Light Colored Scalar as Messenger of Up-Quark Flavor Dynamics in Grand Unified Theories

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Outline

1. Forward-backward asymmetry in $t\bar{t}$ production and colored scalars
2. Charm processes — D–$\bar{D}$ mixing, dijet and single top production
3. Light Δ_6 from GUT point of view

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- Cross section measurements at Tevatron ($\sqrt{s} = 1.96$ TeV)

$$\sigma_{t\bar{t}}^{\text{exp}} = 7.0 \pm 0.6 \text{ pb}$$

CDF exp,2009

$$\sigma_{t\bar{t}}^{SM} = (6.30 \pm 0.19^{+0.31}_{-0.23}) \text{ pb}$$

Ahrens et al, 2010

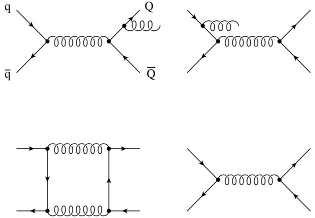
In good agreement.

- Forward-backward asymmetry

$$A_{FB}(s) = \frac{\left(\int_0^1 - \int_{-1}^0\right) d\cos\theta \, \frac{d\sigma_{t\bar{t}}(s,\cos\theta)}{d\cos\theta}}{\sigma_{t\bar{t}}(s)}$$

Is measured to be above the SM prediction by $\sim 2\sigma$. Recently confirmed at high $m_{t\bar{t}}$ by CDF.

Partonic level: $\mathcal{O}(\alpha_s^3)$ interference between tree-level $q\bar{q} \to t\bar{t}$ and two-gluon exchange



CDF

$$A_{FB}|_{1.9fb^{-1}} = 0.17 \pm 0.08$$

$$A_{FB}|_{3.2fb^{-1}} = 0.193 \pm 0.065 \pm 0.024$$

$$A_{FB}^{SM} = 0.051 \pm 0.006$$

Antuñano et al, 2008

- warped models Djouadi et al, Bauer et al
- Extra gauge bosons
  - W' Cheung et al
  - Z' Murayama et al
  - asymmetric left-right W' Barger et al
- s-channel axigluons Kühn et al, Frampton et al, Chivukula et al
- R-parity violating MSSM Cao et al
- t-channel color triplets, sextets Shu et al, Arhrib et al
- colored unparticles Chen et al

$\vdots$

Many (realistic) models

Doršner, Fajfer, Kamenik, NK, PRD81

Non-SUSY SU(5) should contain 5 and 45 scalar representations to provide viable fermion masses
(want to avoid additional fermionic reps or nonrenormalizable operators) Georgi,Glashow

$$5 = (\Psi_D, \Psi_T) = (1, 2, 1/2) \oplus (3, 1, -1/3)$$
$$24 = (\Sigma_8, \Sigma_3, \Sigma_{(3,2)}, \Sigma_{(\bar{3},\bar{2})}, \Sigma_{24})$$
$$45 = (\Delta_1, \ldots, \Delta_6, \Delta_7)$$

- 24 breaks SU(5)
- Matter fermions reside in 10_i and $\bar{5}_i$ representations, $i = 1, 2, 3$

$$10_i = (1, 1, 1) \oplus (\bar{3}, 1, -2/3) \oplus (3, 2, 1/6), \qquad \bar{5}_i = (1, 2, -1/2) \oplus (\bar{3}, 1, 1/3)$$

- Another fermionic $24_F = (\rho_8, \rho_3, \ldots)$ in order to have type I+III seesaw ν masses
- 45 contains scalars, which contribute to $t\bar{t}$ production at tree-level, and is present in many GUT models

Yukawa couplings of 45 to matter

$$(Y_1)_{ij} (10^{\alpha\beta})_i (\bar{5}_\delta)_j 45^{*\delta}_{\alpha\beta}, \qquad \epsilon_{\alpha\beta\gamma\delta\epsilon} (Y_2)_{ij} (10^{\alpha\beta})_i (10^{\zeta\gamma})_j 45^{\delta\epsilon}_{\zeta}$$

It has been known scalar diquark can enhance A_{FB} (Murayama), which is present in 45 as $\Delta_6 = (\bar{3}, 1, 4/3)$. Also suitable is color octet $\Delta_1 = (8, 2, 1/2)$.

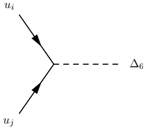
Yukawa couplings of Δ_6 to up-quarks are antisymmetric in flavor — antisymmetric color couplings enforce antisymmetry in flavor

$$\mathcal{L}_{\Delta_6} = \sqrt{2}[(Y_2)_{ij} - (Y_2)_{ji}]\, \epsilon_{abc}\, \bar{u}_{ia} P_L u^C_{jb}\, \Delta_{6c} + (Y_1)^{ij}\, \bar{e}_i P_L d^C_{ja}\, \Delta^*_{6a} + \mathrm{H.c.}$$

(Note that $\epsilon_{abc} \bar{u}_a u^C_b = 0$)

- Diquark coupling Y_2, leptoquark coupling Y_1
- In mass-basis, Yukawa couplings retain antisymmetry

$$g_6^{ij} \equiv 2\sqrt{2}\left[U_R^\dagger (Y_2 - Y_2^T) U_R^*\right]^{ij}, \qquad g_6^{ij} = -g_6^{ji}$$



- Baryon and lepton number violating, however antisymmetry in turn forbids dimension-6 operators mediating proton decay

$$\sim \frac{1}{m^2_{\Delta_6}} g_6^{ij} Y_1^{kl} \bar{u}_i \bar{u}_j \bar{e}_k \bar{d}_l$$

- Contributions to $t\bar{t}$ in the u-channel

- Charged and neutral states — Δ_1^{0A} and Δ_1^{+A}
- Richer set of interactions — charged and neutral currents

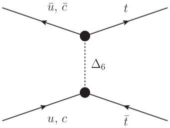
$$-\sqrt{2}(Y_1)_{ij}\, d_{ai}^T T_{ab}^A C d_{bj}^C\, \Delta_1^{0A*} \qquad -2(Y_2)_{ij}^{AS}\, u_{ai}^T T_{ab}^A C u_{bj}^C\, \Delta_1^{0A}$$
$$-\sqrt{2}(Y_1)_{ij}\, u_{ai}^T T_{ab}^A C d_{bj}^C\, \Delta_1^{+A*} \qquad 2(Y_2)_{ij}^{AS}\, d_{ai}^T T_{ab}^A C u_{bj}^C\, \Delta_1^{+A}$$

- Light Δ_1 and Δ_6 not dangerous by themselves for proton decay
- In GUT, they can affect proton lifetime indirectly by lowering the unification scale M_{GUT}

Color triplet Δ_6 and octet Δ_1 in $t\bar{t}$ production

Partonic level cross section

Triplet Δ_6 partonic cross-section (u-channel mediation)

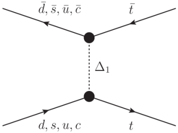


$$\frac{d\sigma_6^{q\bar{q}}(\hat{s})}{d\hat{t}} = \frac{d\sigma_{SM}^{q\bar{q}}(\hat{s})}{d\hat{t}} \underbrace{- \frac{\alpha_s |g_6^{qt}|^2}{9\hat{s}^3} \frac{m_t^2 \hat{s} + (m_t^2 - \hat{u})^2}{m_{\Delta_6}^2 - \hat{u}}}_{\Delta_6 \times \text{SM interference term}} + \frac{|g_6^{qt}|^4}{48\pi\hat{s}^2} \frac{(m_t^2 - \hat{u})^2}{(m_{\Delta_6}^2 - \hat{u})^2}$$

$$\hat{t} = (p_u - p_t)^2$$

$$\hat{u} = (p_{\bar{u}} - p_t)^2$$

Octet Δ_1 partonic cross-section (t-channel)

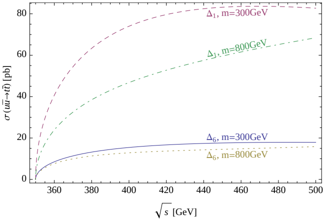


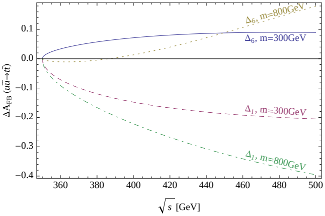
$$\frac{d\sigma_1^{q\bar{q}}(\hat{s})}{d\hat{t}} = \frac{d\sigma_{SM}^{q\bar{q}}(\hat{s})}{d\hat{t}} + \frac{2\alpha_s |g_1^{qt}|^2}{27\hat{s}^3} \frac{m_t^2 \hat{s} + (m_t^2 - \hat{t})^2}{m_{\Delta_1}^2 - \hat{t}} + \frac{|g_1^{qt}|^4}{18\pi\hat{s}^2} \frac{(m_t^2 - \hat{t})^2}{(m_{\Delta_1}^2 - \hat{t})^2}$$

$$g_1^{ut} \equiv 4(Y_2^{ut} - Y_2^{tu}) \qquad g_1^{dt} \equiv 4\sqrt{(Y_2^{dt} - Y_2^{td})^2 + (Y_1^{dt*})^2/8}$$

- Neglect interference between Δ_1 and Δ_6
- Consider mass range 300–1000 GeV for $\Delta_{1,6}$

Examples of partonic cross sections and FBA





- Stronger enhancement of σ by Δ_1

- Δ_1 reduces A_{FB}
- Δ_6 enhances it well above threshold

Towards A_{FB} enhancement

Δ_6 tends to correct A_{FB} in the right direction, whereas contributions of Δ_1, if light, must be suppressed.

- Model independently this can be arranged.
- In GUT model we have a freedom to reduce Y_1 couplings of Δ_1

- Convolute partonic distribution with PDFs

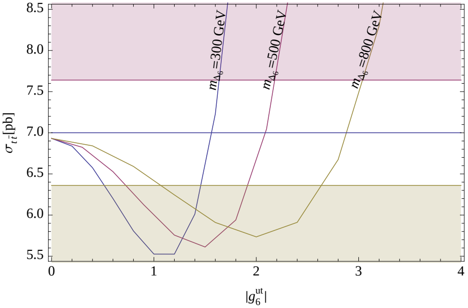
$$\frac{d\sigma(s)}{dt} = \sum_{p,p'=q,g} \int_{x_0}^{1} dx_1 \int_{x_0}^{1} dx_2 x_1 x_2 \frac{d\sigma^{pp'}(\hat{s})}{d\hat{t}} f_p(x_1) f_{p'}(x_2)$$

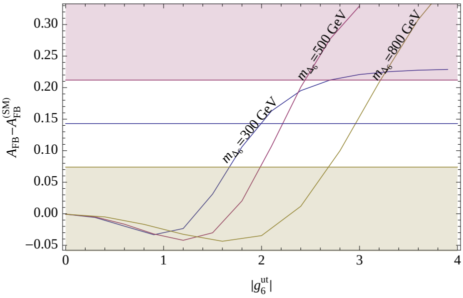
$$\hat{s} = x_1 x_2 s, \qquad \hat{t} = x_1 x_2 (t - m_t^2) + m_t^2$$

$$\frac{d\sigma(s)}{d\cos\theta} = \frac{s\sqrt{1 - 4m_t^2/\hat{s}}}{2} \frac{d\sigma(s)}{dt(\cos\theta)}$$

$$t(\cos\theta) = -s(1 - \cos\theta\,\beta_t)/2 + m_t^2$$

- We use CTEQ5 PDFs and rescale our results in each bin of $m_{t\bar{t}}$ so that our LO QCD results match with the reference NLO QCD Frederix, Maltoni

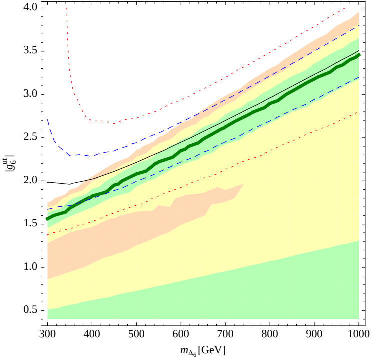




- Mass m_{Δ_6} and coupling g_6^{ut} are positively correlated

Color triplet in $t\bar{t}$ production

Correlating g_6^{ut} and m_{Δ_6}



From $t\bar{t}$ production constraints

$$|g_6^{ut}| = 0.9(2) + 2.5(4)\frac{m_{\Delta_6}}{1\ \mathrm{TeV}}$$

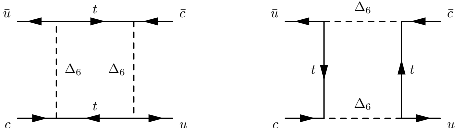
Perturbativity only for light Δ_6.

We need large coupling, $g_6^{ut} \sim \mathcal{O}(1)$. Together with other couplings g_6^{ct}, g_6^{uc} FCNC effects in the up-quarks are possible.

Outline

Doršner, Fajfer, Kamenik, NK, PRD82

- Only $g_6^{ut} g_6^{ct*}$ contributes because of antisymmetry of g_6 — pure short distance diagrams



$$\mathcal{H}_{\rm eff} = C_6 Q_6, \qquad Q_6 = (\bar{u}_R \gamma^\mu c_R)(\bar{u}_R \gamma_\mu c_R),$$

$$C_6(m_{\Delta_6}) = \frac{(g_6^{ut} g_6^{ct*})^2 h(m_t^2/m_{\Delta_6}^2)}{64\pi^2 m_{\Delta_6}^2}, \qquad h(x) = \frac{-x^2 + 2x\log x + 1}{(1-x)^3}.$$

- Data on D–$\bar{D}$ mixing is rich, interpretation in the SM not straightforward.

$$|D_{1,2}\rangle = p\,|D^0\rangle \pm q\,|\bar{D}^0\rangle$$

$$x = \frac{m_H - m_L}{\Gamma}$$

$$-|q/p|e^{i\phi} = \frac{q}{p}\frac{\langle K^+K^- | \mathcal{H} | \bar{D}^0\rangle}{\langle K^+K^- | \mathcal{H} | D^0\rangle}$$

HFAG

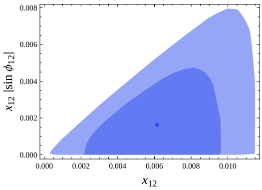
$$x = (0.59 \pm 0.20)\%, \qquad y = (0.81 \pm 0.13)\%,$$

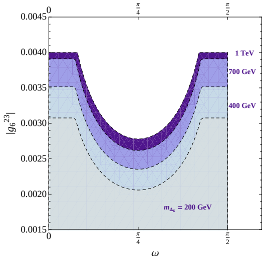
$$|q/p| = 0.98^{+0.15}_{-0.14}, \qquad \phi = -0.051^{+0.112}_{-0.115}.$$

- CP violating phase in mixing is small, consistent with the SM
- Prediction of x is long-distance dominated in the SM

- Δ_6 only contributes to M_{12}
- Fit of x_{12} and ϕ_{12} observables [$x_{12} \equiv 2|M_{12}|/\Gamma$, $\phi_{12} \equiv \arg(M_{12}/\Gamma_{12})$], assuming $x_{12} < x_{12}^{\rm exp}$
  Gedalia et al
- 2σ upper bounds

$$x_{12} < 9.6 \times 10^{-3}, \qquad x_{12}|\sin\phi_{12}| < 4.4 \times 10^{-3}$$



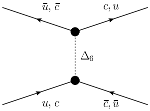


$\omega = \arg(g_6^{ct}/g_6^{ut})$

- Using the known value of g_6^{ut}:

> Phase dependent bound from ϕ constraint, g_6^{ct} is of order $\lesssim 10^{-3}$

- Constraints from $c \to u\gamma$ penguin diagrams with Δ_6 are far weaker

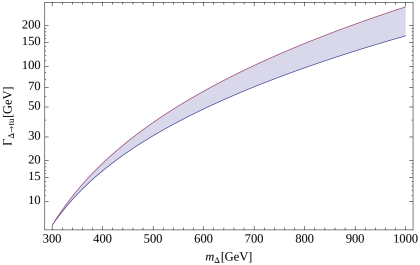


+ crossed diagrams

$$\hat{s} = (p_{\bar{u}} + p_u)^2$$
$$\hat{t} = (p_u - p_c)^2$$
$$\hat{u} = (p_{\bar{u}} - p_c)^2$$

$$\frac{d\sigma_6^{u\bar{u}\to c\bar{c}}(\hat{s})}{d\hat{t}} = \frac{d\sigma_{SM}^{u\bar{u}\to c\bar{c}}(\hat{s})}{d\hat{t}} + \frac{|g_6^{uc}|^4}{48\pi\hat{s}^2}\frac{\hat{u}^2}{\left(m_{\Delta_6}^2 - \hat{u}\right)^2 + \Gamma_{\Delta_6}^2} - \frac{\alpha_s|g_6^{uc}|^2}{9\hat{s}^3}\frac{\hat{u}^2\left(m_{\Delta_6}^2 - \hat{u}\right)}{\left(m_{\Delta_6}^2 - \hat{u}\right)^2 + \Gamma_{\Delta_6}^2}$$

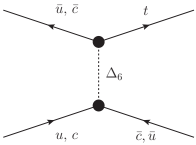
We regularize on-shell poles by Δ_6 width



$$\Gamma(\Delta_6 \to tq_i) = \frac{|g_6^{it}|^2\left(m_{\Delta_6}^2 - m_t^2\right)^2}{16\pi m_{\Delta_6}^3}$$

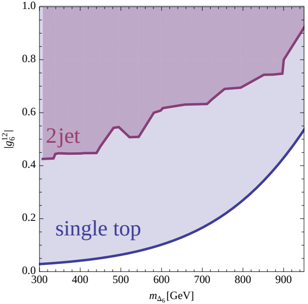
- comparable to exp. bin size in dijet invariant mass
- Compare PDF-convoluted hadronic cross section against CDF measured spectrum

Search for excess in single top production at Tevatron — g_6^{uc}



$$\frac{d\sigma^{u\bar{u}\to t\bar{c}}}{d\hat{t}} = -\frac{|g_6^{ut*}\, g_6^{uc}|^2}{48\pi \hat{s}^2} \frac{(\hat{s}+\hat{t})\hat{u}}{(\hat{u}-m_{\Delta_6}^2)^2+\Gamma_{\Delta_6}^2}$$

$$+ \text{ s–channel}$$



- Conservative approach: compare only Δ_6 contribution with the experimental error of the cross section $\sigma_{1t} = 2.76^{+0.58}_{-0.47}$ pb (CDF)

We require $\Delta\sigma_{1t} < 1$ pb at 95 % C.L.

Coupling g_6^{uc} of the order $\lesssim 0.1$

Recapitulation

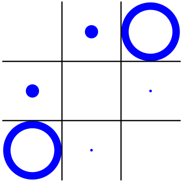
Scalar triplet $\Delta_6 = (\bar{3}, 1, 4/3)$ alone can explain the observed A_{FB} excess

- Provided its mass is below 1 TeV
- Provided its coupling to ut is large, and correlated with m_{Δ_6}

$$|g_6^{ut}| = 0.9(2) + 2.5(4)\frac{m_{\Delta_6}}{1\ \mathrm{TeV}}$$

Remaining couplings have to be small

- D–$\bar{D}$ mixing measurements imply $g_6^{ct} \lesssim 4 \times 10^{-3}$
- Single-top production cross section implies $g_6^{uc} \lesssim 10^{-2}$
- Particular structure of g_6 matrix



- Does not depend on the underlying model
- Is $m_{\Delta_6} < 1\ \mathrm{TeV}$ a viable SU(5) GUT scenario?

1. Forward-backward asymmetry in $t\bar{t}$ production and colored scalars
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3. Light Δ_6 from GUT point of view

The most pressing constraints are

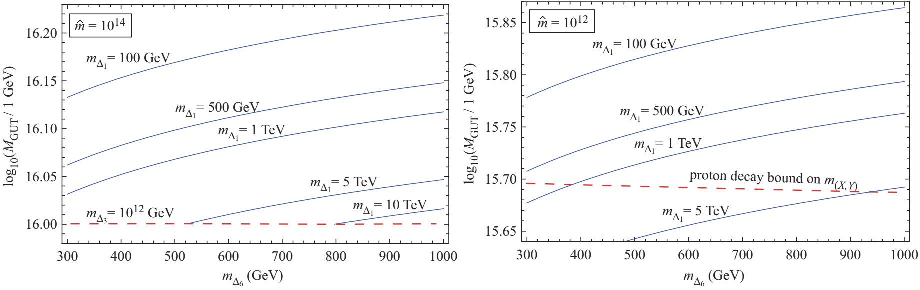
- unification of couplings at M_{GUT}
- proton stability, $\tau_{p\to\pi^0 e^+} > 8.2\times 10^{33}\mathrm{yr}$: M_{GUT} should not be too low, as well as masses of particles mediating proton decay

$$\Gamma \approx \frac{m_p}{f_\pi^2}\frac{\pi}{4}A_L^2|\alpha|^2(1+D+F)^2\frac{\alpha_{GUT}^2}{m_{X,Y}^4}[A_{SR}^2+4A_{SL}^2] \qquad \gamma_{L(R)i}=(23(11)/20,9/4,2)$$

$$A_{SL(R)}=\prod_{i=1,2,3}\prod_{I}^{M_Z\le m_I\le M_{GUT}}\left[\frac{\alpha_i(m_{I+1})}{\alpha_i(m_I)}\right]^{\gamma_{L(R)i}/(\sum_J^{M_Z\le m_J\le m_I} b_{iJ})}$$

- Ψ_T, Δ_3, and Δ_5 should be heavier than 10^{12} GeV
- ρ_8 must be above 10^6 GeV to accomodate BBN constraints

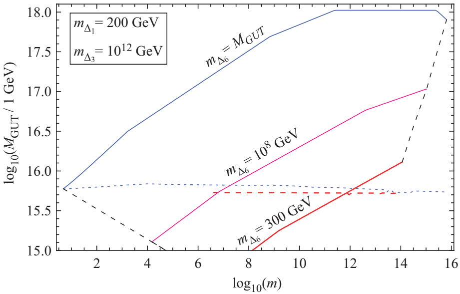
We determine upper bound on M_{GUT} for $m_{\Delta_6}\in[300\ \mathrm{GeV}, 1\ \mathrm{TeV}]$, while requiring unification and satisfying the above constraints.



$$\hat{m} \equiv m_{\rho_8} / m_{\rho_3}$$

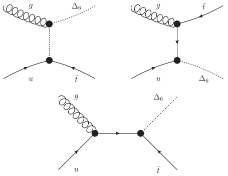
- Also the octet Δ_1 must be light $\Rightarrow$ need to suppress Y_1
- Whole region $m_{\Delta_6} \in [300\ \mathrm{GeV}, 1\ \mathrm{TeV}]$ would be excluded if proton lifetime was larger by factor 6

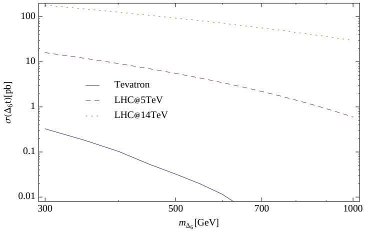
Proton decay and unification

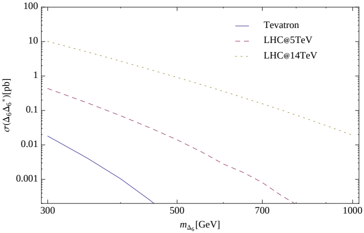


Direct searches

- LEP bound: $m_{\Delta_6} > 105$ GeV
- LHC production cross sections of $\Delta_6 \bar{t}$ and $\Delta_6 \Delta_6^*$ comparable to $t\bar{t}$ production







Conclusions and perspectives

Model independent study of octet $\Delta_1 = (8, 2, 1/2)$ and triplet $\Delta_6 = (\bar{3}, 1, 4/3)$ scalars in $\sigma_{t\bar{t}}$ and A_{FB}

- Δ_1 aggravates the discrepancy in A_{FB} whereas Δ_6 coupling to ut should be $g_6^{ut} \sim 1$
- Can be realized in SU(5) GUT model, where Δ_1 and Δ_6 should be light
- Proton decay lifetime could soon rule out GUT scenario $(6 \times \tau_p)$
- Simple structure of Δ_6 couplings to up quarks allows to constrain them in D–$\bar{D}$ mixing and top quark physics
- g_6 structure implies the upper bound on v_{45} (Dorsner,Fajfer,Kamenik,NK, PRD82)

Study underway of Δ_6 leptoquark couplings Y_1 to $d\ell$. Interesting signatures in

- Down-quarks FCNCs (e.g. B_s–$\bar{B}_s$ mixing Dighe et al)
- lepton flavor violation (e.g. μ–e conversion)
- a_e, a_μ