Automatic Nelson-Barr from Gauged Flavor and ALP searches at FASER .

Saturnalia - Universidad de Zaragoza - December 2023



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Based on <u>"Automatic Nelson-Barr from Gauged Flavor"</u> (to appear) in collaboration with B. Gavela and B. Grinstein
and on <u>"FASER as a Light Shining through Walls Experiment"</u> Phys.Rev.D 106 (2022) 5, 055036 in collaboration with F. Kling 2204.03599

The Strong CP problem

Neutron EDM (Electric Dipole Moment)



[B.Fillipone via diLuzio]

$$\mathcal{L}_{QCD} \supset \mathcal{L}_{CP} = -\bar{q}me^{i\beta}q + \theta_{QCD}\frac{\alpha_s}{8\pi}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

One physical CPV phase:

$$\bar{\theta} = \theta_{QCD} + \arg \det M$$

 $d_n \approx 10^{-16} |\bar{\theta}| e \cdot cm$ $\bar{\theta} \lesssim 10^{-10}$ Why is it so small?

The Strong CP problem hint

Neutron EDM (Electric Dipole Moment)



The QCD axion

- → Solves the Strong CP problem
- → Excellent Dark Matter candidate

[Peccei+Quinn 77] [Weinberg, 78] [Wilczek, 78] [Abbot+Sikivie, 83] [Dine and W. Fischler, 83] [Preskil et al, 91]



The QCD axion

CAST

 10^{-9}

 10^{-10}

 10^{-11}

 10^{-12}

 10^{-13}

 10^{-17}

 10^{-18}

 10^{-19}

 10^{-20}

 10^{-12} 10^{-11} 10^{-10}

 $\frac{\left[\frac{g_{a\gamma}}{10^{-16}}\right]^{10-16}}{10^{-12}}$

Astrophysics

 10^{-9} 10^{-8}

 10^{-7}

- → Solves the Strong CP problem
- **Excellent Dark Matter candidate** \rightarrow





→ CP is conserved exactly in the UV => **NO PHASES**



$$\bar{\theta} \equiv \theta_{\text{QCD}} + \text{Arg}(\det M) = 0 \text{ and } \delta_{KM} = 0$$



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 \rightarrow At low energies CP is spontaneously broken $\langle \eta \rangle$ is complex.

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$$\theta_{QCD} \frac{\alpha_s}{8\pi} G\tilde{G} \qquad \bar{\theta} \equiv \theta_{QCD} + \operatorname{Arg}(\det M) = 0 \text{ and } \delta_{KM} = 0$$

- \rightarrow At low energies CP is spontaneously broken $\langle \eta \rangle$ is complex.
- → The fermion mass matrices pattern only generates $\delta_{\rm KM}$ but no θ Ex. BBP model $\mathcal{L} \supset -\mu \bar{q}_L q_R - \lambda \eta \bar{q}_L D_R - y \Phi \bar{Q}_L D_R$ [Bento, Branco, Parada, 91]

$$M = \left(\begin{array}{cc} \mu & \lambda \langle \eta \rangle \\ 0 & m_d \end{array}\right)$$

 $\theta_{QCD} \frac{\alpha_s}{\delta_s} GG$

DEVI COMDIEX

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Ex. BBP model $\mathcal{L} \supset -\mu \bar{q}_L q_R - \lambda \eta \, \bar{q}_L D_R - y \Phi \bar{Q}_L D_R$

[Bento, Branco, Parada, 91]

$$M = \begin{pmatrix} \mu & \lambda \langle \eta \rangle \\ 0 & m_d \\ REAL \end{pmatrix} \implies \arg \det M \big|_{\text{tree level}} = 0 \implies \bar{\theta} \big|_{\text{tree level}} = 0$$



→ CP is conserved exactly in the UV => **NO PHASES**



Challenges of the NB mechanism

X 1. Enforcing the NB structure

[Dine+Draper, 15]

WHY?
$$M = \begin{pmatrix} \mu & \lambda \langle \eta \rangle \\ 0 & m_d \end{pmatrix}$$
 Ex. $\eta \bar{q}_L q_R$

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$$M = \begin{pmatrix} \mu & \lambda \langle \eta \rangle \\ 0 & m_d \end{pmatrix}$$
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X 2. Higher dimensional operators
$$\frac{1}{\Lambda} \eta \eta \bar{q}_L q_R$$

 $\bar{\theta} \lesssim 10^{-10}$

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[Dine+Draper, 15]

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 \mathbf{X} 2. Higher dimensional operators

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 $\bar{\theta} \lesssim 10^{-10}$

 \mathbf{X} 3. Loop corrections







Automatic Nelson-Barr from Gauged Flavor

B. Gavela, B. Grinstein and P. Q. To appear

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BSM reach of Flavor Physics



Hatched bars: MFV Darker colors: midterm prospects

[European Strategy for Particle Physics, 19] by Aloni, Dery+Gavela+Nir

Gauged flavor symmetries

[Chakrabarti, 79] [Barr, Zee, 78] [Wilczek, Zee, 78] [Georgi, Chivukula, 87]

Gauging the non abelian quark flavor symmetry

 $G_f = SU(3)_{Q_L} \otimes SU(3)_{u_R} \otimes SU(3)_{d_R}$

[Grinstein+Redi+Villadoro, 10]

- Gauging the non abelian lepton flavor symmetry $SU(3)_{\ell} \times SU(3)_{e} \quad SU(3)_{\ell} \times SU(3)_{e} \times SU(3)_{e} \times SU(3)_{N} \quad \begin{array}{l} \text{[Alonso, Fernandez-Martinez,} \\ \text{Gavela, Grinstein, Merlo, PQ, 16]} \end{array}$
- The Yukawas $\mathcal{Y}_u, \mathcal{Y}_d$ are promoted to dynamical fields whose vevs break spontaneously the SM flavor symmetry

Largest non-abelian symmetry in the massless limit?

 $G_f = SU(3)_{Q_L} \otimes SU(3)_{u_R} \otimes SU(3)_{d_R}$ [Grinstein+Redi+Villadoro, 10]

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Exotic fermions are needed: $\Psi_{u_R}, \Psi_{d_R}, \Psi_{u_L}, \Psi_{d_L}$

 $G_f = SU(3)_{Q_L} \otimes SU(3)_{u_R} \otimes SU(3)_{d_R}$

[Grinstein+Redi+Villadoro, 10]

Most general renormalizable Lagrangian

$$-\mathcal{L}_{int} = \lambda_u \overline{Q}_L \tilde{H} \Psi_{u_R} + \lambda'_u \overline{\Psi}_{u_L} \mathcal{Y}_u \Psi_{u_R} + M_u \overline{\Psi}_{u_L} U_R + \lambda_d \overline{Q}_L H \Psi_{d_R} + \lambda'_d \overline{\Psi}_{d_L} \mathcal{Y}_d \Psi_{d_R} + M_d \overline{\Psi}_{d_L} D_R + h.c.$$

 $G_f = SU(3)_{Q_L} \otimes SU(3)_{u_R} \otimes SU(3)_{d_R}$

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See-saw mechanism for all fermions

$$\begin{pmatrix} \overline{U}_L & \overline{\Psi}_{u_L} \end{pmatrix} \begin{pmatrix} 0 & \lambda_u \frac{v}{\sqrt{2}} \\ M_u & \lambda'_u \hat{\mathcal{Y}}_u V \end{pmatrix} \begin{pmatrix} U_R \\ \Psi_{U_R} \end{pmatrix}; \qquad \begin{pmatrix} \overline{D}_L & \overline{\Psi}_{d_L} \end{pmatrix} \begin{pmatrix} 0 & \lambda_d \frac{v}{\sqrt{2}} \\ M_d & \lambda'_d \hat{\mathcal{Y}}_d \end{pmatrix} \begin{pmatrix} D_R \\ \Psi_{D_R} \end{pmatrix}$$



NB from Gauged flavor

- ▷ Let's impose CP in the UV
- \triangleright CP arises spontaneously through the vevs $\langle \mathcal{Y}_{u,d}
 angle$

NB from Gauged flavor

- Let's impose CP in the UV
- \triangleright CP arises spontaneously through the vevs $\langle \mathcal{Y}_{u,d}
 angle$
- Seesaw-like mass matrices already present BN structure!!

$$\left(\begin{array}{cc} \overline{U}_{L} & \overline{\Psi}_{u_{L}} \end{array} \right) \begin{pmatrix} 0 & \lambda_{u} \frac{v}{\sqrt{2}} \\ M_{u} & \lambda'_{u} \hat{\mathcal{Y}}_{u} V \end{pmatrix} \begin{pmatrix} U_{R} \\ \Psi_{U_{R}} \end{pmatrix}; \qquad \left(\begin{array}{cc} \overline{D}_{L} & \overline{\Psi}_{d_{L}} \end{array} \right) \begin{pmatrix} 0 & \lambda_{d} \frac{v}{\sqrt{2}} \\ M_{d} & \lambda'_{d} \hat{\mathcal{Y}}_{d} \end{pmatrix} \begin{pmatrix} D_{R} \\ \Psi_{D_{R}} \end{pmatrix}$$
$$\\ \left. \overline{\theta}_{\text{QCD}} \right|_{tree} = \theta_{\text{QCD}} + \arg\left(\det\left(\mathcal{M}_{u} \mathcal{M}_{d} \right) \right) = 0$$

Intuitive interpretation:

$$\bar{\theta}_{\text{QCD}} = \theta_{\text{QCD}} + \arg\left(\det\left(m_u \, m_{u'} \, m_d \, m_{d'}\right)\right) = \arg\left(\det\left(\frac{1}{\hat{\mathcal{Y}}_u}\right)\right) + \arg\left(\det\left(\hat{\mathcal{Y}}_u\right)\right) + \arg\left(\det\left(\frac{1}{\hat{\mathcal{Y}}_d}\right)\right) + \arg\left(\det\left(\hat{\mathcal{Y}}_d\right)\right) = 0$$

Solved challenges in NB from gauged flav.

1. Enforcing the NB structure

Enforced by the gauged flavor symmetry

WHY?
$$\mathcal{M}_u = \begin{pmatrix} 0 & \lambda_u \frac{v}{\sqrt{2}} \\ M_u & \lambda'_u \hat{\mathcal{Y}}_u V \end{pmatrix}; \qquad \mathcal{M}_d = \begin{pmatrix} 0 & \lambda_d \frac{v}{\sqrt{2}} \\ M_d & \lambda'_d \hat{\mathcal{Y}}_d \end{pmatrix}$$

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2. Higher dimensional operators

Higher dimensional operators

$$\mathcal{O}_{d,A} = \frac{1}{\Lambda^{\alpha+1}} \overline{Q}_L H f_\alpha(H_u, H_d) \mathcal{Y}_d^{\dagger} u_R , \qquad \mathcal{O}_{d,B} = \frac{1}{\Lambda^{\alpha}} \overline{Q}_L H f_\alpha(H_u, H_d) \Psi_{d_R}$$
$$\mathcal{O}_{d,C} = \frac{1}{\Lambda^{\alpha+1}} \overline{\Psi}_{d_L} \mathcal{Y}_d f_\alpha(H_u, H_d) \mathcal{Y}_d^{\dagger} u_R , \qquad \mathcal{O}_{d,D} = \frac{1}{\Lambda^{\alpha}} \overline{\Psi}_{d_L} \mathcal{Y}_d f_\alpha(H_u, H_d) \Psi_{d_R}$$
$$f_\alpha(H_u, H_d) = H_u^p H_d^q H_u^r H_d^s \dots , \qquad H_u = \mathcal{Y}_u^{\dagger} \mathcal{Y}_u \qquad H_d = \mathcal{Y}_d^{\dagger} \mathcal{Y}_d ,$$

$$\bar{\theta} \sim \operatorname{Im} \operatorname{Tr} \left[H_u^p H_d^q H_u^r H_d^s \dots \right]$$
$$\bar{\theta} \sim \operatorname{Im} \operatorname{Tr} \left[H_u H_d H_d^2 H_d^2 \right]$$

Higher dimensional operators \overline{O} $U f (U U) \chi^{\dagger}$ \overline{O} Relevant contribution ∝ Jarlskog invariant $\operatorname{Im}\operatorname{Tr}\left[H_{u}H_{d}H_{u}^{2}H_{d}^{2}\right] \propto \frac{M_{d}^{6}M_{u}^{6}v^{12}}{\left(\det h_{u}h_{d}\right)^{2}}\operatorname{Im}\operatorname{Tr}\left[h_{u}h_{d}h_{u}^{2}h_{d}^{2}\right]$ $\propto (m_t^2 - m_c^2) (m_t^2 - m_u^2) (m_c^2 - m_u^2) (m_b^2 - m_s^2) (m_s^2 - m_d^2) (m_b^2 - m_d^2)$ $\times c_{12}c_{23}c_{13}^2s_{12}s_{23}s_{13}\sin\delta_{\rm KM}$

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A Higher dimensional operators

Enforced by the gauged flavor symmetry

$$\bar{\theta} \sim \operatorname{Im} \operatorname{Tr} \left[H_u H_d H_u^2 H_d^2 \right] \ll 10^{-10}$$

Solved challenges in NB from gauged flav.

1. Enforcing the NB structure

Enforced by the gauged flavor symmetry

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$$\mathcal{M}_u = \begin{pmatrix} 0 & \lambda_u \frac{v}{\sqrt{2}} \\ M_u & \lambda'_u \hat{\mathcal{Y}}_u V \end{pmatrix}; \qquad \mathcal{M}_d = \begin{pmatrix} 0 & \lambda_d \frac{v}{\sqrt{2}} \\ M_d & \lambda'_d \hat{\mathcal{Y}}_d \end{pmatrix}$$

Higher dimensional operators $\bar{\theta} \sim \operatorname{Im} \operatorname{Tr} \left[H_u H_d H_u^2 H_d^2 \right] \ll 10^{-10}$

3. Loop corrections

Loop corrections to θ



 $\bar{\theta}|_{\text{loop}} = \text{Im}\,\text{Tr}\,[m_U^{-1}\,\varepsilon_{u,A}] \supset \text{Im}\,\text{Tr}\,[m_U^{-1}\lambda_U^a\,m_U\,f(h_u)\,\lambda_L^b\,g(h_d)\,]\,\left(\mathcal{M}_A^{-2}\right)_{ab}$

A bit complicated... but with Caley-Hamilton Th. one can get rid of the Gell-Mann matrices and obtain polynomial invariants of the basic flavons

Loop corrections to θ



Solved challenges in NB from gauged flav. 1. Enforcing the NB structure **Enforced by the gauged flavor symmetry WHY?** $\mathcal{M}_u = \begin{pmatrix} 0 & \lambda_u \frac{v}{\sqrt{2}} \\ M_u & \lambda'_u \hat{\mathcal{Y}}_u V \end{pmatrix}; \qquad \mathcal{M}_d = \begin{pmatrix} 0 & \lambda_d \frac{v}{\sqrt{2}} \\ M_d & \lambda'_d \hat{\mathcal{Y}}_d \end{pmatrix}$ ✓ 2. Higher dimensional operators Enforced by the gauged flavor symmetry $\bar{\theta} \sim \operatorname{Im} \operatorname{Tr} \left[H_u H_d H_u^2 H_d^2 \right] \ll 10^{-10}$ **3**. Loop corrections **Enforced by the gauged flavor symmetry** $\left. \theta \right|_{2-\text{loop}} \ll 10^{-10}$

ALP Searches at the LHC: FASER as a Light Shining through Walls Experiment

Felix Kling and Pablo Quilez Phys.Rev.D 106 (2022) 5, 055036 2204.03599 [hep-ph]



Beyond the canonical band

 $g_{a\gamma}$

- A) Photophilic/photophobic axions
- 1. Single scalar: Playing with fermionic representations

"Preferred axion window" "Axion from monopoles"

[Di Luzio, Mescia, Nardi, 16] [Di Luzio, Mescia, Nardi, 18] [Sokolov, Ringwald, 21]

2. Multiple scalars: Alignment in field space

"Clockwork axion" "KNP alignment" "Multi-higgs models"

[Farina et al, 17] [Coy, Frigerio, 17] [Kim et al, 04] [Choi et al, 14 and 16] [Kaplan et al 16] [Giudice et al 16]

[Agrawal et al 17] [Kim et al, 04] + Refs in FIPs report [2102.12143] [Di Luzio, Mescia, Nardi, 17] [Di Luzio, Giannotti, Nardi, Visinelli, 16] [Darmé, Di Luzio, Giannotti, Nardi, 20]



B) Heavy/even lighter axions

1. Heavy axions: extra instantons

[Rubakov, 97] [Berezhiani et al ,01] [Fukuda et al, 01] [Hsu et al, 04] [Gianotti, 05] [Hook et al, 14] [Chiang et al, 16] [Khobadize et al,] [Dimopoulos et al, 16] [Gherghetta et al, 16] [Agrawal et al, 17] [Gaillard, Gavela, Houtz, Rey PQ, 18] [Fuentes-Martin et al, 19] [Csaki et al, 19] [Gherghetta et al, 20]

2. Even lighter QCD axion

[Hook, 18] [Luzio, Gavela, PQ, Ringwald, 21] [Luzio, Gavela, PQ, Ringwald, 21]

Light Shining through Walls

 $\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$



FASER: ForwArd Search ExpeRiment



FASER as a LSW experiment



FASER as a LSW experiment



FASER as a LSW experiment



Adapted from AxionLimits [Ciaran O'hare, 20]

Conclusions I

- → The strong CP problem can be solved automatically à la Nelson-Barr in the context of gauged flavor models.
- → The flavour gauge symmetry solves also common issues of NB constructions
 - NB structure automatically enforced
 - Proteccion against higher dim. operators
 - Loop contributions under control
- → There is life beyond the axion!
- → FASER can work as a LSW experiment to look for ALPs.

Thank you

Backup slides

Loop corrections to
$$\bar{\theta}_{\bar{Q}_{L}}$$

$$\bar{\theta}|_{\text{loop}} = \text{Im}\,\text{Tr}\,[m_U^{-1}\,\varepsilon_{u,A}] \supset \text{Im}\,\text{Tr}\,[m_U^{-1}\lambda_U^a\,m_U\,f(h_u)\,\lambda_L^b\,g(h_d)\,]\,\left(\mathcal{M}_A^{-2}\right)_{ab}$$

A bit complicated... but with Caley-Hamilton Theorem

$$\mathcal{M}_{A}^{-2} = \frac{1}{\det\left[\mathcal{M}_{A}^{2}\right]} \operatorname{adj}\left[\mathcal{M}_{A}^{2}\right] \qquad \operatorname{adj}(\mathbf{A}) = \sum_{s=0}^{n-1} \mathbf{A}^{s} \sum_{k_{1},k_{2},\dots,k_{n-1}} \prod_{\ell=1}^{n-1} \frac{(-1)^{k_{\ell}+1}}{\ell^{k_{\ell}} k_{\ell}!} \operatorname{tr}\left(\mathbf{A}^{\ell}\right)^{k_{\ell}}$$

 $\mathrm{adj}(\mathbf{A}) = \frac{1}{2} \mathbf{I}_3 \left((\mathrm{tr}\,\mathbf{A})^2 - \mathrm{tr}\,\mathbf{A}^2 \right) - \mathbf{A}(\mathrm{tr}\,\mathbf{A}) + \mathbf{A}^2$

One can get rid of the gell-mann matrices and obtain polynomial invariants of the basic flavons

Gauged flavor

Flavor gauge bosons

$$\mathcal{L}_{mass} = Tr\left[\left(D_{\mu} \mathcal{Y}_{u} \right)^{\dagger} \left(D^{\mu} \mathcal{Y}_{u} \right) \right] + Tr\left[\left(D_{\mu} \mathcal{Y}_{d} \right)^{\dagger} \left(D^{\mu} \mathcal{Y}_{d} \right) \right]$$
(1.12)

$$\supset Tr \left| g_Q \mathcal{Y}_u A_Q^{\mu} - g_U A_U^{\mu} \mathcal{Y}_u \right|^2 + Tr \left| g_Q \mathcal{Y}_d A_Q^{\mu} - g_D A_D^{\mu} \mathcal{Y}_d \right|^2 \tag{1.13}$$

$$= \frac{1}{2} \chi^T_\mu \left(\mathcal{M}^2_A \right) \chi^\mu \tag{1.14}$$

where $\chi_{\mu}^{T} = \left(A_{Q\mu}^{1}, ..., A_{Q\mu}^{8}, A_{U\mu}^{1}, ..., A_{U\mu}^{8}, A_{D\mu}^{1}, ..., A_{D\mu}^{8}\right)$ and \mathcal{M}_{A}^{2} is a 24 × 24 matrix:

$$\mathcal{M}_{A}^{2} = \begin{pmatrix} M_{QQ}^{2} & M_{QU}^{2} & M_{QD}^{2} \\ M_{UQ}^{2} & M_{UU}^{2} & 0 \\ M_{DQ}^{2} & 0 & M_{DD}^{2} \end{pmatrix}$$
(1.15)

Gauged flavor

$$\begin{pmatrix} M_{QQ}^2 \end{pmatrix}_{ab} = \frac{1}{4} g_Q^2 Tr \left[\mathcal{Y}_u \{\lambda^a, \lambda^b\} \mathcal{Y}_u^{\dagger} + \mathcal{Y}_d \{\lambda^a, \lambda^b\} \mathcal{Y}_d^{\dagger} \right. \\ \left. \begin{pmatrix} M_{UU}^2 \end{pmatrix}_{ab} = \frac{1}{4} g_U^2 Tr \left[\mathcal{Y}_u^{\dagger} \{\lambda^a, \lambda^b\} \mathcal{Y}_u \right] \right. \\ \left. \begin{pmatrix} M_{DD}^2 \end{pmatrix}_{ab} = \frac{1}{4} g_D^2 Tr \left[\mathcal{Y}_d^{\dagger} \{\lambda^a, \lambda^b\} \mathcal{Y}_d \right] \right. \\ \left. \begin{pmatrix} M_{QU}^2 \end{pmatrix}_{ab} = \left(M_{UQ}^2 \right)_{ba} = -\frac{1}{2} g_Q g_U Tr \left[\lambda^a \mathcal{Y}_u^{\dagger} \lambda^b \mathcal{Y}_u \right] \right. \\ \left. \begin{pmatrix} M_{QD}^2 \end{pmatrix}_{ab} = \left(M_{DQ}^2 \right)_{ba} = -\frac{1}{2} g_Q g_D Tr \left[\lambda^a \mathcal{Y}_d^{\dagger} \lambda^b \mathcal{Y}_d \right] \right.$$

Gauged flavor



Photon to axion conversion probability



FIG. 2: Differential production rate of photons at 14 TeV LHC predicted by EPOS-LHC in the (θ, p) plane, where θ and p are the proton's angle with respect to the beam axis and momentum, respectively. The angular coverage for FASER and FASER 2 are indicated by the vertical dotted lines.

$$P_{\gamma \to a} \simeq \frac{g_{a\gamma\gamma}^2}{8} \left| \sum_i \vec{B}_i L_i e^{iqz_i} \frac{\sin\left(qL_i/2\right)}{qL_i/2} \right|^2$$

$$q = E_{\gamma} - \left(E_{\gamma}^2 - m_a^2\right)^{1/2} \simeq m_a^2 / (2E_{\gamma})$$