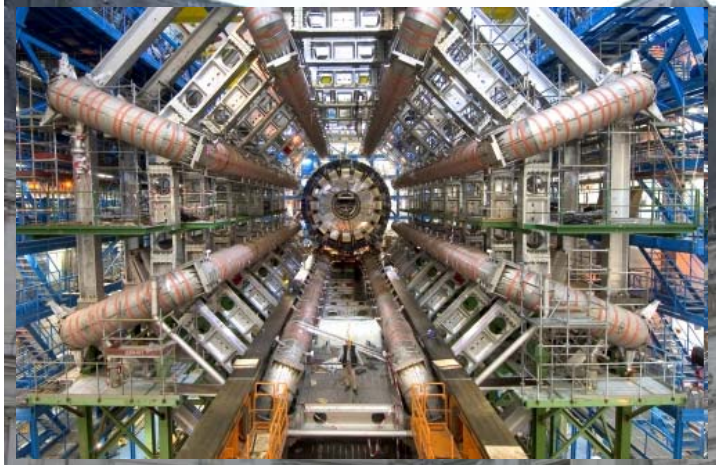
Prospects for m(top) at the LHC



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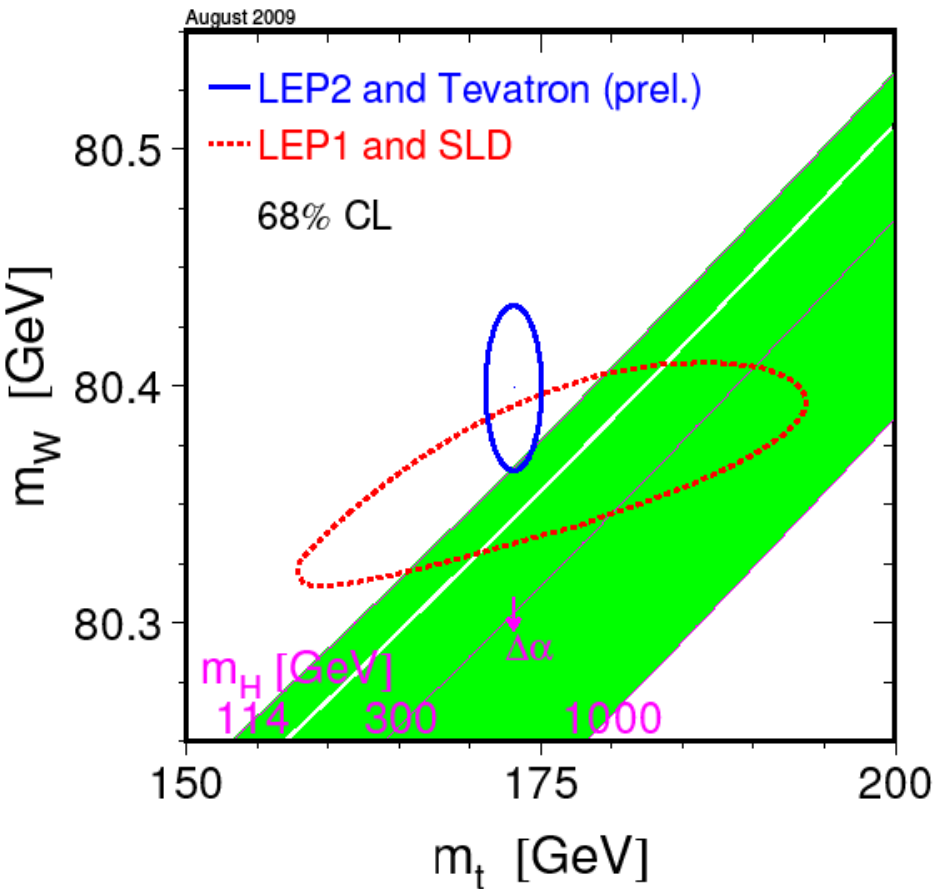
On behalf of the ATLAS and CMS Collaborations

22nd Rencontres de Blois, July 17/2010

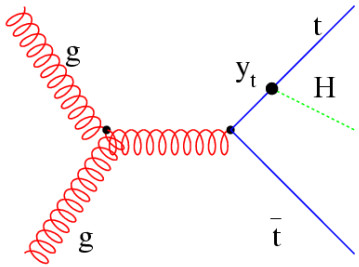
Introduction/Motivation

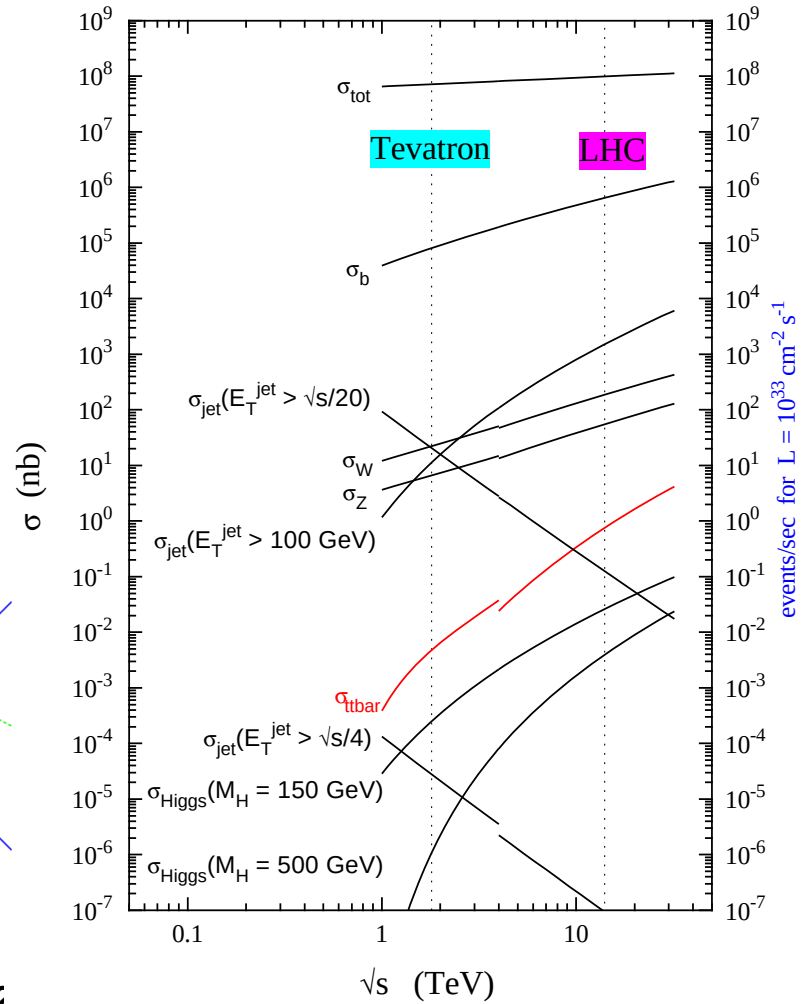
- **In addition to being fundamental parameters of the Standard Model (SM), m(top) and m(W) provide (via precision EWK fits) sharpest constraints on Higgs mass**
  - **Precision mass measurements provide significant test of the SM**



Top Quark Physics at the LHC

- (N)NLO prediction of t-tbar Xsect is 886 pb (14 TeV), > 100X larger than @ Tevatron
  - Expect ~9 million t-tbar pairs per yr at 1E33 lumi. (and 90 million at design lumi of 1E34)
  - LHC will be a top factory!!
- t-tbar production at LHC is ~87% gg and ~13% q-qbar (~ opposite ratio at Tevatron)
- High statistics will enable a very broad and exciting top physics program at the LHC
  - High stats. single top (precision Vtb, …)
  - Searches for anomalous behavior (t-tbar resonances, FCNC decays, anomalous couplings, …)
  - Possible measurement of top Yukawa coupling via t-tbar H associated production
  - Precision m(top) measurement





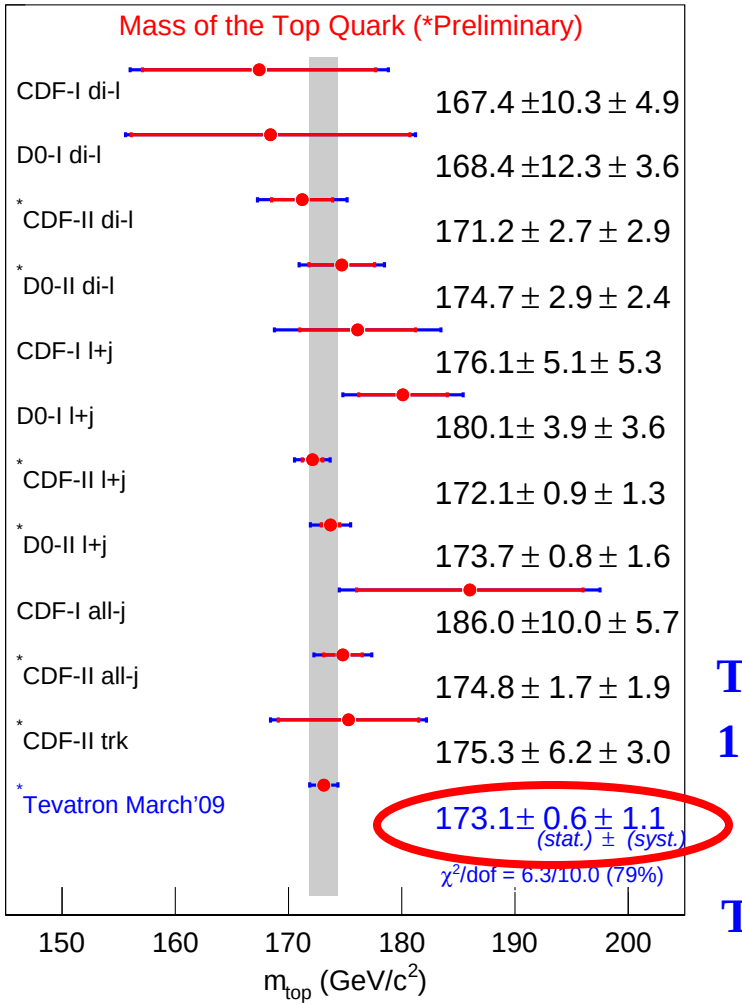
Tevatron measurements of top quark mass

- **Tevatron combination from March 2009**
  (up to 3.6 fb^{-1}/expt)

  (arXiv: 0903.2503)

(New combination expected next week at ICHEP)
(up to 5.6 fb^{-1}/expt)

New CDF Average
173.13 ± 0.67 ± 0.95 GeV
just released



Tevatron Avg (Mar.09)
173.1 ± 0.6 ± 1.1 GeV

Total error = 1.3 GeV
(0.75%)

Top mass prospects at the LHC

- **ATLAS and CMS have done many studies of the long term prospects for trying to improve on the precision of the m(top) determination**
  - **Studies for 1 – 100 fb^{-1} at sqrt(s) = 14 TeV**

- **Before discussing those, let's look first at short term prospects using early data**
  - **Most studies have been done for 14 TeV, with some done for 10 TeV**
  - **(N)NLO t-tbar Xsect (mtop = 172.5 GeV)**
    arXiv:0906.5273

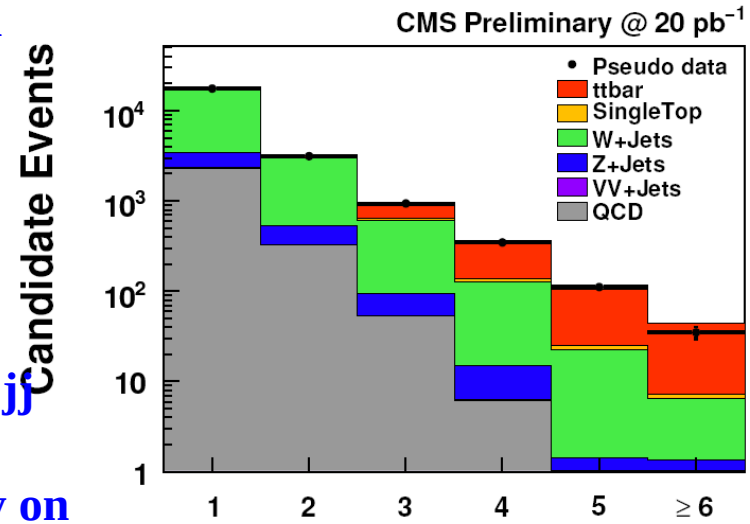
$\sqrt{s}$	$\sigma(t\bar{t})$
14 TeV	886 pb
10 TeV	403 pb
7 TeV	161 pb

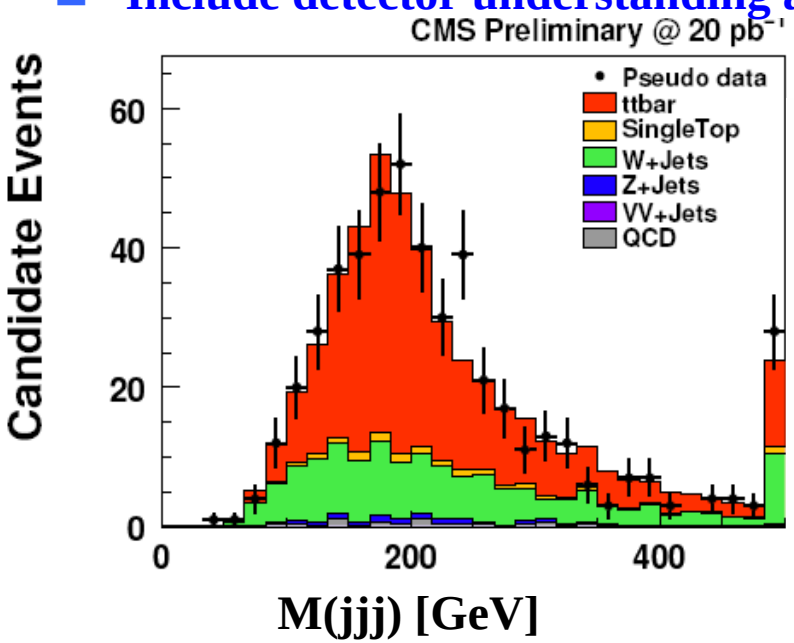
⇒ Signal rate at 7 TeV lower by factor ~2.5 (5.5) compared to 10 (14) TeV

Top observation prospects with early LHC data

Example (CMS, 10 TeV): single muon + jets channel

- Simple and robust cuts and analysis
- Single tight isolated muon with pT > 40 GeV
- pT(lead jet) > 65 GeV, pT(other jets) > 40 GeV
- Look at jet multiplicity distribution →
- Then require Njet ≥ 4, and look at 3jet mass for jjj system with highest E_T
- Include detector understanding as expected early on





	$t\bar{t}$+jets s.l. μ	$t\bar{t}$+jets other	Single top s-Ch.	Single top t-Ch.	Single top tW	W+jets	Z+jets	VV+jets	QCD
AllEvents	1,220	7,060	32	832	580	912,000	76,240	236	2,546,279
Trigger	978	1,418	10	260	147	168,633	20,952	100	2,032,021
$\geq$ 1 tight μ	620	345	5	140	69	110,509	15,296	73	7,200
$<$ 2 tight μ	620	309	5	140	66	110,509	9,300	62	7,200
no tight e	620	264	5	140	62	110,508	9,292	53	7,200
veto on loose μ	618	228	5	140	60	110,503	5,492	44	7,192
veto no loose e	616	183	5	140	56	110,469	5,415	34	7,188
$\geq$ 1 jet	614	180	4	125	55	16,998	1,325	18	2,701
$\geq$ 2 jets	593	158	3	63	47	3,076	256	5	387
$\geq$ 3 jets	489	99	1	18	27	651	51	1	60
$\geq$ 4 jets	277	43	0	5	9	140	10	0	7

Signal = 320 evts, with S/B = 1.9 (20 pb^{-1})

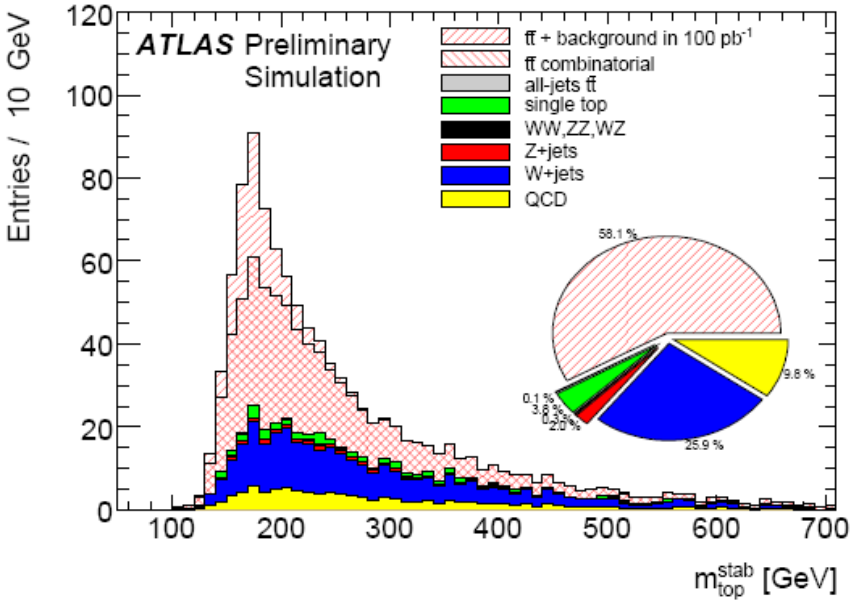
Top mass prospects with early LHC data

- **Example (ATLAS, 10 TeV): single lepton plus jets**

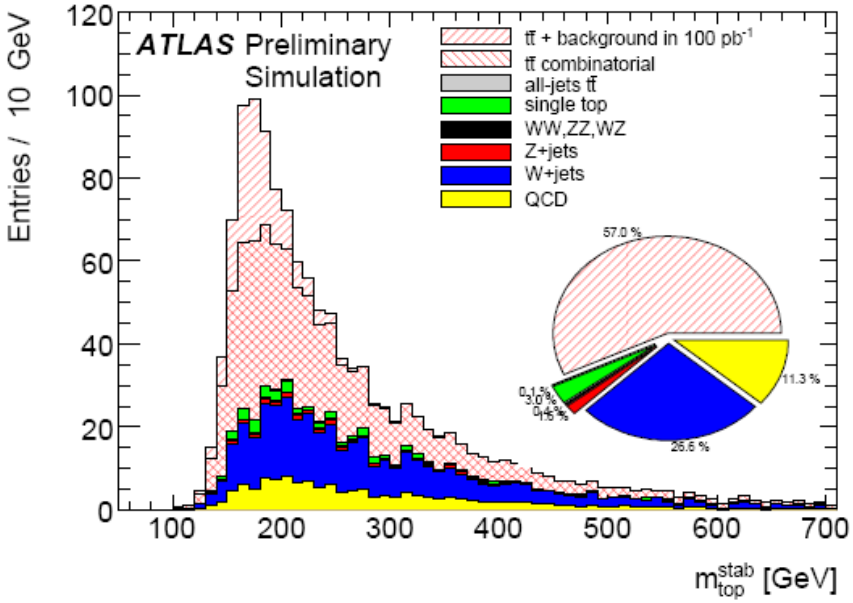
For e/mu separately, stat. error ~ 10 GeV (10 pb^{-1})

Statistical uncertainty [GeV] as a function of $\mathscr{L}_{int}$			
	10 pb^{-1}	30 pb^{-1}	100 pb^{-1}
Electron channel	10.8 ± 3.5	7.0 ± 2.1	2.7 ± 1.3
Muon channel	9.9 ± 3.9	5.8 ± 1.5	2.8 ± 0.8

Stat. error decreasing to < 3 GeV (100 pb^{-1})



(a) Electron channel



(b) Muon channel

- **Reduce JES sensitivity by fitting** $m_{top}^{stab} = \frac{m_{top}^{reco}}{m_W^{reco}} \times m_W^{PDG}$

Top mass prospects with early LHC data

- **Example (ATLAS, 10 TeV): single lepton plus jets**

100 pb^{-1}

Statistical and systematic uncertainties [GeV]			
	1-d per channel		2-d combined
	Electron	Muon	
Statistics 100 (1000) pb^{-1}	2.7	2.8	1.8 (0.6)
Method calibration	0.8	0.6	0.4
Signal MC generator (AcerMC vs. MC@NLO)	0.8	1.3	0.5
ISR and FSR (signal only)	2.5	1.1	1.0
Proton PDF uncertainty	1.1	0.8	0.1
Fast vs. full sim (signal only)	0.6	0.7	0.2
Assumed background fraction ($\pm 50\%$, $^{+100}_{-50}\%$)	0.8	0.9	0.1
W/Z+jets background SHERPA vs. ALPGEN	0.5	0.5	na
Alternative QCD shape	0.6	0.5	na
Single-top shape	0.8	0.3	na
Jet energy scale ($\pm 5\%$)	1.4	2.2	na
Relative b-jet to light jet energy scale ($\pm 2.5\%$)	1.6	2.1	1.6
b-tagging performance	na	na	0
E_T^{miss}($\pm 5\%$)	na	na	0.2
Jet energy resolution ($\pm 20\%$)	na	na	0.1
Total systematic	3.8	3.9	2.0

Syst. Error ~ 2 GeV

<u>1-d analysis</u> (e/mu separately)

- **template fitting to mass of highest E_T jjj system**
- **total syst. error per chan < 4 GeV**

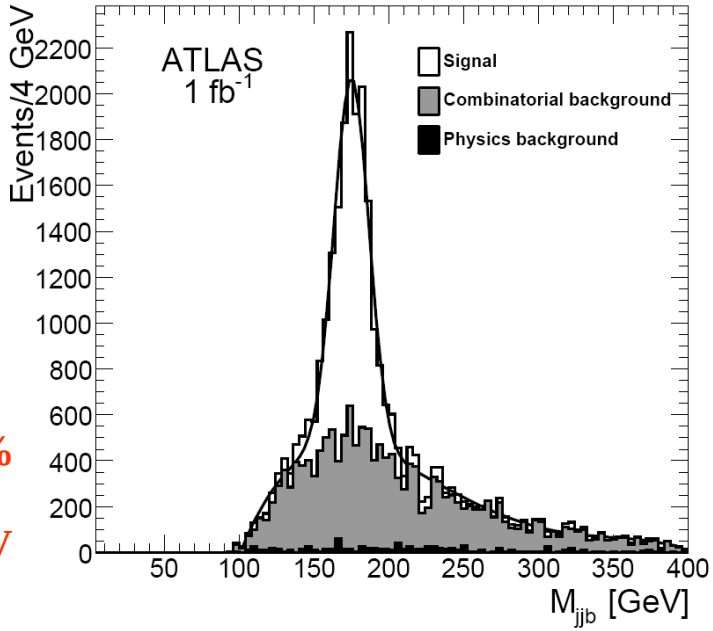
<u>2-d analysis</u> (with e/mu combined)

- **kinematic fit of entire event, with simultaneous determination of mtop, JES**

Longer term prospects for m(top): lepton+jets

- **Example (ATLAS, 14 TeV)**
  - p_T(lep)>20, MET>20, ≥4 jets with E_T>40, 2 btags
  - For 1 fb^{-1}, ~16k signal events with S/B ~ 10/1

  gives Stat. error on m(top) ~ 0.2 – 0.4 GeV
  - Several methods to reconstruct the event (ie. jet-to-parton assignment) investigated



JES

- **Systematic errors**
  - Expect to know @1% level with 1 fb^{-1} ⇒Syst. error 0.2 GeV

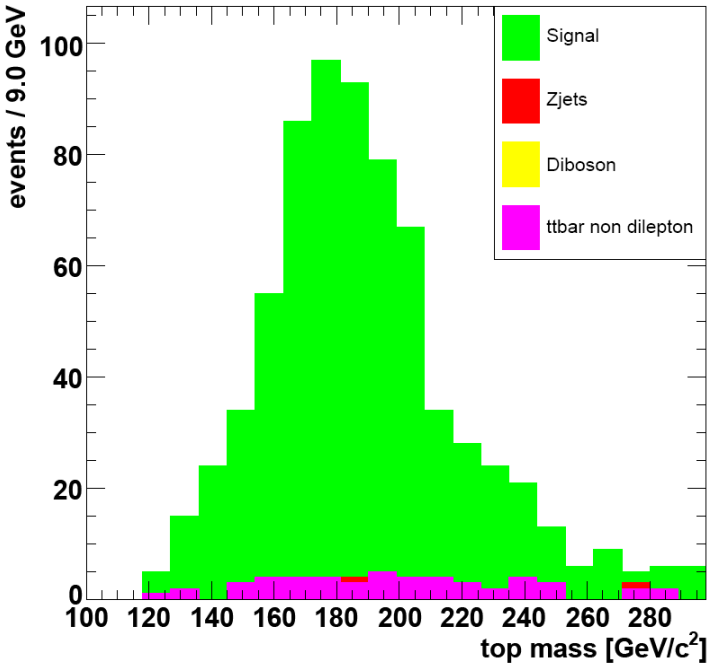
Systematic uncertainty	χ^2 minimization method
Light jet energy scale	0.2 GeV/%
b jet energy scale	0.7 GeV/%
ISR/FSR	$\simeq$ 0.3 GeV
b quark fragmentation	$\leq$ 0.1 GeV
Background	negligible
Method	0.1 to 0.2 GeV

b-JES (relative to light jets)

- Start with MC corrections, supplement later with Z+b data
- Syst. error 0.7-3.5 GeV assuming bJES @ 1-5% level

m(top) in dilepton final states

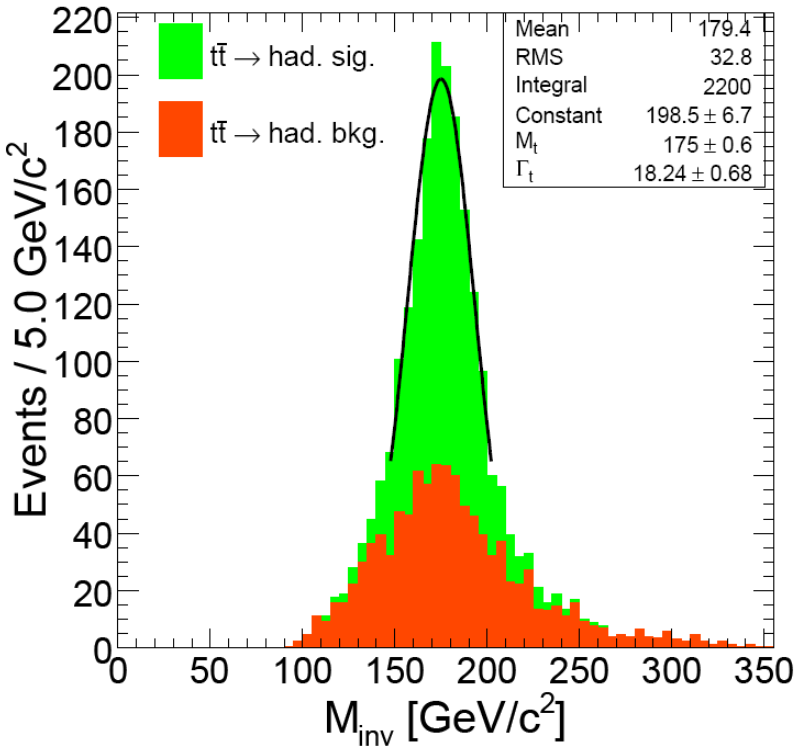
- **Example (CMS, 14 TeV)**
  - **≥2 opp. sign lep with p_T>20 [anti-Z cut], MET>40, ≥2 btagged jets with E_T>30**
  - **S/B ~ 7.3/1**
  - **Reconstruct the event kinematics and select solution with highest weight**



- **Expected precision: ± 1.5 ± 2.9 GeV (1 fb^{-1}) [main syst. are JES, ISR/FSR]**
  improving to ± 0.5 ± 1.1 GeV (10 fb^{-1})

m(top) in all-jets final states

- **Example (CMS, 14 TeV)**
  - **$6 \leq$ Njet ≤ 8 with E_T>30, ≥1 btagged jets, + topological cuts**
  - **S/B ~ 1/17 for 1 btag, ~ 1/9 for 2 btags**
  - **Reconstruct the event kinematics using likelihood (kinematics, topology) to perform jet-to-parton assignment**

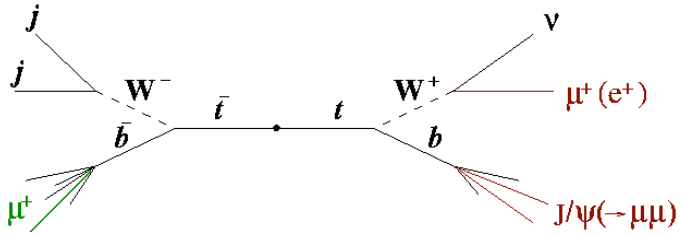


- **Expected precision: ± 0.6 ± 4.2 GeV (1 fb^{-1})** **[main syst. are JES, ISR/FRS]**

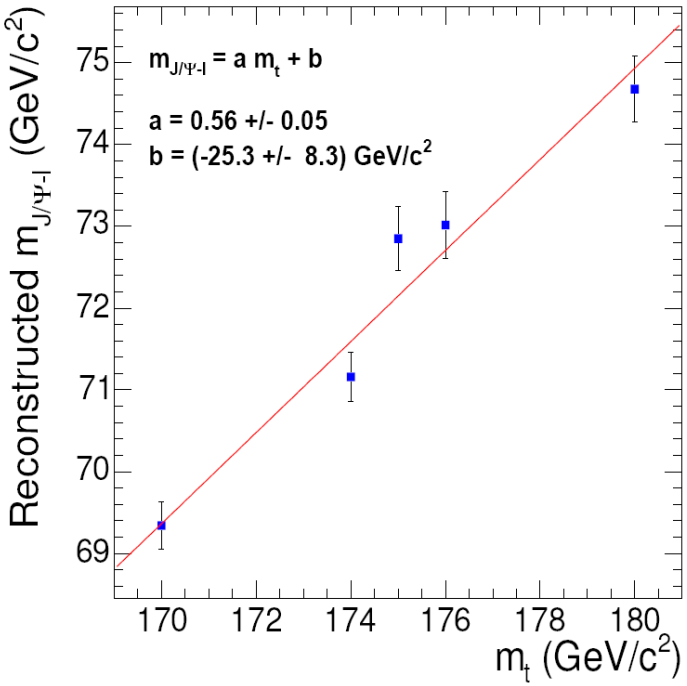
Some other possible methods (less dep. on bjet calib.)

Example 1: t-tbar events with J/ψ in final state

- CMS study for 14 TeV, 100 fb^{-1}



- Exploit correlation between mtop, m(lep J/ψ)
- Small BR ⇒ Stat. error ~ 1.2 GeV for 20 fb^{-1}
- Syst. error ~ 1.5 GeV
  - Insensitive to JES, bjet calibration
  - Dominated by "theoretical" uncertainties (b-frag,, …)



Example 2: high pT top events (ATLAS study for 14 TeV)

- Consider pT(top) > 200 GeV events (~2%) with all 3 jets from hadronic top decay within a single large cone of deltaR
- Reconstruct top as invariant mass over all calorimeter towers within single cone
- Need to subtract energy within cone from UE
- Syst error < 2%
  - Dominated by UE subtraction, mass scale calib

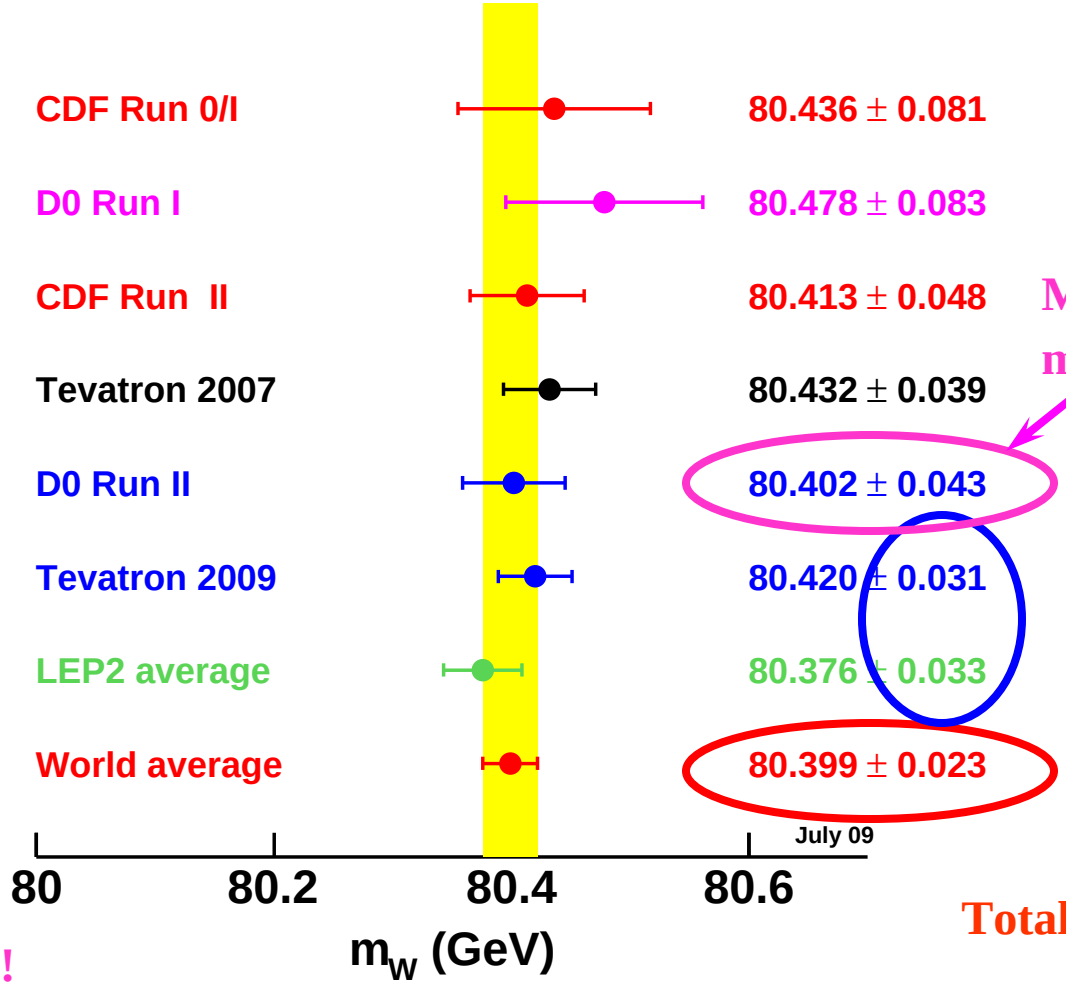
Some other possible methods

- **Further ideas exist for other methods with different systematics**
  - **eg. focus on tracking quantities to reduce/eliminate dependence on calorimetric measures of JES, bjets**

- **One example: determine m(top) by exploiting correlations with boost of resultant decay products**
  - **Lepton p_T**
  - **Boost of b-quark, as measured by transverse secondary vertex decay length (L_{xy})**
  - **Investigated at Tevatron (CDF, 1.9 fb^{-1}, PRD 81 (2010) 032002), but there it is not competitive statistically:**
    - **Result is m(t) = 170.7 ± 6.3 ± 2.6 GeV (combining p_T(lep), L_{xy})**

- **Another note: in a test of CPT, DØ (1 fb^{-1}) [PRL 103 (2009) 132001] has published first measurement of the mass difference between top and anti-top quarks**
  - **Result is Δm ≡ m(t) – m(tbar) = 3.8 ± 3.4 ± 1.2 GeV = 3.8 ± 3.7 GeV**
  - **New prelim. CDF result (5.6 fb^{-1}) is Δm = -3.3 ± 1.4 ± 1.0 GeV**

Status of W mass measurements



200 pb^{-1}

1 fb^{-1}

Further improvements to be expected from Tevatron!

Most precise single measurement to date

Hadron collider measurements have taken over lead in m(W) precision

Total error = 23 MeV/c^2 (0.03%)

W mass prospects at LHC

- **At the LHC, the large cross-section will allow very early accumulation of large W (and Z) samples**
  - **eg. table from ATLAS "CSC Note" of expected m(W) precision for 15 pb^{-1} (14 TeV)**

(using ~67k W→eν, ~120k W→μν and ~3k Z →ee, ~10k Z→μμ events)

	Method	$p_T(e)$ [MeV]	$p_T(\mu)$ [MeV]	$M_T(e)$ [MeV]	$M_T(\mu)$ [MeV]
Stat.	δm_W (stat)	120	106	61	57
	δm_W (α_E)	110	110	110	110
	δm_W (σ_E)	5	5	5	5
	δm_W (tails)	28	< 28	28	< 28
	δm_W (ε)	14	–	14	–
	δm_W (recoil)	–	–	200	200
	δm_W (bkg)	3	3	3	3
Syst.	δm_W (exp)	114	114	230	230
	δm_W (PDF)	25	25	25	25
Total	Total	167	158	239	238

- **In long term, hope to improve on overall world-average m(W) precision**
  - **eg. see table from CMS "Physics TDR" in backup**

Summary

- **The LHC is starting the process of "re-discovering the Standard Model"**
  - **First W, Z signals observed**
  - **First t-tbar candidate events should be just around the corner**

- **Within a short time (weeks?), with as little as a few pb^{-1}, ATLAS and CMS should have statistically significant t-tbar signals**
  - **Will mark the beginning of a broad and exciting program of LHC top quark physics**

- **The enormous t-tbar sample that will eventually be accumulated at the LHC gives great potential for precision measurement of m(top)**
  - **Employ "standard" Tevatron-style methods with much greater statistics**
  - **Exploit specialized subsamples and/or methods which require large statistics to be feasible and which are sensitive to different systematic effects**
  - **Combine the various measurements to try improve the overall precision**
  - **However, given the high precision of the Tevatron m(top) measurements, this will be challenging, and will require significant samples (and effort!)**
  - **We have a lot of work to do! (after many yrs of construction, we can't wait!!)**

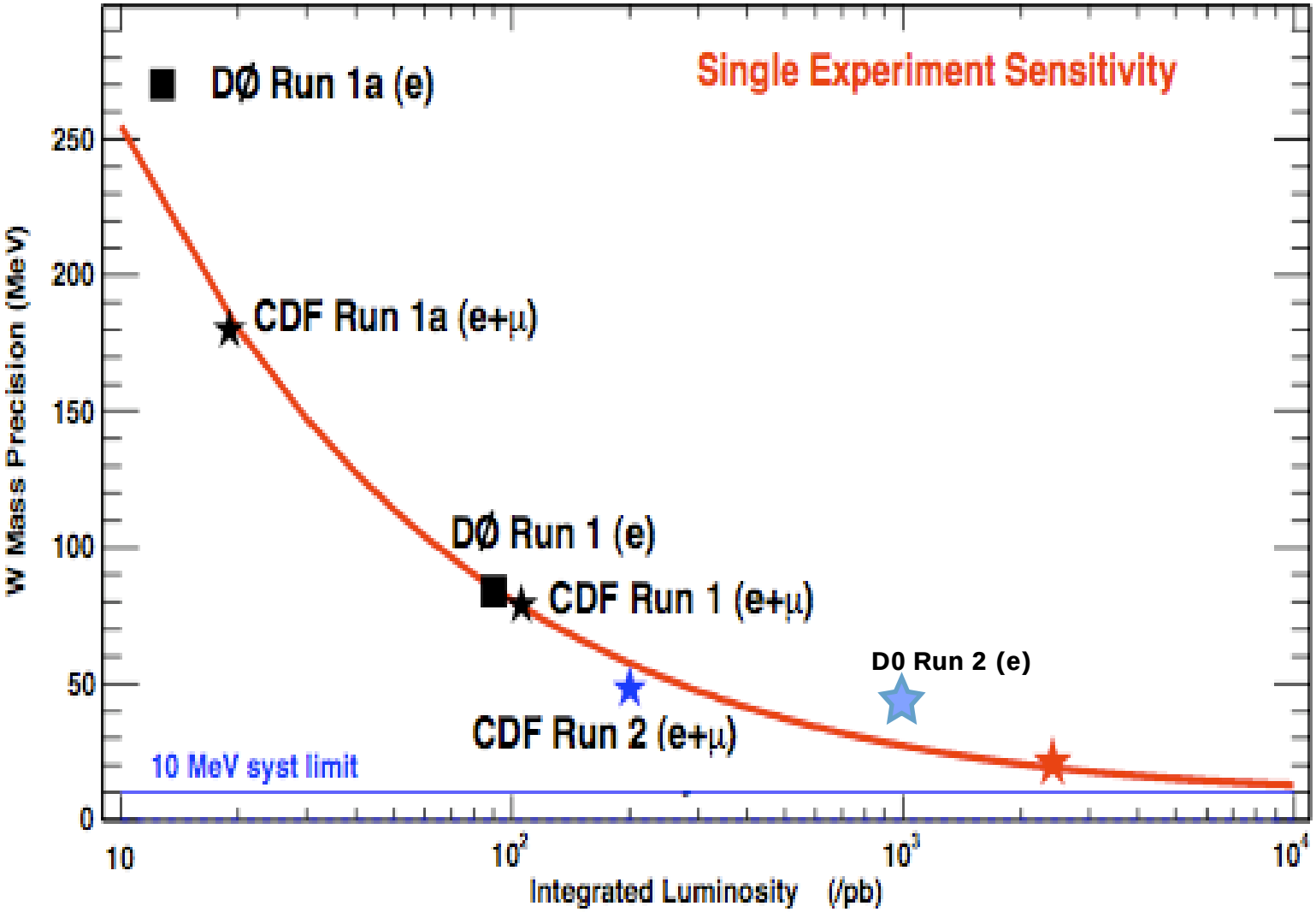
Backup Slides

Longer Term Prospects for m(W) Measurement

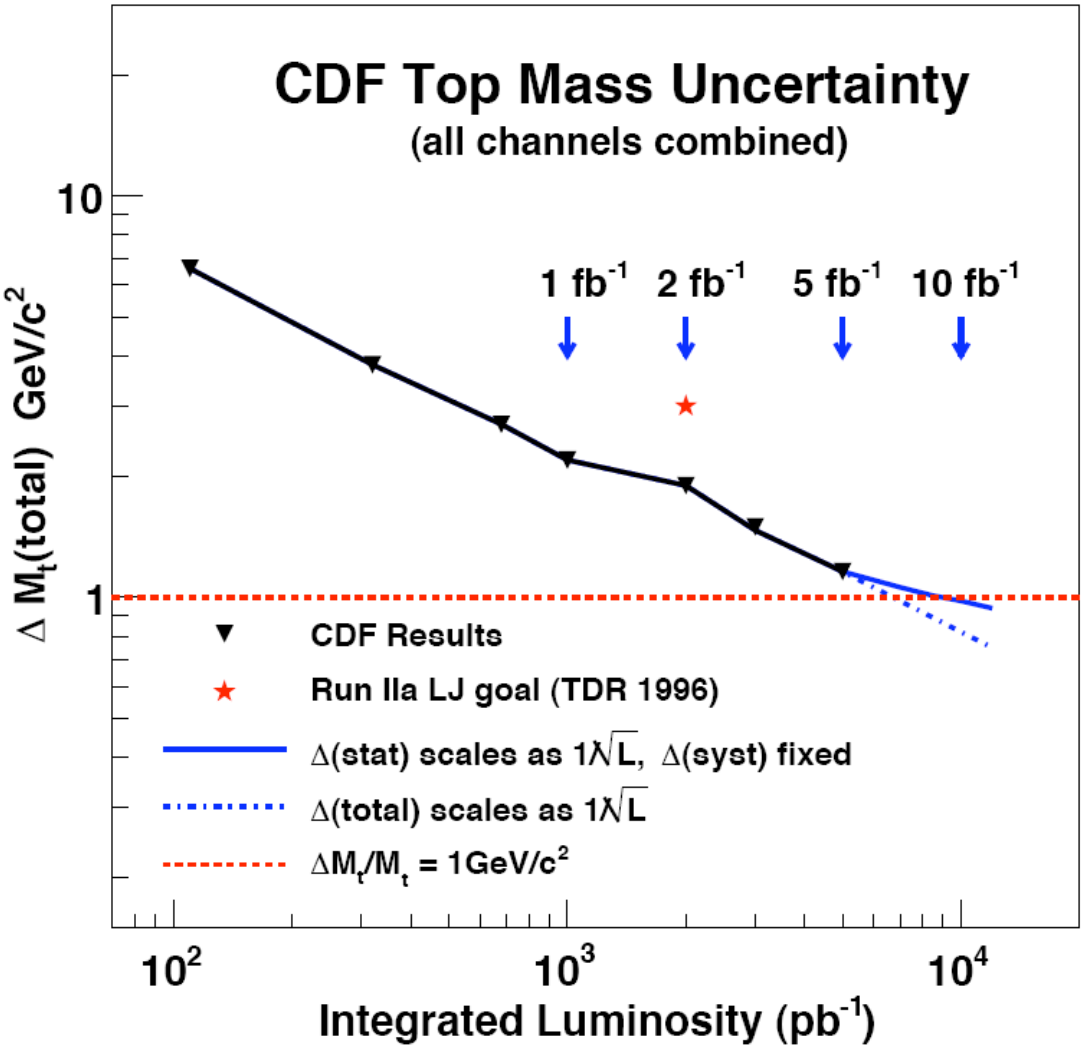
eg. table of projected uncertainties from CMS Physics TDR

Source of uncertainty	uncertainty	ΔM_W [MeV/c^2] with 1 fb^{-1}	uncertainty	ΔM_W [MeV/c^2] with 10 fb^{-1}
scaled lepton-p_T method applied to W$\rightarrow e\nu$				
statistics		**40**		15
background	10%	10	2%	2
electron energy scale	0.25%	10	0.05%	2
scale linearity	0.00006/ GeV	30	<0.00002/ GeV	<10
energy resolution	8%	5	3%	2
MET scale	2%	15	<1.5%	<10
MET resolution	5%	9	<2.5%	< 5
recoil system	2%	15	<1.5%	<10
total instrumental		**40**		**<20**
PDF uncertainties		20		<10
Γ_W		15		<15
p_T^W		30		30 (or NNLO)
transformation method applied to W$\rightarrow \mu\nu$				
statistics		**40**		15
background	10%	4	2%	negligible
momentum scale	0.1%	14	<0.1%	<10
$1/p^T$ resolution	10%	30	<3%	<10
acceptance definition	η-resol.	19	$< \sigma_\eta$	<10
calorimeter E_T^{miss}, scale	2%	38	$\leq$1%	<20
calorimeter E_T^{miss}, resolution	5%	30	<3%	<18
detector alignment		12	–	negligible
total instrumental		**64**		**<30**
PDF uncertainties		$\approx$20		<10
Γ_W		10		< 10

Tevatron W mass projections



CDF top mass projection

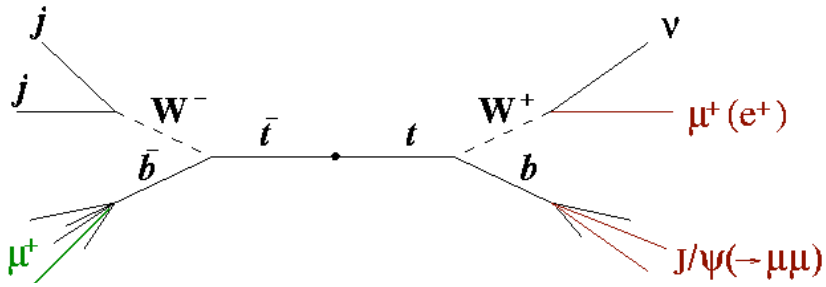


Some other possible methods

- **Exploit high statistics to develop methods with less dependence on bjet calib.**

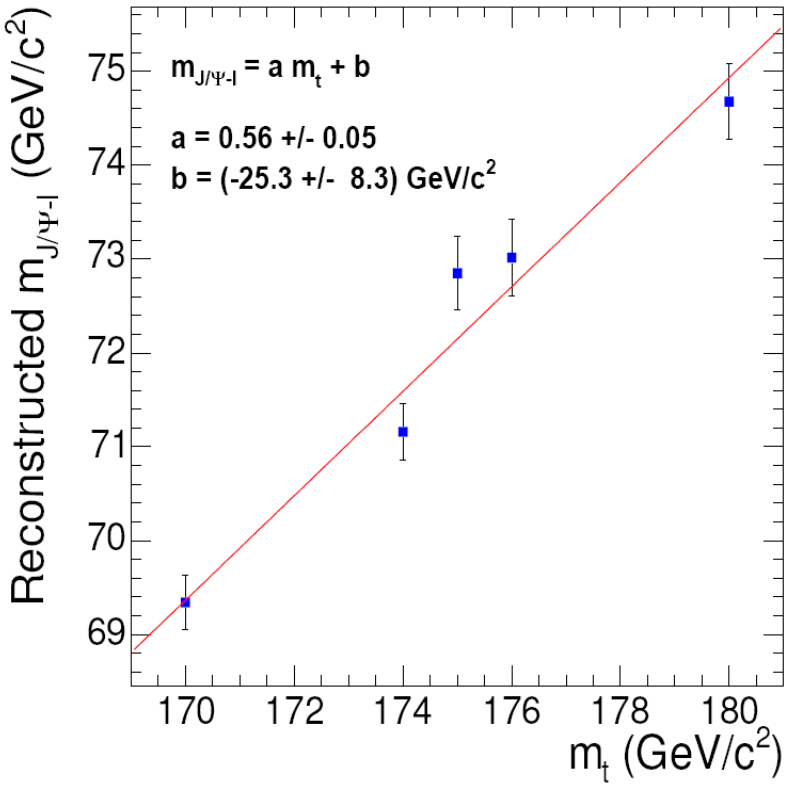
Example 1: t-tbar events with J/ψ in final state

- **CMS study for 14 TeV, 100 fb^{-1}**



- **Exploit correlation between mtop, m(lep J/ψ)**
- **Small BR ⇒ need a lot of data**
  - **Stat. error ~ 1.2 GeV for 20 fb^{-1}**

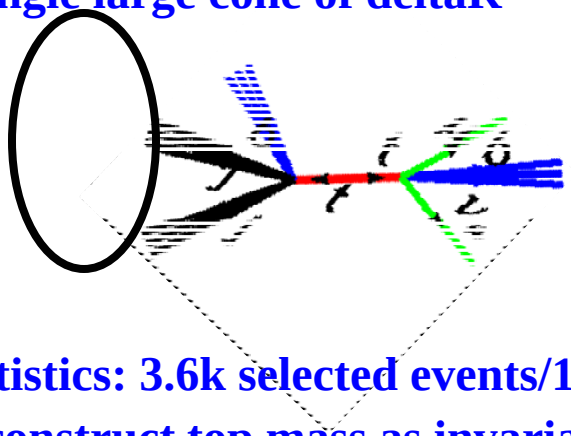
- **Syst. error ~ 1.5 GeV**
  - **Insensitive to JES, bjet calibration**
  - **Dominated by "theoretical" uncertainties (b-fragmentation, UE, modeling, …) as opposed to detector effects**

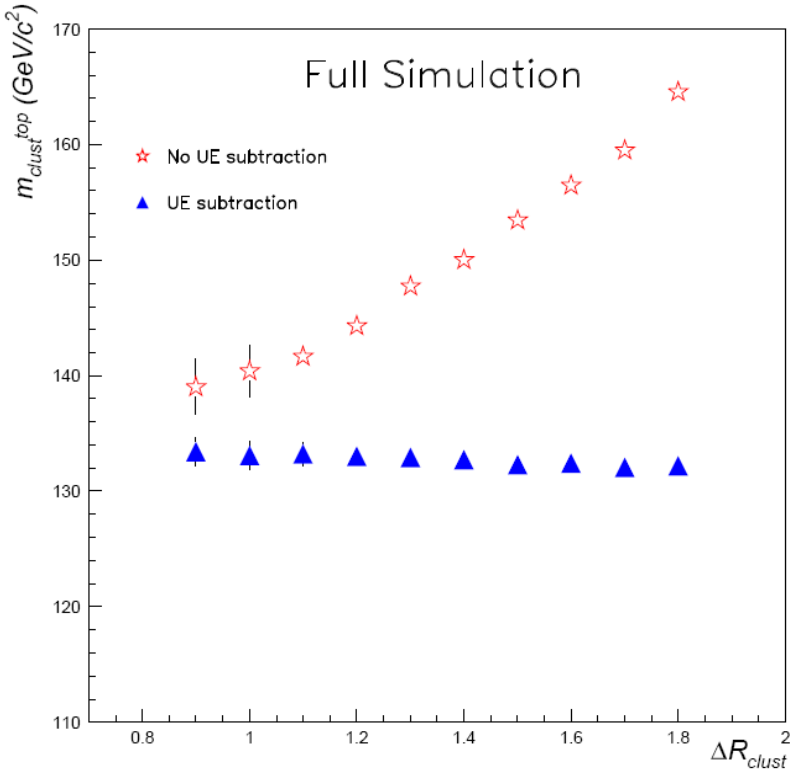


Some other possible methods (cont'd)

Example 2: high pT top events

- ATLAS study for 14 TeV
- Consider pT(top) > 200 GeV events (~2%) with all 3 jets from hadronic top decay within a single large cone of deltaR





- Statistics: 3.6k selected events/10 fb^{-1}
- Reconstruct top mass as invariant mass over all calorimeter towers within the single cone
- Need to subtract energy within cone from UE
- Syst error < 2%
  - Dominated by UE subtraction, mass scale calib

- Large BSM interest in boosted top has led to significant recent developments (eg. jet substructure tools, etc.) that could potentially have some relevance here