



Measurements of the top quark pair production cross section at 7 TeV

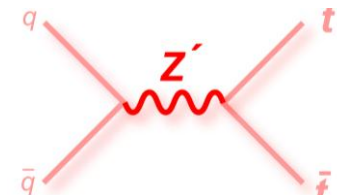
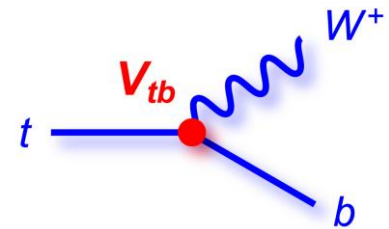
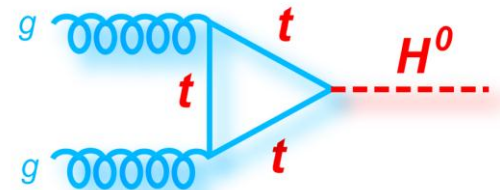
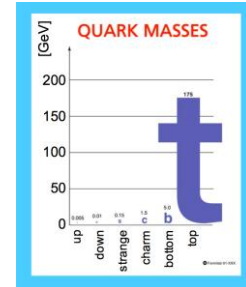
Sadia Khalil

On behalf of the CMS Collaboration

DPF, Aug 9th, 2011

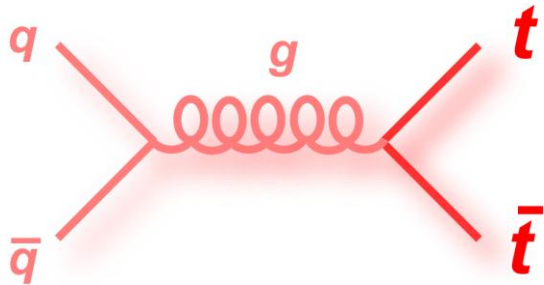
The Top Quark is unique

- **Standard Model measurements**
 - Heaviest known elementary particle
 - Electroweak and QCD precision measurement
 - Only quark with natural mass, $y_t \sim 1$
 - Decays before hadronisation
- **A window to new physics**
 - New physics might couple preferentially to top
 - New particles may decay to top
 - Non-standard couplings
- **In many new physics scenarios (e.g. SUSY) top is dominant BG**
- **Great tool to calibrate detector and test physics objects**

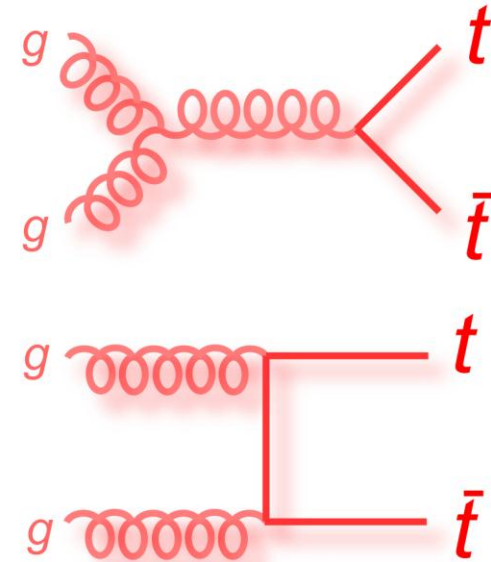


Top Quark Pair Production

- 8 pb (Tevatron 1.96 TeV ppbar)
- 165 pb (LHC 7 TeV)



85% (Tevatron)
13% (LHC)

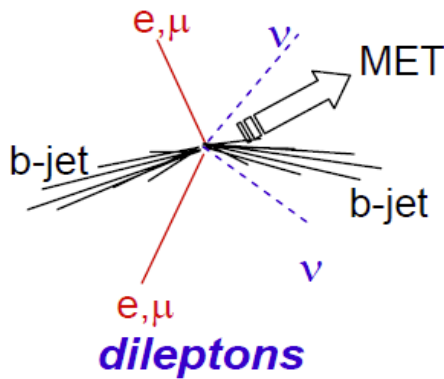
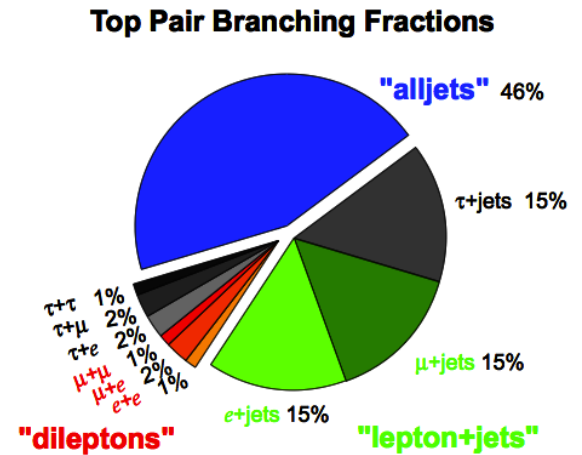


15% (Tevatron)
85% (LHC)

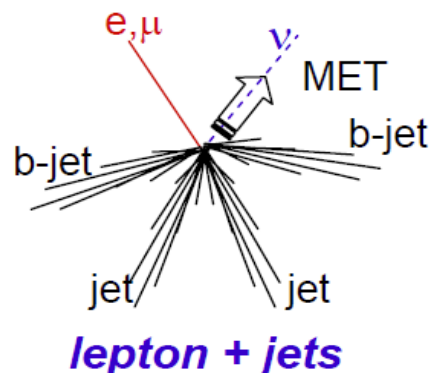
Consequences for searches & charge asymmetry

Outline

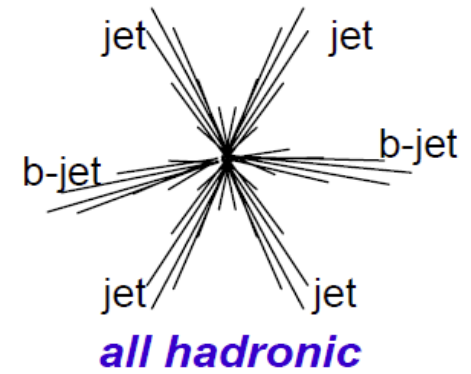
- Top Pair cross section final state categorized by the decay of the W boson
 - *Golden channels:* lepton + jets and dilepton
 - *Challenging channels:* full hadronic, tau + mu



1 36 pb⁻¹



2 36 pb⁻¹



3 1.1 fb⁻¹

Dilepton channel-event selection

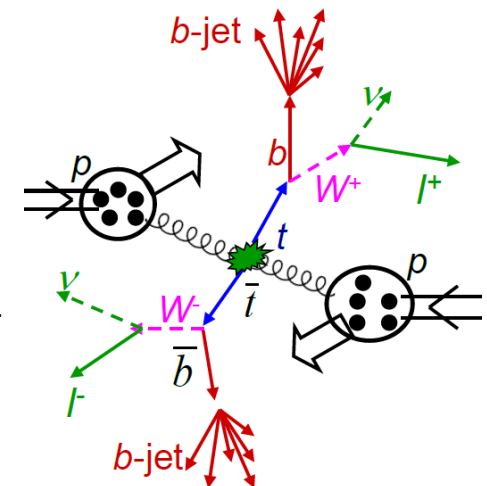
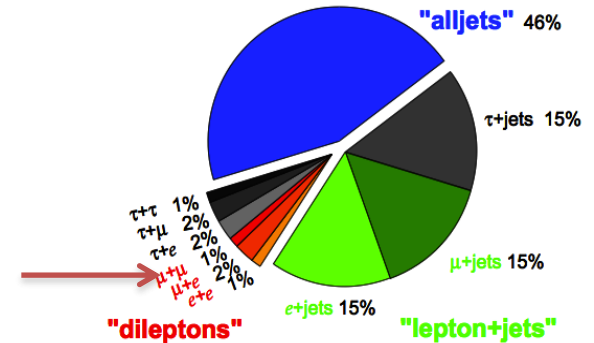
- Inclusive single lepton triggers
- 3 decay channels with two isolated, opposite charge leptons (ee/eμ/μμ)
 - $p_T > 20$ GeV, $|\eta_\mu| < 2.4$, $|\eta_e| < 2.5$
 - Good ID, conversion rejection for electrons
 - Relative isolations < 0.15

$$Rel.Iso. = \frac{\overbrace{\hat{a} P_T^{track} + \hat{a} P_T^{ECAL} + \hat{a} P_T^{HCAL}}^{\text{Detected energy around lepton}}}{P_T(\text{lepton})}$$

$R < 0.3$ $R < 0.3$ $R < 0.3$

- Z-boson veto (ee/μμ)
 - $|M(H) - M(Z)| > 15$ GeV
- Jets
 - $p_T > 30$ GeV, $|\eta_\mu| < 2.5$
 - B-jet identified using track-counting algorithm
 - Separately for events with ≥ 2 jets; ≥ 2 jets, 1 b-tag; 1 jet
- Missing E_T (MET), in (ee/μμ)
 - MET $> 30(50)$ for events with $\geq 2(1)$ jets

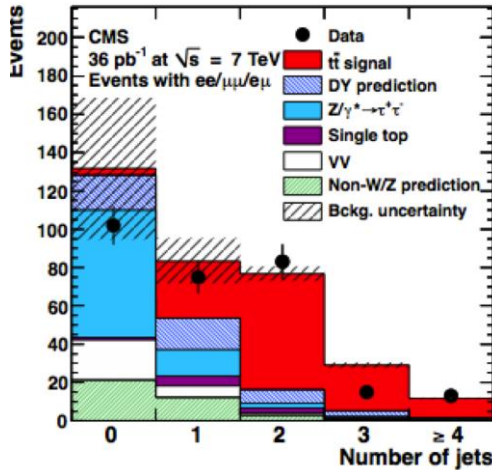
Top Pair Branching Fractions



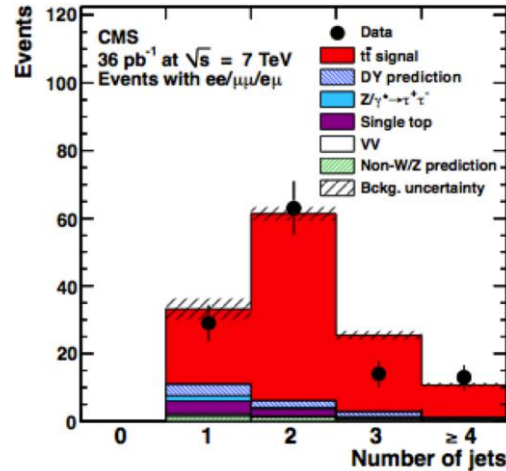
Top Pair Cross Section in Dilepton channel

arXiv:1105.5661, acc. By JHEP

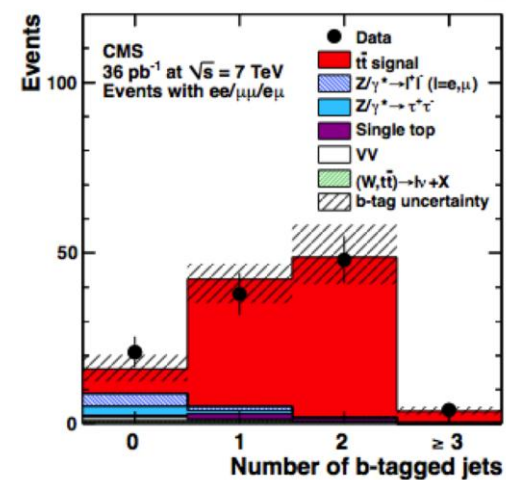
number of jets, after full event selection, before b-tagging:



number of jets, after full event selection, after b-tagging:



number of b-tagged jets, after full event selection, with ≥ 2 jets



Very pure sample of Top events!

Main backgrounds from data-driven methods:

- Drell-Yan, after Z-veto:
 - $N(\text{in veto, data}) \cdot R(\text{out/in, MC})$
- Non-W/Z leptons (mainly QCD and W+jets):
 - fake rate measured from QCD sample

Main systematics:

- Data-driven background estimates
- Jet energy scale
- b-tagging efficiency

Top Pair Cross Section in Dilepton channel

arXiv:1105.5661, acc. by JHEP

Combination of cross-section measurements

Counting Experiment

• three categories for each mode, ee, μμ, eμ:

- ≥ 2 jets, no b-tagging
- ≥ 2 jets, ≥ 1 b-jet
- 1 jet, no b-tagging
- **nine cross-section measurements**

Here and elsewhere:
Luminosity error: 4%

Combine cross-section

$$\sigma(pp \rightarrow t\bar{t}) = 168 \pm 18 \text{ (stat.)} \pm 14 \text{ (syst.)} \pm 7 \text{ (lumi.) pb}$$

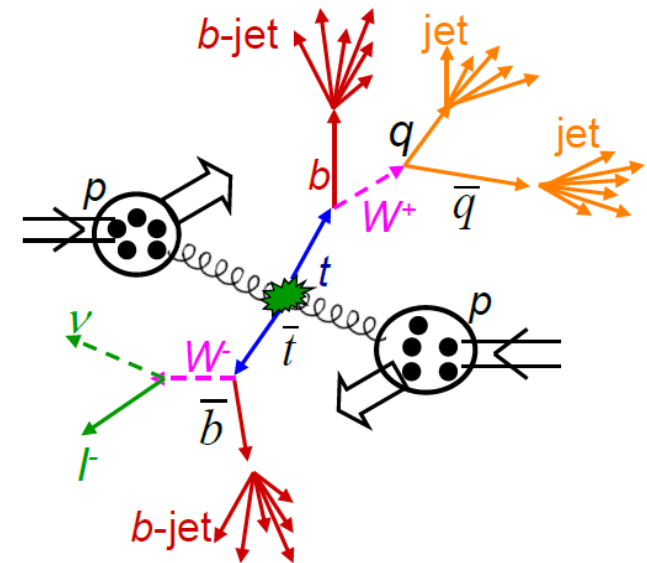
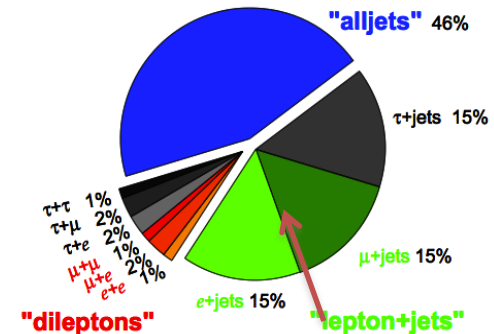
14% relative uncertainty

Final state	e ⁺ e ⁻	μ ⁺ μ ⁻	e ⁺ μ ⁺
At least two jets, no b-tagging requirement			
Events in data	23	28	60
Simulated backgrounds	1.4 ± 0.3	1.5 ± 0.3	5.2 ± 1.2
Z/γ* → e ⁺ e ⁻ /μ ⁺ μ ⁻	3.0 ± 1.8	7.4 ± 4.1	-
Non-W/Z	1.1 ± 1.4	0.6 ± 1.1	1.4 ± 1.6
All backgrounds	5.5 ± 2.3	9.5 ± 4.3	6.7 ± 2.0
Total acceptance \mathcal{A} (%)	0.259 ± 0.021	0.324 ± 0.025	0.928 ± 0.057
Cross section (pb)	189 ± 52 ± 29	159 ± 45 ± 39	160 ± 23 ± 12
At least two jets, at least one b-jet			
Events in data	15	24	51
Simulated backgrounds	0.7 ± 0.2	0.8 ± 0.3	2.5 ± 0.7
Z/γ* → e ⁺ e ⁻ /μ ⁺ μ ⁻	0.7 ± 0.7	2.6 ± 1.8	-
Non-W/Z	0.9 ± 1.2	0.3 ± 0.8	0.5 ± 1.1
All backgrounds	2.3 ± 1.4	3.8 ± 2.0	3.0 ± 1.4
Total acceptance \mathcal{A} (%)	0.236 ± 0.022	0.303 ± 0.028	0.857 ± 0.068
Cross section (pb)	150 ± 46 ± 22	186 ± 45 ± 25	156 ± 23 ± 13
One jet, no b-tagging requirement			
Events in data	8	10	18
Simulated backgrounds	1.6 ± 0.4	1.9 ± 0.4	3.6 ± 0.9
Z/γ* → e ⁺ e ⁻ /μ ⁺ μ ⁻	0.2 ± 0.3	5.2 ± 4.3	-
Non-W/Z	0.3 ± 0.5	0.1 ± 0.4	1.3 ± 1.3
All backgrounds	2.1 ± 0.7	7.1 ± 4.3	4.9 ± 1.5
Total acceptance \mathcal{A} (%)	0.058 ± 0.007	0.074 ± 0.008	0.183 ± 0.024
Cross section (pb)	282 ± 135 ± 45	107 ± 119 ± 163	200 ± 65 ± 35

Lepton+jets - event selection

- Inclusive single lepton triggers
- Considered modes: e+jets, μ +jets
- Exactly one isolated lepton
 - Muons:
 - $p_T > 20$ GeV, $|\eta| < 2.1$
 - Relative Isolation < 0.05
 - Electrons:
 - $p_T > 30$ GeV, $|\eta| < 2.5$
 - Relative Isolation, conversion veto
- Jets
 - $p_T > 30$ GeV, $|\eta| < 2.4$
- Analysis without b-tagging
 - Use MET shape as discriminating distribution
- Analysis with b-tagging
 - MET > 20 GeV
 - Secondary Vertex (SV) algorithm

Top Pair Branching Fractions

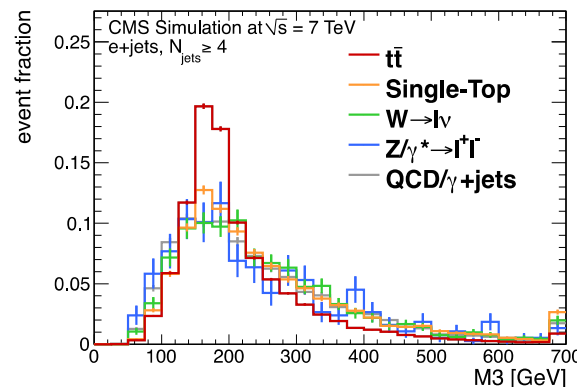
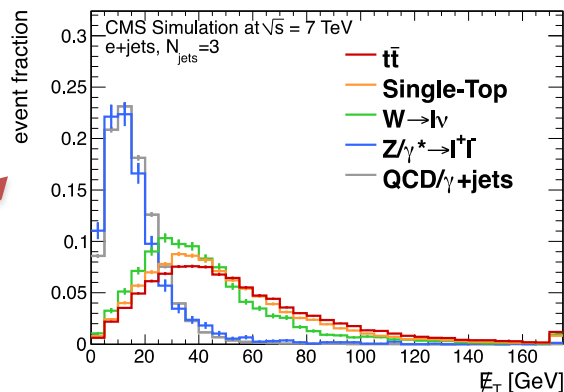


Top pair cross-section in lepton +jets without b-tagging

arXiv:1106.0902, subm. to EPJC

- Method: simultaneous template fit in two distributions to extract $N(ttbar)$

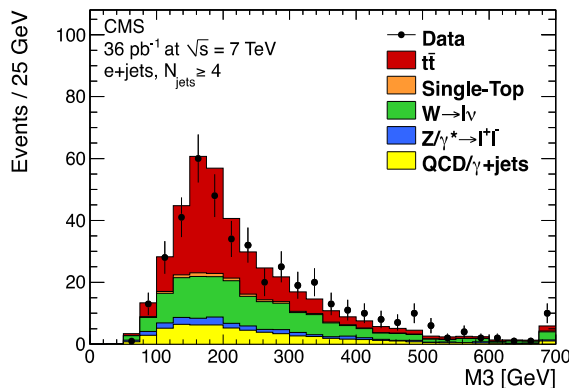
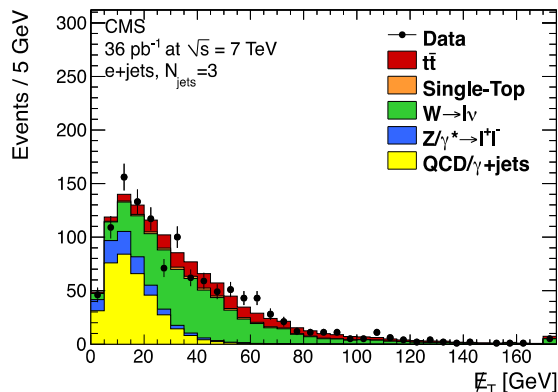
simulation



MET,
 $N(jets) = 3$

M3: mass of three jets that maximize vectorially the p_T sum). $N(jets) \geq 4$

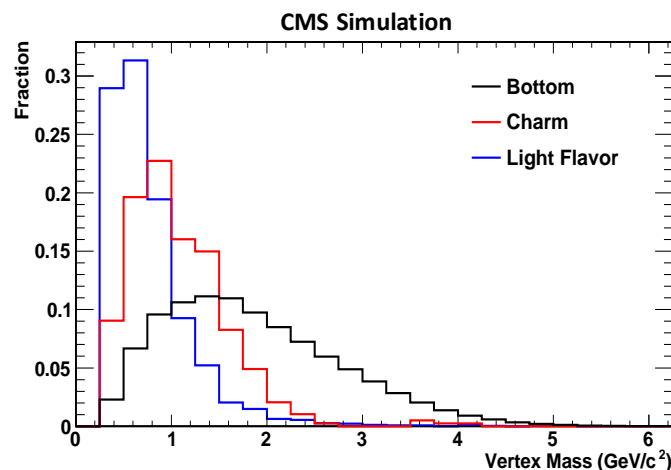
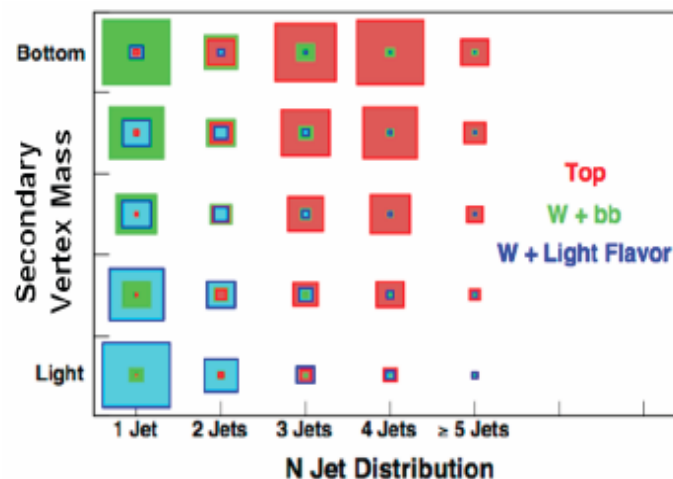
Data - simulation comparison.
Simulation normalized to fit result



e+jets	$\sigma_{t\bar{t}} = 180^{+45}_{-38} (\text{stat.} + \text{syst.}) \pm 7 (\text{lumi.}) \text{ pb.}$
mu+jets	$\sigma_{t\bar{t}} = 168^{+42}_{-35} (\text{stat.} + \text{syst.}) \pm 7 (\text{lumi.}) \text{ pb}$
combined	$\sigma_{t\bar{t}} = 173^{+39}_{-32} (\text{stat} + \text{syst}) \pm 7 (\text{lumi}) \text{ pb}$

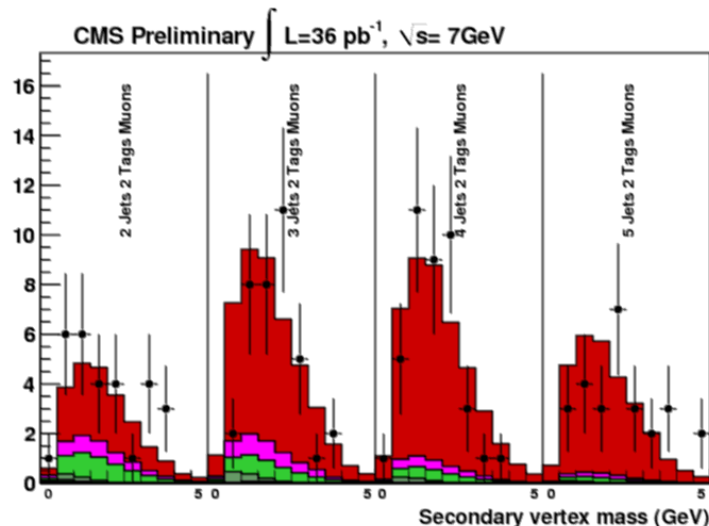
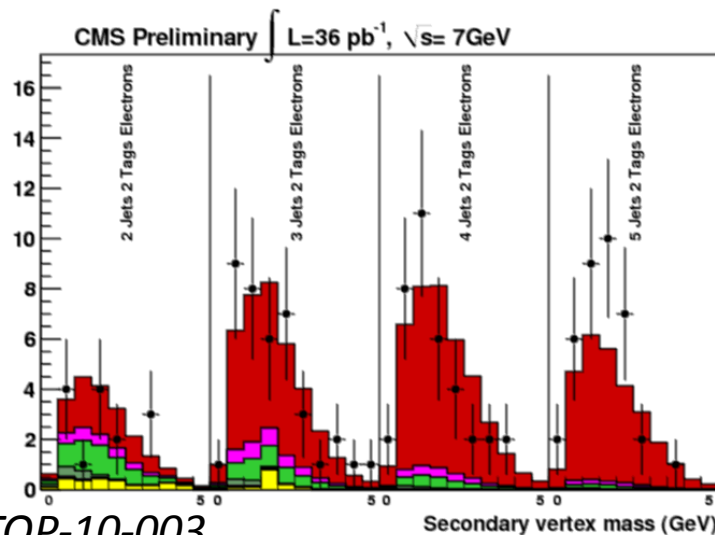
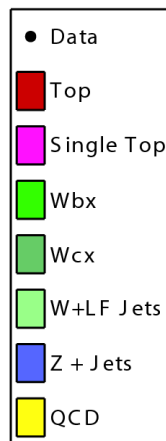
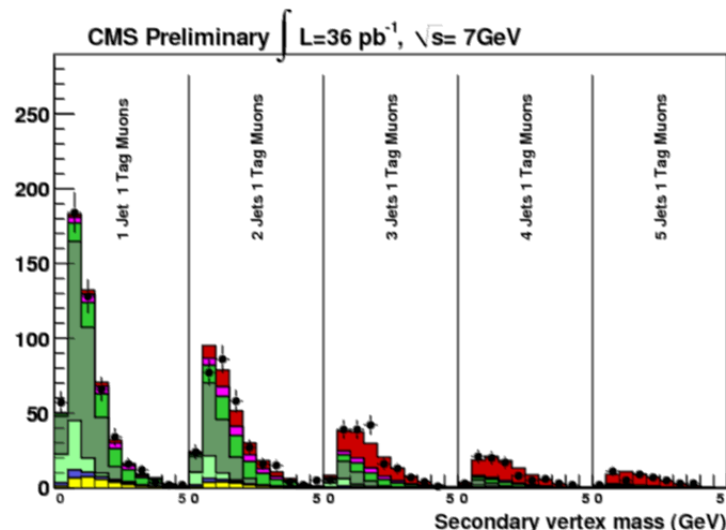
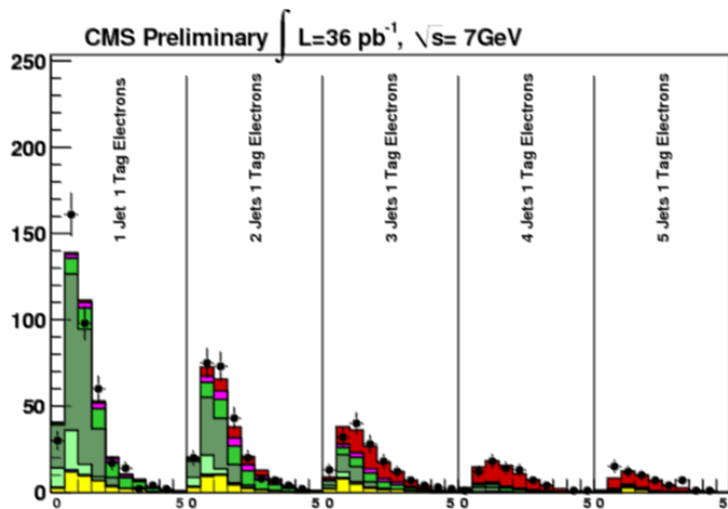
Top Pair Cross Section: Lepton + jets + MET + b-tags

- Observable:
Secondary vertex mass
 - Discriminates between different jet flavours
- Template fit of SV mass in 2D $N(\text{jets}), N(\text{tags})$ plane
 - Separation of signal and various backgrounds
- Categorise events by muon/electron, numbers of jets (1-5) and b-tags (1, 2)
- Data constrains uncertainties
 - jet energy scale
 - b-tagging efficiency
 - $W+\text{Jets}$ factorisation scale



Top Pair Cross Section: Lepton + jets + MET + b-tags

Fit result: SV mass distributions in 5(4) 1(2)-tag bins per channel (e+jets, mu+jets)



Top Pair Cross Section: Lepton + jets + MET + b-tags

- Obtained result for BG normalizations :

BG Scale factor	Fit result
W+b scale factor (w.r.t. MC sc. to incl. NNLO)	1.9 +0.6-0.5
W+c-- -jets scale factor (w.r.t. MC sc. to incl. NNLO)	1.4 +/- 0.2

- JES/ b-tag SF consistent with input, but uncertainty reduced!

- Result

$$\sigma_{t\bar{t}} = 150 \pm 9 \text{ (stat.)} \pm 17 \text{ (syst.)} \pm 6 \text{ (lumi.) pb}$$

Source	Uncertainty (%)
Systematic uncertainties	
Lepton ID/reco/trigger	3
Unclustered MET resolution	< 1
$t\bar{t}$ + Jets Q^2	2
ISR/FSR	2
ME to PS matching	2
PDF	3.4
Profile likelihood parameters	
Jet energy scale and resolution	7.0
b tag efficiency	7.5
W+Jets Q^2	9.1
Combined	11.6

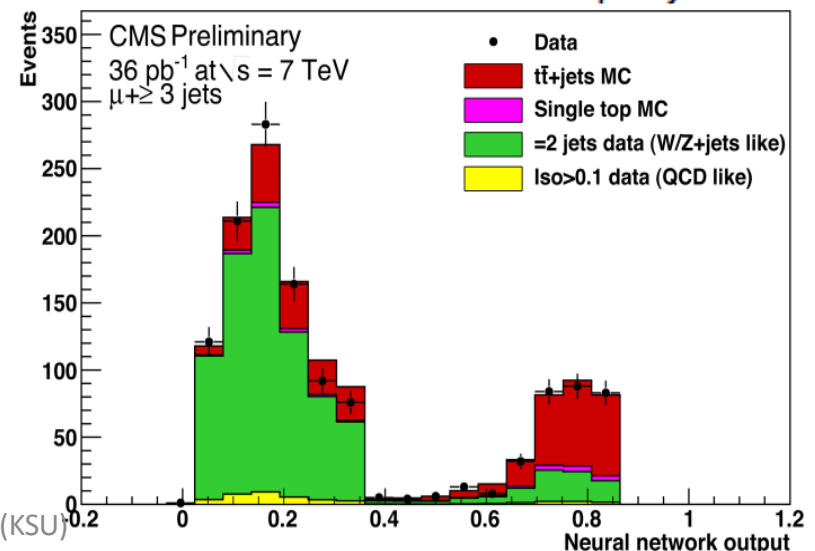
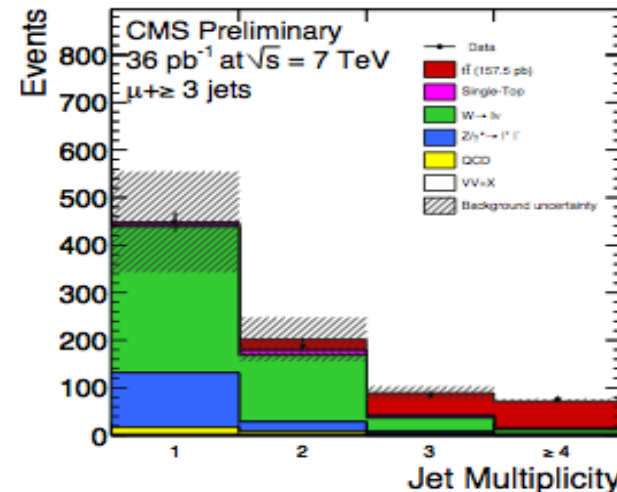
13% relative uncertainty

Top Pair Cross Section: Lepton + jets + MET + b-tags

Cross check analyses

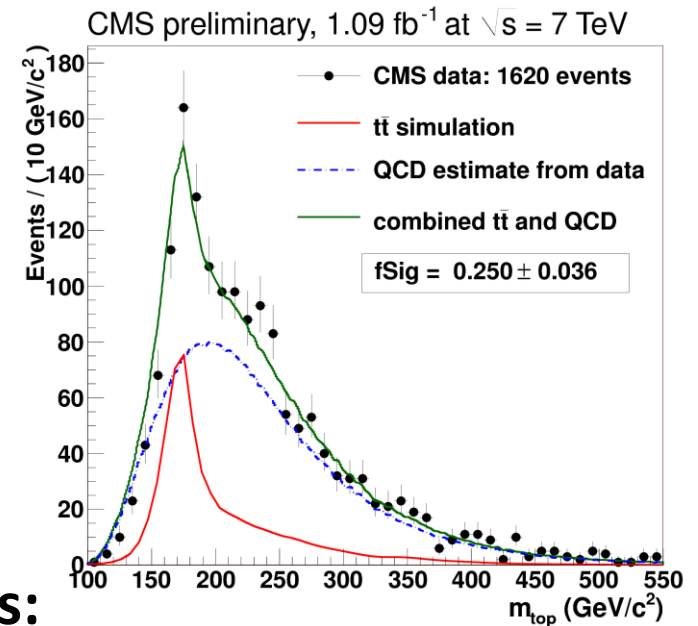
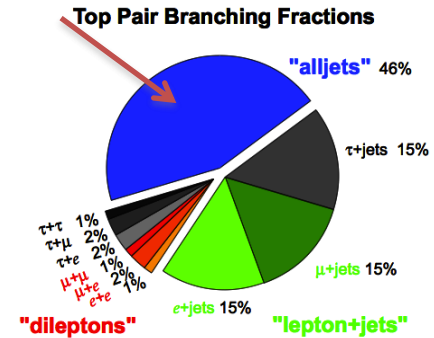
- Soft muon tagging in μ +jets
 - Orthogonal method to identify b-jets
 - Suffers from reduced efficiency
- Counting experiment in e+jets
 - Use Berends scaling to estimate $W+\geq(n)/W+\geq(n+1)$ jets background
- Neural network analysis in μ +jets
 - NN input variables:
 $\Delta R(\text{jet1}, \text{jet2}), \eta_\mu, \text{b-tag}$

All in good agreement!



Cross Section: Full-hadronic Channel (1.09/fb)

- Selection
 - 6 jets
 - 2 b-tagged jets
- Kinematic fit
 - Exploit known W mass and equality of top masses
 - Require χ^2 probability $> 1\%$
- Cross section measurement:
Fit of signal + background shapes to data

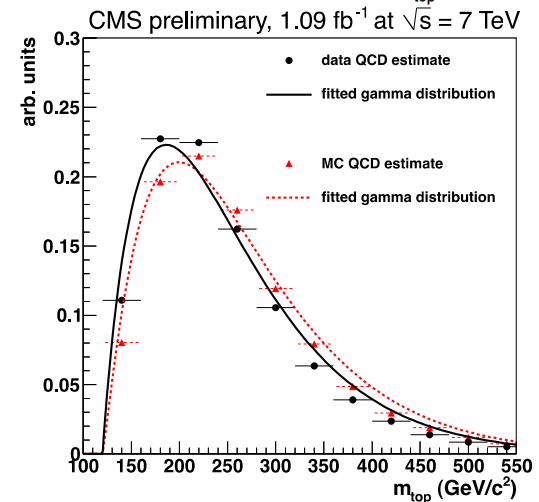
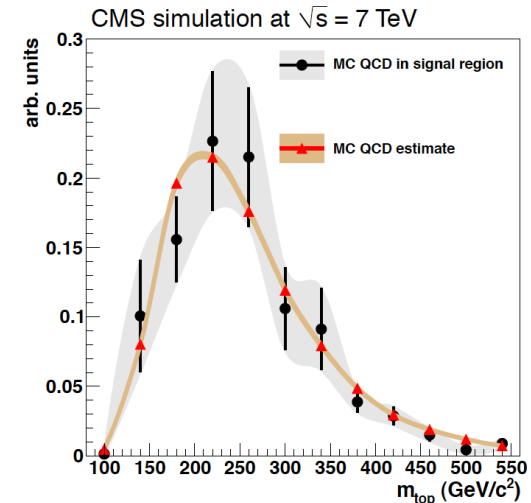


Top quark mass:

Good discrimination between signal and background

Cross Section: Full-hadronic Channel (1.09/fb)

- QCD estimation:
 - Weight non-b-tagged events to match p_T and η distributions of b-candidates from kinematic fit
 - The backgrounds derived from data are compared to MC
- Dominant systematics
 - B-tagging (16%)
 - Jet energy scale (14%)
 - Background (12%)
- **33% uncertainty**
- **First measurement in pp collisions at 7 TeV**

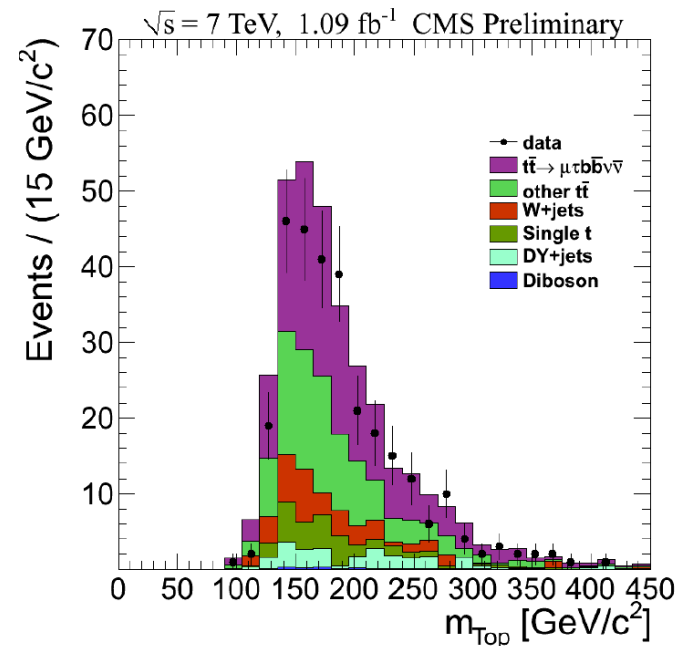
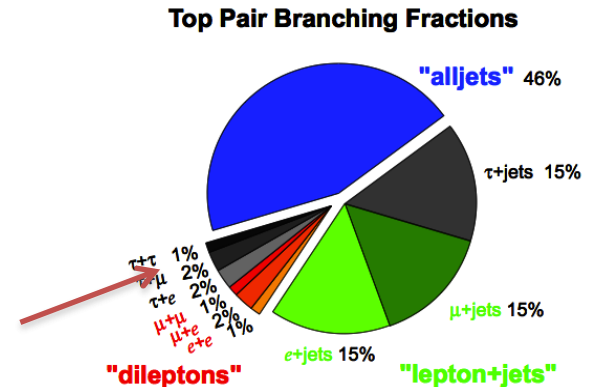


$$\sigma_{t\bar{t}} = 136 \pm 20 \text{ (stat.)} \pm 40 \text{ (sys.)} \pm 8 \text{ (lumi.) pb}$$

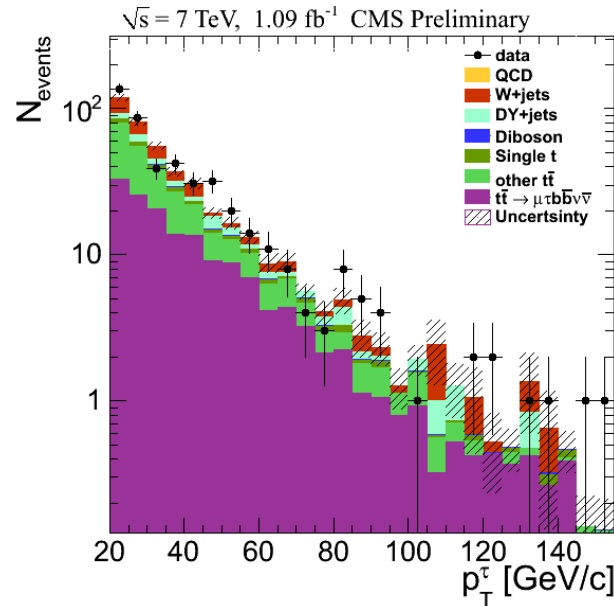
Top Pair Cross Section: muon + tau (1.09/fb)

- Counting experiment
- Select events with
 - Isolated muon and 3 jets
 - Missing ET
 - ≥ 1 b-tag
 - 1 reconstructed tau

Selected events are consistent with top pair production



Muon + tau: Results

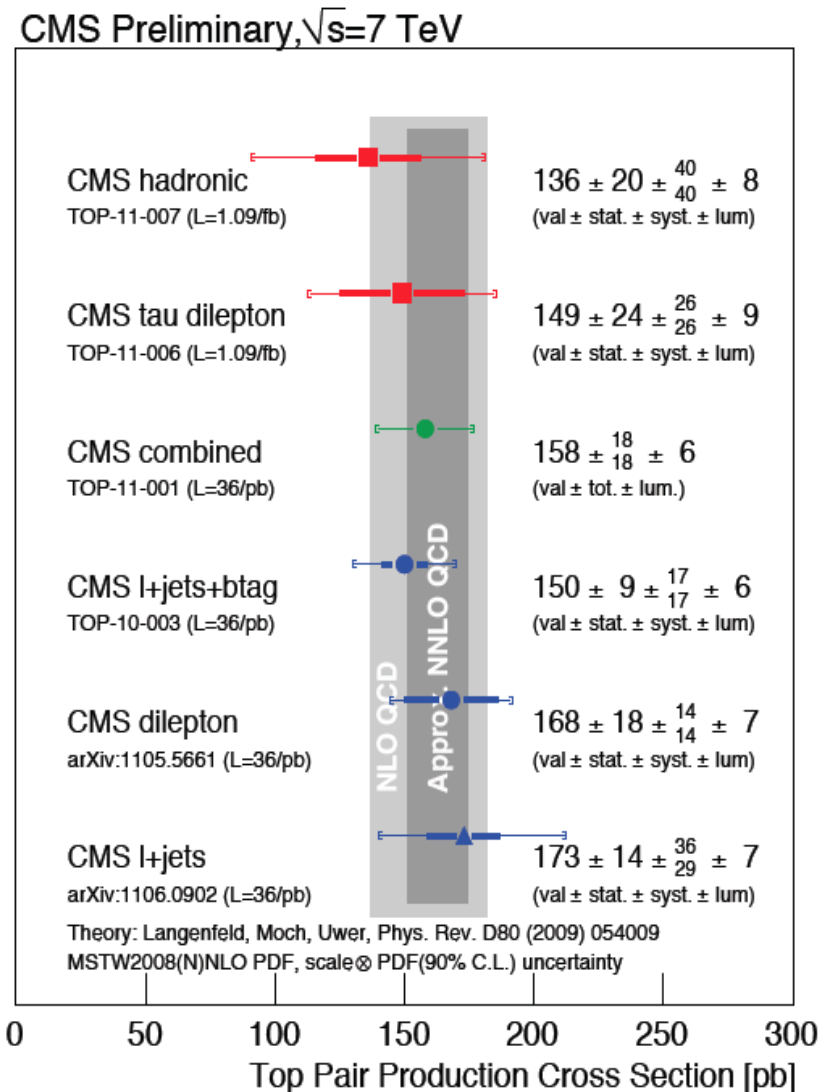


- **Muon + tau** major systematic uncertainties:
 - Tau misidentification (13%), tau identification (7.3%), b-tagging (5.5%), jet energy scale (4.4%)
- Total systematic uncertainty 17%
- **First measurement in this channel in pp collisions at 7 TeV**

$$\sigma_{t\bar{t}}^{\tau-dil} = 148.7 \pm 23.6(\text{stat.}) \pm 26.0(\text{syst.}) \pm 8.9(\text{lumi.}) \text{ pb}$$

Top Pair Cross Section Summary

- 2011, 1.09 fb^{-1} results
 - New, challenging channels
- 2010, 36 pb^{-1}
 - Precise measurements in lepton + jets/dilepton
- 2010 combination: 12% total uncertainty
- Starting to constrain NLO calculations



References

- [arXiv:1105.5661](#) (dilepton cross section, accepted by JHEP)
- [arXiv:1106.0902](#) (lepton + jets cross section, submitted to EPJC)

- PAS TOP-10-003 (lepton + jets + b-tag)
- PAS TOP-11-006 (tau + muon cross section)
- PAS TOP-11-007 (full-hadronic cross section)
- PAS TOP-11-001 (cross section combination)

Backup

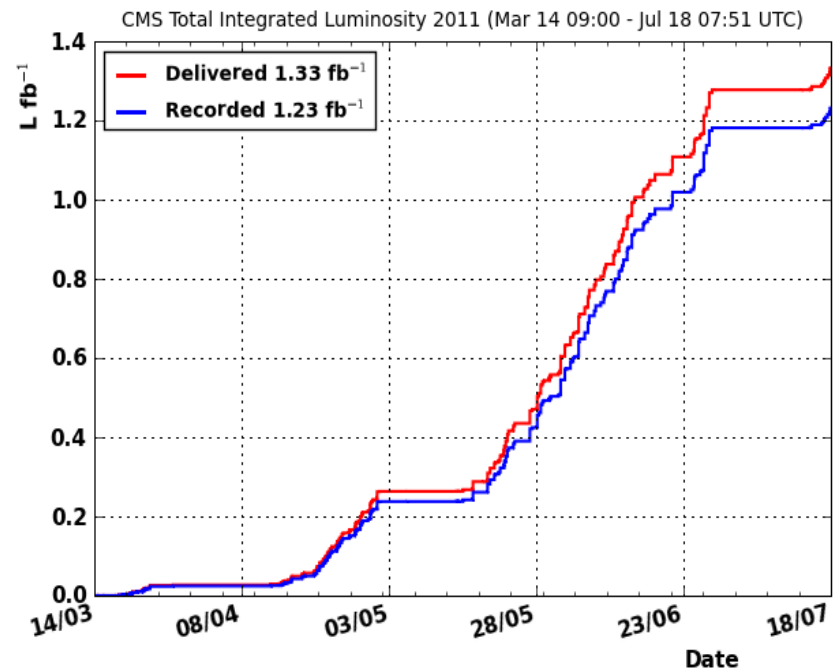
LHC Performance

- LHC Performance
 - ~ 200,000 top quark pairs produced
 - ~ 90,000 single top quarks

More top quark pairs
than Tevatron

(~ 80,000)

(NB: Tevatron more top pairs
from $q\bar{q}$ initial state)

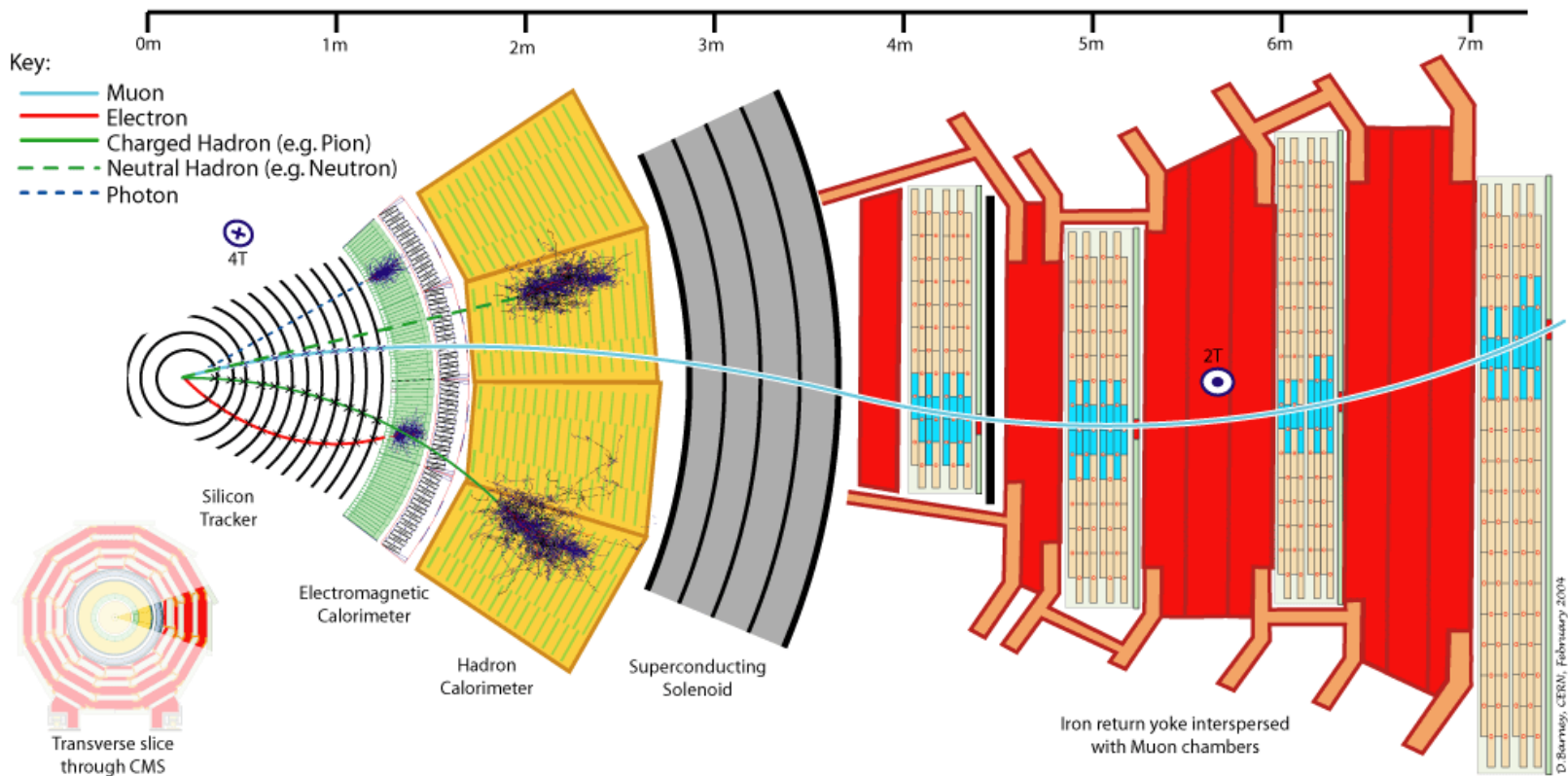


CMS Detector

Top physics needs all sub-detectors:

Jets (also forward), b-tagging, muons, electrons, missing energy, charged hadrons

- Significant improvements due to particle flow reconstruction



Dilepton channel- background estimates

- $Z/\gamma^* \rightarrow e^+e^-$ and $\mu^+\mu^-$

$$N_{Z/g^*}^{out} = R_{out/in} N_{Z/g^*}^{in}$$

Evts passing the ZVeto

Ratio of failing to passing evts in Z mass window (MC)

Non-DY contributions, evts failing the pure DY sample

- Combine systematics (50%)

- Non-W/Z decays
 - R_{TL} : Fraction passing the full selection criteria relative to passing the loose
 - Loose muons: $I_{rel} < 0.4$ (1.0)
 - Loose electrons: no CALO cluster shape or cluster-to-track matching and $I_{rel} < 1.0$
 - In data select single loose lepton in the pure multijet background sample by vetoing W/Z events in W-transverse mass (M_{WT})
 - Combine systematics: 50%(75%) events with one non-W/Z and 100% with 2 non-W/Z events

Top pair cross-section in lepton +jets without b-tagging

arXiv:1106.0902, subm. to EPJC

- use a binned likelihood fit

$$\mu_j[i] = \sum_k \beta_k \cdot \alpha_{jk}[i],$$

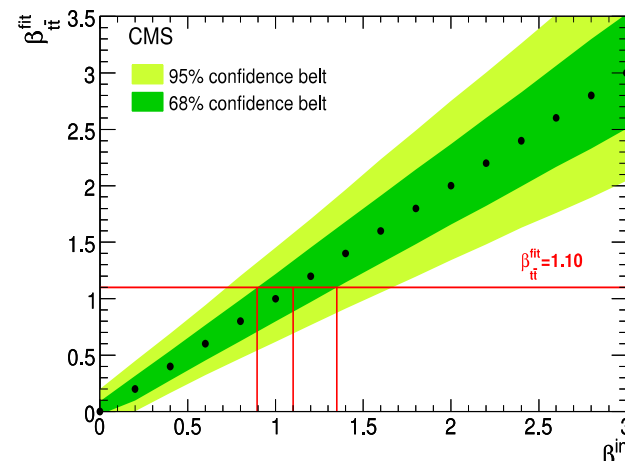
number of expected events in each bin i of the distribution j (either MET or M3)

binned contribution for variable j and process k

$$\beta_k = \frac{\sigma_k}{\sigma_k^{\text{pred}}}$$

Ratio of measured and predicted cross-section

all processes as $t\bar{t}$, W+jets, Z+jets, single-top



Systematics

	combined result	
	stat.+syst. uncertainty	syst. only
Stat. uncertainty	+8.7% -8.4%	-
JES	+20.3% -17.6%	+18.3% -15.5%
Factorization scale	+11.2% -10.6%	+7.1% -6.5%
Matching threshold	+10.5% -9.8%	+5.9% -5.0%
Pileup	+9.3% -9.3%	+3.3% -4.0%
ID/reconstruction	+9.2% -8.7%	+3.0% -2.3%
QCD rate & shape	+9.1% -8.9%	+2.7% -2.9%
ISR/FSR variation	+9.0% -8.6%	+2.3% -1.8%
JER	+8.8% -8.4%	+1.3% -0.0%
PDF uncertainty	+8.7% -8.5%	+0.0% -1.3%
Total	+23.5% -19.3%	+21.8% -17.4%

e+jets $\sigma_{t\bar{t}} = 180_{-38}^{+45} (\text{stat.} + \text{syst.}) \pm 7 (\text{lumi.}) \text{ pb}$

mu+jets $\sigma_{t\bar{t}} = 168_{-35}^{+42} (\text{stat.} + \text{syst.}) \pm 7 (\text{lumi.}) \text{ pb}$

combined $\sigma_{t\bar{t}} = 173_{-32}^{+39} (\text{stat} + \text{syst}) \pm 7 (\text{lumi}) \text{ pb}$