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Top Physics with CMS

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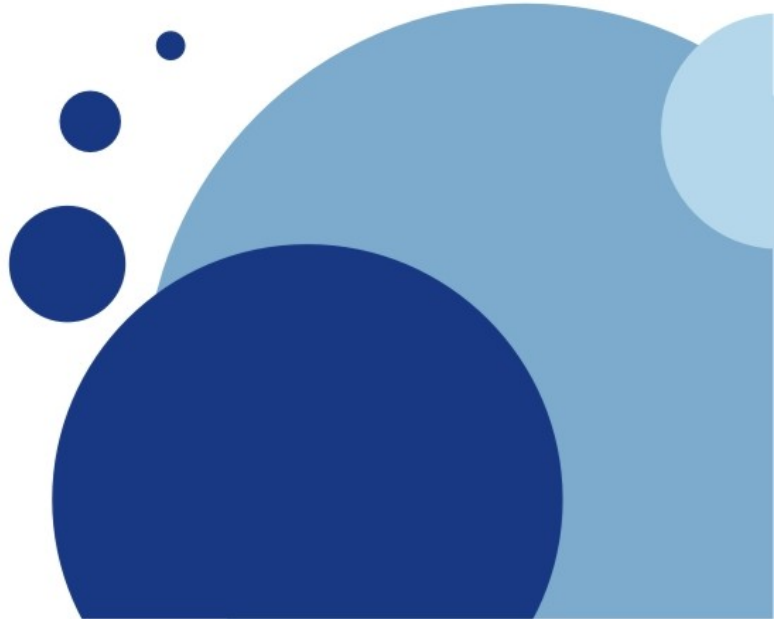
II CPAN DAYS

Nov. 29th – Dec. 1th

Outline

- **Introduction to the top quark physics:**
  - Motivation for the top quark physics
  - Top quark production
  - Top quark decays
- **First measurements of the top quark pair cross section production at $\sqrt{s}$ = 7 TeV in the dileptonic channel**
  - first hint of the top mass as a proof of the top-like signal
- **First results in the semileptonic channel at $\sqrt{s}$ = 7 TeV**
- **Prospects in top quark studies**
  - Single top production
  - Search for resonances decaying into top pair
- **Conclusion**

Introduction to the top quark physics



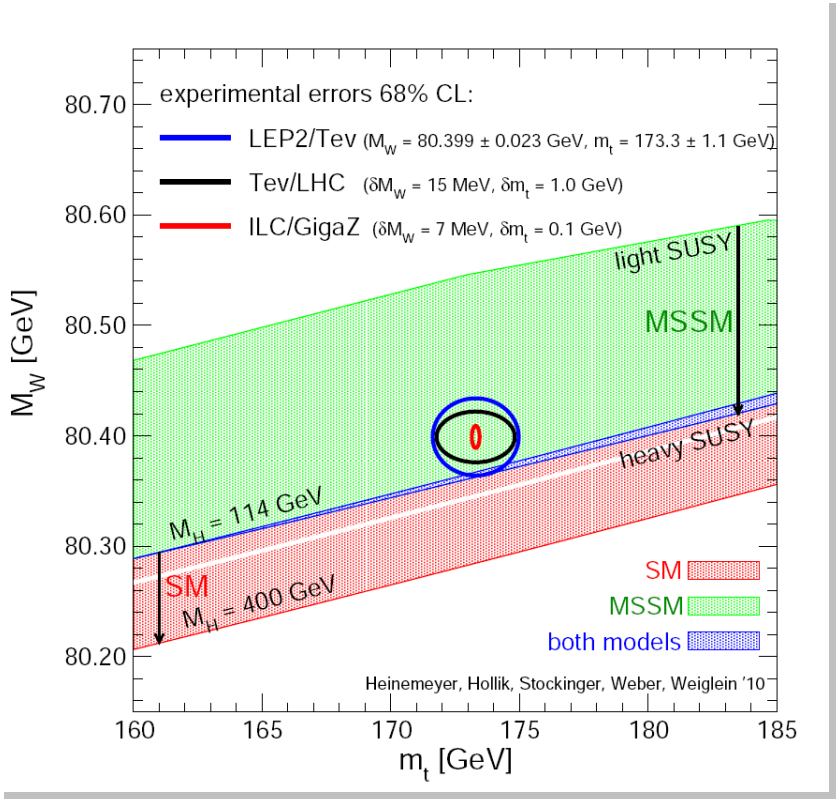
Top physics: Which measurements @ LHC ?

Top quark is unique and powerful instrument to study SM physics and search for manifestation of New Physics beyond SM

➔ **Precision measurements:**
- **precise mass determination**
  - together with the W mass, probes SM consistency
  - provides Higgs mass constraint
- **Production cross section**
  - ratio between single top production mechanisms probes SM

➔ **Top properties**
spin polarization
electric charge
top couplings

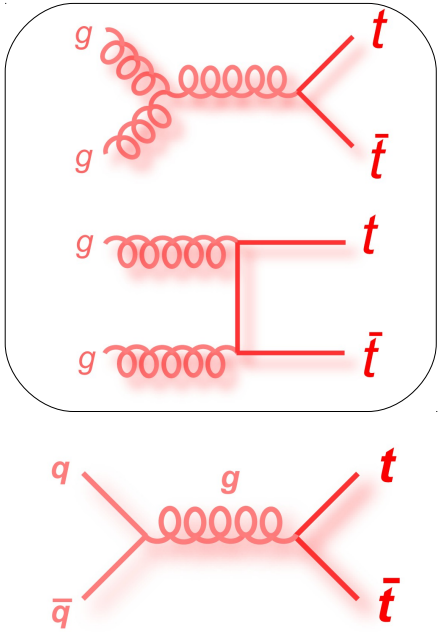
➔ **Important background to many physics signals: susy,exotic processes**
a good understanding is essential !!!



➔ **Detector commissioning:** contains all relevant signatures (leptons, MET, jets...) top as calibration point for jet energy scale, MET, b-tagging

Top quark production

- **Top quark pairs produced in strong interaction via**
  - gluon-gluon fusion: dominant mode at LHC (~90% at 14 TeV)
  - quark- antiquark annihilation

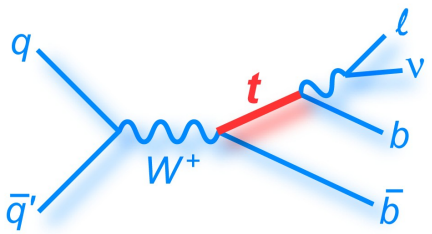


Cross section (NNLO) at mt = 172.5 GeV

Tevatron (1.96TeV) ~ 7.46 pb
LHC (7 TeV) ~ 160.8 pb → 20 times higher than at Tevatron
LHC(14 TeV) ~ 886.3 pb

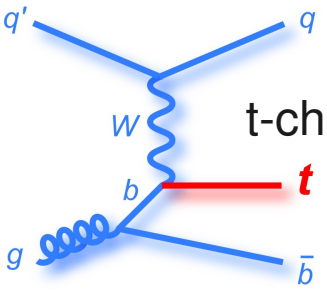
~10 top pairs/sec at high luminosity

- **Single top quarks produced via EW interaction:**
  t-channel, s-channel, tW-channel



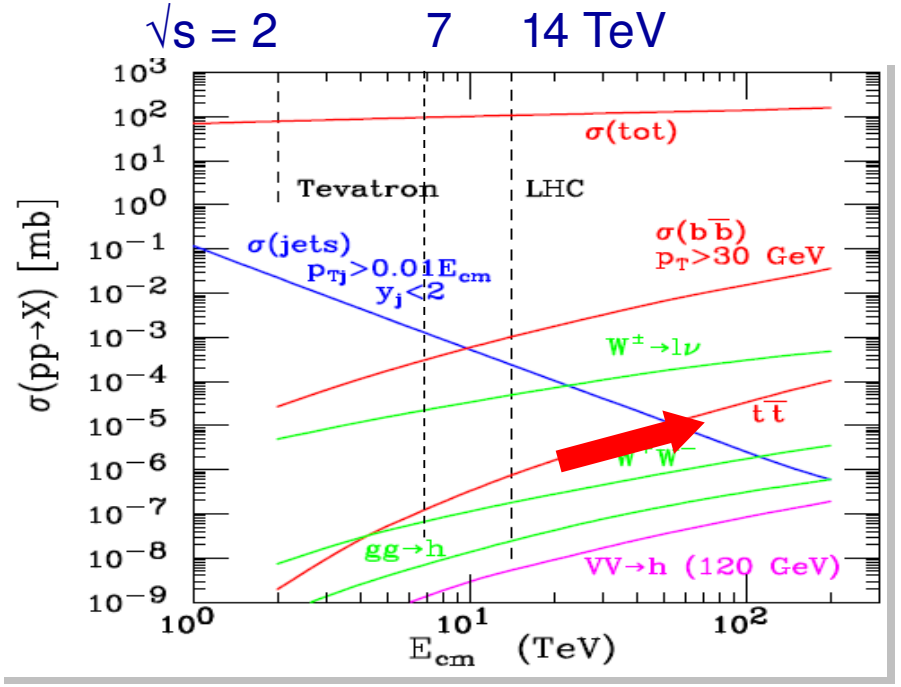
s-channel

σ=5 pb @ 10TeV
σ=4 pb @ 7TeV



t-channel

σ=134 pb @ 10TeV
σ=65 pb @ 7TeV

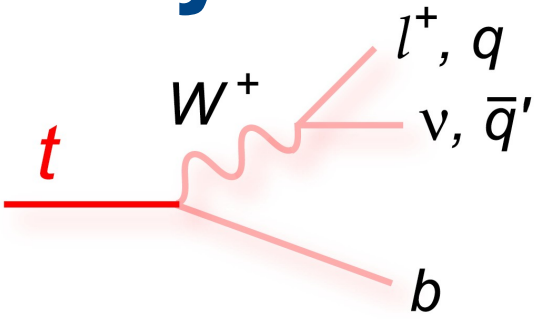


Top-pair Quark Decay

➔ **Top decays before it can hadronize**

Lifetime 10^{-25} << scale QCD = 10^{-24}

➔ **In SM top decays to W+b 99.9% of the time**



Different signatures according to the W decay:

Dileptonic channel (BR ~ 10%):

both Ws decaying leptonically

- 2 isolated leptons
- high MET from 2 neutrinos
- 2 b-jets

Semileptonic channel (BR ~ 45%) :

1 W decaying leptonically

- 1 isolated lepton
- MET from 1 neutrino
- 4 jets (2bjets + 2 light quark jets)

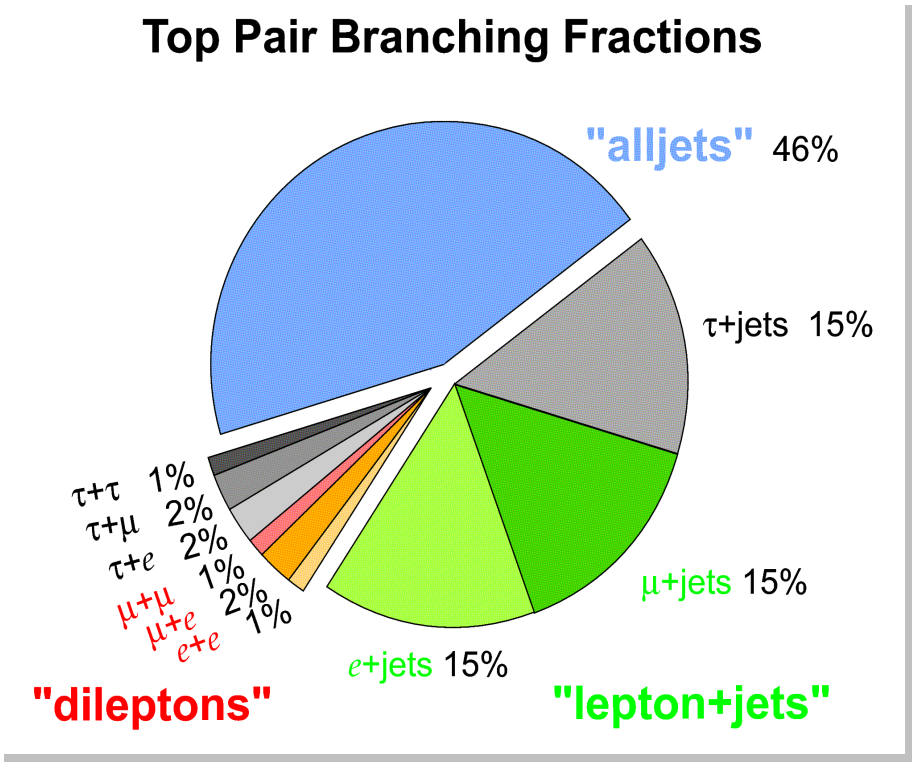
Fully hadronic channel (BR ~ 45%) :

both Ws decaying hadronically

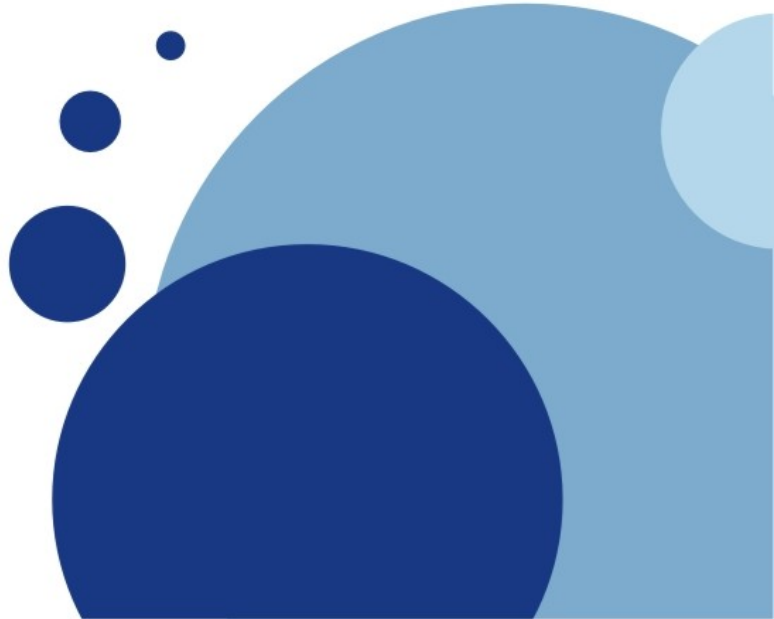
No high pt leptons so hardest to

At least 6 jets (4 light jets + 2 b-jets)

study (large QCD bkgs)

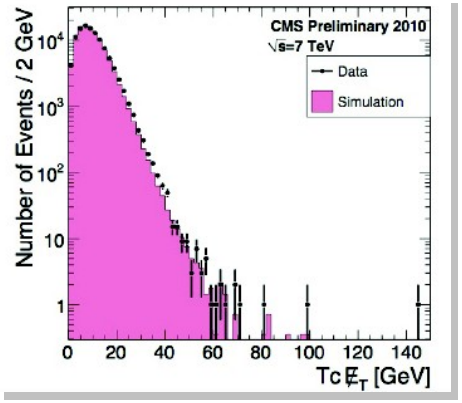


First results of the top quark physics in CMS

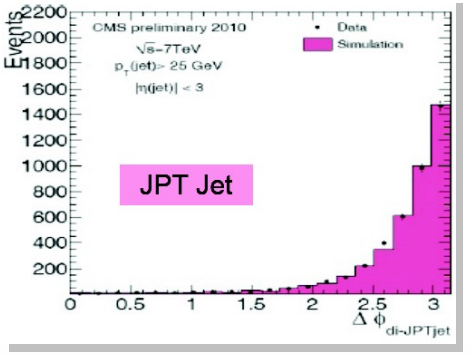


The CMS detector

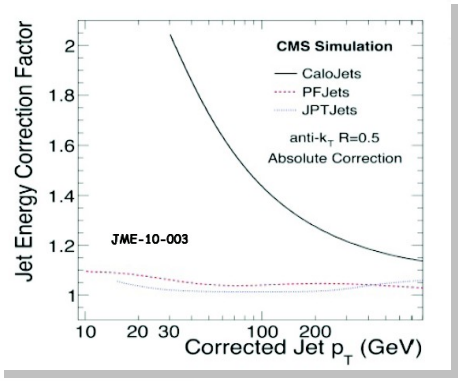
Missing transverse energy



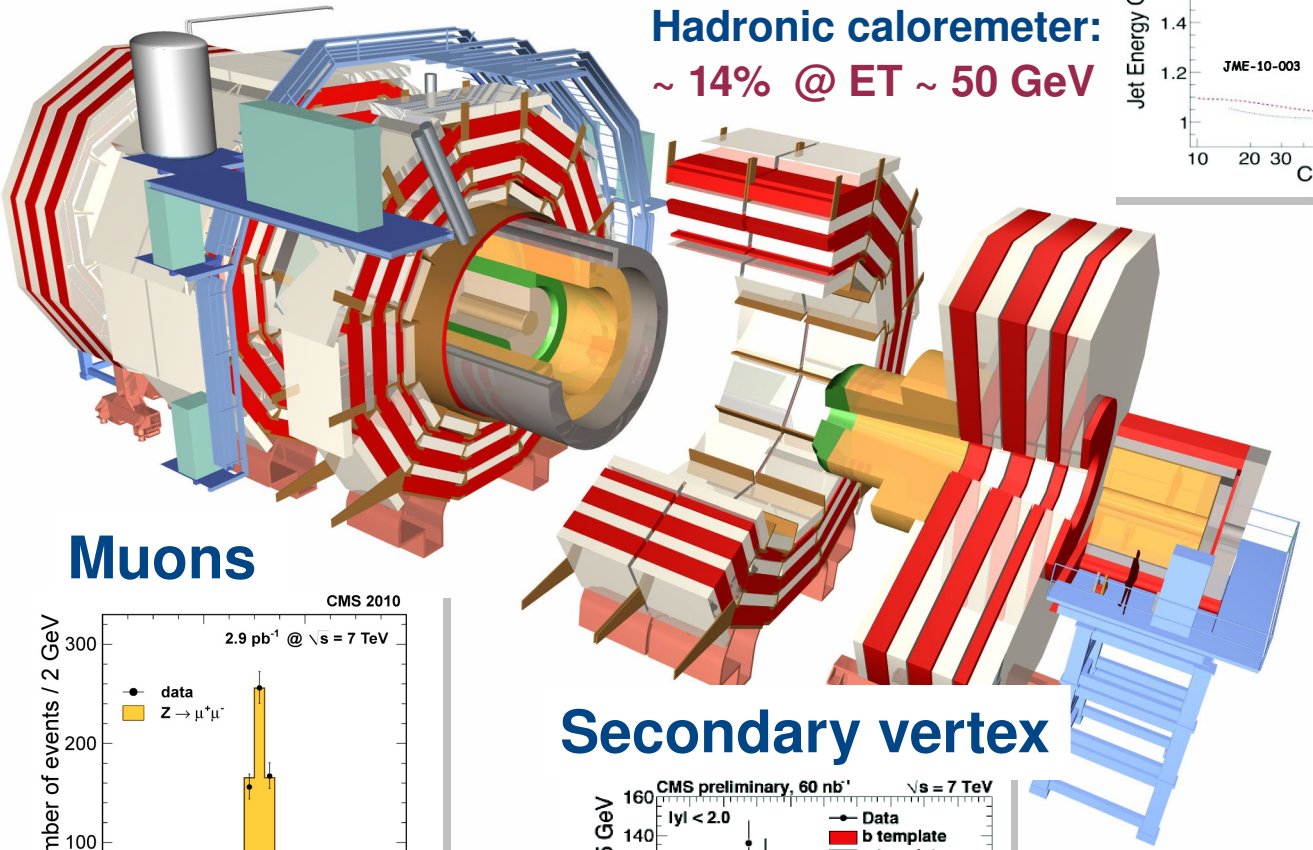
EM caloremeter:
~ 0.5% @ ET ~ 50 GeV



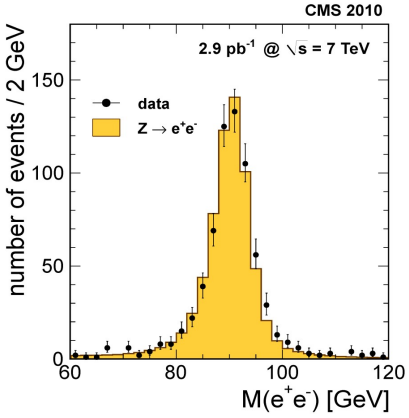
JETS



Hadronic caloremeter:
~ 14% @ ET ~ 50 GeV



Electrons

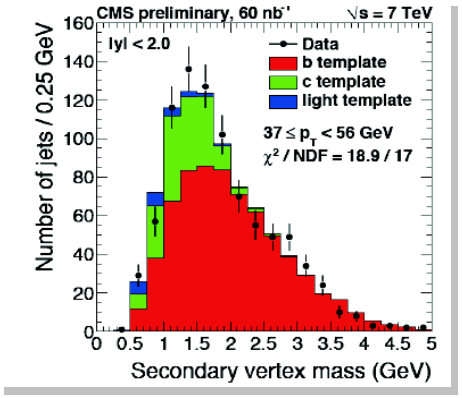


ΔMee / Mee, Δ Mγγ / Mγγ ≈ 1% at 100 GeV

Muons

ΔMμμ / Mμμ ≈ 1% at 100 GeV

Secondary vertex



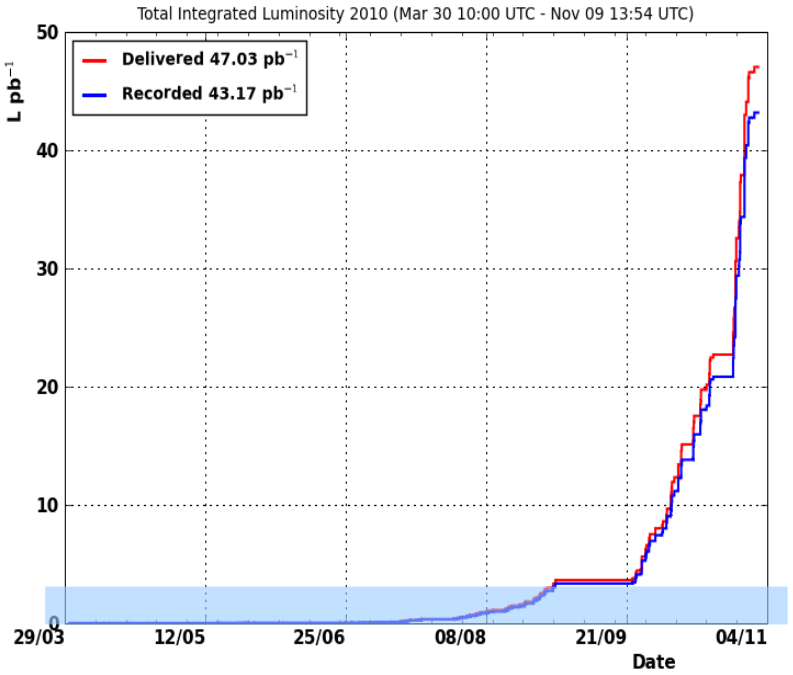
Tracking system:
pT ≤ 100 GeV, ΔpT / pT ≈ 0.5-2%
Δdxy≈10 μm
Δz≈20-40 μm

First top quark physics with the CMS detector

In this talk …

- Dilepton channel: first measurement of top pair production cross section
  Used only the first 3.1 pb-1 of data !!
- Lepton+jets channel: established signal for top quark production
  Updated results since ICHEP with 0.84 pb-1

LHC is a top factory!



But … much larger sample in hand

> 35 pb-1 of integrated luminosity recorded

Working hard for updated results with the full 2010 luminosity!

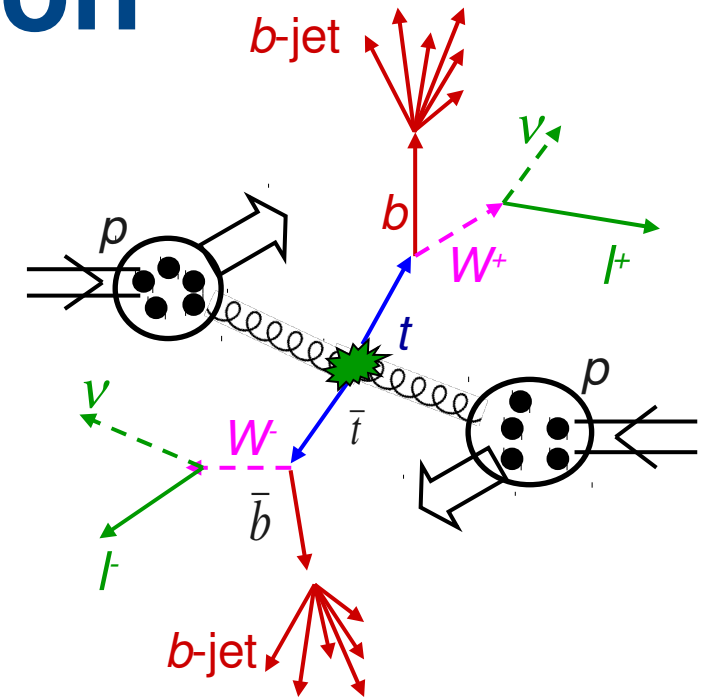
Dilepton Selection

- **Dilepton channels: *ee, μμ, eμ***

  - One or more single lepton triggers and event cleaning.
  - 2 isolated, prompt, oppositely charged leptons (l = e,μ) of good quality
    - $p_T(l) > 20$ GeV/c
    - $|\eta_\mu| < 2.4$, $|\eta_e| < 2.4$
    - Relative isolation:

$$\text{Rel.isol.} = \frac{\overbrace{\sum_{R<0.3} p_T^{\text{track}} + \sum_{R<0.3} p_T^{\text{ECAL}} + \sum_{R<0.3} p_T^{\text{HCAL}}}^{\text{Detected energy around lepton}}}{p_T(\text{lepton})} < 15\ \%$$

  - Missing transverse energy (MET)
    - using calorimeter⊕tracking
    - MET > 30 (20) GeV (in *eμ+X*)



- *Z*-boson veto:
  - $76 < M_{ee,\mu\mu} < 106$ GeV/c²
- Count additional jets:
  - anti-k_T jets, $R = 0.5$
  - using calorimeter⊕tracking info
  - $|\eta| < 2.4$, $p_T > 30$ GeV/c

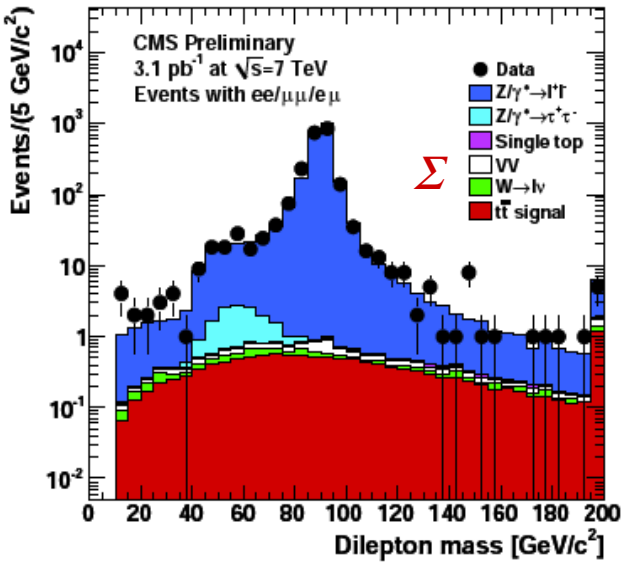
≥ 2 jets typical for ttbar

➔ **Apply b-tag to the jets**

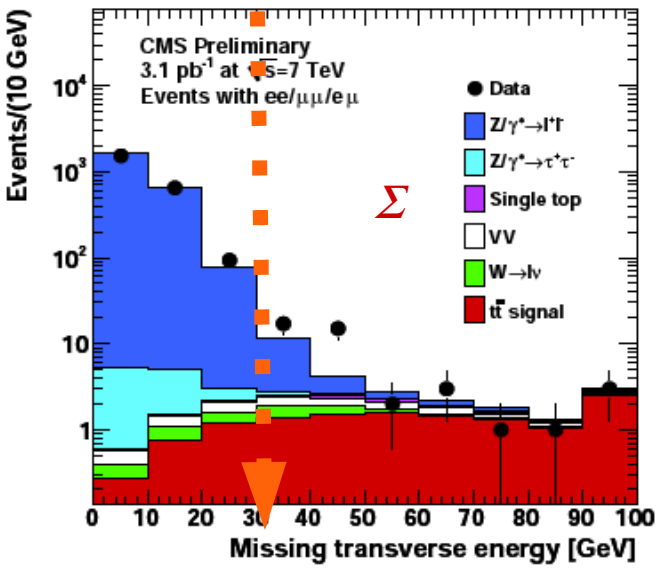
3.1 pb^{-1}

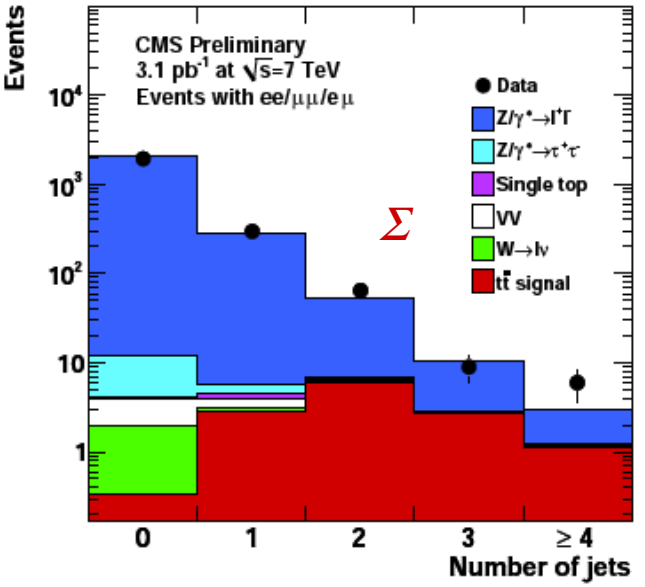
Dilepton Channel

- **Before apply the full selection: no Z veto, MET or jets requirements.**



ttbar dilepton dominant at high MET values





- **Event yields after full selection**

Source	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$	All
Dilepton $t\bar{t}$	1.5 ± 0.1	1.7 ± 0.1	4.5 ± 0.2	7.7 ± 0.5
VV	0.03 ± 0.02	0.03 ± 0.01	0.08 ± 0.04	0.13 ± 0.07
Single top - tW	0.05 ± 0.03	0.05 ± 0.25	0.15 ± 0.08	0.25 ± 0.13
Drell-Yan $\tau\tau$	0.04 ± 0.02	0.07 ± 0.03	0.07 ± 0.04	0.16 ± 0.09
Drell-Yan $ee, \mu\mu$	$0.8 \pm 0.4 \pm 0.4$	$0.6 \pm 0.4 \pm 0.3$	N/A	$1.4 \pm 0.5 \pm 0.5$
Events with fake leptons	$0.3 \pm 0.4 \pm 0.2$	$0.1 \pm 0.2 \pm 0.2$	$-0.3^{+0.4\ +0.2}_{-0.1\ -0.1}$	$0.1 \pm 0.5 \pm 0.3$
Total backgrounds	1.2 ± 0.7	0.8 ± 0.6	$0.3^{+0.4}_{-0.1}$	2.1 ± 1.0
Data	3	3	5	11

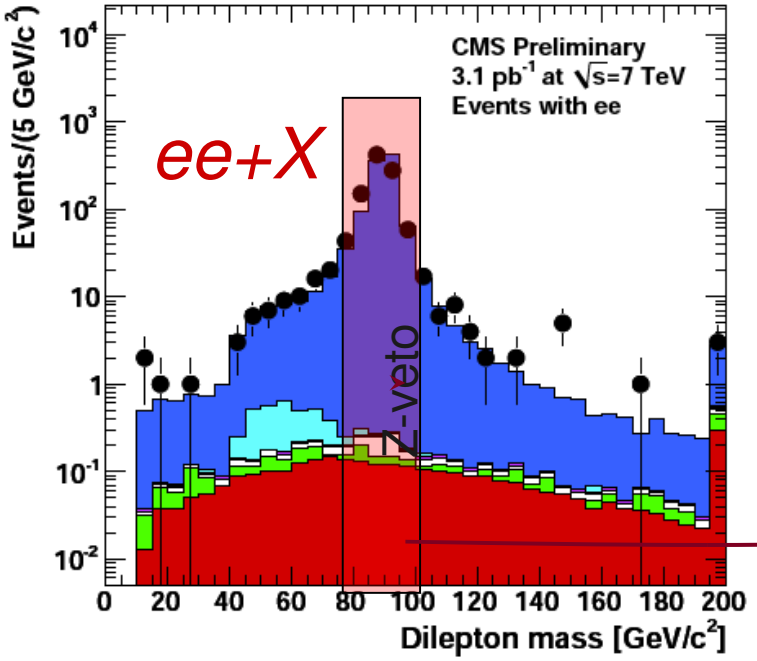
Single top, Drell-Yan ($\tau\tau$ channel) and double boson from simulations

Drell-Yan (ee, μμ) and fake leptons from data-driven techniques

Top events constitute about the 70% of the sample

Data-Driven Drell-Yan Estimate

✔ **Estimate Drell-Yan background outside Z-veto region from events inside**



ratio outside/inside from *DY* simulation

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

correction for non-DY contribution in *Z*-veto region from $e\mu$ sample

Dependence of R_{out} on selection:

- Set 50% uncertainty on Drell-Yan estimate

Sample	$N_{\text{jet}} = 0$	$N_{\text{jet}} = 1$	$N_{\text{jet}} \geq 2$
e^+e^-			
$Z/\gamma^\star$ simulation	0.20 ± 0.04	0.27 ± 0.05	0.14 ± 0.03
Estimate from data	$0.01\ ^{+0.3}_{-0.01}\ ^{+0.2}_{-0.01}$	$0.3 \pm 0.2 \pm 0.2$	$0.8 \pm 0.4 \pm 0.4$
$R_{\text{out/in}}$	0.26 ± 0.05	0.17 ± 0.03	0.10 ± 0.02
$\mu^+\mu^-$			
$Z/\gamma^\star$ simulation	0.54 ± 0.07	0.68 ± 0.07	0.28 ± 0.05
Estimate from data	$0.0\ ^{+0.3}_{-0.0}\ ^{+0.2}_{-0.0}$	$1.7 \pm 0.7 \pm 0.8$	$0.6 \pm 0.4 \pm 0.3$
$R_{\text{out/in}}$	0.44 ± 0.06	0.28 ± 0.03	0.15 ± 0.03

Data-Driven Estimate of Fake Leptons

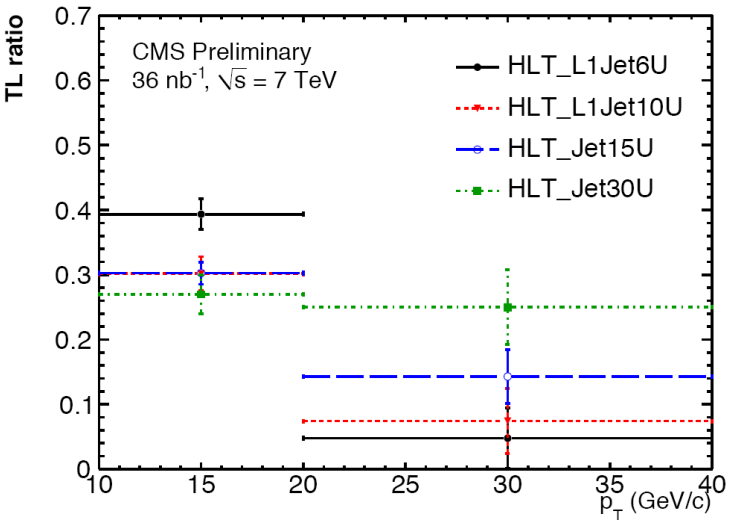
Background from events with fake leptons:

- W+jets events with one fake lepton
- QCD processes with two fake leptons

Computing tight-to-loose ratio (TL) in lepton depleted data

- Inclusive jet sample used

$$F(p_T,\eta,\ldots)=\frac{\text{analysis object }(p_T,\eta,\ldots)}{\text{denominator object }(p_T,\eta,\ldots)}$$



Electron fake rate from a multijet sample

Applying to events with one (two) loose leptons failing tight selection to predict fakes from W+jets (QCD) events:

$$N_{nn}^{QCD}=\sum_{i,j}\frac{TL_iTL_j}{(1-TL_i)(1-TL_j)}N_{\overline{nn}}^{ij}$$

$$N_{nn}^{WJets}=\sum_{i,j}\frac{TL_i}{(1-TL_i)}N_{\overline{nn}}^{ij}$$

(with corrections for top and QCD contamination)

Systematic uncertainties from TL dependence on data sample:

- 50% for W+jets, 100% for QCD estimate

3.1 pb^{-1}

Bottom-Jet Identification

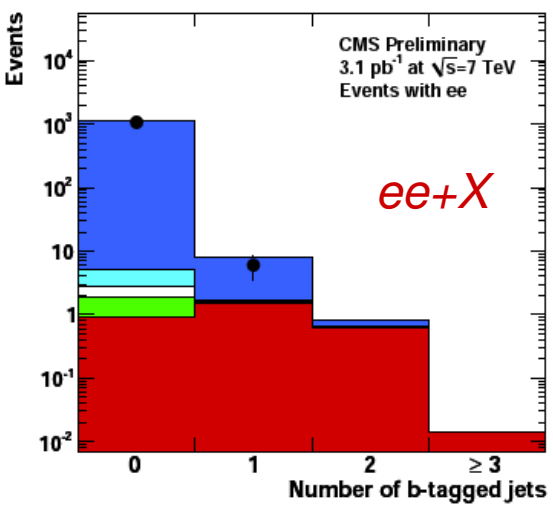
- Require b-tagging jets: pure selection, almost background free
- Jets from *b*-quarks are a telling feature of top-quark decays

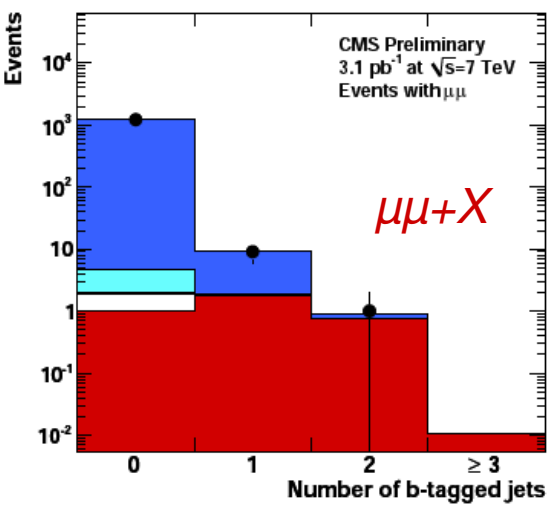
b-tagging techniques rely on:

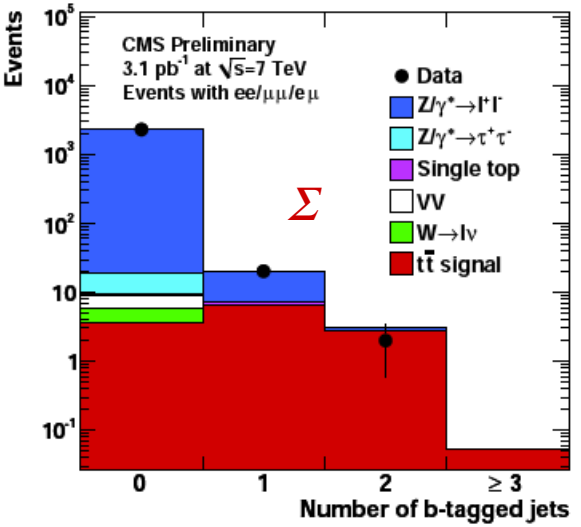
- impact parameter significance of decay tracks associated with the jets
- primary/secondary vertex separation
- Jet probability
- targeting b and c semileptonic decays (pT lepton or IP)

Tagging efficiencies for b jets of the order 88% - 100% with ~10% systematic error

Wo MET and Z veto







Using a b tagger based on the IP significance and a loose working point

To be tightened as luminosity increases to improve purity of b-tagged jets

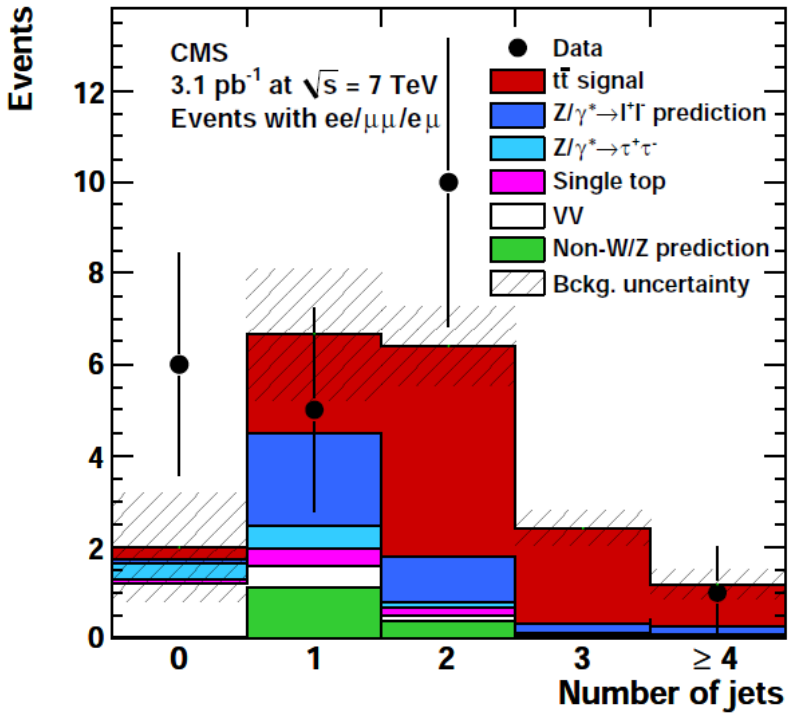
Xsec in dilepton channel

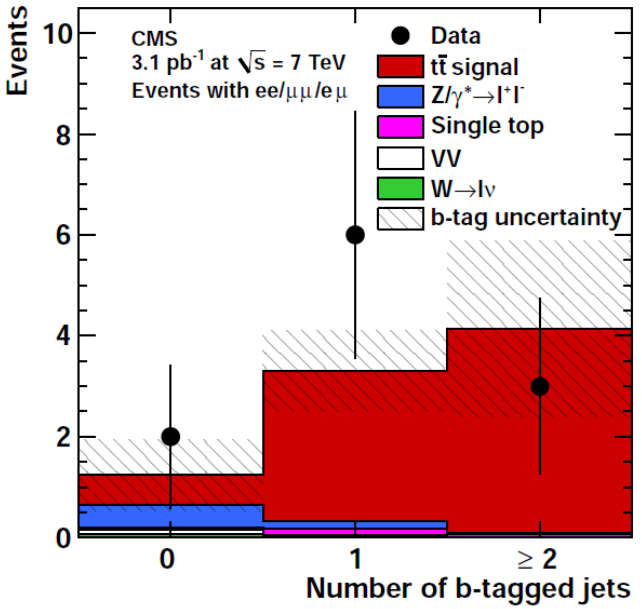
CMS has perform the first measurement of the cross section for Top-Quark pair production in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with only 3.1 pb-1 !!!!!

$$\sigma^{t\bar{t}}_{\text{data}} = \sigma^{t\bar{t}}_{\text{theory}} \frac{S_{\text{obs}}}{SF \cdot S_{\text{exp}}} = \frac{S_{\text{obs}}}{SF \cdot \mathcal{L} \cdot A}$$

- Simple counting experiment
- Signal includes t→W→lν where l = e, μ, τ→e, μ

➢ **After full selection**





Jet b-tagging not used in this measurement but already apply: great background reduction

Will be apply in the cross section measurement With the full 2010 statistics.

3.1 pb^{-1} Xsec in dilepton channel

Uncertainties

- ✔ Dilepton efficiency: ~ 4.4% (all channels)
- ✔ Energy scale systematic is derived by scaling jets and hadronic component of MET up and down by 5% ~ 3.7%
- ✔ From theory (ISR/FSR and decay models) are derived by running on various monte carlo samples ~ 1%/2% (from PDF < 0.1%)
- ✔ Backgroudn stimations: ~ 15 %
- ✔ Branching ratio ~ 1.7%
- ✔ Luminosity: ~ 11%

Final result

$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}}) = 194 \pm 72(\mathrm{stat.}) \pm 24(\mathrm{syst.}) \pm 21(\mathrm{lumi.})\ \mathrm{pb}.$$

Expected cross-section from NLO theoretical calculation for a top mass of mt = 172.5 GeVv

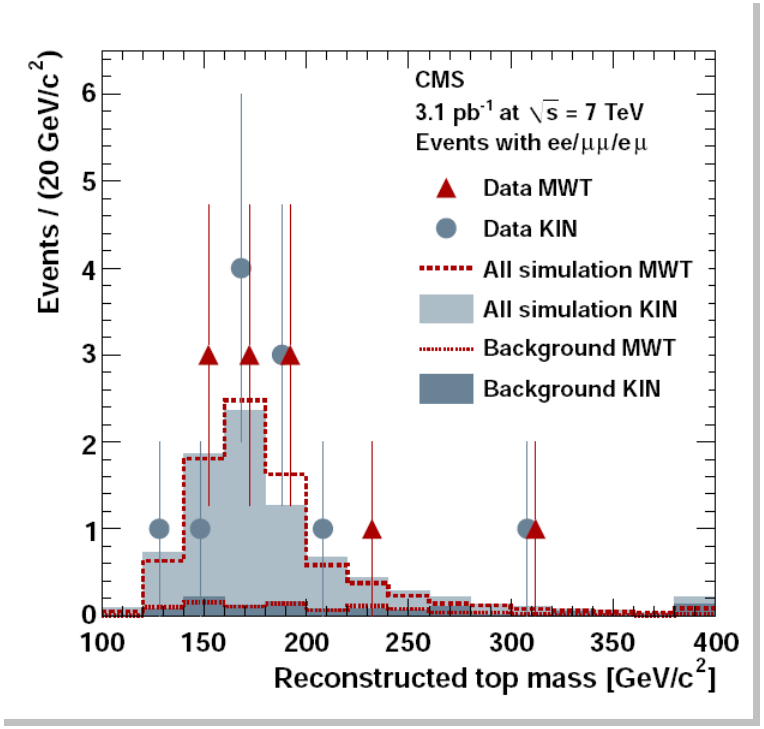
$$157.5^{+23.2}_{-24.4}\ \mathrm{pb}$$

arXiv:1010.5994v1 [hep-ex] 28 Oct 2010
Alredy accepted in Physics Letters B

3.1 pb^{-1} Sensitivity to the Top Mass

Use two independent methods to calculate the top mass for events passing our selections

→ Both methods used at CMS: numerical solutions to the kinematic equations of the ttbar decay: 2 b-jets, 2 charged leptons, 2 neutrinos



Matrix Weighting Algorithm

System solve for a range of top quark mass values
Assign weights based on the likelihood of each solution.
Mass with the largest weight is the mass estimator.

Full Kinematics Analysis (KIN analysis)

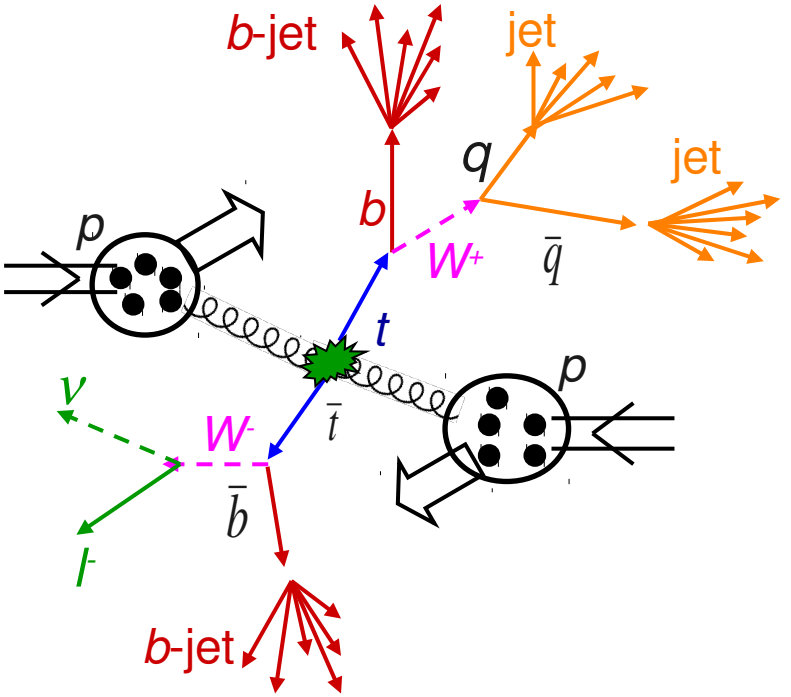
Additional equation for the longitudinal imbalance of the ttbar system.
Assumed is not top mass dependent → take it from simulation
Top mass → the mass value with the largest number of solutions

Compatible with top mass:
CDF+D0 combination : Mtop =173.1 ± 1.3 GeV/c2

Lepton+Jets Selection

- **Channels: *e*+jets, *μ*+jets**
  - Ask for exactly 1 prompt, isolated electron (muon) of good quality
  - Very similar selection of *e,μ* as before, but
    - ✗ tightened ID requirements and isolation:
      - Rel.isol. < 10%(*e*), 5%(*μ*)

      due to larger backgrounds
    - ✗ p_T(e) > 30 GeV/c
    - ✗ $p_T(\mu)$ > 20 GeV/c, $|\eta_\mu| < 2.1$
  - Do not apply (yet) any requirement of significant missing transverse energy (MET)



- Count additional jets
  - ✗ anti-k_T jets, $R = 0.5$
  - ✗ using calorimeter info
  - ✗ $|\eta| < 2.4$, $p_T > 30$ GeV/c

  ≥ 4 jets is typical for ttbar

0.84 pb^{-1}

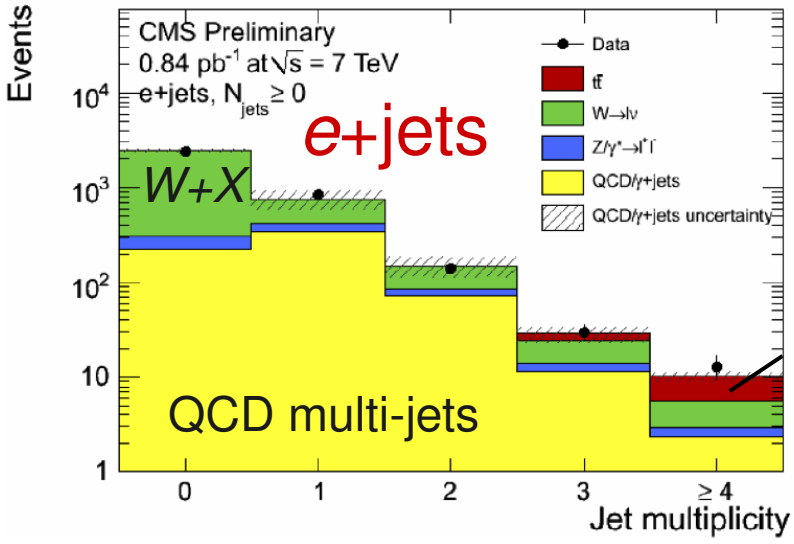
L+Jets Channel

e + jets channel

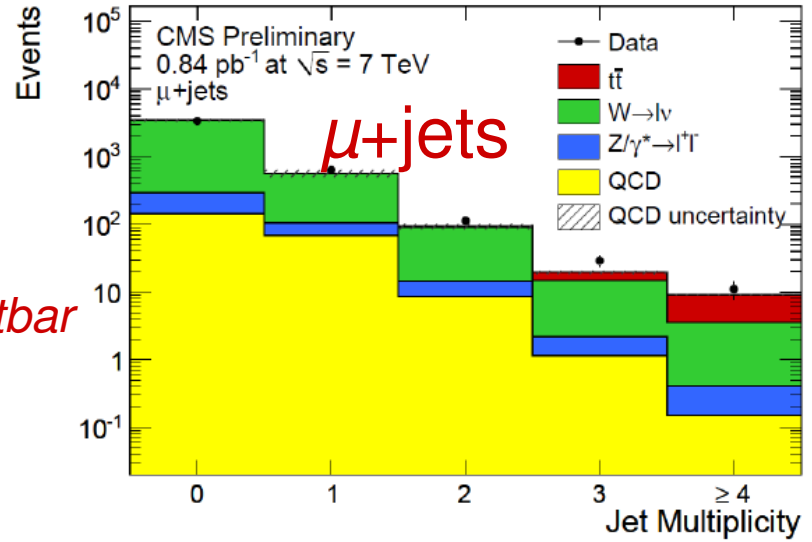
Jet multiplicity	ttbar	single top	W+jets	Z+jets	QCD	Sum MC	Data
$N_{jets} \geq 0$	12 ± 2	3.4 ± 0.4	2619 ± 317	180 ± 21	658 ± 73	3472 ± 326	3434
$N_{jets} \geq 1$	12 ± 2	3.1 ± 0.4	419 ± 77	92 ± 11	436 ± 62	962 ± 99	1022
$N_{jets} \geq 2$	11 ± 2	1.9 ± 0.3	74 ± 18	19 ± 5	85 ± 22	191 ± 29	183
$N_{jets} \geq 3$	8.9 ± 1.8	0.70 ± 0.14	13 ± 4	3.3 ± 1.0	14 ± 5	40 ± 7	43
$N_{jets} \geq 4$	4.8 ± 1.2	0.21 ± 0.06	2.6 ± 1.1	0.60 ± 0.23	2.3 ± 1.1	11 ± 2	13

μ + jets channel

Jet multiplicity	ttbar	single top	W+jets	Z+jets	QCD	Sum MC	Data
$N_{jets} \geq 0$	13 ± 3	4.2 ± 0.4	3708 ± 448	192 ± 29	223 ± 25	4140 ± 450	4142
$N_{jets} \geq 1$	13 ± 3	3.9 ± 0.4	552 ± 106	42 ± 12	79 ± 17	690 ± 108	789
$N_{jets} \geq 2$	13 ± 2	2.3 ± 0.3	92 ± 24	7.1 ± 4.4	10 ± 3	124 ± 25	153
$N_{jets} \geq 3$	10 ± 2	0.82 ± 0.15	16 ± 5	1.3 ± 0.9	1.3 ± 0.5	29 ± 5	40
$N_{jets} \geq 4$	5.6 ± 1.4	0.24 ± 0.06	3.1 ± 1.2	0.25 ± 0.18	0.15 ± 0.07	9.3 ±1.9	11



ttbar

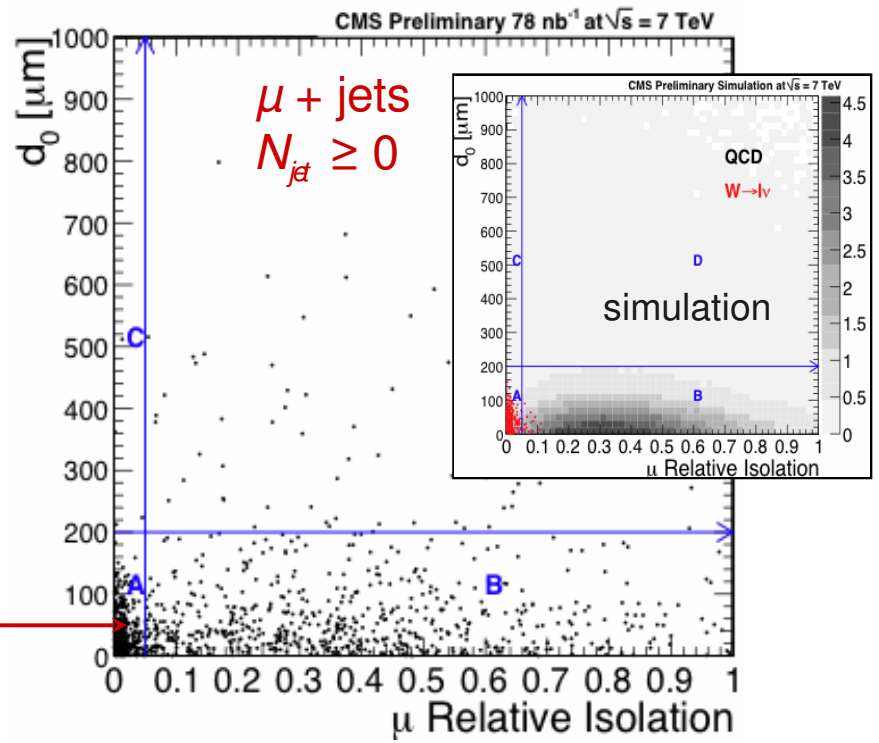


Error ~50/100% on QCD data-driven estimation

Background Estimation in L+Jets

Estimate of backgrounds with fake isolated and prompt leptons from data

"ABCD" method with 2 ~ uncorrel. variables



signal region A

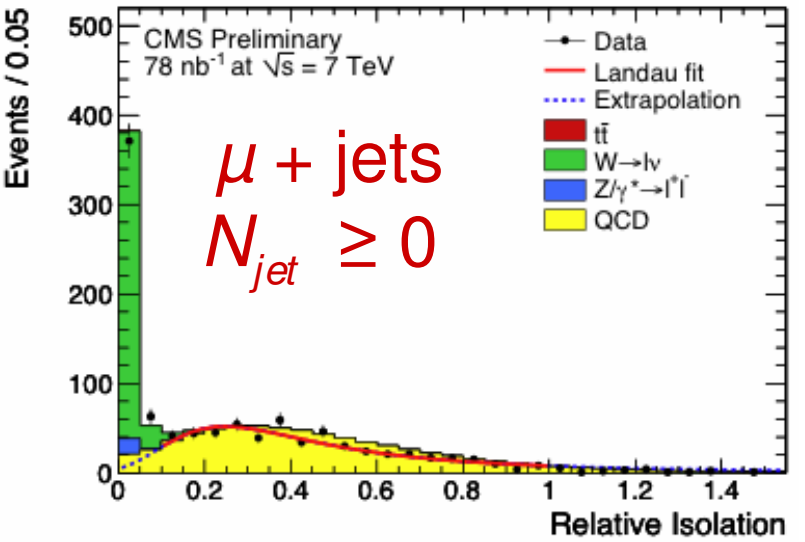
μ + jets	$N_{jet} \geq 0$	$N_{jet} \geq 1$
ABCD	57 ± 29	30 ± 15
Rel. isol. fit	7 ± 4	6 ± 3
Simulation	21 ± 2	7 ± 2

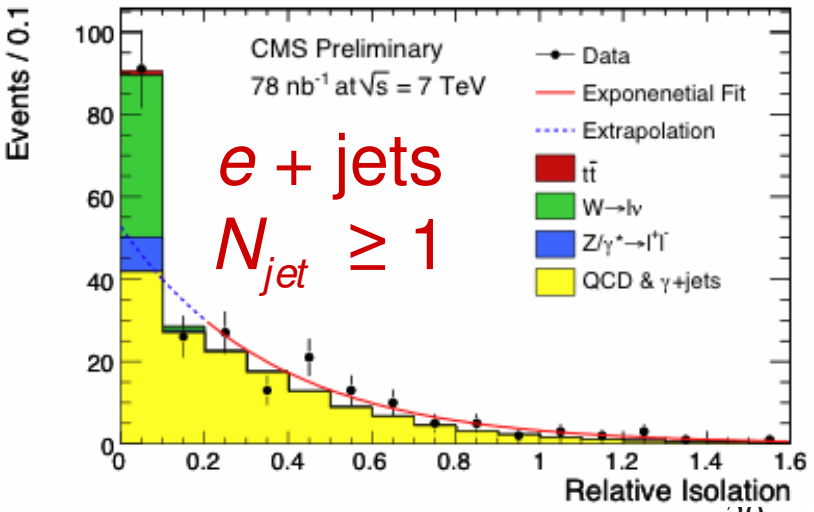
e + jets	$N_{jet} \geq 0$	$N_{jet} \geq 1$
Rel. isol. fit	70 ± 35	44 ± 22
Simulation	63 ± 7	42 ± 6

disagreement currently u.i. with more data... Now, we assign 100% uncert. on N_{QCD} in μ+jets

(100% is OK, as BG small in $N_j \geq 4$)

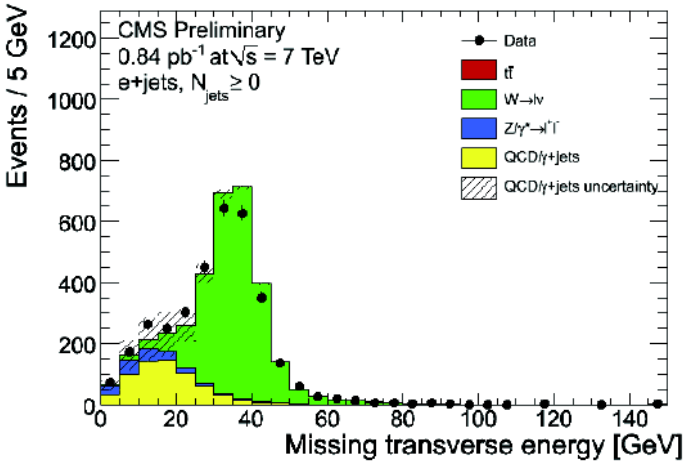
Fit & extrapolation to signal region:



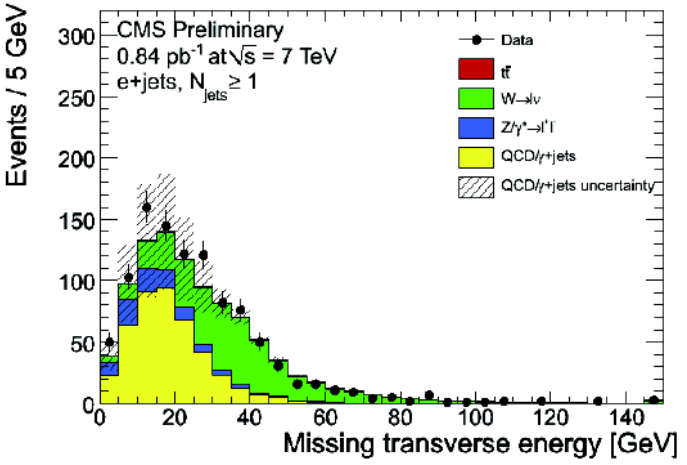


0.84 pb^{-1} e+Jets Channel

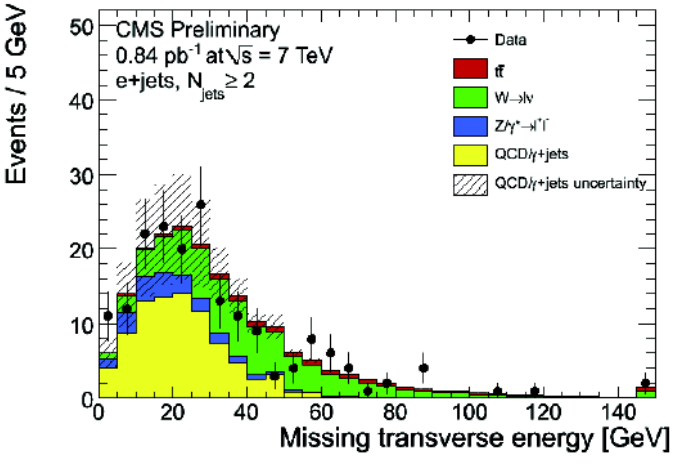
N (jets) >= 0



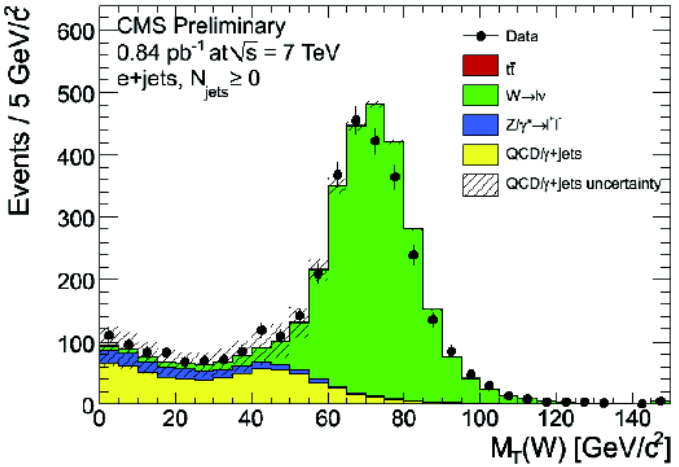
N (jets) >= 1

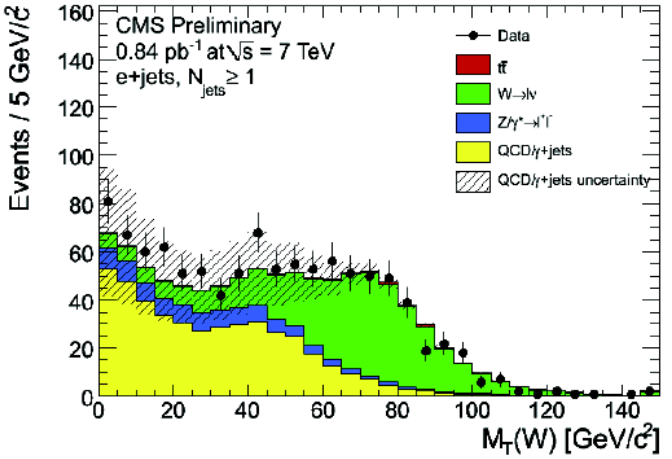


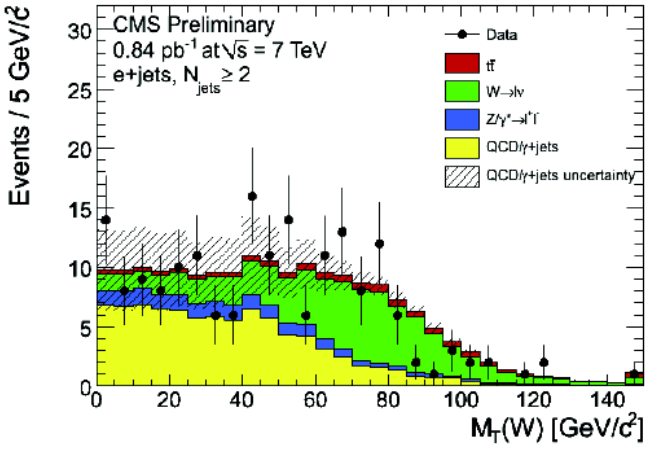
N (jets) >= 2



N (jets) >= 2Missing ET (hard to get right, important for any top quark measurement)





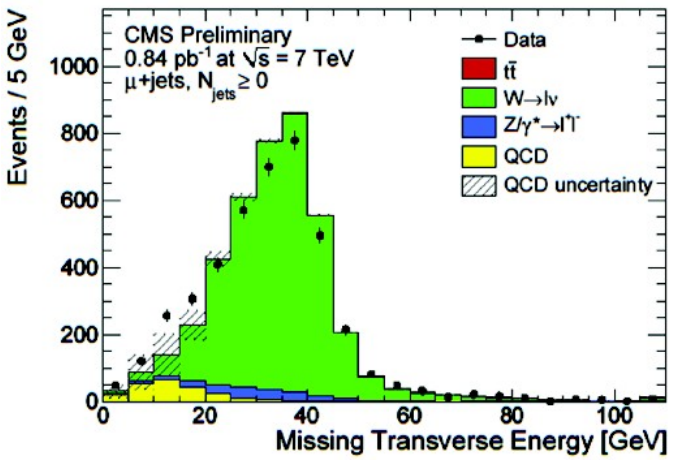


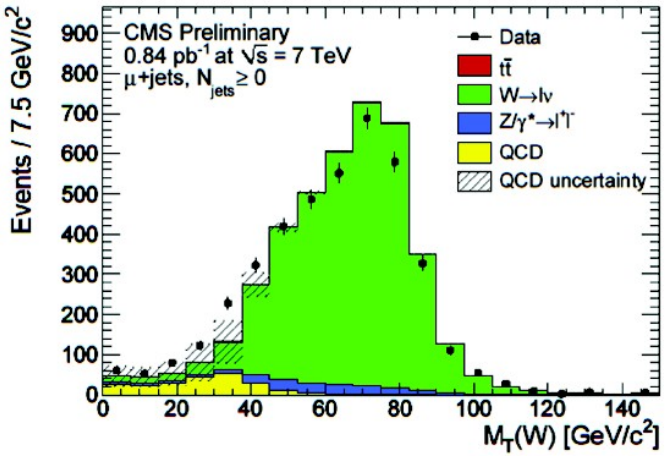
M_T(W): transverse W mass (calculated from lepton+MET)

Error band: 50% on QCD (from data-driven methods)

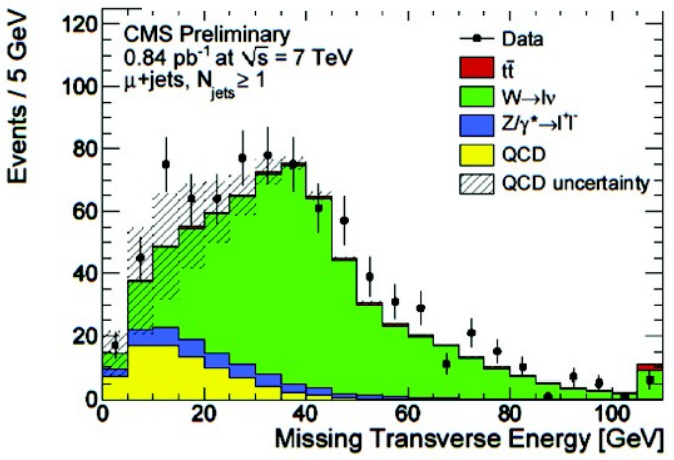
0.84 pb^{-1} μ+Jets Channel

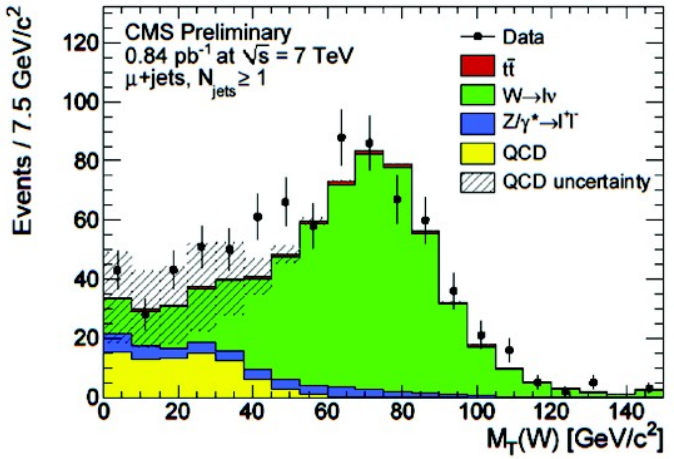
N (jets) >= 0



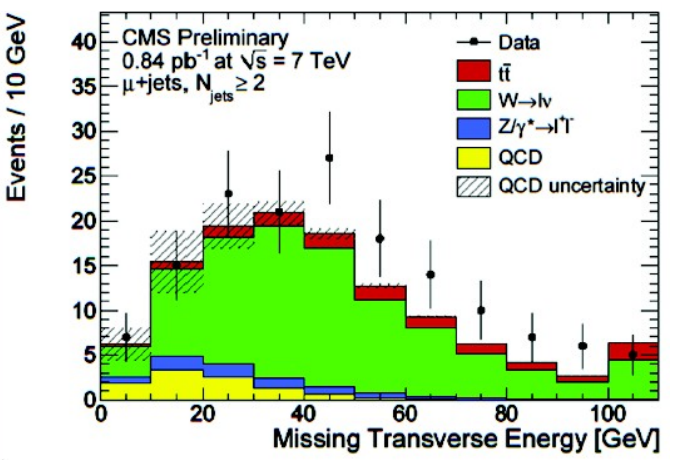


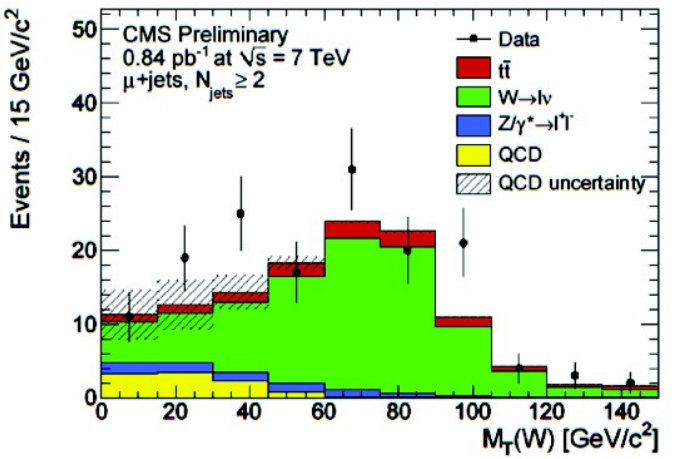
N (jets) >= 1





N (jets) >= 2





- Excess in data at low energy compatible with QCD underestimated by a factor 2
- Data slightly above background estimate also at higher energy: expect significant uncertainties from JES and theory

Error band: 100% on QCD (from data-driven methods)

Lepton+Jets Distributions

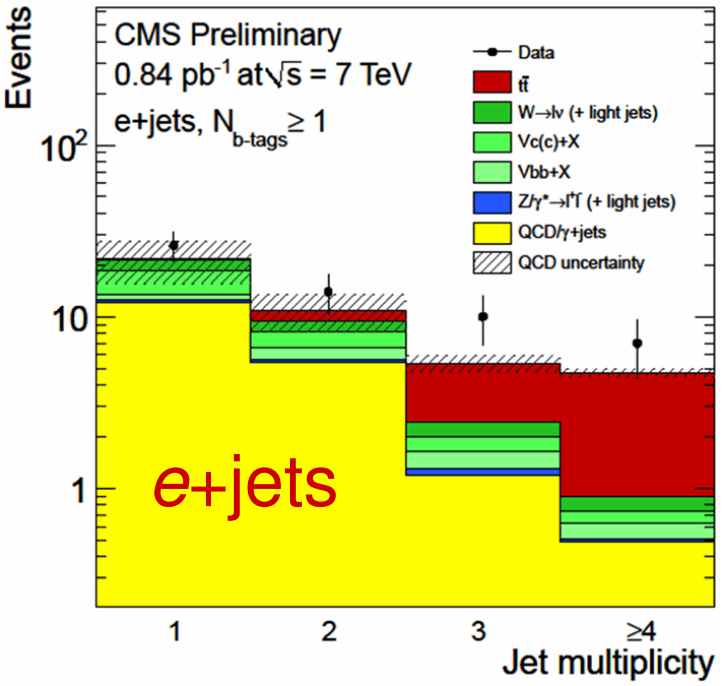
Xs extracted by means of binned likelihood template fits to discriminating variables (M3, M3', $\eta(\mu)$)

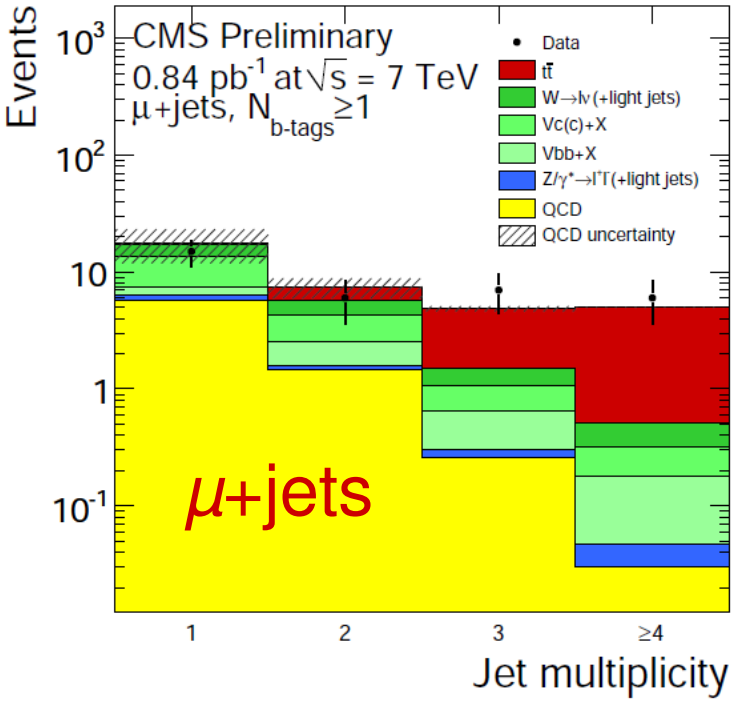
M3: M_{jjj} of the three-jet system that maximizes

$$\left|\sum_{jjj} p_T(\text{jet})\right|$$

Very soon to be publish the top quark pair **cross section** and top **mass** measurements in the lepton+jets (aso in dilepton) channel with the **full 2010 luminosity: > 35 pb-1**

Events with ≥1 loosely tagged jet



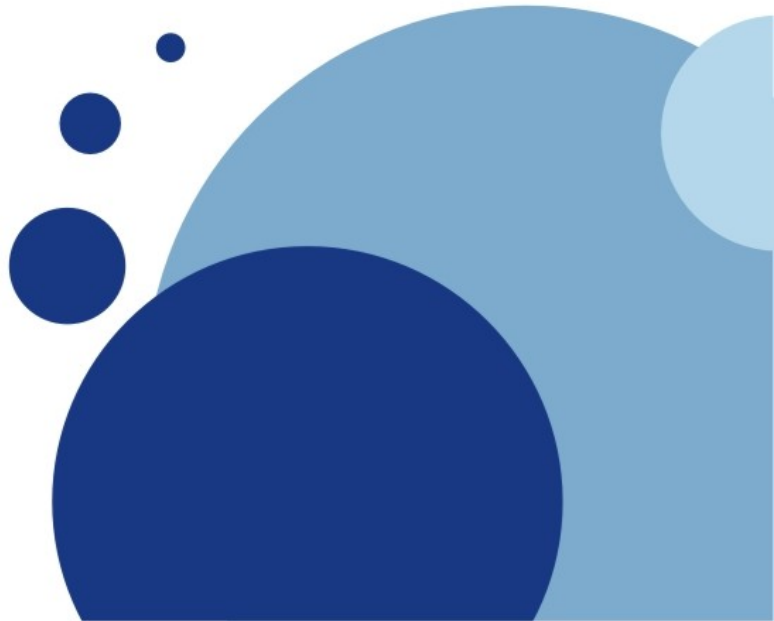


Apply b-tagging to the jets to clean up the sample:

(here used secondary vertex b-tagger)

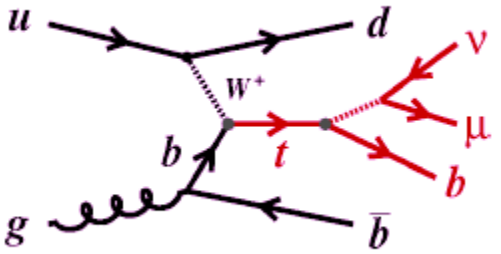
Prospects in top quark studies

Many analysis on the pipeline of CMS to cover top quark physics and beyond, but I will not be able to cover everything in this talk...



Single top production

Production modes: t-channel, s-channel, tW
Smaller xs and large bkgs → more sophisticated methods needed to extract the signal



t-channel (largest xs) :

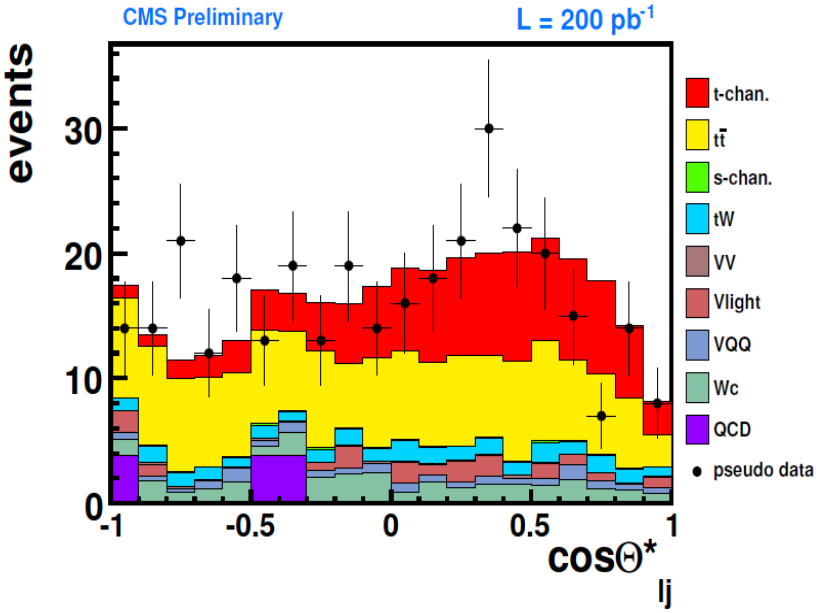
- Signal: 1 isolated lepton, MET, 1 light forward hadronic jet + 1 b-jet
- Bkgs: ttbar, W+jets, Wbbar+jets, QCD mutijets (data-driven methods)

Prospects for t-channel cross section measurement at 10TeV @ 200 pb^{-1}

Analysis strategy

• Xs determined by the angular correlations of the top decays and performing a binned likelihood fit to cosθlj

$\Delta\sigma/\sigma = \pm 35\%$ (stats) $\pm 14\%$ (syst) $\pm 10\%$ (lum)
Sensitivity of 2.7σ can be achieved

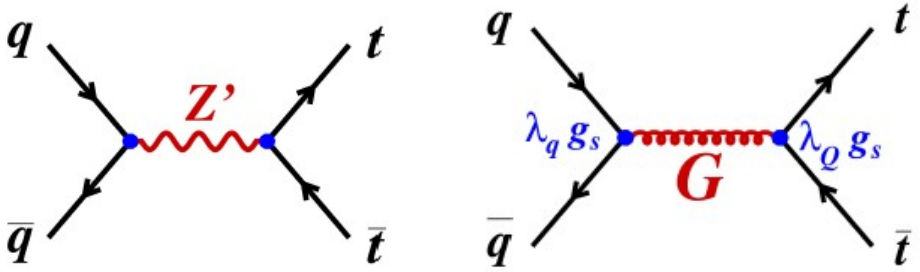


Expected **single top cross section** measurement in the **t-channel** using the full 2010 luminosity.

Search for Resonances decaying into Top Quark Pairs

100 pb^{-1} @ $\sqrt{s}$ = 10 TeV

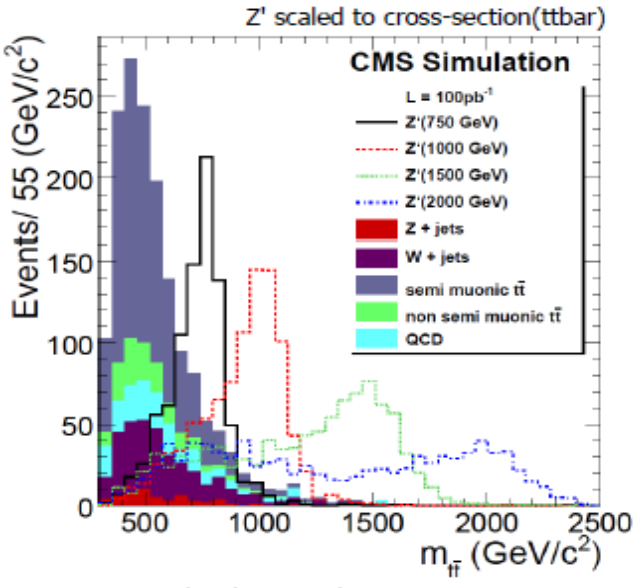
Top quarks originating from a decay of a high mass resonance are boosted → different event topology than in SM.

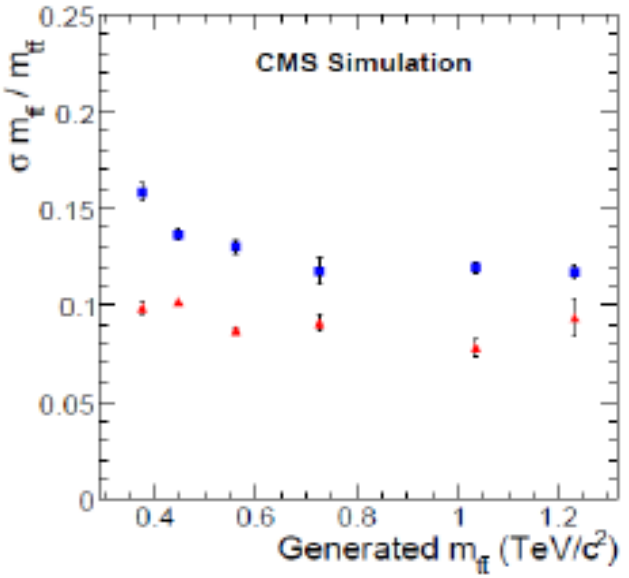


Special reconstruction and selection methods required for "boosted tops"

semileptonic final state with a muon

If the new exchange particle is heavy and narrow, the distribution of the invariant mass of the top quark pair system will show resonances.





Might reach limits on resonance cross section of a few pb soon.

Conclusions

The success of the CMS top group results speak to the success of all of CMS over the last 20 years and the great performance and understanding of the detector!

- **With only 3.1 pb-1 we have produced the first measurement of the top quark pair cross-section at $\sqrt{s}$ = 7 TeV**
  - ✔ with a center of mass energy a factor of 3.5 higher than ever before seen in a lab
  - ✔ we are probing new production mechanisms (gluon-gluon fusion vs. quark-quark at the Tevatron, proton on proton vs anti-proton on proton)

We have shown that we are ready for not only SM physics, but also what may come ahead

Coming very soon …

New results using the full luminosity recorded by the CMS experiment in 2010:

$$\mathcal{L} > 35 \text{ pb}^{-1}$$

More precise measurements:

- Mass and top quark pair cross section production both in the leptonic and semileptonic decay channels

- also profit from a better understanding of the jet b-tagging

CMS is already ready to continue top quark physics program next year at $\sqrt{s}$ = 8 TeV

References

- CMS twiki page with results for Top Physics
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
- First Measurement of the Cross Section for Top-Quark Pair Production in Proton-Proton Collisions at $\sqrt{s}$ = 7 TeV

  arXiv:1010.5994 ; CERN-PH-EP-2010-039 ; CMS-TOP-10-001
- First Measurement of Top-Quark Pair Production Cross Section in Proton-Proton Collisions at $\sqrt{s}$ = 7 TeV
  CMS-PAS-TOP-10-001 (2010)
- Selection of Top-Like Events in the Dilepton and Lepton-plus-Jets channels in Early 7 TeV data. CMS Physics Analysis Summary
  CMS-PAS-TOP-10-004 (2010)
- Prospects for the measurement of the single-top t -channel cross section in the muon channel with 200pb-1
  CMS PAS TOP-09-005
- Search for narrow resonances in top-pair production close to threshold in the semileptonic muon channel at $\sqrt{s}$ = 10 TeV
  CMS PAS TOP-09-009

Backup

Backgrounds

Events with real W or Z bosons

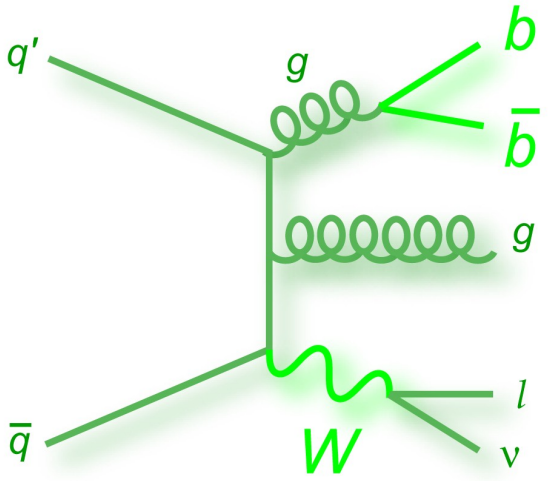
- W+jets
- Z+jets
- WW, WZ, ZZ

Events with misidentified leptons

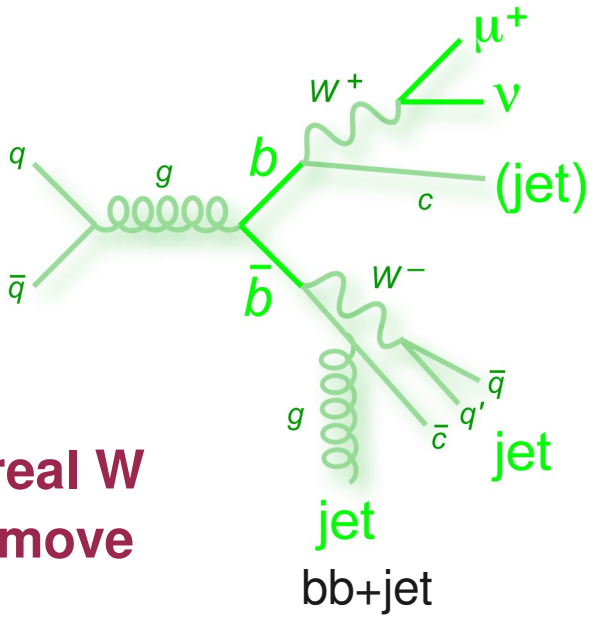
- Multijet events with a jet misidentified as an electron
- bb+jets with a misidentified electron or muon from a b decay

Miscellaneous sources

- Cosmic rays, multiple pp interactions, pattern recognition mistakes, etc.



W+jets

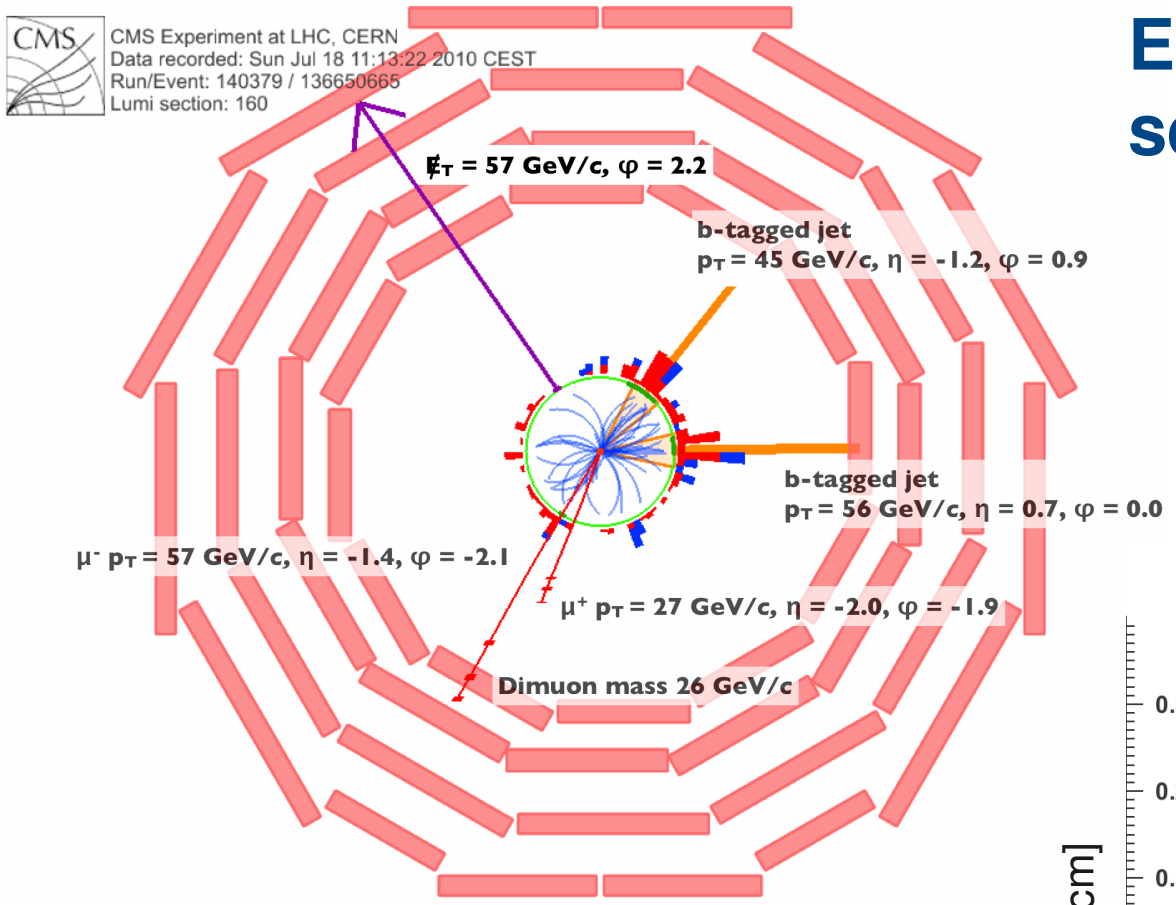


bb+jet

➔ **For most tt decay channels, processes with a real W boson and real b jets are the most difficult to remove**

➔ **Identification of b-quarks through secondary vertex is a critical point to reduce backgrounds**

μμ +Jets Candidate Event (from July 18)

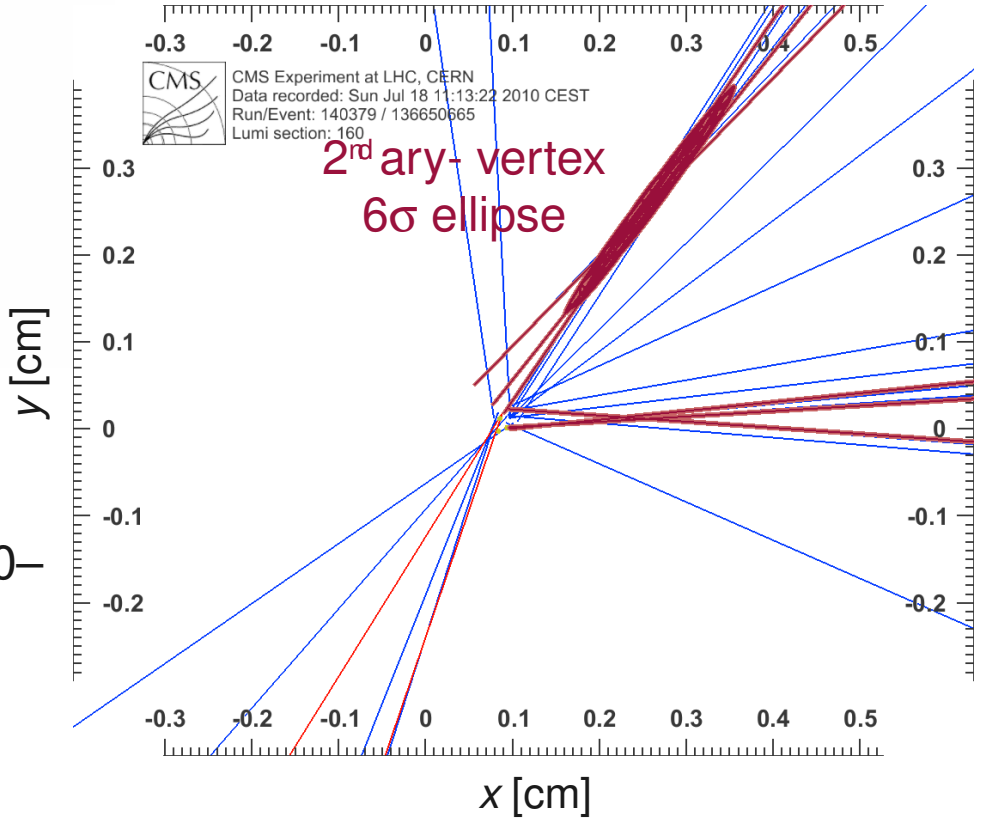


m(μμ) = 26 GeV/c²

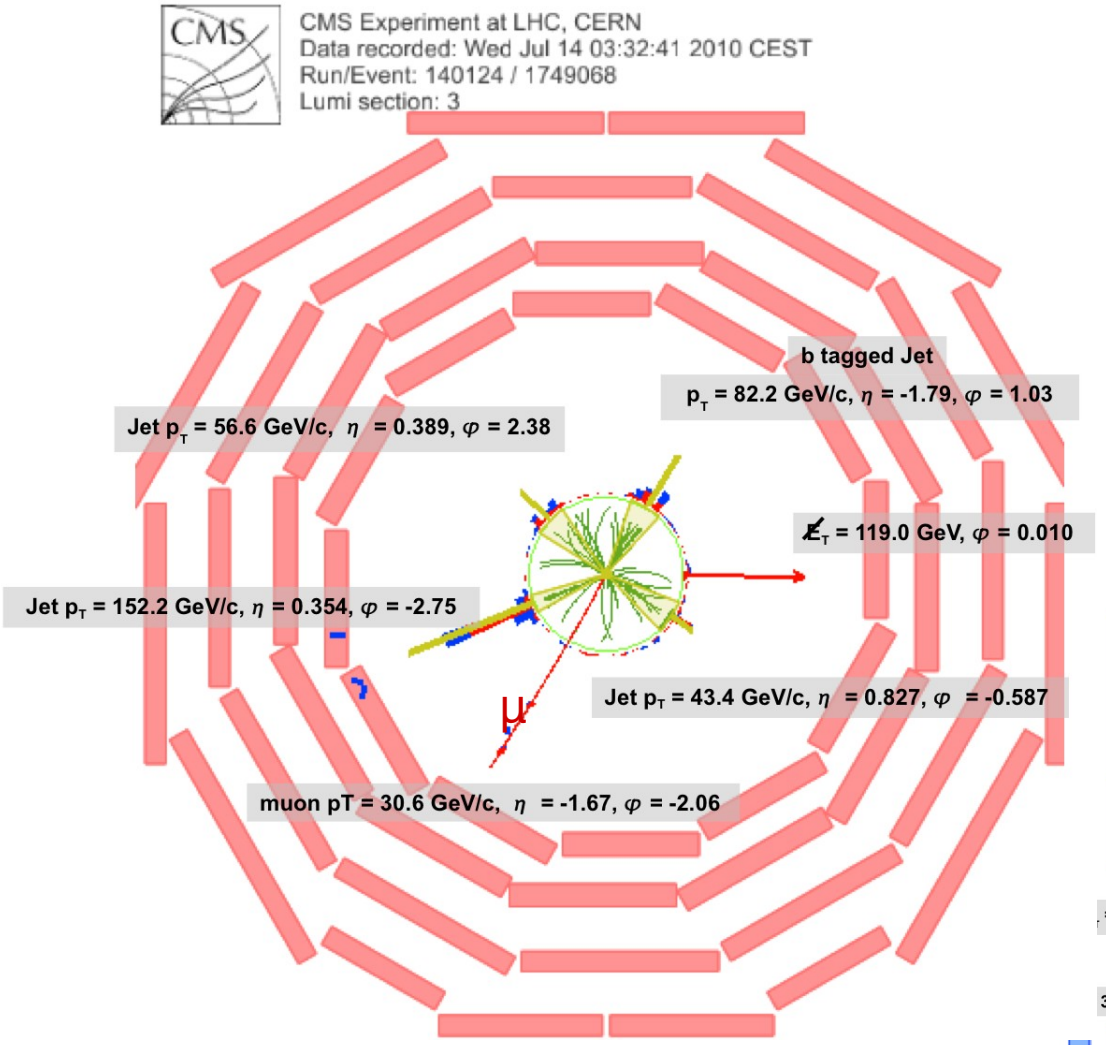
Preliminarily reconstr. mass is in the range 160–220 GeV/c² (consistent with m_{top})

Event passes all cuts of full selection:

2 muons with opposite charge
2 jets, both w/ good/clear *b*-tags (and secondary vertices!)
significant MET (>50 GeV)

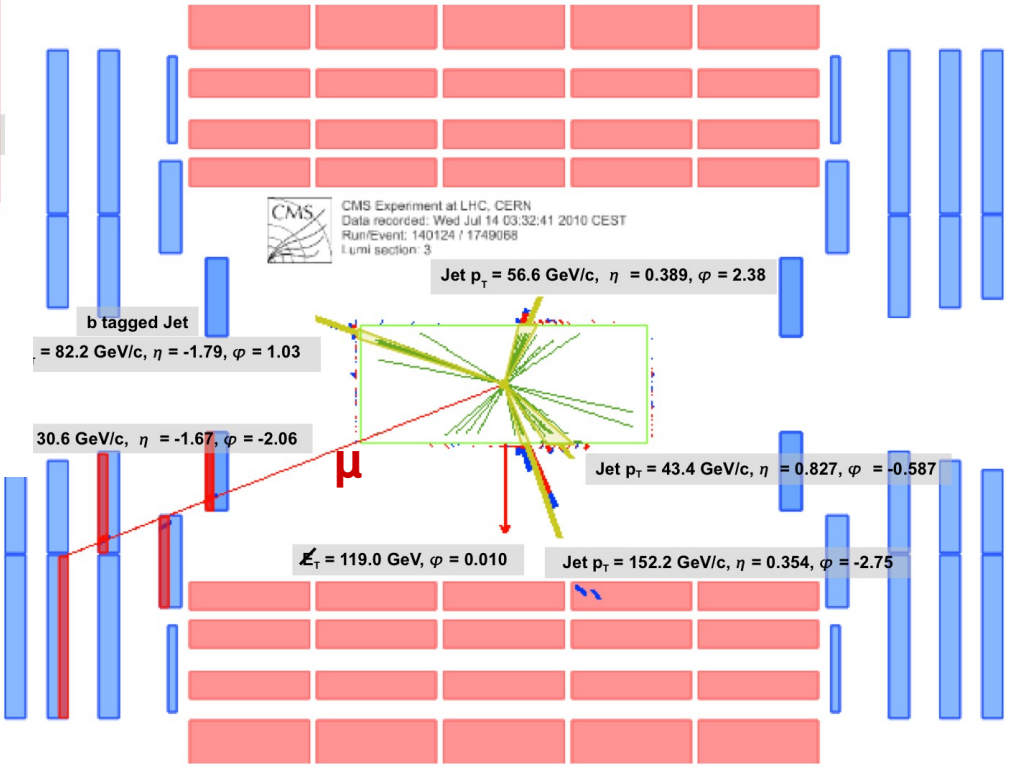


μ+Jets Candidate Event (from July 14!)



Event passes all cuts of full selection

1 high-momentum muon
significant MET > 100
m_T(W) = 104 GeV/c²
4 high-p_T jets,
one of which with good *b*-tag



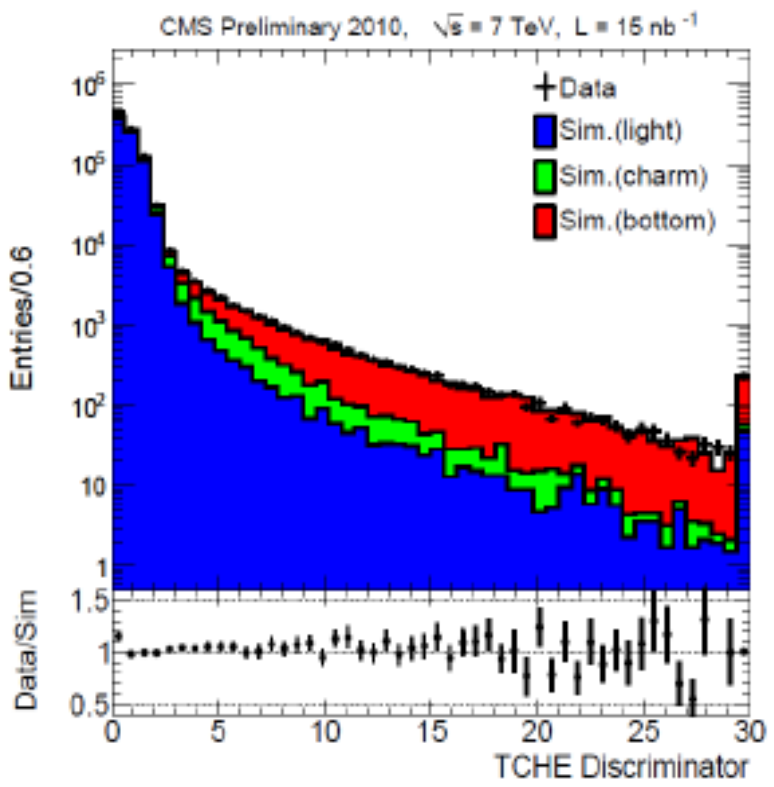
reconst. top mass around 210 GeV/c²

masses of 2 untagged jets (3 possible comb.): 104, 105, 151 GeV/c²

B-tagging at CMS

"Track counter" tagger

Discriminator: IP significance of the n_{th} track



Secondary vertex tagger

Discriminator based on 3D flight distance