

RPV SUSY
+ LONG LIVED SUSY
+ OTHER EXOTIC SUSY

Tim Cohen

University of Oregon



Experimental Challenges for the LHC Run II
KITP UC Santa Barbara
April 26, 2016

DISCLAIMER

Barely scratch the surface of these three distinct (and fascinating) topics.

Tim sits down to write his talk...



Results shown accidentally ATLAS heavy (sorry CMS friends!)
Citations are in no way comprehensive.

RPV SUSY

Comprehensive review of theory and constraints:

R. Barbier, C. Bérat, M. Besançon, M. Chemtob, A. Deandrea, E. Dudas, P. Fayet, S. Lavignac, G. Moreau, E. Perez, and Y. Sirois

[hep-ph/0406039](https://arxiv.org/abs/hep-ph/0406039)

A few modern reviews of the experimental status:

[Franceschini \[Adv.High Energy Phys. \(2015\)\]](#); [Redelbach \[arXiv:1512.05956\]](#)

RENORMALIZABLE SUPERPOTENTIAL

Matter particles carry +1 R -parity.

Superpartners carry -1 R -parity.

Recall how to interpret superpotential:

Replace any 2 with fermions (the rest are scalars).

Trivially get Yukawa couplings from any trilinear term.

MSSM SUPERPOTENTIAL:

$$W_{\text{MSSM}} = \mu H_u H_d + \lambda_{ij}^e H_d L_i E_j^c + \lambda_{ij}^d H_d Q_i D_j^c - \lambda_{ij}^u H_u Q_i U_j^c$$

RPV SUPERPOTENTIAL:

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

RPV PHENOMENOLOGY

Lepton number violation

Baryon number violation

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

Non-CKM flavor!!

Subtlety: can rotate away μ_i :

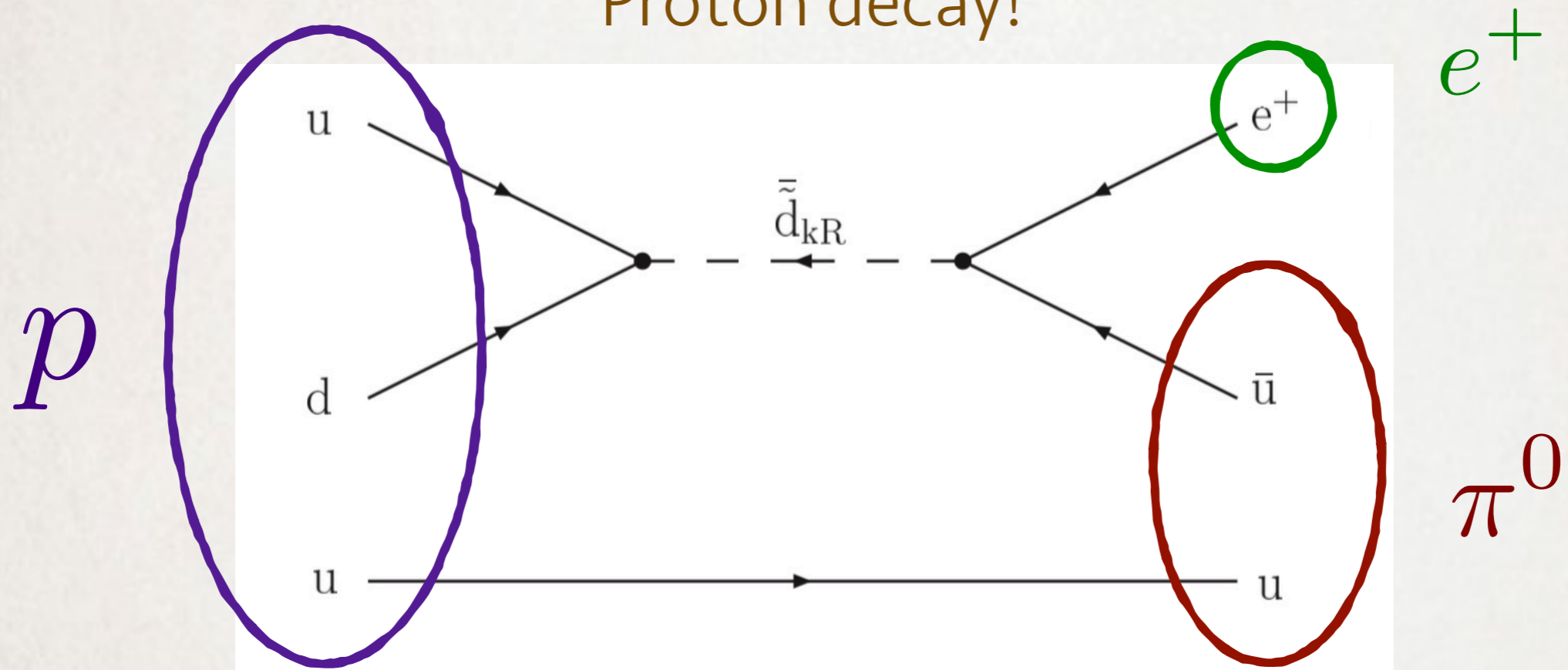
$$H_d \rightarrow H'_d \propto \mu H_d + \mu_i L_i$$

Many analyses only consider tri-linear interactions.

TURNING ON TWO OPERATORS

Violate B and L simultaneously.

Proton decay!



$$|\lambda'_{11k} \lambda''_{11k}| \lesssim 10^{-25} \left(\frac{1 \text{ TeV}}{m_{\tilde{d}_{R,k}}} \right)^2$$

Loop process gives flavor independent constraint:

$$|\lambda'_{ijk} \lambda''_{i'j'k'}| \lesssim 10^{-9} \text{ for } 1 \text{ TeV squarks.}$$

TURN ON ONE AT A TIME

More than one RPV operator active yields very strong indirect constraints!

Additionally, strong constraints for events with extra leptons.

Imagine lepton number is good symmetry.

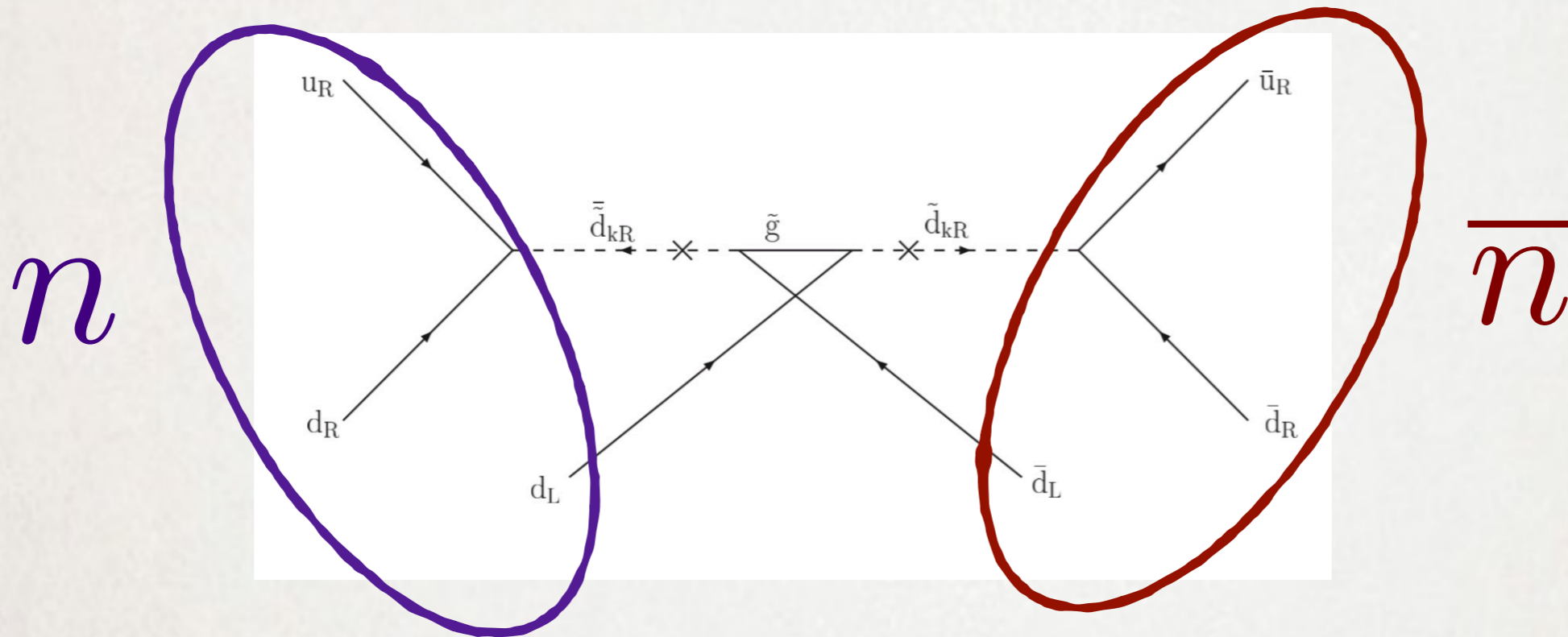
Focus on baryonic RPV operator:

$$W_{\text{RPV}} = \frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c$$

CONSTRAINTS

$$W_{\text{RPV}} = \frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c$$

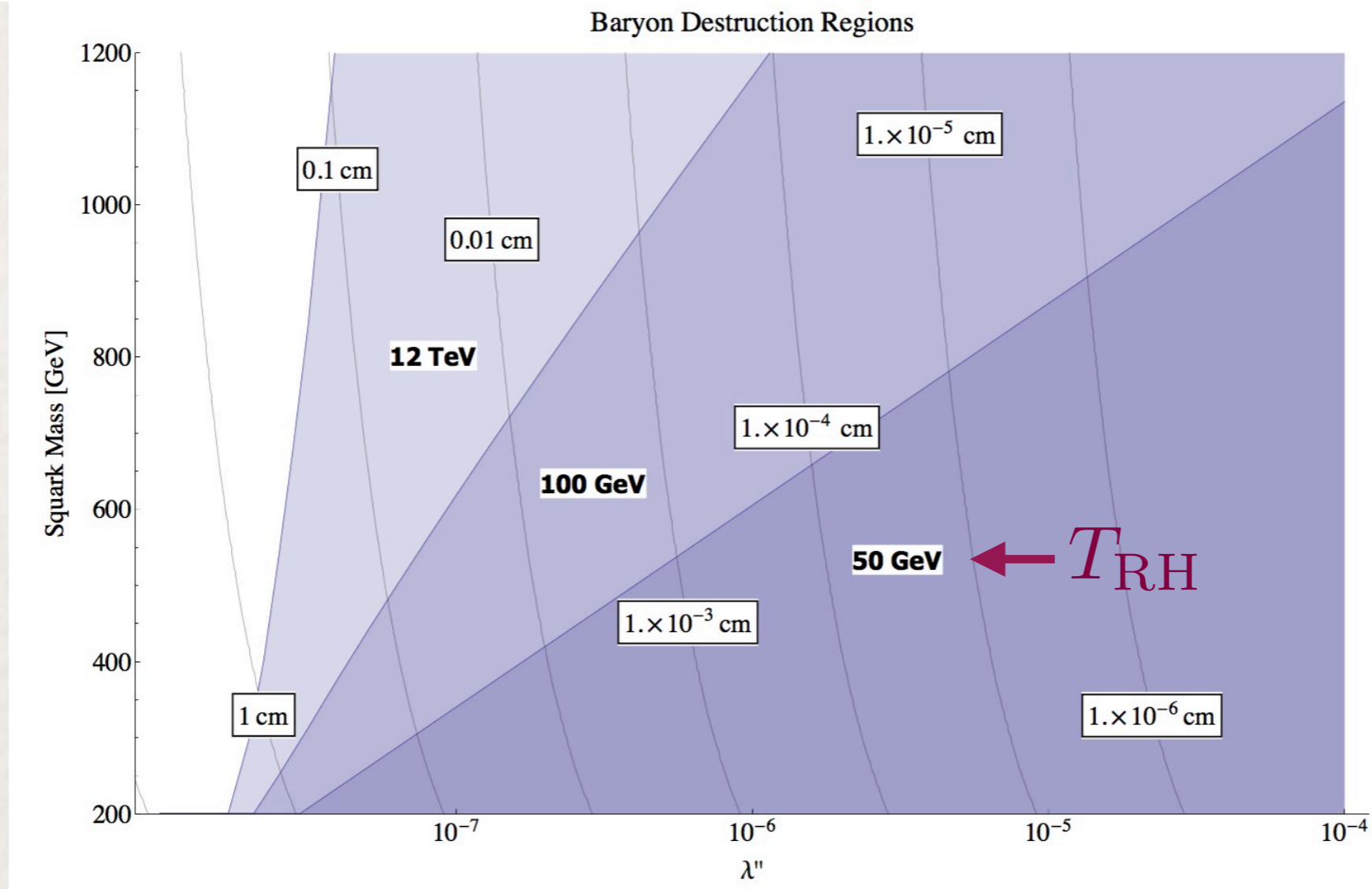
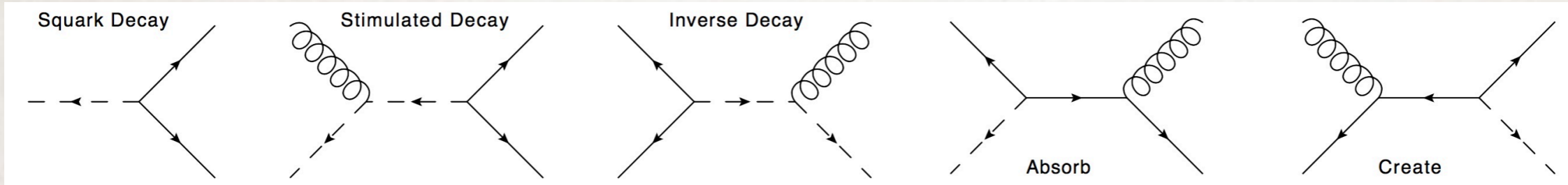
$n - \bar{n}$ oscillations



$$|\lambda''_{11k}| \lesssim 10^{-5} \frac{10^8 \text{ s}}{\tau_{\text{Soc}}} \left(\frac{\tilde{m}}{1 \text{ TeV}} \right)^{5/2}$$

COSMOLOGY

Baryon asymmetry can be washed out.



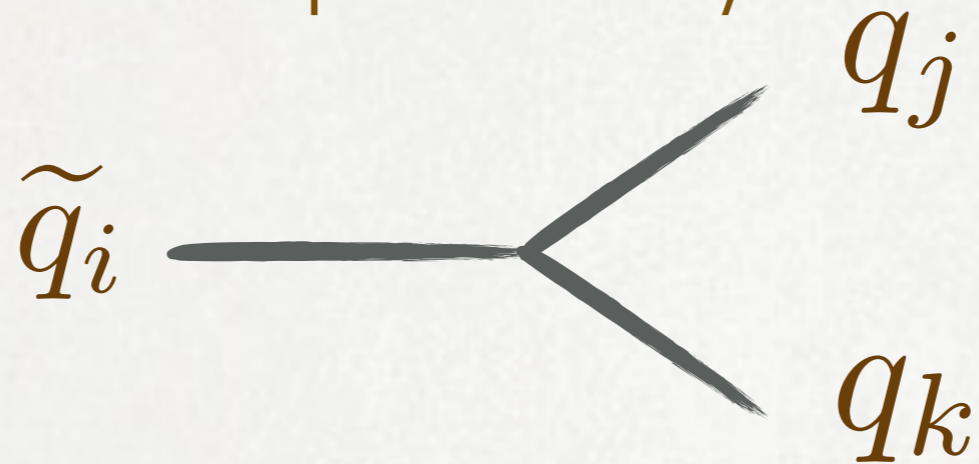
Barry, Graham, Rajendran [arXiv:1310.3853]

NEW DECAYS

$$W_{\text{RPV}} = \frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c$$

Lightest superpartner is no longer stable.

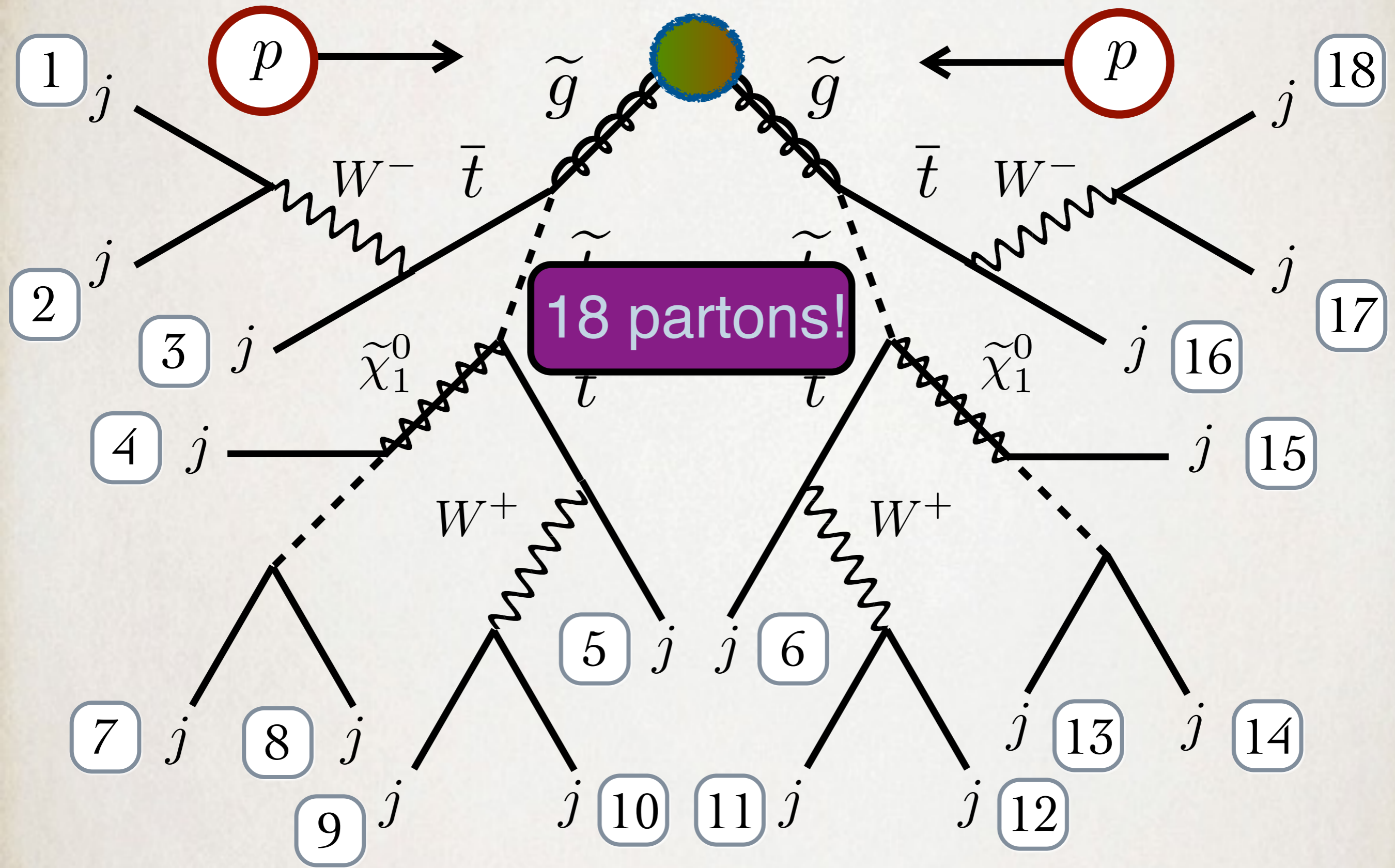
Squark decay:



Neutralino decay:



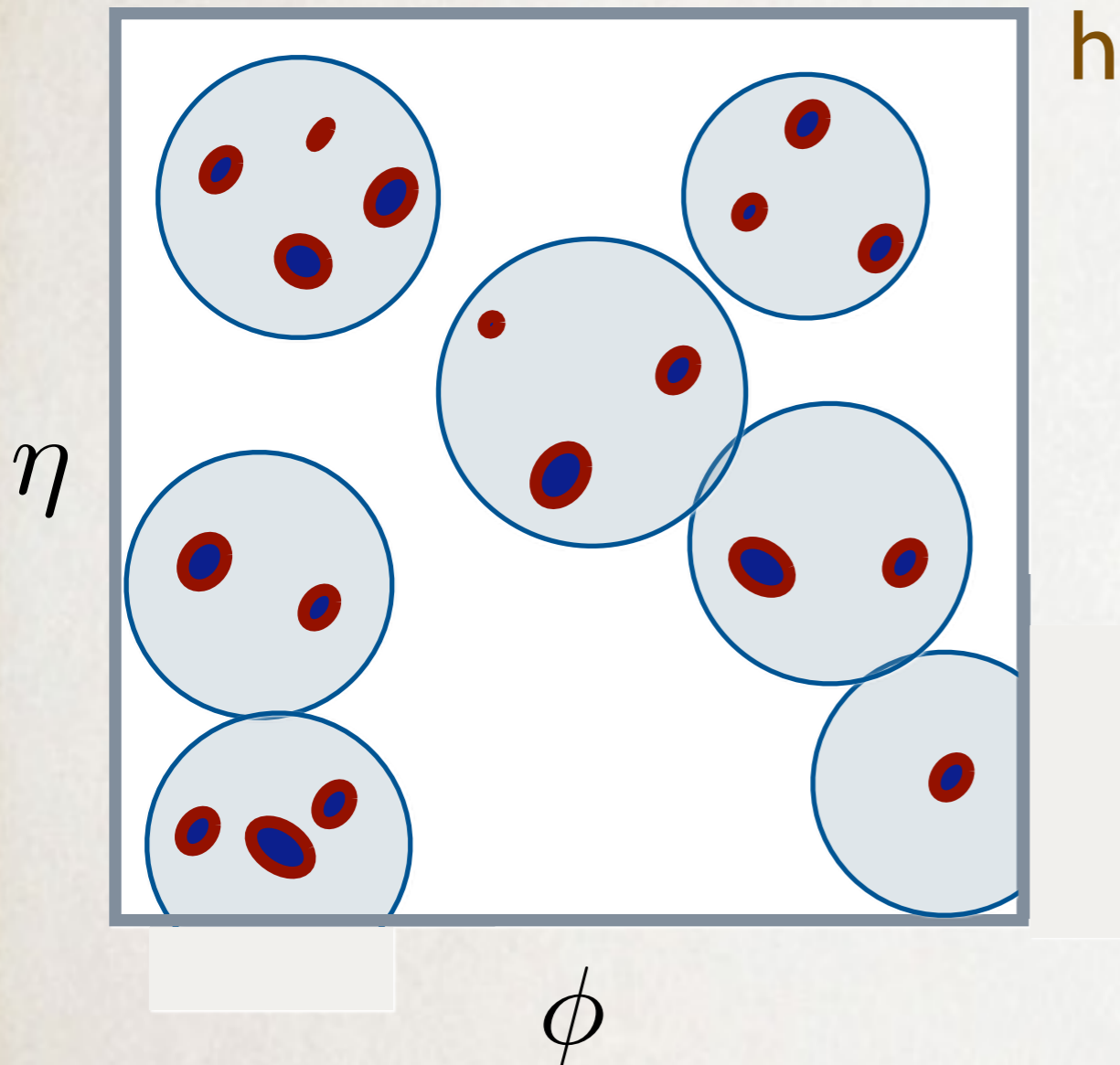
HIGH MULTIPLICITY



$j = u, d, c, s, b + \text{h.c.}$

ACCIDENTAL SUBSTRUCTURE

18 partons



New physics manifests as high multiplicity hadronic event.

Occasional hard partons will cluster into same fat jet:

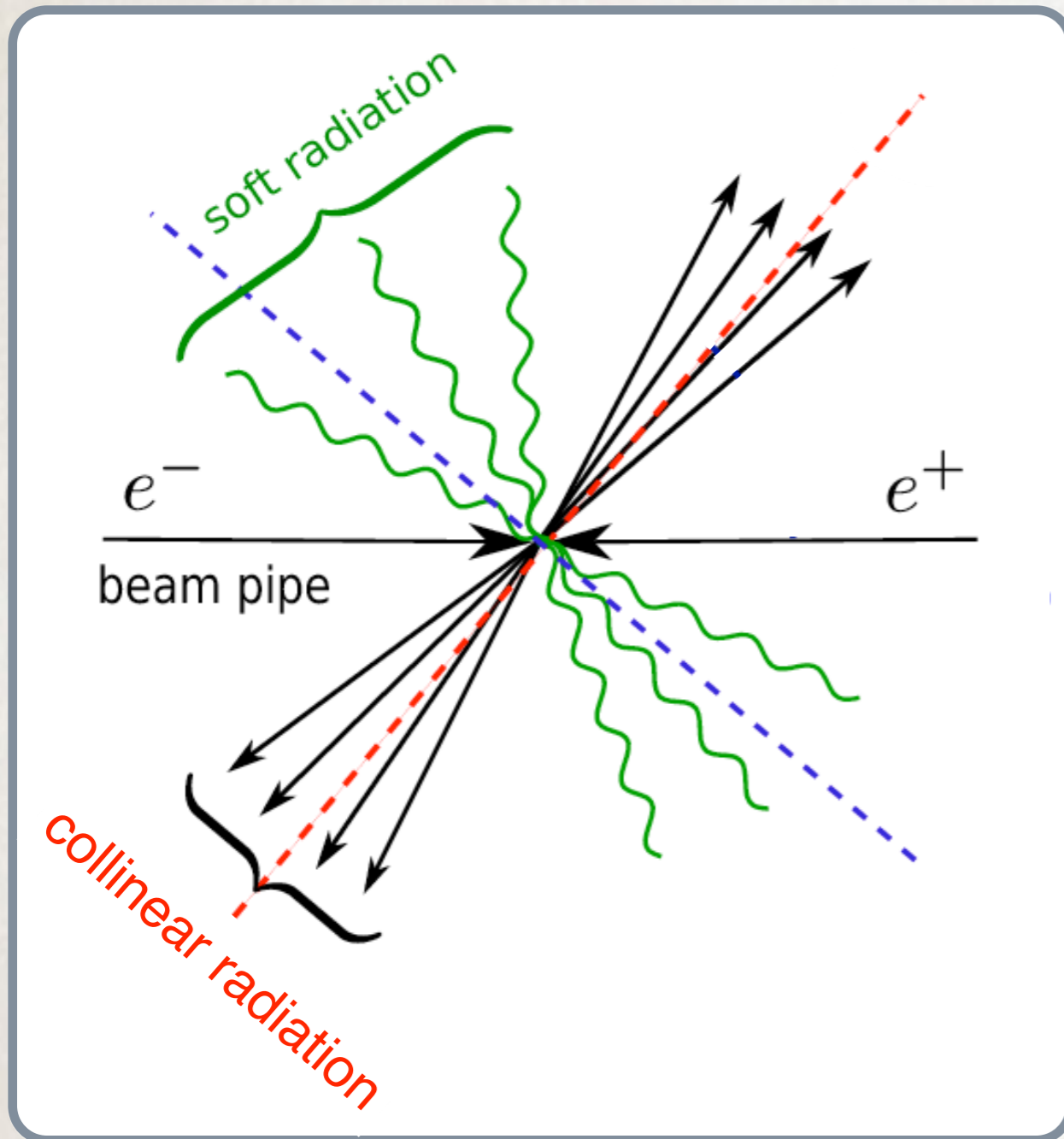


Accidental substructure.

Hook, Izzaguirre, Lisanti, Wacker [arXiv:1202.0558];
TC, Izzaguirre, Lisanti, Lou [arXiv:1212.1456];
El Hedri, Hook, Jankowiak, Wacker [arXiv:1302.1870]

Jet substructure without boosts!

QCD JETS ARE SKINNY



IR structure of QCD:
radiation tends to be
soft or **collinear**.

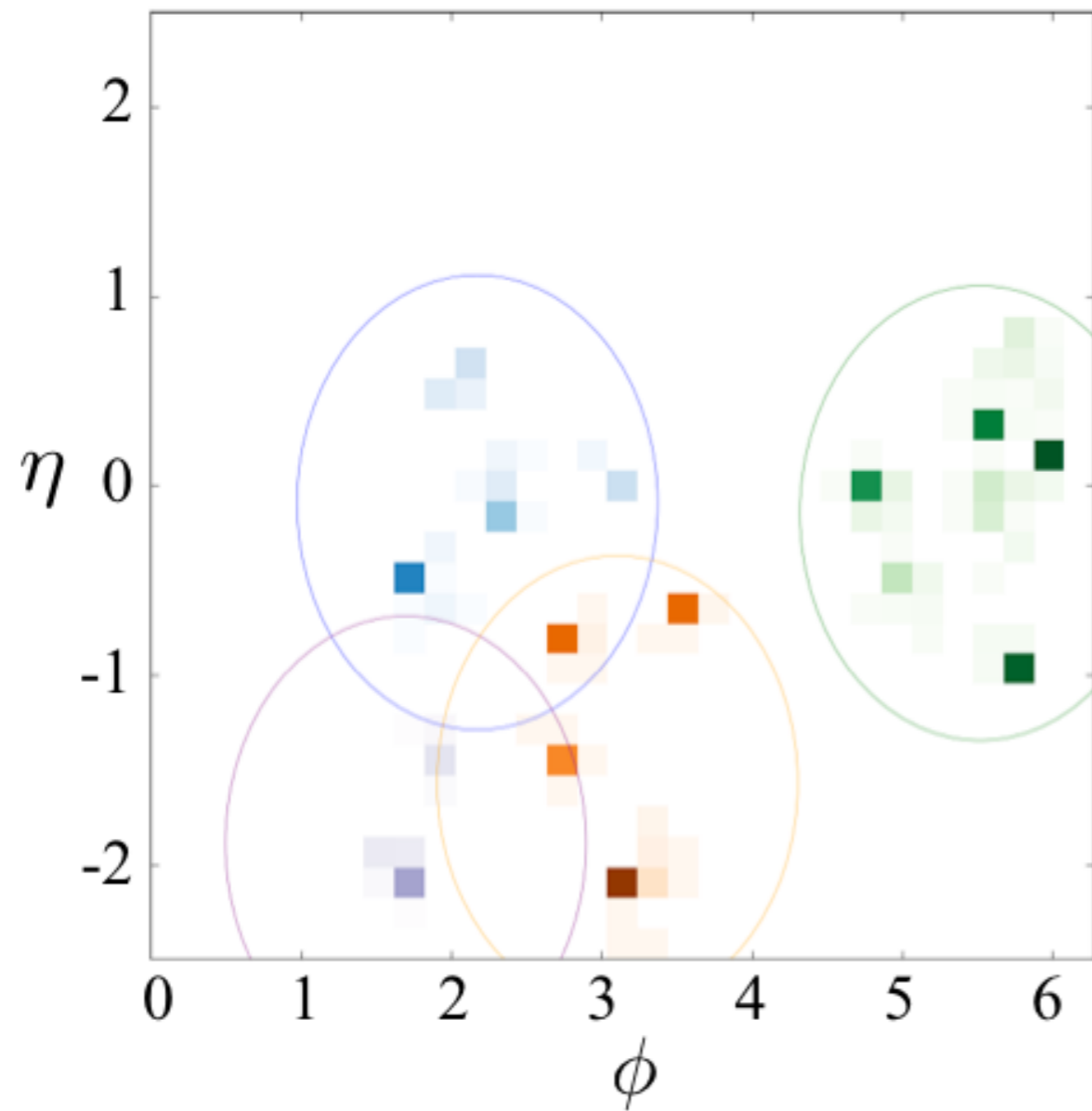
Hard partons are rare.

Difficult to satisfy a
multi-fat jet selection.

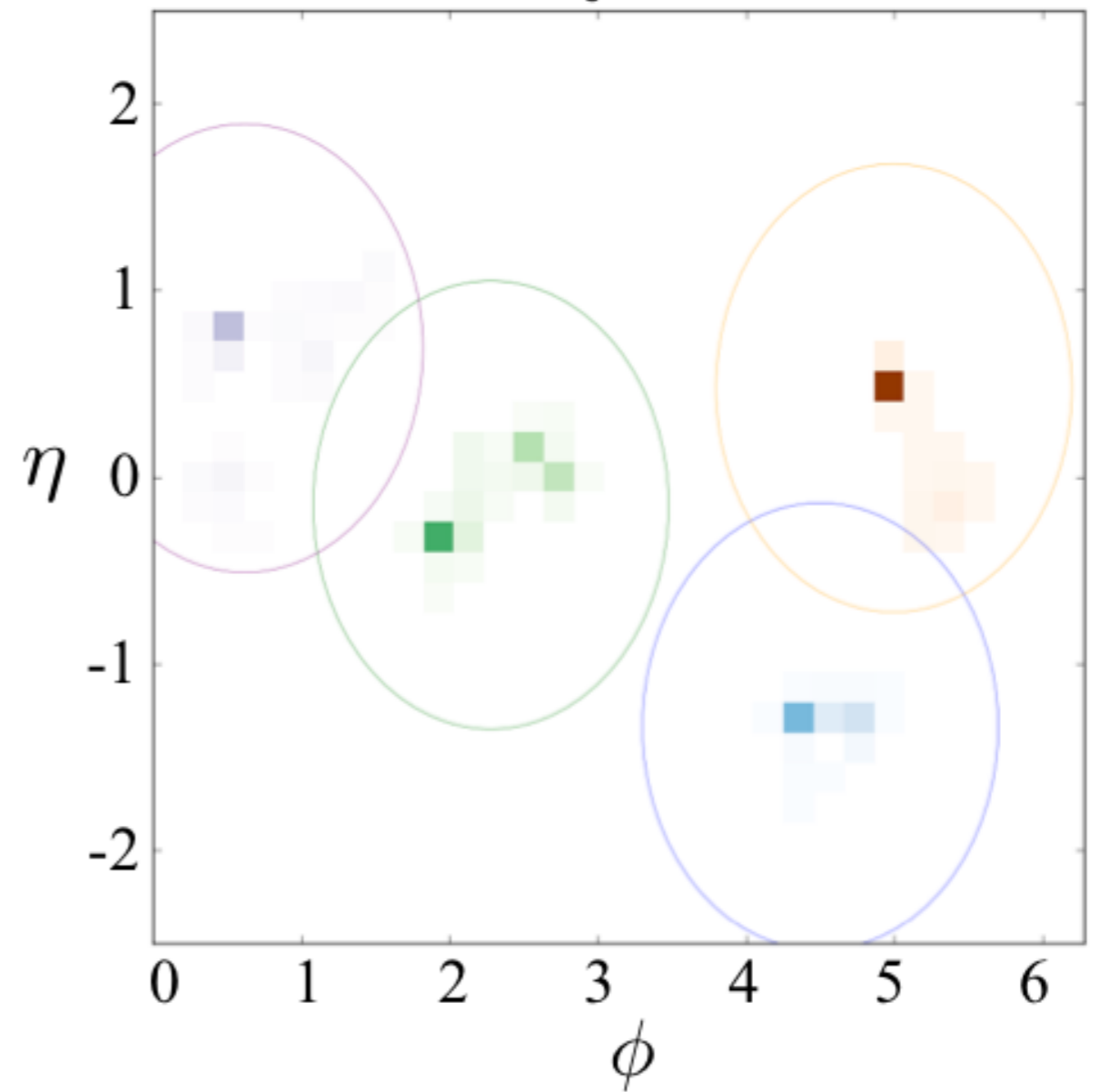
Mass and substructure are
effective discriminators.

SIGNAL VERSUS BACKGROUND

$\tilde{g} \rightarrow t\bar{t} + 3j$



QCD

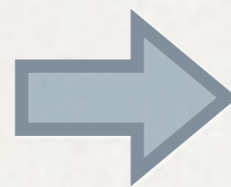
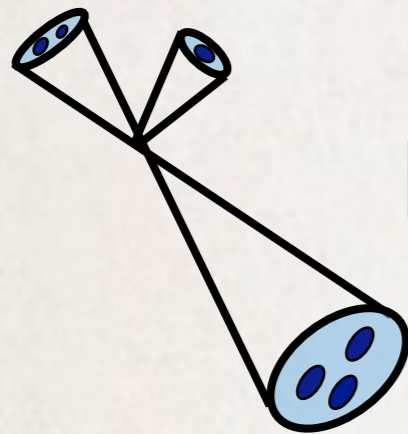


TC, Izzaguirre, Lisanti, Lou [arXiv:1212.1456]

JET SUBSTRUCTURE TEMPLATES

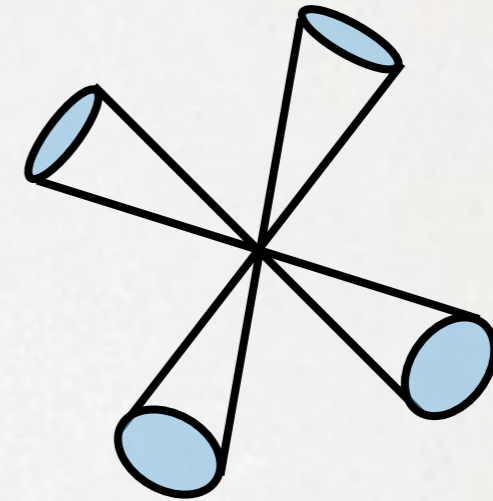
Physical assumption: jets factorize.

Training Sample

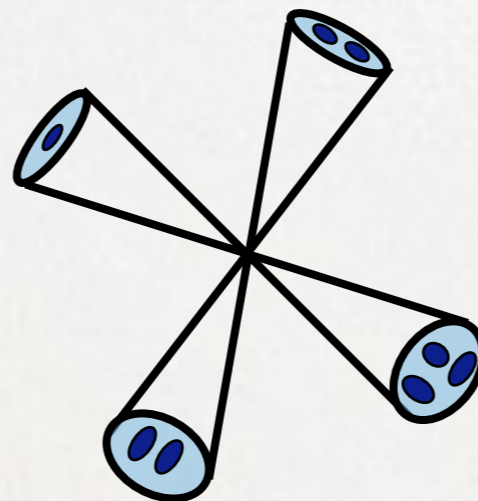


Template

Kinematic Sample

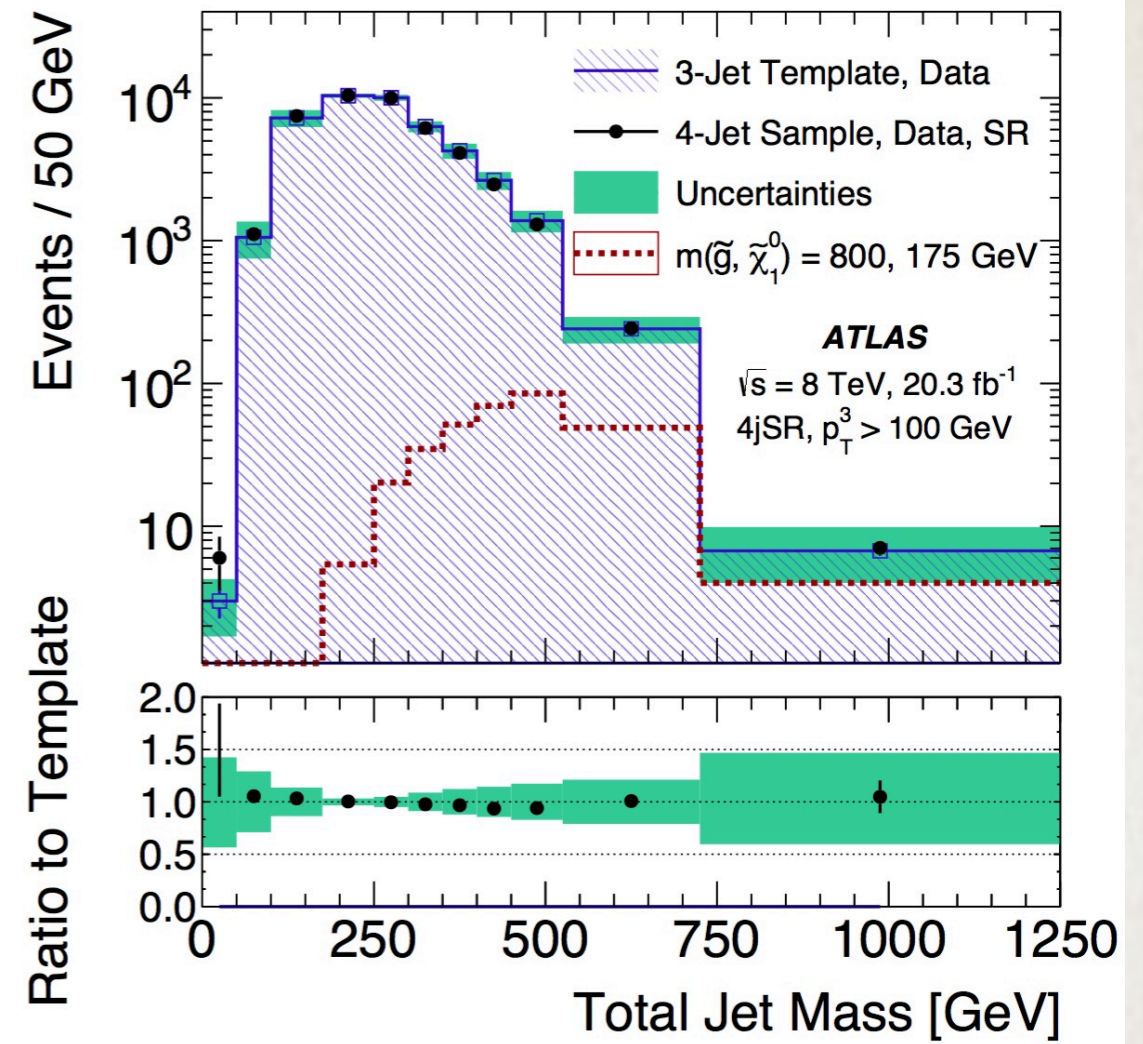
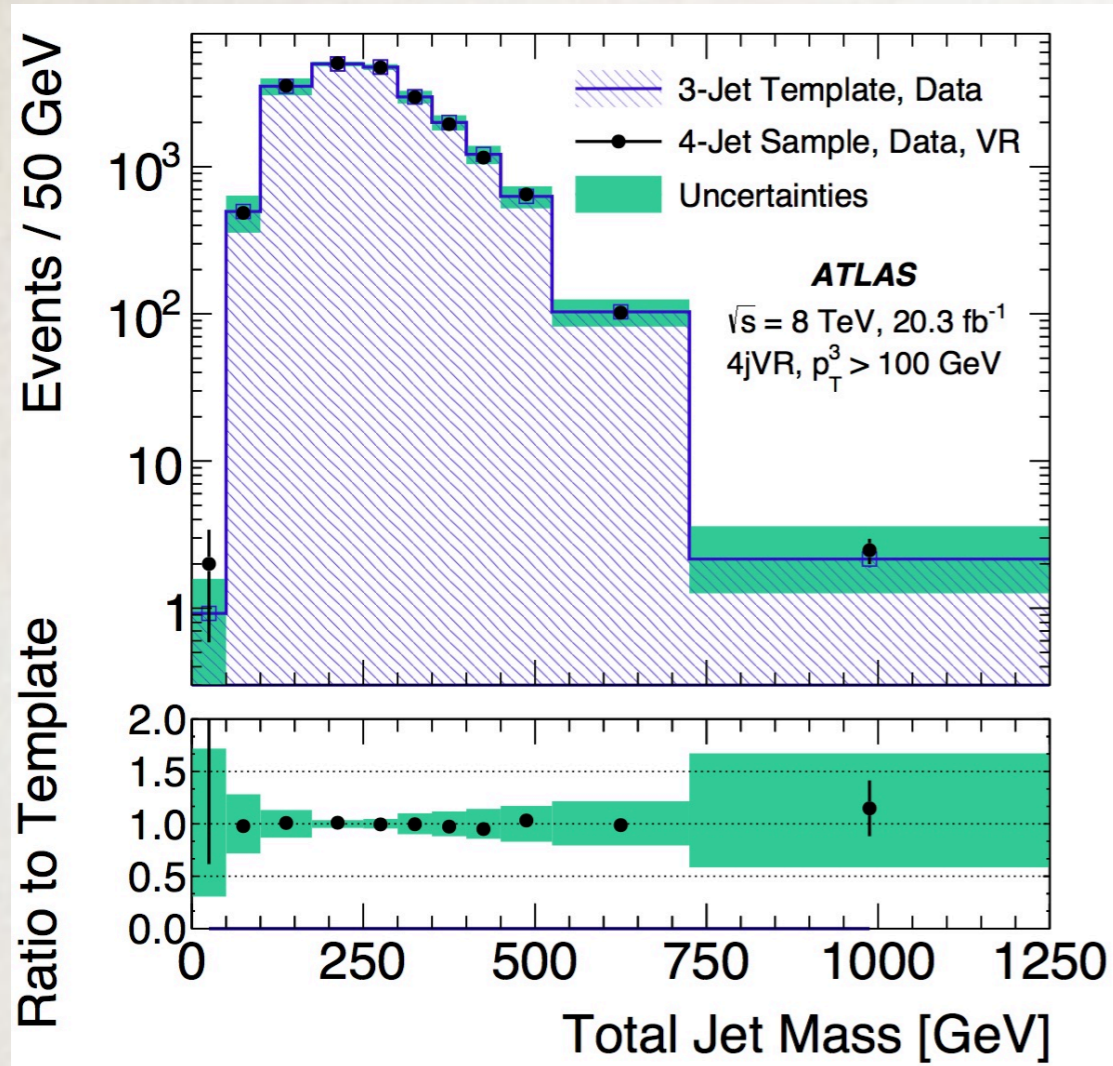


Dressed Sample



TC, Jankowiak, Lisanti, Lou, Wacker [arXiv:1402.0516]

SUBSTRUCTURE TEMPLATES IN DATA

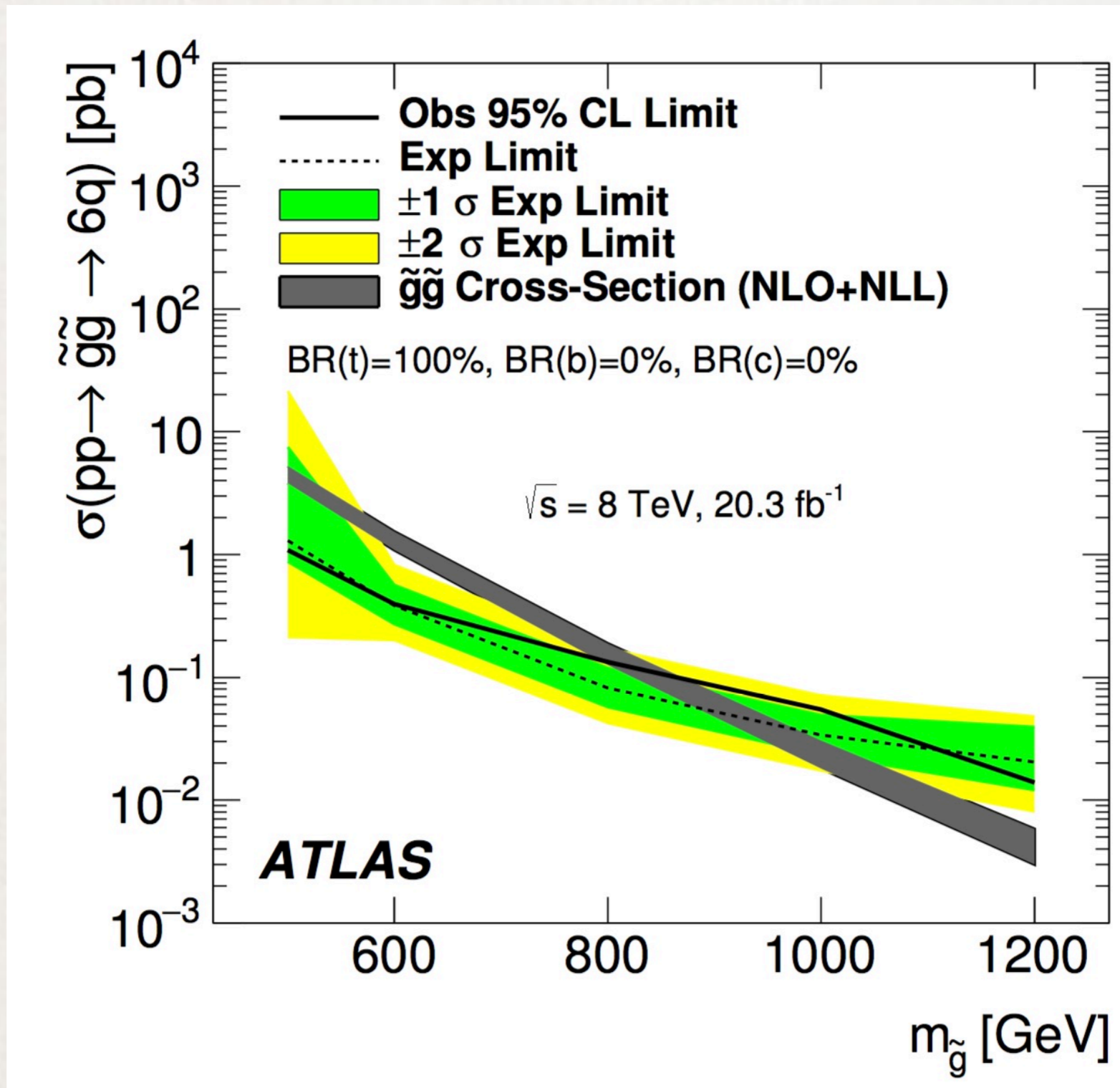


ATLAS [arXiv:1502.05686]

Kernel smoothing techniques used to derive template error bars.

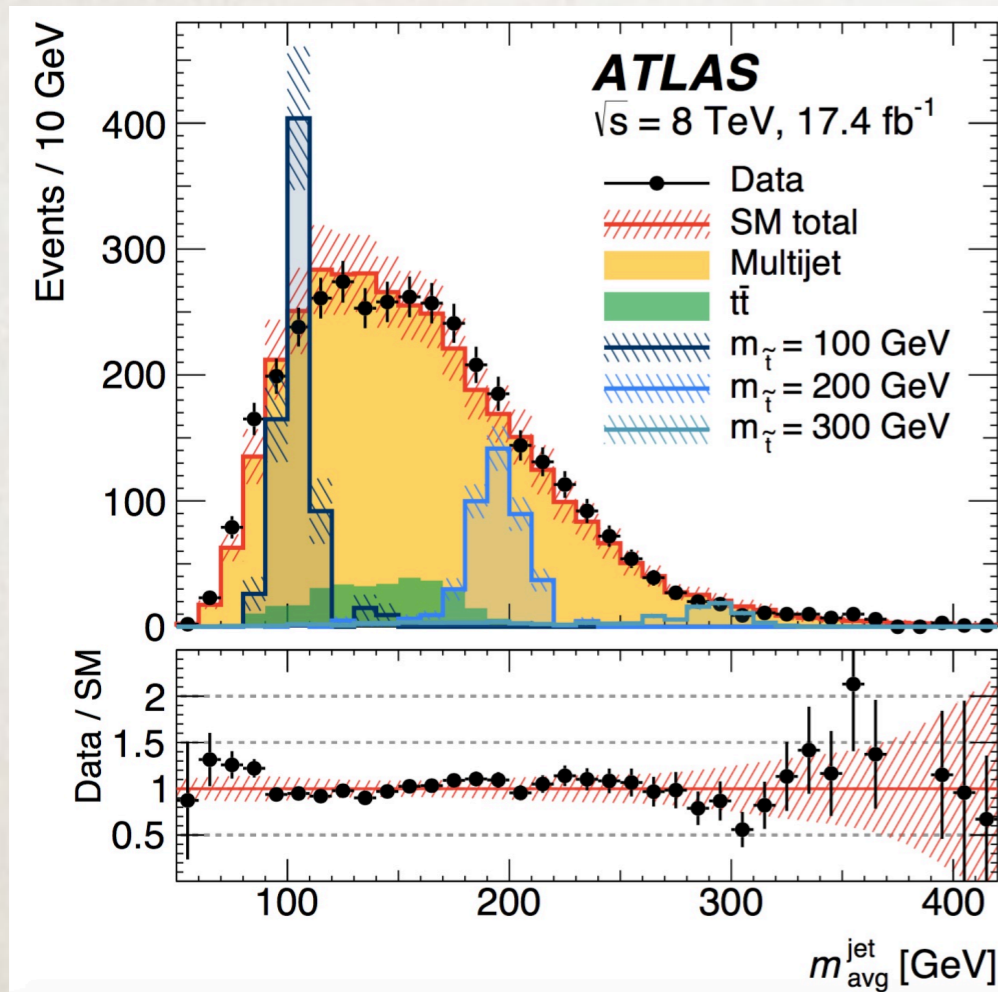
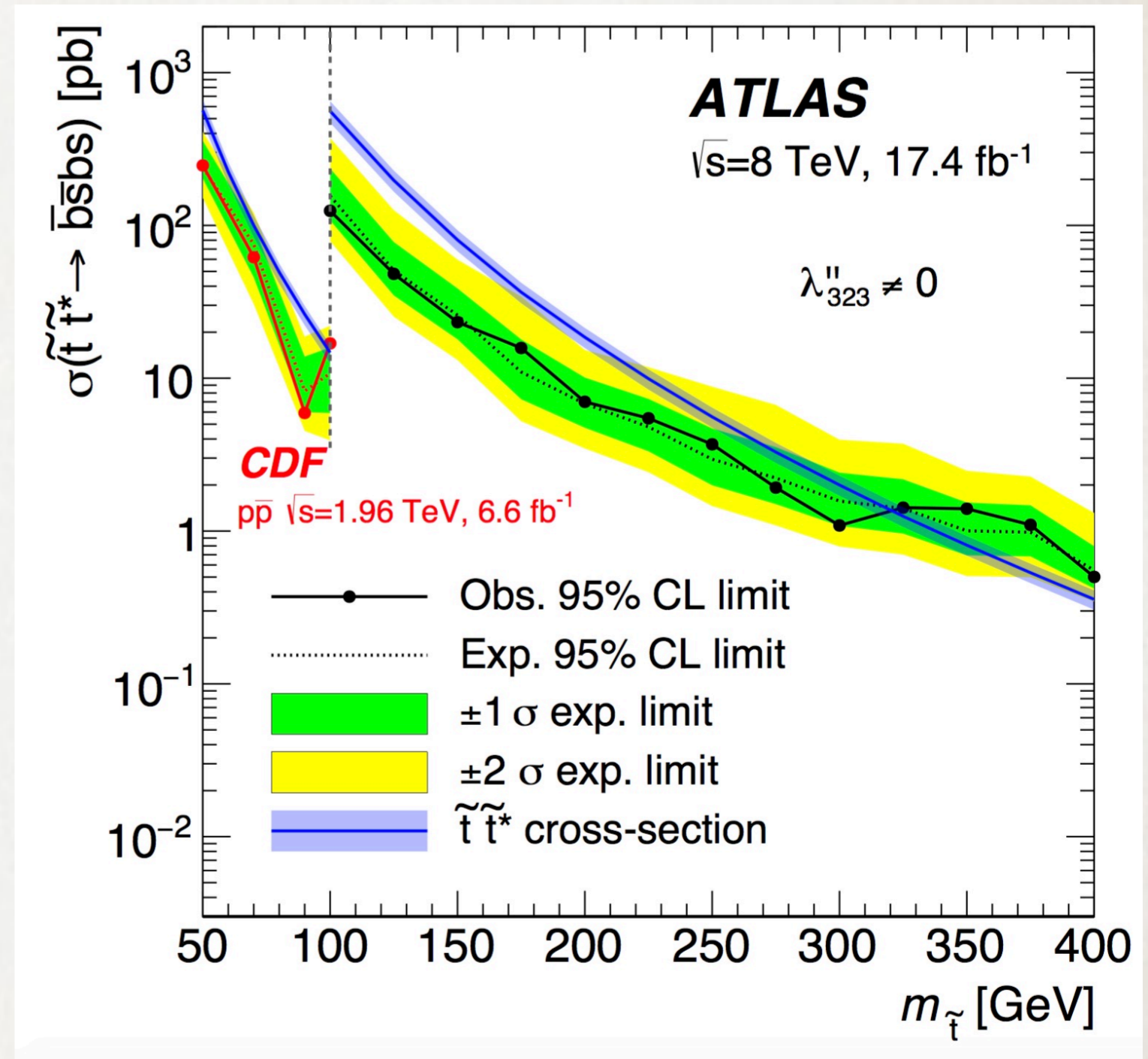
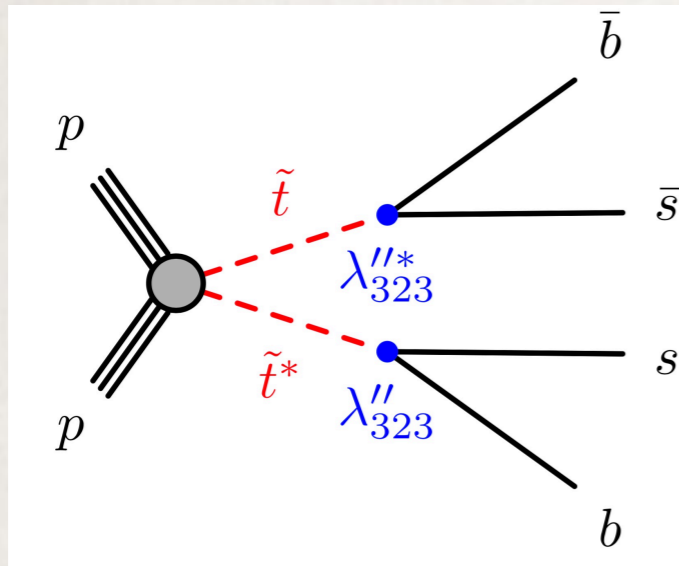
TC, Jankowiak, Lisanti, Lou, Wacker [arXiv:1402.0516]

LHC CONSTRAINTS



[ATLAS \[arXiv:1502.05686\]](https://arxiv.org/abs/1502.05686)

RPV STOPS



ATLAS [arXiv:1601.07453]

LONG LIVED (SPLIT)SUSY

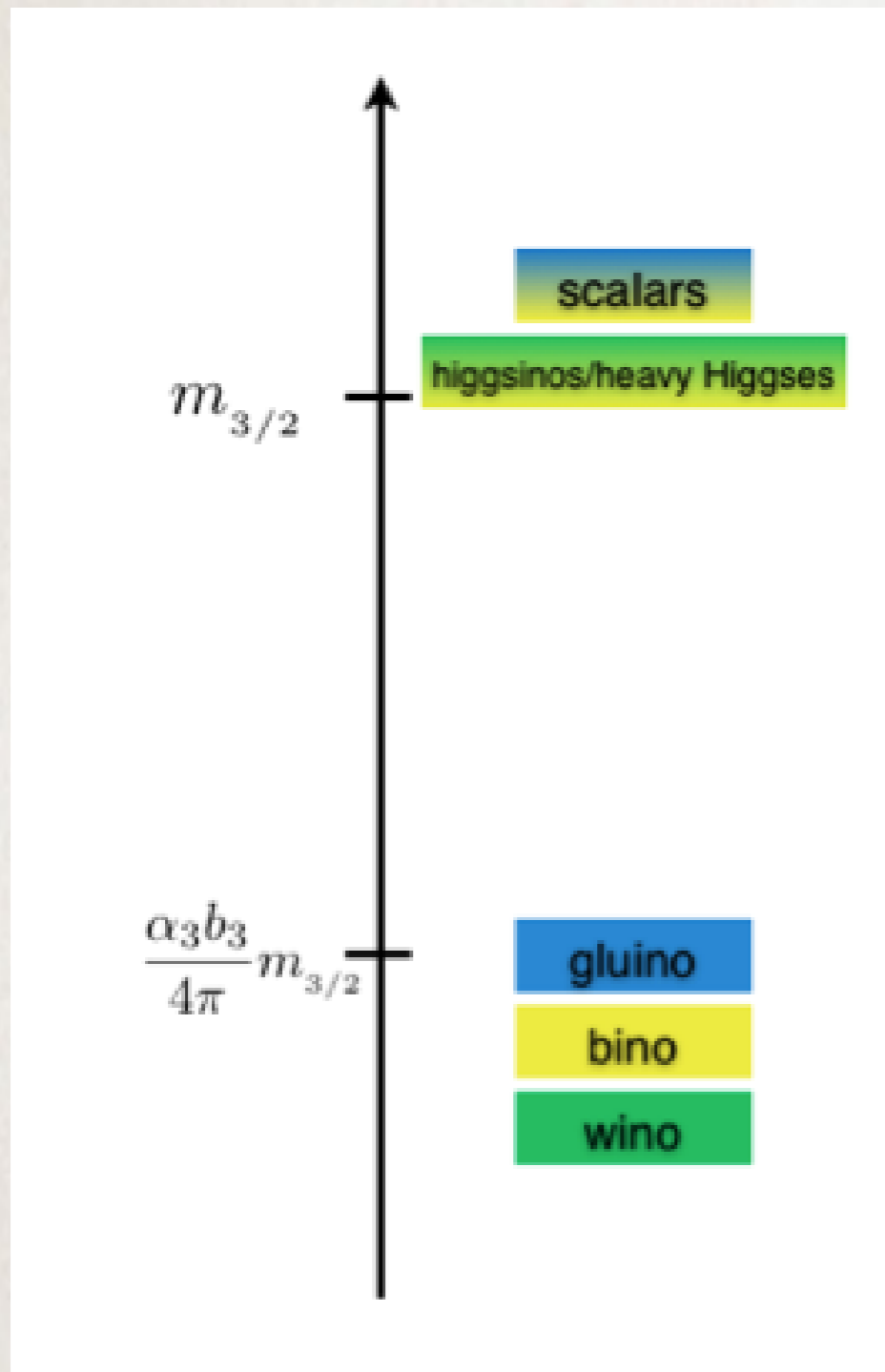
SPLIT SUSY

MSSM (with conserved R -parity)

Compelling SUSY breaking scheme:
Gravity + Anomaly mediation

Tuned electroweak scale.

(Will avoid the dreaded “a” word.)



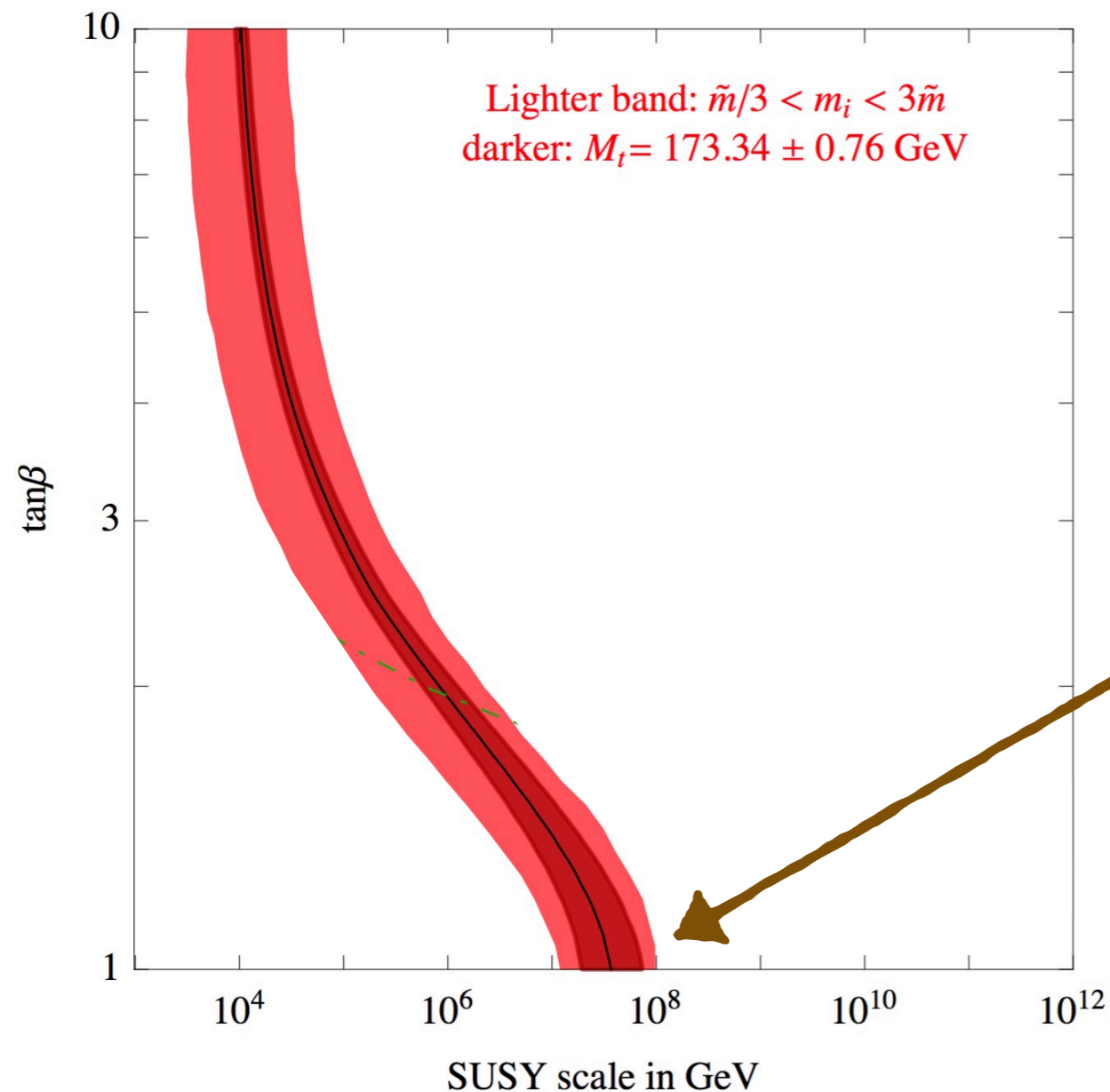
Ask Nathaniel or me about this

TC, Craig, Knapen [arXiv:1512.06128]



Features:
dark matter
gauge coupling unification
less severe flavor problems
accommodate Higgs mass

FROM HIGGS MASS TO GLUINO MASS



Bagnaschi, Giudice, Slavich, Strumia [arXiv:1407.4081]

Most pessimistic estimate:

$$m_{\tilde{g}} \sim \frac{1}{16\pi^2} m_{\tilde{f}}$$

$$m_{\tilde{f}} \lesssim 10^8 \text{ GeV}$$

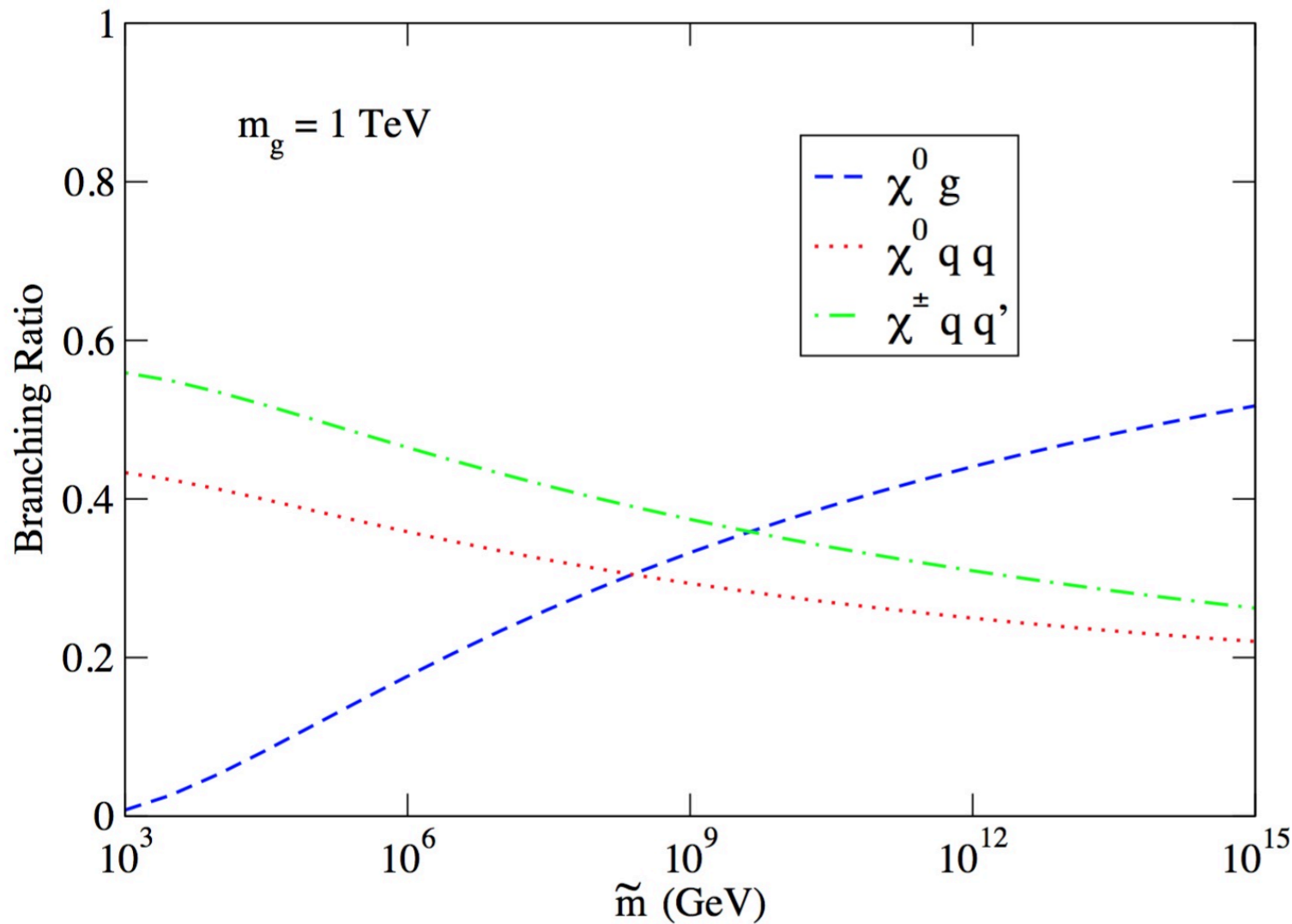


$$m_{\tilde{g}} \lesssim \text{few} \times 100 \text{ TeV}$$

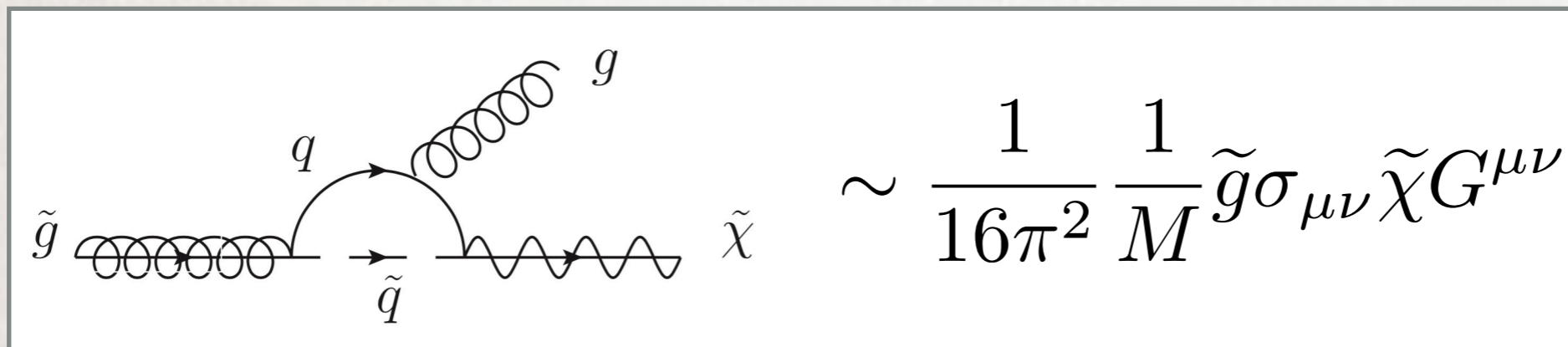
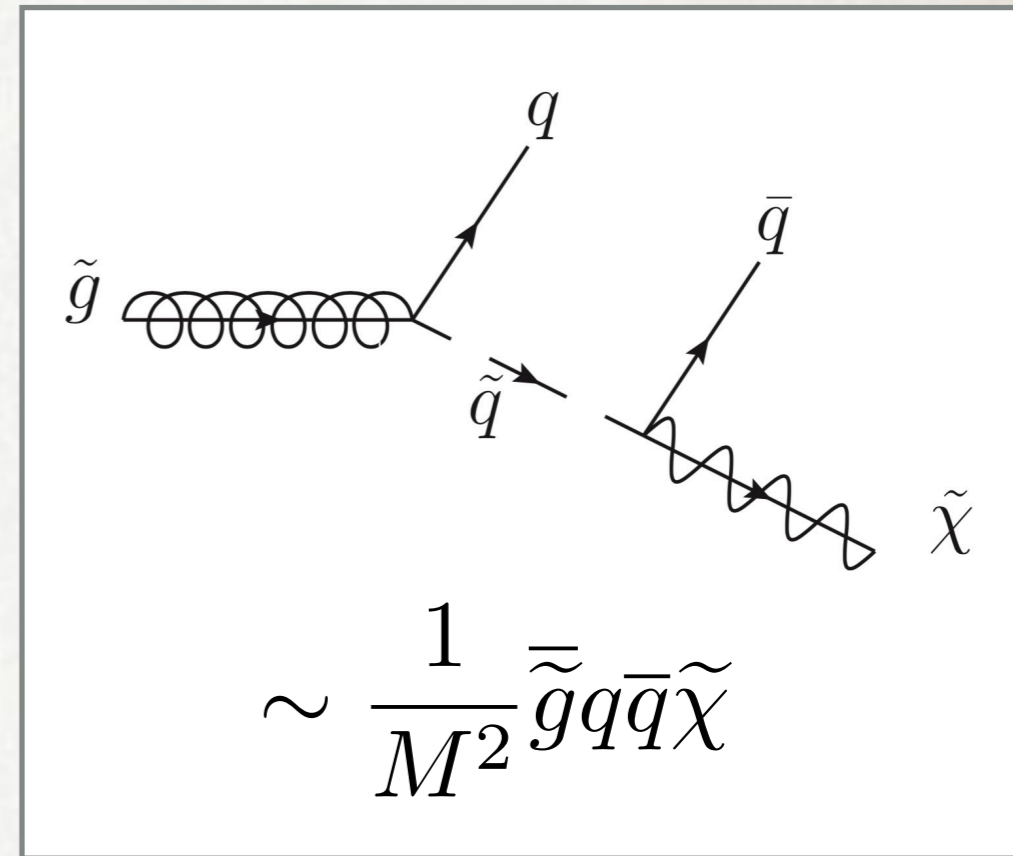
Note: Fast function of $\tan \beta$!

$\tan \beta \gtrsim 2$ yields LHC accessible gluinos.

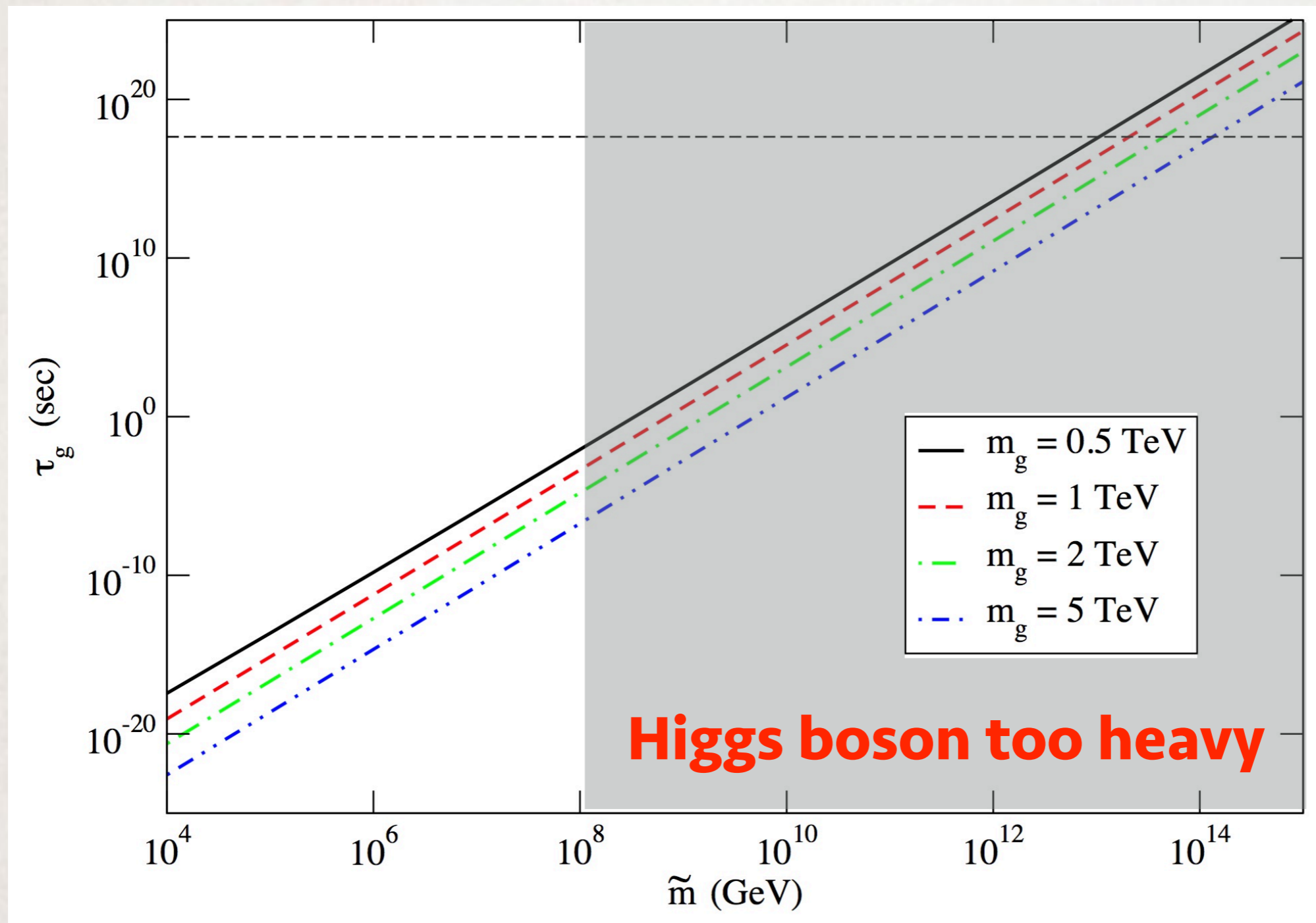
GLUINO DECAYS



Bagnaschi, Giudice, Slavich, Strumia [arXiv:1407.4081]



GLUINO LIFETIME



Gambino, Giudice, Slavich [arXiv:hep-ph/0506214]

LONG LIVED GLUINOS

Gluinos hadronize.

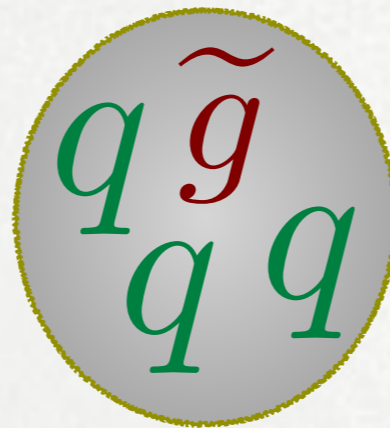
Implemented in Pythia.

Must model transitions between these states.

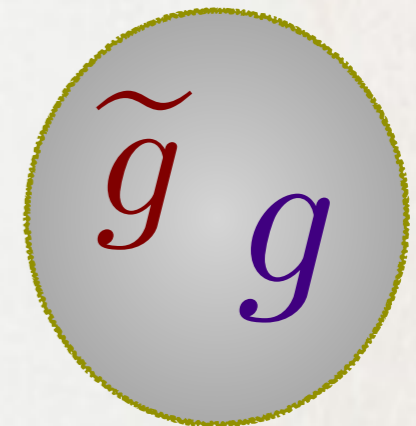
R-mesons



R-baryons



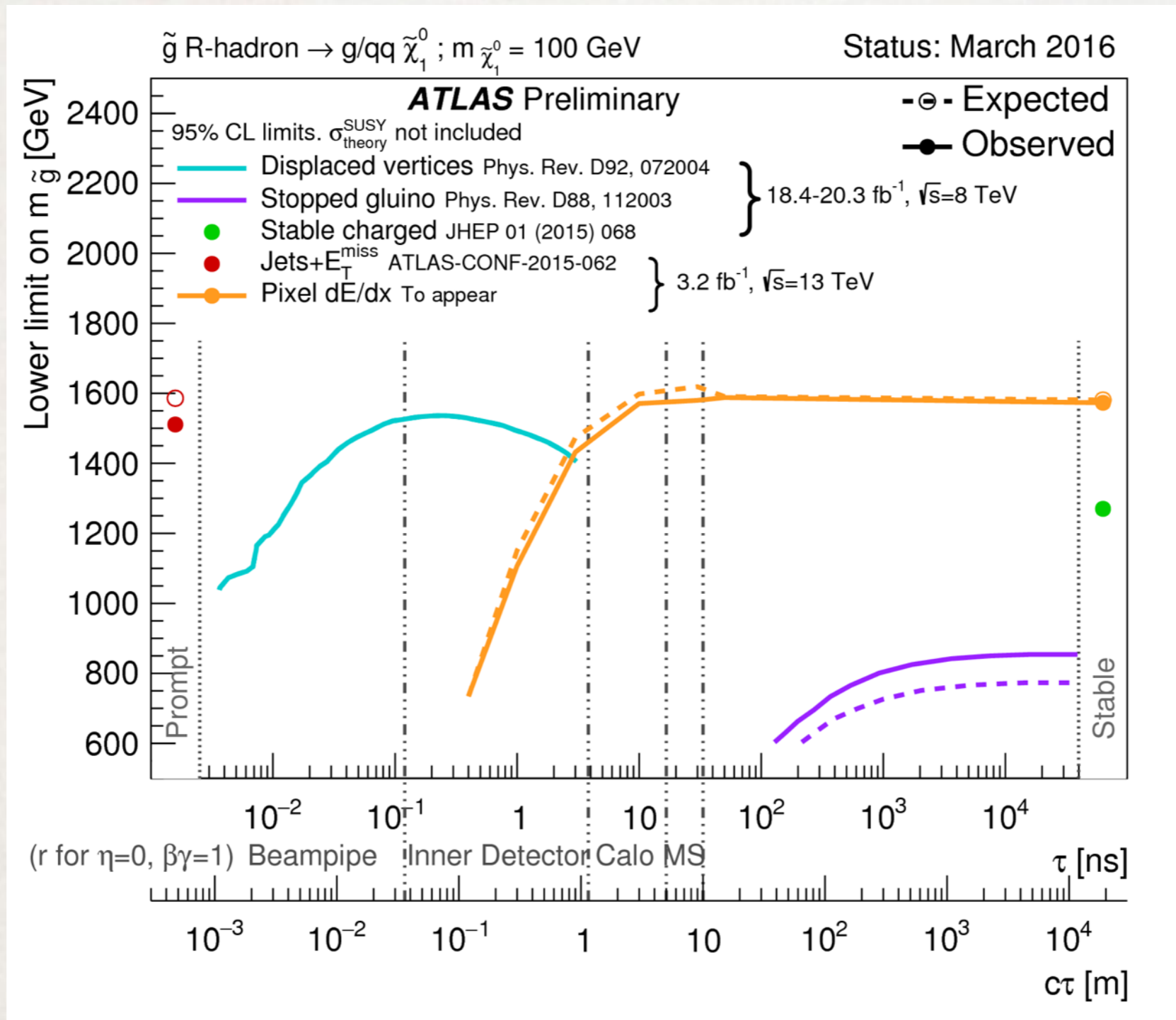
R-gluinoballs



Roughly two regimes (impacts search strategy):

From slow to stopped.

CONSTRAINTS



See G. Redlinger's talk for experimental details.

OTHER EXOTIC SUSY

NEUTRAL NATURALNESS

Can the top partners be uncolored?

Fermionic top partners: Twin Higgs

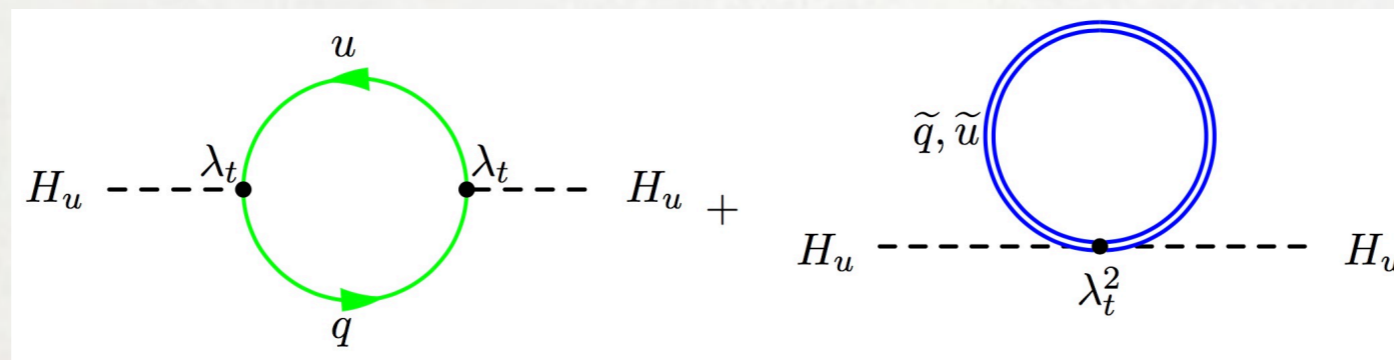
Chacko, Goh, Harnik [arXiv:hep-ph/0506256]

Scalar top partners: Folded SUSY

Burdman, Chacko, Goh, Harnik [arXiv:hep-ph/0609152]

Both mechanisms have \mathbb{Z}_2 mirror sector.

Dark QCD!



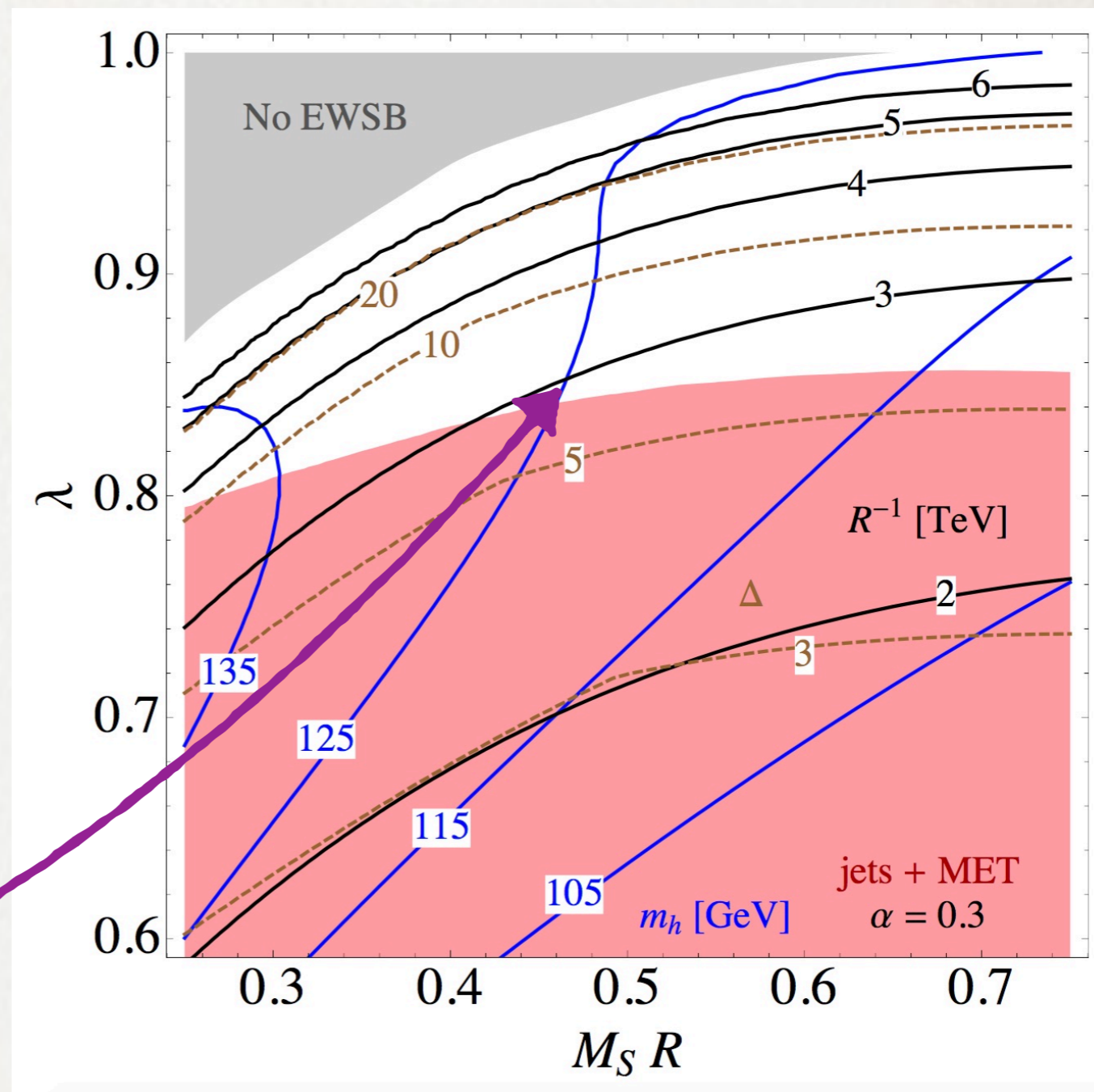
$$(\lambda_t H_u q u + \text{h.c.}) + \lambda_t^2 |\tilde{q} H_u|^2 + \lambda_t^2 |\tilde{u}|^2 |H_u|^2$$

See N. Craig's talk.

Folded squarks

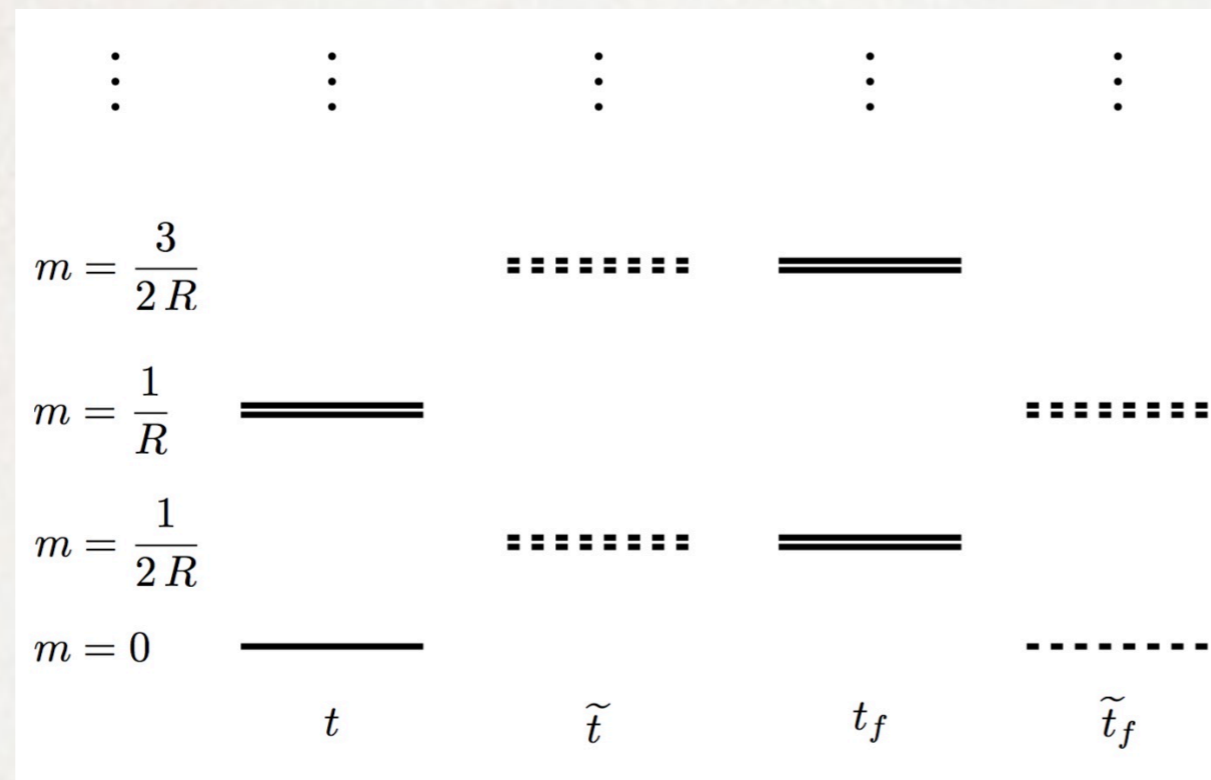
FOLDED SUSY

5D MSSM + Singlet;
NMSSM-like coupling
and singlet mass;
Fully calculable model;
125 GeV Higgs mass with
minimal tuning.



TC, Craig, Lou, Pinner [arXiv:1508.05396]

FOLDED (S)QUIRKS



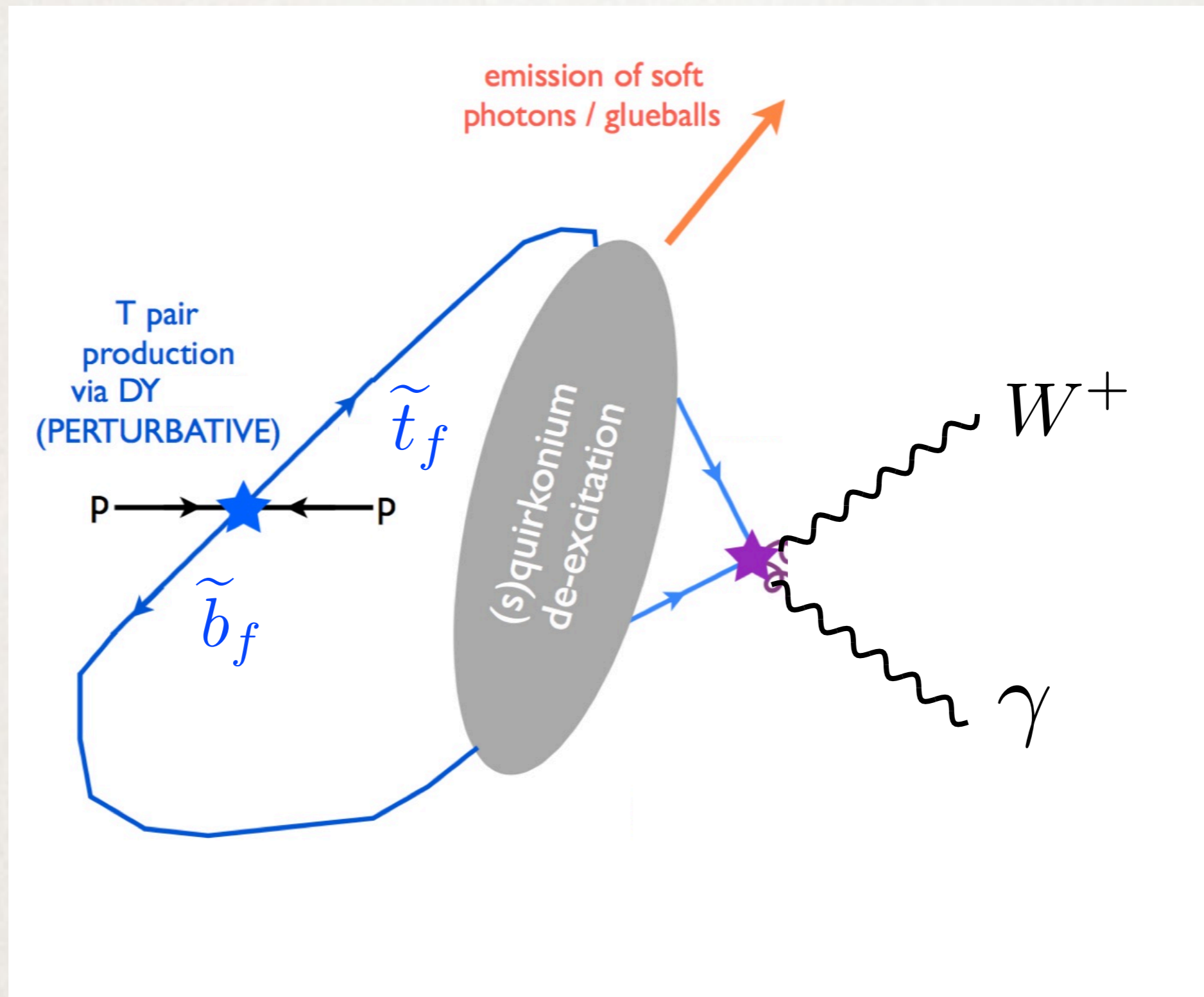
Dark QCD.

Folded squarks without light folded quarks.

$$m_{\tilde{t}_f} \gg \Lambda_{\text{QCD}}^{\text{Dark}}$$

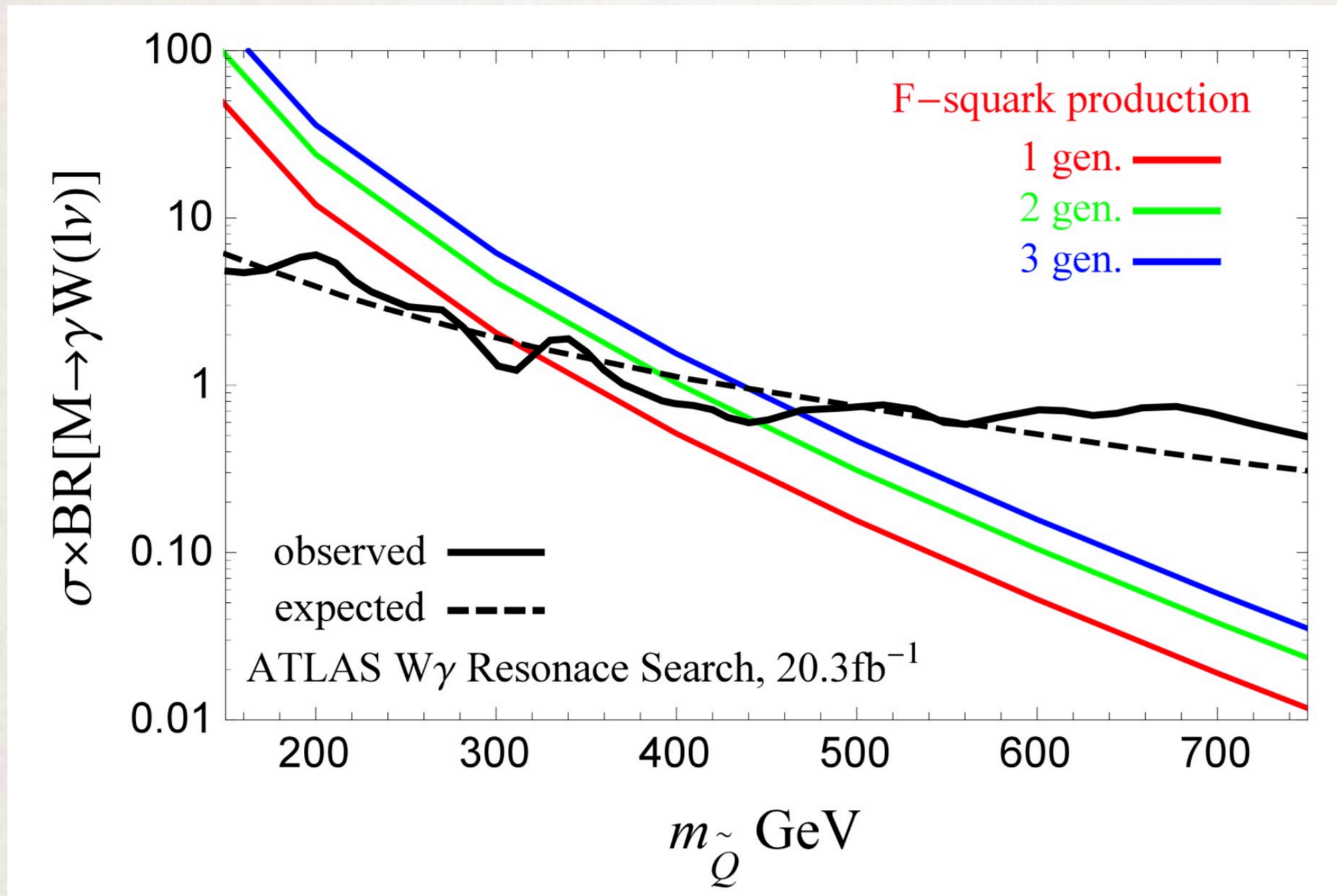
Pair produce folded stops;
 connected by long (dark) color strings;
 radiate (dark) glueballs and then annihilate at rest.

SIGNATURES



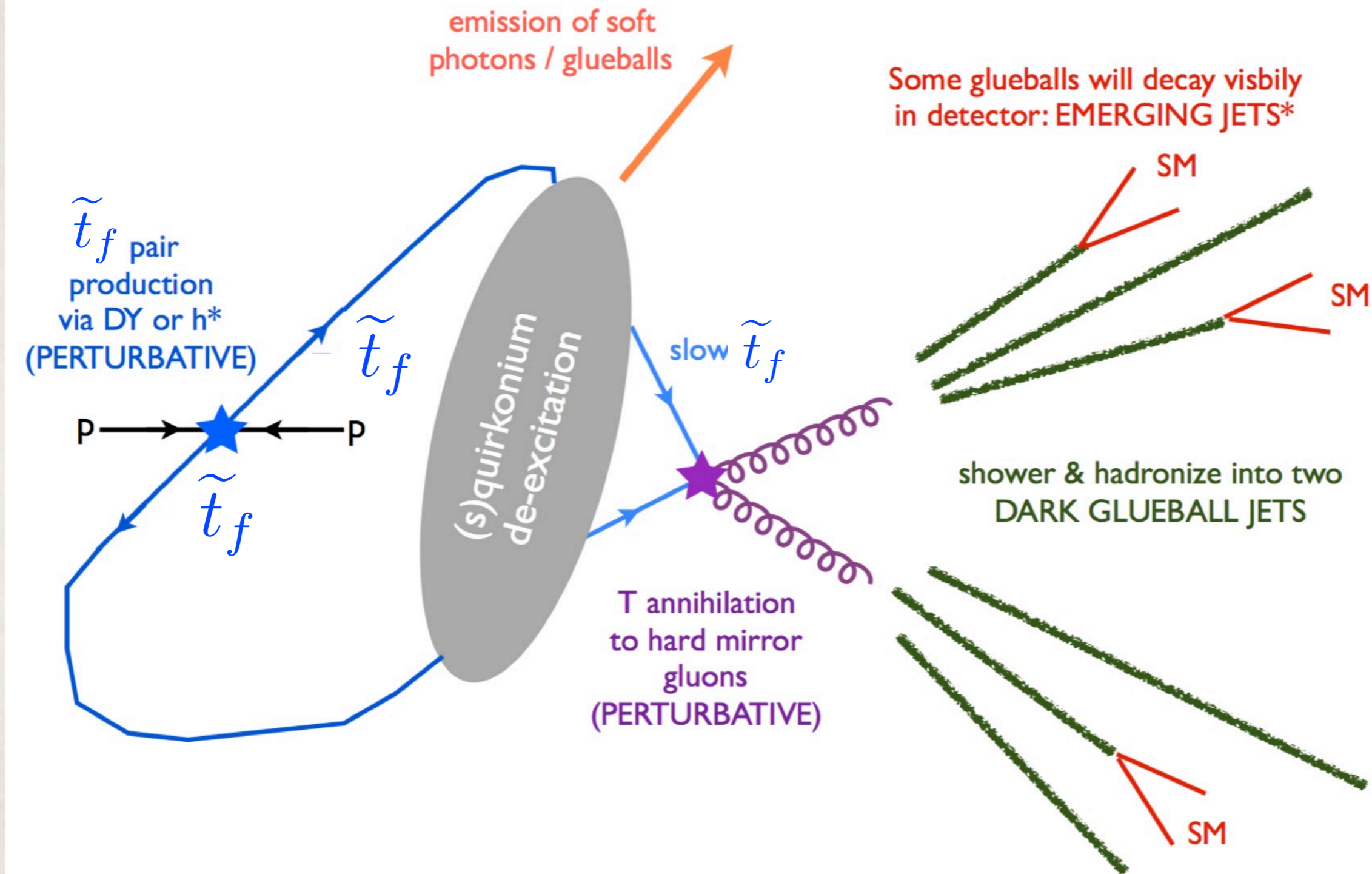
Sketch stolen (and modified) from David Curtin

ELECTROWEAK RESONANCE



[Burdman, Chacko, Harnik, de Lima, Verhaaren \[arXiv:1411.3310\]](#)

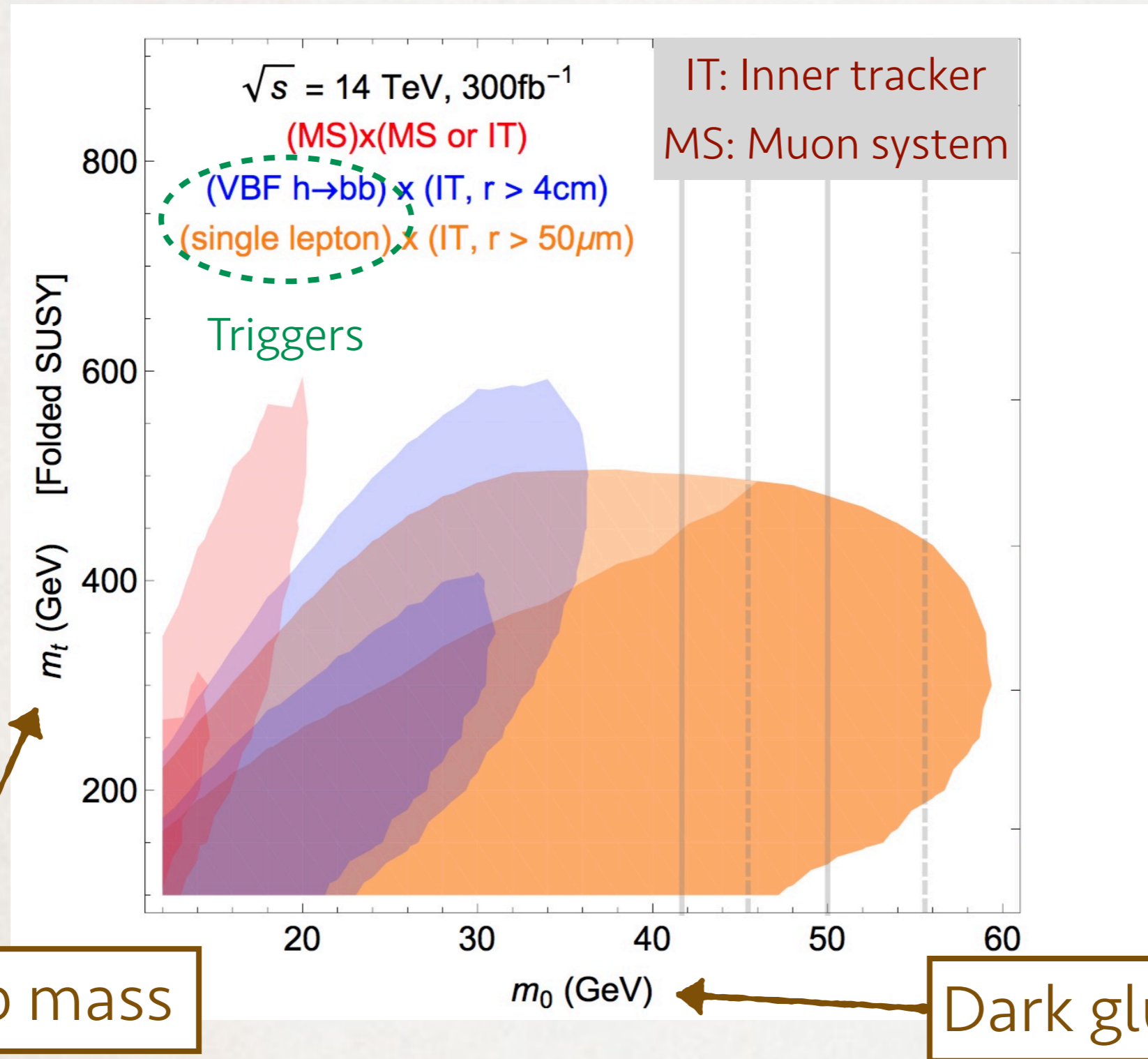
SIGNATURES



* see also 1502.05409 Schwaller, Stolarski, Weiler

Sketch stolen from David Curtin

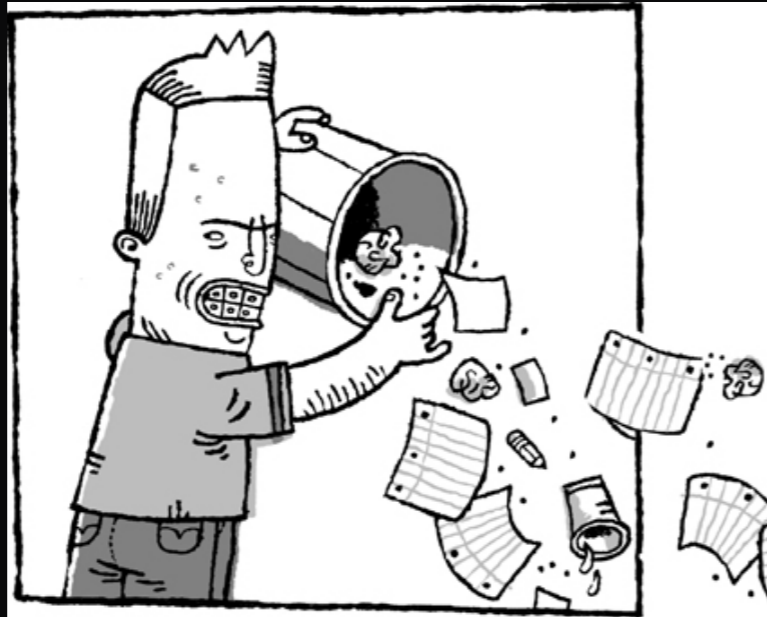
PROSPECTS FOR LHC



Curtin, Verhaaren [arXiv:1512.05782], see also Chacko, Curtin, Verhaaren [arXiv:1512.05782]

OUTLOOK

SO MANY EXCITING SIGNATURES!!



Neutral Naturalness

Folded stops with dark QCD
[quirky annihilations,
rare Higgs decays, ...]

Split SUSY

Long lived gluinos
[slow to stopped]



Baryonic RPV

No missing energy
[accidental substructure]