Model-independent search for Z' at hadron colliders

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Abstract

The model-independent search for Z' boson at hadron collides is described. In this approach, not only the mass $m_{Z'}$ but also the couplings of the Z' to fermions are arbitrary parameters. The key observation here is that the specific relations between the couplings take place. The most important is the universality of the axial-vector coupling a_f^2 which is the same for all the leptons and quarks and independent of the type of them. So, just this parameter is a pronounced signal of the particle.

On the base of these relations, we construct the observable which uniquely picks out the signals of the virtual (as well as real) Z' boson for both type the Tevatron and LHC experiments. This variable accounts for the specific role of the a_f^2 coupling and suppresses the signals of other possible virtual states. It is constructed on the base of the well known process: $\bar{q}q \to \mu^+\mu^-(e^+e^-)$, with PDFs taken into consideration. Then, the results of the current experiments can be analyzed and compared with the ones of the model-dependent searches.

Outline

- Abelian Z' boson, its status and models
- Model-dependent and model-independent searches for Z'
- Effective lagrangian at low energies
- Model-independent (RG) relations between Z' couplings
- Estimates from LEP1 and LEP2 experiments
- Z' production cross-section and width
- Observable to pick out a_f in Drell-Yan process
- Observable for model-independent estimations of $m_{Z'}$
- One parameter and two parameters fittings of a_f and $m_{Z'}$
- Discussion

Abelian Z' boson

- determined the SM parameters and particle masses at the level of radiative corrections
- afforded an opportunity for searching for signals of new heavy particles beyond the SM.

At LEP2 experiments. No new particles were discovered,
the energy scale of new physics was estimated as of the order 1 TeV.

- Experiments at LHC - new stage in high energy physics.

A lot of extended models includes Z' gauge boson – a massive neutral vector particle associated usually with an extra $U(1)$ subgroup of the underlying group.

Z' is predicted by a number of GUTs (the E_6 and $SO(10)$ based models – LR, , $\chi - \psi$ and so on are often discussed).

- Present day status of Abelian Z'

$$\Big(SU(2)_{ew} \times U(1)_Y \times SU(3)_c\Big) \times \tilde{U}(1)_{\tilde{Y}} \tag{1}$$

Model-dependent search for Z' at LEP2 gave: $m_{Z'} > 400 - 800$ GeV.

Model-dependent results from Tevatron: $m_{Z'} > 800$ GeV,

and LHC: $m_{Z'} > 2$ TeV.

Approaches of searches for Z'

- Model-dependent (MD) searching for Z'

Effects of Z' are calculated within a specific model beyond SM.
Free parameters are $m_{Z'}$ and $\Gamma_{Z'}$.
All the couplings are fixed.
It is usually believed that Z' is a narrow state with small width: $\Gamma/m_{Z'} \ll 1$.
About 100 Z' models are discussed.

- Model-independent (MinD) searching for Z'

Analysis is covering a lot of models.

Effects of Z' are calculated within a specific low energy effective lagrangian.

Relations which hold in any model of the Z'

Gulov, Skalozub (2000)

Assumptions:

1) Only one Z' exists at energy scale $1 - 10$ TeV;

2) At low energies, it phenomenologically is described by the known effective lagrangian (see, below);

3) Z' is decoupled at considered energies and the SM or the THDM are used as low energy effective theories;

4) SM is the subgroup of the extended gauge group. So, the only origin of possible three-level interaction Z' with the SM particles is $Z - Z'$ mixing.

These relations (RG relations) are the consequences of a renormalizability (see review Gulov, Skalozub (2010)).

Effective lagrangian at low energies

At low energies, the Z'-boson can manifest itself by means of the couplings to the SM fermions and scalars as a virtual intermediate state. The Z-boson couplings are also modified due to a Z–Z' mixing.

Significant signals beyond the SM can be inspired by the couplings of renormalizable types. Such couplings can be described by adding new $\tilde{U}(1)$-terms to EW covariant derivatives D^{ew} in the lagrangian Cvetic (1986), Degrassi (1989)

$$L_f = i\sum_{f_L} \bar{f}_L\gamma^\mu\left(\partial_\mu - \frac{ig}{2}\sigma_a W^a_\mu - \frac{ig'}{2}B_\mu Y_{f_L} - \frac{i\tilde{g}}{2}\tilde{B}_\mu\tilde{Y}_{f_L}\right) f_L \quad (2)$$

$$+ i\sum_{f_R} \bar{f}_R\gamma^\mu\left(\partial_\mu - ig' B_\mu Q_f - \frac{i\tilde{g}}{2}\tilde{B}_\mu\tilde{Y}_{f_R}\right) f_R,$$

$$L_\phi = \left|\left(\partial_\mu - \frac{ig}{2}\sigma_a W^a_\mu - \frac{ig'}{2}B_\mu Y_\phi - \frac{i\tilde{g}}{2}\tilde{B}_\mu\tilde{Y}_\phi\right)\phi\right|^2, \quad (3)$$

where left-handed doublets, $f_L = (f_u)_L, (f_d)_L$, right-handed singlets, $f_R = (f_u)_R, (f_d)_R$.

$g, g', \tilde{g}$ are the charges associated with the $SU(2)_L, U(1)_Y$, and the Z' gauge groups, respectively,

σ_a are the Pauli matrices, Q_f denotes the charge of f in positron charge units, Y_ϕ is the $U(1)_Y$ hypercharge, and $Y_{f_L} = -1$ for leptons and $1/3$ for quarks.

Generators $\tilde{Y}_{f_L}$= diag$(\tilde{Y}_{f_u}, \tilde{Y}_{f_d})$ and $\tilde{Y}_\phi$ = diag$(\tilde{Y}_{\phi,1}, \tilde{Y}_{\phi,2})$ are diagonal 2×2 matrices.

As for the scalar sector, the lagrangian can be simply generalized for the case of SM with two Higgs doublets (THDM).

Lagrangian (3) leads to the Z–Z' mixing.

the mixing angle θ_0 is

$$\theta_0 = \frac{\tilde{g}\sin\theta_W\cos\theta_W}{\sqrt{4\pi\alpha_{\mathrm{em}}}}\frac{m_Z^2}{m_{Z'}^2}\tilde{Y}_\phi + O\left(\frac{m_Z^4}{m_{Z'}^4}\right), \tag{4}$$

where θ_W is the SM Weinberg angle, and α_{em} is the electromagnetic fine structure constant.

Other Z' couplings

$$v_f = \tilde{g}\frac{\tilde{Y}_{L,f} + \tilde{Y}_{R,f}}{2}, \qquad a_f = \tilde{g}\frac{\tilde{Y}_{R,f} - \tilde{Y}_{L,f}}{2}. \tag{5}$$

Lagrangian (2) leads to the interactions:

$$\begin{aligned}
\mathcal{L}_{Z\bar{f}f} &= \frac{1}{2}Z_\mu\bar{f}\gamma^\mu\left[(v^{\mathrm{SM}}_{fZ} + \gamma^5 a^{\mathrm{SM}}_{fZ})\cos\theta_0 + (v_f + \gamma^5 a_f)\sin\theta_0\right] f, \\
\mathcal{L}_{Z'\bar{f}f} &= \frac{1}{2}Z'_\mu\bar{f}\gamma^\mu\left[(v_f + \gamma^5 a_f)\cos\theta_0 - (v^{\mathrm{SM}}_{fZ} + \gamma^5 a^{\mathrm{SM}}_{fZ})\sin\theta_0\right] f,
\end{aligned} \tag{6}$$

where f is a SM fermion state; v^{SM}_{fZ}, a^{SM}_{fZ} are the SM couplings of the Z-boson.

At low energies, the dimensionless couplings

$$\bar{a}_f = \frac{m_Z}{\sqrt{4\pi} m_{Z'}} a_f, \quad \bar{v}_f = \frac{m_Z}{\sqrt{4\pi} m_{Z'}} v_f, \tag{7}$$

which can be constrained by experiments.

MinD (RG) relations between Z' couplings

In a particular model, $\tilde{Y}_\phi$, $\tilde{Y}_{L,f}$, $\tilde{Y}_{R,f}$ take some specific values.
If the model is unknown, these parameters
remain potentially arbitrary numbers.

- This is not the case

if the underlying extended model is a renormalizable one.

The couplings are correlated(Gulov, Skalozub (2000)):

$$\tilde{Y}_{\phi,1} = \tilde{Y}_{\phi,2} \equiv \tilde{Y}_\phi, \qquad \tilde{Y}_{L,f} = \tilde{Y}_{L,f^*}, \quad \tilde{Y}_{R,f} = \tilde{Y}_{L,f} + 2T_{3f}\, \tilde{Y}_\phi. \tag{8}$$

Here f and f^* are the partners of the $SU(2)_L$ fermion doublet ($l^* = \nu_l, \nu^* = l, q_u^* = q_d$ and $q_d^* = q_u$),

T_{3f} is the third component of weak isospin.

Z' couplings to the vector and axial-vector fermion currents (5),

$$v_f - a_f = v_{f^*} - a_{f^*}, \qquad a_f = T_{3f}\tilde{g}\tilde{Y}_\phi. \tag{9}$$

Hence it follows:

- The couplings of Z' to the axial-vector fermion current have the universal absolute value proportional to the Z' coupling to the scalar doublet.
- Z–Z' mixing angle (4) can be determined by the axial-vector coupling.

Since a_f is universal, we introduce the notation

$$\bar{a} = \bar{a}_d = \bar{a}_{e^-} = -\bar{a}_u = -\bar{a}_\nu, \tag{10}$$

and find

$$\theta_0 = -2\bar{a}\frac{\sin\theta_W \cos\theta_W}{\sqrt{\alpha_{em}}}\frac{m_Z}{m_{Z'}}. \tag{11}$$

From (9) it follows for each fermion doublet

$$\bar{v}_{f_d} = \bar{v}_{f_u} + 2\bar{a}. \tag{12}$$

Thus, Z' couplings can be parameterized by seven independent couplings

$$\bar{a}, \bar{v}_u, \bar{v}_c, \bar{v}_t, \bar{v}_e, \bar{v}_\mu, \bar{v}_\tau. \tag{13}$$

Estimates from LEP1 and LEP2 experiments

MinD limits on Z' couplings from LEP1 and LEP2
at $1-2\sigma$ CL (Gulov, Skalozub (2010))

- Axial-vector coupling $\bar{a}$ can be constrained by LEP1 (through the mixing angle) and LEP2 ($e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$) data with ML value

$$\bar{a}^2 = 1.3 \times 10^{-5} \tag{14}$$

and 2σ CL interval:

$$0 < \bar{a}^2 < 3.61 \times 10^{-4}. \tag{15}$$

- Electron vector coupling $\bar{v}_e$ can be constrained by LEP2 ($e^+e^- \to e^+e^-$)

  2σ CL interval:

$$4 \times 10^{-5} < \bar{v}_e^2 < 1.69 \times 10^{-4}. \tag{16}$$

Constrain $\bar{v}_u, \bar{v}_c, \bar{v}_t, \bar{v}_\mu, \bar{v}_\tau$ by the widest interval from 2σ CL intervals for $\bar{v}_e$, $\bar{a}$:

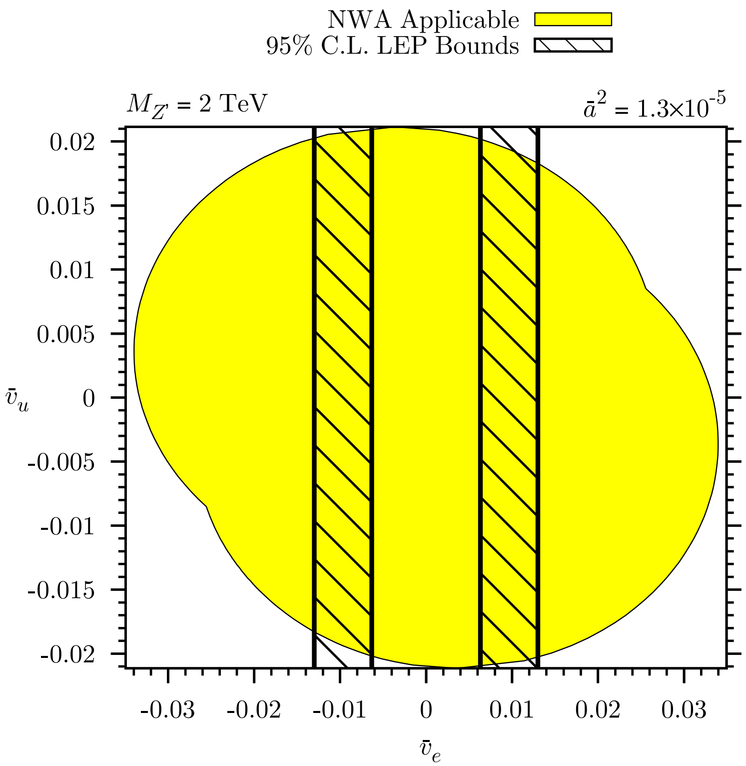
$$0 < \bar{v}_{other}^2 < 4 \times 10^{-4}. \tag{17}$$

Expected parameters for Z' searching

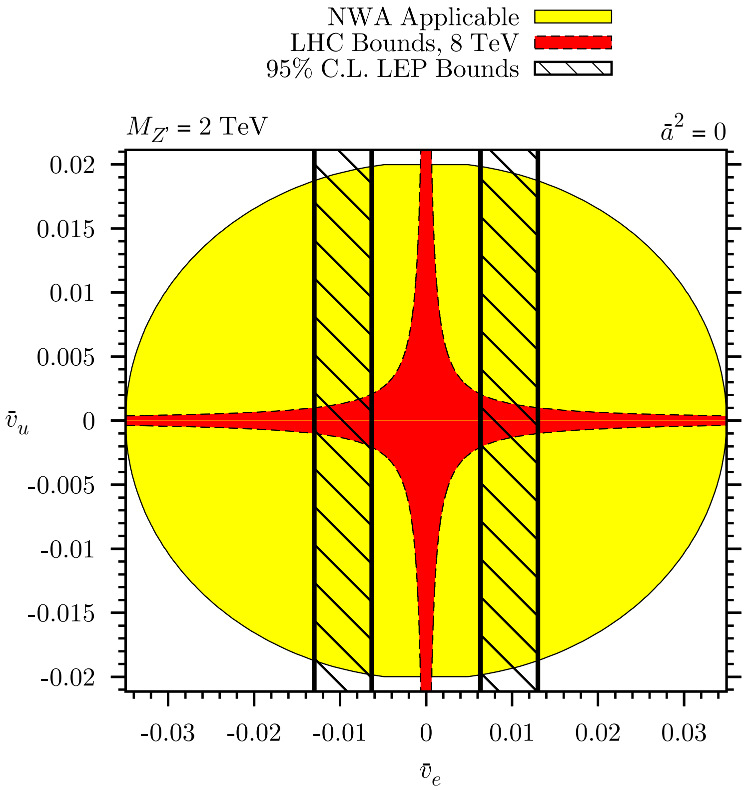
- spin 1
- charge 0
- mass $m_{Z'} \leq 2$ TeV, width $\Gamma_{Z'} = 150 - 200$ GeV
- mixing angle Θ_0
- coupling $\tilde{g}$
- axial-vector coupling constant $\bar{a}^2 = 1.3 \times 10^{-5}$
- vector coupling constant $4 \times 10^{-5} < \bar{v}_e^2 < 1.69 \times 10^{-4} (2\sigma\ CL)$

Z' production CS and width

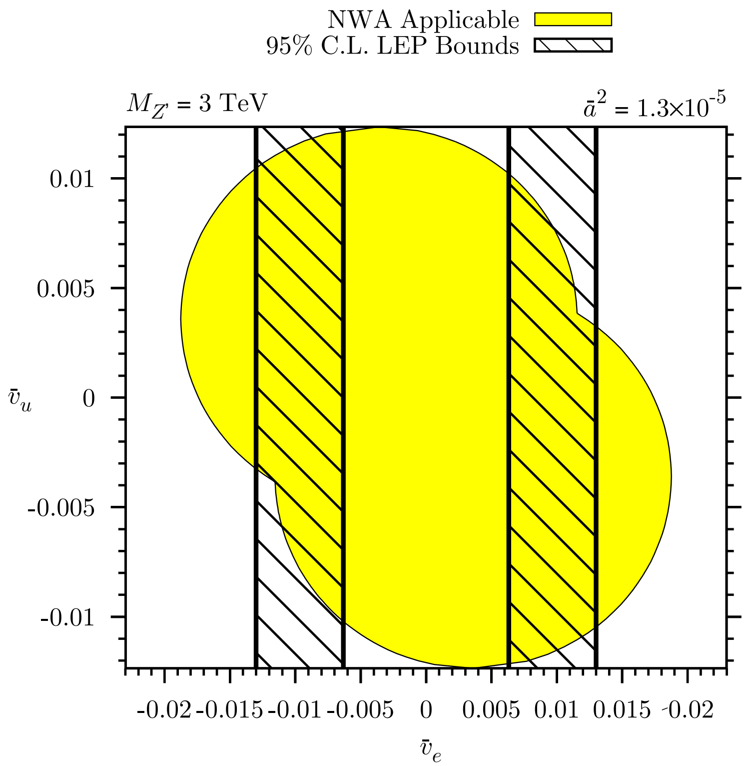
Gulov, Kozhushko (2013)

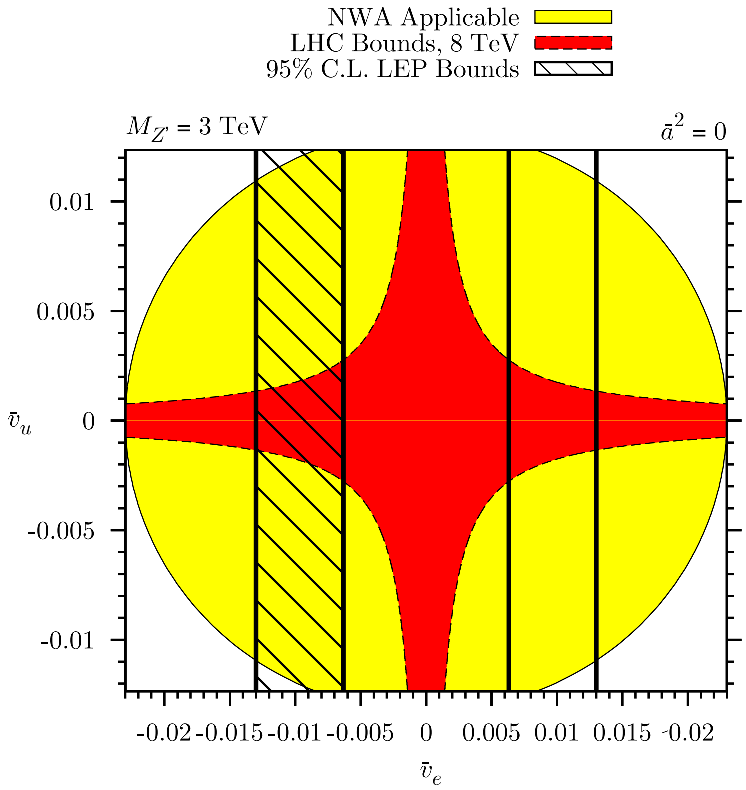


NWA Applicable
95% C.L. LEP Bounds
$M_{Z'}$ = 2 TeV
$\bar{a}^2 = 1.3\times10^{-5}$
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
$\bar{v}_u$
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
$\bar{v}_e$



NWA Applicable
LHC Bounds, 8 TeV
95% C.L. LEP Bounds
$M_{Z'}$ = 2 TeV
$\bar{a}^2$ = 0
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
$\bar{v}_u$
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
$\bar{v}_e$


NWA Applicable
95% C.L. LEP Bounds
$M_{Z'}$ = 3 TeV
$\bar{a}^2$ = 1.3×10^{-5}
0.01
0.005
$\bar{v}_u$
0
-0.005
-0.01
-0.02 -0.015 -0.01 -0.005 0 0.005 0.01 0.015 0.02
$\bar{v}_e$


NWA Applicable
LHC Bounds, 8 TeV
95% C.L. LEP Bounds
$M_{Z'}$ = 3 TeV
$\bar{a}^2$ = 0
$\bar{v}_u$
$\bar{v}_e$
0.01
0.005
0
-0.005
-0.01
-0.02 -0.015 -0.01 -0.005 0 0.005 0.01 0.015 -0.02

Observable for $\bar{a}$ in Drell-Yan process

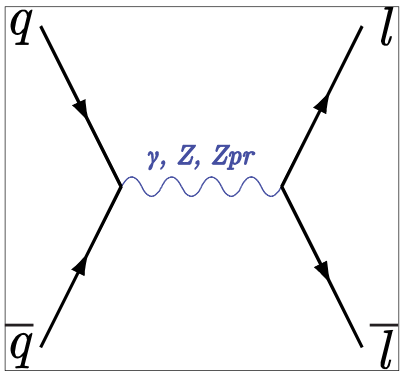
Skalozub, Tukhtarov (2012)

- Cross-section (CS) $q\bar{q} \to l\bar{l}$

At parton level, Drell-Yan process

$$p\bar{p}(pp) \to Z' \to l\bar{l} + X \tag{18}$$

is reduced to quark annihilations $q\bar{q} \to (Z, \gamma, Z') \to l\bar{l}$.

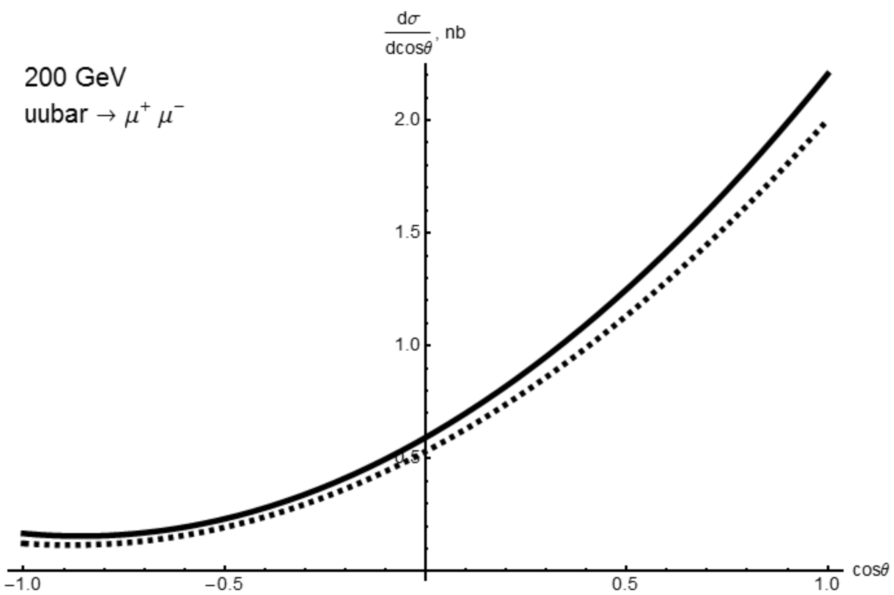


CM system

We plot Figures for $m_{Z'} = 1.2\ TeV, \Gamma_{Z'} = 120\ GeV$.

Structure of differential CS

Differential CS of quark-antiquark pairs to leptons



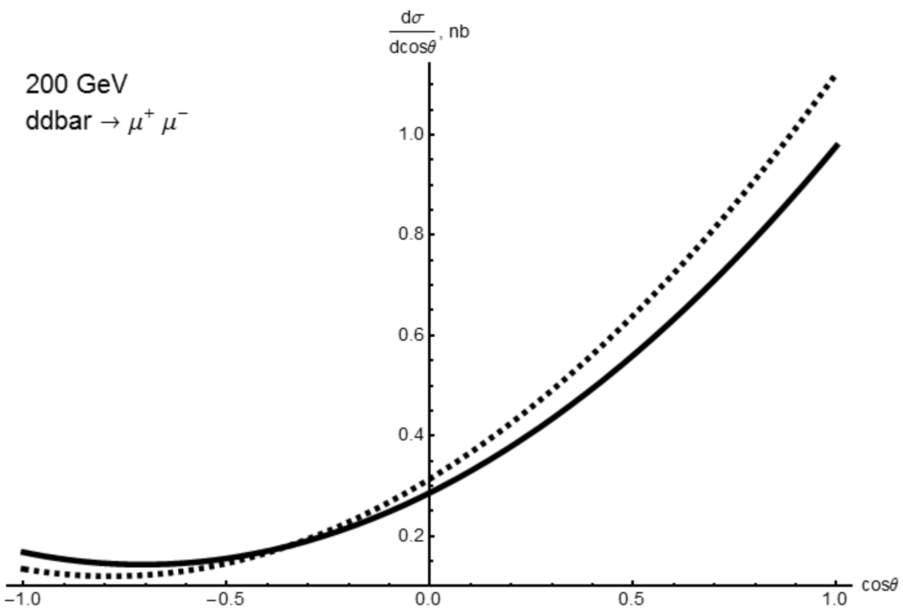


Fig.2

Structure of the Z' boson contributions

$$
\begin{aligned}
\Delta\frac{d\sigma}{dz} &= \frac{d\sigma}{dz} - \Big(\frac{d\sigma}{dz}\Big)_{SM} = F_a(E,z)\bar{a}^2 \\
&+ F_{av}(E,z)a\bar{v}_q + F_{vv}(E,z)\bar{l}\bar{v}_q + ..., z = \cos\theta
\end{aligned} \quad (19)
$$

where

$$
F_a = \sum_{q=u,d} f_a^q(E,z), F_{av} = \sum_{q=u,d} f_{av}^q(E,z), F_{vv} = \sum_{q=u,d} f_{vv}^q(E,z)... \quad (20)
$$

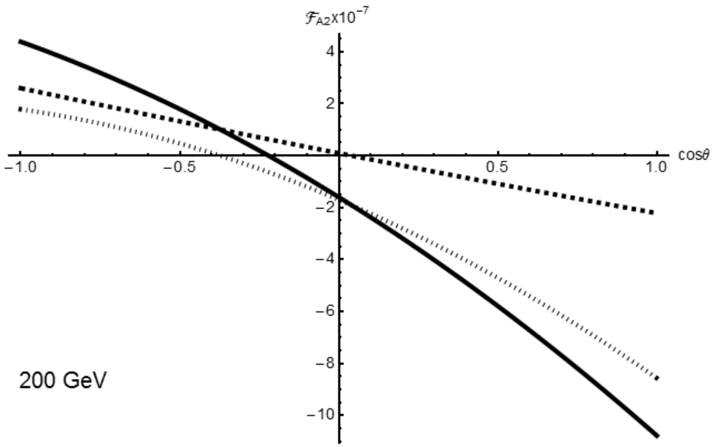
Behavior of form-factors

$F(E,z)$ - solid line;

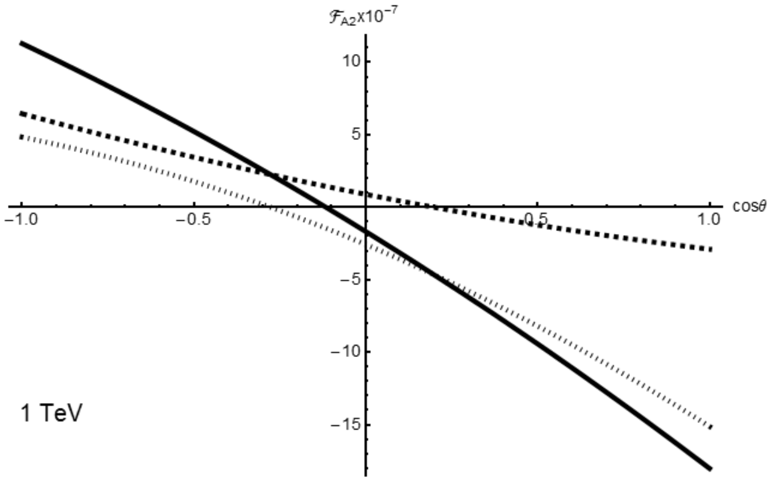
$f^u(E,z)$ - dashed line;

$f^d(E,z)$ - point line.

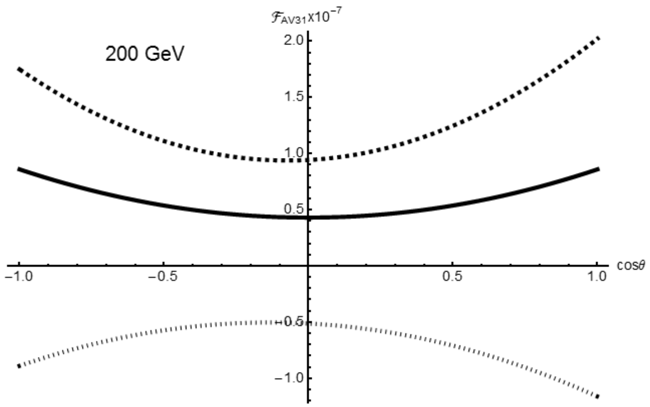
form-factor $F_a(E, z)$



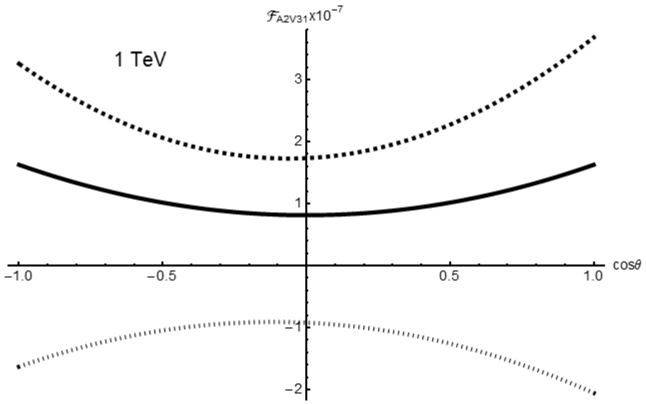
form-factor $F_a(E, z)$



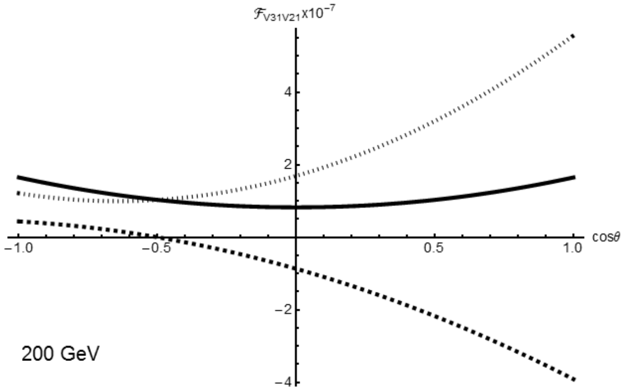
form-factor $F_{av}(E, z)$



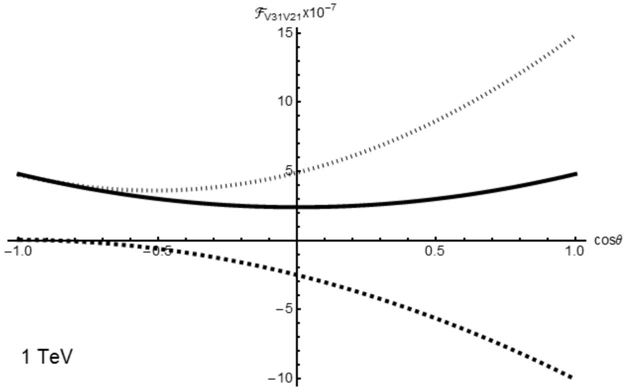
form-factor $F_{av}(E, z)$

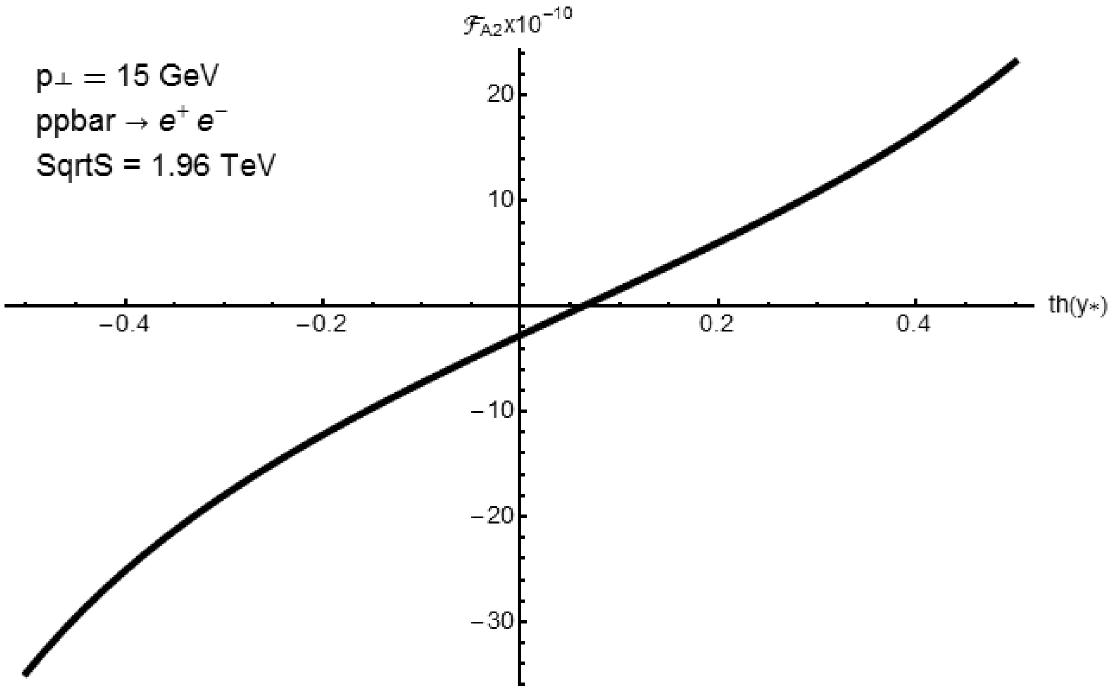


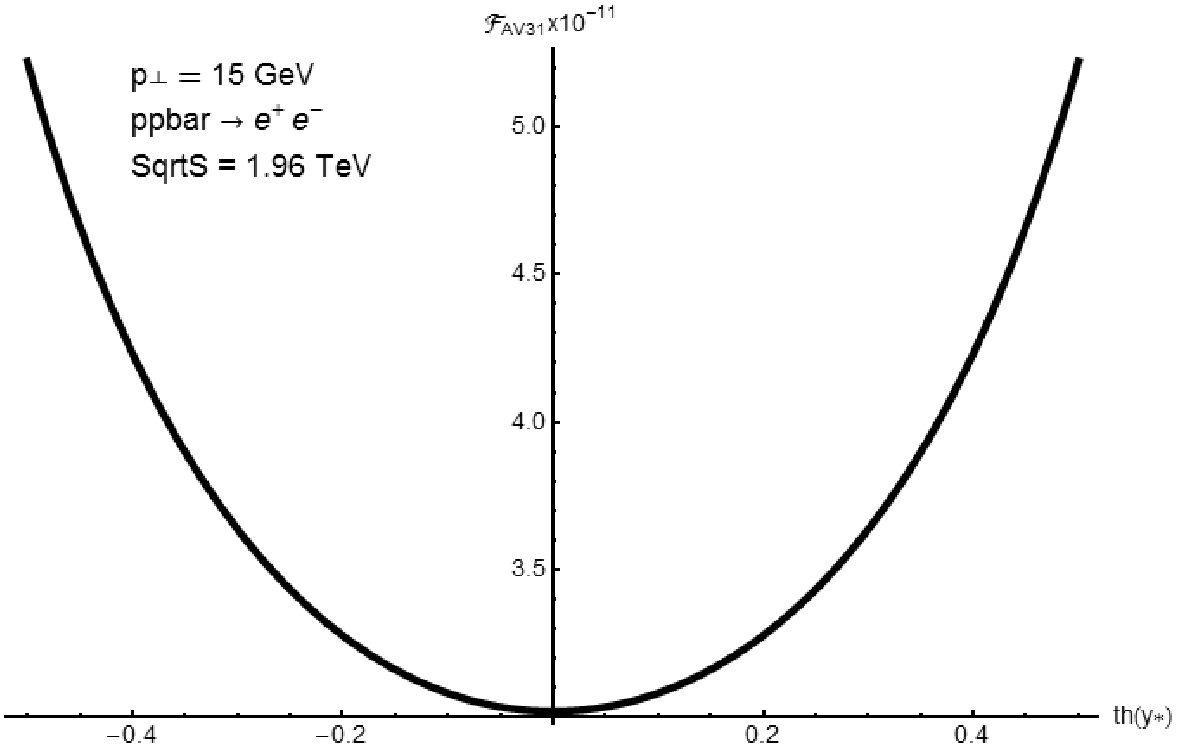
form-factor $F_{vv}(E, z)$



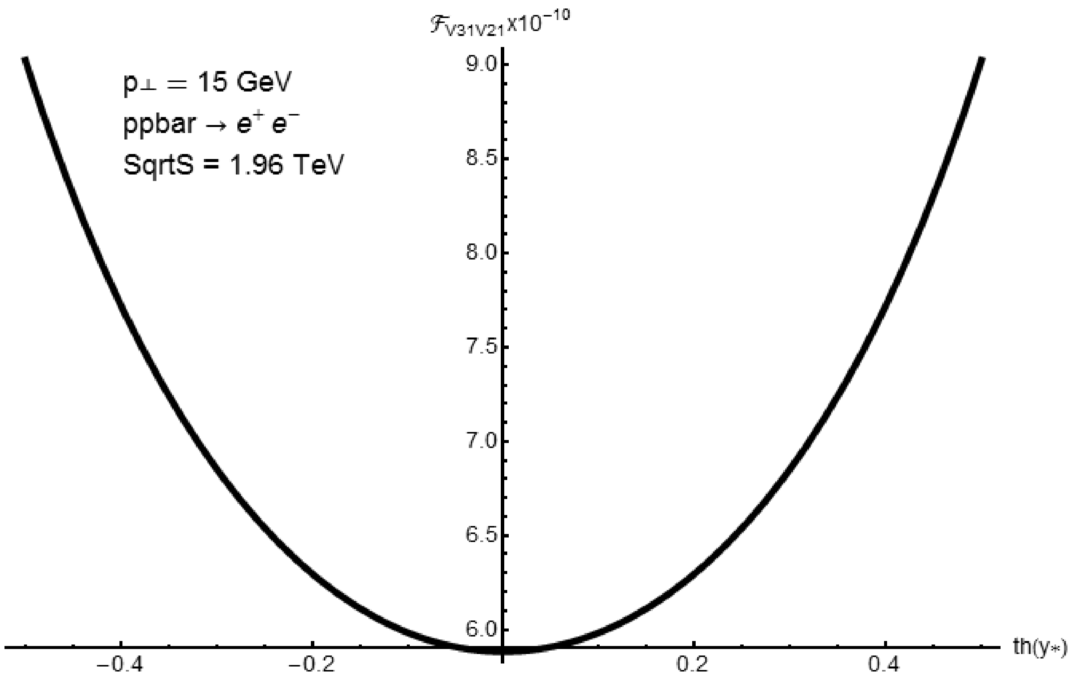
form-factor $F_{vv}(E, z)$




$\mathcal{F}_{A2}$x10^{-10}
p⊥ = 15 GeV
ppbar → $e^+ e^-$
SqrtS = 1.96 TeV
20
10
−10
−20
−30
−0.4
−0.2
0.2
0.4
th(y*)

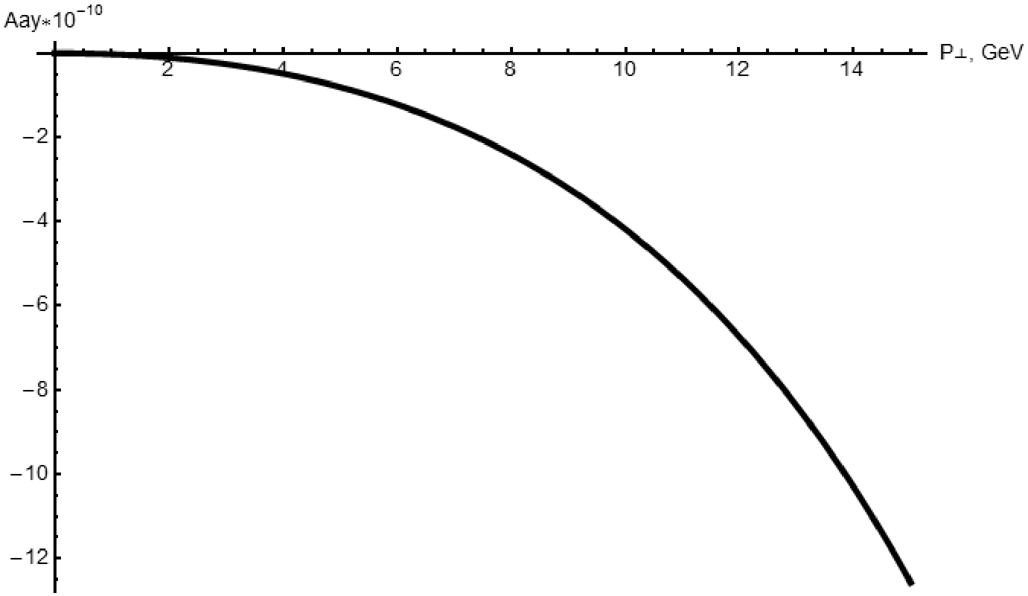


$\mathcal{F}_{AV31}$x10^{-11}
p⊥ = 15 GeV
ppbar → $e^+ e^-$
SqrtS = 1.96 TeV
5.0
4.5
4.0
3.5
th(y*)
−0.4
−0.2
0.2
0.4



$\mathcal{F}_{V31V21}$x10^{-10}
p⊥ = 15 GeV
ppbar → $e^+ e^-$
SqrtS = 1.96 TeV
9.0
8.5
8.0
7.5
7.0
6.5
6.0
−0.4
−0.2
0.2
0.4
th(y*)

Function $A^{ay}(p_\perp)$ ($\sqrt{S} = 1.96$ TeV)



Forward-backward asymmetry A_{FB}

Accounting for symmetries of form-factors, we introduce A_{FB}:

$$A_{FB} = \frac{\int\limits_{-1}^{0} \Delta \frac{d\sigma}{dz} dz - \int\limits_{0}^{1} \Delta \frac{d\sigma}{dz} dz}{\int\limits_{-1}^{1} \Delta \frac{d\sigma}{dz} dz} \tag{21}$$

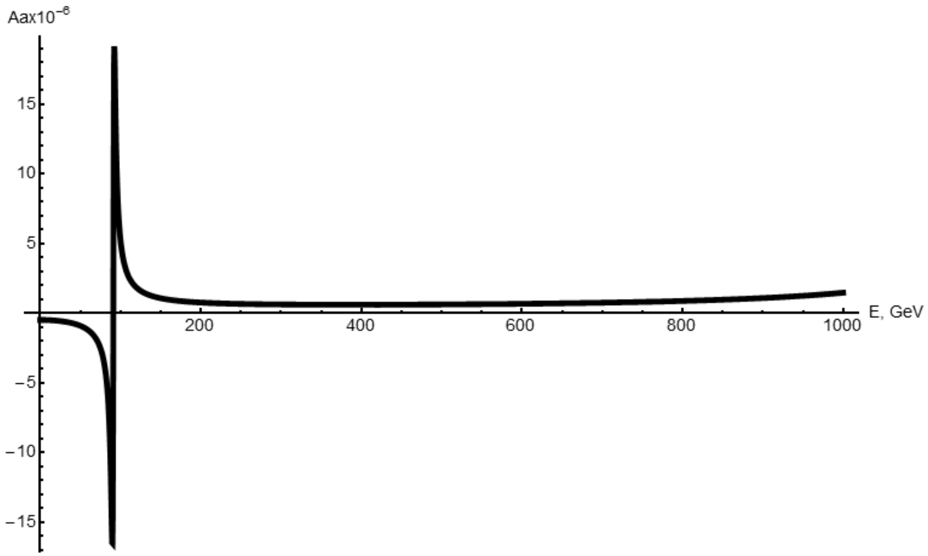
It is determined by

$$A_{FB} = \sum_{i=a,av,vv} A^i, \tag{22}$$

and

$$A^a (\int\limits_{-1}^{1} \Delta \frac{d\sigma}{dz} dz) = \int\limits_{-1}^{0} F_a dz - \int\limits_{0}^{1} F_a dz, ... \tag{23}$$

Function $A^a(E)$



Values of quark asymmetries A^a, A^{av}, A^{vv}

E (GeV)	100	300	600	800	1000
$A^a \times 10^{-7}$	51.7	6.2	6.7	8.7	14.7
$A^{av} \times 10^{-23}$	1610	1.3	1.3	2.6	5.3
$A^{vv} \times 10^{-23}$	74	0	0	0	0

Table 1.

- Differential CS $p\bar{p} \to l\bar{l}$

$$\sigma_{AB} = \sum_q \int_0^1 dx_1 \int_0^1 dx_2 f_{q,A}(x_1, Q^2) f_{\bar{q},B}(x_2, Q^2) \times \sigma(q\bar{q} \to f\bar{f}), \tag{24}$$

$Q^2 = m_{Z'}$. Packet MSTW PDF was used.

Rapidities $y = \frac{1}{2}(y_{l^+} - y_{l^-}); Y = \frac{1}{2}(y_{l^+} - y_{l^-})$.

Variables in lepton CM system
Rapidities $y_{l^+} = -y_{l^-} = y_*$.

Now, differential CS (19) reads:

$$\Delta\frac{d\sigma}{dz} = F_a(\sqrt{s}, p_\perp, z)\bar{a}^2 + F_{av}(\sqrt{s}, p_\perp, z)\bar{a}\bar{v}_u + F_{vv}(\sqrt{s}, p_\perp, z)\bar{v}_l\bar{v}_u + ..., z = \tanh y_*. \quad (25)$$

For Tevatron energy $\sqrt{s} = 1.96$ TeV.

Form-factors F_a, F_{av}, F_{vv}

Fig. 4

Asymmetry A_y with PDF accounted for:

$$A_y = \frac{\int\limits_{-z_{max}}^{0} \Delta\frac{d\sigma}{dz}dz - \int\limits_{0}^{z_{max}} \Delta\frac{d\sigma}{dz}dz}{\int\limits_{-z_{max}}^{z_{max}} \Delta\frac{d\sigma}{dz}dz}. \tag{26}$$

It is determined by

$$A_{iy} = \sum_{i=a,av,vv} A^i, \tag{27}$$

and

$$A^{ay} = (\int\limits_{-z_{max}}^{z_{max}} \Delta\frac{d\sigma}{dz}dz) = \int\limits_{-z_{max}}^{0} F_a dz - \int\limits_{0}^{z_{max}} F_a dz, ... \tag{28}$$

Values of quark asymmetries A^{ay}, A^{avy}, A^{vvy}

$p_\perp$ (GeV)	5	10	15
$A^{ay} \times 10^{-11}$	- 8.0	-41.8	- 125.7
$A^{avy} \times 10^{-27}$	0	4.8	22.6
$A^{vvy} \times 10^{-27}$	-3.2	- 25.8	- 51.7

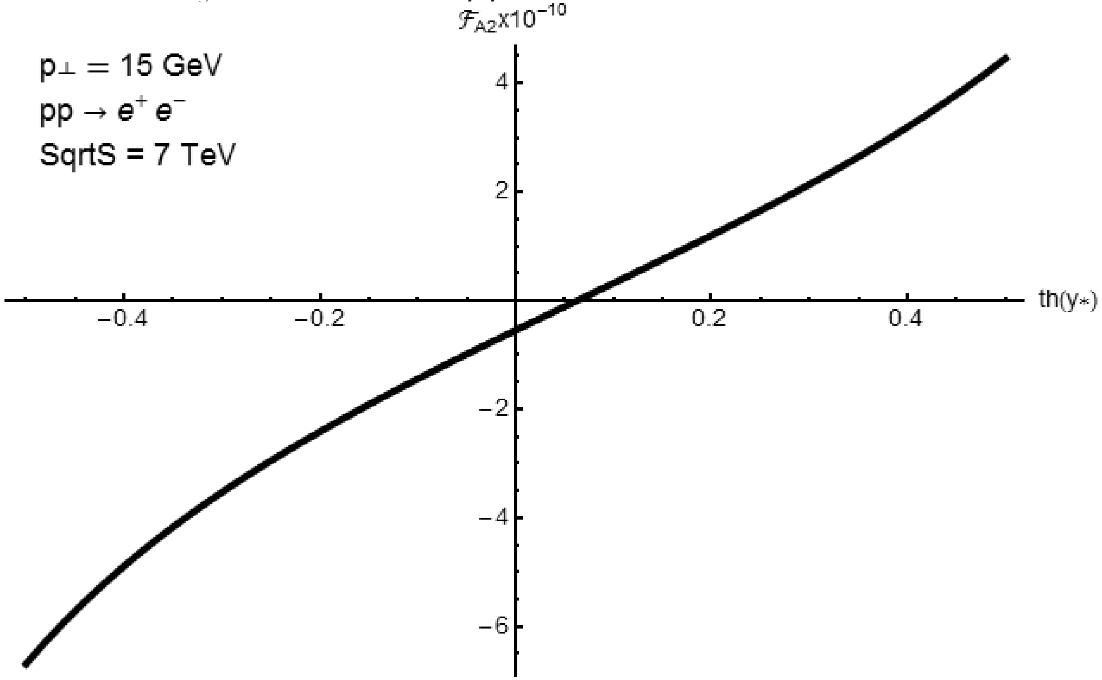
Table 2.

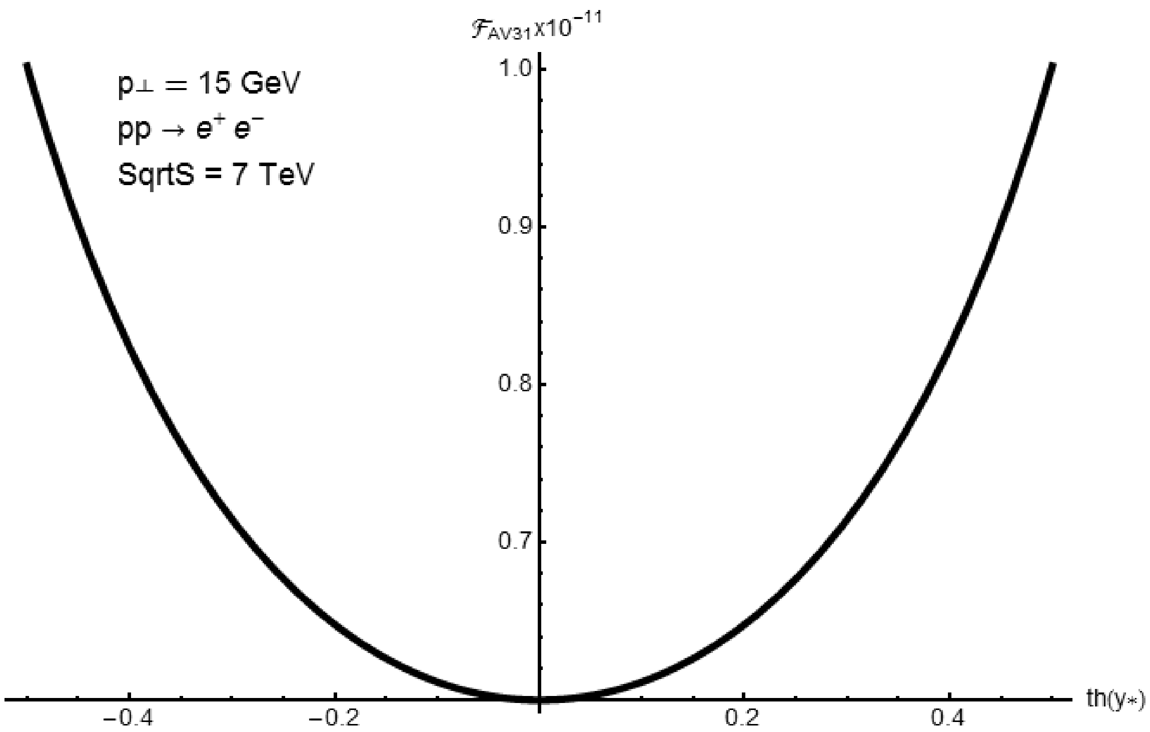
Asymmetries of pure quark processes

preserve all their properties been expressed in terms of $p_\perp, y_+, y_-$ for final leptons.

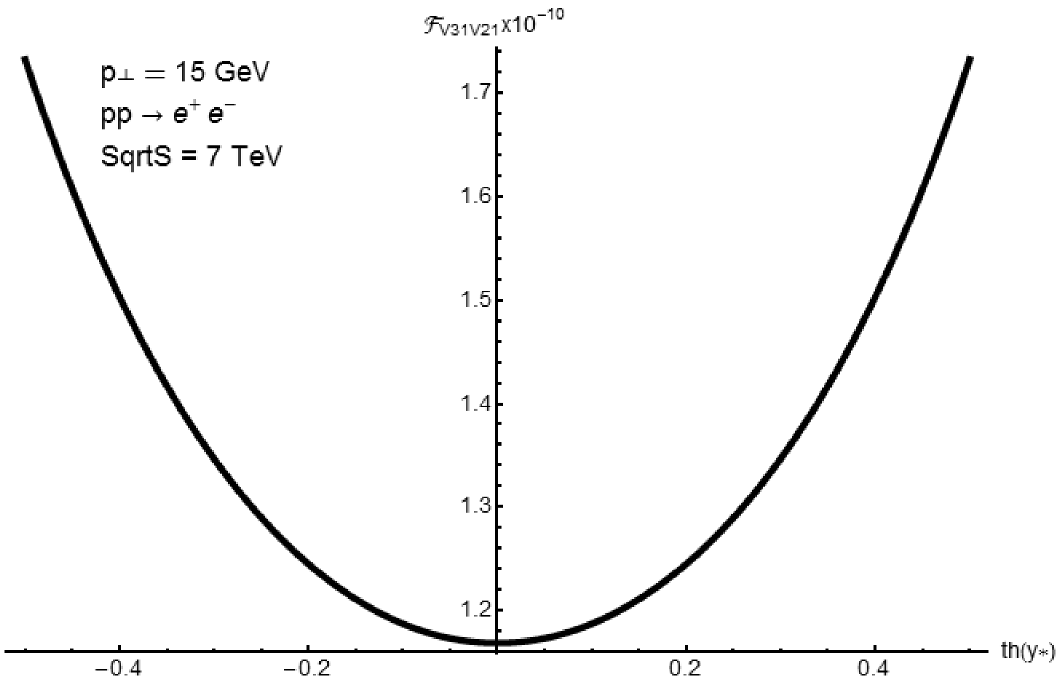
After integration of A^{ay} over $p_\perp$ we get equations for $\bar{a}^2$ and $m_{Z'}$.

Estimate of asymmetries for pp PDF



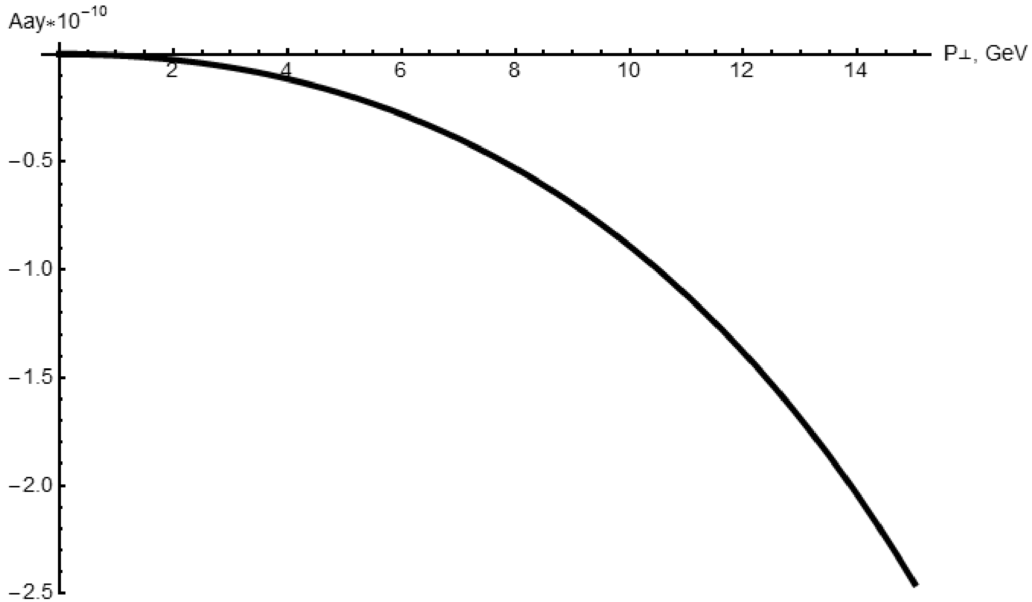


$\mathcal{F}_{AV31}$x10^{-11}
1.0
0.9
0.8
0.7
$p_\perp = 15$ GeV
$pp \to e^+ e^-$
SqrtS = 7 TeV
−0.4
−0.2
0.2
0.4
th(y*)



$\mathcal{F}_{V31V21}$x10^{-10}
p⊥ = 15 GeV
pp → $e^+ e^-$
SqrtS = 7 TeV
1.7
1.6
1.5
1.4
1.3
1.2
−0.4
−0.2
0.2
0.4
th(y*)

Function $A^{ay}(p_\perp)$ ($\sqrt{S} = 7$ TeV)



Values of quark asymmetries A^{ay}, A^{avy}, A^{vvy}

$p_\perp$ (GeV)	5	10	15
$A^{ay} \times 10.^{-11}$	-1.9	-8.9	-24.5
$A^{avy} \times 10.^{-29}$	5.0	80.8	404.0
$A^{vvy} \times 10.^{-27}$	2.4	-3.2	0.

Table 3.

Observable for MinD estimations of $m_{Z'}$

Asymmetry A^{ay} pick out $\bar{a}^2$ form-factor:

$$A^{ay}(\sqrt{s}, p_\perp, m_{Z'}) = F_a(\sqrt{s}, p_\perp, m_{Z'})\ \bar{a}^2. \tag{29}$$

The observable $R^a = A^{ay}(\sqrt{s}, p_\perp^{(2)}, m_{Z'})/A^{ay}(\sqrt{s}, p_\perp^{(1)}, m_{Z'})$ serves for MinD searching for $m_{Z'}$.

For close $p_\perp^{(2)} = p_\perp^{(1)} + \Delta p_\perp$ it reads

$$R^a(\sqrt{s}, p_\perp^{(1)}, m_{Z'}) = 1 + \frac{\partial F_a(p_\perp)}{\partial p_\perp} \frac{\Delta p_\perp}{F_a(p_\perp)}\Big|_{|p_\perp^{(1)}}. \tag{30}$$

Then, substituting $m_{Z'}$ in (29) we estimate $\bar{a}^2$.

The variable $p_\perp$ is important.

- These are MinD estimates of $\bar{a}^2$ and $m_{Z'}$

Asymmetries of pure quark processes

preserve all their properties been expressed in terms of $p_\perp, y_+, y_-$ for final leptons.

After integration of A^{ay} over $p_\perp$ we get equations for $\bar{a}^2$ and $m_{Z'}$.

Estimate of asymmetries for pp PDF looks similarly.

- These are MinD estimates of $\bar{a}^2$ and $m_{Z'}$

Fittings of a_f and $m_{Z'}$

1) Most simple is a two-parameter fit of a_f and $m_{Z'}$
by applying χ^2 - method for the differential CS.

2) Other way is based on one-parameter fit for R^a
within χ^2 - method,
and then, using the estimated value of $m_{Z'}$,
the same can be done for a_f.
For efficiency of calculations the variable $p_\perp$ is important.

Discussion and conclusions

- Axial-vector coupling constant $\bar{a}^2$ is universal coupling for Z'
- Observable for MinD searching for Z' in DY process is proposed
- A_{FB} in variables y_{L^+}, y_{L^-}, $p_\perp$ may serve as MinD signal of Z'.
- This observable can be used for treating of results from Tevatron, LHC and ILC experiments
- Experimental results from Tevatron and LHC in terms of y_{L^+}, y_{L^-}, $p_\perp$ are welcomed.
- Comparison of MD and MinD searching for Z'.