

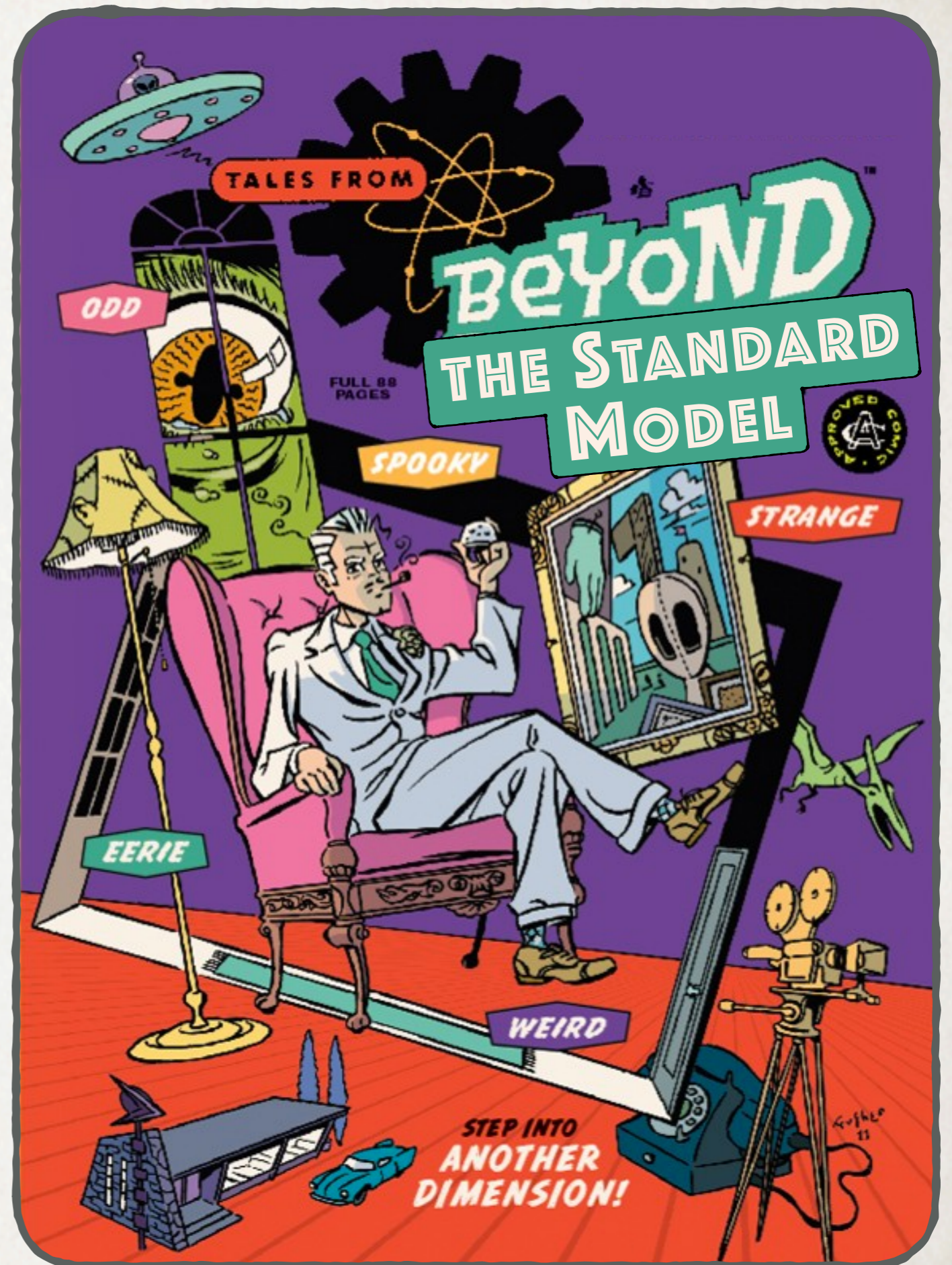
BEYOND MINIMAL SUSY

Tim Cohen

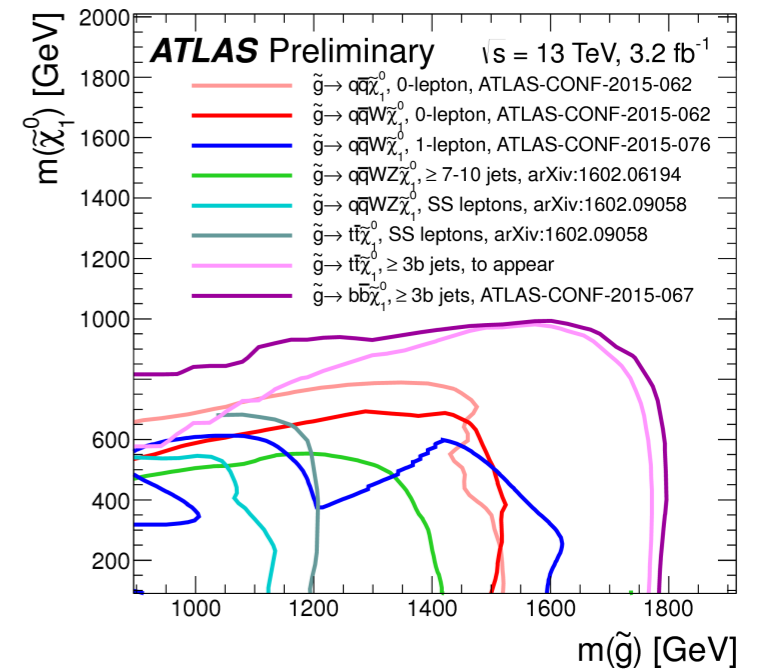
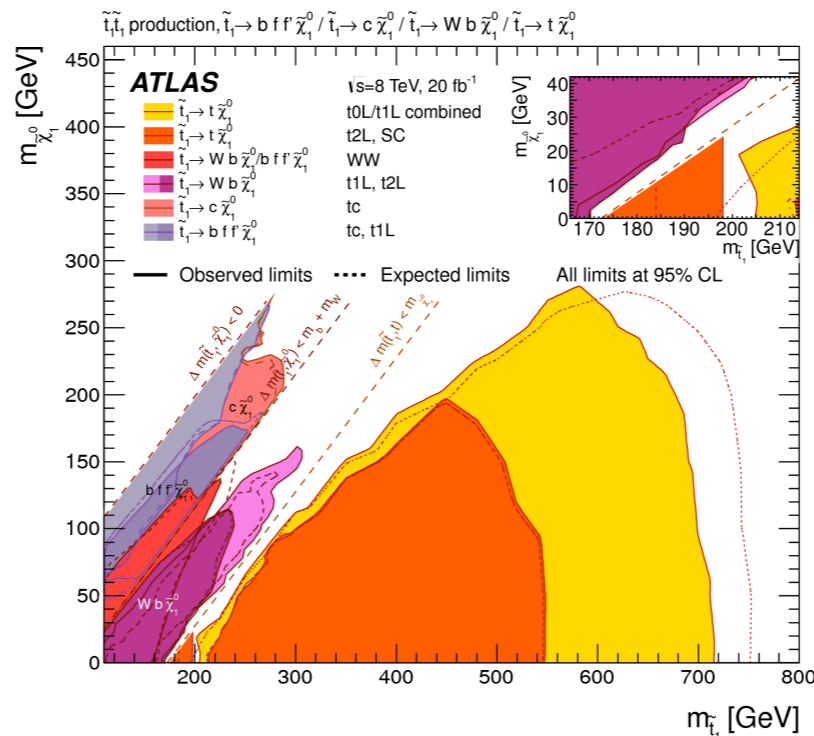
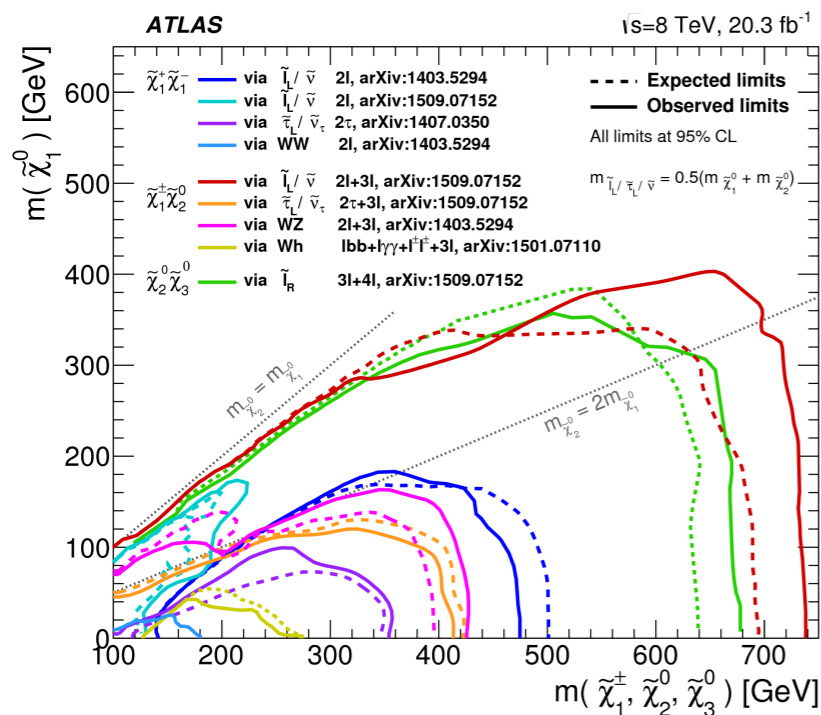
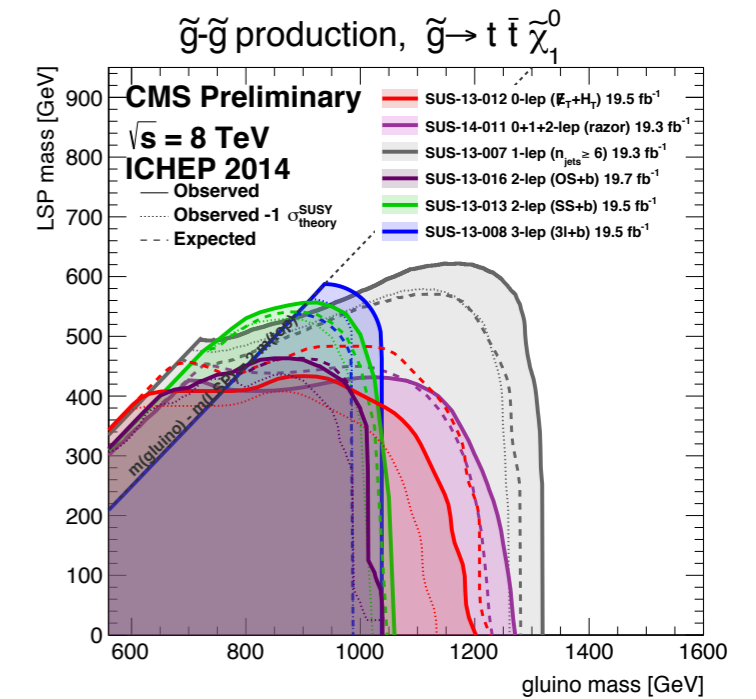
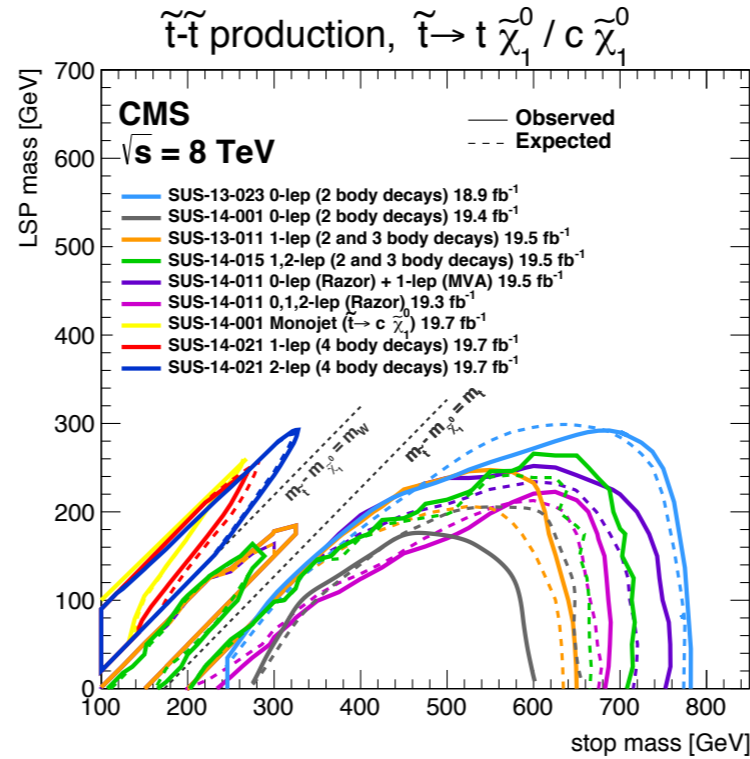
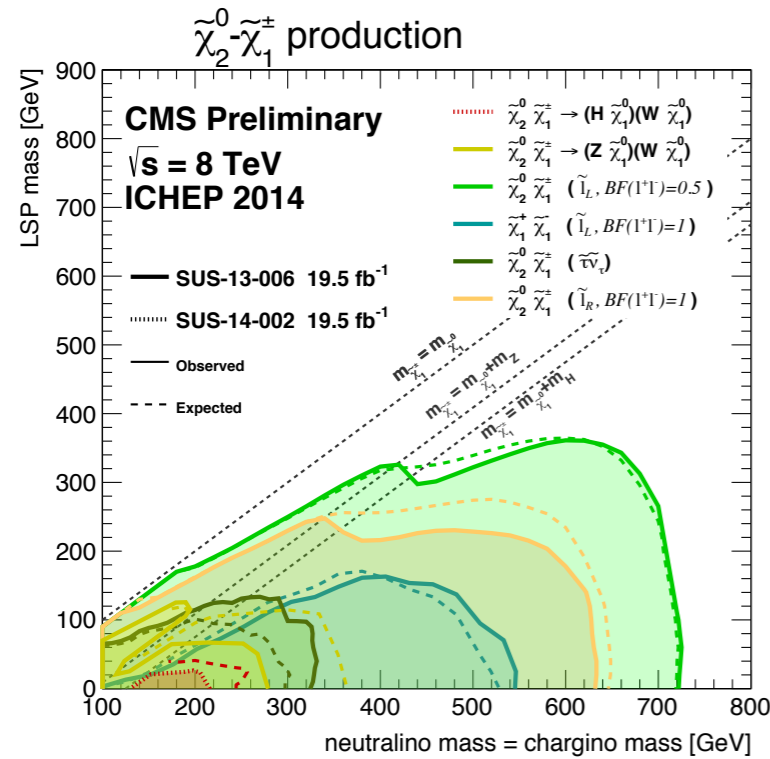
University of Oregon



MC4BSM 2016
UCAS - YuQuan Campus
July 22, 2016

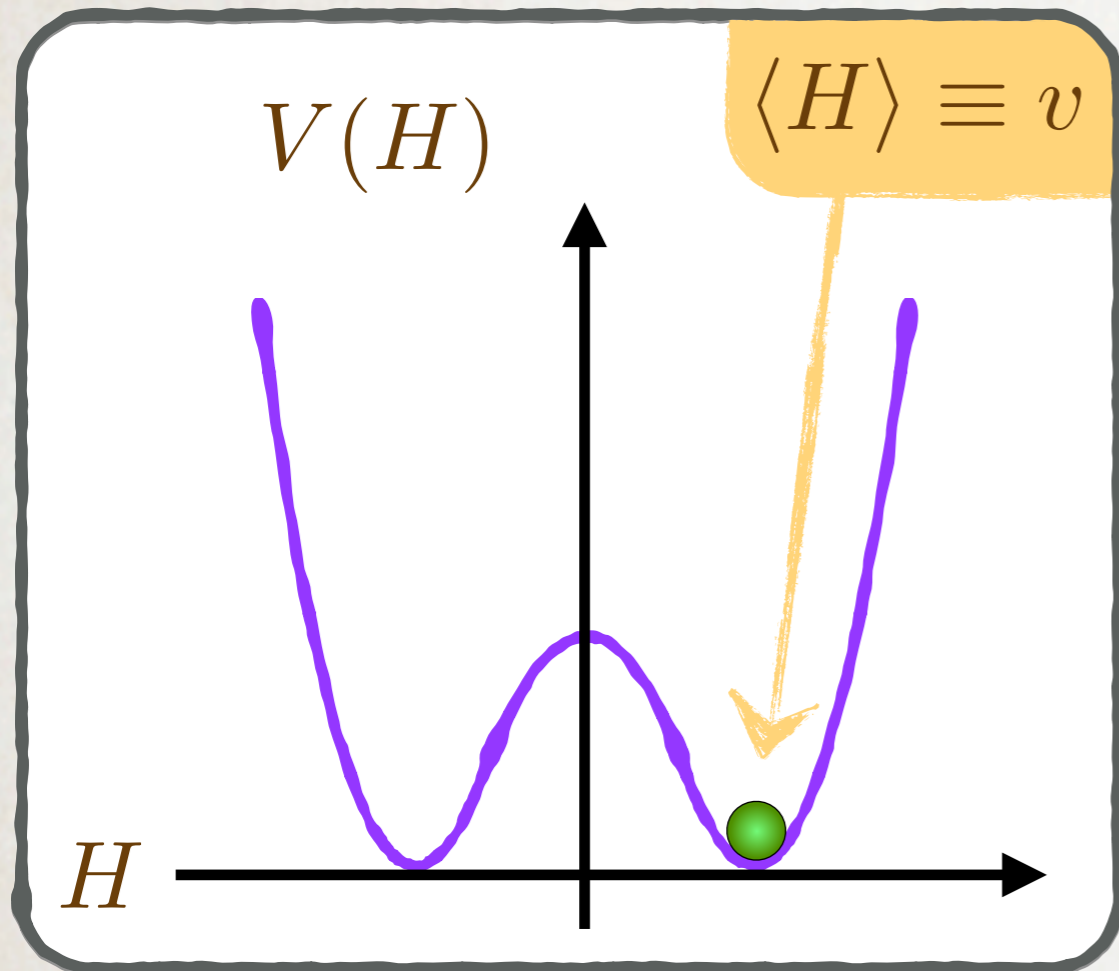


WHERE'S THE NEW PHYSICS?!?



PERTURBATIVITY

$$V(v, H) = -\frac{\mu^2}{2} |v + H|^2 + \frac{\lambda_H}{16} |v + H|^4$$



W^\pm mass $\Rightarrow v \simeq 246$ GeV

Higgs mass $\Rightarrow m_H \simeq 125$ GeV

Yields $\lambda_H \simeq 0.26$
 $\mu \simeq 88$ GeV

**All SM parameters perturbative!
(at weak scale)**

WHY SUSY?

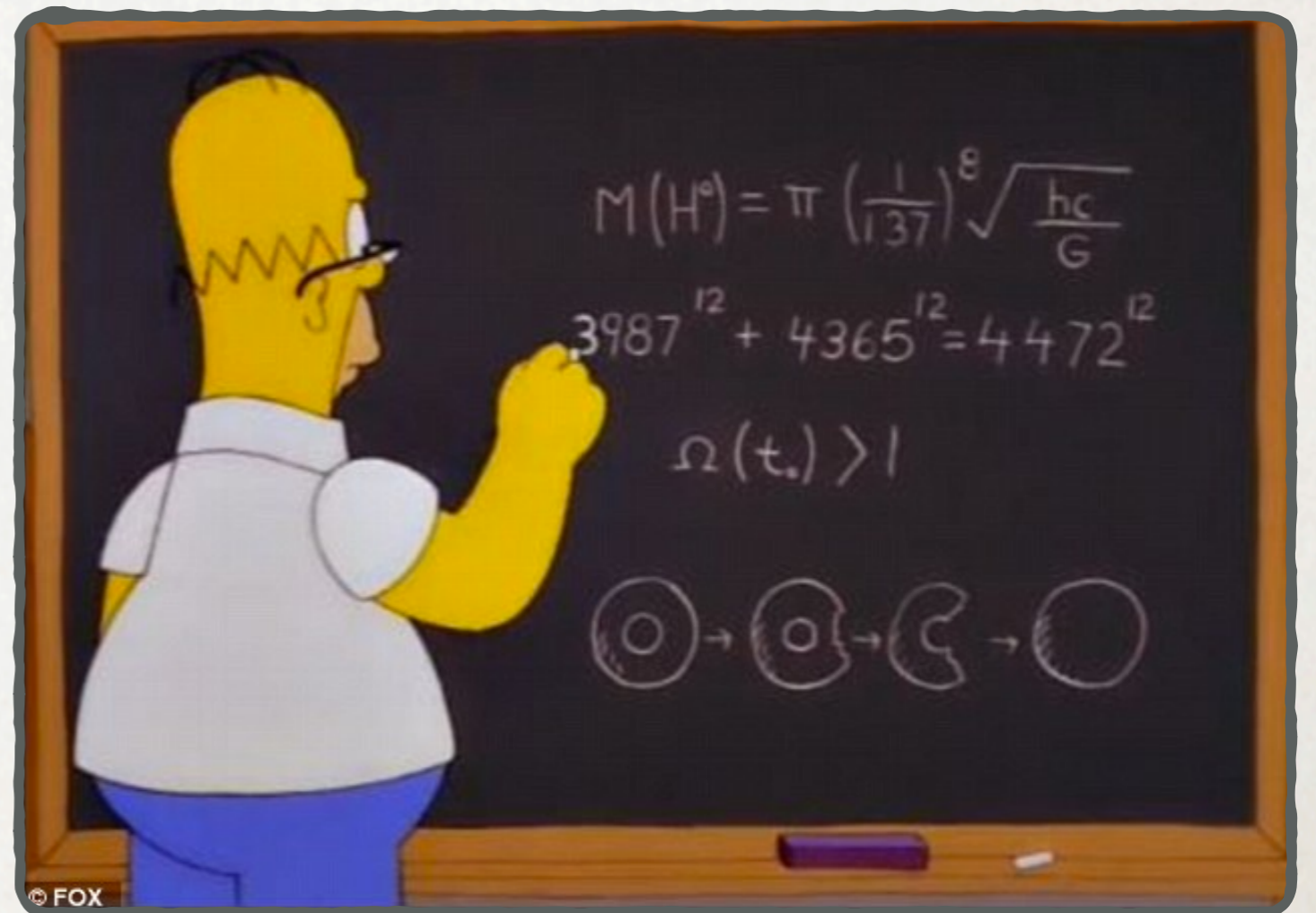
Perturbativity implies calculational control.

STANDARD MODEL

“Model” of electroweak symmetry breaking.
Higgs mass is *not* calculable.

SUSY MODEL

“Theory” of electroweak symmetry breaking.
Higgs mass is *finite*.
Can interpret fine-tuning.

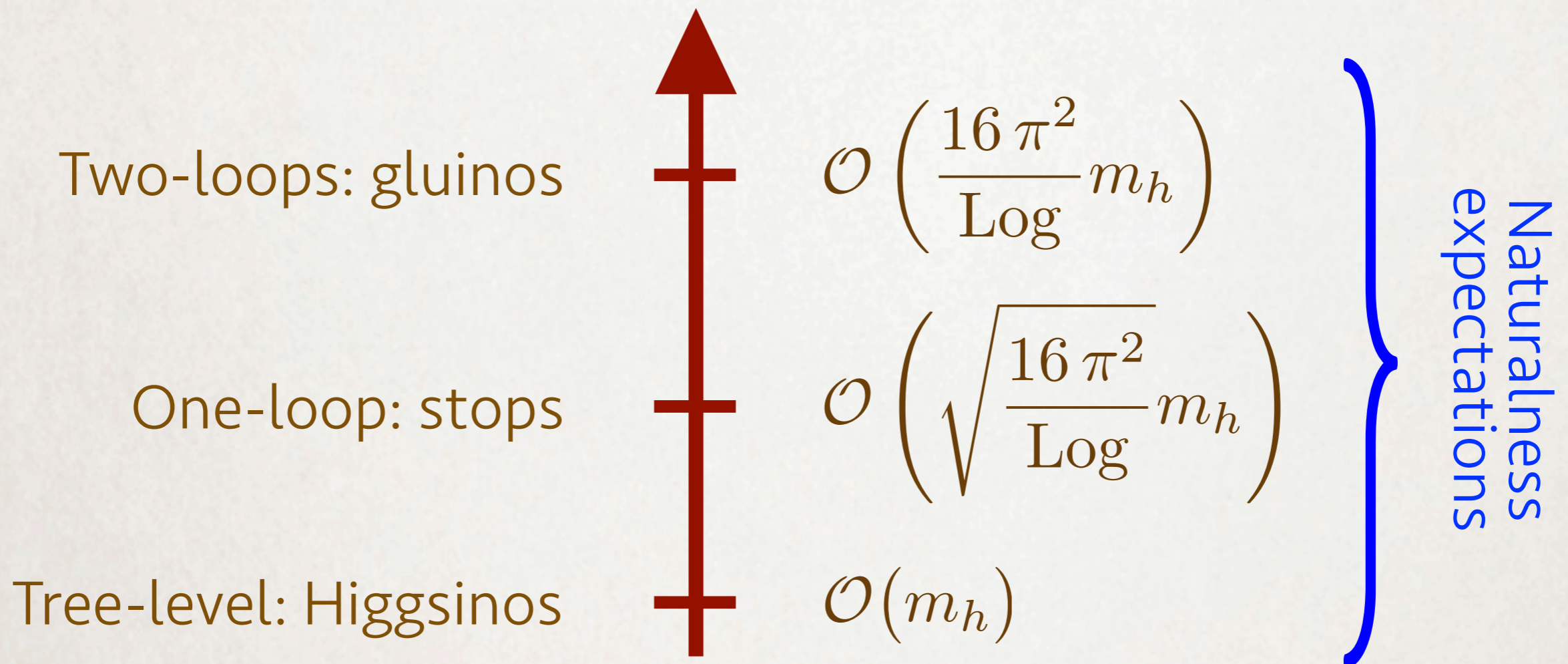
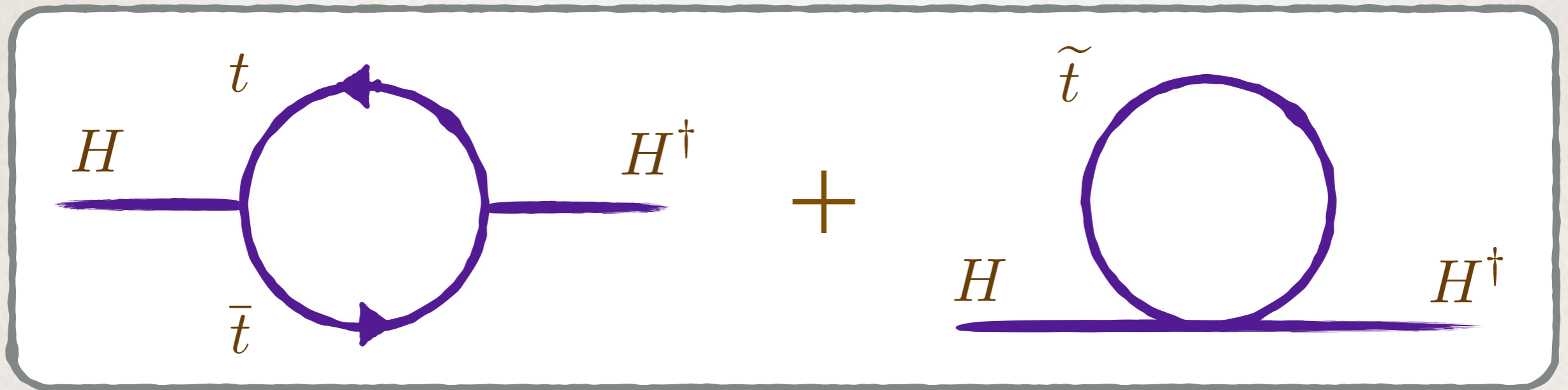


GUIDANCE FROM NATURALNESS

DO THIS
NOT THAT



MINIMAL REQUIREMENTS



"NATURAL SUSY"

Dimopoulos and Giudice [arXiv:hep-ph/9507282]
Cohen, Kaplan, Nelson [arXiv:hep-ph/9607394]

~20%
tuning

HIGGSINO

$$\mu \lesssim 200 \text{ GeV} \left(\frac{\Delta^{-1}}{20\%} \right)^{-1/2}$$

STOP

$$m_{\text{stop}} \lesssim 500 \text{ GeV} \frac{\sin \beta}{\sqrt{1 + (A_t/m_{\text{stop}})^2}} \sqrt{\frac{3}{\log(\Lambda/\text{TeV})}} \left(\frac{\Delta^{-1}}{20\%} \right)^{-1/2}$$

GLUINO

$$m_{\text{gluino}} \lesssim 1000 \text{ GeV} \sin \beta \frac{3}{\log(\Lambda/\text{TeV})} \left(\frac{\Delta^{-1}}{20\%} \right)^{-1/2}$$

Tuning: $\Delta \equiv \frac{2 \delta m_H^2}{m_h^2}$

Papucci, Ruderman, Weiler [arXiv:1110.6926]
Brust, Katz, Lawrence, Sundrum [arXiv:1110.6670]

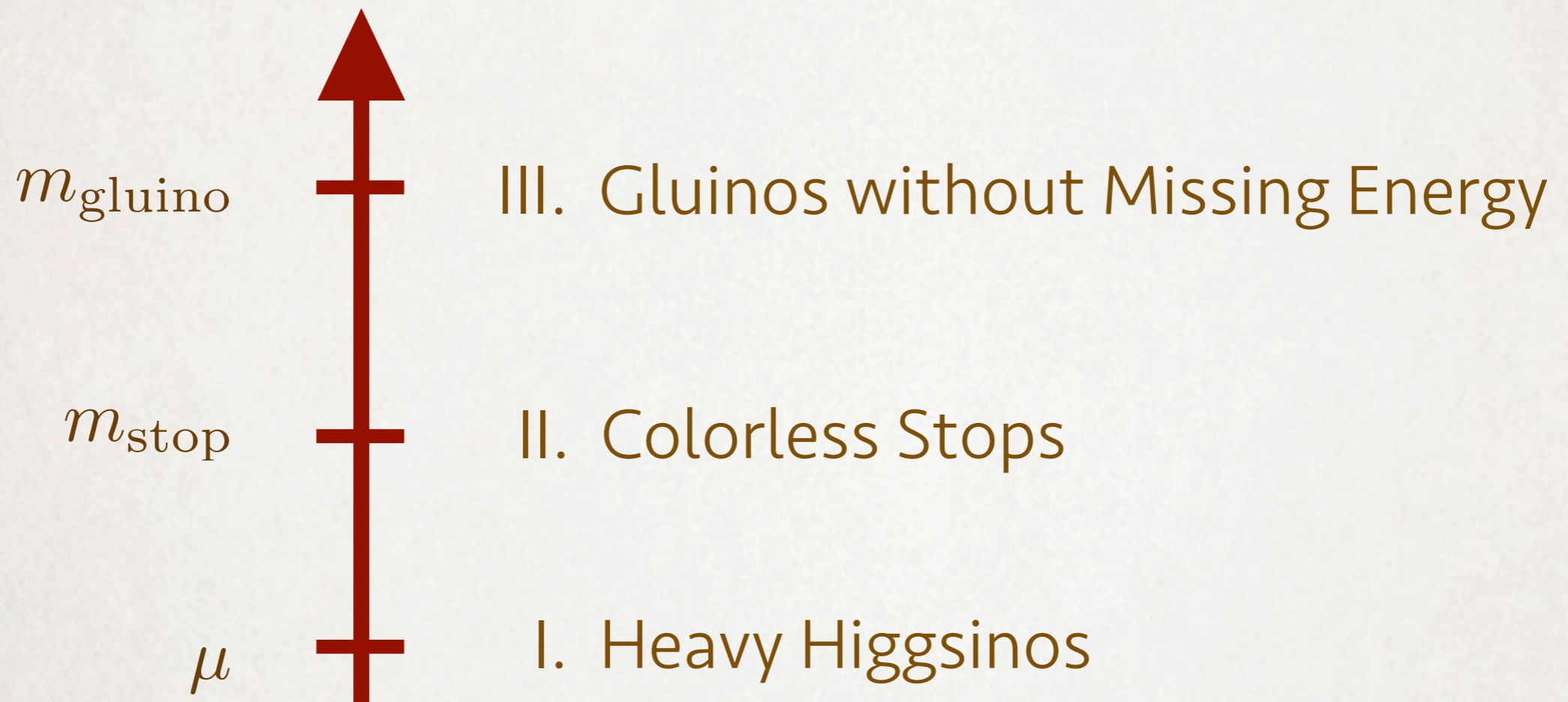
DISCLAIMER

Moving well
beyond minimality.

Asking what is
possible.
Won't worry too
much about what
is beautiful.



THREE VIGNETTES

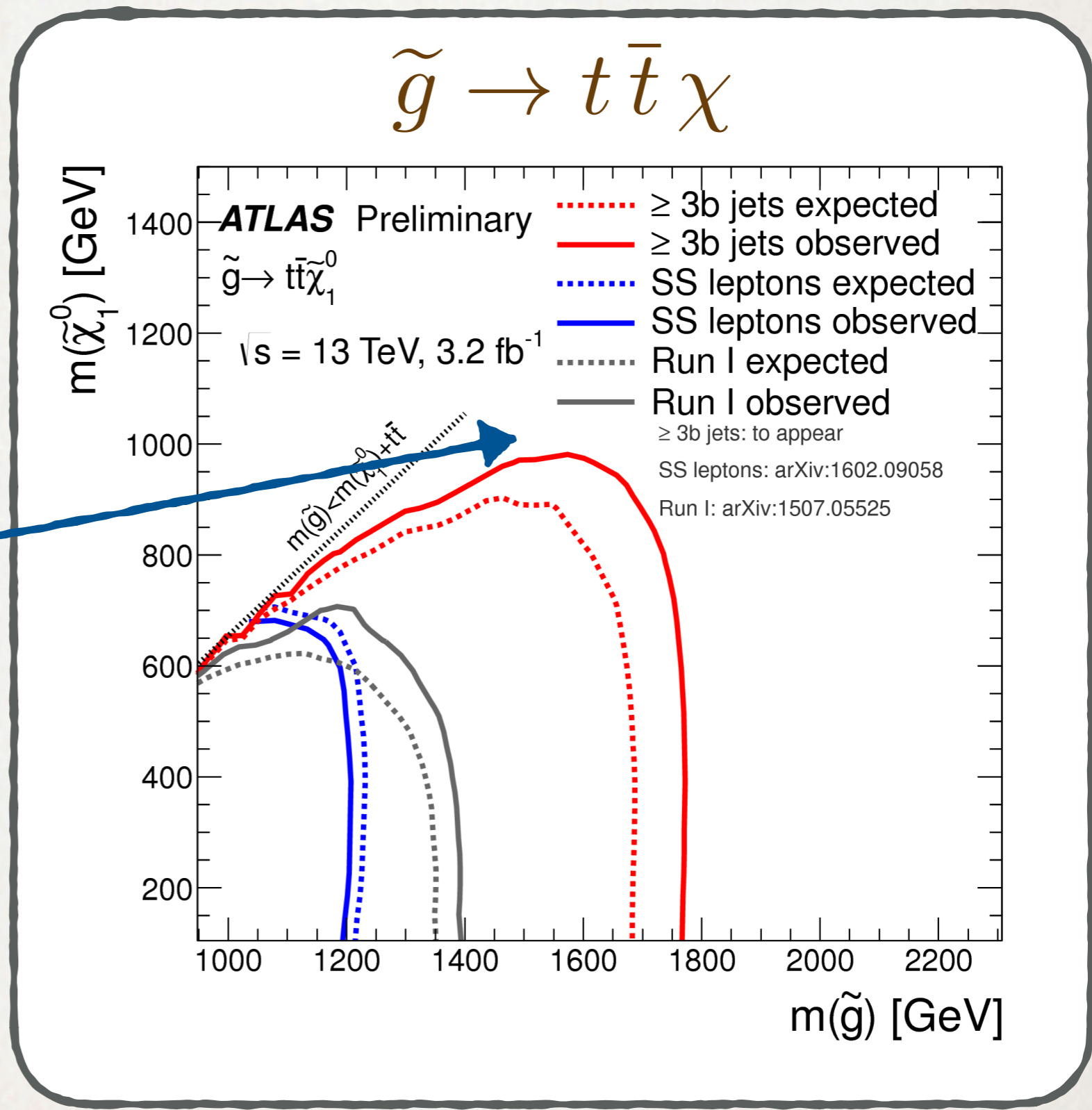


HEAVY HIGGSINOS

LHC LIMITS WITH A HEAVY LSP

$$\tilde{g} \rightarrow t\bar{t}\chi$$

No limit for $m_\chi \gtrsim 1 \text{ TeV}$



HEAVY HIGGSINOS WITHOUT TUNING



DOUBLE PROTECTION

Two symmetries:
SUSY + global symmetry

Calculable
scalar masses

Massless
Goldstone
Higgs

A MODEL

“Minimal Composite Higgs” symmetry breaking: $SO(5)/SO(4)$.

Agashe and Contino [arXiv:hep-ph/0510164]

Embed the MSSM Higgses into fundamental of $SO(5)$.

$$\Phi_a = \frac{1}{\sqrt{2}} \begin{pmatrix} f \\ -i(H_u^1 + H_d^2) \\ H_u^1 - H_d^2 \\ i(H_u^2 - H_d^1) \\ H_u^2 + H_d^1 \end{pmatrix} \quad \leftarrow \text{SO}(5) \text{ breaking vev.}$$

Symmetry preserving interactions:

$$W = \frac{\lambda}{2} S \Phi_a \Phi_a - \frac{\kappa}{3} S^3$$

plus soft breaking.

$$\langle S \rangle \neq 0 \quad \longrightarrow \quad \mu_{\text{eff}} = \lambda \langle S \rangle$$

TC, Kearney, Luty [arXiv:1501.01962]

For an effective operator approach, see Nelson and Roy [arXiv:1501.03251]

EXPLICIT BREAKING

Need explicit $SO(5)$ breaking to lift Higgs potential.

SUPERPOTENTIAL TERMS

$$\Delta W = \frac{\lambda'}{2} S \Phi_0^2 + \frac{\eta}{2} S^2 \Phi_0 - \frac{\kappa'}{2} \Phi_0^3$$

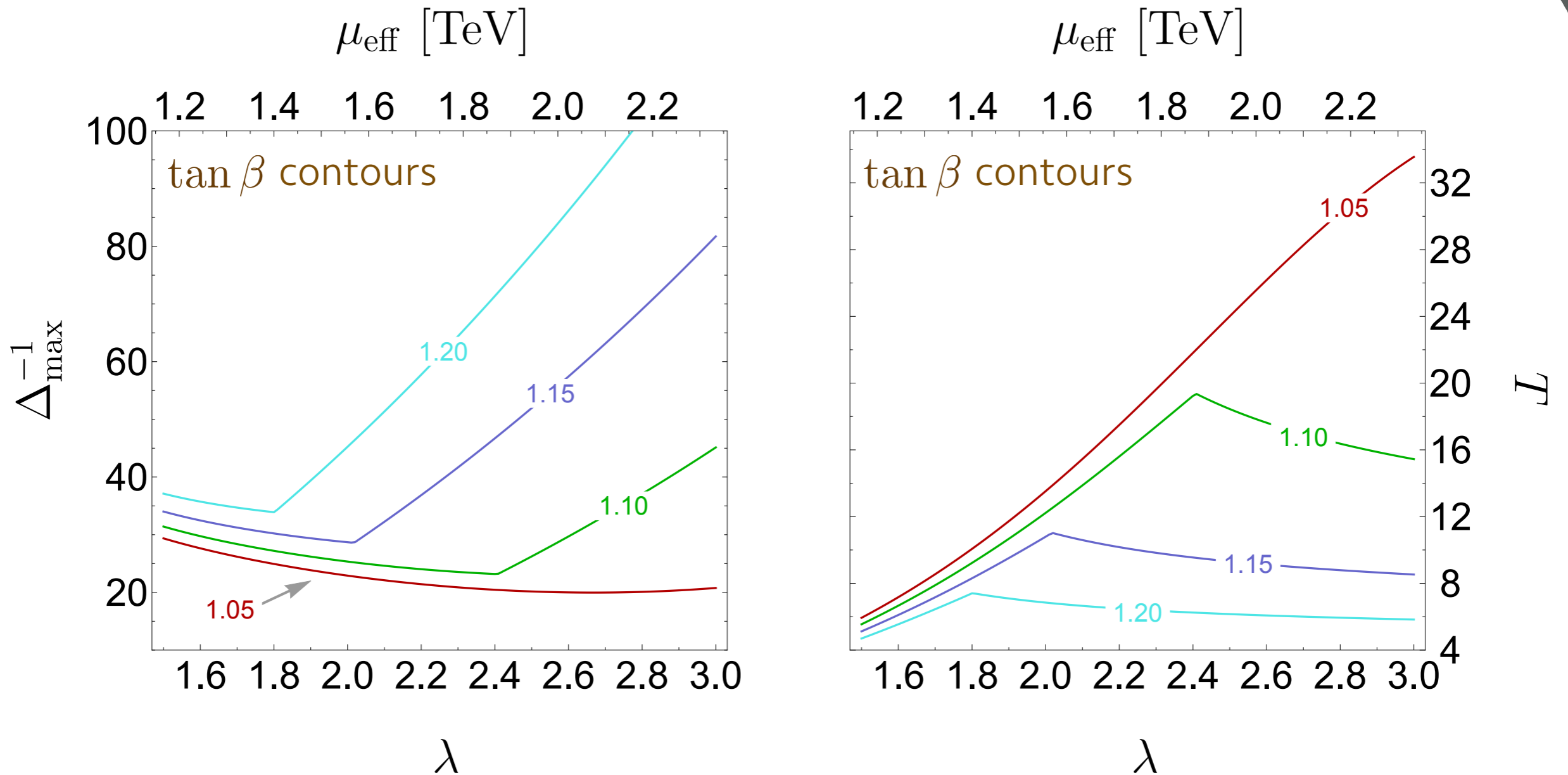
Yields "misalignment" tuning: $\Delta_{\text{Goldstone}}^{-1} \sim \frac{f^2}{v^2}$.

YUKAWA AND GAUGE TERMS

Standard MSSM contributions to Higgs potential.

$$\Delta_{\text{radiative}}^{-1} \sim \frac{3 y_t^2}{32 \pi^2} \frac{m_{Q_3}^2}{v^2} \log \left(\frac{M_{\text{SUSY}}^2}{m_{\tilde{t}_1} m_{\tilde{t}_2}} \right)$$

REDUCED TUNING



Beat MSSM tuning as coupling increases.

$$T \equiv \Delta_{\text{Goldstone}}^{-1} / \Delta_{\text{MSSM}}^{-1}$$

TC, Kearney, Luty [arXiv:1501.01962]

TIM COHEN [UNIVERSITY OF OREGON]

COLORLESS STOPS

MUST TOP PARTNERS BE COLORED?

New symmetry commutes with SM gauge groups.

Naively, implies top partners carry color.

NEUTRAL NATURALNESS

Introduce mirror sector.

Impose \mathbb{Z}_2 parity symmetry on top Yukawa and strong coupling.

Mirror partners can yield calculable Higgs mass.



“Twin-Higgs”

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

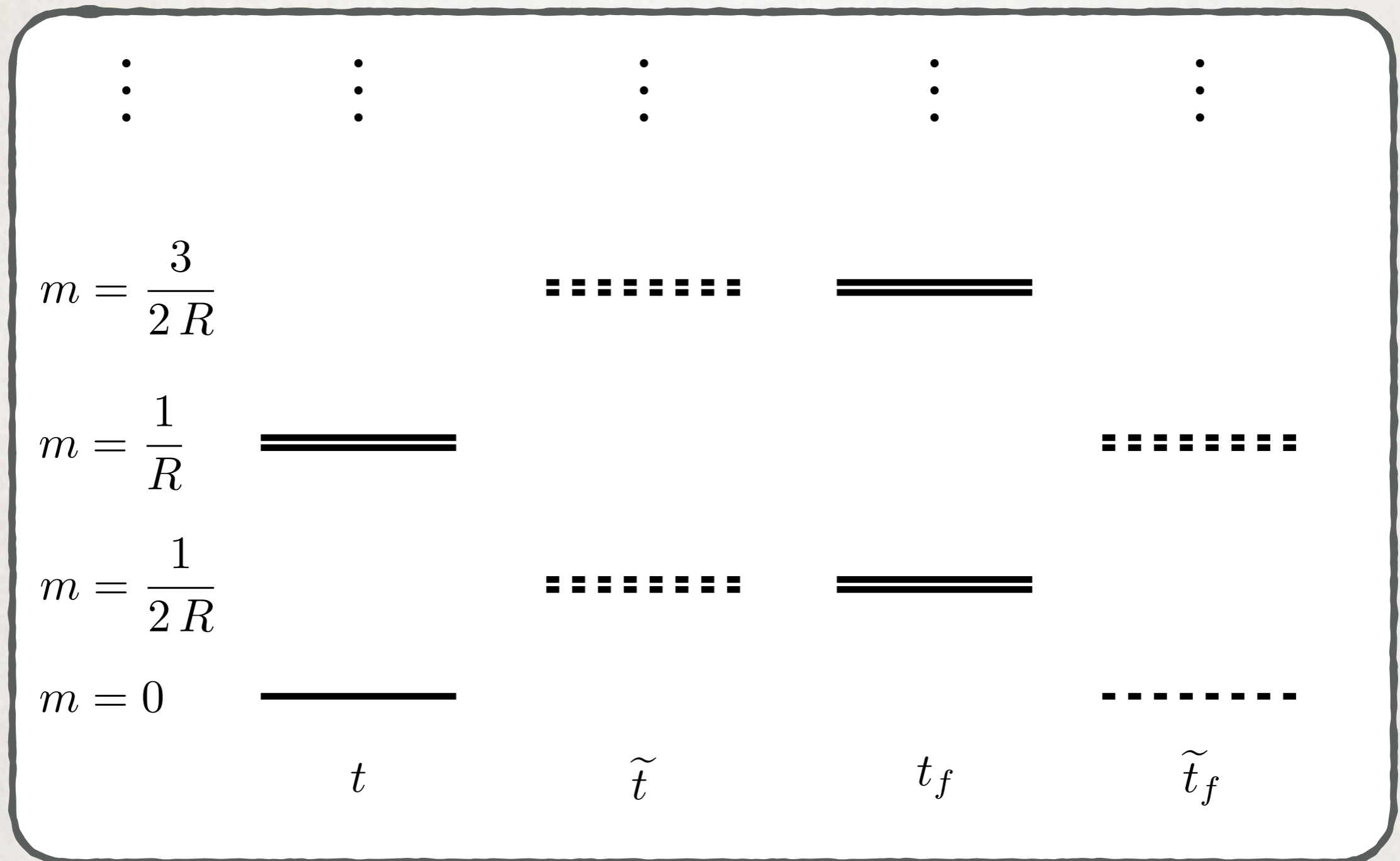
“Folded-SUSY”

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

FOLDED SUSY LIVES IN 5D

\mathbb{Z}_2 and SUSY breaking with boundary conditions.

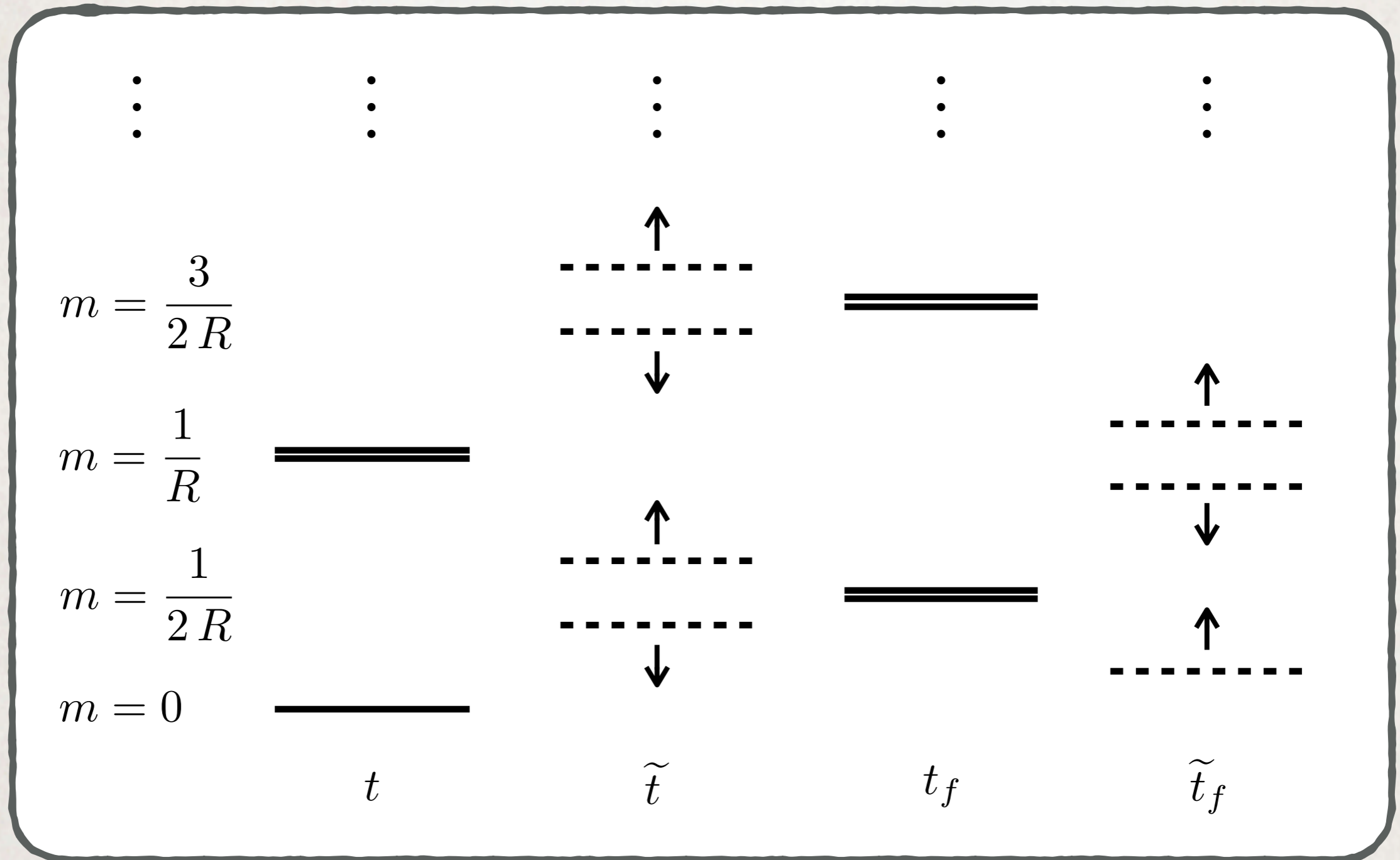
Scherk and Schwarz [PLB 1979]



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

WITH A TWIST

Additional allowed parameter for boundary conditions: α .



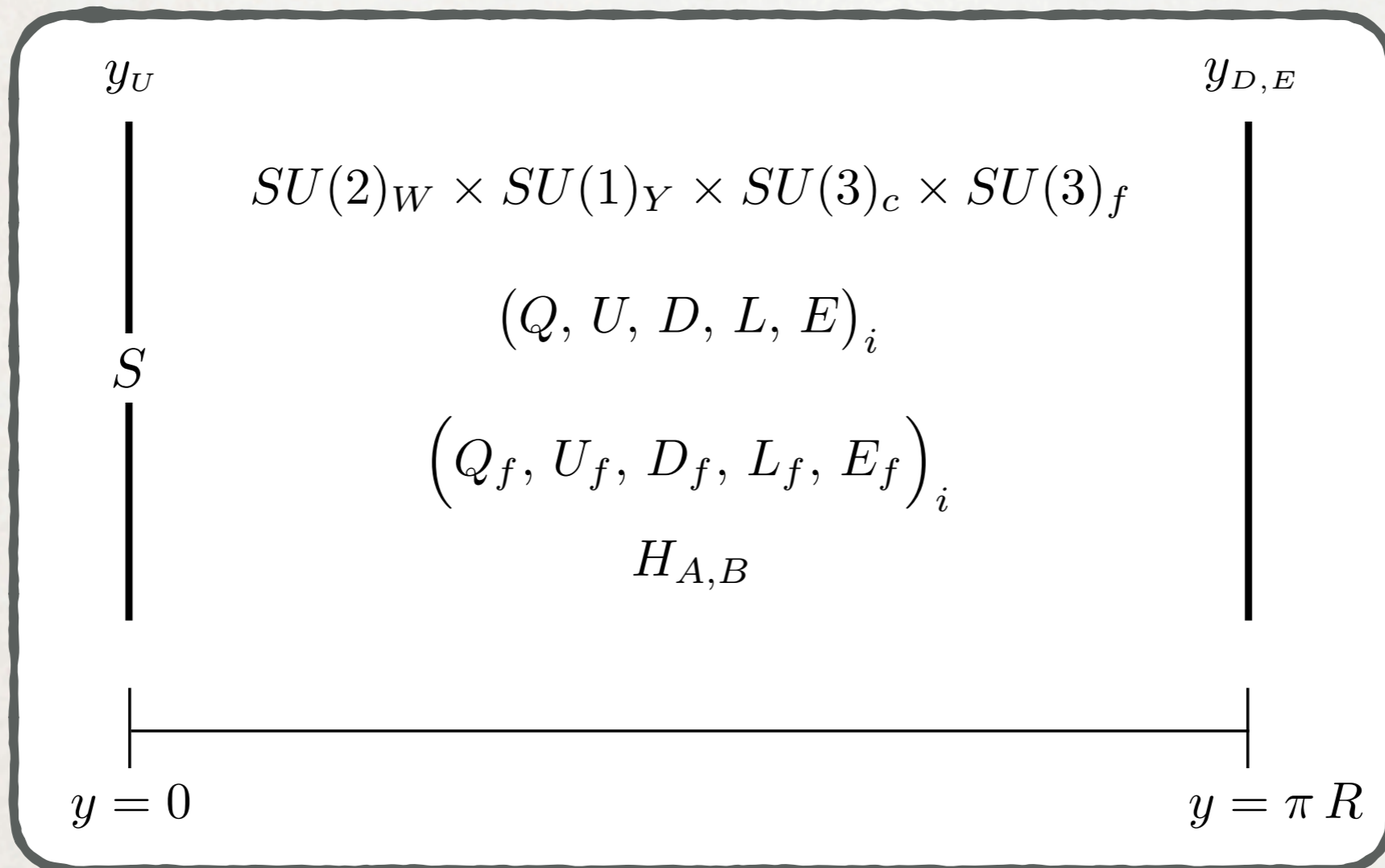
TC, Craig, Lou, Pinner [arXiv:1508.05396]

A MODEL

Matter and folded matter in bulk.

Gauge groups in bulk.

Singlet on brane.



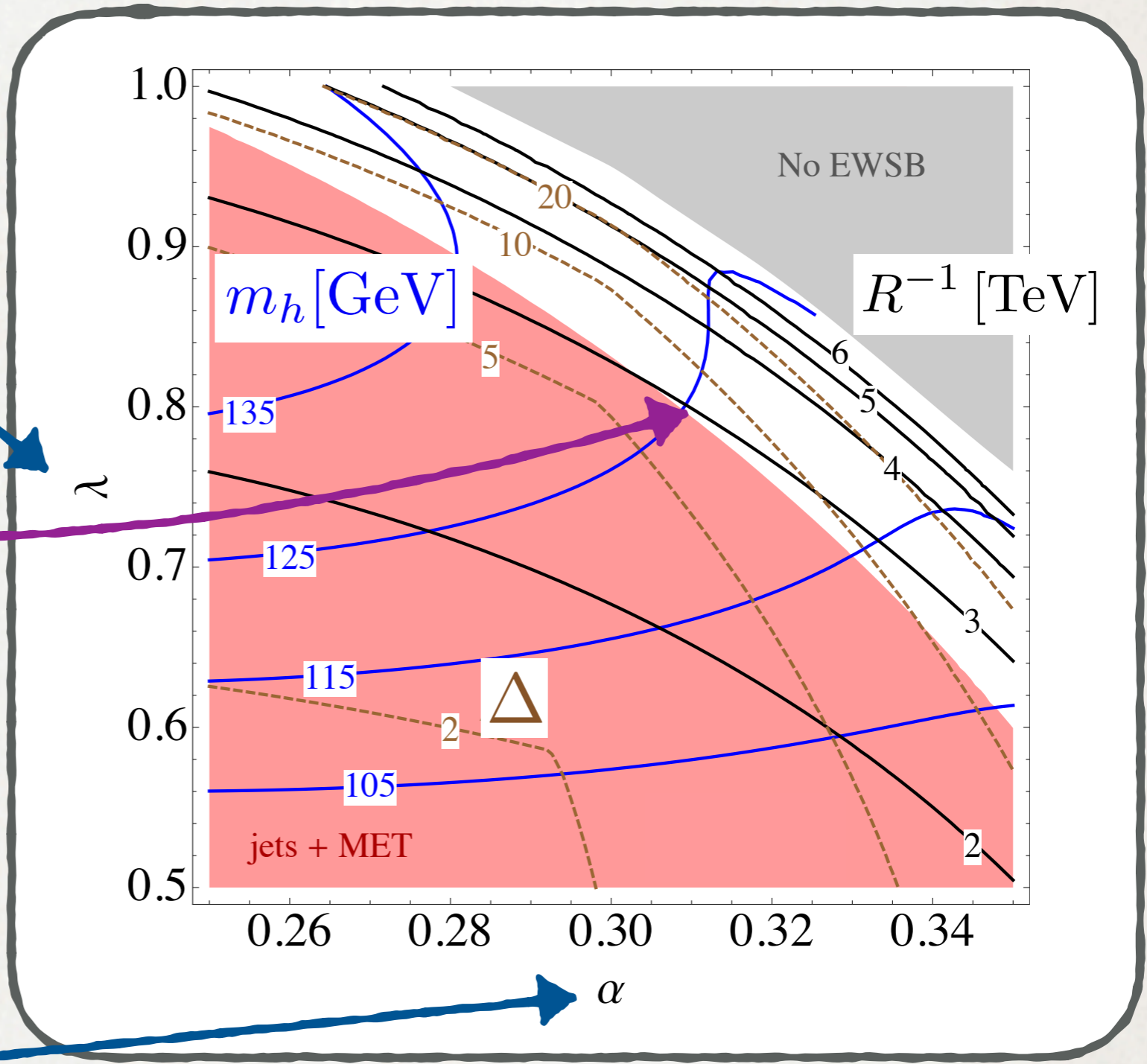
$$\mathcal{W} = \delta(y) \left(\lambda^{(5)} S H_A H_B^c + \frac{M_S}{2} S^2 + y_t^{(5)} H_A (Q U + Q_f U_f) \right)$$

PARAMETER SPACE

NMSSM-like coupling

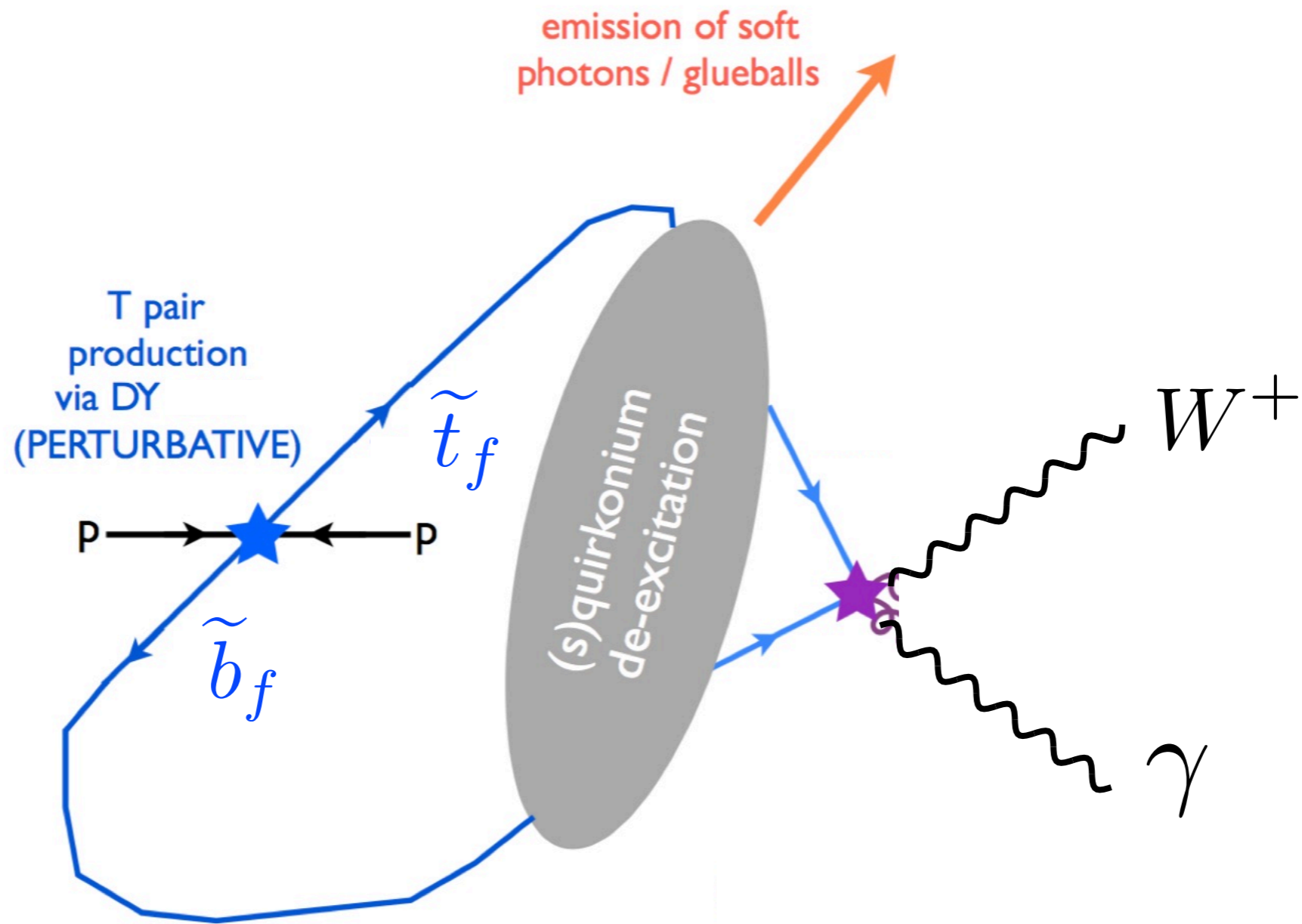
125 GeV Higgs mass with minimal tuning

Twist parameter



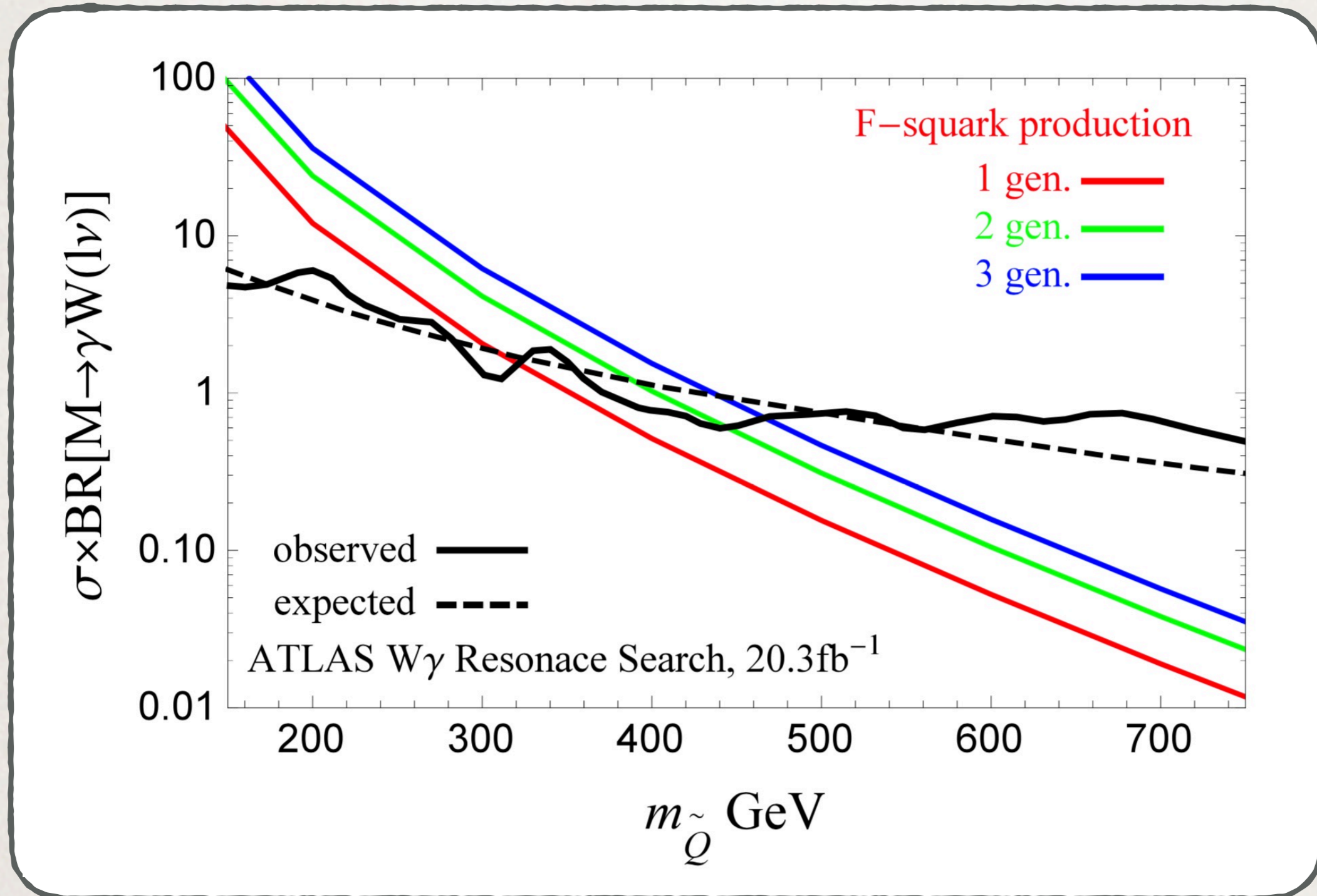
TC, Craig, Lou, Pinner [arXiv:1508.05396]

FOLDED PHENO



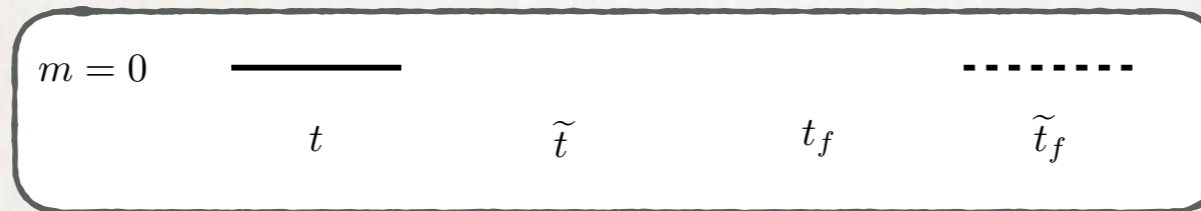
Sketch stolen (and modified) from David Curtin

ELECTROWEAK RESONANCE



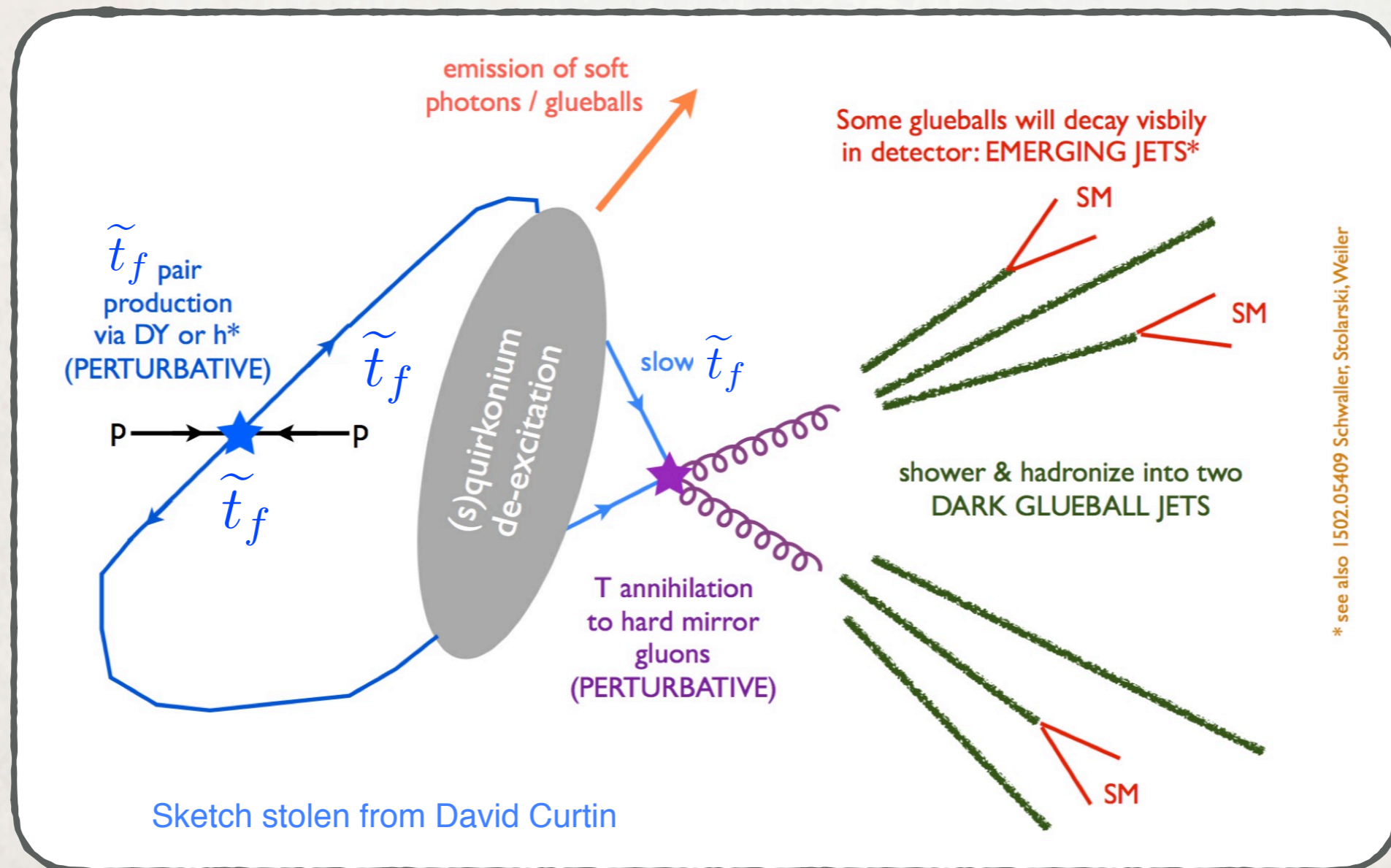
Burdman, Chacko, Harnik, de Lima, Verhaaren [arXiv:1411.3310]

MORE FOLDED PHENO

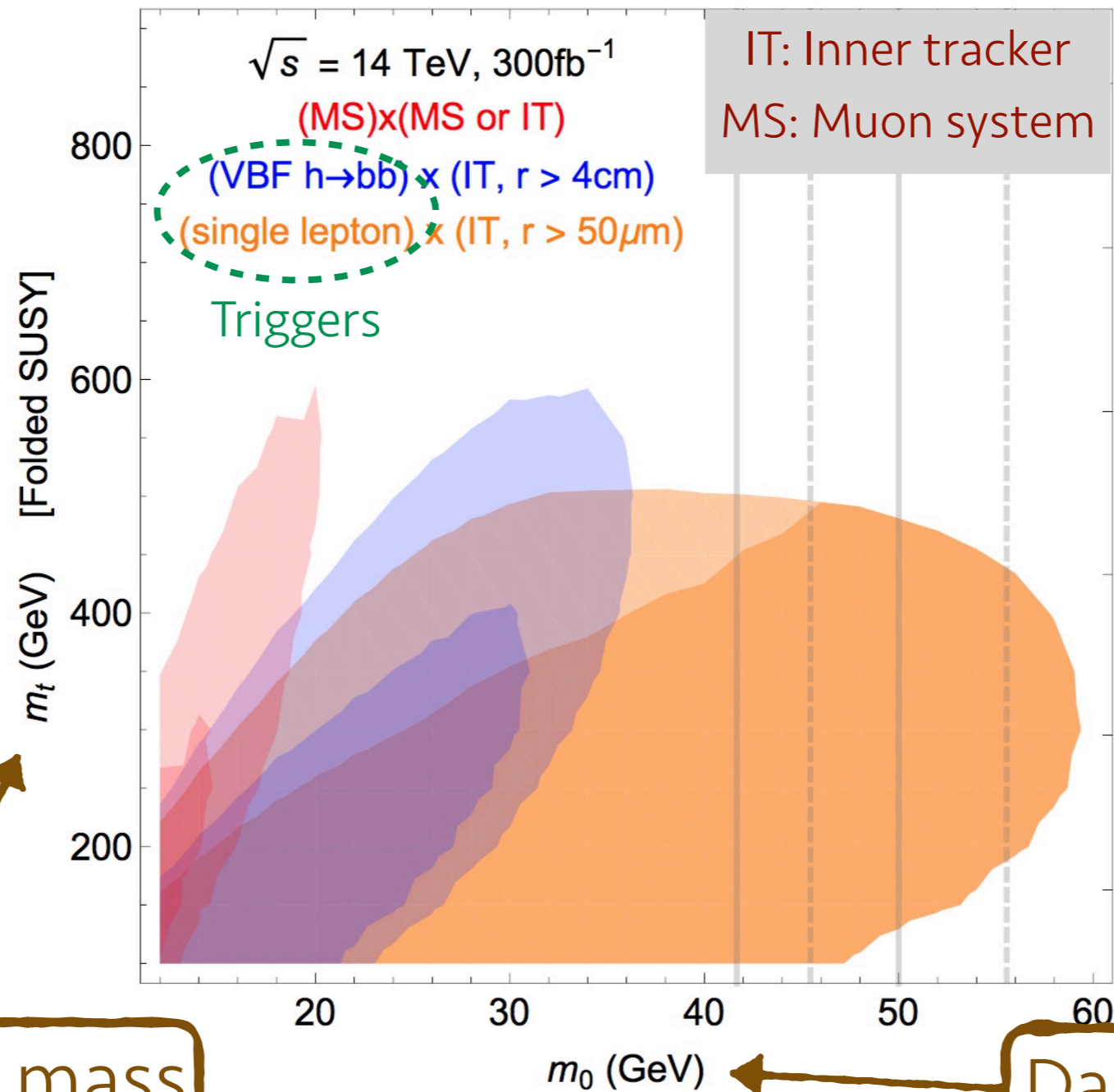


Folded color without folded quarks.
 Long color strings can form, *i.e.*, quirks.

Kang and Luty [arXiv:0805.4642]



PROSPECTS FOR LHC



Curtin and Verhaaren [arXiv:1506.06141]

see also Burdman, Chacko, Harnik, do Lima, Verhaaren [arXiv:1411.3310];
Burdman and D'Agnolo [arXiv:1512.00040]; Chacko, Curtin, Verhaaren [arXiv:1512.05782];

GLUINOS WITHOUT MET

BARYONIC RPV

More than one R-parity violating (RPV) operator active yields very strong constraints!

Additionally, strong constraints for events with extra leptons.

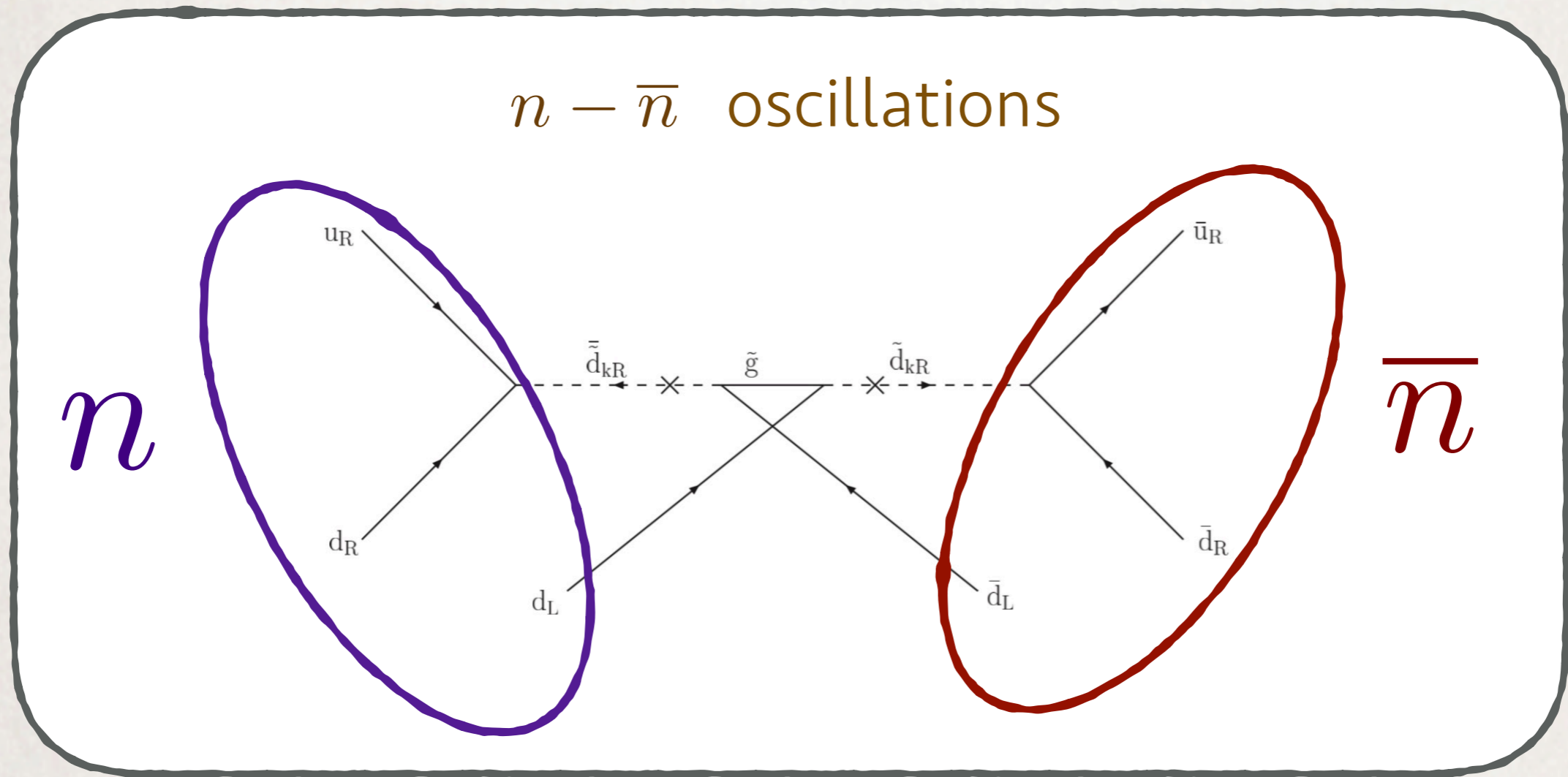
Imagine lepton number is good symmetry.

Focus on baryonic RPV operator:

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

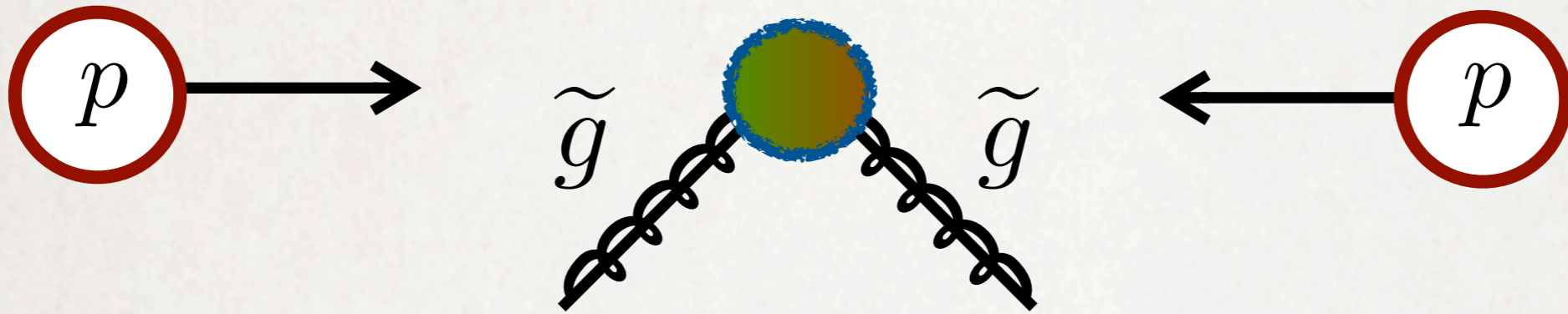
CONSTRAINTS

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



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

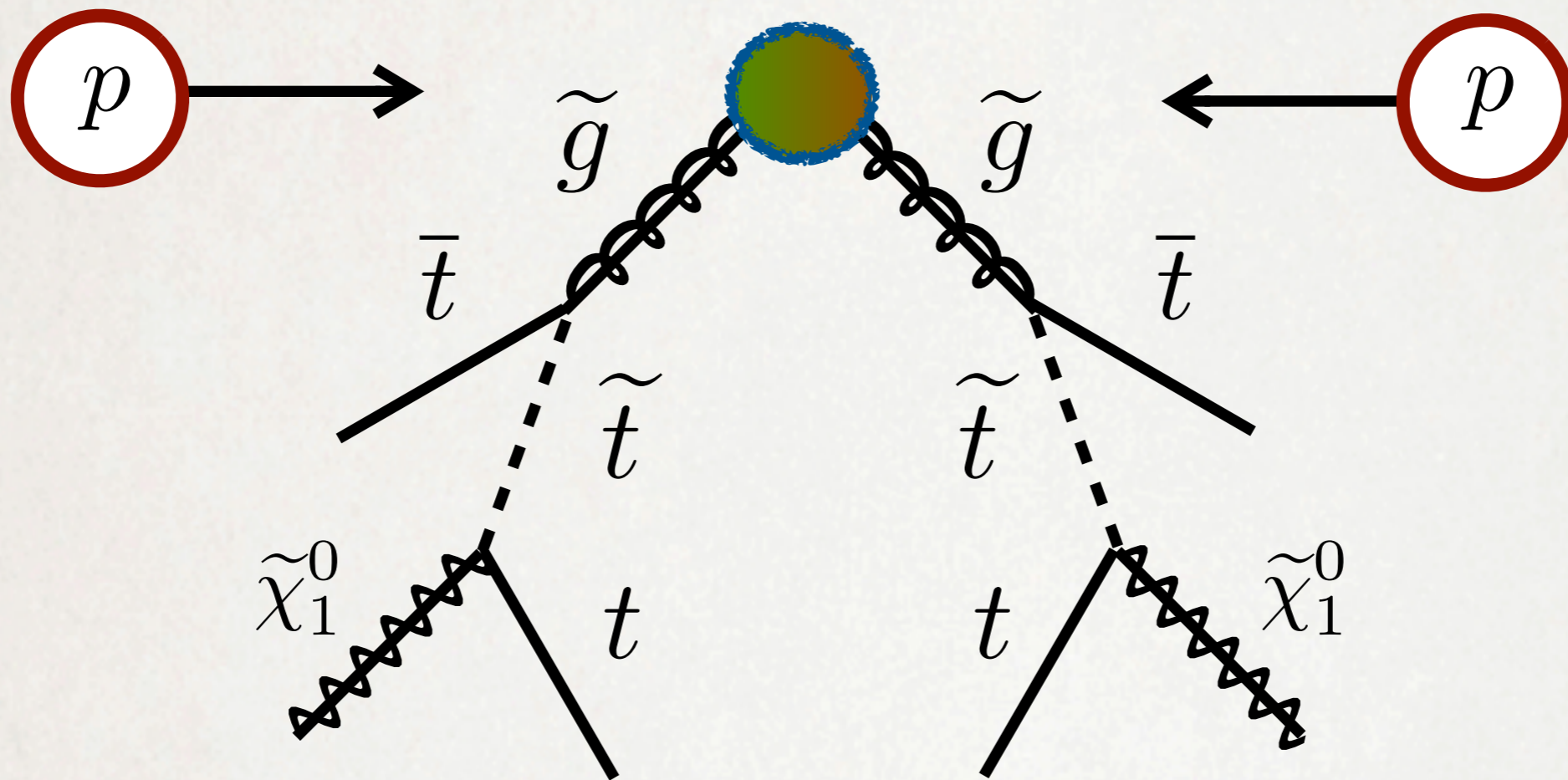
HIGH MULTIPLICITY



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

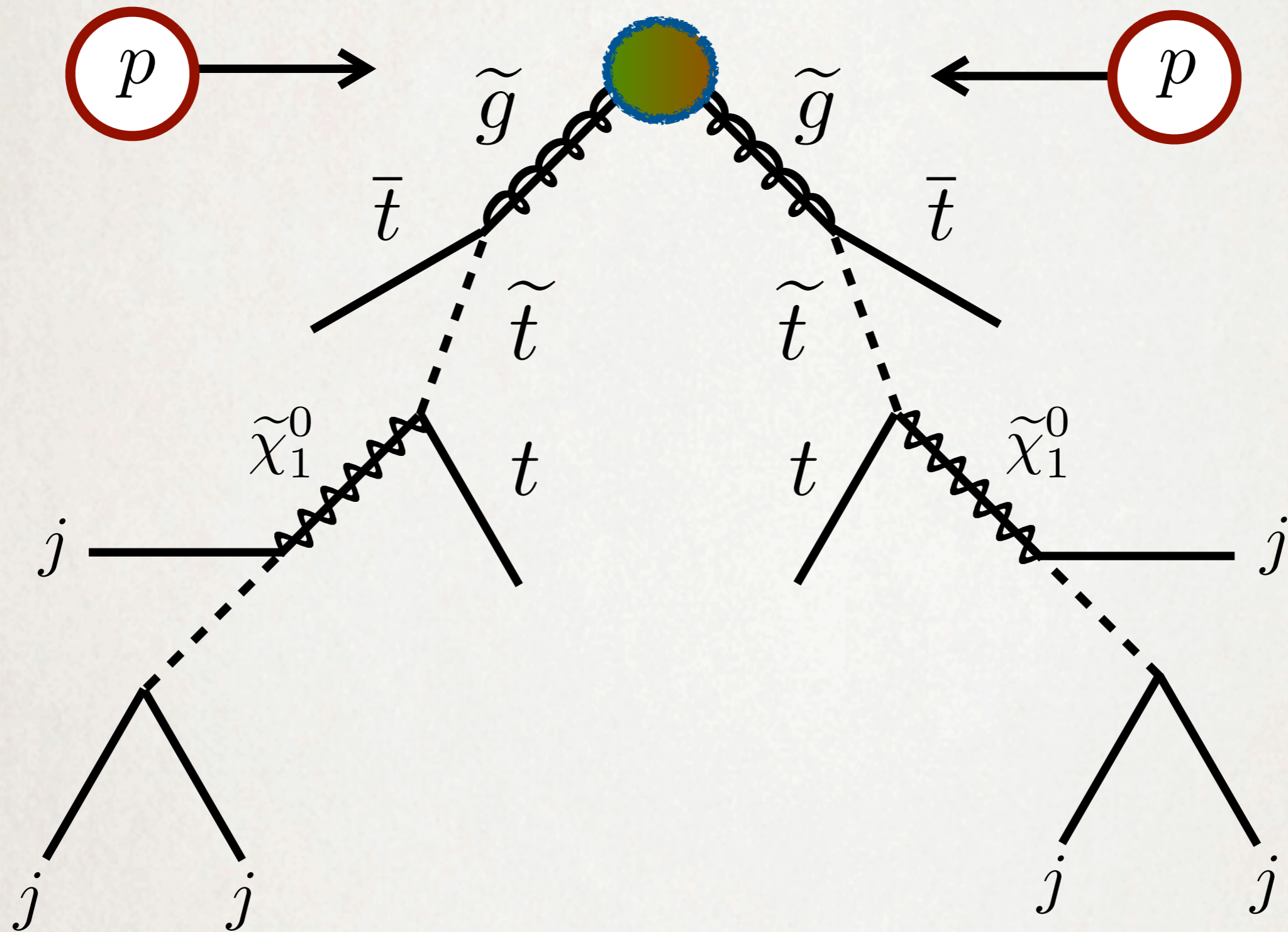
TIM COHEN [UNIVERSITY OF OREGON]

HIGH MULTIPLICITY



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

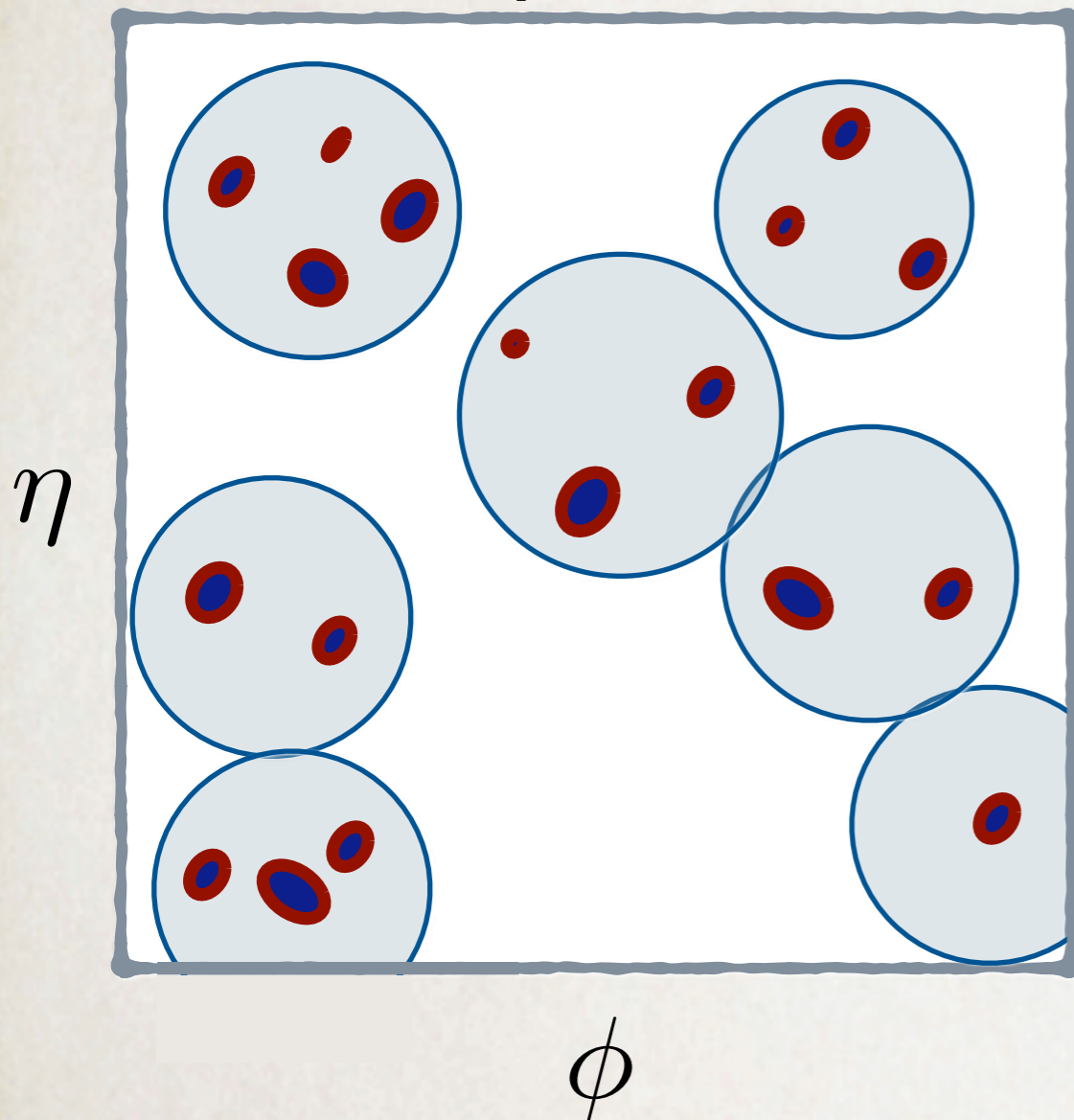
HIGH MULTIPLICITY



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

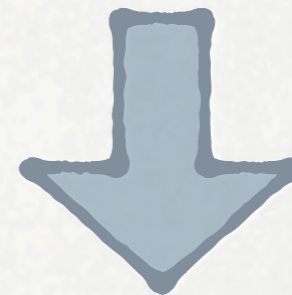
ACCIDENTAL SUBSTRUCTURE

18 partons



New physics manifests as high multiplicity hadronic event.

Occasional hard partons will cluster into same fat jet:

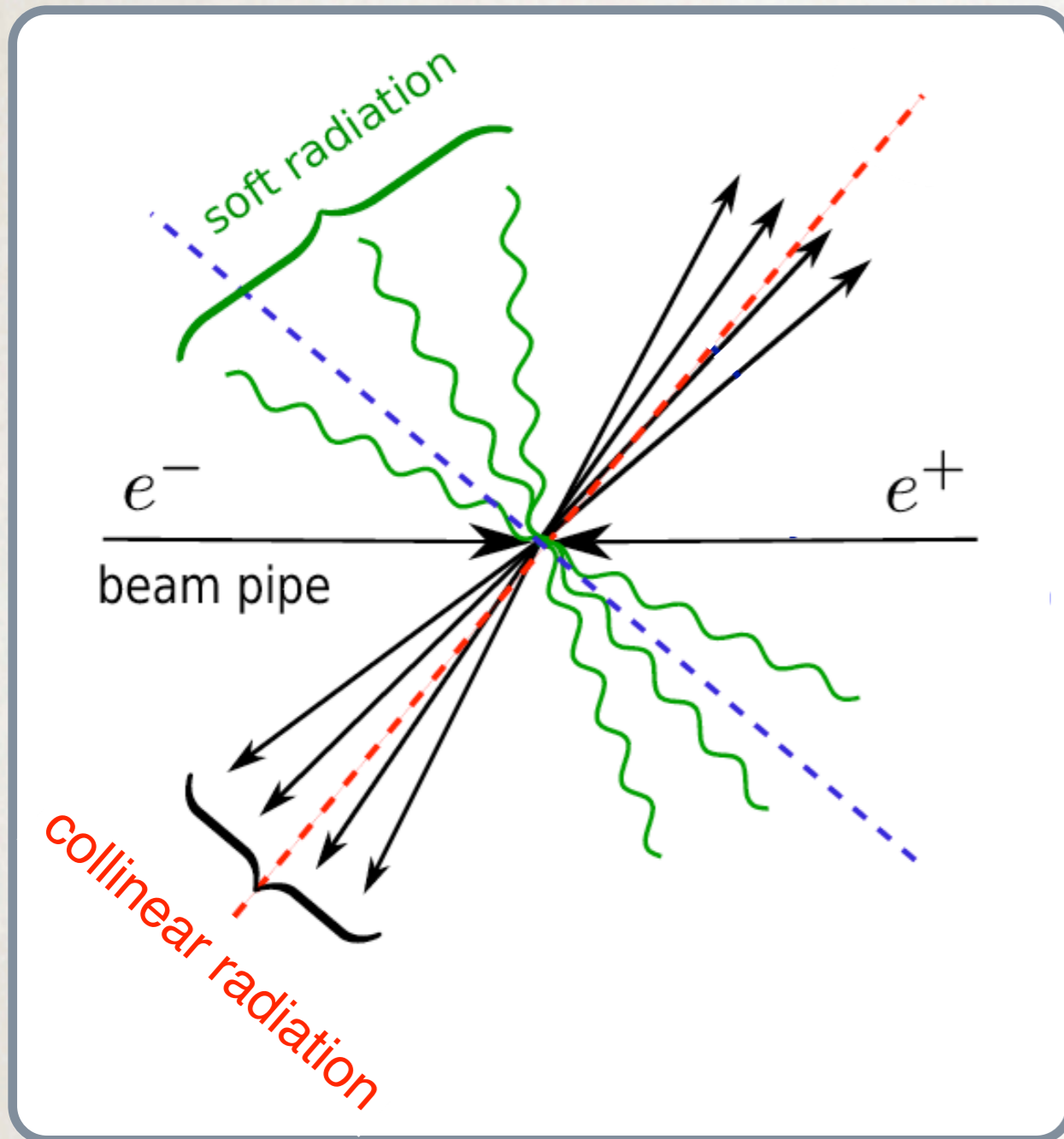


Accidental substructure.

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**.

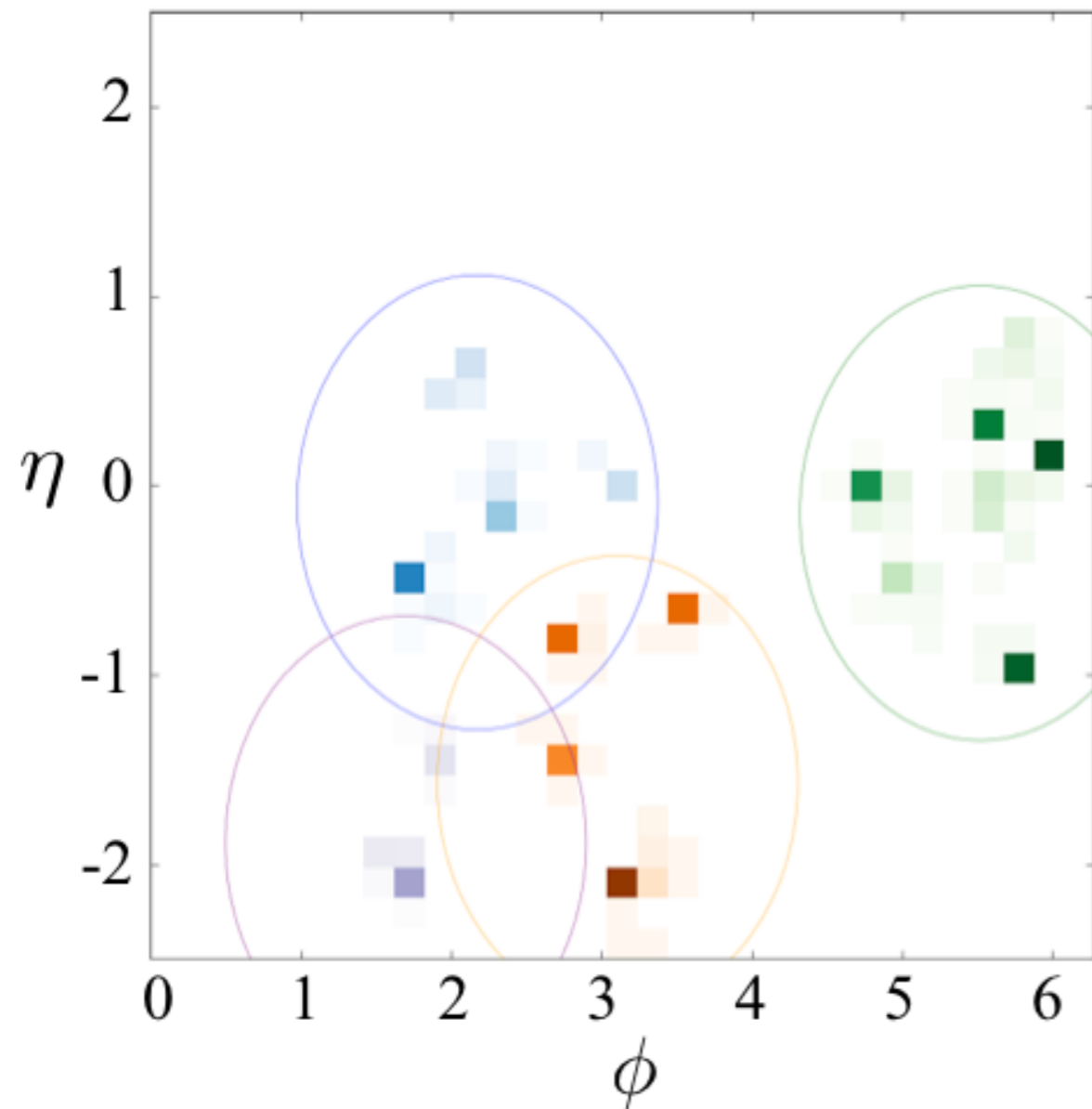
Hard partons are rare.

Difficult to satisfy a
multi-fat jet selection.

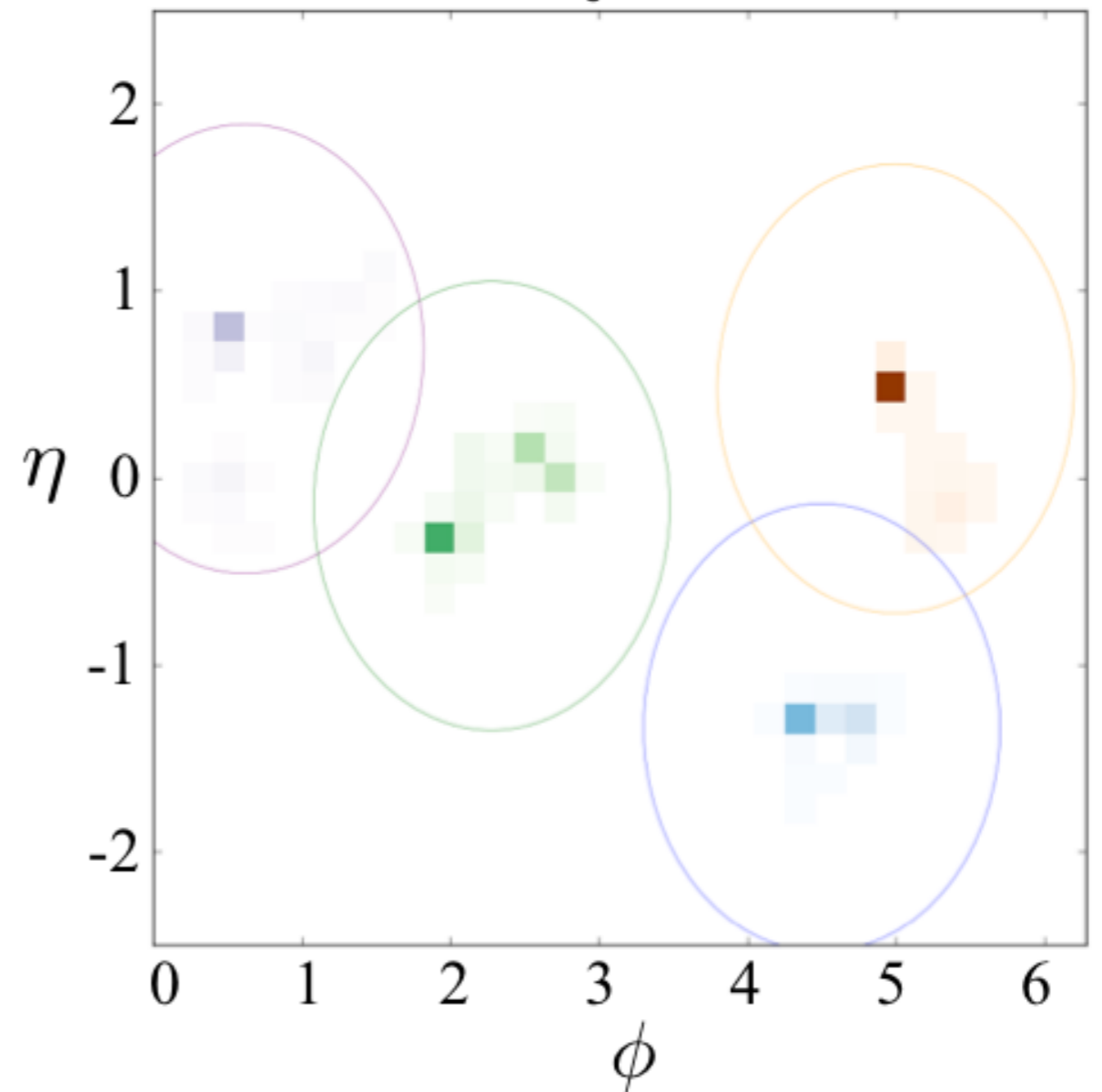
Mass and substructure are
effective discriminators.

SIGNAL VERSUS BACKGROUND

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



QCD



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

JET SUBSTRUCTURE TEMPLATES

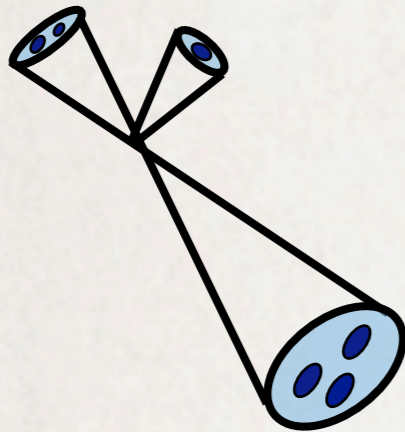
Physical assumption: jets factorize.

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

JET SUBSTRUCTURE TEMPLATES

Physical assumption: jets factorize.

Training Sample

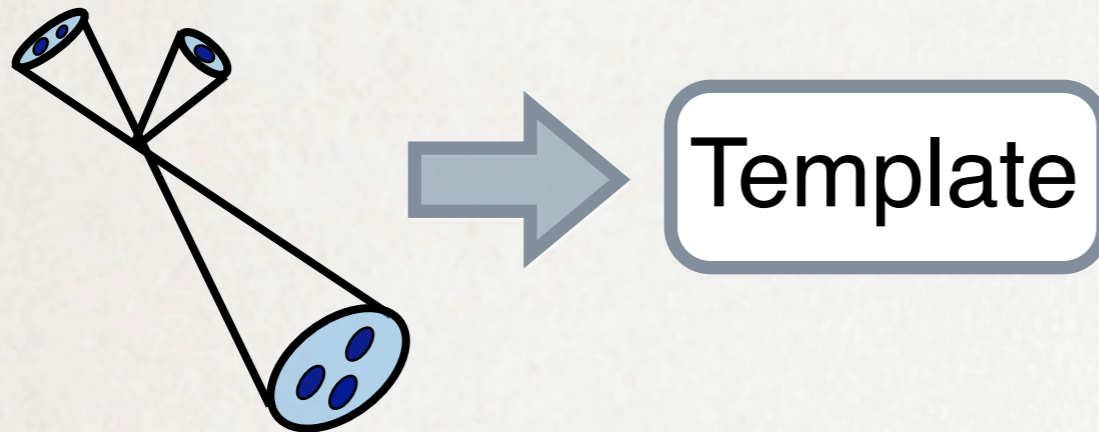


TC, Jankowiak, Lisanti, Lou, Wacker [arXiv:1402.0516]

JET SUBSTRUCTURE TEMPLATES

Physical assumption: jets factorize.

Training Sample

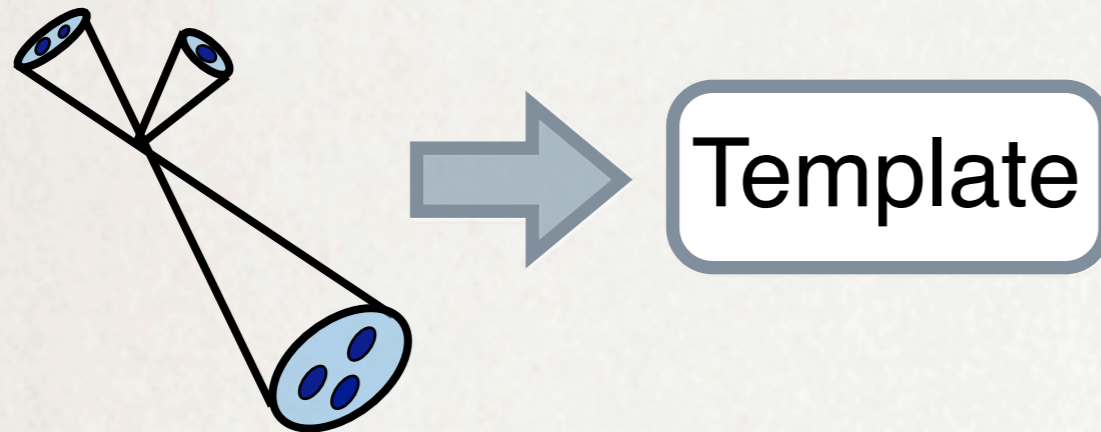


TC, Jankowiak, Lisanti, Lou, Wacker [arXiv:1402.0516]

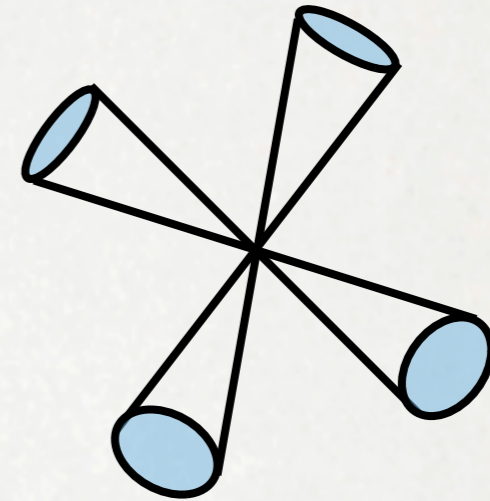
JET SUBSTRUCTURE TEMPLATES

Physical assumption: jets factorize.

Training Sample



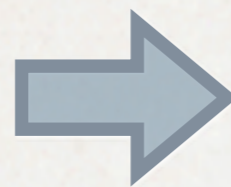
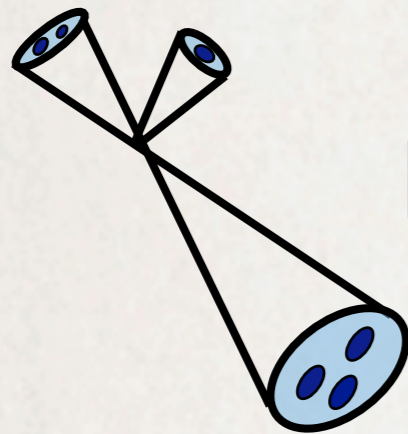
Kinematic Sample



JET SUBSTRUCTURE TEMPLATES

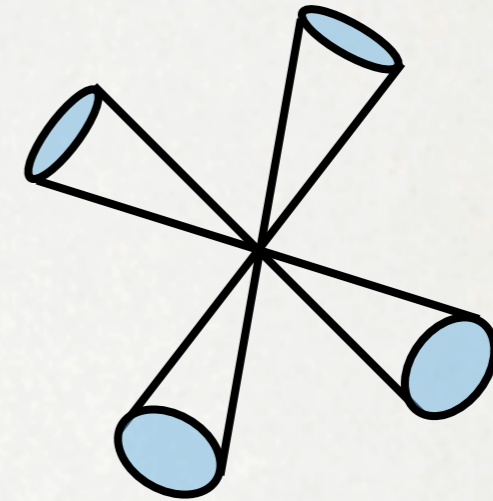
Physical assumption: jets factorize.

Training Sample

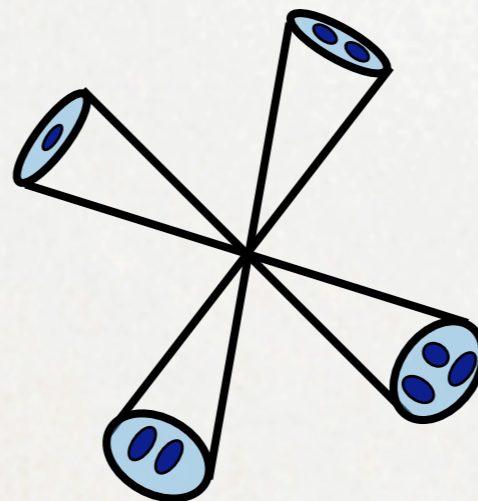


Template

Kinematic Sample

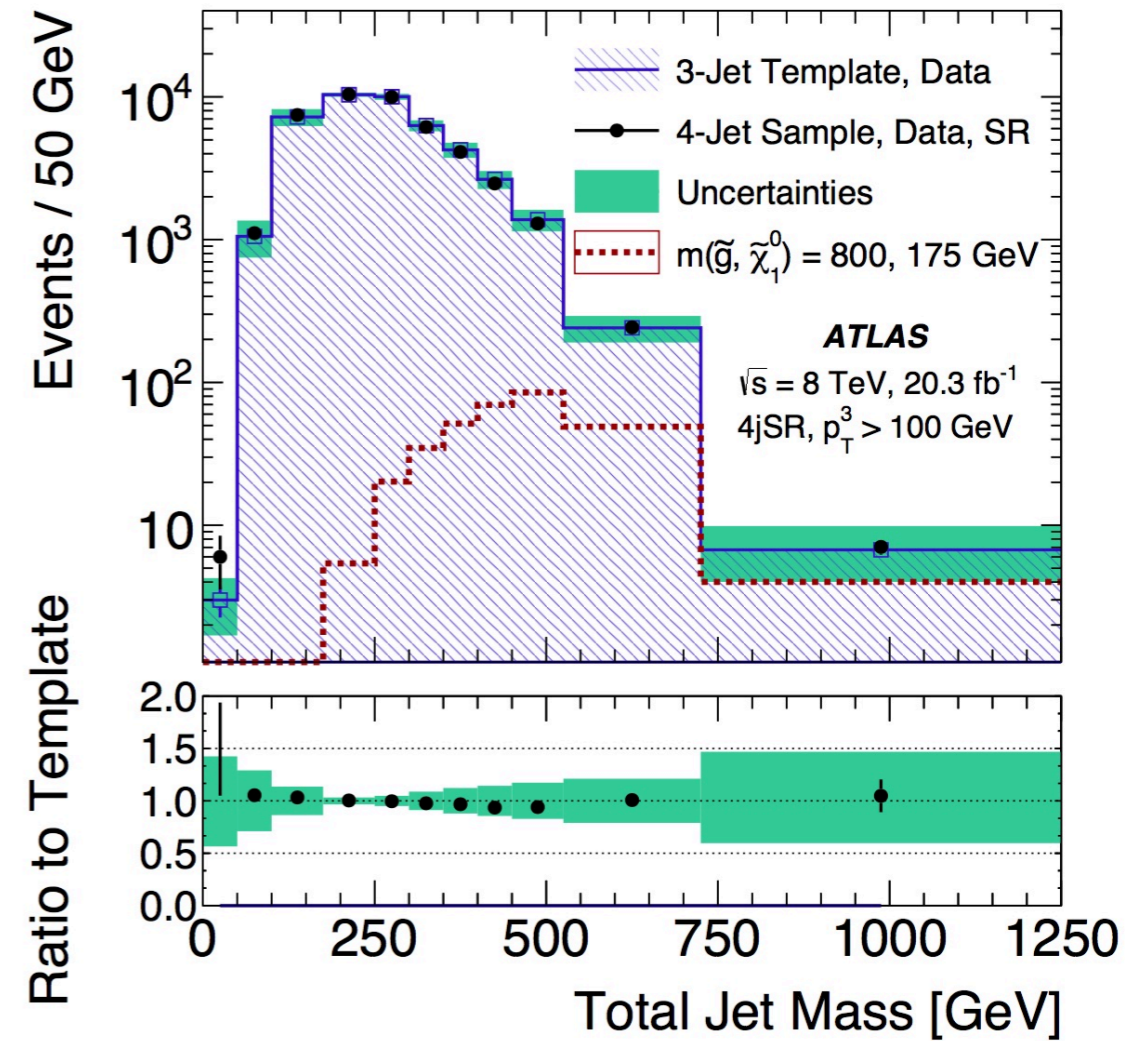
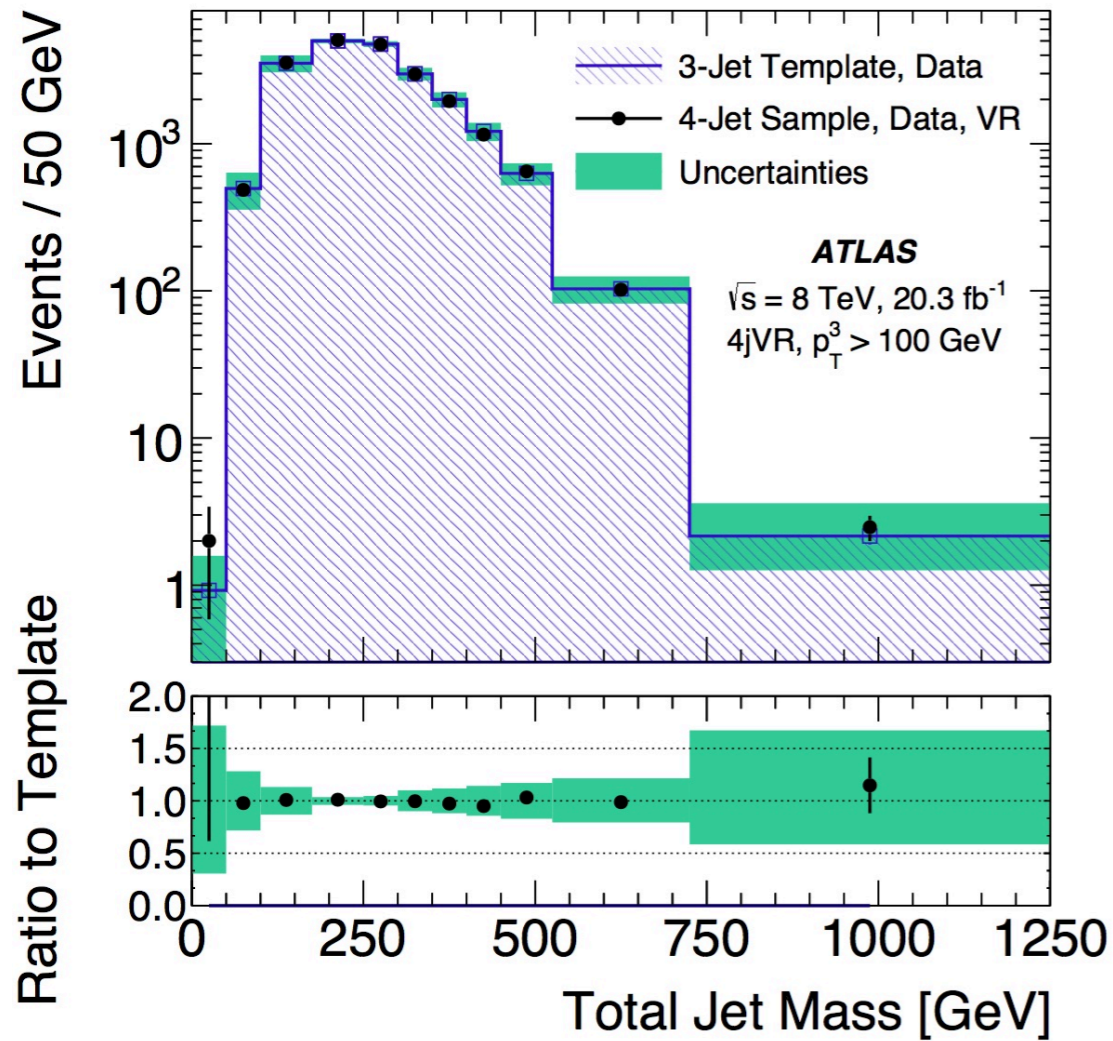


Dressed Sample



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

SUBSTRUCTURE TEMPLATES IN DATA



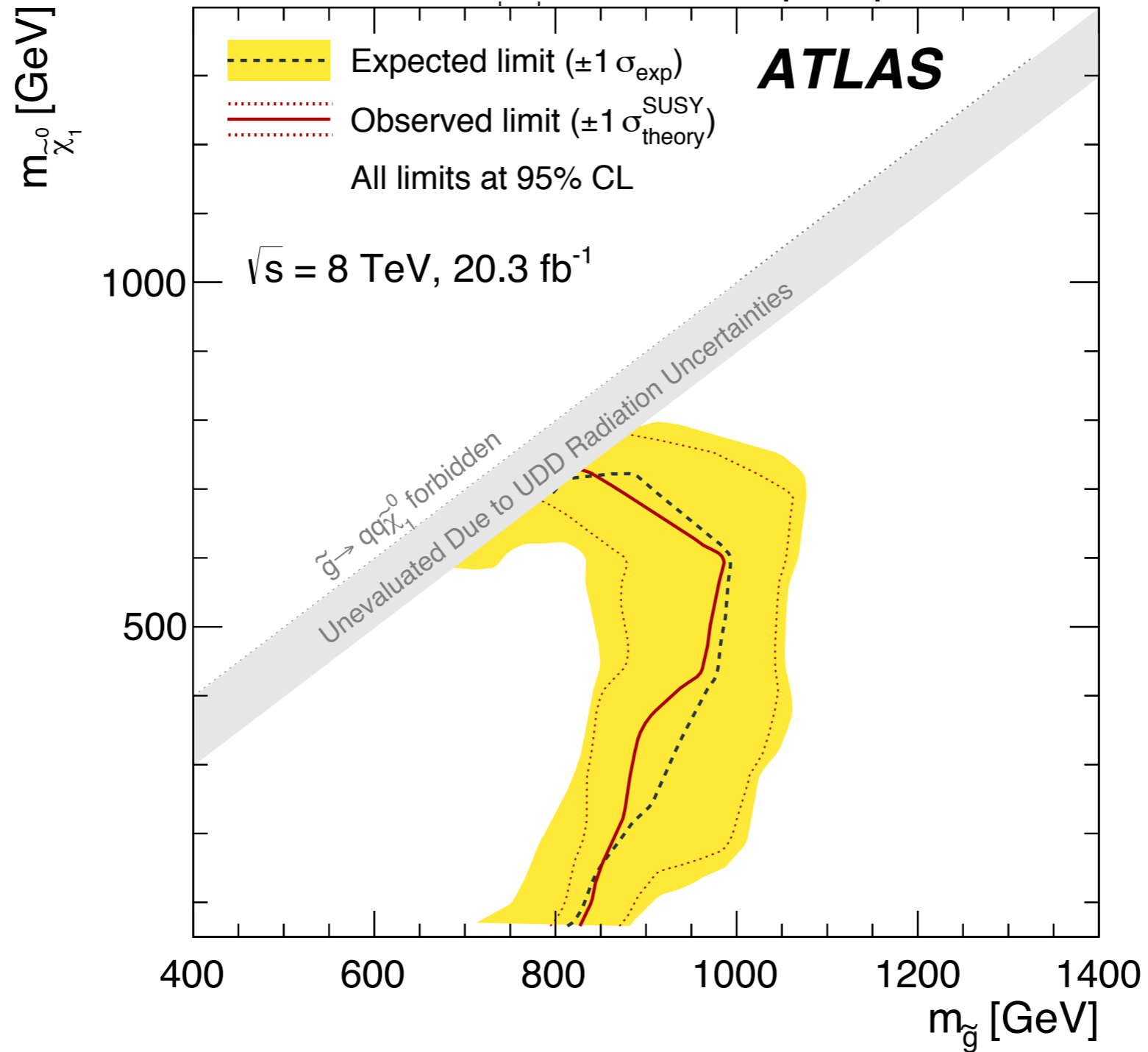
ATLAS [arXiv:1502.05686]

Kernel smoothing techniques used to derive template error bars.

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

NO MET: REDUCED LIMITS

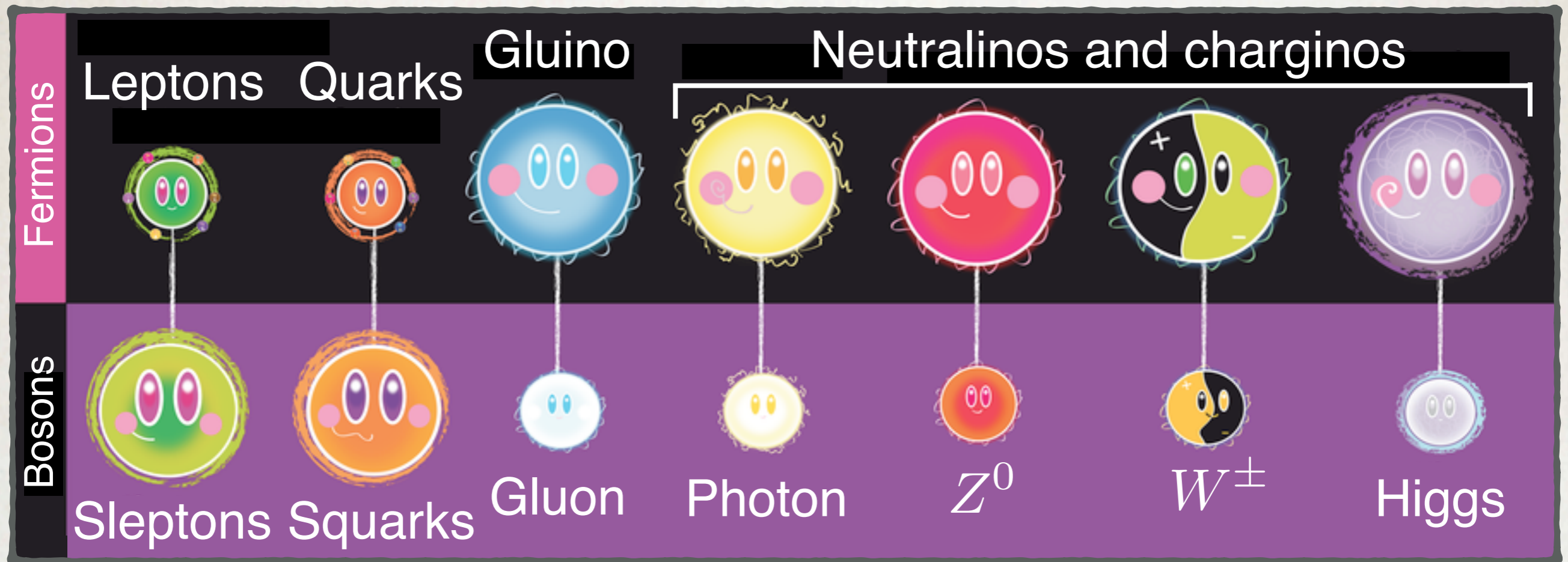
$\tilde{g}\text{-}\tilde{g}$ production, $\tilde{g} \rightarrow qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \rightarrow qq$



ATLAS [arXiv:1502.05686]

OUTLOOK

WHERE IS SUSY?



MINIMAL NATURALNESS EXPECTATIONS

Higgsinos, stops, and gluinos.

Gave examples for modifying each.

Take natural SUSY seriously, but not too seriously.

MANY IDEAS



Stealth SUSY.

Fan, Reece, Ruderman [[arXiv:1105.5135](#)] and [[arXiv:1201.4875](#)];

Fan, Krall, Pinner, Reece, Ruderman [[arXiv:1512.05781](#)]

Dirac Gauginos.

Nelson, Fox, Weiner [[arXiv:hep-ph/0206096](#)]; Kribs, Martin [[arXiv:1203.4821](#)]

Compressed spectra/Auto-concealment.

Dimopoulos, Howe, March-Russell, Scoville [[arXiv:1412.0805](#)]

N naturalness.

Arkani-Hamed, TC, D'Agnolo, Hook, Kim, Pinner [To appear Tuesday!]



ALL THAT MATTERS...

IS THAT WE DISCOVER
THE NEW PHYSICS,
NO MATTER HOW
TRICKY NATURE HAS
MADE IT TO FIND!

