Inverse gluon emission in dilepton production at CMS LHC

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Introduction

Despite the fact that the Standard Model (SM) keeps the status of consistent and experimentally confirmed theory, the search of New Physics

- ⋆ **the supersymmetry**,
- ⋆ **M-theory**,
- ⋆ **DM-particles**,
- ⋆ **axions**,
- ⋆ **feebly interacting particles**,
- ⋆ **extra** spatial dimensions,
- ⋆ **extra** neutral gauge bosons, etc.

is continued.

One of powerful tool in the modern experiments at LHC is the investigation of **dilepton production**

$$pp \to \ell^+ \ell^- X, \quad \ell = \mu, e \tag{1}$$

at **large invariant mass** of lepton pair: $M \geq 1$ TeV.

Current experimental situation at CMS LHC

The measured observable quantities:

- ★ differential cross section $\frac{d\sigma}{dM}$,
- ★ double-differential cross section $\frac{d^2\sigma}{dMdy}$,
- ★ forward-backward asymmetry A_{FB}

are consistent with the SM predictions at

$$\sqrt{S} = 7\text{–}8 \text{ TeV } (19.7 \text{ fb}^{-1}) \text{ for } M \leq 2 \text{ TeV},$$

$$\sqrt{S} = 13 \text{ TeV } (85 \text{ fb}^{-1}) \text{ for } M \leq 3 \text{ TeV}$$

($\sqrt{S}$ – total energy in c.m.s. of hadrons, M – dilepton $\ell^+\ell^-$ invariant mass, y – dilepton rapidity)

- ★ NNLO RCs are taken into account by using of **FEWZ**,
- ★ NNLO PDFs are **CT10 NNLO** and **NNPDF2.1**.

Four mechanisms of dilepton production

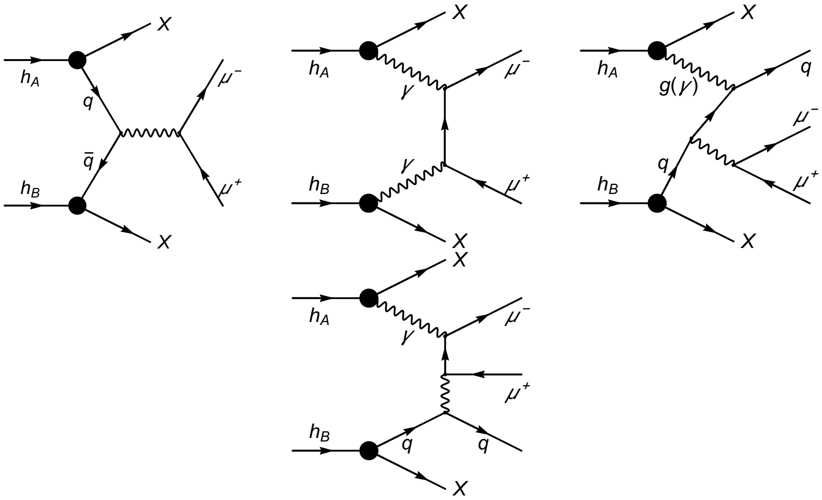

Figure 1: The Drell–Yan process, the photon-photon fusion, inverse gluon or γ emission with quark, inverse γ emission with muon.

Notations, invariants, coupling constants

The standard set of **Mandelstam invariants** for the partonic elastic scattering (with $p_1 + p_2 = p_3 + p_4$):

$$s = (p_1 + p_2)^2, \quad t = (p_1 - p_3)^2, \quad u = (p_2 - p_3)^2. \tag{2}$$

The propagator for j-boson depends on its mass m_j and width Γ_j:

$$D_j(q) = \frac{1}{q^2 - m_j^2 + i m_j \Gamma_j}, \quad j = \gamma, Z. \tag{3}$$

Suitable combinations of coupling constants are:

$$\lambda_{f\,+}^{\,i,j} = v_f^i v_f^j + a_f^i a_f^j, \quad \lambda_{f\,-}^{\,i,j} = v_f^i a_f^j + a_f^i v_f^j, \tag{4}$$

$$v_f^\gamma = -Q_f, \quad a_f^\gamma = 0, \quad v_f^Z = \frac{I_f^3 - 2 s_W^2 Q_f}{2 s_W c_W}, \quad a_f^Z = \frac{I_f^3}{2 s_W c_W}.$$

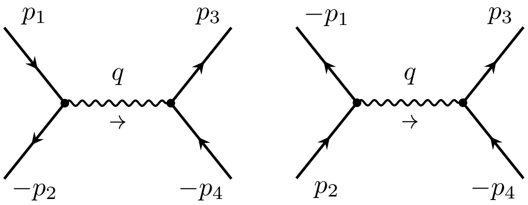

Figure 2: Feynman diagrams of $q\bar{q}(\bar{q}q) \to \ell^-\ell^+$ process at Born level.

Partonic level:

$$d\sigma_0^{q\bar{q}} = \frac{2\pi\alpha^2}{s^2} \sum_{i,j=\gamma,Z} D_i D_j^* \sum_{\chi=+,-} \lambda_{q}{}_{\chi}^{i,j} \lambda_{\ell}{}_{\chi}^{i,j} (t^2 + \chi u^2) dt. \tag{5}$$

$\gamma\gamma$-fusion Born: diagrams and cross sections

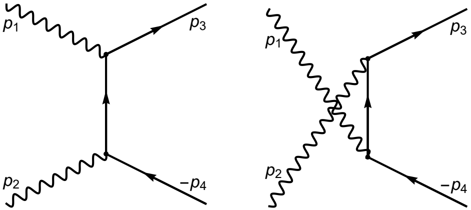

Figure 3: Feynman diagrams of $\gamma\gamma \to \ell^-\ell^+$ process at Born level.

Partonic level:

$$d\sigma_0^{\gamma\gamma} = \frac{2\pi\alpha^2}{s^2}\frac{t^2+u^2}{tu}dt. \tag{6}$$

Hadronic level ($\mathcal{C} = \cos\theta$):

$$\frac{d^3\sigma_0^h}{dMdyd\mathcal{C}} = 8\pi\alpha^2 f_\gamma^A(x_1) f_\gamma^B(x_2)\frac{t^2+u^2}{SM^5(1-\mathcal{C}^2)}\Theta. \tag{7}$$

Inverse photon/gluon emission diagrams

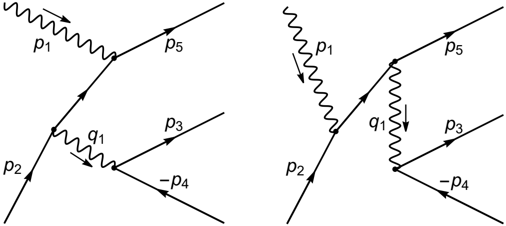

Figure 4: Feynman diagrams of $\gamma q(gq) \to \ell^- \ell^+ q$ process.

Partonic level:

$$d\sigma_{\gamma q} = \frac{1}{2^6 \pi^5 s} \sum_{a,b} \overline{\sum_{\mathrm{pol}}} \mathcal{M}^a_{\gamma q} (\mathcal{M}^b_{\gamma q})^+ d\Phi_3. \tag{8}$$

Hadronic level:

$$d\sigma^{\mathrm{ex}}_{\gamma q} = \sum_{q} \sum_{r_1, r_2} f_\gamma^{r_1, A}(x_1, Q^2) dx_1 \, f_q^{r_2, B}(x_2, Q^2) dx_2 \, d\sigma_{\gamma q}. \tag{9}$$

Some details for hadronic cross section

After using quark-parton model rules and some algebra:

$$d\sigma^{\rm ex}_{\gamma q} = \frac{\alpha^3 J_x}{\pi^2 s} \sum_q Q_q^2 \, f_\gamma^A(x_1) f_q^B(x_2) \left[V_{q\ell}(q_1)\, S_V^{\gamma q} + A_{q\ell}(q_1)\, S_A^{\gamma q} \right] d\Phi_3 \, dMdy, \tag{10}$$

where vector and axial combinations are factorized as following:

$$\begin{aligned} V_{q\ell}(q_1) &= \sum_{a,b=\gamma,Z} \lambda_{qV}^{ab} \lambda_{\ell V}^{ab} D_a(q_1) D_b^*(q_1), \\ A_{q\ell}(q_1) &= \sum_{a,b=\gamma,Z} \lambda_{qA}^{ab} \lambda_{\ell A}^{ab} D_a(q_1) D_b^*(q_1). \end{aligned} \tag{11}$$

For Jacobian of transition to experimental variables we have:

$$dx_1 dx_2 = |J_x| dMdy, \quad J_x = \frac{2M(E_5 + \sqrt{E_5^2 + M^2})}{S\sqrt{E_5^2 + M^2}}. \tag{12}$$

Phase space

$$d\Phi_3 = \delta(\dots)\frac{d^3\mathbf{p_3}}{2E_3}\frac{d^3\mathbf{p_4}}{2E_4}\frac{d^3\mathbf{p_5}}{2E_5} \to \frac{\pi|\mathbf{p_3}||\mathbf{p_5}|}{4E_4\mathcal{F}}d(\cos\theta_3)dE_5 d(\cos\theta_5)d\varphi_5.$$

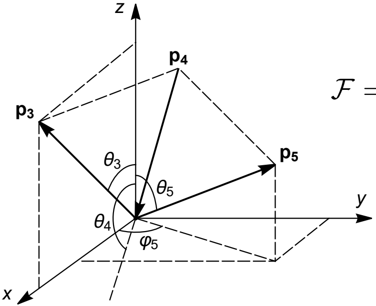

Figure 5: Configuration of final 3-vectors

$$\mathcal{F} = 1 + E_3\left(1 + \mathcal{B}/|\mathbf{p_3}|\right)\left(\mathcal{A} + E_3^2 + 2\mathcal{B}|\mathbf{p_3}|\right)^{-\frac{1}{2}},$$

where coefficients look like

$$\mathcal{A} = m_4^2 - m_3^2 + |\mathbf{p_5}|^2,$$
$$\mathcal{B} = |\mathbf{p_5}|\cos\theta_{35},$$
$$\mathcal{C} = E_1 + E_2 - E_5,$$

$$\cos\theta_{35} = \cos\theta_3\cos\theta_5 + \sin\theta_3\sin\theta_5\cos\varphi_5.$$

$$E_3 = \frac{1}{2(\mathcal{B}^2 - \mathcal{C}^2)}\left(\mathcal{C}(\mathcal{A} - \mathcal{C}^2) + \mathcal{B}\sqrt{(\mathcal{A} - \mathcal{C}^2)^2 + 4m_3^2(\mathcal{B}^2 - \mathcal{C}^2)}\right),$$

Quark mass singularity

To get physical cross section we should subtract Quark mass Singularity (QS) term

$$d\sigma_{\gamma q}^{\mathrm{IGE}} = d\sigma_{\gamma q}^{\mathrm{ex}} - d\sigma_{\gamma q}^{\mathrm{QS}}, \tag{13}$$

where

$$d\sigma_{\gamma q}^{\mathrm{QS}} = \frac{\alpha}{2\pi} \sum_q Q_q^2 \log \frac{M^2}{m_q^2} \int_0^1 d\eta \, f_\gamma^A(x_1) f_q^B(x_2) \, P_{\gamma q}(\eta) \, J_\eta \, d\sigma_{\bar{q}q}^0(\eta) J_x \, dM dy. \tag{14}$$

To obtain this nontrivial QS-term we apply leading logarithmic approximation working at point

$$p_5 = (1-\eta) p_1. \tag{15}$$

As sequence in cross section (14) we get the jacobian and splittig function (Altarelli & Parisi, Nucl. Phys. B. – 1977):

$$J_\eta = \frac{2\eta(1+\eta)}{(1+\eta+(1-\eta)\cos\theta_3)^2}, \quad P_{\gamma q}(\eta) = (1-\eta)^2 + \eta^2. \tag{16}$$

To numbers

It is time to show some numbers. Firstly, main features of EWK and QCD NLO RCs calculation are following:

- The notations, the Feynman rules are inspired by review of **M. Böhm, H. Spiesberger, and W. Hollik, 1986**,
- ★ **the t'Hooft–Feynman gauge**,
- ★ **on-mass renormalization scheme** ($\alpha, \alpha_s, m_W, m_Z, m_H$ and the fermion masses as independent parameters),
- QCD result is obtained from QED one by substitution:

$$Q_q^2\alpha \to \sum_{a=1}^{N^2-1} t^a t^a \alpha_s = \frac{N^2-1}{2N} I \alpha_s \to \frac{4}{3}\alpha_s, \tag{17}$$

  here $2t^a$ – Gell-Mann matrices, and $N = 3$,
- ★ **ultrarelativistic approximation** where it is possible.

Some modern codes for NLO and NNLO RCs for hadronic colliders (in the ABC order)

- ★ DYNNLO (S. Catani, L. Cieri, G. Ferrera et al.)
- ★ FEWZ (R. Gavin, Y. Li, F. Petriello, S. Quackenbush)
- ★ HORACE (C.Carloni Calame, G.Montagna, et al.)
- ★ MC@NLO (S. Frixione, F. Stoeckli, P. Torrielli et al.)
- ★ PHOTOS (N. Davidson, T. Przedzinski, Z. Was et al.)
- ★ POWHEG (L. Barze, G. Montagna, P. Nason et al.)
- ★ RADY (S. Dittmaier, A. Huss, C. Schwinn et al.)
- ★ READY (V. Zykunov, RDMS CMS)
- ★ MCSANC (Dubna: A. Andonov, A. Arbuzov, D. Bardin et al.)
- ★ WINHAC (W. Placzek, S. Jadach, M. W. Krasny et al.)
- ★ ZGRAD (U. Baur, W. Hollik, D. Wackeroth et al.)

Code READY and a set of prescriptions

In the following the scale of radiative effects to dilepton production will be discussed using FORTRAN program **READY**: (**R**adiative corr**E**ctions to l**A**rge invariant mass **D**rell–**Y**an process).

We used the following set of prescriptions:

- ★ standard PDG set of SM input electroweak parameters,
- ★ "effective" quark masses ($\Delta\alpha^{(5)}_{had}(m_Z^2) = 0.0276$),
- ★ 5 active flavors of quarks in proton,
- ★ CTEQ, CT10, and MHHT14 sets of PDFs,
- ★ choice for PDFs: $Q = M_{sc} = M$.

CMS detector setup

We impose the experimental restriction conditions

- ★ on the detected lepton angle $-\zeta^* \leq \cos\theta \leq \zeta^*$ (or on the rapidity $|y(l)| \leq y(l)^*$); for CMS detector the cut values of ζ^* (or $y(l)^*$) are determined as

$$\zeta^* \approx 0.986614 \quad (\text{or} \quad y(l)^* = 2.5),$$

- ★ the second standard CMS restriction $p_T(l) \geq 20$ GeV,
- ★ the "bare" setup for muon identification requirements (no smearing, no recombination of muon and photon/gluon).

Forward-backward asymmetry

Forward-backward asymmetry $A_{\rm FB}$ is important observable in dilepton production **with a dual nature – electroweak and kinematical**:

$$A_{\rm FB} = \frac{\sigma^h_{\rm F} - \sigma^h_{\rm B}}{\sigma^h_{\rm F} + \sigma^h_{\rm B}}, \tag{18}$$

where according **J. Collins & D. Soper (1977)**:

- $\sigma^h_{\rm F}$ is "forward" cross section ($\cos\theta^* > 0$),
- $\sigma^h_{\rm B}$ is "backward" cross section ($\cos\theta^* < 0$).

In the Collins–Soper system $\cos\theta^*$ looks like:

$$\cos\theta^* = \mathrm{sgn}[x_2(t+u_1) - x_1(t_1+u)] \frac{tt_1 - uu_1}{M\sqrt{s(u+t_1)(u_1+t)}}.$$

Forward, Backward (and Experimental) borders

For the case of nonradiative kinematics the $\cos\theta^*$ has especially simple view:

$$\cos\theta^* = \mathrm{sgn}[x_1 - x_2]\frac{u-t}{s} = \mathrm{sgn}\left[e^y - e^{-y}\right]\frac{(1+\mathcal{C})e^{-y} - (1-\mathcal{C})e^y}{(1+\mathcal{C})e^{-y} + (1-\mathcal{C})e^y}.$$

Solving $\cos\theta^* = 0$ we get **two conditions** for border dividing the regions of σ^h_{F} and σ^h_{B}:

$$y = 0, \quad \mathcal{C} \equiv \cos\theta = \mathrm{th}\, y.$$

The CMS experimental condition $|\cos\theta| < \zeta^*$ is trivial but the second one $|\cos\alpha| < \zeta^*$ is rather sophisticated:

$$\cos\left(\arccos\frac{\cos\theta - \mathrm{th}\, y}{r} + \arcsin\frac{\sin\theta\,\mathrm{th}\, y}{r}\right) = \pm\xi^*,$$

where

$$r = \sqrt{1 - 2\cos\theta\,\mathrm{th}\, y + \mathrm{th}^2\, y}.$$

Forward, Backward (and Experimental) regions

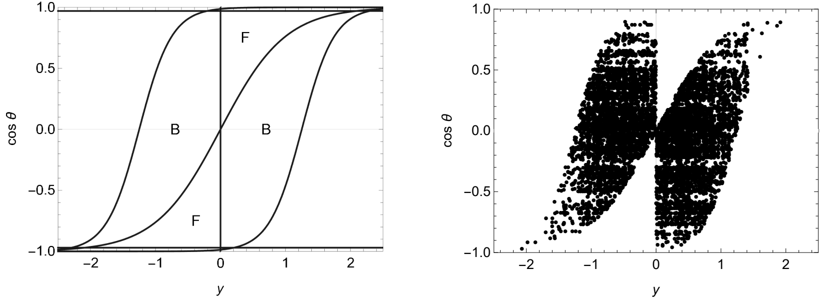

Figure 6: Left – Forward, Backward and CMS regions in y and $\cos\theta$ variables (**borders are**: $y = 0$, $\cos\theta = \operatorname{th} y$, $\cos\theta = \pm\zeta^*$, and $\cos\alpha = \pm\zeta^*$, where $\zeta^* \approx 0.9866$),
right – the points sampled by Monte-Carlo generator of VEGAS **for Backward CMS region**.

Additive relative corrections to $A_{\rm FB}$

Let 0 denotes the Born DY contribution, and for adiitional effect we use c:

$$c = \rm NLO\ EW\ DY, NLO\ QCD\ DY, NLO\ \gamma\gamma, IGE.$$

Corrected forward-backward asymmetry is defined as follows

$$\begin{aligned} A^c_{\rm FB} &= \frac{\sigma^0_{\rm F} + \sum_c \sigma^c_{\rm F} - \sigma^0_{\rm B} - \sum_c \sigma^c_{\rm B}}{\sigma^0_{\rm F} + \sum_c \sigma^c_{\rm F} + \sigma^0_{\rm B} + \sum_c \sigma^c_{\rm B}} = \\ &= \frac{\sigma^0_{\rm F} - \sigma^0_{\rm B}}{\sigma^0_{\rm F} + \sigma^0_{\rm B}} \times \frac{1 + \sum_c \delta^c_-}{1 + \sum_c \delta^c_+} = \\ &= A^0_{\rm FB} \times \frac{1 + \sum_c \delta^c_-}{1 + \sum_c \delta^c_+}, \end{aligned} \tag{19}$$

where

$$\delta^c_+ = \frac{\sigma^c_{\rm F} + \sigma^c_{\rm B}}{\sigma^0_{\rm F} + \sigma^0_{\rm B}}, \quad \delta^c_- = \frac{\sigma^c_{\rm F} - \sigma^c_{\rm B}}{\sigma^0_{\rm F} - \sigma^0_{\rm B}}.$$

Dependance of $\delta^c_\pm$ on quark mass

n	M_1, TeV	M_2, TeV	δ^c_+			δ^c_-		
			$\delta^{\rm ex}_+$	$\delta^{\rm LL}_+$	$\delta^{\rm IGE}_+$	$\delta^{\rm ex}_-$	$\delta^{\rm LL}_-$	$\delta^{\rm IGE}_-$
-3	0.106	0.12	8.139	8.070	-0.383	5.257	5.128	-0.253
-2			6.771	6.694	-0.376	4.375	4.199	-0.248
-1			5.393	5.322	-0.378	3.479	3.302	-0.250
0			4.019	3.951	-0.364	2.590	2.426	-0.248
-3	0.51	0.60	4.185	4.101	-0.244	3.710	3.632	-0.255
-2			3.544	3.458	-0.243	3.130	3.057	-0.259
-1			2.902	2.816	-0.242	2.560	2.483	-0.254
0			2.259	2.173	-0.240	1.984	1.908	-0.254
-3	1.0	1.2	2.812	2.757	-0.206	2.829	2.791	-0.236
-2			2.392	2.337	-0.207	2.399	2.364	-0.240
-1			1.972	1.918	-0.206	1.969	1.936	-0.243
0			1.553	1.498	-0.205	1.545	1.509	-0.240
-3	3.0	6.5	1.240	1.219	-0.144	1.505	1.499	-0.184
-2			1.059	1.039	-0.144	1.284	1.280	-0.185
-1			0.880	0.859	-0.144	1.064	1.060	-0.186
0			0.699	0.679	-0.144	0.843	0.840	-0.186

$$m_q = 10^n m_u, \quad n = (-3, -2, -1, 0), \quad m_u = 0.06983 \text{ GeV}$$

Additive relative corrections for Run3 of CMS LHC

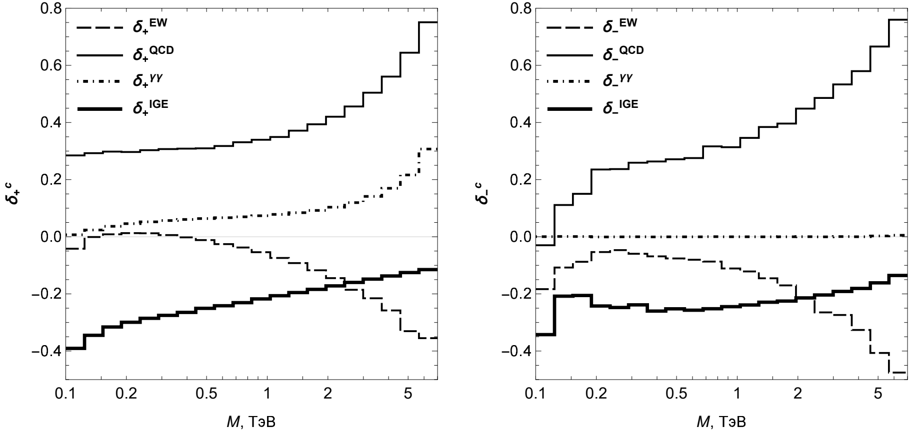

Figure 7: Additive relative corrections (left – "plus", right – "minus") for Run3 of CMS LHC ($\mu^+\mu^-$-production, $|y| < 2.5$).

Net effect for $A_{\rm FB}$ (Run3 of CMS LHC)

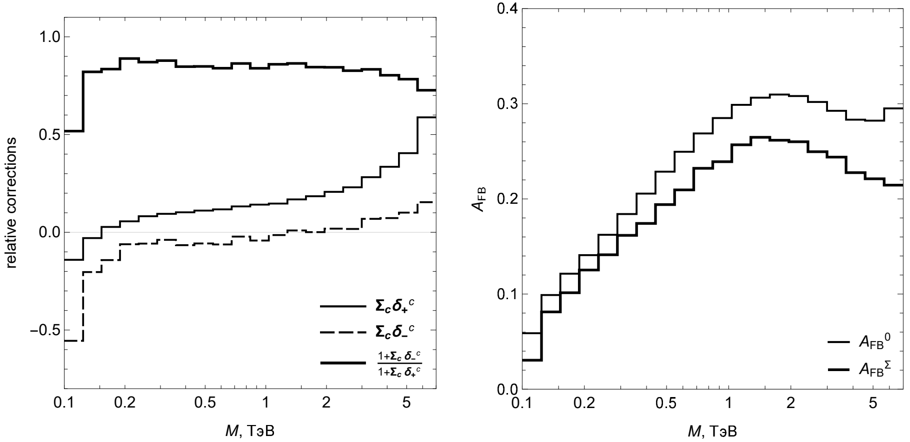

Figure 8: Total relative corrections (left) and $A_{\rm FB}$ (right) for Run3 of CMS LHC ($\mu^+\mu^-$-production, $|y| < 2.5$).

Conclusions & Acknowledgement

- ★ **The Inverse Gluon Emission** in dilepton production has been studied. It has been ascertained that the considered in Run 3 region IGE effect changes the cross sections and A_{FB} **significantly**.
- ★ **The net result** (NLO EW DY + NLO QCD DY [+ IGE] + NLO $\gamma\gamma$-fusion) to A_{FB} has been studied using **additive relative corrections technics**.

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