Goldstone Gauginos

UC IRVINE
May 20, 2015

Jamison Galloway

in collaboration with
D. Alves, M. McCullough, N. Weiner

Sketch

PART 1

- WEAK SCALE SUSY:
  - the dream
  - the reality
- NATURALNESS:
  - checking vitals
  - naturalness by design (alternatives in the __SSM)

PART 2

- DIRAC GAUGINOS:
  - the good (naturalness, pheno)
  - the bad (tachyons)
  - the ugly (tuning in/and models)
- GOLDSTONE GAUGINOS
  - mechanism and models
  - comparative phenomenology

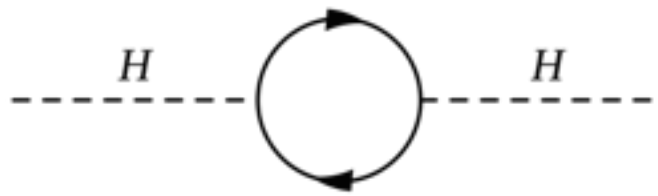
PART 1

WEAK SCALE SUSY

The Dream

- Stabilizes weak scale, provided $m_{\text{soft}} \sim m_{\text{weak}}$

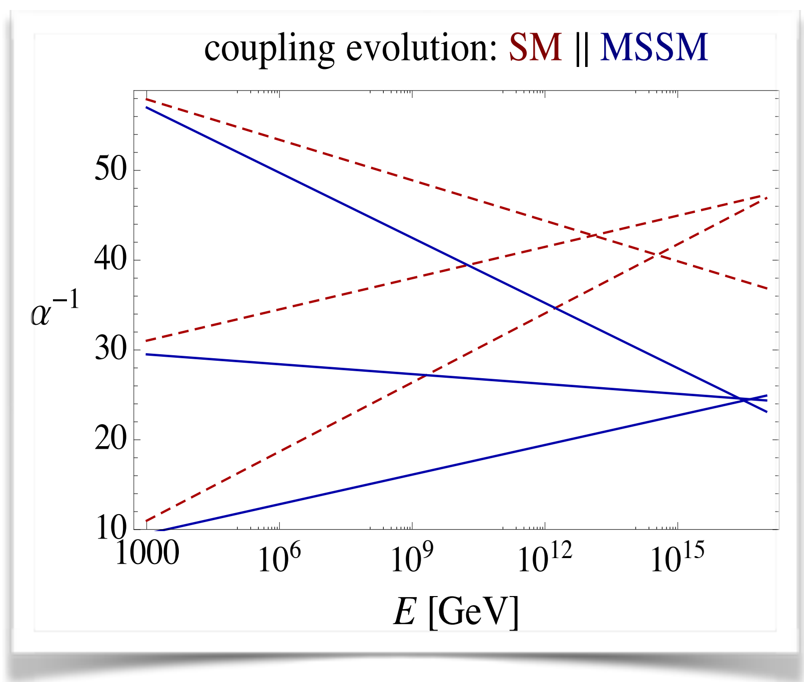
δm_H^2 :



$+$

$\propto m_{\text{soft}}^2 \ln \Lambda$

- Gauge coupling unification

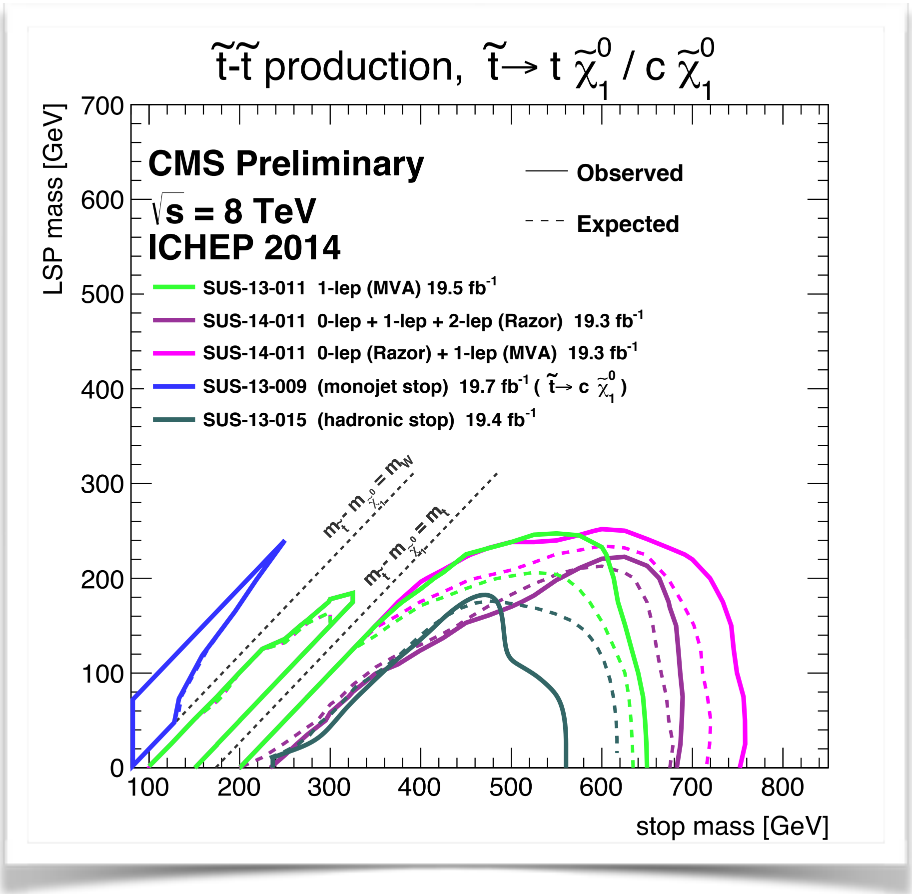


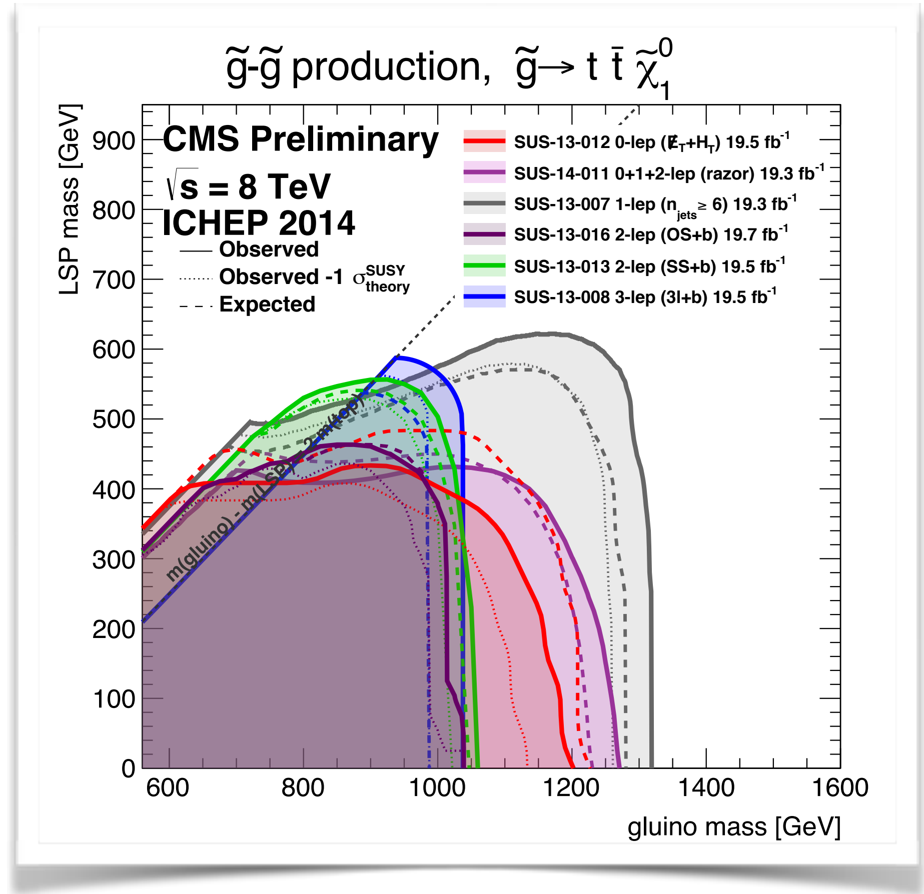
- Natural dark matter candidate

WEAK SCALE SUSY

The Reality

LHC results, e.g.:



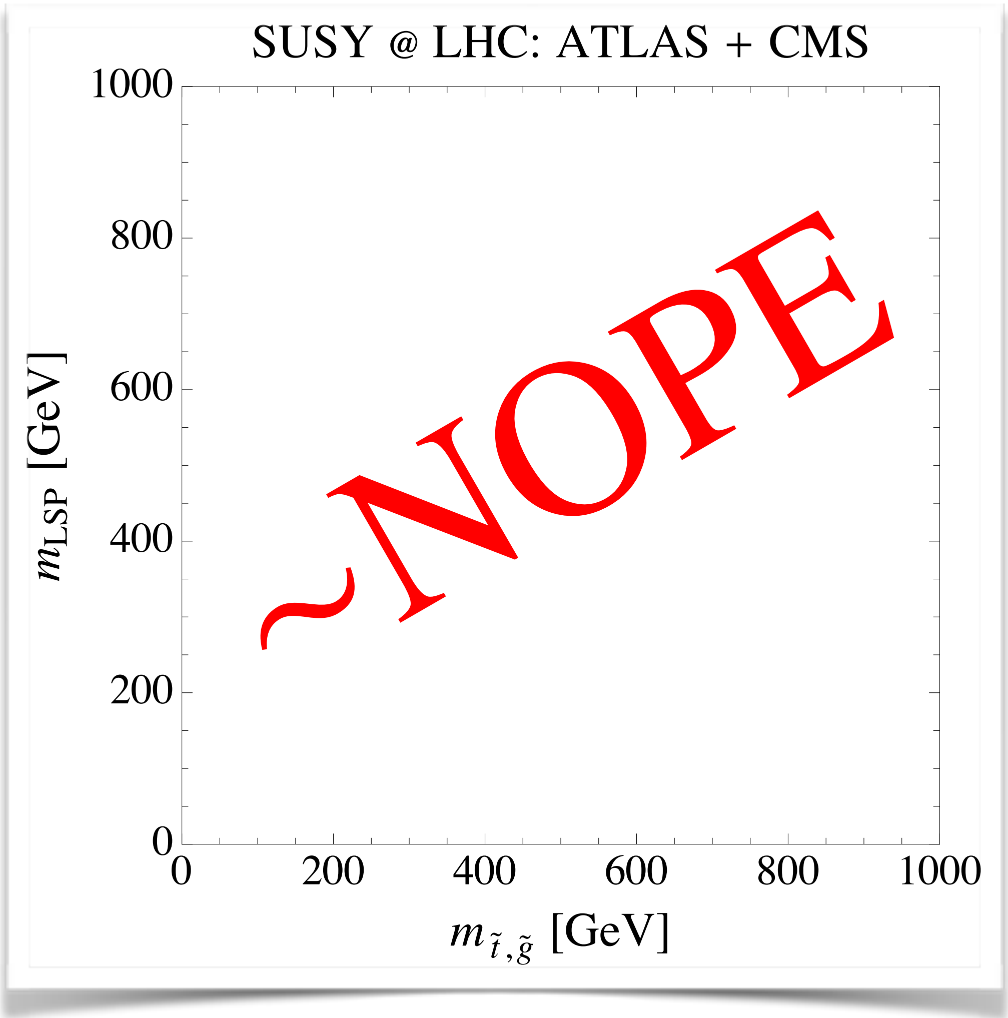


WEAK SCALE SUSY

The Reality

Theorist's combination:

(ie assumption for this talk)



More careful takeaway for conventional SUSY:

$$m_{\tilde{t}} \gtrsim 600\,\mathrm{GeV}$$

$$m_{\tilde{g}} \gtrsim 1200\,\mathrm{GeV}$$

SUSY'lessness endures

NATURALNESS

Checking Vitals

tuning at one and two loops:

Light Higgs wants a light stop: $\delta m_H^2 \sim \frac{-N_c}{8\pi^2} y_t^2 m_{\tilde{t}}^2 \ln(\Lambda^2/m_{\tilde{t}}^2)$

Light stop wants a light gluino: $\delta m_{\tilde{t}}^2 \sim \frac{8\alpha_s}{3\pi} M_{\tilde{g}}^2 \ln(\Lambda^2/m_{\tilde{g}}^2)$

⇒ Naturalness would prefer $m_{\tilde{t}} \lesssim 700\,\mathrm{GeV}$, $m_{\tilde{g}} \lesssim 2m_{\tilde{t}}$

$$\left.\begin{aligned} m_{\tilde{t}} &\gtrsim 600\,\mathrm{GeV} \\ m_{\tilde{g}} &\gtrsim 1200\,\mathrm{GeV} \\ \Lambda &= 10^5\,\mathrm{GeV} \end{aligned}\right\} \quad \mathrm{FT} \lesssim 5\%$$

* dependence on cutoff: 100 TeV → FT x 10, 10 TeV → FT x 5

NATURALNESS

Checking Vitals

* dependence on cutoff: 100 TeV ➡ FT x 10, 10 TeV ➡ FT x 5

- soft masses via dimensionless spurion with gaugino mediation

$$\left.\begin{array}{c}\Delta W = \frac{X}{M} W^\alpha W_\alpha \\ \Downarrow \\ \text{spurion} = \theta^2 F_X / M\end{array}\right\} \qquad \Delta K_Q = \frac{\theta^4 F_X^\dagger F_X}{M^2} Q^\dagger Q$$

- marginal operator from Kahler term; nothing prevents divergent counterterm

$$\delta m_Q^2 \propto m_{\text{soft}}^2 \times \boxed{\ln(\Lambda)}$$

- residual dependence on high scale due to ***Majorana*** nature of gaugino

NATURALNESS

Alternatives: naturalness by design

— or — naturalness in the __SSM

This page intentionally left blank

PART 2

DIRAC GAUGINOS

***Setup*: cf. Fayet '78, Fox et al '02**

Input: SUSY broken by a *D* term of *U*(1)'

fields of SM x *U*(1)':

$$A \sim (\mathbf{Adj}, 0)$$
$$T \sim (\square, 1)$$
$$\bar{T} \sim (\overline{\square}, -1)$$

$$W = y\bar{T}AT + m\bar{T}T$$

$$\Downarrow$$

$$W_{\rm IR} \sim \frac{gy}{m} W' {\rm Tr}\left(W_{\rm SM} A\right) + \ldots$$

"supersoft classic": $W_{\rm IR} \sim \frac{gy}{m} W' {\rm Tr}\left(W_{\rm SM} A\right) \begin{cases} W' & \sim \theta D' \\ W_J & \sim \lambda_J + \theta D_J + \ldots \\ A_J & \sim A_J + \theta \psi_J \end{cases}$

$$\Delta\mathcal{L} \sim m_D \lambda_J \psi_J + m_D^2\, {\rm Re}\left(A_J\right)^2$$

$$\delta m_{\tilde{f}}^2 \propto m_D^2 \ln(m_{{\rm Re}A}^2 / m_D^2)$$

DIRAC GAUGINOS

Setup: cf. Fayet '78, Fox et al '02

Input: SUSY broken by a D term of $U(1)'$

fields of SM x $U(1)'$:

$$A \sim (\mathbf{Adj}, 0)$$

$$T \sim (\Box, 1)$$

$$\bar{T} \sim (\overline{\Box}, -1)$$

$$W = y\bar{T}AT + m\bar{T}T$$

$$W_{\rm IR} \sim \frac{gy}{m} W' {\rm Tr}\,(W_{\rm SM} A) + \dots$$

$$\Delta\mathcal{L} \sim m_D \lambda_J \psi_J + m_D^2\, {\rm Re}\,(A_J)^2$$

$$\delta m^2_{\tilde{f}} \propto m_D^2 \ln(m^2_{{\rm Re}A}/m_D^2)$$

to notice:

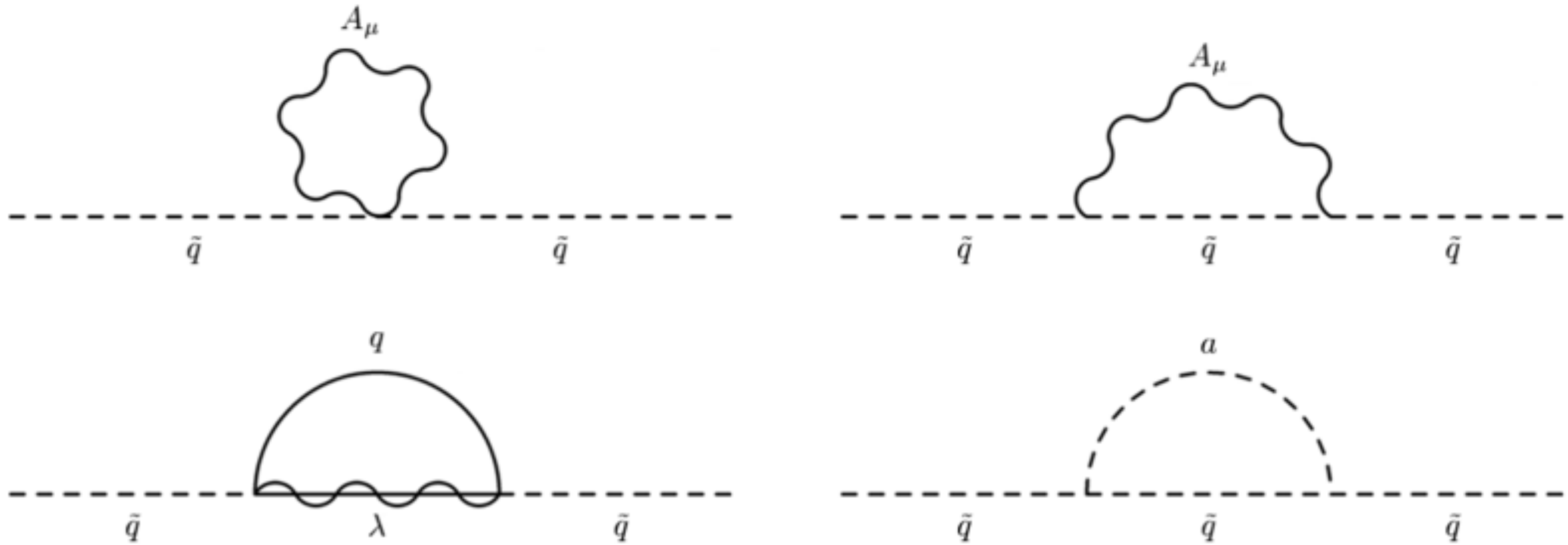
- pseudoscalar massless so far
- squark masses fixed by *finite* log
- more explicitly, ln(4)~1.4 => factor of 5-10 in FT

DIRAC GAUGINOS

Naturalness: cf. Fox et al '02, Csaki et al '13

$$\delta m_{\tilde{f}}^2 \propto m_D^2 \ln(m_{\mathrm{Re}A}^2 / m_D^2)$$

diagrammatic derivation:

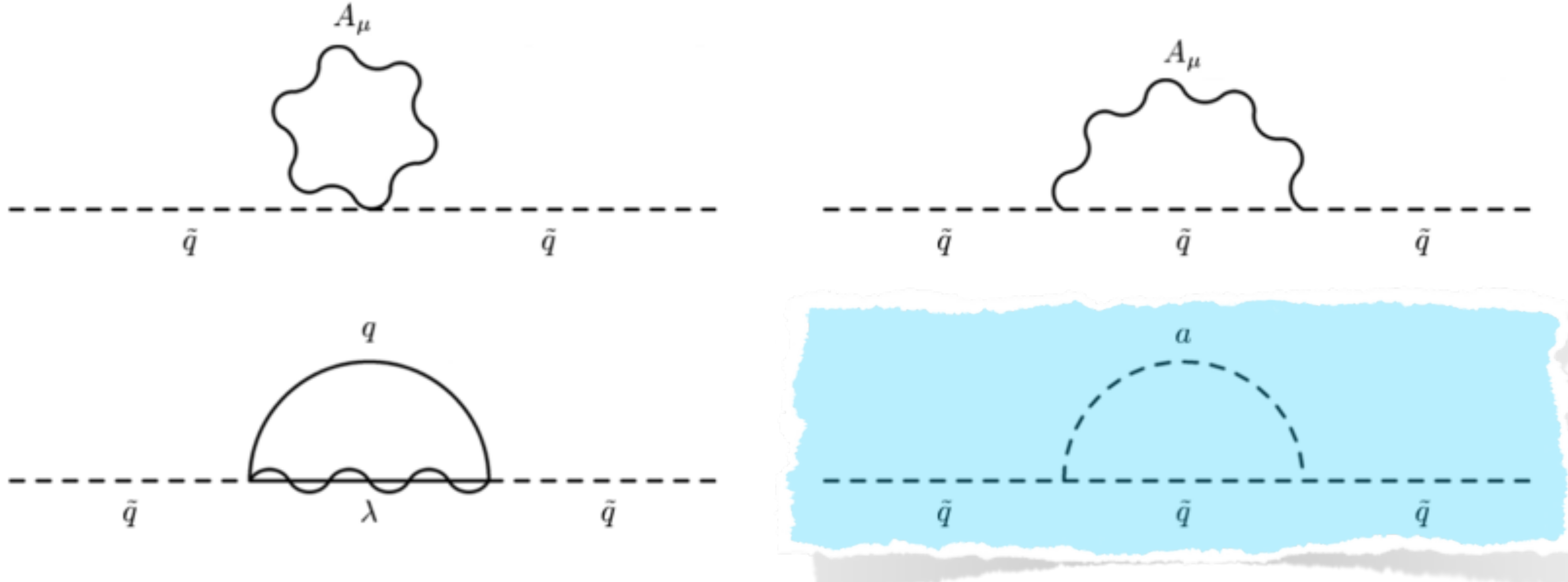


DIRAC GAUGINOS

Naturalness: cf. Fox et al '02, Csaki et al '13

$$\delta m_{\tilde{f}}^2 \propto m_D^2 \ln(m_{\mathrm{Re}A}^2/m_D^2)$$

diagrammatic derivation:



$$\delta m_0^2 \propto g^2 \int d^4p \left[\frac{1}{p^2} - \frac{1}{p^2 - m_D^2} + \frac{m_D^2}{p^2(p^2 - m_{a_R}^2)}\right]$$

$$\sim g^2 \ln\left(\frac{m_{a_R}^2}{m_D^2}\right)$$

DIRAC GAUGINOS

***Naturalness*: cf. Fox et al '02, Csaki et al '13**

$$\delta m_{\tilde{f}}^2 \propto m_D^2 \ln(m_{\mathrm{Re}A}^2/m_D^2)$$

power-counting derivation: recall Majorana case

$$\Delta W = \frac{X}{M} W^\alpha W_\alpha$$

$$\Downarrow$$

$$\text{spurion} = \theta^2 F_X/M$$

$$\Delta K_Q = \frac{\theta^4 F_X^\dagger F_X}{M^2} Q^\dagger Q$$

DIRAC GAUGINOS

***Naturalness*: cf. Fox et al '02, Csaki et al '13**

$$\delta m^2_{\tilde{f}} \propto m_D^2 \ln(m^2_{\mathrm{Re}A}/m_D^2)$$

power-counting derivation: Dirac case

$$\Delta W = \frac{W'}{M} \mathrm{Tr}\left(W_{\mathrm{SM}} A\right)$$

$$\text{spurion} = \theta D'/M$$

$$\Delta K_Q = \boxed{\frac{1}{\Lambda^2}} \frac{\theta^4 D'^4}{M^4} Q^\dagger Q$$

DIRAC GAUGINOS

***Naturalness*: cf. Fox et al '02, Csaki et al '13**

$$\delta m^2_{\tilde{f}} \propto m_D^2 \ln(m^2_{\mathrm{Re}A}/m_D^2)$$

power-counting derivation: Dirac case

$$\Delta W = \frac{W'}{M} \mathrm{Tr}\,(W_{\mathrm{SM}} A)$$

$$\Downarrow$$

$$\text{spurion} = \theta D'/M$$

$$\Delta K_Q = \boxed{\frac{1}{\Lambda^2}} \frac{\theta^4 D'^4}{M^4} Q^\dagger Q$$

---

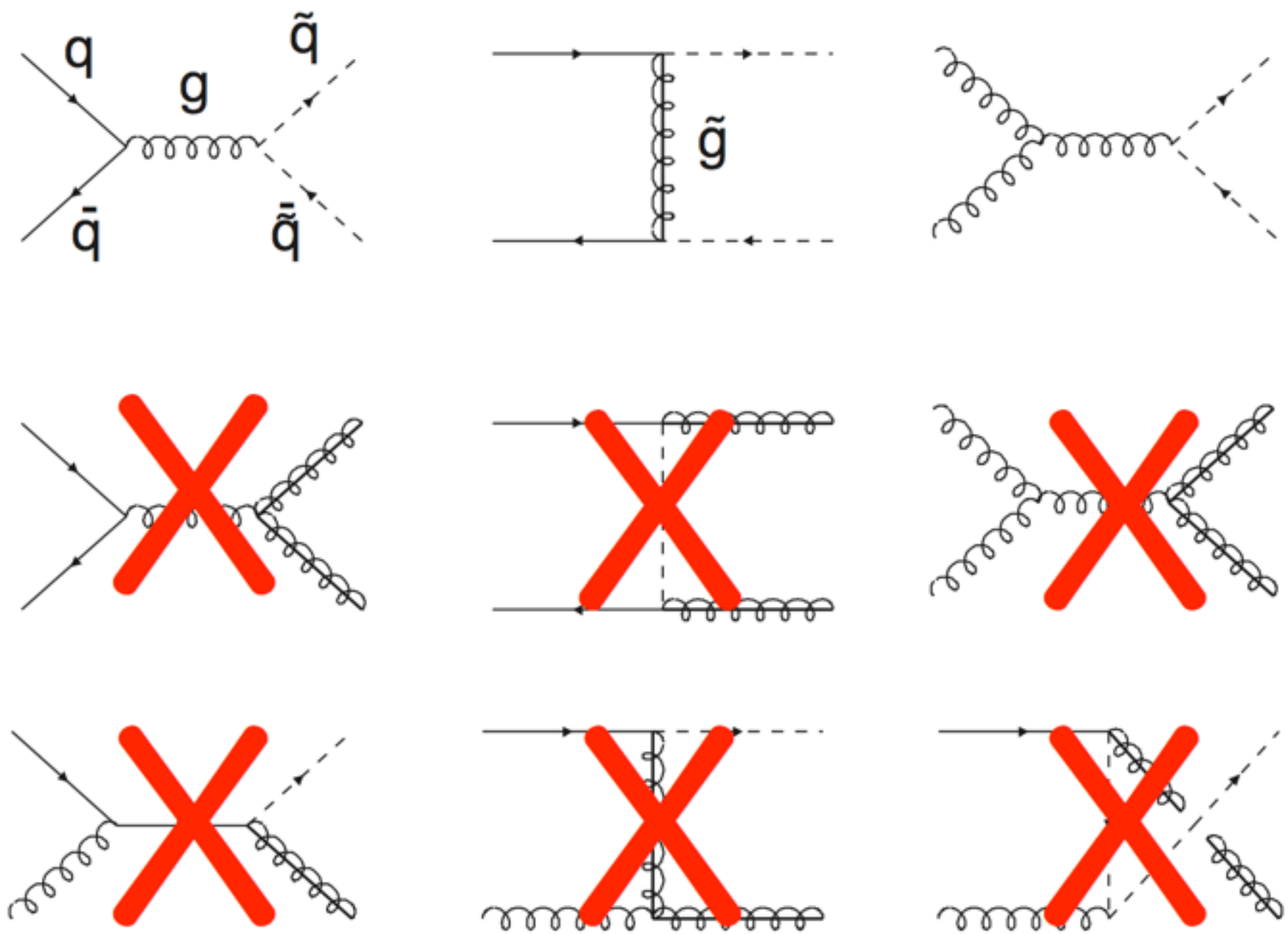
notice:

- such an argument relies crucially on U(1)' gauge invariance
- e.g. compare Nelson/Roy '15: supersoft operators violating U(1)' are typically NOT supersoft at one loop

DIRAC GAUGINOS

***Phenomenological safety*: cf. Martin & Kribs '12**

Production of colored states diminished by kinematics alone

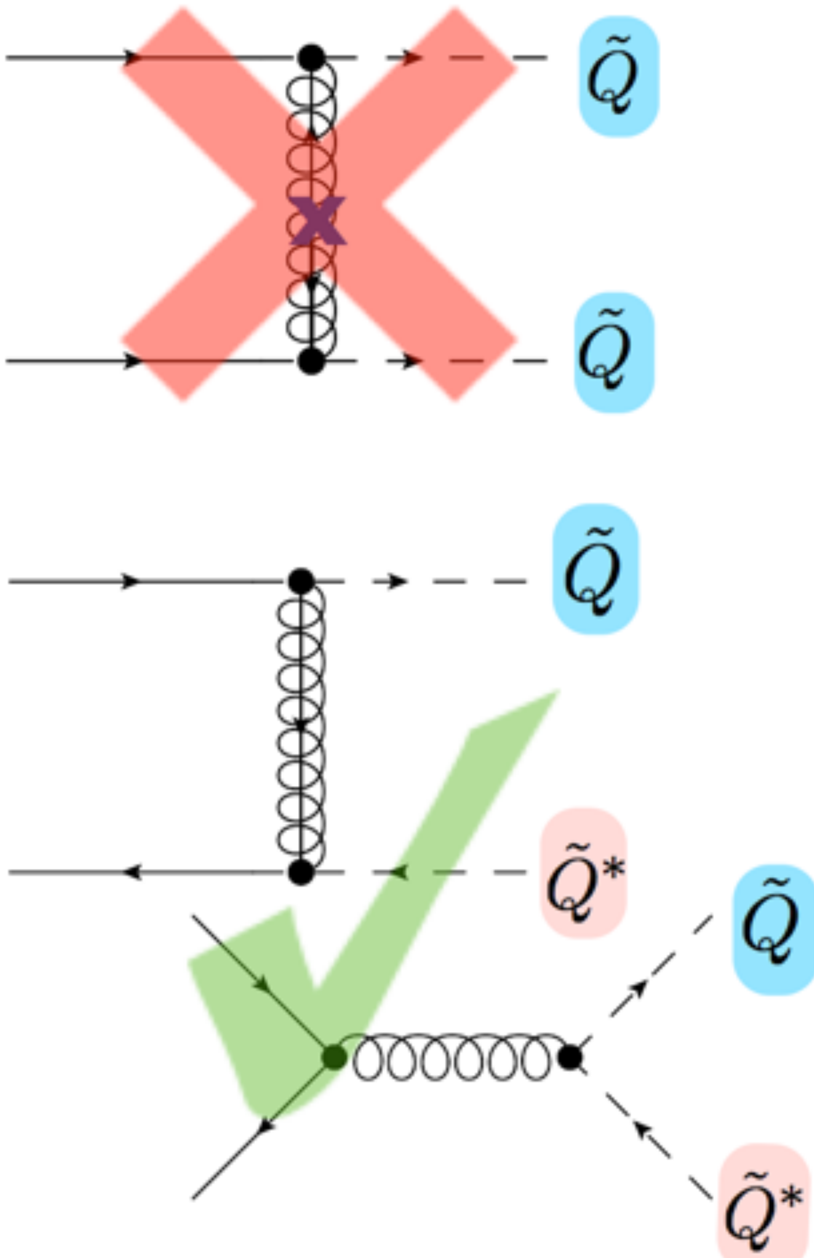


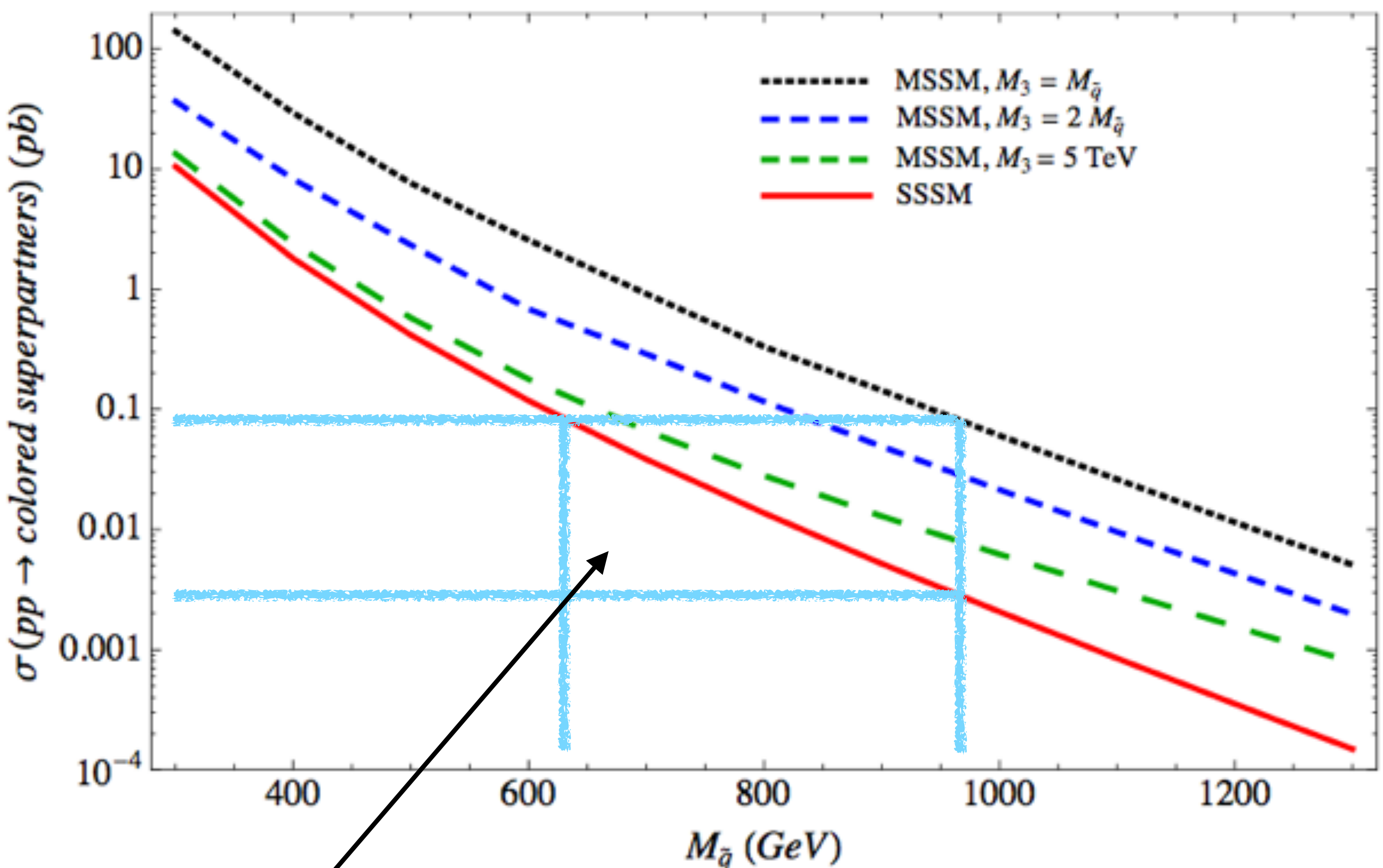
(graphics ruthlessly stolen from A. Martin)

DIRAC GAUGINOS

***Phenomenological safety*: cf. Martin & Kribs '12**

Further suppression with R-symmetry (qq^* final states only)





affords a factor ≳10 in xs
or ≳1.5 in squark mass

DIRAC GAUGINOS

all good, except…

"supersoft lemon-twist": $$\frac{1}{\Lambda^2} W'^2 \, \mathrm{Tr}\,(A^2) \quad \begin{cases} W' & \sim \theta D' \\ W_J & \sim \lambda_J + \theta D_J + \ldots \\ A_J & \sim A_J + \theta \psi_J \end{cases}$$

Nothing obvious to prevent this…

DIRAC GAUGINOS

all good, except…

"supersoft lemon-twist": $$\frac{1}{\Lambda^2} W'^2 \,\mathrm{Tr}\,(A^2) \quad \begin{cases} W' & \sim \theta D' \\ W_J & \sim \lambda_J + \theta D_J + \ldots \\ A_J & \sim A_J + \theta \psi_J \end{cases}$$

…and indeed is typically generated

DIRAC GAUGINOS

all good, except…

"supersoft lemon-twist": $\frac{1}{\Lambda^2} W'^2 \,\mathrm{Tr}\,(A^2)$ $\begin{cases} W' & \sim \theta D' \\ W_J & \sim \lambda_J + \theta D_J + \ldots \\ A_J & \sim A_J + \theta \psi_J \end{cases}$

$$\Delta\mathcal{L} \sim m_D^2 \left(\mathrm{Re}(A_J)^2 - \mathrm{Im}(A_J)^2\right)$$

DIRAC GAUGINOS

all good, except…

"supersoft lemon-twist": $\frac{1}{\Lambda^2} W'^2 \, \mathrm{Tr}\left(A^2\right)$ $\begin{cases} W' & \sim \theta D' \\ W_J & \sim \lambda_J + \theta D_J + \ldots \\ A_J & \sim A_J + \theta \psi_J \end{cases}$

$$\Delta \mathcal{L} \sim m_D^2 \left(\mathrm{Re}(A_J)^2 - \mathrm{Im}(A_J)^2 \right)$$

$\times \mathcal{O}(16\pi^2)$

i.e. mass *squared* generated at same loop order as Dirac mass

"The Bad" $\gg$ "The Good"

** For heavy Dirac gauginos *to be natural*, there's work to be done **

DIRAC GAUGINOS

lifting tachyons

- Soft mass m_A^2 for adjoint (cf. Goodsell ’12)
  - two-loop squark mass running: $\partial_t m_Q^2 \propto g^4 m_A^2$;
  - $m_A^2 \gtrsim 16\pi^2 m_D^2 \implies m_Q^2 < 0$, color broken by squark VEV
- Holomorphic (SUS’ic) mass M for adjoint (cf. Fox et al ’02)
  - $m^2 = \frac{C_i(r)\alpha_i m_i^2}{\pi}\left[\log\left(\frac{M^2+\delta^2}{m_i^2}\right) - \frac{M}{2\Delta}\log\left(\frac{2\Delta+M}{2\Delta-M}\right)\right]$,
  - sufficiently large M leaves massless squarks, $\lim_{M\to\infty} m^2 = 0$
- BOTH CASES REQUIRE COUPLING SQUARKS to new F TERMS

TACHYONS $\Rightarrow$ ~~SUPERSOFT~~

* cf. Arvanitaki et al ’13 for more

DIRAC GAUGINOS

tuning options: cf. Fox et al '02, Csaki et al '13

- Lemon-twist in a nutshell: a one-loop diagram is *O*(100) larger than desired
- All* we need to do is find a way to cancel this
- Pitting two *O*(100) numbers against each other: ~1% tuning introduced

---

* Can be done — Ask Yuri (or see arXiv:1310.4504)

A generic issue:
deflection in U(1)' beta function crossing a messenger threshold

$$\Delta W = \left(\frac{1}{4g^2(\Lambda)} + \frac{b'}{16\pi^2} \log \frac{\mu^2}{m_T^2} + \boxed{\frac{b}{16\pi^2} \log \frac{m_T^2}{\Lambda^2}} \right) W'W'$$

$$\to \left(\frac{1}{4g^2(\Lambda)} + \frac{b'}{16\pi^2} \log \frac{\mu^2}{\Lambda^2} - \frac{q^2}{8\pi^2} \log \frac{\det(m_T + yM)}{\Lambda^n} \right) W'W'$$

$$\supset \frac{1}{m_T^2} \frac{q^2 y^2}{16\pi^2} \mathrm{Tr}\left(M^2\right) W'W'$$

→ tachyonic direction persists

Escape hatch: construct *O*(D) contribution to lemon twist

GOLDSTONE GAUGINOS

Mechanism

$\mathcal{L}_1 \sim m^2 \, \mathrm{Re}\,(A)^2;$ $\mathcal{L}_2 \sim 16\pi^2 m^2 \left[\mathrm{Re}\,(A)^2 - \mathrm{Im}\,(A)^2\right]$

Treat Im(*A*) as angular variable, $\Sigma = f e^A$, with symmetry under a shift:

$$\mathrm{Im}\,(A) \mapsto \mathrm{Im}\,(A) + c \;\Rightarrow\; \delta S = 0$$

Goldstone theorem protects its mass, *forbids lemon-twist*

---

salient stuff:

- All members of χSF massless before SUSY breaking
- fermions and *real* scalars become massive with *D'*
- imaginary component protected in absence of explicit breaking
- to do: couple Goldstone (broken generator) to two vector currents

GOLDSTONE GAUGINOS

Mechanism

$\mathcal{L}_1 \sim m^2 \,\mathrm{Re}\,(A)^2;$ $\mathcal{L}_2 \sim 16\pi^2 m^2 \left[\mathrm{Re}\,(A)^2 - \mathrm{Im}\,(A)^2\right]$

Treat Im(A) as angular variable, $\Sigma = f e^A$, with symmetry under a shift:

$$\mathrm{Im}\,(A) \mapsto \mathrm{Im}\,(A) + c \;\Rightarrow\; \delta S = 0$$

Goldstone theorem protects its mass, *forbids lemon-twist*

Historical Interlude

[notation: $T =$ unbroken, $X =$ broken]

$$[T, T] \sim T$$
$$[X, T] \sim X$$
$$[X, X] \sim T$$

immediate *practical* implication:

$$\mathrm{Tr}\,(T^n X^{m=\mathrm{odd}}) = 0$$

i.e. CCWZ doesn't couple single π to gauge fields…

…but this concerns only terms that are *invariant*

GOLDSTONE GAUGINOS

Mechanism

$\mathcal{L}_1 \sim m^2\,\mathrm{Re}\,(A)^2;$ $\quad$ $\mathcal{L}_2 \sim 16\pi^2 m^2\left[\mathrm{Re}\,(A)^2 - \mathrm{Im}\,(A)^2\right]$

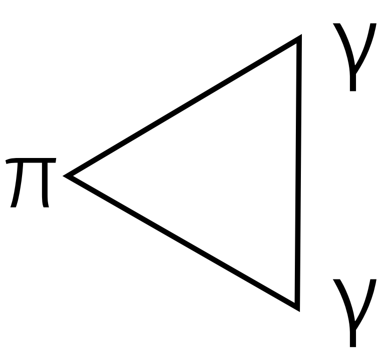
Treat Im(A) as angular variable, $\Sigma = f e^{A}$, with symmetry under a shift:

$$\mathrm{Im}\,(A) \mapsto \mathrm{Im}\,(A) + c \;\Rightarrow\; \delta S = 0$$

Goldstone theorem protects its mass, *forbids lemon-twist*

Historical Interlude

classic example: $\pi^0 \to \gamma\gamma$



$$\Rightarrow \delta(\partial\cdot j^5) \sim \frac{\alpha N_c}{4\pi} F\tilde{F}$$

IR theory needs to inherit shift (anomaly)

$$\begin{cases} \pi^a\,\mathrm{Tr}\,(X^a Q^2) F\tilde{F} \\ \to \pi^0 F\tilde{F} \end{cases}$$

$\mathcal{L}$ shifts appropriately under axial; developed by Wess & Zumino, Witten

worth an NB: no coupling of two neutral pions to two photons in chiral lag.

GOLDSTONE GAUGINOS

Mechanism

$\mathcal{L}_1 \sim m^2 \,\mathrm{Re}\,(A)^2;$ $\quad \mathcal{L}_2 \sim 16\pi^2 m^2 \left[\mathrm{Re}\,(A)^2 - \mathrm{Im}\,(A)^2\right]$

Treat Im(A) as angular variable, $\Sigma = f e^A$, with symmetry under a shift:

$$\mathrm{Im}\,(A) \mapsto \mathrm{Im}\,(A) + c \;\Rightarrow\; \delta S = 0$$

Goldstone theorem protects its mass, *forbids lemon-twist*

Any new twists?

Shift symmetry above is consistent with other operators:

$$\Delta K = \frac{1}{\Lambda^2} W'^{\alpha} D_\alpha V' (A + A^\dagger)^2$$

$$\Rightarrow \Delta \mathcal{L} \sim m_D^2 \,\mathrm{Re}\,(A)^2$$

BUT this is inconsistent with *gauged* $U(1)$'…

…so anomaly-free $U(1)$' **forbids new twists**

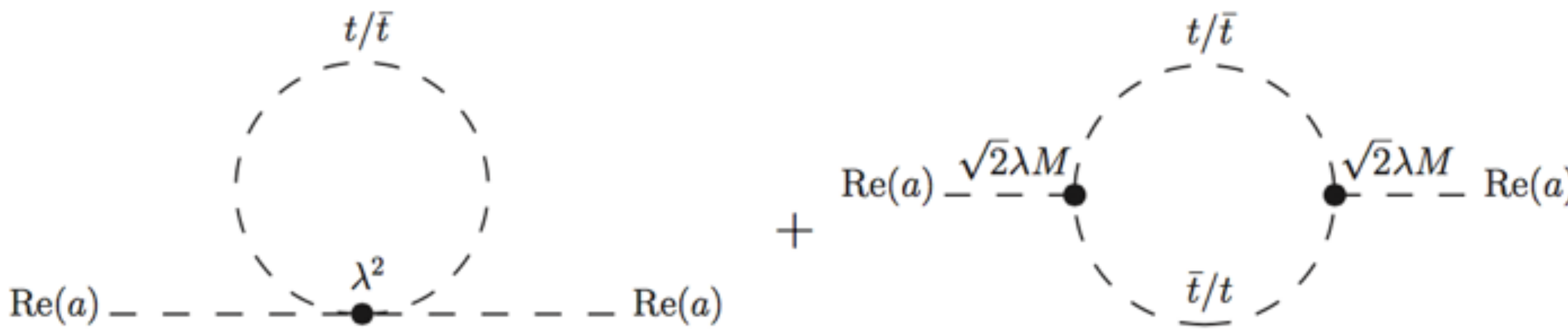
GOLDSTONE GAUGINOS

GoGa fields and lemon-twist

$$W_{\rm SS}^{(\rm UV)} = MT\bar{T} + yAT\bar{T}$$

(assume real mass and Yukawa for the sake of argument)

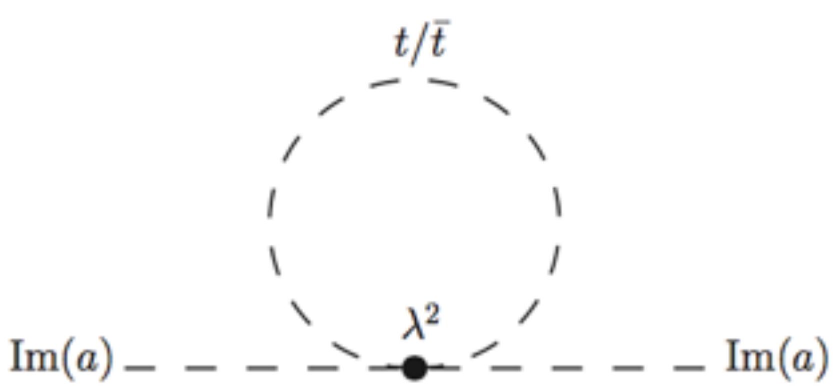
scalar



$$= \frac{\lambda^2}{8\pi^2}\frac{D^2}{M^2}$$

tachyon

pseudo-scalar



$$= -\frac{\lambda^2}{8\pi^2}\frac{D^2}{M^2}.$$

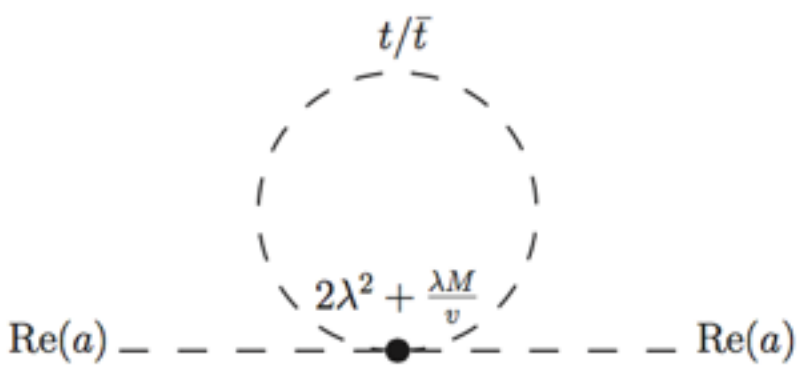
GOLDSTONE GAUGINOS

GoGa fields and lemon-twist

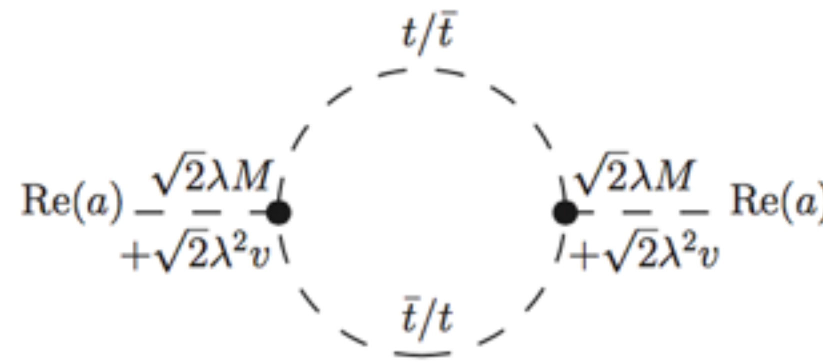
$$W_{\rm GG} = MT\bar{T} + yT\Sigma\bar{T}$$
$$= MT\bar{T} + yfT\bar{T} + yAT\bar{T} + \frac{y}{2f}A^2T\bar{T} + \ldots$$

$$\left(\Sigma \equiv f e^{A/f}\right)$$

scalar

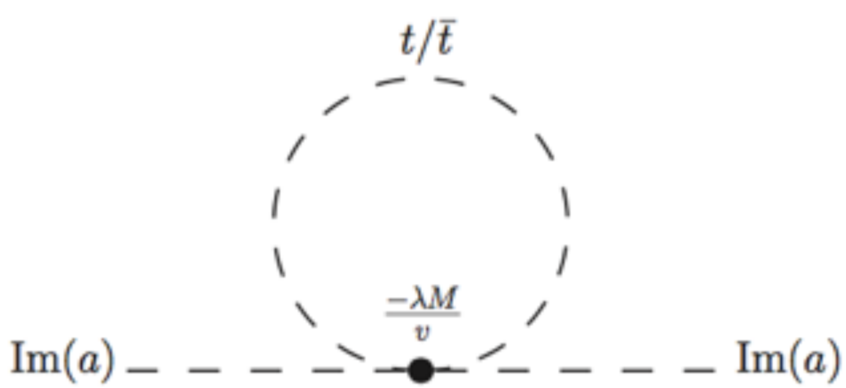


$+$



$$= -\frac{\lambda}{8\pi^2}\frac{M}{v}\frac{D^2}{(M+\lambda v)^2}$$

pseudo-scalar



$$= \frac{\lambda}{8\pi^2}\frac{M}{v}\frac{D^2}{(M+\lambda v)^2}$$

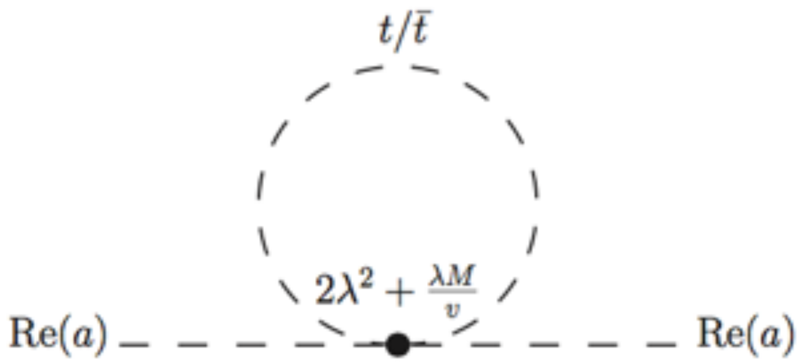
tachyon *

GOLDSTONE GAUGINOS

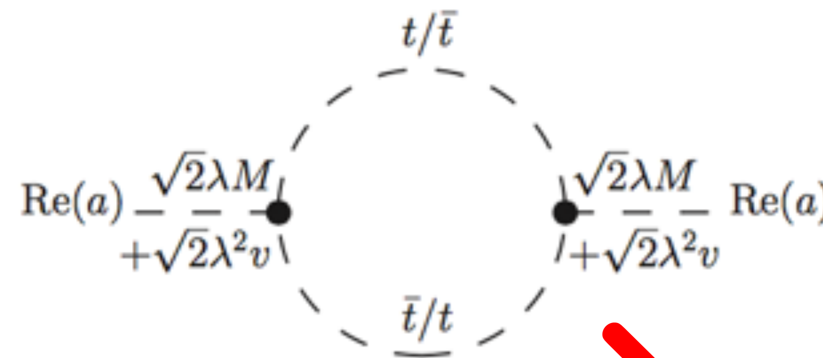
GoGa fields and lemon-twist

$$W_{\rm GG} = MT\bar{T} + yT\Sigma\bar{T}$$
$$= MT\bar{T} + yfT\bar{T} + yAT\bar{T} + \frac{y}{2f}A^2T\bar{T} + \dots$$

scalar

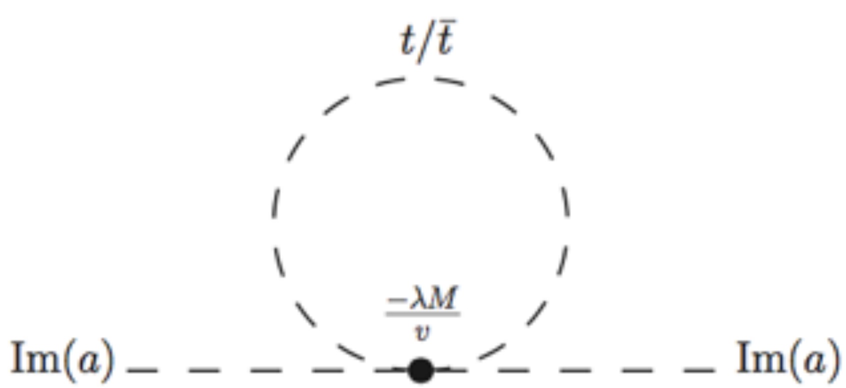


+



$$= -\frac{\lambda}{8\pi^2}\frac{M}{v}\frac{D^2}{(M+\lambda v)^2}$$

pseudo-scalar



$$= \frac{\lambda}{8\pi^2}\frac{M}{v}\frac{D^2}{(M+\lambda v)^2}$$

tachyon *

*** *but*: ALL radiative masses VANISH with explicit breaking removed**

GOLDSTONE GAUGINOS

A Model

Get Goldstones 'for free' from confinement (NLSM)…
…consider well-known models of SUSY QCD

	$SU(N)$	$SU(F)$	$SU(F)$	$U(1)_B$	$U(1)_A$	$U(1)_{R'}$	$SU(F)_V$	$U(1)_R$
Q	$\square$	$\square$	1	1	1	1	$\square$	$\frac{F-N}{F}$
$\bar{Q}$	$\overline{\square}$	1	$\overline{\square}$	-1	1	1	$\overline{\square}$	$\frac{F-N}{F}$

IR confined (mesons) ($SU(N)$) · **anomaly-free** ($U(1)_B$) · **weakly gauged (SM)** ($SU(F)_V$)

$$\text{mesons: } M \sim Q\bar{Q} \sim (\text{singlet} + \text{adjoint}) \text{ under } SU(F)_V$$

GOLDSTONE GAUGINOS

A Model

Get Goldstones ‘for free’ from confinement (NLSM)…
…consider well-known models of SUSY QCD

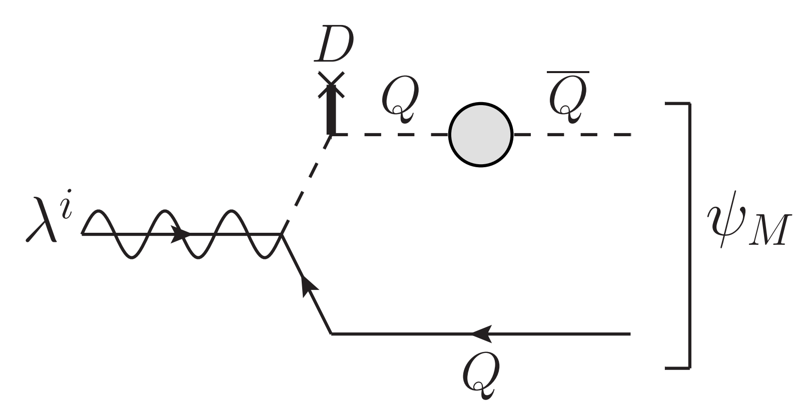
	$SU(N)$	$SU(F)$	$SU(F)$	$U(1)_B$	$U(1)_A$	$U(1)_{R'}$	$SU(F)_V$	$U(1)_R$
Q	$\square$	$\square$	1	1	1	1	$\square$	$\frac{F-N}{F}$
$\bar{Q}$	$\overline{\square}$	1	$\overline{\square}$	-1	1	1	$\overline{\square}$	$\frac{F-N}{F}$

IR confined (mesons) **anomaly-free** **weakly gauged (SM)**

- weakly gauged vector subgroup of flavor = (part of) SM
- composite (Goldstone) adjoint from confined $\langle Q^i \bar{Q}_j \rangle \propto \delta^i_j$
- simple choice from vacuum solution with quark mass *m*:

$$M^i_j = (m^{-1})^i_j (\Lambda^b \det m)^{1/N}$$

- $F = N$ delivers



GOLDSTONE GAUGINOS

A Model

Get Goldstones 'for free' from confinement (NLSM)…
…consider well-known models of SUSY QCD

	$SU(N)$	$SU(F)$	$SU(F)$	$U(1)_B$	$U(1)_A$	$U(1)_{R'}$	$SU(F)_V$	$U(1)_R$
Q	$\square$	$\square$	1	1	1	1	$\square$	$\frac{F-N}{F}$
$\bar{Q}$	$\overline{\square}$	1	$\overline{\square}$	-1	1	1	$\overline{\square}$	$\frac{F-N}{F}$

IR confined (mesons) **anomaly-free** **weakly gauged (SM)**

What about other values of F?
(answer: *all* masses = 0 w/o explicit breaking via SUS'ic quark mass)

F	IR Fields	$\langle M\rangle/\Lambda^2$	m_σ	m_π
$N-1$	M^i_j	$(\Lambda/m)^{1/N}$	$(N-1)(N-2)\times\frac{m}{2}\left(\frac{m}{\Lambda}\right)^{1/N}$	$\frac{m}{4}\left(\frac{m}{\Lambda}\right)^{1/N}$
N	$M^i_j, B, \bar{B}$	1	$N(N-1)\times\frac{\Lambda}{2}$	$\frac{m}{4}$
$N+1$	$M^i_j, B_i, \bar{B}^j$	$(m/\Lambda)^{1/N}$	$N(N+1)\times\frac{m}{2}\left(\frac{\Lambda}{m}\right)^{1/N}$	$\frac{m}{4}\left(\frac{\Lambda}{m}\right)^{1/N}$

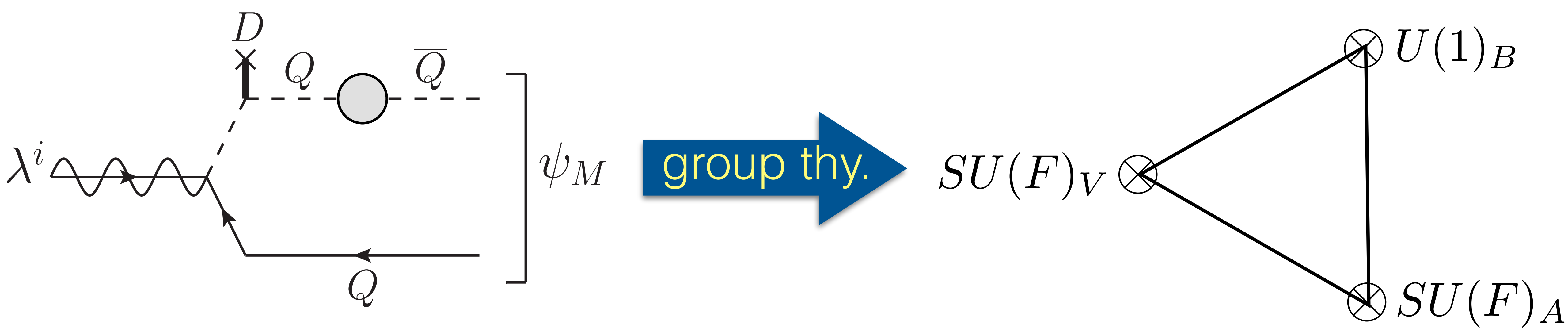
***** No parametric separation between sigma and pion modes *****

(lemon-twist persists for singlet; OK only if its SUS'ic 'mass' is large)

GOLDSTONE GAUGINOS

F = N SQCD

$$W = X(\det M - B\bar{B} - \Lambda^{2N}) + \text{masses}\,; \quad \langle M \rangle = \Lambda^2 \times \mathbf{1}_F$$



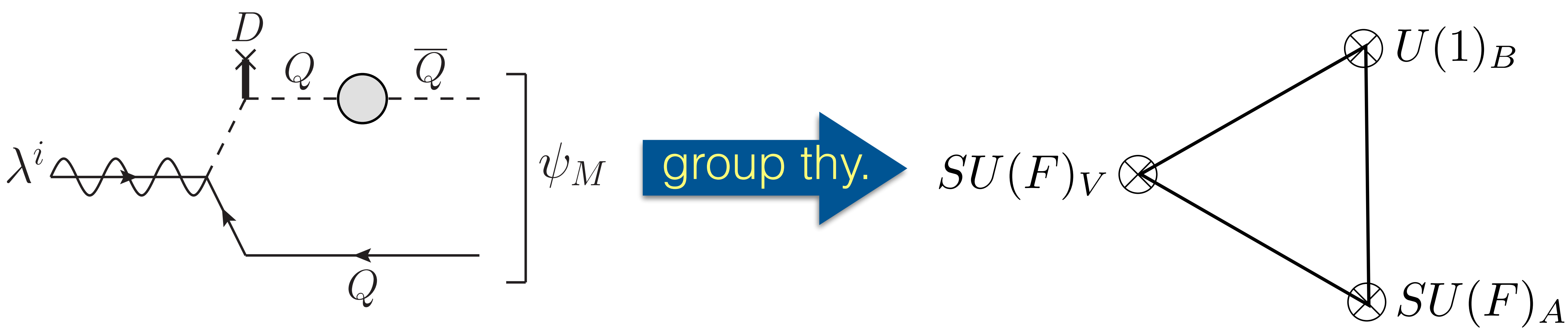
symmetry requirements:
- SUSY breaking via SQCD squark masses
- *C* parity breaking via squark mass *splitting*
- *R* breaking (if applicable) via small SUS'ic mass

coupling to external currents:
- $SU(F)_V$: SM gauge
- $U(1)_B$: SQCD squark (soft) mass splitting
- $SU(F)_A$: meson breaking global symmetry

GOLDSTONE GAUGINOS

F = N SQCD

$$W = X(\det M - B\bar{B} - \Lambda^{2N}) + \text{masses}\,; \quad \langle M\rangle = \Lambda^2 \times \mathbf{1}_F$$



$SU(F)^2 \times U(1)_B$ anomaly readily computed in UV: $A = N/2$

and IR: $A = 0$

$$\propto \mathrm{Tr}\,(X_A^{\hat{a}}\{T_V^b, T_B\}) = 2\delta^{\hat{a}b}$$

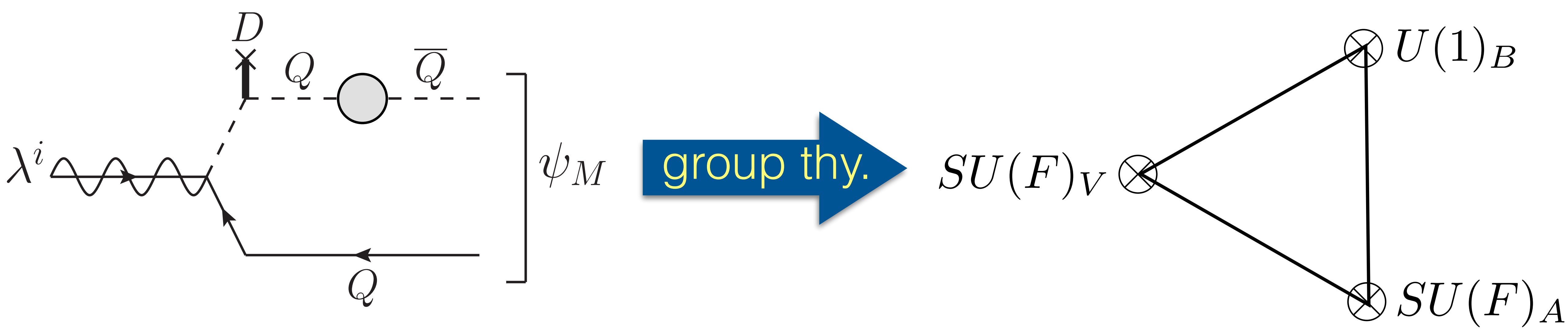
$$\Rightarrow \Delta W = \frac{N}{4\pi}\mathrm{Tr}\left(W_{\mathrm{SM}} W_B \ln\frac{M}{\langle M\rangle}\right)$$

$$\Rightarrow m_D = \frac{gN}{4\pi}\frac{m_{\tilde{Q}}^2 - m_{\tilde{\bar{Q}}}^2}{\Lambda}$$

GOLDSTONE GAUGINOS

F = N SQCD

$$W = X(\det M - B\bar{B} - \Lambda^{2N}) + \text{masses}\,; \quad \langle M \rangle = \Lambda^2 \times \mathbf{1}_F$$



$$\Rightarrow \Delta W = \frac{N}{4\pi}\mathrm{Tr}\left(W_{\mathrm{SM}} W_B \ln \frac{M}{\langle M \rangle}\right)$$

$$\Rightarrow m_D = \frac{gN}{4\pi}\frac{m^2_{\tilde{Q}} - m^2_{\tilde{\bar{Q}}}}{\Lambda}$$

Meanwhile twists are absent, as advertised

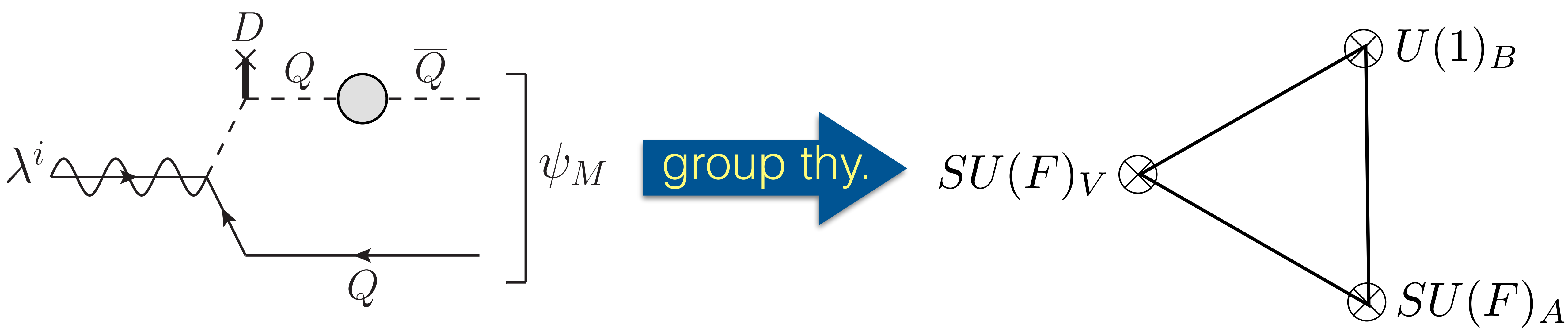
imaginary component's mass *only* from explicit breaking* (gauging, explicit quark mass)

*just as QCD chiral Lag. had no 2π+2γ coupling

GOLDSTONE GAUGINOS

F = N SQCD

$$W = X(\det M - B\bar{B} - \Lambda^{2N}) + \text{masses}\,; \quad \langle M \rangle = \Lambda^2 \times \mathbf{1}_F$$



$$\Rightarrow \Delta W = \frac{N}{4\pi} \mathrm{Tr}\left(W_{\rm SM} W_B \ln \frac{M}{\langle M \rangle} \right)$$

$$\Rightarrow m_D = \frac{gN}{4\pi} \frac{m^2_{\tilde{Q}} - m^2_{\tilde{\bar{Q}}}}{\Lambda}$$

imaginary component's mass:

$$m^2_{a_I} \propto g^2 \ln m^2_{a_R}$$

(explicit calculation from diagrams like those controlling squark masses in conventional supersoft)

GOLDSTONE GAUGINOS

F = N from F = N+1

$$\Rightarrow \Delta W = \frac{N}{4\pi}\mathrm{Tr}\left(W_{\rm SM}W_B \ln\frac{M}{\langle M\rangle}\right)$$

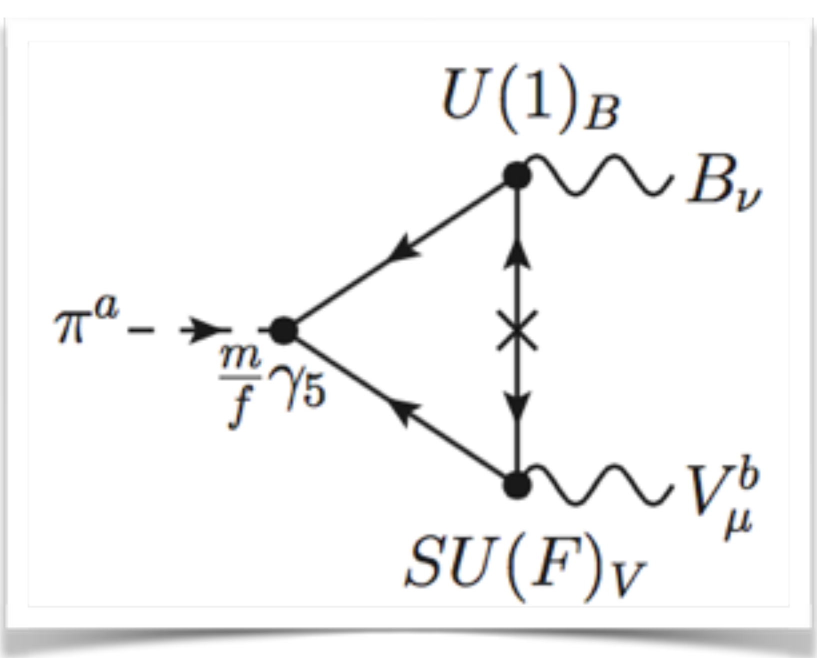
$$\Rightarrow m_D = \frac{gN}{4\pi}\frac{m^2_{\tilde{Q}} - m^2_{\tilde{\bar{Q}}}}{\Lambda}$$

Any other way to see this?

Yes…

$$W = \frac{\lambda}{\Lambda_{N+1}^{2N-1}}\left(\mathcal{B}\mathcal{M}\overline{\mathcal{B}} - \det\mathcal{M}\right) + m q_F \bar{q}_F$$

-> decouple (fundamental) baryon with Yukawa and meson VEV
-> non-decoupling remnant, *exactly as with nonlinear chiral quarks*



$$\Delta\mathcal{L} = -\frac{gN}{16\pi^2 f}\pi^i F^i_{\mu\nu}\tilde{B}^{\mu\nu}$$

— i.e. — $\Delta W \propto \mathrm{Tr}\left(W_{\rm SM}W_B \ln\frac{M}{\langle M\rangle}\right)$

GOLDSTONE GAUGINOS

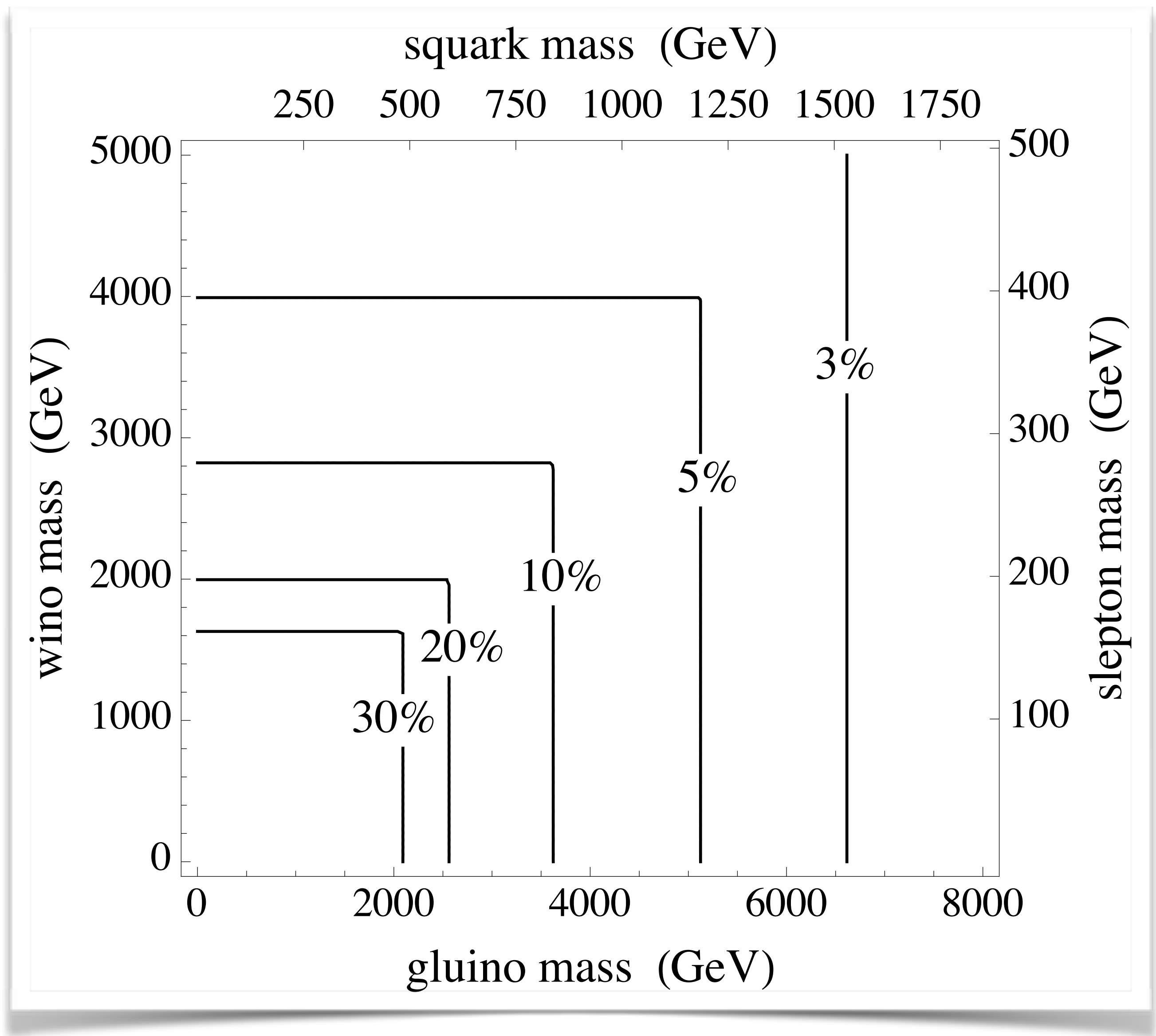
Naturalness Effects

$$\delta\tilde{m}_h^2\big|_{1-\text{loop}} = \frac{2\alpha_2\ln(4)}{3\pi}m_{D2}^2,$$

$$\delta\tilde{m}_h^2\big|_{2-\text{loop}} = \frac{3}{8\pi^2}y_t^2 m_{\tilde{t}}^2\ln(m_{D3}/\tilde{m}_{\tilde{t}}),$$

$$= \frac{\alpha_3 y_t^2\ln(4)}{2\pi^3}\ln(3\pi/4\alpha_3\ln(4))m_{D3}^2$$

current (naive) bound on stops puts gluinos out of reach, but requires only ~20% tuning



GOLDSTONE GAUGINOS

Naturalness Effects

$$\delta\tilde{m}_h^2\big|_{1-\text{loop}} = \frac{2\alpha_2\ln(4)}{3\pi}m_{D2}^2,$$
$$\delta\tilde{m}_h^2\big|_{2-\text{loop}} = \frac{3}{8\pi^2}y_t^2 m_{\tilde{t}}^2\ln(m_{D3}/\tilde{m}_{\tilde{t}}),$$
$$= \frac{\alpha_3 y_t^2\ln(4)}{2\pi^3}\ln(3\pi/4\alpha_3\ln(4))m_{D3}^2$$

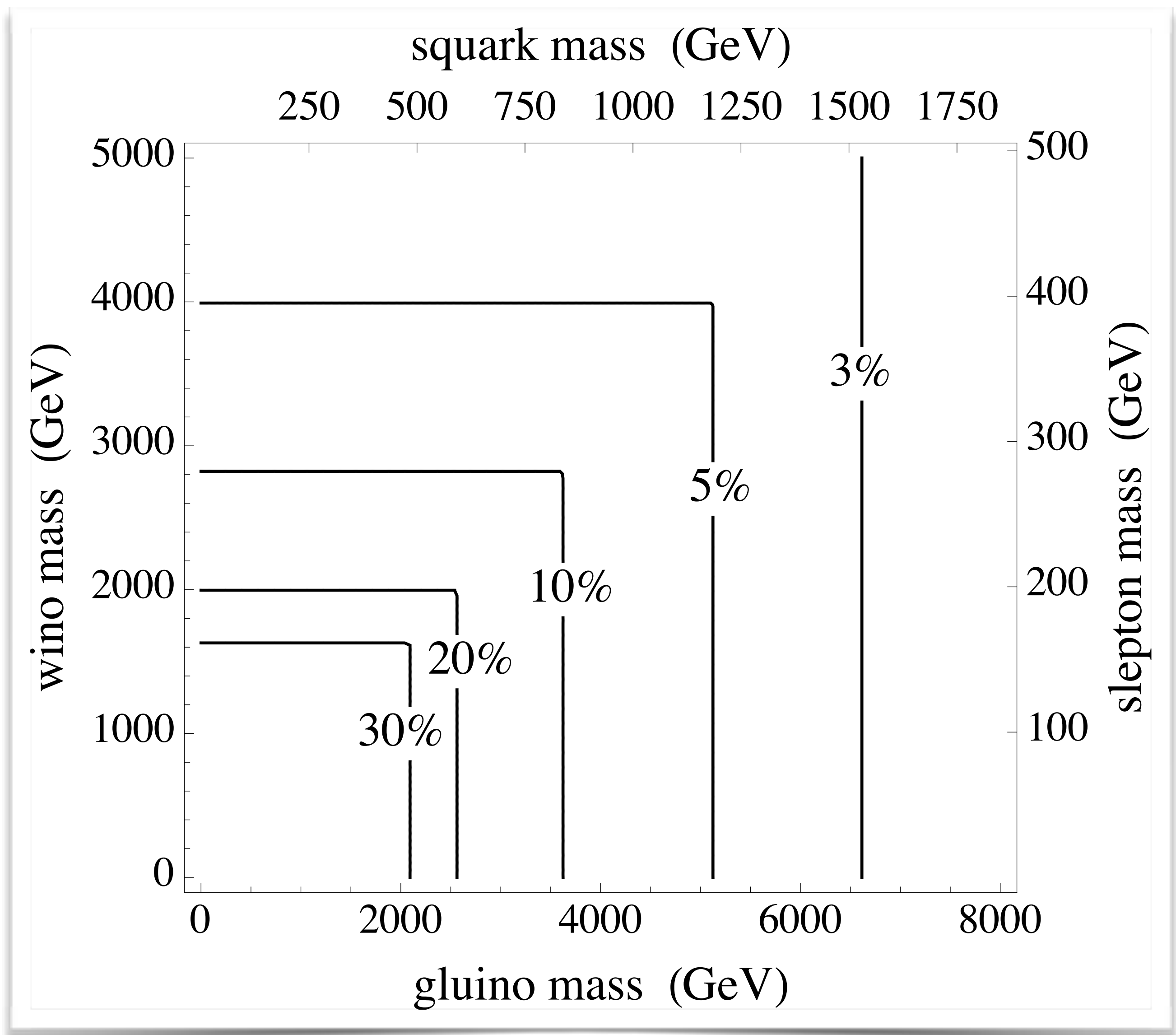
—WITH—

characteristic spectrum
(from trinified model)

$m_{a_I} \approx 800\,\text{GeV}$

$m_{\tilde{g}} \approx 3\,\text{TeV}$

→ $\text{FT} \sim \mathcal{O}(10\%)$

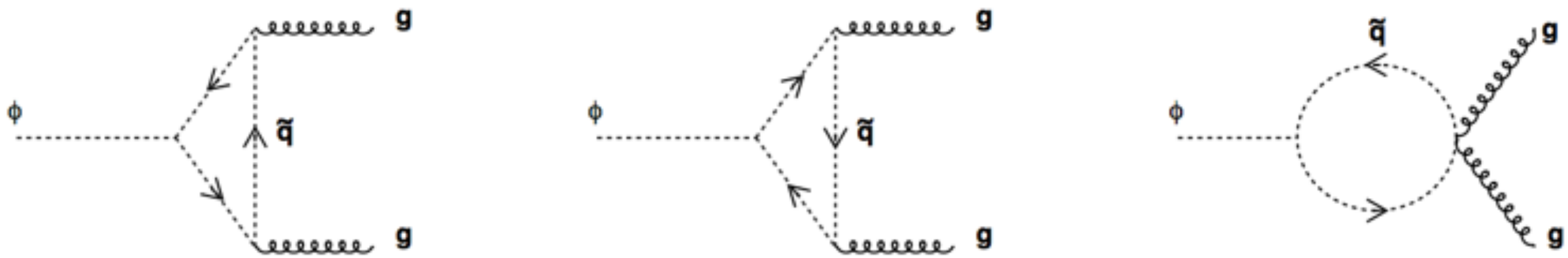


GOLDSTONE GAUGINOS

"Seeking Sgluons": Plehn and Tait '08

- (p)sgluon coupling to quarks

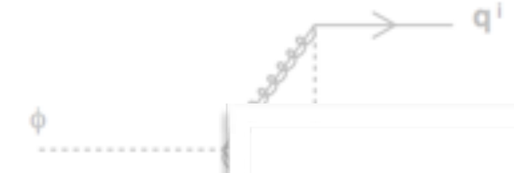
- and to gluons



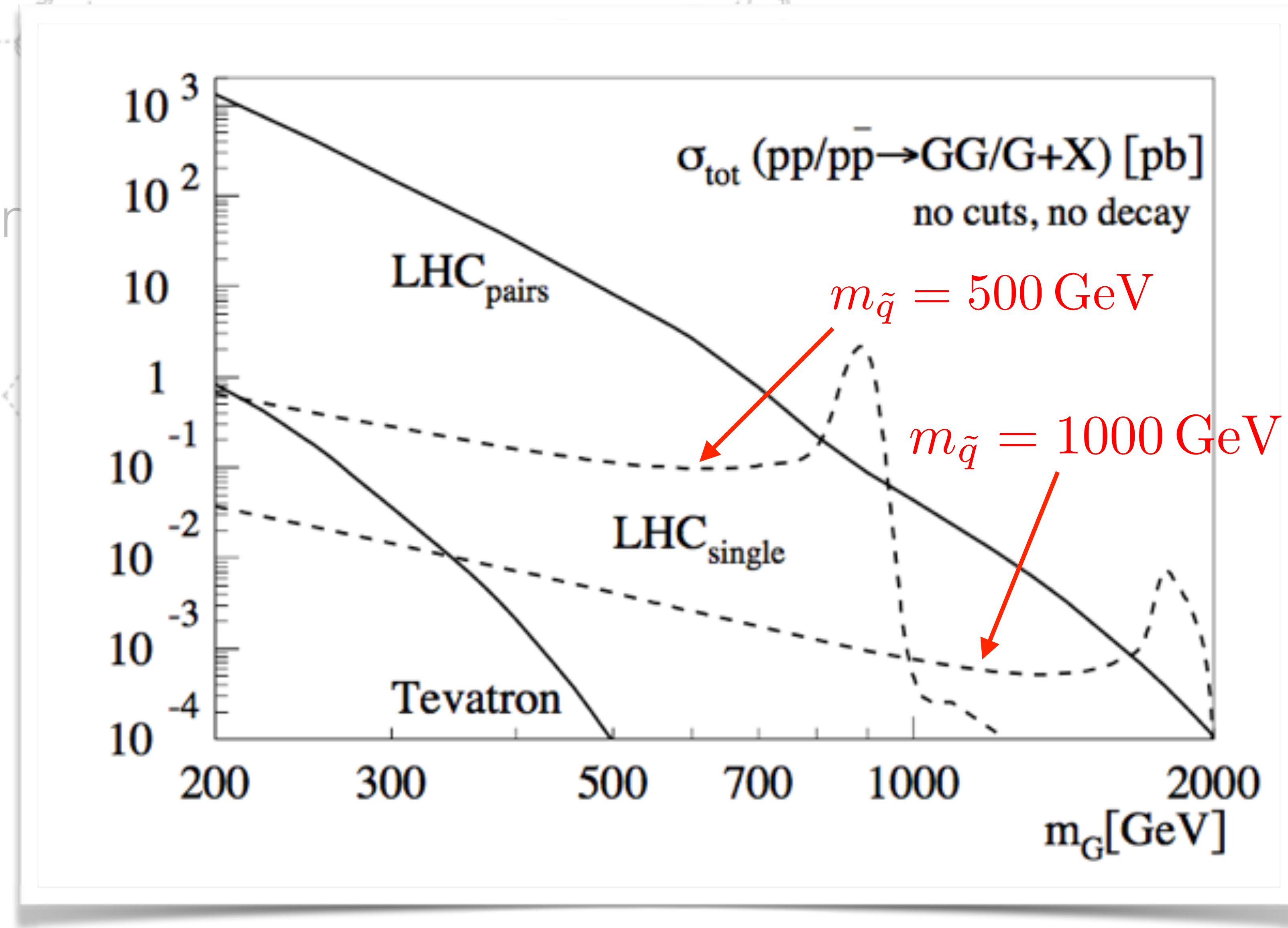
GOLDSTONE GAUGINOS

"Seeking Sgluons": Plehn and Tait '08

- sgluon coupling to quarks



- and to gluon



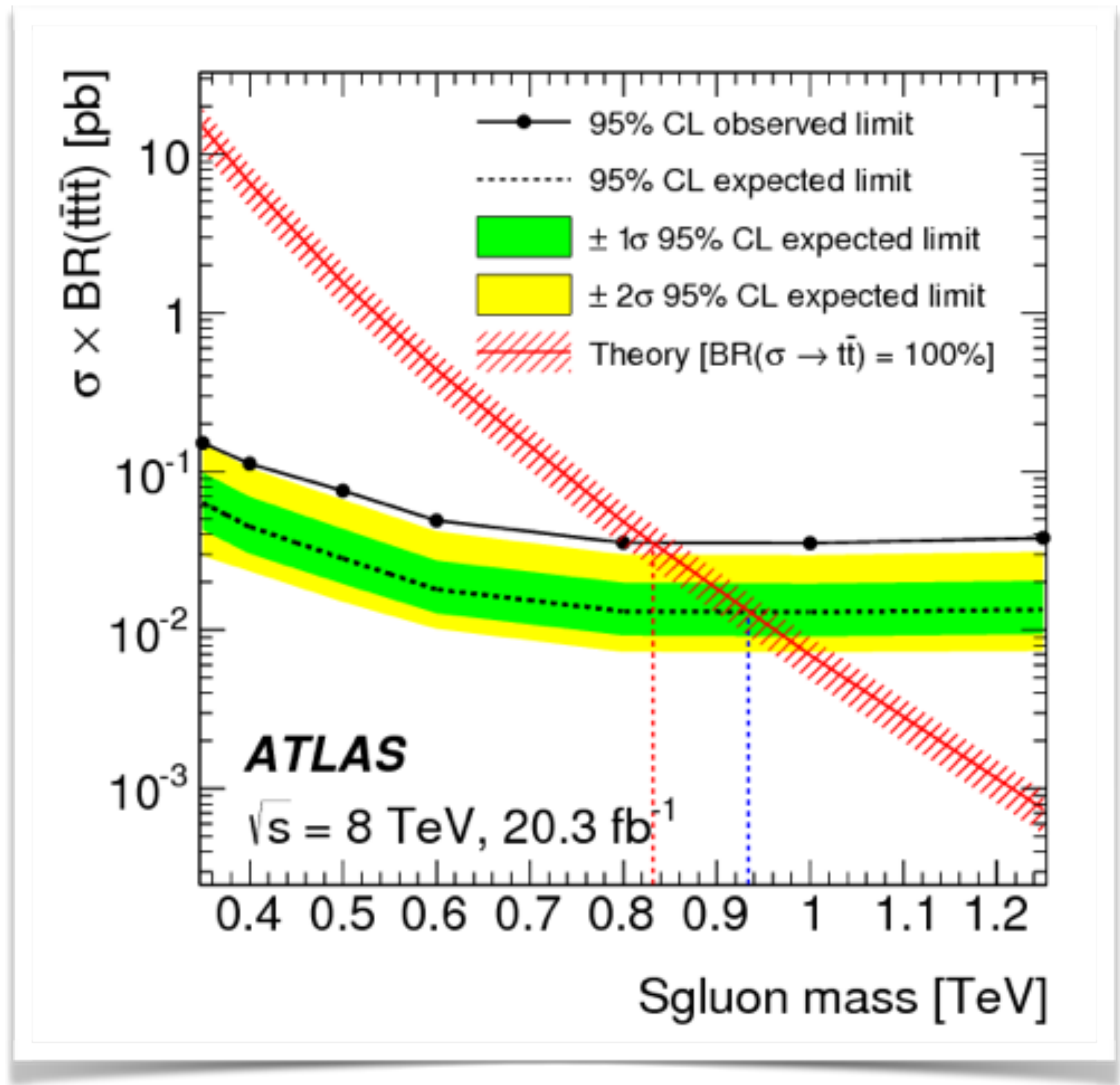
GOLDSTONE GAUGINOS

***"Seeking Sgluons"*: Plehn and Tait '08**

lo and behold…
(arXiv:1504.04605)

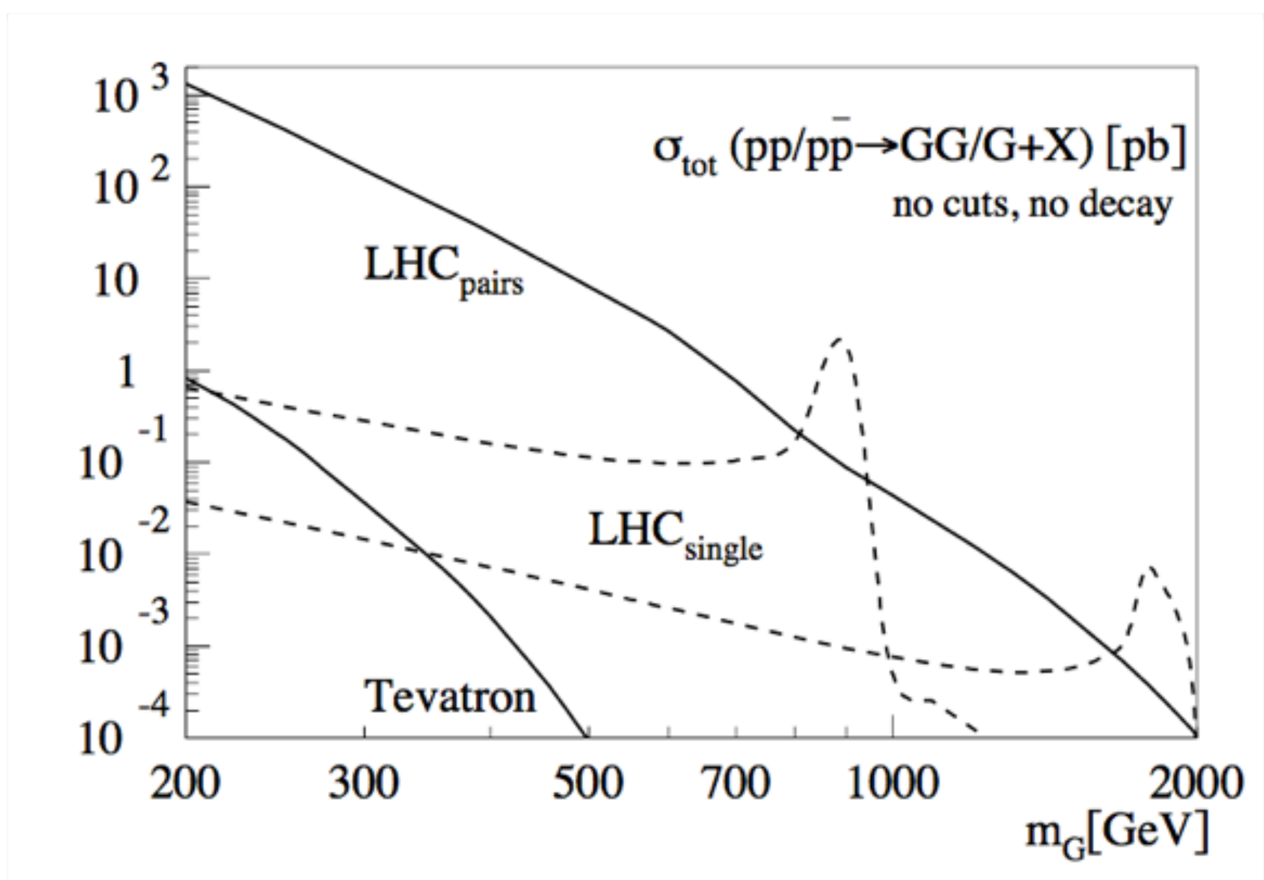
- Pair-produced sgluons
- each sgluon -> ttbar:

$$g_{Gqq} \propto m_q$$



GOLDSTONE GAUGINOS

Comparative Pheno



Single production discrimination:

- ‘conventional’ story: sgluon << psgluon
- expect single production if m ~ TeV
- *reversed* hierarchy with GoGa fields
- single production only via anomaly

.
.
.

→ ultimately a model-dependent question…

…*but* single production absent in simplest GoGa setups

Conclusions / Prospects

- One of two supersoft operators excluded by shift symmetry

$$\Delta\mathcal{L}_1 \sim m_D \lambda \cdot \psi + m_D^2 \,\mathrm{Re}\,(A_J)^2 \quad ✓$$

$$\Delta\mathcal{L}_2 \sim 16\pi^2 m_D^2 \left[\mathrm{Re}\,(A_J)^2 - \mathrm{Im}\,(A_J)^2\right] \quad ✗$$

- Dirac gaugino mass realized via Wess-Zumino-Witten in $F = N$ SQCD; shifts under axial symmetry to total derviative

- New scalar adjoint '(p)sgluons' at colliders, cf. Plehn & Tait, 0810.3919

- Going forward:
    - Enlarge picture to fully address *V(H)*
    - unification (trinification works; others??)
    - plenty of etc…

Dirac masses remain viable,
allowing 'natural SUSY' via light sfermions alone @ LHC

RESERVE

Goldstone Gauginos: Case Study

Brief review of confining SQCD with $F = N\,(\pm 1)$

F	IR Fields	$\langle M \rangle / \Lambda^2$	m_σ	m_π
$N-1$	M^i_j	$(\Lambda/m)^{1/N}$	$(N-1)(N-2) \times \frac{m}{2}\left(\frac{m}{\Lambda}\right)^{1/N}$	$\frac{m}{4}\left(\frac{m}{\Lambda}\right)^{1/N}$
N	$M^i_j, B, \bar{B}$	1	$N(N-1) \times \frac{\Lambda}{2}$	$\frac{m}{4}$
$N+1$	$M^i_j, B_i, \bar{B}^j$	$(m/\Lambda)^{1/N}$	$N(N+1) \times \frac{m}{2}\left(\frac{\Lambda}{m}\right)^{1/N}$	$\frac{m}{4}\left(\frac{\Lambda}{m}\right)^{1/N}$

- **N-1**: baryons absent; ADS potential $W \sim (\Lambda^b / \det M)^{1/(N-F)}$
  adjoint and singlet masses scale together
  => twist even for singlet alone affects all fields

- **N**: singlet baryons; constraint potential $W \sim (\det M - B\bar{B} - \Lambda^{2N})$
  adjoint parametrically separated from *heavy(!)* singlet
  => twist for singlet is safe, small perturbation of SQCD

- **N+1**: fundamental baryons; superpotential $W \sim (BM\bar{B} - \det M)$
  conclusions match those of *F=N-1*

Goldstone GLUINOS: Case Study

Spectrum of mesons, with $\Delta W = \mathrm{Tr}\, mM$.

SUS'ic) $$M = \Box \times \overline{\Box} \to 1 + \mathbf{Adj} \text{ under } SU(F)_V$$

"σ" → 1, "π" → $\mathbf{Adj}$

$$m_\sigma \sim \Lambda \qquad m_\pi \sim m$$

Superpotential (holomorphic) masses:
singlet mass from *M-B* constraint, adjoint from explicit breaking

Soft) $$K = \frac{1}{\Lambda_p^2} M^\dagger M, \quad \Lambda_p :\ U(1)_A \text{ and RG invariant}$$

(Arkani-Hamed, Rattazzi: hep-th/9804068)

$$\Rightarrow \underbrace{m^2_{\tilde{\sigma}} \sim \frac{3N - 2F}{b} \times (m^2_{\tilde{Q}} + m^2_{\tilde{\bar{Q}}})}_{\textit{quasi}\ \text{NGB}}; \ \underbrace{m^2_{\tilde{\pi}} = 0}_{\text{NGB}}$$

(See also nice qualitative discussion in Shifman's lecture, hep-th/9704114)

Goldstone GLUINOS: Case Study

Spectrum of mesons, with $\Delta W = \mathrm{Tr}\, mM$.

Assume that masses lifting tachyons in messenger model leave sfermion soft masses alone (see again 1309.3568)

QCD messenger model

$$m^2 \propto m_D^2 \ln(m_{\mathrm{Re}A}^2/m_D^2)$$

QCD Goldstone model

Includes holomorphic masses, *M*, for new adjoints:

$$m^2 \propto m_D^2 \ln((M^2 + m_{\mathrm{Re}A}^2)/m_D^2) + \dots$$

(further contributions unimportant as *M* sent to zero)