QCD effects in searches for GeV-scale new physics

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Widely accepted statements

- Standard Model nicely explains
  almost all results of particle physics experiments
- We definitely need New particle Physics
  - neutrino oscillations
  - baryon asymmetry
  - dark matter
  - inflation-like stage in the early Universe

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- New Heavy particle contribution to the Higgs boson mass lifts it up
  but miraculously $m_h \sim E_{EW}$

Guesswork: a logically possible option

- All the new particles are at (below) E_{EW}
  then quantum contributions to $m_h \sim E_{EW}$ are safe
- Why so far no evidences for such light New Particles ?
- They are only feebly coupled to the Standard Model
  - they are SM gauge singlets (not a GUT)
  - new Yukawa-type couplings ?
  - portal-like couplings ?

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Main task

- Moreover, there are many concrete BSM theories which suggest such theoretical motivations
- Then the problem is how to properly account for the new particle (SM gauge singlet) effective coupling to the SM strongly-interacting states
  - for $m \gg 1$ GeV it couples to partons
  - for $m \ll 1$ GeV it couples to hadrons
  - how to calculate the new particle production and decay rates for $m \simeq 1$ GeV ?
  - in the concrete models "parton" and "hadron" answers often mismatch
- Eventually we must predict the signal rate 'in observed particles': pions, kaons, etc

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Three Portals to the hidden World

Renormalizable interaction including SM field and new (hypothetical) fields singlets with respect to the SM gauge group

Attractive feature: couplings are insensitive to energy in c.m.f., hence low energy experiments (intensity frontier) are favorable

- Scalar portal: SM Higgs doublet H and hidden scalar S

  the simplest dark matter

$$\mathscr{L}_{\text{scalar portal}} = -\beta H^\dagger H S^\dagger S - \mu H^\dagger H S$$

- Spinor portal: SM lepton doublet L, Higgs congugate field $\tilde{H} = \varepsilon H^*$ and hidden fermion N

  sterile neutrino !!

$$\mathscr{L}_{\text{spinor portal}} = -y \bar{L} \tilde{H} N$$

- Vector portal: SM gauge field of $U(1)_Y$ and gauge hidden field of abelian group $U(1)'$

  hidden photon

$$\mathscr{L}_{\text{vector portal}} = -\frac{\varepsilon}{2} B_{\mu\nu}^{U(1)_Y} B_{\mu\nu}^{U(1)'}$$

Massive vectors (paraphotons)

NA64

Vector portal to a secluded sector:

one more $U(1)'$ gauge group [spontaneously broken] in secluded sector

e.g. with Dark matter Ψ

0711.4866

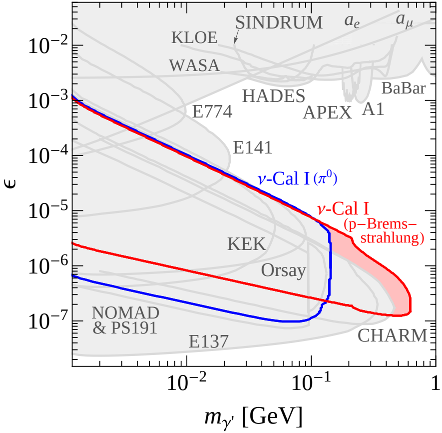
$$\mathscr{L}_{\text{DM+mediator}} = \bar{\Psi}\left(i\gamma^\mu\partial_\mu - e'\gamma^\mu A'_\mu - m_\Psi\right)\Psi - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{m^2_{\gamma'}}{2}A'_\mu A'^\mu + \varepsilon A'_\mu \partial_\nu B^{\mu\nu}$$

when $m_\Psi > m_{\gamma'} \sim 1$ GeV

- limit from BBN:

$$\tau_V < 1\,\text{s}, \quad \Longrightarrow \varepsilon^2 \left(\frac{m_{\gamma'}}{1\,\text{GeV}}\right) \gtrsim 10^{-21}$$

- light for $(g-2)$
- light for Pamela, Fermi, etc



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Production by virtual photon $\sigma \propto \varepsilon^2$

Decay through virtual photon, $\Gamma \propto \varepsilon^2$

$V \to e^+e^-$, $\mu^+\mu^-$, etc

Massive vectors: decays are under control

Decay into SM via mixing with photon

into leptons

$$\Gamma_{A'}^{l^+l^-} = \frac{1}{3}\alpha_{\text{QED}}\, m_{A'}\,\varepsilon^2 \sqrt{1-\frac{4m_l^2}{m_{A'}^2}}\left(1+\frac{2m_l^2}{m_{A'}^2}\right),$$

into hadrons

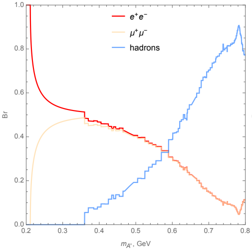
$$\Gamma_{A'}^{\text{hadrons}} = \frac{1}{3}\alpha_{\text{QED}}\, m_{A'}\,\varepsilon^2 \cdot R(m_{A'}),$$

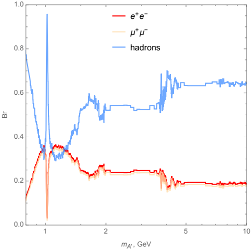
where

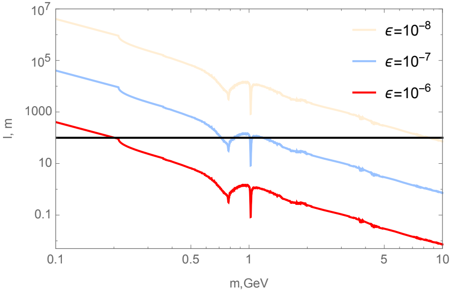
$$R(\sqrt{s}) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

and

$$\Gamma_{A'}^{\text{tot}} = \Gamma_{A'}^{e^+e^-} + \Gamma_{A'}^{\mu^+\mu^-} + \Gamma_{A'}^{\text{hadrons}}$$







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Massive vectors: production by protons

- decays of π^0, η^0 and $\rho^\pm$, ρ^0, ω

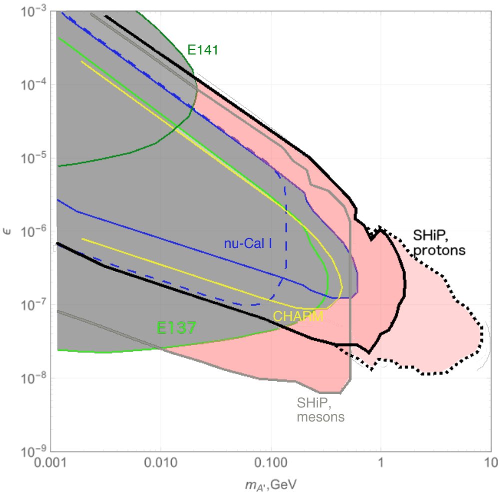
$$\mathrm{Br}_{\pi^0\to A'\gamma} \simeq 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 \mathrm{Br}_{\pi^0\to\gamma\gamma}$$

- proton bremsstrahlung
  concervatively corrected by the Dirac (electric) form factor of proton

$$F_1 = \frac{1}{\left(1+\frac{q^2}{m_D^2}\right)^2} \to \frac{1}{m_{A'}^4}$$

  with Dirac mass squared $m_D^2 = 12/r_D^2$
  and the Dirac radius $r_D \approx 0.8\,\mathrm{fm}$

- quark bremsstrahlung ??
  still under study...



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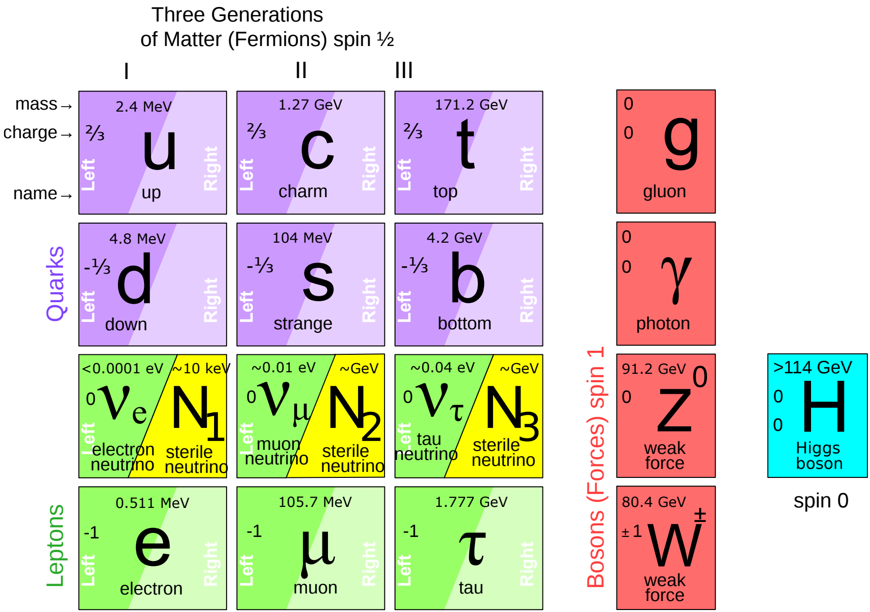

Three Generations
of Matter (Fermions) spin ½
I
II
III
mass →
charge →
name →
2.4 MeV
⅔
u
up
1.27 GeV
⅔
c
charm
171.2 GeV
⅔
t
top
0
0
g
gluon
Quarks
4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
4.2 GeV
-⅓
b
bottom
0
0
γ
photon
<0.0001 eV
~10 keV
0
ν_e
N_1
electron neutrino
sterile neutrino
~0.01 eV
~GeV
0
ν_μ
N_2
muon neutrino
sterile neutrino
~0.04 eV
~GeV
0
ν_τ
N_3
tau neutrino
sterile neutrino
91.2 GeV
0
Z^0
weak force
>114 GeV
0
0
H
Higgs boson
spin 0
Leptons
0.511 MeV
-1
e
electron
105.7 MeV
-1
μ
muon
1.777 GeV
-1
τ
tau
80.4 GeV
±1
$W^\pm$
weak force
Bosons (Forces) spin 1
Left
Right

Seesaw type I mechanism: $M_N \gg m_{active}$

$$\mathcal{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.}$$

where $I = 1,2,3$ and $\alpha = e, \mu, \tau$ $\quad \tilde{H}_a = \varepsilon_{ab} H_b^*$

When Higgs gains $\langle H \rangle = v/\sqrt{2}$ we get in neutrino sector

$$\mathcal{V}_N = v\,\frac{f_{\alpha I}}{\sqrt{2}}\,\overline{\nu}_\alpha N_I + \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.} = \frac{1}{2}\left(\overline{\nu}_\alpha\,, \overline{N}_I^c\right)\begin{pmatrix} 0 & v\,\frac{\hat{f}}{\sqrt{2}} \\ v\,\frac{\hat{f}^T}{\sqrt{2}} & \hat{M}_N \end{pmatrix}\left(\nu_\alpha^c\,, N_I\right)^{\mathrm{T}} + \text{h.c.}$$

Then for $M_N \gg \hat{M}_D = v\,\frac{\hat{f}}{\sqrt{2}}$ we find the eigenvalues:

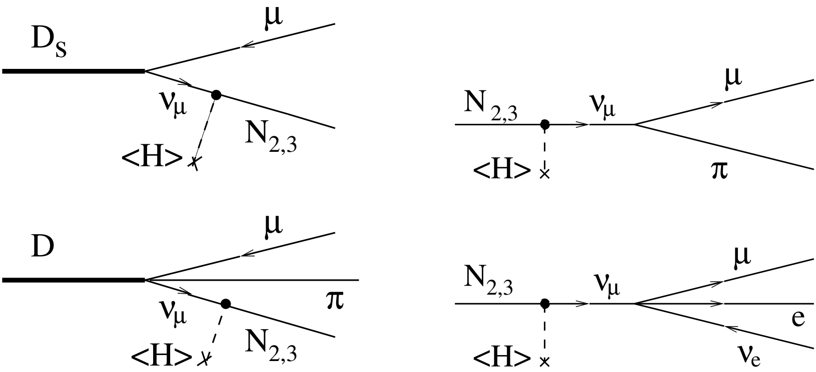
$$\simeq \hat{M}_N \qquad \text{and} \qquad \hat{M}^\nu = -\hat{M}_D \frac{1}{\hat{M}_N}\hat{M}_D^T \propto f^2 \frac{v^2}{M_N} \lll M_N$$

Mixings: flavor state $\nu_\alpha = U_{\alpha i}\nu_i + \theta_{\alpha I} N_I$

active-active mixing: (PMNS-matrix U) $\qquad U^T \hat{M}^\nu U = diag\,(m_1\,, m_2\,, m_3)$

active-sterile mixing: $\qquad \theta_{\alpha I} = \frac{M_{D_{\alpha I}}}{M_I} \propto \hat{f}\,\frac{v}{M_N} \ll 1$

Sterile neutrinos: production and decays



Interaction via neutral and charged weak hadronic currents

Do we need multimeson modes?

Actually not: 20% to production...

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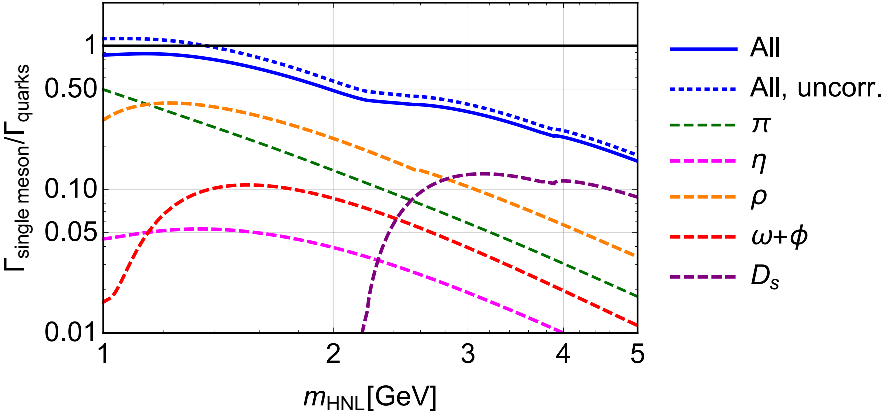


Decay modes normalized to quarks with QCD-corrections from

$\tau \to \nu +$ hadrons

And we use hadronic form factors...

Renormalizable inflaton at GeV scale

0912.0390

$$S_{XSM} = \int \sqrt{-g}\, d^4x \left(\mathscr{L}_{\rm SM} + \mathscr{L}_{\rm ext} + \mathscr{L}_{\rm grav}\right),$$

$$\mathscr{L}_{\rm ext} = \frac{1}{2}\partial_\mu X \partial^\mu X + \frac{1}{2} m_X^2 X^2 - \frac{\beta}{4} X^4 - \lambda \left(H^\dagger H - \frac{\alpha}{\lambda} X^2\right)^2,$$

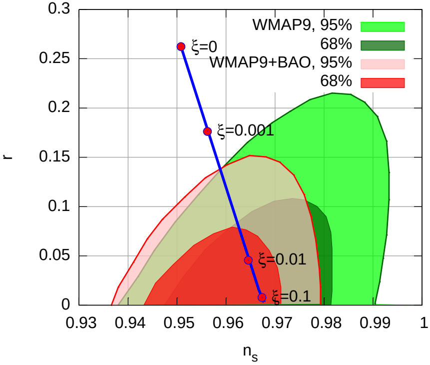
$$\mathscr{L}_{\rm grav} = -\frac{M_P^2 + \xi X^2}{2} R,$$

inflaton mass

$$m_\chi = m_h \sqrt{\frac{\beta}{2\alpha}} = \sqrt{\frac{\beta}{\lambda \theta^2}}.$$

phenomenology is fixed by
mixing with Higgs

$$\theta^2 = \frac{2\beta v^2}{m_\chi^2} = \frac{2\alpha}{\lambda}.$$



QCD modes: claimed uncertainties upto 10^2

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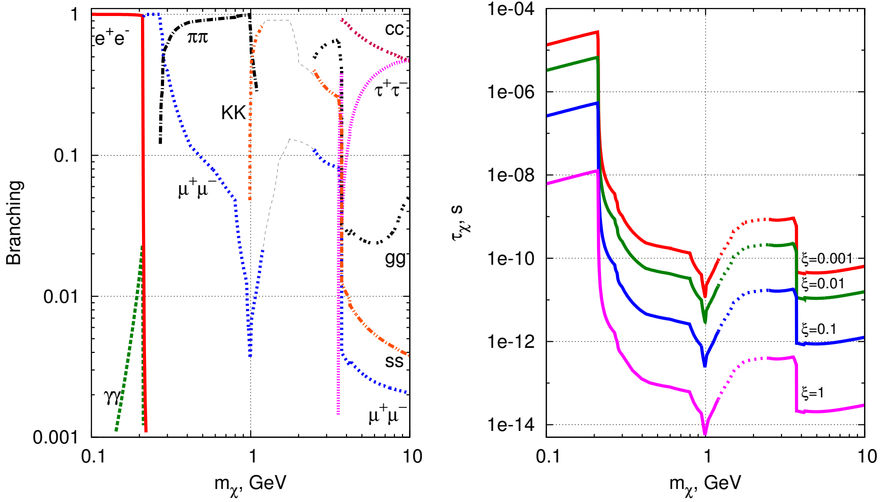

Interaction among the final hadronic states

following J.Donoghue, J.Gasser and H Leutwyler (1990)

Limits from LHCb

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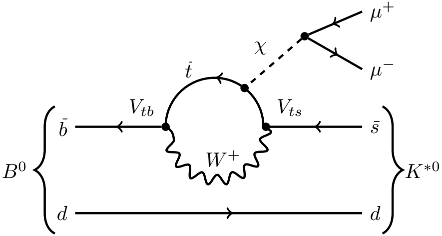

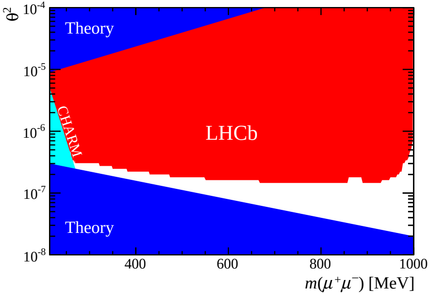

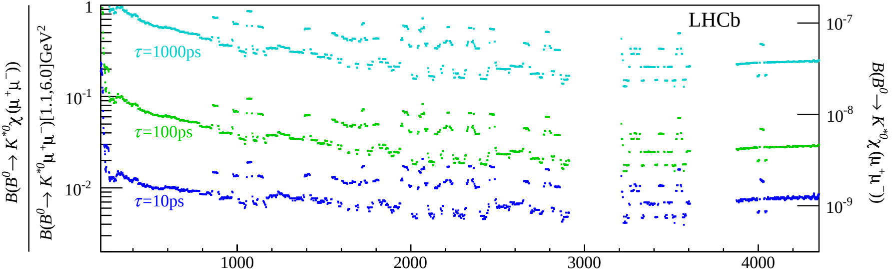

We need to know the scalar form factors

$$\mathscr{L} = -\theta \sum_f \frac{m_f}{v} \bar{\psi}_f \psi_f S,$$

all meson channels are interesting, $\pi\pi$, KK, $\eta\eta$, 4π, etc

$$\langle \pi^i(p)\pi^k(p')|\theta^\mu_\mu|0\rangle \equiv \Theta_\pi(s)\delta^{ik},$$
$$\langle \pi^i(p)\pi^k(p')|m_u\bar{u}u + m_d\bar{d}d|0\rangle \equiv \Gamma_\pi(s)\delta^{ik},$$
$$\langle \pi^i(p)\pi^k(p')|m_s\bar{s}s|0\rangle \equiv \Delta_\pi(s)\delta^{ik},$$

$$G_\pi(s) = \frac{2}{9}\Theta_\pi(s) + \frac{7}{9}(\Gamma_\pi(s) + \Delta_\pi(s)).$$

At small $s = (p+p')^2 = M_S^2$ we can compute them within ChPT

$$\Theta_\pi(s) = s + 2m_\pi^2, \qquad \Theta_K(s) = s + 2m_K^2,$$
$$\Gamma_\pi(s) = m_\pi^2, \qquad \Gamma_K(s) = \frac{1}{2}m_\pi^2,$$
$$\Delta_\pi(s) = 0, \qquad \Delta_K(s) = m_K^2 - \frac{1}{2}m_\pi^2.$$

The estimates BSM people use

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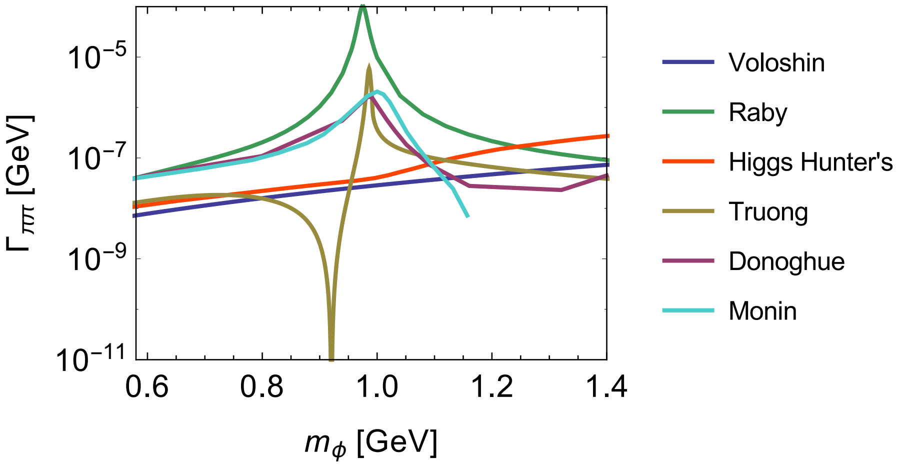

These estimates are based on dispersion relations

There are several issues, e.g. 1812.08088

- Unitarity requires $\Theta(\infty) = 0$, while $\Theta(s) \propto s$

  — ignore (why not important for low s ?) J.Donoghue, J.Gasser, H.Leutwyler (1990)

  — make $\Theta(\infty) = 0$ by hand (changes or not low s, always changes high s behaviour)

- There are many channels, but people typically reduce to the 2-channels system, $\pi\pi$, KK

  — we need more to make predictions

  $\eta\eta$, 4π, ... hep-ph/9909292

  — the truncation is not justified

  some channels are strongly coupled,

  e.g. $\text{Br}(f_0(1500) \to \pi\pi) \simeq 35\%$, $\text{Br}(f_0(1500) \to 4\pi) \simeq 50\%$,

  results depend on the way one adds a new channel 1809.06867

- Nobody calculate the uncertainty of their results:

  30% (like typically in ChPT), 'factor of 2', '10' ?

Summary

- If some exotics even feebly couples to QCD-stuff
- QCD-effects MUST BE properly accounted for
- help from QCD-people are welcome !!
- It would be nice to 'measure' the scalar form-factors, but we need all the three...
- some work has been already done...

Backup slides

Dispersion system truncated

$$F_1(s) = \sum_{j=1}^{N} \int \frac{ds'}{\pi} \frac{T^*_{1j}(s')\sigma_j(s')}{s'-s} F_j(s') + \left\{ \sum_{j=N+1}^{M} \int \frac{ds'}{\pi} \frac{T^*_{1j}(s')\sigma_j(s')}{s'-s} F_j(s') \right\}$$

$$F_2(s) = \sum_{j=1}^{N} \int \frac{ds'}{\pi} \frac{T^*_{2j}(s')\sigma_j(s')}{s'-s} F_j(s') + \left\{ \sum_{j=N+1}^{M} \int \frac{ds'}{\pi} \frac{T^*_{2j}(s')\sigma_j(s')}{s'-s} F_j(s') \right\}$$

. . . .

$$F_N(s) = \sum_{j=1}^{N} \int \frac{ds'}{\pi} \frac{T^*_{Mj}(s')\sigma_j(s')}{s'-s} F_j(s') + \left\{ \sum_{j=N+1}^{M} \int \frac{ds'}{\pi} \frac{T^*_{Nj}(s')\sigma_j(s')}{s'-s} F_j(s') \right\}$$

Light sgoldstinos in SUSY models

SUSY is spontaneously broken

breaking of $SU(2)_W \times U(1)_Y$ by the $\langle H \rangle = v$

Goldstones bosons couple to all massive fields

(Goldberger–Treiman formula like for pion)

$$\mathscr{L} = \frac{1}{v} J^{\mu}_{SU(2)_W \times U(1)_Y} \partial_\mu H$$

breaking of SUSY by $\langle F_\varphi \rangle = F$

Goldstone fermion: goldstino

$$\mathscr{L}_\psi \propto \frac{1}{F} J^{\mu}_{SUSY} \partial_\mu \psi$$

Goldstino supermultiplet: (boson φ (sgoldstino), fermion ψ (goldstino))

~~SUSY~~ $\longleftrightarrow$ $F \equiv \langle F_\varphi \rangle \neq 0$ $\qquad \Phi = \varphi + \sqrt{2}\theta\psi + F_\varphi \theta\theta$ $\qquad \frac{1}{\sqrt{2}}\left(\varphi + \varphi^\dagger\right) \equiv S$ — scalar

sgoldstino: $\mathscr{L}_{S,P} \propto \frac{M_{soft}}{F}$ $\qquad F \sim$ (~~SUSY~~ scale)^2 $\qquad \frac{1}{i\sqrt{2}}\left(\varphi - \varphi^\dagger\right) \equiv P$ — pseudoscalar

M_{soft}: MSSM soft terms

superpartner masses and trilinear couplings,

massless at tree level
naturally may be light...

gauginos:

$$M_\lambda \lambda\lambda \longrightarrow \frac{M_\lambda}{F} S F_{\mu\nu} F^{\mu\nu}\,, \quad \frac{M_\lambda}{F} P F_{\mu\nu} \tilde{F}^{\mu\nu}$$

squarks, sleptons:

$$A_{ij} h_u \tilde{q}_i \tilde{u}_j \longrightarrow \frac{A_{ij}}{F} S h_u q_i u_j\,, \quad \frac{A_{ij}}{F} P h_u q_i u_j$$

Direct coupling to gluonic tensor

- For $M_S \ll 1$ GeV estimate coupling to pions through the triangle anomaly in $T_{\mu\mu}$
  M.Voloshin, V.Zakharov (1980)

$$-\langle \pi\pi \left| \frac{bg_s^2}{32\pi^2} G^a_{\mu\nu} G^a_{\mu\nu} \right| 0\rangle = \langle \pi\pi \,|\, T_{\mu\mu} \,|\, 0\rangle = q^2 \varphi^\alpha_\pi \varphi^\alpha_\pi / 2$$

hence we get an amplification 1511.05403

$$\Gamma(S \to \pi^0\pi^0) \approx \frac{\alpha_s^2(M_3)}{\beta^2(\alpha_s(M_3))} \frac{\pi m_S^3 M_3^2}{4F^2} \sqrt{1 - \frac{4m^2_{\pi^0}}{m_S^2}},$$

- For $M_S \gg 1$ GeV we have gluons and a suppression — $g_s^2 G^2_{\mu\nu}$ is a renorm-invariant

$$\Gamma(S \to gg) = \left(\frac{\alpha_s(m_S)\beta(\alpha_s(M_3))}{\beta(\alpha_s(m_S))\alpha_s(M_3)} \right)^2 \frac{m_S^3 M_3^2}{4\pi F^2}.$$

- The two rates mismatch by orders...