Measurement of Differential Top Quark Pair Production cross sections at 7 TeV with the CMS experiment

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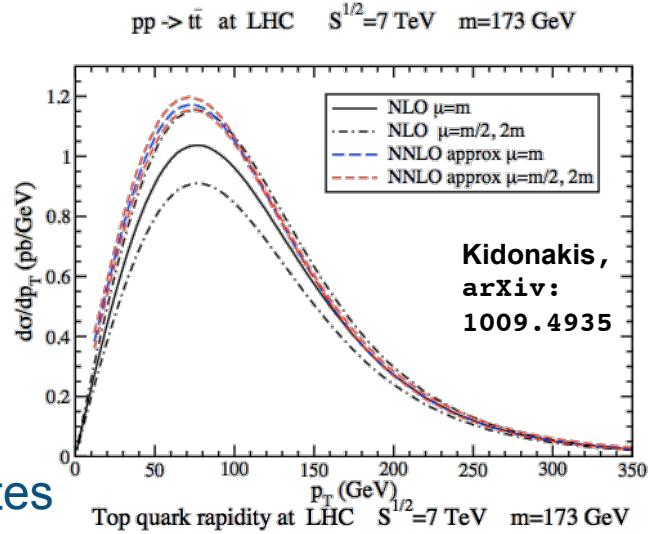
DESY

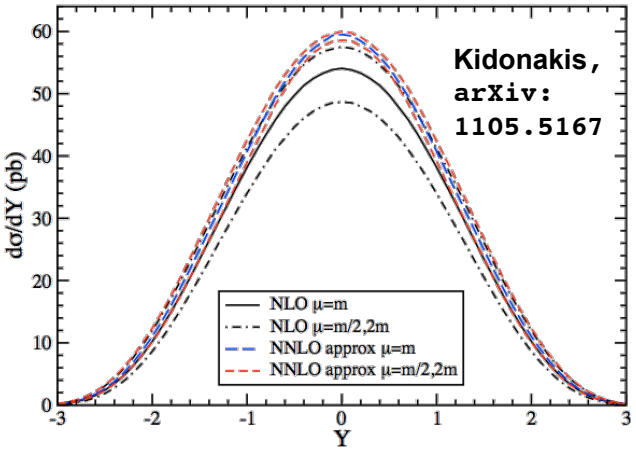
for the CMS Collaboration

36th International Conference on High Energy Physics
4 – 11 July 2012

Why measure differentially?

- Precise understanding of top quark distributions is crucial:
  - Precise tests of pQCD for top quark production at the LHC energy regime
  - Theory predictions and models need to be tuned and tested with measurements
  - Top quark is background for many BSM searches
  - New physics can potentially manifest in top final states





- In its 2 years of operation, the LHC has proven to be a 'top factory':

~800K ttbar events in 5 fb^{-1} of data @ 7 TeV

Entering the era of precision measurements in top-pair production

Analysis overview

First measurement of normalized differential ttbar production cross sections at 7 TeV

- 9 kinematic observables:
  - Lepton: $p_T(l)$, $\eta(l)$
  - Lepton pair: $p_T(ll)$, $m(ll)$
  - Top quark: $p_T(t/tbar)$, $y(t/tbar)$
  - Top-quark pair: $p_T(ttbar)$, $y(ttbar)$, $m(ttbar)$

$$\frac{1}{\sigma_{t\bar{t}}}\frac{d\sigma_{t\bar{t}}}{dX}$$

CMS-PAS TOP-11-013

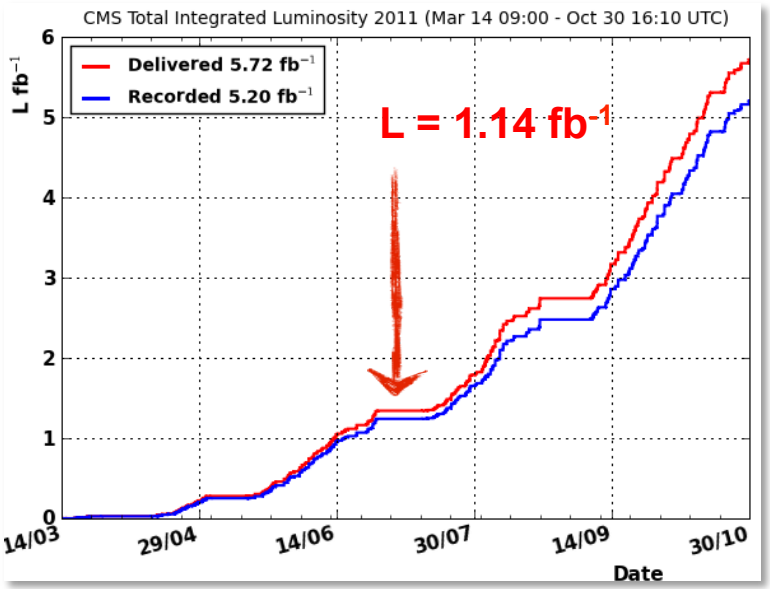
http://cdsweb.cern.ch/record/1422425

- Shape measurement: normalization to the total cross section σ_{ttbar}

→ Correlated systematic uncertainties cancel

- Dilepton & lepton+jets channels:
  - in "visible" phase space
  - corrected for detector effects
  - corrected to parton level

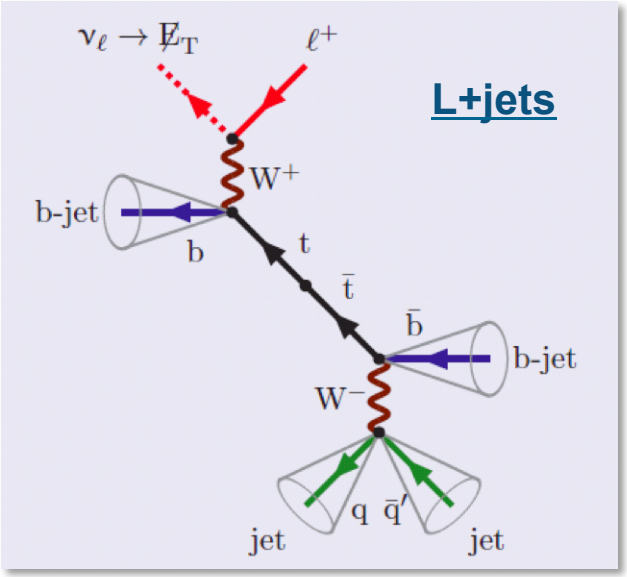
- Using 1.1 fb^{-1} of collected data by CMS in 2011 in pp collisions at 7 TeV



Event selection

Lepton+jets:

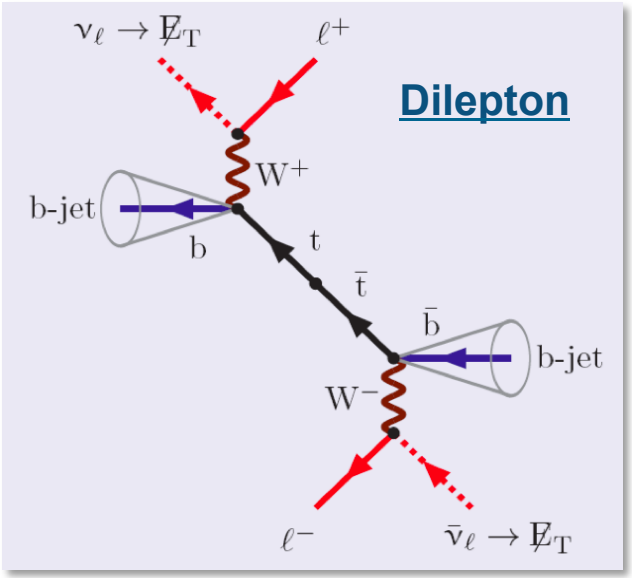
- Exactly 1 isolated high-p_T lepton (μ or e)
  - μ: p_T > 20 GeV, |η| < 2.1
  - e: p_T > 30 GeV, |η| < 2.5
- Veto additional leptons
- ≥ 4 jets, p_T > 30 GeV, |η| < 2.4
- ≥ 2 b-tagged jets



Dileptons:

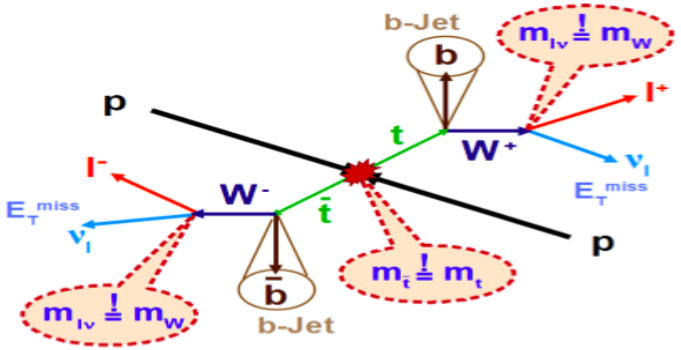
- 2 opp.-sign, high-p_T isolated leptons (ee, μμ, μe)
  - μ: p_T > 20 GeV, |η| < 2.1
  - e: p_T > 20 GeV, |η| < 2.4
- QCD veto: m_{ll} < 12 GeV
- ≥ 2 jets, p_T > 30 GeV, |η| < 2.4
- ≥ 1 b-tagged jets
- ee, μμ channels: E_T^{miss} > 30 GeV

  Z veto: 76 GeV < m_{ll} < 106 GeV



Reconstruction of the ttbar pair

- Needed to reconstruct top and ttbar observables



Lepton+jets: Kinematic fit

- Input: 4-vectors
  - Lepton and up to 5 leading jets
  - 2-btagged jets
  - ν_l: E_T^{miss} with $p_z = 0$ initially
- Vary 4-vectors within their resolutions to satisfy:
  - $m_t = m_{tbar}$
  - $m_W = 80.4$ GeV
- Permutation with the minimum χ^2 is taken

Dileptons: Kinematic reco

- Underconstrained (2 neutrinos)
- 2 b-jets (or leading jets), 2 leptons, E_T^{miss}
- Constraints:
  - $m_W = 80.4$ GeV
  - $p_{x,y}(\nu_1) + p_{x,y}(\nu_2) = E_T^{miss}{}_{x,y}$
  - $m_t = m_{tbar}$ = fixed

    with m_t varied in steps of 1 GeV, between 100 - 300 GeV
- Solution with most probable $E(\nu)$ compared to simulated spectrum is taken

For $d\sigma/dm_{tt}$ only:

- 4-vector sum of the 2 leading jets, 2 leptons and E_T^{miss}

Basic kinematic distributions

Lepton+jets:

- μ+jets: 2657 events
- e+jets: 1797 events

of which 93% ttbar
(rest: single top, W+jets)

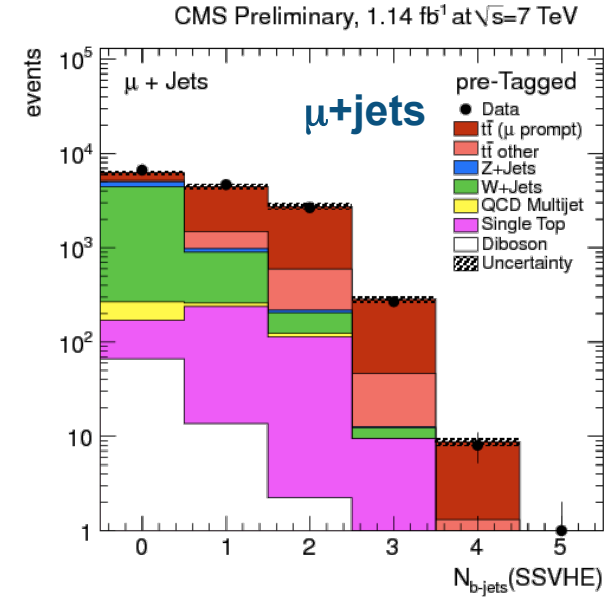
Dileptons:

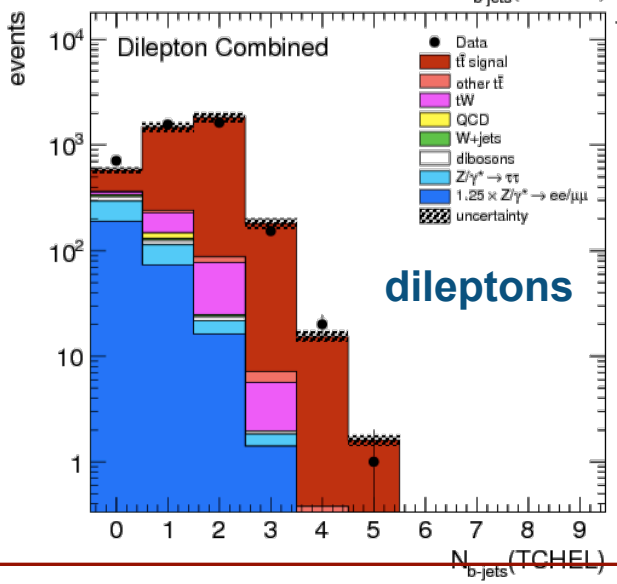
- μμ: 612 events
- ee: 597 events
- μe: 1764 events

of which 90-93% ttbar
(rest: Z+jets, single top)

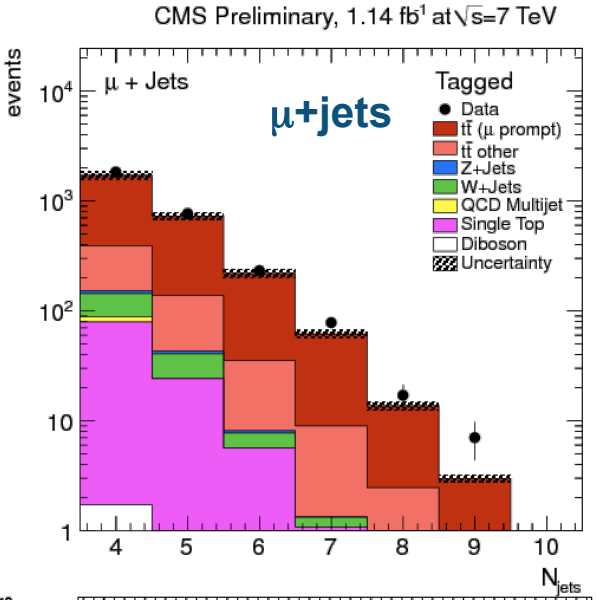
Good agreement between data and simulation in all channels

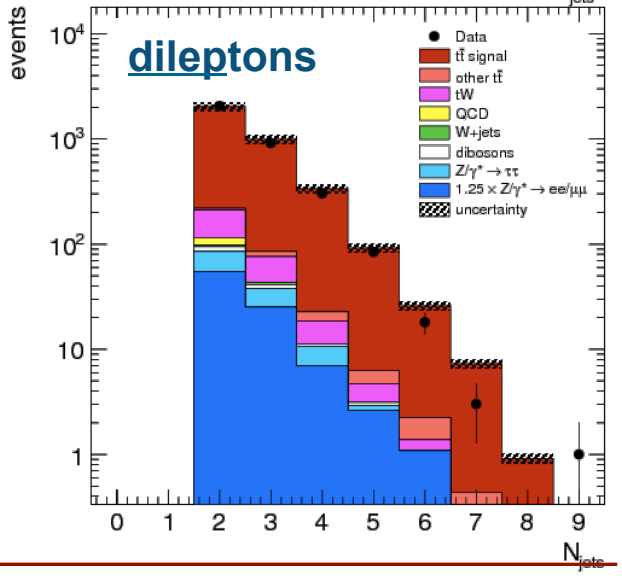
B-tag multiplicity



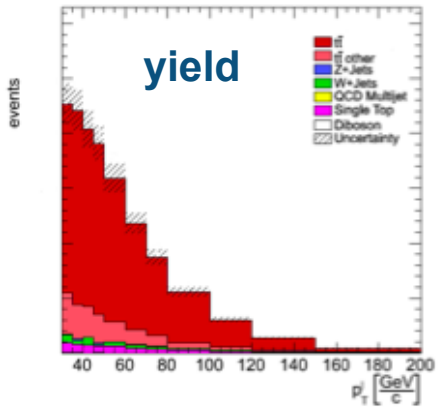


Jet multiplicity

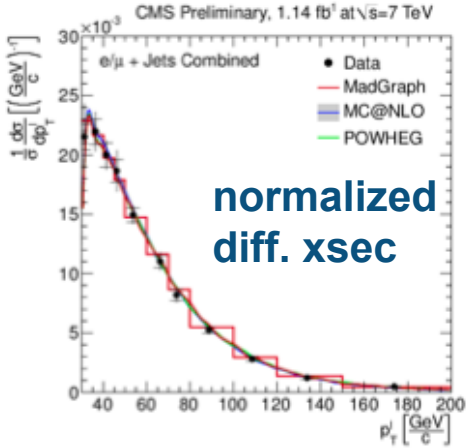




Normalized differential cross sections



$$\frac{1}{\sigma}\frac{d\sigma^i}{dX} = \frac{1}{\sigma}\frac{N^i_{\mathrm{Data}} - N^i_{\mathrm{BG}}}{\Delta^i_X \epsilon^i L}$$



- Cut-and-count method
- Background: data-driven (Z+jets & QCD in dileptons) and simulation
- Corrected back to parton level in visible phase space:

l+jets
- quarks p_T > 30 GeV, $|\eta|$ < 2.4
- lepton p_T > 30 GeV, $|\eta|$ < 2.1

dileptons
- quarks p_T > 30 GeV, $|\eta|$ < 2.4
- lepton p_T > 20 GeV, $|\eta|$ < 2.4

- Corrected for detector effects (finite experimental resolution)
  - Bin-by-bin correction: bin optimized for purity (migration in bin i) and stability (migration out of bin i)
  - Full unfolding (SVD) for $d\sigma/dm_{tt}$ in the dilepton channel only

$$\epsilon^i = \frac{N^i_{\mathrm{rec}}}{N^i_{\mathrm{gen}}}$$

- Normalized to unity (i.e, divided by total cross section)

Systematic uncertainties

- Determined individually for each bin of the measurement
- Normalized cross sections: only shape uncertainties contribute, correlated uncertainties cancel

Typical values per bin

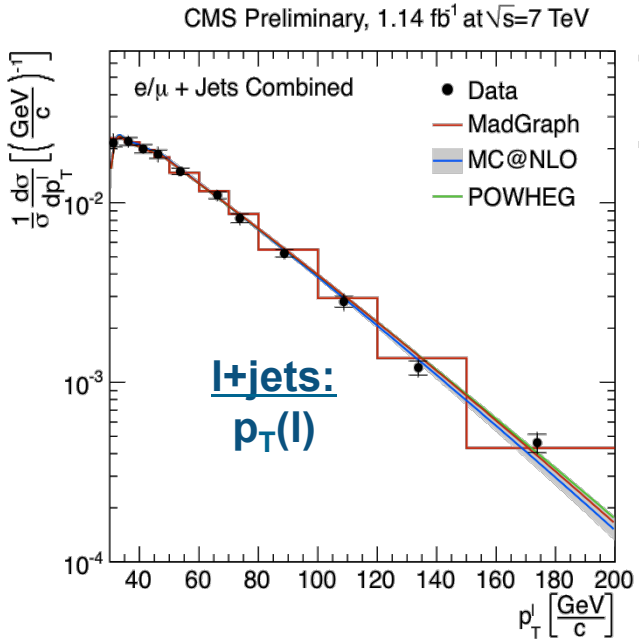
	Source	Method	l+jets (in %)	dilepton (in %)
Experimental	Background	vary with 30–50%	0.5	3.0
	Trigger & lepton eff.	p_T, η dependent	0.5	2
	Jet Energy Scale	p_T, η dependent	0.5	1.0
	Jet Energy Resolution	p_T, η dependent	1.0	<1.0
	Pile-up	vary $\pm$0.6 PU evts	<1.0	<1.0
	b-tagging	p_T, η dependent	1–4	1.7
	Kinematic reconstruction	p_T, η dependent	–	1–4
Model	Q^2, matching scale	vary factor 0.5–2	3.5	1.2
	Hadronisation	Pythia vs Herwig	2–4	2–10
	Top Quark Mass	172.5 ± 0.9	0.5	0.5
	PDF	PDF4LHC	0.5	0.5

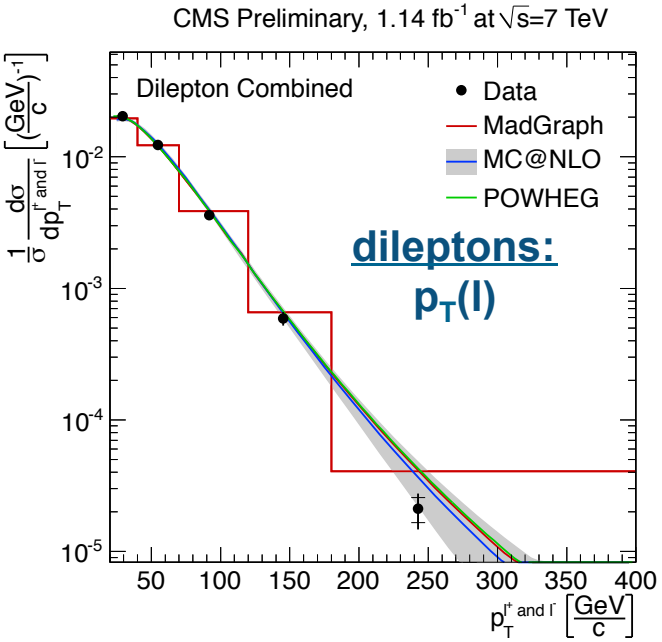
Results: leptons, lepton pair

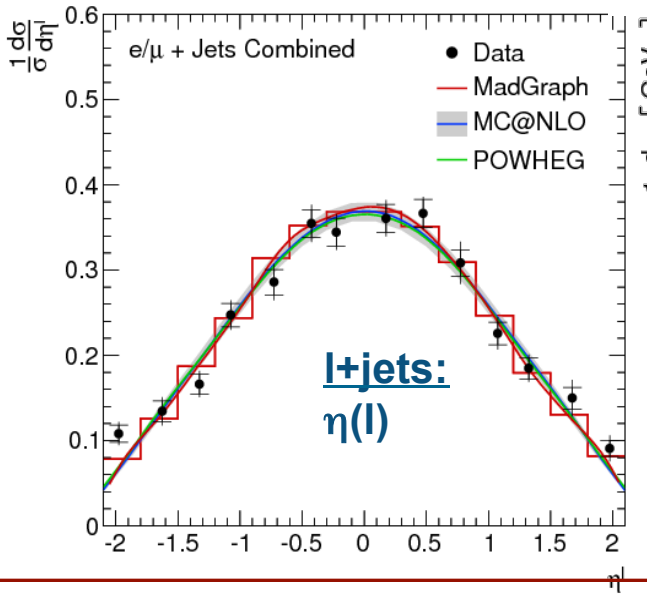
- Comparison to different theory predictions:
  - MadGraph
  - MC@NLO
  - POWHEG
- Horizontal bin center correction wrt MadGraph for showing the data

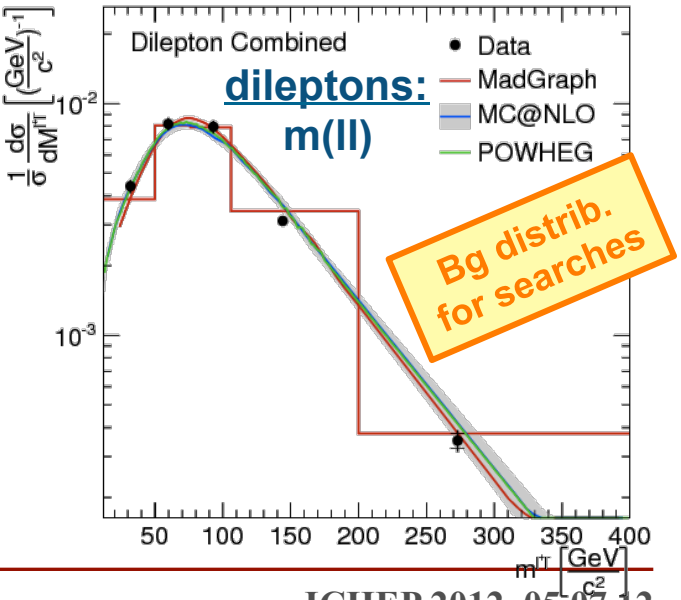
Lafferty, Wyatt, NIM A 355 541-547

Good agreement between:
- data and predictions
- different predictions
- different channels







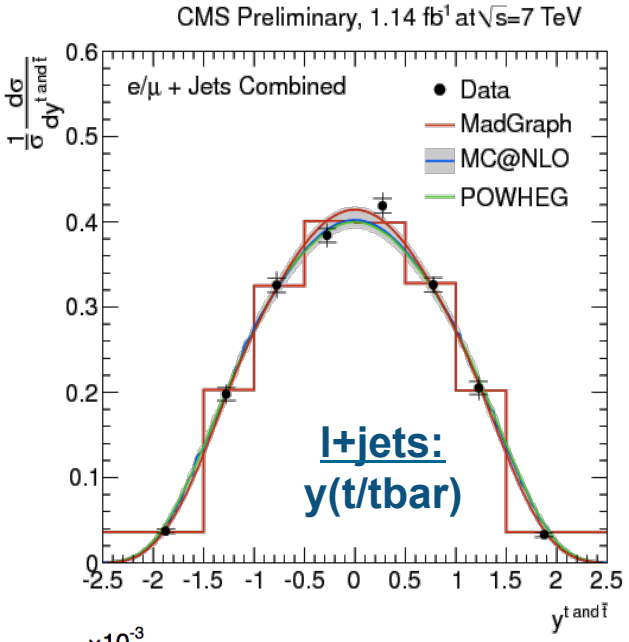


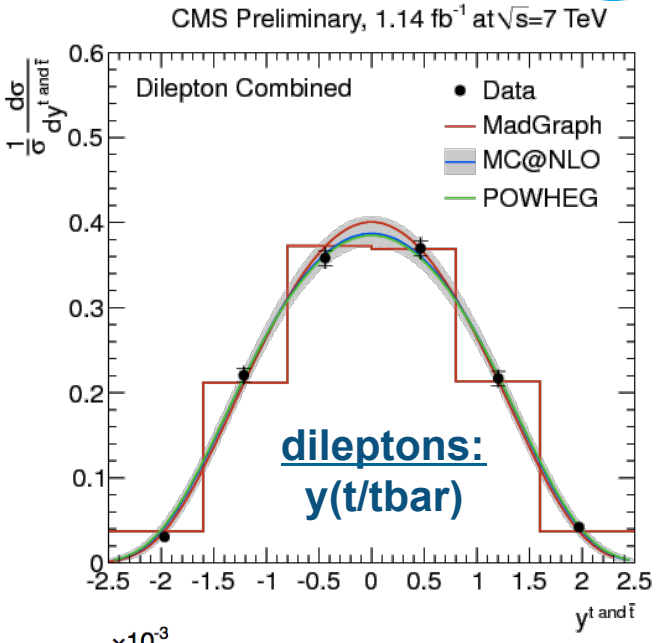
Results: top quarks

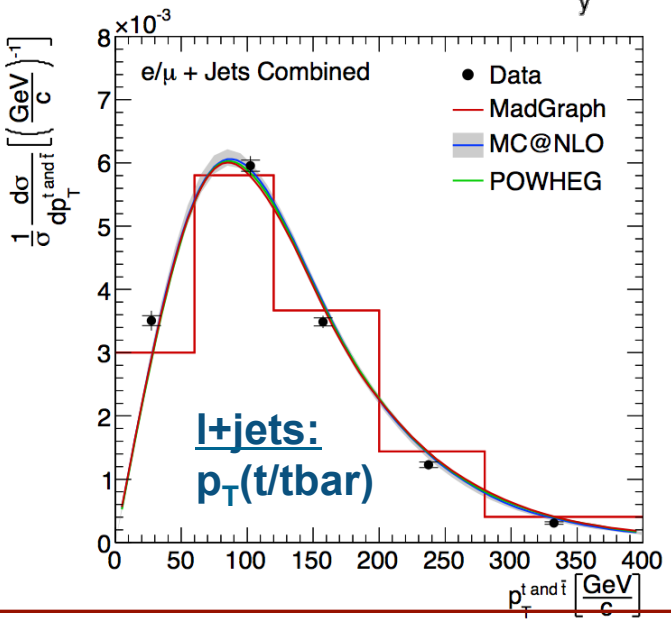
- Comparison to different theory predictions:
  - MadGraph
  - MC@NLO
  - POWHEG
- Horizontal bin center correction wrt MadGraph for showing the data

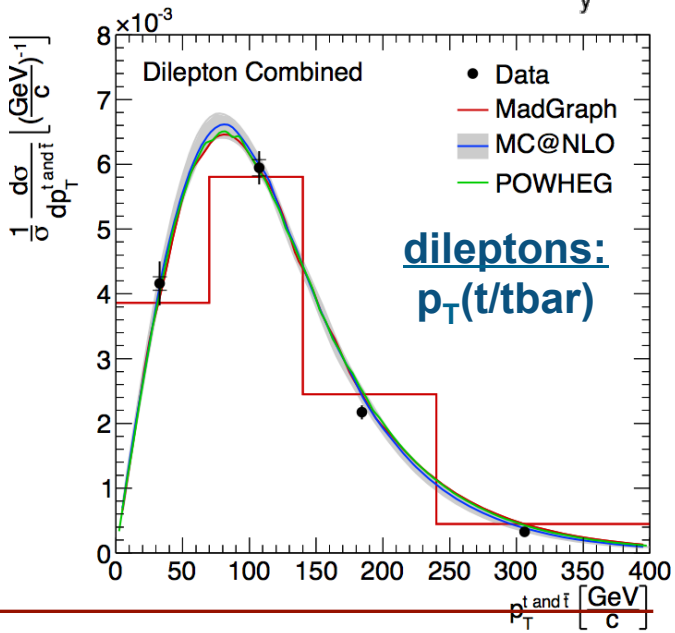
Lafferty, Wyatt, NIM A 355 541-547

Reasonable agreement between data and predictions for top p_T:
measured spectrum slightly softer than predicted









Results: top-quark pair (I)

- Comparison to different theory predictions:
  - MadGraph
  - MC@NLO
  - POWHEG
- Horizontal bin center correction wrt MadGraph for showing the data

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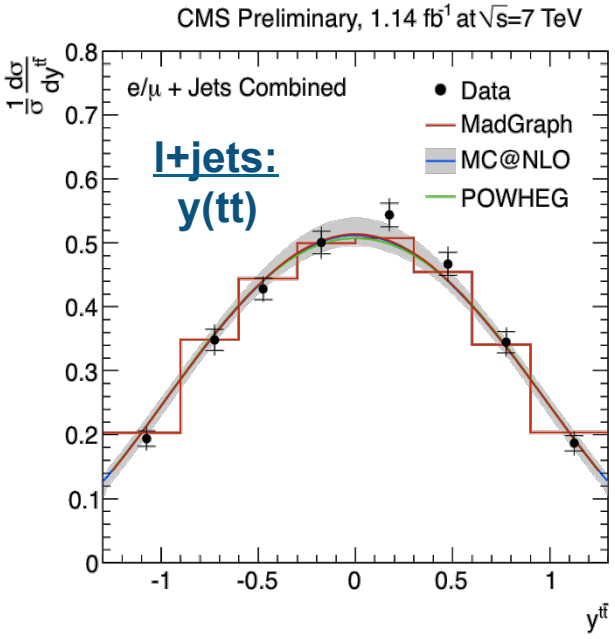
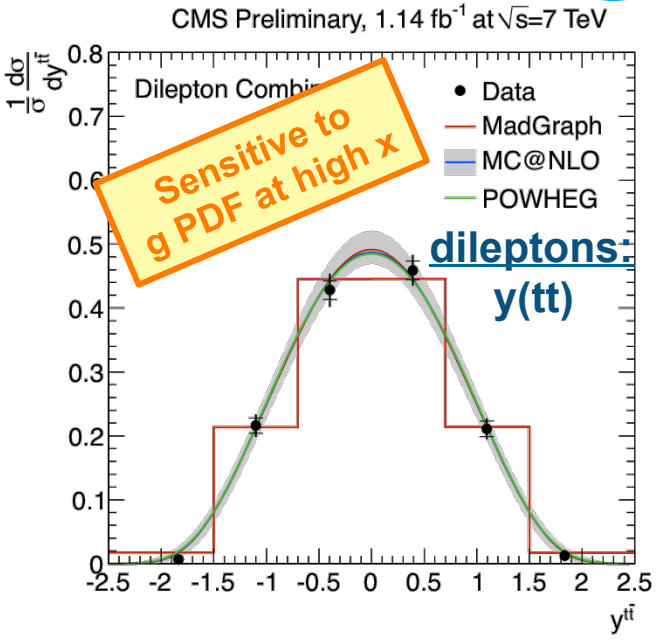
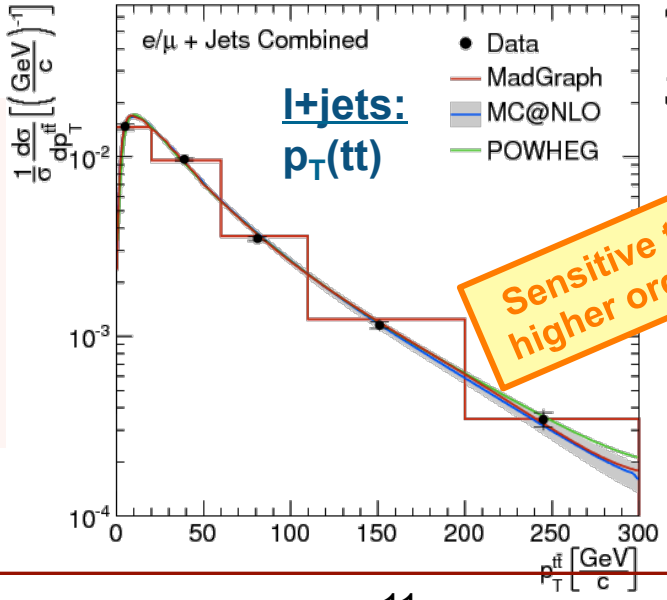
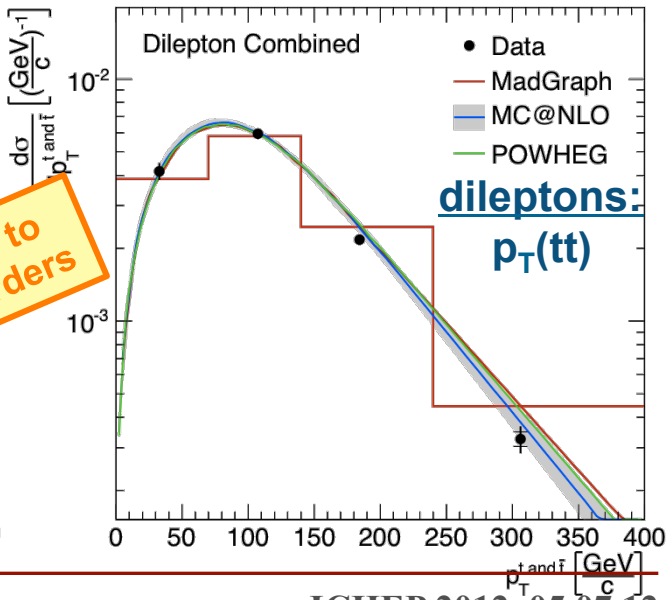
Good agreement between:
- data and predictions
- different predictions
- different channels









Results: top-quark pair (II)

- Comparison to different theory predictions:
  - MadGraph
  - MC@NLO
  - POWHEG
- Horizontal bin center correction wrt MadGraph for showing the data

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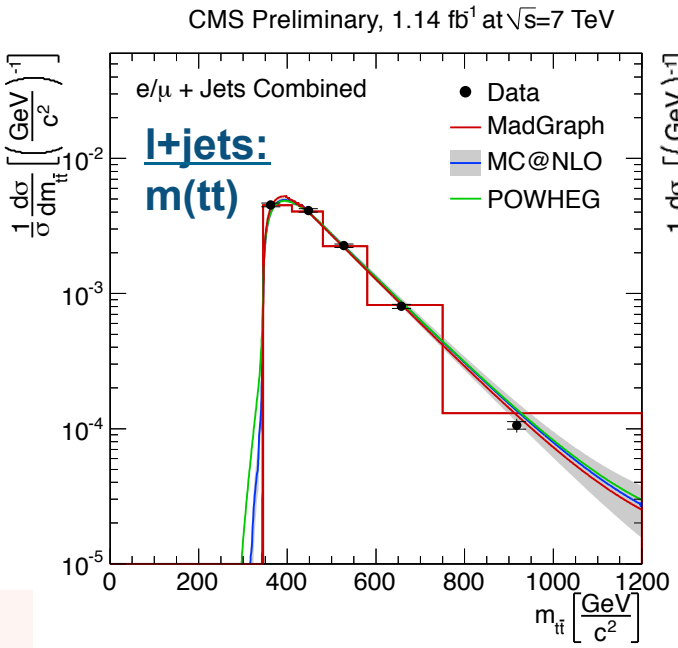
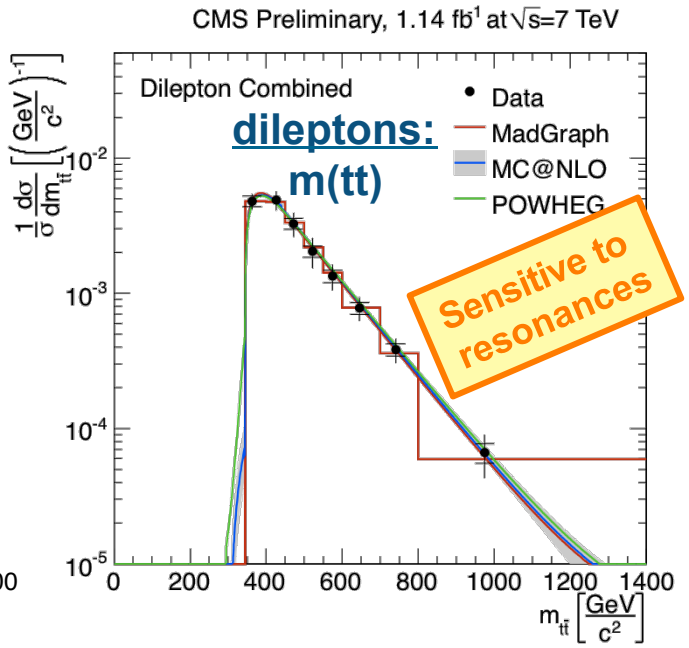




Good agreement between:

- data and predictions
- different predictions
- different channels

Summary & outlook

- First measurement of differential production cross sections at 7 TeV
  - Already possible with 1.1 fb^{-1} of collected data !
- Five different lepton+jets and dilepton channels
- Suite of kinematic variables for different observables
  - Top quarks, top-quark pairs, leptons, lepton pairs
- Normalized using the inclusive cross section
  - Many systematic uncertainties cancel
  - 5% – 10% precision

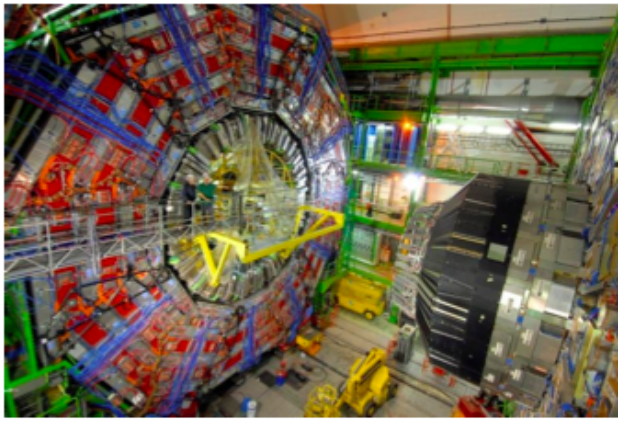
CMS-PAS TOP-11-013
http://cdsweb.cern.ch/record/1422425

- So far, good agreement with various QCD calculations at NLO
- Results based on 5 fb^{-1} of data (full dataset at 7 TeV) in the pipeline
  - More observables, comparison with more theory predictions

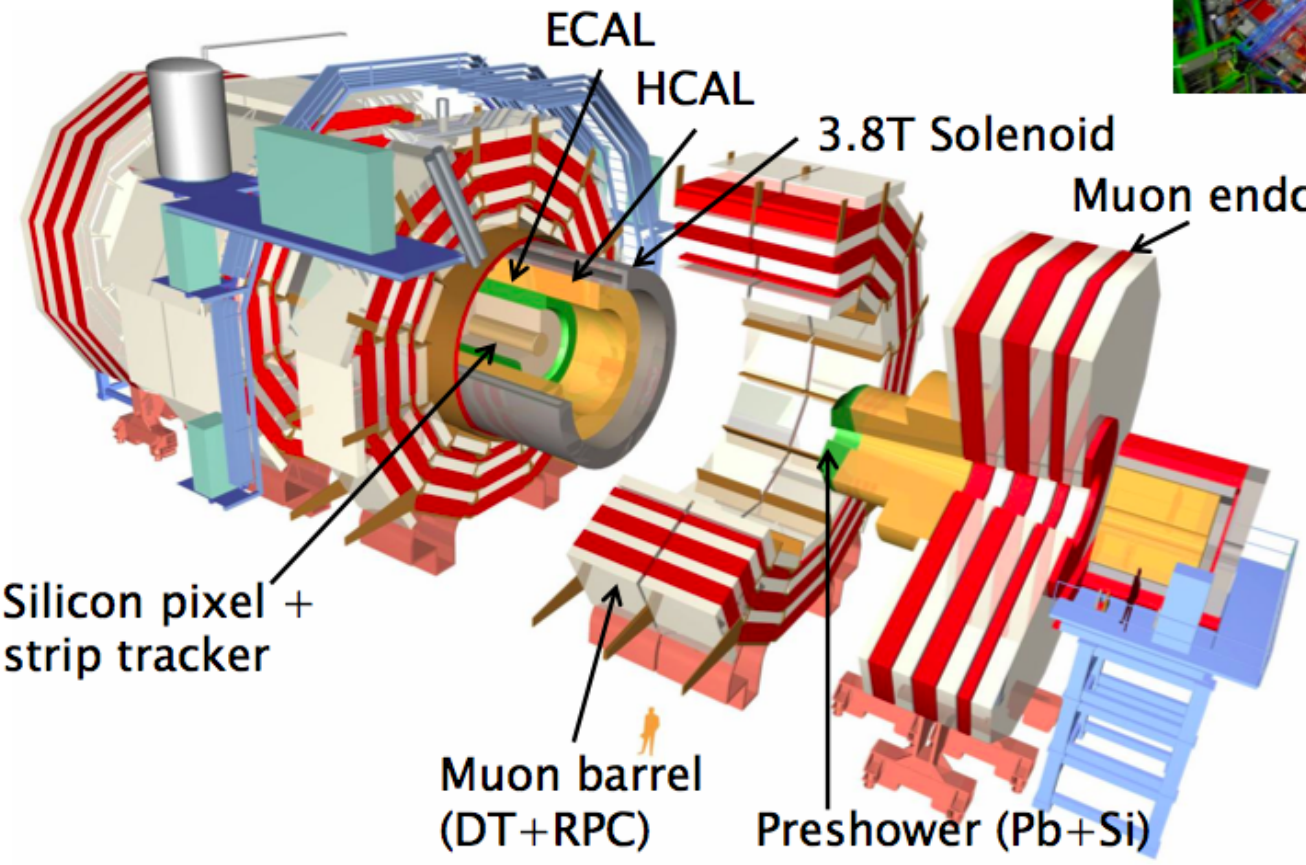
Thank you for your attention !

Additional information

The Compact Muon Solenoid detector

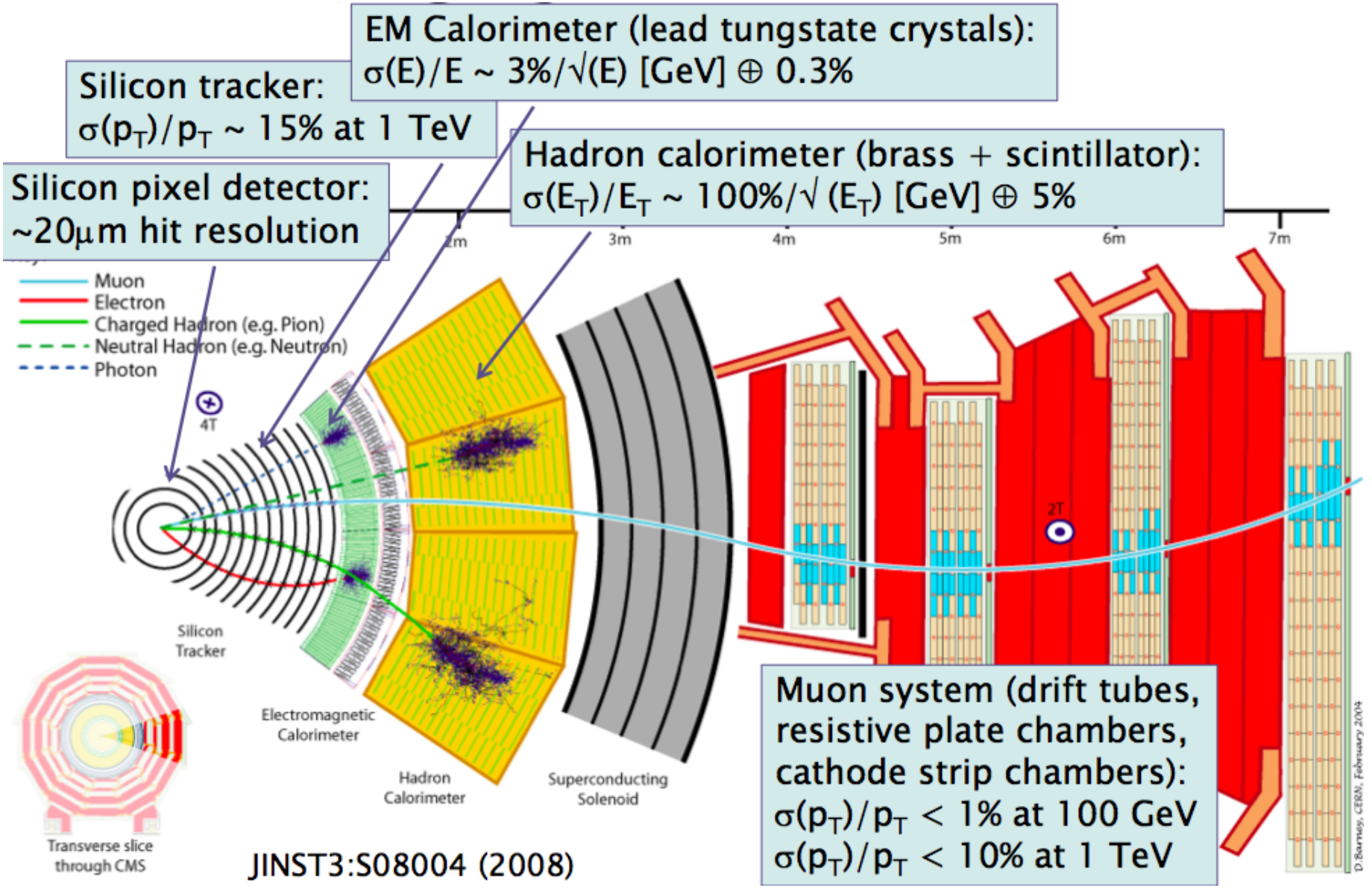


- 21m long, 15m in diameter
- 14000 tons



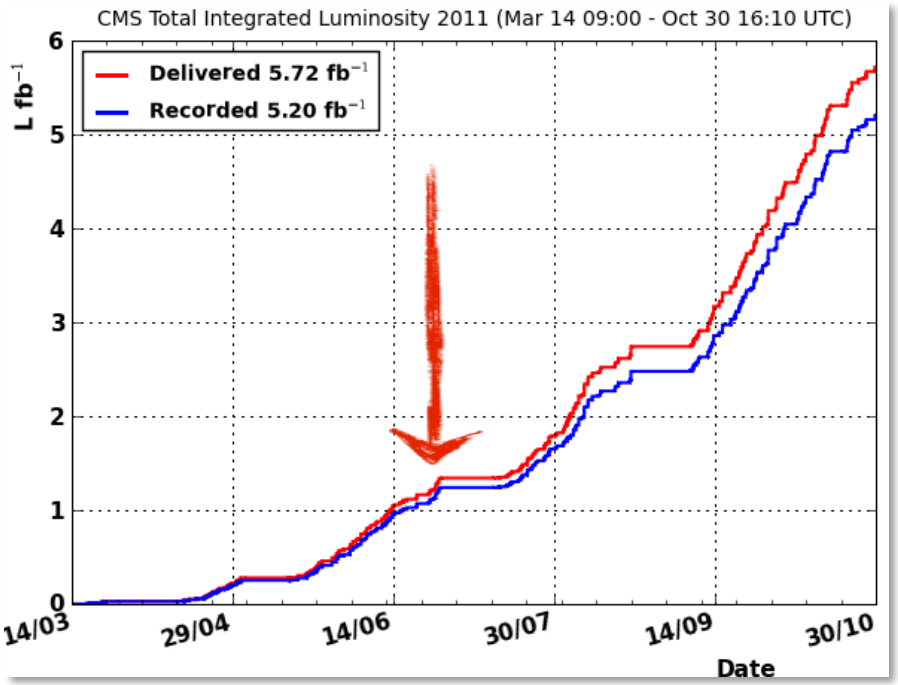
CMS Collaboration:
- *~2500 scientists + engineers*
- *~850 students*
- *173 institutes*
- *40 countries*

A slice of CMS



Dataset and simulation

- Using 1.14 fb^{-1} of collected data by CMS in 2011 in pp collisions at 7 TeV
- σ_{ttbar} ~ 164 pb → 187000 ttbar pairs !
- Around 5 interactions/bunch crossing
  → Offline algorithms subtract activity not coming from event primary vertex
- Channel-optimized triggers
- Simulation:
  - MadGraph (ttbar, W/Z+jets)
  - POWHEG (single top)
  - Pythia (QCD, dibosons)
- ttbar sample normalized to measured xsec:
  - l+jets: 164.4 ± 12.2 pb (TOP-11-003)
  - dileptons: 169.9 ± 16.8 pb (TOP-11-005)



Channel	Trigger
μ+jets	IsoMu17
e+jets	Ele25_TriJet30
$\mu^+\mu^-$	DoubleMu7, Mu13_Mu7
$e^{\pm}\mu^{\mp}$	Ele17_Ele8
e^+e^-	Ele17_Mu8, Mu17_Ele8

Background determination

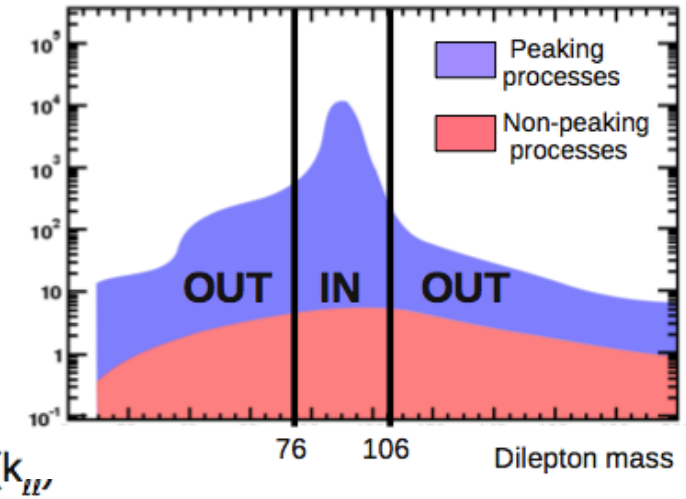
- L+jets: normalization from MC (expected composition: 93% ttbar + 4% single top)
- Dileptons:
  - Drell-Yan scaled to data using Z veto region:

Estimation of the contribution outside the Z-veto region using the number of events inside the Z-veto region

$$N_{\text{out}}^{e^+e^-,\text{exp}} = R_{\text{out/in}}^{e^+e^-}\left(N_{\text{in}}^{e^+e^-} - 0.5N_{\text{in}}^{e^\pm\mu^\mp}k_{ee}\right)$$

from simulation, $R_{out/in} = N_{out}$(DY MC)/ N_{in}(DY MC)

non-peaking processes from eμ channel data corrected for lepton eff (k_{ll})



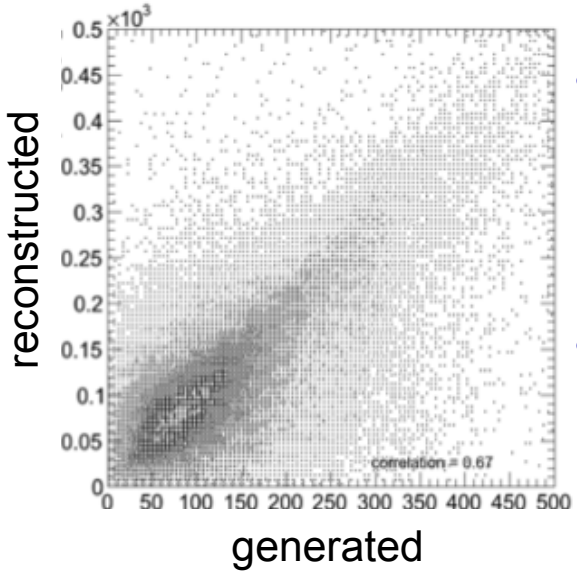
Similar for the μμ channel

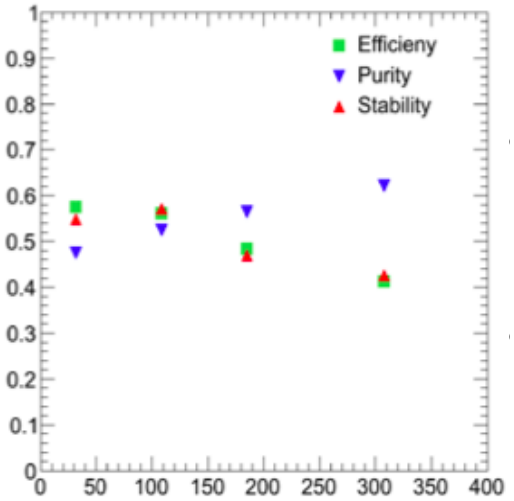
  - Contribution from fake or real leptons within jets determined using like-sign events in a non-isolated region:

$$N_{\text{QCD}}^{\pm\mp} = f_{\text{QCD}} \times N_{\text{data}}^{\text{non-iso},\pm\mp} \qquad f_{\text{QCD}} = \frac{N_{\text{data}}^{\pm\pm} - N_{\text{MC}}^{\pm\pm}}{N_{\text{data}}^{\text{non-iso},\pm\pm}} = \frac{N_{\text{QCD}}^{\pm\pm}}{N_{\text{data}}^{\text{non-iso},\pm\pm}}$$

N_{QCD} < 1%, consistent with MC

Bin-by-bin correction





Bin migration correction factor included in the definition of efficiency:

$$\epsilon^i = \frac{N^i_{rec}}{N^i_{gen,tot}}$$

Bins optimised according to purity p, stability s >≈ 50%

- p: migration in bin; s: out of bin
- limit bin migration
- limits the number of bins

$$p^i = \frac{N^i_{rec\&gen}}{N^i_{rec}}$$

$$s^i = \frac{N^i_{rec\&gen}}{N^i_{gen}}$$

Statistical error is clearly defined ($\sqrt{Nreco}$), no correlation matrix

Potential biases from model assumptions accounted for in systematic uncertainties

- variation of the assumed model (Madgraph / Powheg)