Phenomenology of the W and Z boson and of new massive states decays

at LHC and ILC (FCC) (project 10-138)

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- In Cracow since more than 40 years now, Monte Carlo programs, phenomenology tools for accelerator experiments are developed.
- My domain is theoretical and Monte Carlo side of Standard Model predictions for accelerator experiments, such as Aleph, Atlas, Belle 2, and now FCC too.
- Visits to french labs such as CPPM Marseille, Ecole Polytechnique, LAL Orsay and LAPP Annecy, were important for me and and projects. It started in 80's. Points covered last year in Strasbourg, now I will present last year results only.
- My talk focus:

(i) Precision Monte Carlo and anomalous dipole moments

(ii) Use of prepared tools, colaboration 11-142

- The usual scheme of collaboration remain: Cracow side perform evaluations of SM or New Physics predictions, prepare computer programs, french experimental side develop applications and define priorities.
- First, I will concentrate on applications for anomalous electric and magnetic dipole moments for applications at FCC and LHC conditions.
- Visits of physicists, often PhD students and post-docs, between Cracow and LAPP Annecy were frequent. Lots of discussions at CERN too.
- Now temporarily of Cracow, Kharkov professor, visits LAPP Annecy. His and mine talks are planned Nov 24 in Annecy. Participation of researcher from Ukraine, open opportunity for extension of activities and for new people. Hopefully international situation will improve, and in any case it is important to keep old links open.

- **Two examples:**

(i) `TauSpinner` for weight embedding anomalous dipole moment into pp collision simulation samples.

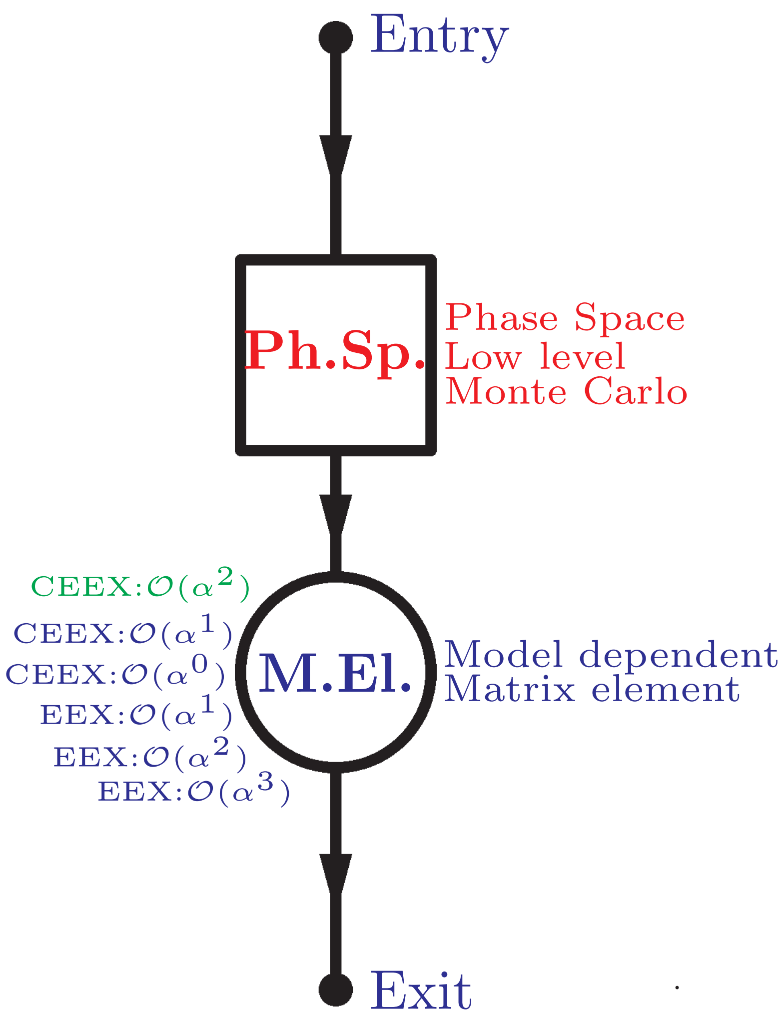
(ii) Algorithm and results of anomalous moment weights, calculated simultaneously with run of `KKMC` Monte Carlo for $e^+e^- \to l^+l^-(n\gamma)$ at low energies and now also for FCC center of mass energies.

(iii) I recall results from e-Print: 2307.03526 Sw. Banerjee, A.Yu. Korchin,, E. Richter-Was, Z. Was, *Electron-positron, parton-parton and photon-photon production of τ-lepton pairs: anomalous magnetic and electric dipole moments spin effects*.

(iv) May be these examples offer hints for applications outside HEP?

(v) NOTE: weights – ratios of matrix element squared, calculated in well defined points of phase space, but with distinct physics assumptions.

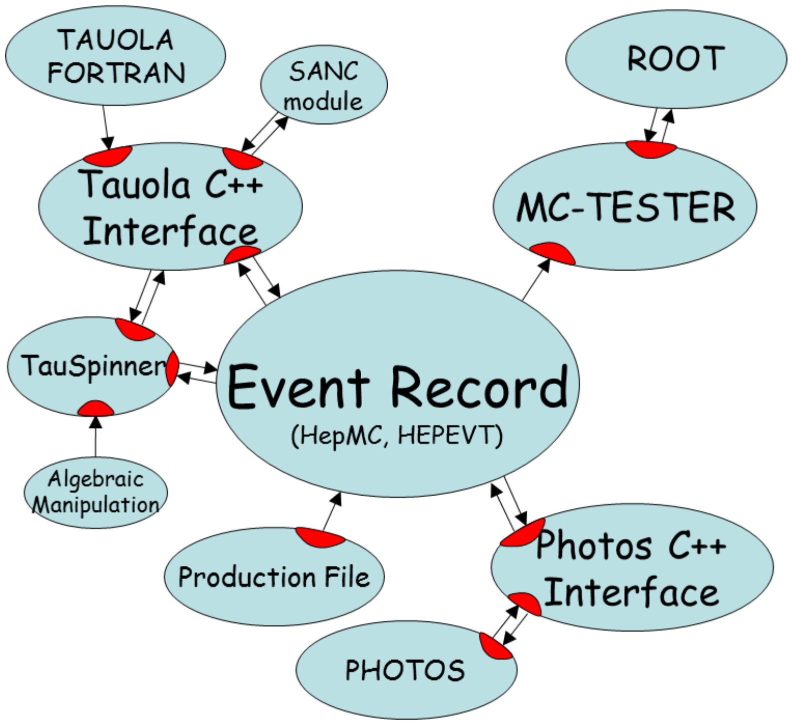
KKMC follow textbook principle “matrix element $\times$ full phase space”



- Phase-space Monte Carlo simulator is a module producing “raw events” (including importance sampling for possible intermediate resonances/singularities)
- Library of Matrix Elements; input for “model weight”; independent module
- This was used already for LEP precision Monte Carlos, like KKMC. Now it is used for Belle (FCC ...) collaboration for τ lepton pair production with decays and multi-photon radiation.
- Correlated samples techniques. Lots of technicalities collected in Phys. Rev. D41 (1990) 1425.
- Solutions useful for New Physics event weights!

approximate phase space and Event record

`TauSpinner` **communicate through event record:**



- That is advantageous: simultaneous event generation and weight calculation:

variants of New Physics models re-use the same (stored) events with detector response.

TauSpinner construction requires:

- Good control of theory.
- Good understanding of tools on user side.
- Rigorous checks on event record contents.

Simultaneous generation and weight calculation:

- easier to control and to assure precision for New Physics.
- Convenient for authors, less so for users.

Add extra interactions:

To start: M^{SM} and M^{SM+NP} are needed.

• OK, for **anomalous magnetic/electric dipole** moments implementation in $e^+e^- \to \tau^+\tau^-(n\gamma)$ process (τ decays included).

• Seem trivial, but one has to keep in mind practical details.

• I will say little about reliability proofs, even though they are essential.

• Important is to preserve SM (interfering-) bulk of the process!

• Check if factorization properties for NP match with what is in SM. Precision requirements for New Physics implementation are not high. Use of interpolated Born configurations in presence of hard bremsstrahlung photons is OK.

• For New Physics weights evaluation simplified kinematic (see last year slides on details and limitations) is used.

Add extra interactions:

Formalism for $\tau^+\tau^-$: phase space $\times$ M.E. squared

- Because narrow τ width (τ propagator works as Dirac δ), cross-section for $f\bar{f} \to \tau^+\tau^- Y; \tau^+ \to X^+\bar{\nu}; \tau^- \to \nu\nu$ reads (norm. const. dropped):

$$d\sigma = \sum_{spin} |\mathcal{M}|^2 d\Omega = \sum_{spin} |\mathcal{M}|^2 d\Omega_{prod}\, d\Omega_{\tau^+}\, d\Omega_{\tau^-}$$

$$\mathcal{M} = \sum_{\lambda_1\lambda_2=1}^{2} \mathcal{M}^{prod}_{\lambda_1\lambda_2}\, \mathcal{M}^{\tau^+}_{\lambda_1} \mathcal{M}^{\tau^-}_{\lambda_2}$$

- Pauli matrices orthogonality $\delta^{\lambda'}_{\lambda}\delta^{\bar{\lambda}'}_{\bar{\lambda}} = \sum_\mu \sigma^\mu_{\lambda\bar{\lambda}}\sigma^{\lambda'\bar{\lambda}'}_\mu$ completes condition for production/decay separation with τ spin states.

- **core formula of spin algorithms, wt is product of density matrices of production and decays**, $0 < wt < 4$, $< wt >= 1$ useful properties.

$$d\sigma = \Big(\sum_{spin} |\mathcal{M}^{prod}|^2\Big)\Big(\sum_{spin} |\mathcal{M}^{\tau^+}|^2\Big)\Big(\sum_{spin} |\mathcal{M}^{\tau^-}|^2\Big) wt\; d\Omega_{prod}\, d\Omega_{\tau^+}\, d\Omega_{\tau^-}$$

Add extra interactions:

Simplified kinematic for NP implementation. Cross section:

$$wt_{ME} = \Big(\sum_{spin} |\mathcal{M}^{prod\ SM+NP}|^2\Big) / \Big(\sum_{spin} |\mathcal{M}^{prod\ SM}|^2\Big)$$

Complicated is spin weight

$$wt_{spin} = \Big(\sum_{ij} R_{ij}^{SM+NP} h_+^i h_-^j\Big) / \Big(\sum_{ij} R_{ij}^{SM} h_+^i h_-^j\Big)$$

The R_{ij} depend on kinematic of τ-pair production, $h_\pm^i$ on $\tau^\pm$ decays.

Spin quantization frames orientation need care. It must be the same for production and decay.

We use $\mathtt{KKMC}$ routines to transfer $h_\pm^i$ to lab frame and another routines to transfer back to $\tau^\pm$ but oriented as in New Physics calculation.

In this way reference frames are OK and impact of photons on phase space parametrisations is under control.

Solution works for all τ decays!

Add extra interactions:

Tree of frames used for spin; must be tuned between production and decay

Figure 2

$$
\begin{tikzcd}
\mathrm{RS}(\tau^+) \arrow[r, "B_3(\eta_\tau)"] & \mathrm{QMS} \arrow[d, dash, "R_1(-\theta)"] & \mathrm{RS}(\tau^-) \arrow[l, "B_3(-\eta_\tau)"'] \\
\mathrm{RS}_1(e^+) \arrow[r, "B_3(\eta_e)"] \arrow[d, dash, "R_3(\phi)"] & \mathrm{CMS}_1 \arrow[d, dash, "R_3(\phi)"] & \mathrm{RS}_1(e^-) \arrow[l, "B_3(-\eta_e)"'] \arrow[d, dash, "R_3(\phi)"] \\
\mathrm{RS}(e^+) \arrow[r, "B_3(\eta_e)"] & \mathrm{CMS} & \mathrm{RS}(e^-) \arrow[l, "B_3(-\eta_e)"']
\end{tikzcd}
$$

(2a)

$$
\begin{tikzcd}
\mathrm{RS}(\tau^+) \arrow[r, "B_3(\eta_\tau)"] & \mathrm{QMS} \arrow[d, dash, "R_1(-\theta_2)"] & \mathrm{RS}(\tau^-) \arrow[l, "B_3(-\eta_\tau)"'] \\
& \mathrm{QMS}_\gamma \arrow[d, dash, "B_3(\zeta)R_3(\phi)"] & \\
& \mathrm{CMS}_\gamma \arrow[d, dash, "R_1(-\theta_1)"] & \\
\mathrm{RS}_1(e^+) \arrow[r, "B_3(\eta_e)"] \arrow[d, dash, "R_3(\phi_1)"] & \mathrm{CMS}_1 \arrow[d, dash, "R_3(\phi_1)"] & \mathrm{RS}_1(e^-) \arrow[l, "B_3(-\eta_e)"'] \arrow[d, dash, "R_3(\phi_1)"] \\
\mathrm{RS}(e^+) \arrow[r, "B_3(\eta_e)"] & \mathrm{CMS} & \mathrm{RS}(e^-) \arrow[l, "B_3(-\eta_e)"']
\end{tikzcd}
$$

(2b)

Add extra interactions:

Reference frames of host program

- **Use of host program frames is convenient but not essential:** better precision, no need to worry about bremsstrahlung impact etc. Use of internal program variables is helpful too.
- **On the other hand**, this prevents re-use of events for distinct models
- **So far nothing new since last year slides ...**
- **NEW:**
  For FCC (`KKMC`): extension of re-weighting algorithm to FCC center of mass energies, electroweak corrections included.
  For LHC (`TauSpinner`): $\gamma\gamma$ parton level processes added, explicit spin correlation matrix R_{ij} prepared for quark initialized processes as well.

Amplitudes for reweighting

$$\mathcal{M}^{IBA} = \frac{e^2 Q_f Q_i}{s} V_{fi}(s,t)\,\gamma_\mu \otimes \gamma^\mu + \left(\frac{g_Z}{2}\right)^2 \frac{Z_{fi}(s,t)}{d(s)}\,\gamma_\mu[v_i(s,t) - a_i\gamma_5] \otimes \gamma^\mu[v_f(s,t) - a_i\gamma_5], \quad (1)$$

$$v_i(s,t) = T_{3i} - 2Q_i s_W^2 K_i(s,t), \qquad v_f(s,t) = T_{3f} - 2Q_f s_W^2 K_f(s,t), \quad (2)$$

$$V_{fi}(s,t) = \Gamma_{vp}(s) + \left(\frac{g_Z}{e}\right)^2 s_W^4 Z_{fi}(s,t) \frac{s}{d(s)}[K_{fi}(s,t) - K_f(s,t)K_i(s,t)], \quad (3)$$

$$\mathcal{M}^{DM} = \frac{e^2 Q_f Q_i}{s} V_{fi}(s,t)\,\gamma_\mu \otimes [A\gamma^\mu + \frac{(p_+ - p_-)^\mu}{2m}(A - iB\gamma_5)] + \left(\frac{g_Z}{2}\right)^2 \frac{Z_{fi}(s,t)}{d(s)}\,\gamma_\mu[v_i(s,t) - a_i\gamma_5] \otimes [X\gamma^\mu + \frac{(p_+ - p_-)^\mu}{2m}(X - iY\gamma_5)], \quad (4)$$

Complete amplitude $\mathcal{M} = \mathcal{M}^{IBA} + \mathcal{M}^{DM}$ (fermions spinors dropped).

Spin correlation matrix and results

At Z boson peak we get for leading parts:

$$
\begin{aligned}
R_{11}^{(Z)} &= -R_{22}^{(Z)} = -\frac{g_Z^4\, a_\tau^4\, \beta^2\, M_Z^2}{64\,\Gamma_Z^2}\, \sin^2(\theta), \\
R_{12}^{(Z)} &= R_{21}^{(Z)} = -\frac{g_Z^4\, a_\tau^3\, \beta\, M_Z^2}{32\,\Gamma_Z^2}\, \sin^2(\theta)\, \mathrm{Im}(X), \\
R_{13}^{(Z)} &= -R_{31}^{(Z)} = -\frac{g_Z^4\, a_\tau^3\, \beta^2\, M_Z^2}{64\,\Gamma_Z^2}\, \gamma \sin(2\theta)\, \mathrm{Im}(Y), \\
R_{23}^{(Z)} &= R_{32}^{(Z)} = -\frac{g_Z^4\, a_\tau^3\, \beta\, M_Z^2}{64\,\Gamma_Z^2}\, \gamma \sin(2\theta)\, \mathrm{Im}(X), \\
R_{14}^{(Z)} &= R_{41}^{(Z)} = -\frac{g_Z^4\, a_\tau^3\, \beta\, M_Z^2}{64\,\Gamma_Z^2}\, \gamma \sin(2\theta)\, \left[\mathrm{Re}(X) + v_\tau \gamma^{-2}\right], \\
R_{24}^{(Z)} &= -R_{42}^{(Z)} = \frac{g_Z^4\, a_\tau^3\, \beta^2\, M_Z^2}{64\,\Gamma_Z^2}\, \gamma \sin(2\theta)\, \mathrm{Re}(Y), \\
R_{34}^{(Z)} &= R_{43}^{(Z)} = -\frac{g_Z^4\, a_\tau^3\, \beta\, M_Z^2}{32\,\Gamma_Z^2}\, \Big\{\big(1 + \cos^2(\theta)\big)\, \left[v_\tau + \mathrm{Re}(X)\right] \\
&\quad + 2 v_\tau\, \beta\, \cos(\theta)\Big\}, \\
R_{44}^{(Z)} &= R_{33}^{(Z)} = \frac{g_Z^4\, a_\tau^4\, \beta^2\, M_Z^2}{64\,\Gamma_Z^2}\, \big(1 + \cos^2(\theta)\big),
\end{aligned}
\tag{5}
$$

where $\gamma = M_Z/(2m_\tau) \approx 25.7$ and $\beta \approx 1$.

Spin correlation matrix and results

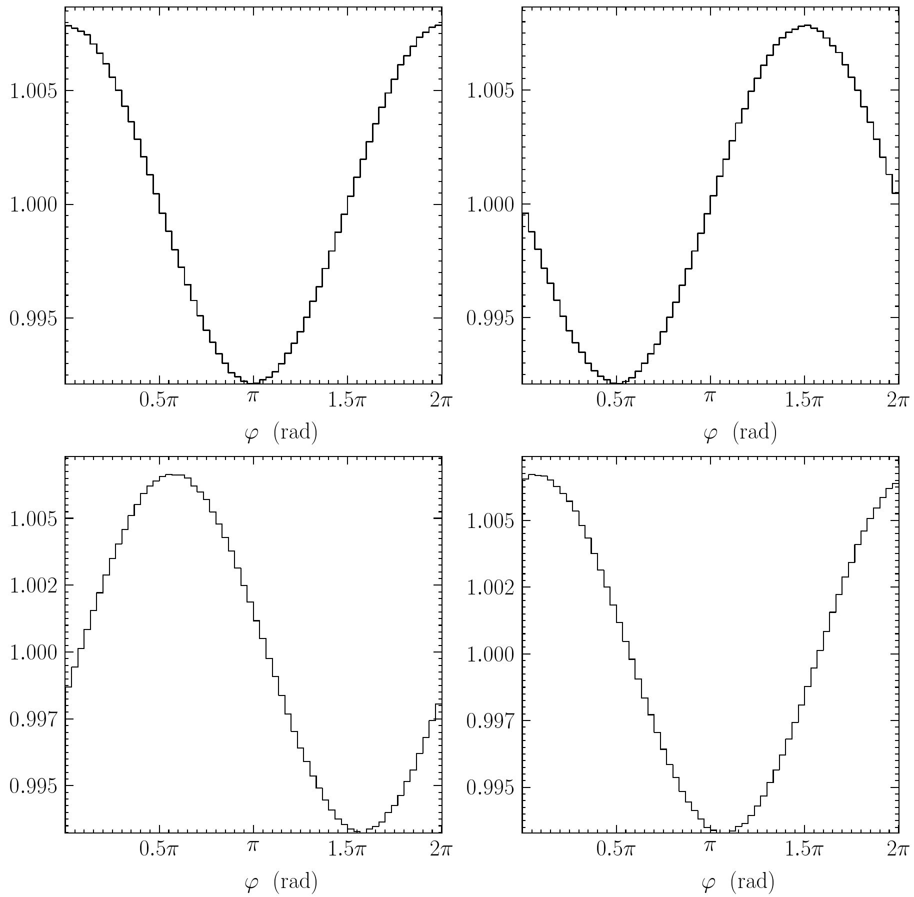


Figure 1: Ratio of number of events with and without weak dipole moments, in function of acoplanarity φ at $\sqrt{s} = M_Z$. The selected events of scattering angles $\cos(\theta) < 0$ are taken. The top left plot for $\mathrm{Re}(X) = 0.0004$, the top right plot for $\mathrm{Re}(Y) = 0.0004$, the bottom left for $\mathrm{Im}(X) = 0.0004$, and the bottom right for $\mathrm{Im}(Y) = 0.0004$ are taken . For the imaginary form-factors, additional constraint $E_{\pi^+} > E_{\bar{\nu}_\tau}$ is taken the τ^+ side. The form-factors $A(M_Z^2) = B(M_Z^2) = 0$ are set. The decays $\tau^- \to \pi^-\pi^0\nu$ and $\tau^+ \to \pi^+\nu$ are taken.

NEW: $\gamma\gamma \to \tau^+\tau^-$ parton level process.

We define the factor $D \equiv 1 - \beta^2 \cos^2\theta$. The elements of the matrix $R^{\gamma\gamma}_{i,j}$ and $R^{\gamma\gamma}_{44}$ (for brevity $A \equiv A(0)$ and $B \equiv B(0)$):

$$
\begin{aligned}
R^{\gamma\gamma}_{11} &= \frac{e^4}{8D^2}\big[-\beta^2(\beta^2-4A-2)\cos(4\theta)+4\beta^2(\beta^2-2)\cos(2\theta) \\
&\quad +4A\,(7\beta^2-8)-11\beta^4+22\beta^2-8\big], \\
R^{\gamma\gamma}_{12} &= -R^{\gamma\gamma}_{21} = \frac{e^4 B}{4D^2}\,\beta\left(\beta^2\cos(4\theta)+4\cos(2\theta)+15\beta^2-20\right), \\
R^{\gamma\gamma}_{13} &= R^{\gamma\gamma}_{31} = \frac{e^4}{2D^2}\,\gamma\,\beta^2\big[(\beta^2+A\,(\beta^2-2)-1)\cos(2\theta)+A\beta^2-\beta^2+1\big]\,|\sin(2\theta)|, \\
R^{\gamma\gamma}_{22} &= \frac{e^4}{8D^2}\big[-\beta^4\cos(4\theta)+4\beta^2(\beta^2+4A)\cos(2\theta)+16A\,(\beta^2-2) \\
&\quad -11\beta^4+16\beta^2-8\big], \\
R^{\gamma\gamma}_{23} &= -R^{\gamma\gamma}_{32} = \frac{e^4 B}{2D^2}\,\gamma\,\beta\,(\beta^2\cos(2\theta)-3\beta^2+2)\,|\sin(2\theta)|, \\
R^{\gamma\gamma}_{33} &= \frac{e^4}{8D^2}\big[\beta^2(\beta^2-4A-2)\cos(4\theta)-4\beta^4\cos(2\theta)+4A\,(9\beta^2-8) \\
&\quad +11\beta^4+2\beta^2-8\big], \\
R^{\gamma\gamma}_{44} &= \frac{e^4}{8D^2}\big[-\beta^4\cos(4\theta)+4\beta^2(\beta^2-4A-2)\cos(2\theta)-16A\,(\beta^2-2) \\
&\quad -11\beta^4+8\beta^2+8\big].
\end{aligned} \tag{6}
$$

These elements satisfy the condition $R^{\gamma\gamma}_{i,j}(\theta)=R^{\gamma\gamma}_{i,j}(\pi-\theta)$ for $0\leq\theta\leq\pi$, as follows from identity of the photons.

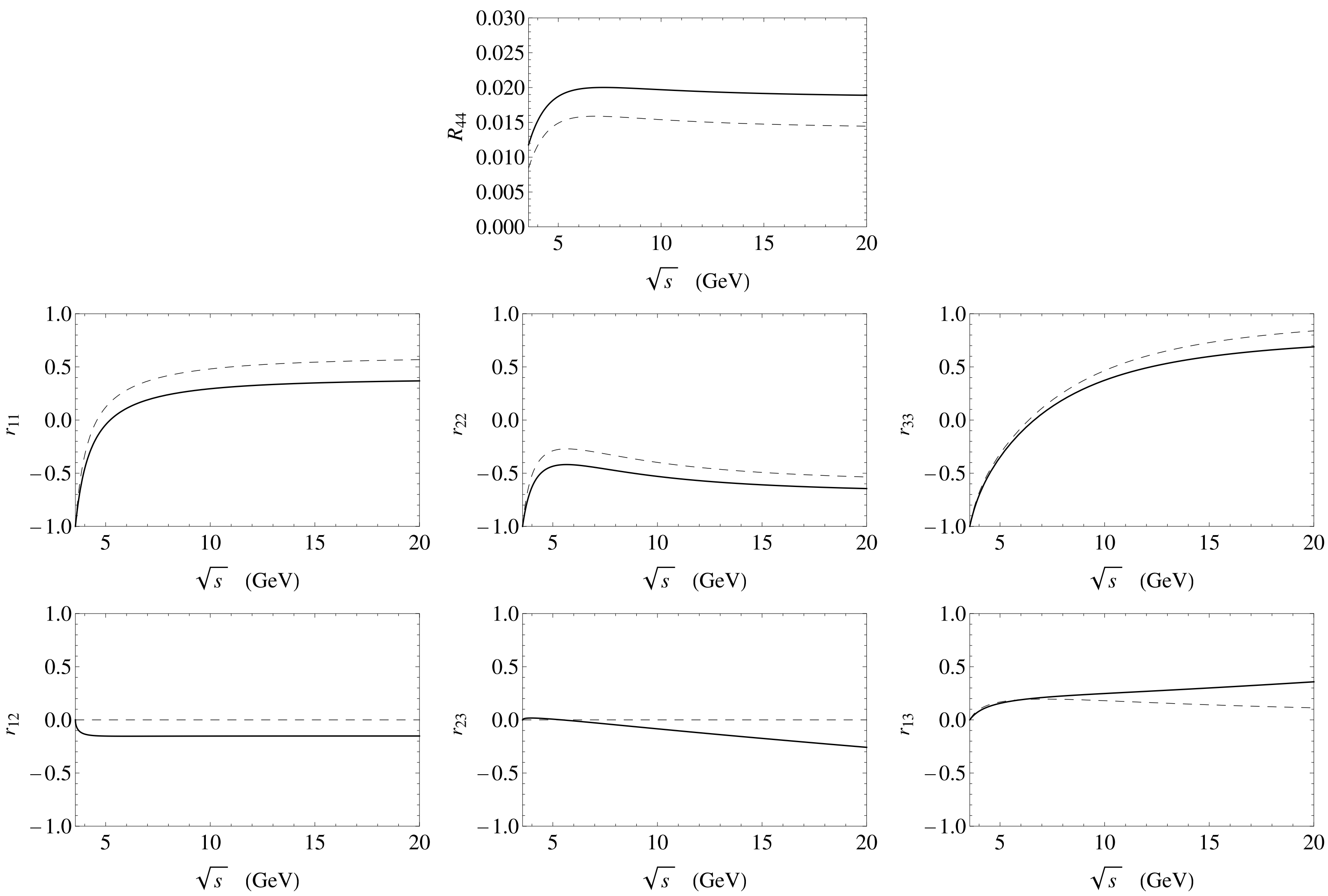


Figure 2: Energy dependence of $R_{44}^{\gamma\gamma}$ and $r_{i,j}^{\gamma\gamma}$. Solid lines are calculated for the values $A = 0.1$ and $B = 0.1$; dashed lines – for $A = B = 0$. The angle θ is chosen $\pi/3$.

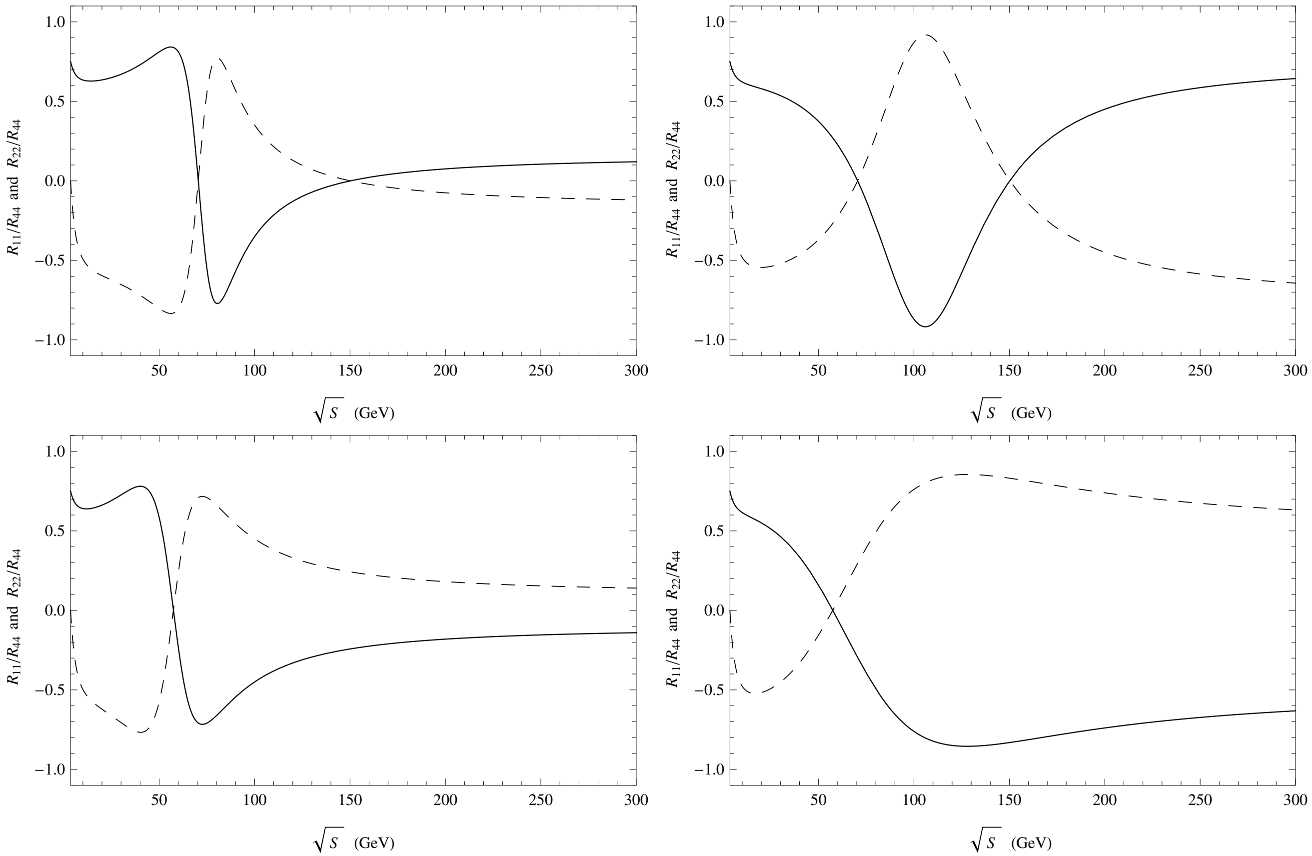


Figure 3: Transverse spin-correlation components r_{11} (solid lines) and r_{22} (dashed lines) for the $u\,\bar{u}$ (top plots) and $d\,\bar{d}$ (bottom plots) initial states. The angle θ of quark vs τ^- is chosen $\pi/3$ in the left plots and $2\pi/3$ in the right plots. The effective couplings of Z to quarks from Table **??** are used. Dipole moments are not included.

Thank you for listening