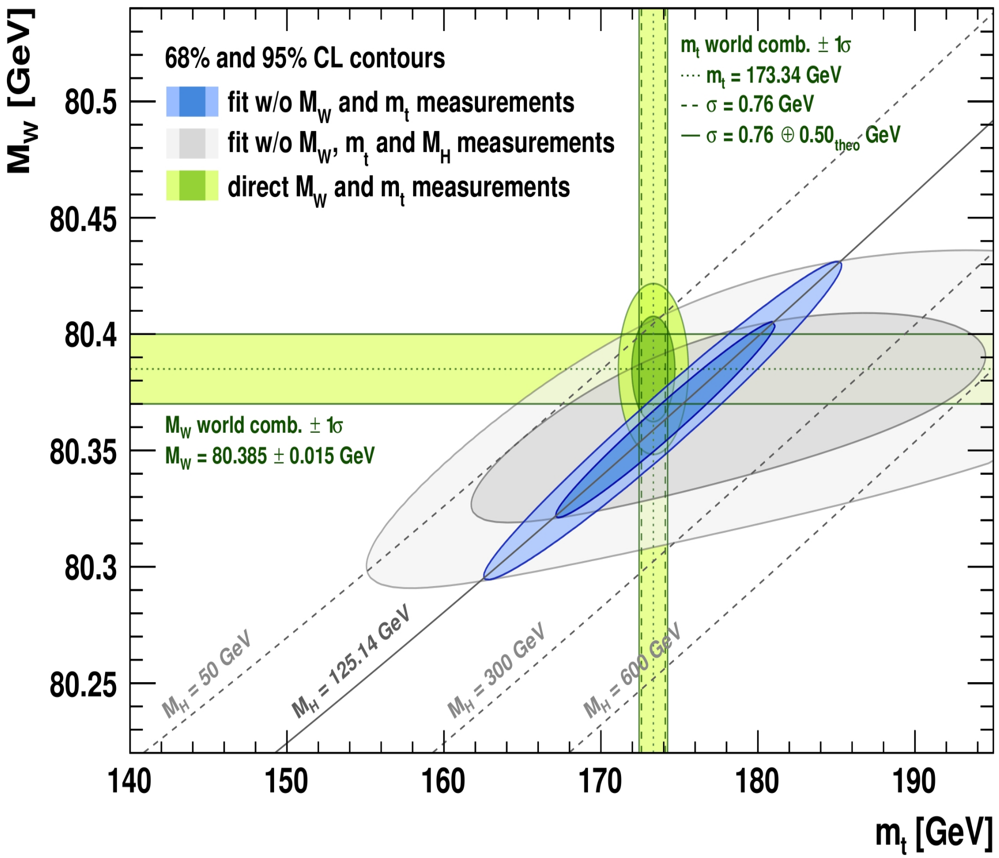
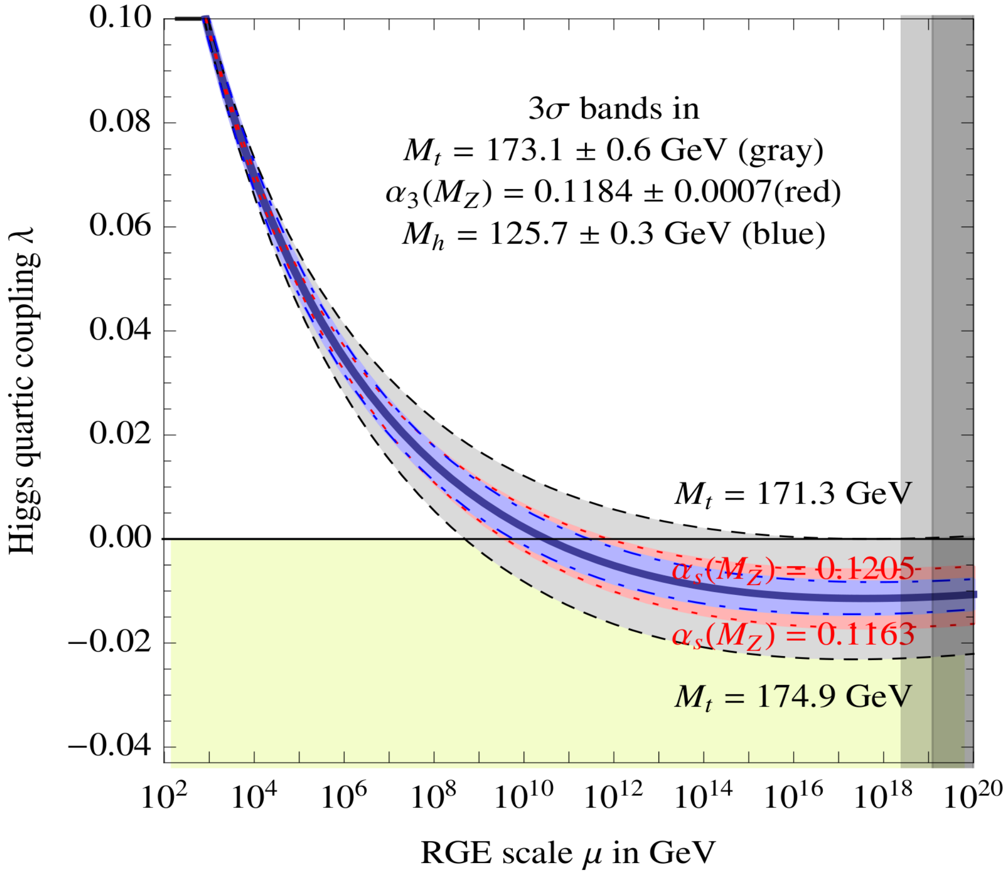
Измерение массы топ-кварка в эксперименте CDF

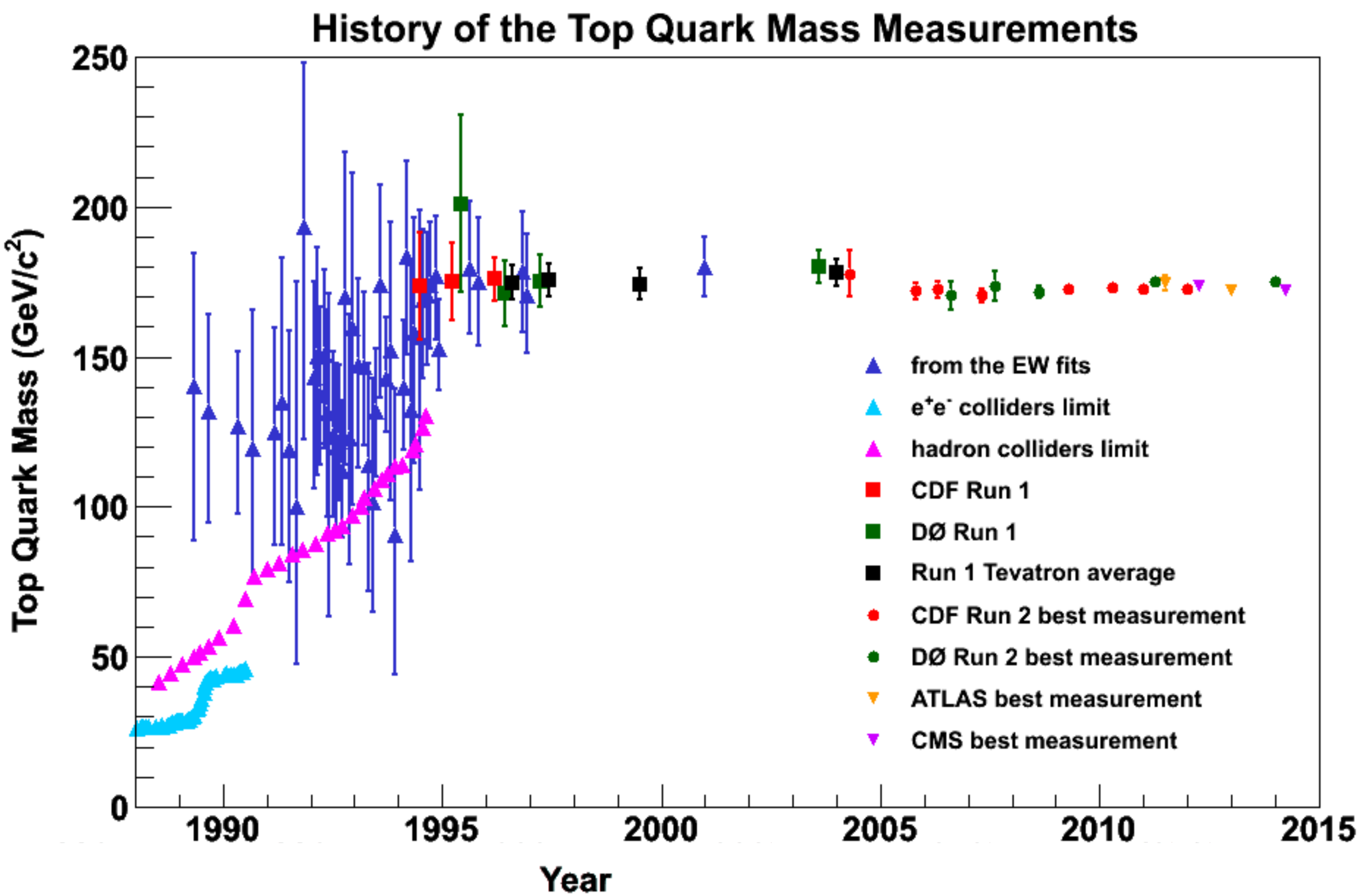
Суслов И.А.





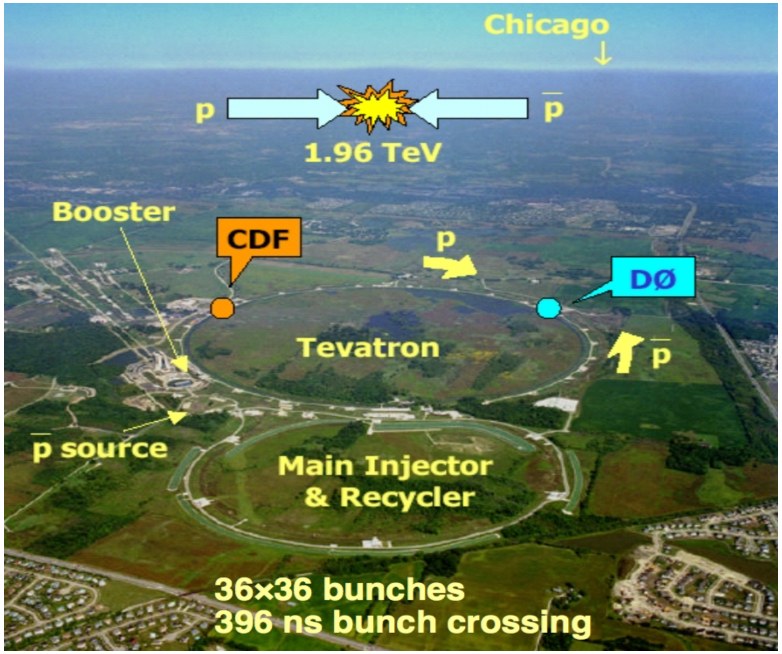
Mt :

- **фундаментальный параметр СМ**
- **тесты внутренней согласованности СМ и ограничения в моделях новой физики**

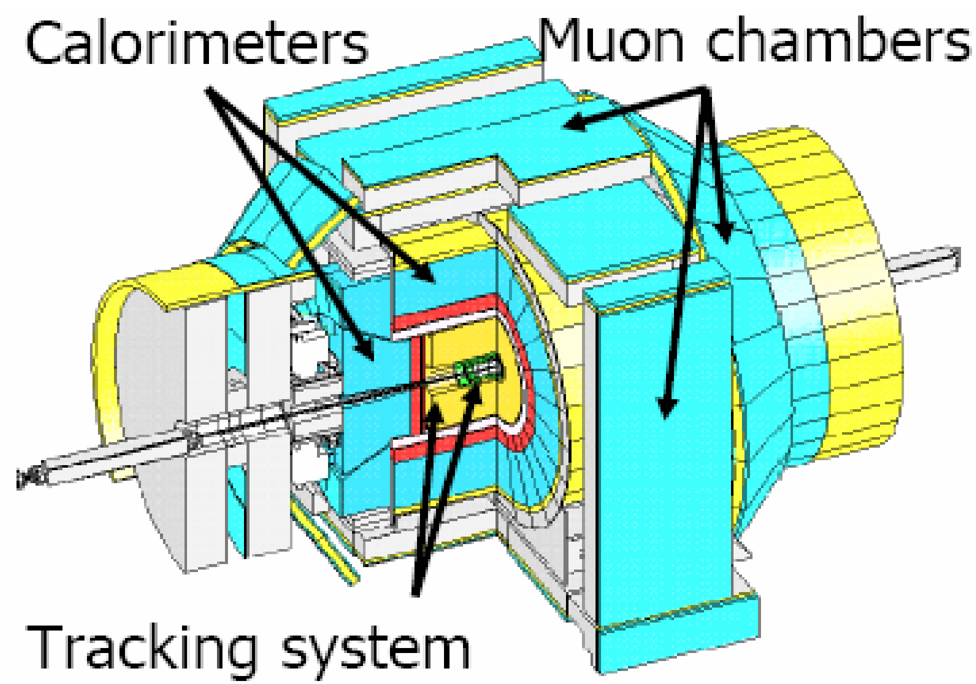


any of these analysis techniques have been pioneered at Tevatron M

Тэватрон и CDF

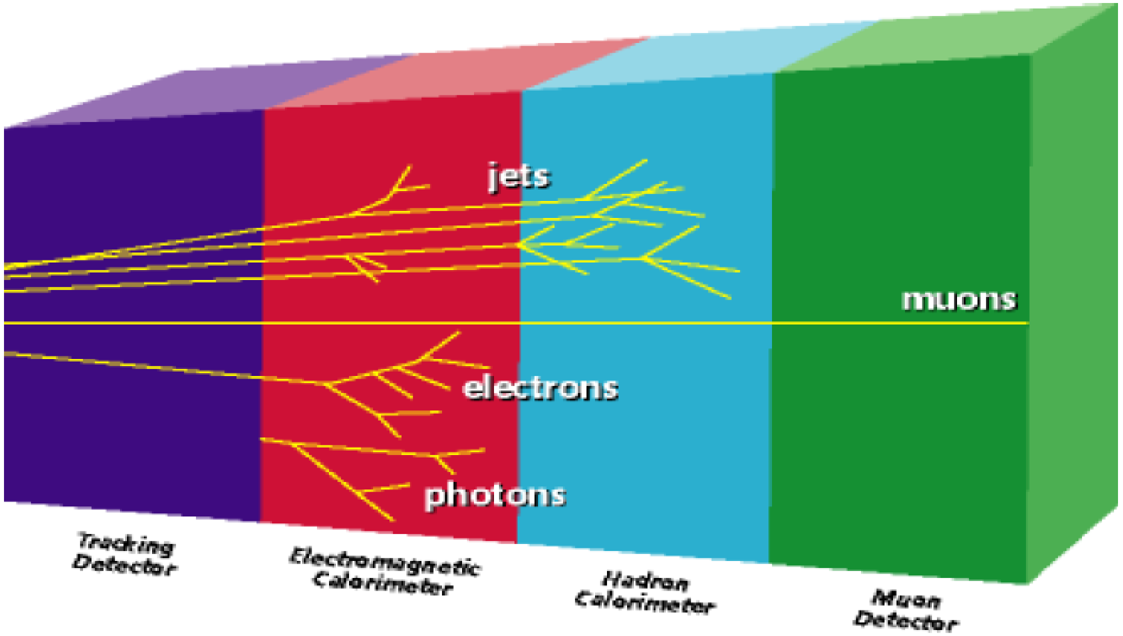


- Протон-антипротонные столкновения
- $\sqrt{s}$ = 1.96 ТэВ
- ~10 fb^{-1}



- **Трековая система**
  определение траекторий и импульсов заряженных частиц
- **Калориметрическая система**
  измерений энергий проходящих частиц (электронов, фотонов, адронов)
- **Мюонная система**
  идентификация мюонов
- **Система сбора данных**
  задание триггера и накопление данных

Reconstructed objects



Electrons:

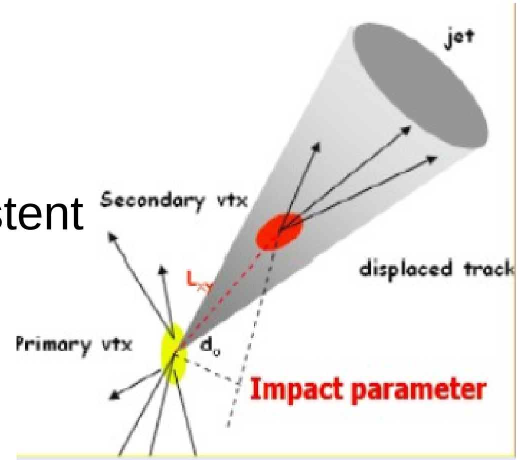
- small hadronic energy
- isolated in calorimeter
- good EM shower shape
- well-matching good track

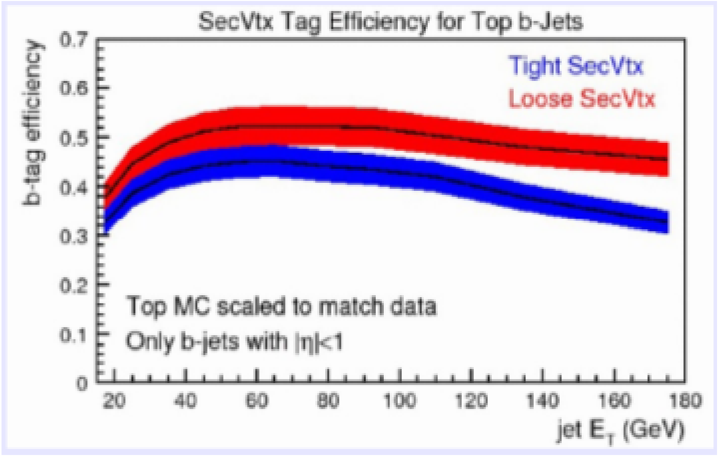
Muons:

- MIP in calorimeter
- isolated
- hits in muon chamber
- well-matching good track

Jets:

- cluster energy in cones of $\Delta R<0.4$
- calorimeter signature must be inconsistent with electron signatures
- b-tagging





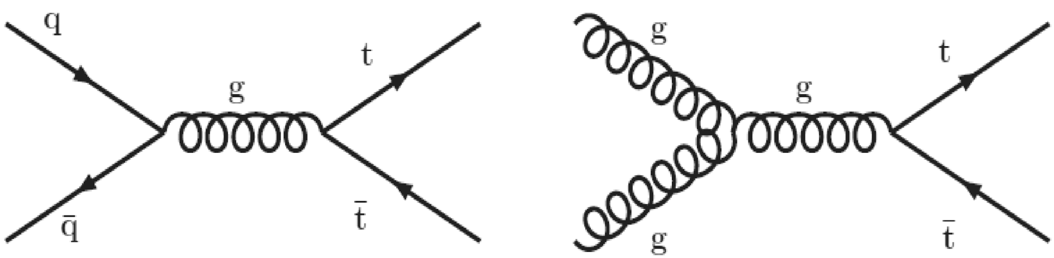
Missing E_T:

- energy imbalance in reconstructed event, associated with neutrino

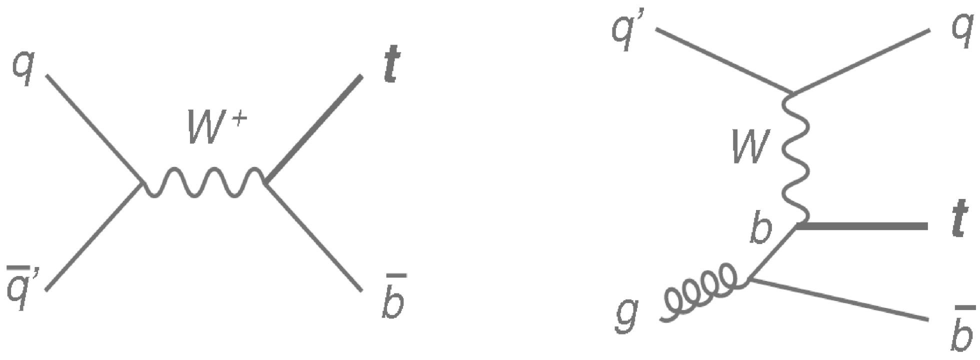
$$\vec{\not{E}}_T = -\sum_i \vec{E}_T^i$$

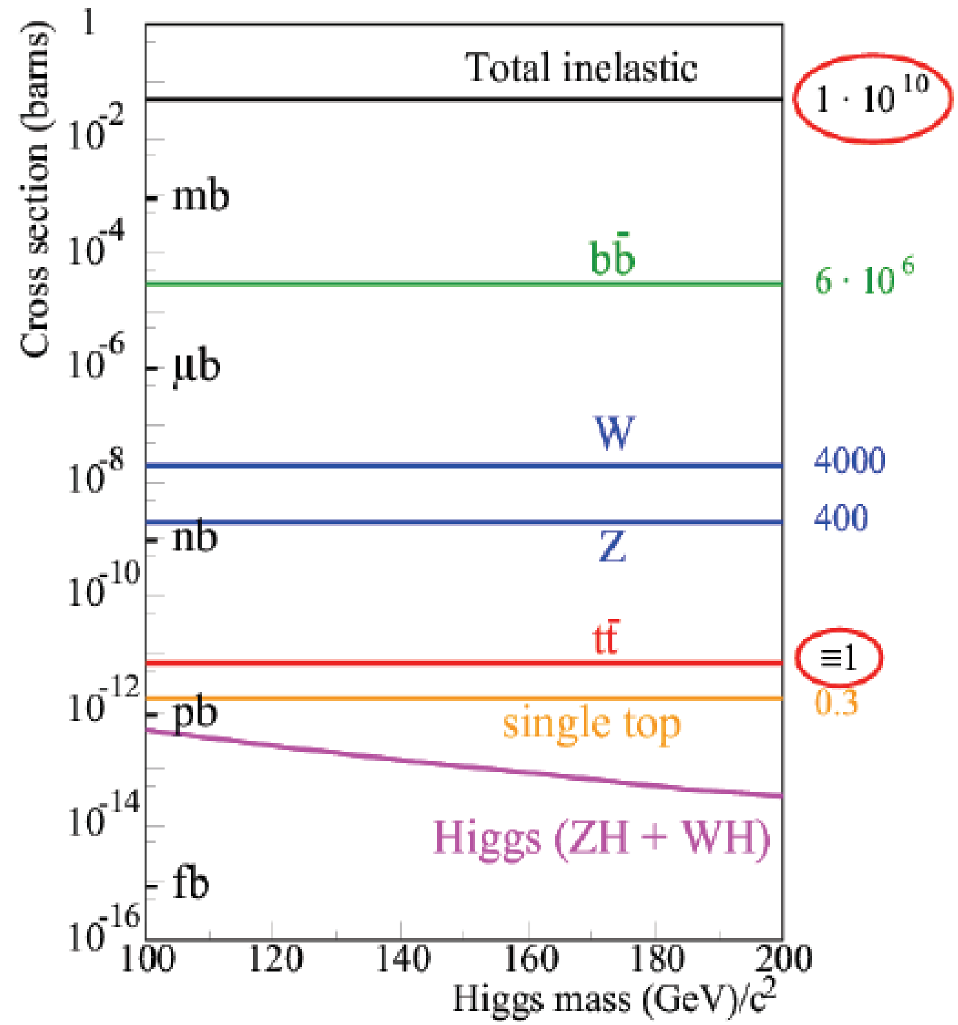
Топ-кварк на Тэватроне

Парное рождение



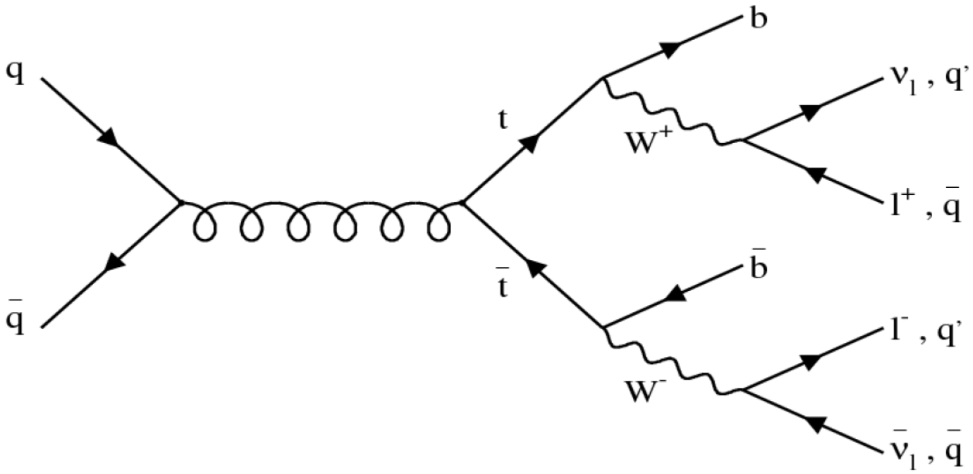
Одиночное рождение

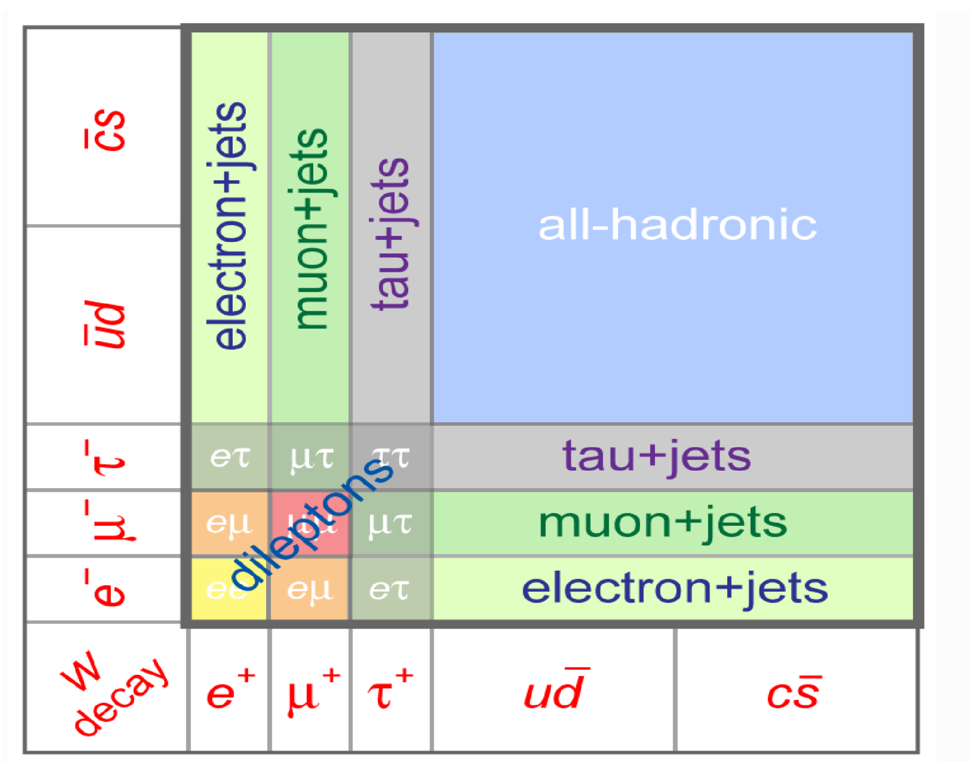




One top pair per 10 billion inelastic collisions

Сигнальные события





➢Dilepton sample

- Two high-P_T isolated leptons
- ≥ Two high-E_T jets
- Large missing transverse energy

➢Lepton+jets sample

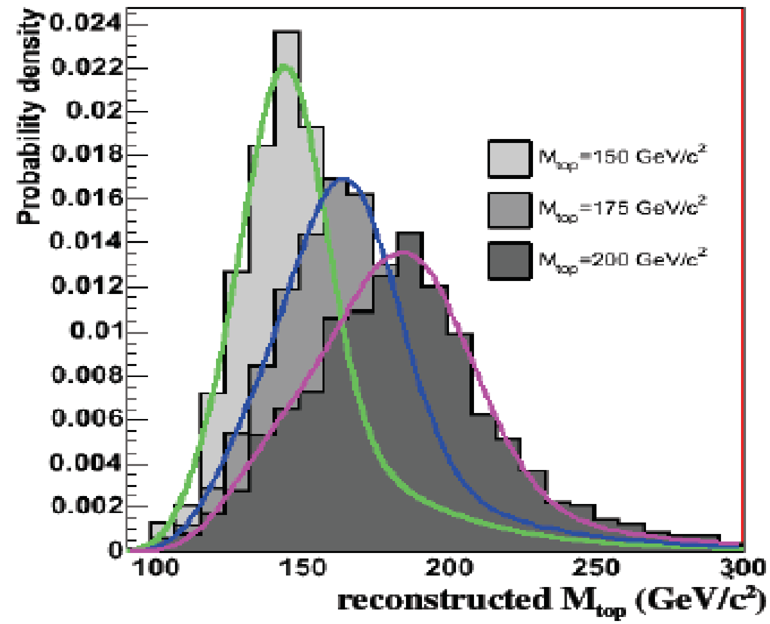
- One high-P_T isolated lepton
- ≥ 4 high-E_T jets
- Large missing transverse energy

➢All-hadronic sample

- ≥ 6 high-E_T jets

Метод шаблонов

- ➢Вычислять для каждого события оценочную переменную, распределение которой чувствительно к Mtop
- ➢Получить распределения для сигнала и фона
- ➢Определить функцию правдоподобия
- ➢Тестировать в псевдоэкспериментах процедуру измерения
- ➢Выполнить фит данных



Метод матричного элемента

- The matrix element method in the lepton+jets channel:
  - maximize the probability for a set of events as a function of the top mass and overall jet energy scale factor

$$P_{\mathrm{evt}} = A(\vec{x})[f P_{\mathrm{sig}}(\vec{x}; m_t, k_{\mathrm{JES}}) + (1-f) P_{\mathrm{bkg}}(\vec{x}; k_{\mathrm{JES}})]$$

acceptance efficiency — signal fraction — signal probability — background probability

$$P_{\mathrm{sig}} = \frac{1}{\sigma^{tt}_{\mathrm{obs}}(m_t, k_{\mathrm{JES}})} \int \sum d\sigma(\vec{y}, m_t) d\vec{q}_1 d\vec{q}_2 f(\vec{q}_1) f(\vec{q}_2) \times W(\vec{x}, \vec{y}; k_{\mathrm{JES}})$$

observed cross section — differential cross section from the LO $q\bar{q} \to t\bar{t}$ matrix element — PDF — transfer functions from reco x to gen y

l+jets

Отбор событий:

- изолированный лептон (e или μ) E_T> 20 ГэВ
- MET>20 ГэВ
- ≥4 адронные струи
- подвыборки событий в зависимости от числа струй с b-метками 0, 1 и 2
- “мягкие” и “жесткие” требования отбора увеличивают число подвыборок до 5

	0-tag	1-tagL	1-tagT	2-tagL	2-tagT
W+jets	703 ± 199	170 ± 60	102 ± 37	11.6 ± 4.9	8.4 ± 3.5
Z+jets	52.3 ± 4.4	8.9 ± 1.1	5.9 ± 0.7	0.8 ± 0.1	0.5 ± 0.1
Single top	4.8 ± 0.5	10.5 ± 0.9	6.8 ± 0.6	2.2 ± 0.3	1.7 ± 0.2
Diboson	60.3 ± 5.6	111 ± 1.4	8.5 ± 1.1	1.0 ± 0.2	0.8 ± 0.1
Multijets	143 ± 114	34.5 ± 12.6	20.7 ± 16.6	4.4 ± 2.5	2.5 ± 2.4
Background	963 ± 229	235 ± 61	144 ± 41	19.9 ± 5.5	13.8 ± 4.2
$t\bar{t}$ signal	645 ± 86	695 ± 87	867 ± 108	192 ± 30	304 ± 47
Expected	1608 ± 245	930 ± 106	1011 ± 115	212 ± 30	318 ± 47
Observed	1627	882	997	208	275

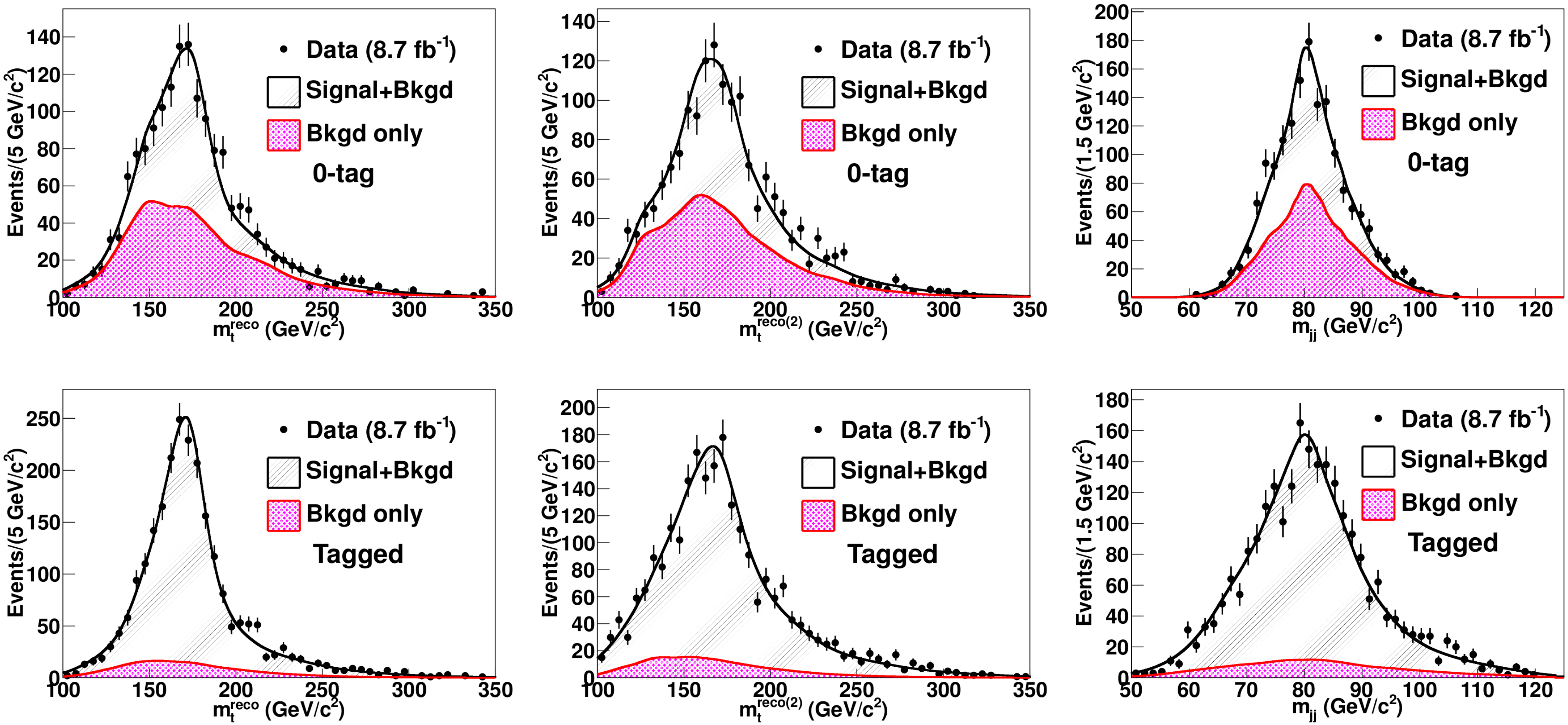
Кинематическая реконструкция:

$$\chi^2 = \sum_{l,\text{jets}} \frac{[\hat{p}_T - p_T]^2}{\sigma^2_{p_T}} + \sum_{i=x,y} \frac{[\hat{U}_i - U_i]^2}{\sigma^2_{U_i}} + \frac{(M_{l\nu} - M_W)^2}{\sigma^2_{M_W}} + \frac{(M_{jj} - M_W)^2}{\sigma^2_{M_W}} + \frac{(M_{l\nu j} - M_{\text{top}})^2}{\sigma^2_{M_{\text{top}}}} + \frac{(M_{jjj} - M_{\text{top}})^2}{\sigma^2_{M_{\text{top}}}}$$

l+jets

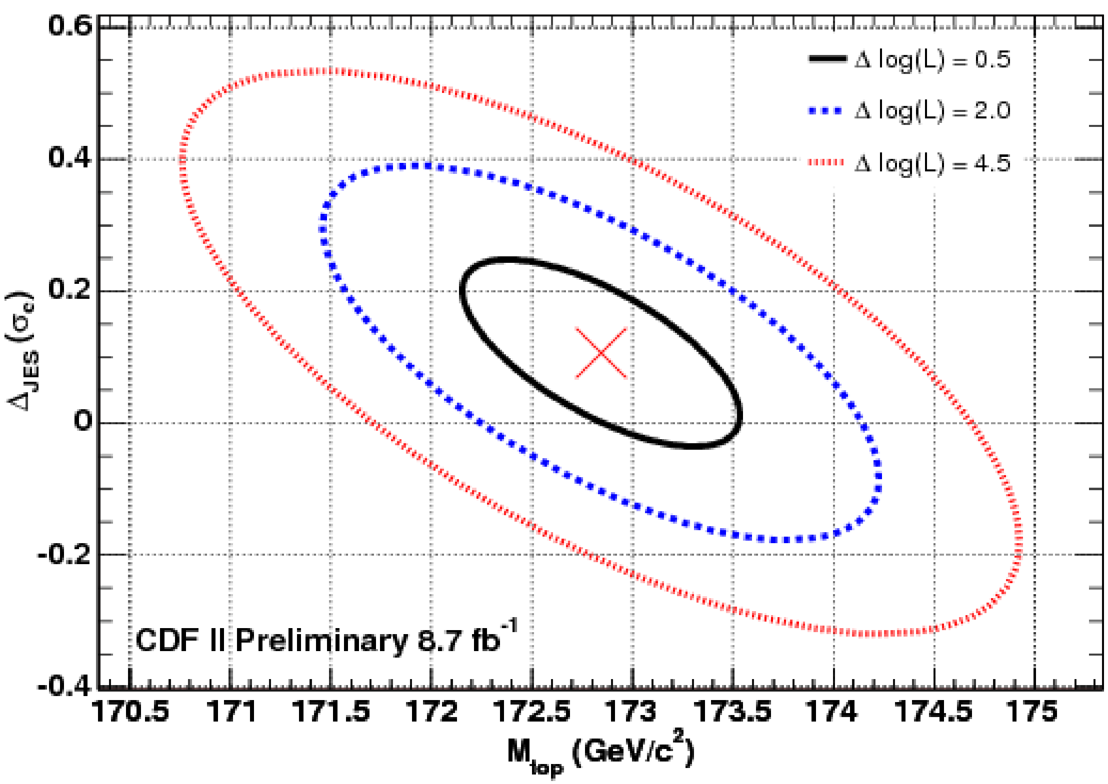
3D шаблоны: Mt^{reco}, $M_{W\to jj}$, $Mt^{reco(2)}$

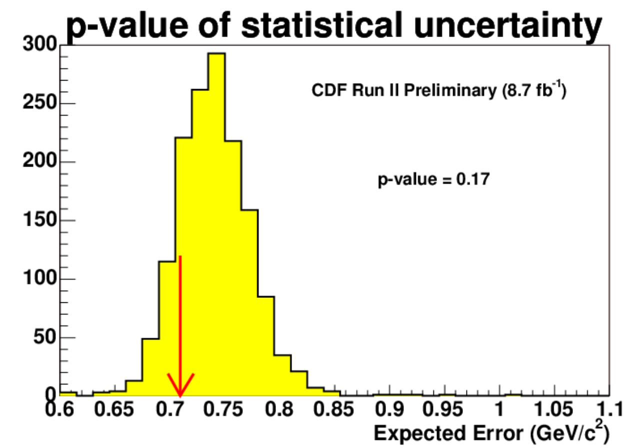
$$\mathcal{L}_k = \exp\left(-\frac{(n_b - n_b^0)^2}{2\sigma_{n_b}^2}\right) \times \prod_{i=1}^{N} \frac{n_s P_{sig}(m_t^{\text{reco}}, m_{\text{jj}}, m_t^{\text{reco(2)}}; M_{top}, \Delta_{JES}) + n_b P_{bg}(m_t^{\text{reco}}, m_{\text{jj}}, m_t^{\text{reco(2)}}; \Delta_{JES})}{n_s + n_b}$$



l+jets

M_{top} = 172.85 ± 0.71 (stat.+JES) ± 0.84 GeV/c^2 (syst)





Systematic	GeV/c^2
Residual JES	0.52
Generator	0.56
Next Leading Order	0.09
PDFs	0.08
b jet energy	0.10
b tagging efficiency	0.03
Background shape	0.20
gg fraction	0.03
Radiation	0.06
MC statistics	0.05
Lepton energy	0.03
MHI	0.07
Color Reconnection	0.21
Total systematic	0.84

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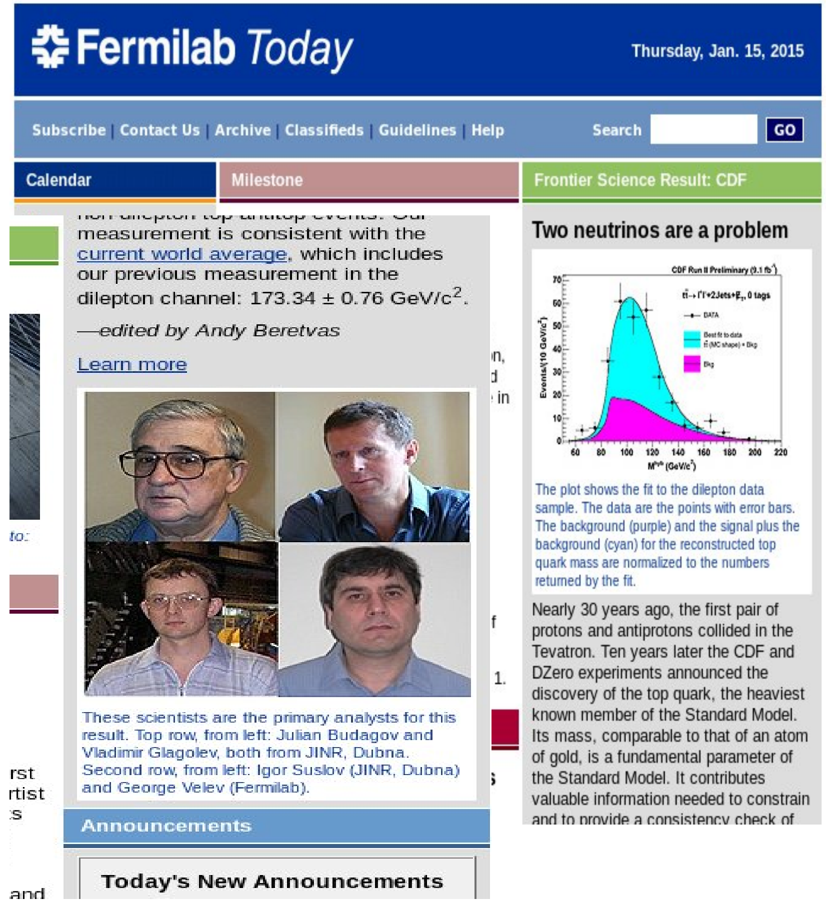
Dilepton

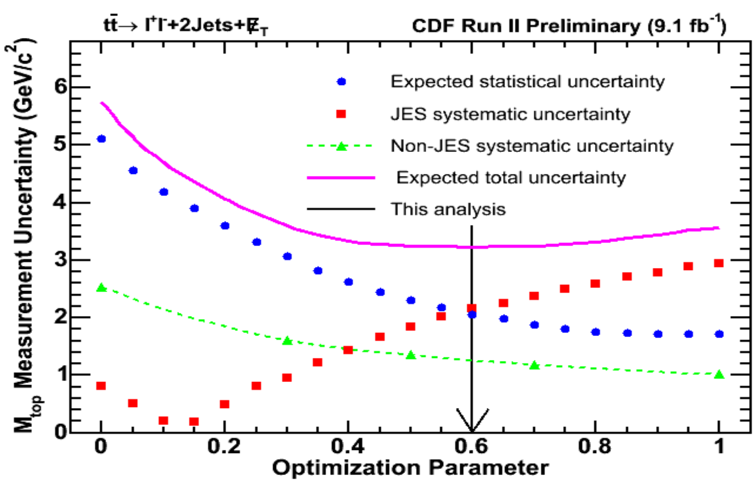
Отбор событий:

- два лептона (e или μ) Eт> 20 ГэВ
- MET>25 ГэВ
- ≥2 адронные струи Eт> 15 ГэВ
- MET>50 ГэВ если Δφ(MET, l or jet) < 20º
- MET significance > 4 ГэВ$^{1/2}$ для Z кандидатов
- Hт>200 ГэВ
- две подвыборки событий в зависимости от числа струй с b-метками (0, ≥1)



CDF Run II Preliminary (9.1 fb^{-1})

$t\bar{t}$ dilepton sample		
Source	Tagged events	0 tag events
WW	0.57 ± 0.15	16.4 ± 3.6
WZ	0.12 ± 0.03	5.2 ± 1.0
ZZ	0.20 ± 0.06	3.0 ± 0.5
DY/Z	4.4 ± 0.4	51.2 ± 8.0
Fakes	8.6 ± 2.7	21.4 ± 6.2
Total background	13.9 ± 2.8	97.2 ± 14.5
$t\bar{t}$ (σ = 7.4 pb)	227.2 ± 16.2	173.2 ± 13.3
Total SM expectation	241.1 ± 16.4	270.3 ± 26.4
Observed	230	290



Оптимизация по отношению к общей ошибке измерения

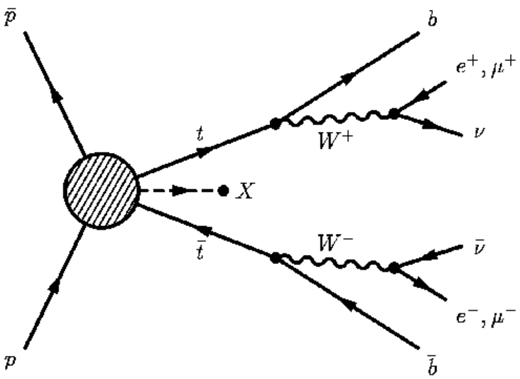
- "гибридная" переменная для анализа

$$M^{\mathrm{hyb}} = w \cdot M_t^{\mathrm{reco}} + (1 - w) \cdot M_{\ell b}^{\mathrm{alt}}$$

$$M_{\ell b}^{\mathrm{alt}} = c^2 \sqrt{\frac{\langle \ell_1, b_1 \rangle \cdot \langle \ell_2, b_2 \rangle}{E_{b_1} \cdot E_{b_2}}}$$

Dilepton

PHI-метод (Neutrino φ weighting method)



✓ используется оценочная переменная m_{rec}, полученная из кинематического фита (минимизация $\chi 2$-функции):

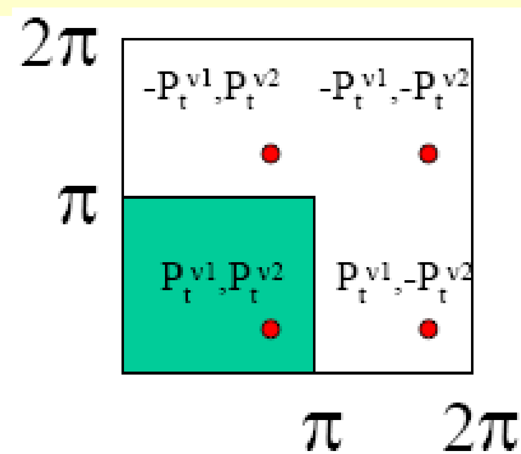
$$\chi^2 = \chi^2_{resol} + \chi^2_{constr}$$

$$\chi^2_{resol} = \sum_{l=1,2} \frac{(P_T^l - \widetilde{P}_T^l)^2}{\sigma_l^2} + \sum_{j=1,2} \frac{(P_T^j - \widetilde{P}_T^j)^2}{\sigma_j^2} + \sum_{i=x,y} \frac{(UE^i - \widetilde{UE}^i)^2}{\sigma^2_{UE^{i2}}}$$

$$\chi^2_{constr} = \frac{(M_{l_1\nu_1} - M_W)^2}{\Gamma^2_{M_W}} + \frac{(M_{l_2\nu_2} - M_W)^2}{\Gamma^2_{M_W}} + \frac{(M_{j_1 l_1 \nu_1} - \widetilde{m}_t)^2}{\Gamma^2_{M_t}} + \frac{(M_{j_2 l_2 \nu_2} - \widetilde{m}_t)^2}{\Gamma^2_{M_t}}$$

✓ Сканировать $\phi_{\nu_1}, \phi_{\nu_2}$ плоскость, чтобы учесть недостающее число кин. связей

12×12 сеть решений в квадранте $(0,\pi) x (0,\pi)$



Dilepton

PHI-метод (Neutrino φ weighting method)

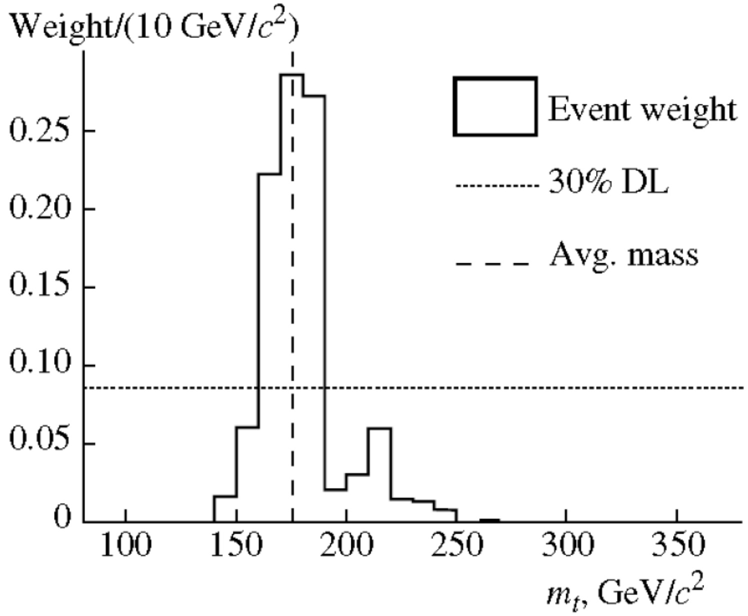
- 8 решений в каждой из 144 точек сети
  - Неопределенность на P_z^{ν} и соотнесение b-струй и лептонов
  - Выбирается решение с наименьшим χ^2

- Выбранные 144 решения взвешиваются согласно их χ2

$$w_{ij} = \frac{e^{-\chi'^2_{ij}/2}}{\sum_{i=1}^{12}\sum_{j=1}^{12} e^{-\chi'^2_{ij}/2}}$$

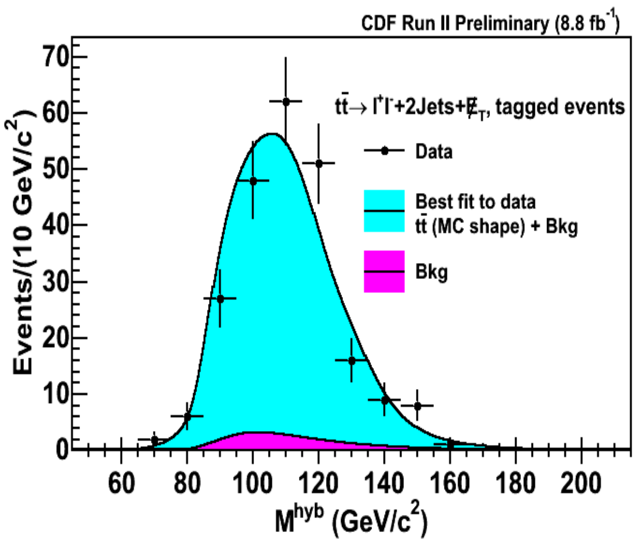
- для получения оценочной переменной вычисляется взвешенное среднее

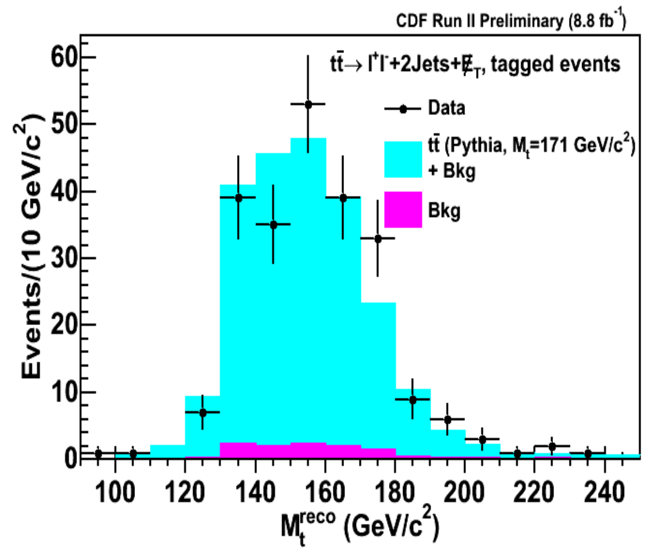
$$m_{\text{rec}} = \frac{\sum_{ij} w'_{ij} \cdot m_t^{ij}}{\sum_{ij} w'_{ij}}$$

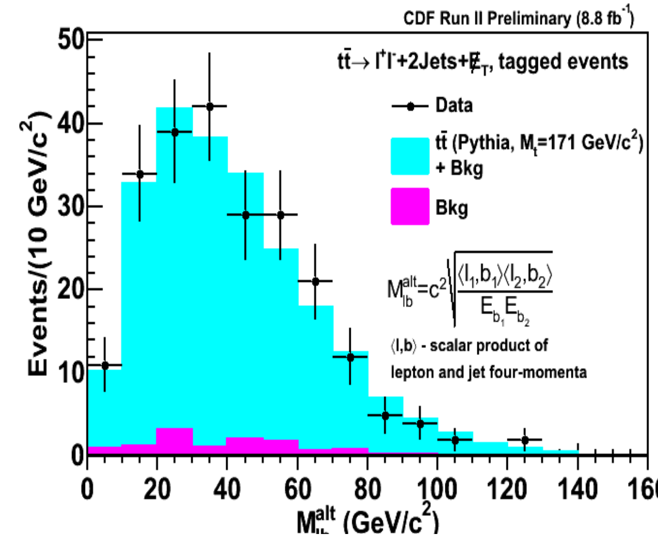


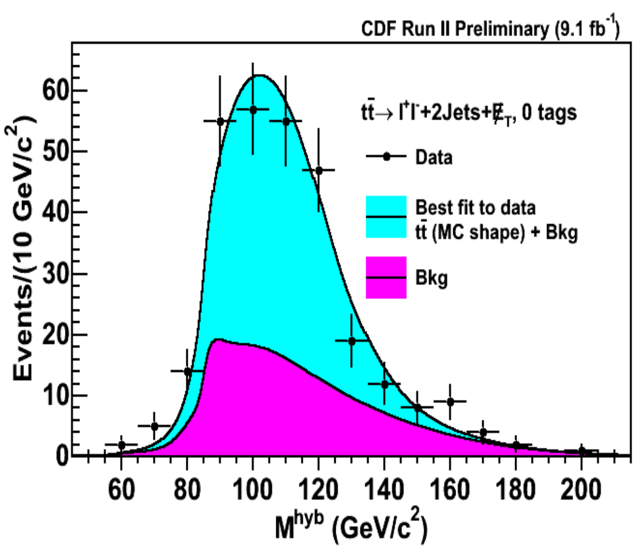
Пример распределения масс m_t^{ij} с учетом весов для отдельного $t\bar{t}$-события.

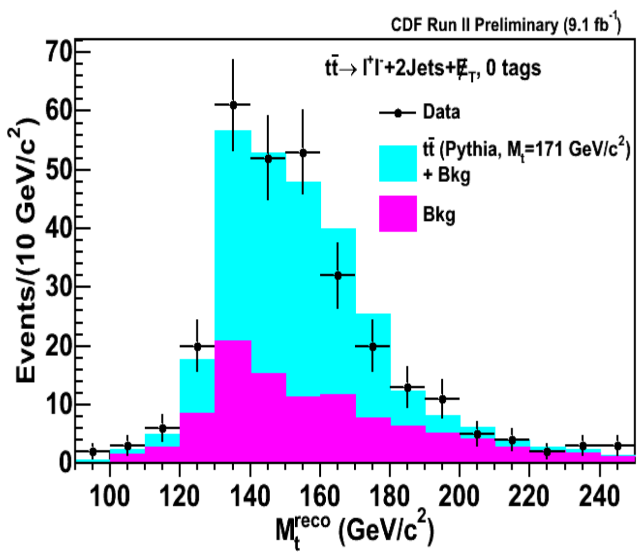
Dilepton

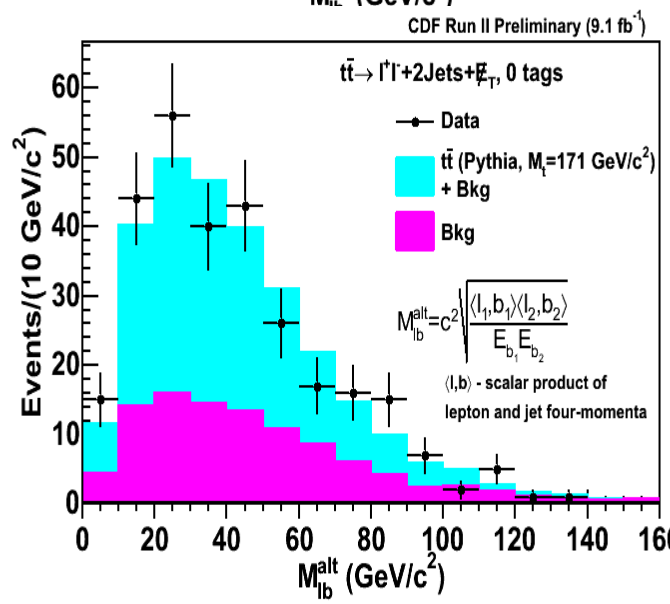

CDF Run II Preliminary (8.8 fb-1)
tt̄→ l+l-+2Jets+E̸T, tagged events
Data
Best fit to data
tt̄ (MC shape) + Bkg
Bkg
Events/(10 GeV/c2)
Mhyb (GeV/c2)


CDF Run II Preliminary (8.8 fb-1)
tt̄→ l+l-+2Jets+E̸T, tagged events
Data
tt̄ (Pythia, Mt=171 GeV/c2)
+ Bkg
Bkg
Events/(10 GeV/c2)
Mtreco (GeV/c2)


CDF Run II Preliminary (8.8 fb-1)
tt̄→ l+l-+2Jets+E̸T, tagged events
Data
tt̄ (Pythia, Mt=171 GeV/c2)
+ Bkg
Bkg
Mlbalt=c2√(⟨l1,b1⟩⟨l2,b2⟩ / Eb1Eb2)
⟨l,b⟩ - scalar product of
lepton and jet four-momenta
Events/(10 GeV/c2)
Mlbalt (GeV/c2)

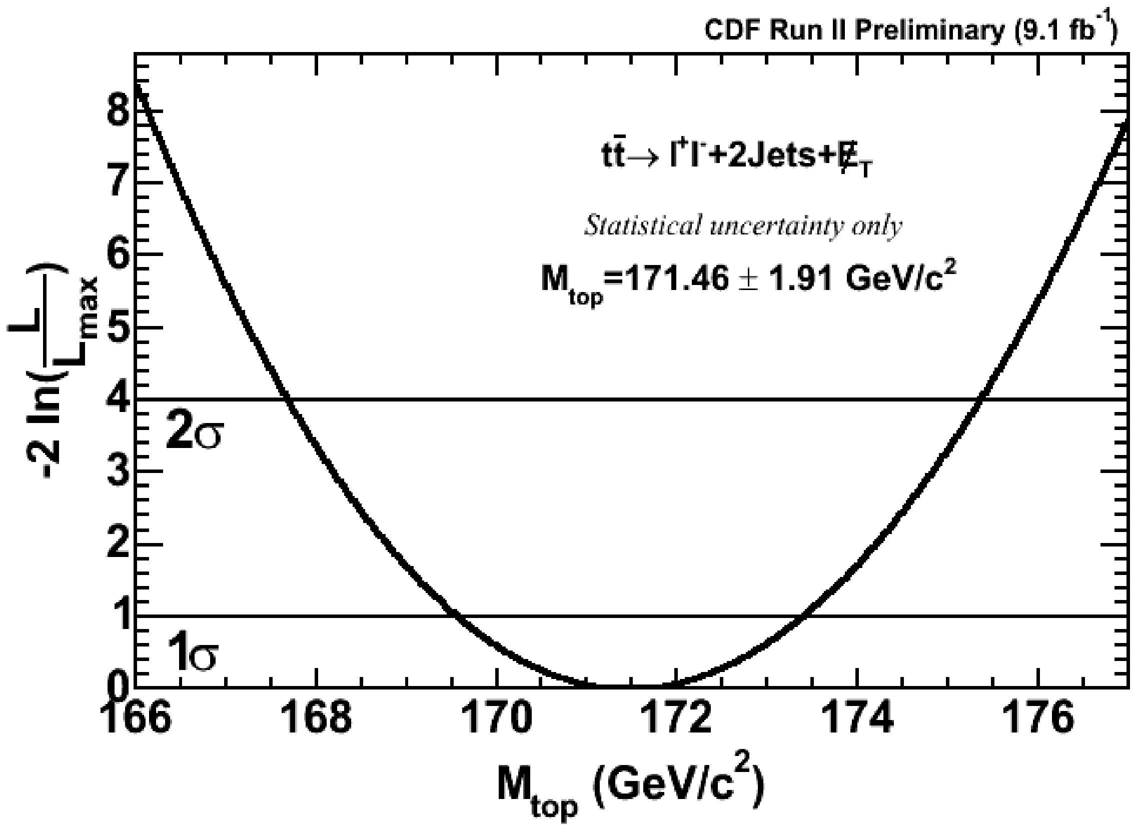

CDF Run II Preliminary (9.1 fb-1)
tt̄→ l+l-+2Jets+E̸T, 0 tags
Data
Best fit to data
tt̄ (MC shape) + Bkg
Bkg
Events/(10 GeV/c2)
Mhyb (GeV/c2)


CDF Run II Preliminary (9.1 fb-1)
tt̄→ l+l-+2Jets+E̸T, 0 tags
Data
tt̄ (Pythia, Mt=171 GeV/c2)
+ Bkg
Bkg
Events/(10 GeV/c2)
Mtreco (GeV/c2)


CDF Run II Preliminary (9.1 fb-1)
tt̄→ l+l-+2Jets+E̸T, 0 tags
Data
tt̄ (Pythia, Mt=171 GeV/c2)
+ Bkg
Bkg
Mlbalt=c2√(⟨l1,b1⟩⟨l2,b2⟩ / Eb1Eb2)
⟨l,b⟩ - scalar product of
lepton and jet four-momenta
Events/(10 GeV/c2)
Mlbalt (GeV/c2)

Dilepton

M_{top} = 171.5 ± 1.9 (stat) ± 2.5 GeV/c^2 (syst)



CDF Run II Preliminary (9.1 fb^{-1})

M_{top} Measurement in the $t\bar{t}$ Dilepton Final State	
Source	Uncertainty (GeV/c^2)
Jet energy scale	2.17
NLO effects	0.67
Monte Carlo generators	0.50
Lepton energy scale	0.41
Background modeling	0.39
Initial and final state radiation	0.38
gg fraction	0.31
b-jet energy scale	0.30
Luminosity profile (pileup)	0.27
Color reconnection	0.24
MC sample size	0.20
Parton distribution functions	0.16
b-tagging	0.05
Total systematic uncertainty	2.51
Statistical uncertainty	1.91
Total	**3.15**

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All Hadronic

Отбор событий:

- запрет на лептоны
- MET significance < 3 ГэВ$^{1/2}$
- 6, 7 или 8 адронных струй E_T>15 ГэВ и ΔR_{min}>0.5
- подвыборки событий (1 и 2 b-метки)
- NN отбор

$$\not{E}_T^{\,sig} \equiv \not{E}_T / \sqrt{\textstyle\sum_{jets} E_T}$$

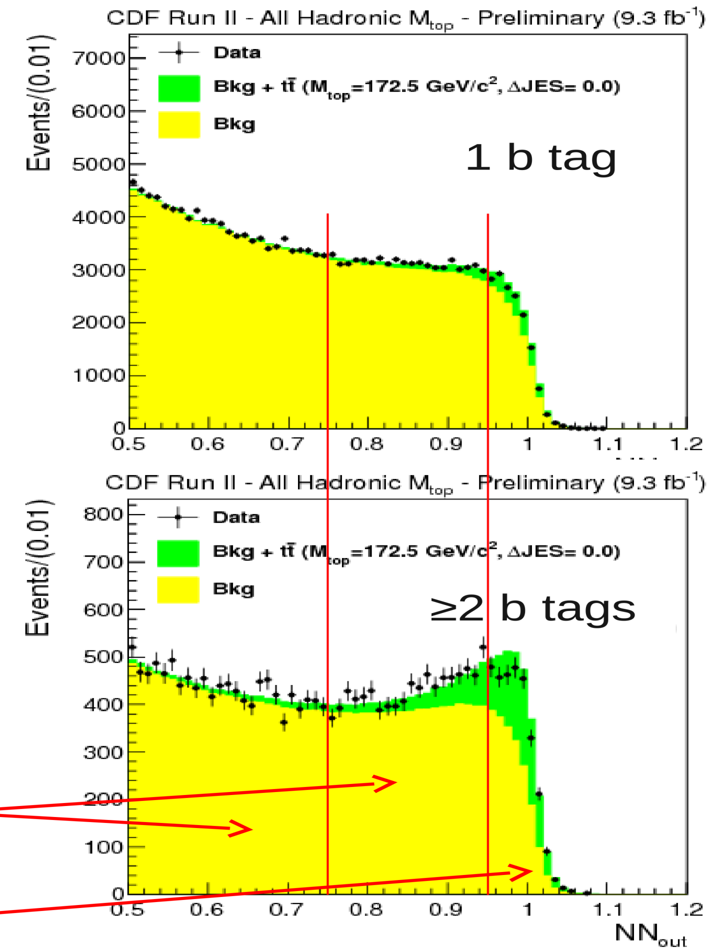
$$\chi^2 = \frac{(m_{jj}^{(1)} - M_W)^2}{\Gamma_W^2} + \frac{(m_{jj}^{(2)} - M_W)^2}{\Gamma_W^2} + \frac{(m_{jjb}^{(1)} - m_t^{rec})^2}{\Gamma_t^2} + \frac{(m_{jjb}^{(2)} - m_t^{rec})^2}{\Gamma_t^2} + \sum_{i=1}^{6} \frac{(p_{T,i}^{fit} - p_{T,i}^{meas})^2}{\sigma_i^2}$$

S_{jes} 1tag sample: NN>0.97, χ_W<2

S_{Mtop} 1tag sample:NN>0.97, χ_{Mt}<3

S_{jes} 2tag sample: NN>0.94, χ_W<3

S_{Mtop} 2tag sample: NN>0.94, χ_{Mt}<4



Control Regions

Signal Region

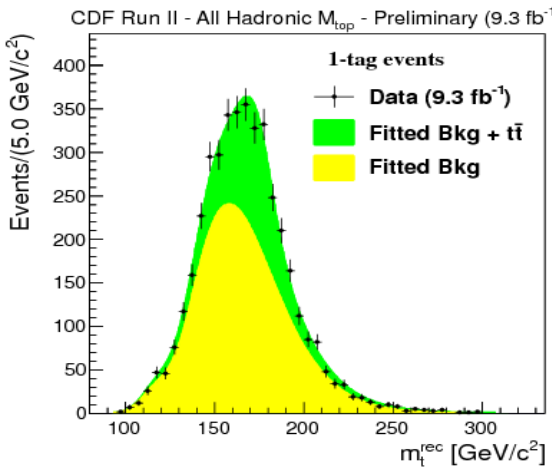
CDF Run II - All Hadronic M_{top} - Preliminary (9.3 fb^{-1})

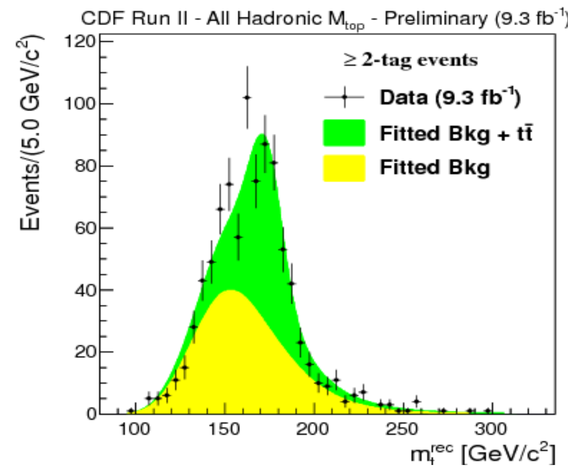
Sample		N_{obs}	Expected $t\bar{t}$ (S) ($M_{top} = 172.5$ GeV/c^2, ΔJES $= 0$)	Expected Background (B) ($N_{obs} - S$)	S/B
1-tag	S_{JES}	7890	1886 ± 150	6004 ± 174	1 / 3.2
	S_{Mtop}	4130	1270 ± 101	2860 ± 120	1 / 2.2
$\geq$ 2-tags	S_{JES}	1758	782 ± 64	976 ± 77	1 / 1.2
	S_{Mtop}	901	514 ± 42	387 ± 52	1 / 0.75

All Hadronic

m_t^{rec}

1 tag



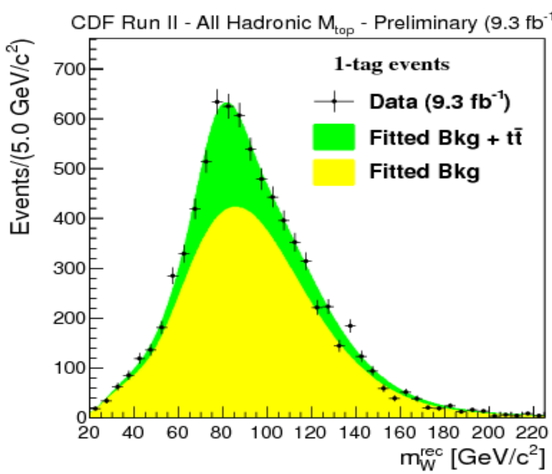


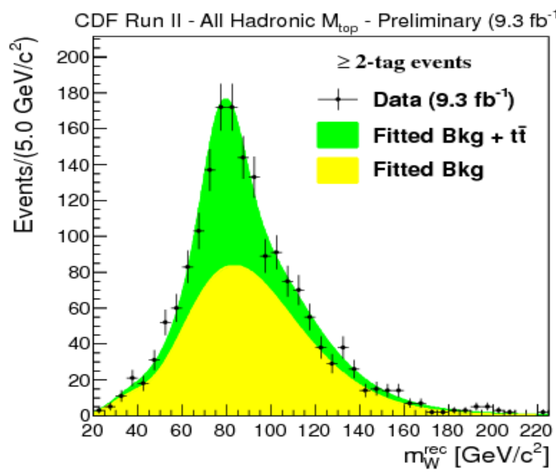
m_t^{rec}

≥2 tags

m_W^{rec}

1 tag





m_W^{rec}

≥2 tags

$$\mathcal{L} = \mathcal{L}_{1\,tag} \times \mathcal{L}_{\geq 2\,tags} \times \mathcal{L}_{\Delta \mathrm{JES}_{constr}}$$

$$\mathcal{L}_{1,\geq 2\,tags} = \mathcal{L}_{\Delta \mathrm{JES}} \times \mathcal{L}_{M_{\mathrm{top}}} \times \mathcal{L}_{evts}$$

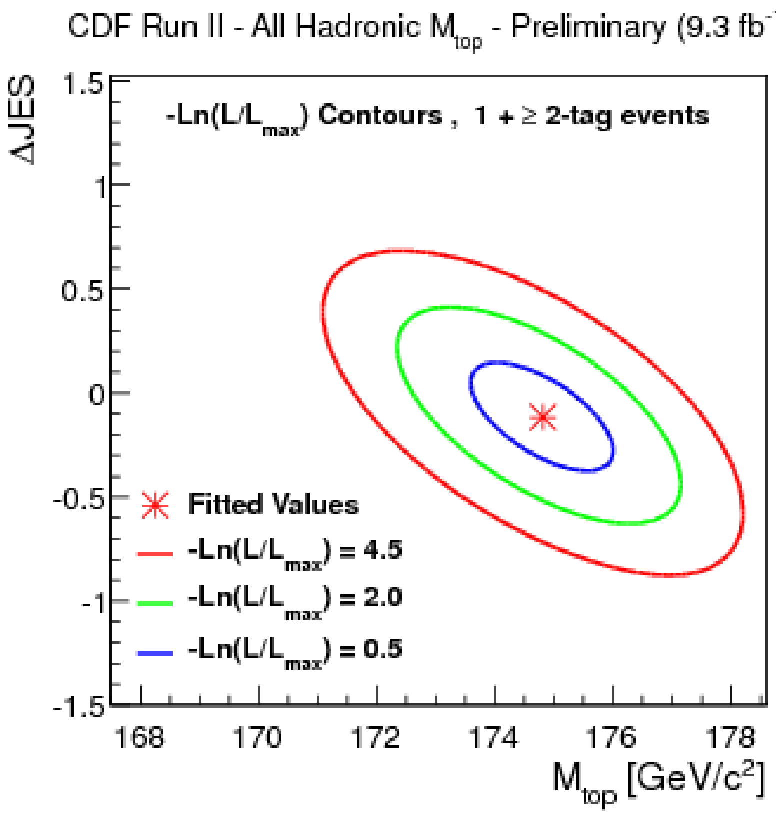
$$\mathcal{L}_{\Delta \mathrm{JES}} = \prod_{i=1}^{N_{obs}^{S_{\mathrm{JES}}}} \frac{n_s \cdot P_s^{m_W^{rec}}(m_{W,i} \,|\, M_{\mathrm{top}}, \Delta\mathrm{JES}) + n_b \cdot P_b^{m_W^{rec}}(m_{W,i})}{n_s + n_b}$$

$$\mathcal{L}_{M_{\mathrm{top}}} = \prod_{i=1}^{N_{obs}^{S_{M_{\mathrm{top}}}}} \frac{\mathcal{A}_s(M_{\mathrm{top}}, \Delta\mathrm{JES}) \cdot n_s \cdot P_s^{m_t^{rec}}(m_{t,i} \,|\, M_{\mathrm{top}}, \Delta\mathrm{JES}) + \mathcal{A}_b \cdot n_b \cdot P_b^{m_t^{rec}}(m_{t,i})}{\mathcal{A}_s(M_{top}, \Delta\mathrm{JES}) \cdot n_s + \mathcal{A}_b \cdot n_b}$$

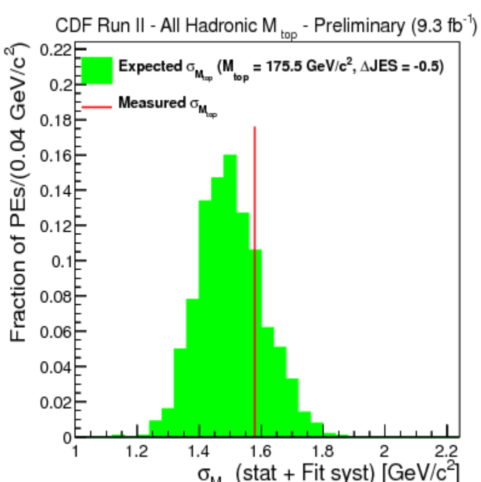
$$\mathcal{L}_{evts} = \sum_{r_s + r_b = N_{obs}^{S_{JES}}} P(r_s, n_s) \cdot P(r_b, n_b) \cdot \left[\sum_{\substack{t_s \leq r_s,\; t_b \leq r_b \\ t_s + t_b = N_{obs}^{S_{M_{top}}}}} B(t_s, r_s, \mathcal{A}_s) \cdot B(t_b, r_b, \mathcal{A}_b) \right]$$

All Hadronic

m_t=175.07±1.19(stat)±1.57(syst) GeV/c^2



Source	$\sigma_{M_{\rm top}}$ (GeV/c^2)	$\sigma_{\Delta_{\rm JES}}$
Generator (hadronization)	0.29	0.273
Parton distribution functions	$^{+0.18}_{-0.36}$	$^{+0.096}_{-0.052}$
Initial / Final state radiation	0.13	0.232
Color reconnection	0.32	0.101
$\Delta_{\rm JES}$ fit	0.97	−−
$M_{\rm top}$ fit	−−	0.207
Other free parameters of the fit	0.41	0.040
Templates sample size	0.34	0.071
$t\bar{t}$ cross section	0.15	0.034
Integrated luminosity	0.15	0.032
Trigger	0.61	0.188
Background shape	0.15	0.014
b-tagging	0.04	0.018
b-jets energy scale	0.20	0.035
Pileup	0.22	0
Residual JES	0.57	−−
Residual bias / Calibration	$^{+0.27}_{-0.24}$	$^{+0.077}_{-0.096}$
Total	$^{+1.55}_{-1.58}$	$^{+0.492}_{-0.488}$



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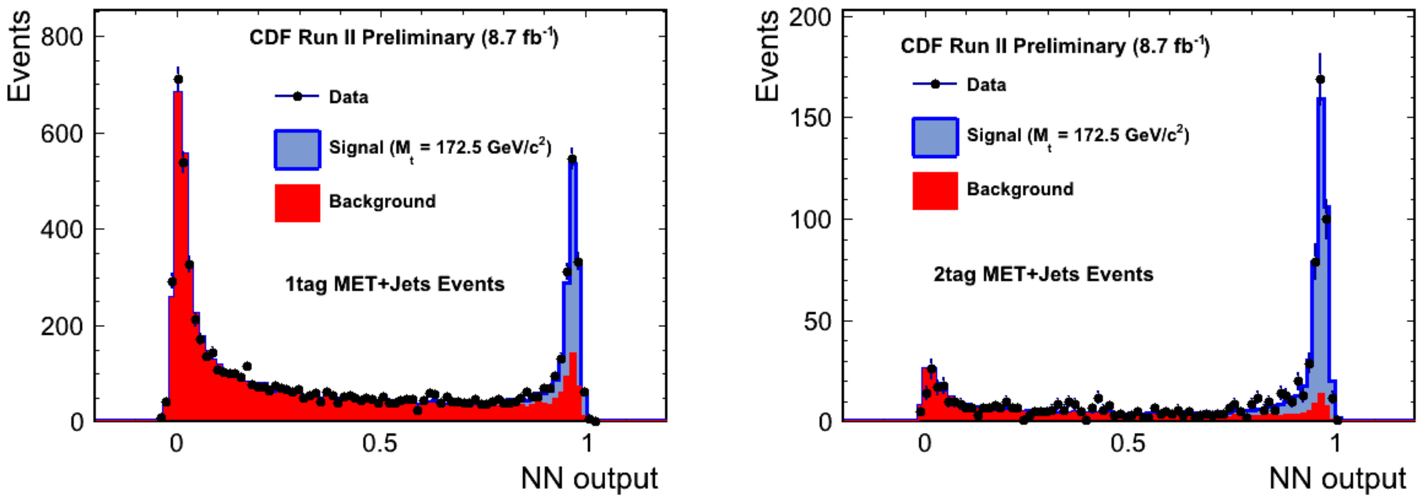
MET+Jets

Отбор событий:

- online: ≥4 кластеров в калориметре с E_T>15 ГэВ и ΣE_T >175 ГэВ
- запрет на лептоны
- 4, 5 и 6 адронных струй E_T>15 ГэВ
- MET significance > 3 ГэВ$^{1/2}$
- подвыборки событий в зависимости от числа струй с b-метками 1 и 2
- NN отбор

$$\not{E}_T^{\mathrm{sig}} \equiv \not{E}_T / \sqrt{\sum_{\mathrm{jets}} E_T}$$

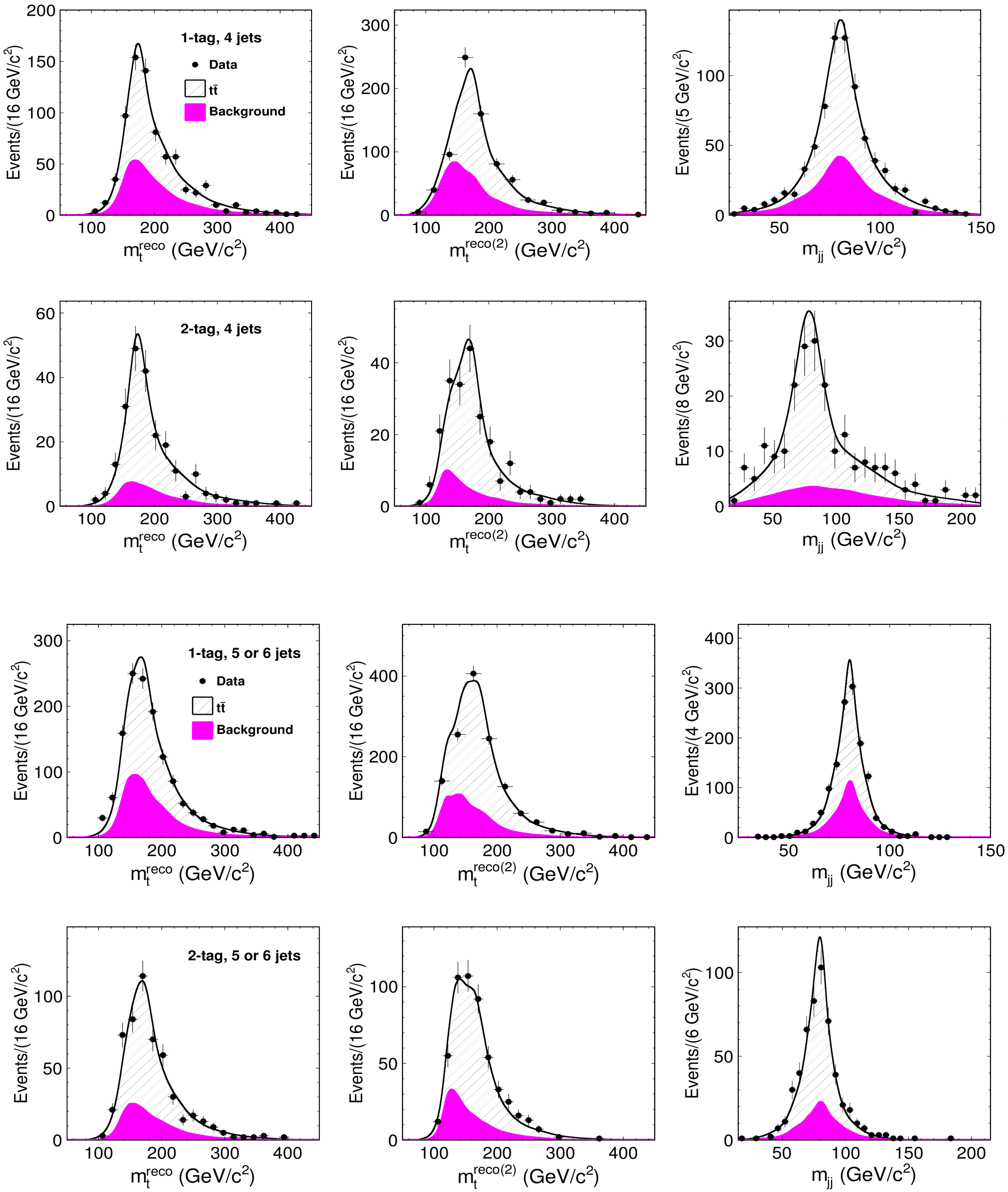


CDF II Preliminary 8.7 fb^{-1}

b-tagging	jet-multiplicity	$t\bar{t}$	Background	Total Expected	Observed
1tag	4 jets	427 ± 50	262 ± 22	690± 55	761
	5 or 6 jets	801±70	450±29	1251 ± 76	1341
2tag	4 jets	179±23	43±11	222 ±26	225
	5 or 6 jets	373 ± 37	125±23	498 ± 44	550

MET+Jets

3D шаблоны: Mt^{reco}, Mw, $Mt^{reco(2)}$

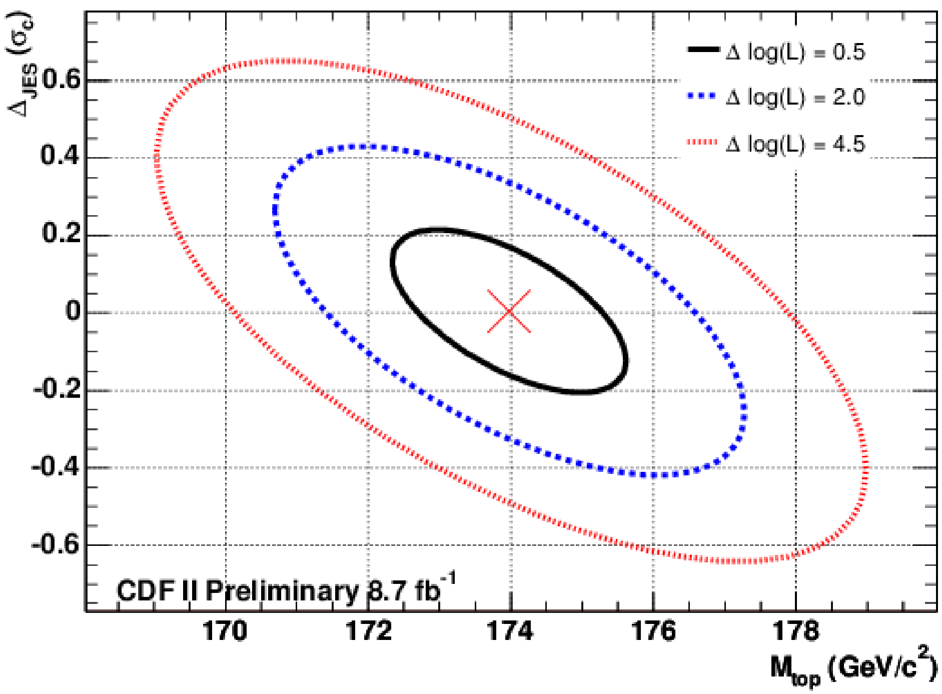


$$\chi^2 = \sum_{i=4\text{jets}} \frac{(p_T^{i,\text{fit}} - p_T^{i,\text{meas}})^2}{\sigma_i^2} + \sum_{k=x,y} \frac{(U_{T_k}^{\text{fit}} - U_{T_k}^{\text{meas}})^2}{\sigma_k^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{\text{missing}} - M_W)^2}{\Gamma_W^2} + \frac{(M_{b,\text{missing}} - m_t^{\text{reco}})^2}{\Gamma_t^2} + \frac{(M_{bjj} - m_t^{\text{reco}})^2}{\Gamma_t^2}, \quad (1)$$

$$\mathcal{L}_k = \exp\left(-\frac{(n_b - n_b^0)^2}{2\sigma_{n_b}^2}\right) \times \prod_{i=1}^{N} \frac{n_s P_{sig}(m_t^{reco}, m_{jj}, m_t^{reco(2)}; M_{top}, \Delta_{JES}) + n_b P_{bg}(m_t^{reco}, m_{jj}, m_t^{reco(2)}; \Delta_{JES})}{n_s + n_b}$$

MET+Jets

M_{top} = 173.9 ± 1.6 (stat.+JES) ± 0.9 GeV/c^2 (syst)



Source	Uncertainty (GeV/c^2)
Residual jet-energy scale	0.44
MC generator	0.36
Color reconnection	0.28
gg fraction	0.27
Radiation	0.28
PDFs	0.16
b-jet energy scale	0.19
Background	0.15
Calibration	0.21
Multiple hadron interaction	0.18
Trigger modeling	0.13
Total systematic uncertainty	0.87

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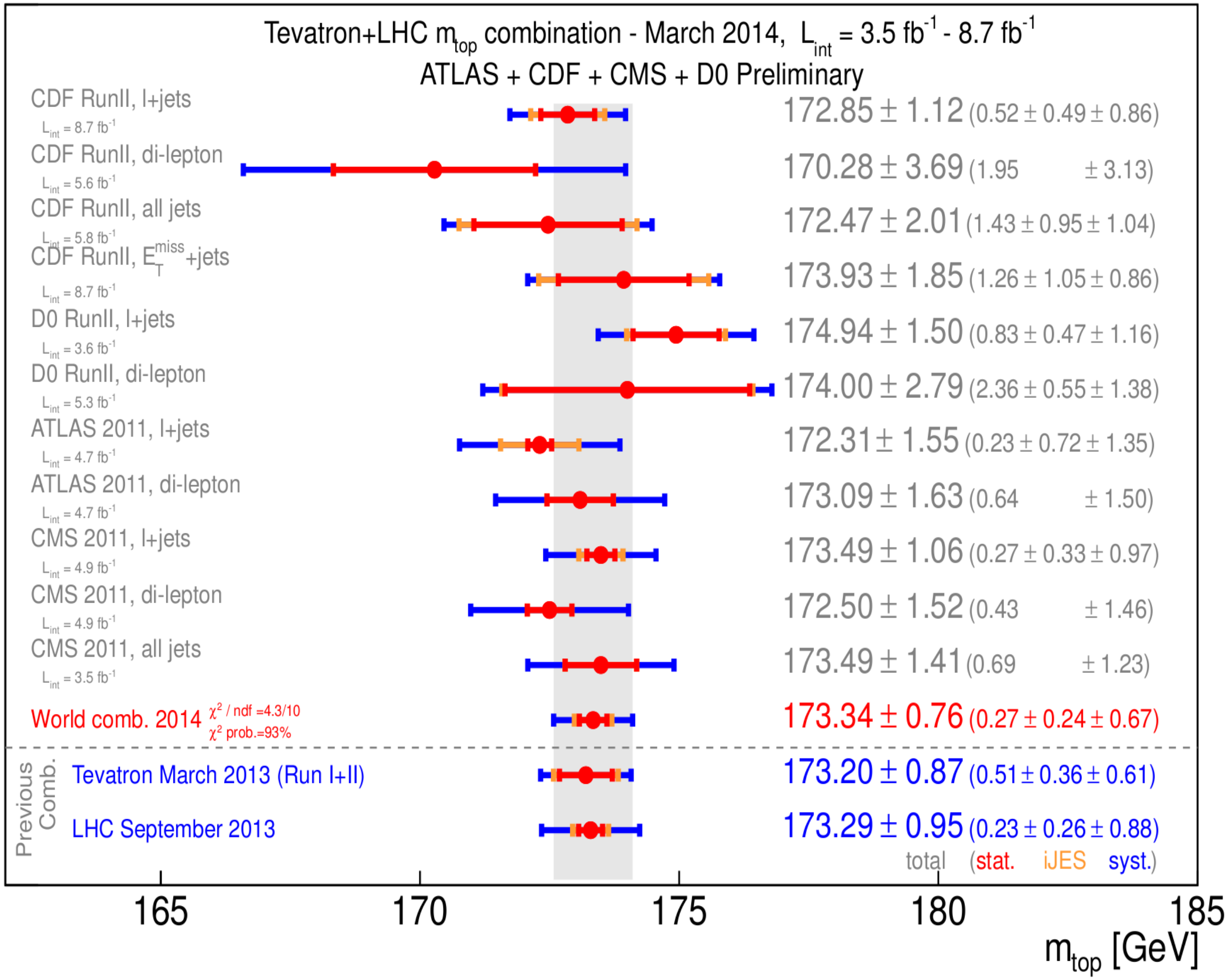
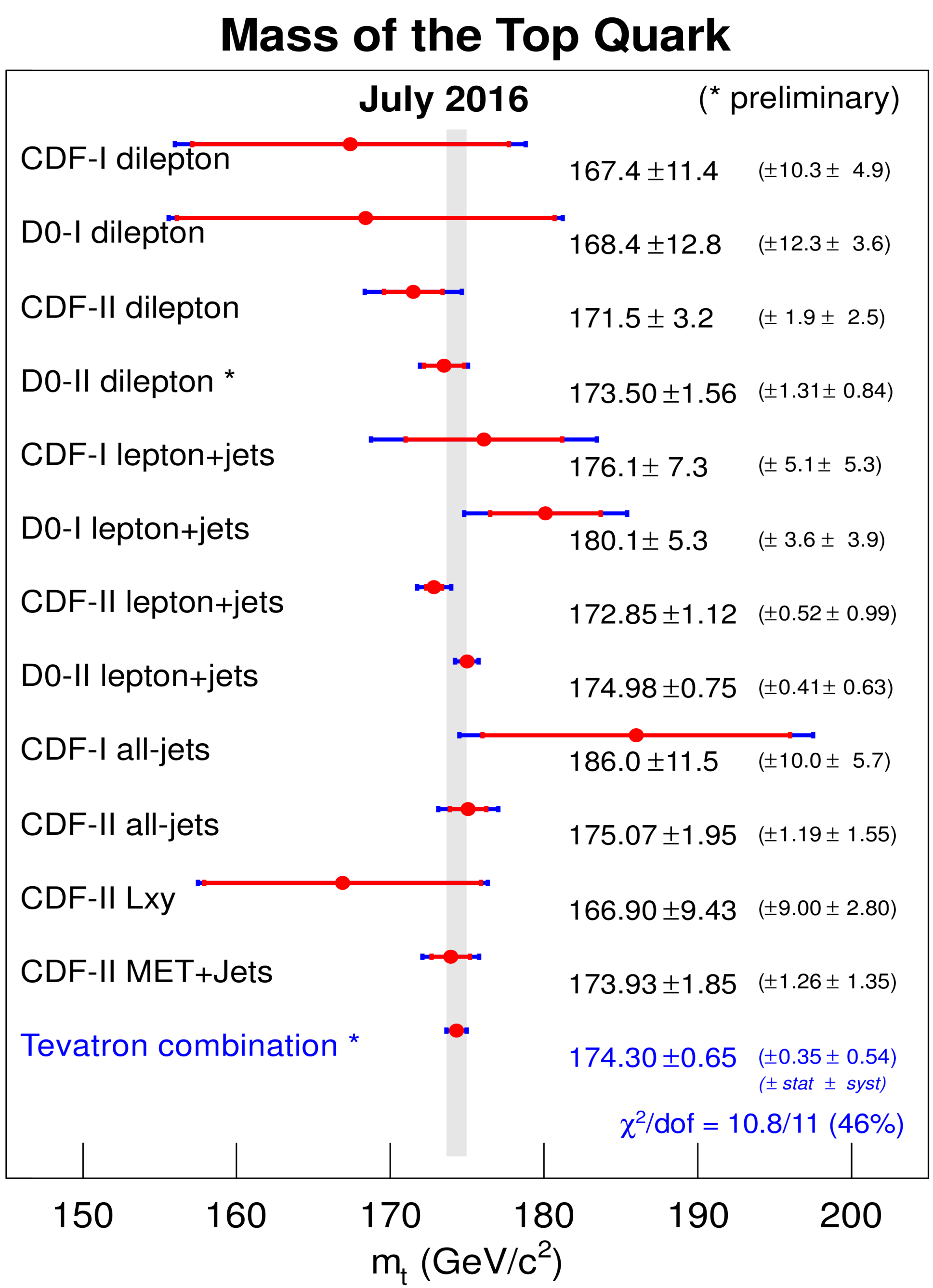
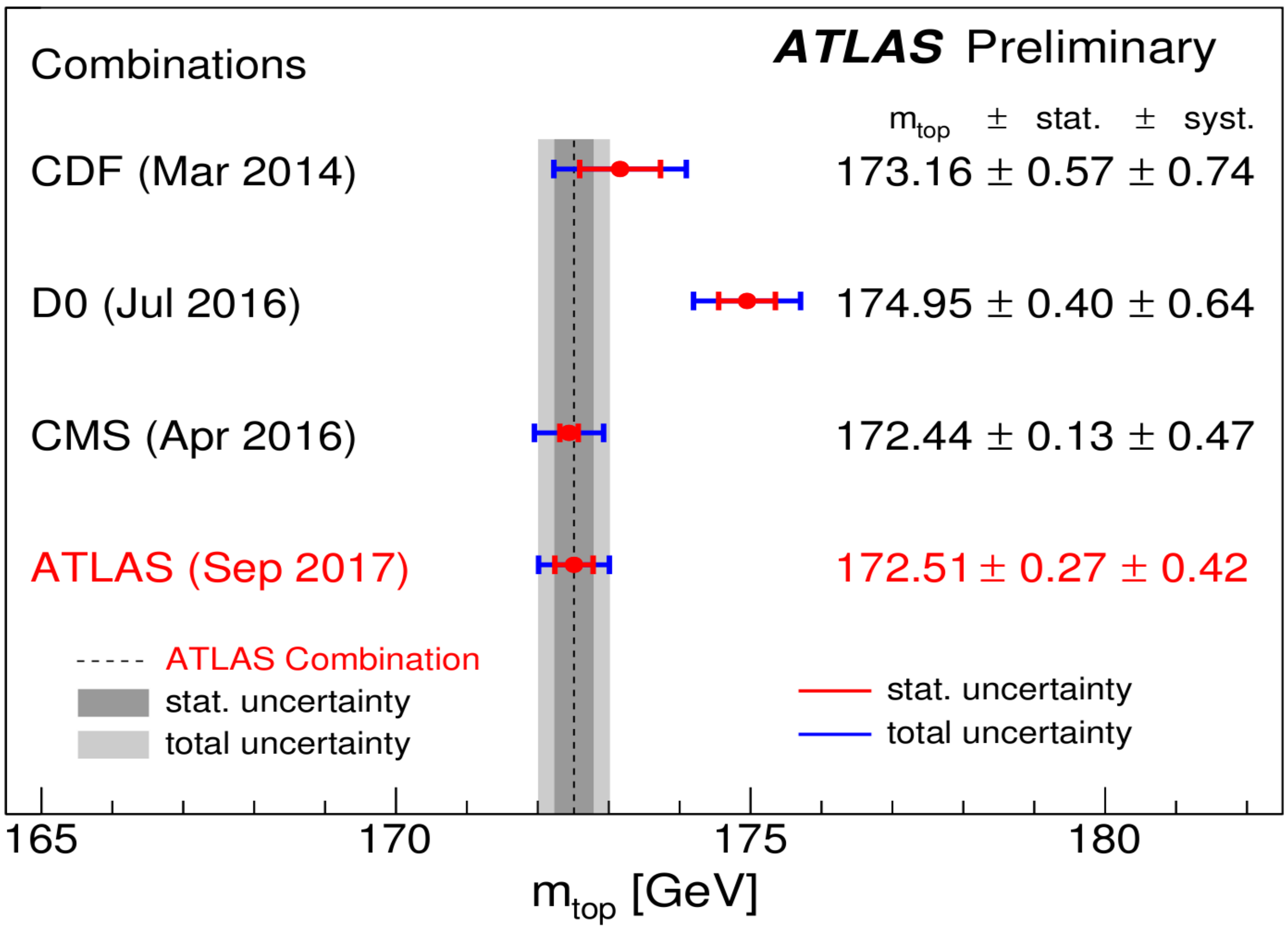
Tevatron & LHC combination



Tevatron combination




Combinations
ATLAS Preliminary
m_top ± stat. ± syst.
CDF (Mar 2014)
173.16 ± 0.57 ± 0.74
D0 (Jul 2016)
174.95 ± 0.40 ± 0.64
CMS (Apr 2016)
172.44 ± 0.13 ± 0.47
ATLAS (Sep 2017)
172.51 ± 0.27 ± 0.42
ATLAS Combination
stat. uncertainty
total uncertainty
stat. uncertainty
total uncertainty
165
170
175
180
m_top [GeV]