Parity violation in QCD process via SUSY

ACP Seminar @ Kavli IPMU

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(Osaka Univ. ⟶ Kavli IPMU)

8 May 2013

Outline

1, Motivation

2, Parity violation in top pair production @ LHC
(PV)

3, Parity violation in meson decay (and nucleon interactions)

4, Summary

1, Motivation

Supersymmetry (SUSY) : promising candidate Beyond the SM (BSM)

(Dark Matter, Grand Unification, . . .)

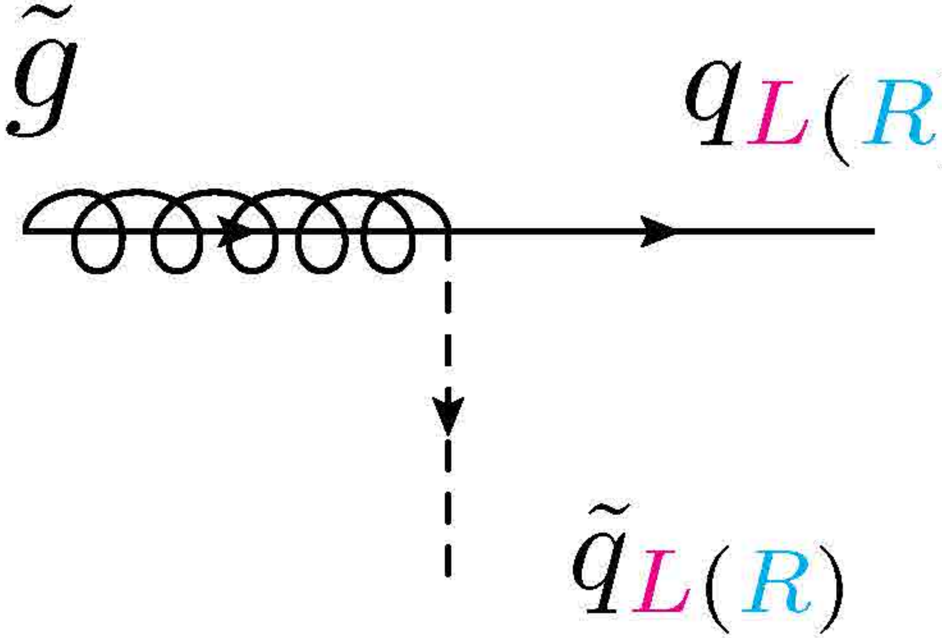
remarkable point

Parity is violated even in QCD process via SUSY

(QED) (no PV in SM QCD)

quark-squark-gluino interaction

$$\mathcal{L}_{\text{int}} \supset \sqrt{2} g_s \tilde{g}^a \bar{q}_{L(R)} T^a \tilde{q}_{L(R)} + h.c.$$



← L (R) : chirality

← L (R) : just a label

In general, $\boxed{\mathbf{m}_{\tilde{\mathbf{q}}_\mathbf{L}} \neq \mathbf{m}_{\tilde{\mathbf{q}}_\mathbf{R}}}$

Motivation

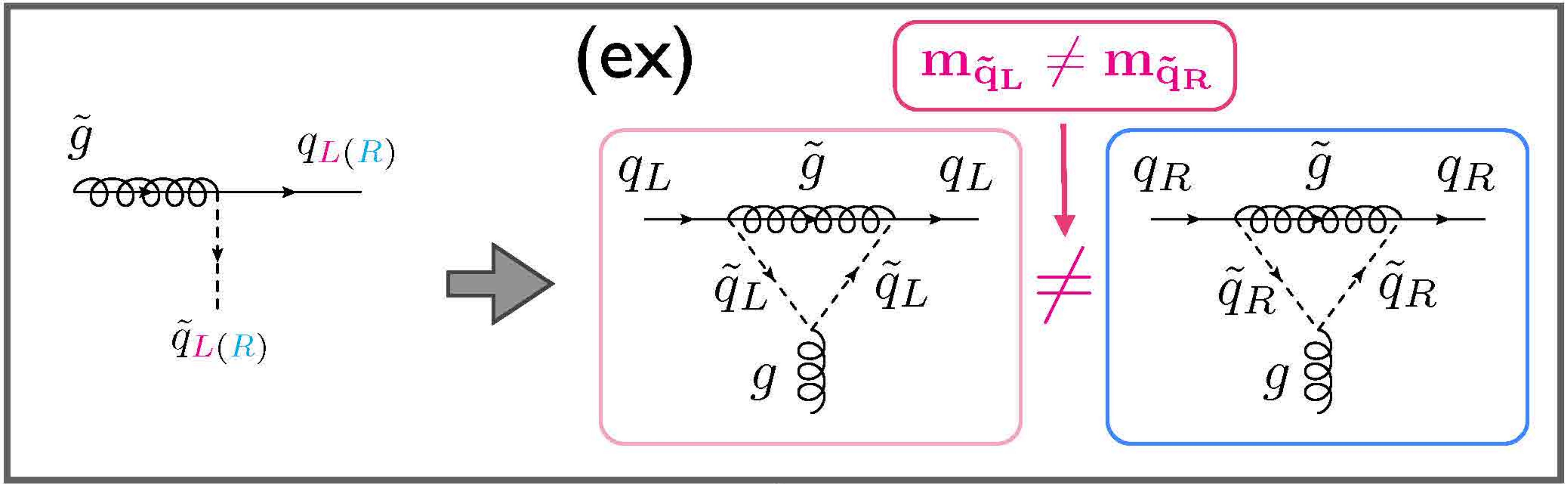
$$\boxed{\mathbf{m_{\tilde{q}_L} \neq m_{\tilde{q}_R}}}$$

↓

PV is induced by squark loop

(ex)

$$\mathbf{m_{\tilde{q}_L} \neq m_{\tilde{q}_R}}$$



↓

(contributions from OPs more than dim.6)

① indirect search of new physics

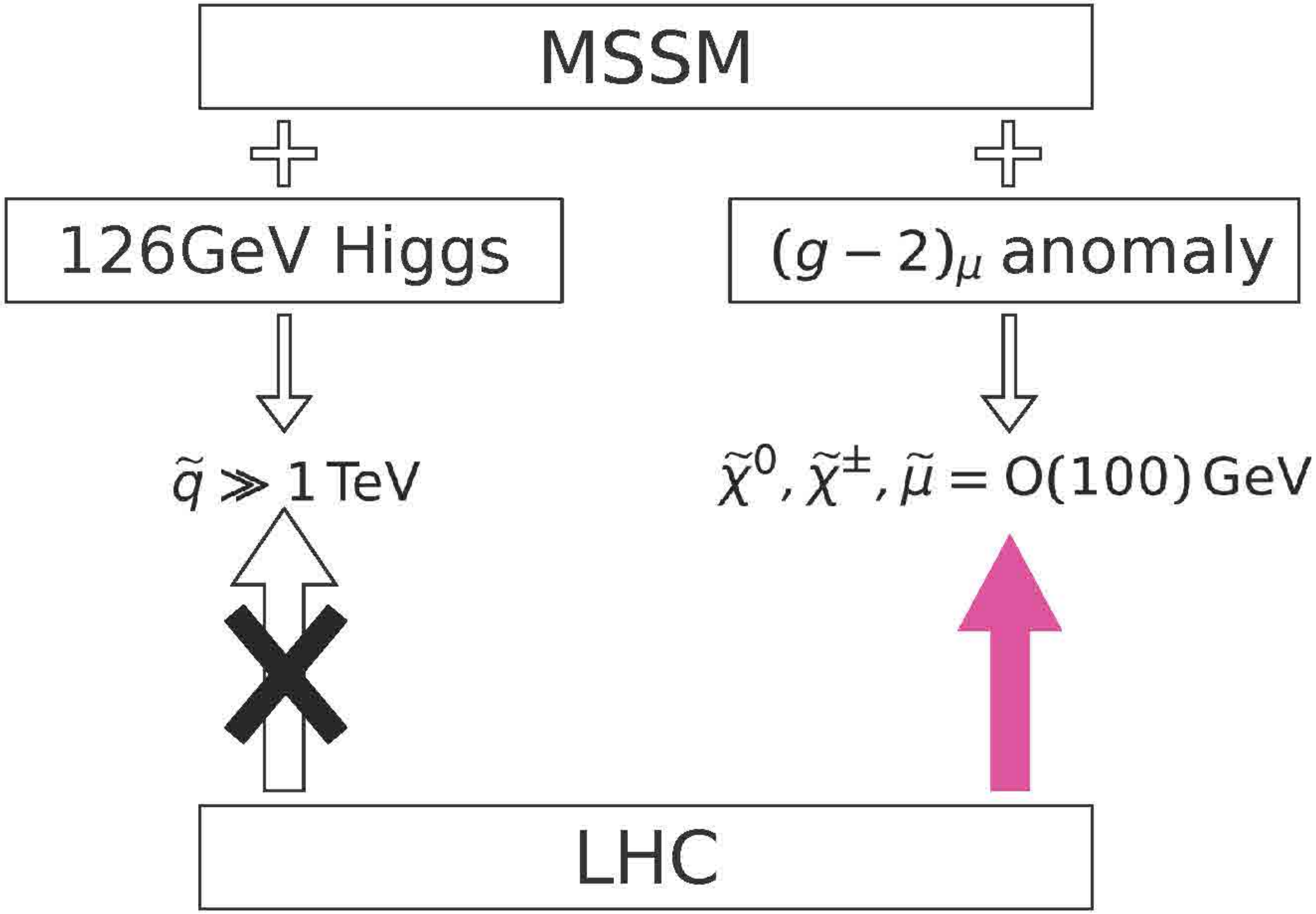
② non-degeneracy bound for $m_{\tilde{q}_L}$ and $m_{\tilde{q}_R}$

- top quark pair production
- meson decay, etc.

from S.Iwamoto's talk of ACP seminar on 1 May

Endo, Hamaguchi, *SI*, Yoshinaga [1303.4256]

◉ **Topic 1.** (Minimal SUSY Standard Model)



MSSM

+ 126GeV Higgs $\Rightarrow$ $\tilde{q} \gg 1\,\mathrm{TeV}$

+ $(g-2)_\mu$ anomaly $\Rightarrow$ $\tilde{\chi}^0, \tilde{\chi}^\pm, \tilde{\mu} = \mathrm{O}(100)\,\mathrm{GeV}$

LHC

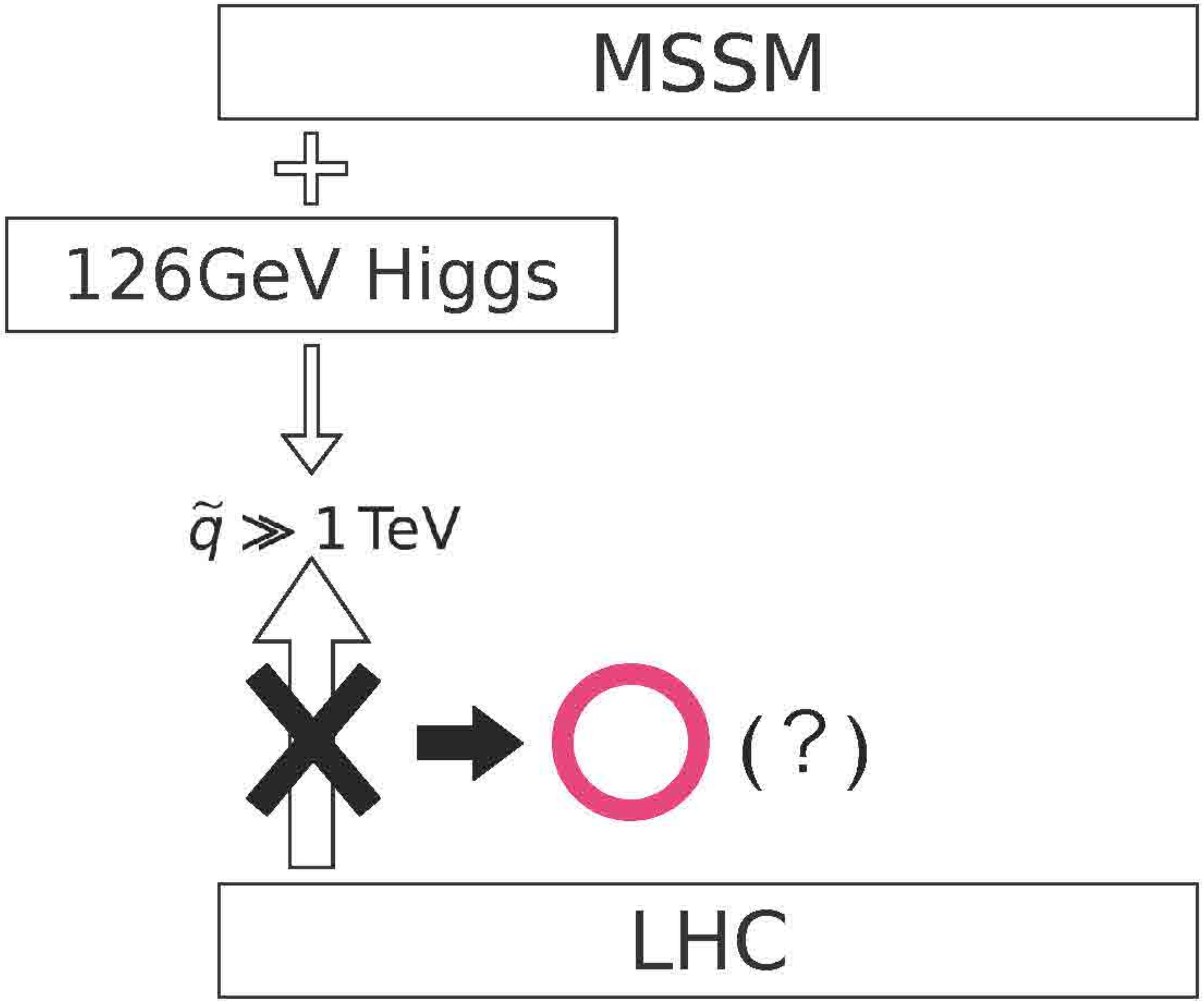
from S.Iwamoto's talk of ACP seminar on 1 May

Today's Topics

Endo, Hamaguchi, *SI*, Yoshinaga [1303.4256]

Topic 1.

(Minimal SUSY Standard Model)



MSSM

126GeV Higgs

$\tilde{q} \gg 1\,\text{TeV}$

(?)

LHC

① indirect search of new physics

2, Parity violation in top pair production @ LHC

N. Haba, KK, S. Matsumoto, T. Nabeshima, S. Tsuno,
arXiv:1109.5082 [hep-ph], PhysRevD.85.014007

candidates of BSM : SUSY, Universal Extra Dimension (UED), . . .

(dark matter, . . .)

PV in top pair production @ LHC

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How can we distinguish SUSY and UED？

Their signal is similar ☹

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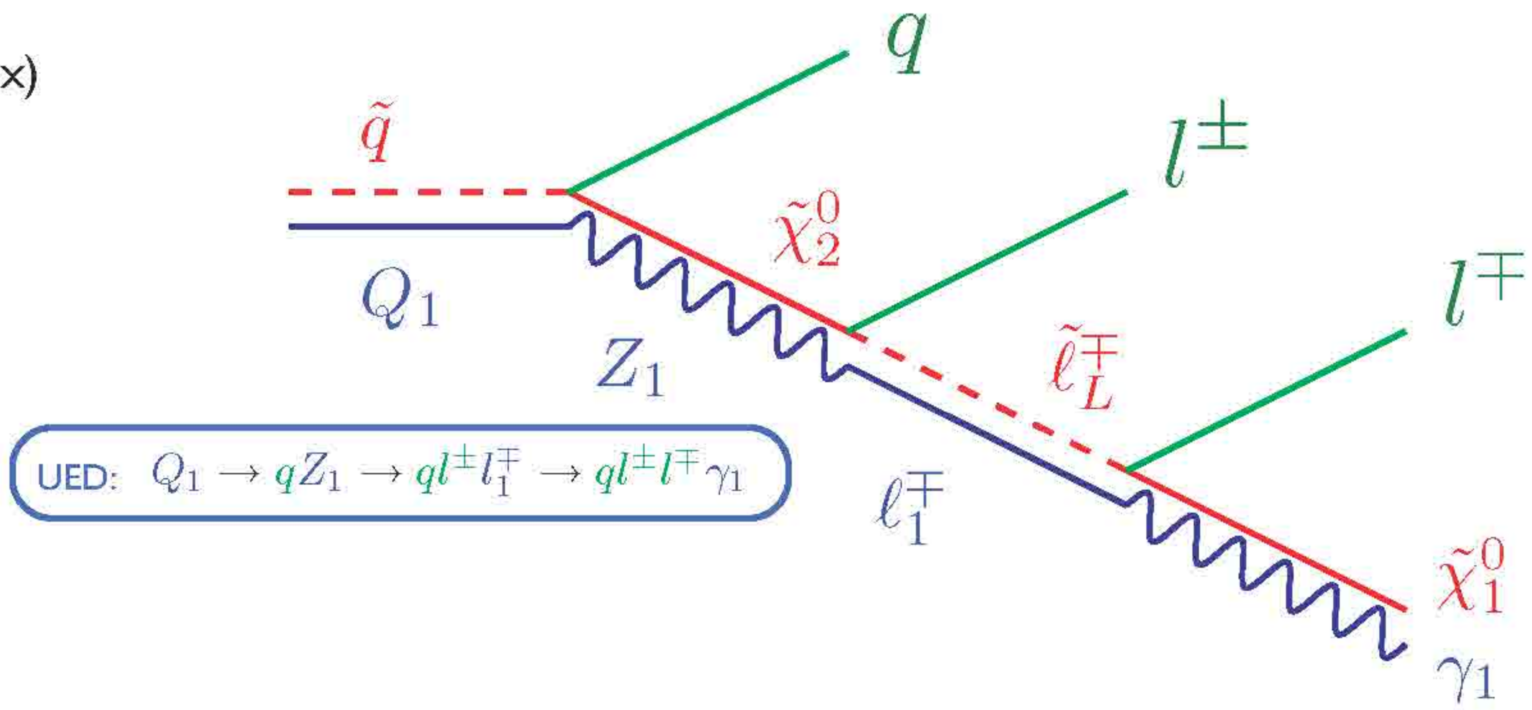

UED: $Q_1 \to qZ_1 \to ql^{\pm}l_1^{\mp} \to ql^{\pm}l^{\mp}\gamma_1$

A.Datta, et al., PRD72, 09006

SUSY: $\tilde{q} \to q\tilde{\chi}_2^0 \to ql^{\pm}\tilde{l}_L^{\mp} \to ql^{\pm}l^{\mp}\tilde{\chi}_1^0$

final state particles:
1 quark + 2 charged leptons + missing energy

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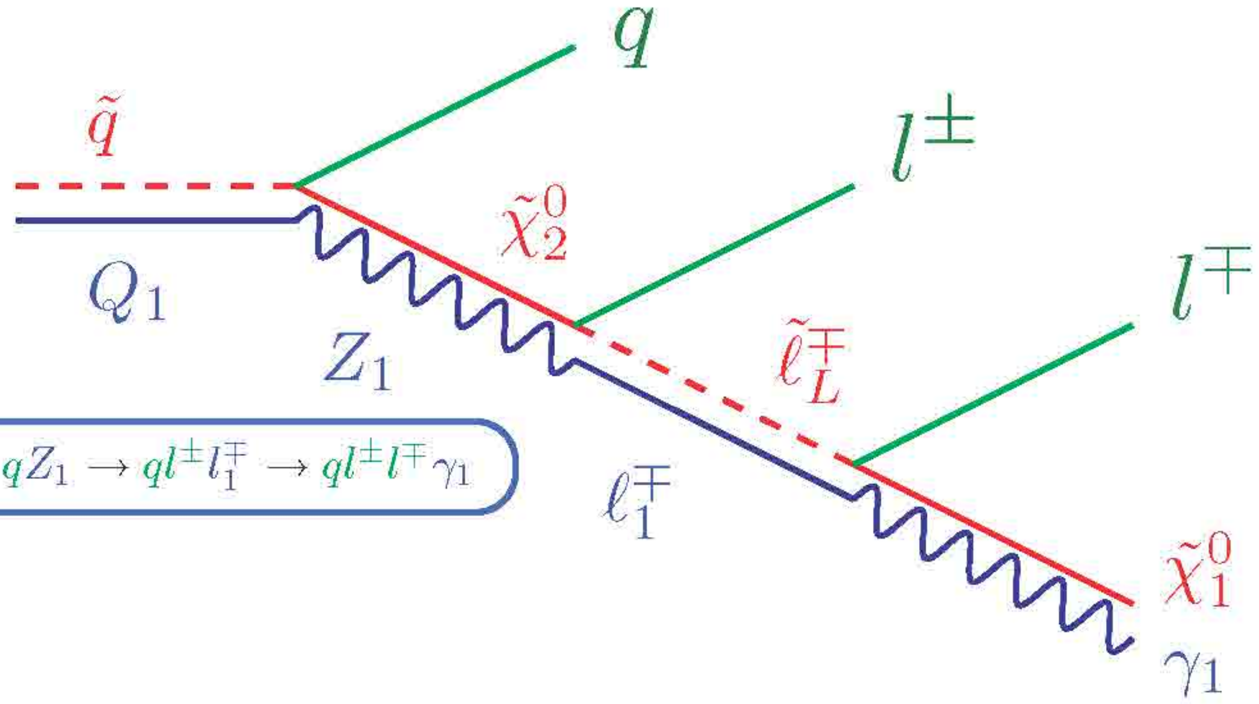

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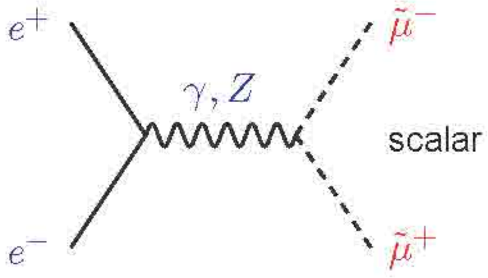
Spin measurement $\tilde{q}$ and Q_1 is necessary → difficult @ LHC ... → @ ILC

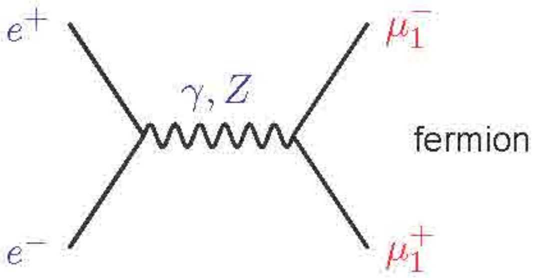
@ ILC

SUSY



$$\left.\frac{d\sigma}{d\cos\theta}\right|_{\text{SUSY}} \sim 1 - \cos^2\theta$$

UED



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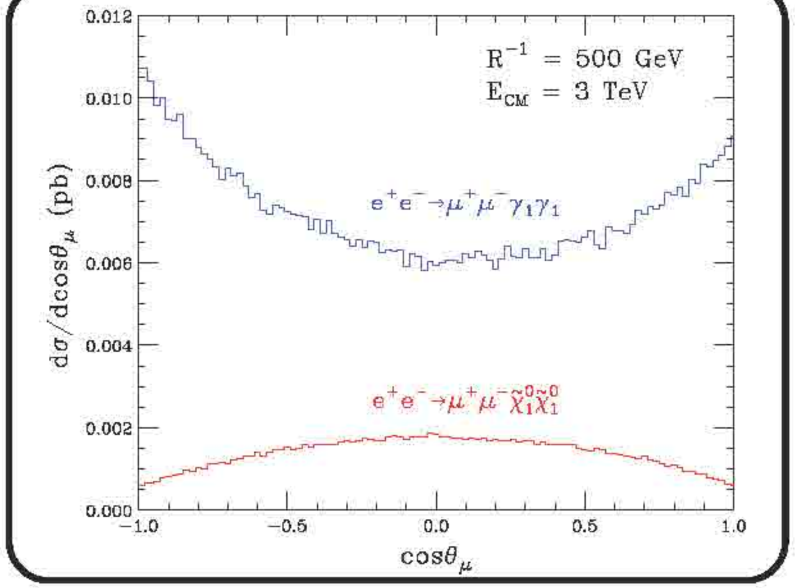

Should we wait ILC?

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We can do something @ LHC

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That is ...

Should we wait ILC?

We can do something @ LHC

That is ...

PV in QCD process

SUSY QCD PV	⟷	UED no QCD PV

There is a possibility to distinguish SUSY from UED @ ***LHC***

(even if SUSY particles are heavy to observe)

N. Haba, KK, S. Matsumoto, T. Nabeshima, S. Tsuno,
PhysRevD.85.014007

Parity Violation @ *LHC*

focus on $\sigma(pp \to t_L \bar{t}_L) \neq \sigma(pp \to t_R \bar{t}_R)$

☆ Why top quark？

top quark: heaviest particle in SM particles

life time

$\tau \sim 10^{-24}\mathrm{s}$

<

hadronizatin time

$\tau \sim \Lambda_{\mathrm{QCD}}^{-1} \sim 10^{-23}\mathrm{s}$

top quark decays before forming a hadron

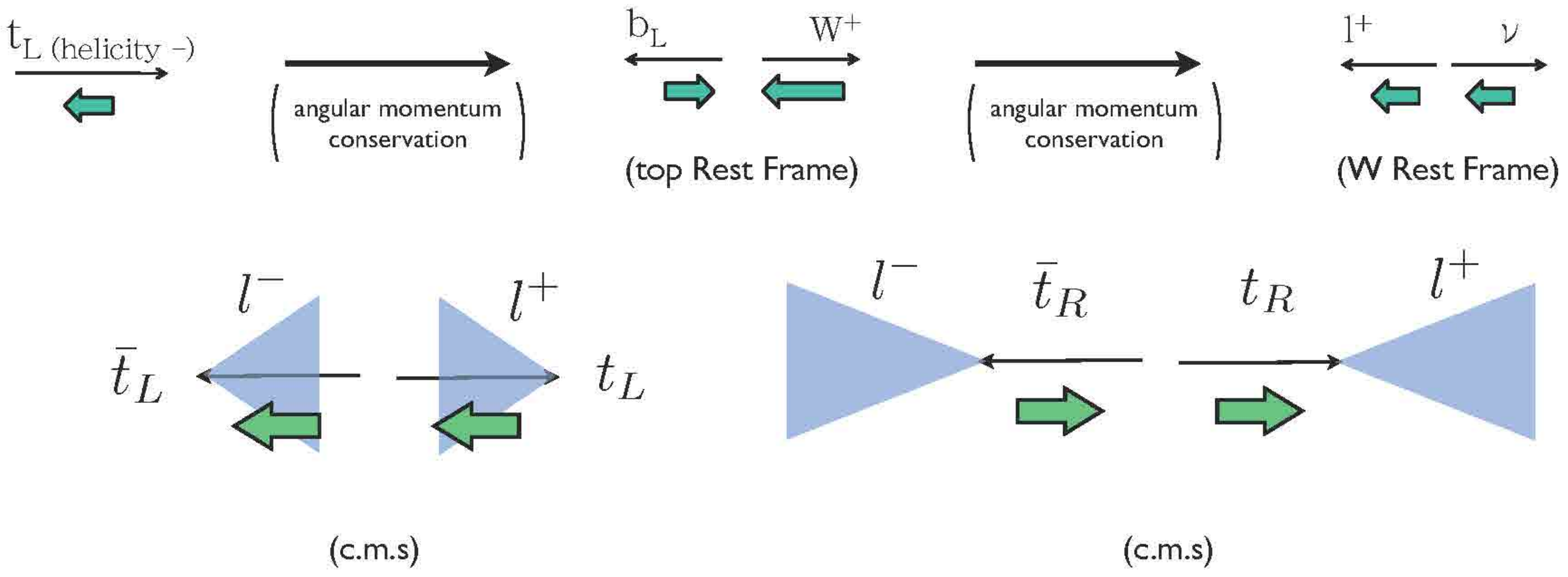
||

We can measure helicity only for top quark

Parity Violation @ LHC

top quark helicity; measured by $W^{\pm}$ *polarization*

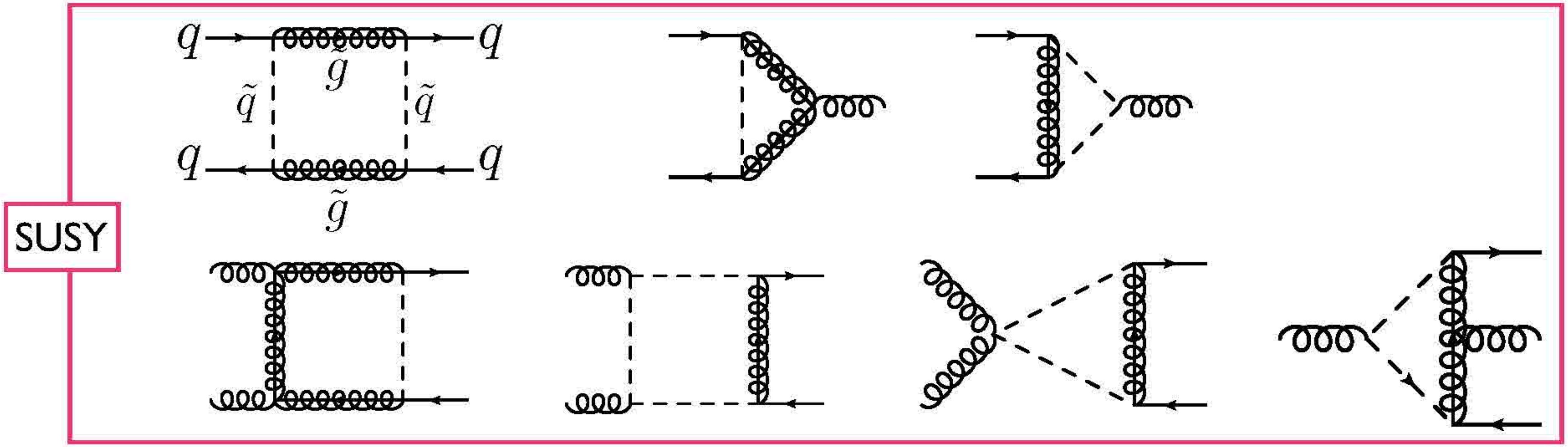
ex)



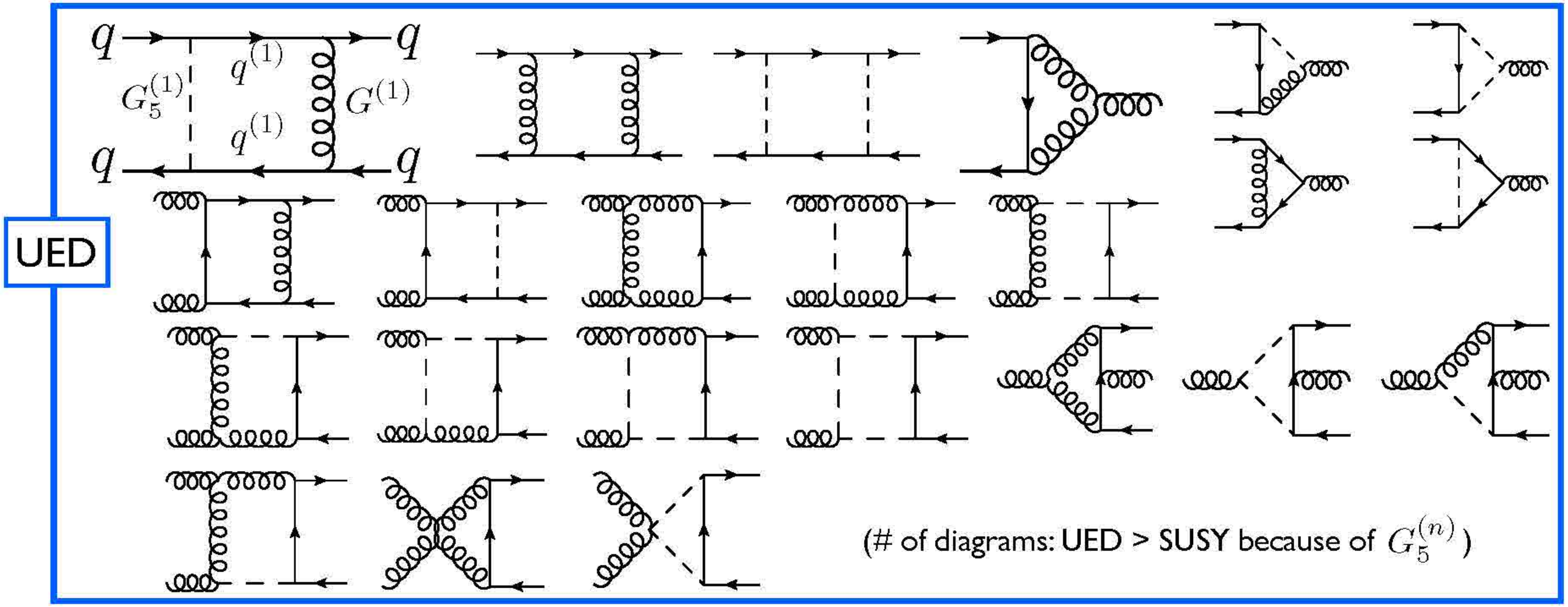
Analysis : dim. 6 OP (up to $\mathcal{O}(g_s^4)$)

($\rightarrow$ $t_L\bar{t}_R$, $t_R\bar{t}_L$: next order)

SUSY



UED



(# of diagrams: UED > SUSY because of $G_5^{(n)}$)

to obtain **dim.6 OP**

effective action is defined by integrating out heavy fields (ϕ_h) → written in terms of only SM fields

(heavier than SM fileds)

$$e^{iS_{\text{eff}}[\phi_{SM}]} = \int \mathcal{D}\phi_h e^{iS[\phi_{SM},\phi_h]}$$

$$S_{\text{eff}}[\phi_{SM}] = S_{SM} + \underline{S_2[\phi_{SM}]} + \cdots$$

$$\mathcal{L}_2 = \sum_i \underline{c_i}\,\underline{\mathcal{O}_i^{(6)}}$$

Wilson coefficients

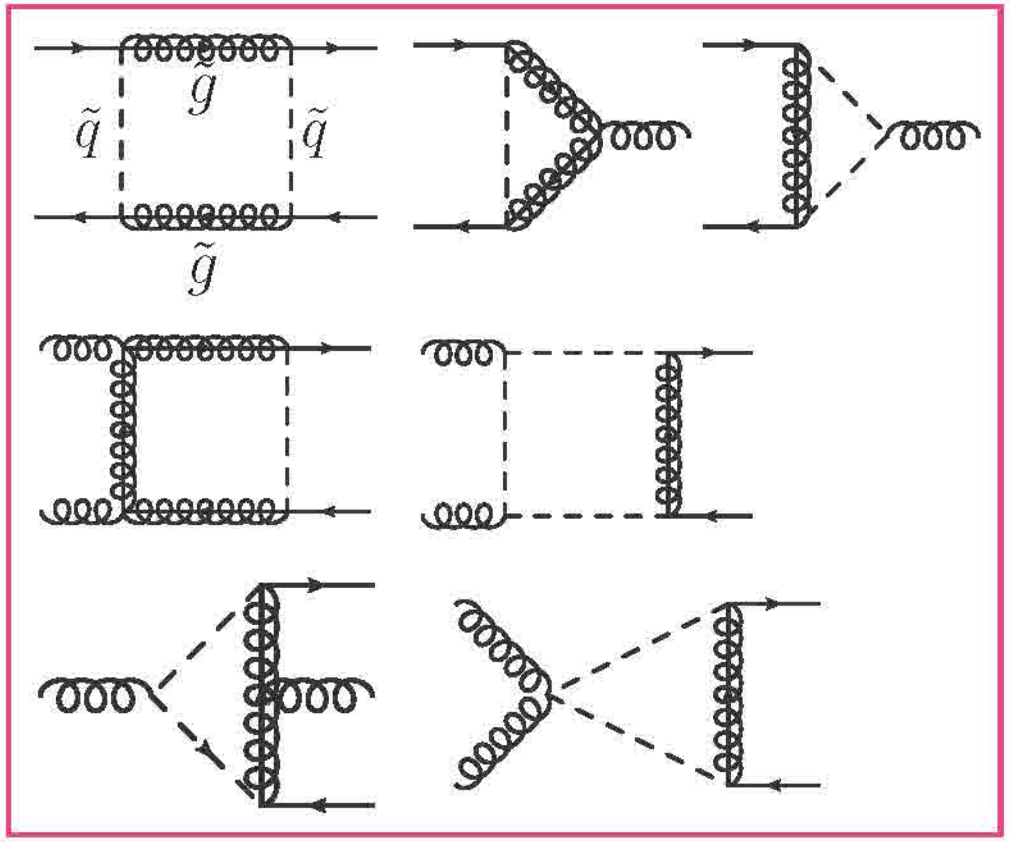
dim.6 operators

merit : systematic and accurate calculation

demerit : calculation becomes complex in higher order /many ϕ_h

not applicable when E $\geq$ heavy particle mass

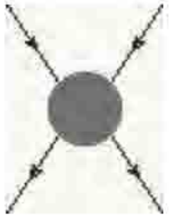
(ex. SUSY)



$\tilde{q}_L,\ \tilde{q}_R,\ \tilde{g}$

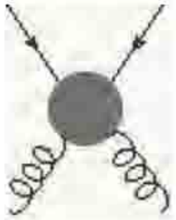
integrating out →

3 types



$$\mathcal{O}_{4F} \sim (\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma^\mu q_L),\quad (\bar{q}_R\gamma^\mu q_R)(\bar{q}_R\gamma^\mu q_R),\ \cdots$$

$$\mathcal{O}_{qqG} \sim \bar{q}_L\Gamma^\mu_L G_\mu q_L,\ \bar{q}_R\Gamma^\mu_R G_\mu q_R$$



$$\mathcal{O}_{qqGG} \sim \bar{q}_L\Gamma^{\mu\nu}_L G_\mu G_\nu q_L,\quad \bar{q}_R\Gamma^{\mu\nu}_R G_\mu G_\nu q_R,\ \cdots$$

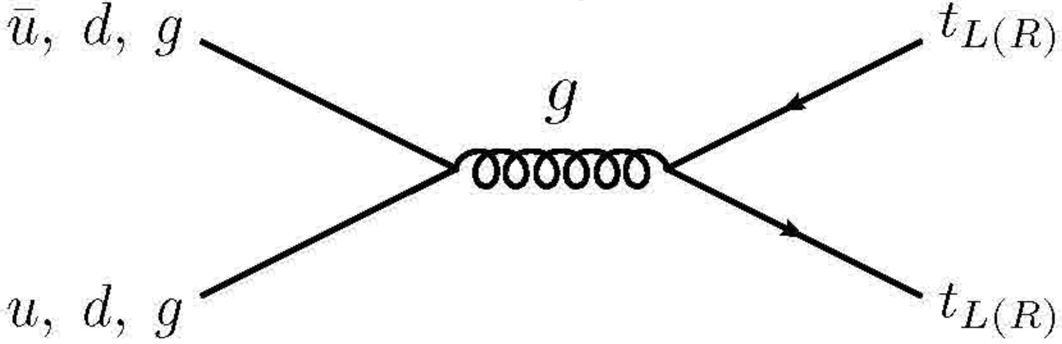
(coefficients of OPs of L and R are different)

helicity dependent top pair production

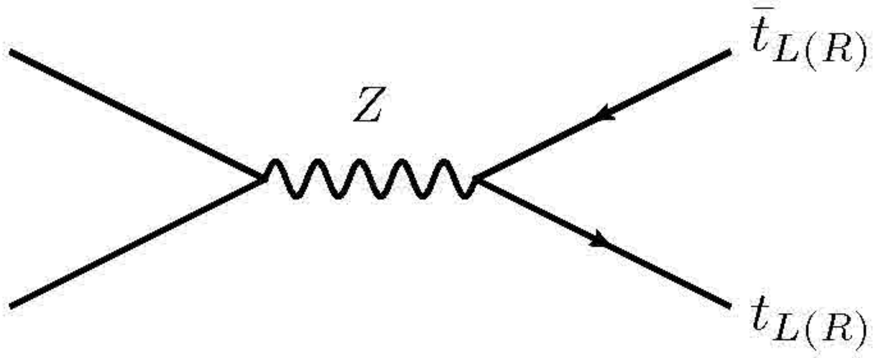
typical diagrams

SM

SM QCD

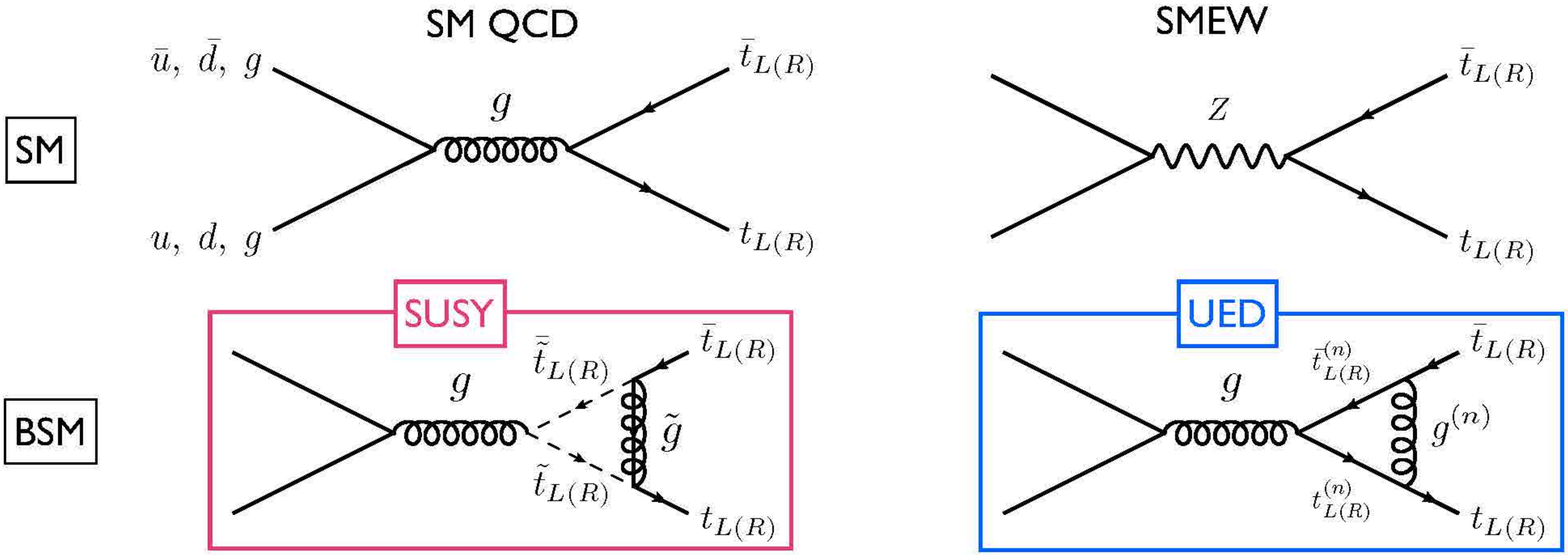


SMEW



helicity dependent top pair production

typical diagrams



$$\delta m_{t_L^{(n)}} = \left(\frac{n}{R}\right)\left(3\frac{g_s^2}{16\pi^2} + \frac{27}{16}\frac{g^2}{16\pi^2} + \frac{1}{16}\frac{g'^2}{16\pi^2}\right)\log\frac{\Lambda^2}{\mu^2}$$

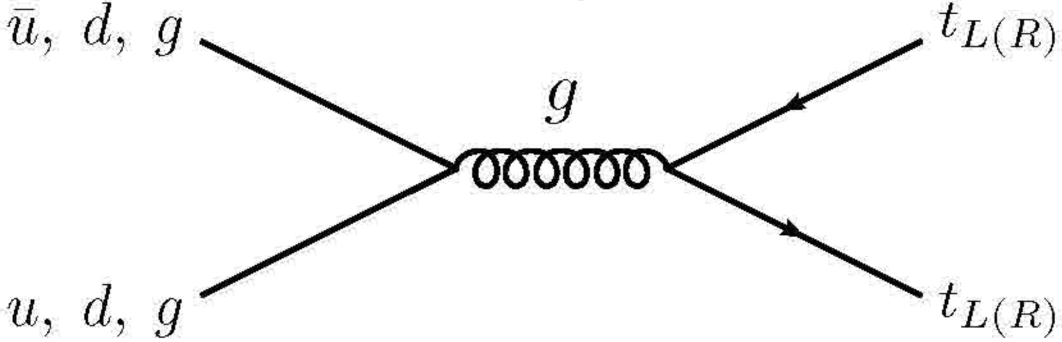
$$\delta m_{t_R^{(n)}} = \left(\frac{n}{R}\right)\left(3\frac{g_s^2}{16\pi^2} + \frac{g'^2}{16\pi^2}\right)\log\frac{\Lambda^2}{\mu^2}$$

helicity dependent top pair production

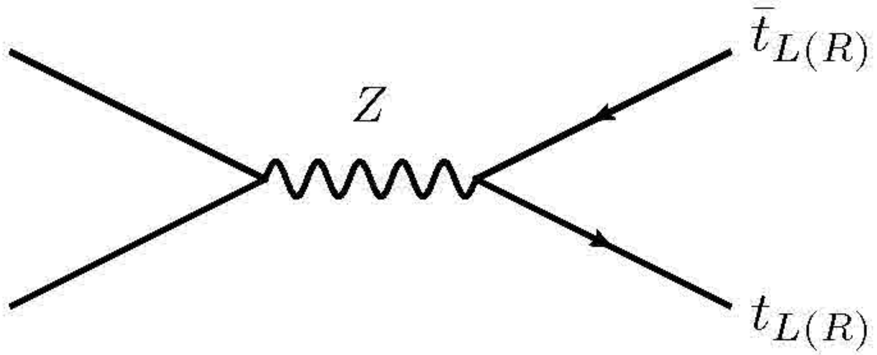
typical diagrams

SM

SM QCD

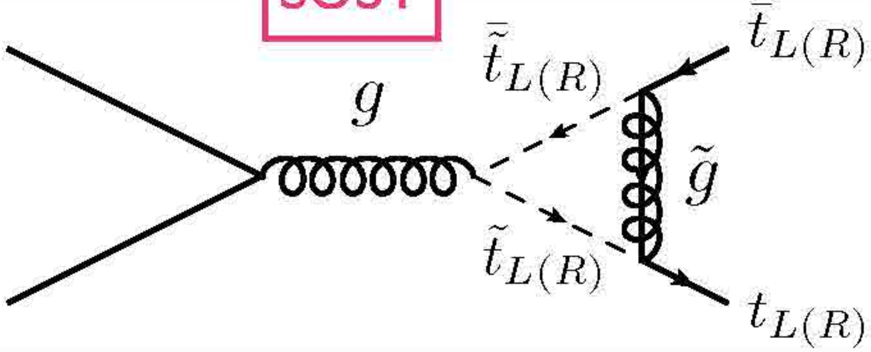


SMEW

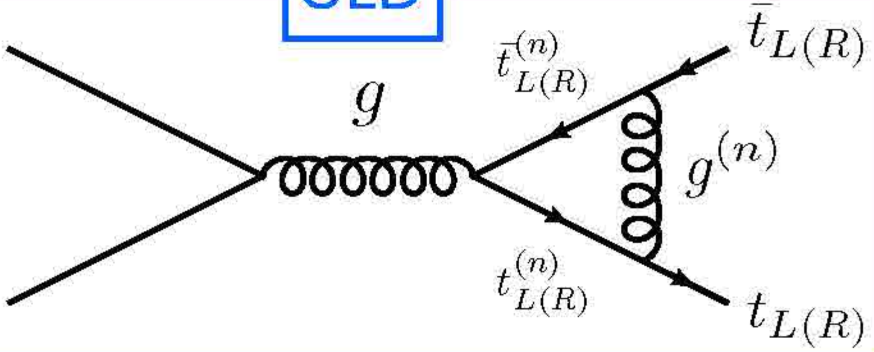


BSM

SUSY



UED



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Little Higgs

$$\mathcal{O}^{\rm LH} = \frac{g_w^2}{2}\cos^2\beta\frac{1}{k_W^2 - M_W^2}(\bar{t}\gamma^\mu P_L b)(\bar{b}\gamma^\mu P_L t)$$

$$+\sum_q^{\rm flavor}\frac{g_w^2}{3}\tan^2\theta_W\cos^2\beta\frac{1}{k_Z^2 - M_Z^2}(\bar{q}\gamma^\mu P_L q)(\bar{t}\gamma^\mu P_L t)$$

$$\cos\beta \sim 1 - \frac{v}{2f}$$

VEV of SM Higgs

VEV of LH

(tree)

helicity dependent top pair production

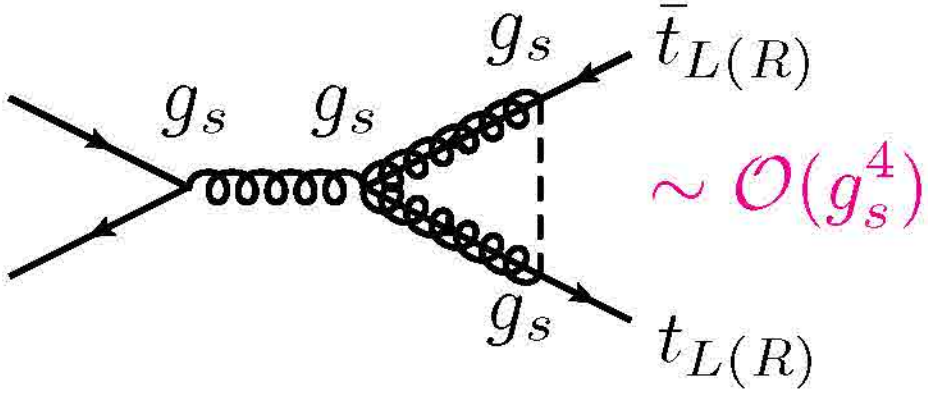
helicity asymmetry

$$\delta A_{LR} = \frac{\frac{d\sigma_{RR}}{dm_{t\bar{t}}} + \frac{d\sigma_{RL}}{dm_{t\bar{t}}} - \frac{d\sigma_{LL}}{dm_{t\bar{t}}} - \frac{d\sigma_{LR}}{dm_{t\bar{t}}}}{\frac{d\sigma_{RR}}{dm_{t\bar{t}}} + \frac{d\sigma_{RL}}{dm_{t\bar{t}}} + \frac{d\sigma_{LL}}{dm_{t\bar{t}}} + \frac{d\sigma_{LR}}{dm_{t\bar{t}}}}$$

$\sigma_{\lambda_t \lambda_{\bar{t}}}$ $\begin{cases} \lambda_t : \text{top helicity} \\ \lambda_{\bar{t}} : \text{anti-top helicity} \end{cases}$

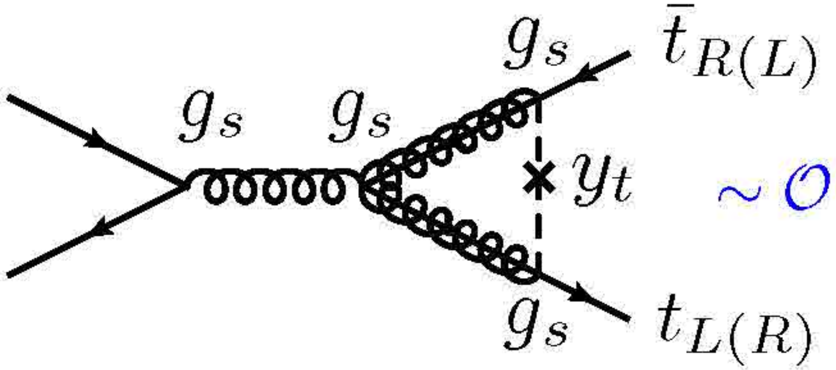
(ex) $\sigma_{RR} = \sigma(pp \to t_R \bar{t}_R)$)

up to $\mathcal{O}(g_s^4)$



$\sim \mathcal{O}(g_s^4)$

($\mathcal{O}(g_s^4 y_t)$ is next order



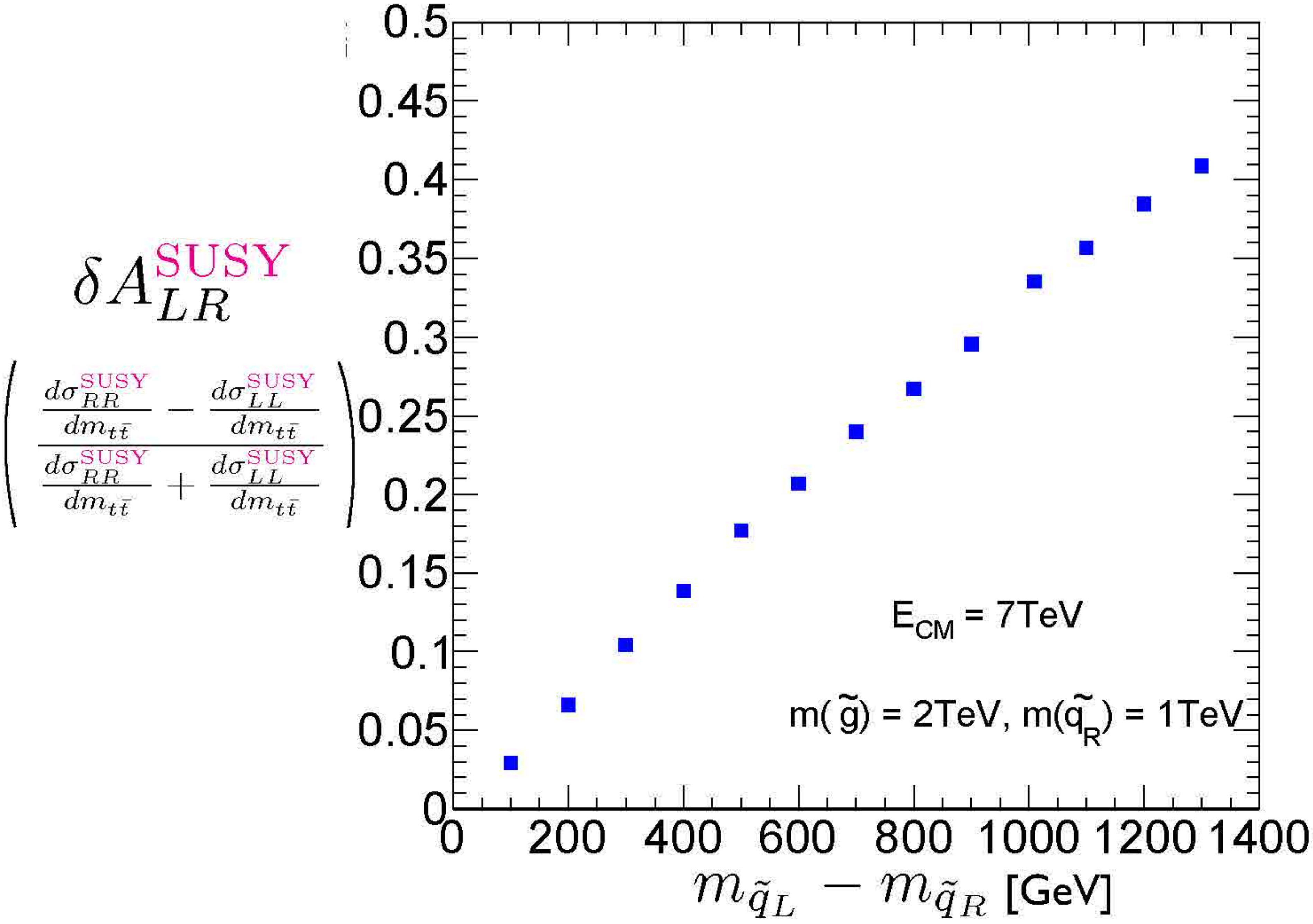
$\sim \mathcal{O}(g_s^4 y_t)$)

(up to $\mathcal{O}(g_s^4)$: σ_{LR} and σ_{RL} are redundant)

$$\delta A_{LR} \sim \frac{\frac{d\sigma_{RR}}{dm_{t\bar{t}}} - \frac{d\sigma_{LL}}{dm_{t\bar{t}}}}{\frac{d\sigma_{RR}}{dm_{t\bar{t}}} + \frac{d\sigma_{LL}}{dm_{t\bar{t}}}}$$

SUSY contribution

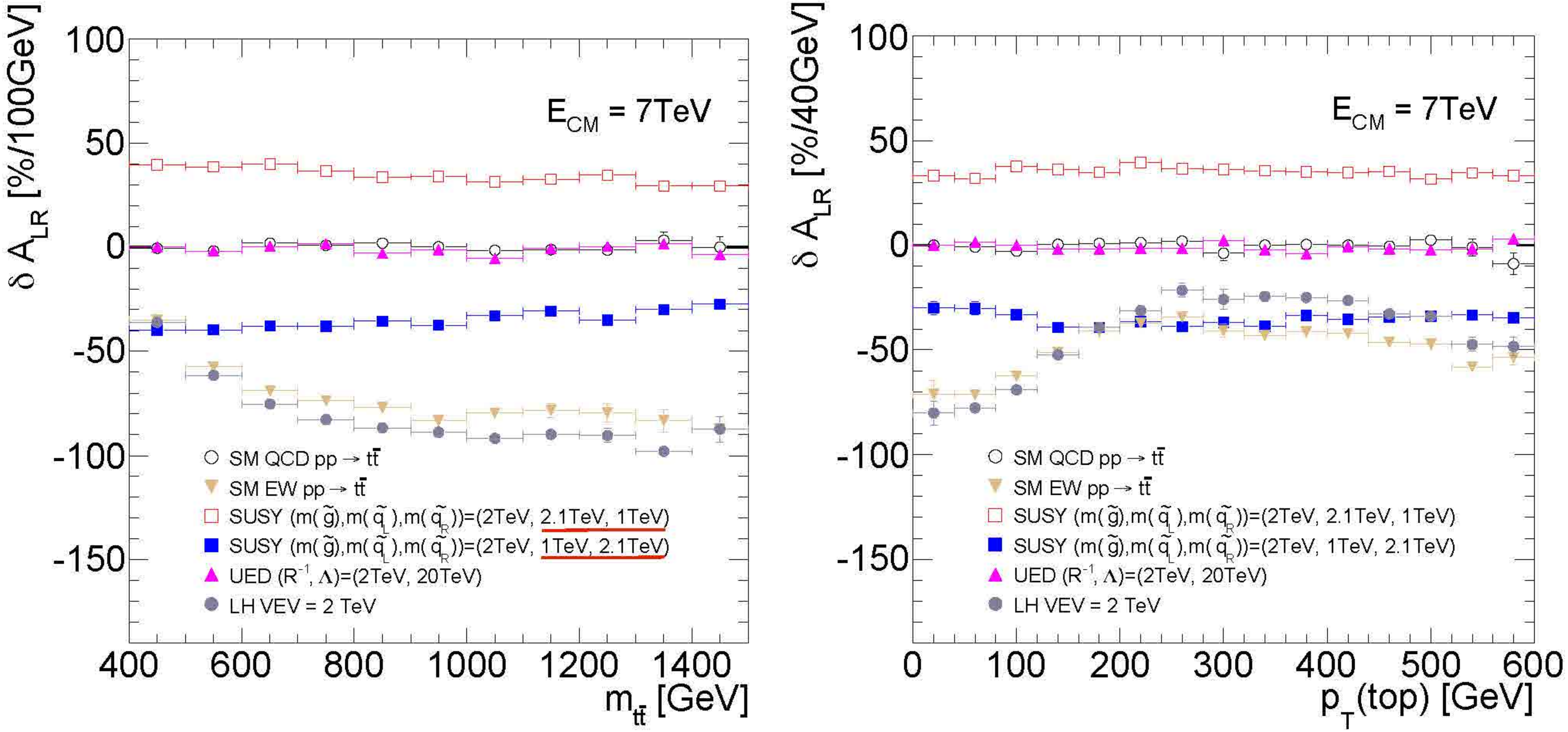
check that $\mathbf{m_{\tilde{q}_L} \neq m_{\tilde{q}_R}}$ contributes the helicity asymmetry



When $m_{\tilde{q}_L} - m_{\tilde{q}_R}$ becomes large, the asymmetry increase.

each contribution of SM, SUSY, UED, LH

tendency of the asymmetry



Clearly there is a difference between SUSY and UED

Interference of SM contribution

☆ cross section in SM : $\boxed{\sigma^{\mathrm{SM}}(pp \to t\bar{t}) \simeq 125 \text{ pb}}$

$$\sigma^{\mathrm{SMEW}} \simeq 3.5 \times 10^{-1} \text{ pb}$$

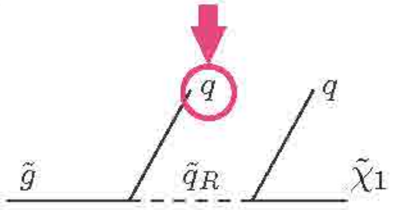
$$\sigma^{\mathrm{QCD}} \simeq 138 \text{ pb}$$

⇕ ⇒ SUSY effect is interfered

☆ cross section in SUSY : $\boxed{\sigma^{\mathrm{SUSY}}(pp \to t\bar{t}) \sim \mathcal{O}(10^{-4}) \text{ pb}}$

$(m_{\tilde{g}}, m_{\tilde{t}_L}, m_{\tilde{t}_R})$ [GeV]	$\sigma^{\mathrm{SUSY}}(pp \to t\bar{t})$ [$\times 10^{-4}$pb]
(i), (2000, 2100, 1000)	1.5
(ii), (2000, 1200, 1000)	2.2
(iii), (400, 1200, 410)	8.8

(large when SUSY particles are light)



(jet ~ mass difference)

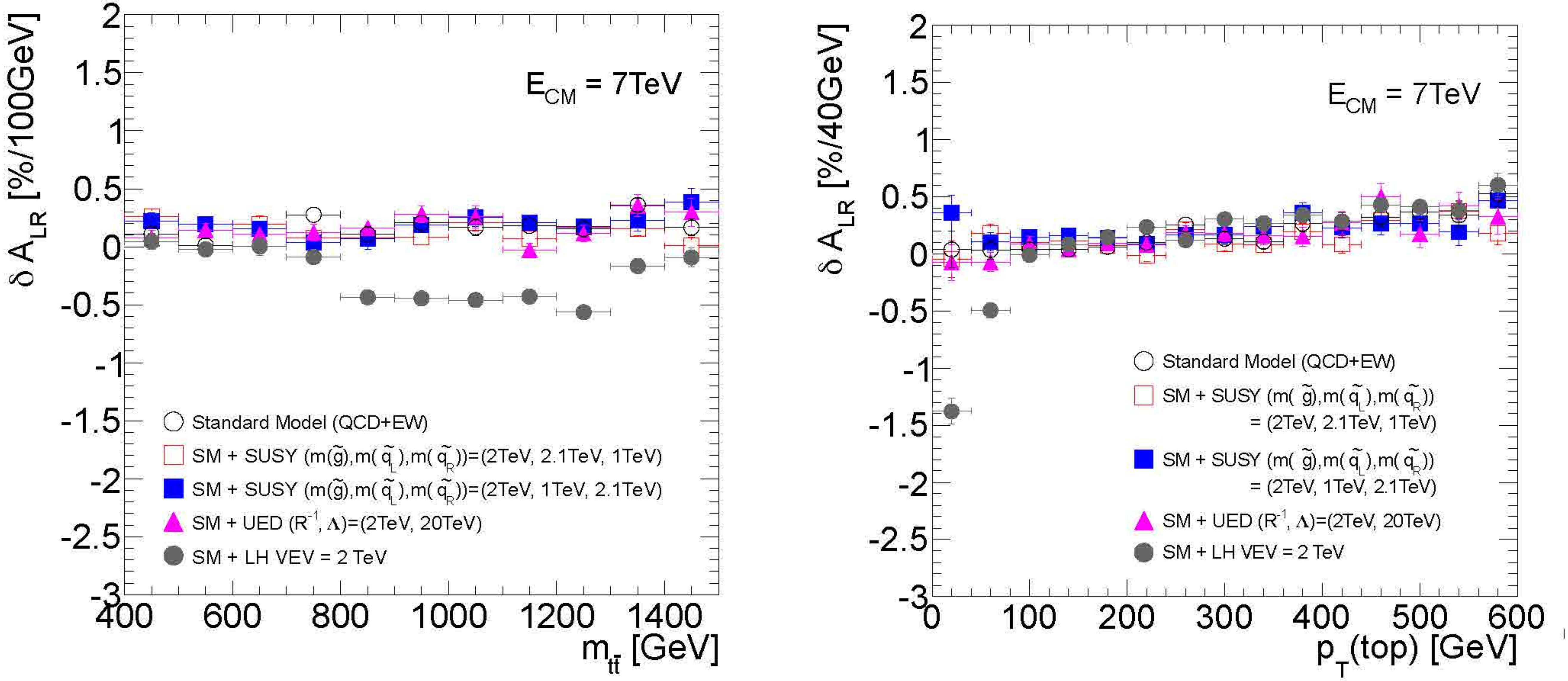
event selection for jets

p_T > 40 GeV (LHC)
p_T > 30 GeV (Tevatron)

$\tilde{g}$ and $\tilde{q}_R$ are degenerate within 30 GeV

Discriminate SUSY from UED

Asymmetry given by SM + SUSY (UED)



It seems difficult to see ...

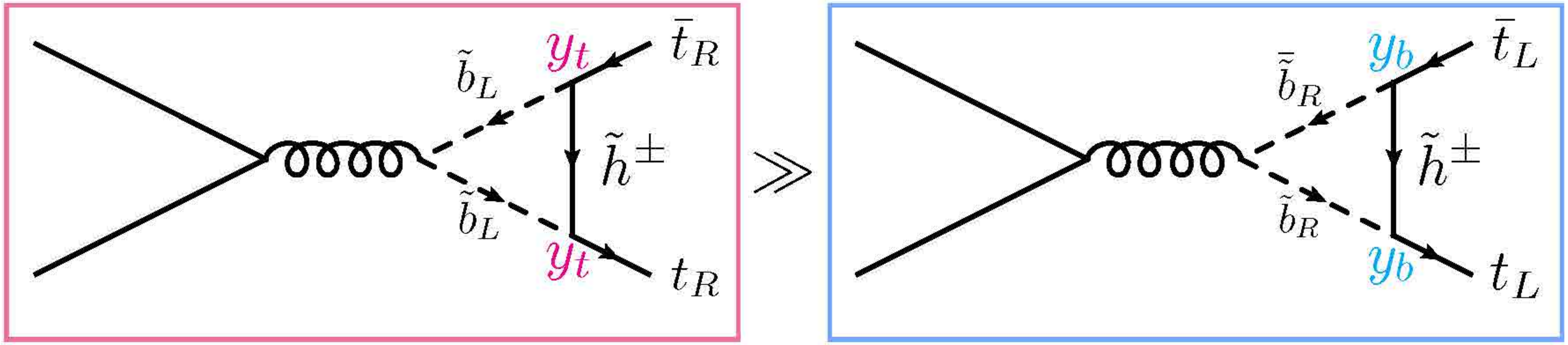
Toward next step (work in progress)

precious analysis was up to $\mathcal{O}(g_s^4)$ ...

asymmetry can be large if we consider contributions of $\mathcal{O}(g_s^2 y_t^2)$

(in small $\tan\beta$)

Higgsino diagrams



(expect $\sigma_{t\bar{t}}^{\rm SUSY} \sim 10^{-2}$ pb)

☆ evaluate not only dim.6 OP but also all contributions from more than dim.6

(preliminary)

② non-degeneracy bound for $m_{\tilde{q}_L}$ and $m_{\tilde{q}_R}$

3, Parity violation in meson decay

(and nucleon interactions)

N. Haba, KK, T. Onogi,
arXiv:1109.5442 [hep-ph], Acta.Phys.Polon.B (to appear)

PV in $(\mathbf{c\bar{c}})$ meson decay

parity violating

$$\boxed{\eta_c \longrightarrow \pi\pi}$$

$J^{PC} = 0^{-+}$ $J^{PC} = 0^{++}$

$\pi : \ J^{PC} = 0^{-+}$

$\pi(p)\pi(-p)$ S-state (L=0, S=0) system

$P = (-)^{L},\ C = (-)^{S+L} \longrightarrow J^{PC} = 0^{++}$

PV in $(c\bar{c})$ meson decay

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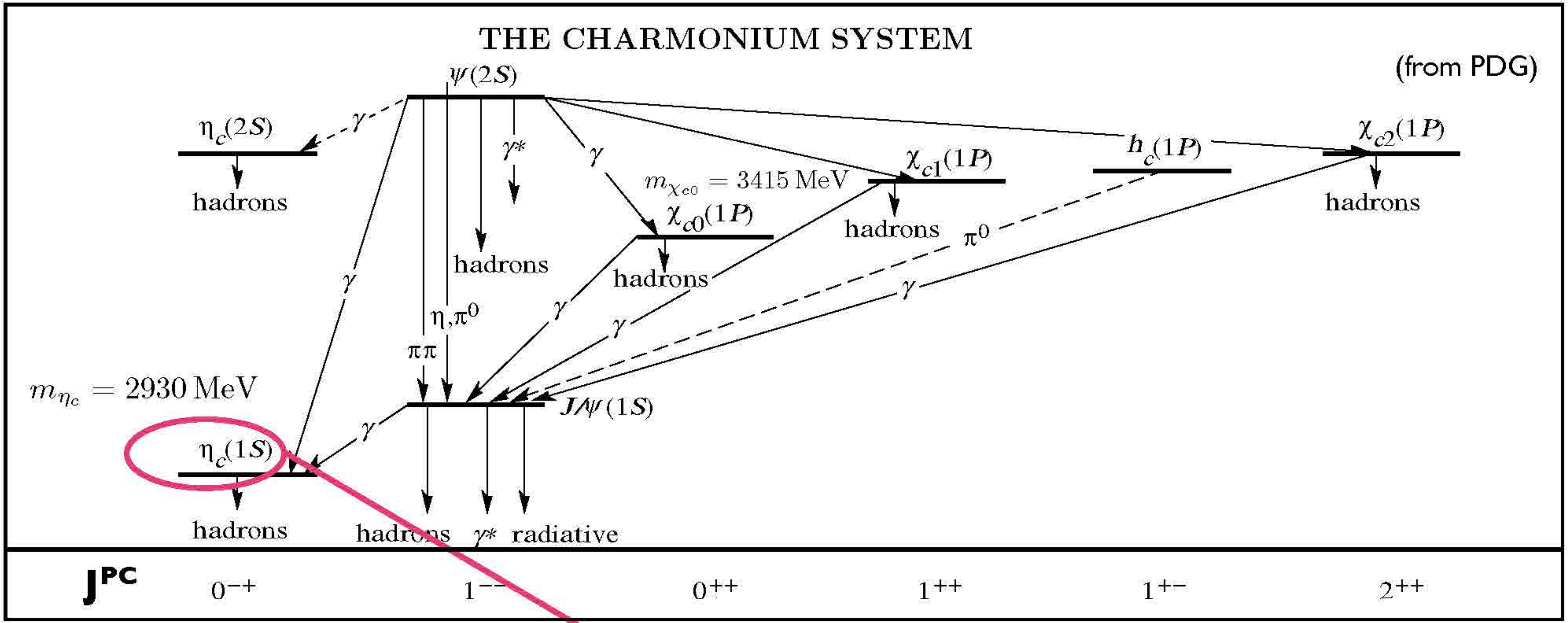


THE CHARMONIUM SYSTEM

(from PDG)

direct PV (decay)

$\pi\pi(0^{++})$

PV in $(c\bar{c})$ meson decay

parity violating

$\eta_c \rightarrow \pi\pi$

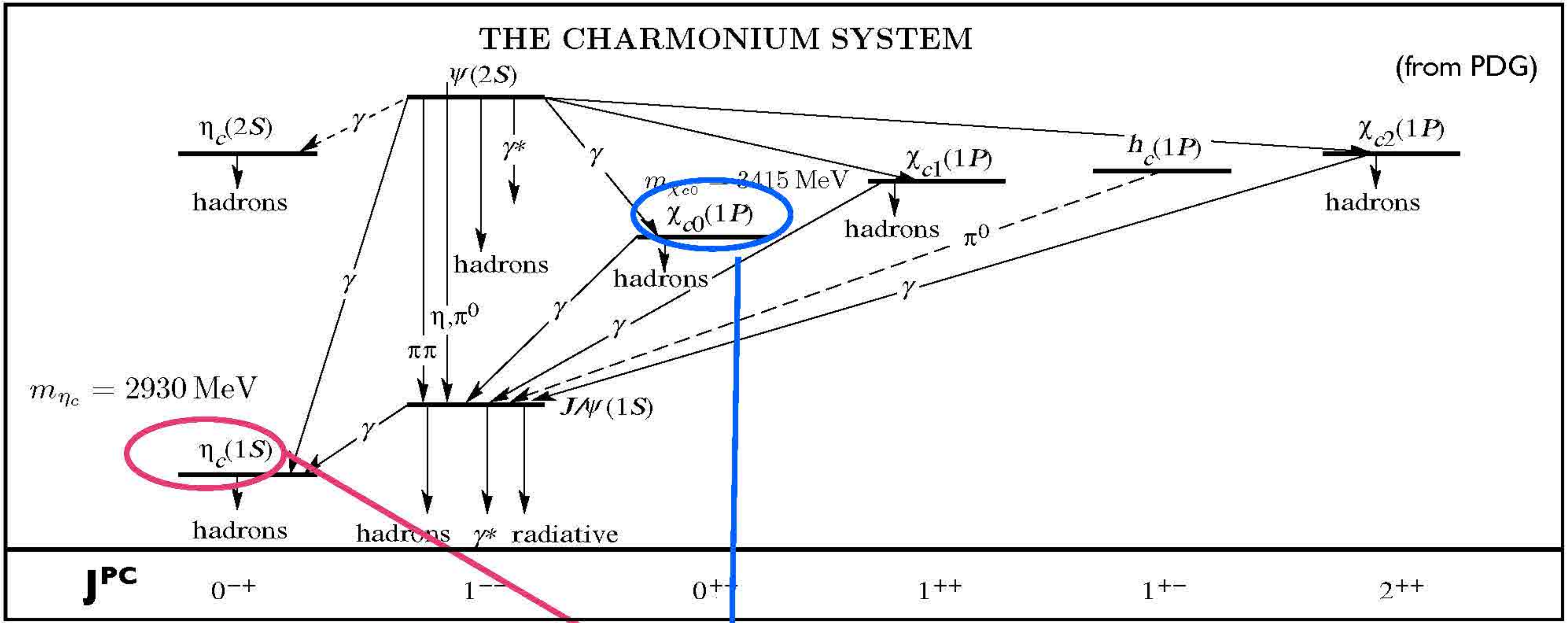
$J^{PC} = 0^{-+}$ $J^{PC} = 0^{++}$

parity conserving

$\chi_{c0} \rightarrow \pi\pi$

$Br(\chi_{c0} \rightarrow \pi\pi) = 8.4 \times 10^{-3}$

$J^{PC} = 0^{++}$ $J^{PC} = 0^{++}$



direct PV (decay)

$\pi\pi(0^{++})$

PV in $(c\bar{c})$ meson decay

parity violating

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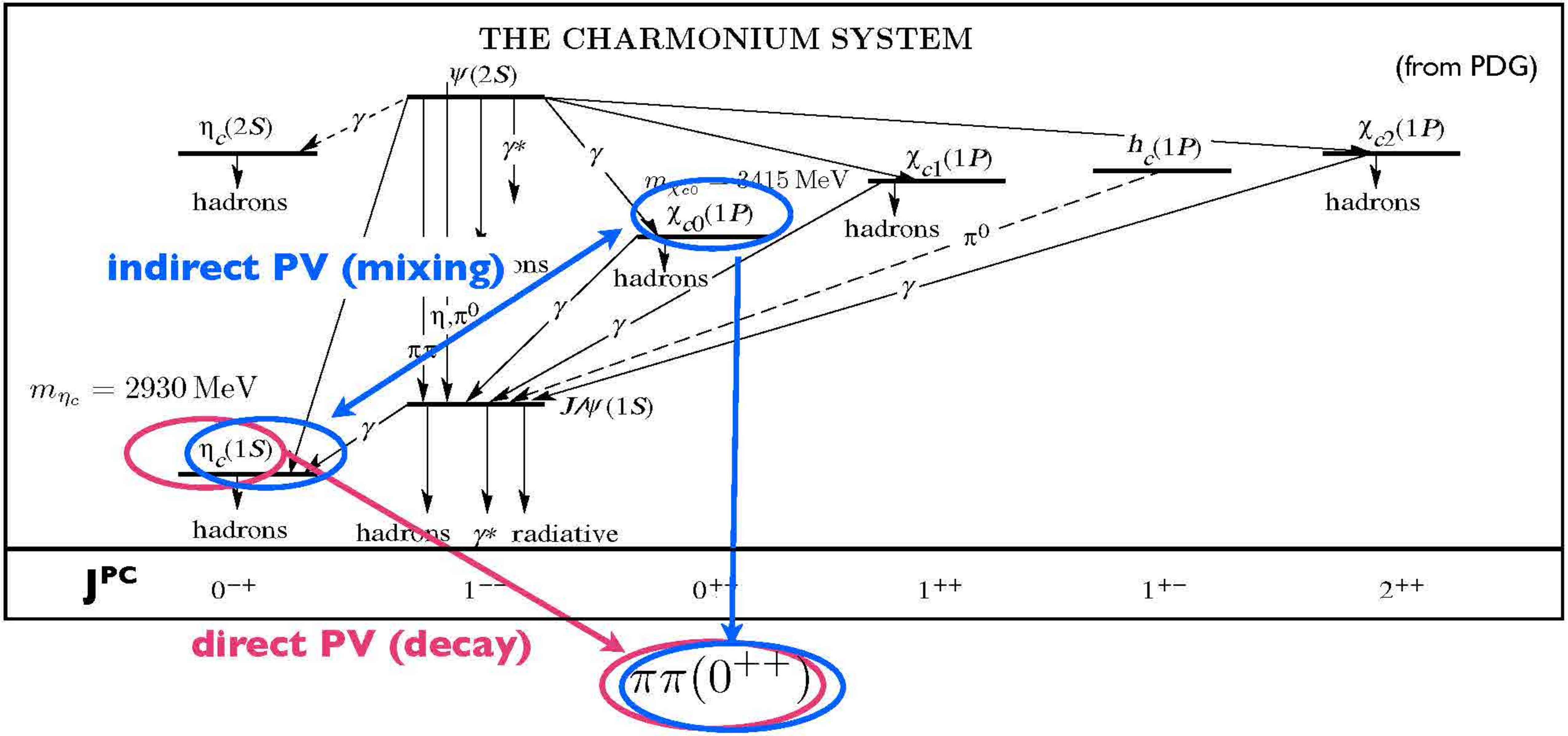


PV in $(c\bar{c})$ meson decay

parity violating

$$\boxed{\eta_c \longrightarrow \pi\pi}$$

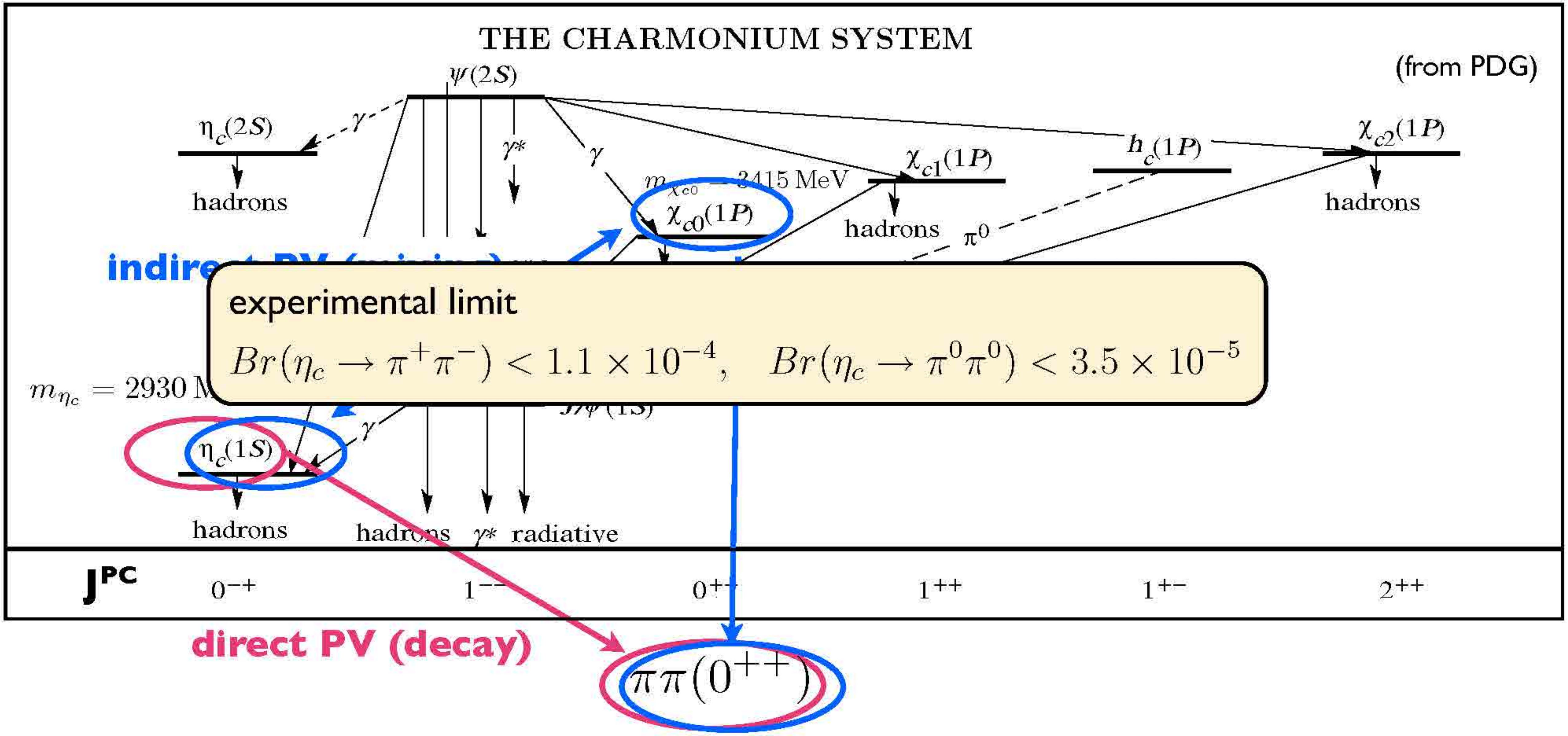
$J^{PC} = 0^{-+}$ $J^{PC} = 0^{++}$

parity conserving

$$\boxed{\chi_{c0} \longrightarrow \pi\pi}$$

$Br(\chi_{c0} \to \pi\pi) = 8.4 \times 10^{-3}$

$J^{PC} = 0^{++}$ $J^{PC} = 0^{++}$



experimental limit

$Br(\eta_c \to \pi^+\pi^-) < 1.1 \times 10^{-4}, \quad Br(\eta_c \to \pi^0\pi^0) < 3.5 \times 10^{-5}$

Method : Non-Relativistic QCD (NRQCD)

(heavy quark)

$(q\bar{q})$ bound state $\xrightarrow{\text{NR-limit}}$ Schrodinger eq.

(QCD) (NRQCD)

Method：Non-Relativistic QCD (NRQCD)

(heavy quark)

$(q\bar{q})$ bound state $\xrightarrow{\text{NR-limit}}$ Schrodinger eq.

(QCD) (NRQCD)

☆ from QCD to NRQCD (3 steps)

Step 1. integrate out gluon from QCD Lagrangian

$$S \sim \int_x [\bar{q}(i\not{\partial} - m)q] + (-i)\int_x \int_y j^\dagger_\mu(x)\mathcal{D}^{\mu\nu}(x-y)j_\nu(y)$$

$$\xrightarrow{\text{NR}} \simeq \delta(x^0 - y^0)\frac{i g_s^2 g^{00}}{4\pi|\vec{x}-\vec{y}|} \quad \text{(tree level)}$$

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Step 2. quark in NR-limit (large m & $v \ll c = 1$)

$$q(x) = \begin{pmatrix} \varphi e^{-imt} + i\frac{\vec{\nabla}\cdot\vec{\sigma}}{2m}\chi e^{imt} \\ \chi e^{imt} - i\frac{\vec{\nabla}\cdot\vec{\sigma}}{2m}\varphi e^{-imt} \end{pmatrix}$$

φ : particle component

χ : anti-particle component

(Foldy-Wouthuysen Transf.)

Parity violation in meson decay

Step 3. introduce a bi-local field

$$\chi^\dagger(x)\sigma^\mu\varphi(y) \Rightarrow \phi^\mu_{\underset{\substack{\uparrow \\ \text{c.m. coordinate}}}{X}}(\underset{\substack{\uparrow \\ \text{relative coordinate}}}{\vec{r}})$$

Hisano, Matsumoto, Nojiri, Saito (2004)

$$\boxed{\begin{aligned} 1 &= \int \prod_{\mu,\nu} \mathcal{D}s^\mu \mathcal{D}\phi^{\nu\dagger} \ \exp i \int_x \int_y \phi^\dagger_\mu(x,y)(s^\mu(x,y) - \varphi^\dagger(x)\sigma^\mu\chi(y)), \\ 1 &= \int \prod_{\mu,\nu} \mathcal{D}s^{\mu\dagger} \mathcal{D}\phi^{\nu} \ \exp i \int_x \int_y \phi_\mu(x,y)(s^{\mu\dagger}(x,y) - \chi^\dagger(x)\sigma^\mu\varphi(y)), \end{aligned}}$$

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$$\boxed{S_{\rm eff} = \int_X \int_{\vec{r}} \phi^{\mu\dagger}_X(\vec{r}) \left[i\partial^0_X - \frac{\Delta^2_X}{4m} + H(r) \right] \phi_X(\vec{r})}$$

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$$H(r) \equiv -\nabla^2_r/m + V(r) \leftarrow$$ (gluon) potential

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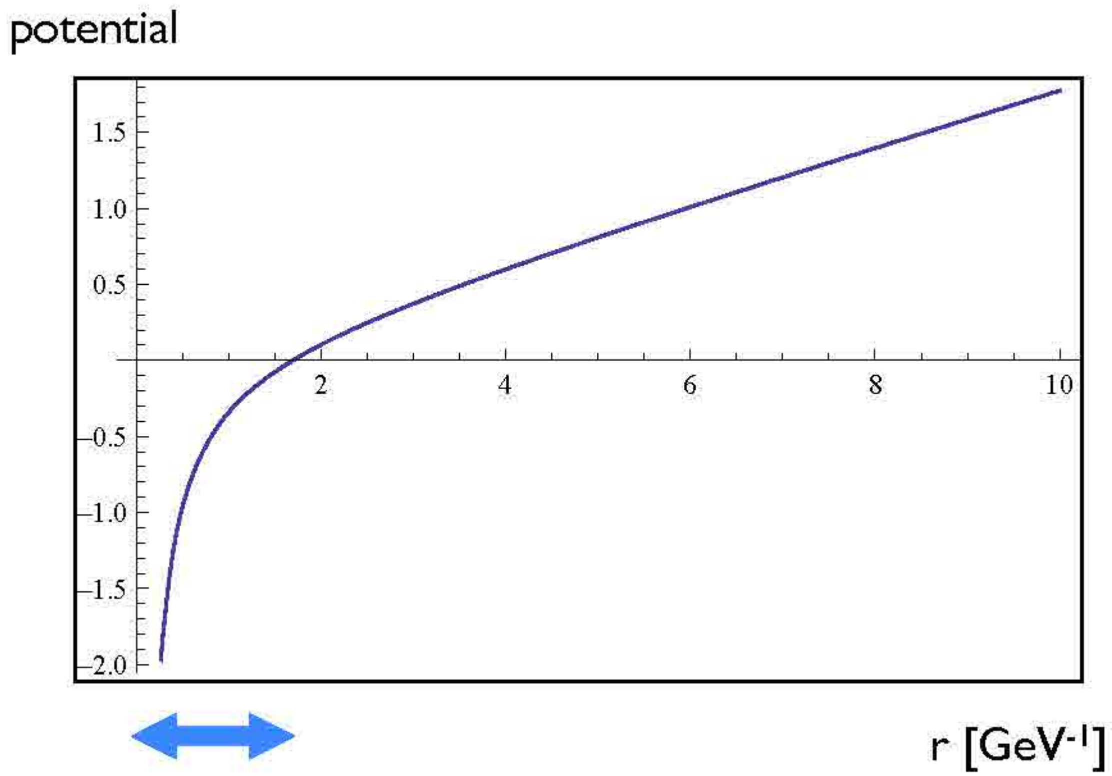

- Coulomb potential is dominant
  (Schrodinger eq. is analytically solvable)

$$V(r) = -\underset{\uparrow}{\frac{\kappa}{r}} + \underset{\uparrow}{\frac{r}{a^2}}$$

: Cornel potential

(κ = 0.52, a = 2.34 GeV^{-1})

Coulomb linear (confinement eff.)

Schrodinger eq. cannot be solved analytically.

↓

numerical analysis is needed

E.Eichten, et. al, Phys.Rev., D17, 3090

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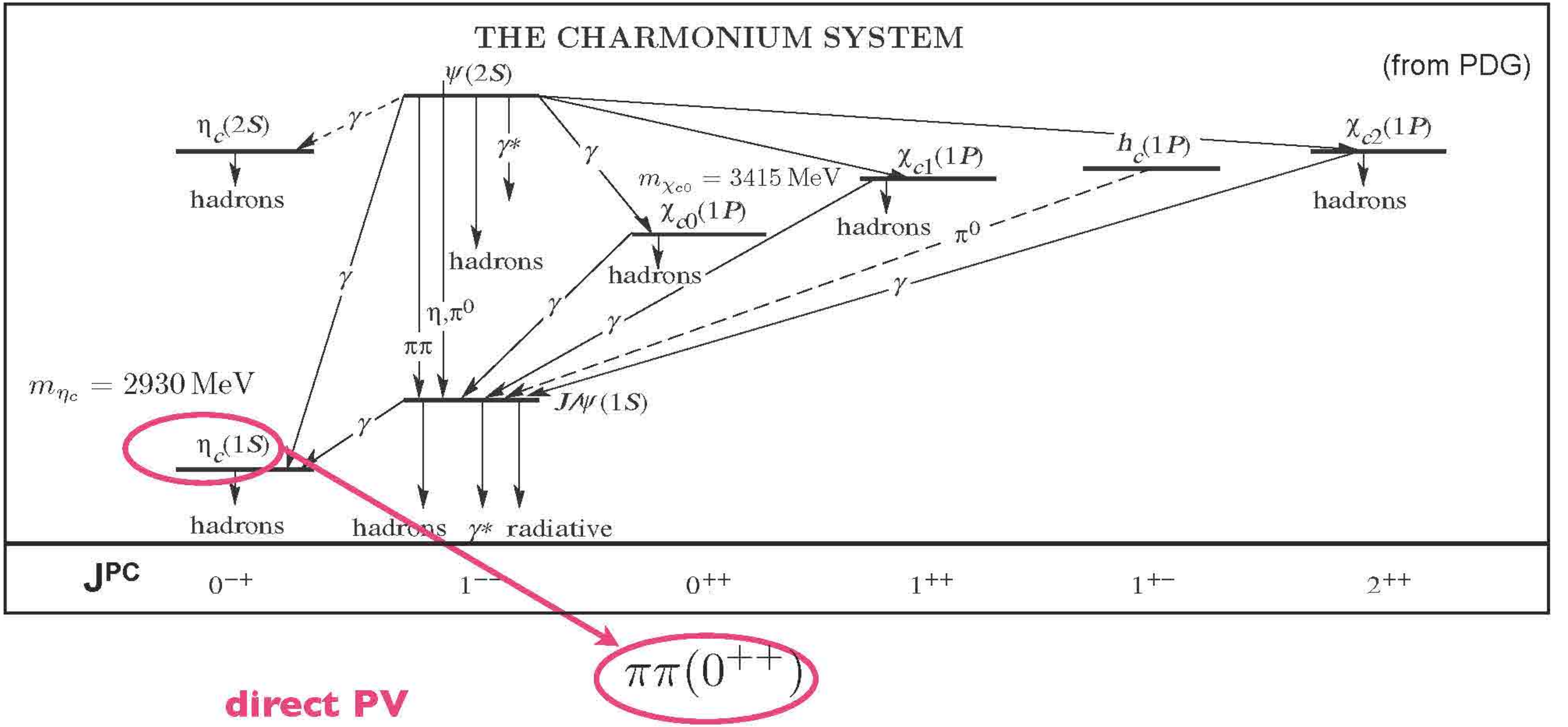
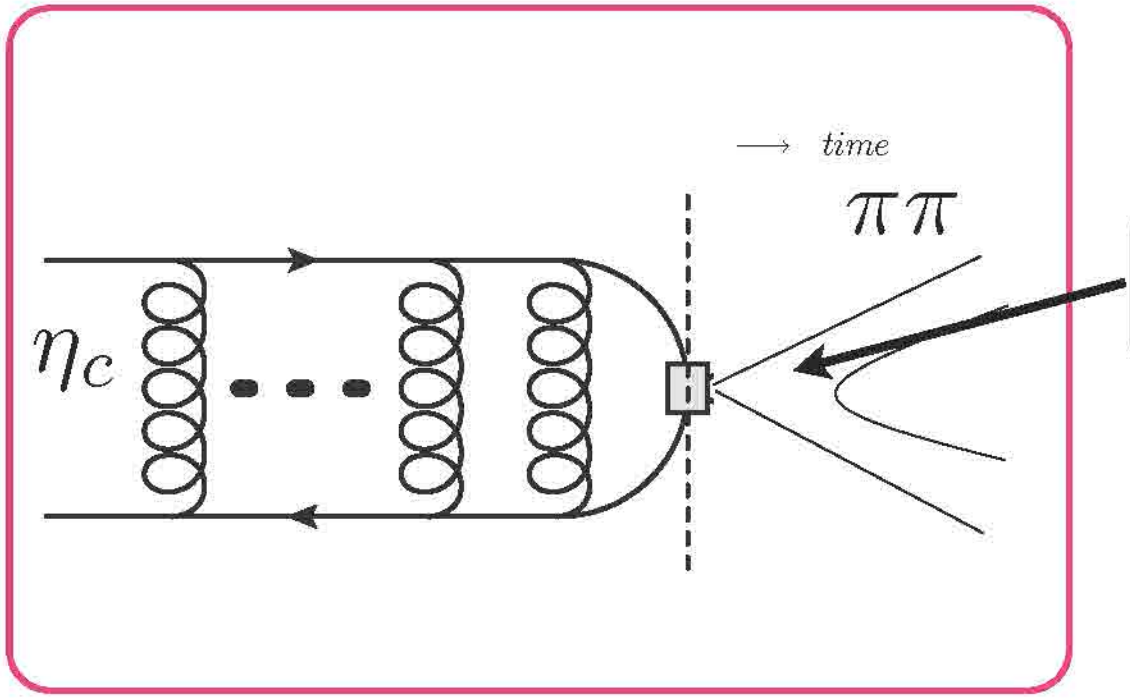
$$a^0_{\eta_c}(X)\psi_{\eta_c}(\vec{r}) \xrightarrow{\text{direct PV}} \pi\pi(0^{++})$$

Parity violation in meson decay



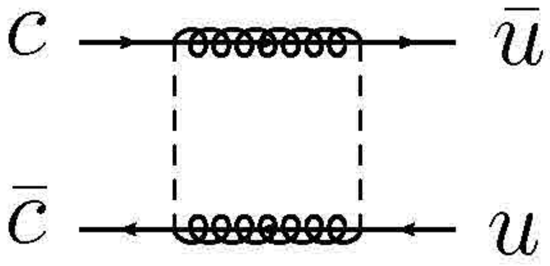
direct PV

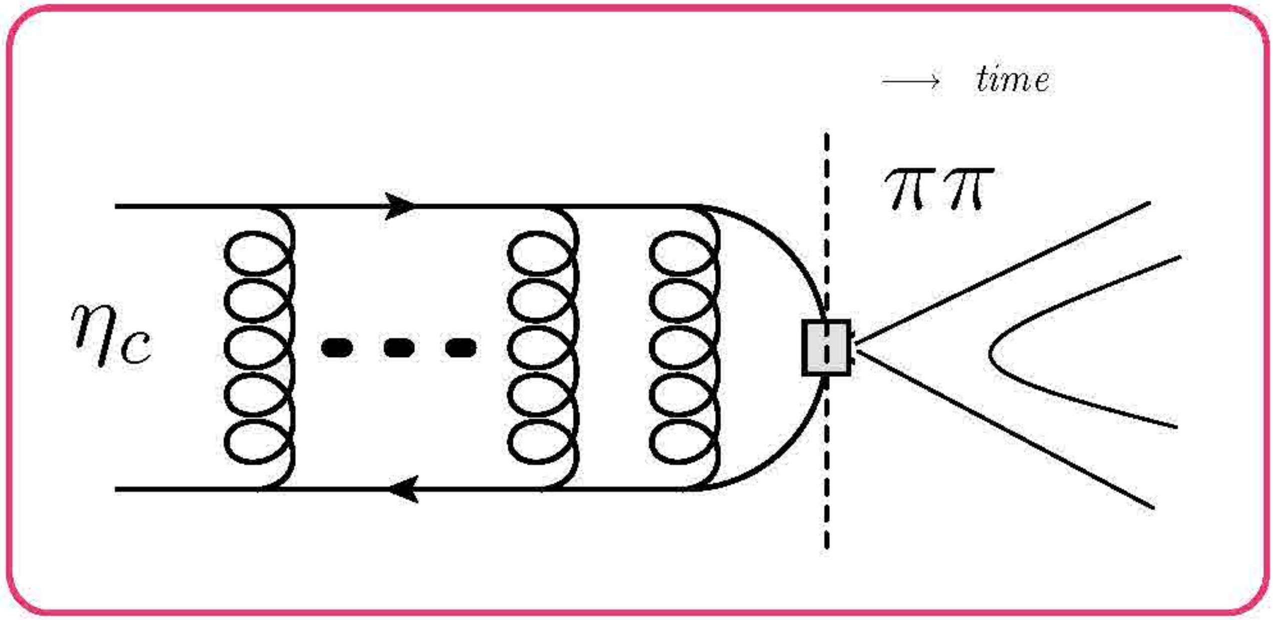


Parity Violating dim.6 OP

direct PV

contribution to the PV





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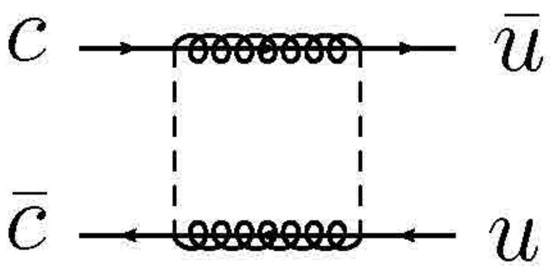
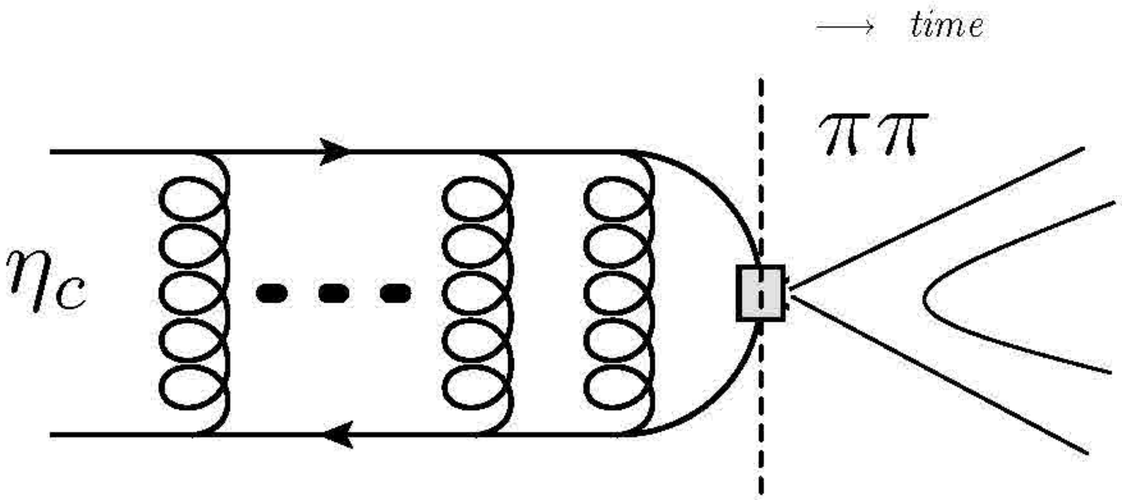


dim.6 OP



$$\langle \pi\pi \mid \mathcal{O}^{\rm p.v}_{4F} \mid \eta_c\rangle \sim -\frac{1}{2}\underline{(A_{uc}+B_{cu})}\delta^4(x-y)\underbrace{\langle\pi\pi \mid u^\dagger(x)u(y)\mid 0\rangle}_{\begin{gathered}\|\\ F^s(m_{\eta_c})\end{gathered}}\underbrace{\langle 0\mid \chi^\dagger(x)\phi(y)\mid\eta_c\rangle}_{\begin{gathered}\|\\ \eta_c\end{gathered}}$$

decay constant

(π (scalar) form factor @ m_{η_c})

$$\langle 0 \mid \phi^0_X(\vec{r}) \mid \eta_c\rangle = \psi_{\eta_c}(\vec{r})e^{-iP\cdot X}$$

(S-wave solution of $H^{\rm QCD}\psi_n(\vec{r}) = E_n\psi_n(\vec{r})$)

$$A_{uc} \equiv \frac{12g_s^4}{192\pi^2}\frac{1}{4}(-C_{LL}^{(\tilde{u},\tilde{c})}+C_{RR}^{(\tilde{u},\tilde{c})}+C_{LR}^{(\tilde{u},\tilde{c})}-C_{RL}^{(\tilde{u},\tilde{c})})$$

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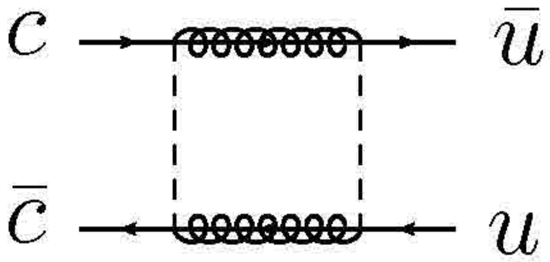
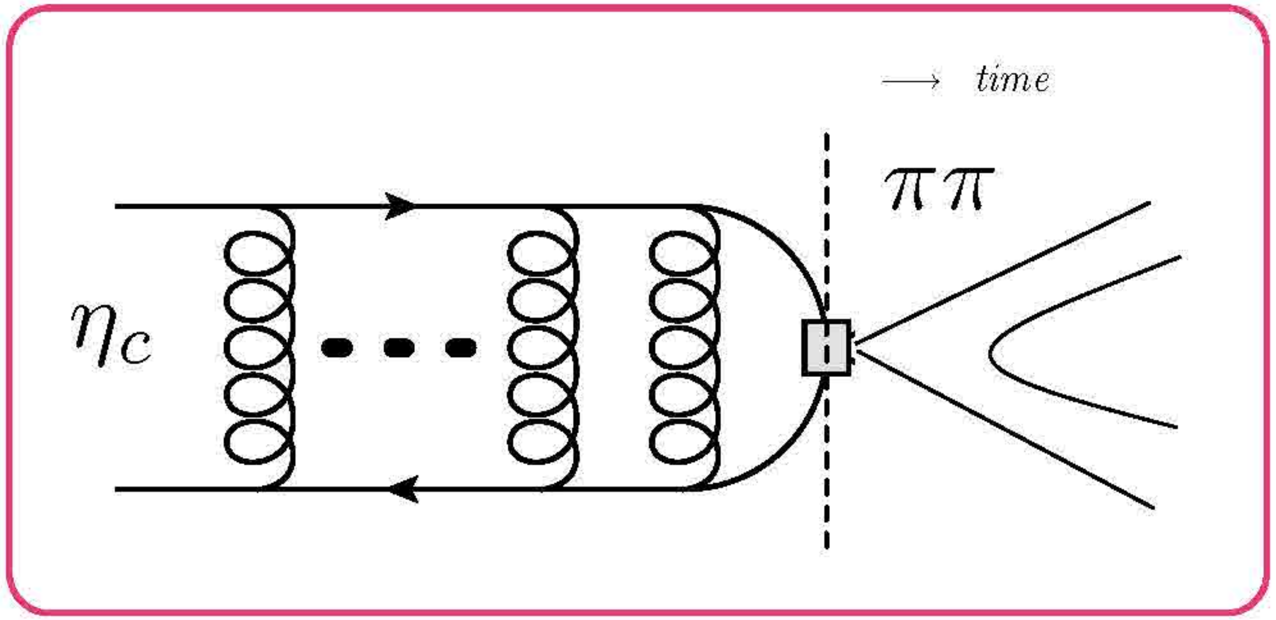
Coeffs. of dim.6 OP : PV from $m_{\tilde{c}_L} \neq m_{\tilde{c}_R}$, ...

direct PV

contribution to the PV





dim.6 OP

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Coeffs. of dim.6 OP : PV from $m_{\tilde{c}_L} \neq m_{\tilde{c}_R}$, ...

$$\Rightarrow \langle \pi\pi \mid \mathcal{O}^{\rm p.v}_{4F} \mid \eta_c\rangle \sim -\frac{1}{2}(A_{uc}+B_c)F^s(m_{\eta_c})\psi_{\eta_c}(0)$$

r=0: contact interaction

$$\Rightarrow \boxed{\Gamma_{\eta_c\to\pi\pi} \sim \mid A_{uc}+A_{dc}+B_{cu}+B_{cd}\mid^2 \frac{|F^s(m_{\eta_c})|^2|\psi_{\eta_c}(0)|^2}{16m^2_{\eta_c}}.}$$

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c.m. coordinate ↑ X relative coordinate ↑ $\vec{r}$

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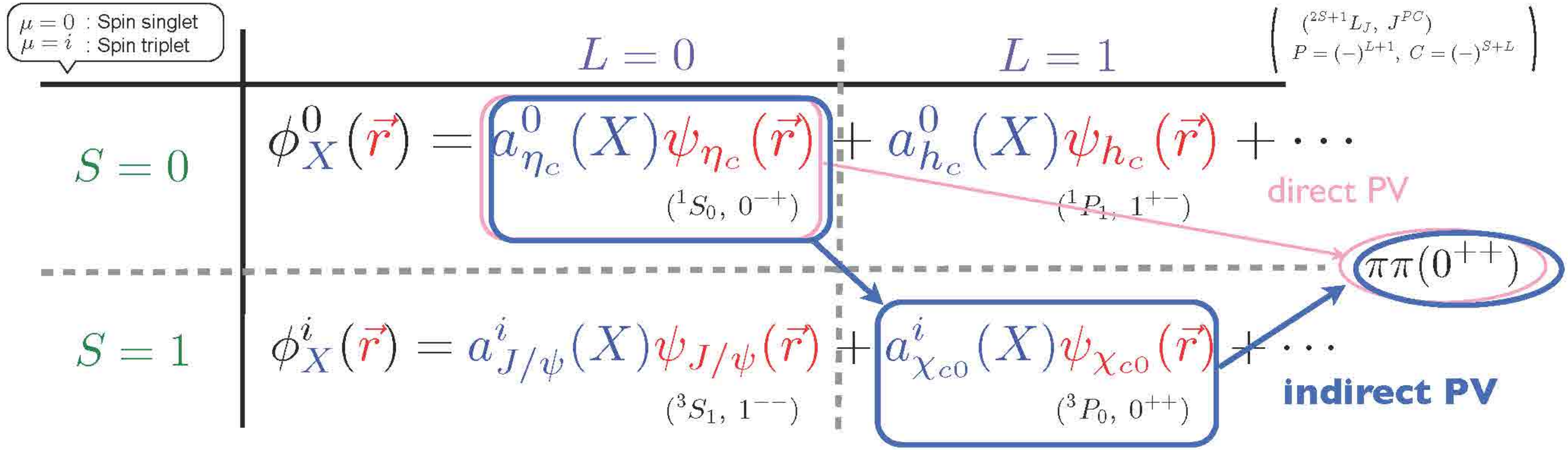

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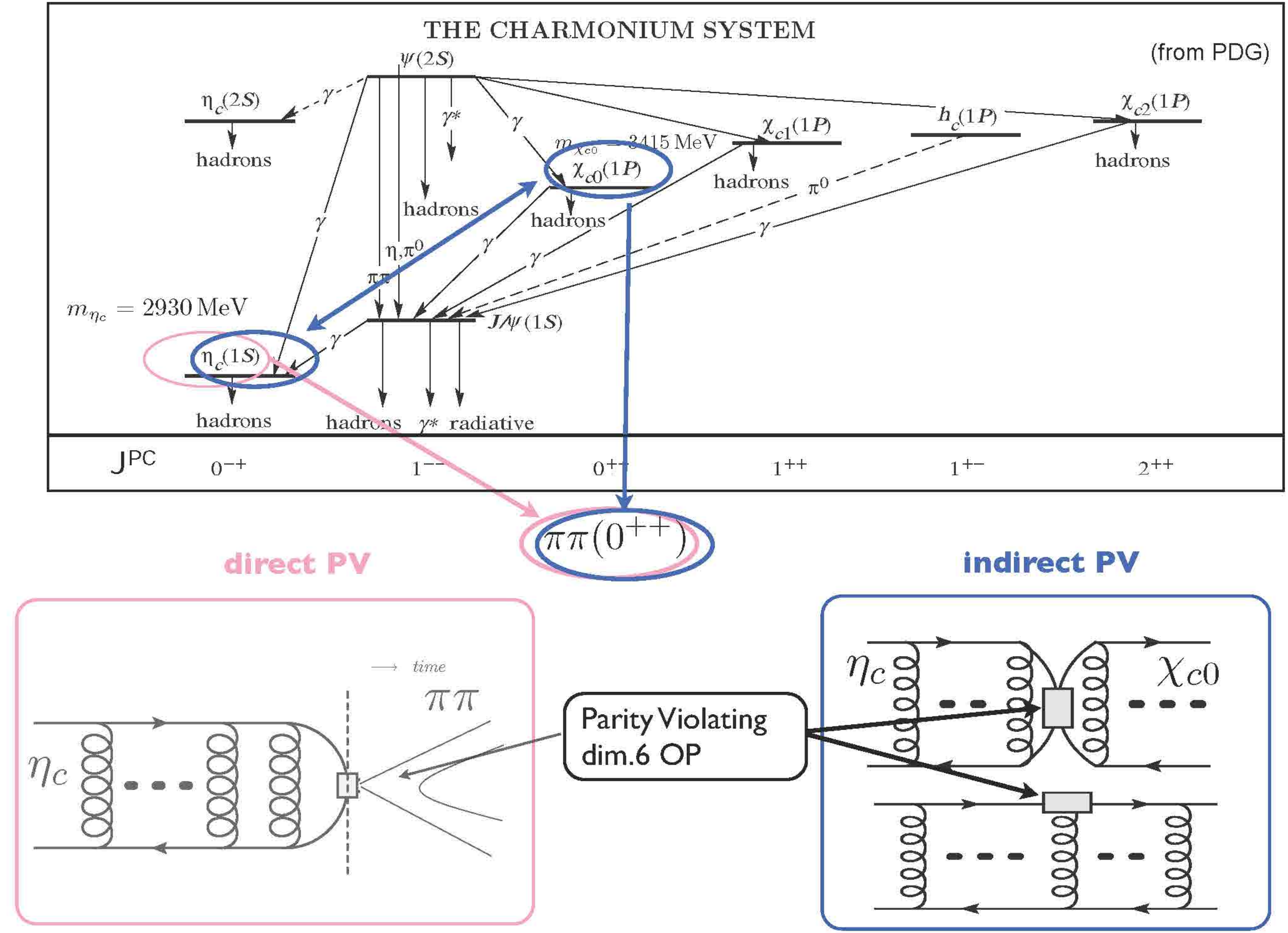
direct PV

$\pi\pi(0^{++})$

indirect PV

Parity violation in meson decay

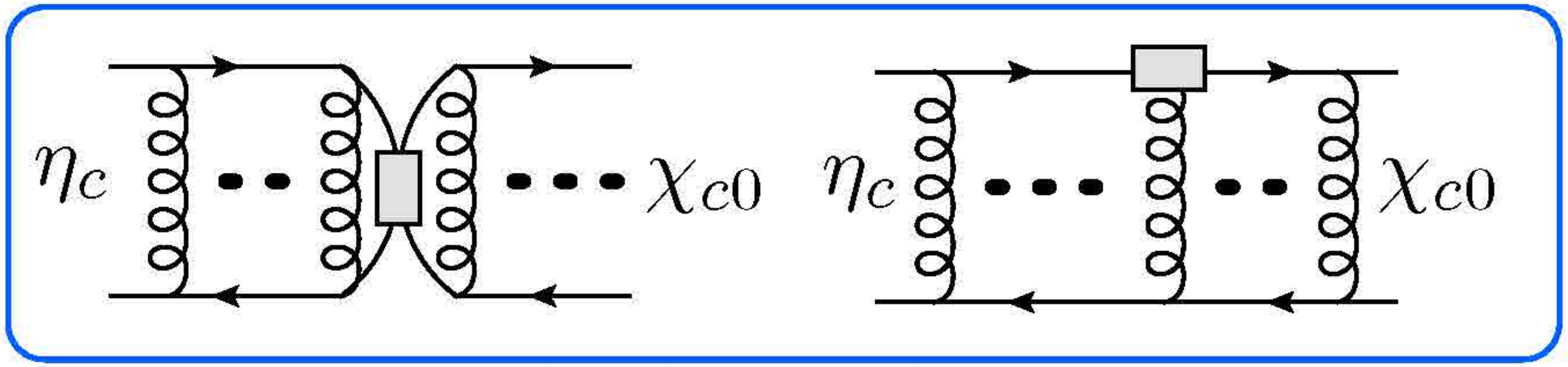


direct PV

indirect PV

Parity Violating
dim.6 OP

indirect PV



SUSY-induced PV potential

☆ introduce PV potential to the NRQCD action

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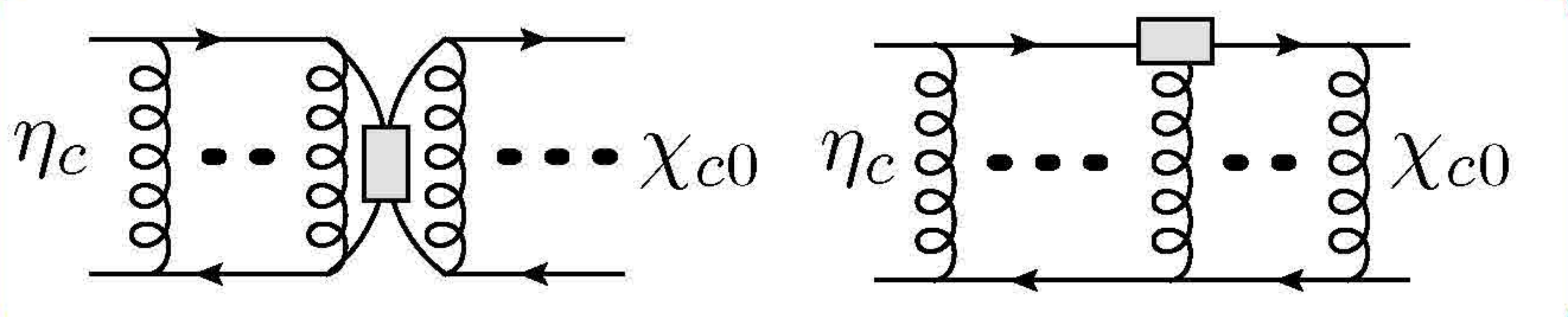

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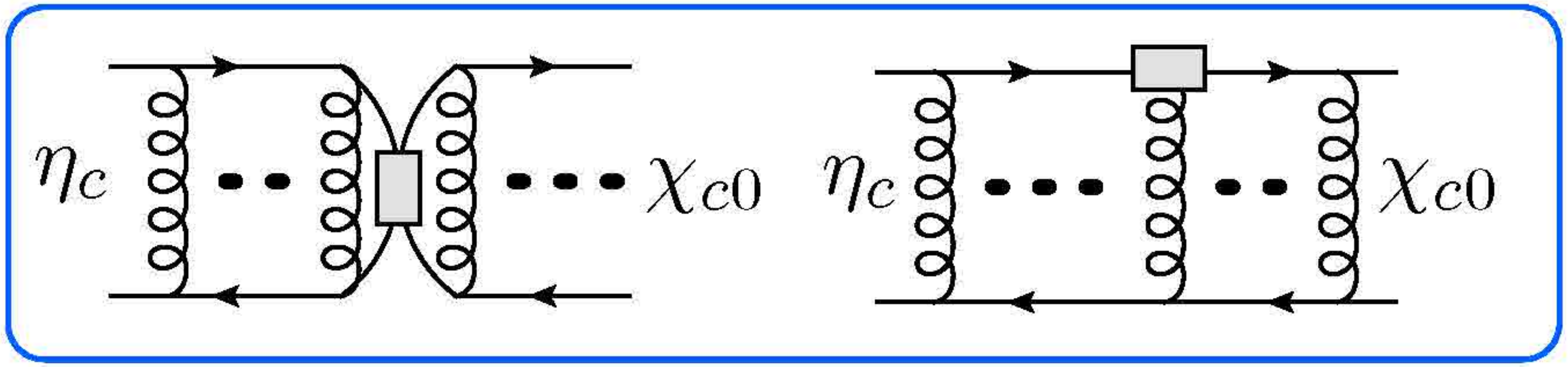
PV potential (e.g. 4 Fermi OP)

$$\mathcal{O}^{4\mathrm{F}} \supset \frac{12g_s^4}{192\pi^2}\frac{1}{2}\underline{\left(C_{RR}^{(\tilde{c},\tilde{c})} - C_{LL}^{(\tilde{c},\tilde{c})}\right)}\delta^4(x-y)[\bar{c}(x)\gamma^\mu c(x)][\bar{c}(y)\gamma_\mu\gamma^5 c(y)] \longrightarrow \delta V_{\mu\nu}^{4\mathrm{F}} \supset \frac{12g_s^4}{192\pi^2}\frac{i}{8m_c N_C}\underline{\left(C_{RR}^{(\tilde{c},\tilde{c})} - C_{LL}^{(\tilde{c},\tilde{c})}\right)}\begin{pmatrix} 0 & 4\mathcal{V}(r)\partial_r^j \\ 4\overleftarrow{\partial}_r^i\mathcal{V}(r) & 4i\epsilon^{ijk}\overleftarrow{\partial}_r^k\mathcal{V}(r) \end{pmatrix}$$

PV form $m_{\tilde{c}_L} \neq m_{\tilde{c}_R}$

NR & bilocal fields

indirect PV



SUSY-induced PV potential

☆ introduce PV potential to the NRQCD action

$$S = \int_X \int_{\vec{r}} \phi_X^{\mu\dagger}(\vec{r}) \left[i\partial_X^0 - \frac{\Delta_X^2}{4m} + H(r) + \underline{\delta V(r)} \right]_{\mu\nu} \phi_X^{\nu}(\vec{r})$$

PV potential (e.g. 4 Fermi OP)

$$\mathcal{O}^{4\mathrm{F}} \supset \frac{12 g_s^4}{192\pi^2} \frac{1}{2} \underline{\left(C_{RR}^{(\tilde{c},\tilde{c})} - C_{LL}^{(\tilde{c},\tilde{c})} \right)} \delta^4(x-y) [\bar{c}(x)\gamma^\mu c(x)][\bar{c}(y)\gamma_\mu \gamma^5 c(y)] \longrightarrow \delta V_{\mu\nu}^{4\mathrm{F}} \supset \frac{12 g_s^4}{192\pi^2} \frac{i}{8 m_c N_C} \underline{\left(C_{RR}^{(\tilde{c},\tilde{c})} - C_{LL}^{(\tilde{c},\tilde{c})} \right)} \begin{pmatrix} 0 & 4\mathcal{V}(r)\partial_r^j \\ 4\overleftarrow{\partial}_r^i \mathcal{V}(r) & 4i\epsilon^{ijk}\overleftarrow{\partial}_r^k \mathcal{V}(r) \end{pmatrix}$$

PV form $m_{\tilde{c}_L} \neq m_{\tilde{c}_R}$

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☆ expand by new eigenfunctions

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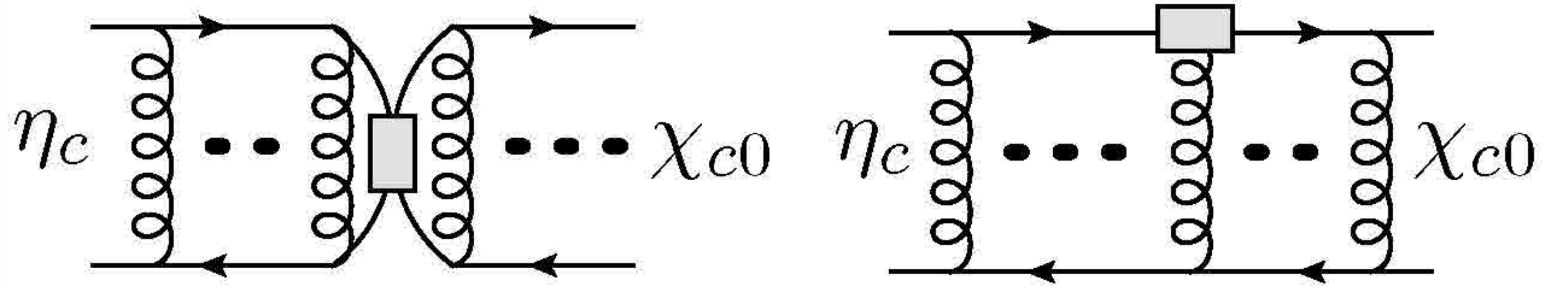

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$$H^{\mathrm{QCD}} \psi_n(\vec{r}) = E_n \psi_n(\vec{r})$$

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$$\Psi_n \to \psi_n \ (\delta V \to 0)$$

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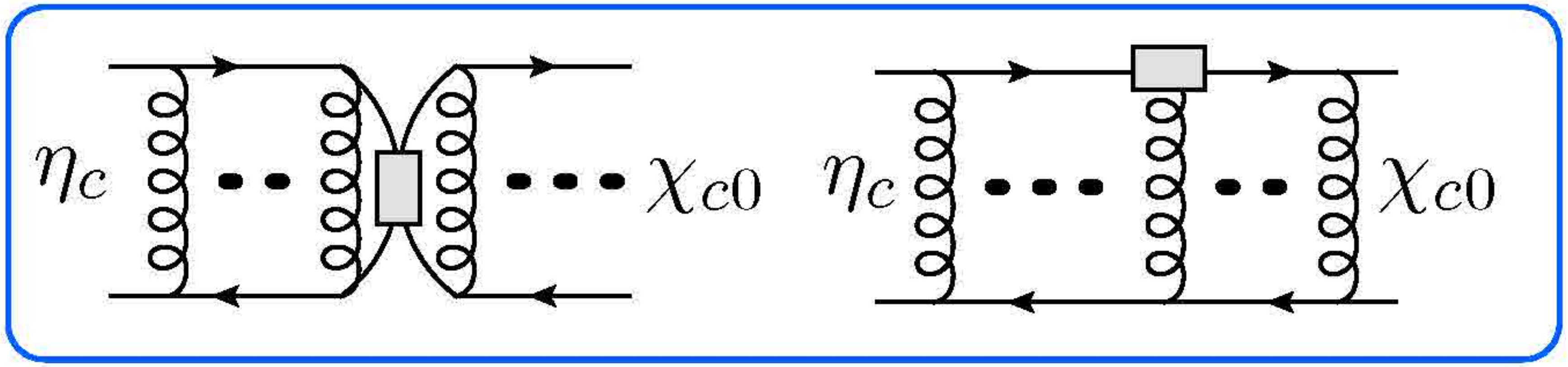
indirect PV



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☆$(\eta_c,\ \chi_{c0})$mixing

$$\boxed{|\eta_c\rangle_{\mathrm{obs.}} = |\eta_c\rangle + \frac{V_{\eta_c,\chi_{c0}}}{E_{\eta_c} - E_{\chi_{c0}}}|\chi_{c0}\rangle}$$

$J^{PC} = 0^{-+}$ $J^{PC} = 0^{++}$

$$\boxed{\Gamma(\eta_c \to \pi\pi) \sim \left|\frac{V_{\eta_c,\chi_{c0}}}{E_{\eta_c} - E_{\chi_{c0}}}\right|^2 \Gamma(\chi_{c0} \to \pi\pi).}$$

Numerical Results

Direct PV

parameters

GeV	$m_{\tilde{g}}$	$m_{\tilde{u}_R}$	$m_{\tilde{u}_L}$	$m_{\tilde{d}_R}$	$m_{\tilde{d}_L}$	$m_{\tilde{c}_R}$
(a)	1400	2000	2500	2100	2600	2200
(b)	850	860	2500	870	2600	880

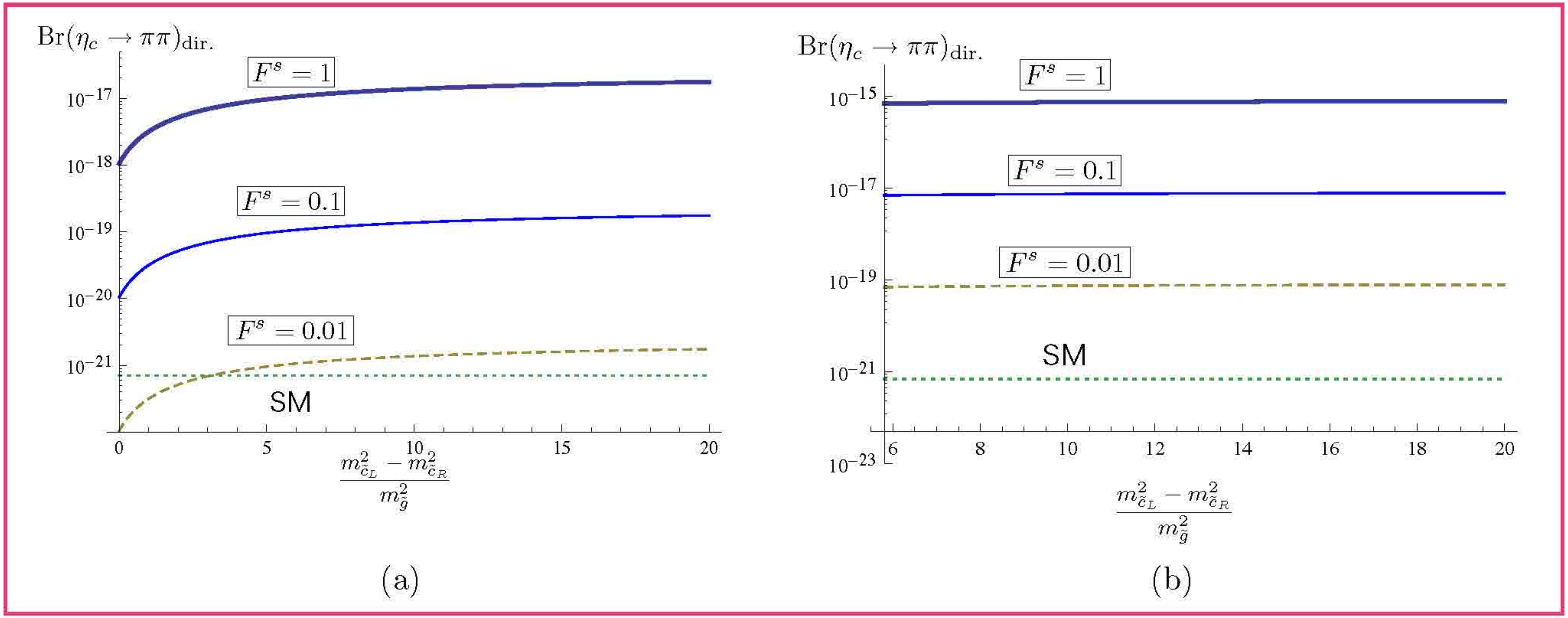
degenerate

experimental bounds

$$Br(\eta_c \to \pi^+\pi^-) < 1.1 \times 10^{-4}, \quad Br(\eta_c \to \pi^0\pi^0) < 3.5 \times 10^{-5}.$$

SMEW background

$$Br(\eta_c \to \pi\pi)_{\rm SM} \simeq 7.0 \times 10^{-22}$$



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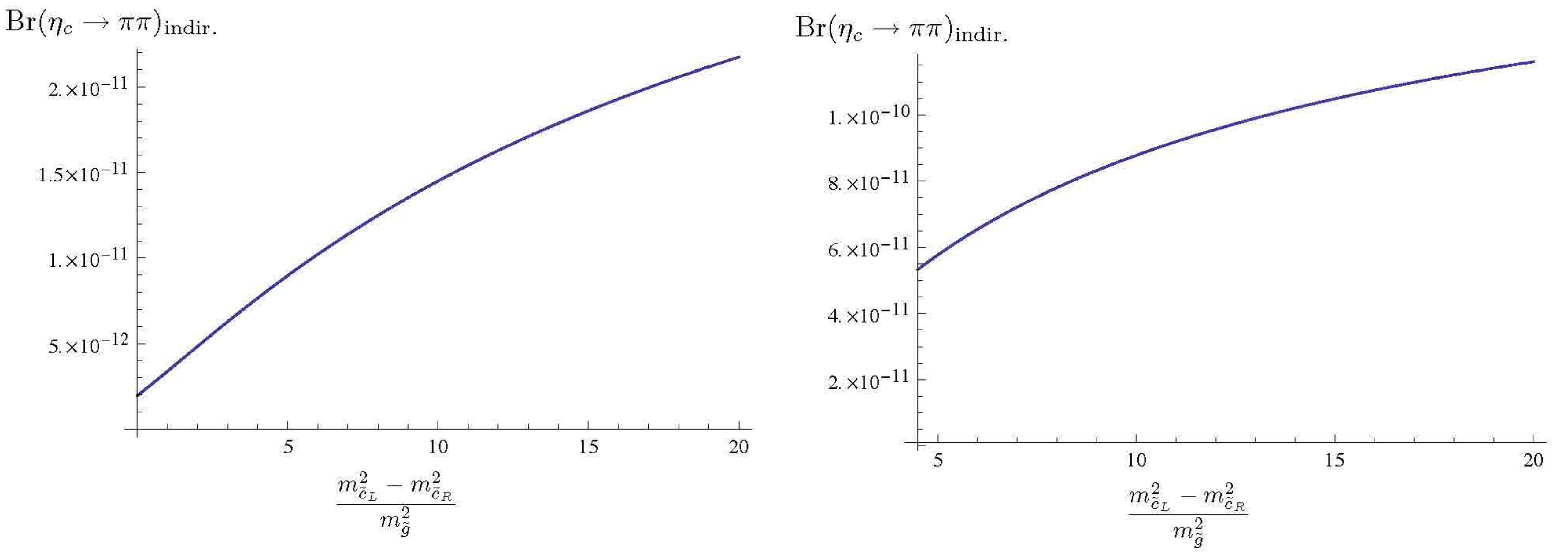

(a) (b)

$\mathbf{m}_{\tilde{\mathbf{u}}_{\mathbf{L},\mathbf{R}}}$, $\mathbf{m}_{\tilde{\mathbf{d}}_{\mathbf{L},\mathbf{R}}}$ non-degeneracy bound from nucleon interaction

$(\pi,\ \omega,\ \rho) - N$ couplings (there are experimental bounds)

- PV in SMEW $\geq$ PV in SUSY

$\Longrightarrow$ bounds for $m_{\tilde{u}_L} \neq m_{\tilde{u}_R}$ & $m_{\tilde{d}_L} \neq m_{\tilde{d}_R}$

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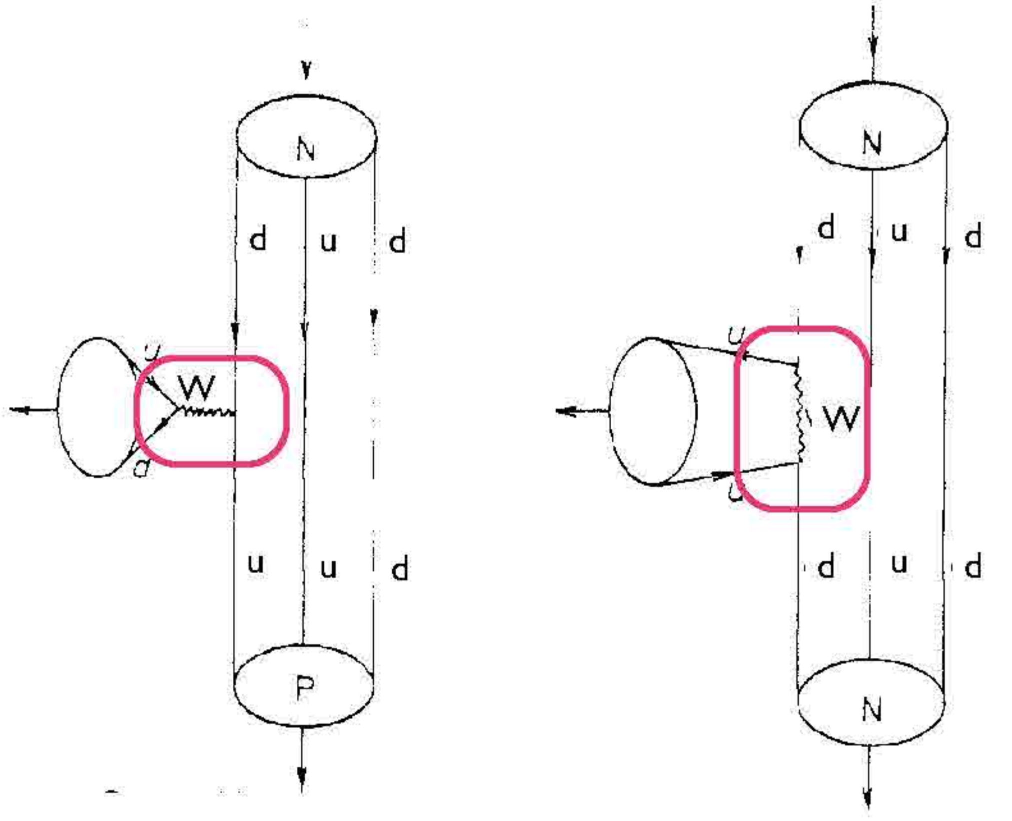
PV in the SM



4-Fermi $\longrightarrow$

ω-N, ρ-N couplings

$$\mathcal{L}^{\mathrm{SEW}}(\Delta I = 0) = \frac{G_{\mathrm{W}}\cos^2\theta_{\mathrm{C}}}{2\sqrt{2}}\bar{q}\gamma^{\mu}q\bar{q}\gamma_{\mu 5}q - \tfrac{1}{3}\sqrt{2}\,G_{\mathrm{W}}\left(2\sin^2\theta_{\mathrm{W}} - \sin^2\theta_{\mathrm{C}}\right)\bar{q}\gamma^{\mu}t^{i}q\bar{q}\gamma_{\mu 5}t^{i}q\,,$$

π-N coupling

$$\mathcal{L}^{\mathrm{SEW}}(\Delta I = 1) = -\tfrac{1}{3}\sqrt{2}\,G_{\mathrm{W}}\sin^2\theta_{\mathrm{W}}\bar{q}\gamma^{\mu}q\bar{q}\gamma_{\mu 5}t^{3}q$$

M.J. Duncan (1983)
W. Bertozzi, et. al. (2000)

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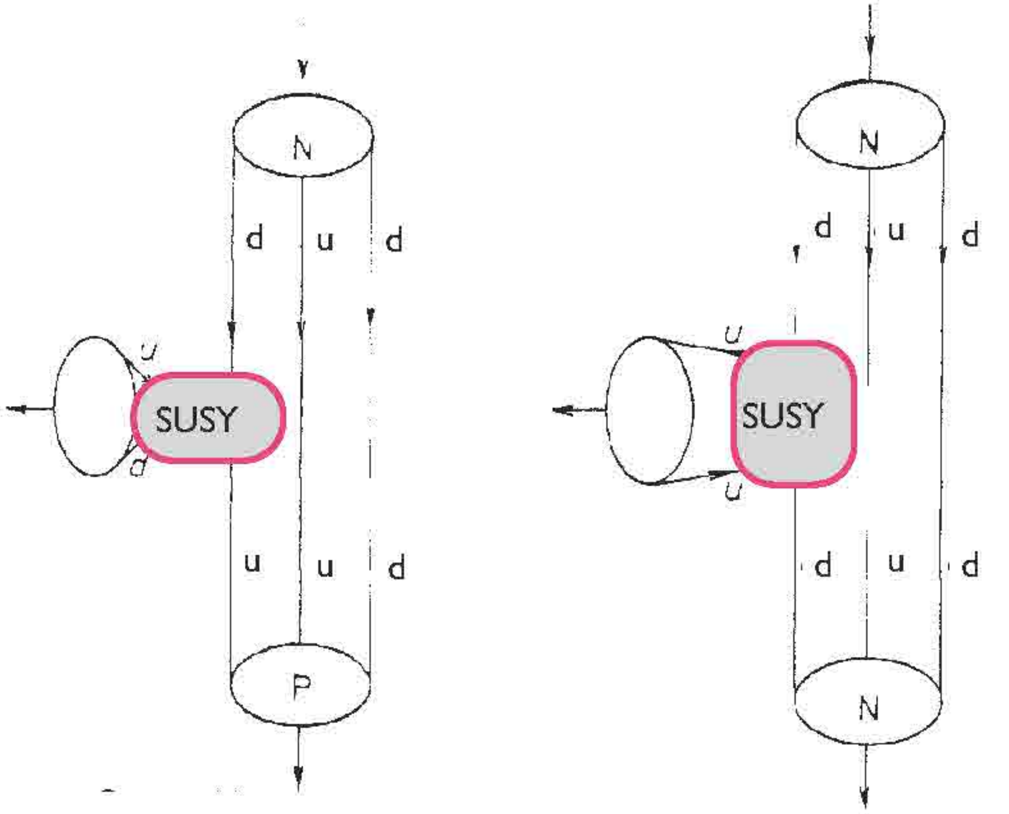
PV in SUSY



coeffs. of 4-fermi operators

$$C^p(\pi) = \frac{4}{3}\frac{\alpha_s^2}{12}\rho\left[c(m_{\tilde{u}_R}) - c(m_{\tilde{u}_L}) - c(m_{\tilde{d}_R}) + c(m_{\tilde{d}_L})\right]$$

$$C^p(\omega) = \frac{1}{3}\frac{\alpha_s^2}{24}\rho\left[c(m_{\tilde{u}_R}) - c(m_{\tilde{u}_L}) + c(m_{\tilde{d}_R}) - c(m_{\tilde{d}_L})\right]$$

$$C^p(\rho) = \frac{2}{3}\frac{\alpha_s^2}{24}\rho\left[c(m_{\tilde{u}_R}) - c(m_{\tilde{u}_L}) + c(m_{\tilde{d}_R}) - c(m_{\tilde{d}_L})\right]$$

$$C^b_-(\pi) = -\frac{\alpha_s^2}{27}\rho\left[f_1(m_{\tilde{u}_L}, m_{\tilde{d}_R}) - f_1(m_{\tilde{u}_R}, m_{\tilde{d}_L}) - f_2(m_{\tilde{u}_L}, m_{\tilde{d}_R}) + f_2(m_{\tilde{u}_R}, m_{\tilde{d}_L})\right]$$

$$\begin{aligned} C^b_+(\omega) = -\frac{3\alpha_s^2}{48}\left(\frac{2}{9}+\frac{8}{27}\right)\rho\,\big[&2f_1(m_{\tilde{u}_L}, m_{\tilde{d}_L}) - 2f_1(m_{\tilde{u}_R}, m_{\tilde{d}_R}) - f_2(m_{\tilde{u}_L}, m_{\tilde{d}_L}) + 2f_2(m_{\tilde{u}_R}, m_{\tilde{d}_R}) \\ &- f_1(m_{\tilde{d}_L}, m_{\tilde{d}_L}) - f_1(m_{\tilde{d}_R}, m_{\tilde{d}_R}) - f_1(m_{\tilde{u}_L}, m_{\tilde{u}_L}) - f_1(m_{\tilde{u}_R}, m_{\tilde{u}_R}) \\ &+ f_2(m_{\tilde{d}_L}, m_{\tilde{d}_L}) + f_2(m_{\tilde{d}_R}, m_{\tilde{d}_R}) + f_2(m_{\tilde{u}_L}, m_{\tilde{u}_L}) + f_2(m_{\tilde{u}_R}, m_{\tilde{u}_R})\big] \end{aligned}$$

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$$(\ c(m_{\tilde{q}}),\ f_1(m_{\tilde{q}}),\ f_2(m_{\tilde{q}}) \sim M_{\mathrm{SUSY}}^{-2}\ )$$

$\mathbf{m_{\tilde{u}_{L,R}}}$, $\mathbf{m_{\tilde{d}_{L,R}}}$ non-degeneracy bound from nucleon interaction

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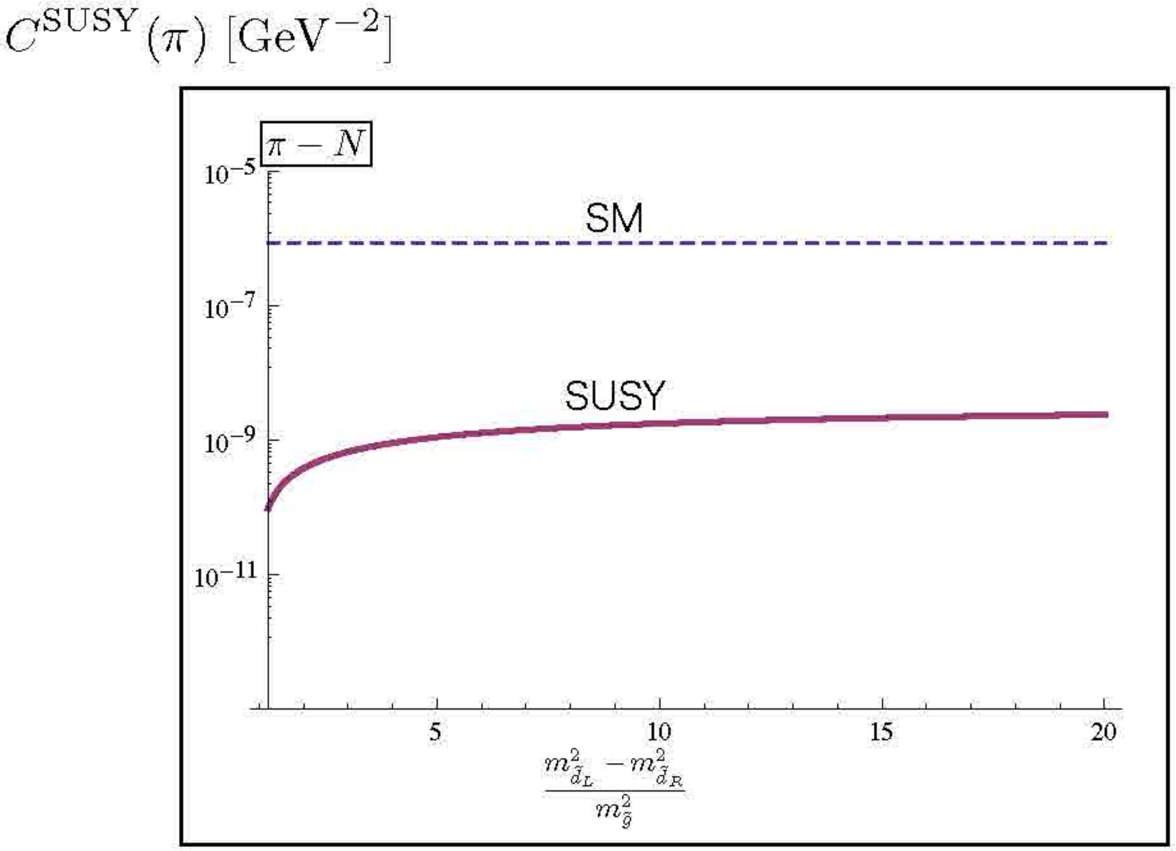
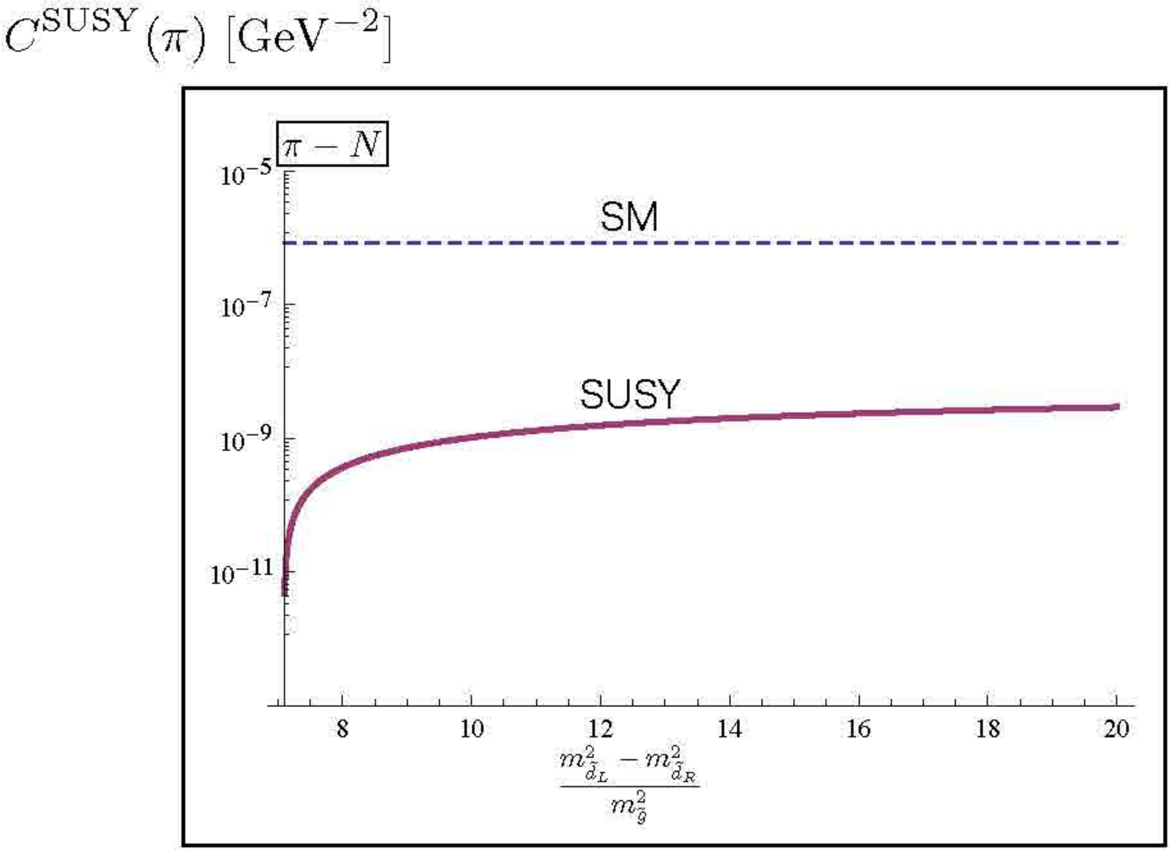
$\pi - N$ coupling



heavy



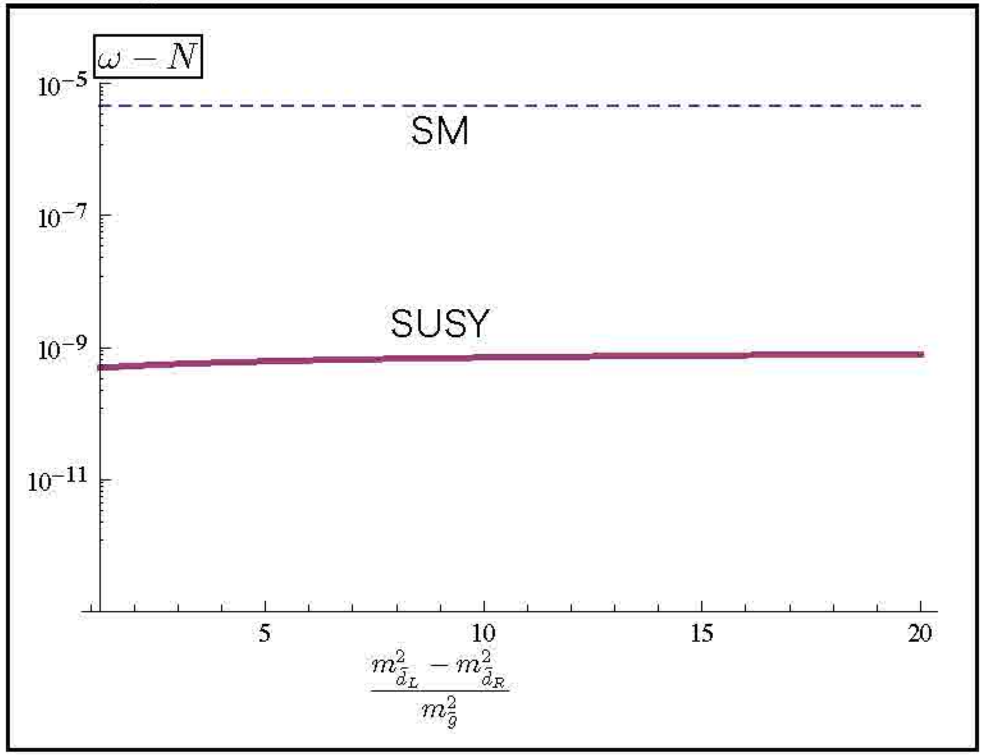
‘degenerate’

$\boxed{\omega - N \text{ coupling}}$

heavy

'degenerate'

$C^{\mathrm{SUSY}}(\omega)\ [\mathrm{GeV}^{-2}]$



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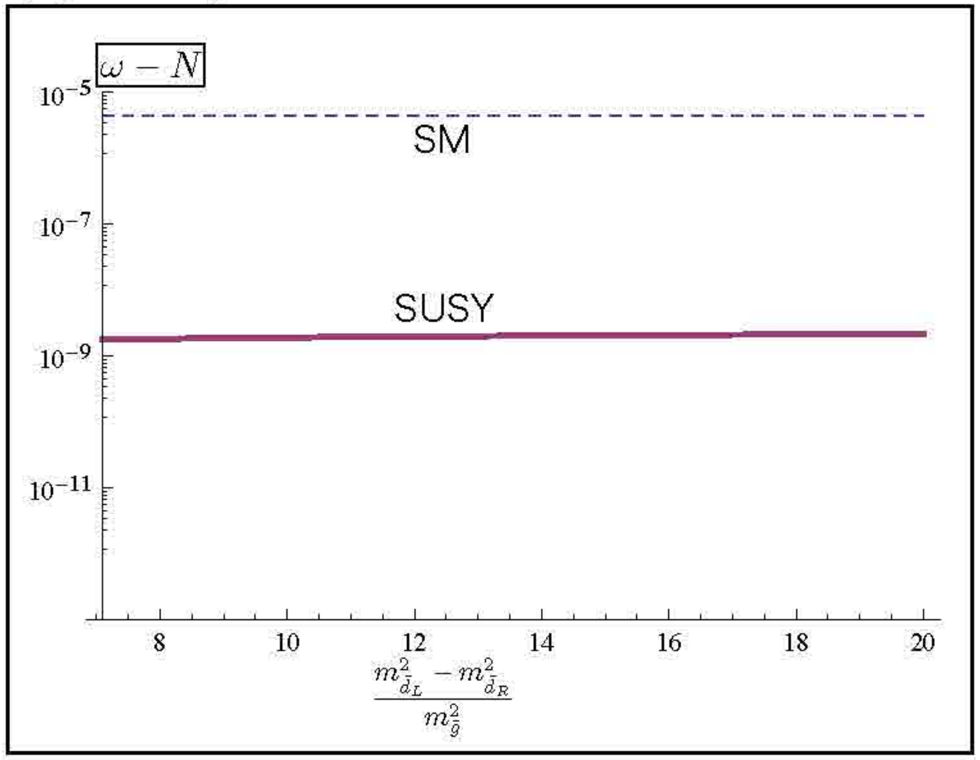

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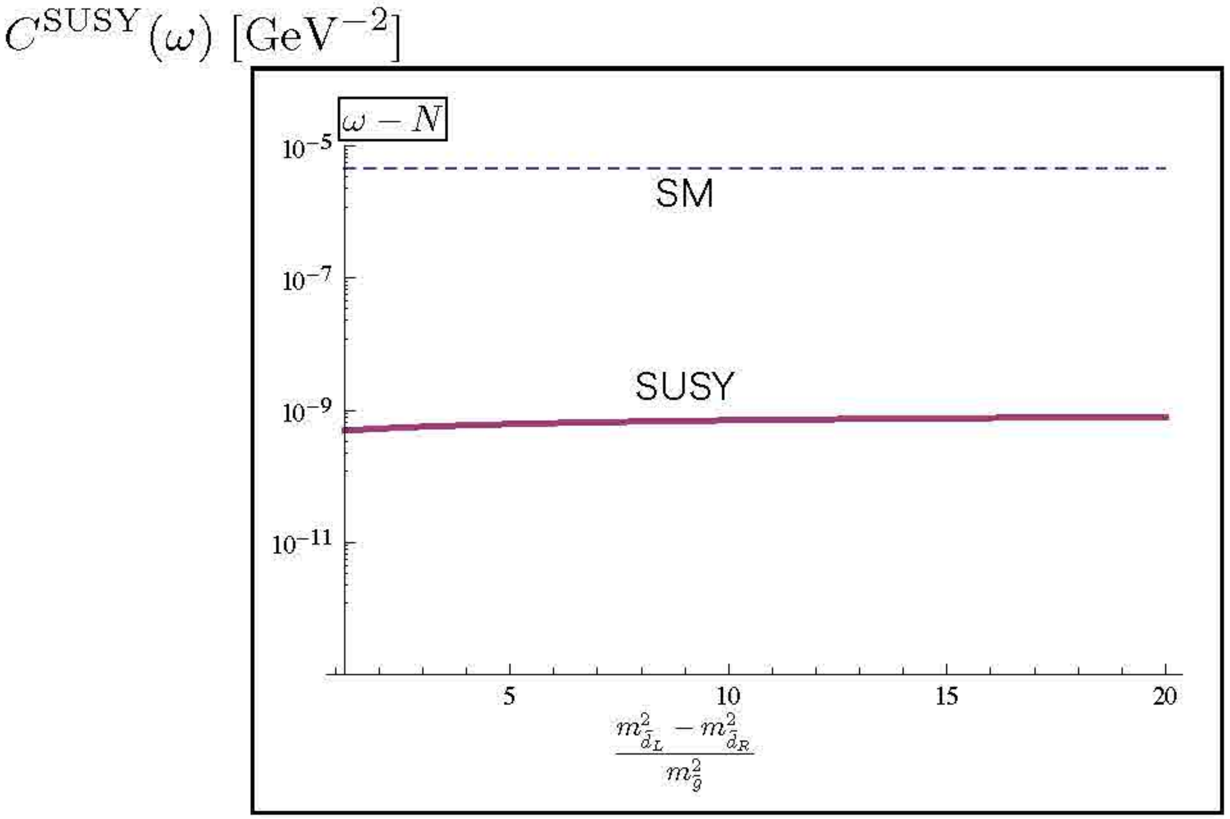
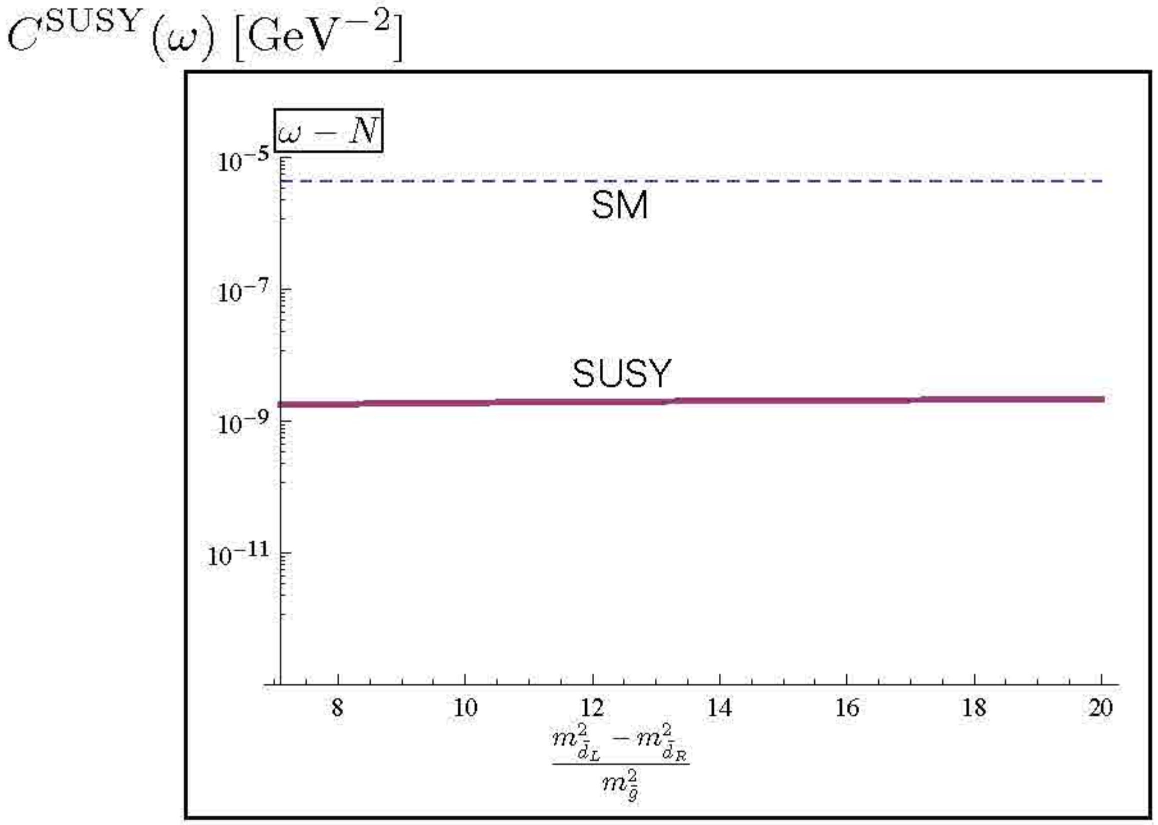
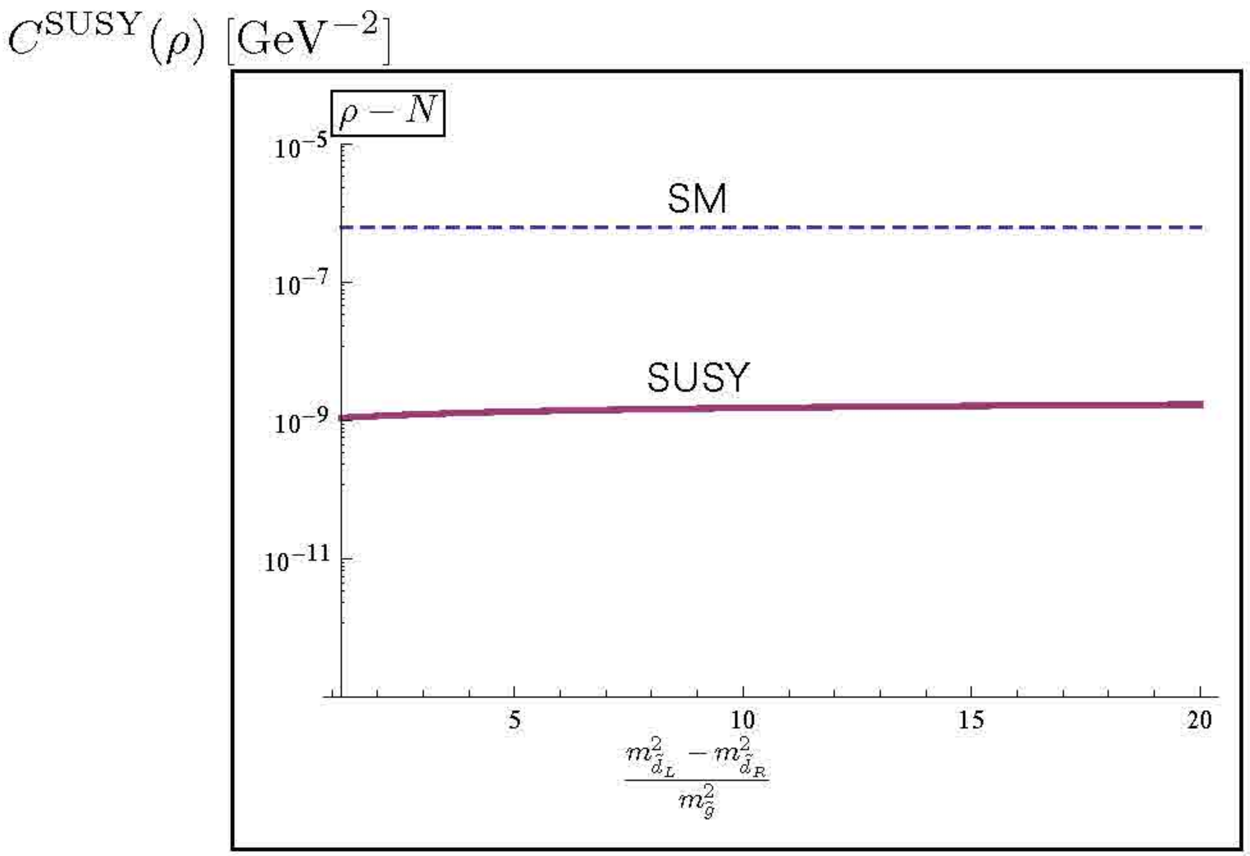


'degenerate'



$\rho - N$ coupling

heavy



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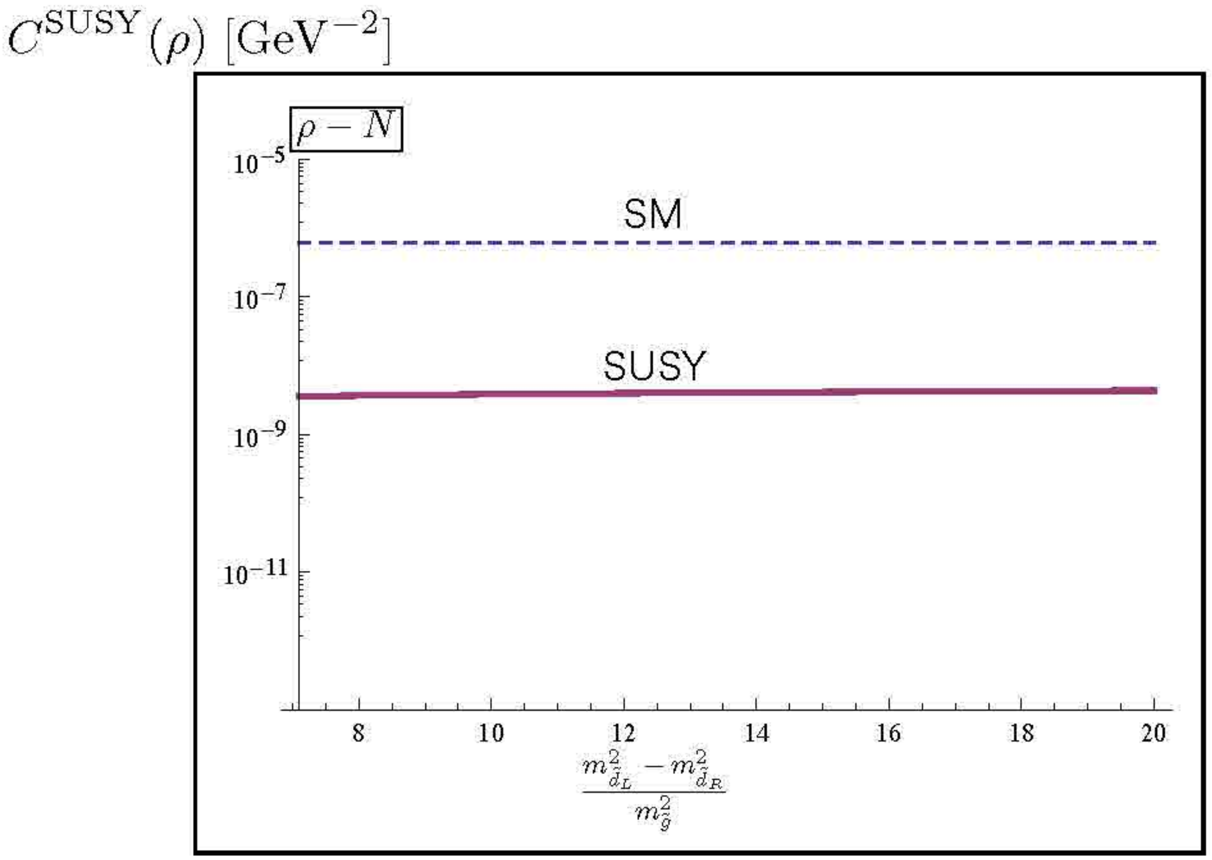

4, Summary

Summary

Parity is violated even in QCD process via SUSY

$$\mathcal{L}_{\rm int} \supset \sqrt{2} g_s \tilde{g}^a \bar{q}_{L(R)} T^a \tilde{q}_{L(R)} + h.c. \quad \& \quad \boxed{\mathbf{m_{\tilde{q}_L} \neq m_{\tilde{q}_R}}}$$

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☆ ① indirect search of new physics

⟹ We analyzed helicity dependence of top pair production @ LHC

(⟹ sizable asymmetry can be appeared)

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☆ ② non-degeneracy bound for $m_{\tilde{q}_L}$ and $m_{\tilde{q}_R}$

⇒ PV has not seen in QCD process

⇒ $m_{\tilde{q}_L} \neq m_{\tilde{q}_R}$ non-degeneracy bound should exist

⇒ We evaluated PV in meson decay (but small)

◎ Our method is applicable for other new physics inducing PV