BEYOND MINIMAL SUSY

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ICTP Conference
A First Glance Beyond the Energy Frontier
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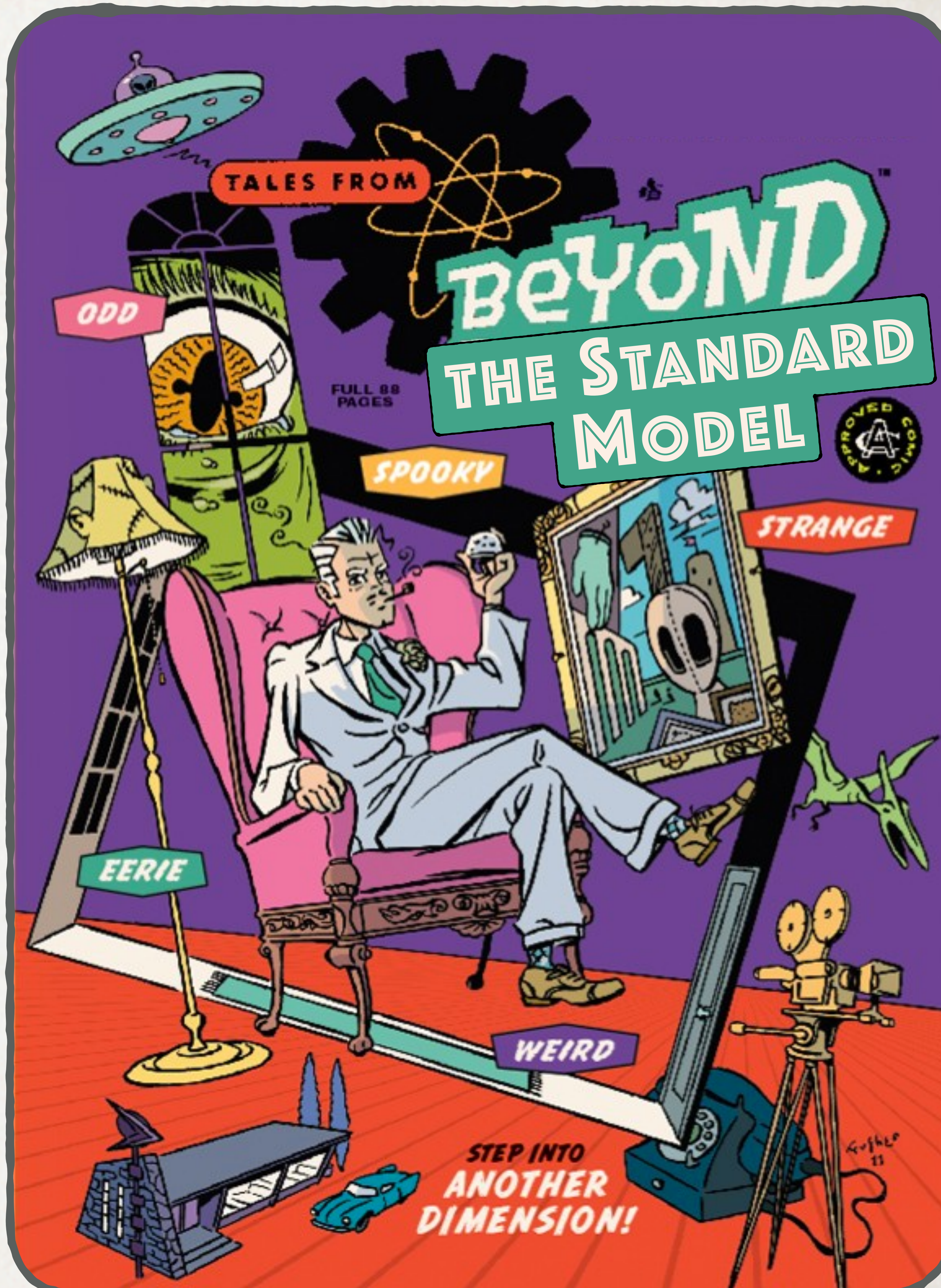
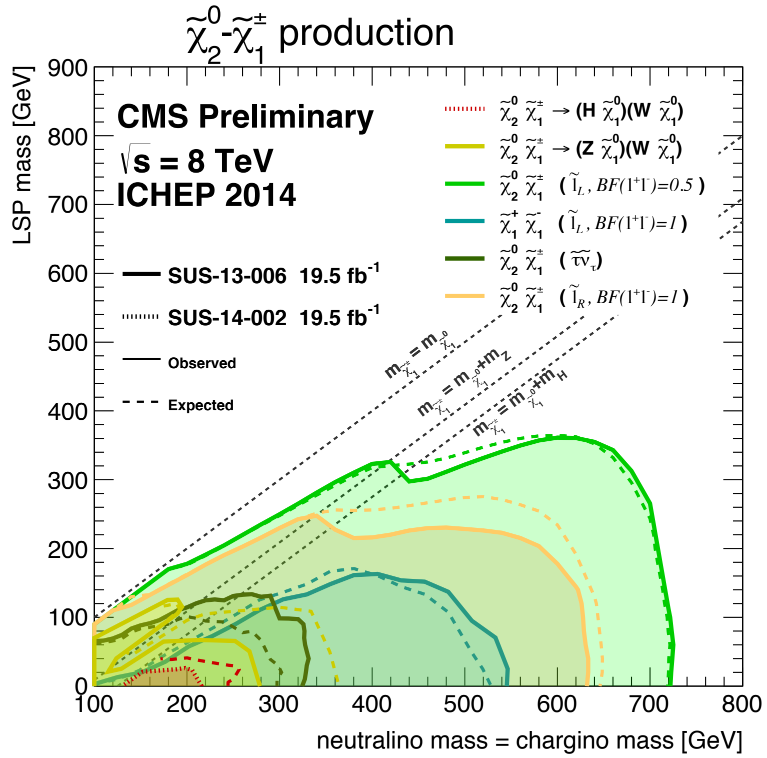
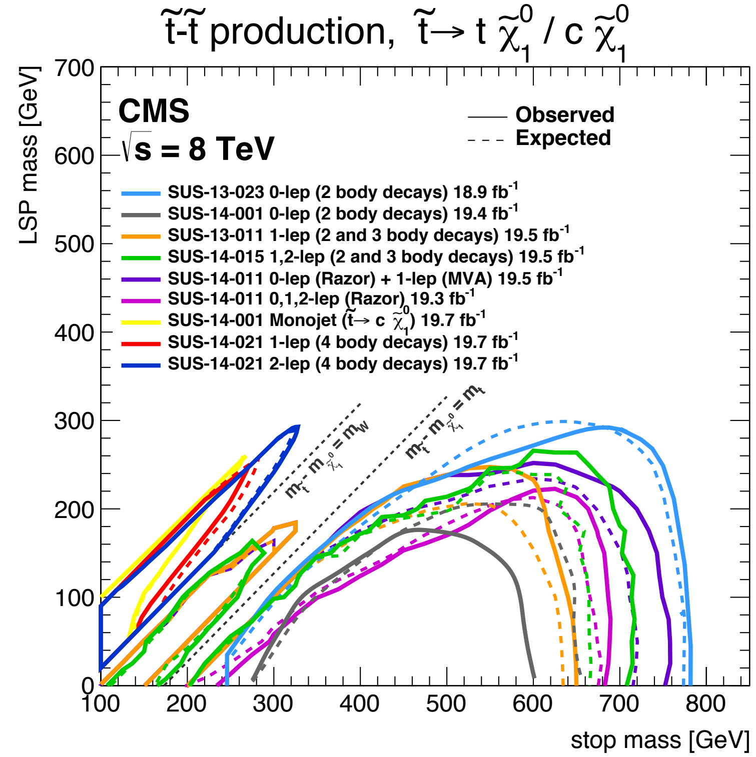
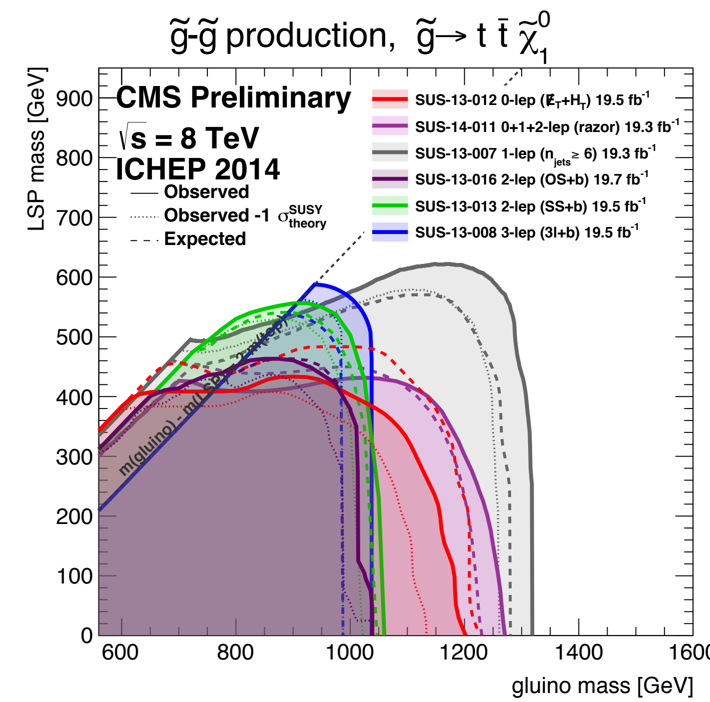
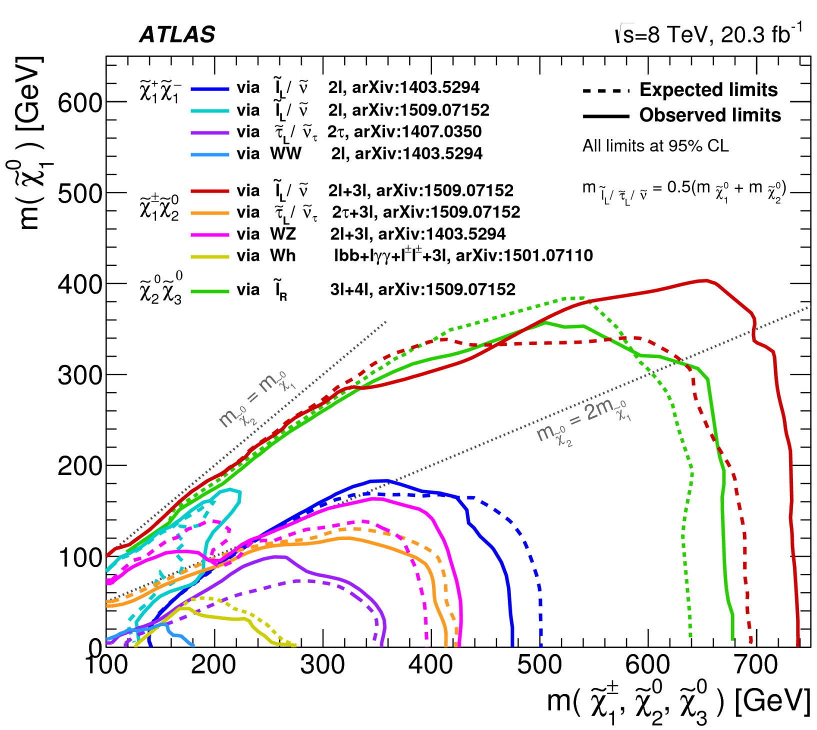


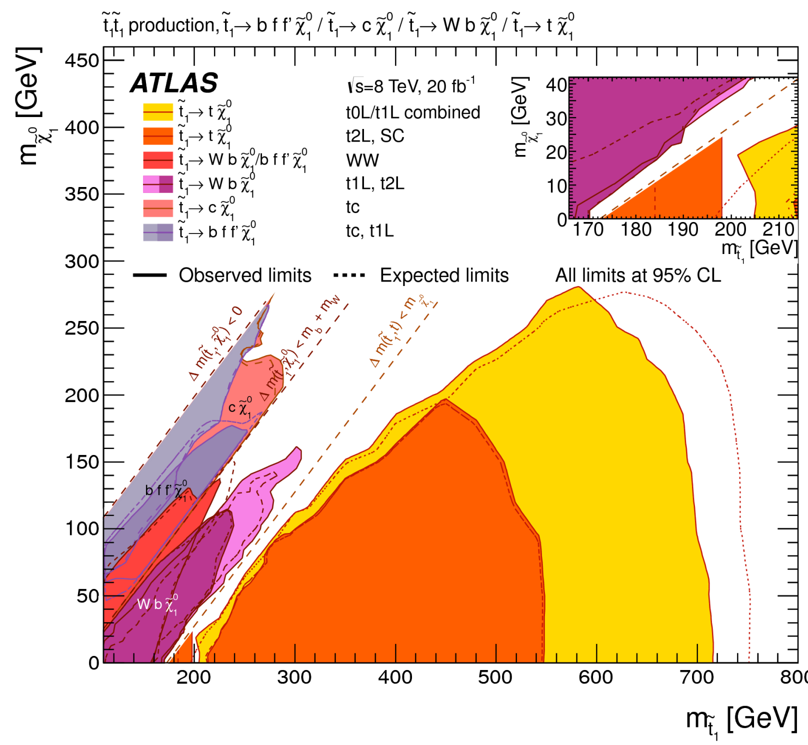
WHERE'S THE NEW PHYSICS?!?

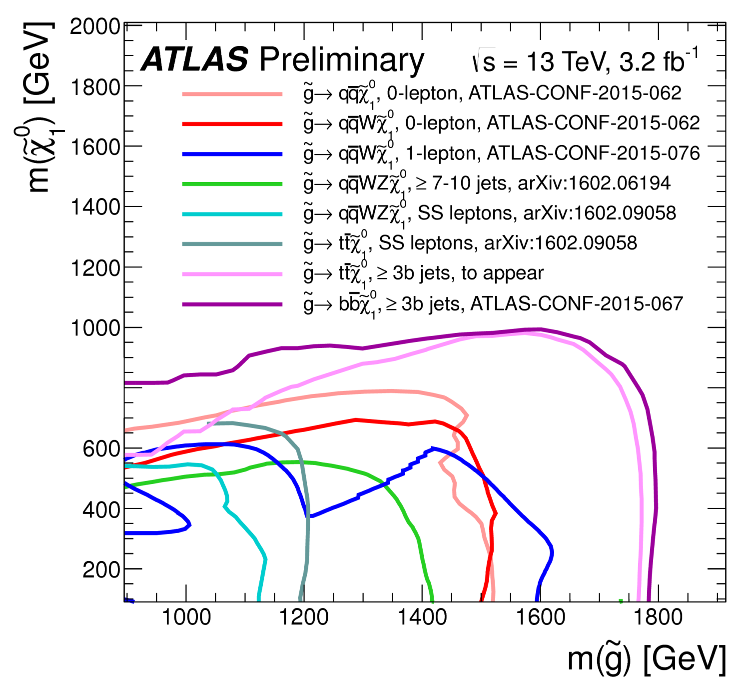






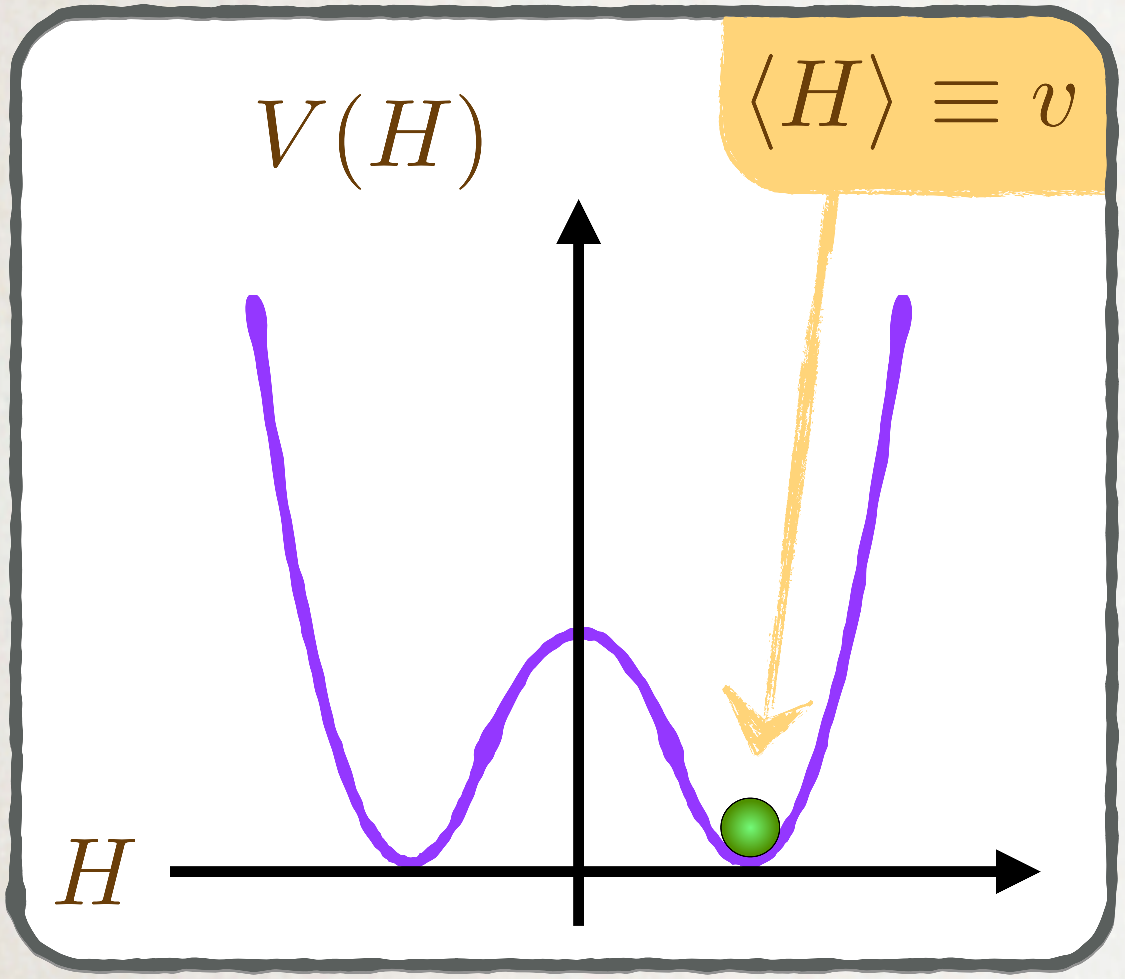






PERTURBATIVITY

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



$W^{\pm}$ 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

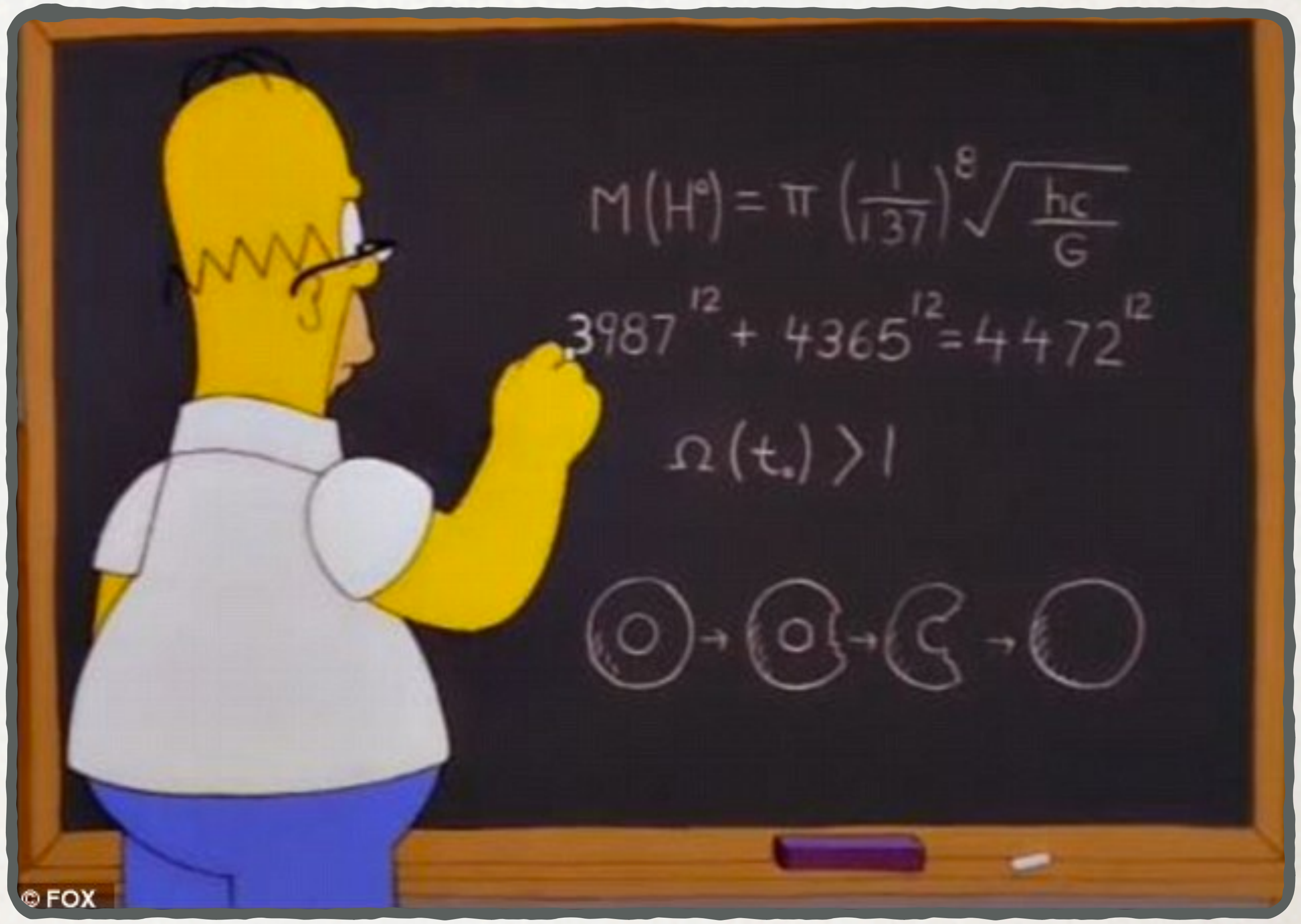
"Model" of electroweak symmetry breaking.
Higgs mass is *not* calculable.

SUSY Model

"Theory" of electroweak symmetry breaking.

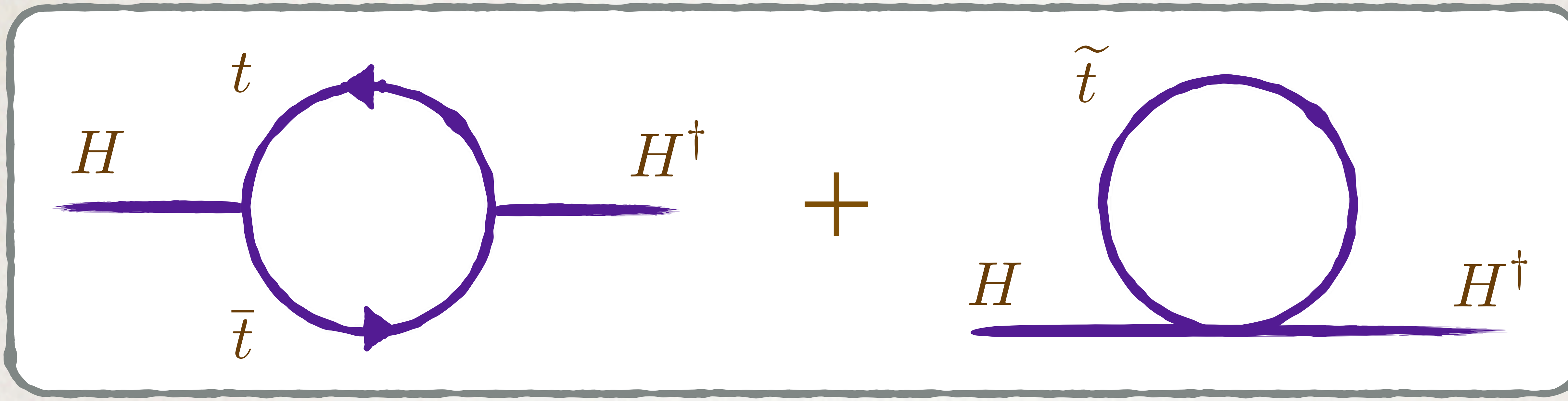
Higgs mass is *finite*.

Can interpret fine-tuning.



GUIDANCE FROM NATURALNESS

MINIMAL REQUIREMENTS



Two-loops: gluinos $\mathcal{O}\left(\frac{16\,\pi^2}{\text{Log}} m_h\right)$

One-loop: stops $\mathcal{O}\left(\sqrt{\frac{16\,\pi^2}{\text{Log}}} m_h\right)$

Tree-level: Higgsinos $\mathcal{O}(m_h)$

Naturalness expectations

"NATURAL SUSY"

~20% tuning

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

HIGGSINO

See David Shih's Talk!

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

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: $\Delta \equiv \dfrac{2\,\delta m_H^2}{m_h^2}$

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

DISCLAIMER

Moving well
beyond minimality.

Goal is to
understand
what is possible.

THREE VIGNETTES

III. Gluinos without Missing Energy

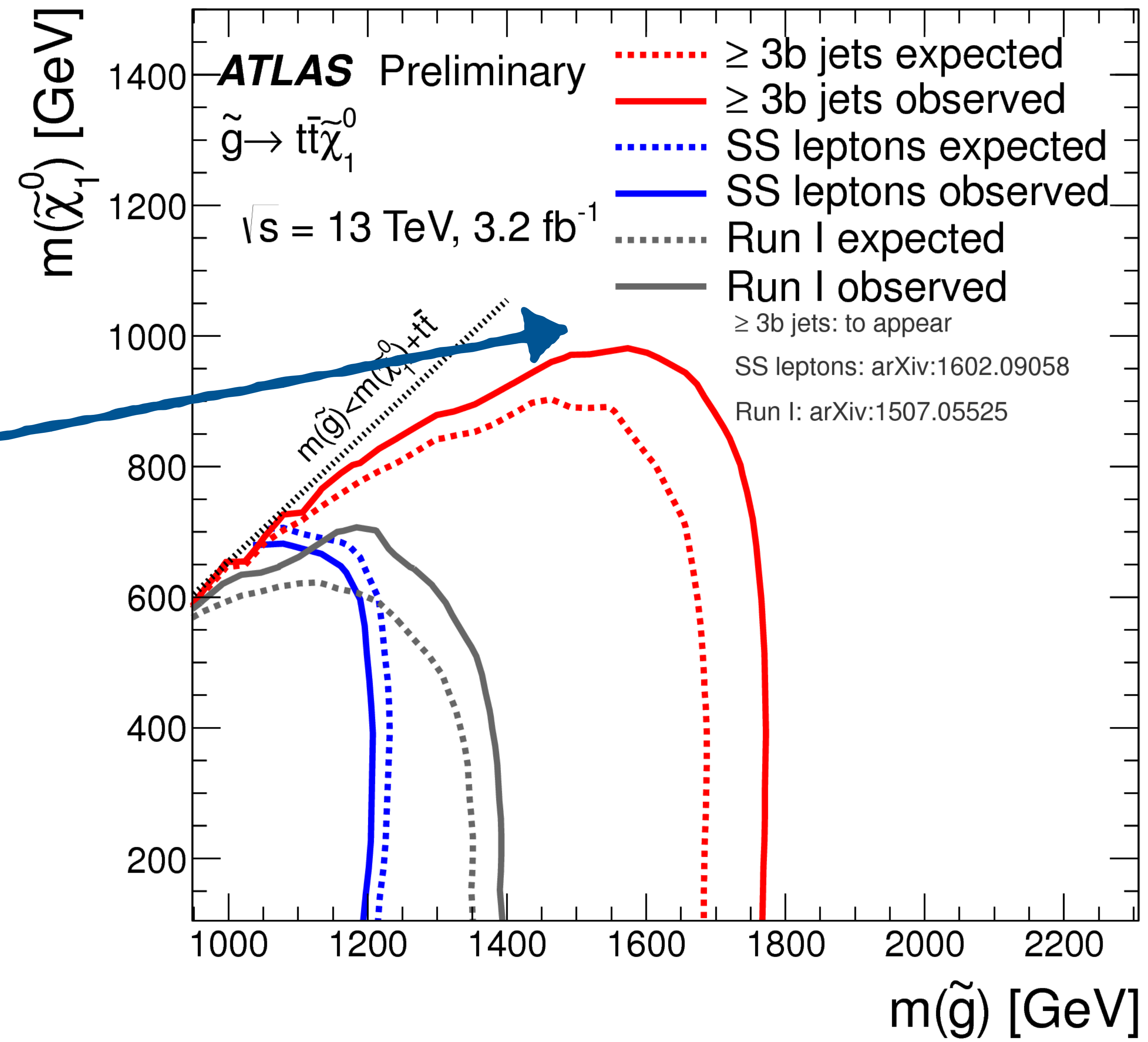
II. Colorless Stops

I. Heavy Higgsinos

HEAVY HIGGSINOS

LHC LIMITS WITH A HEAVY LSP

$$\tilde{g} \to t\,\bar{t}\,\chi$$



No limit for $m_\chi \gtrsim 1$ 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 $SO(5)$.

$$\Phi_a = \frac{1}{\sqrt{2}} \begin{pmatrix} f \\ -i(H_u^1 + H_d^2) \\ H_u^1 - H_d^2 \\ i(H_u^2 - H_d^1) \\ H_u^2 + H_d^1 \end{pmatrix}$$

$SO(5)$ breaking vev.

Symmetry preserving interactions:

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

plus soft breaking.

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

TC, Kearney, Luty [arXiv:1501.01962]
For an effective operator approach, see Nelson and Roy [arXiv:1501.03251]
For a 5D model, see Dimopoulos, Howe, March-Russell [arXiv:1404.7554]

EXPLICIT BREAKING

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

SUPERPOTENTIAL TERMS

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

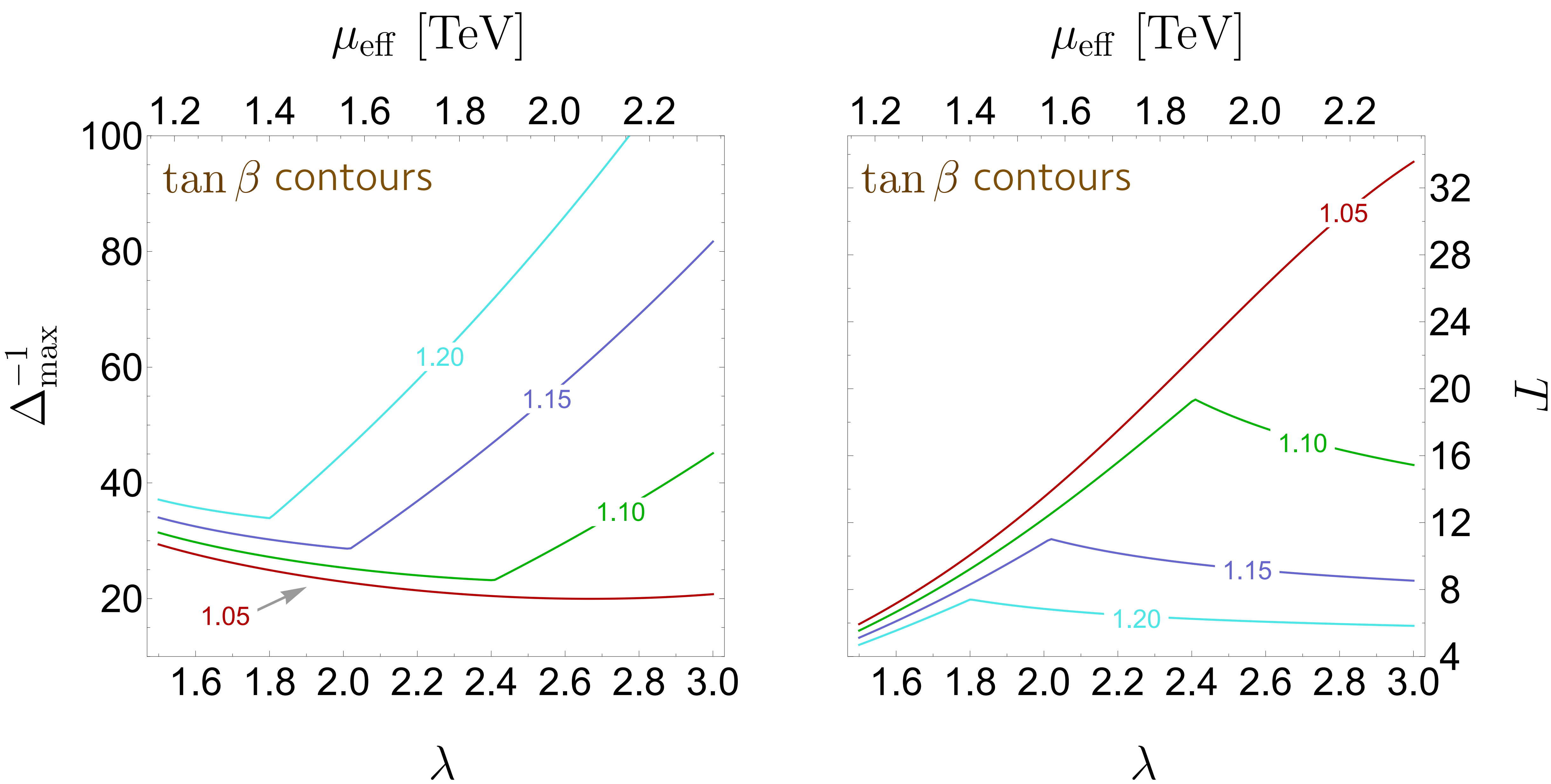
Yields “misalignment" tuning: $\Delta^{-1}_{\text{Goldstone}} \sim \dfrac{f^2}{v^2}.$

YUKAWA AND GAUGE TERMS

Standard MSSM contributions to Higgs potential.

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

REDUCED TUNING



Beat MSSM tuning as coupling increases.

$$T \equiv \Delta^{-1}_{\rm Goldstone}/\Delta^{-1}_{\rm MSSM}$$

TC, Kearney, Luty [arXiv:1501.01962]

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]

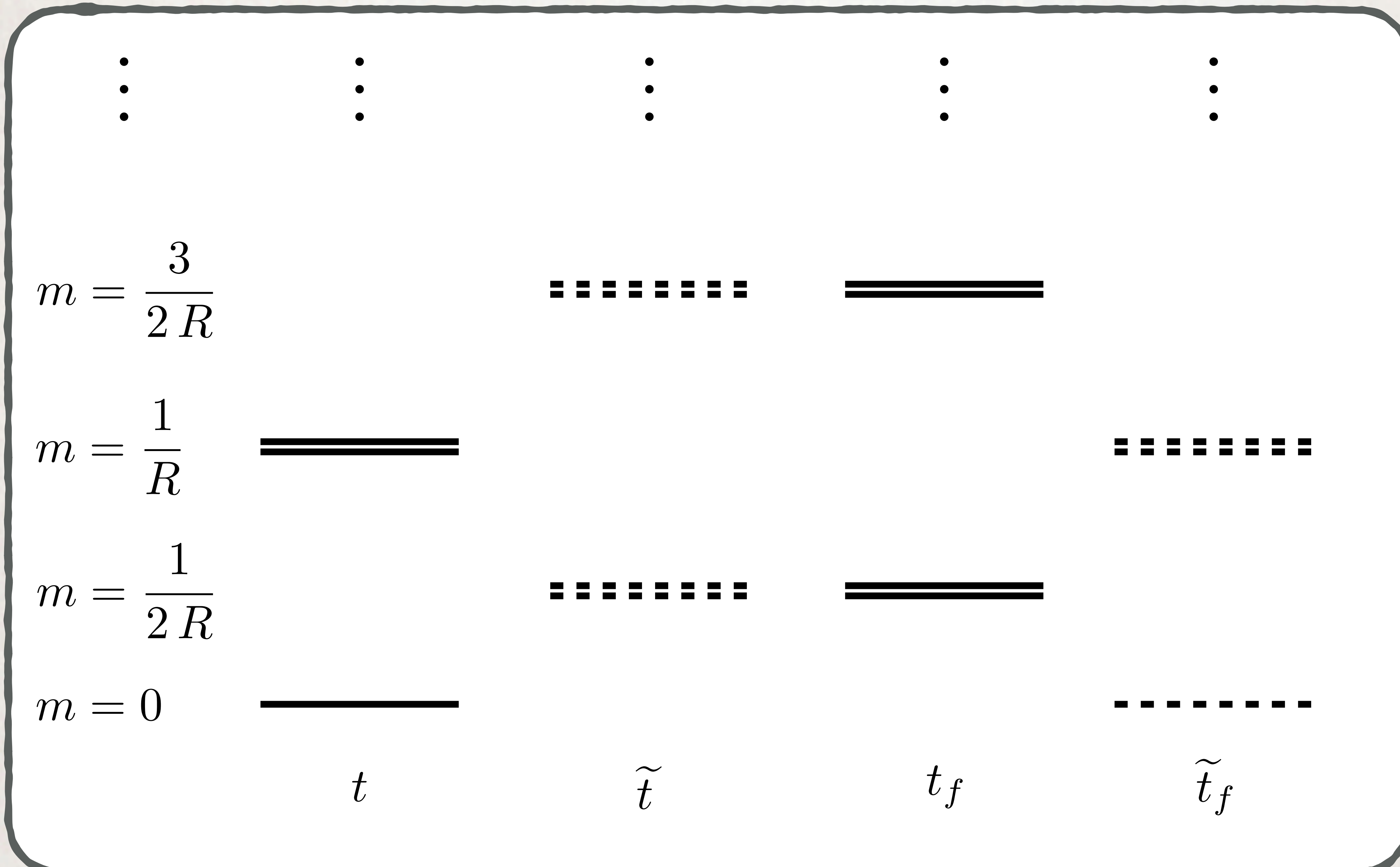
“Folded-SUSY”

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

FOLDED SUSY LIVES IN 5D

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

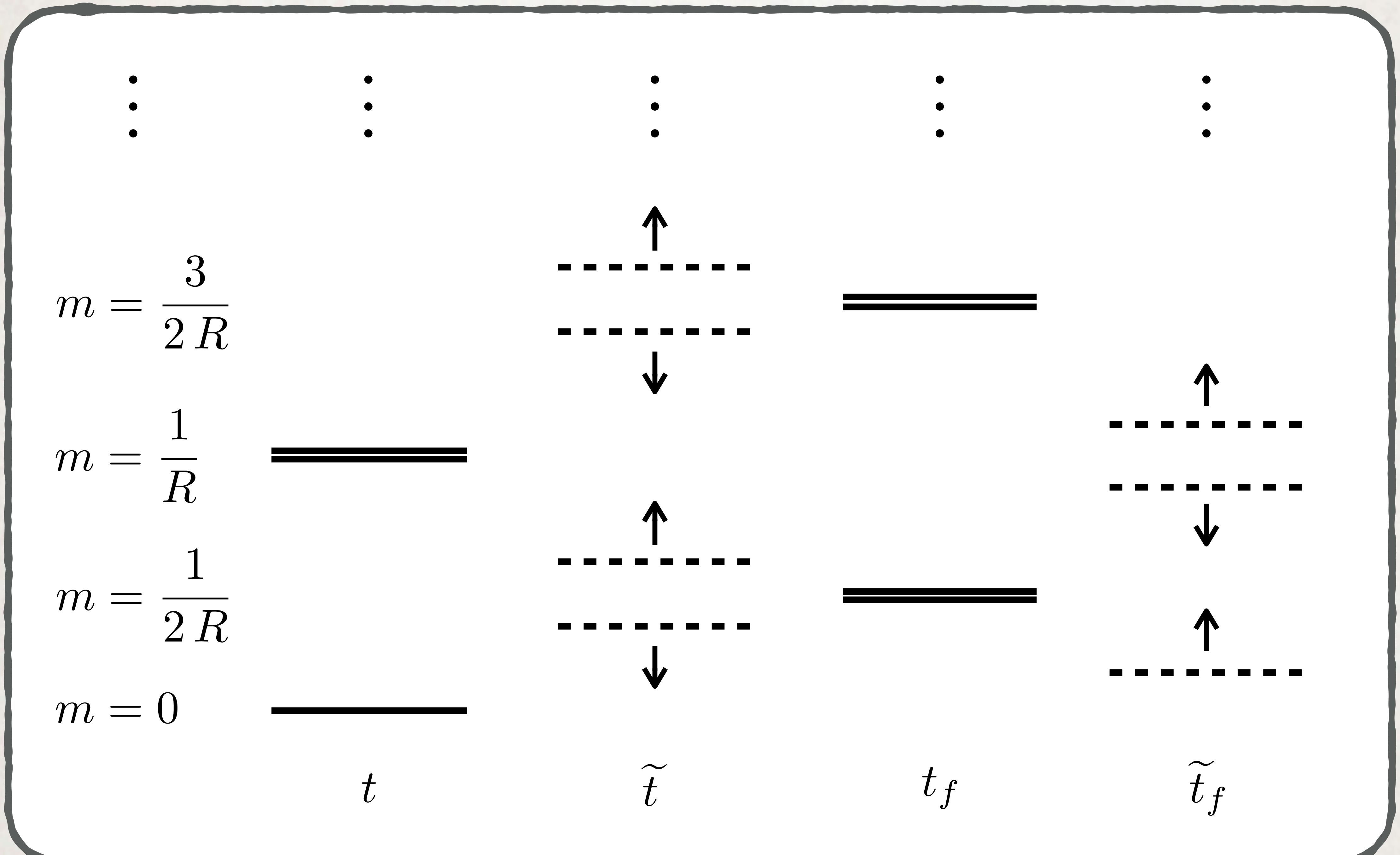
Scherk and Schwarz [PLB 1979]



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.

y_U $\qquad$ $y_{D,E}$

$$SU(2)_W \times SU(1)_Y \times SU(3)_c \times SU(3)_f$$

$$\big(Q,\, U,\, D,\, L,\, E\big)_i$$

S

$$\Big(Q_f,\, U_f,\, D_f,\, L_f,\, E_f\Big)_i$$

$$H_{A,B}$$

$y = 0$ $\qquad$ $y = \pi\, R$

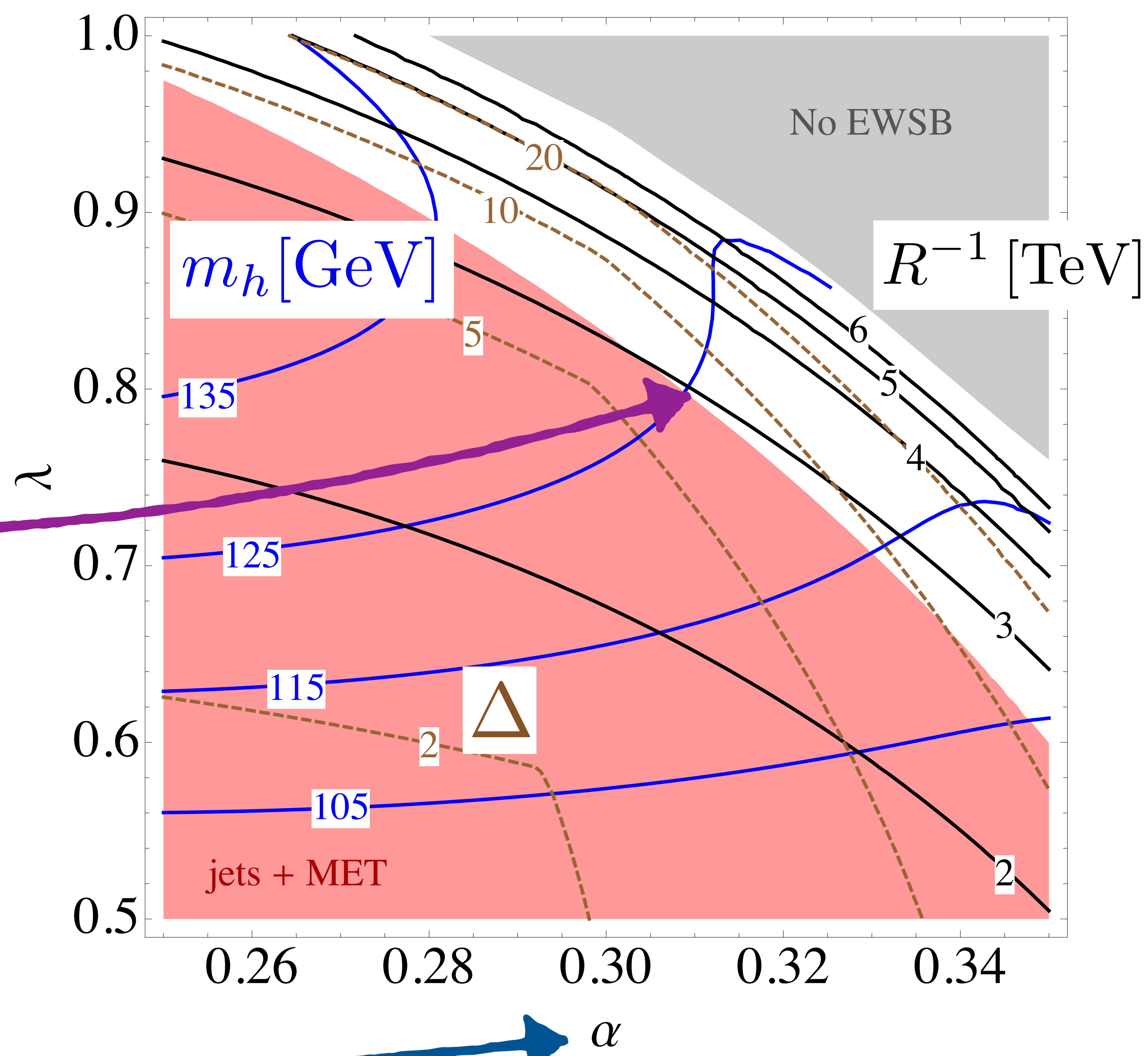
$$\mathcal{W} = \delta(y)\left(\lambda^{(5)}\, S\, H_A\, H_B^c + \frac{M_S}{2} S^2 + y_t^{(5)}\, H_A\, (Q\, U + Q_f\, U_f)\right)$$

PARAMETER SPACE

NMSSM-like coupling

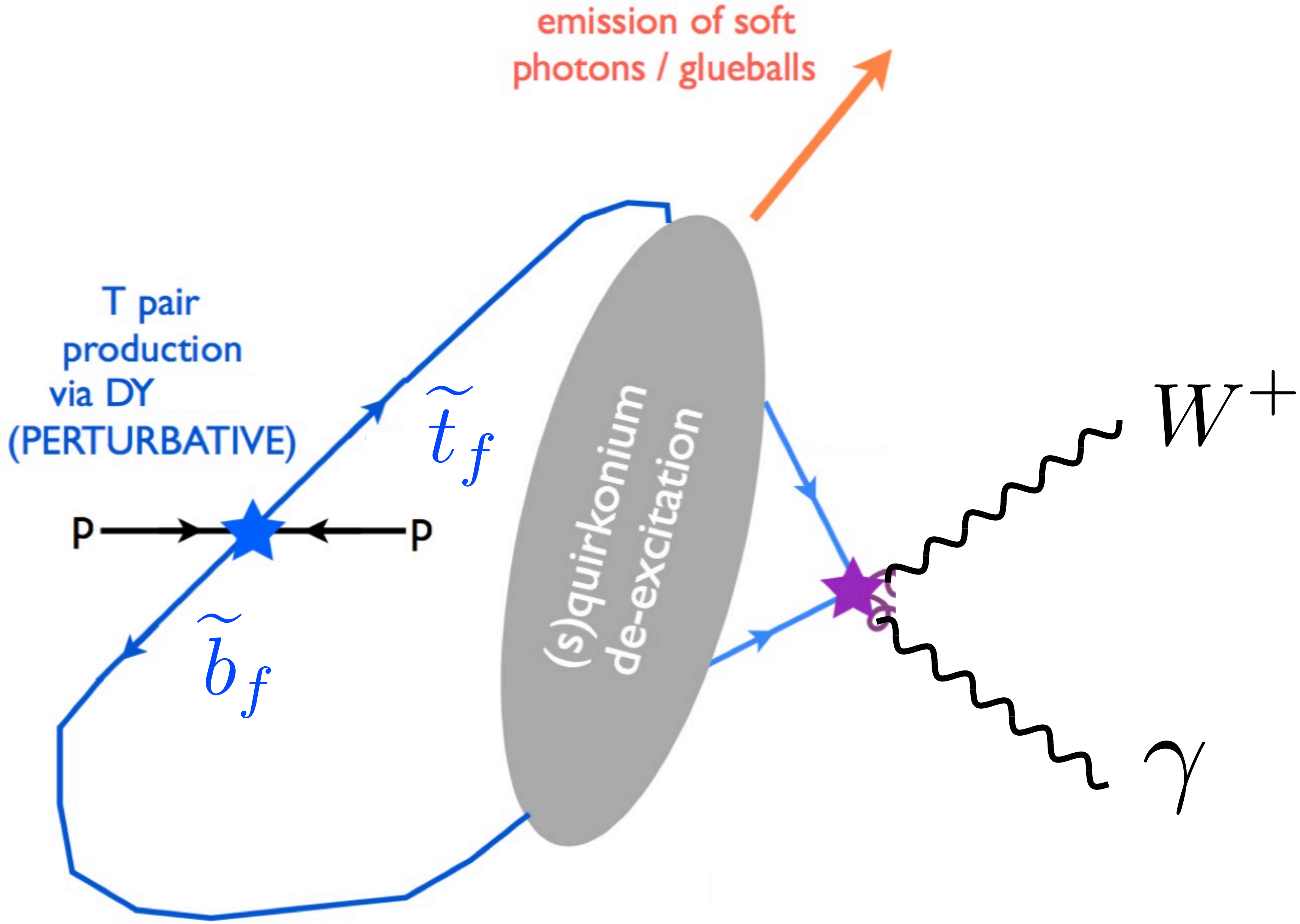
125 GeV Higgs mass with minimal tuning

Twist parameter



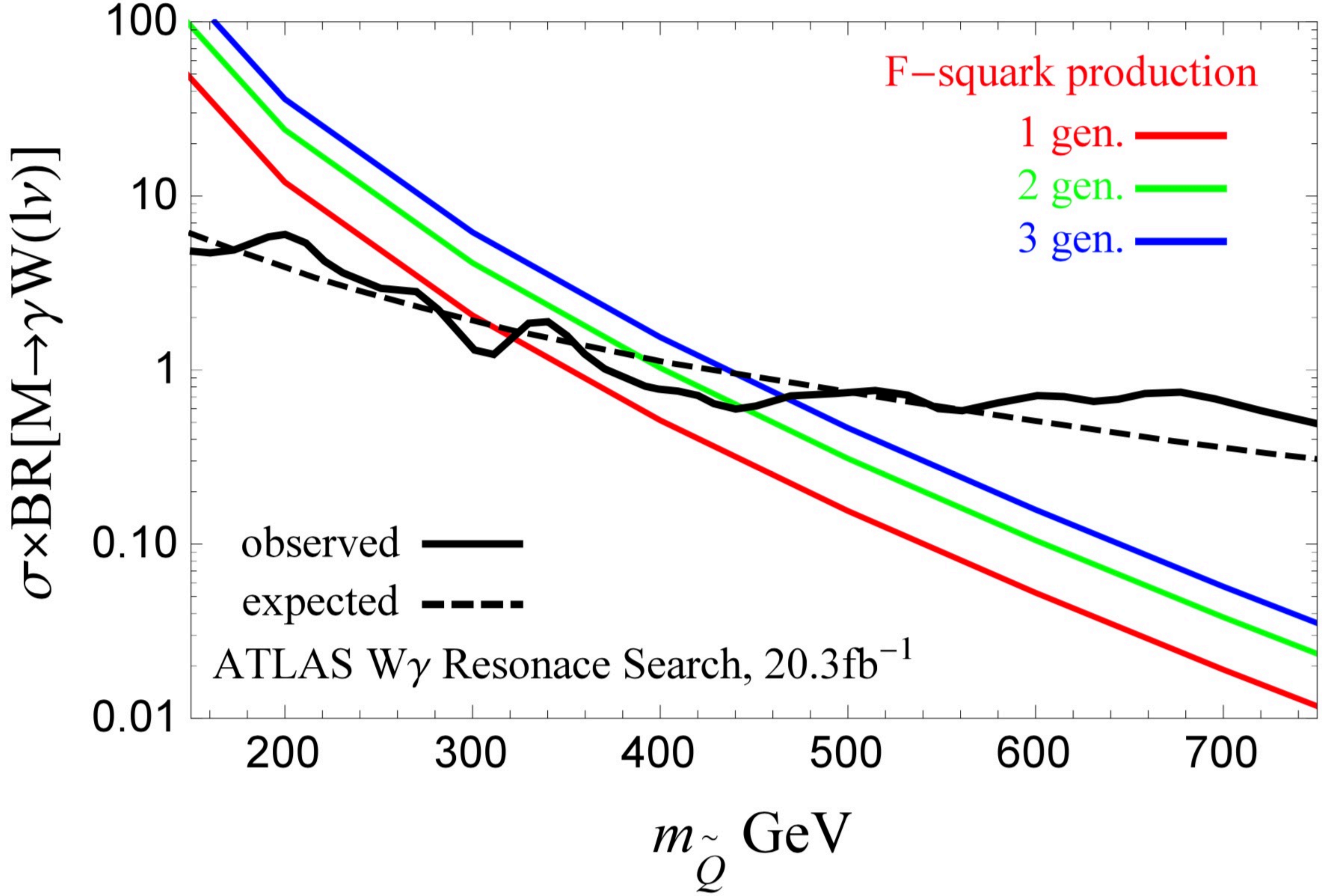
TC, Craig, Lou, Pinner [arXiv:1508.05396]

FOLDED PHENO



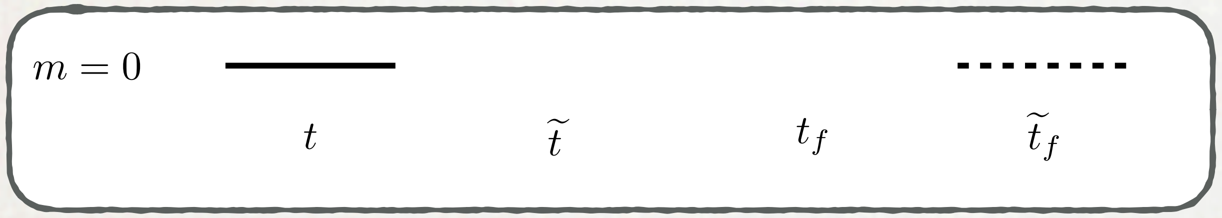
Sketch stolen (and modified) from David Curtin

ELECTROWEAK RESONANCE



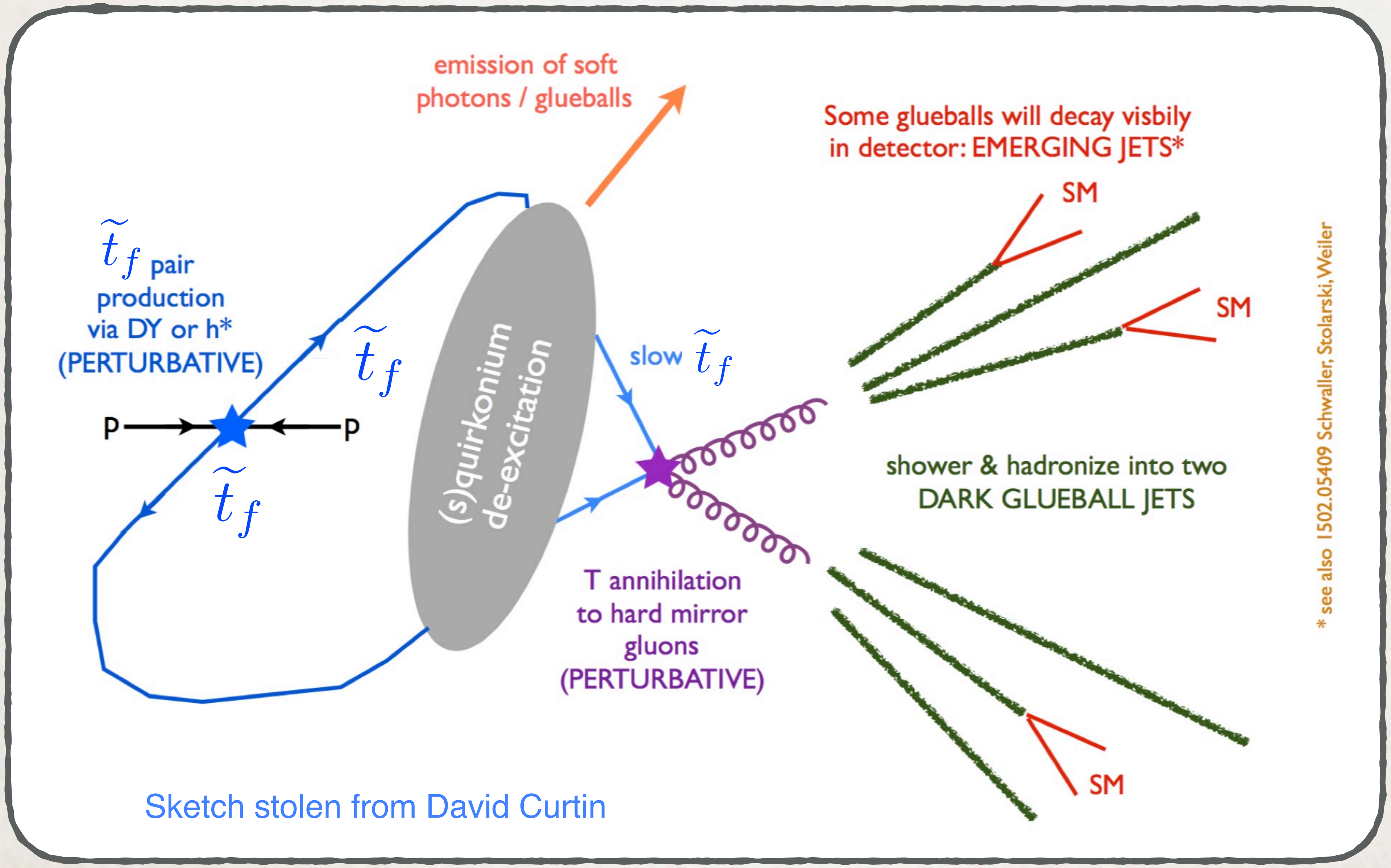
Burdman, Chacko, Harnik, de Lima, Verhaaren [arXiv:1411.3310]

MORE FOLDED PHENO

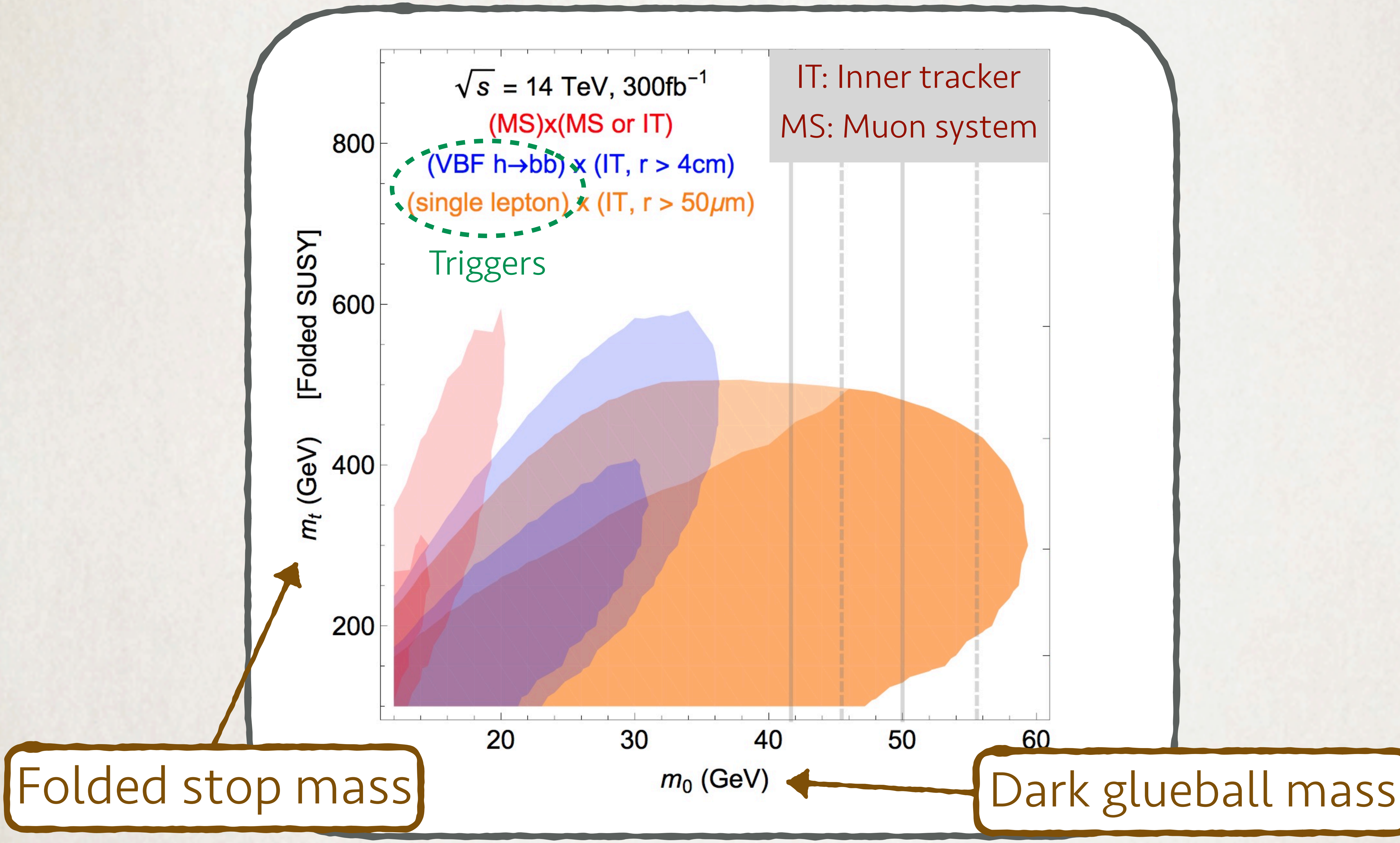


Folded color without folded quarks.
Long color strings can form, *i.e.*, quirks.

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.

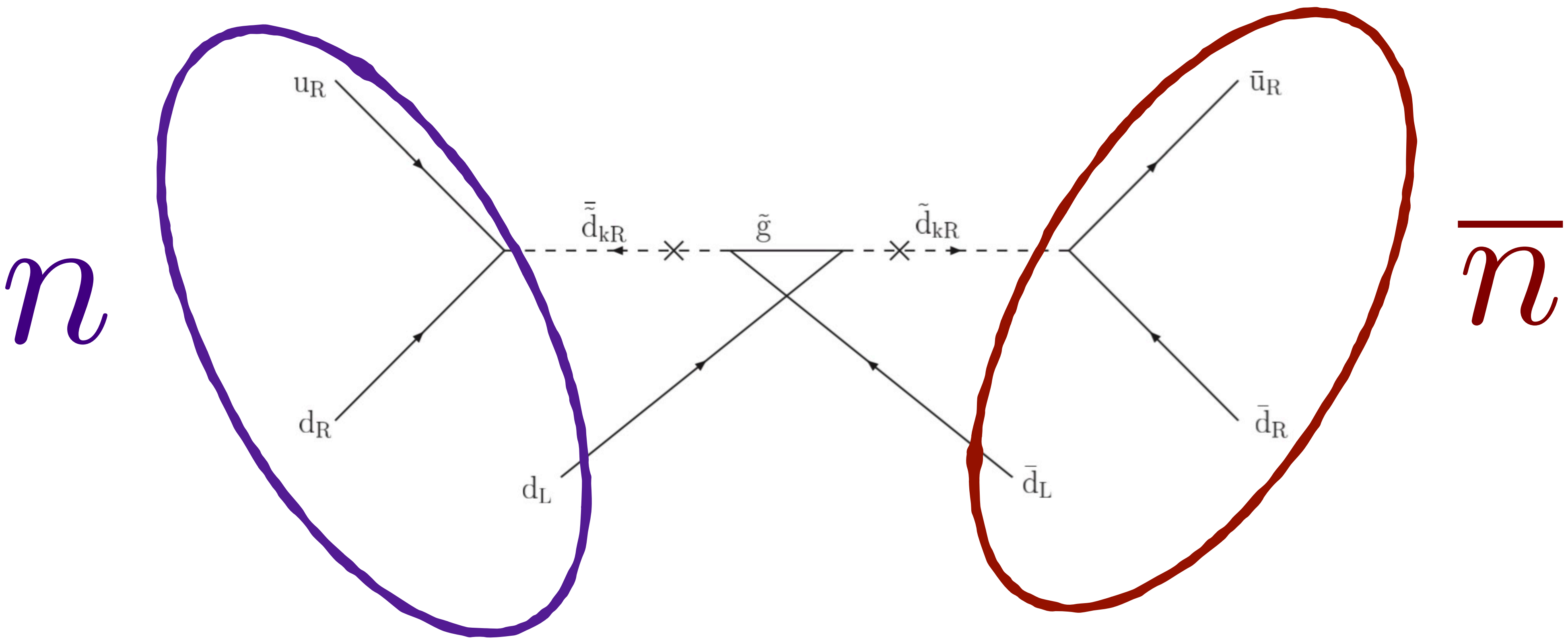
Focus on baryonic RPV operator:

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

CONSTRAINTS

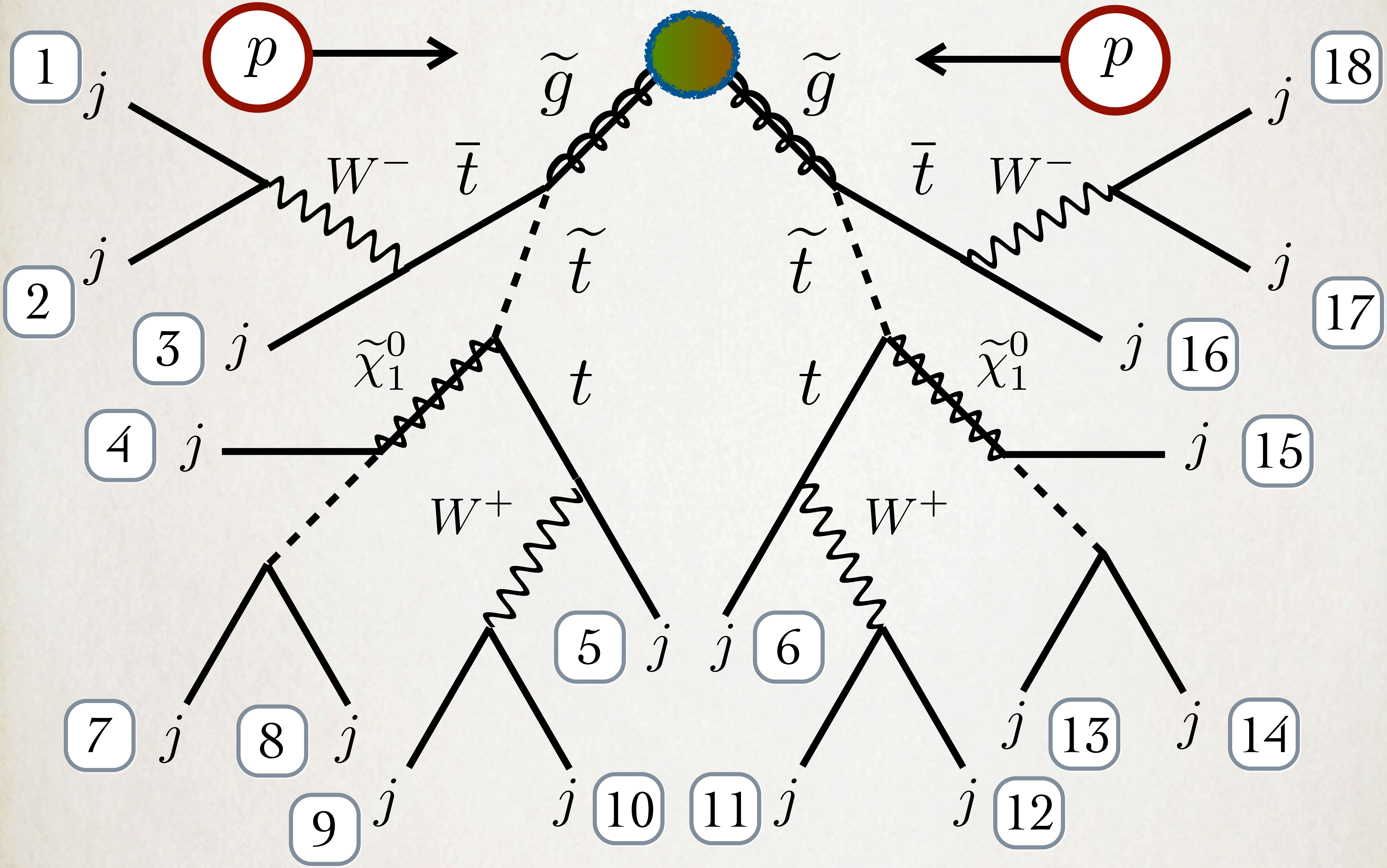
$$W_{\mathrm{RPV}} = \frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c$$

$n - \overline{n}$ oscillations



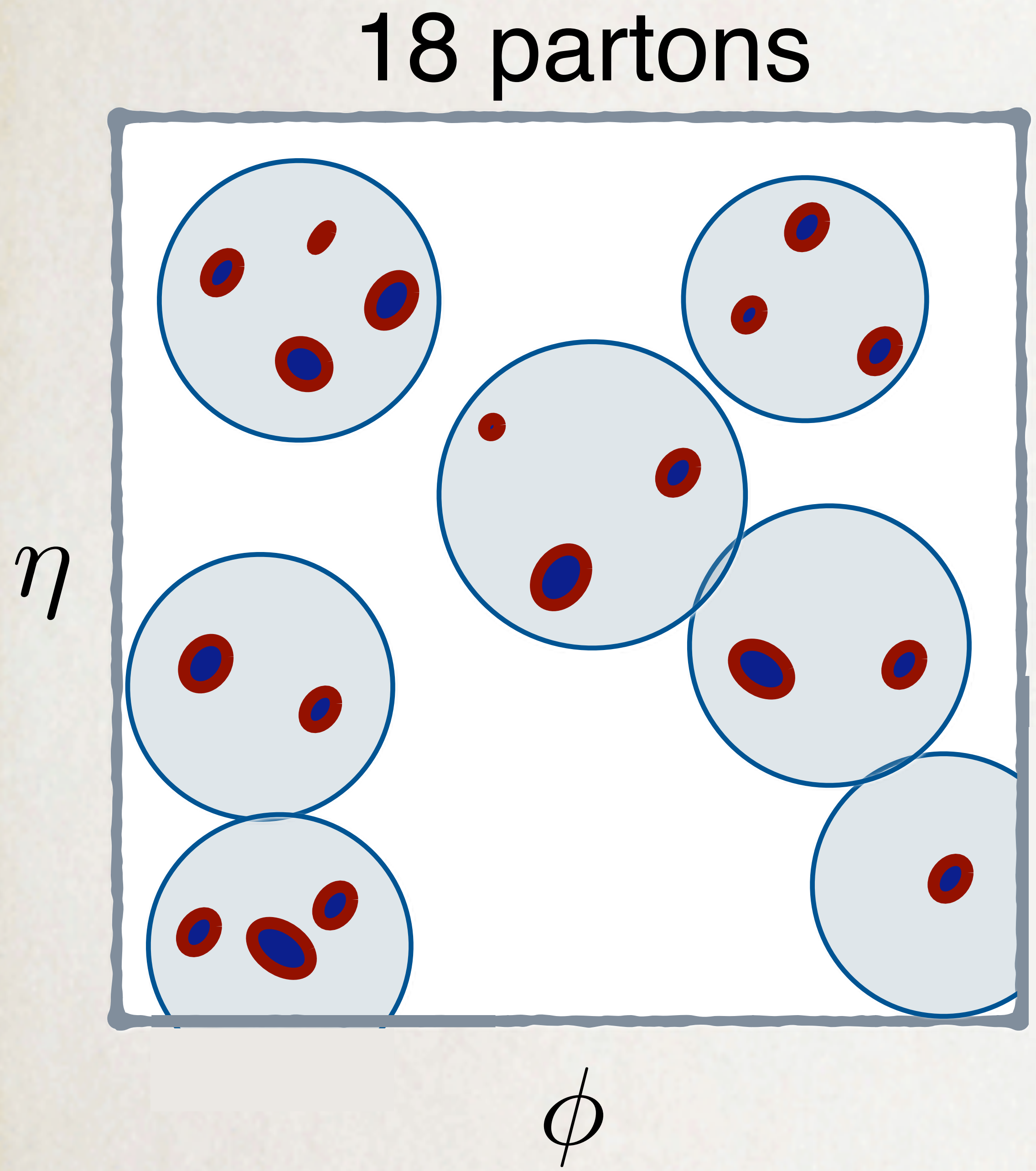
$$|\lambda''_{11k}| \lesssim 10^{-5}\,\frac{10^8\ \mathrm{s}}{\tau_{\mathrm{soc}}}\left(\frac{\tilde{m}}{1\ \mathrm{TeV}}\right)^{5/2}$$

HIGH MULTIPLICITY



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

ACCIDENTAL SUBSTRUCTURE



New physics manifests as high multiplicity hadronic event.

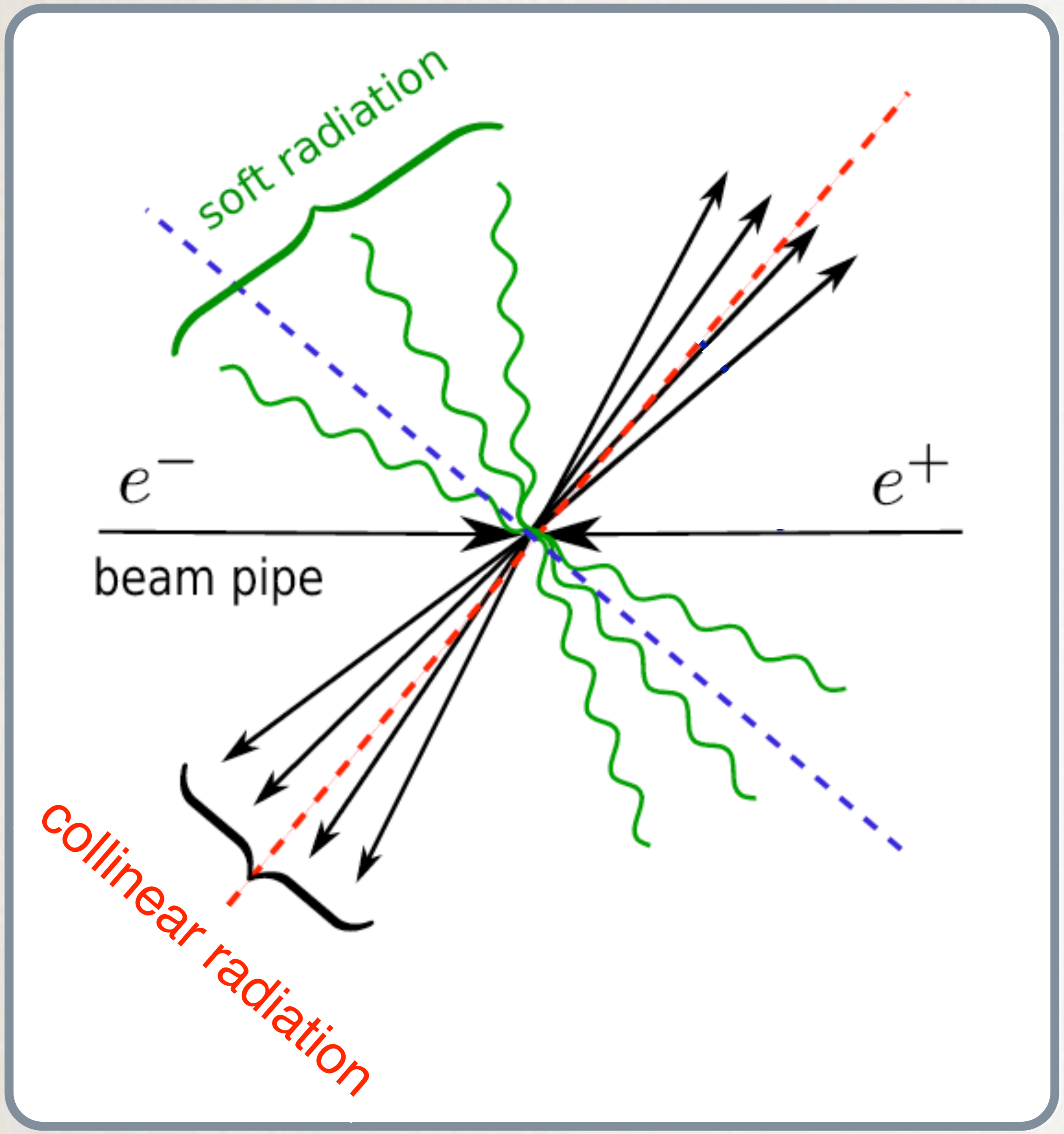
Occasional hard partons will cluster into same fat jet:

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



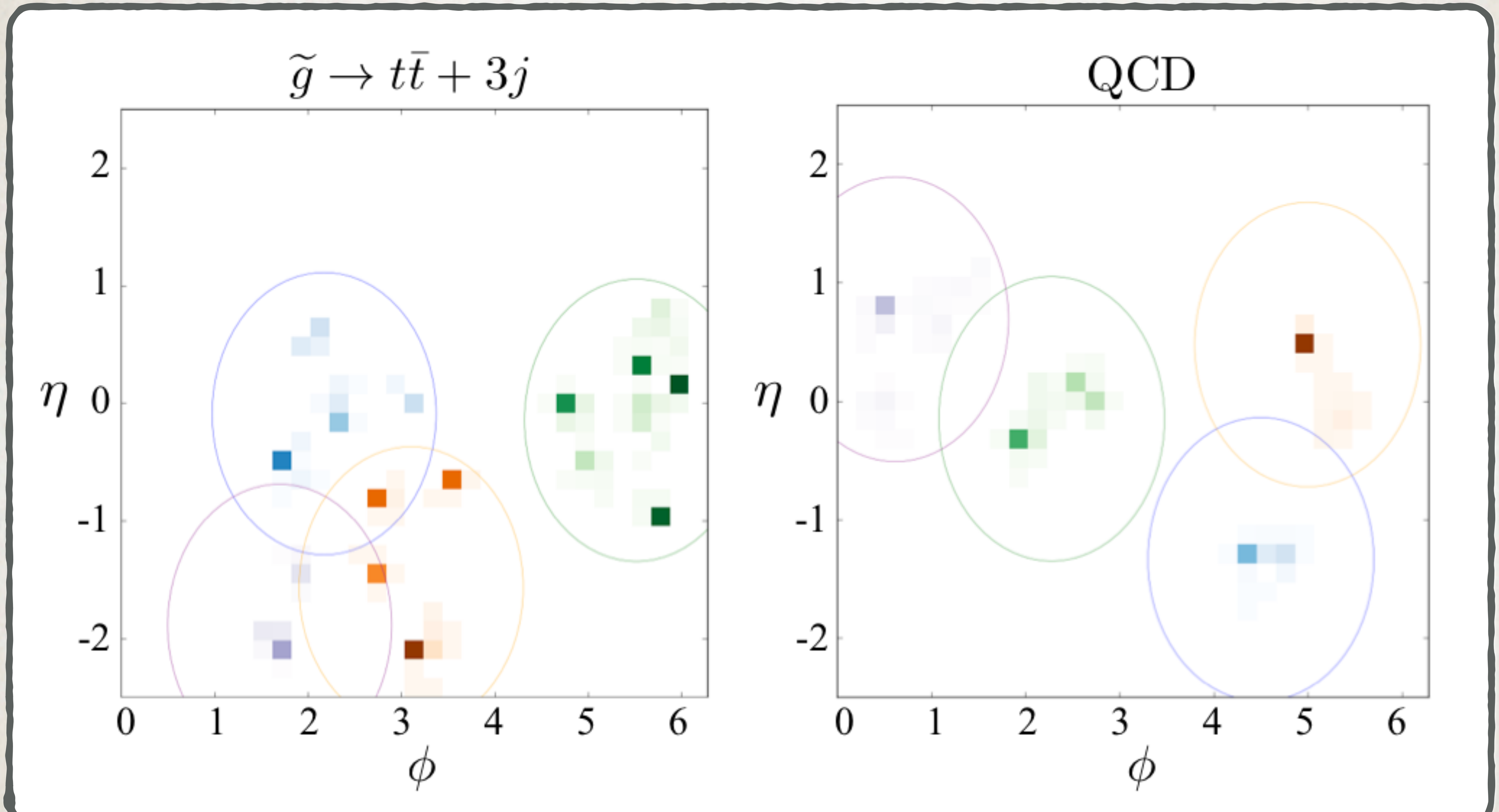
IR structure of QCD: radiation tends to be soft or collinear.

Hard partons are rare.

Difficult to satisfy a multi-fat jet selection.

Mass and substructure are effective discriminators.

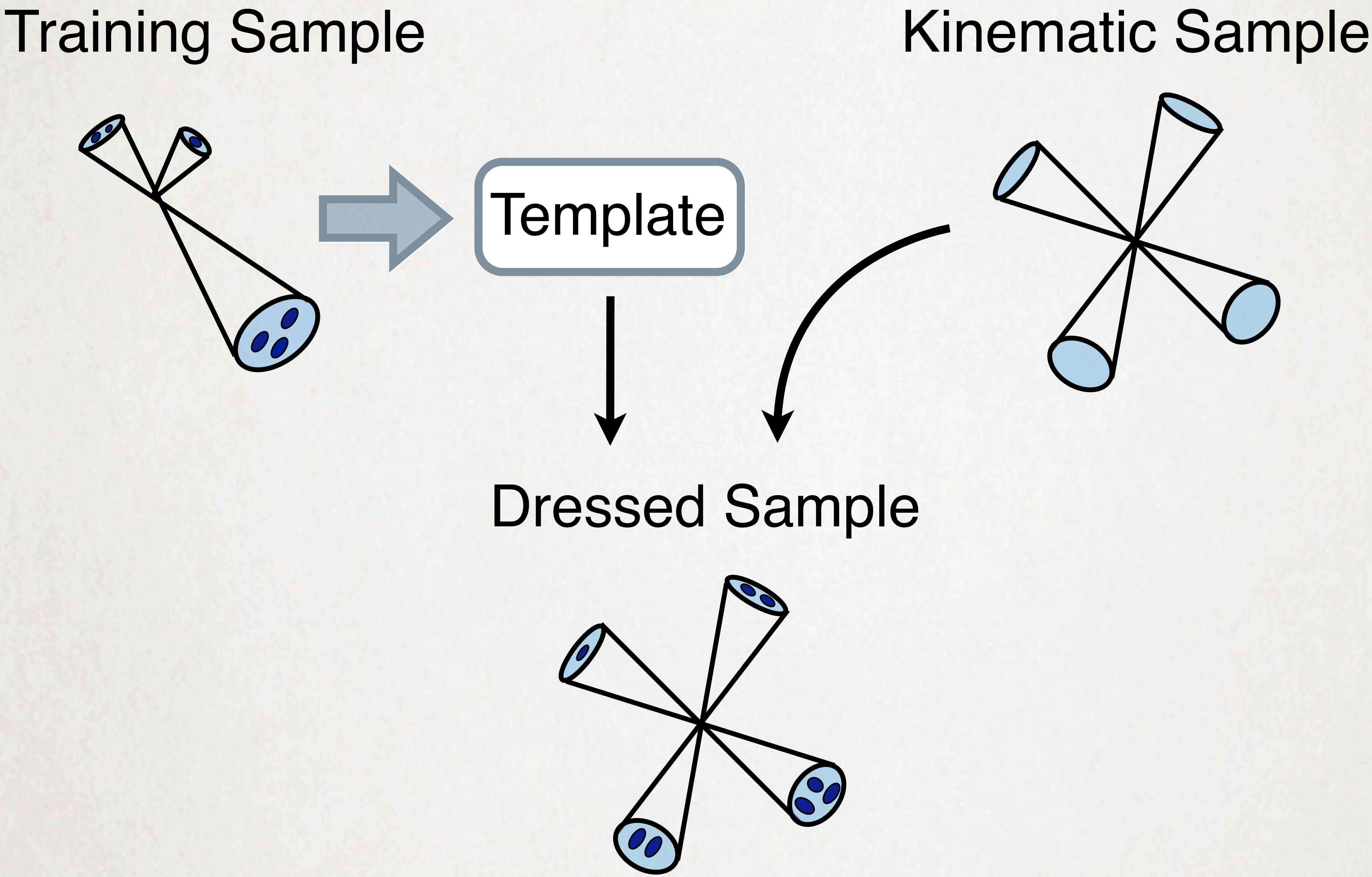
SIGNAL VERSUS BACKGROUND



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

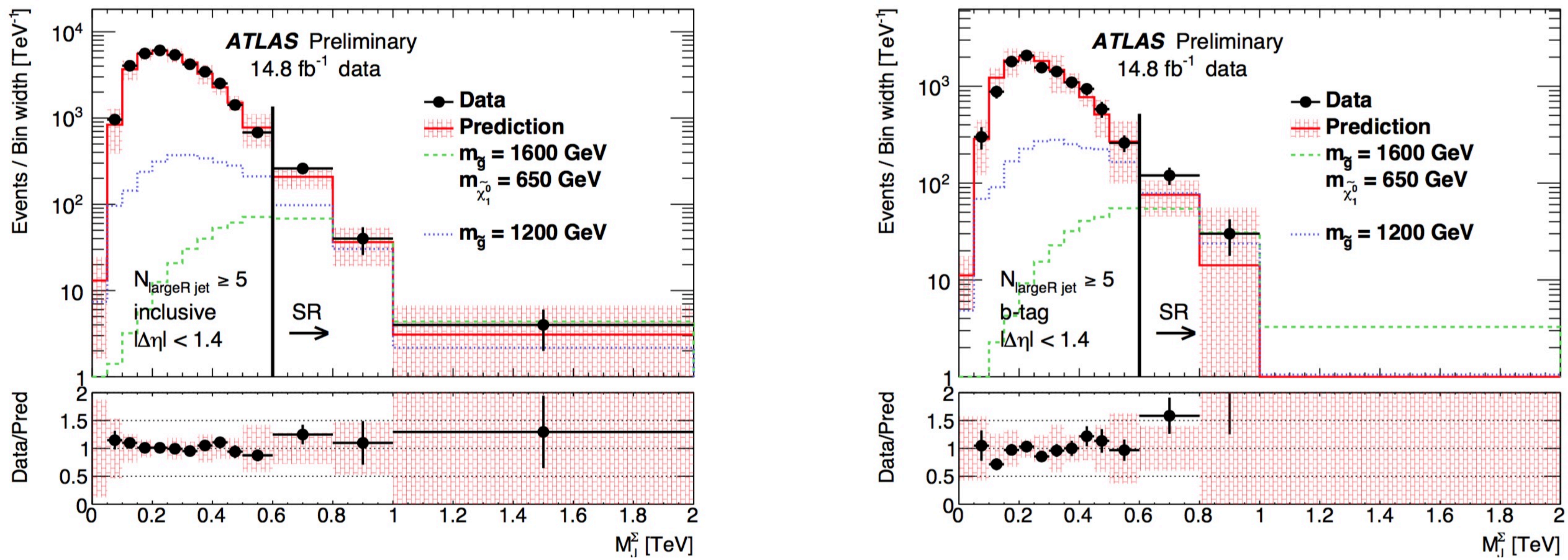
JET SUBSTRUCTURE TEMPLATES

Physical assumption: jets factorize.



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

SUBSTRUCTURE TEMPLATES IN DATA



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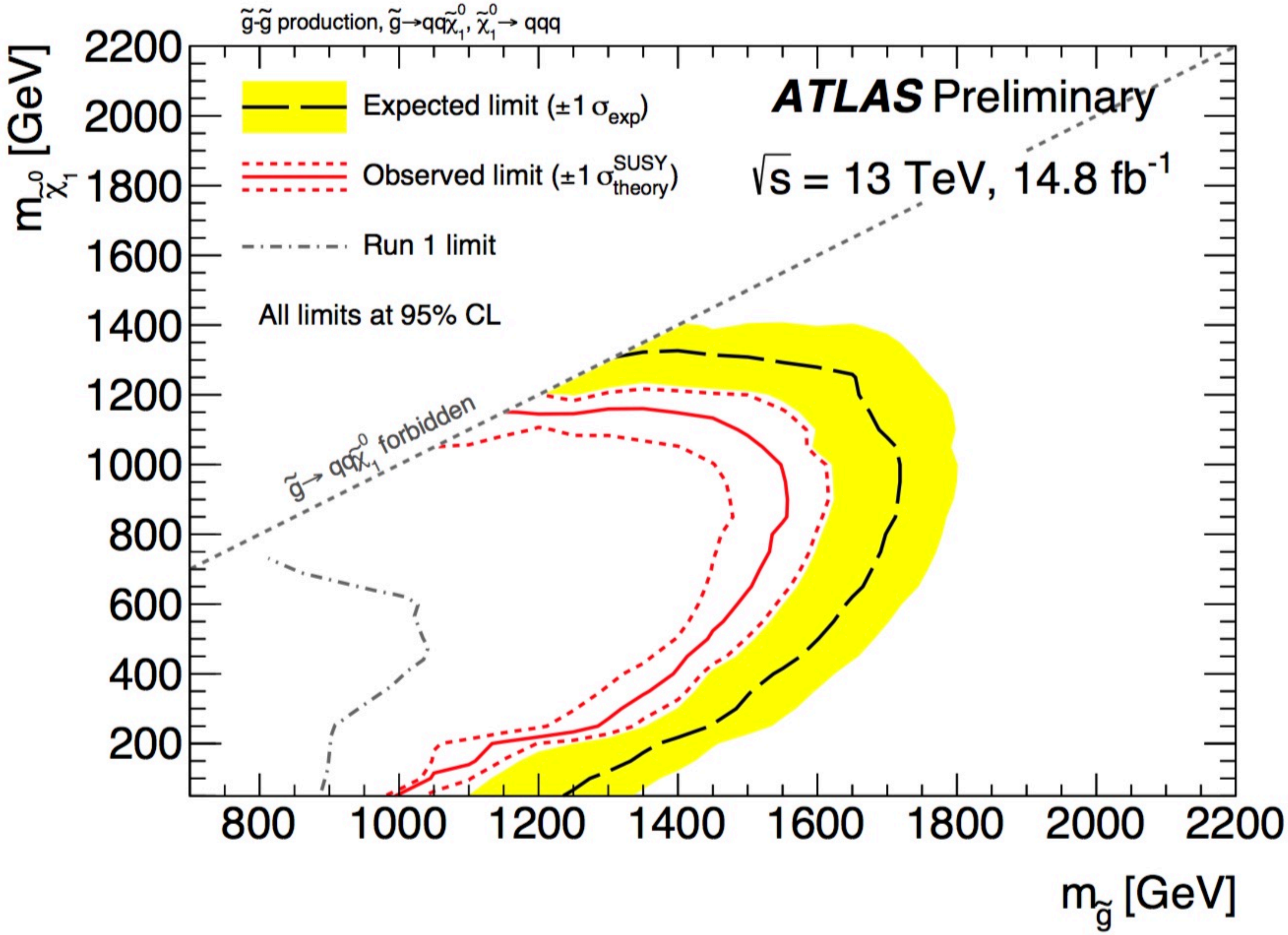
see also CMS and ATLAS [arXiv:1502.05686]

Kernel smoothing techniques used to derive template error bars.

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

NO MET: REDUCED LIMITS

$\tilde{g}$-$\tilde{g}$ production, $\tilde{g} \to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to qqq$



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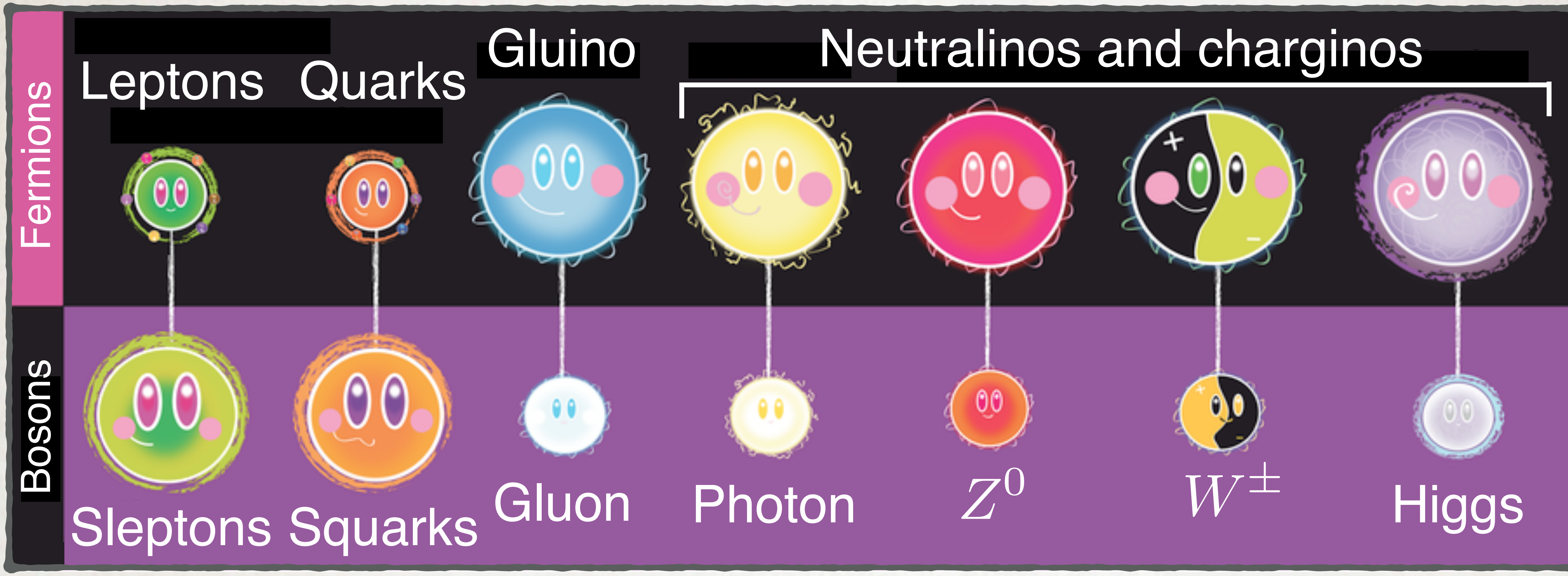
OUTLOOK

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 [arXiv:1607.06821]

⋮

ALL THAT MATTERS...

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