Combination of the top-quark mass measurements from the Tevatron and from the LHC colliders

Tevatron: arXiv:1207.1069
ATLAS-CONF-2012-095, CMS PAS TOP-12-001

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The top quark

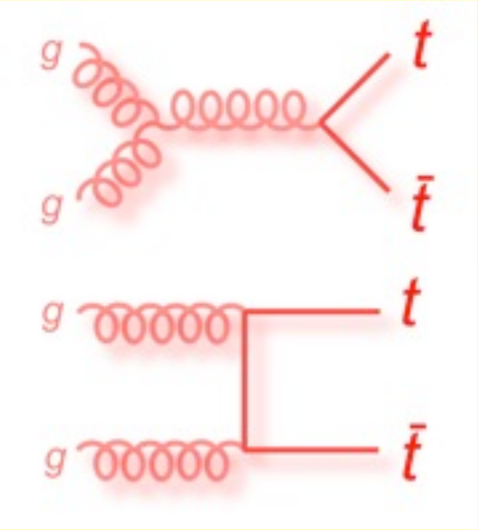
- The top quark is unique
  - ➔ heaviest elementary particle
  - ➔ Yukawa coupling to the Higgs boson close to 1:
    special role in the electroweak symmetry breaking ?
  - ➔ decays before hadronizing: unique way to observe a bare quark

$$\mathcal{L}_{\text{Yukawa}} = -\lambda_t \overline{\psi_{Lt}} \Phi \psi_{Rt}$$

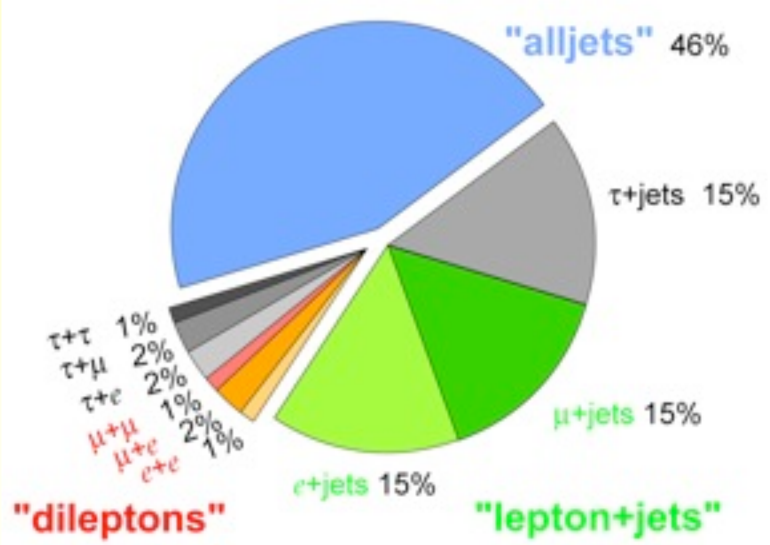
$$\lambda_t \approx 1 \ !!$$

$$m_t >> m_b$$

$$\tau \approx 5.10^{-25}\text{s} << \Lambda_{\text{QCD}}^{-1}$$



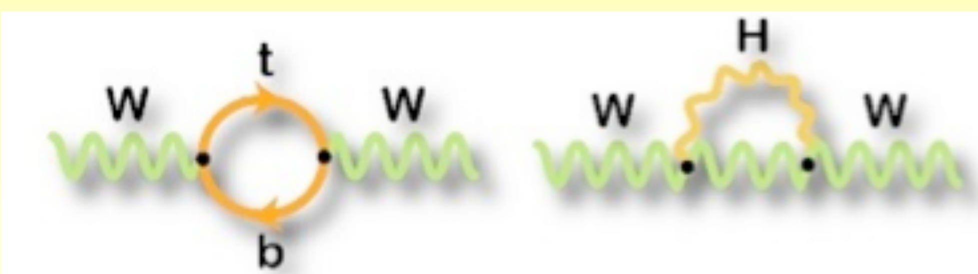
- Main production: tt̄ pairs by strong interaction
  - ➔ properties are studied using this mode
- Decay
  - ➔ B(t →Wb) ≈1 in the standard model
  - ➔ tt̄ signature classified according to the W decay



The top-quark mass

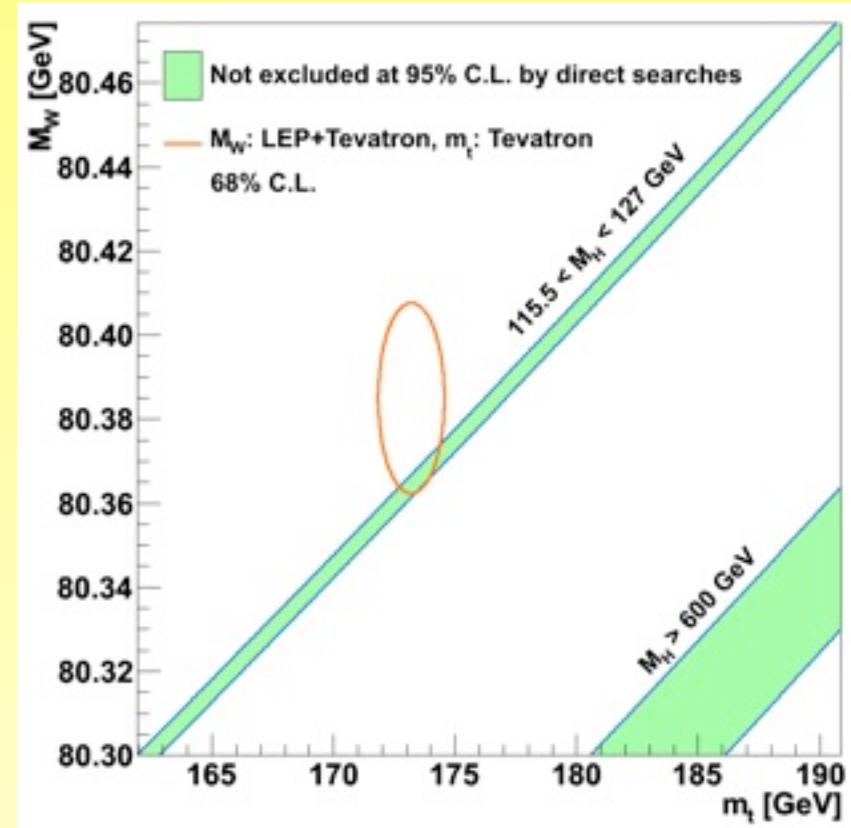
- free parameter of the standard model
  - ➔ precision on m_t important
    (loop corrections involving the top quark)
  - ➔ test of the consistency of the SM (direct vs indirect Higgs mass)

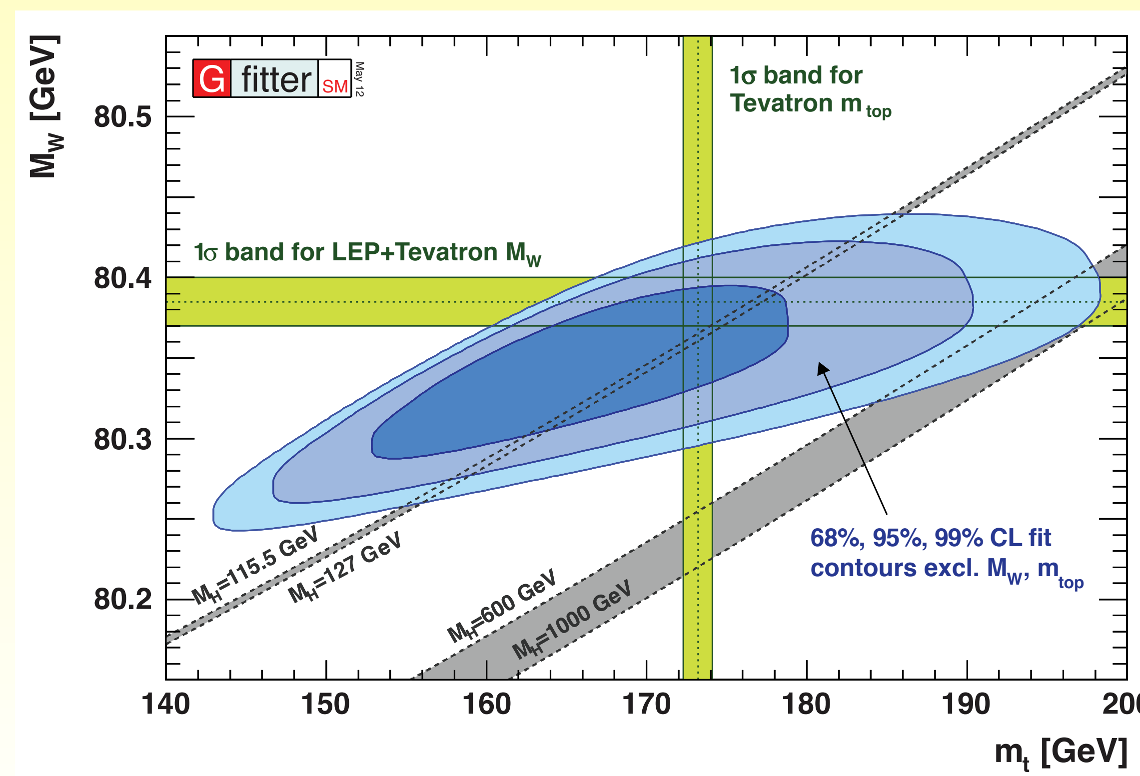
$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F \sin^2\theta_W}\frac{1}{1-\Delta r}$$



$\Delta r \propto m_t^2$ $\Delta r \propto \ln m_H$

$$\begin{aligned} m_H &= 94^{+29}_{-24}\ \text{GeV} \\ m_H &< 152\ \text{GeV @ 95\% CL} \end{aligned}$$





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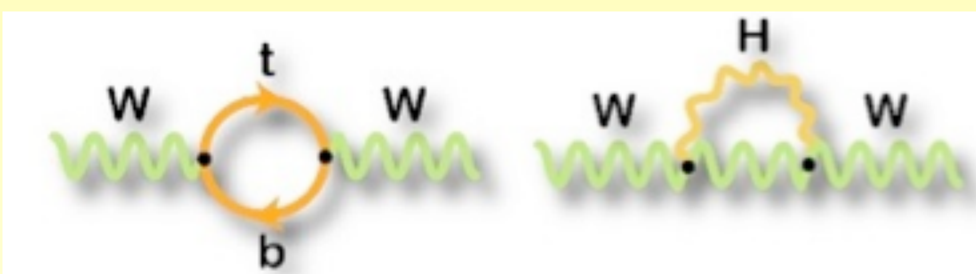

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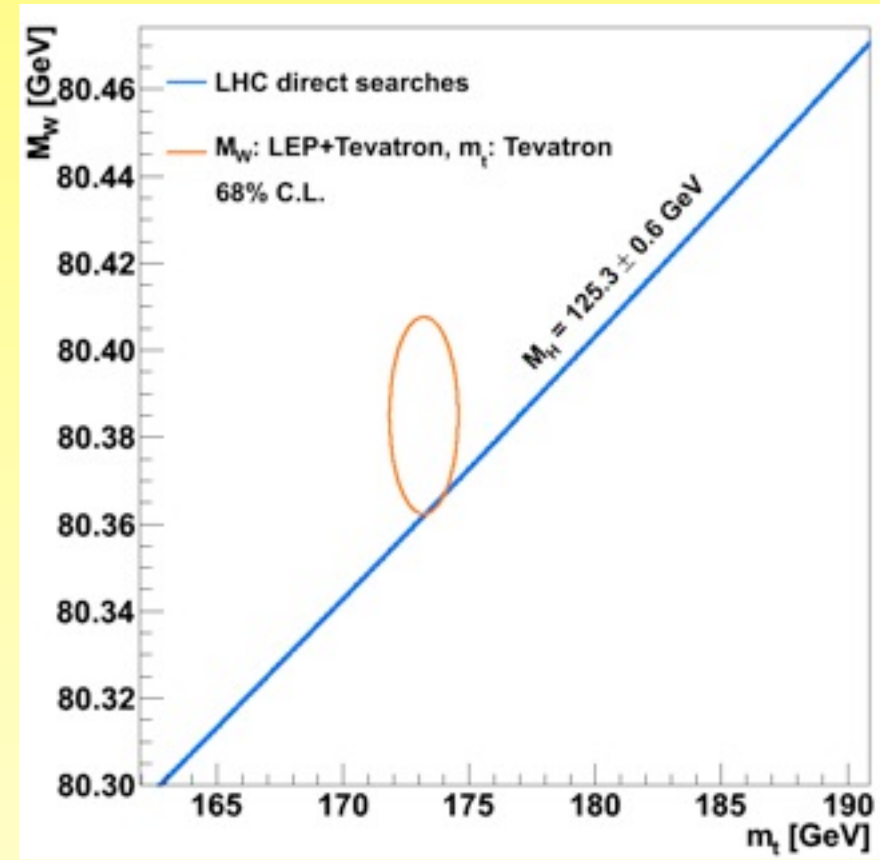
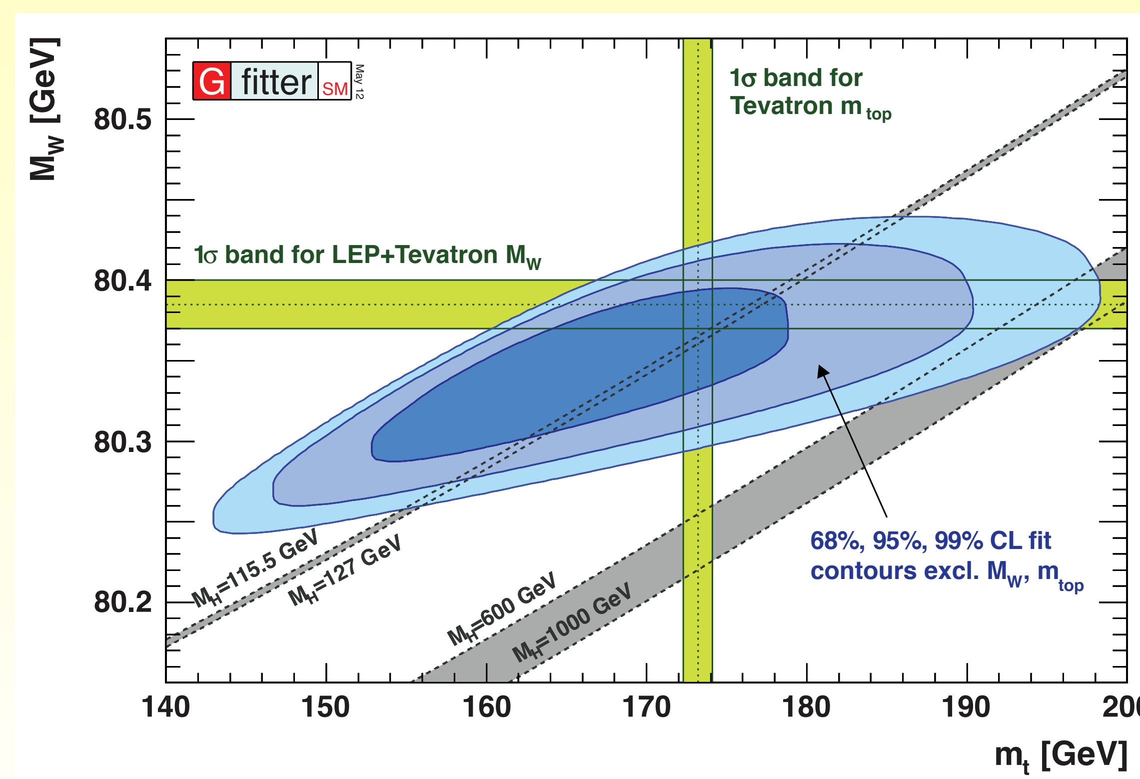




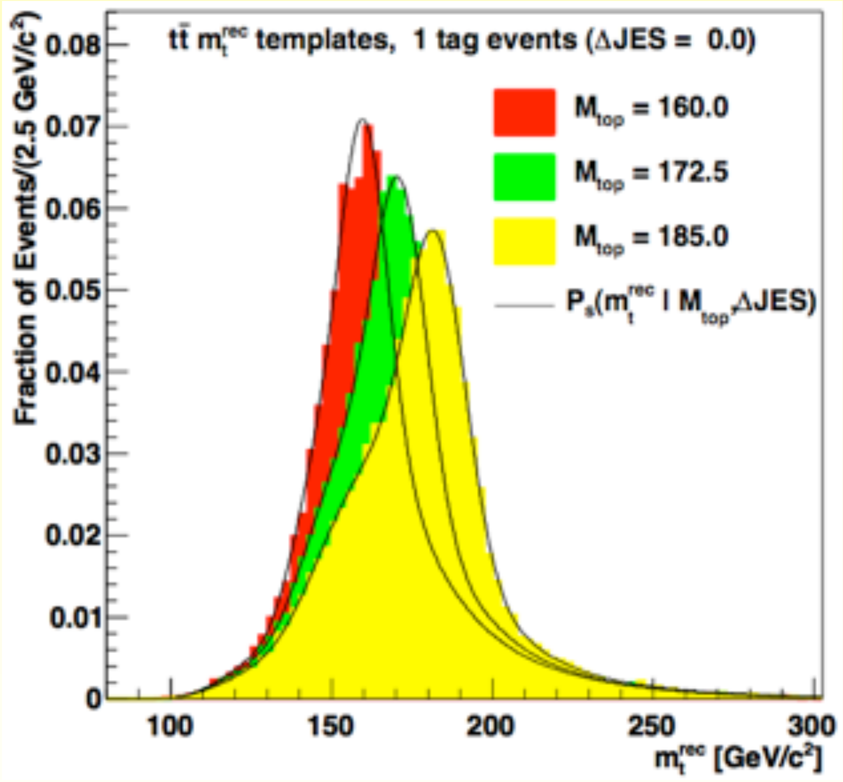
How to measure the top-quark mass ?

- 3 different methods to extract directly the top-quark mass
  - ➔ template method:

    compare an observable in data with MC generated with different masses
  - ➔ matrix element method:

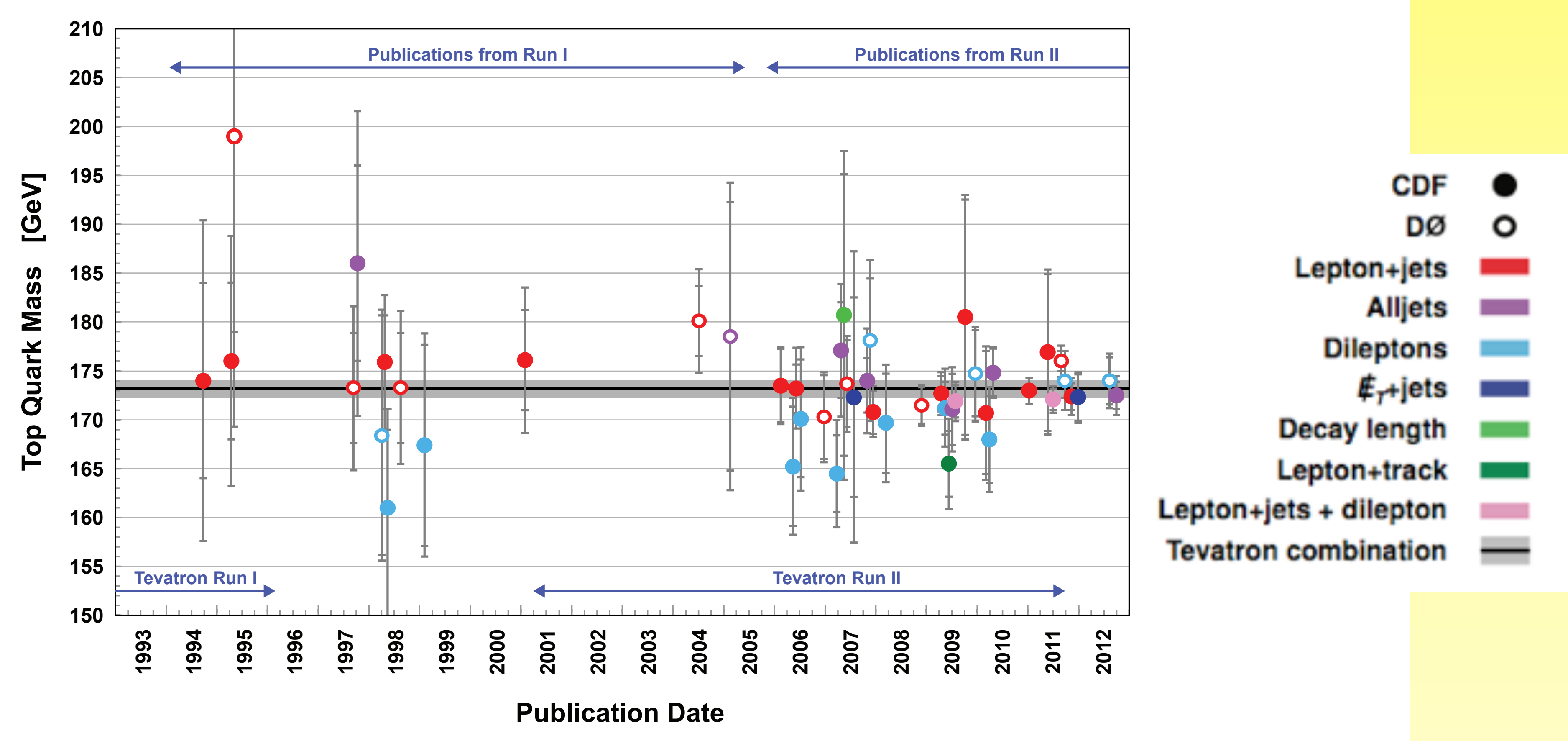
    build an event probability based on the LO $t\bar{t}$ matrix element using the full kinematics of the event
  - ➔ ideogram method:

    event likelihood computed as a convolution of a Gaussian resolution function with a Breit-Wigner (signal)



- for channel with at least one W decaying hadronically, can calibrate the jet energy scale (JES) constraining M_{jj} to M_W
- need to calibrate the method to correct for any potential biases

Top-quark mass measurements at the Tevatron



- Tevatron combination (using up to 5.8 fb^{-1})

➔ choose the best (independent) measurement per channel in each experiment

Decay channel or method	Tevatron period	Experiment	Integrated luminosity [fb^{-1}]	Number of events	Background [%]	m_t [GeV]	Uncertainty on m_t [%]
Lepton+jets	Run II	CDF	5.6	1087	17	173.00 ± 0.65 ± 1.06	0.72
Lepton+jets	Run II	D0	3.6	615	27	174.94 ± 0.83 ± 1.24	0.85
Lepton+jets	Run I	CDF	0.1	76	54	176.1 ± 5.1 ± 5.3	4.2
Lepton+jets	Run I	D0	0.1	22	22	180.1 ± 3.6 ± 3.9	2.9
Alljets	Run II	CDF	5.8	2856	71	172.47 ± 1.43 ± 1.40	1.2
Alljets	Run I	CDF	0.1	136	79	186.0 ± 10.0 ± 5.7	6.2
Dileptons	Run II	CDF	5.6	392	23	170.28 ± 1.95 ± 3.13	2.2
Dileptons	Run II	D0	5.3	415	21	174.00 ± 2.36 ± 1.44	1.6
Dileptons	Run I	CDF	0.1	8	16	167.4 ± 10.3 ± 4.9	6.8
Dileptons	Run I	D0	0.1	6	25	168.4 ± 12.3 ± 3.6	7.6
$\not{E}_T$+jets	Run II	CDF	5.7	1432	32	172.32 ± 1.80 ± 1.82	1.5
Decay length	Run II	CDF	1.9	375	30	166.90 ± 9.00 ± 2.82	5.7

Combination of the top-quark mass at the Tevatron

- Method: Best Linear Unbiased Estimate

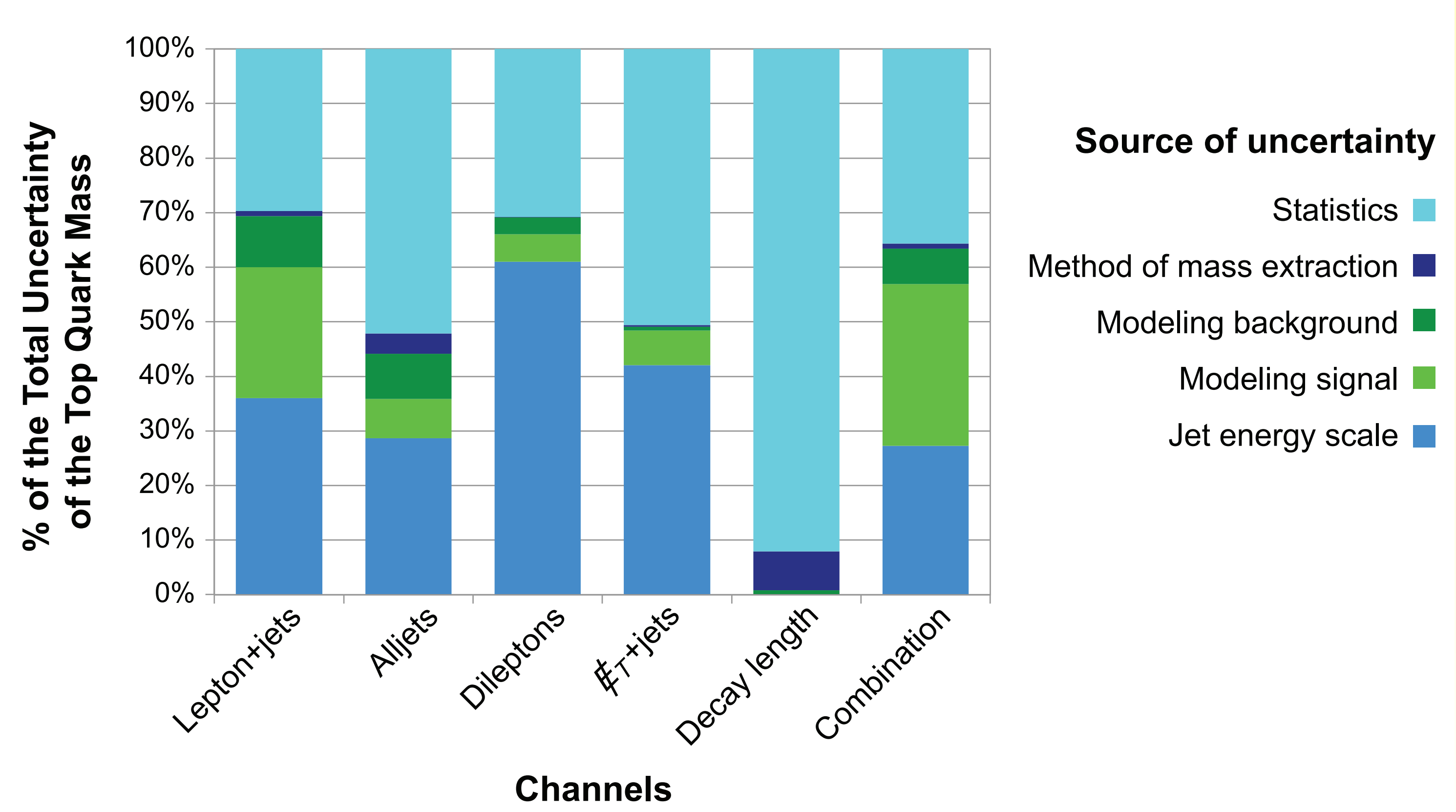
$$m_t^{\text{comb}} = \sum_{i=1}^{12} w_i \, m_t^i$$

$$w_i = \frac{\sum_{j=1}^{12} \text{Covariance}^{-1}\left(m_t^i, m_t^j\right)}{\sum_{i=1}^{12} \sum_{j=1}^{12} \text{Covariance}^{-1}\left(m_t^i, m_t^j\right)}$$

- Systematics

➔ separated into 14 parts to get the correct pattern of correlation between channels, run periods and experiments

➔ several years of discussion between CDF and D0 to agree on a common list of systematics on systematic evaluations, on systematic splitting, and on systematic correlations



Jet energy scale systematics

- Large source of systematic uncertainties: splitted in 7 parts

  * Light-jet response (1) (rJES): specific to CDF measurements, calibration of JES using single-pion response in data and in MC by tuning the simulation

    100% correlated only within CDF

  * Light-jet response (2) (dJES): absolute and relative (η-dependent) calibration of JES using γ+jets events in D0, η-dependent calibration in CDF

    100% correlated within the same experiment and the same run period

  * Out-of-cone corrections (cJES): out-of-cone corrections to MC showers for CDF and D0 Run I

    100% correlated between all measurements

  * Offset (UN/MI): noise from uranium decay, only for D0 Run I

    100% correlated within D0 Run I

  * Model for b jets (bJES): from difference between models of b-jet hadronization

    100% correlated between all measurements

  * Response for b/q/g jets (aJES): difference in response between b, quark and gluon jets

    100% correlated within the same experiment and the same run period

  * in-situ light-jet calibration (iJES): for channel with at least one W decaying hadronically, calibrate the jet energy scale constraining M_{jj} to M_W (scaling with statistics)

    uncorrelated

Other systematics

- 7 non-JES uncertainty sources:

  * Jet modeling: from uncertainties in jet identification efficiency and jet smearing at D0

    100% correlated within D0 Run II

  * Lepton modeling: electron and muon pt scale uncertainties (+ muon smearing for D0)

    100% correlated within the same experiment and the same run period

  * Signal modeling: PDF, $q\bar{q}$/gg fraction, higher-order QCD corrections, ISR/FSR, hadronization model, color reconnection

    100% correlated between all measurements

  * Multiple interaction model: from modeling of pile-up in the MC

    100% correlated within the same experiment and the same run period

  * Background from theory: NLO fraction of heavy flavor jets in W+jets, factorization/renormalization scales in W+jets simulation, theoretical cross sections used for MC normalization

    100% correlated between all measurements in the same channel

  * Background based on data: MC/data difference in background distributions, signal/bkg fraction

    100% correlated within the same experiment and the same run period in the same channel

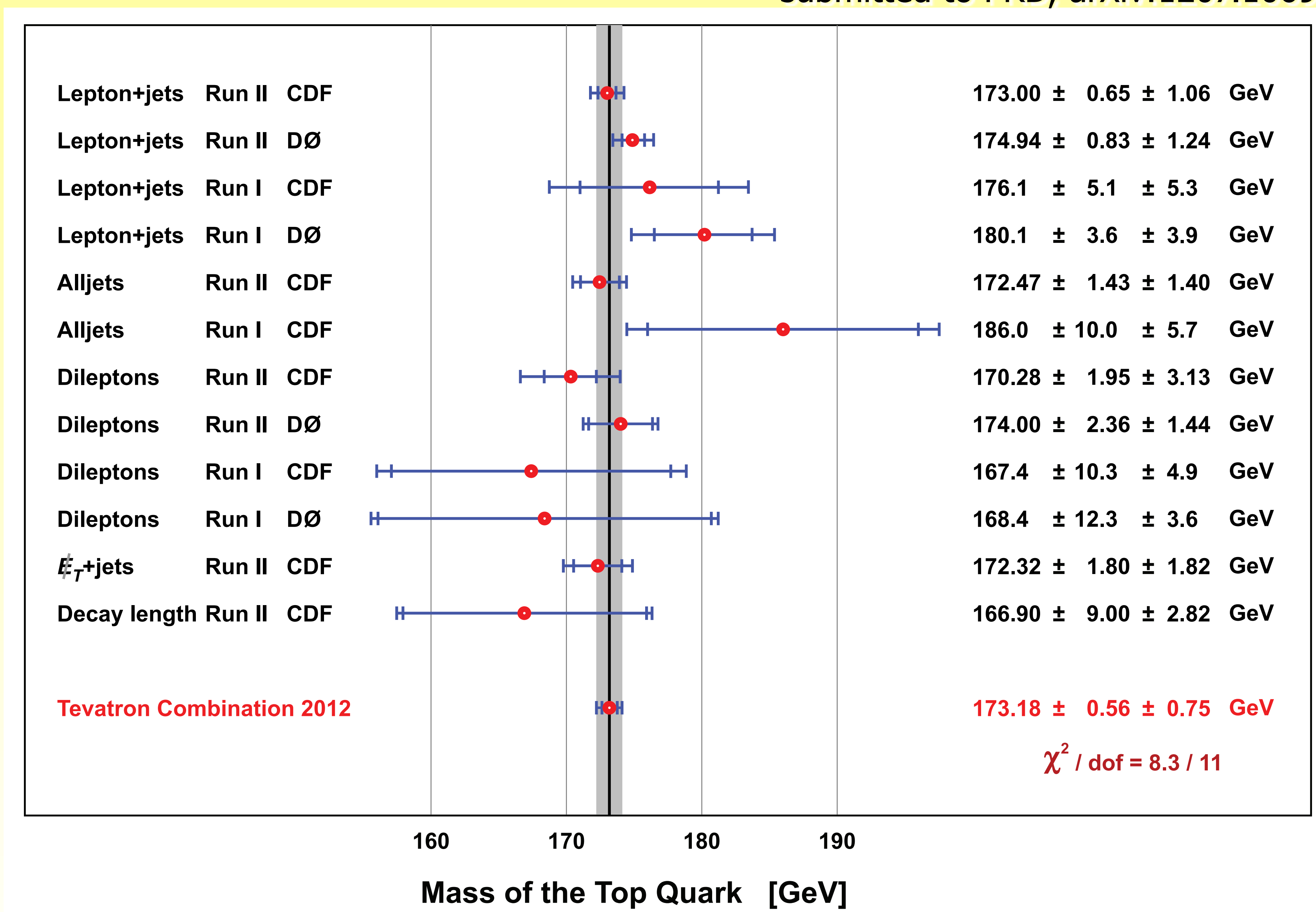
  * Calibration method: uncertainty from the calibration curve

    uncorrelated between all measurements

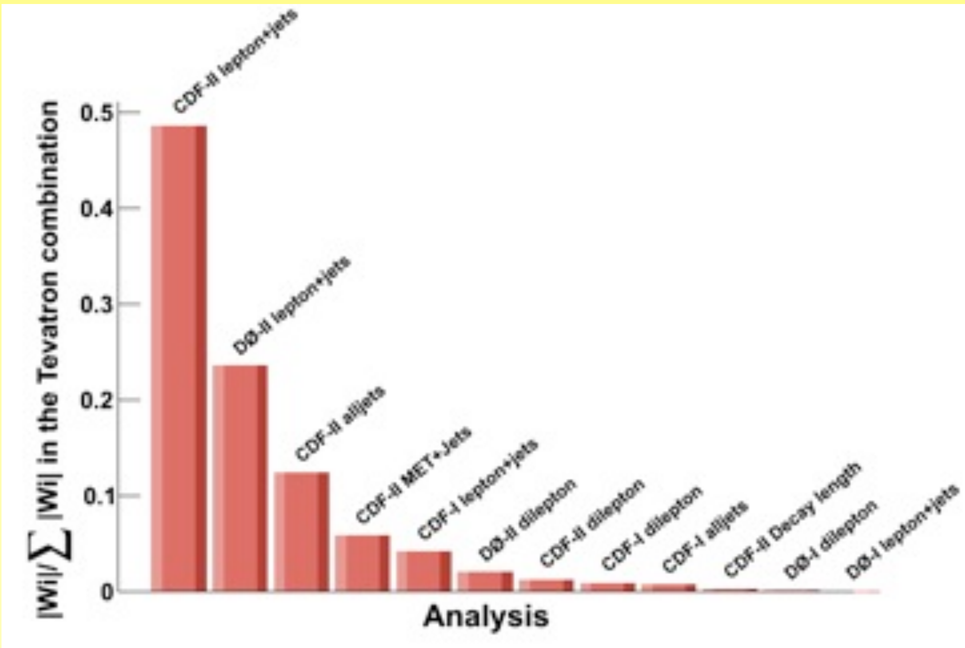
Tevatron top mass combination results

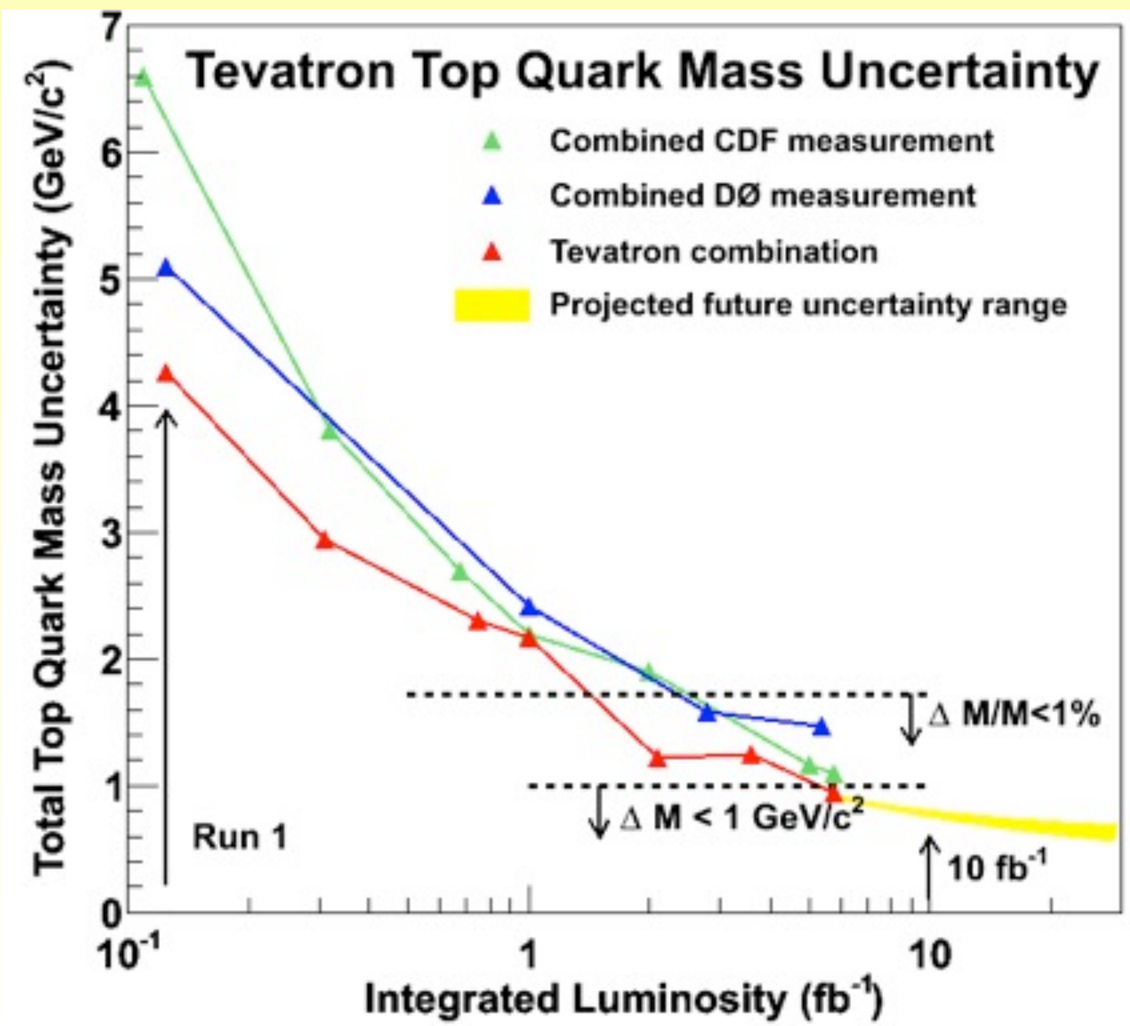
$$m_t^{comb} = 173.18 \pm 0.56\,(\text{stat}) \pm 0.75\,(\text{syst})\ \text{GeV}$$
$$= 173.18 \pm 0.94\ \text{GeV}$$

submitted to PRD, arXiv:1207.1069



Tevatron combination and perpectives





Source of uncertainty	Combination uncertainty (GeV)
Jet energy scale systematics	
Light-jet response (1)	0.12
Light-jet response (2)	0.19
Out-of-cone correction	0.04
Offset	0.00
Model for b jets	0.15
Response to $b/q/g$ jets	0.12
in-situ light-jet calibration	0.39
Other systematics	
Jet modeling	0.11
Lepton modeling	0.10
Signal modeling	0.51
Multiple interactions model	0.00
Background from theory	0.14
Background based on theory	0.11
Calibration method	0.09
Statistical uncertainty	0.56
Total JES uncertainty	0.49
Other systematic uncertainty	0.57
Total uncertainty	0.94

- Expectation for the final top-quark mass measurement at Tevatron
  - ➔ precision around 0.7-0.8 GeV

Top-quark mass measurements at the LHC

- 7 inputs to the the combination (LHC @ 7 TeV)
  - ➔ ATLAS: l+jets 2010 (35 pb^{-1}), l+jets 2011 (1.0 fb^{-1}), alljets 2011 (2.0 fb^{-1})
  - ➔ CMS: dilepton 2010 (36 pb^{-1}), l+jets 2010 (36 pb^{-1}), dilepton 2011 (2.3 fb^{-1}), μ+jets 2011 (4.7 fb^{-1})

- use the same systematic categories as the Tevatron

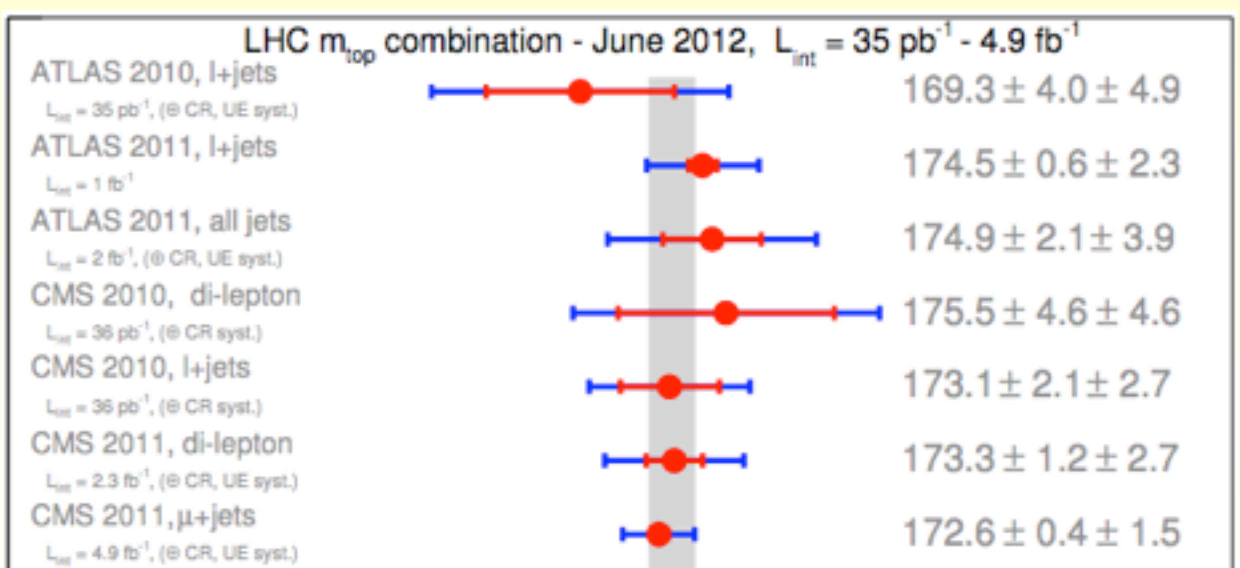
  ➔ some categories are unused:

  aJES, cJES included into dJES

  ➔ additional categories:

  * split Signal modeling systematics (ISR/FSR, hadronization assumed 50% correlated between exp)

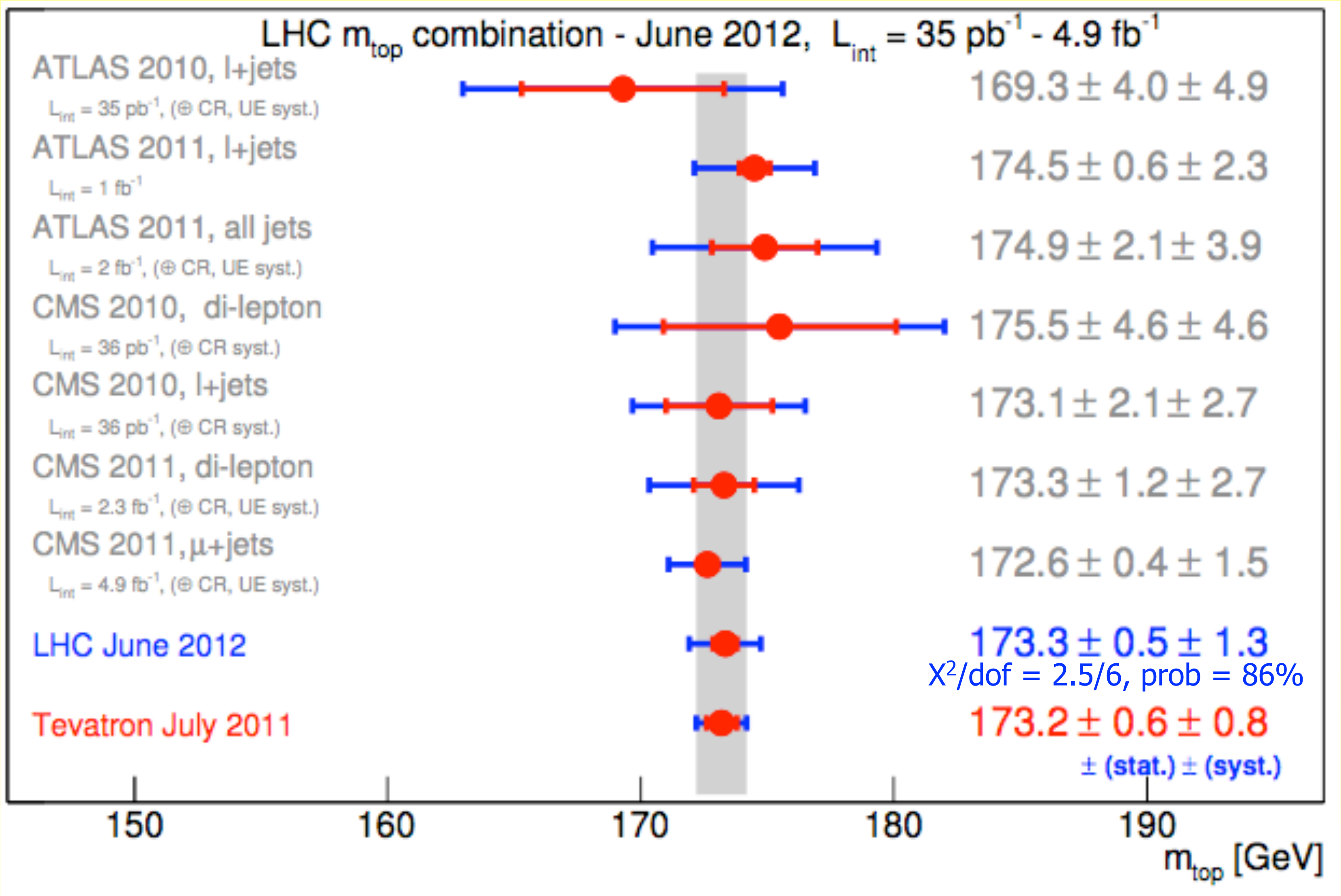
  * Underlying Event (not a separated source for Tevatron)



	ATLAS			CMS			
	2010	2011		2010		2011	
	l+jets	l+jets	all jets	di-l	l+jets	di-l	μ+jets
[GeV]							
Measured m_{top}	169.3	174.5	174.9	175.5	173.1	173.3	172.6
Stat	4.0	0.6	2.1	4.6	2.1	1.2	0.4
iJES	n/a	0.4	n/a	n/a	n/a	n/a	0.4
aJES	n/a	n/a	n/a	n/a	n/a	n/a	n/a
bJES	2.5	1.6	1.4	0.9	0.9	1.1	0.7
cJES	n/a	n/a	n/a	n/a	n/a	n/a	n/a
dJES	2.1	0.7	2.1	2.1	2.1	2.0	0.2
rJES	n/a	n/a	n/a	3.3	n/a	n/a	n/a
Lept	n/e	n/e	n/e	0.3	n/e	0.2	n/e
MC	1.0	0.4	0.5	0.4	n/e	0.1	n/e
Rad	2.5	1.0	1.7	0.9	1.2	0.8	0.8
CR	0.6	0.6	0.6	0.5	0.5	0.5	0.5
PDF	0.5	0.1	0.6	0.5	0.1	0.4	0.1
DTMO	1.2	0.3	0.5	0.6	0.4	0.7	0.3
UE	0.6	0.6	0.6	1.4	0.2	0.6	0.6
BGMC	1.8	0.1	n/a	0.1	0.2	n/a	0.1
BGDT	0.6	0.5	1.9	n/a	0.4	0.4	n/a
Meth	0.4	0.1	1.0	0.3	0.1	0.4	0.2
MHI	0.7	< 0.05	n/e	1.0	0.1	0.2	0.4
[GeV]							
Total Syst. Unc	4.9	2.3	3.9	4.6	2.7	2.7	1.5
Total Unc.	6.3	2.4	4.4	6.5	3.4	3.0	1.5
Comb. Coeff.[%]	-6.8	29.9	-0.4	-1.9	-0.2	-4.8	84.3
Relative importance[%]	5.3	23.3	0.3	1.5	0.2	3.7	65.7
Pull	-0.6	0.6	0.4	0.3	-0.1	0.0	-1.1

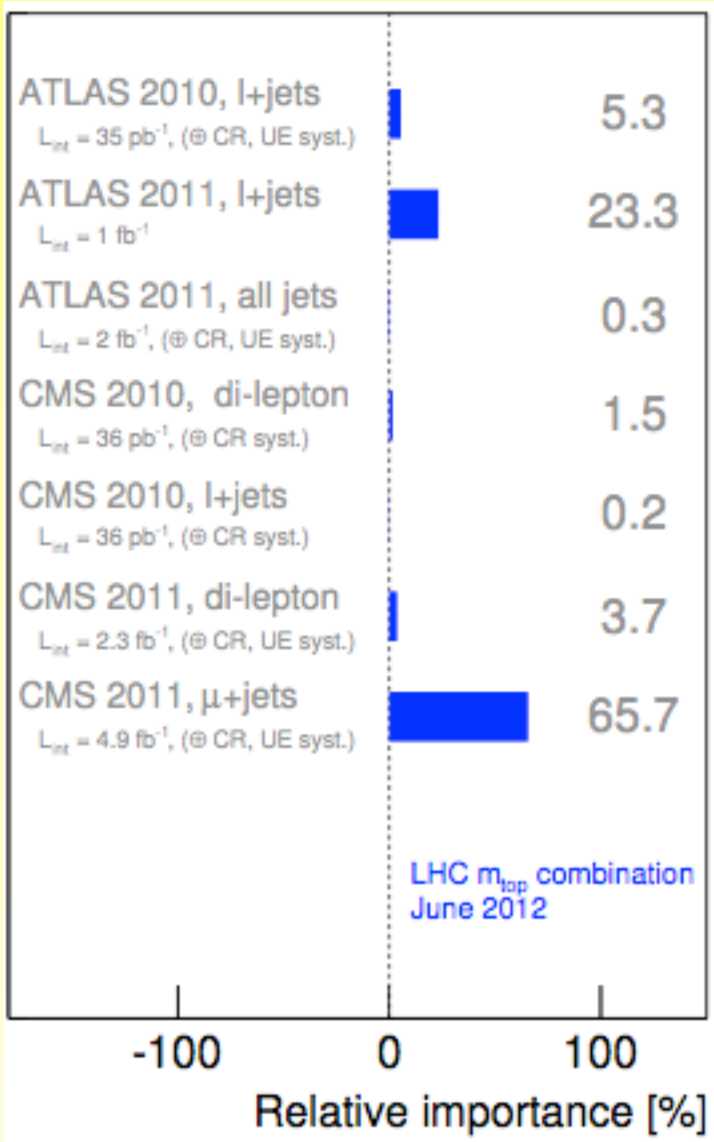
LHC top-quark mass combination result

$$m_{top} = 173.3 \pm 0.5\ (\text{stat}) \pm 1.3\ (\text{syst})\ \text{GeV}$$



LHC top-quark mass combination

	LHC	Tev. 2011
	comb.	comb.
[GeV]		
Measured m_{top}	173.34	173.18
Stat	0.47	0.56
iJES	0.38	0.39
aJES	n/a	0.09
bJES	0.68	0.15
cJES	n/a	0.05
dJES	0.07	0.20
rJES	0.06	0.12
Lept	0.01	0.10
MC	0.04	
Rad	0.69	
CR	0.55	
PDF	0.01	0.51
DTMO	0.19	0.10
UE	0.47	0.00
BGMC	0.01	0.14
BGDT	0.16	0.11
Meth	0.13	0.09
MHI	0.25	0.08
[GeV]		
Total Syst. Unc	1.33	0.75
Total Unc.	1.40	0.94
Comb. Coeff.[%]	χ^2/ndf = 2.5/6	
Relative importance[%]	χ^2 prob = 87%	
Pull		

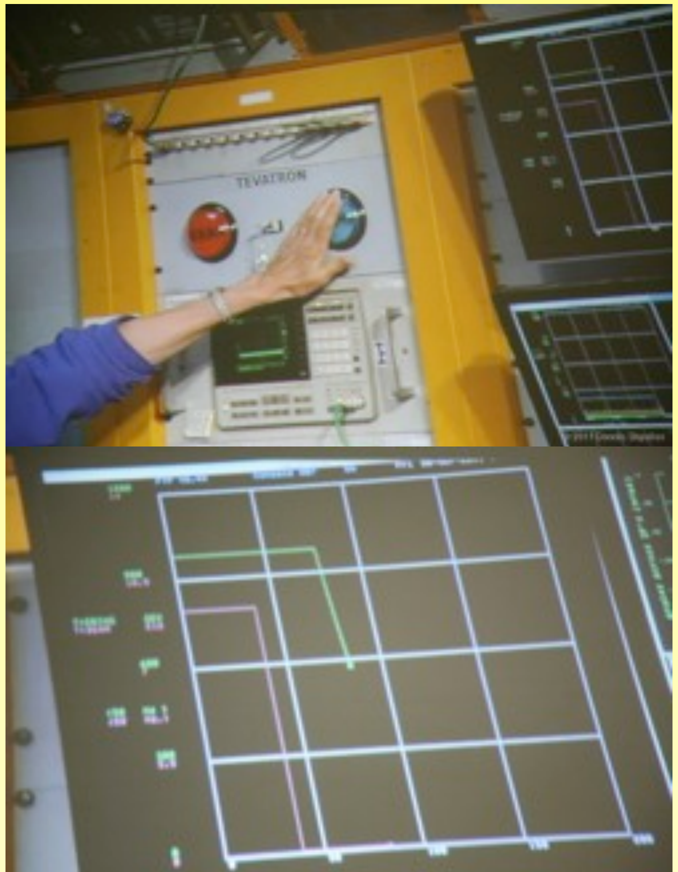


- correlation checks
  ➔ assumed correlations varied from 100% to 0%:
  negligible influence on the result (below 200 MeV)

Conclusion

- First publication of the combination of top-quark mass measurement from the Tevatron (using up to 5.8 fb^{-1}): arXiv:1207.1069
  - ➔ total uncertainty below 1 GeV
  - ➔ 0.7-0.8 could be expected with the final mass measurements

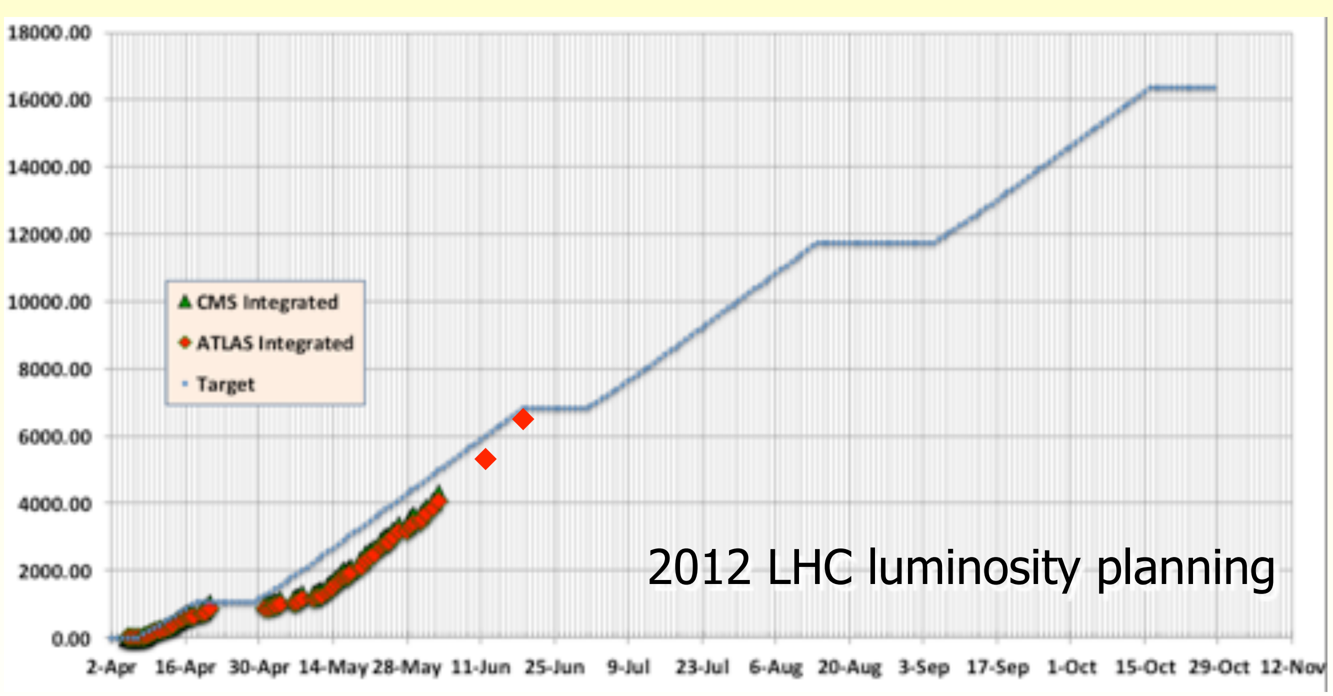
$$m_t^{\rm comb} = 173.18 \pm 0.56\,({\rm stat}) \pm 0.75\,({\rm syst})\ \ {\rm GeV}$$
$$= 173.18 \pm 0.94\ {\rm GeV}$$



- First combination of the LHC top-quark mass measurements
  - ➔ total uncertainty: 1.4 GeV

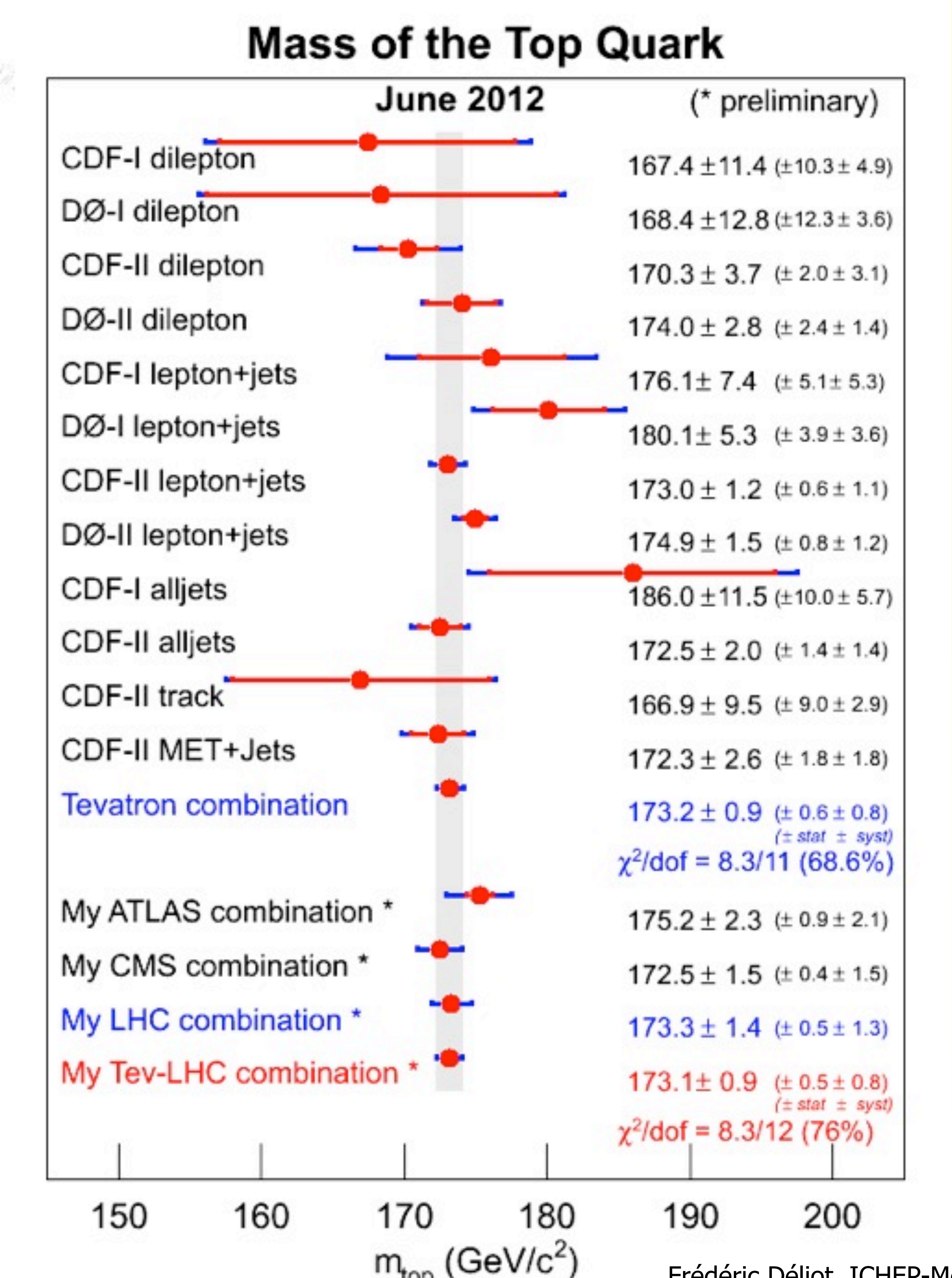
$$m_{\rm top} = 173.3 \pm 0.5\ ({\rm stat}) \pm 1.3\ ({\rm syst})\ \ {\rm GeV}$$

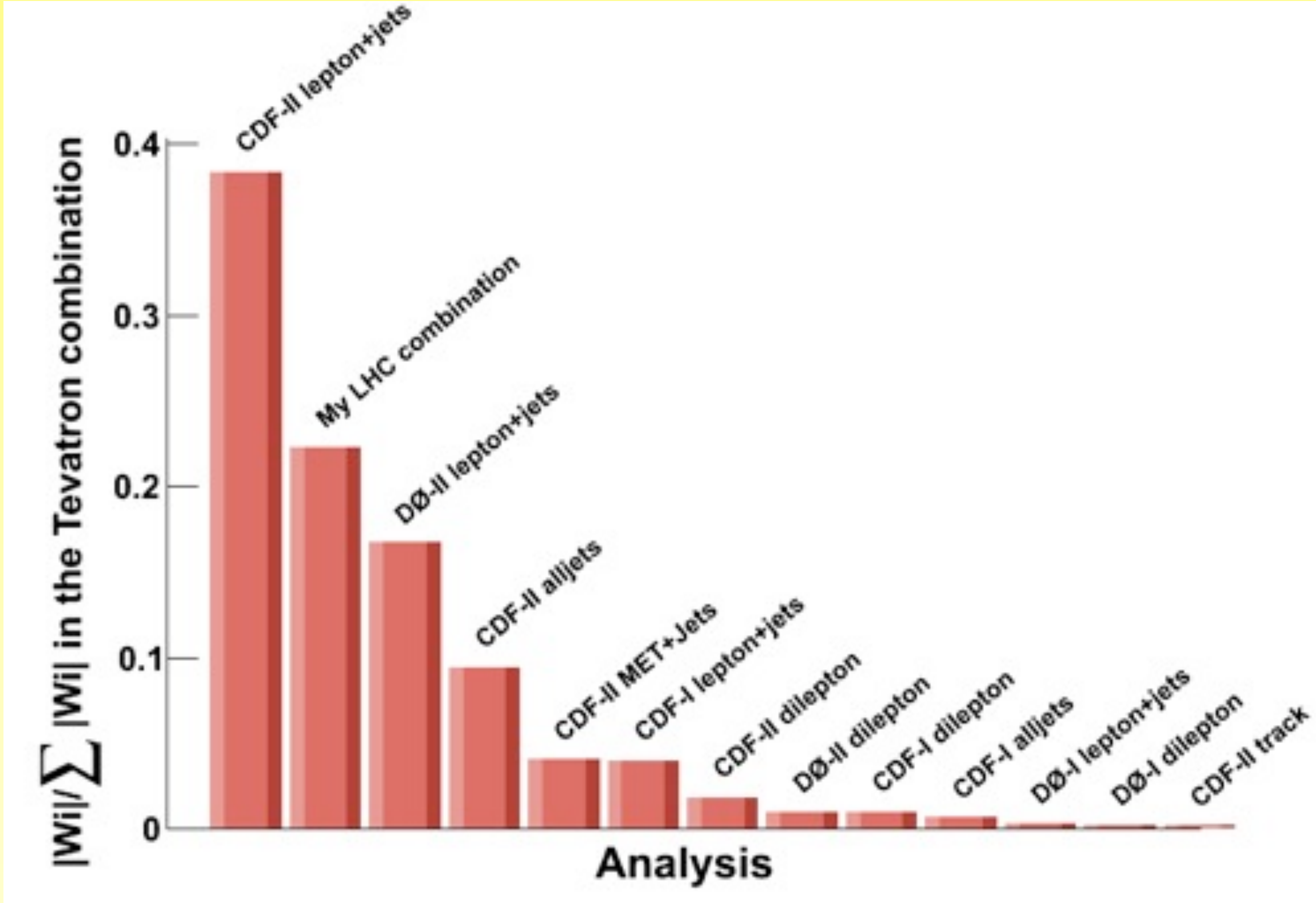
  - ➔ with more statistics, m_{top} in specific phase-space regions



Backup

Tevatron + LHC top mass combination





With some naive assumptions for some of the systematic correlations, the weight of the LHC combination is ~ 25%.

Top-quark mass inputs for the Tevatron combination

to be submitted to PRD

			Light-jet response (1)	Light-jet response (2)	Out-of-cone correction	Offset	Model for b jets	Response to $b/q/g$ jets	*In-situ* light-jet calibration	Jet modeling	Lepton modeling	Signal modeling	Multiple interactions model	Background from theory	Background based on data	Calibration method	**Statistical uncertainty**	**Total JES uncertainty**	**Other systematic uncertainty**	**Total uncertainty**
Channel	Run	Exp.	Jet energy scale systematics							Other systematics										
Lepton+jets	II	CDF	0.41	0.01	0.27	n/a	0.23	0.13	0.58	0.00	0.14	0.56	0.10	0.27	0.06	0.10	0.65	0.80	0.67	1.23
Lepton+jets	II	D0	n/a	0.63	n/a	n/a	0.07	0.26	0.46	0.36	0.18	0.77	0.05	0.19	0.23	0.16	0.83	0.83	0.94	1.50
Lepton+jets	I	CDF	3.4	0.7	2.7	n/a	0.6	n/e	n/a	n/e	n/e	2.7	n/e	1.3	n/e	0.0	5.1	4.4	2.8	7.3
Lepton+jets	I	D0	n/a	2.5	2.0	1.3	0.7	n/e	n/a	n/e	n/e	1.3	n/e	1.0	n/e	0.6	3.6	3.5	1.6	5.3
Alljets	II	CDF	0.38	0.04	0.24	n/a	0.15	0.03	0.95	0.00	n/a	0.64	0.08	0.00	0.56	0.38	1.43	1.06	0.91	2.00
Alljets	I	CDF	4.0	0.3	3.0	n/a	0.6	n/e	n/a	n/e	n/a	2.1	n/e	1.7	n/e	0.6	10.0	5.0	2.6	11.5
Dileptons	II	CDF	2.01	0.58	2.13	n/a	0.33	0.14	n/a	0.00	0.27	0.80	0.23	0.24	0.14	0.12	1.95	3.01	0.88	3.69
Dileptons	II	D0	n/a	0.56	n/a	n/a	0.20	0.40	0.55	0.50	0.35	0.86	0.00	0.00	0.20	0.51	2.36	0.90	1.11	2.76
Dileptons	I	CDF	2.7	0.6	2.6	n/a	0.8	n/e	n/a	n/e	n/e	3.0	n/e	0.3	n/e	0.7	10.3	3.9	3.0	11.4
Dileptons	I	D0	n/a	1.1	2.0	1.3	0.7	n/e	n/a	n/e	n/e	1.9	n/e	1.1	n/e	1.1	12.3	2.7	2.3	12.8
$\not{E}_T$+jets	II	CDF	0.45	0.05	0.20	n/a	0.00	0.12	1.54	0.00	n/a	0.78	0.16	0.00	0.12	0.14	1.80	1.64	0.78	2.56
Decay length	II	CDF	0.24	0.06	n/a	n/a	0.15	n/e	n/a	0.00	n/a	0.90	0.00	0.80	0.20	2.50	9.00	0.25	2.80	9.43

Top-quark mass inputs for the LHC combination

Uncertainty Categories			Size [GeV]							Correlation	
			ATLAS			CMS					
Tevatron	ATLAS	CMS	2010 l+jets	2011 l+jets	2011 all jets	2010 di-l	2010 l+jets	2011 di-l	2011 μ+jets	ρ_{exp}	ρ_{LHC}
Statistics			4.0	0.6	2.1	4.6	2.1	1.2	0.4	0	0
iJES	Jet Scale Factor	Jet Scale Factor		0.4					0.4	0	0
aJES											
bJES	JES_{b-jet}	JES_{b-jet}	2.5	1.6	1.4	0.9	0.9	1.1	0.7	1	0.5
cJES											
dJES	$JES_{light-jet}$	$JES_{light-jet}$	2.1	0.7	2.1	2.1	2.1	2.0	0.2	1	0
rJES		residual-JES				3.3				0	0
LepPt		Lepton p_T Scale				0.3		0.2		1	0
MC	MC Generator	MC Generator	0.7	0.3	0.5	0.4		0.1			
	Hadronisation		0.7	0.2	(*)						
	Sum	Sum	1.0	0.4	0.5	0.4		0.1		1	0.5
Rad	ISR/FSR	ISR/FSR	2.5	1.0	1.7	0.2	0.2				
		Q-Scale				0.6	1.1	0.4	0.8		
		Jet-Parton Scale				0.7	0.4	0.7	0.3		
	Sum	Sum	2.5	1.0	1.7	0.9	1.2	0.8	0.8	1	0.5
CR	Colour Recon.		*0.6*	0.6	*0.6*	*0.5*	*0.5*	0.5	0.5	1	1
PDF	Proton PDF	Proton PDF	0.5	0.1	0.6	0.5	0.1	0.4	0.1	1	1
	Jet Energy Res.	Jet Energy Res.	0.9	0.1	0.3	0.5	0.1	0.3	0.2		
	Jet Rec. Eff.		0.5	< 0.05	0.2						
	b-tagging	b-tagging	0.5	0.3	0.3	0.4	0.1	0.5	0.2		
	E_T^{miss}	E_T^{miss}		0.1		0.1	0.4	0.4	0.1		
DetMod	Sum	Sum	1.2	0.3	0.5	0.7	0.4	0.7	0.3	1	0
UE	Underlying Event	Underlying Event	*0.6*	0.6	*0.6*	1.4	0.2	*0.6*	*0.6*	1	0
	W+jet Norm.		1.6								
	W+jet Shape		0.8	0.1							
		background				0.1	0.2		0.1		
BGMC	Sum	Sum	1.8	0.1		0.1	0.2		0.1	1	1
	W+jet Norm.			0.4							
	QCD Norm.	QCD Norm.	0.5	0.2			0.4	0.4			
	QCD Shape		0.4	0.3	1.9						
BGData	Sum	Sum	0.6	0.5	1.9		0.4	0.4		0	0
Method	Method Calib.	Method Calib.	0.4	0.1	1.0	0.3	0.1	0.4	0.2	0	0
MHI	Pile-up	Pile-up	0.7	< 0.05		1.0	0.1	0.2	0.4	1	1

Cross checks of the Tevatron combination

- Combinations
  - ➔ for each tt decay mode
  - ➔ for each run period
  - ➔ for each experiment

Subset	m_t^{comb}	Consistency χ^2 (Degrees of freedom = 1)						χ^2 probability					
		Lepton+jets	Alljets	Dileptons	$\not\!\!E_T$+jets	Run II – Run I	CDF – D0	Lepton+jets	Alljets	Dileptons	$\not\!\!E_T$+jets	Run II – Run I	CDF – D0
Lepton+jets	173.4 ± 1.0	—	0.14	1.51	0.28			—	71%	22%	60%		
Alljets	172.7 ± 1.9	0.14	—	0.40	0.04			71%	—	53%	85%		
Dileptons	171.1 ± 2.1	1.51	0.40	—	0.12			22%	53%	—	73%		
$\not\!\!E_T$+jets	172.1 ± 2.5	0.28	0.04	0.12	—			60%	85%	73%	—		
Run II	173.6 ± 1.0					2.89						9%	
Run I	180.0 ± 4.1												
CDF	172.5 ± 1.0						2.56						11%
D0	174.9 ± 1.4												