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Review of the Recent Tevatron Results

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Abstract

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New results obtained by D0 and CDF Collaborations on the top quark and W boson masses, weak mixing angle, and forward-backward asymmetry in $t\bar{t}$ production are presented. These results are used to test CPT invariance, EW vacuum stability, and SM self-consistency and predictions. Recent data of D0 Collaboration on the new narrow $X(5568)$ exotic state are discussed.

Аннотация

Денисов С.П. Обзор новых результатов экспериментов на Тэватроне: Препринт НИЦ «Курчатовский институт» – ИФВЭ 2018-1. – Протвино, 2018. – 13 с., 6 рис., 2 табл., библиогр.: 47.

Представлены новые результаты, полученные коллаборациями D0 и CDF по массам топ-кварка и W-бозона, слабому углу смешивания и асимметрии вперёд-назад в рождении $t\bar{t}$. Эти результаты используются для проверки CPT инвариантности, стабильности электрослабого вакуума и самосогласованности и предсказаний Стандартной Модели. Обсуждаются последние результаты коллаборации D0 по новому узкому экзотическому состоянию $X(5568)$.

Introduction

The Tevatron is a proton-antiproton collider located at Fermi National Accelerator Laboratory (Batavia, USA). During 2 physics runs in 1988-1996 and 2001-2011 two general purpose detectors CDF and D0 collected 10 fb^{-1} integrated luminosity each. The center-of-mass energy was 1.8 TeV in the Run I and 1.96 TeV in the Run II. The maximum instantaneous luminosity reached in the Run II is equal to 4.3×10^{32} $cm^{-2}s^{-1}$.

In the section 2 the top quark mass (m_t) measurements with high precision are discussed and new results of the top quark mass obtained at the Tevatron and LHC are presented. The 3-rd section deals with the CPT-invariance test based on $m_t - m_{\bar{t}}$ mass difference. The stability of the electroweak (EW) vacuum and Standard Model (SM) self-consistency are discussed in the next two sections. New results on the search for exotic particles and on the measurements of the forward-backward asymmetry in $t\bar{t}$, production are presented in the sections 6 and 7. A short conclusion is given in the final section.

1. Top quark mass measurements and results

The top quark was discovered in 1995 by CDF and D0 collaborations with top quark mass values of 176±13 GeV (CDF) and 199±30 GeV (D0) [1,2]. Since that time dozens of m_t measurements were performed at the Tevatron and later at the LHC and now we know its value with uncertainty about two orders of magnitude less and much better than for other quarks. Two questions arise:

Why do we need a precision value of the top quark mass?
Why is it possible to measure m_t with high accuracy?

There are several arguments for high precision measurements of the top quark mass. Five of them are:

- m_t is a fundamental physical constant (SM does not predict quark masses);
- it allows one to perform CPT-invariance test in the quark sector;
- along with Higgs boson mass provides information on EW vacuum stability;
- it is used to test SM self-consistency via loop corrections to the W mass;
- precise m_t value is important for the background estimates in many new physics searches.

One of the unique top quark properties is short lifetime due to heavy mass. SM predicts $\tau_t \sim 5 \cdot 10^{-25}$ s in agreement with the Tevatron and LHC results [3-5]. This time is much shorter than the time ($\sim 2 \cdot 10^{-24}$ s) required for hadronization and hence top quark decays as a free particle before forming a bound state. This allows one to measure top quark properties:

- directly and hence with much less relative uncertainties than for the lighter quarks characteristics extracted from the parameters of their bound states;
- independently for t and $\bar{t}$ quarks.

Thus the high accuracy m_t measurement is not only important but also achievable.

There are several methods of m_t measurements and corresponding m_t definitions [6]. For example pole-mass m^{pole} appears in the top quark propagator $1/[p^2 - (m^{\text{pole}})^2]$ and can be extracted from the mass dependence of the $t\bar{t}$ production cross-sections (see below). But the most precise top mass results came from the analysis of events with reconstructed top quark decays to Wb with “alljets” (46%), “lepton+jets” (45%), “dileptons” (9%) combinations in the final state [7]. Each combination have its advantageous and disadvantageous for the top quark mass measurements. For example, the highest statistics is available for the “all jets” events but QCD backgrounds are high in this case. Dilepton e, μ - events have low background but statistics is about order of magnitude less than that for “all jets”. The best m_t values obtained by the CDF and D0 collaborations for different final states are shown in the Table 1. Table 2 presents the combined m_t results.

Table 1. Results of the top quark mass measurements at the Tevatron.

Experiment	Final states	m_t, GeV	Errors		*Ref.*
			Stat.	Syst.	
CDF	dilepton	171.5	±1.9	±2.5	[8]
D0	dilepton	173.50	±1.31	±0.84	[9]
CDF	lepton+jets	172.85	±0.71	±0.85	[10]
D0	lepton+jets	174.98	±0.41	±0.63	[11]
CDF	all jets	175.07	±1.19	±1.55	[12]
CDF	MET+jets	173.93	±1.28	±1.35	[13]

Table 2. Tevatron and LHC top quark mass combinations.

Combination	Year	m_t, GeV	Errors		Ref.
			Stat.	Syst.	
Tevatron	2016	174.30	±0.35	±0.54	[14]
ATLAS	2017	172.51	±0.27	±0.42	[15]
CMS	2016	172.44	±0.13	±0.47	[16]
Tevatron+LHC	2014	173.34	±0.27	±0.71	[17]

The top quark pole-masses extracted by D0 Collaboration from inclusive $t\bar{t}$ production cross-section is equal to $172.8^{+1.3}_{-0.3}\left(\text{exp.}\right)\pm 1.1\left(\text{theor.}\right)$ GeV [18]. The LHC m^{pole} results are the following:

- ATLAS: 173.2±0.9(stat.) ±0.8(syst.)±1.2(theor.) GeV [19] ,
- CMS: 170.6±2.7 GeV [20].

From the above results one can conclude:

- the results obtained with different combinations in the final state of the top quark decay are in good agreement,
- the Tevatron and LHC results are in agreement within the errors quoted,
- the uncertainties of the Tevatron and LHC measurements are comparable and are mainly due to systematics,
- the total relative errors are about 0.3%, that is much less than for other quarks,
- within the uncertainties there is no difference between m^{pole} and m_t (according to the recent theoretical studies this difference is less than ~0.5 GeV).

2. CPT Theorem Test

The fundamental CPT theorem based on the general principles of local relativistic quantum field theory predicts that particle and antiparticle masses must be the same. The CPT symmetry is rigorously conserved in the SM and it was checked with high accuracy for K_0-$\bar{K}_0$ system: $m(K_0) - m(\bar{K}_0) / \text{average} < 6\times10^{-19}$ at 90% CL [7]. But some SM extensions permit CPT invariance violation.

The CPT invariance test at the quark level is possible only for the top quarks where t and $\bar{t}$ masses can be measured directly and independently. The first $\Delta m_{t\bar{t}} = m_t - m_{\bar{t}}$ measurements were performed at the Tevatron. To discriminate t against $\bar{t}$ the charge of lepton in e/μ+jets events was used. The obtained results are the following:

- D0 (2011) [21]: 0.80±1.8(stat.)±0.5(syst.) GeV,
- CDF (2013) [22]: –1.95±1.11(stat.)±0.59(syst.) GeV.

Much more precise $\Delta m_{t\bar{t}}$ values were obtained recently at the LHC:

- CMS (2017) [23]: –0.15±0.19(stat.)±0.09(syst.) GeV,
- ATLAS (2017) [24]: –0.67±0.61(stat.)±0.41(syst.) GeV.

Thus CPT invariance holds in the quark sector at the level of $\Delta m_{t\bar{t}} / m_t = \sim 10^{-3}$.

3. EW Vacuum Stability Test

The top quark and Higgs boson masses provide information on the EW vacuum stability. As can be seen from the Figure 1 experimental data point to the meta-stable vacuum with >99% CL but the hypothesis that the vacuum is stable and the SM works all the way up to the Planck scale cannot be rejected. Much better precision of the masses (first of all of the top quark mass) is needed for the definite conclusion (>5σ). That is unlikely possible with existing colliders, but certainly may be achieved at the future lepton colliders.

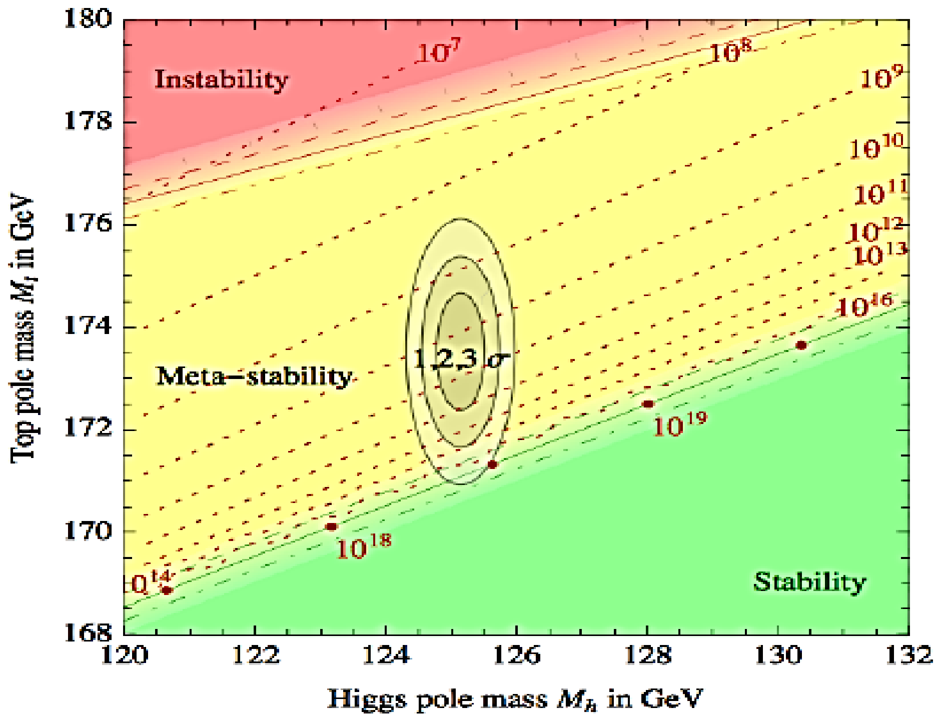

Figure 1. Regions of stability, meta-stability, and instability of the SM vacuum. The numbers at the dotted lines present the renormgroup energy scale μ [25].

4. SM Self-consistency

There are 6 fundamental EW parameters: α, $G_F/(\hbar c)^3$, M_H, M_Z, M_W, and $\sin^2\theta_W$. First four of them are known from Rydberg constant, muon lifetime and LEP and LHC measurements [7]. The most precise M_W measurements are performed at the Tevatron.

The combined CDF and D0 result is M_W=80387±16 MeV [26] (the world average is equal to 80379±12 MeV [7]). The best D0 result on the effective weak mixing angle parameter is $\sin^2\theta^{\mathrm{l}}_{\mathrm{eff}} = 0.23095 \pm 0.00040$ [27].

EW parameters are not independent but related through SM equations:

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}, \quad M_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}. \tag{1}$$

This allows one to check SM self-consistency. The results are shown in Figure 2. The horizontal and vertical green bands present the experimental $\sin^2\theta^{\mathrm{l}}_{\mathrm{eff}}$ and M_W values ±1σ. Green ovals show the areas of $\sin^2\theta^{\mathrm{l}}_{\mathrm{eff}}$ and M_W with 1σ and 2σ CL. Contours of blue, yellow and grey areas indicate 1σ and 2σ boundaries for $\sin^2\theta^{\mathrm{l}}_{\mathrm{eff}}$ and M_W obtained from the fit to equations (1) with and without M_H and Z boson width (Γ_Z) measurements. As can be seen from Figure 2 all areas overlap each other and therefore there is no evidence for the SM non-consistency.

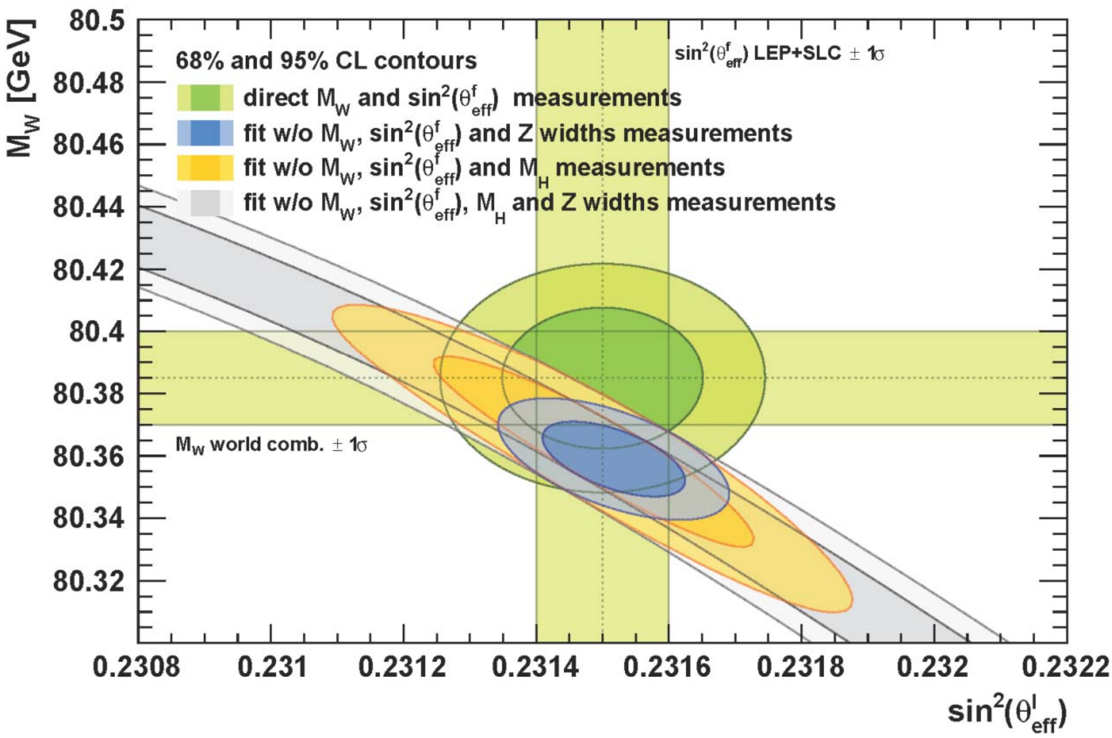

Figure 2. Results of the global fit of SM parameters to equations (1) [28].

Self-consistency of SM can also be tested using the dependence of M_W on m_t and M_H via loop corrections:

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}\left(1+\Delta r\right), \tag{2}$$

where Δr (m_t^2, $\ln M_H$) reflects the loop corrections. The results of the global fit of the precision electroweak data to this relation are presented in Figure 3 [28]. The vertical and horizontal green belts indicate the $\pm\sigma$ regions for the m_t and M_W direct measurements. The blue and grey areas show 1σ and 2σ regions allowed for m_t and M_W masses, derived from the fit. They correspond to cases when measurements of the Higgs boson mass are included (blue) or excluded (grey) from the fit. The allowed regions coincide well with the green areas indicating 1σ and 2σ regions for the m_t and M_W experimental values thus confirming SM self-consistency.

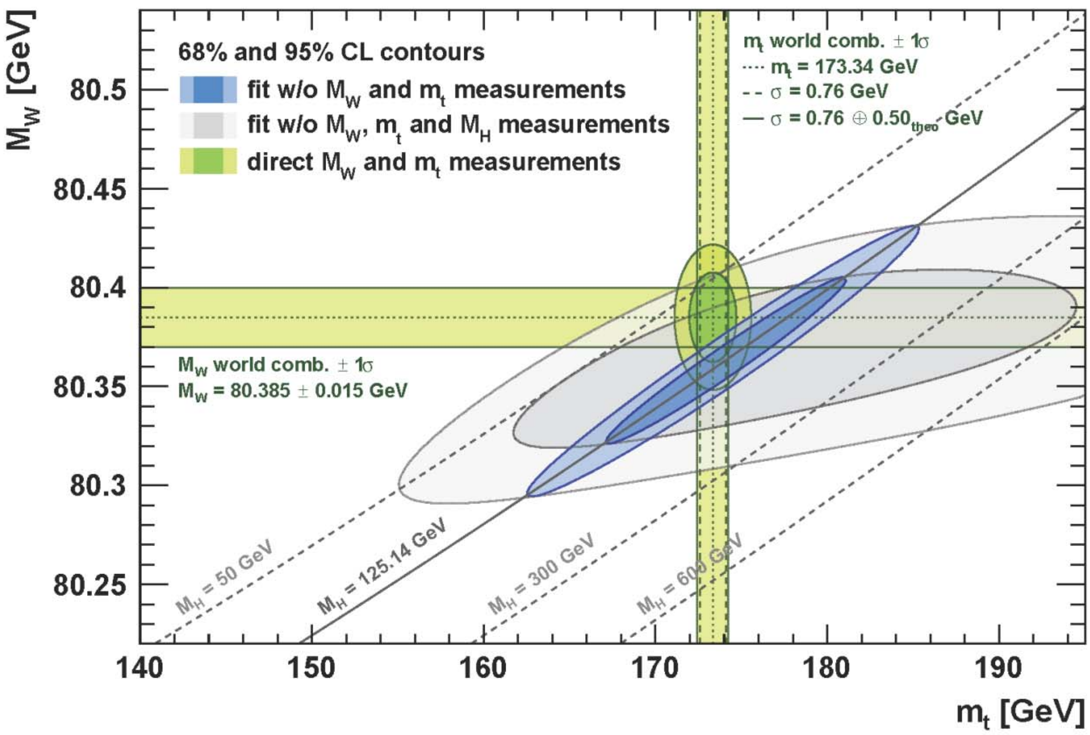

Figure 3. The results of the global fit of electroweak data to the relation (2) [28].

5. Searches for exotic states

In 2016 D0 Collaboration reported observation of a new narrow $X(5568)$ state, potentially consisting of the b, s, u, and d quarks and decaying into $B_s^0\pi^{\pm}$ with $B_s^0 \to J/\psi\ \varphi$, $J/\psi \to \mu^+\ \mu^-$, $\varphi \to K^+\ K^-$ [29]. Thus there are five charged stable particles in the final state as shown in Figure 4. The following cuts were applied to minimize the background-to-signal ratio:

- two oppositely charged particles identified as muons have p_T >1.5 GeV/c and invariant mass in the range from 2.92 to 3.25 GeV consistent with J/ψ mass,
- two oppositely charged particles assumed to be kaons have p_T >0.7 GeV/c and invariant mass in the range from 1.012 to 1.030 GeV consistent with φ mass,
- the fifth charged particle has p_T >0.7 GeV/c and assumed to be a pion,
- $\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2} < 0.3$, where $\Delta\eta$ and $\Delta\varphi$ are pseudorapidity and azimuthal angle intervals between π and B_s^0 trajectories.

Figure 5 shows the $B_s^0\pi^{\pm}$ invariant mass spectrum fitted with the sum of signal and background functions. The signal function is represented by convolution of a relativistic Breit-Wigner function with M_x and Γ_x as free parameters and a Gaussian detector resolution function. The background is well described by the function $F_{bgr}(m_0) = P_4\ exp(P_2)$, where $m_0 = m\left(B_s^0\pi^{\pm}\right) - 5.5$ GeV, P_2 is a second-order polynomial and P_4 is a fourth-order polynomial with a linear term equal to zero. The fit yields the following results:

- $M_x = 5567.8 \pm 2.9(\text{stat.})^{+0.9}_{-1.6}(\text{syst.})$ MeV,
- $\Gamma_x = 21.9 \pm 6.4(\text{stat.})^{+5.0}_{-2.5}(\text{syst.})$ MeV,
- $N_x = 133 \pm 31(\text{stat.}) \pm 15(\text{syst.})$,

where N_x is the number of signal events. The ratio $\rho = \sigma\left[X(5568) \to B_s^0\pi\right] / \sigma\left(B_s^0\right)$ is measured to be [8.6±1.9(stat.)±1.4(syst.)]%. The global significance of the signal including Look Elsewhere Effect [30] and systematic uncertainties is estimated to be 5.1σ. The fitted parameters weekly depends on the ΔR cut but without this cut the global significance reduced to 3.9σ.

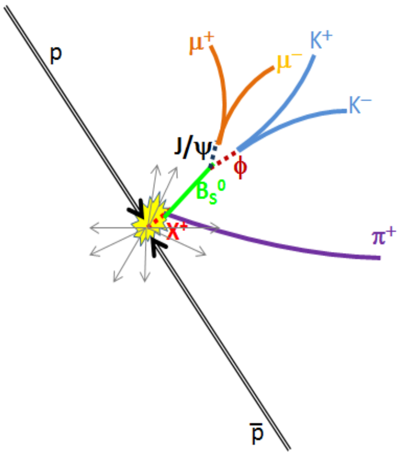

Figure 4. $X(5568)$ decay.

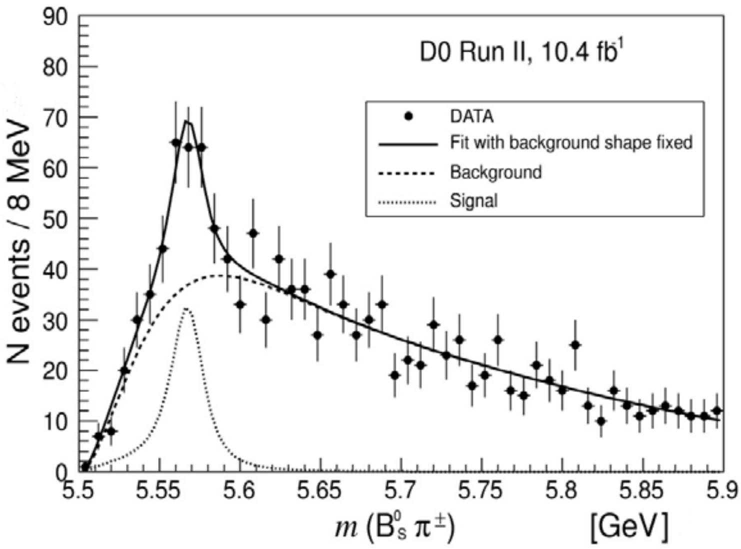

Figure 5. $B_s^0\pi^\pm$ mass spectra for $B_s^0 \to J/\psi\ \varphi$ decays with ΔR<0.3 cut.

Subsequent analyses performed by LHCb [31] and CMS [32] collaborations in 2016 have not confirmed the existence of the $X(5568)$ in pp interactions at $\sqrt{s}$ = 7 and 8 TeV. In particular the upper limits of ρ parameter appeared to be equal to 2.4% (LHCb) and 3.9% (CMS) at 95% CL.

In 2017 the D0 collaboration performed a new search for $X(5568)$ using semileptonic B_s^0 decays: $B_s^0 \to D_s^\pm \mu^\mp \nu$, $D_s^\pm \to \phi(1020)\pi^\pm$, $\phi(1020) \to K^+K^-$ [33]. The $m(B_s^0\pi^\pm)$ distribution for the data is shown in Figure 6 together with the fit results. The fit yields the following values:

- $M_x = 5566.7^{+3.6}_{-3.4}(\text{stat.})^{+1.0}_{-1.0}(\text{syst.})$ MeV,
- $\Gamma_x = 6.0^{+9.5}_{-6.0}(\text{stat.})^{+1.9}_{-4.6}(\text{syst.})$ MeV,
- $N_x = 139^{+51}_{-63}(\text{stat.})^{+11}_{-32}(\text{syst.})$,

which are compatible within the uncertainties with the results from the hadronic channel of B_s^0 decay. The local statistical significance of the peak is 4.5σ, the global statistical significance, taking into account the systematic uncertainties, is 3.2σ. The ratio ρ is measured to be $\left[7.3^{+2.8}_{-2.4}(\text{stat.})^{+0.6}_{-1.7}(\text{syst.})\right]\%$ in agreement with the hadronic channel. The combined significance for semileptonic and hadronic channels, obtained under the assumptions that the same object is observed in both channels and the semileptonic and hadronic measurements are independent, is 5.7σ.

There are no reasonable explanations why $X(5568)$ is seen in two different decay modes in $p\overline{p}$ interactions at 2 TeV and not in pp collisions at 7 and 8 TeV. Thus the question about $X(5568)$ nature remains open.

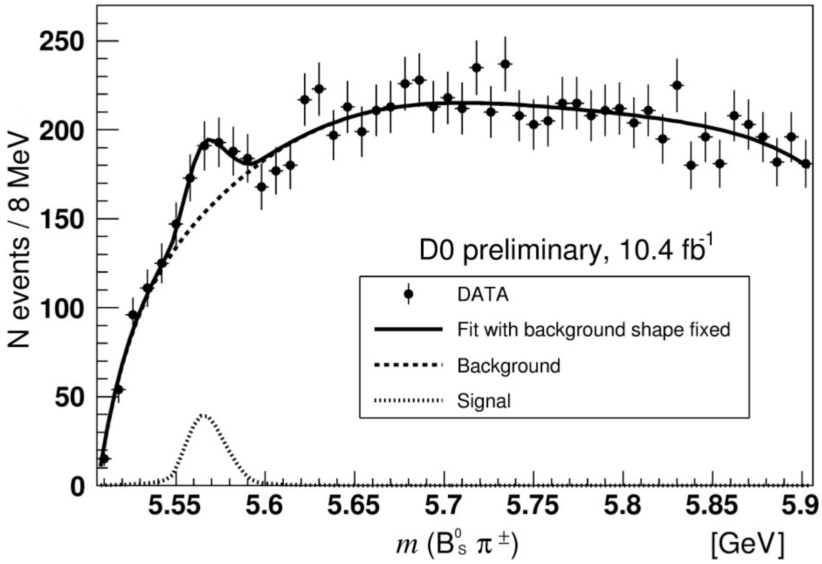

Figure 6. $B^0_s\pi^{\pm}$ mass spectra for semileptonic B^0_s decays.

6. Forward-Backward Asymmetry in $t\overline{t}$ Production

Forward-Backward (FB) asymmetry in $t\overline{t}$ production in the proton-antiproton collisions answers a question: does the top quark prefer the proton direction or the opposite? FB-asymmetry is defined by:

$$A^{t\bar{t}}_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} ,$$

where $\Delta y = y_t - y_{\bar{t}}$ is the rapidity difference between t and $\bar{t}$ quarks and N is a number of events with Δy above or below zero. FB-asymmetry can also be measured using one or two leptons from top quark decays. Corresponding FB-asymmetry definitions are the following:

$$A_{FB}^{l} = \frac{N(q_l\eta_l > 0) - N(q_l\eta_l < 0)}{N(q_l\eta_l > 0) + N(q_l\eta_l < 0)}, \qquad A_{FB}^{ll} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)},$$

where $\Delta\eta = \eta_{l^+} - \eta_{l^-}$ is the pseudorapidity difference between two leptons and q_l is the sign of the lepton electric charge. QCD does not predict asymmetry at the leading order. It arises due to higher order corrections. Thus FB-asymmetry is a precision probe of SM predictions in the top quark sector.

The results of the first FB-asymmetry measurements at Tevatron showed a deviation from existing next-to-leading order (NLO) QCD predictions by more than 3σ [34, 35]. These results stimulated both more precise experimental measurements of $A_{FB}^{t\bar{t}}$ [36-39], A_{FB}^{l} [40-43] and A_{FB}^{ll} [42, 43] and more accurate theoretical calculation including next-to-next-to-leading (NNLO) order [44-46]. As a result by now there is no contradiction between D0 and CDF measurements and theory. For example, the combined CDF and D0 $A_{FB}^{t\bar{t}}$ value of 0.128±0.021(stat.) ± 0.014(syst.) [47] is consistent with NNLO QCD + NLO EW prediction of 0.095±0.007 [44] within 1.3σ.

7. Conclusions

Many new important results were obtained by CDF and D0 collaborations recently. Among them the most precise measurements of the top quark and W boson masses: m_t=174.30±0.35(stat.)±0.54(syst.) GeV, M_W=80387±16 MeV. Better precision of these masses is needed for the definite conclusion about SM vacuum stability and SM self-consistency. The significance of the observation of a new exotic state X(5568) is 5.7σ and the corresponding p-value is 5.6×10^{-9}. As LHCb and CMS experiments do not see this state the question about its nature remains open. New D0 and CDF results of the forward-backward asymmetry studies in $t\bar{t}$ production are consistent with the recent NNLO QCD + NLO EW predictions.

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