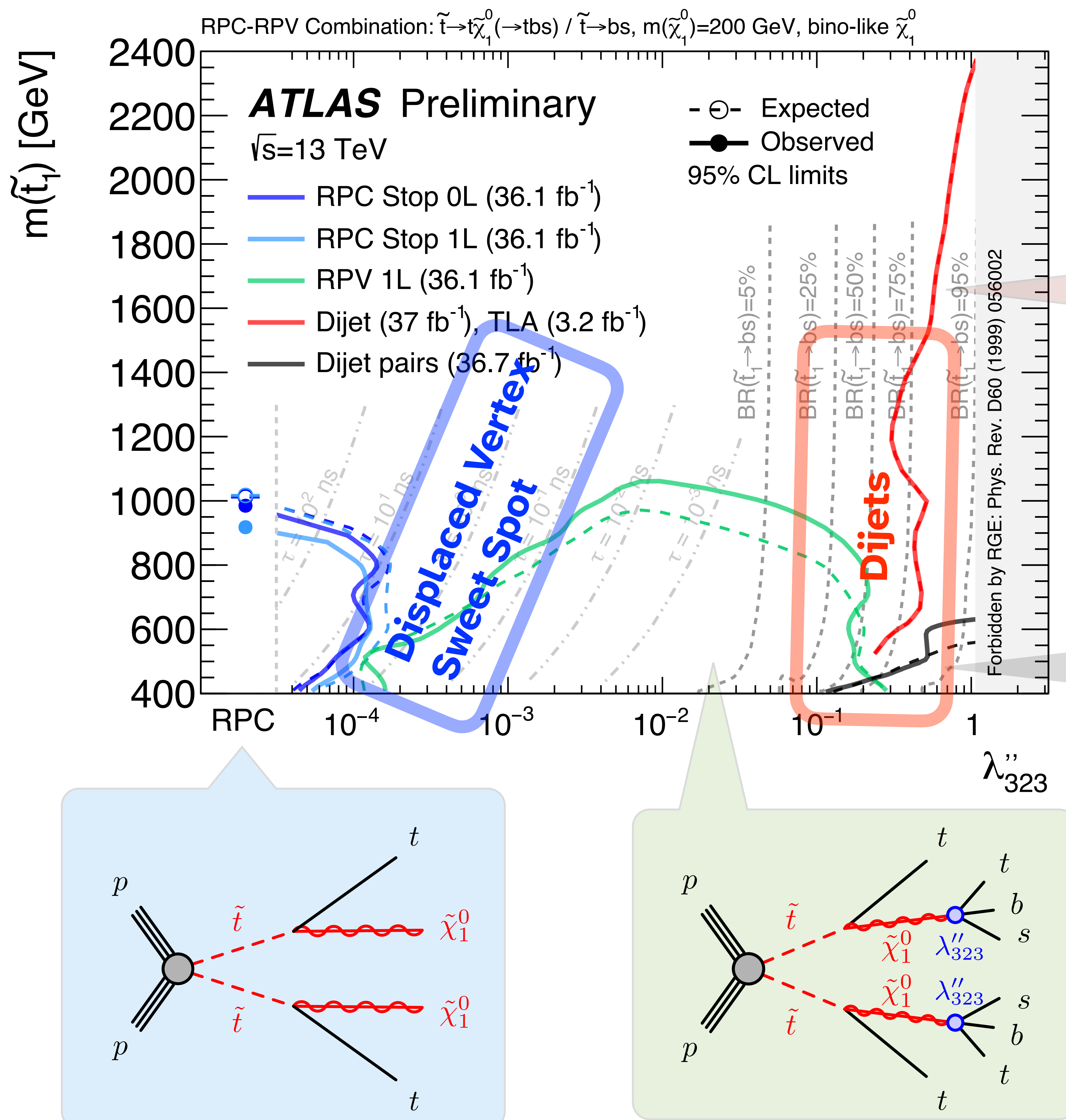




Properly accounting for:
Interplay between RPV and gauge couplings
Even resonant sparticle production

ATLAS-CONF-2018-003

SCANNING RPV STRENGTH



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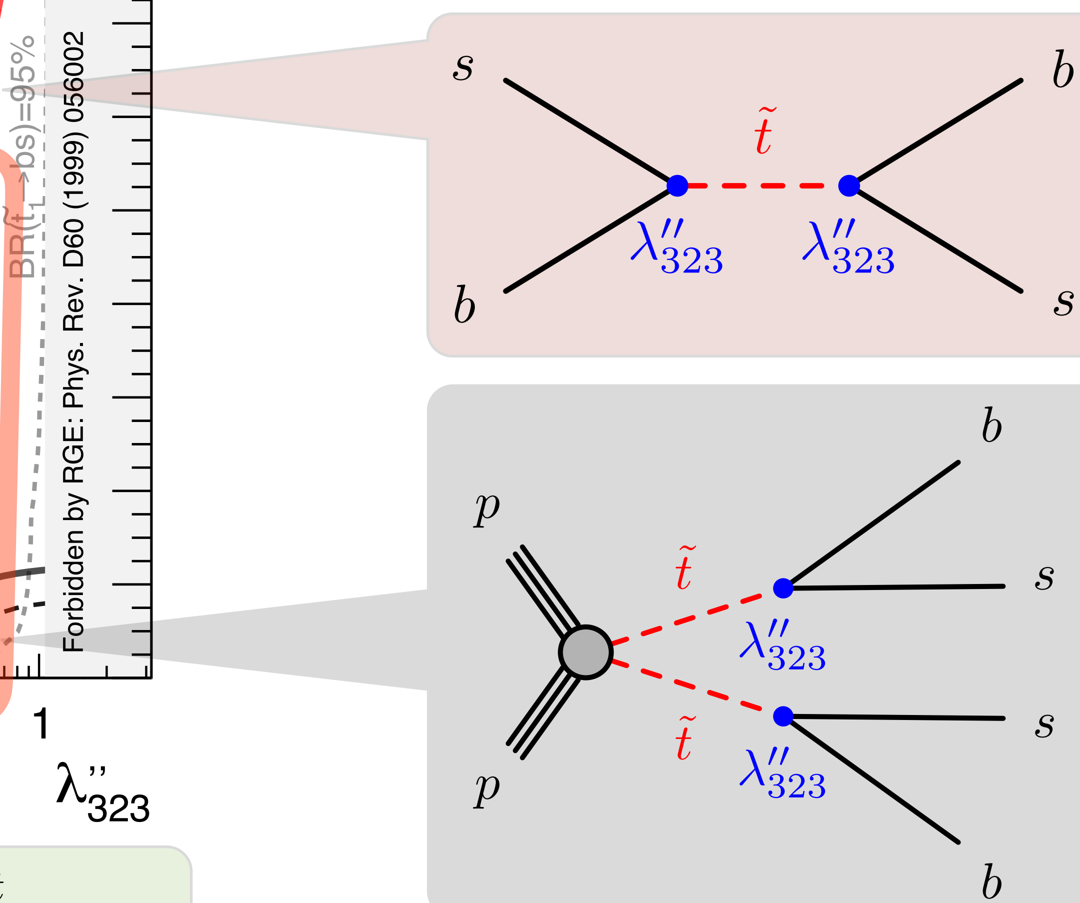

Properly accounting for:
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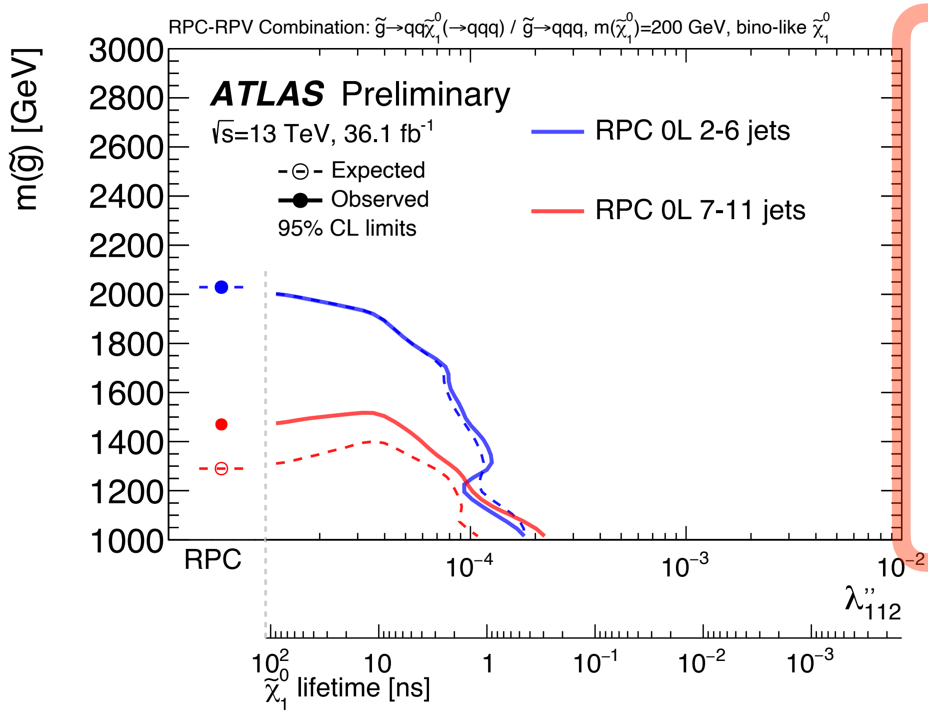
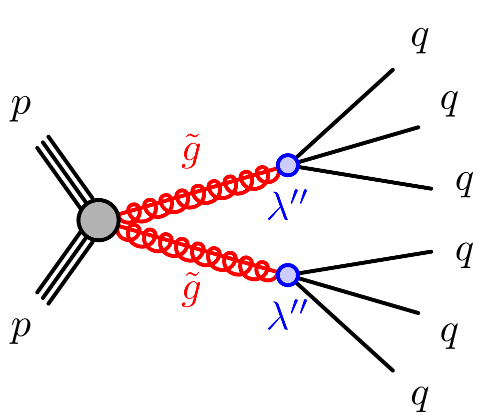
ATLAS-CONF-2018-003

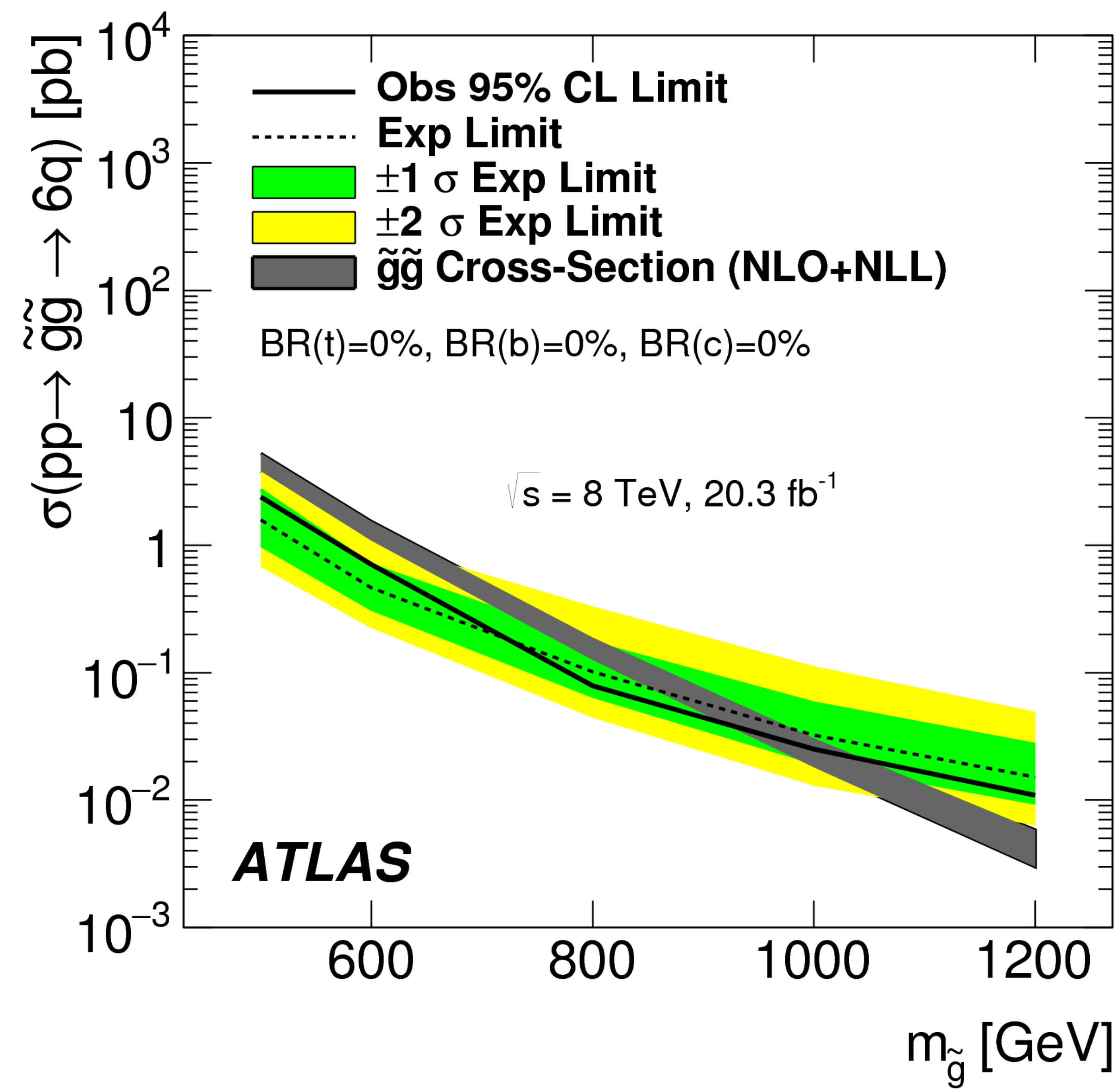
RPV Survey



No ATLAS sensitivity since Run-1! (~1 TeV)



...and any exclusion we have is very shallow...



SUSY-2013-07 ATLAS-CONF-2018-003