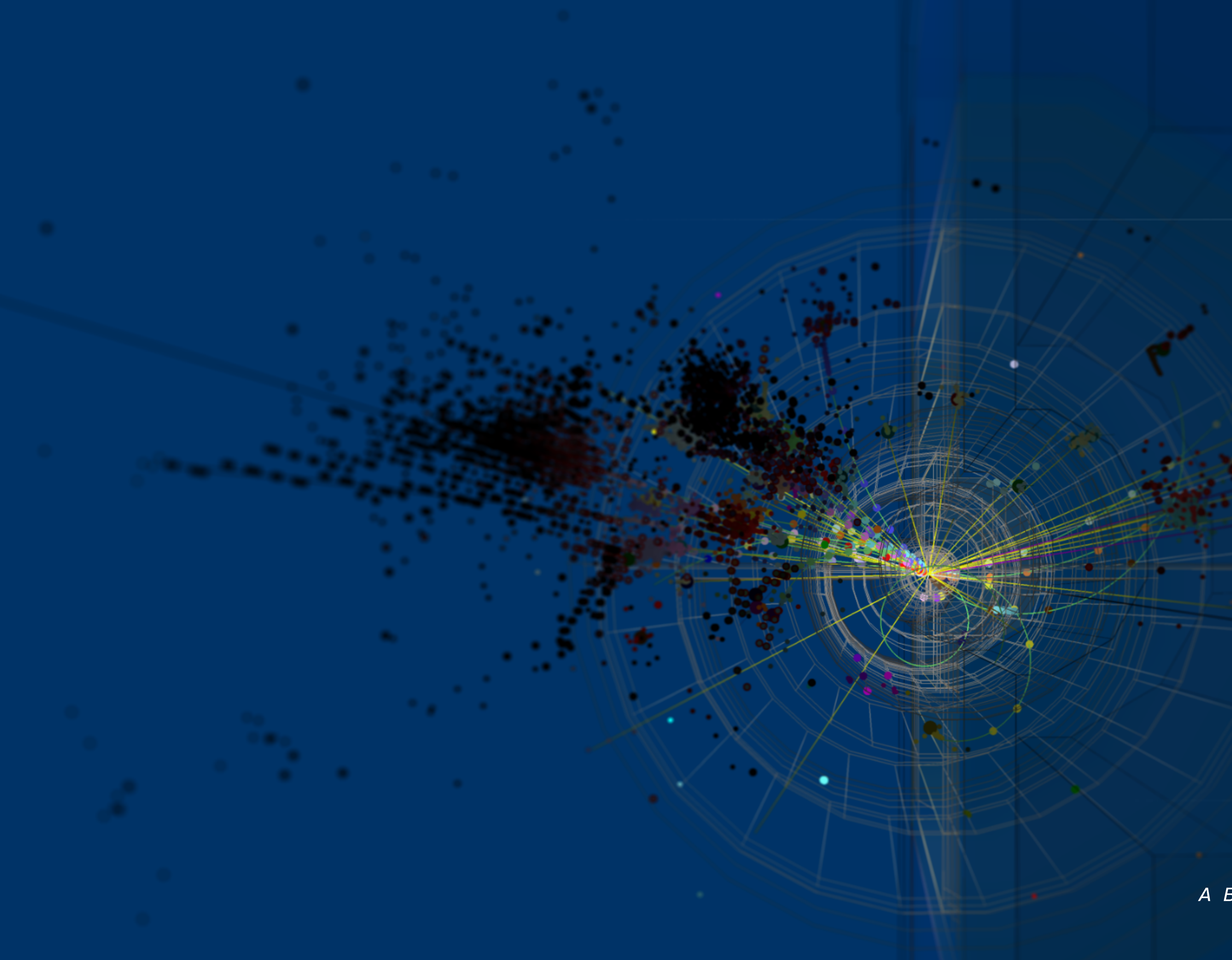


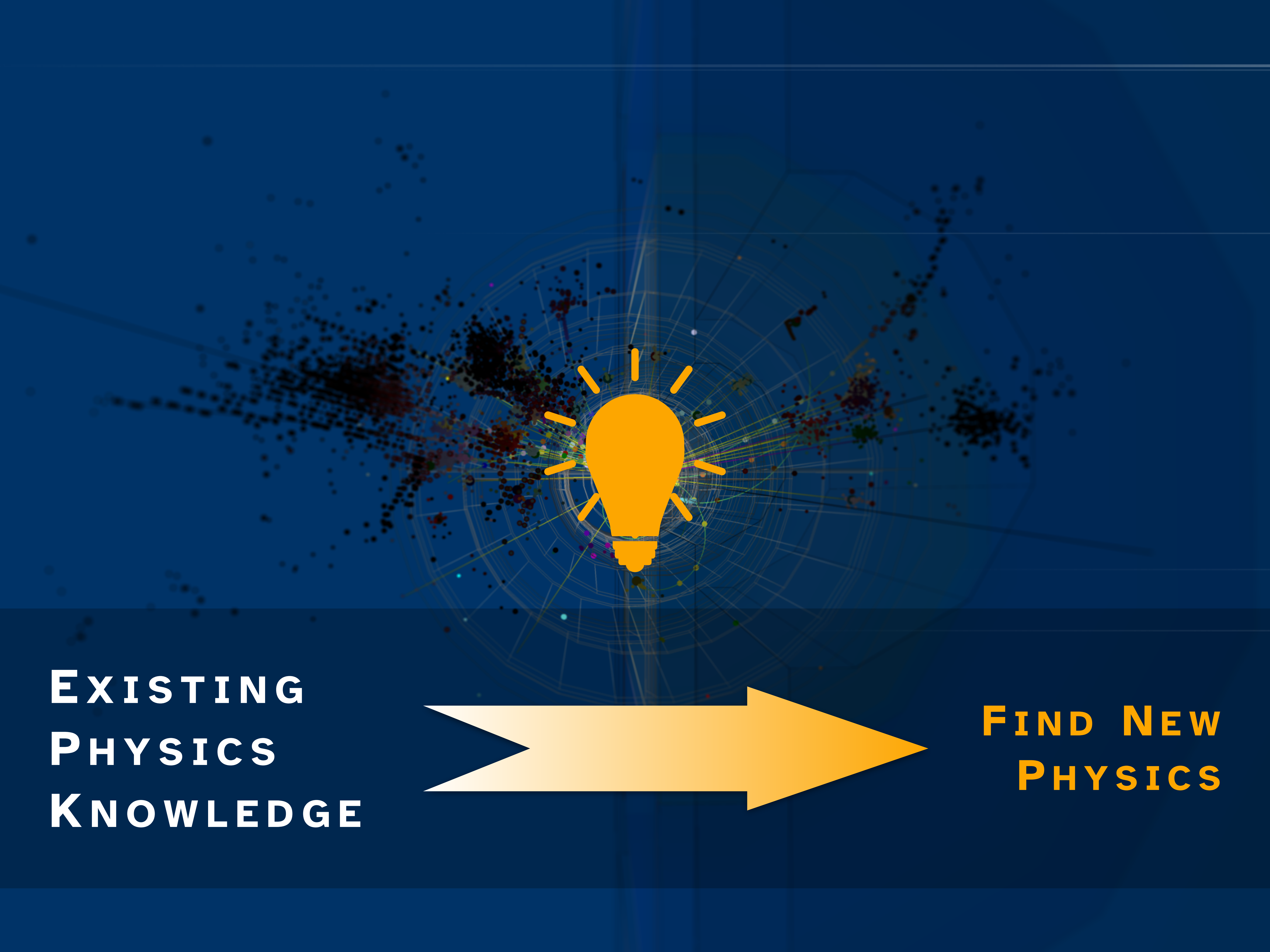
Solving Collider Combinatorial Problems Using Machine Learning

Anthony Badea
Lawrence Lee

Based on arXiv:2201.02205

A Badea, W Fawcett, J Huth, TJ Khoo, R Poggi, LL

The University of Tennessee Knoxville
UTK CMS

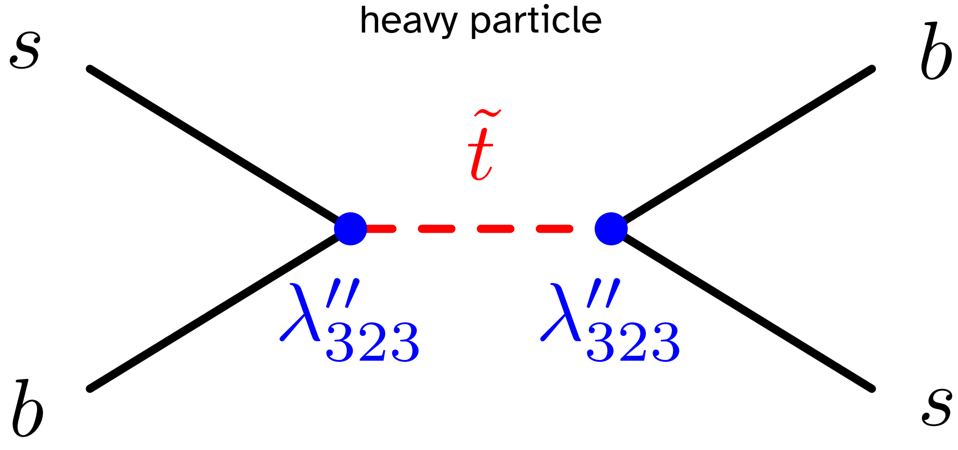

Existing Physics Knowledge
Find New Physics

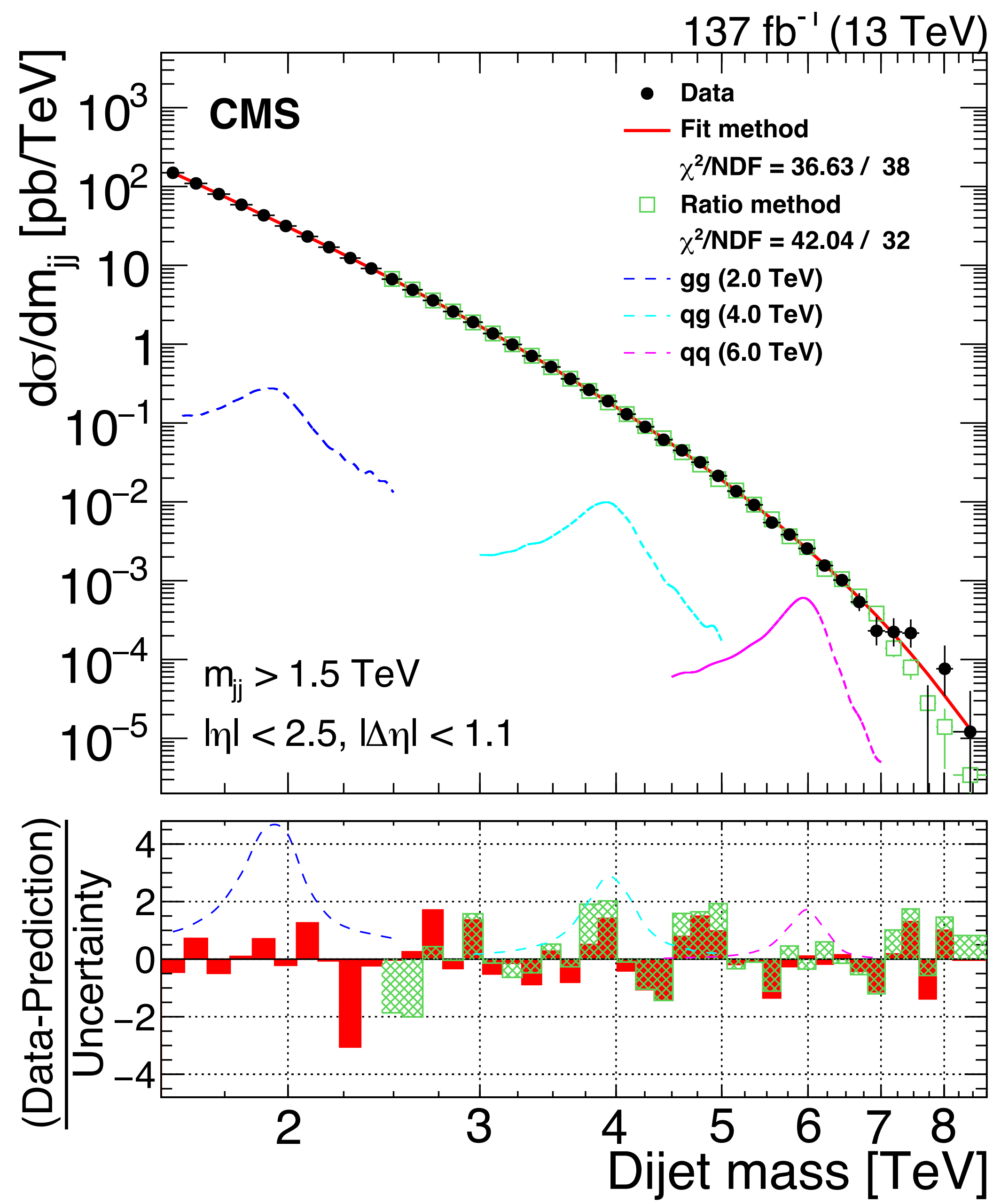
SIMPLE EXAMPLE

Quarks from protons collide

Fuse to become new heavy particle

Decay to two quarks (→jets)





- Measure four-momentum of each jet
- Sum → four-momentum of the new particle
- Relativity tells us how to get mass $(p \cdot p) = m^2$

- Plot mass → new physics signals will peak at the mass of the new thing
- Backgrounds steeply falling distribution

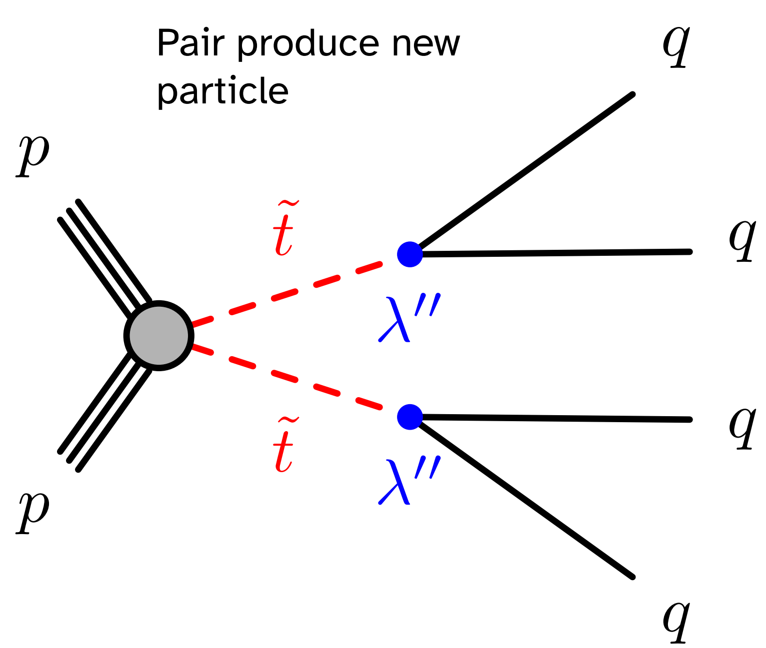
arXiv:1911.03947

Less Simple Example

Each decays to two jets.

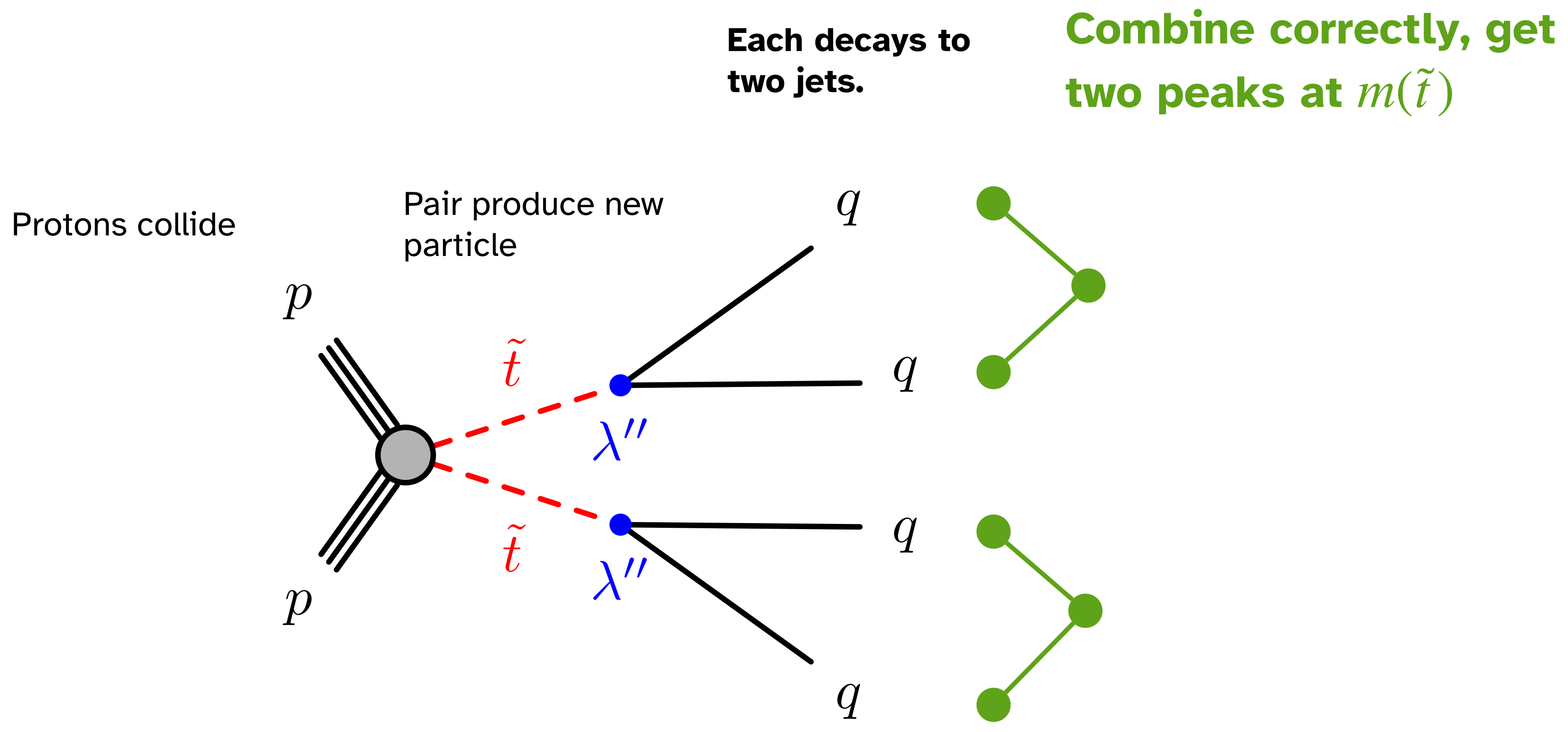
Protons collide

Pair produce new particle



- Increasing multiplicity introduces combinatorial issues
- Wrong combinations don't contain peak-y mass variables → Make signal harder to find.
- Brute-force → Add **combinatorial** background
  - 1 in 3 combs is correct → 200% comb BG

Less Simple Example



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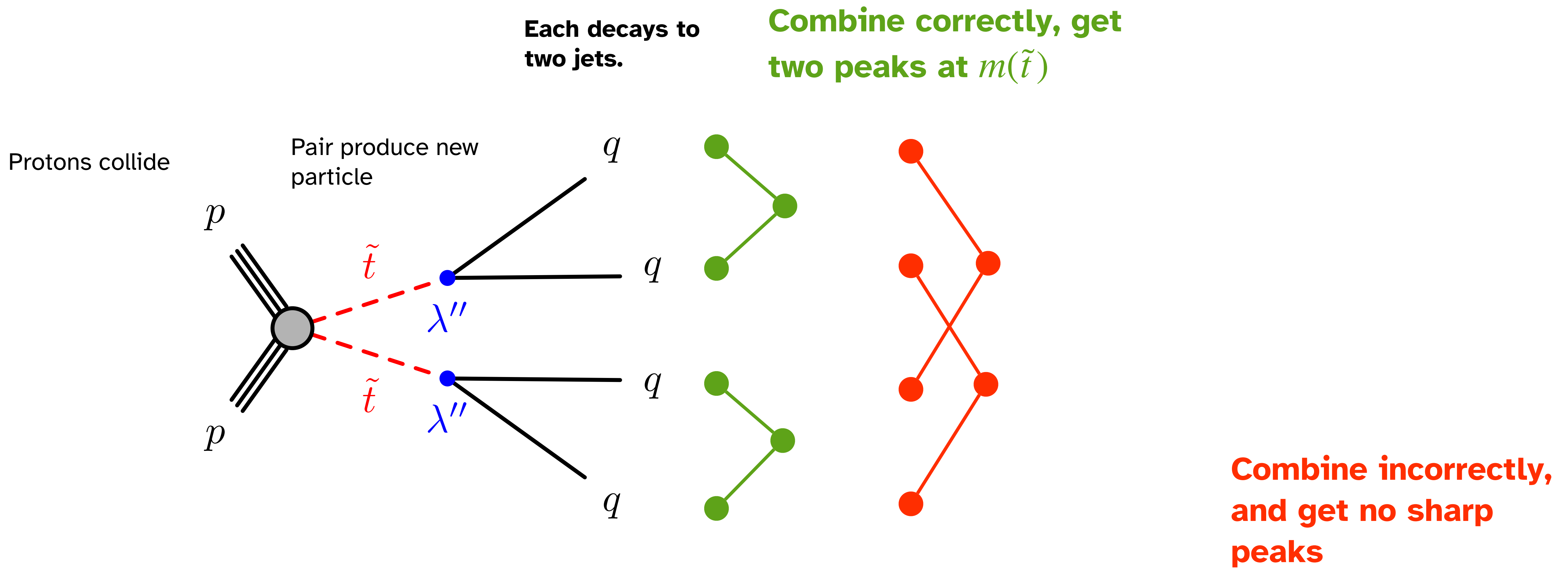

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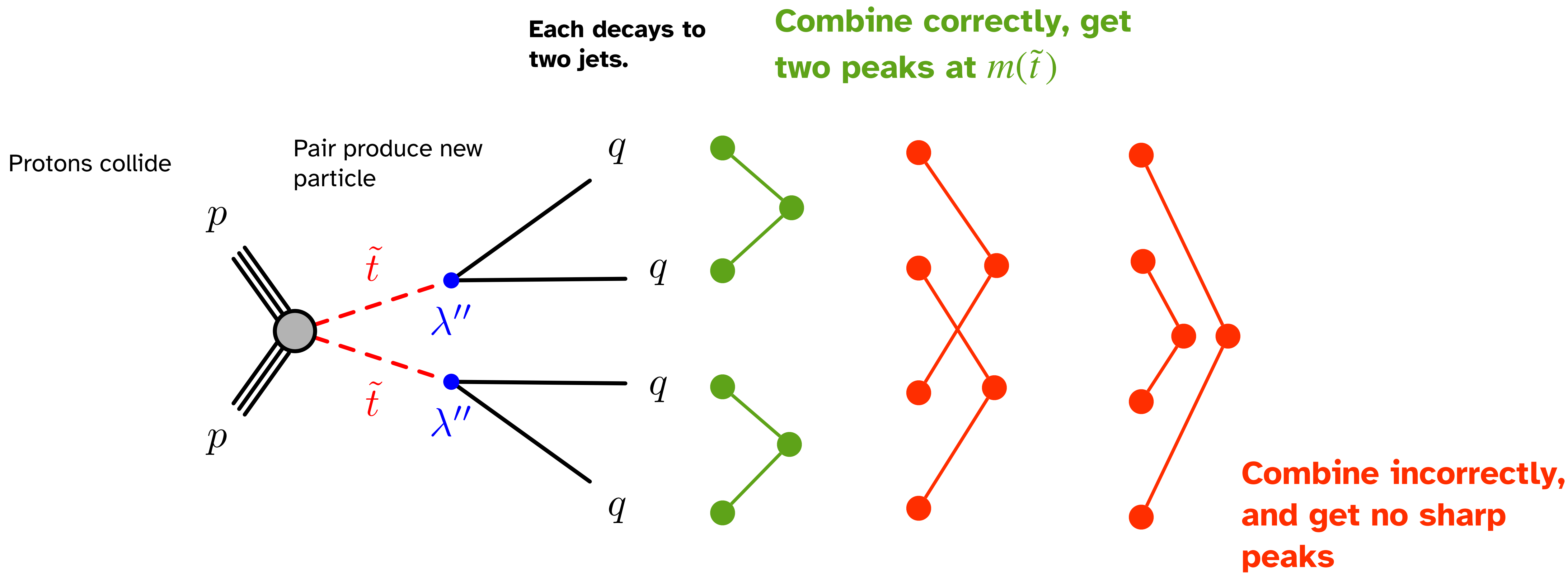

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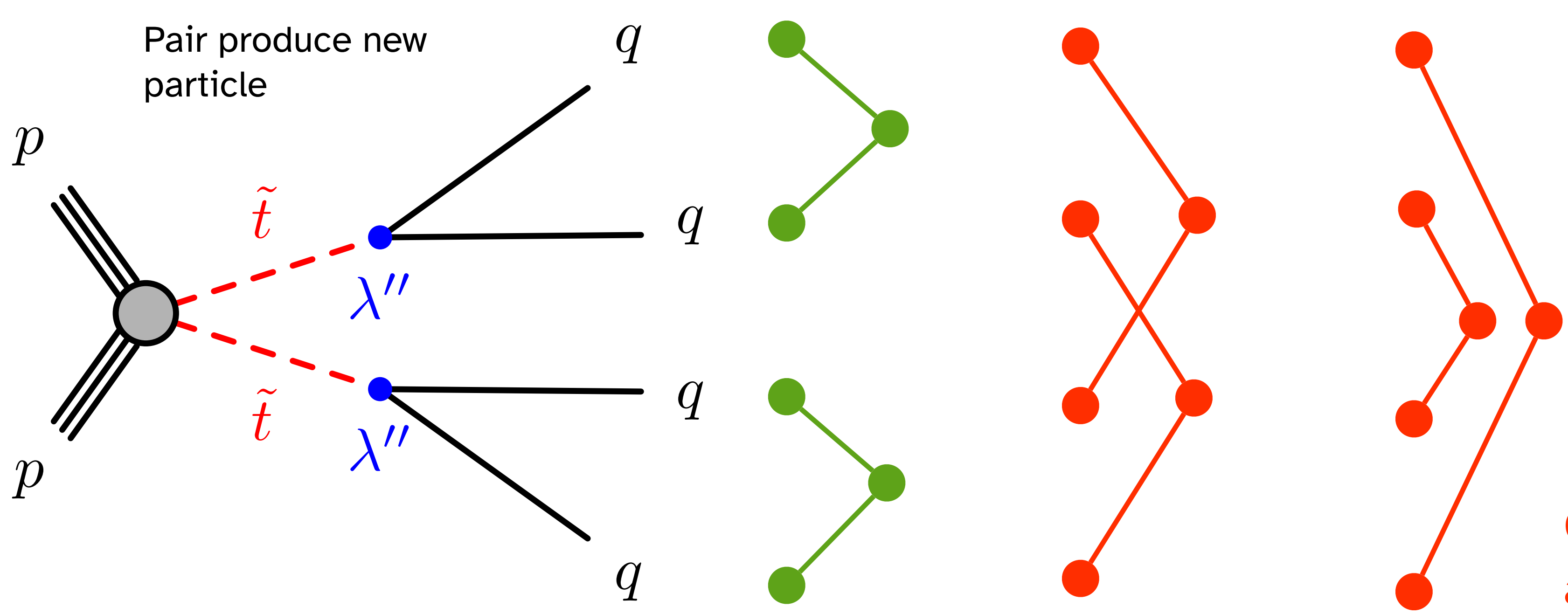
Less Simple Example

Protons collide

Pair produce new particle

Each decays to two jets.

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.
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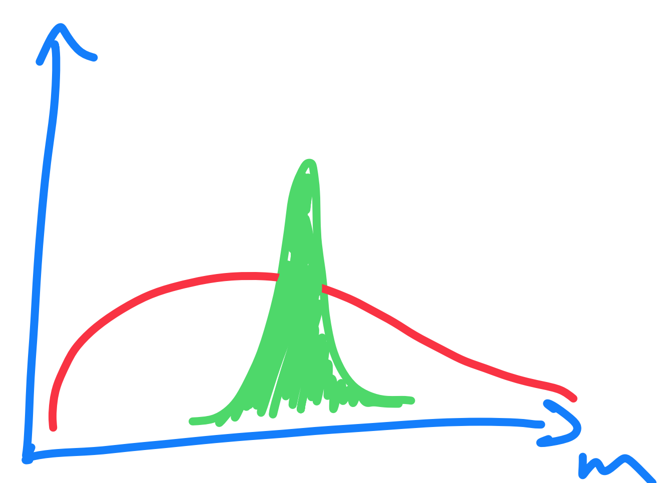
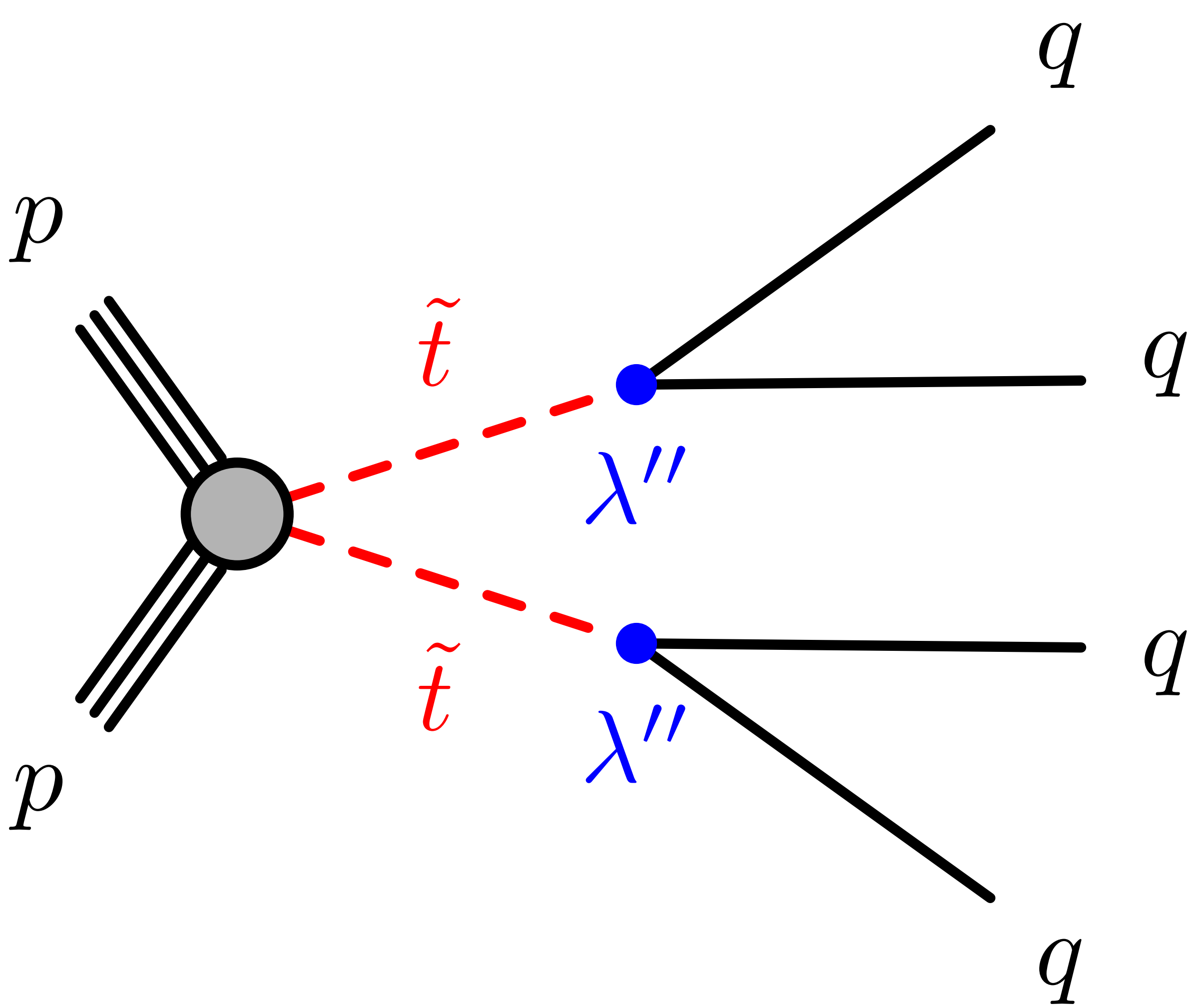
  - 1 in 3 combs is correct → 200% comb BG



"Classical" Combinatorial Soln's



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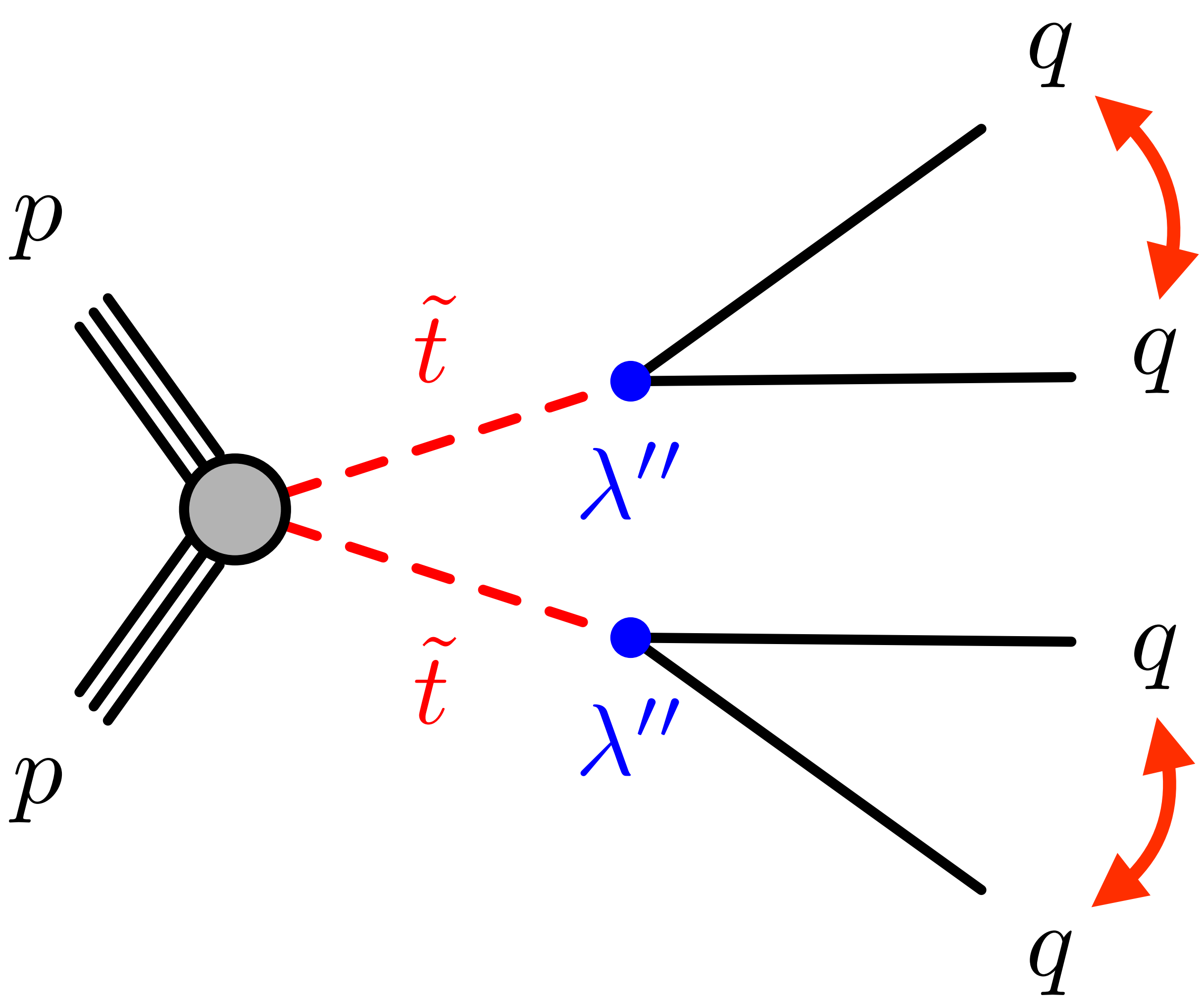
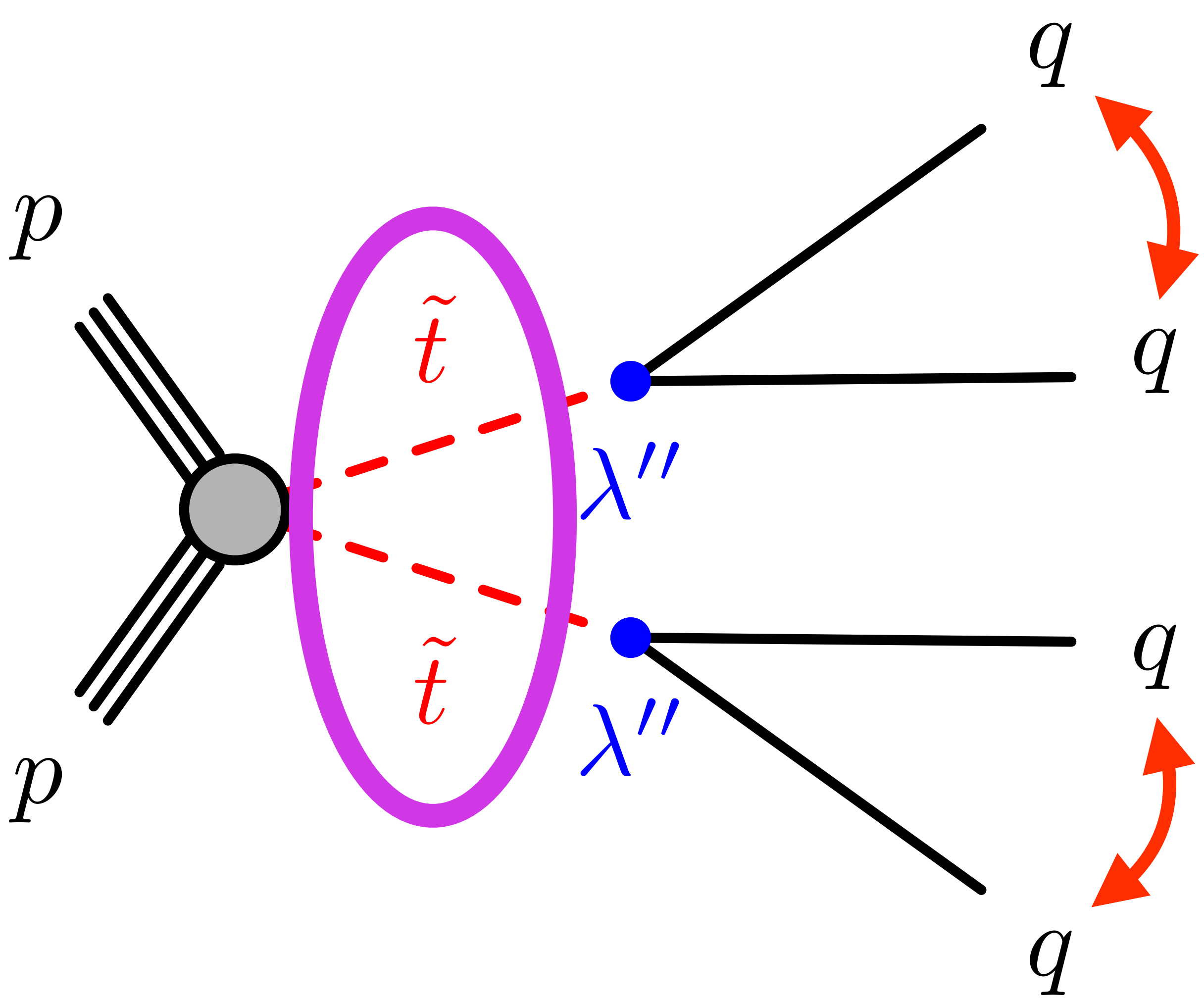


"ΔR$^{\Sigma}$ Minimization"

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

(Used by every LHC search for this.)

"Classical" Combinatorial Soln's



"Mass Asymmetry Minimization"

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

"ΔR^{Σ} Minimization"

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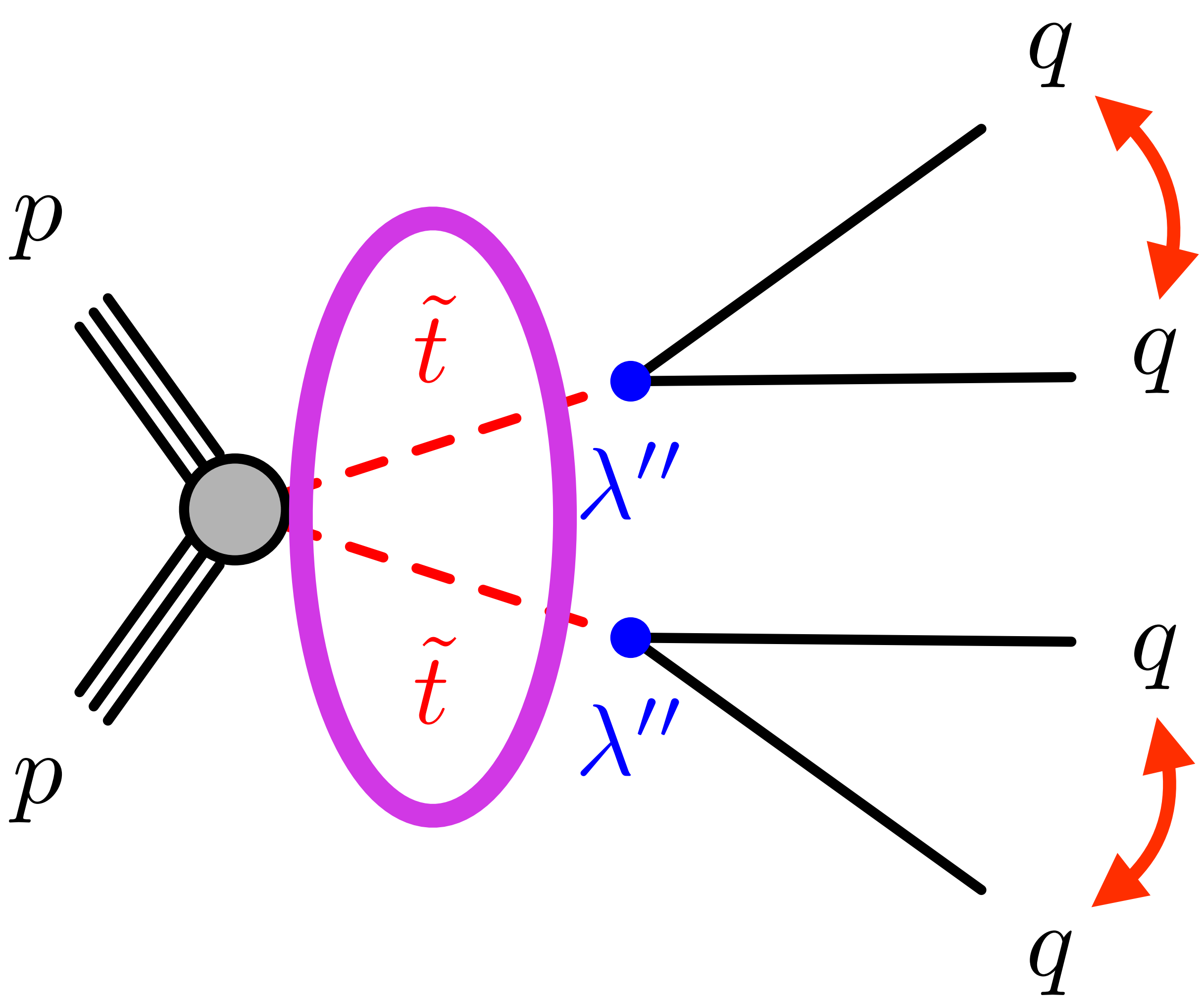

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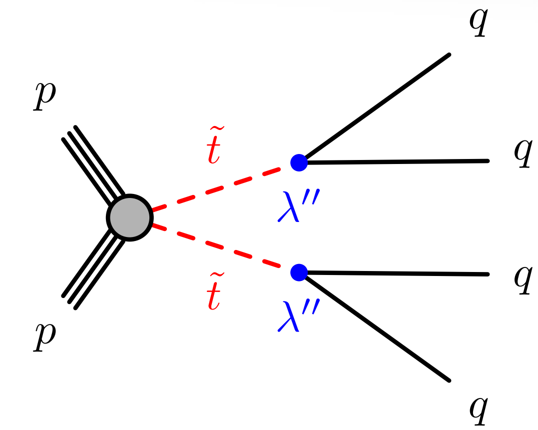
(Used by eve
searc

"Mass Asymmetry Minimization"

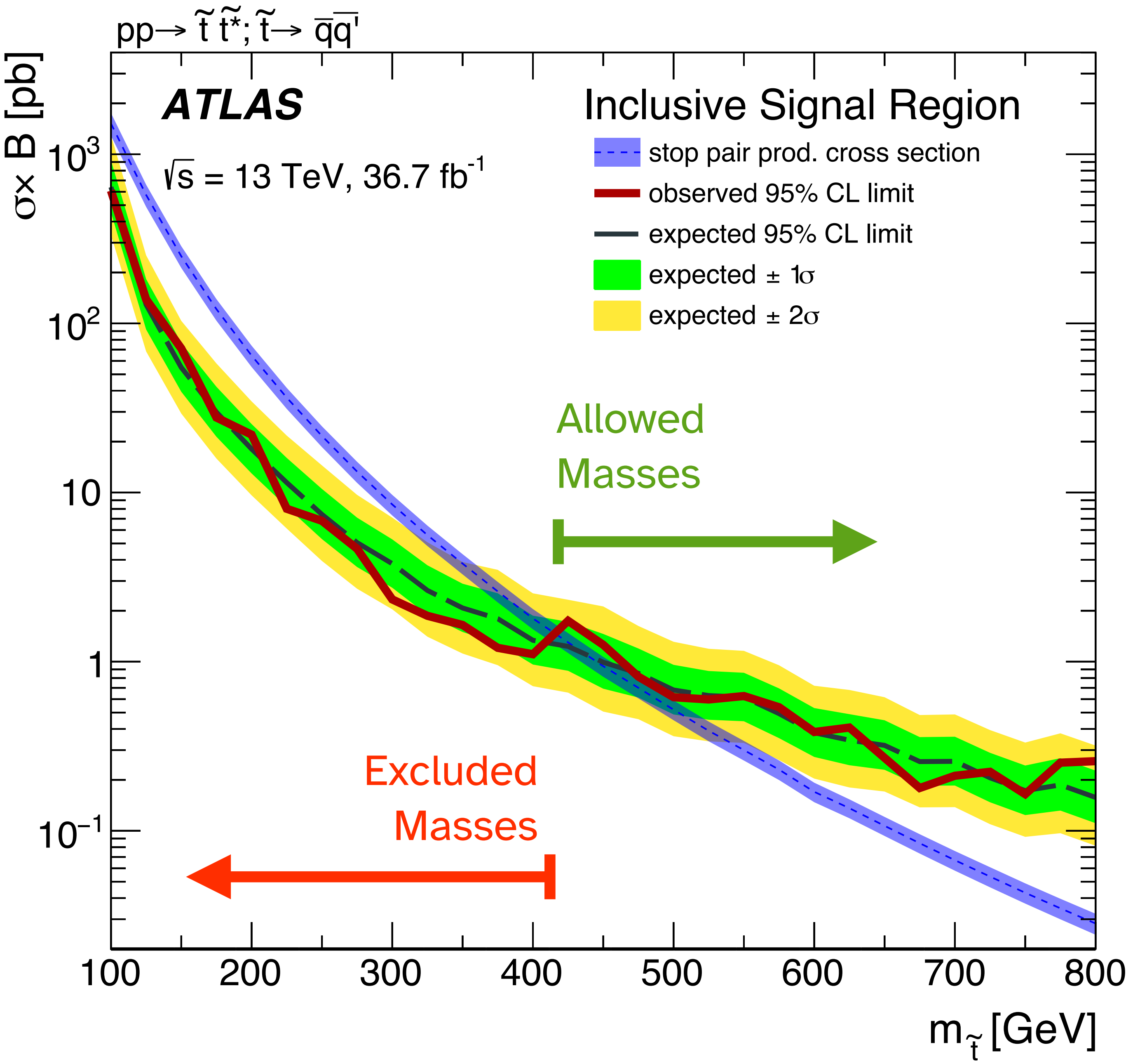
$$\min_{\text{combs}} \left\{ \frac{|m_1 - m_2|}{m_1 - m_2} \right\}$$

POSSIBLE BECAUSE THE MULTIPLICITY IS LOW!

"Classical" 2x2

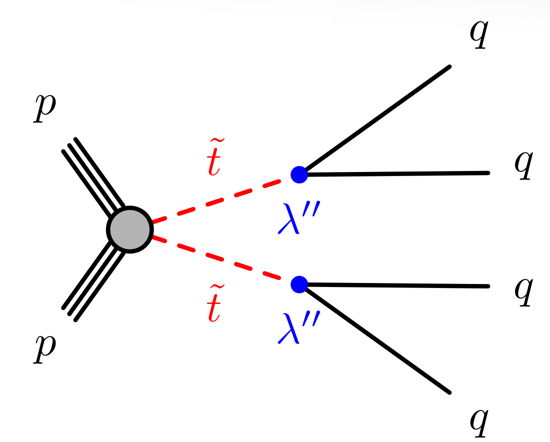


- We can do this search but…
- Sensitivity pretty bad!
- Limits run out at $m(\tilde{t}) \approx 400$ GeV
  - $m(\tilde{t}) \lesssim 1$ TeV well motivated by naturalness!
- Difficult because of combinatorial problem

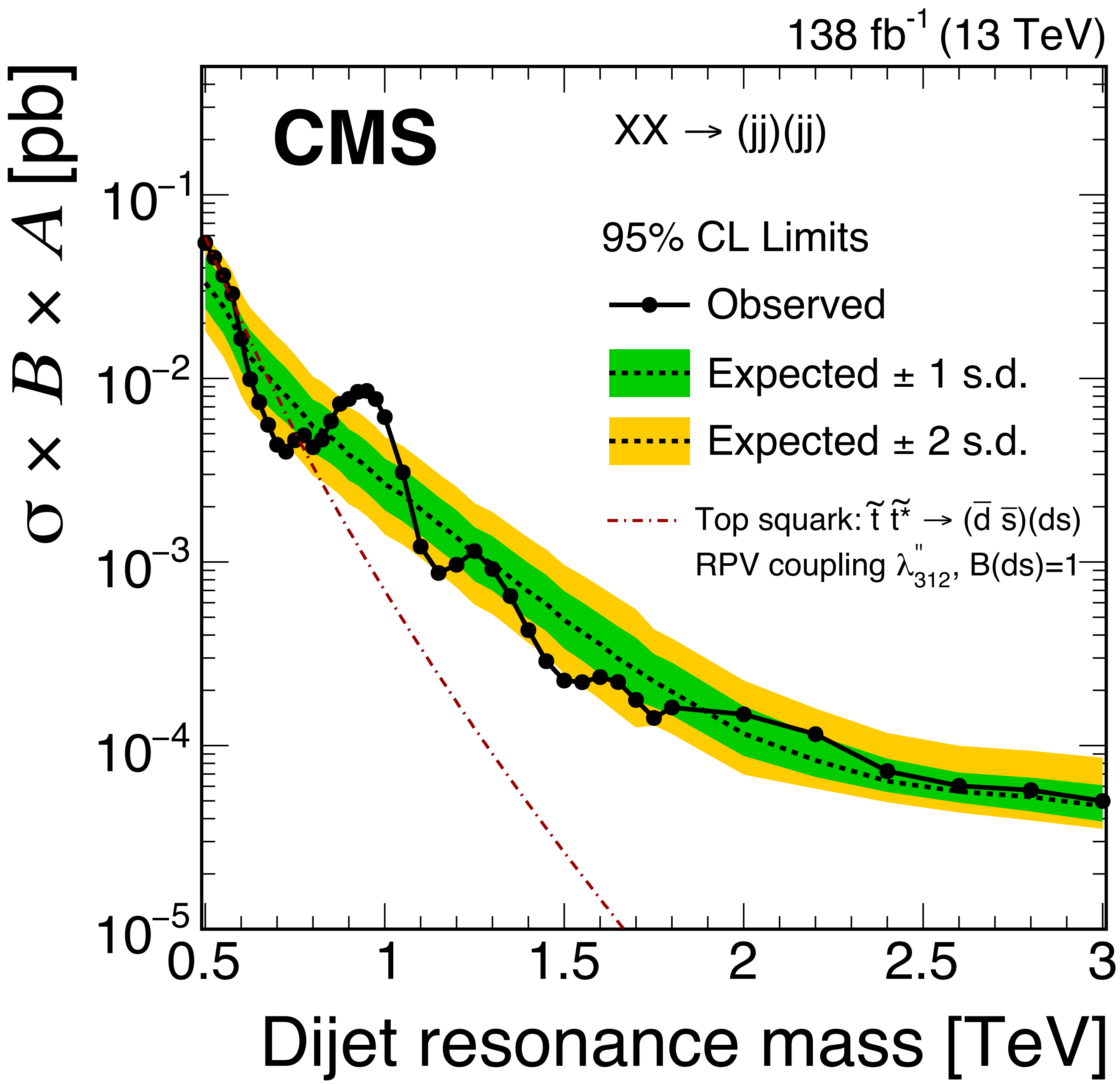


arXiv:1710.07171

"CLASSICAL" 2X2



- Recent CMS Full Run-2 search barely probes 500 GeV for this signature



arXiv:2206.09997

"CLASSICAL" 2X2

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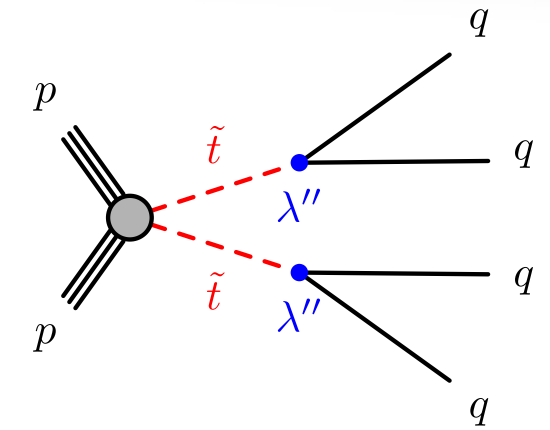
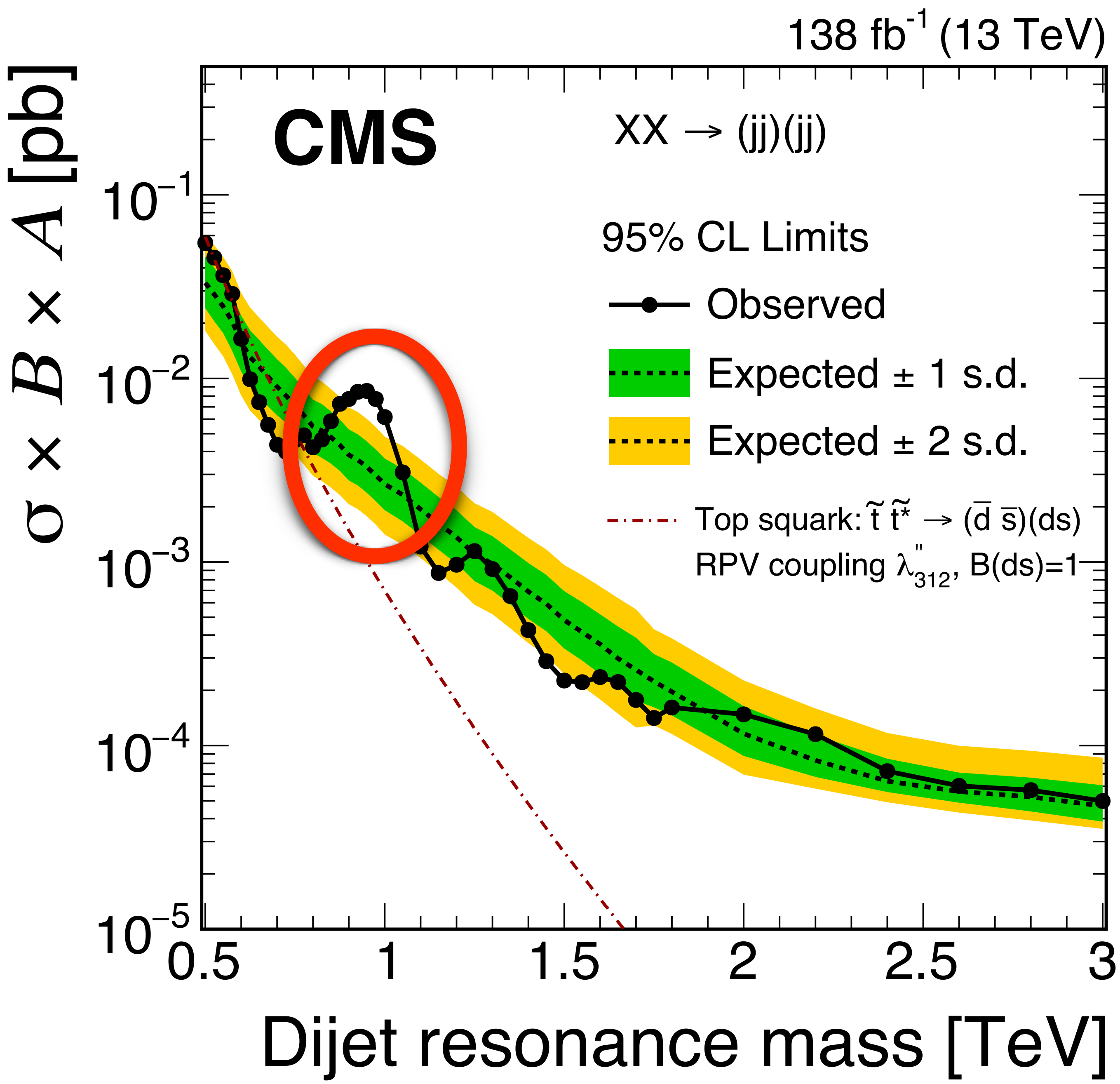
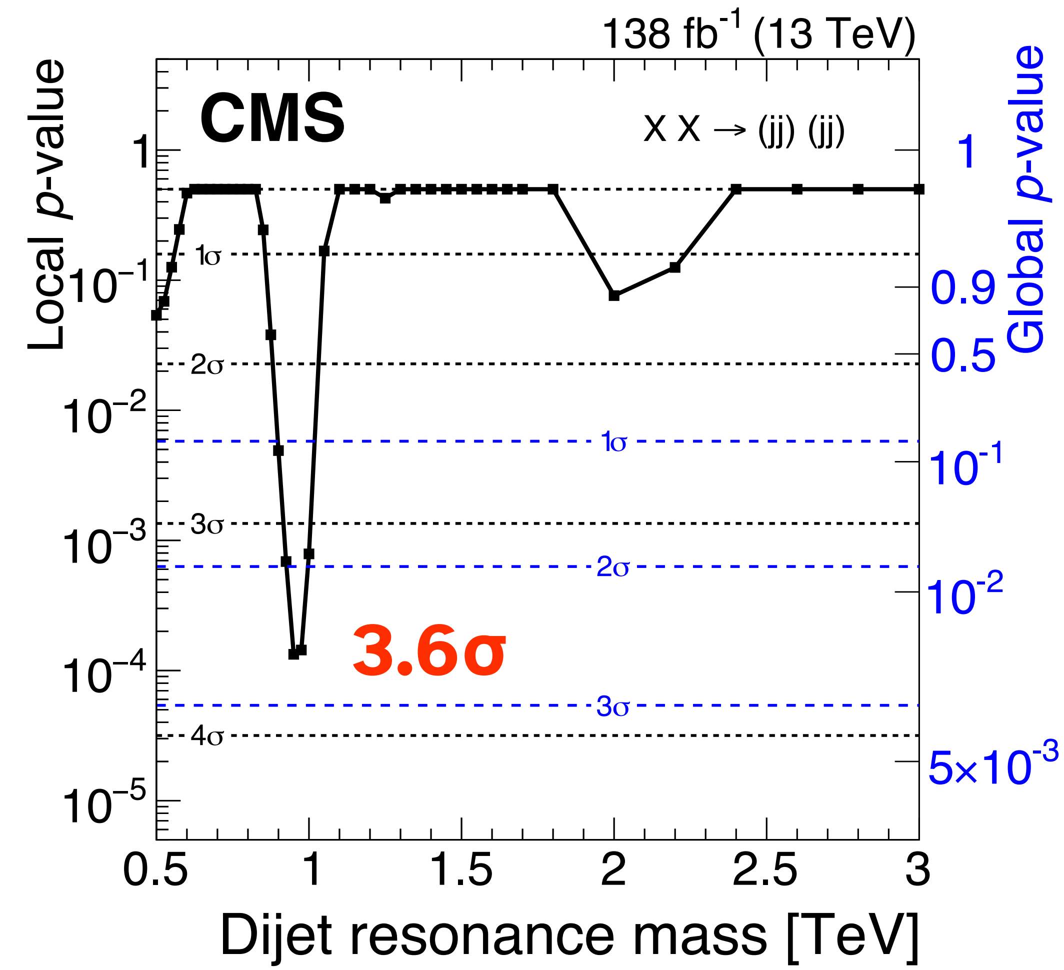
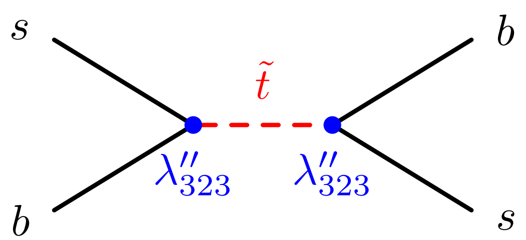


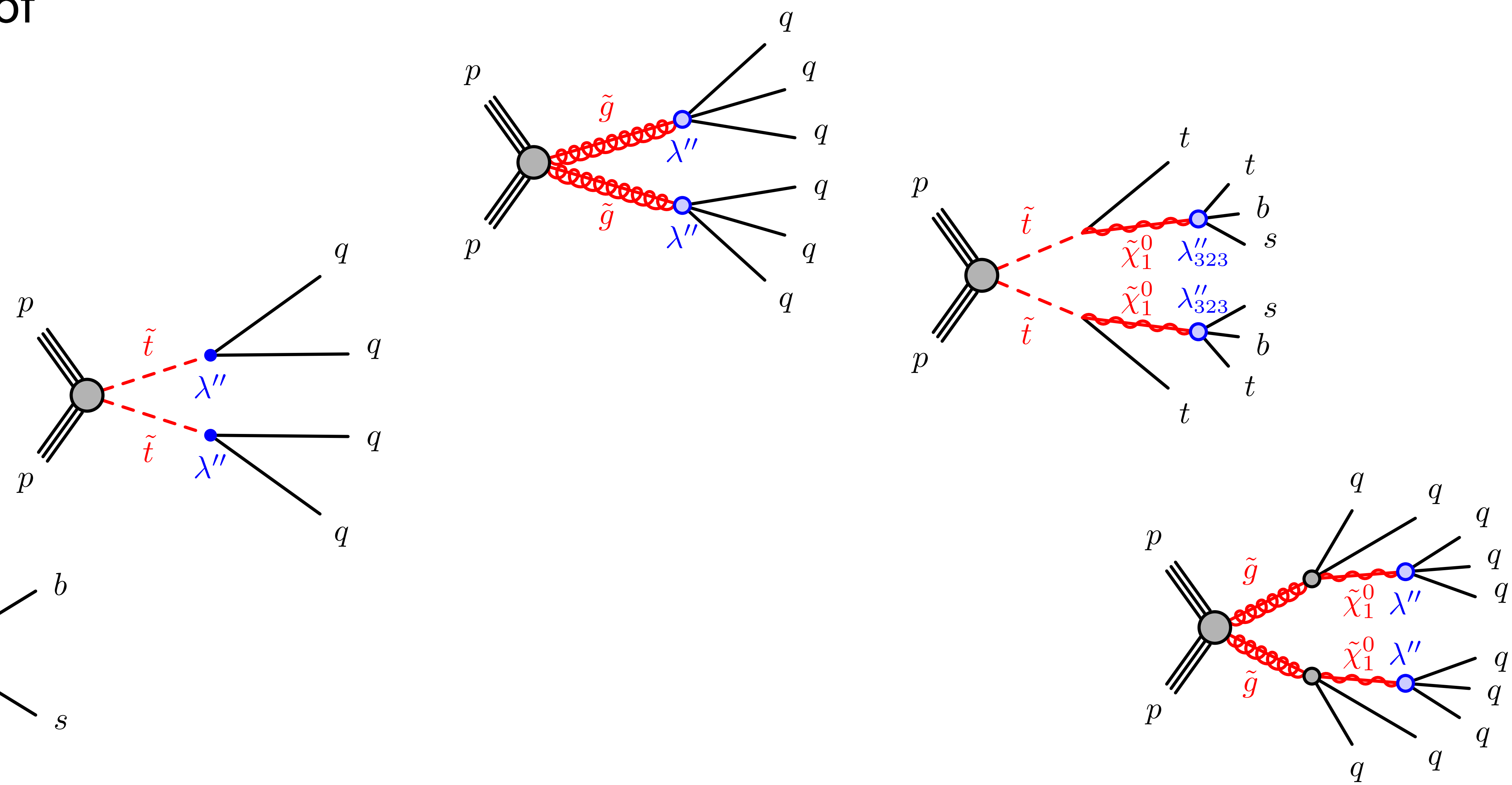




arXiv:2206.09997

Signature zoo of RPV SUSY

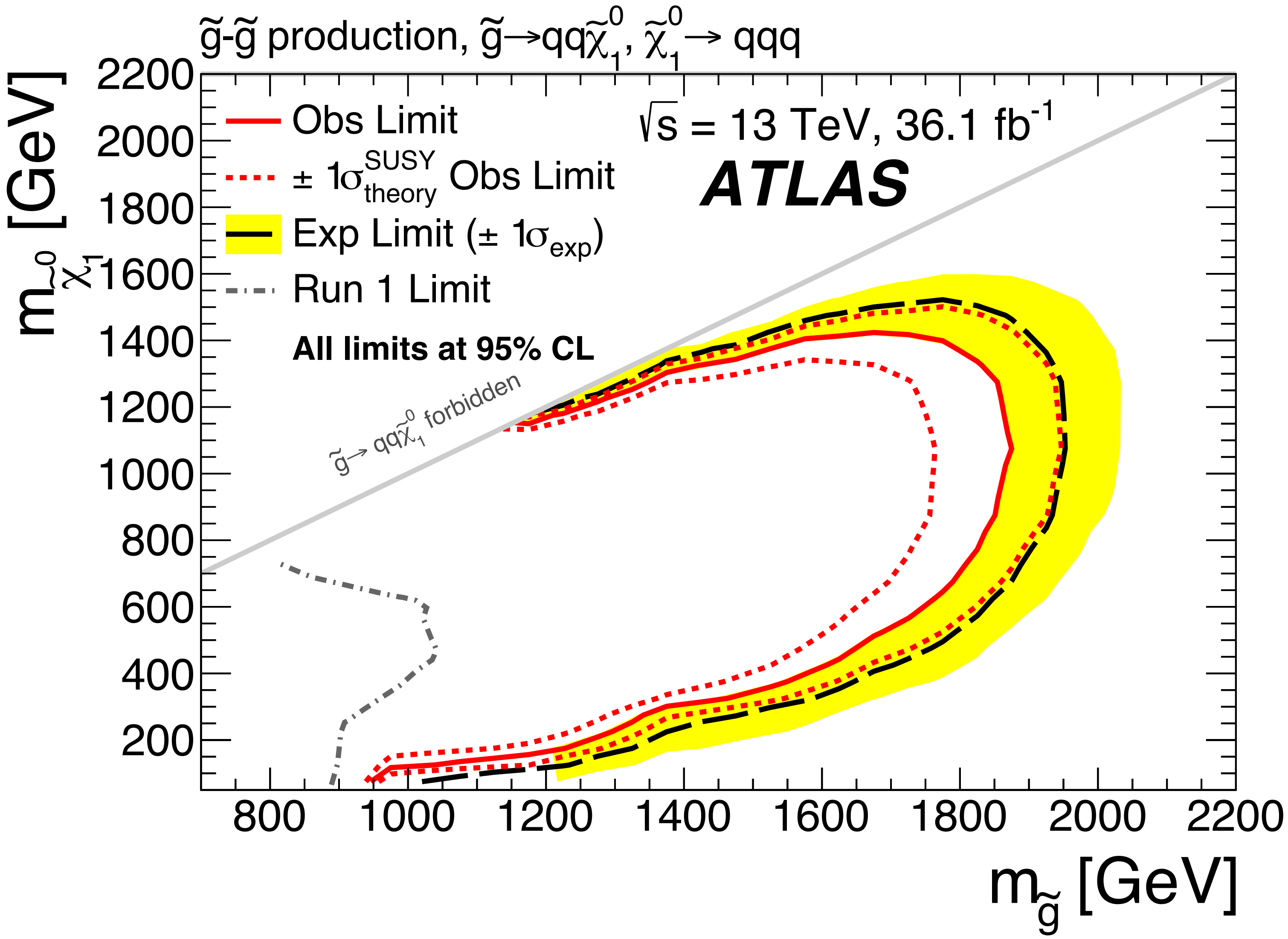




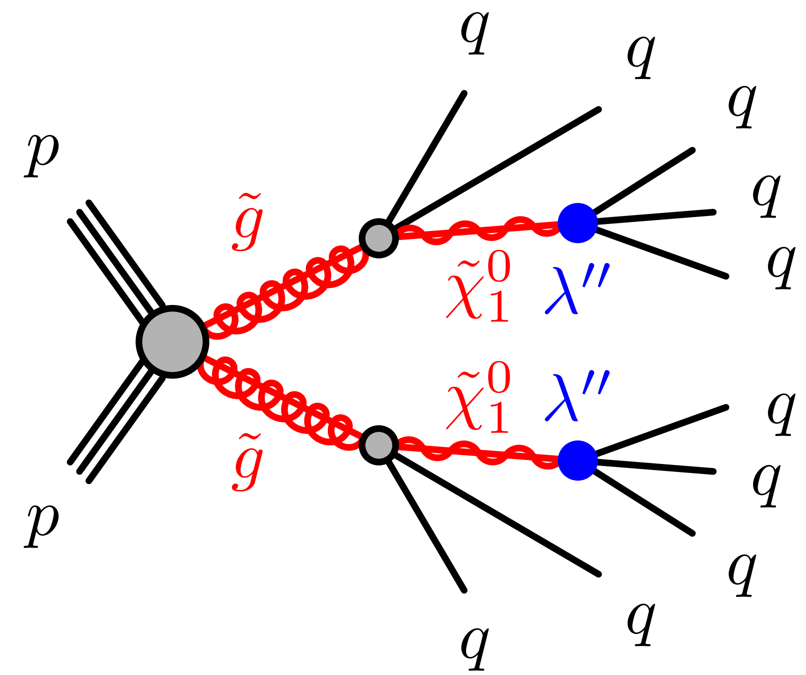
2×1 2×2 2×3 2×4 2×5

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

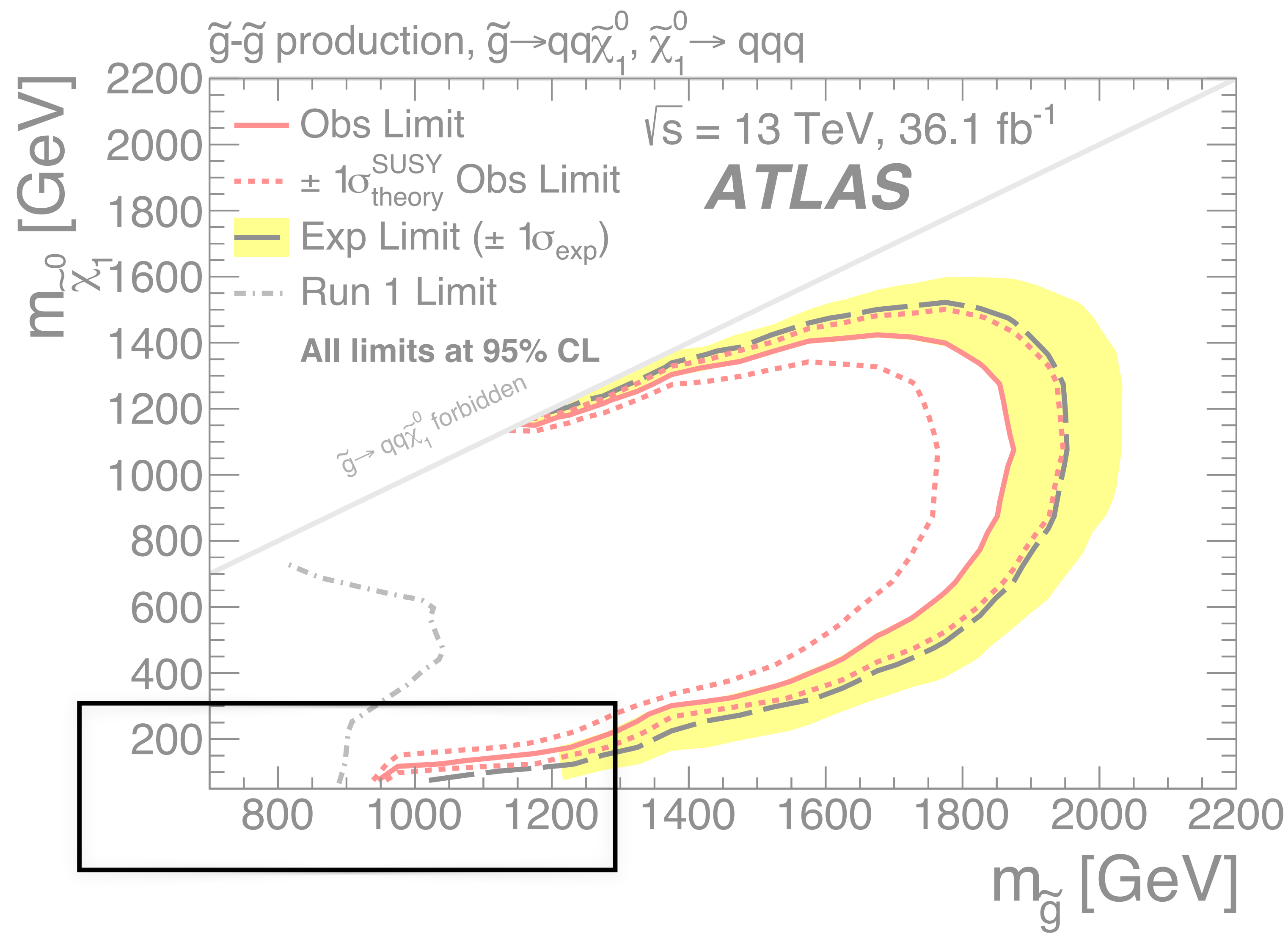
The new particles might like to decay to many more jets!

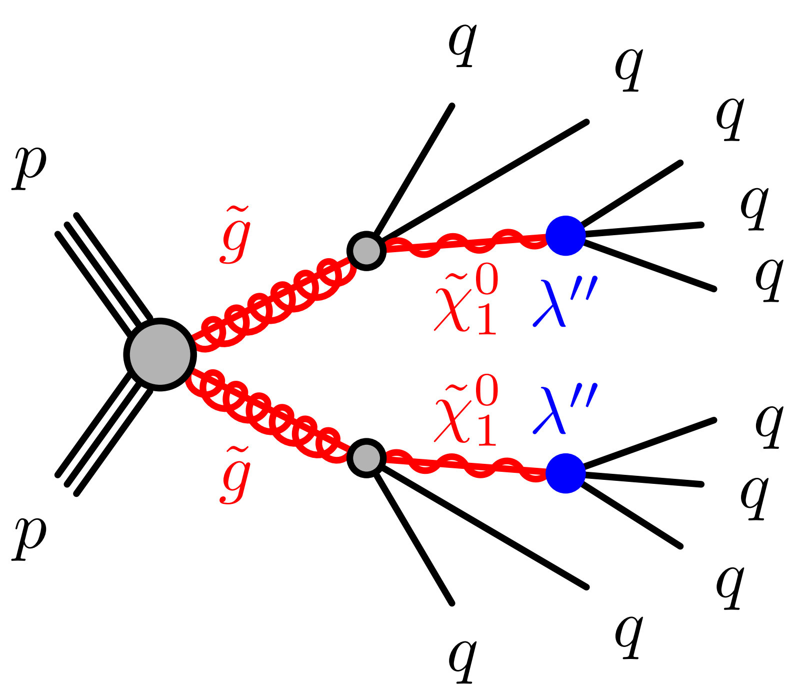


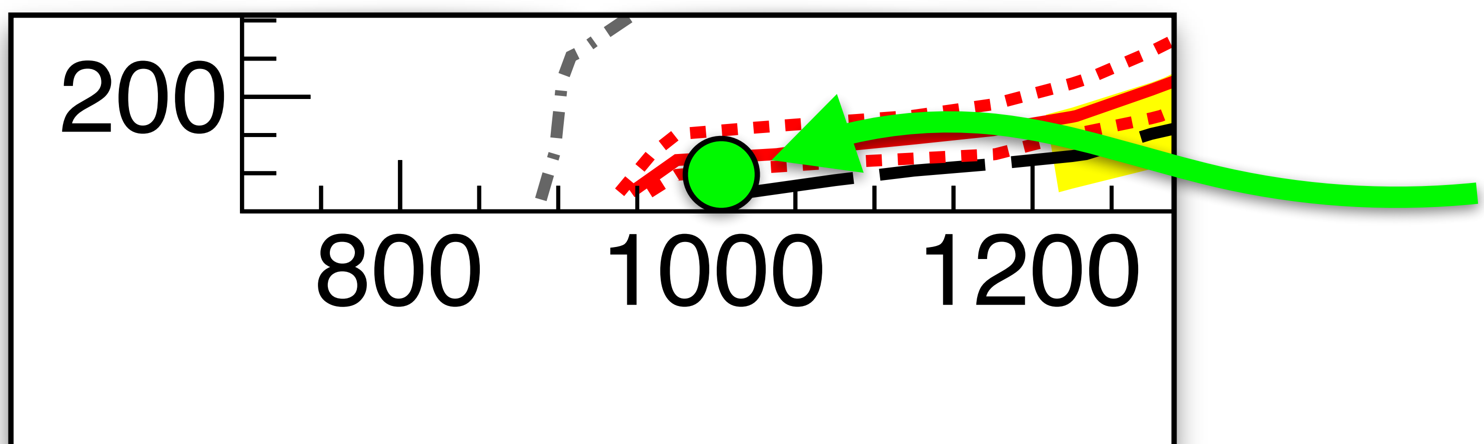
$\tilde{g}$-$\tilde{g}$ production, $\tilde{g}\rightarrow qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow qqq$
Obs Limit
$\pm 1\sigma^{SUSY}_{theory}$ Obs Limit
Exp Limit ($\pm 1\sigma_{exp}$)
Run 1 Limit
All limits at 95% CL
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
ATLAS
$\tilde{g}\rightarrow qq\tilde{\chi}_1^0$ forbidden
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$ [GeV]



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



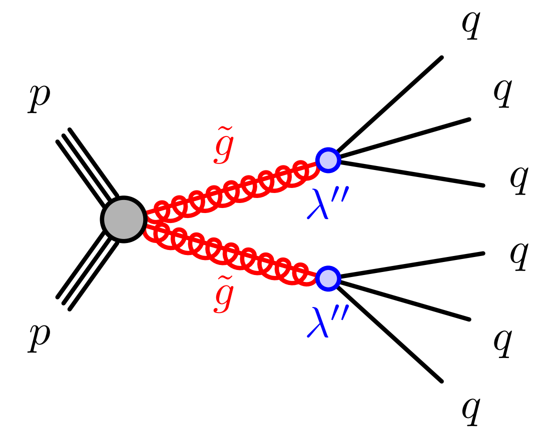


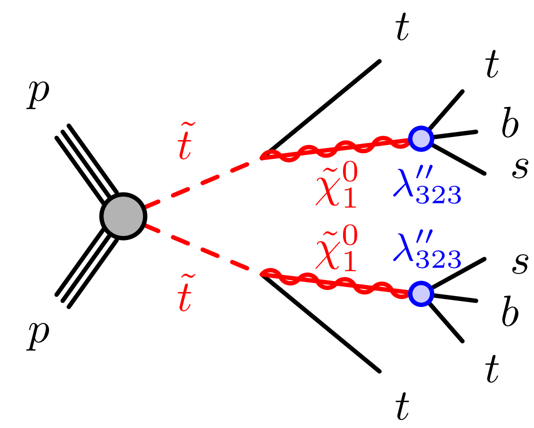


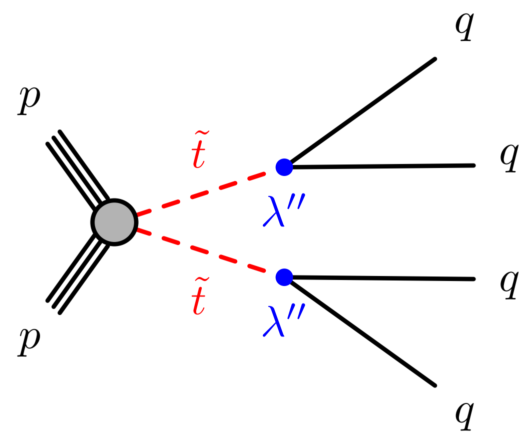
With this coupling on, no sensitivity to

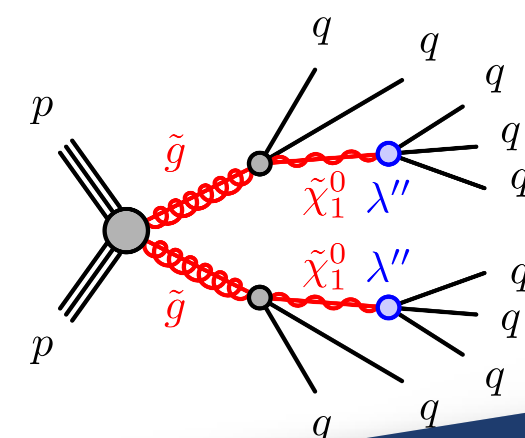
1 TeV Gluino
100 GeV Higgsino

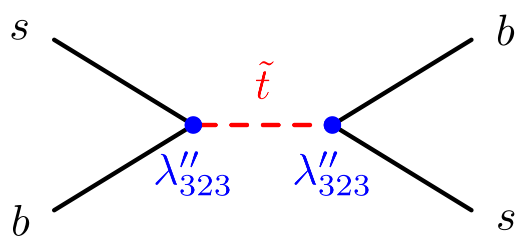
Signature zoo of
RPV SUSY









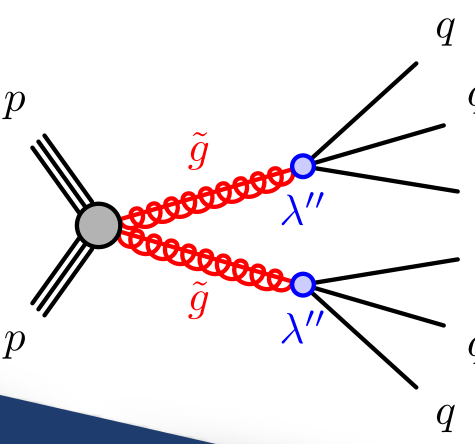


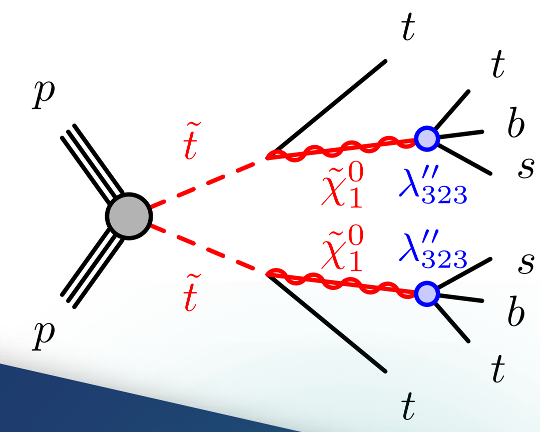
2×I

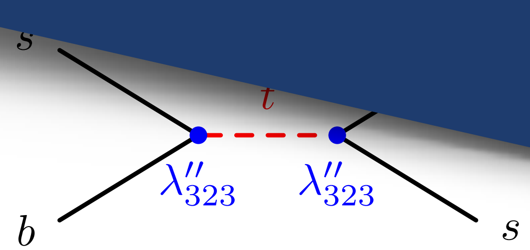
COULD BE HIDING ON DISK!

500 GeV Stops
1 TeV Gluinos
100 GeV Higgsinos

Signature zoo of RPV SUSY





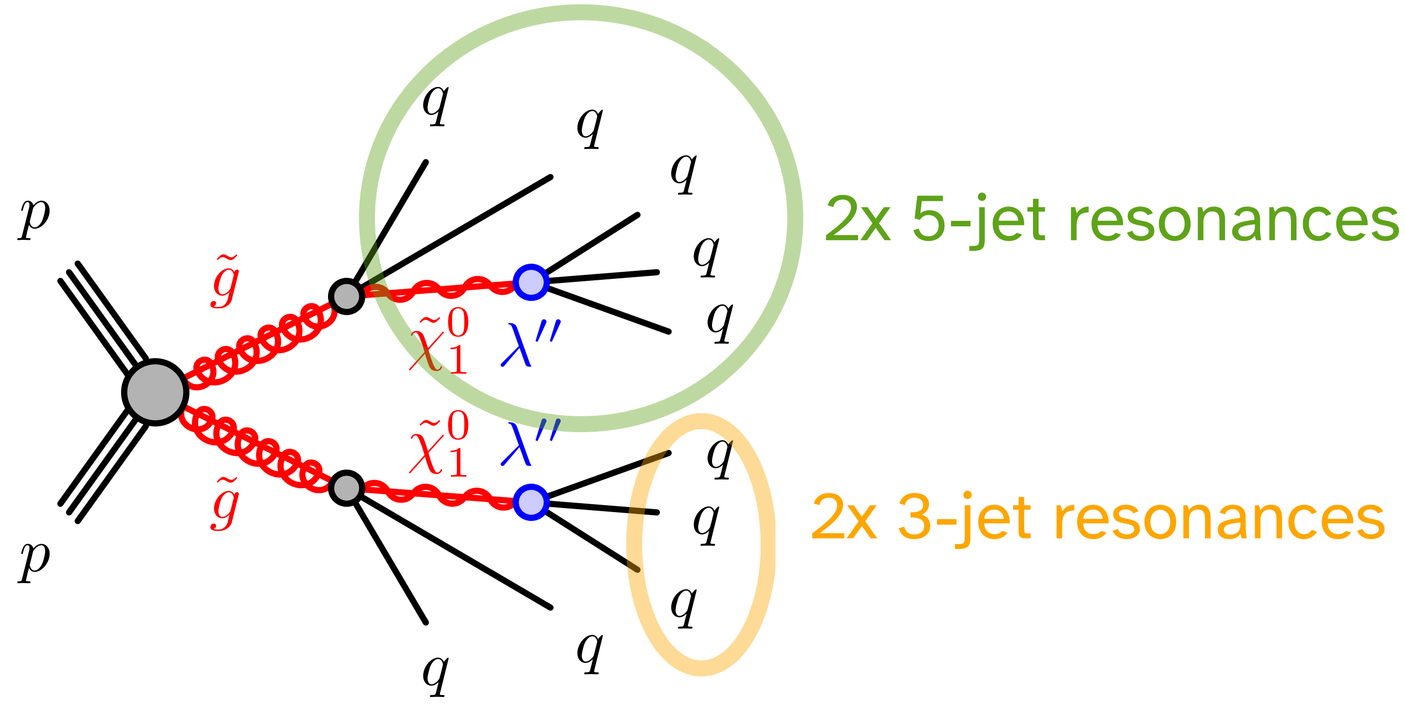


2×I

THE LHC DREAM

COULD BE HIDING ON DISK!

500 GeV Stops
1 TeV Gluinos
100 GeV Higgsinos



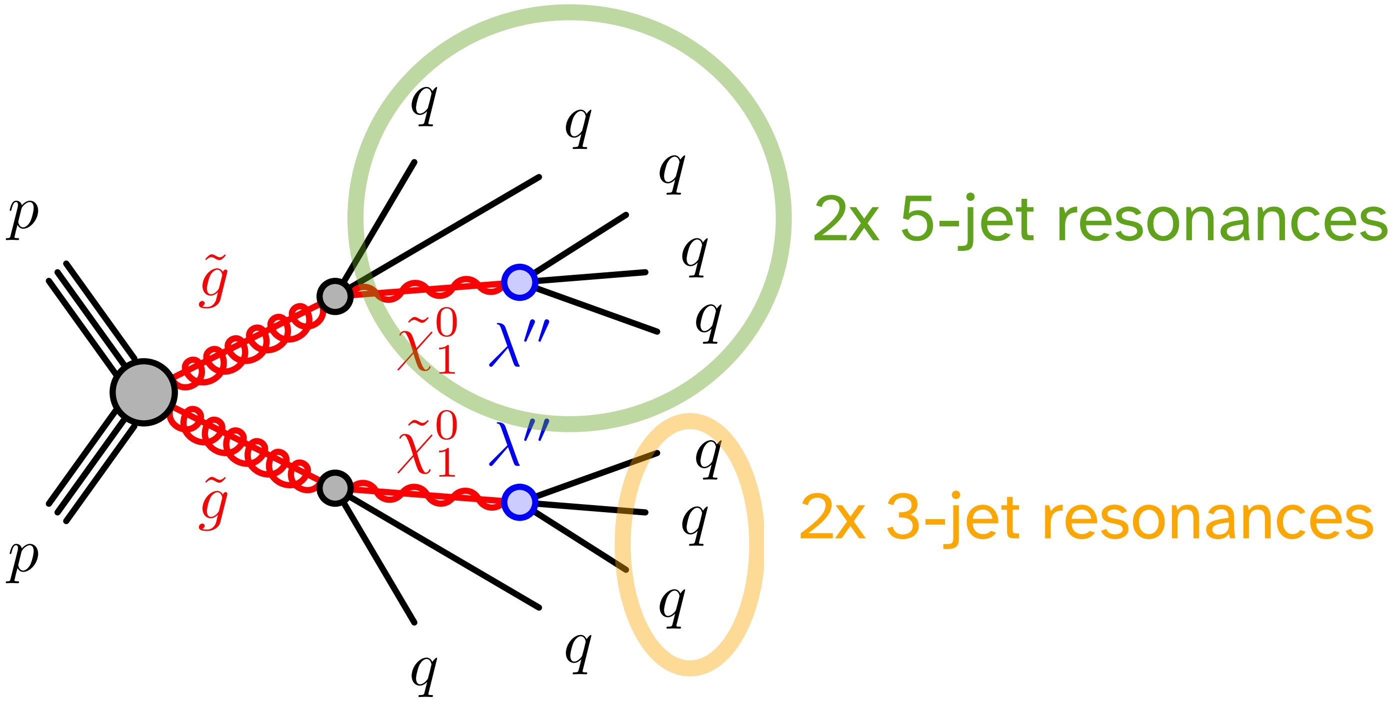
$$\binom{10}{5}/2 = 126$$

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

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

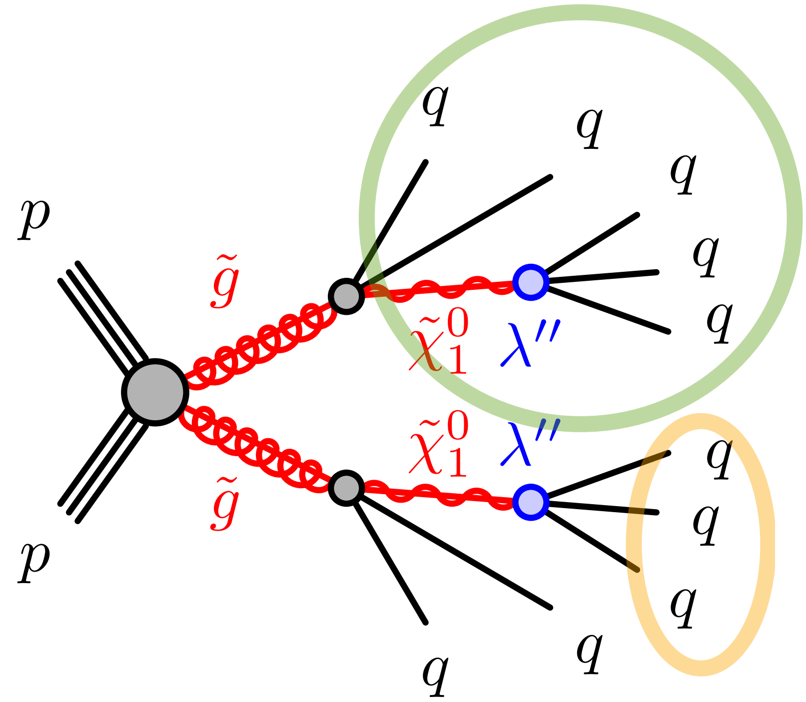
For the one "correct" view of this event,

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…
    - Signal and BG look very different **in 40D**



2x 5-jet resonances

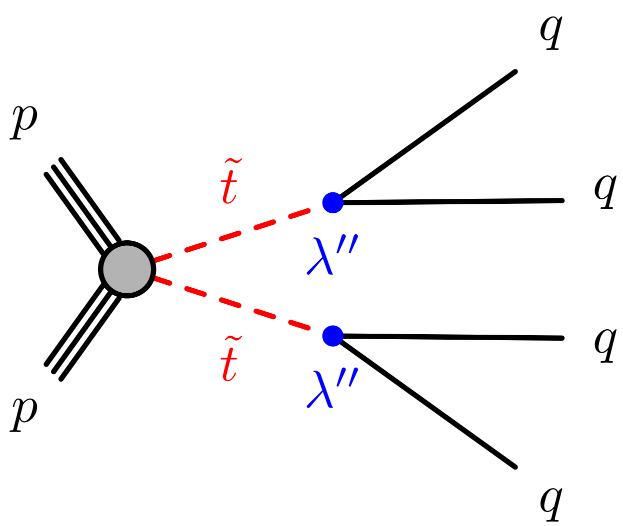
2x 3-jet resonances

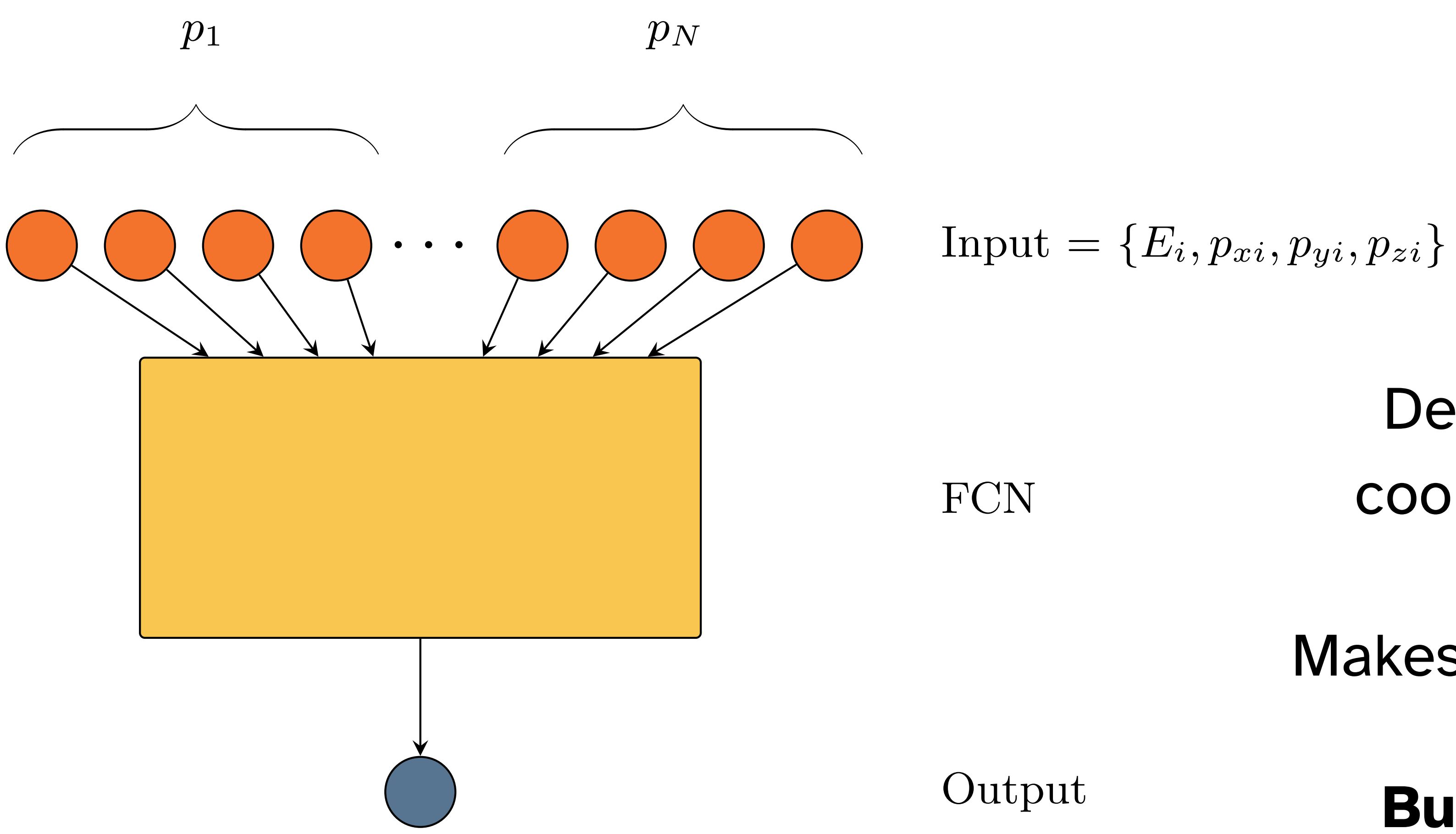
- **Large feature space (40D)**
- Discrimination in **high-level features (masses, etc)**
- This is a **particularly good problem for ML**
  - **(Ask me about past CNN proposals for this)**

…ery different **in 40D**

Back to 2x2

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



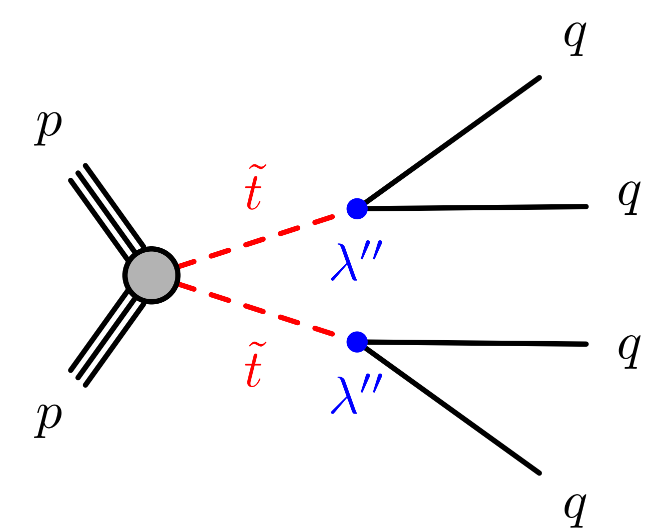


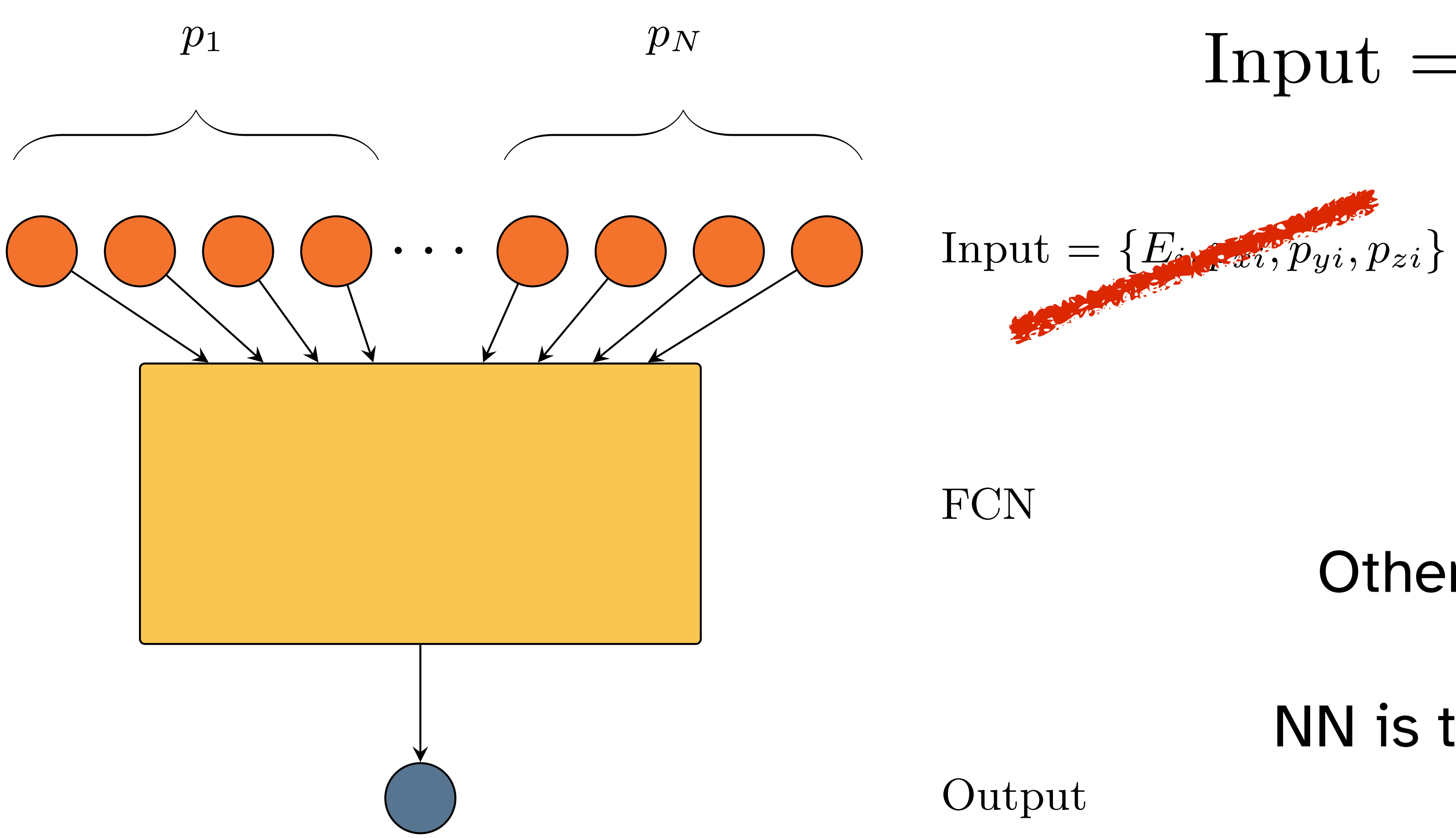
Describing inputs in orthogonal coordinate system $\{E, p_x, p_y, p_z\}$

Makes it easy for NN to sum inputs

But NN needs to learn how to calculate masses, etc!

Back to 2x2





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

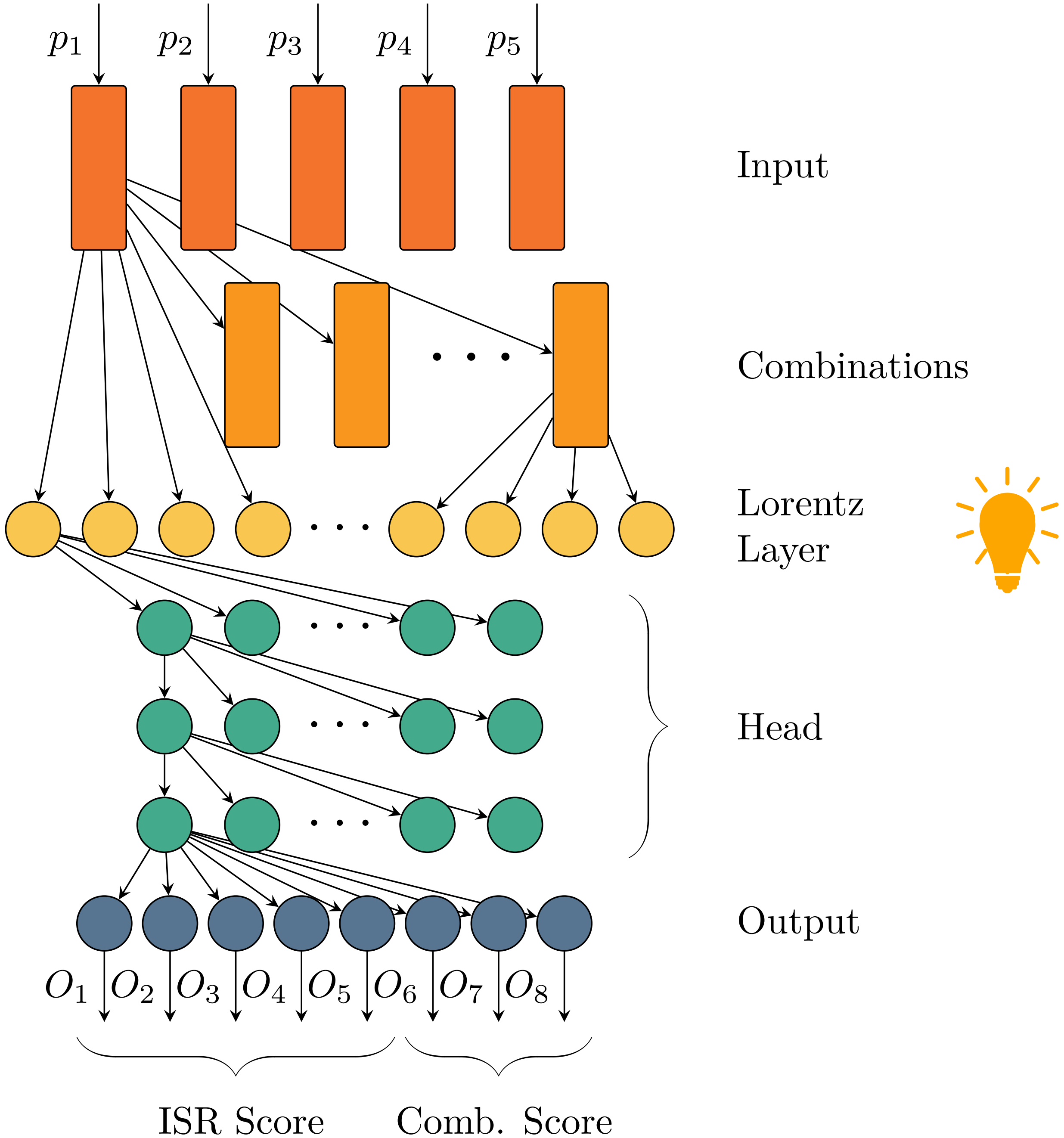
Others might hand it $\{m, p_T, \eta, \phi\}$

NN is told about masses and angles

But it then needs to learn how to combine vectors!

NN w/ Lorentz Layer (LoLa)

- Construct a NN layer that **knows about relativity! (LoLa)**
  - 1707.08966, 1812.09722, etc
- 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



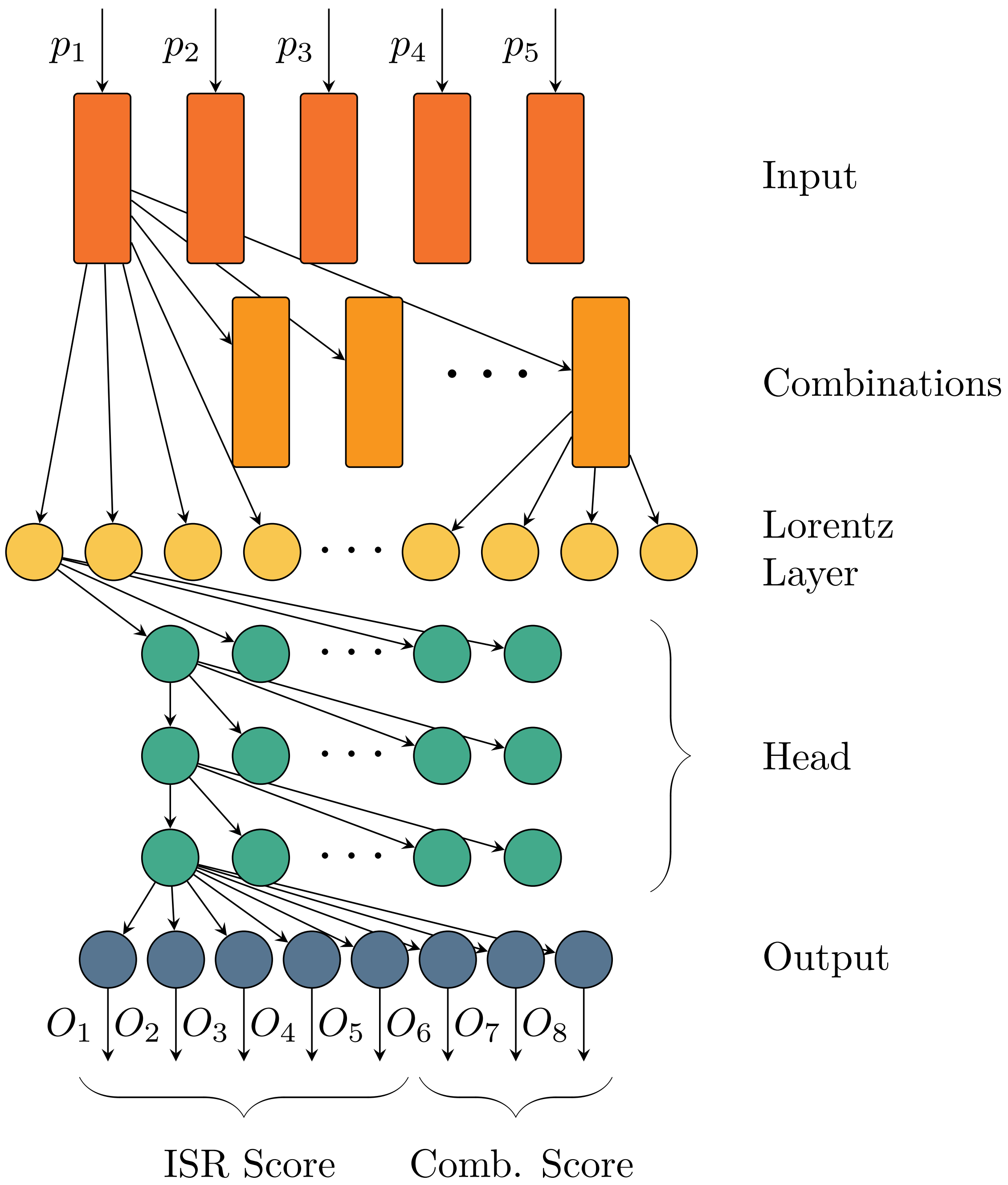
A Badea, W Fawcett, J Huth, TJ Khoo, R Poggi, LL — arXiv:2201.02205

NN w/ Lorentz Layer

Cannonball:

Combinatorial 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



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Combinatorial Artificial NN ON
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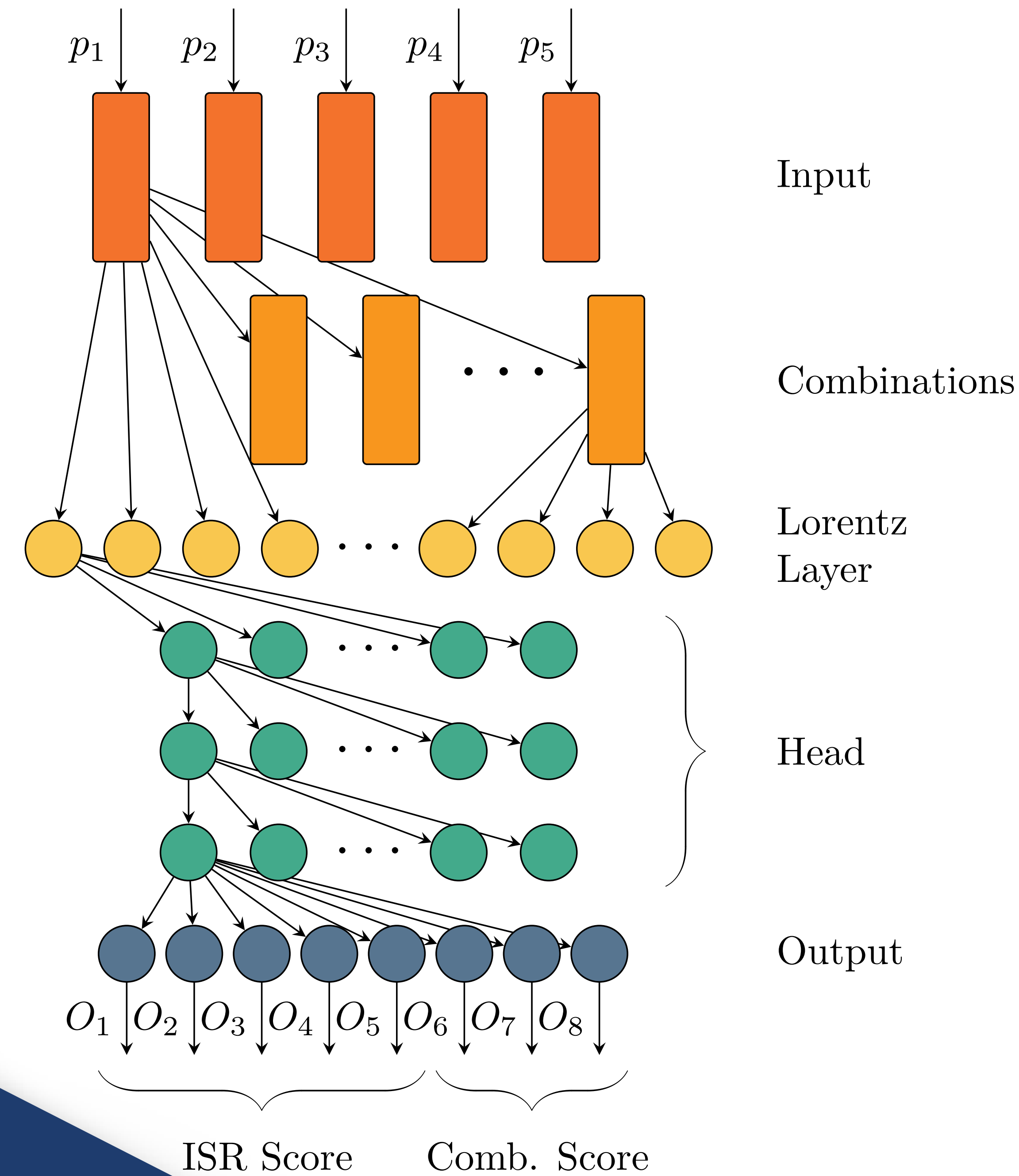
…uts ***interpretation*** **of**

…hoose the "best"

…us

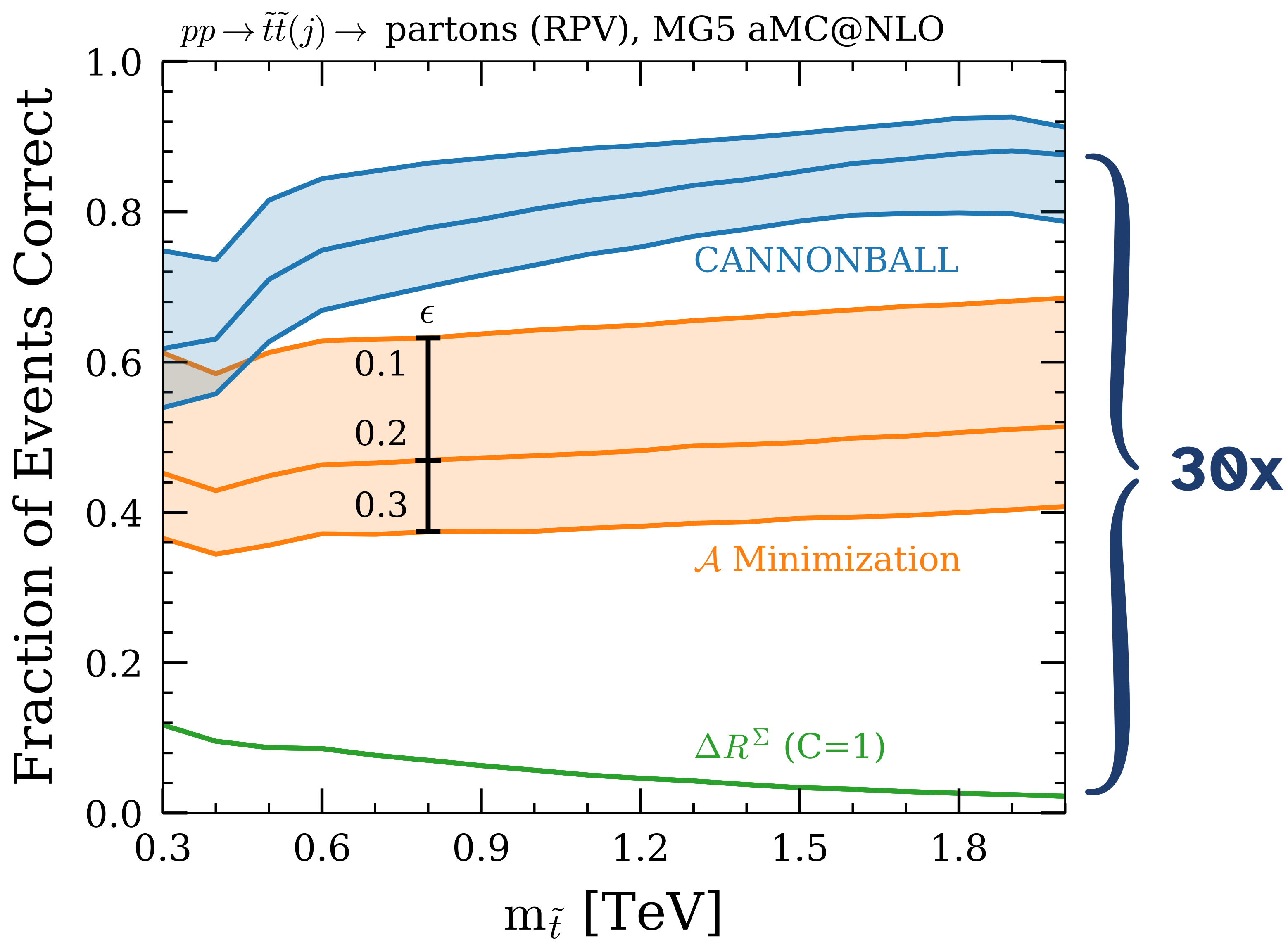
Newly on the Postdoc Job Market!



Anthony Badea

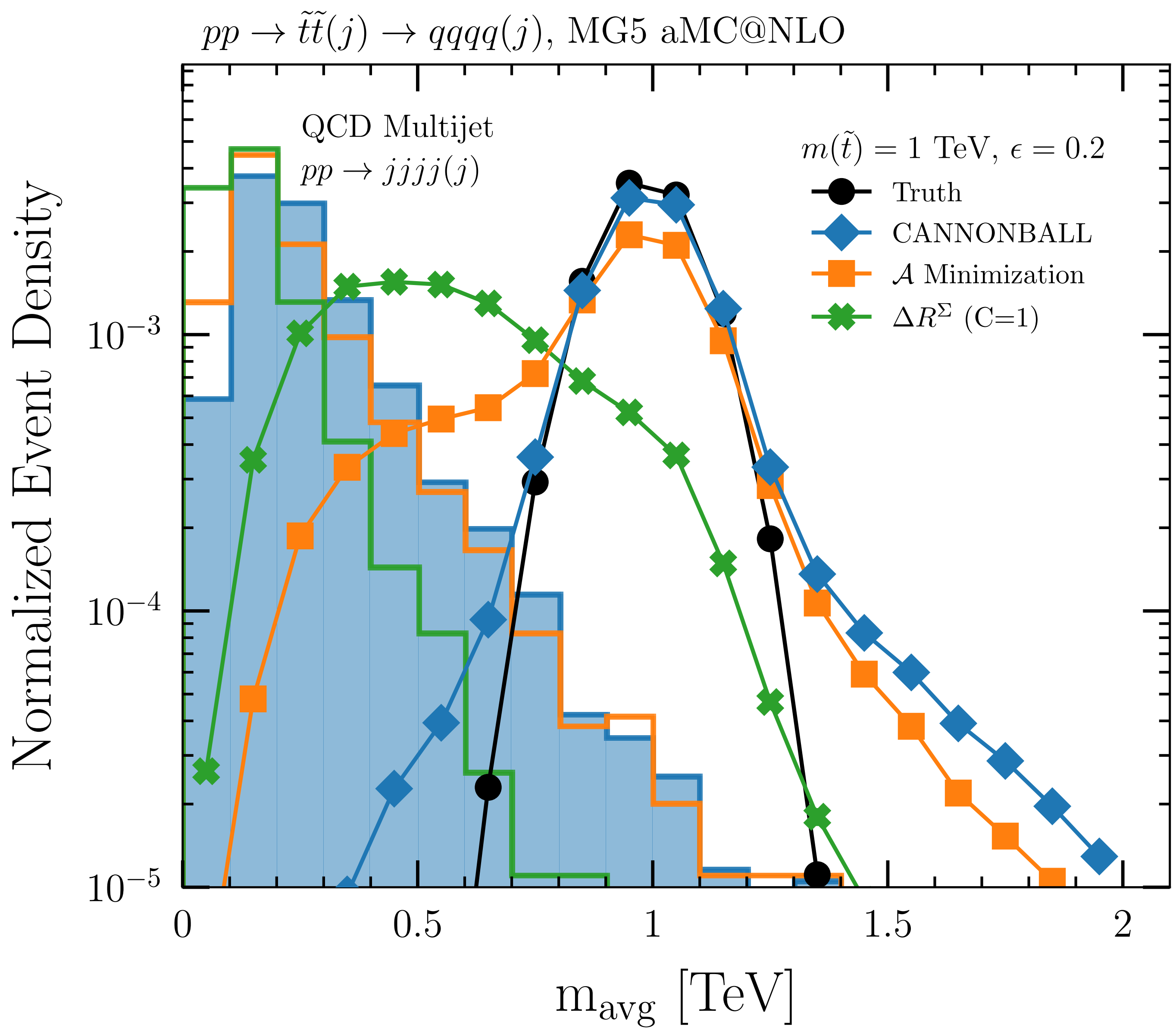
…oggi, LL — arXiv:2201.02205

- ΔR^{Σ} minimization does terribly at getting the right pairing!
  - Requires large boosts
- **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

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



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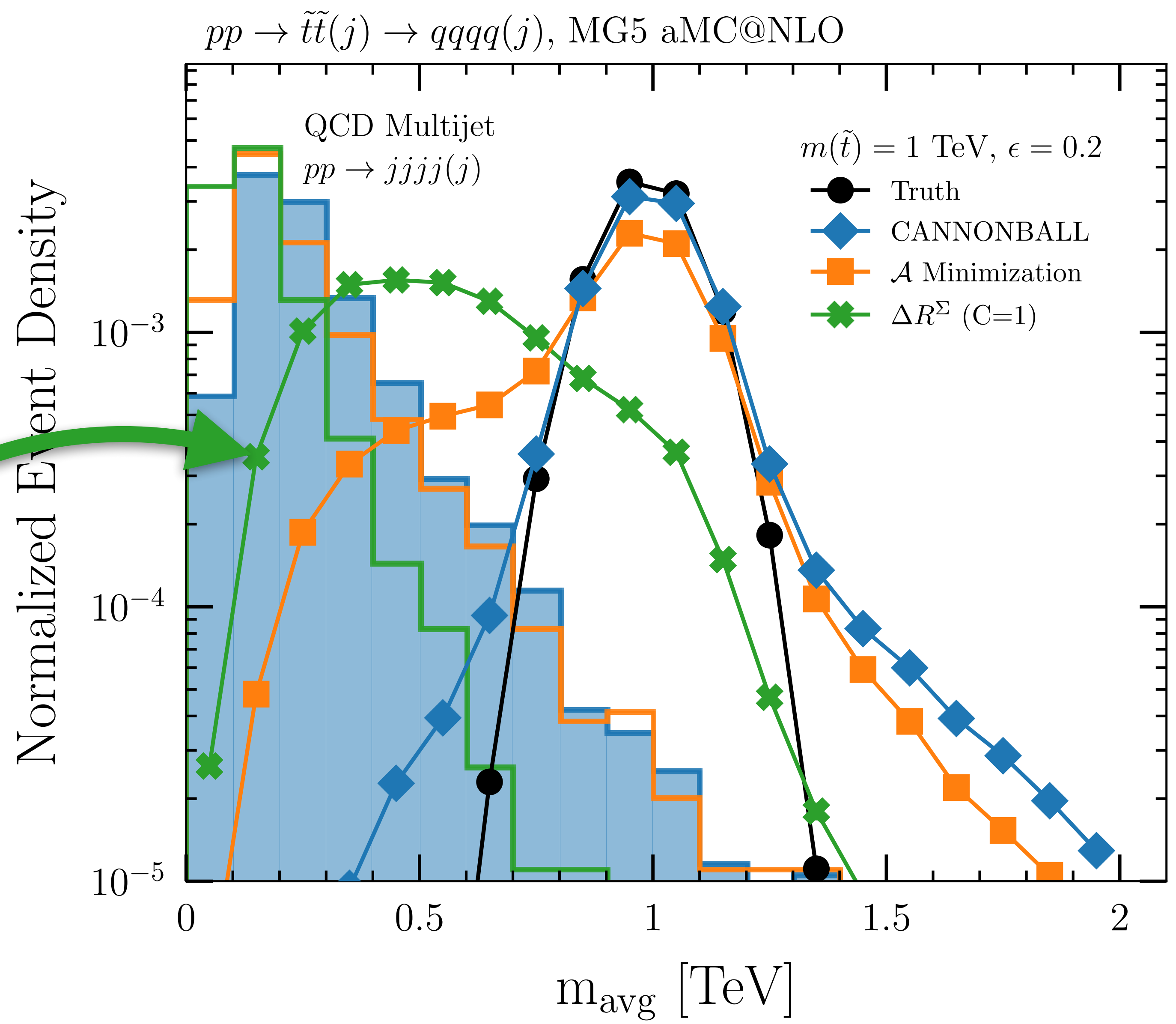
ΔR^{Σ} does terribly unless boosted.



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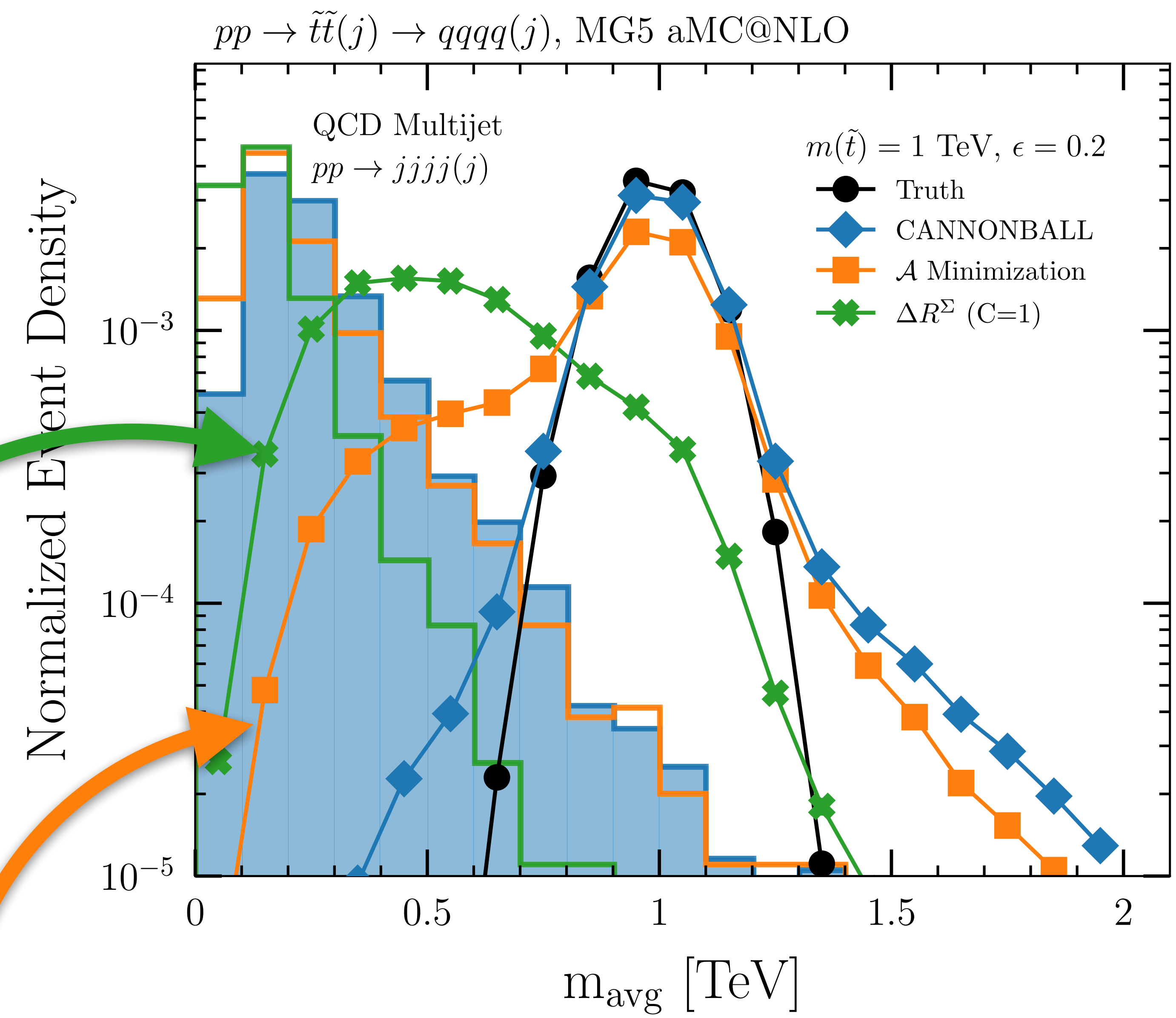

ΔR$^{\Sigma}$ does terribly unless boosted.

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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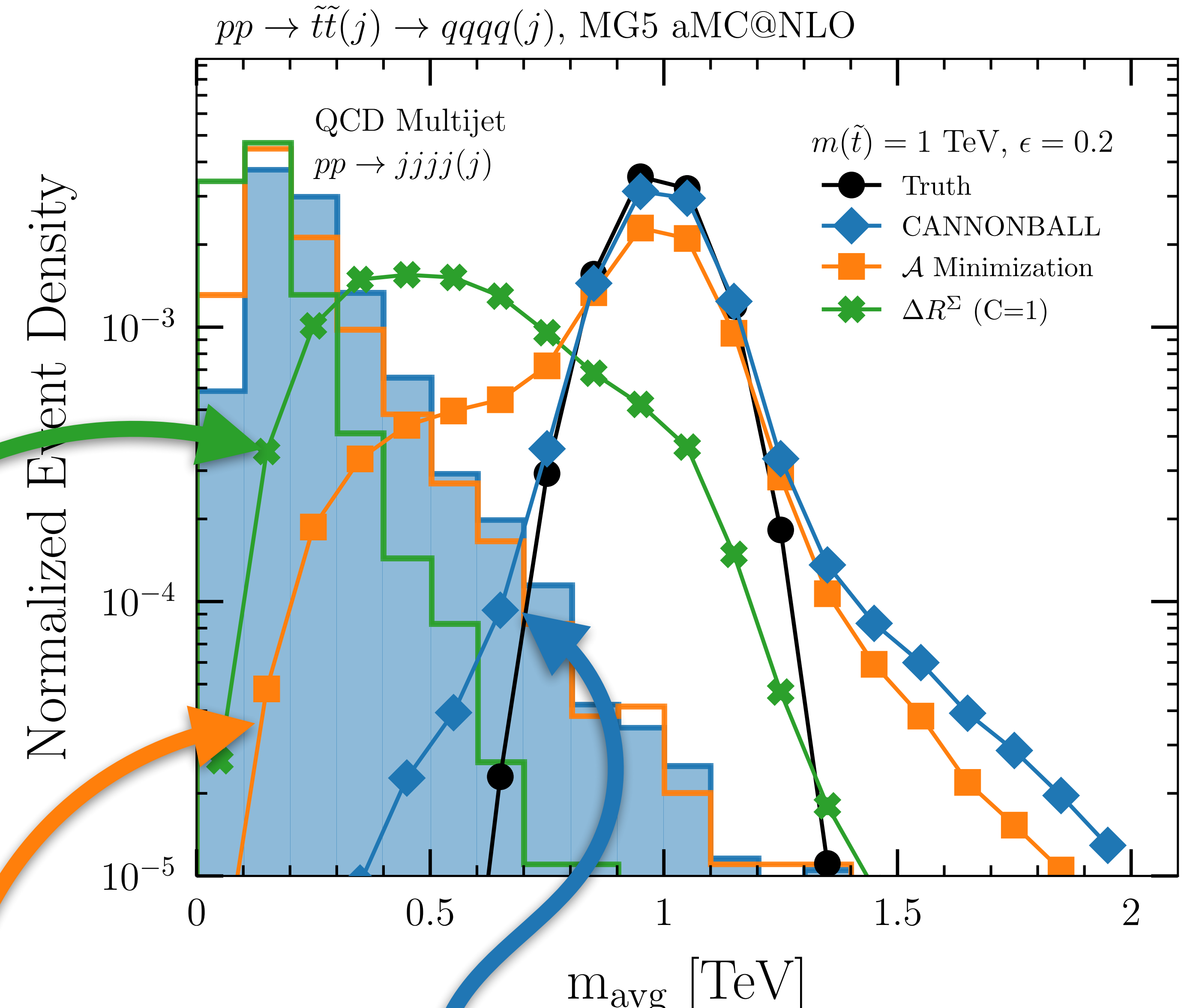

ΔR$^{\Sigma}$ does terribly unless boosted.

Mass Asymmetry Min

Large off-peak contributions…

CANNONBALL

Very close to best case scenario (truth)

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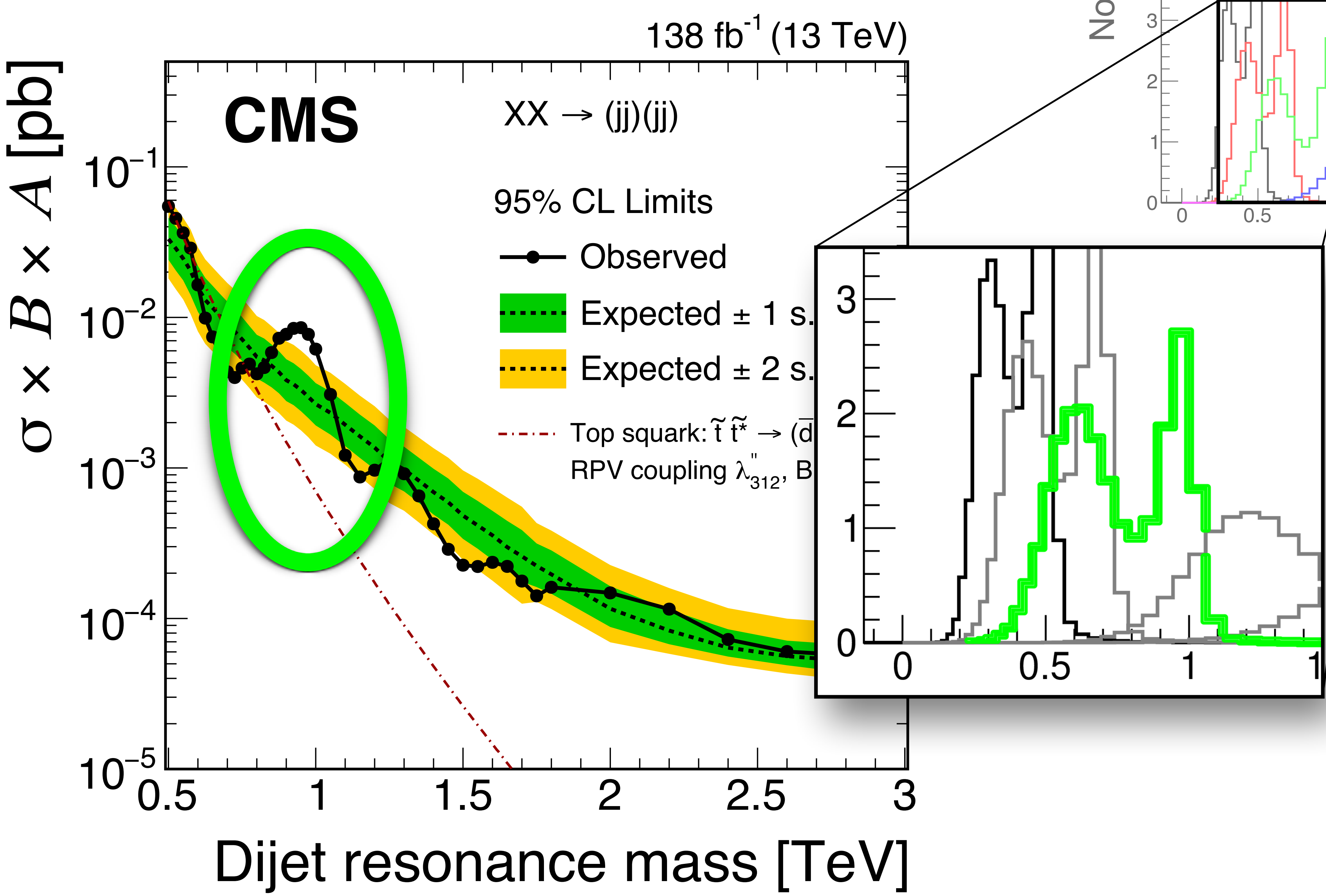
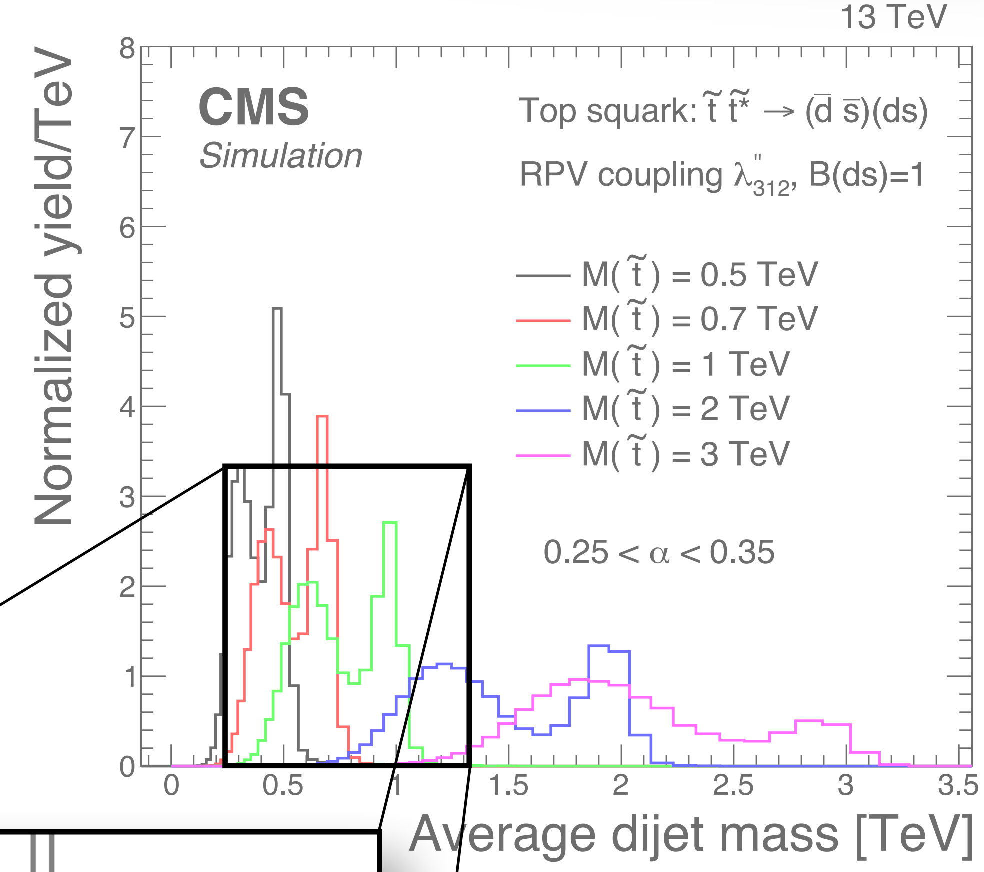
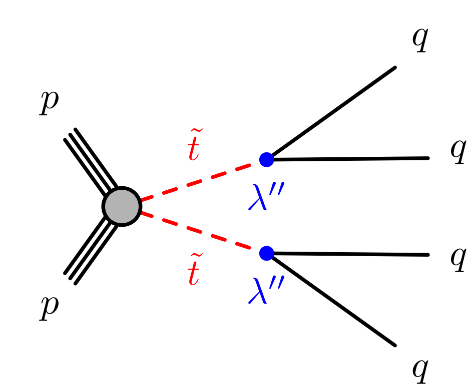
- **If CMS excess real, what could a sharper mass peak do? 3.6σ → ??**







arXiv:2206.09997

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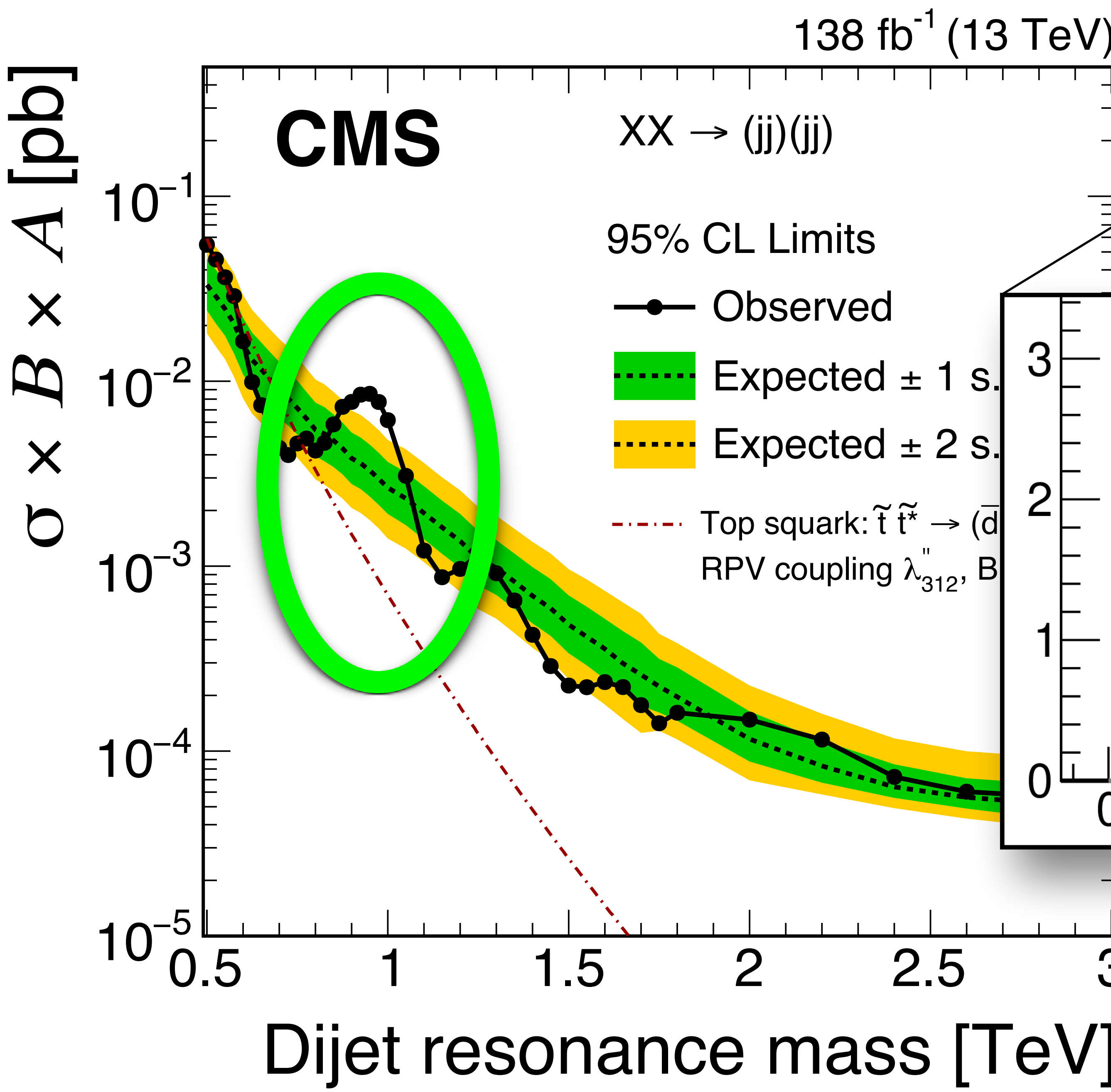
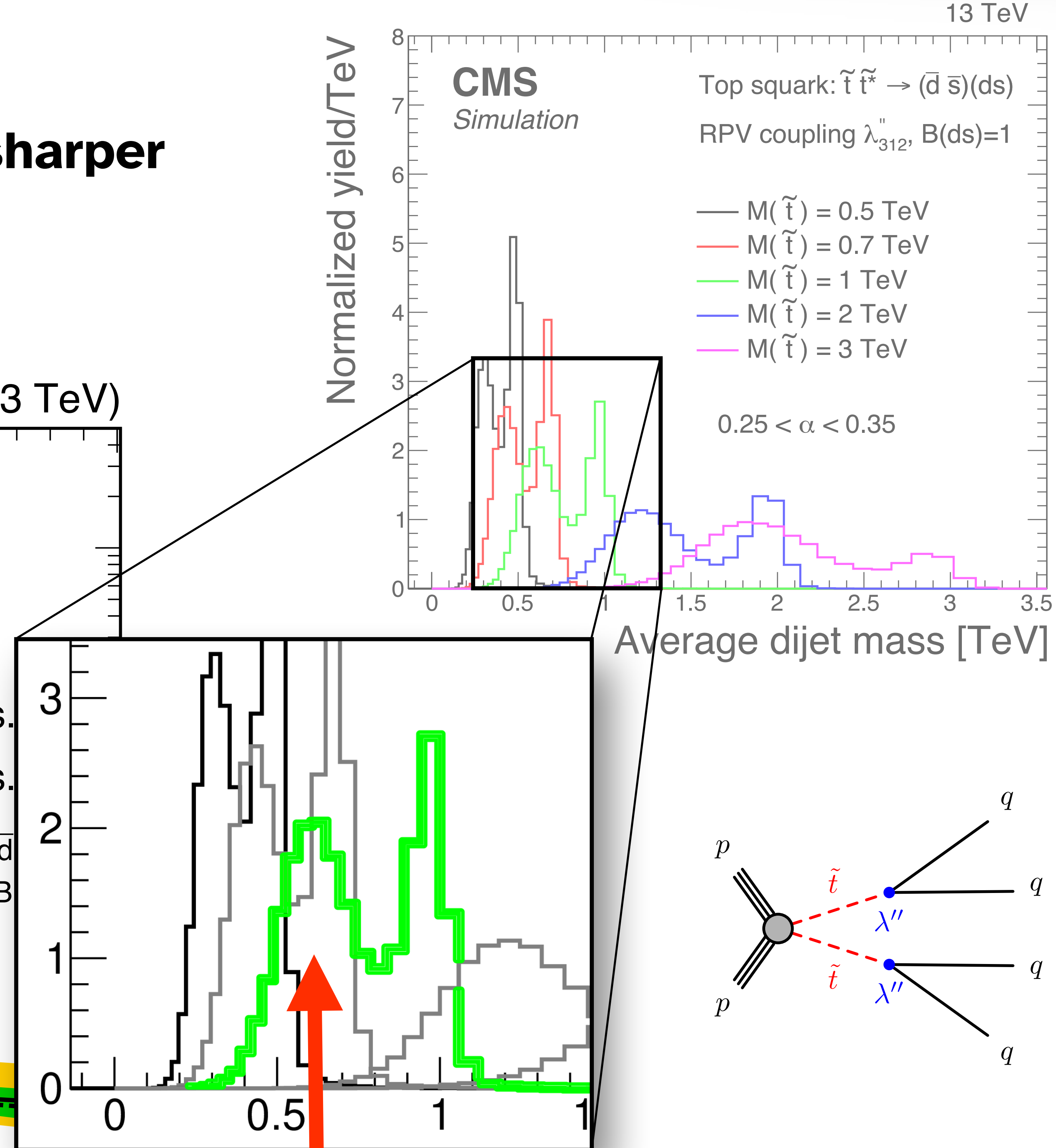
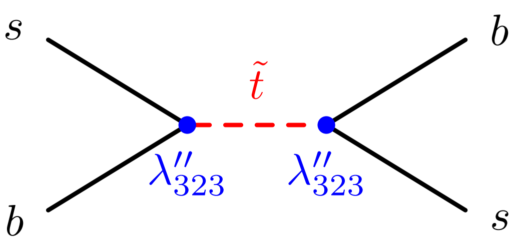
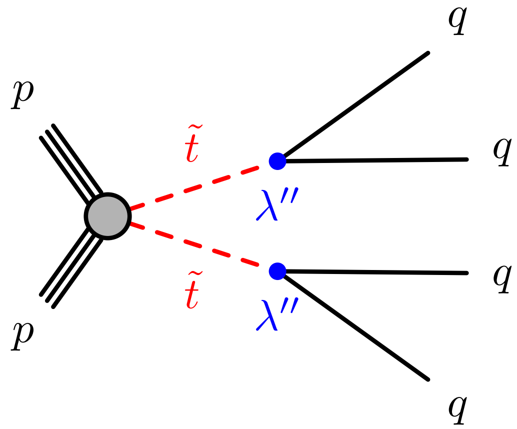


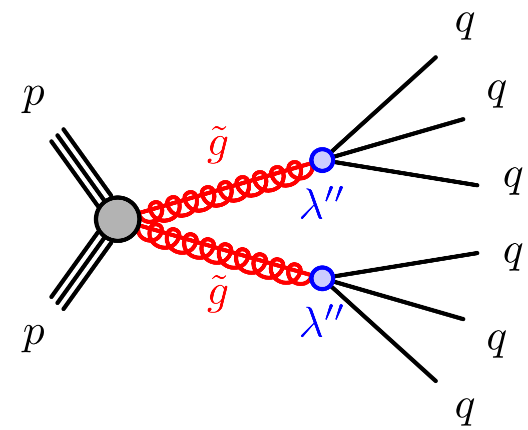


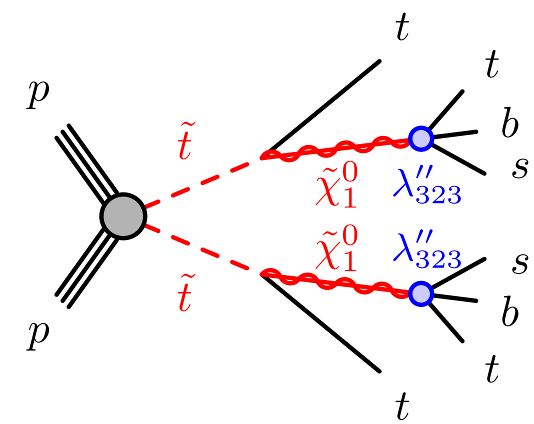
Combinatorial Background!

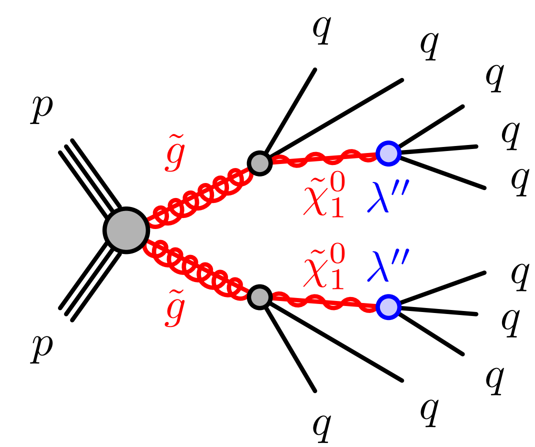
arXiv:2206.09997











2×1 2×2 2×3 2×4 2×5

Does this approach scale?

- Attack large dim feature spaces
- If we think in this way, **realize lots of room for new physics @<1 TeV**
- **Not using** ML to eke out a little more exclusion power

- Attack large dim feature spaces
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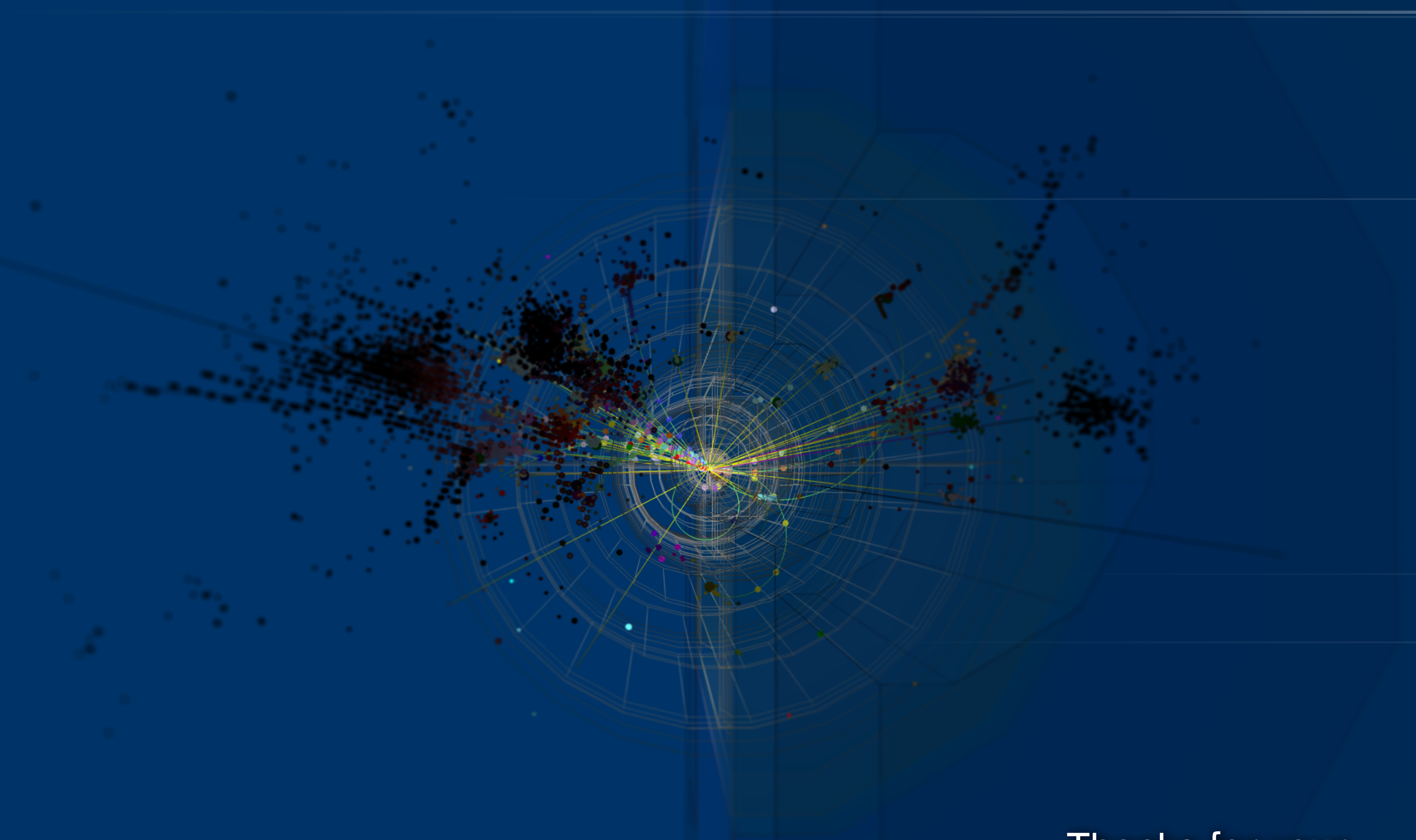
Trying to enable searches that are really (really) hard that might actually **DISCOVER** something.



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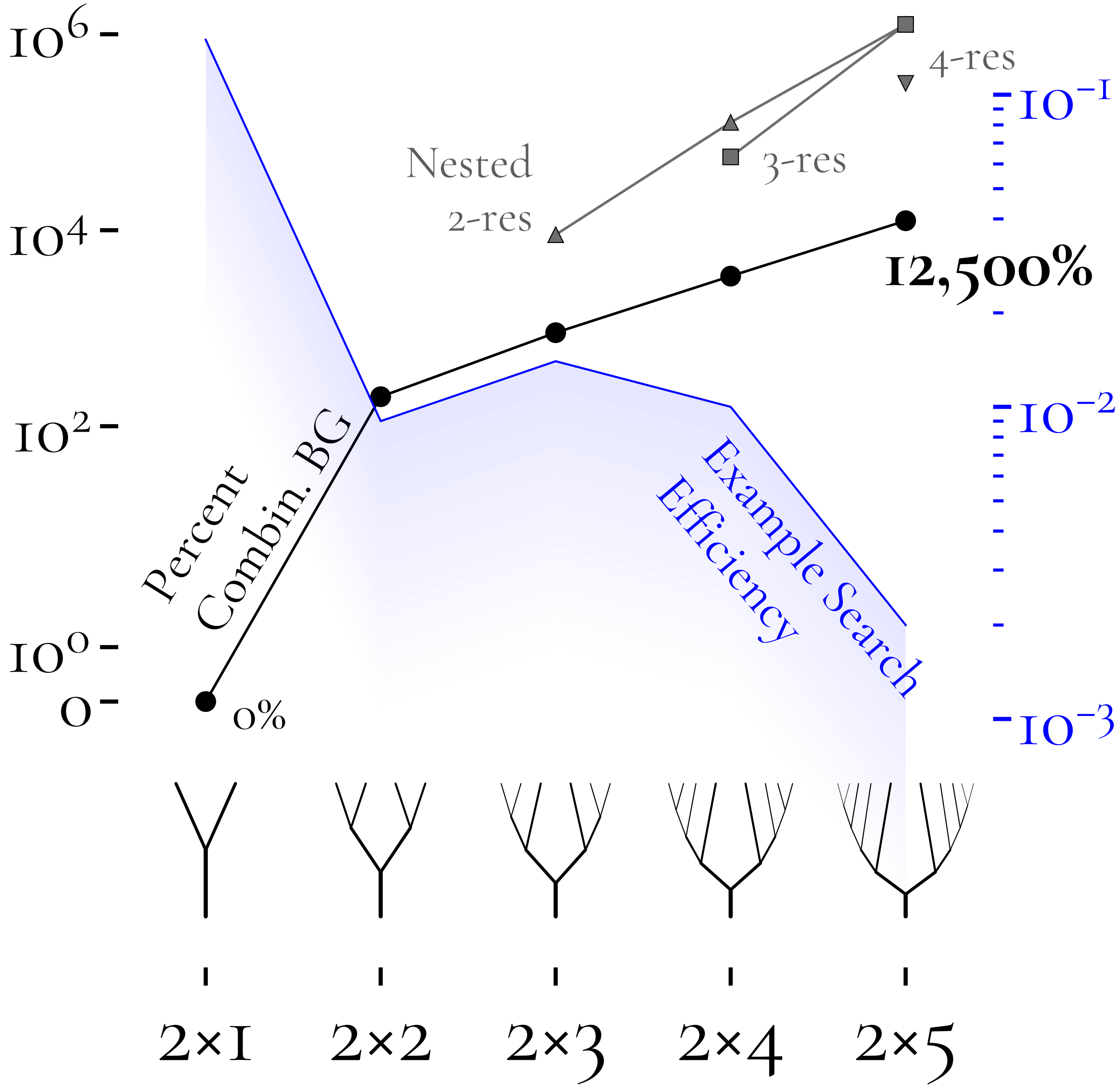
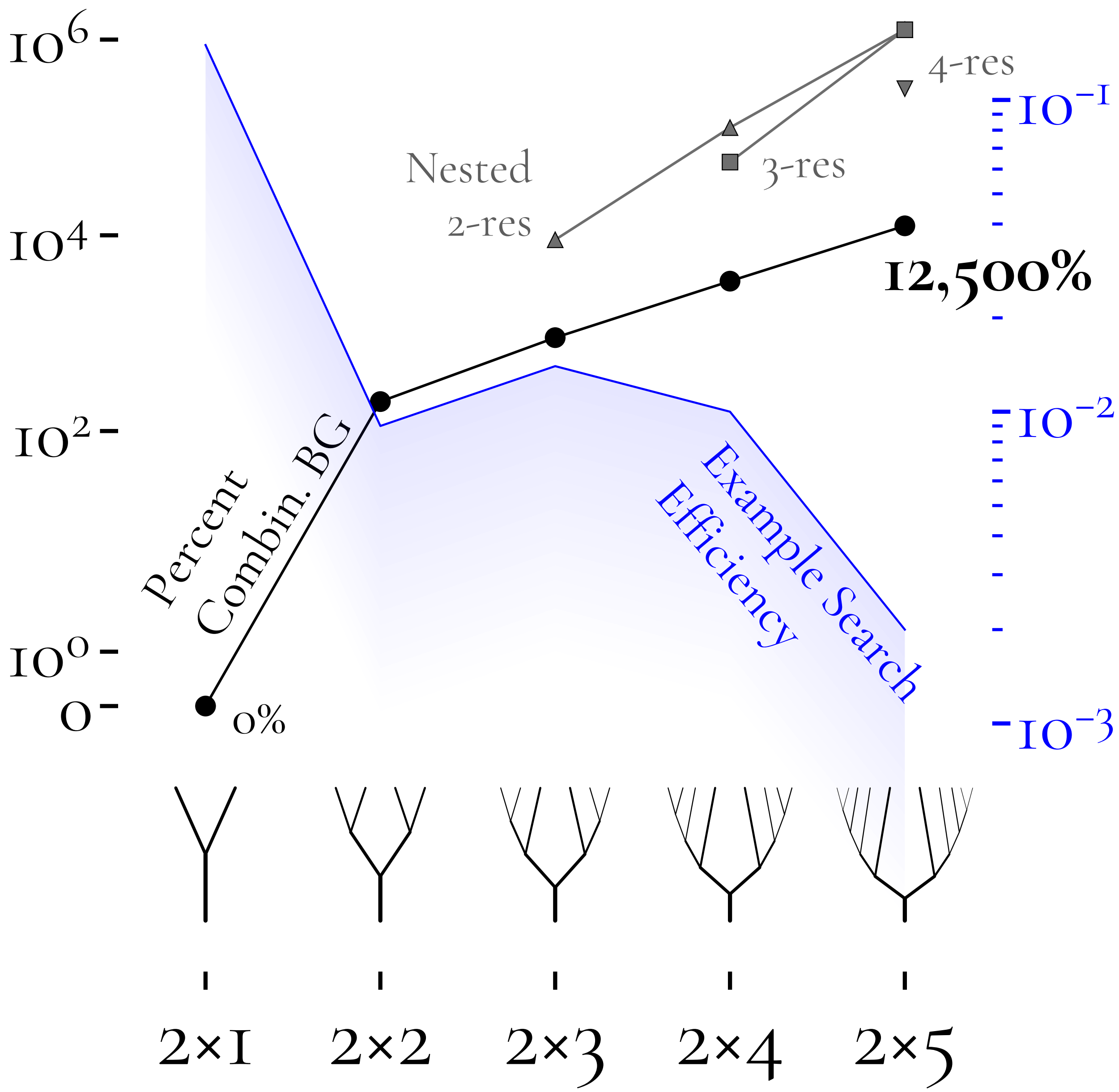
Supported by Department of Energy, Office of Science,
Grant Nos. DE-SC0007881, DE-SC0023321
and ERC Grant 787331

Thanks for your attention!

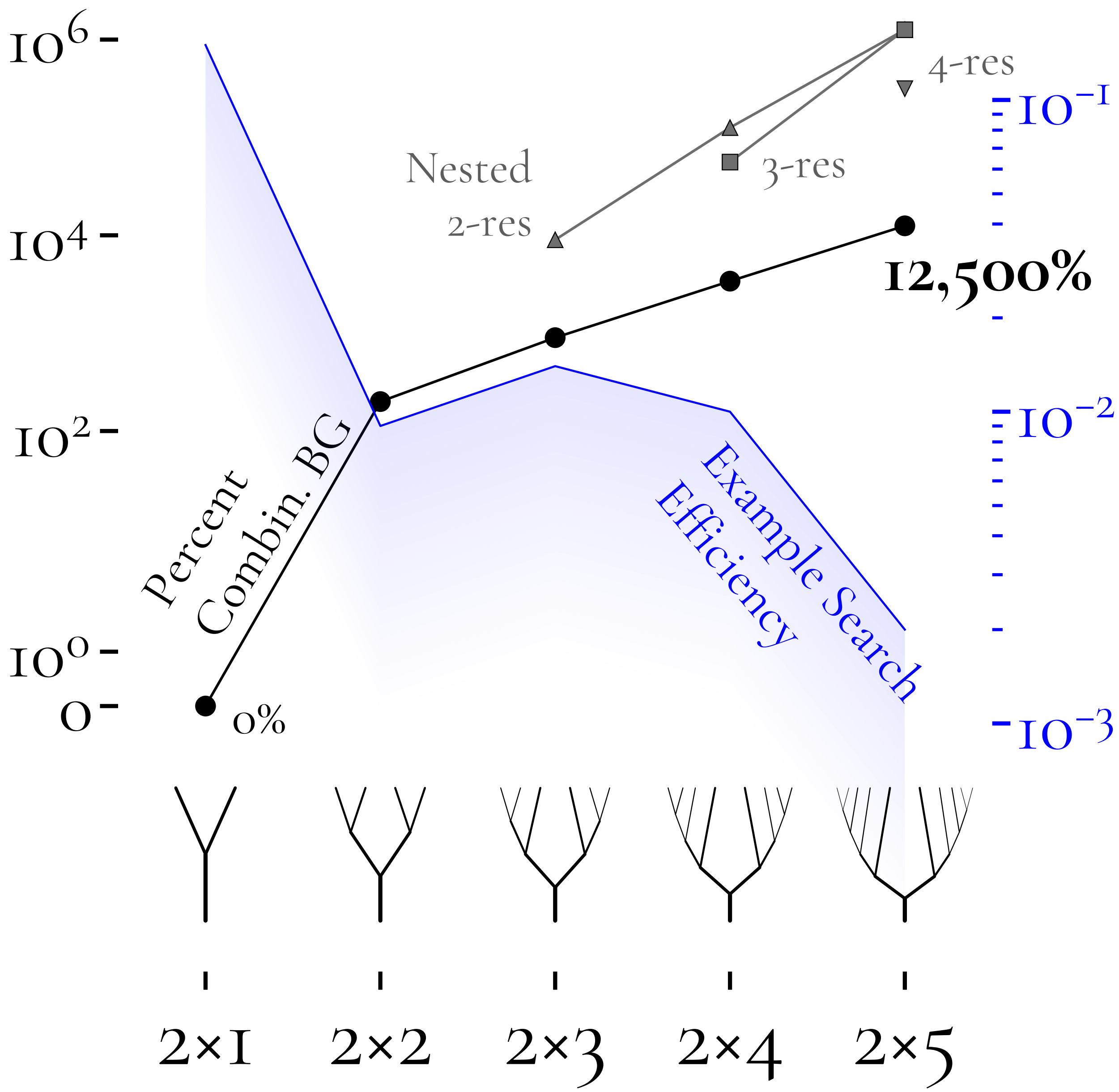


A Badea, W Fawcett, J Huth, TJ Khoo, R Poggi, LL — arXiv:2201.02205



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…

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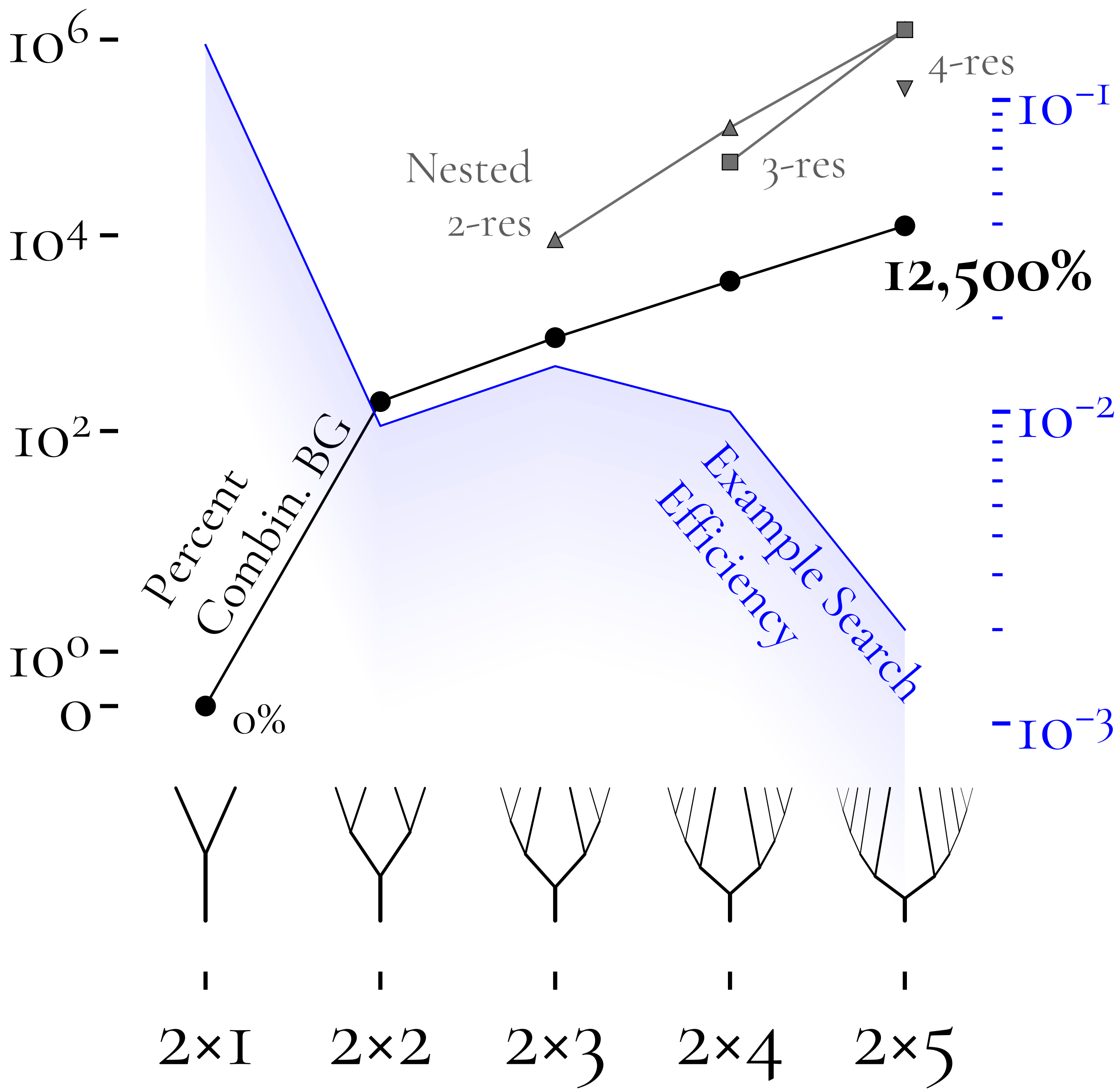

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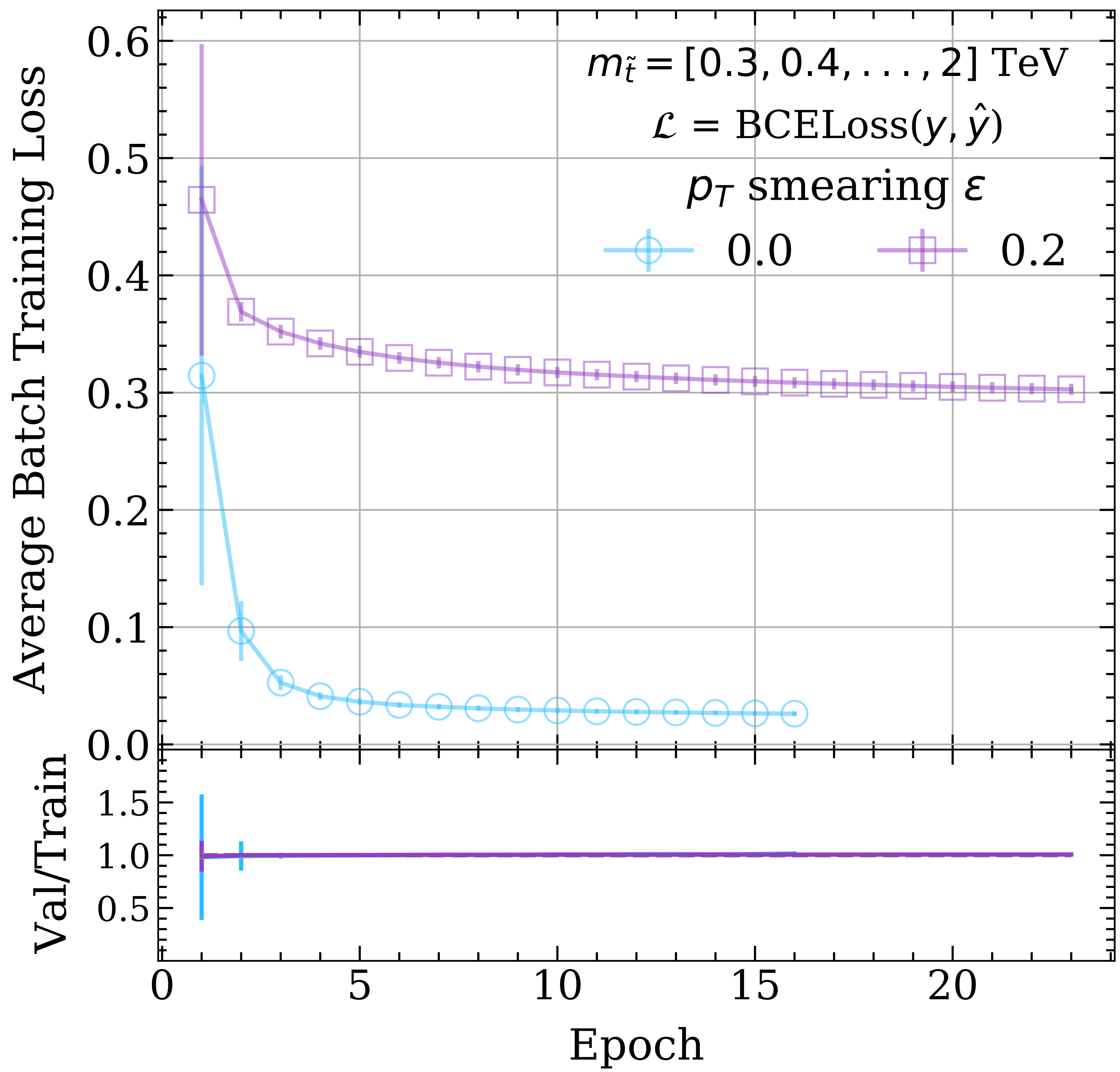
In fact: LHC limits are pretty bad out here

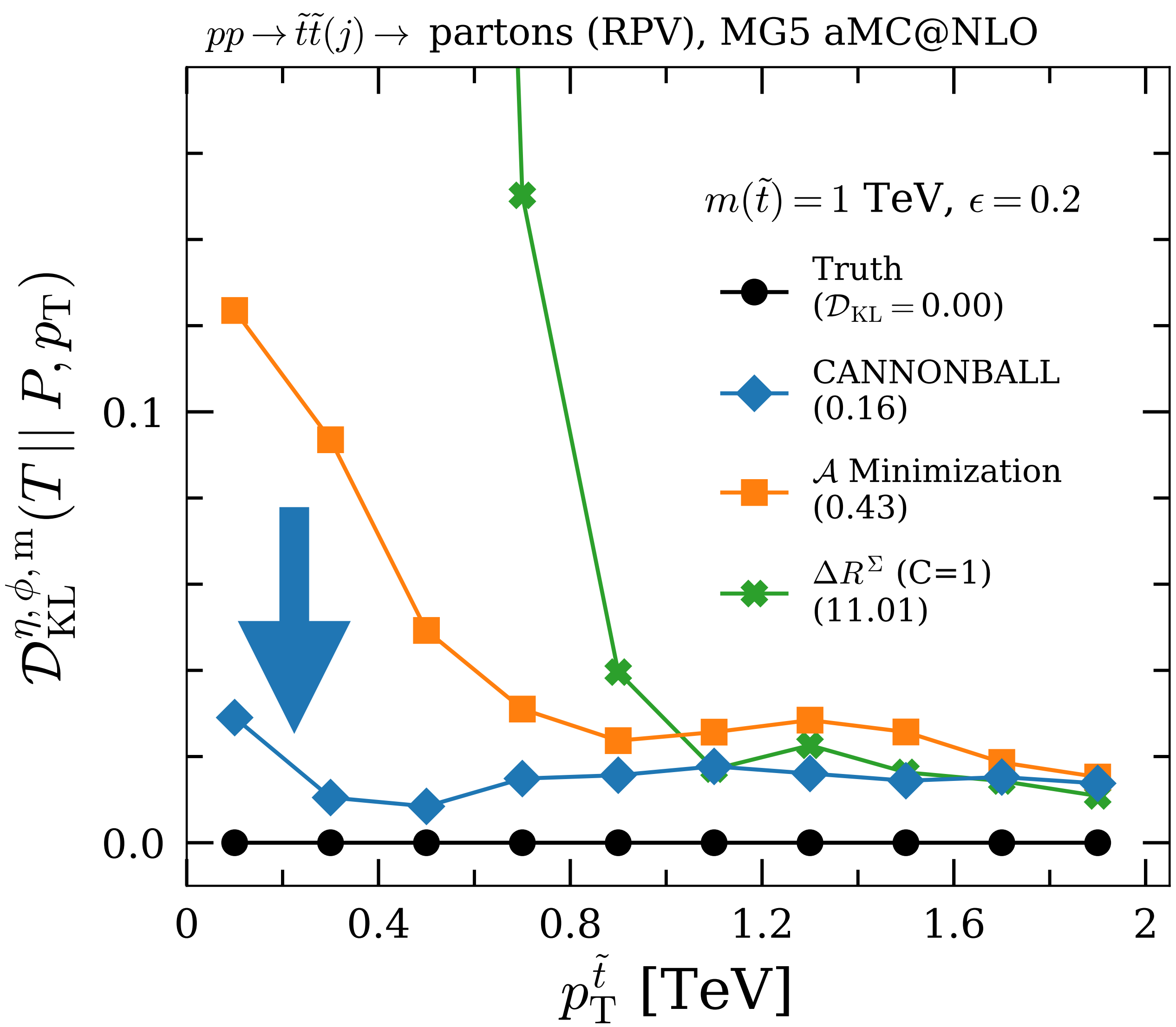
All still possible in RPV SUSY:
- 500 GeV stops
- 1 TeV gluinos
- 100 GeV Higgsinos

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

- 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)



- 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**

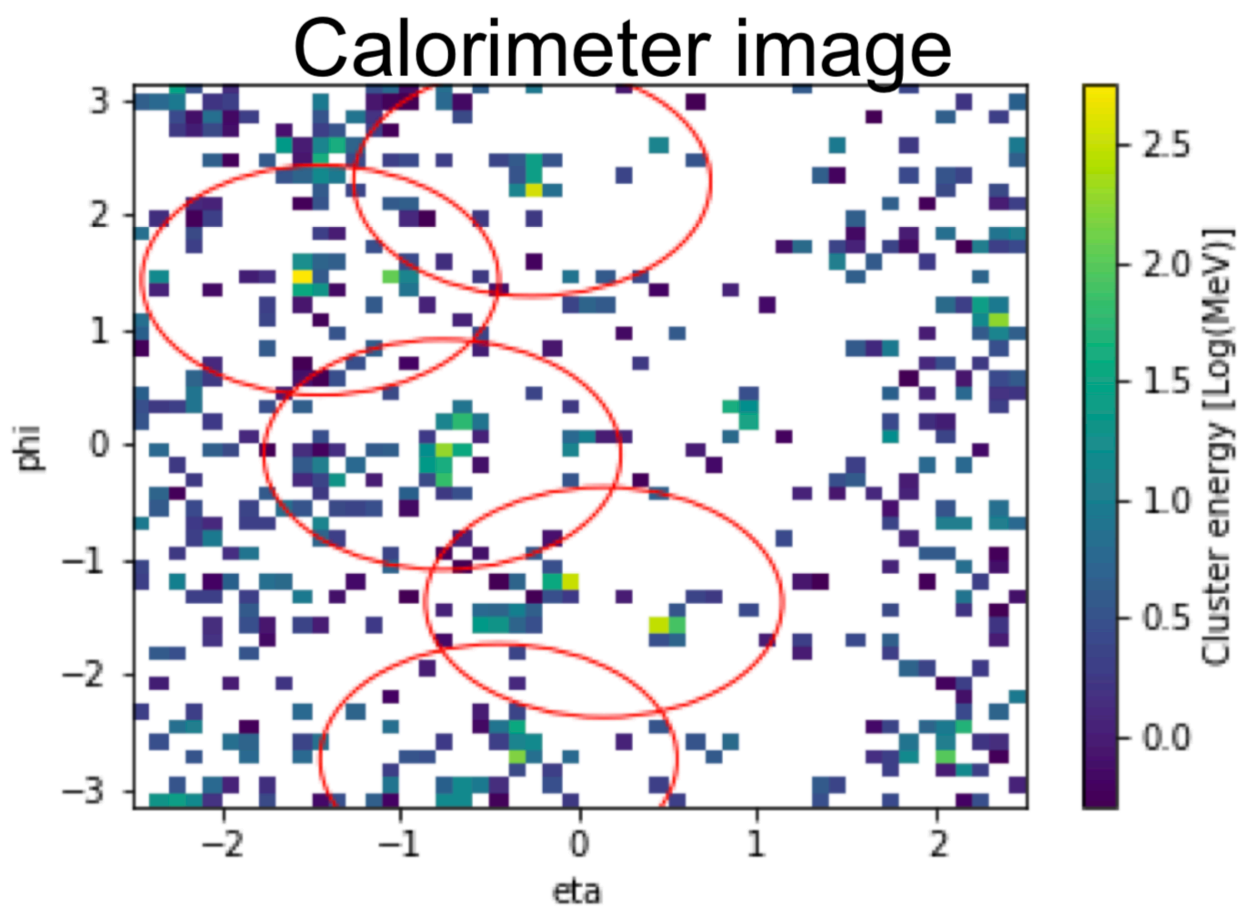


$$\mathcal{D}_{KL}(T||P) = \int T \log\left(\frac{T}{P}\right) dp^{\mu}$$
$$= \sum_{p_T \text{ bins}} \sum_{\eta,\phi,\text{m bins}} T \log\left(\frac{T}{P}\right)$$
$$= \sum_{p_T \text{ bins}} \mathcal{D}_{KL}^{\eta,\phi,\text{m}}(T||P, p_T)$$

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

- 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…

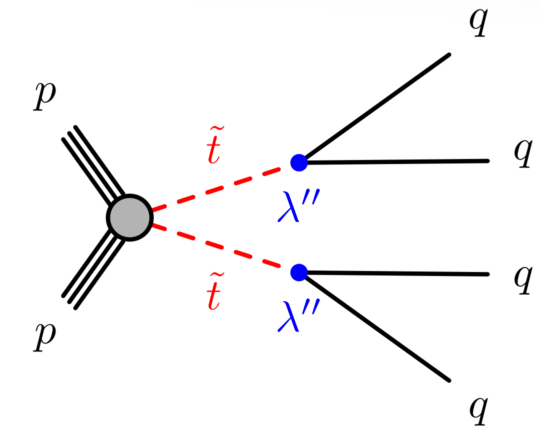


50x50 x 3 layers ~ 7.5k Dimensions!

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

Talk by SFarrell at SUSY Mini-workshop on ML

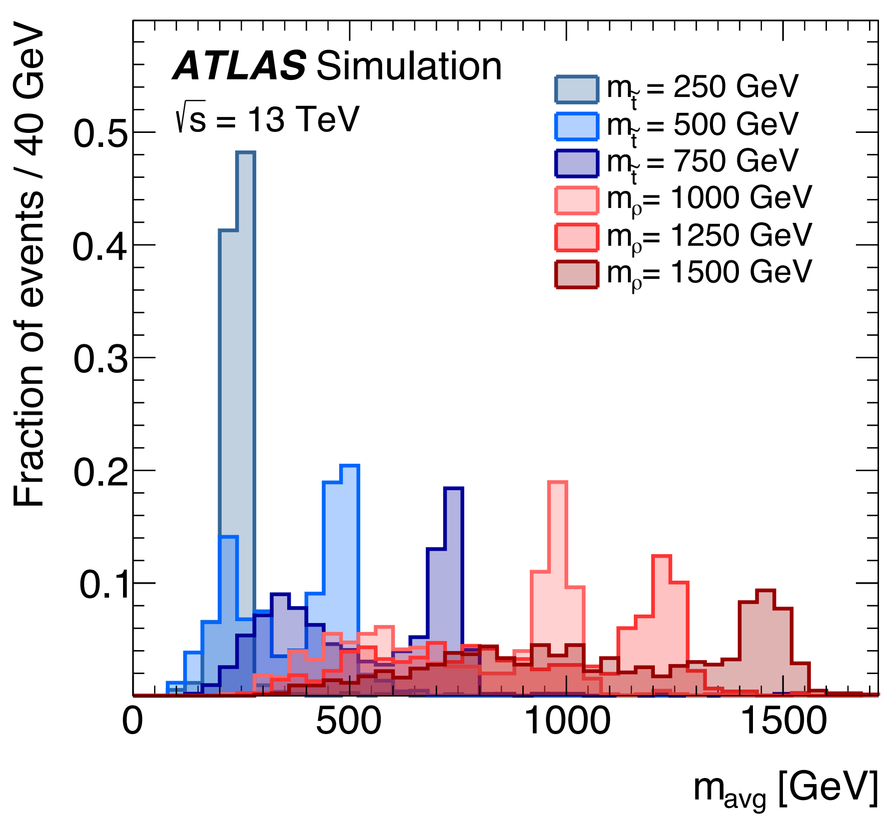
"CLASSICAL" 2X2

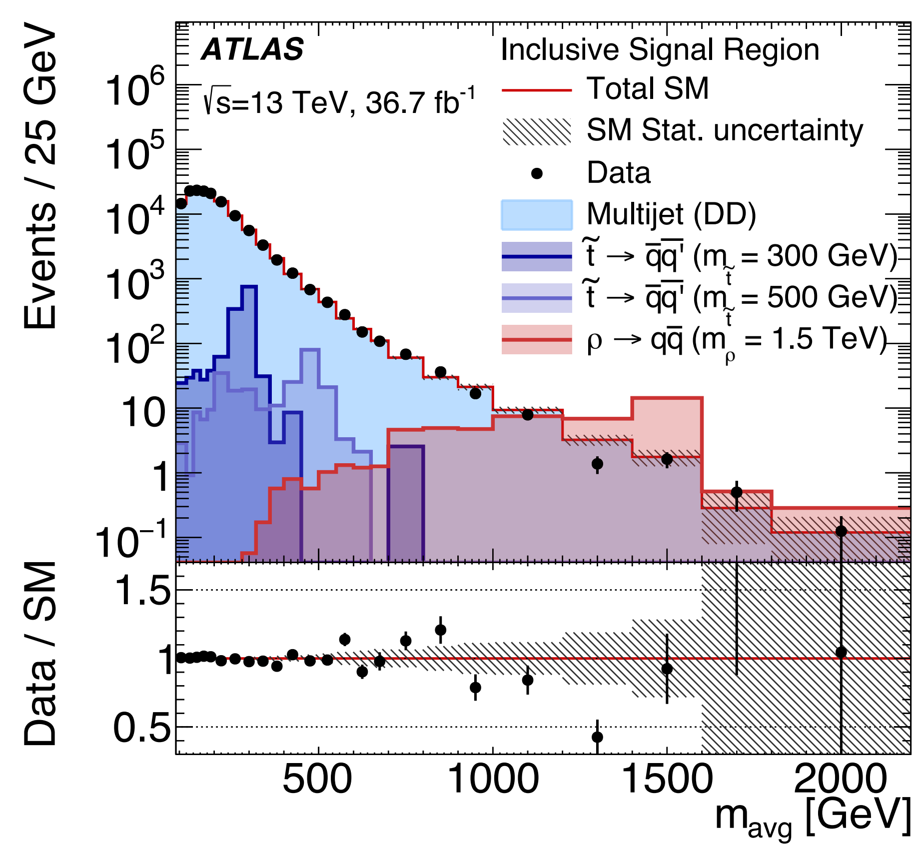


- Example of traditional analysis technique
- Use ΔR^{Σ} to try to get peaking mass
- Do a bump hunt in this mass

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

ΔR^{Σ} MINIMIZATION





arXiv:1710.07171

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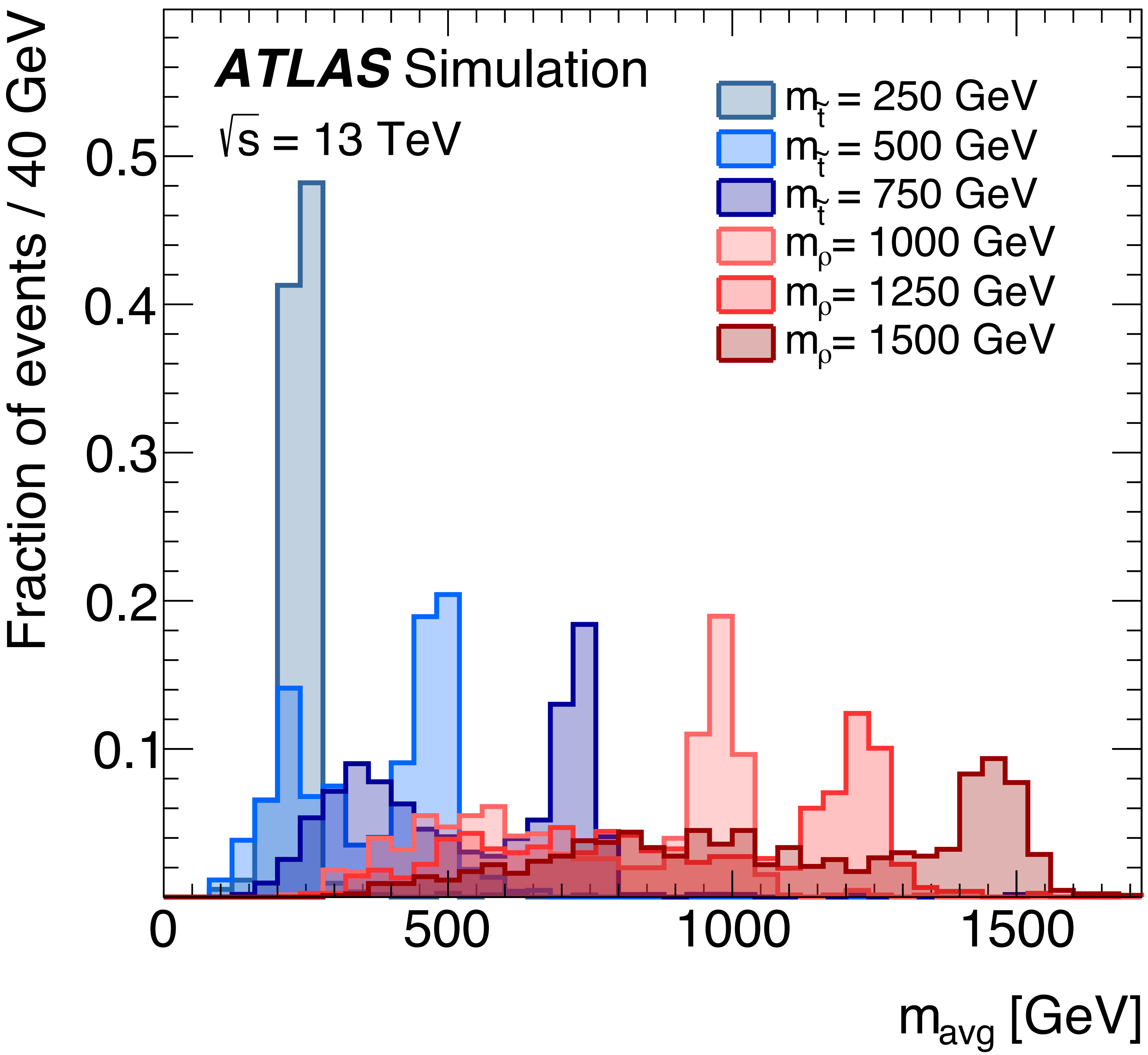
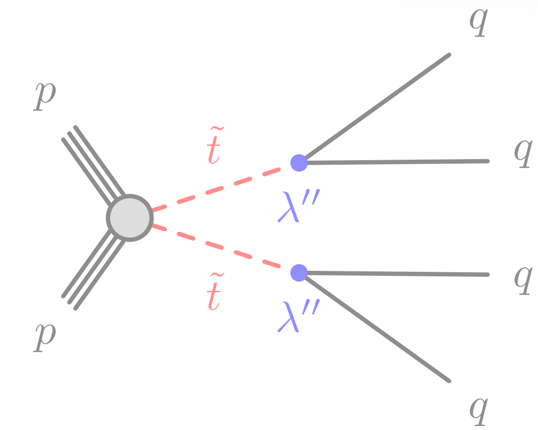
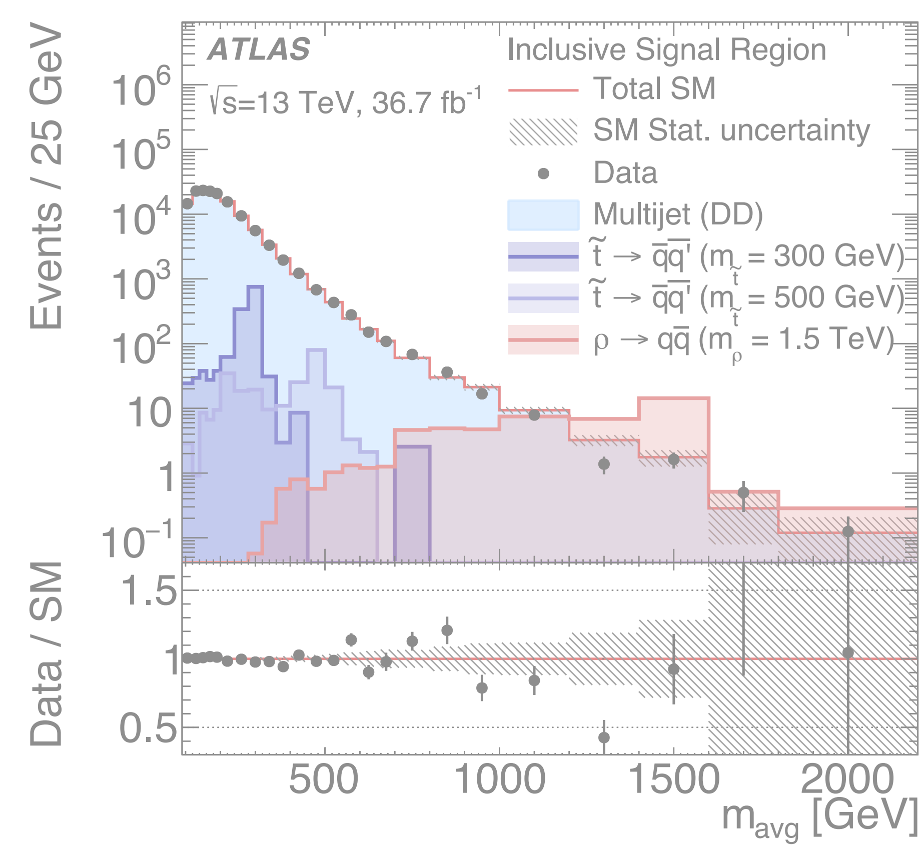




Compare to falling BG



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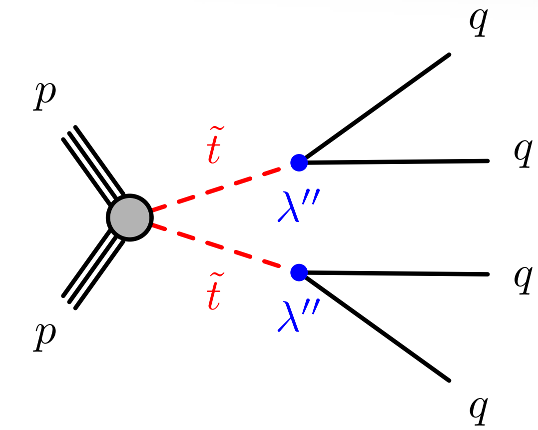
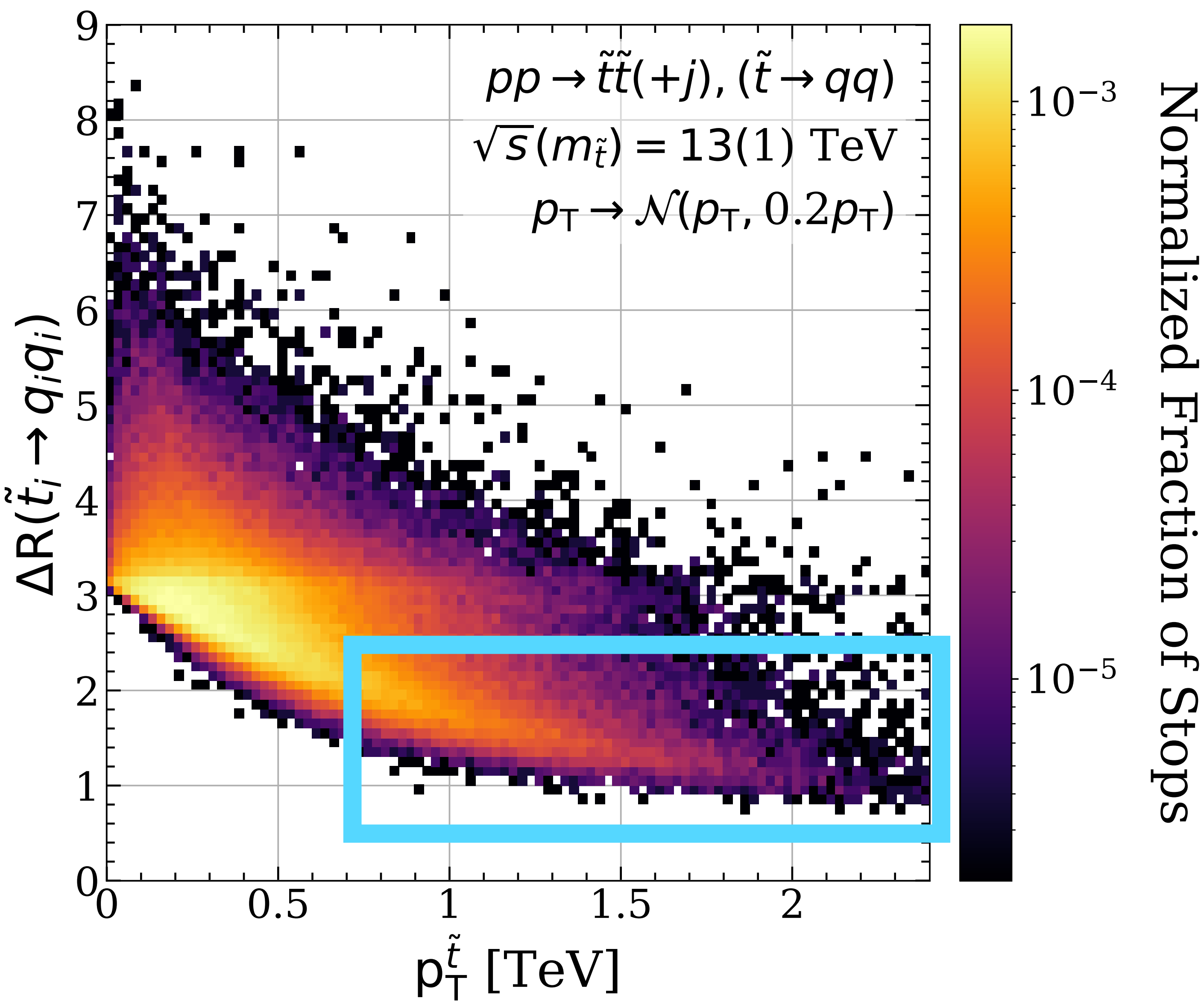


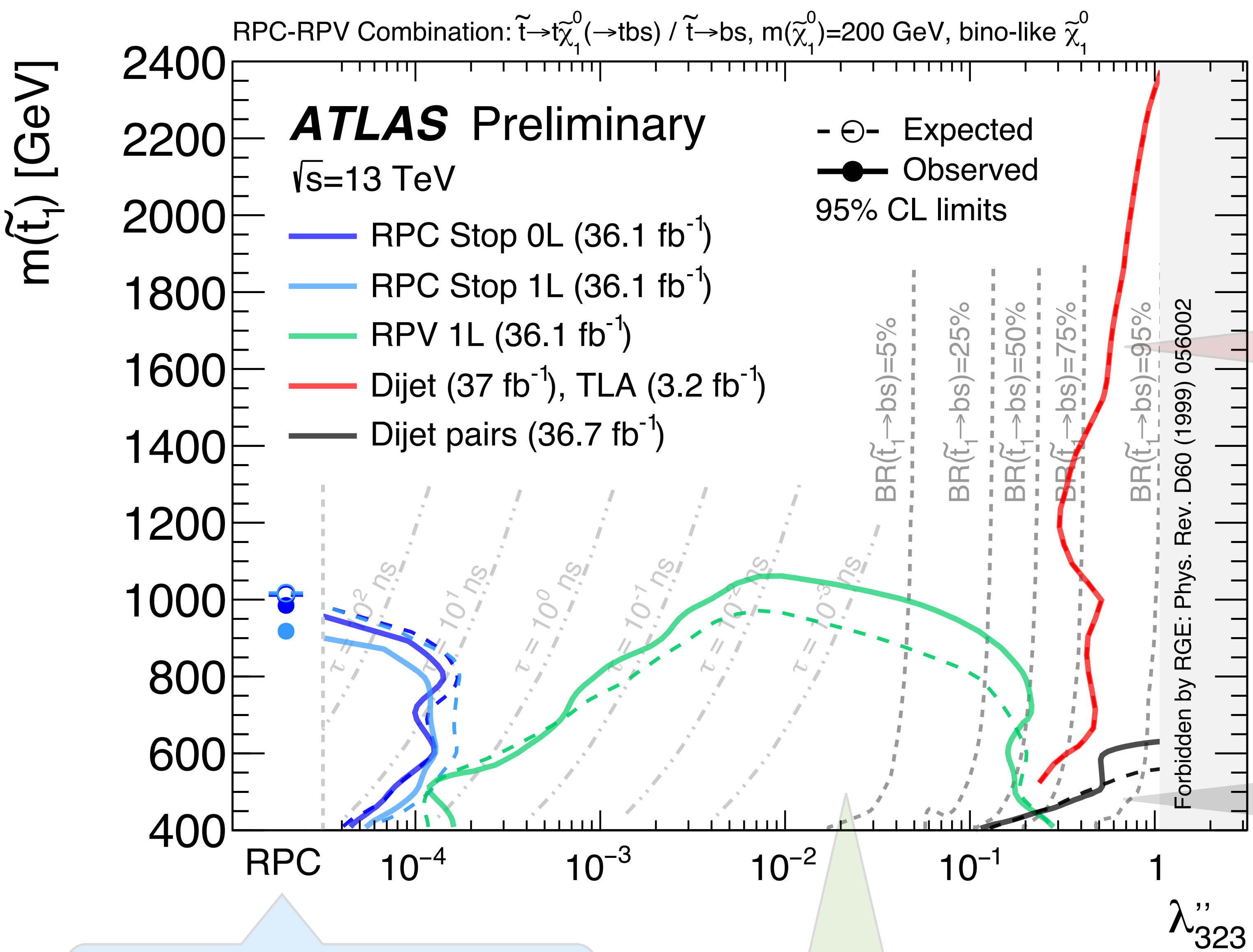
- But in order to get small ΔR^{Σ} values, stops need to be **highly boosted**
- **Low signal acceptance!**
  - Throwing away a lot of the signal…



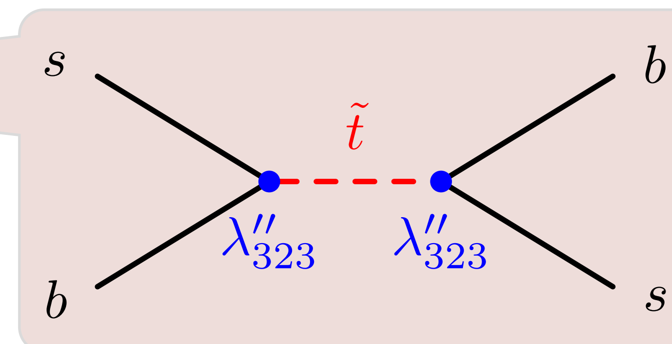
- **Can we do better?**
- Can we scale this to **larger multiplicities?**

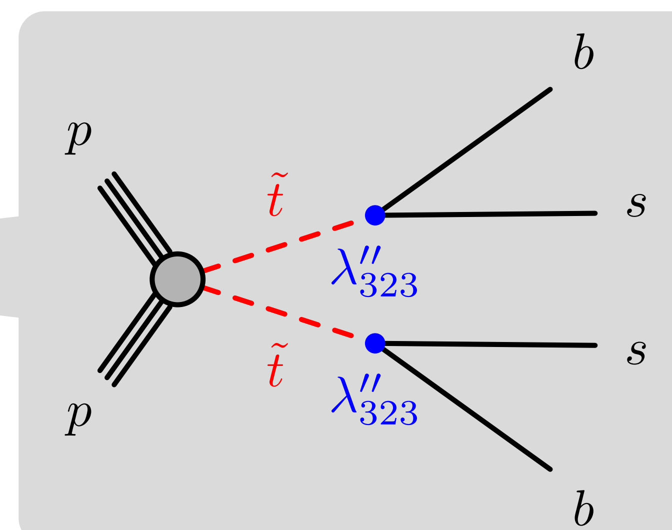
arXiv:1710.07171

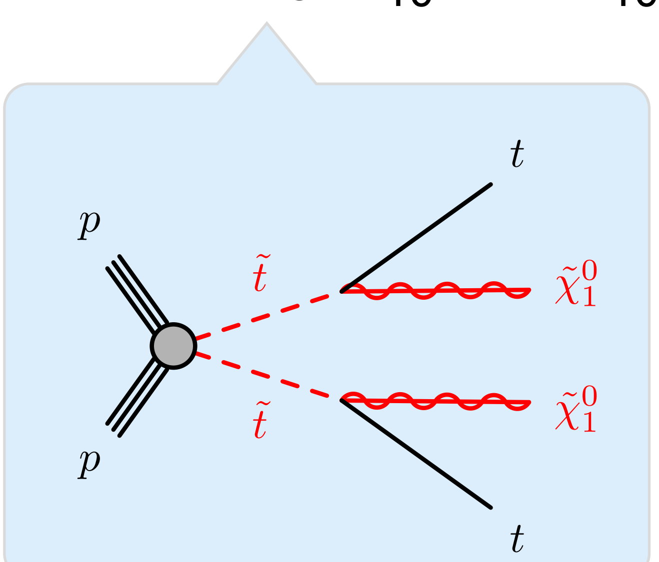
SCANNING RPV STRENGTH

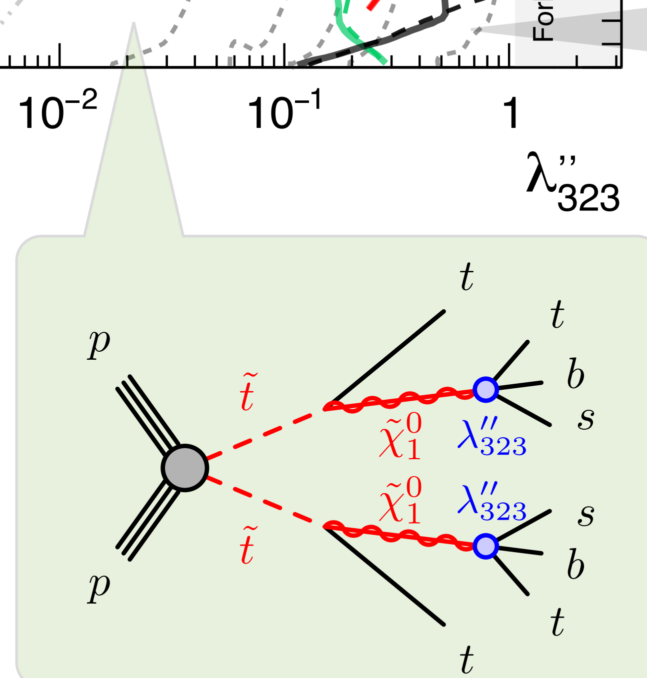


Reinterpret many searches for varying lifetime / BRs





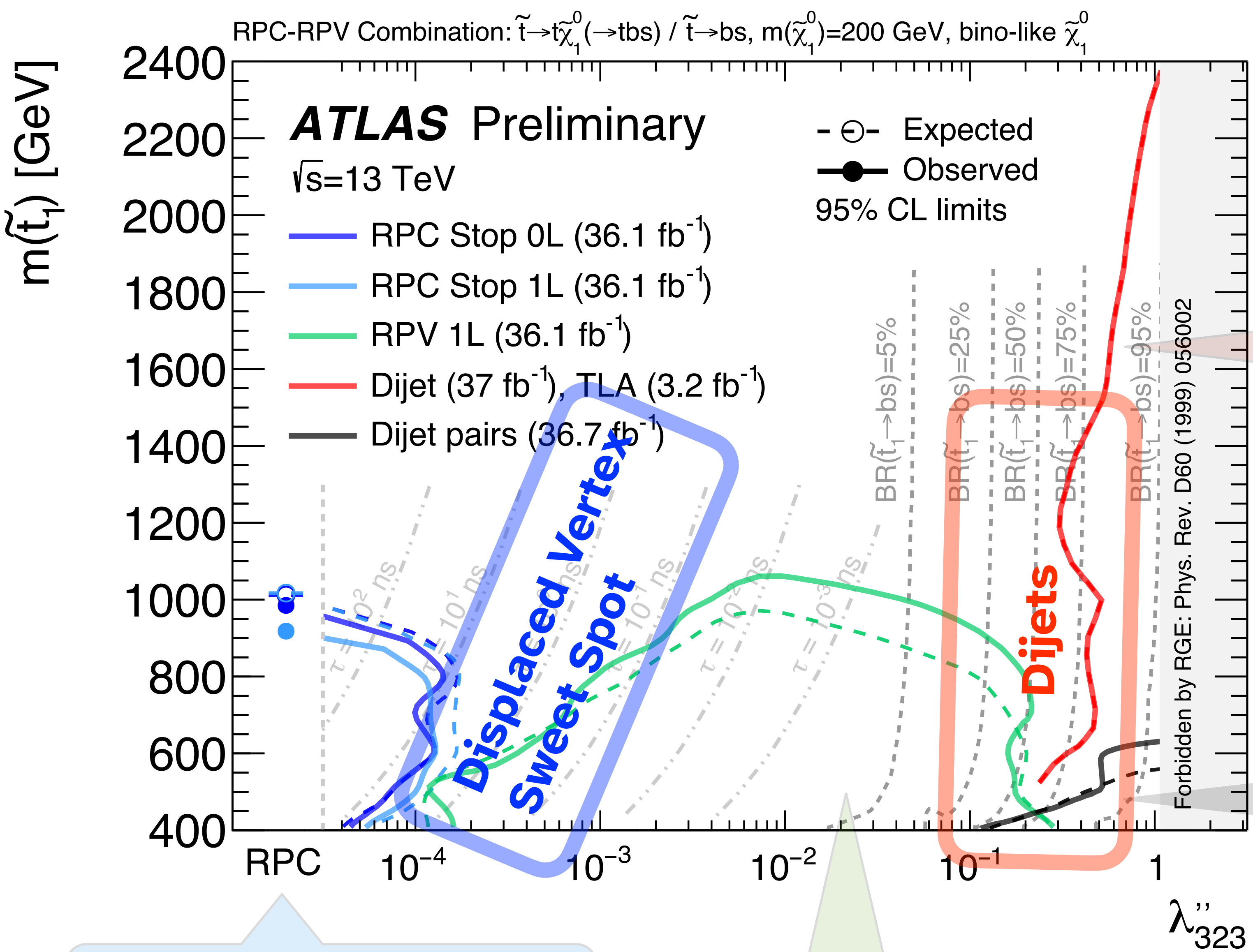




Properly accounting for:
Interplay between RPV and gauge couplings
Even resonant sparticle production

ATLAS-CONF-2018-003

Scanning RPV Strength



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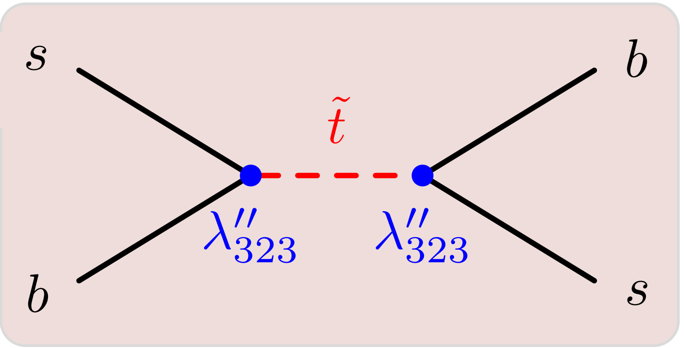

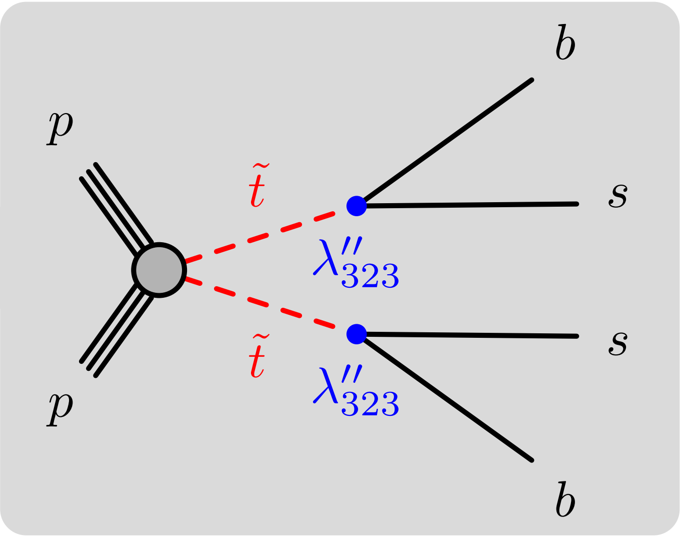

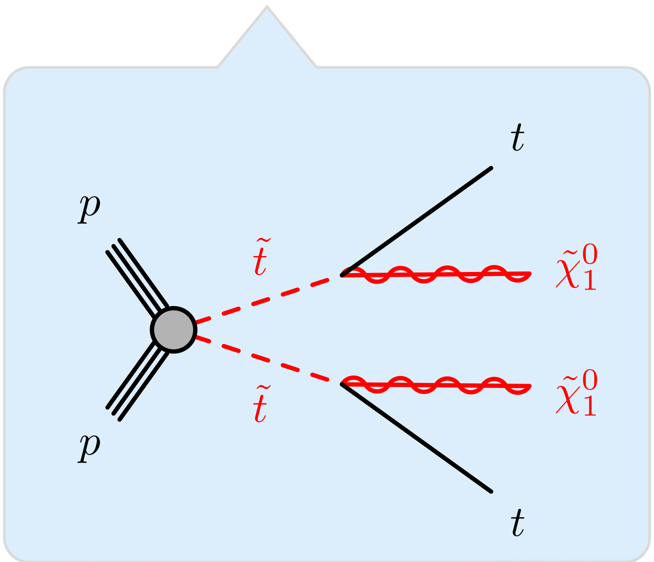

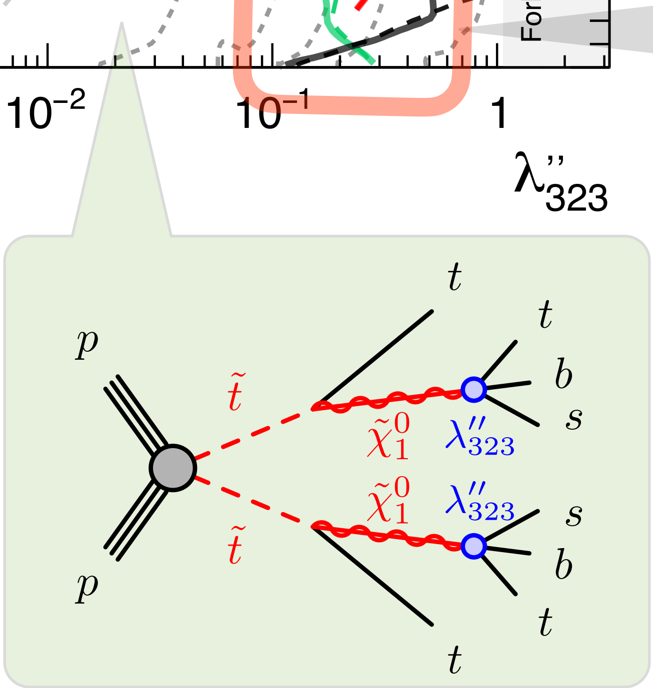

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ATLAS-CONF-2018-003

R-PARITY VIOLATION (RPV)

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Baryon Number

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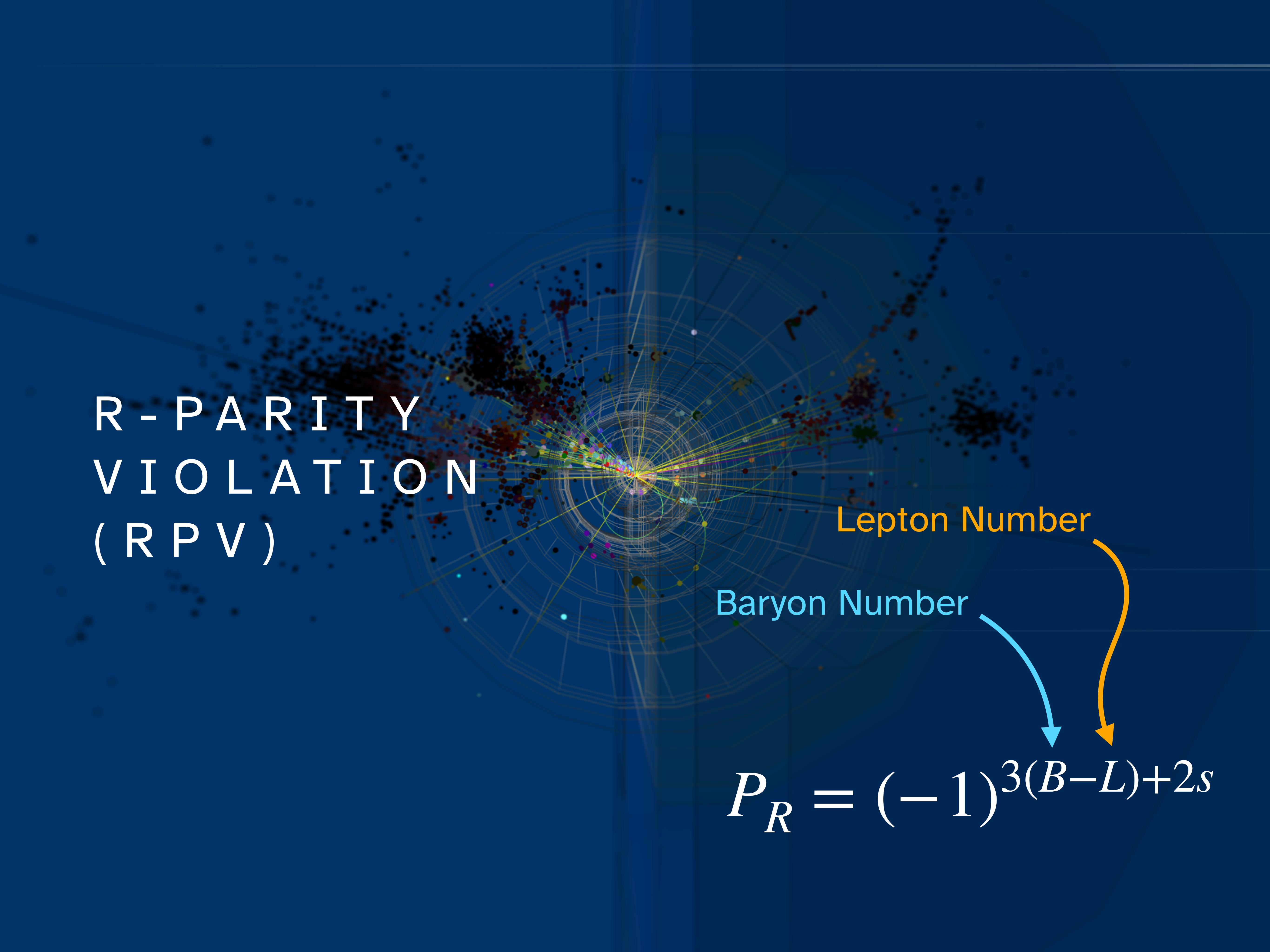
R-PARITY
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R-PARITY VIOLATION (RPV)

Lepton Number

Baryon Number

Spin

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- R-Parity: SUSY-partner-ness
  - +1 SM, -1 SUSY partner

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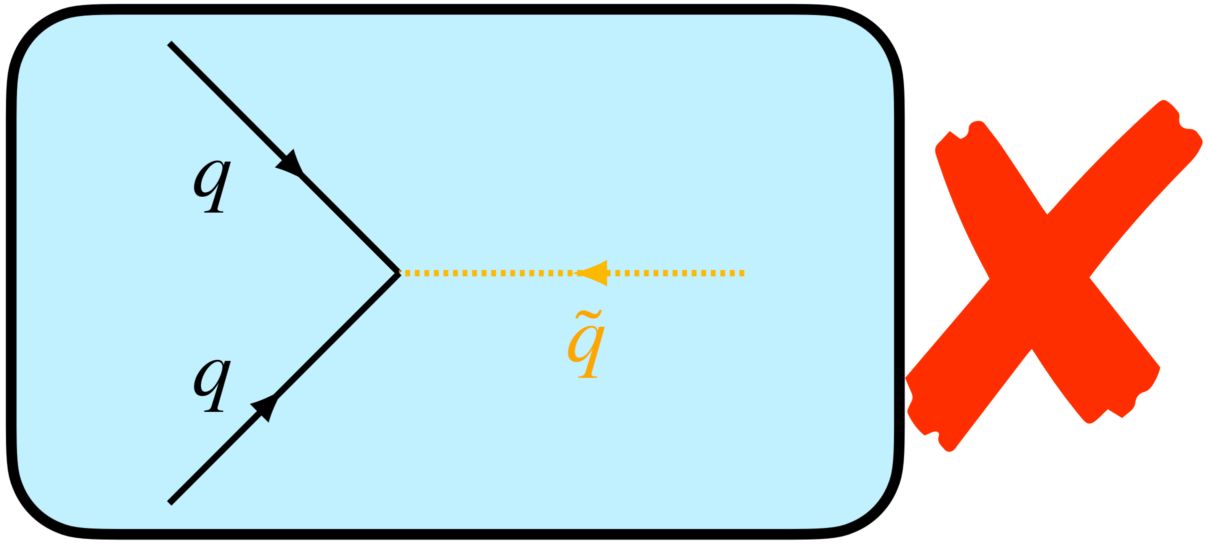
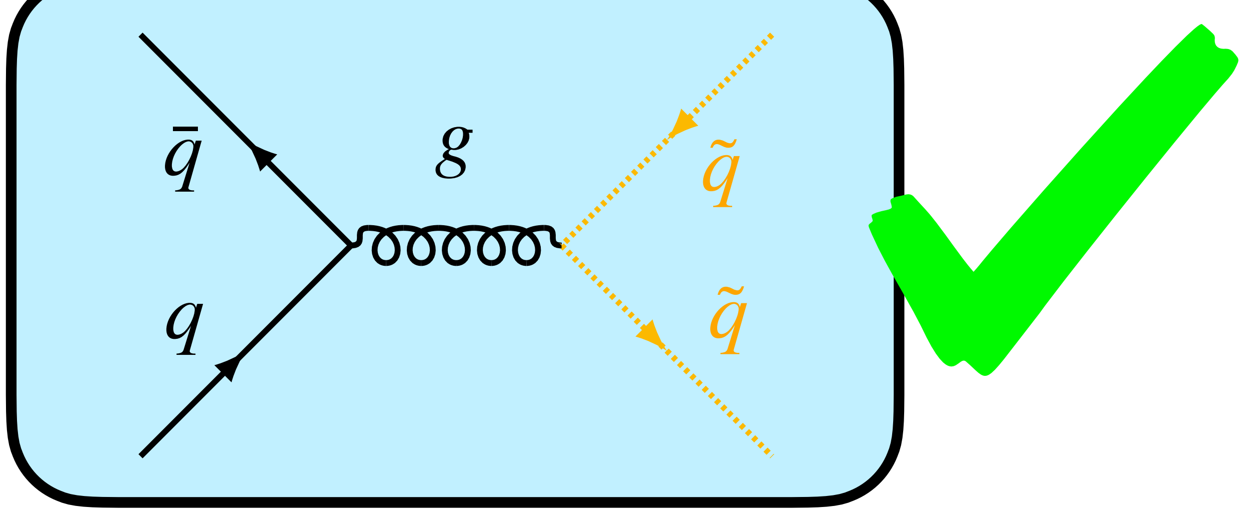
    - Sparticle **pair** production at colliders
    - Lightest sparticle (LSP) must be **stable** (and could be DM)





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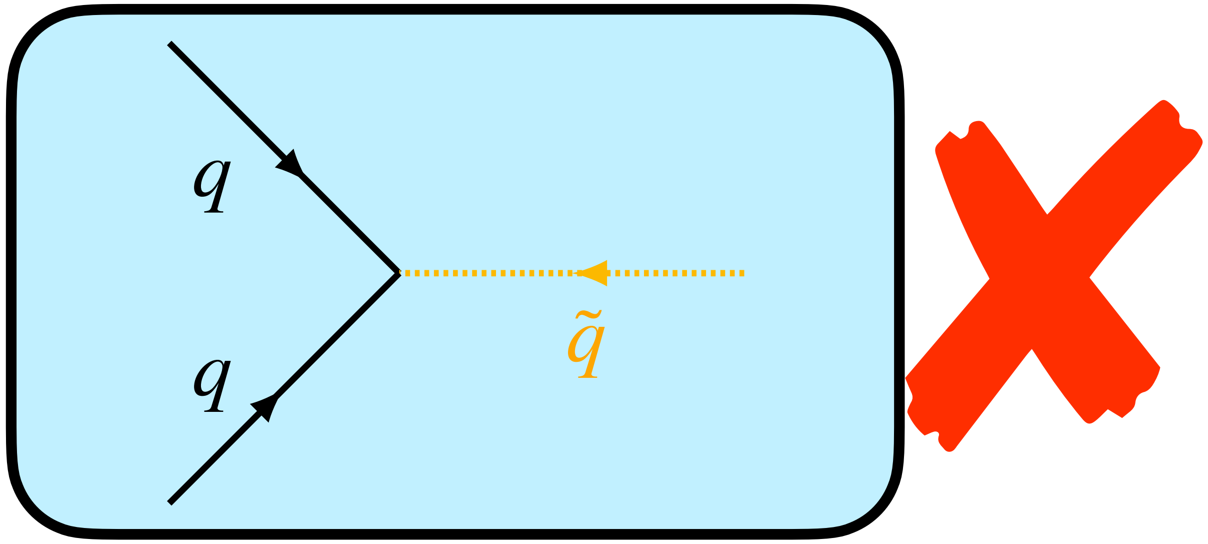

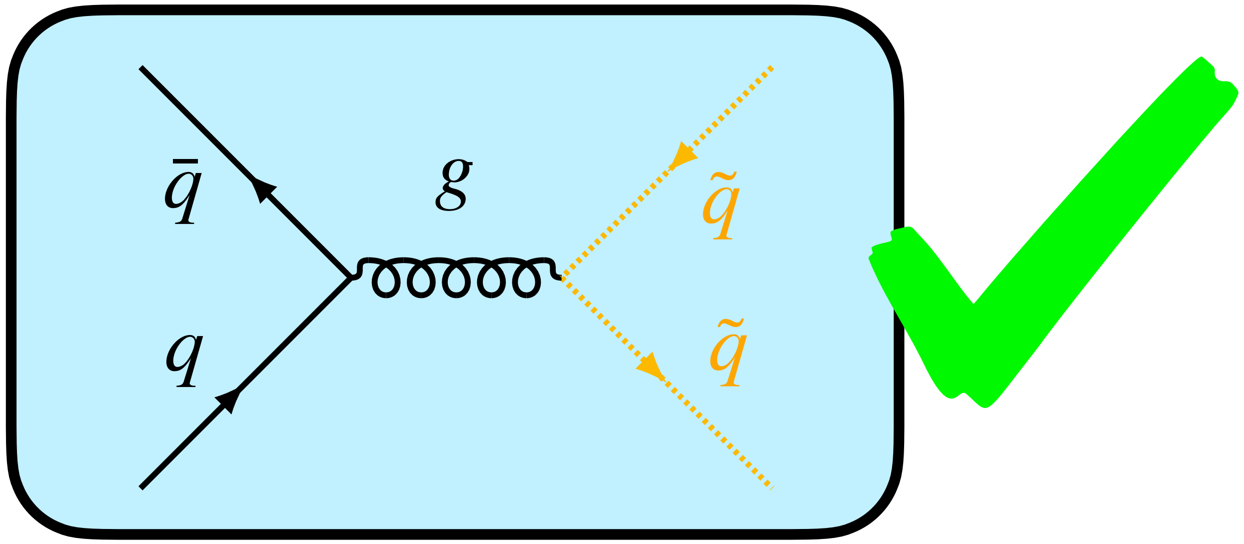

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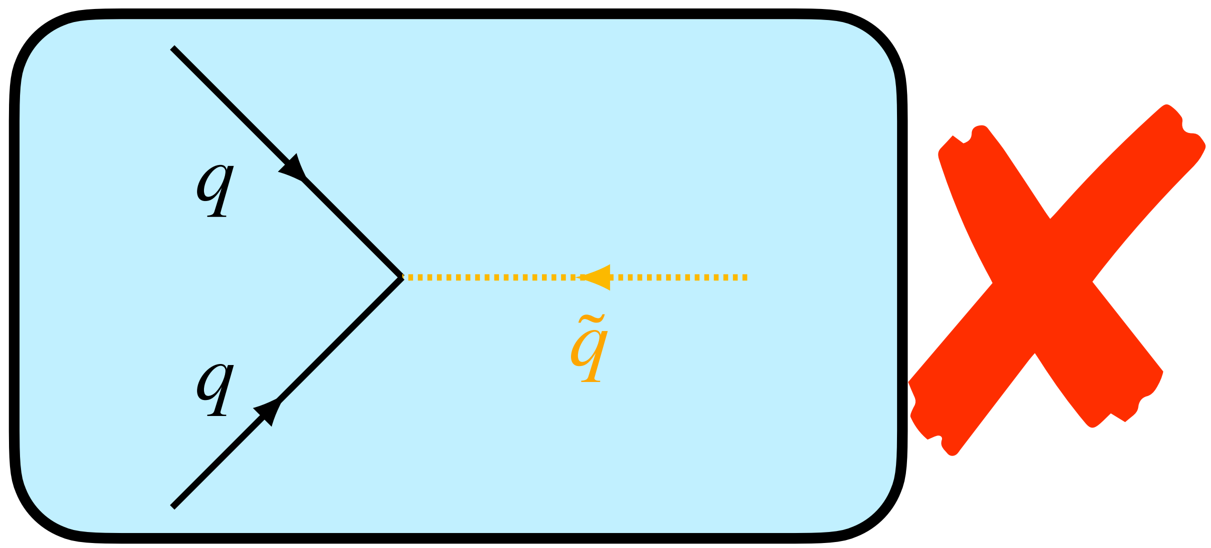
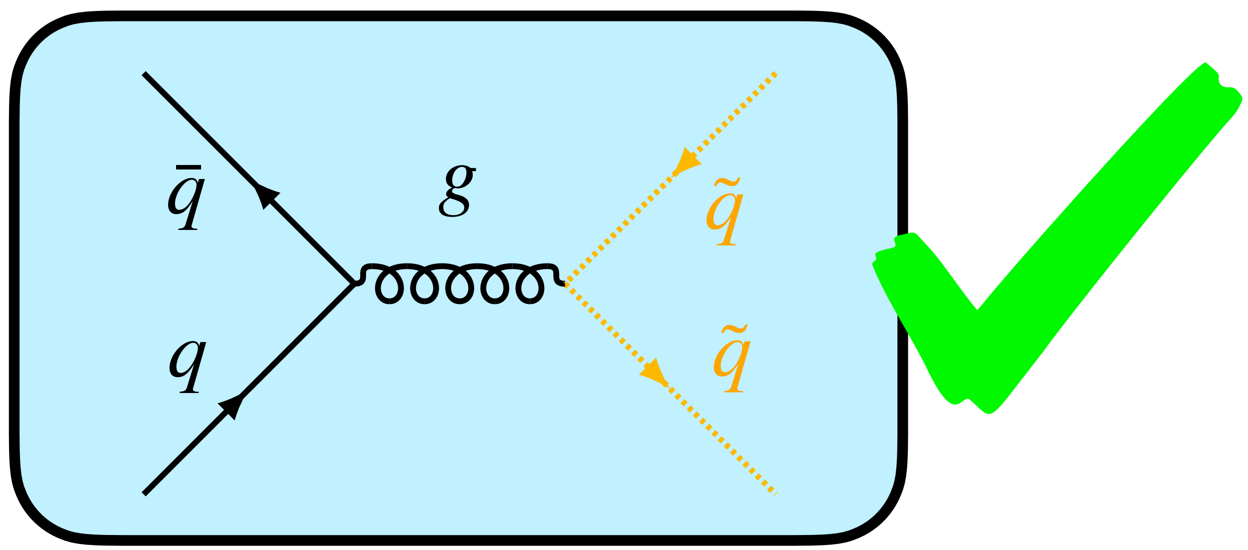
- The vast majority of SUSY searches assume this is conserved

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





But…

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2. **Write a lagrangian w/ all gauge invariant terms**
3. **Solve 👏 so 👏 many 👏 SM 👏 problems**

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

Why Conserve R-Parity?

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    - *Seems more contrived to manually forbid couplings*

R-Parity Violating SUSY

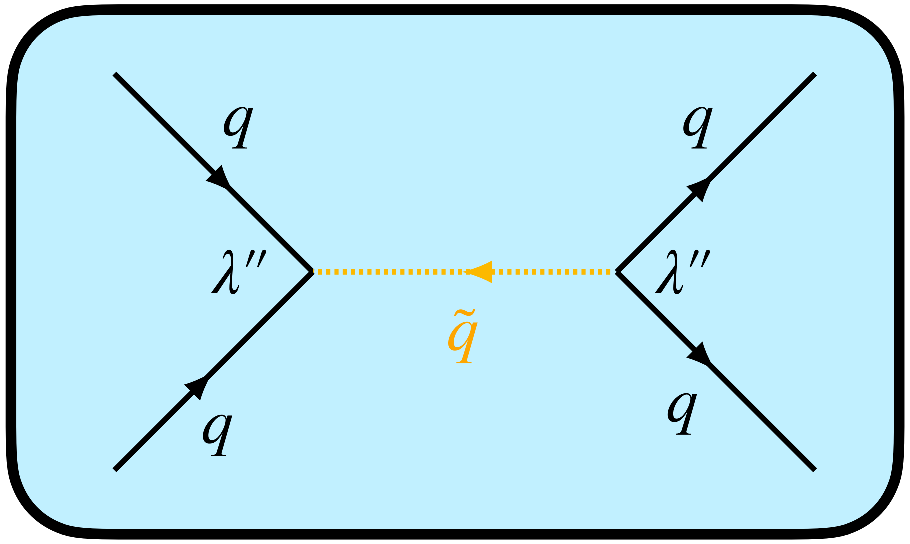
$$W_{RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \frac{1}{2}\lambda''_{ijk} U_i D_j D_k$$

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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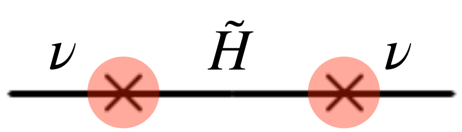
TREE LEVEL NEUTRINO MASSES+MIXING



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L Violating

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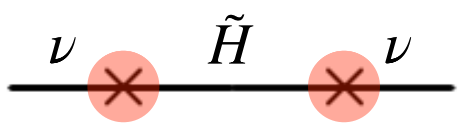
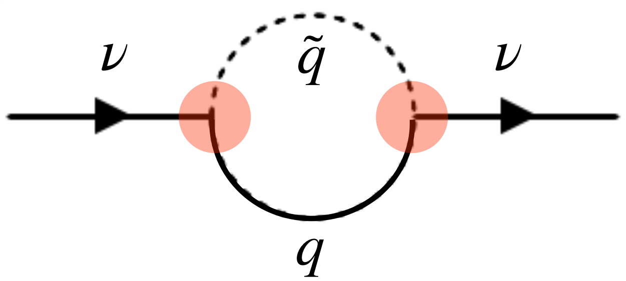
TREE LEVEL NEUTRINO MASSES+MIXING

1-LOOP NEUTRINO MASSES+MIXING





R-Parity Violating SUSY

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

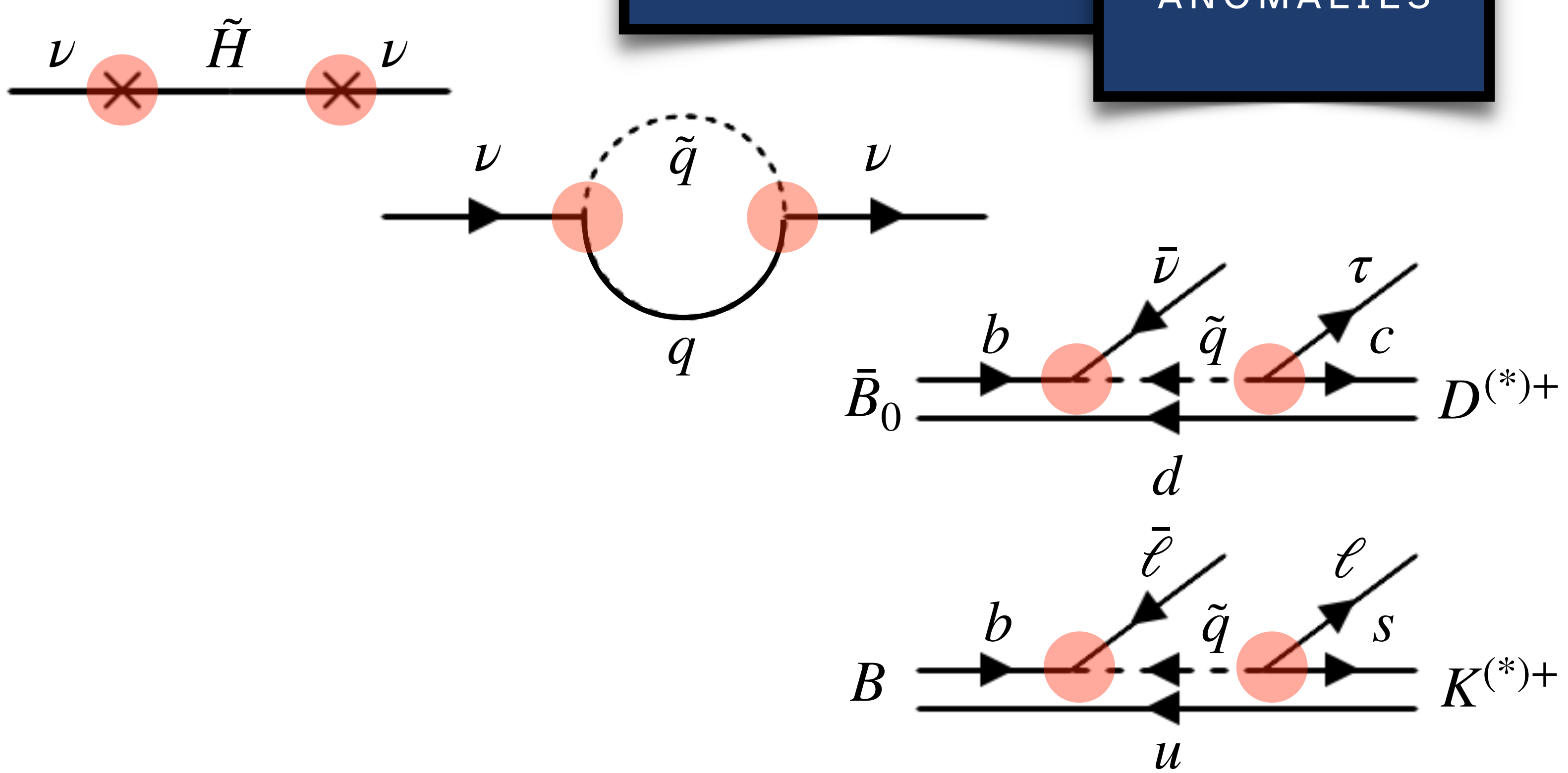
L Violating

B Violating

TREE LEVEL NEUTRINO MASSES+MIXING

1-LOOP NEUTRINO MASSES+MIXING

B-PHYSICS ANOMALIES



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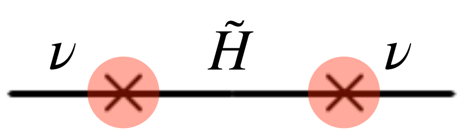
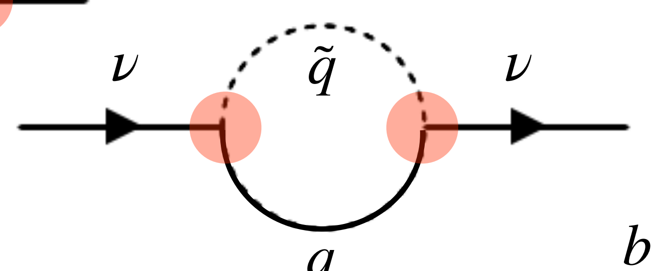
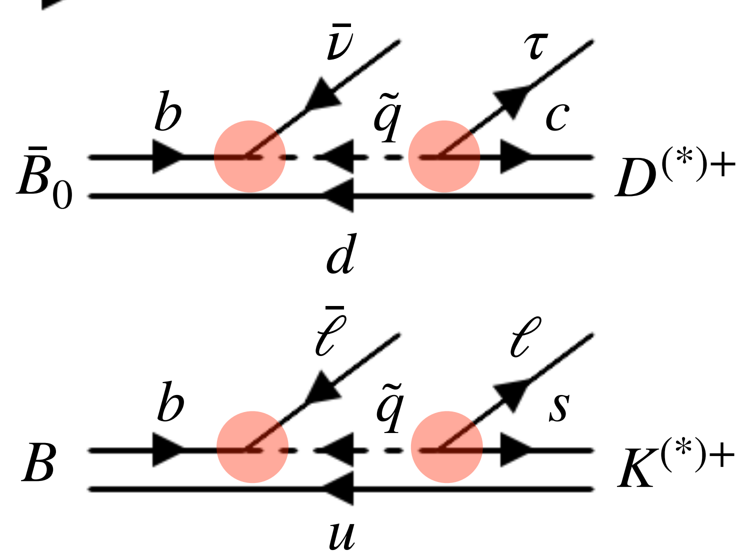
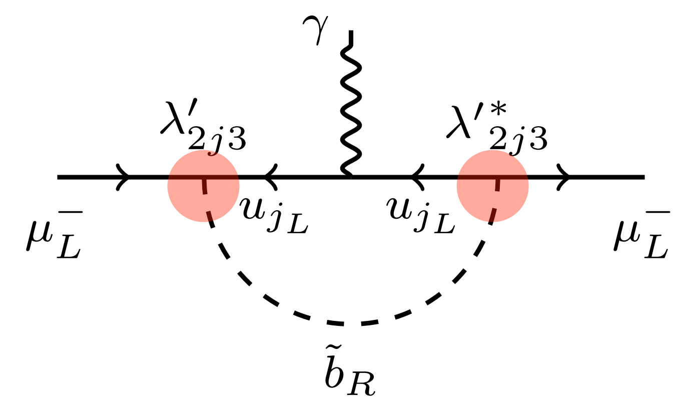
B-PHYSICS ANOMALIES

MUON G-2 ANOMALY









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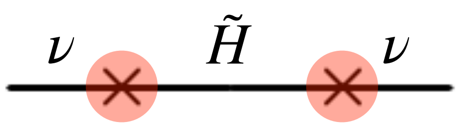
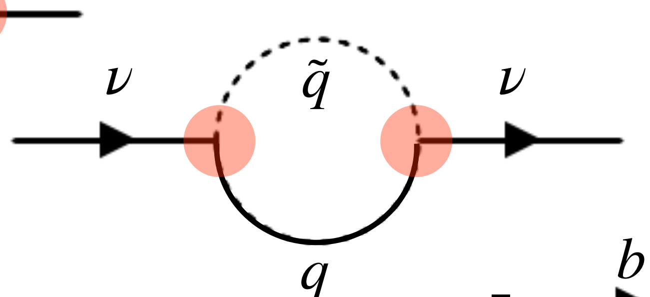
1-LOOP NEUTRINO MASSES+MIXING

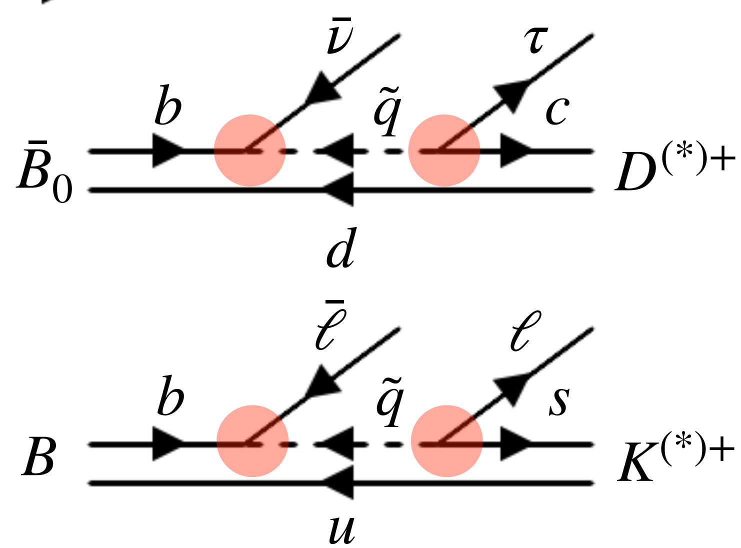
B-PHYSICS ANOMALIES

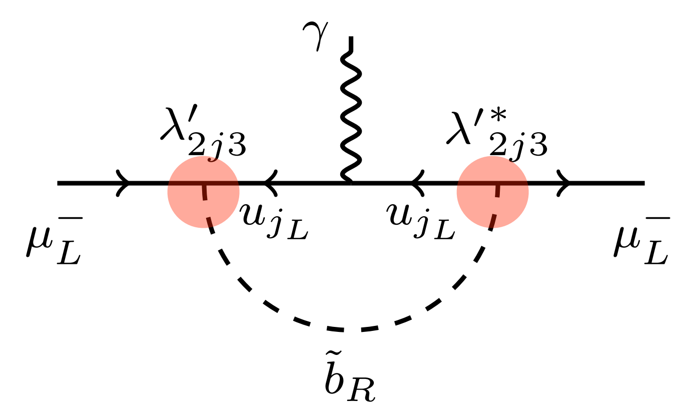
MUON G-2 ANOMALY

NEW ROOM FOR CP VIOLATION!









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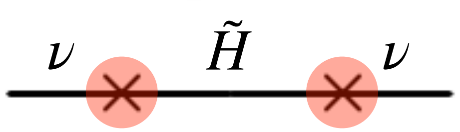

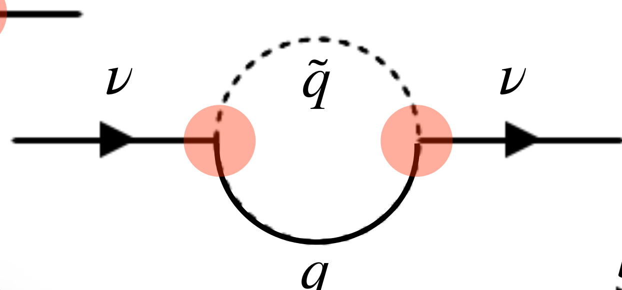

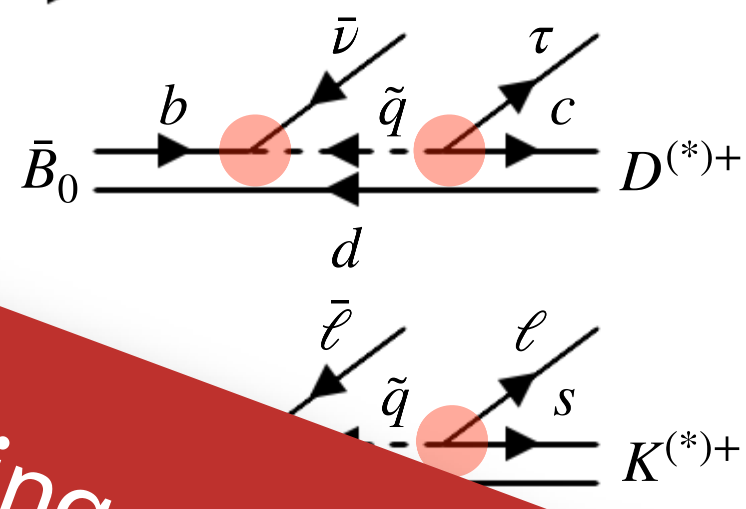

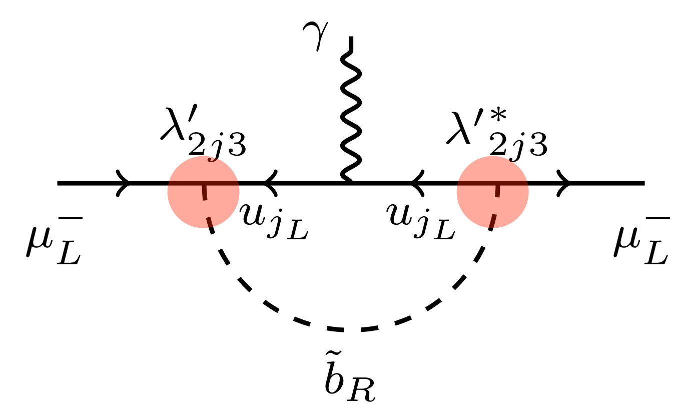

Nonzero RPV Couplings greatly weaken LHC Limits

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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B-PHYSICS ANOMALIES

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!

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

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R-Parity Violating SUSY

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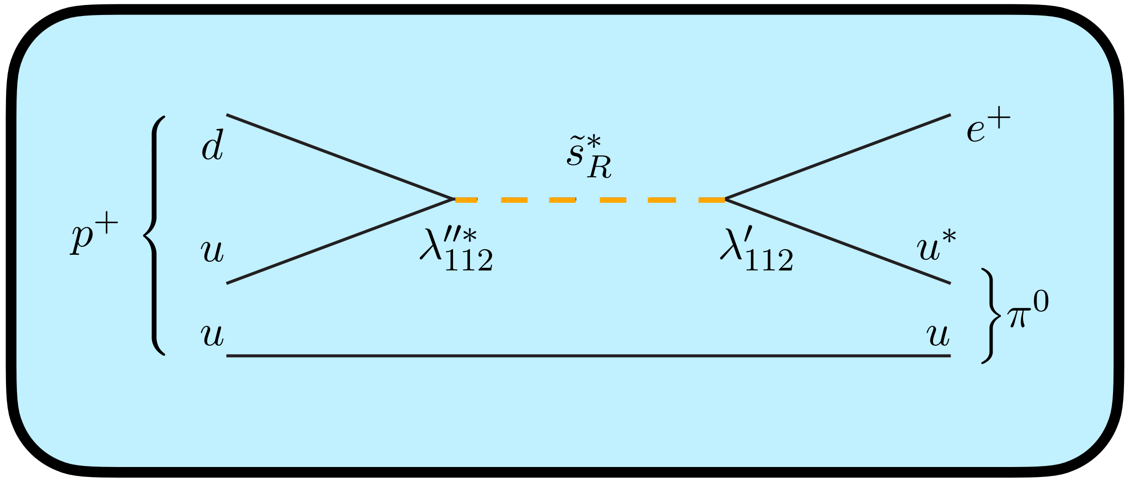
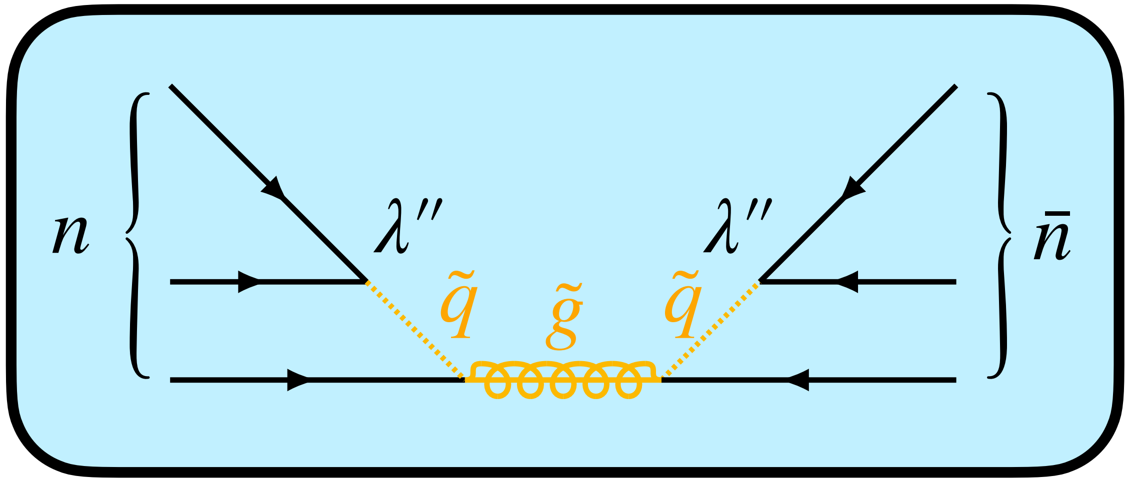
L Violating

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″





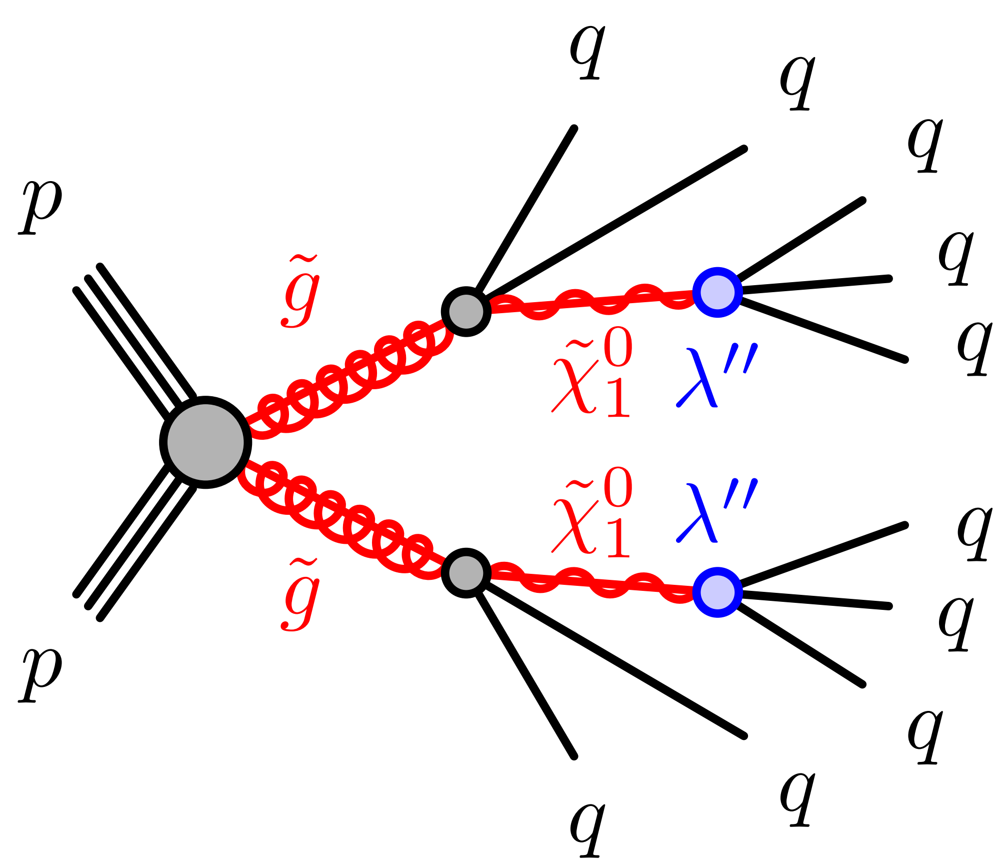
R-Parity Violating SUSY

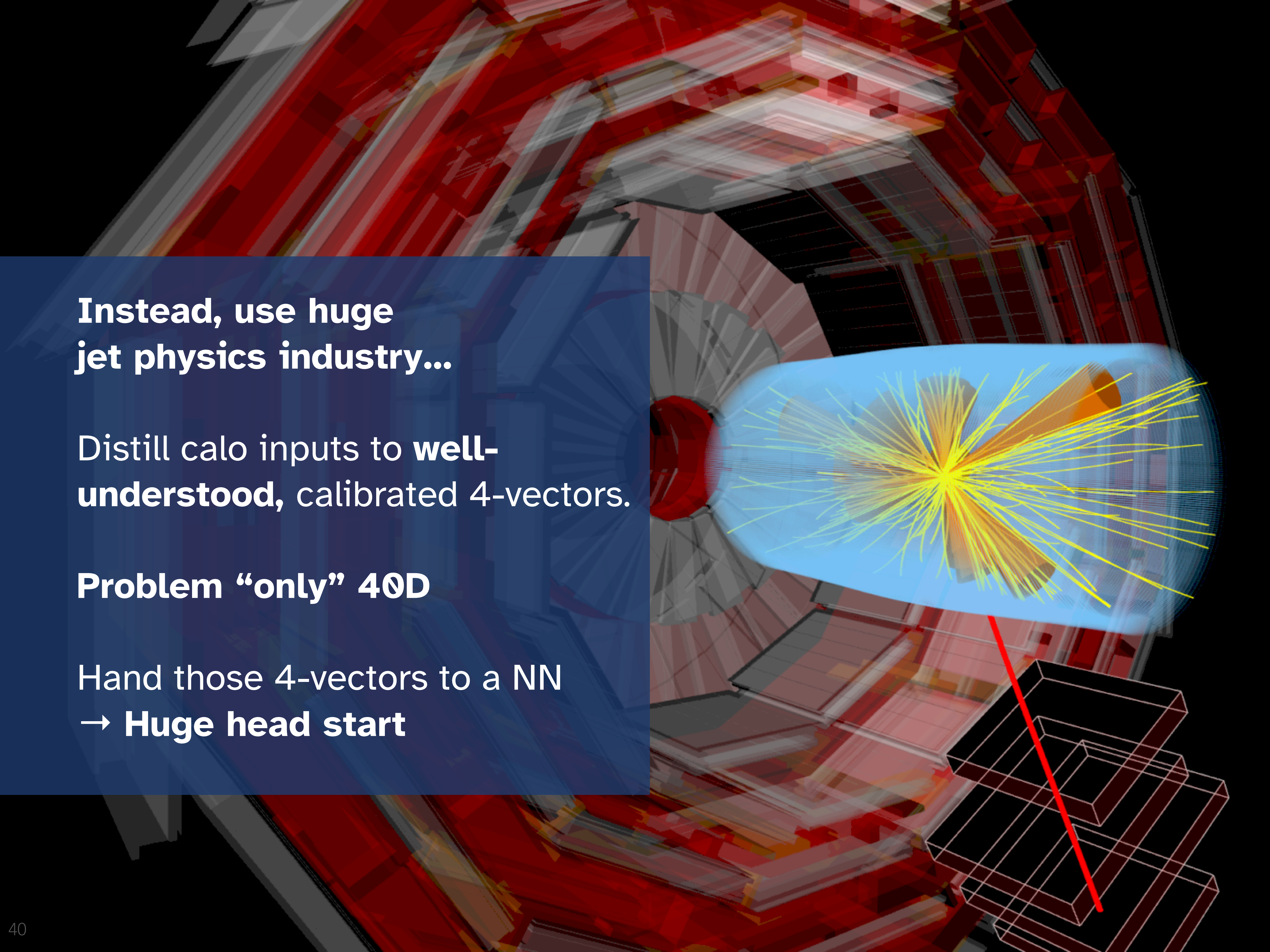
$$W_{RPV} = \mu_i H_u L_i + \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \frac{1}{2}\lambda''_{ijk} U_i D_j D_k$$

L Violating

B Violating

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



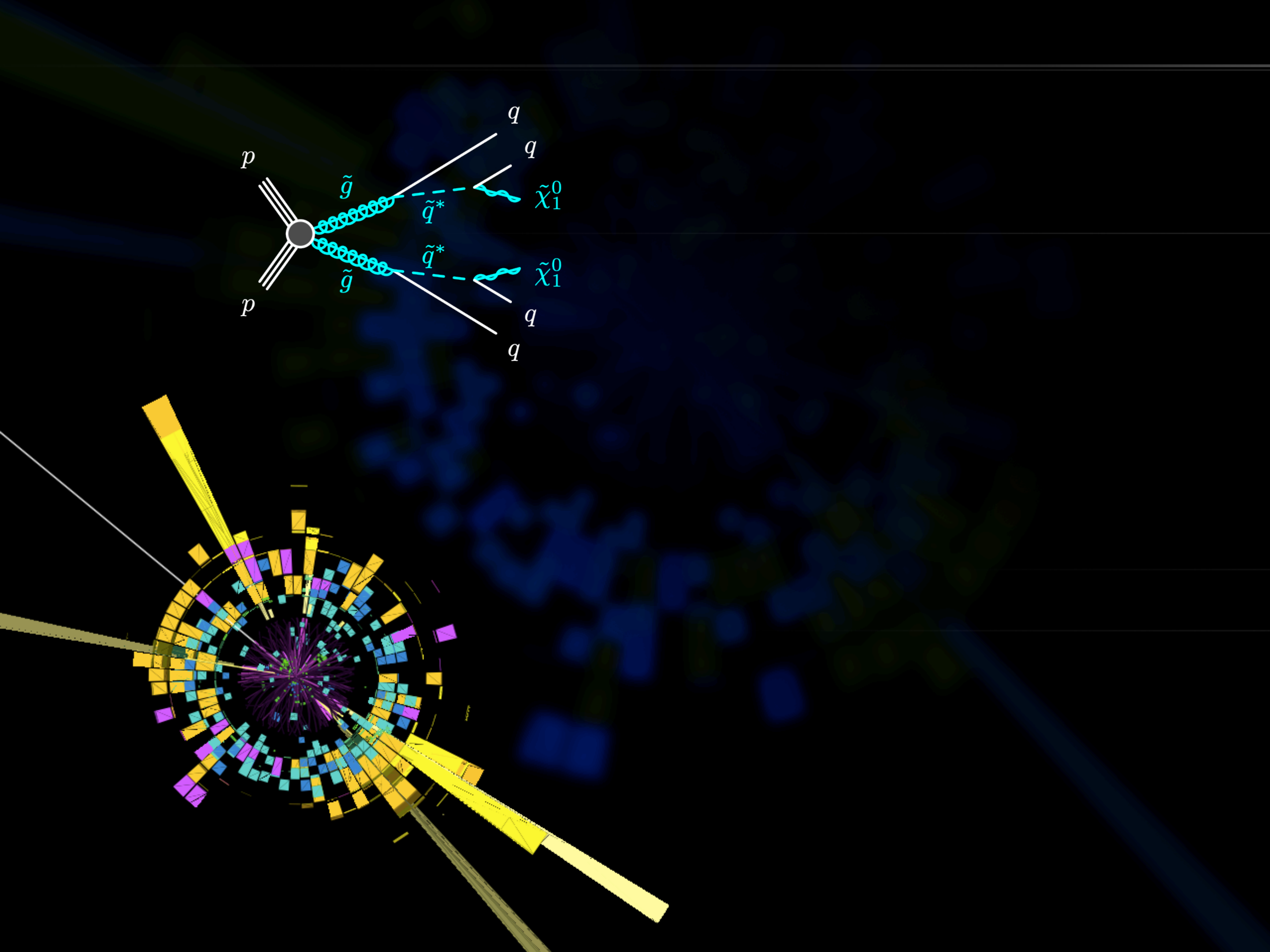


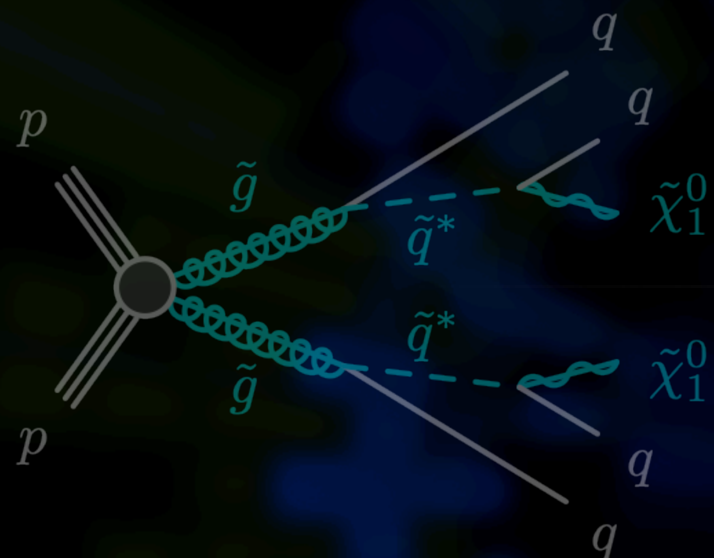
Instead, use huge jet physics industry…

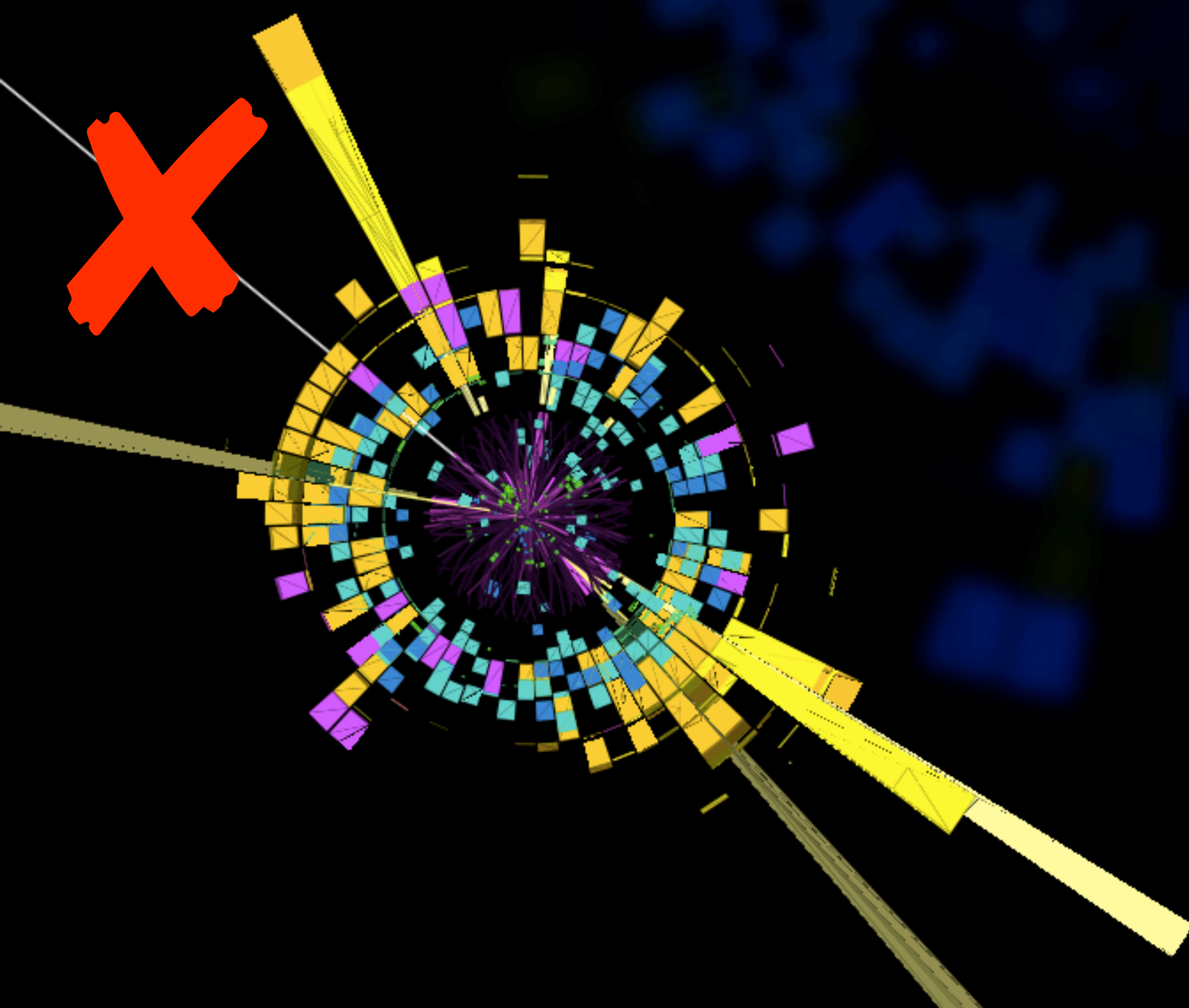
Distill calo inputs to **well-understood,** calibrated 4-vectors.

Problem "only" 40D

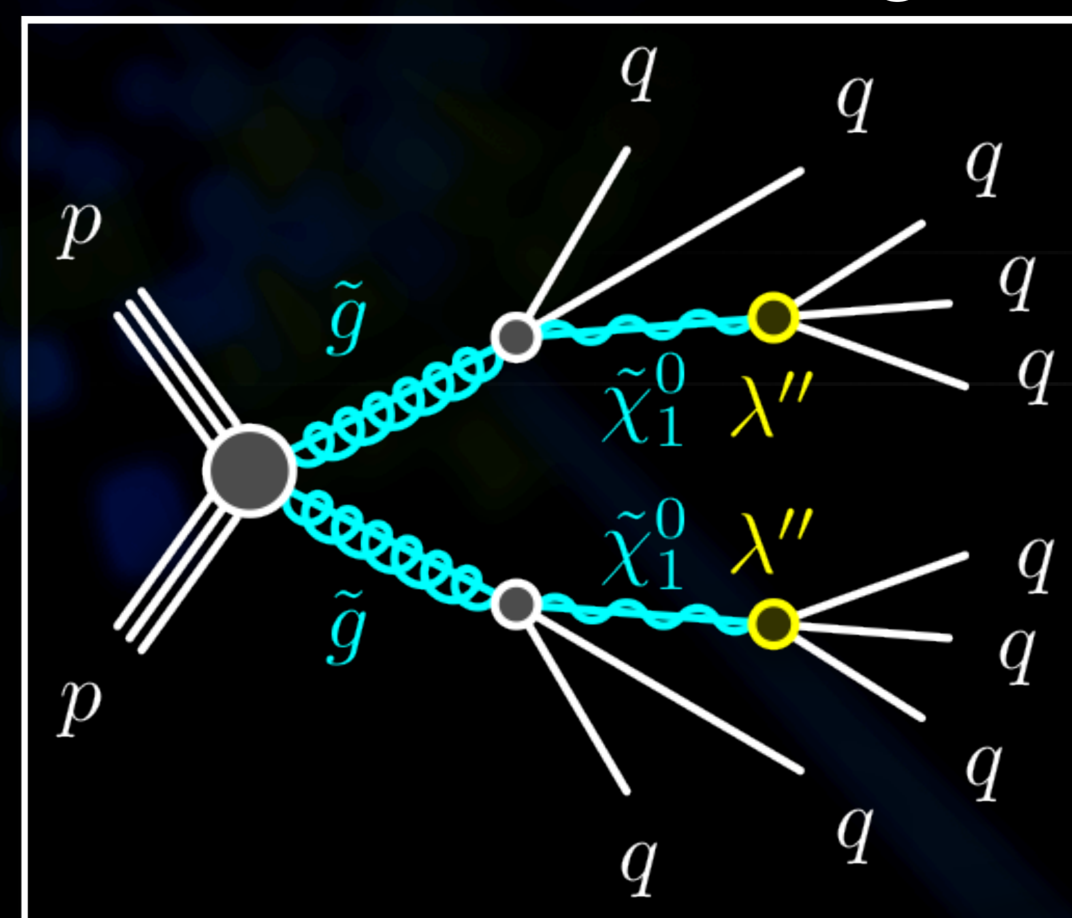
Hand those 4-vectors to a NN
→ **Huge head start**


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

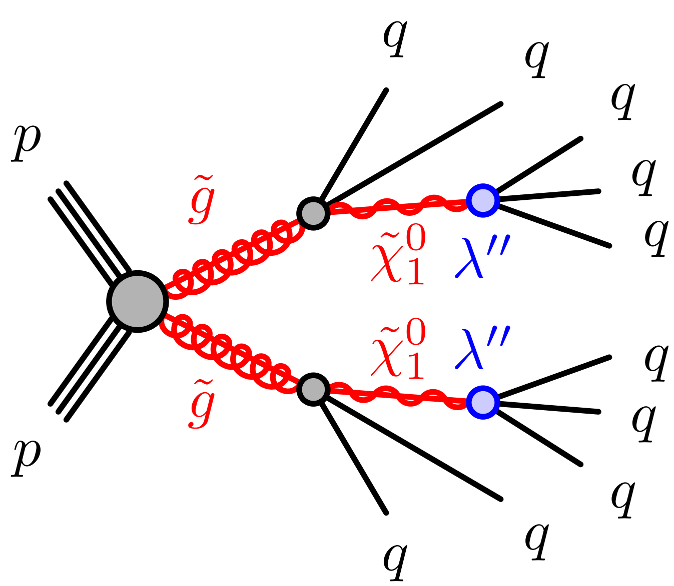


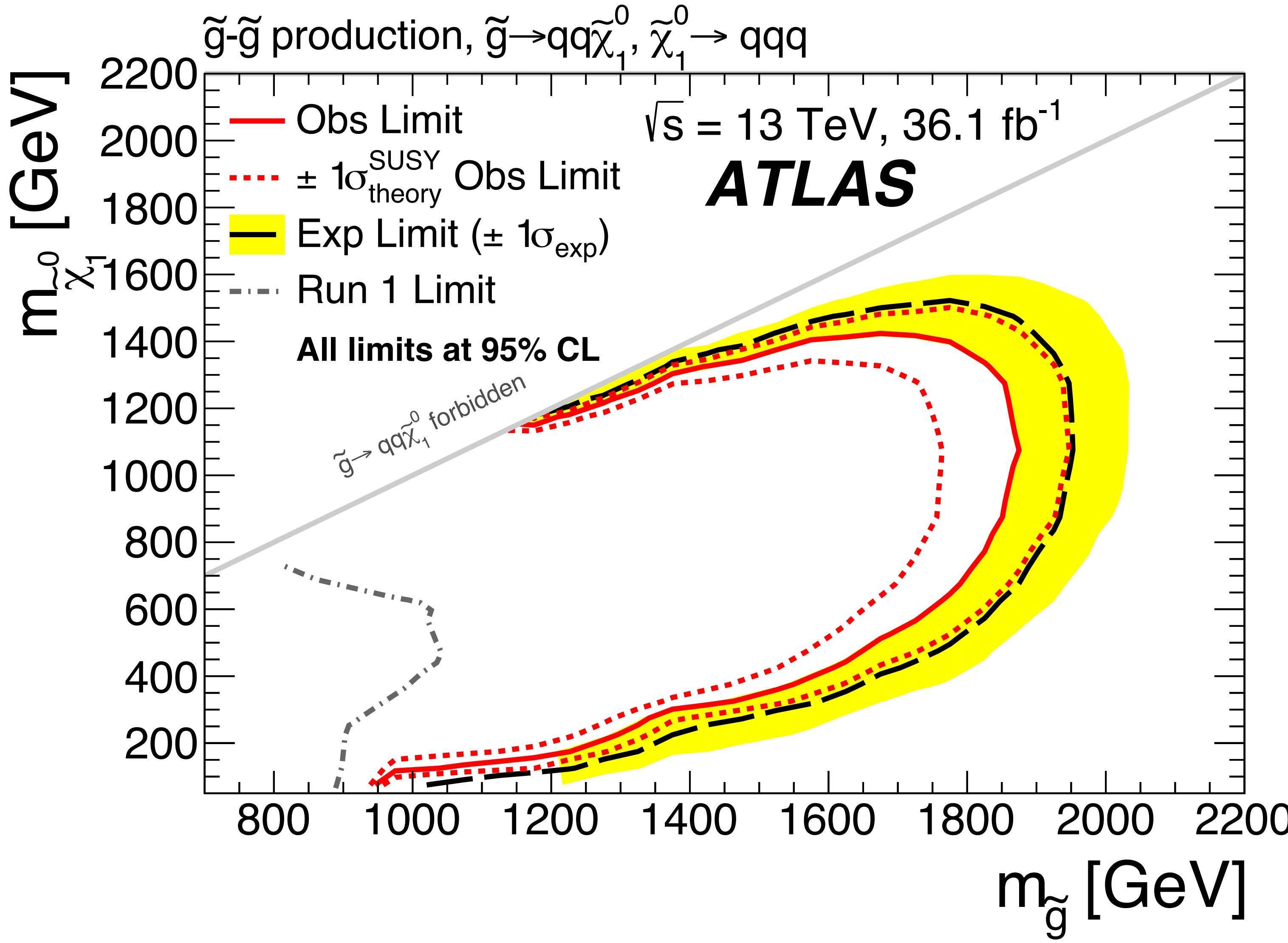


RPV Signal



RPV MULTIJET

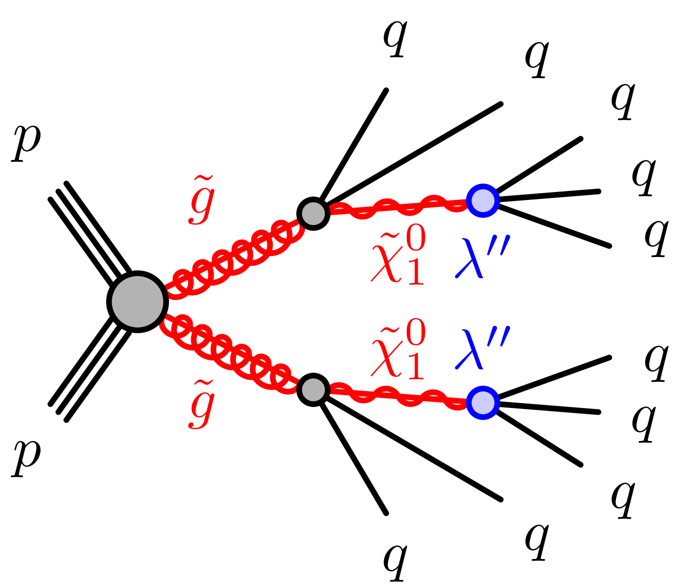


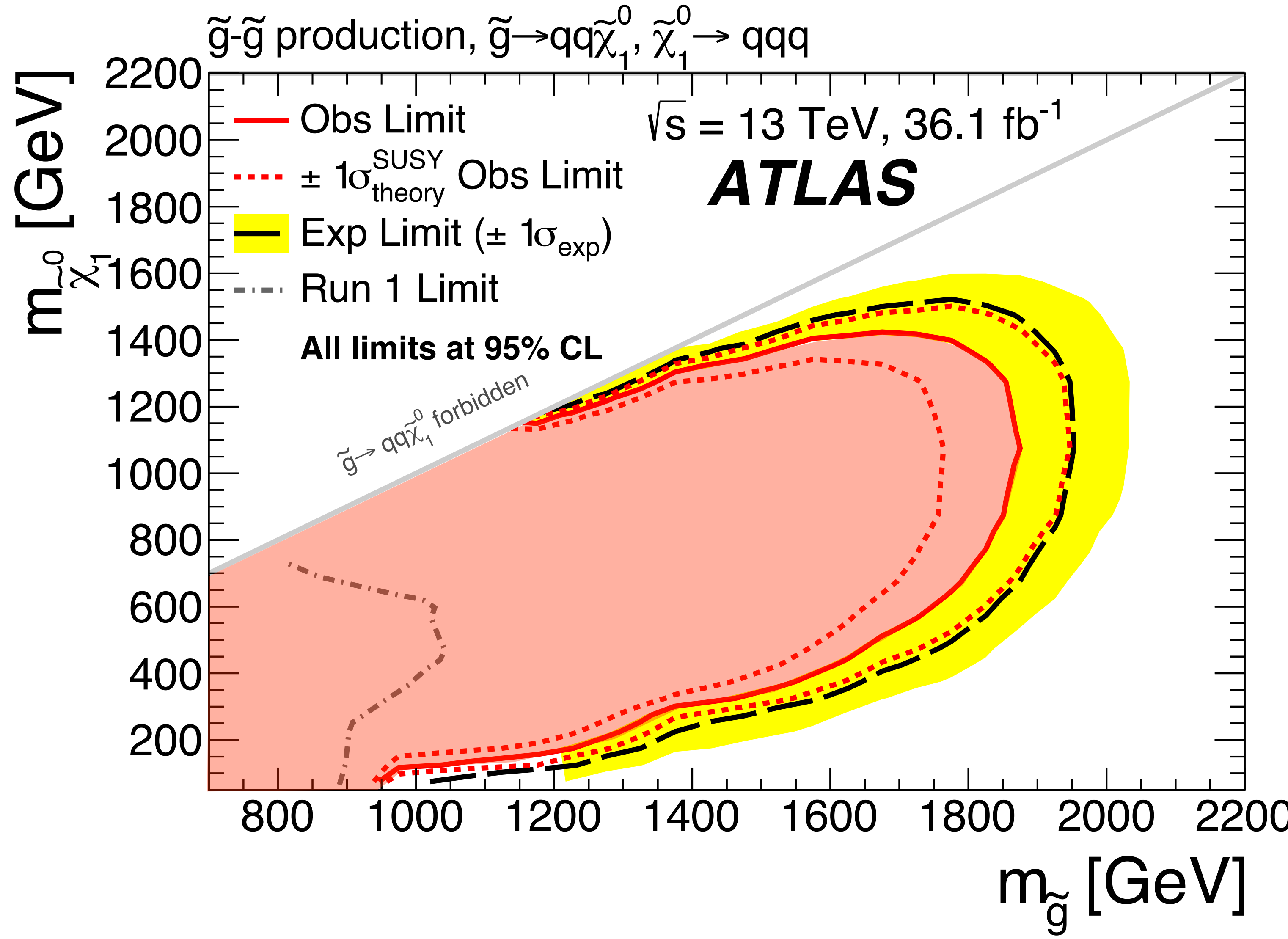


- Look in the tails, see no disagreement with background hypothesis
- Limits up to ~1.9 TeV in gluino mass
  - (But also as weak as ~1 TeV!)

SUSY-2016-22

RPV Multijet





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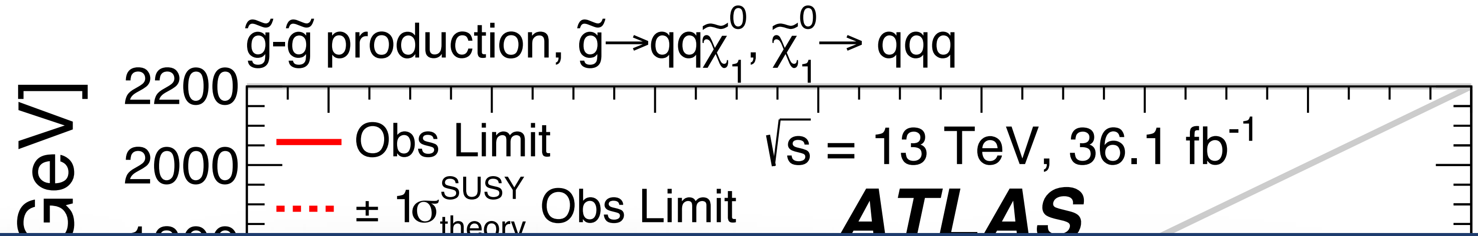
SUSY-2016-22

RPV MULTIJET



COULD BE A GLUINO SITTING THERE AT 1 TEV

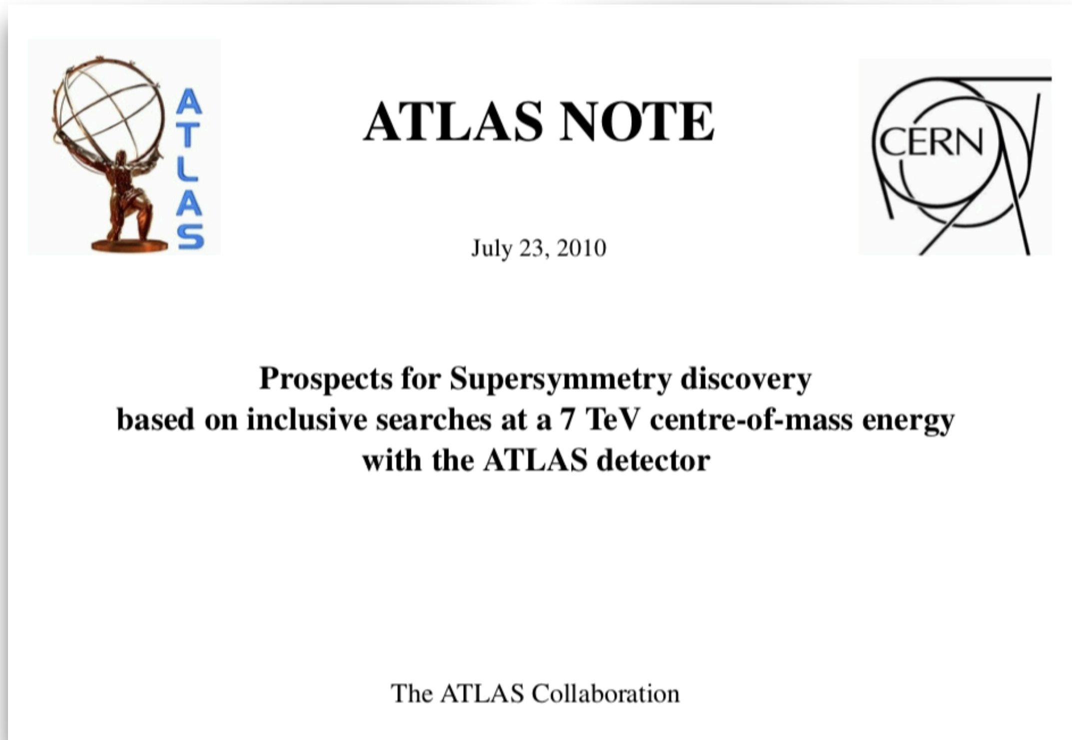
THE LHC DREAM

(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

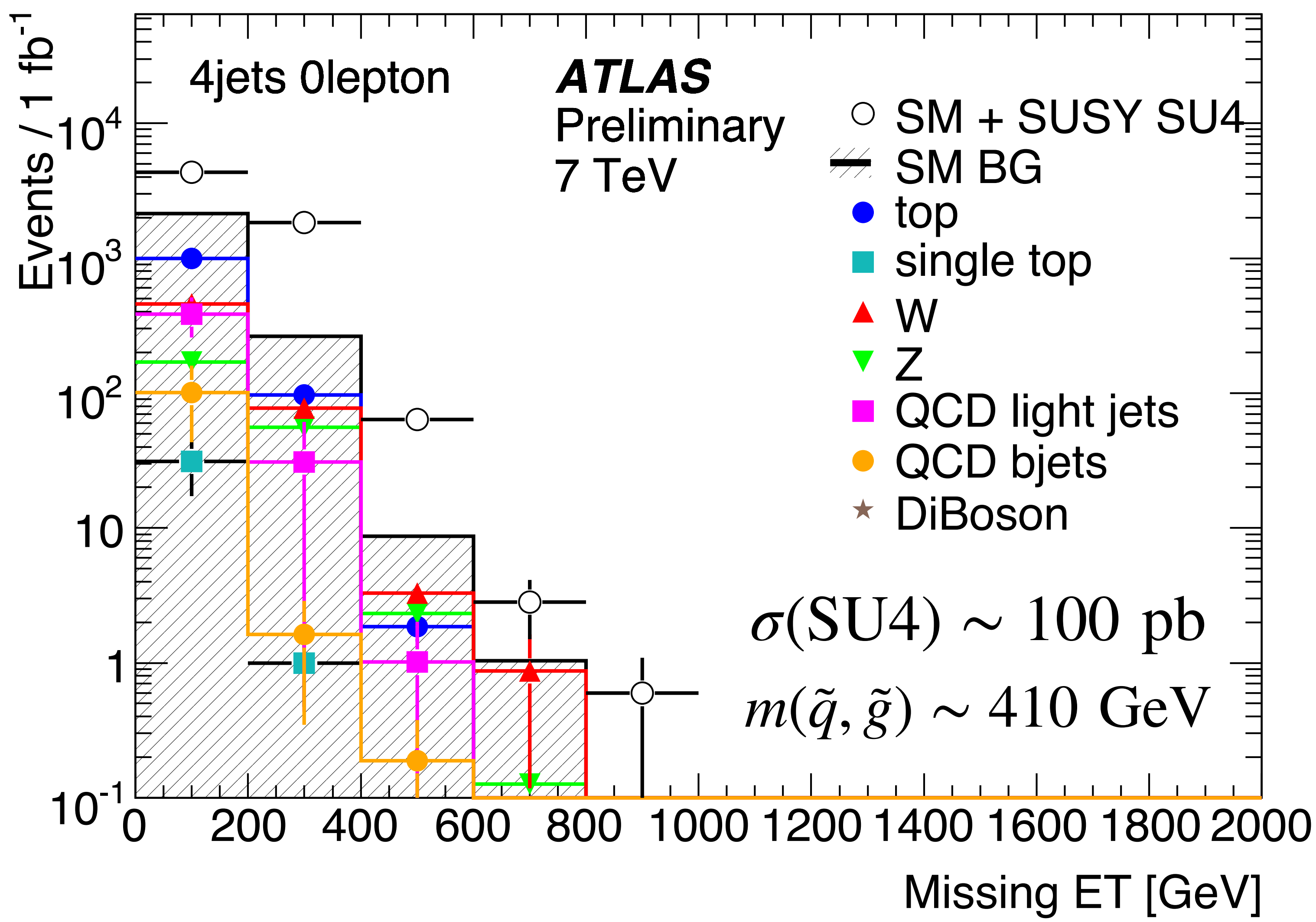
WE WERE A BIT OPTIMISTIC…


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



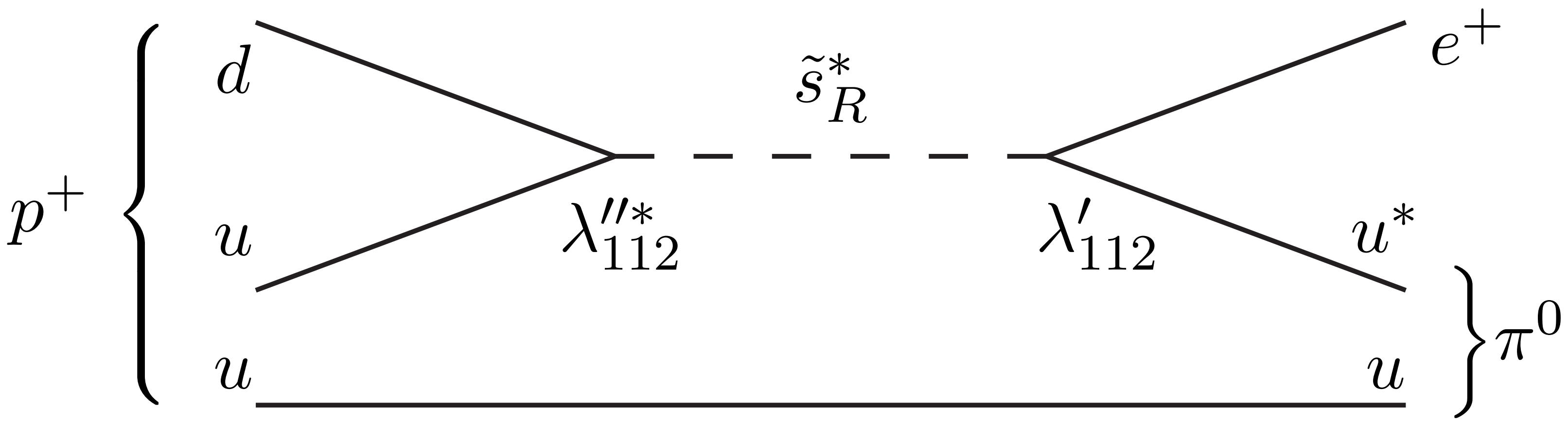
ATL-PHYS-PUB-2010-010

Proton decay

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

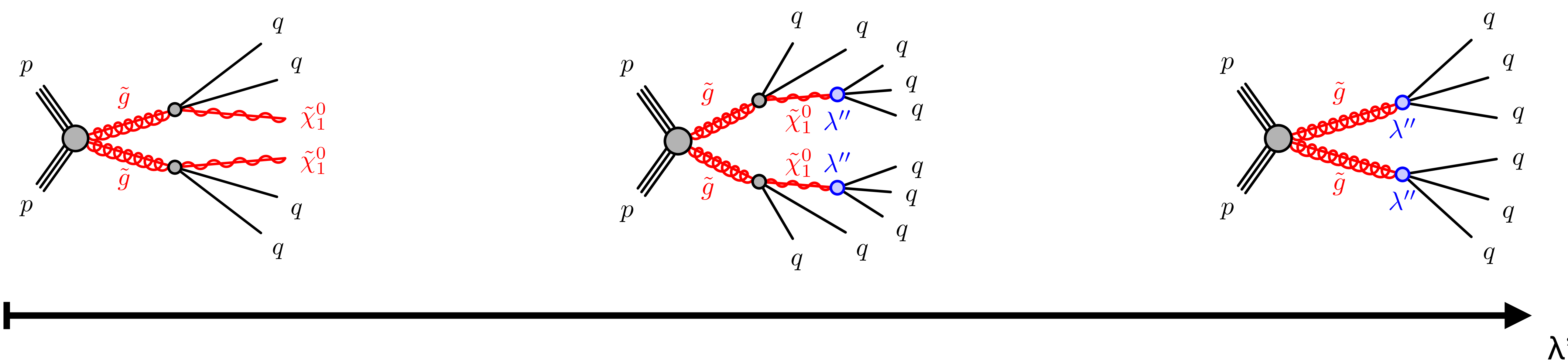
L Violating

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?

Zero RPV coupling
= RPC case

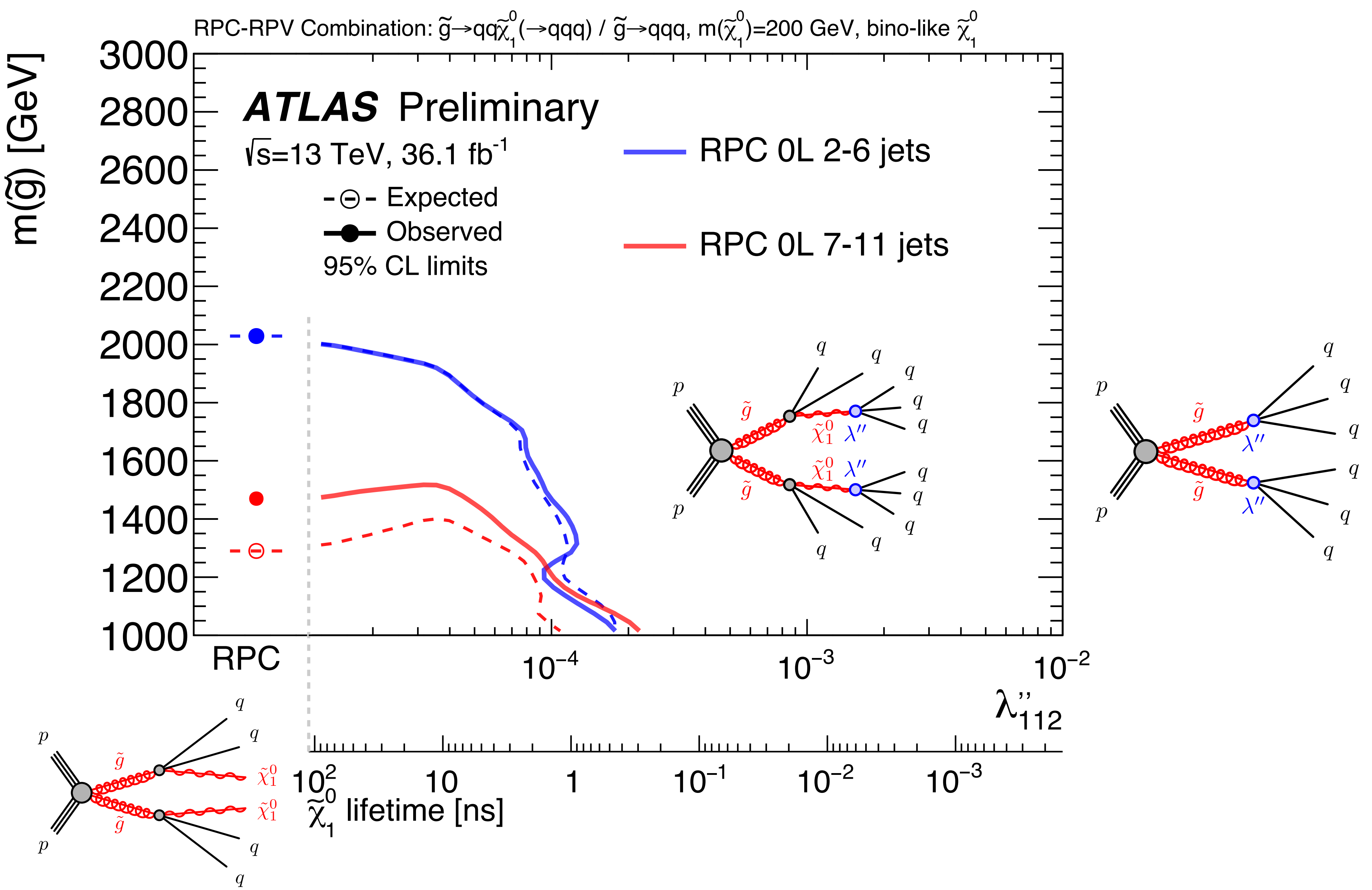
Moderate coupling:
Diagrams still dominated by
gauge couplings

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

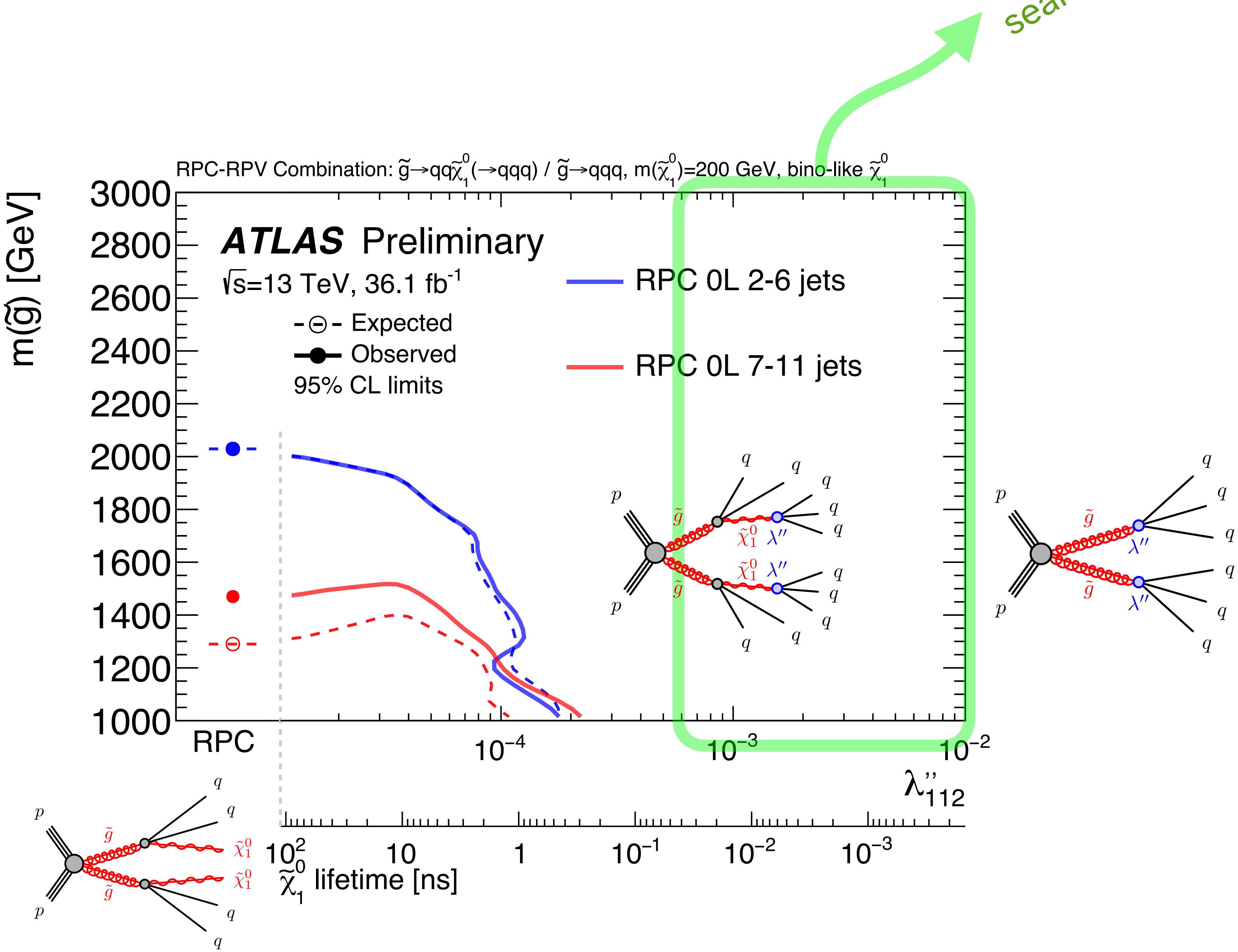
Scanning RPV Strength



ATLAS-CONF-2018-003

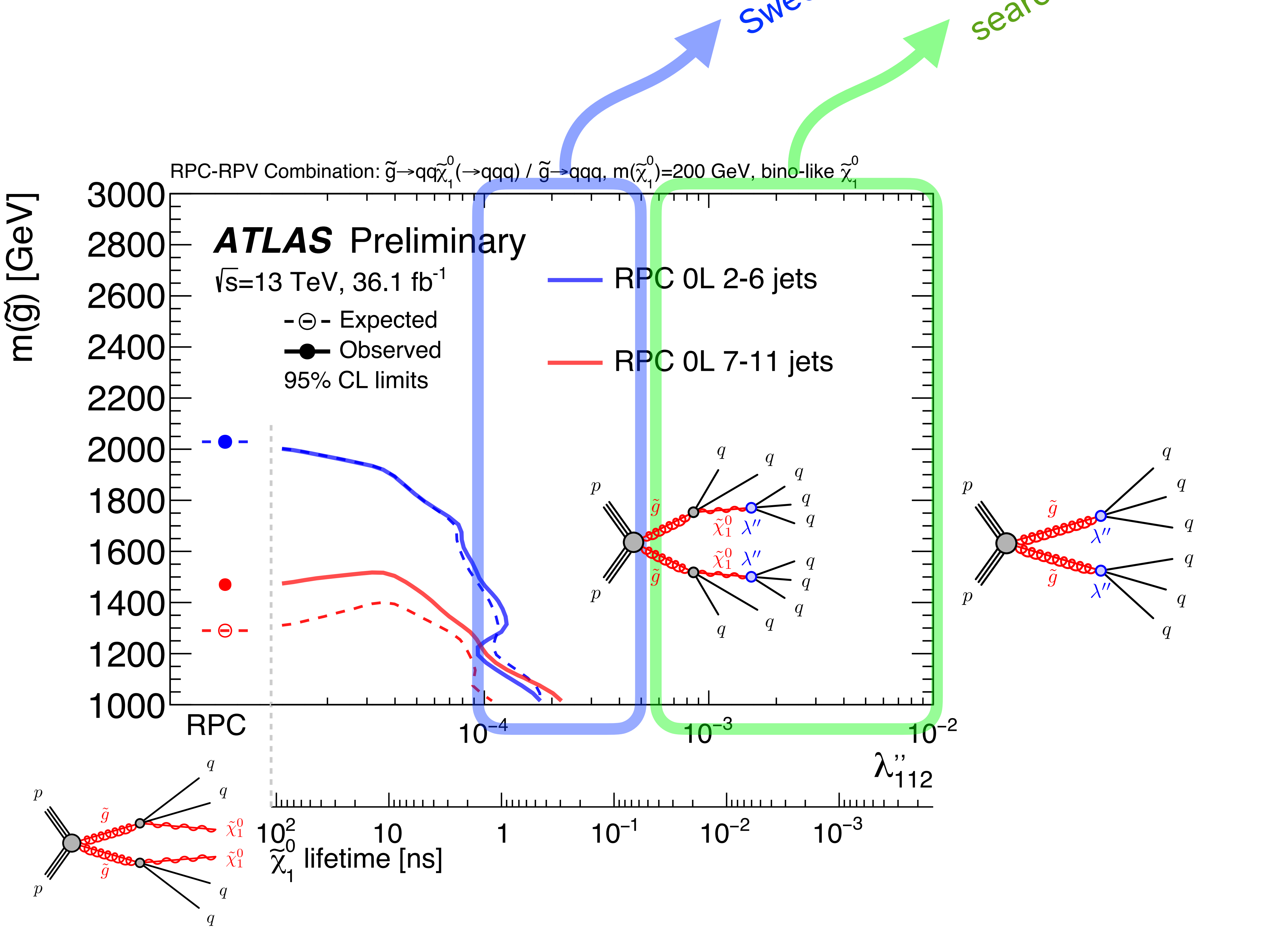
Scanning RPV Strength

Covered by RPV multijet search



ATLAS-CONF-2018-003

Scanning RPV Strength



ATLAS-CONF-2018-003

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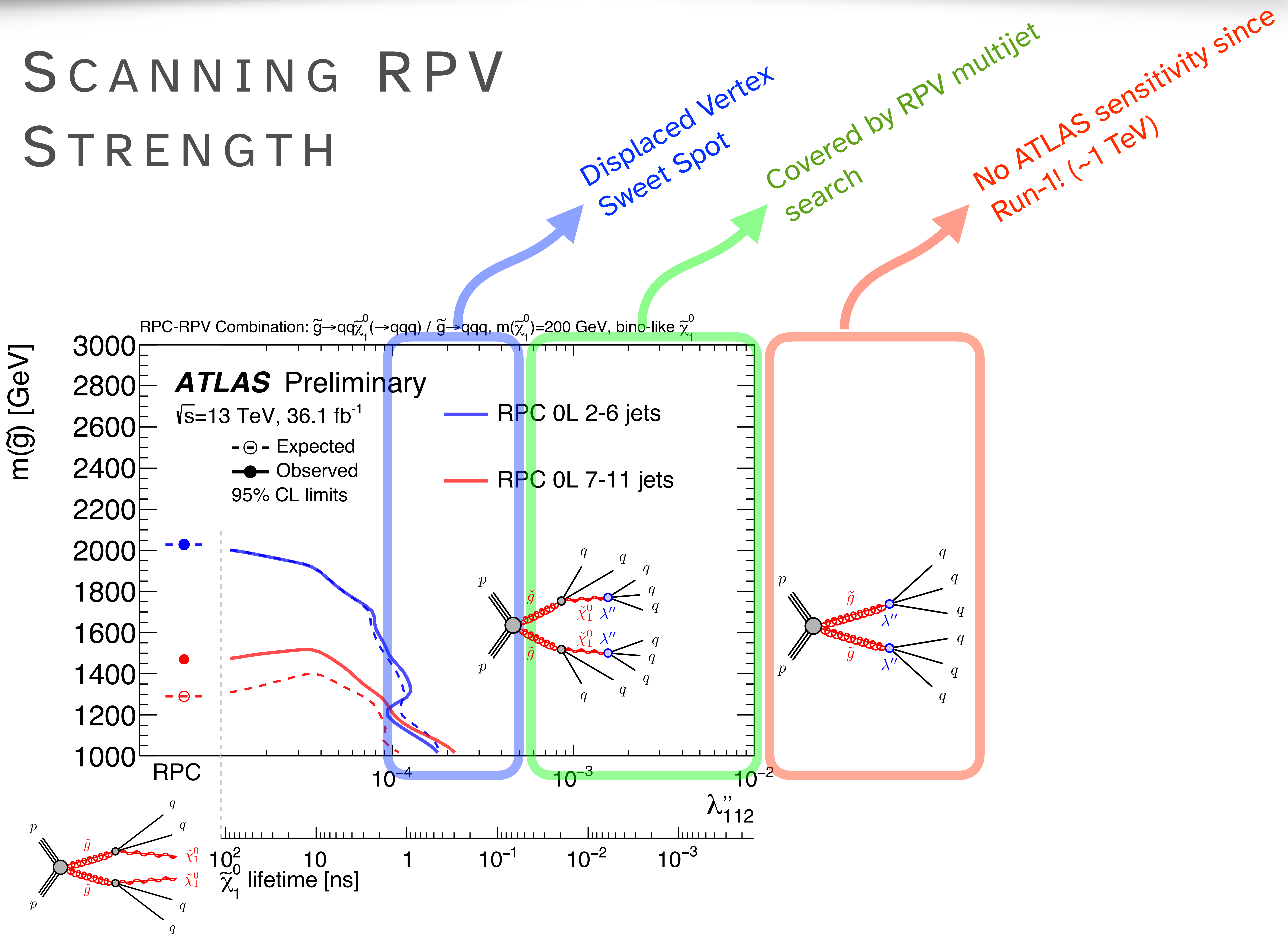
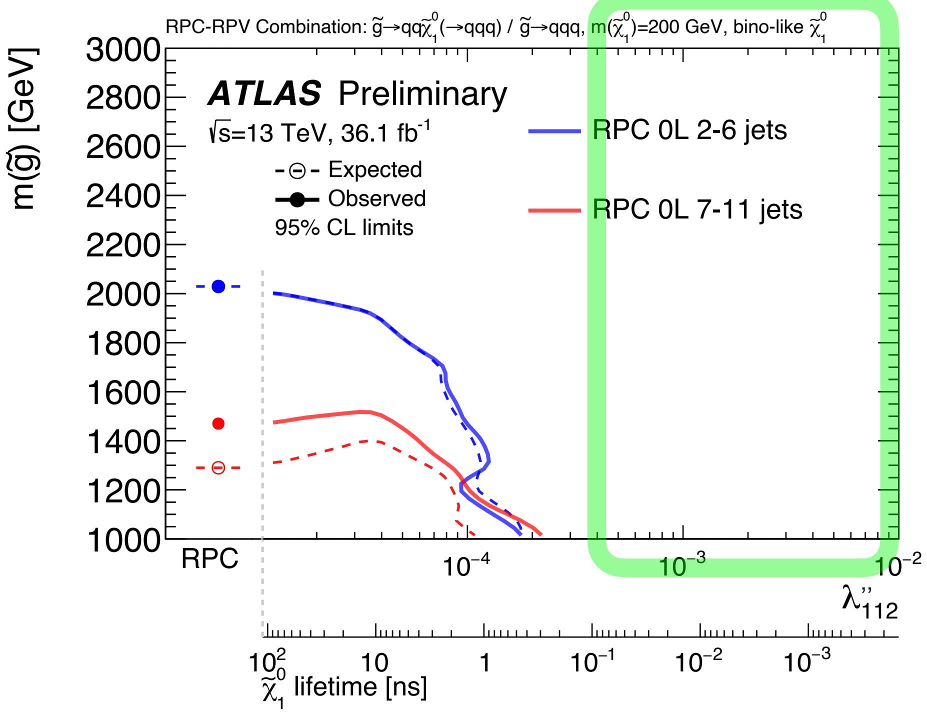
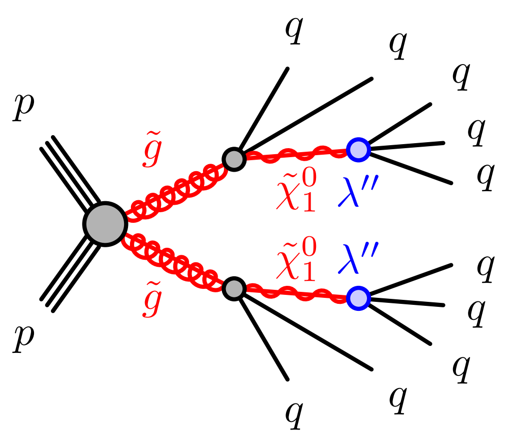


ATLAS-CONF-2018-003

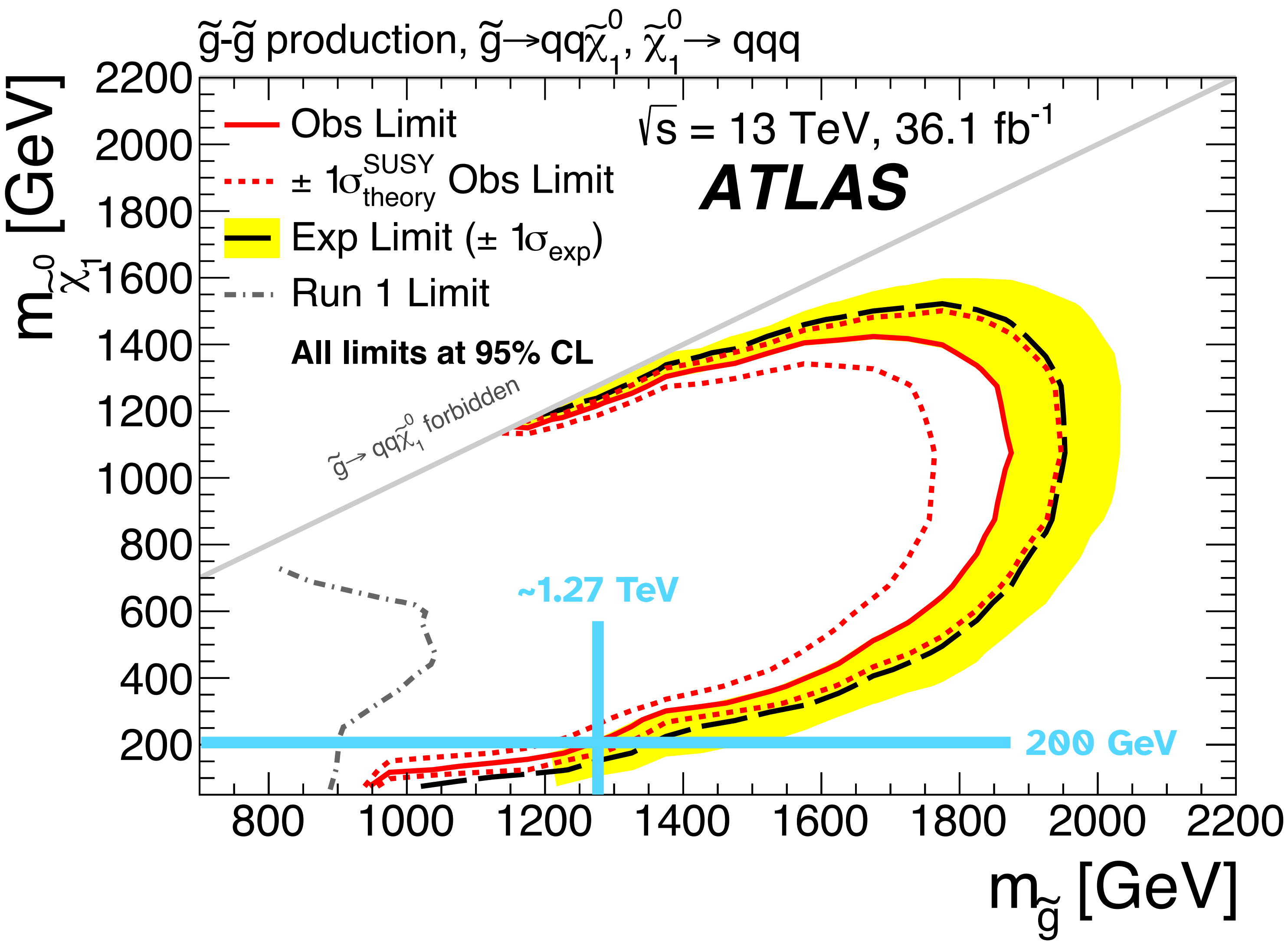
RPV Survey

Covered by RPV multijet?





But not looking great...

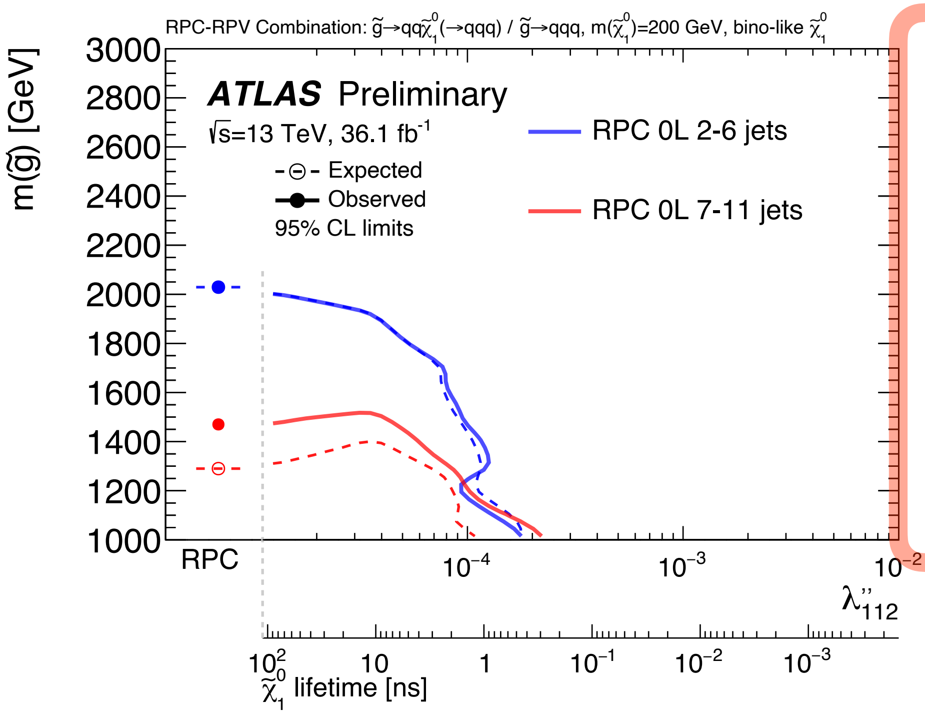


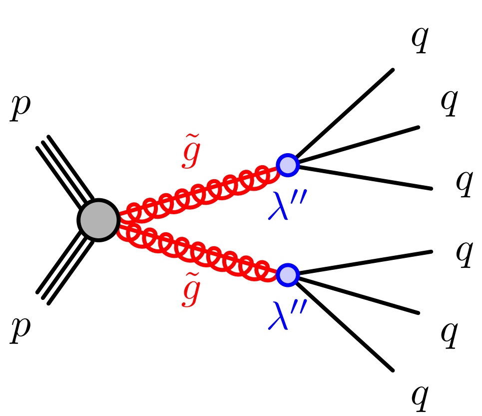
SUSY-2016-22 ATLAS-CONF-2018-003

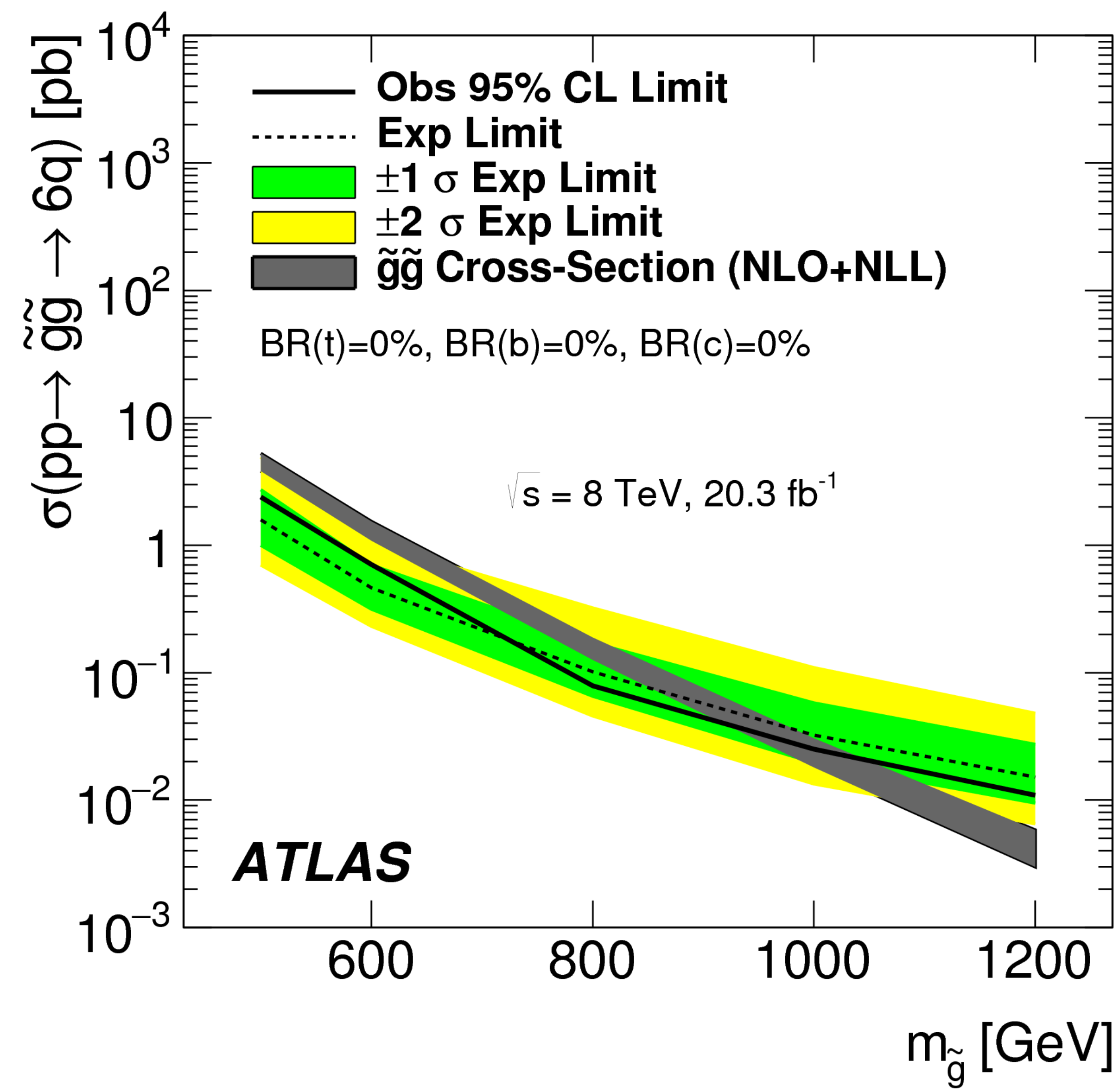
RPV Survey

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

…and any exclusion we have is very shallow…







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