

Dilepton production at CMS LHC: inverse gluon and photon emission vs the Drell–Yan process and photon fusion

V. A. Zykunov (JINR, GSU)

Сессия-конференция “Физика
фундаментальных взаимодействий”

ИЯФ СО РАН (г. Новосибирск),
10 – 13 марта, 2026

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**

$$pp \rightarrow l^+ l^- X, \quad l = \mu, e \quad (1)$$

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

- $\sqrt{S} = 7-8$ TeV, 19.7 fb^{-1}
- $\sqrt{S} = 13$ TeV, 85 fb^{-1}
- $\sqrt{S} = 13.6$ TeV, 285.4 fb^{-1} ($\sim 10\%$ of Run3)

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

- NNLO QCD and NLO EW RCs are taken into account by **FEWZ**.

Four mechanisms of dilepton production

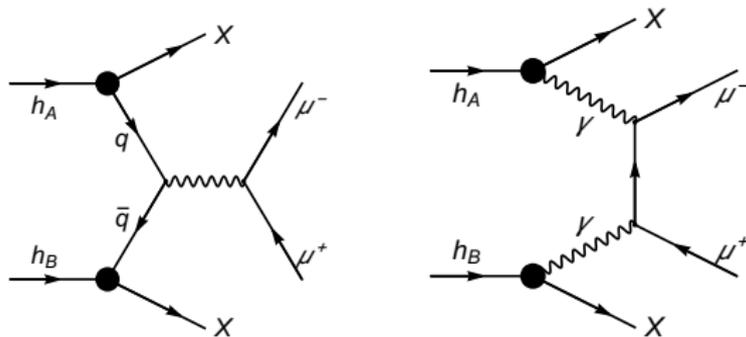


Figure 1: The *Drell-Yan* process, and the *photon-photon* fusion.

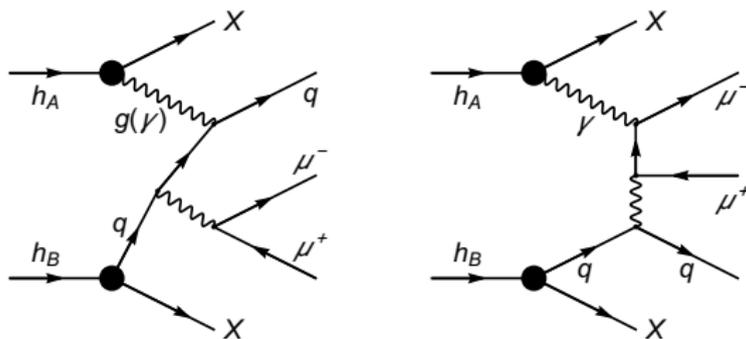


Figure 2: Inverse gluon or γ emission with *quark*, and with *muon*.

Notations: invariants, coupling constants

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

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

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

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

Suitable combinations of coupling constants are:

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

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

$q\bar{q}$ -annihilation Born: diagrams and cross sections

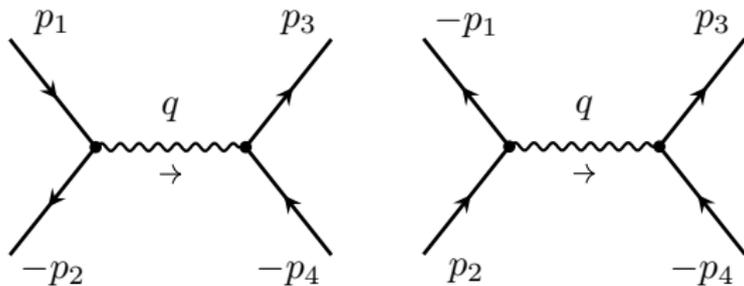


Figure 3: Feynman diagrams of $q\bar{q}(\bar{q}q) \rightarrow \ell^-\ell^+$ process at Born level.

Partonic level:

$$d\sigma_{q\bar{q}}^0 = \frac{2\pi\alpha^2}{s^2} \sum_{i,j=\gamma,Z} D_i D_j^* \sum_{\chi=+,-} \lambda_{q\chi}^{i,j} \lambda_{\ell\chi}^{i,j} (t^2 + \chi u^2) dt. \quad (5)$$

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

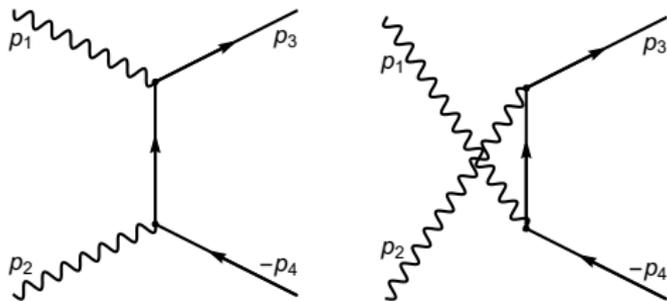


Figure 4: Feynman diagrams of $\gamma\gamma \rightarrow l^-l^+$ process at Born level.

Partonic level:

$$d\sigma_{\gamma\gamma}^0 = \frac{2\pi\alpha^2}{s^2} \frac{t^2 + u^2}{tu} dt. \quad (6)$$

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

$$\frac{d^3\sigma_h^0}{dMdyd\mathcal{C}} = 8\pi\alpha^2 f_\gamma^A(x_1) f_\gamma^B(x_2) \frac{t^2 + u^2}{SM^5(1 - \mathcal{C}^2)} \Theta. \quad (7)$$

Inverse photon/gluon emission diagrams

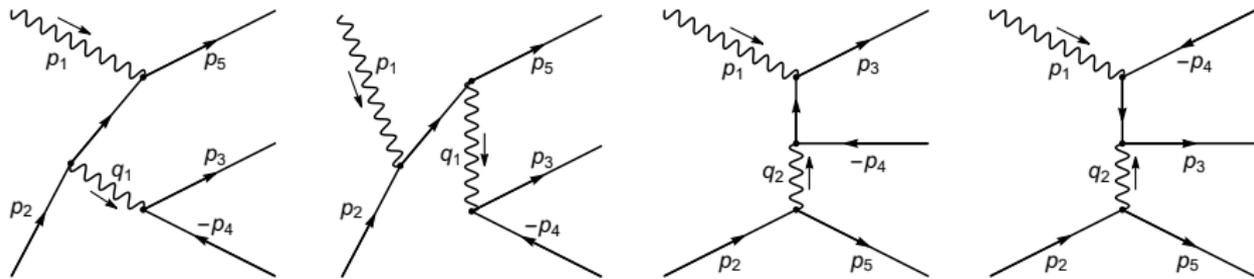


Figure 5: Feynman diagrams of $\gamma q(gq) \rightarrow \ell^- \ell^+ q$ process.

Partonic level:

$$d\sigma_{\gamma q} = \frac{1}{26\pi^5 s} \sum_{a,b} \overline{\sum_{\text{pol}}} \mathcal{M}_{\gamma q}^a (\mathcal{M}_{\gamma q}^b)^+ d\Phi_3. \quad (8)$$

Hadronic level:

$$d\sigma_{\gamma q}^{\text{ex}} = \sum_q f_{\gamma}^A(x_1, Q^2) dx_1 f_q^B(x_2, Q^2) dx_2 d\sigma_{\gamma q}. \quad (9)$$

Some details for hadronic cross section

After using quark-parton model rules and some algebra, $j = (q, \ell, q\ell, \ell q)$:

$$d\sigma_j^{\text{ex}} = \frac{\alpha^3 J_x}{\pi^2 S} \sum_q f_\gamma^A(x_1) f_q^B(x_2) [V_j S_j^V + A_j S_j^A] d\Phi'_3 dMdy, \quad (10)$$

where vector and axial combinations are factorized as following:

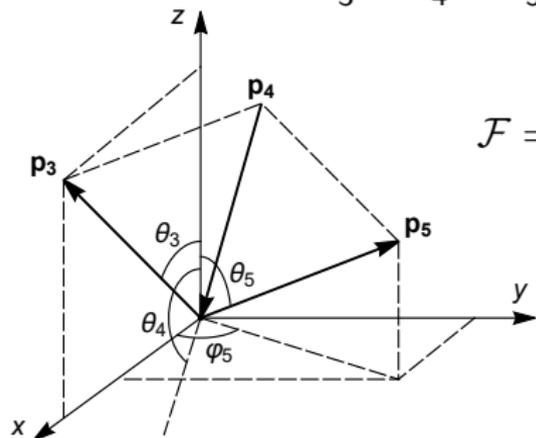
$$\begin{aligned} V_q &= Q_q^2 \sum_{a,b=\gamma,Z} \lambda_{qV}^{ab} \lambda_{\ell V}^{ab} D_a(q_1) D_b^*(q_1), \\ V_\ell &= Q_\ell^2 \sum_{a,b=\gamma,Z} \lambda_{qV}^{ab} \lambda_{\ell V}^{ab} D_a(q_2) D_b^*(q_2), \dots \end{aligned} \quad (11)$$

For Jacobian of transition to experimental variables we have:

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

Phase space

$$d\Phi_3 = \delta(\dots) \frac{d^3\mathbf{p}_3}{2E_3} \frac{d^3\mathbf{p}_4}{2E_4} \frac{d^3\mathbf{p}_5}{2E_5} \rightarrow \frac{\pi |\mathbf{p}_3| |\mathbf{p}_5|}{4E_4 \mathcal{F}} d(\cos \theta_3) dE_5 d(\cos \theta_5) d\varphi_5.$$



$$\mathcal{F} = 1 + E_3 (1 + B/|\mathbf{p}_3|) (\mathcal{A} + E_3^2 + 2B|\mathbf{p}_3|)^{-\frac{1}{2}},$$

where coefficients look like

$$\mathcal{A} = m_4^2 - m_3^2 + |\mathbf{p}_5|^2,$$

$$B = |\mathbf{p}_5| \cos \theta_{35},$$

$$C = E_1 + E_2 - E_5,$$

Figure 6: Configuration of final 3-vectors

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

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

Leading Logarithms (LL) approximation

Photon-quark interaction:

$$p_5 = (1-\eta)p_1, \quad \eta p_1 + p_2 = p_3 + p_4, \quad p_5 = (1-\eta)p_2, \quad p_1 + \eta p_2 = p_3 + p_4,$$

$$L_q = \log \frac{4E_5^2}{m_q^2} = \log \frac{M^2(1-\eta)^2}{m_q^2 \eta}, \quad L_\ell = \log \frac{4E_2^2 E_5^2}{m_q^2 (E_2 - E_5)^2} = \log \frac{M^2(1-\eta)^2}{m_q^2 \eta^3},$$

$$P_{\gamma q} = (1-\eta)^2 + \eta^2,$$

$$P_{\gamma \ell} = [1 + (1-\eta)^2]/\eta,$$

where Splitting functions $P_{\gamma j}$ as by **Altarelli & Parisi (1977)**.

LL cross sections:

$$d\sigma_q^{\text{LL}} = \frac{\alpha}{2\pi} \sum_q Q_q^2 \int_0^1 d\eta f_\gamma^A(x_1) f_q^B(x_2) dx_1 dx_2 L_q P_{\gamma q} J_\eta d\sigma_{\bar{q}q}^0(\eta),$$

$$d\sigma_\ell^{\text{LL}} = \frac{\alpha}{2\pi} \sum_q Q_q^2 \int_0^1 d\eta f_\gamma^A(x_1) f_q^B(x_2) dx_1 dx_2 L_\ell P_{\gamma \ell} J'_\eta d\sigma_{\gamma\gamma}^0(\eta).$$

Quark mass Singularity

To solve the problem of quark mass dependence (i. e. quark singularity, QS) we apply the \overline{MS} -subtraction technics – the subtraction from exact cross section (10) the so-called QS-term

$$d\sigma_j^{\text{IE}} = d\sigma_j^{\text{ex}} - d\sigma_j^{\text{QS}},$$

which looks as LL-terms with prescribed substitutions: for quark case

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

and for lepton case

$$d\sigma_\ell^{\text{QS}} = \frac{\alpha}{2\pi} \sum_q Q_q^2 \int_0^1 d\eta P_{\gamma\ell} \left(\log \frac{M^2}{m_q^2 \eta^2} - 1 \right) J'_\eta d\sigma_{\gamma\gamma}^0(\eta) f_\gamma^A(x_1) f_q^B(x_2) J_x dMdy.$$

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:

$$Q_q^2 \alpha \rightarrow \sum_{a=1}^{N^2-1} t^a t^a \alpha_s = \frac{N^2 - 1}{2N} I \alpha_s \rightarrow \frac{4}{3} \alpha_s, \quad (13)$$

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.)
- MCSANC (Dubna: A. Andonov, A. Arbuzov, D. Bardin et al.) (pioneer work on the topic: **A. B. Arbuzov and R. R. Sadykov, JETP 106, 488 (2008)**)
- 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)
- WINHAC (W. Placzek, S. Jadach, M. W. Krasny et al.)
- ZGRAD (U. Baur, W. Hollik, D. Wackerroth 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**arge 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 ($\Delta\alpha_{had}^{(5)}(m_Z^2) = 0.0276$),
- 5 active flavors of quarks in proton,
- CTEQ, MRST’04, CT10, MHHT14 and NNPDF’24 sets of PDFs,
- choice for PDFs: $Q = M_{sc} = M$.

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

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

- 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_{FB} is important observable in dilepton production **with a dual nature – electroweak and kinematical**:

$$A_{\text{FB}} = \frac{\sigma_{\text{F}}^h - \sigma_{\text{B}}^h}{\sigma_{\text{F}}^h + \sigma_{\text{B}}^h}, \quad (14)$$

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

- σ_{F}^h is “forward” cross section ($\cos \theta^* > 0$),
- σ_{B}^h is “backward” cross section ($\cos \theta^* < 0$).

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

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

Forward, Backward (and Experimental) borders

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

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

Solving $\cos \theta^* = 0$ we get **two conditions** for border dividing the regions of σ_F^h and σ_B^h :

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

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

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

where

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

Forward, Backward (and Experimental) regions

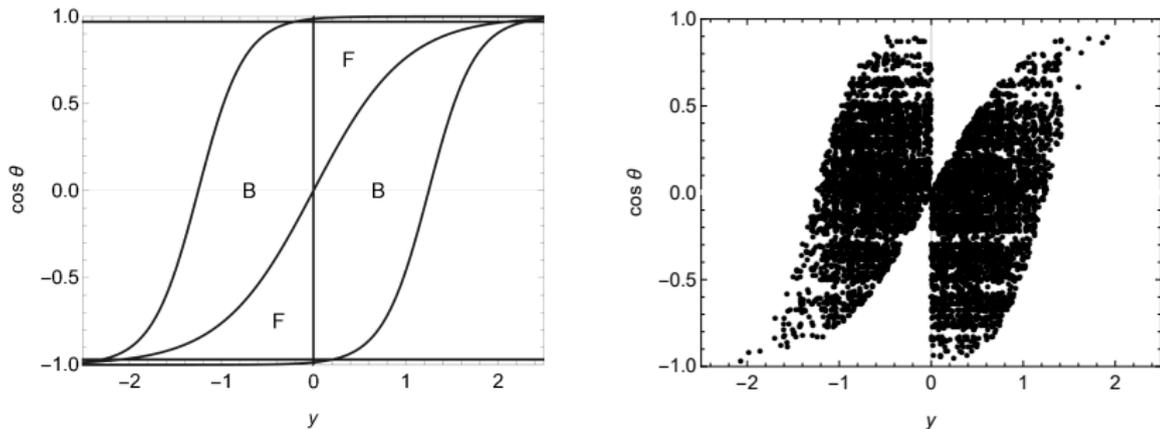


Figure 7: Left – Forward, Backward and CMS regions in y and $\cos \theta$ variables (**borders are:** $y = 0$, $\cos \theta = \text{th } y$, $\cos \theta = \pm \zeta^*$, and $\cos \alpha = \pm \zeta^*$, where $\zeta^* \approx 0.9866$), right – the points sampled by Monte-Carlo generator of VEGAS for **Backward CMS region**.

Additive relative corrections to A_{FB}

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

$$c = \text{NLO EW DY, NLO QCD DY, NLO } \gamma\gamma, \text{IE.}$$

Corrected forward-backward asymmetry is defined as follows

$$\begin{aligned} A_{\text{FB}}^c &= \frac{\sigma_{\text{F}}^0 + \sum_c \sigma_{\text{F}}^c - \sigma_{\text{B}}^0 - \sum_c \sigma_{\text{B}}^c}{\sigma_{\text{F}}^0 + \sum_c \sigma_{\text{F}}^c + \sigma_{\text{B}}^0 + \sum_c \sigma_{\text{B}}^c} = \\ &= \frac{\sigma_{\text{F}}^0 - \sigma_{\text{B}}^0}{\sigma_{\text{F}}^0 + \sigma_{\text{B}}^0} \times \frac{1 + \sum_c \delta_-^c}{1 + \sum_c \delta_+^c} = \\ &= A_{\text{FB}}^0 \times \frac{1 + \sum_c \delta_-^c}{1 + \sum_c \delta_+^c}, \end{aligned} \tag{15}$$

where

$$\delta_+^c = \frac{\sigma_{\text{F}}^c + \sigma_{\text{B}}^c}{\sigma_{\text{F}}^0 + \sigma_{\text{B}}^0}, \quad \delta_-^c = \frac{\sigma_{\text{F}}^c - \sigma_{\text{B}}^c}{\sigma_{\text{F}}^0 - \sigma_{\text{B}}^0}.$$

Dependance of δ_{\pm}^c on quark mass

n	M_1, TeV	M_2, TeV	δ_+^c			δ_-^c		
			δ_+^{ex}	δ_+^{LL}	δ_+^{gIE}	δ_-^{ex}	δ_-^{LL}	δ_-^{gIE}
-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

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

Relative corrections δ_+ for Run3 of CMS LHC

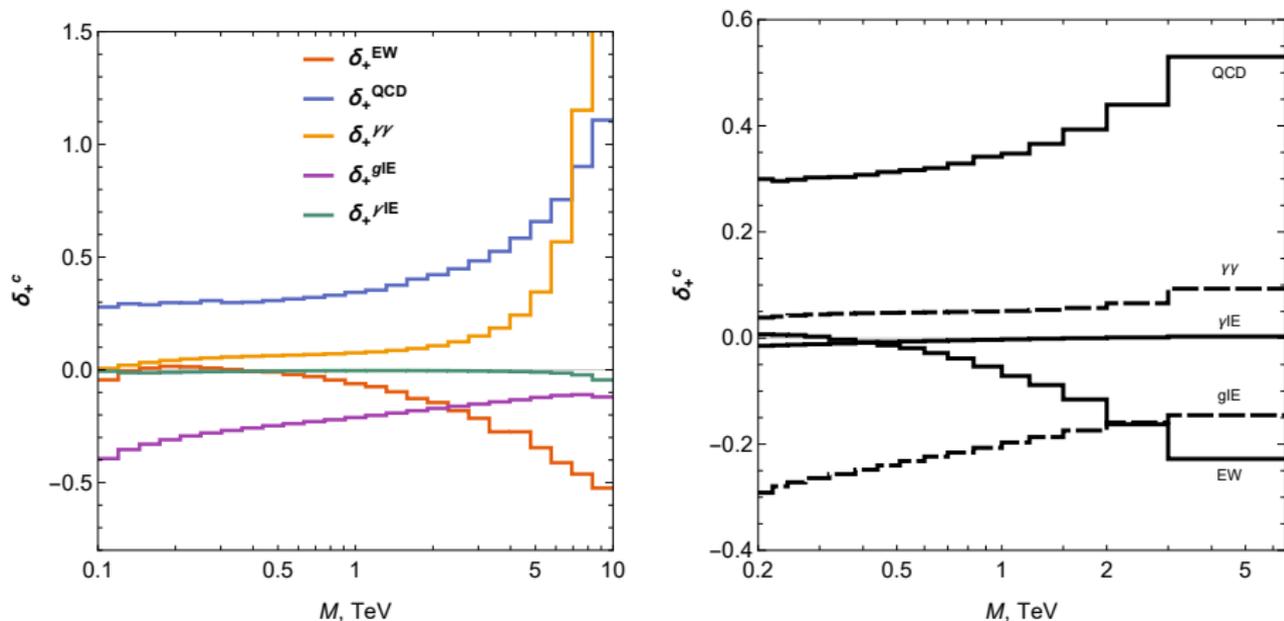


Figure 8: Additive relative corrections δ_+ (left – MRST'04, right – NNPDF'24) for Run3 of CMS LHC ($\mu^+\mu^-$ -production, $|y| < 2.5$).

Relative corrections δ_- for Run3 of CMS LHC

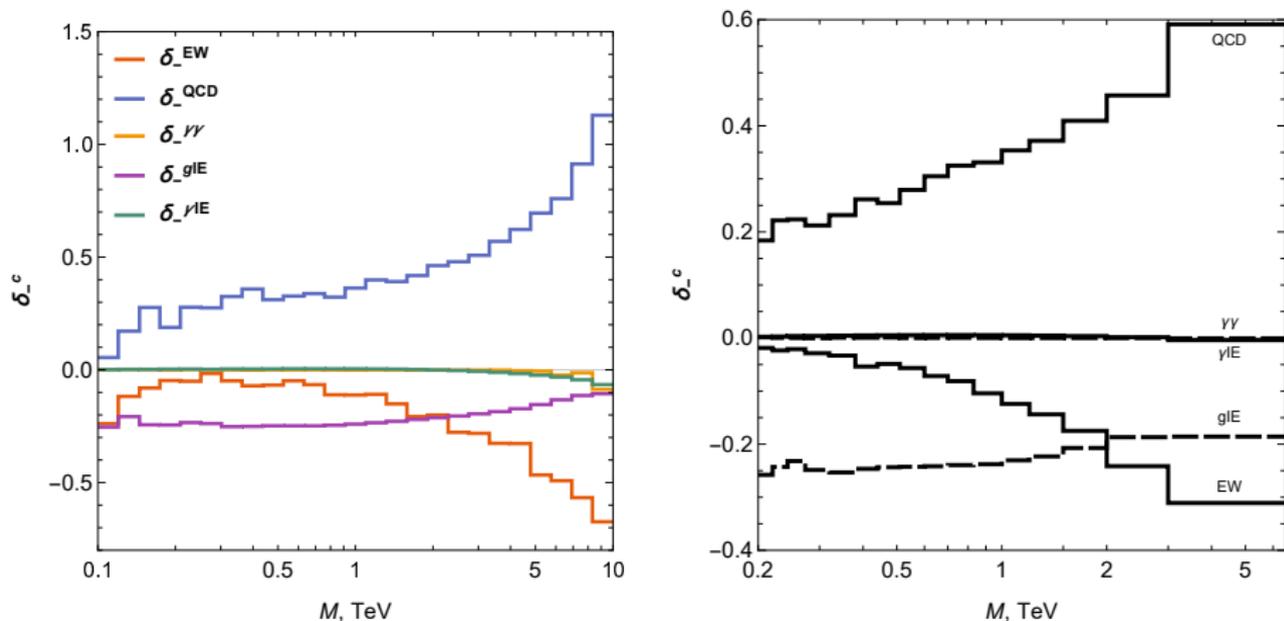


Figure 9: Additive relative corrections δ_+ (left – MRST'04, right – NNPDF'24) for Run3 of CMS LHC ($\mu^+\mu^-$ -production, $|y| < 2.5$).

Net effect for relative corrections (Run3 of CMS LHC)

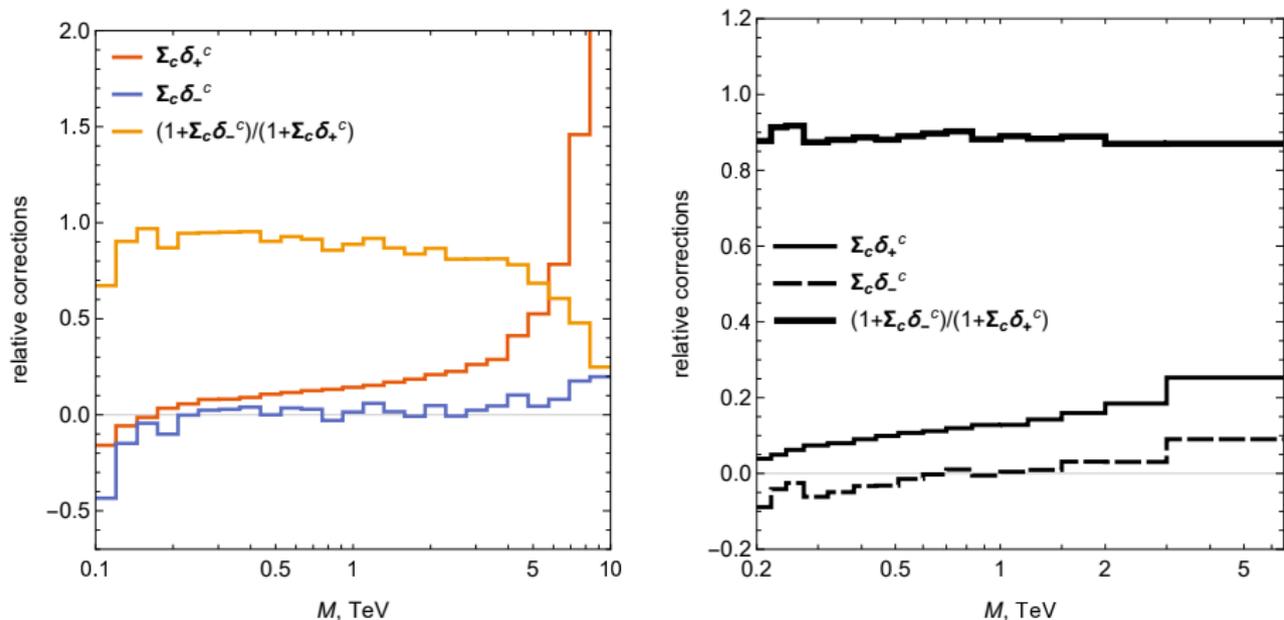


Figure 10: Total relative corrections (left – MRST'04, right – NNPDF'24) for Run3 of CMS LHC ($\mu^+ \mu^-$ -production, $|y| < 2.5$).

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

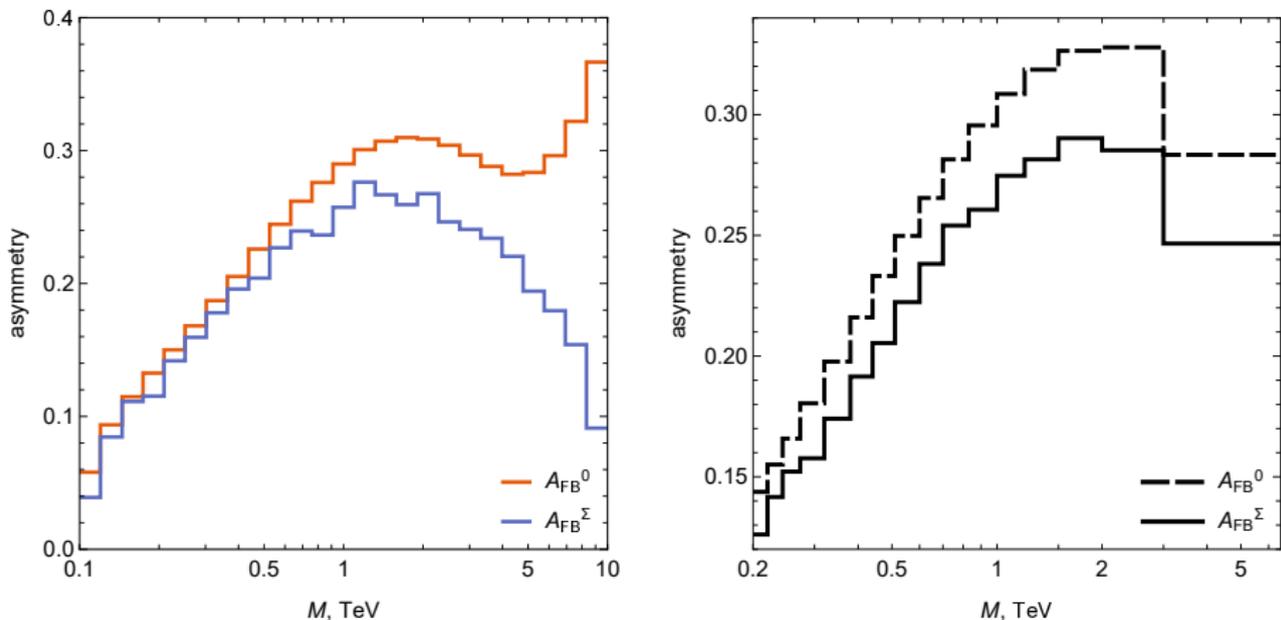


Figure 11: Forward-backward asymmetry A_{FB} (left – MRST'04, right – NNPDF'24) for Run3 of CMS LHC ($\mu^+\mu^-$ -production, $|y| < 2.5$).

- **The g and γ Inverse Emission** in dilepton production has been studied. It has been ascertained that the considered in Run 3 region IE effect changes the cross sections and A_{FB} **significantly**.
- **The net result** (NLO EW DY + NLO QCD DY + NLO $\gamma\gamma$ -fusion + IE) to A_{FB} has been studied using **additive relative corrections technics**.
- The results are published in:
 - g Inverse Emission – V. A. Zykunov, Phys. At. Nucl. **88**, 81 (2025),
 - γ Inverse Emission – V. A. Zykunov, e-Print: 2506.03736 [hep-ph].

Acknowledgement

- I am grateful to Organizers of this Conference for happy possibility to take part.
- I would like to thank the **RDMS CMS group** members for the stimulating discussions and **CERN (CMS Group)** for warm hospitality during my visits.
- This work was supported by the **Convergence-2025** Research Program of Republic of Belarus (Microscopic World and Universe Subprogram).
- The numerical calculation was performed partially by **“HybriLIT”** of the Laboratory of Information Technologies of JINR.