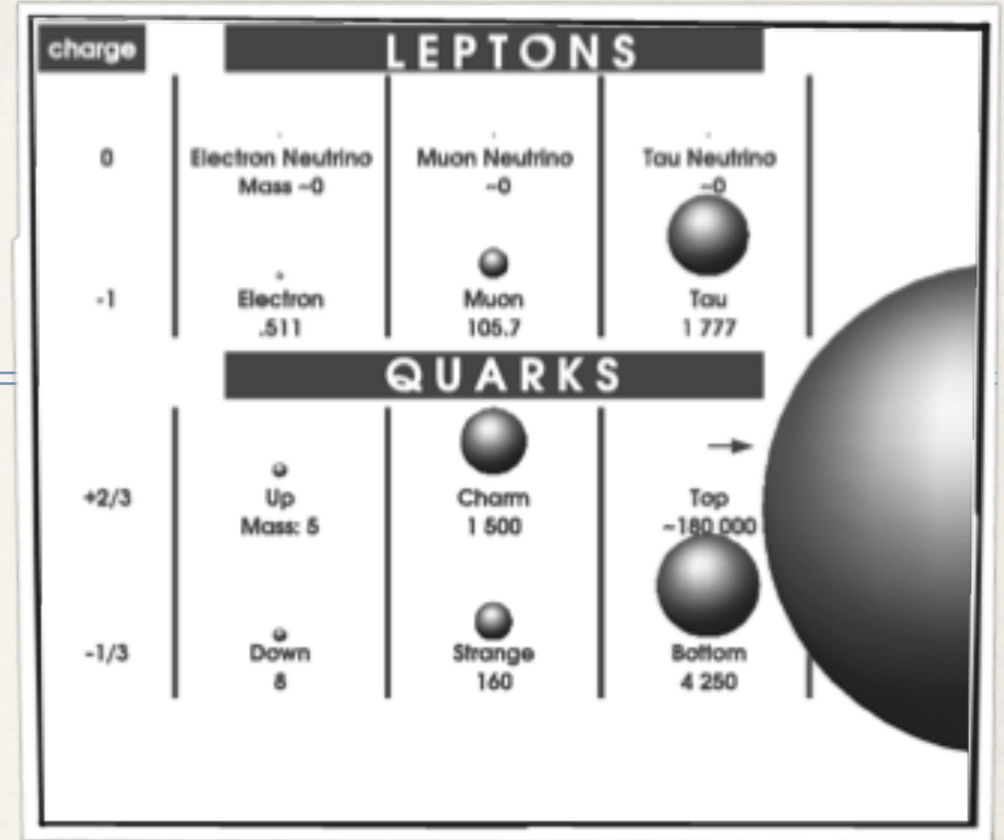
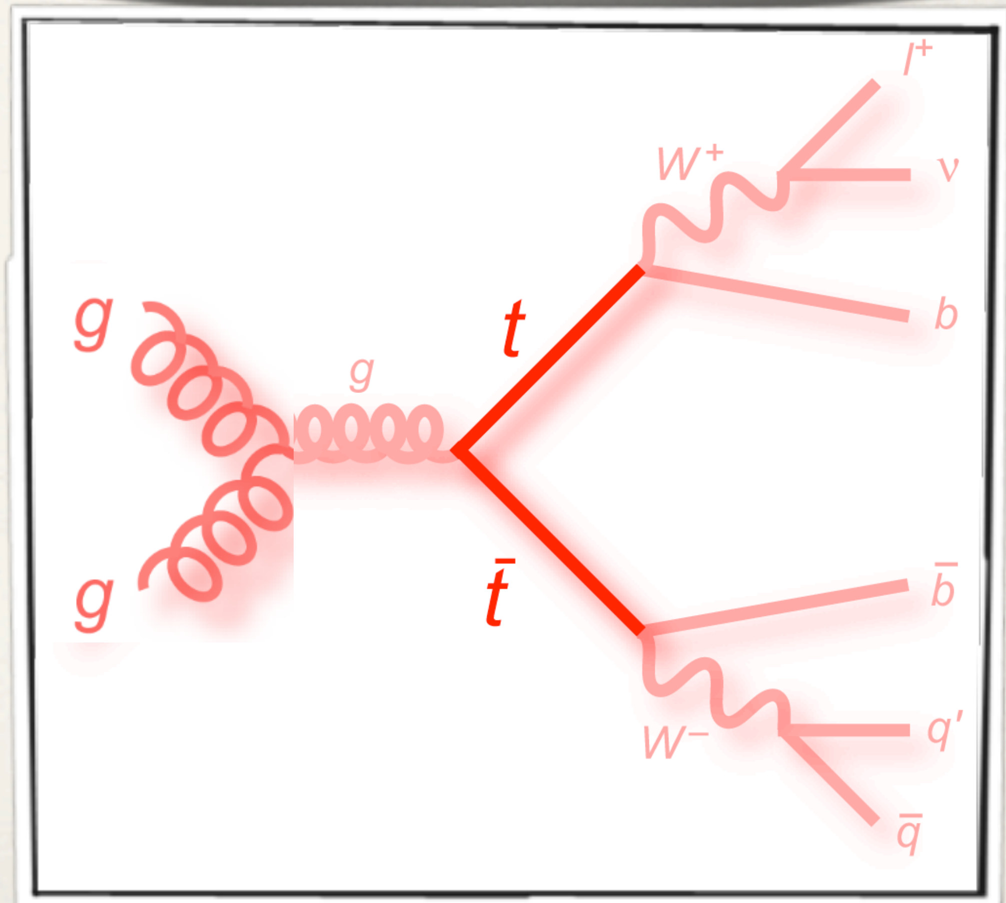
Top Mass and Cross-sections at CMS

Helena Malbouisson (UNL) on behalf of the CMS Collaboration

The Top Quark

- **Standard Model measurements**
  - Heaviest known elementary particle
  - Unique window on bare quarks due to short lifetime
  - Electroweak and QCD precision measurement
  - Constraints on Higgs mass
- **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**

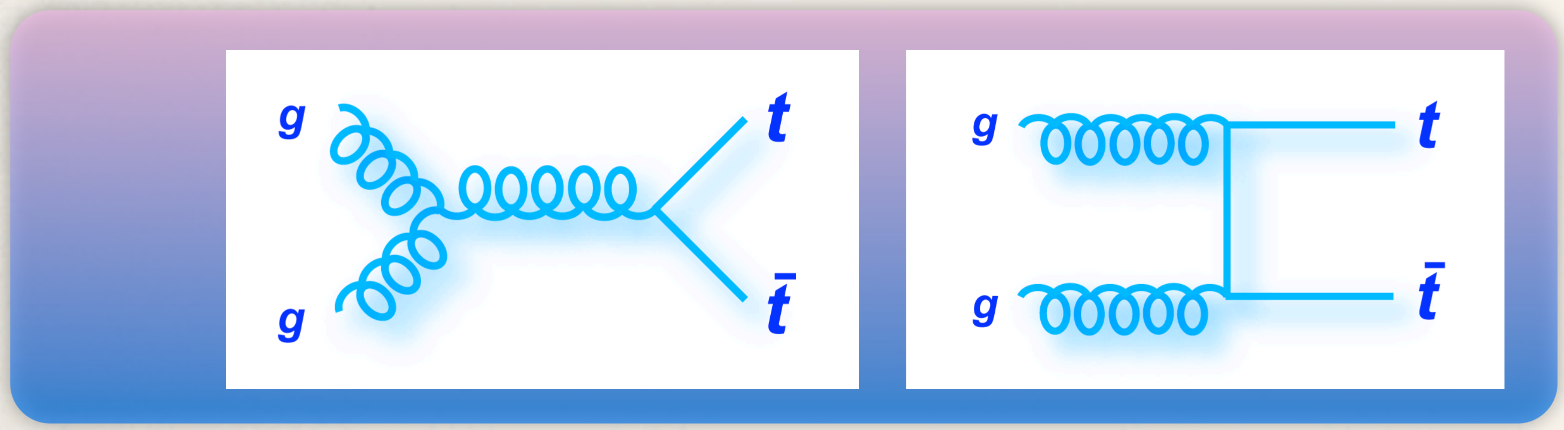


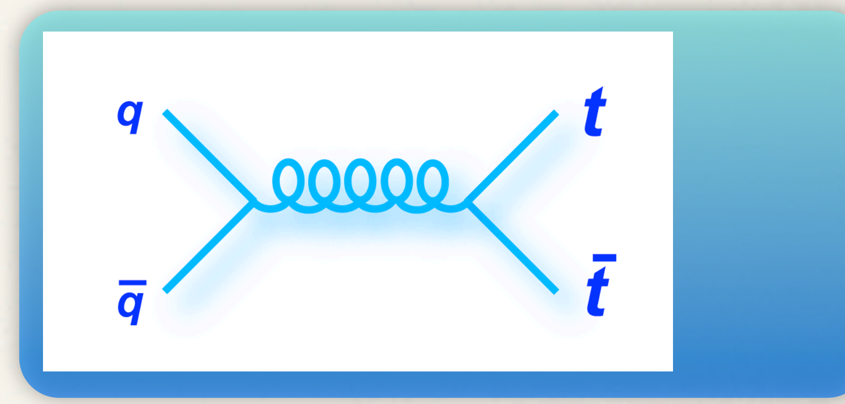


Top quark pair production at the LHC

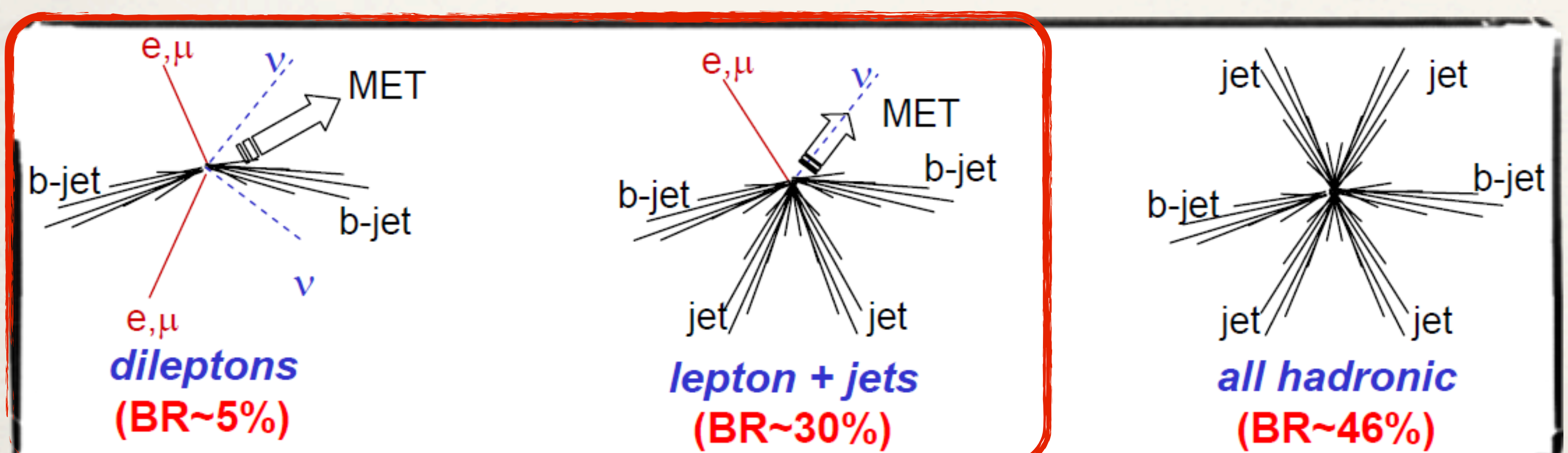
$$\sigma_{t\bar{t}}^{NLO} = 158^{+23}_{-24}\ pb$$

- gluon gluon fusion is the dominant production process



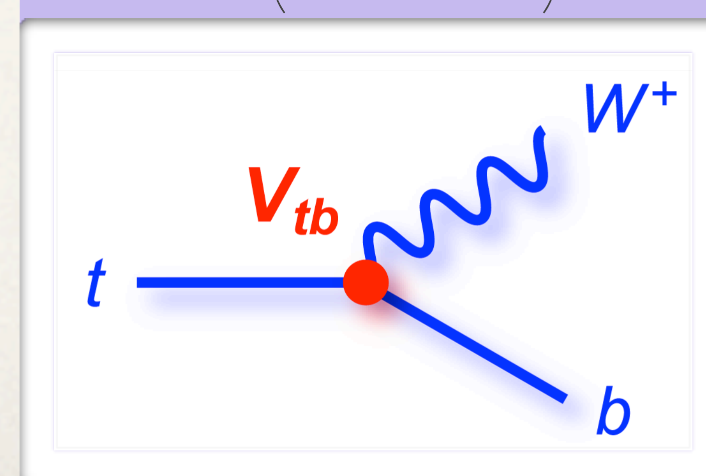


- Final state is categorized by the decay of the W boson



covered in this talk

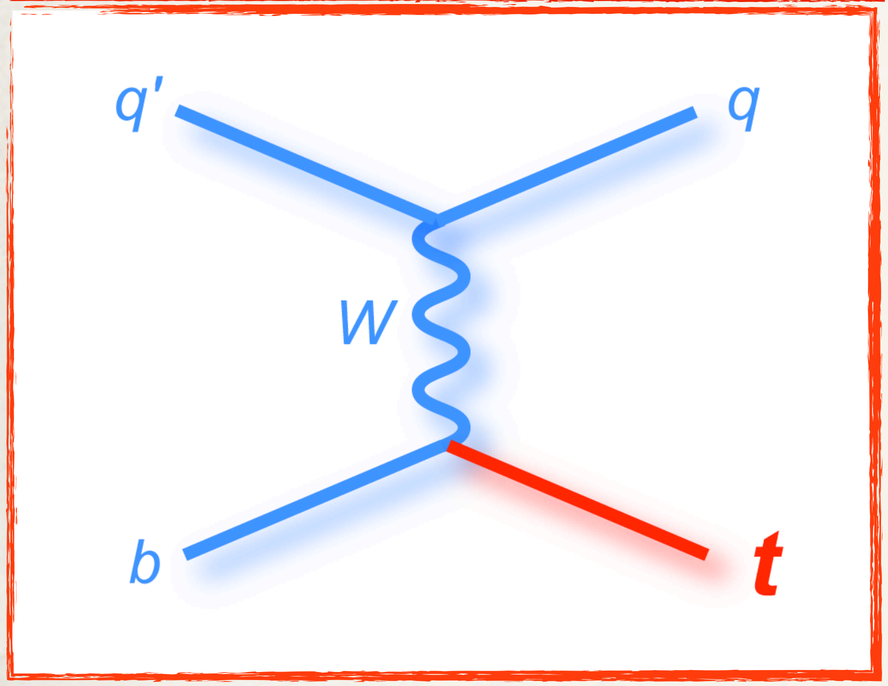
- BR(t->Wb) ~1 .

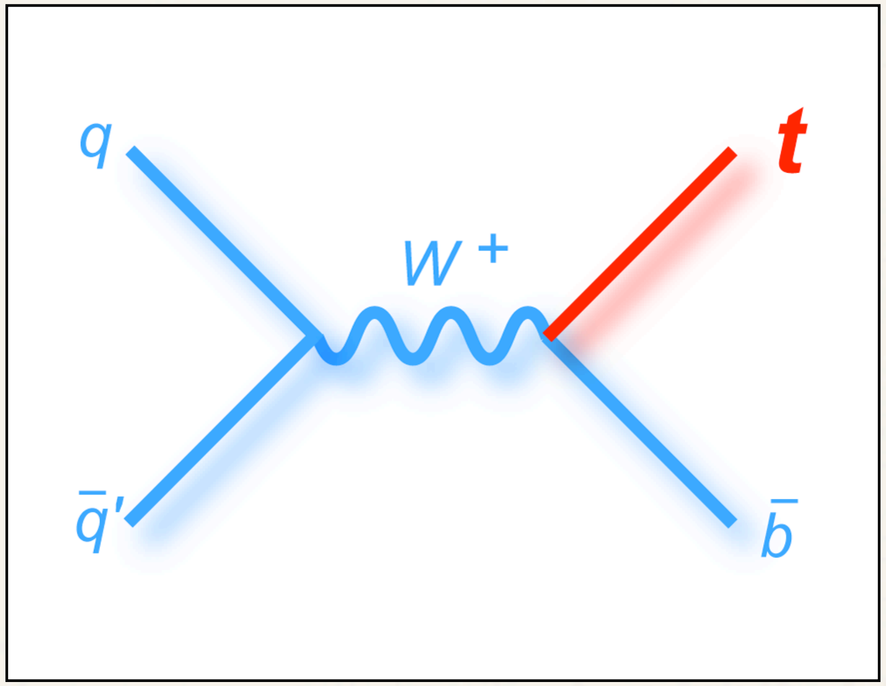


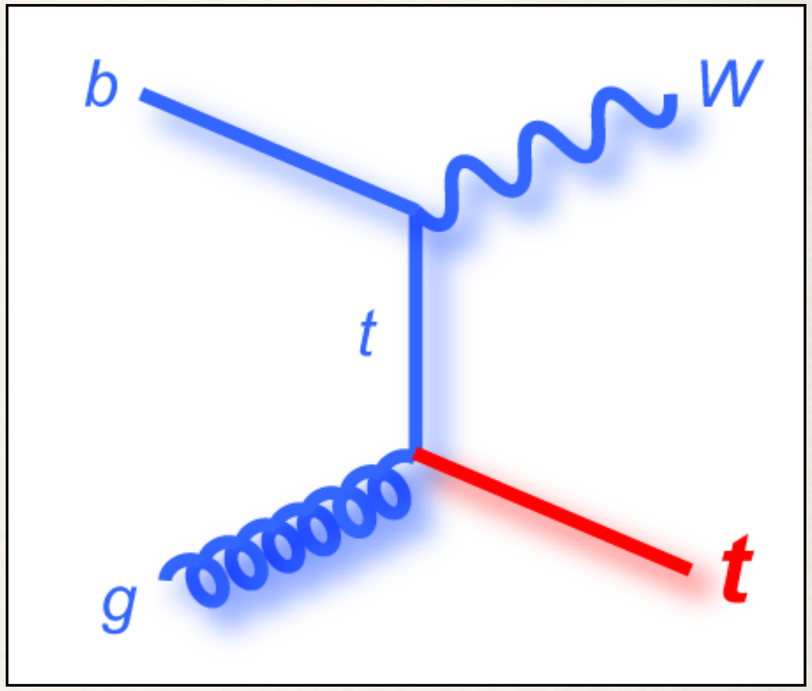
Single Top production at the LHC

Single top quark production, an electroweak interaction

t-channel, σ ~ 64 pb	s-channel, σ ~ 4.6 pb	tW-channel, σ ~ 15.6 pb



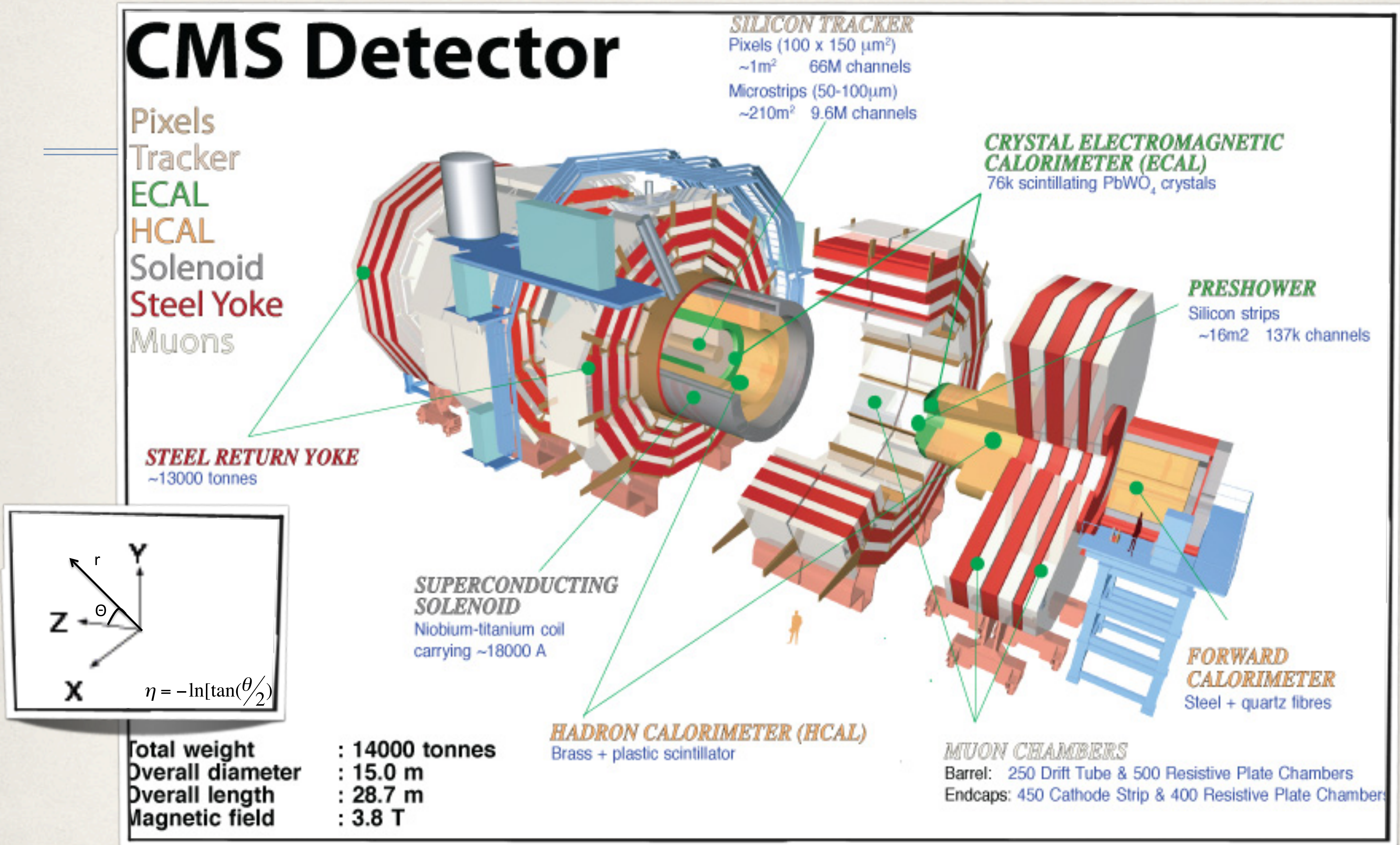




t-channel: measurement covered in this talk.

Decay channels:

- t→eνb
- t→μνb
- t→τνb, with leptonic τ decays

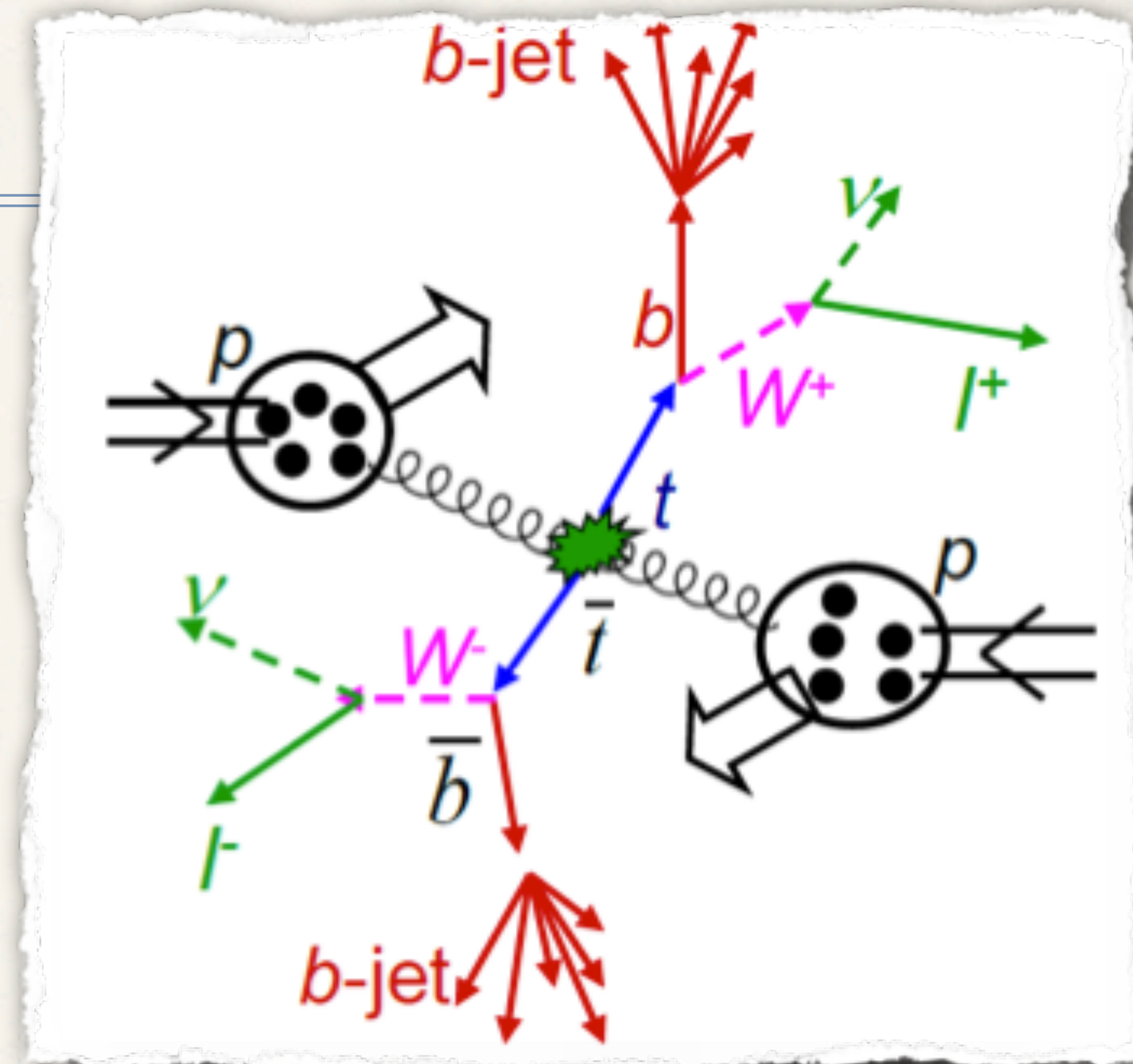

CMS Detector
Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² 66M channels
Microstrips (50-100μm)
~210m² 9.6M channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
76k scintillating PbWO4 crystals
PRESHOWER
Silicon strips
~16m2 137k channels
STEEL RETURN YOKE
~13000 tonnes
SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
FORWARD CALORIMETER
Steel + quartz fibres
MUON CHAMBERS
Barrel: 250 Drift Tube & 500 Resistive Plate Chambers
Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
r
Y
Θ
Z
X
$\eta = -\ln[\tan(\theta/2)]$

Outline

- Top pair cross-section in the dilepton channel
- Top pair cross-section in the lepton+jets channel
- Top Mass measurement in the dilepton channel
- Top Mass measurement in the lepton+jets channel
- t-channel Single Top cross-section
- Summary and outlook

In this talk: CMS data recorded in 2010 (36 pb^{-1})

Dilepton channel - event selection



- **Inclusive single lepton triggers**
  - muons and electrons

- **Two isolated, opposite charge leptons (ee, μμ, eμ)**
  - p_T>20 GeV, $|\eta_\mu|<2.4$, $|\eta_e|<2.5$
  - Good ID, conversion rejection for electrons.
  - Relative isolation<0.15

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

- **Z-boson veto (ee, μμ)**
  - $|M(ll)-M(Z)|>15$ GeV

- **Missing E_T (MET), in ee, μμ**
  - MET>30 (50) for events with ≥ 2 (1) jets

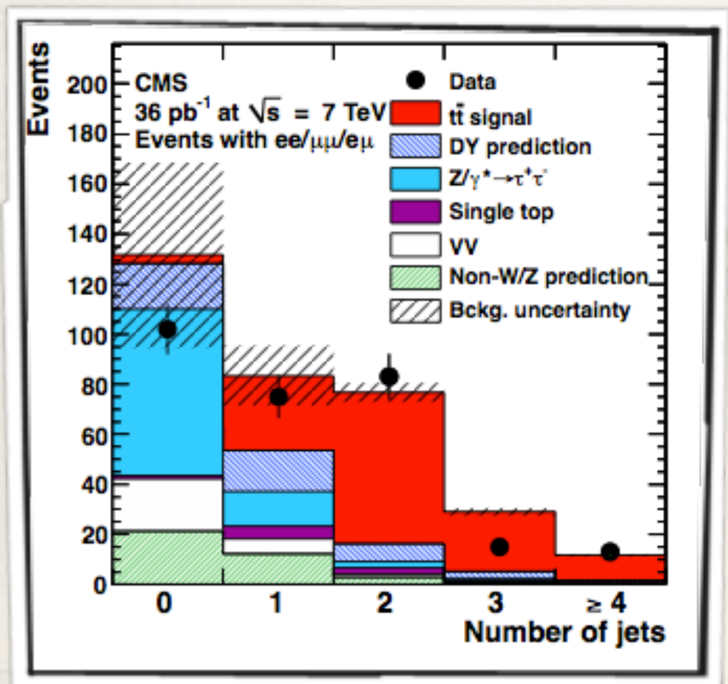
- **Jets**
  - p_T >30 GeV, $|\eta|<2.5$

- **b-jet identification**
  - track-counting algorithm

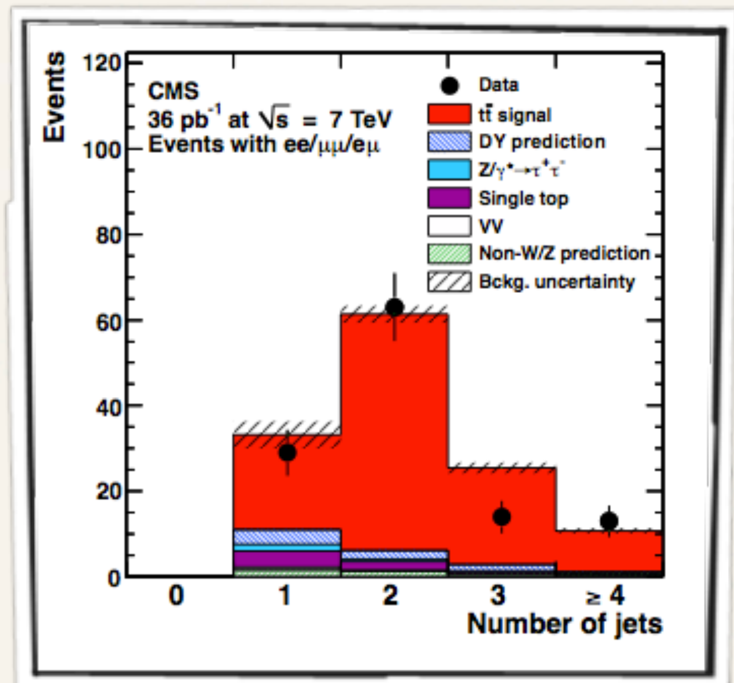
Top pair cross-section in dileptons

arXiv:1105.5661, acc. by JHEP

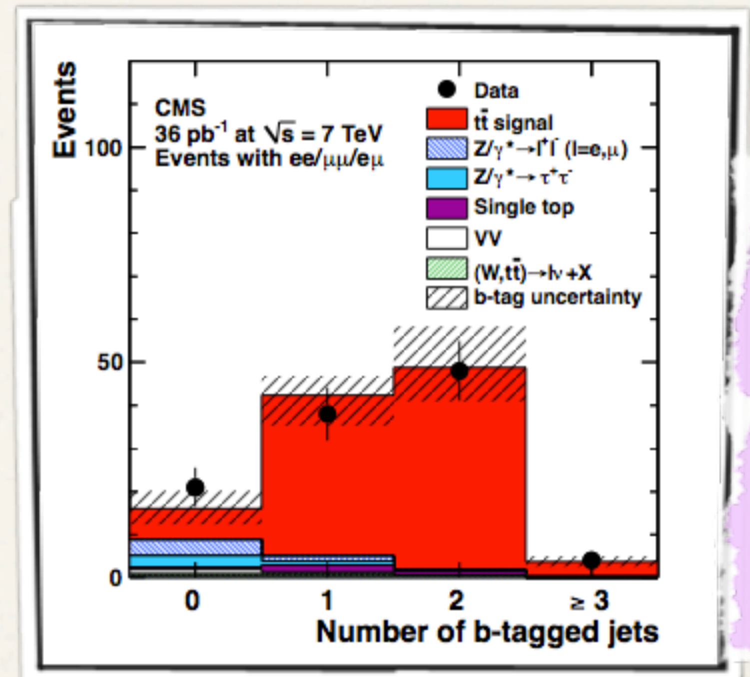
number of jets, after full event selection, before b-tagging:



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(in veto, data)*R(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 dileptons

Combination of cross-section measurements

arXiv:1105.5661, acc. by JHEP

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

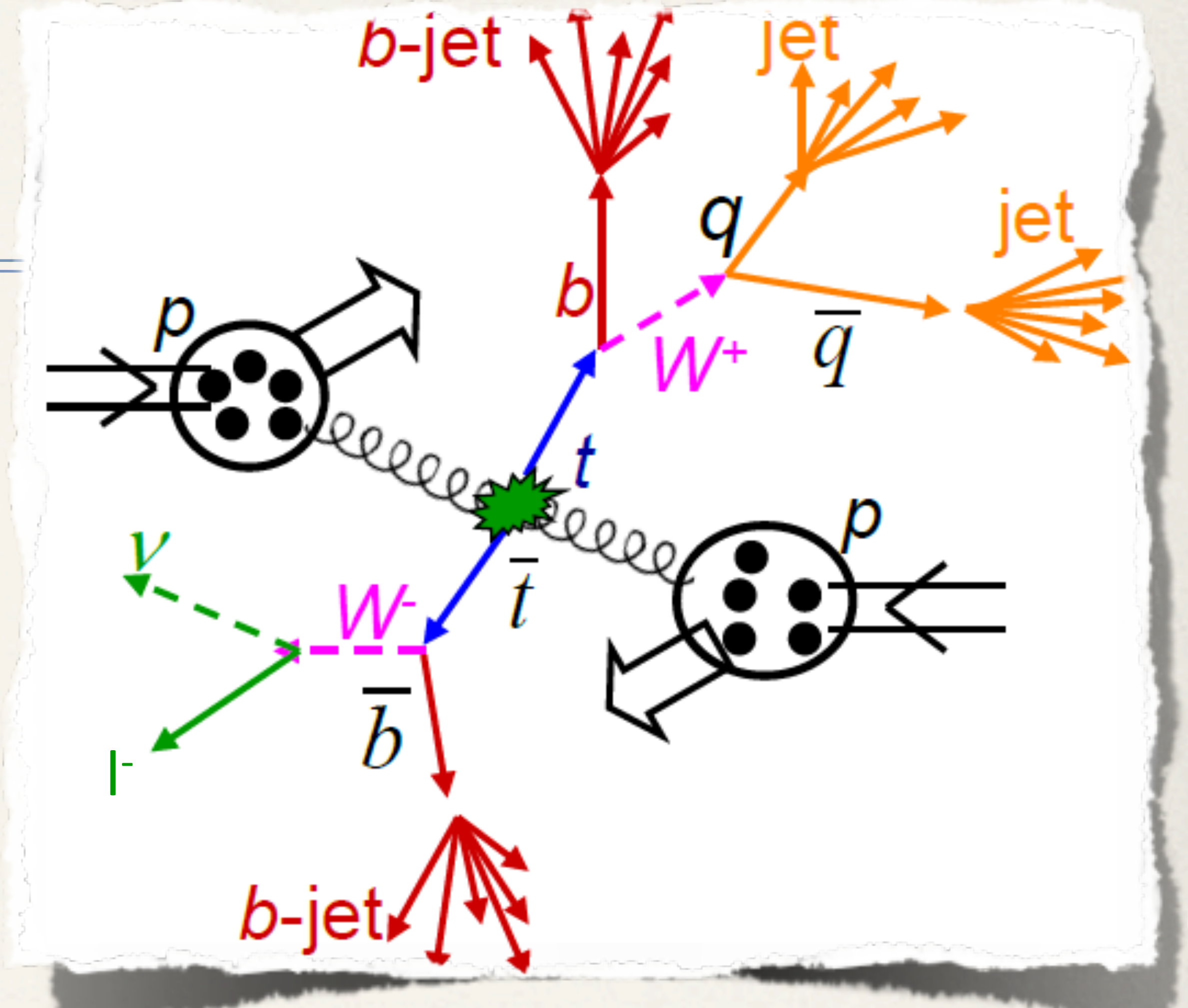
Final state	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
At least two jets, no b-tagging requirement			
Events in data	23	28	60
Simulated backgrounds	1.4 ± 0.3	1.5 ± 0.3	5.2 ± 1.2
$Z/\gamma^\star \to e^+e^-/\mu^+\mu^-$	3.0 ± 1.8	7.4 ± 4.1	–
Non-W/Z	1.1 ± 1.4	0.6 ± 1.1	1.4 ± 1.6
All backgrounds	5.5 ± 2.3	9.5 ± 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)	$189 \pm 52 \pm 29$	$159 \pm 45 \pm 39$	$160 \pm 23 \pm 12$
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
$Z/\gamma^\star \to e^+e^-/\mu^+\mu^-$	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)	$150 \pm 46 \pm 22$	$186 \pm 45 \pm 25$	$156 \pm 23 \pm 13$
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
$Z/\gamma^\star \to e^+e^-/\mu^+\mu^-$	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)	$282 \pm 135 \pm 45$	$107 \pm 119 \pm 163$	$200 \pm 65 \pm 35$

Combined cross-section:

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

Here and elsewhere,
luminosity uncertainty: 4%

Lepton+jets - event selection



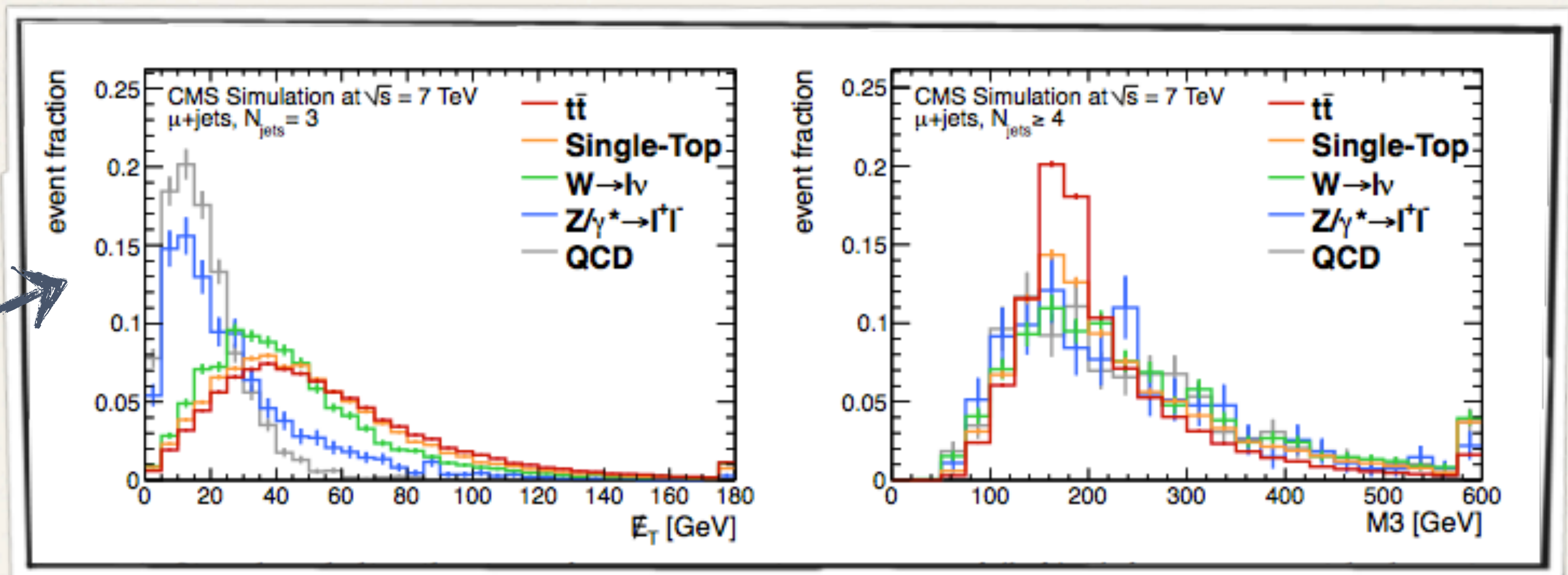
- **Considered modes:**
  - ✳ e+jets, μ+jets
- **Single lepton triggers used**
- **Exactly one isolated lepton**
  - ✳ Muons: pT>20 GeV, |η|<2.1
    - Relative Isolation < 0.05
  - ✳ Electrons: pT>30 GeV, |η|<2.5
    - Relative Isolation, conversion veto
- **Jets**
  - ✳ pT>30 GeV, |η|<2.4
- **Analysis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

Top pair 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)

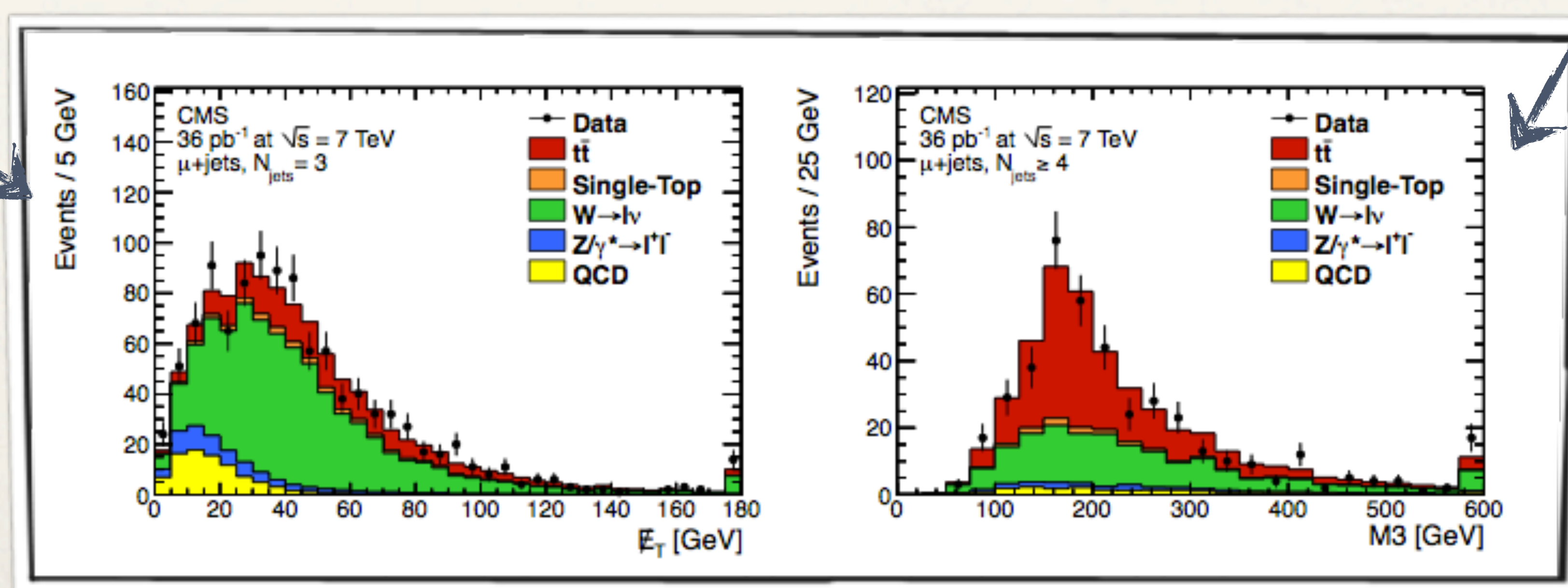
simulation



MET.
N(jets) = 3

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

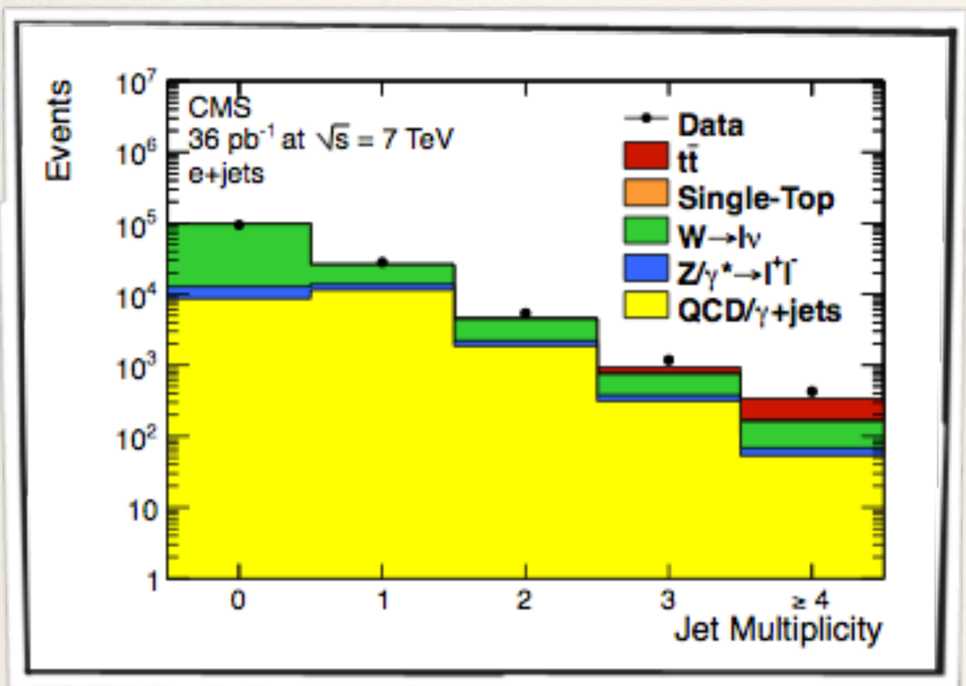
Data - simulation comparison.
Simulation normalized to fit result



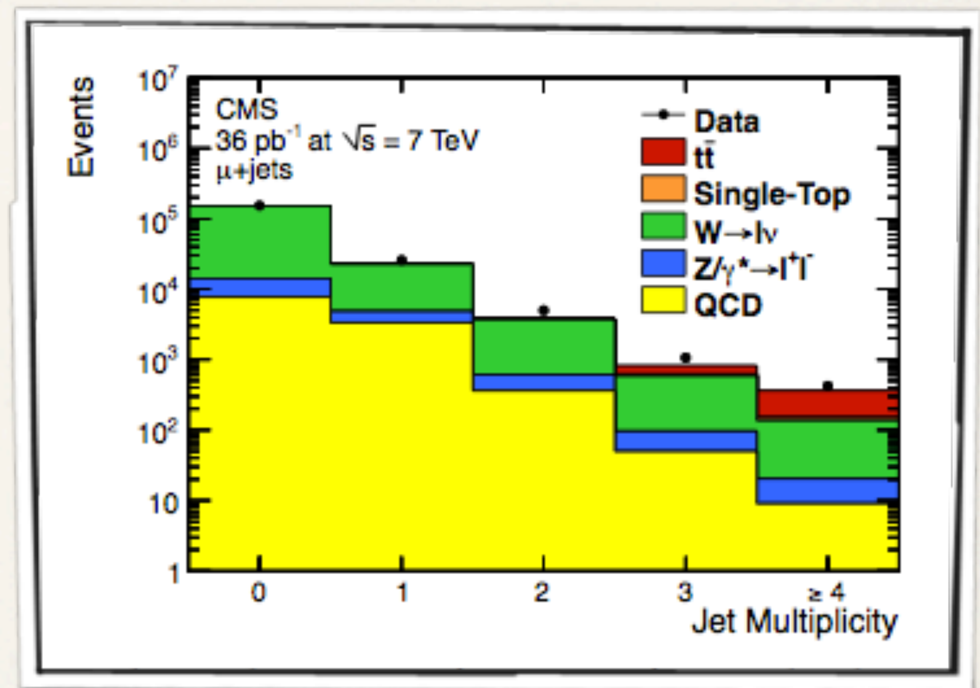
Top pair cross-section in lepton +jets without b-tagging

arXiv:1106.0902, subm. to EPJC

number of jets, after full event selection, **e+jets**:



number of jets, after full event selection, **μ+jets**:



Cross-section

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

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

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

Main systematics:

- Jet Energy Scale
- Factorization scale

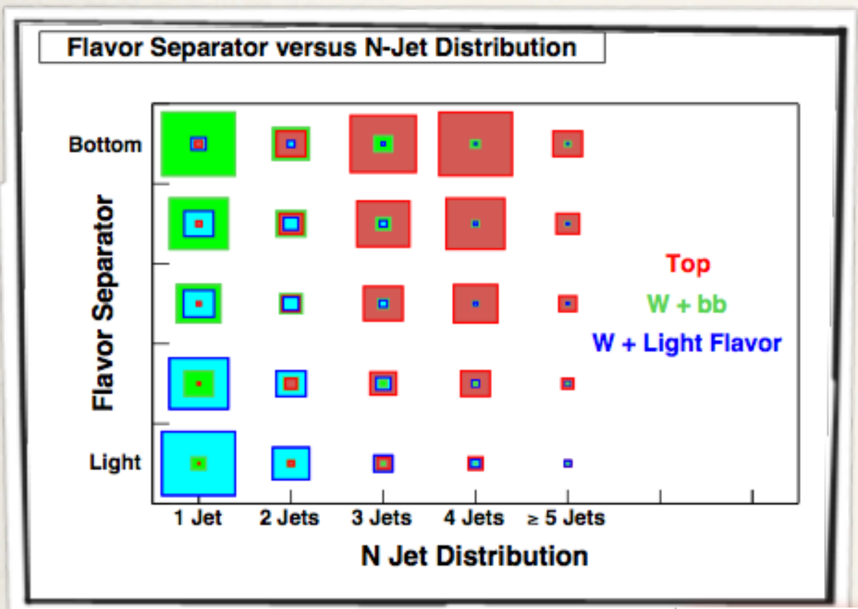
Top pair cross-section in lepton +jets with b-tagging

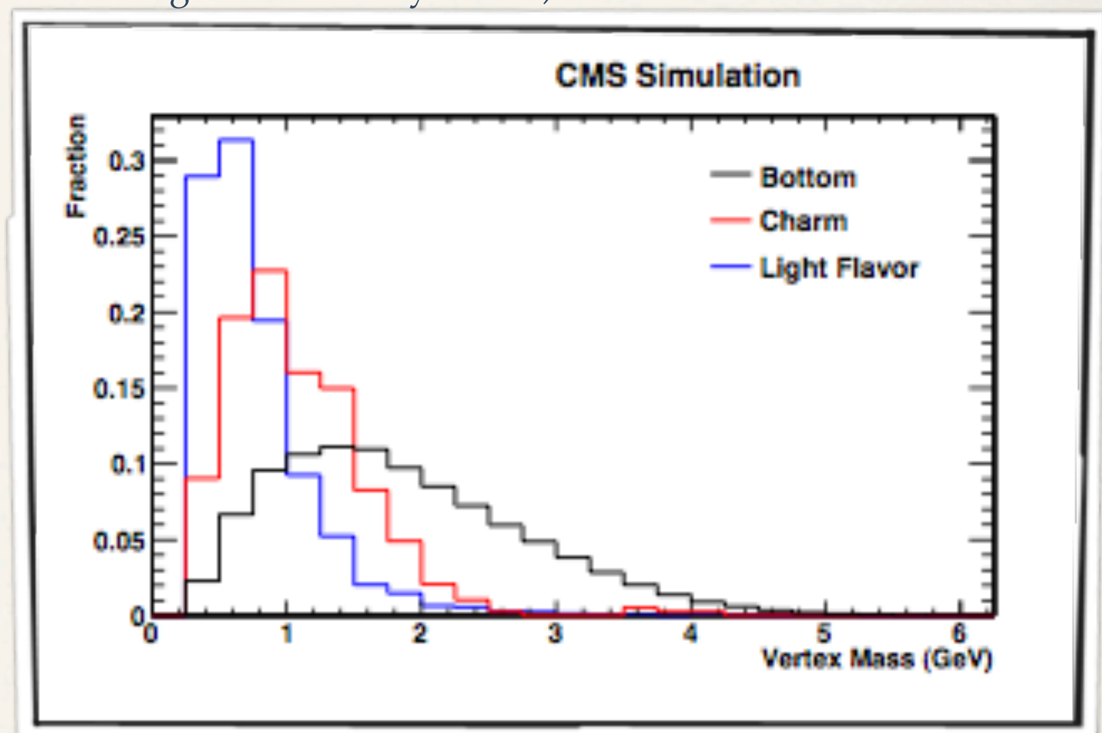
TOP-10-003

- Use events with ≥ 1 b-tag
  - Secondary Vertex (SV) algorithm

- The data are categorized in terms of the **N(jets)** and **N(b-tags)**.

2-D (N_{jets}, $N_{b\text{-}tag}$) template fit of the SV mass (invariant mass of the tracks forming the secondary vertex)





Most important systematics fitted in situ:

- Jet energy scale
- B-tag efficiency
- W+jets renormalization / factorization scale

Top pair cross-section in lepton +jets with b-tagging

TOP-10-003

Fit result.

Secondary Vertex mass distributions in bins of N(jets) and N(b-tag) for μ and e channels:

Combined cross-section

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

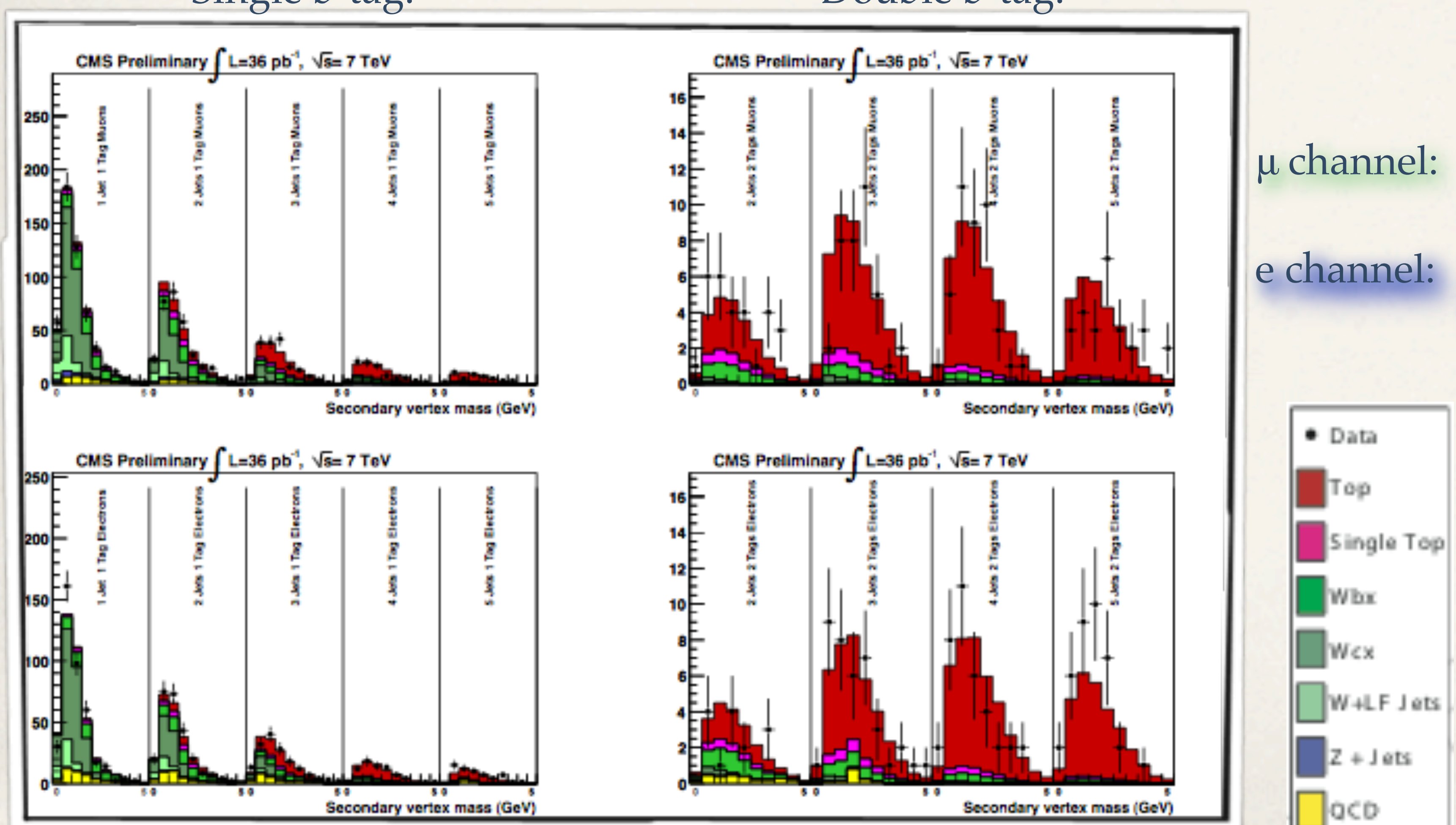
13 % uncertainty

μ channel: $\sigma_{t\bar{t}} = 145 \pm 12\ (\text{stat.}) \pm 18\ (\text{syst.}) \pm 6\ (\text{lum.})\ \text{pb}$

e channel: $\sigma_{t\bar{t}} = 158 \pm 14\ (\text{stat.}) \pm 19\ (\text{syst.}) \pm 6\ (\text{lum.})\ \text{pb}$

Single b-tag:

Double b-tag:



Top pair cross-section in lepton +jets with b-tagging

cross-check analyses

TOP-10-003

- **Soft muon tagging in μ+jets**

  - Orthogonal method to identify b-jets
  - Suffers from reduced efficiency

- **Counting experiment in e+jets**

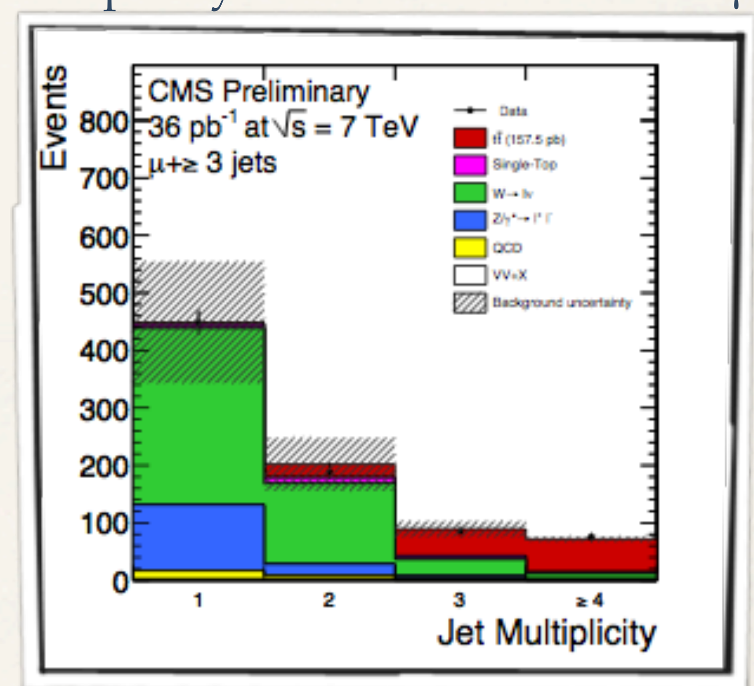
  - W+jets background: assume fixed ratio W+ ≥ n Jets / W + ≥ (n+1) Jets (Berends-Giele method)

- **Neural network analysis in μ+jets**

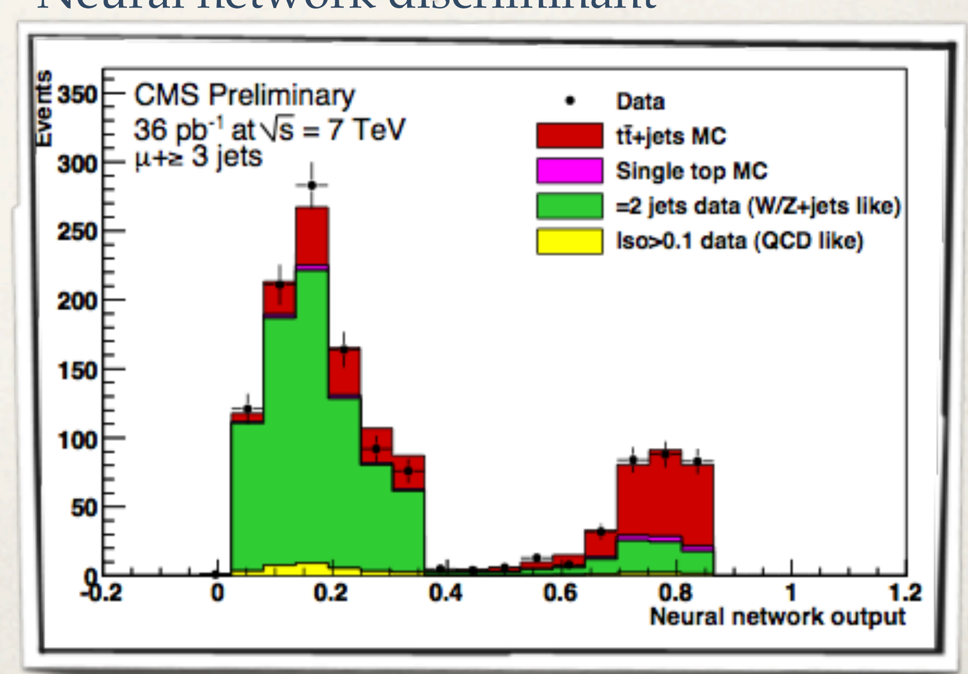
  - NN input variables: ΔR(jet1,jet2), η_μ, b-tag

All in good agreement!

jet multiplicity of events with ≥ 1 soft-μ tag

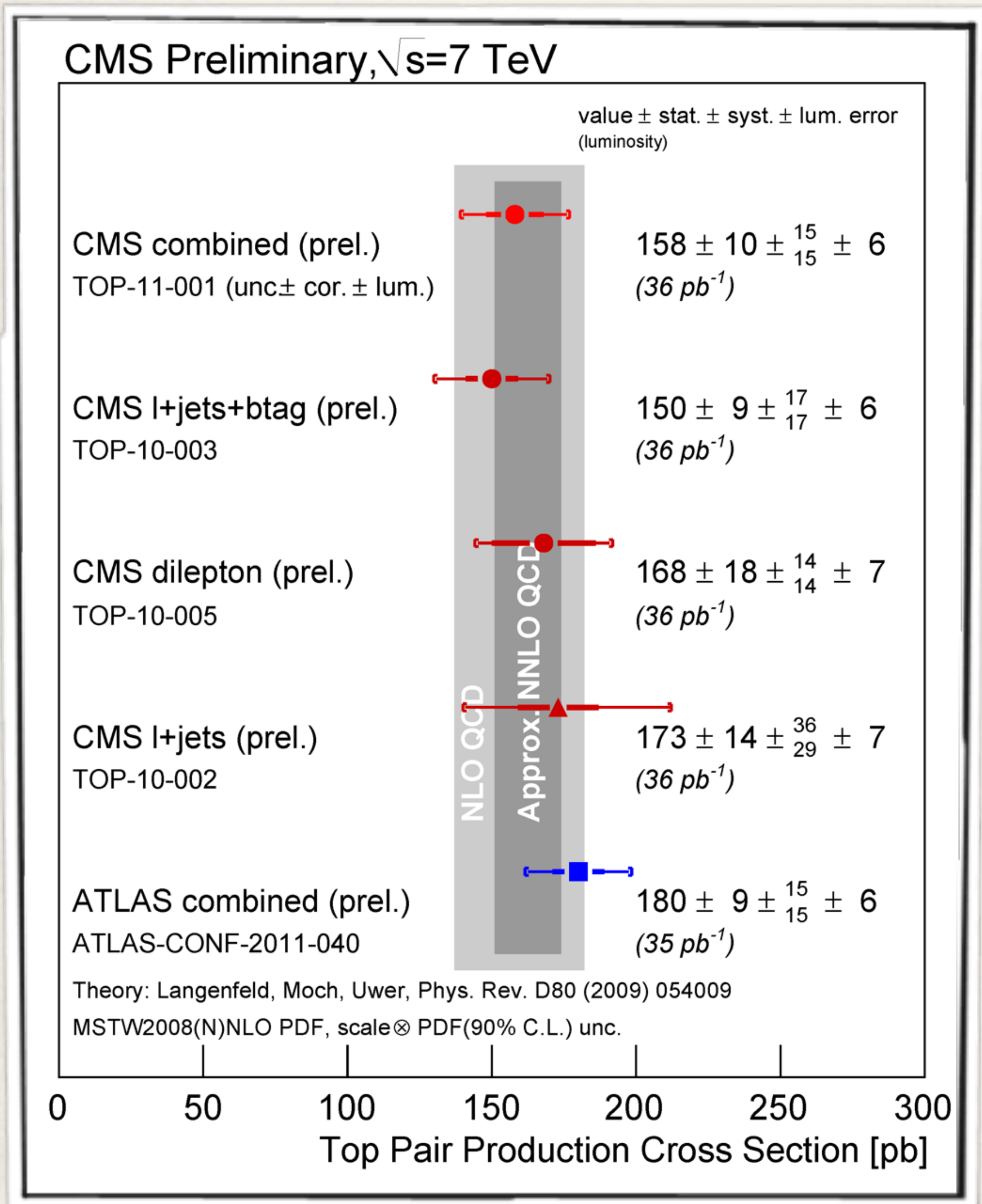


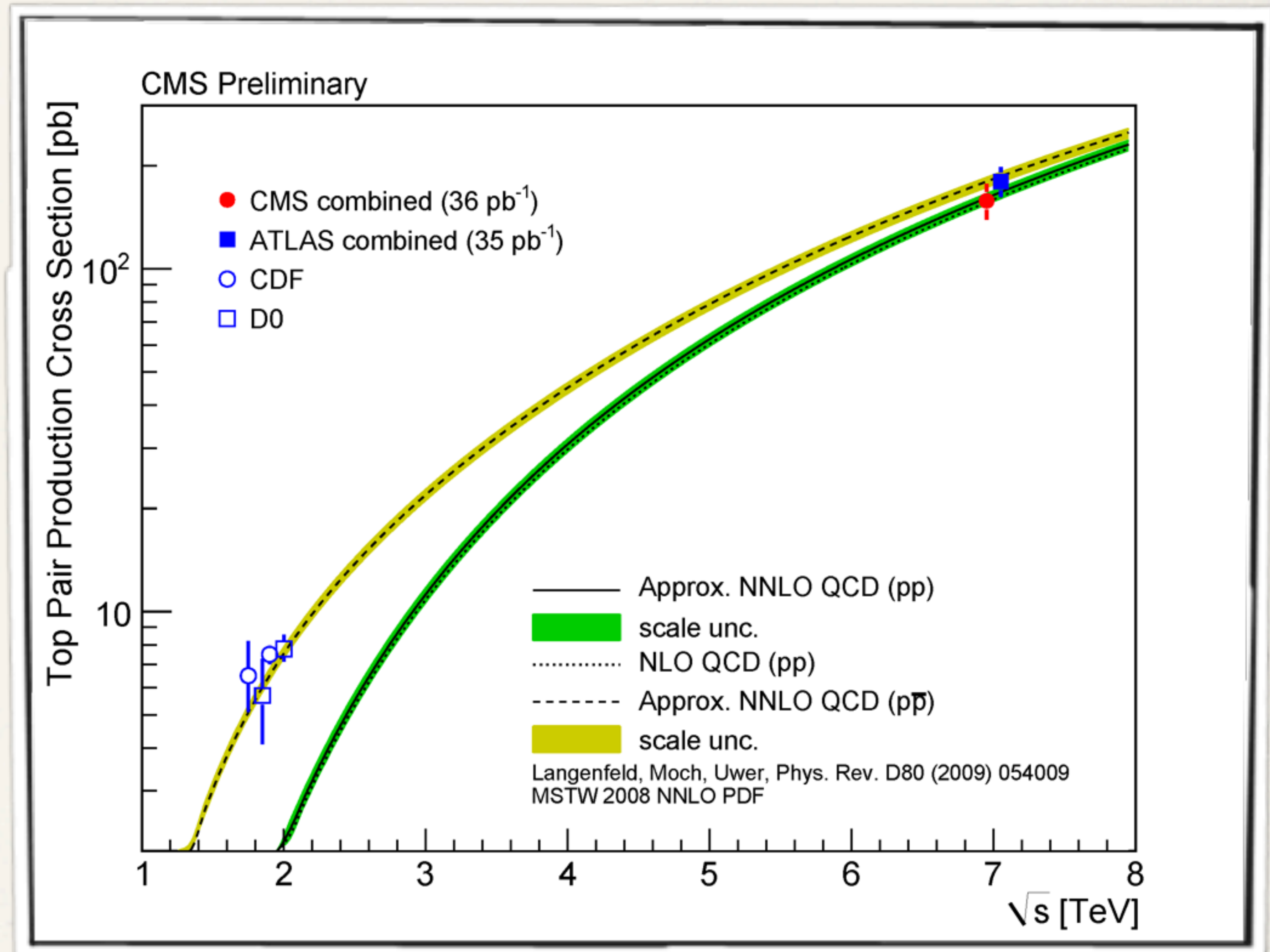
Neural network discriminant



Top pair cross-section combination

TOP-11-001





Precision of CMS combination: 12%

Very good agreement with theory!

Top Mass in dileptons

arXiv:1105.5661, acc. by JHEP

- Event selection similar to dilepton cross-section
- Two methods to deal with under-constrained system.

- **Analytical Matrix Weighting Technique (aMWT):**

  - solves equations for m_{top} and assigns weights to each solution

  - for each event, take the m_{top} with the highest sum of weights

  - based on MWT method from D0: PRL 80 (1998) 2063

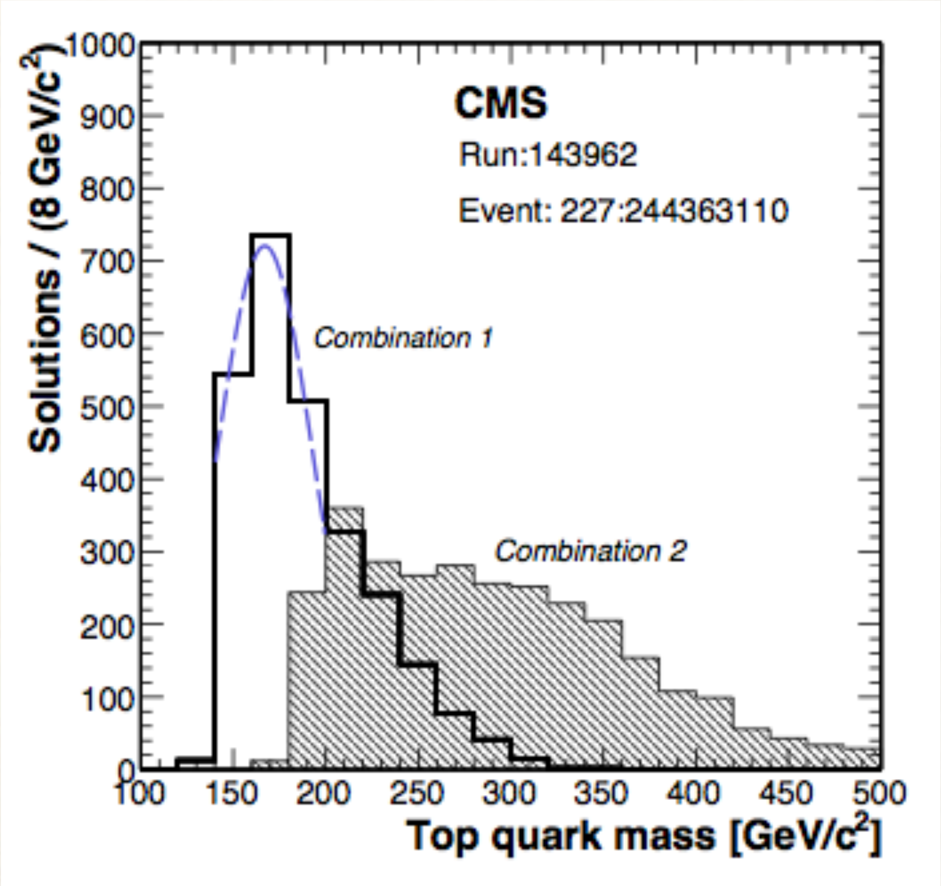
- **KINb Method:**

  - solves kinematic equations and accepts solutions that are within $\Delta m_{top} < 3$ GeV

  - for each event, combination with largest number of solutions is chosen

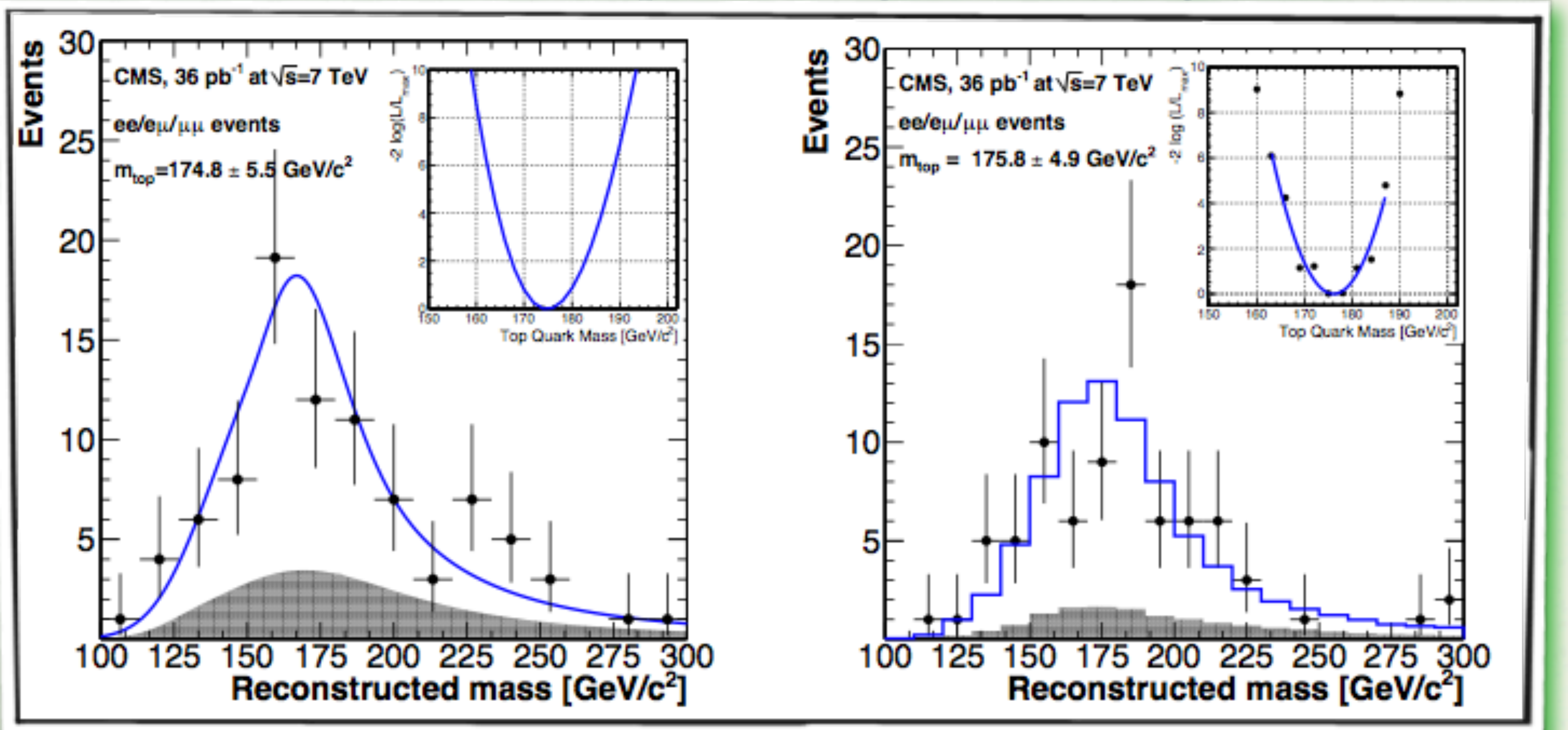
  - mass estimate from Gaussian fit around peak of solutions

  - based on KIN method from CDF: PRD 73 (2006) 112006



Top Mass in dileptons (arXiv:1105.5661)

- **Measure Top mass from a maximum likelihood fit of the mass distribution to the templates of signal and background**



Systematic uncertainties
- jet energy scale
- pile-up
- Underlying Events

First m(top) measurement at LHC!

Good agreement with world average 173.3 ± 1.1GeV

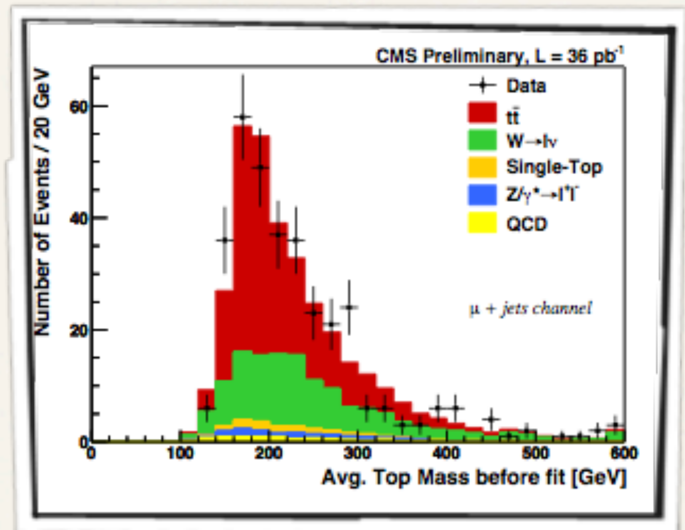
Combined Mass measurement

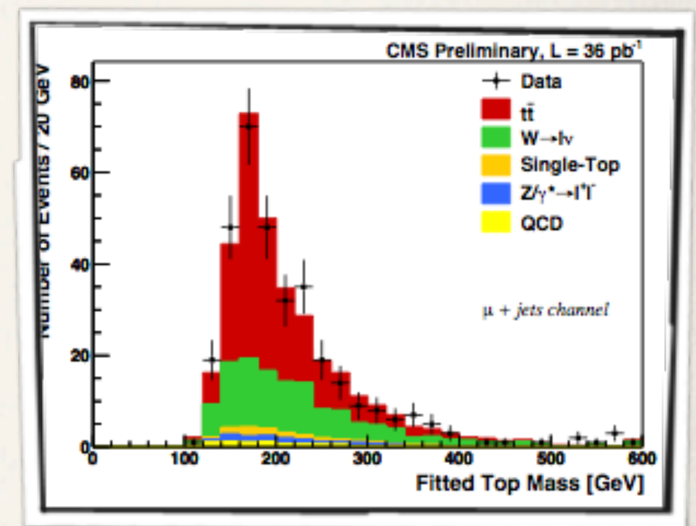
Method	Measured m_{top} (in GeV/c^2)
AMWT	$175.8 \pm 4.9\,(\text{stat.}) \pm 4.5\,(\text{syst.})$
KINb	$174.8 \pm 5.5\,(\text{stat.})^{+4.5}_{-5.0}\,(\text{syst.})$
Combined	$175.5 \pm 4.6\,(\text{stat.}) \pm 4.6\,(\text{syst.})$

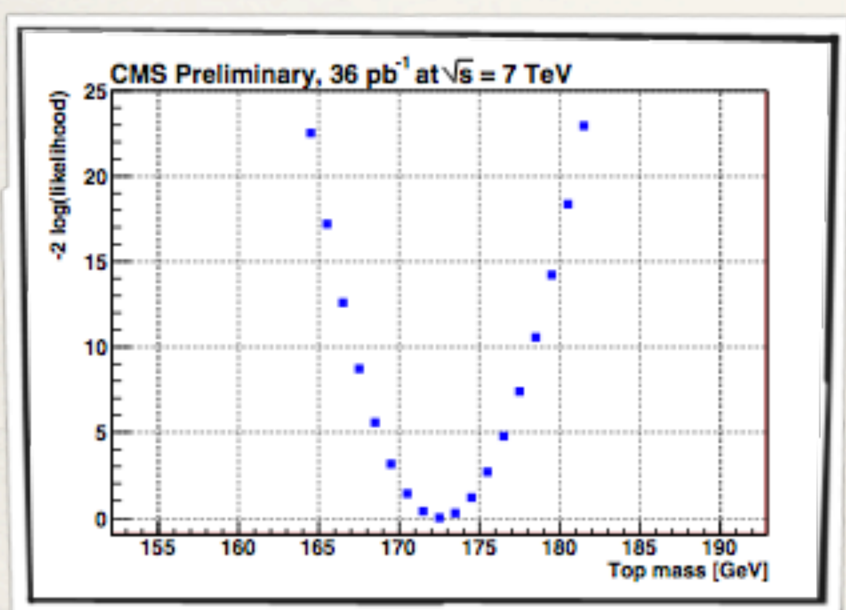
Top Mass in lepton+jets

CMS PAS TOP-10-009

- Using the “Ideogram method” (DELPHI, D0, CDF);
- constrained kinematic fitter used to reconstruct the event’s kinematic;
- event selection as in the cross-section analysis + requirement on the χ^2 of the fit;
- for each event, a likelihood is calculated using the output of the kinematic fit;
- a joint likelihood fit over all the events from the selected sample is used to extract the top quark mass.







- Systematics:
  - dominated by jet energy scale

World average:
173.3 ± 1.1 GeV

Central value (e/μ +jets channels)

$$m_t = 173.1 \pm 2.1(\text{stat})^{+2.4}_{-2.1}(\text{JES}) \pm 1.4(\text{other syst})\ \text{GeV}.$$

Combined measurement with dileptons

$$m_t = 173.4 \pm 1.9(\text{stat}) \pm 2.7(\text{syst})\ \text{GeV}.$$

2% uncertainty!

t-channel single top cross-section

Single top event selection

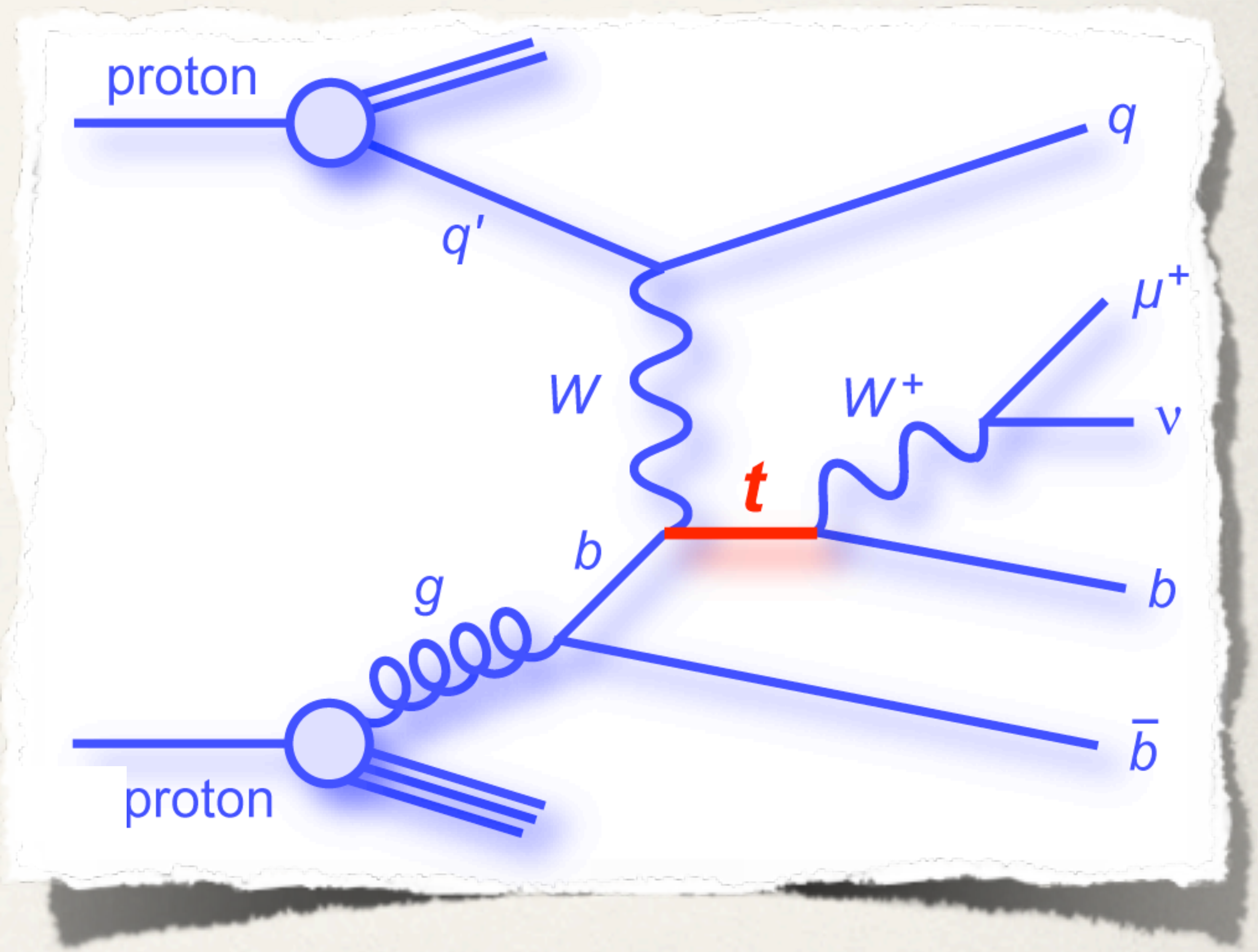
arXiv:1106.3052, subm. to PRL

- 1 isolated electron (p_T>30 GeV) or muon (p_T>20 GeV)

- 2 jets, E_T>30 GeV, $|\eta|$<**5.0**
  - One "tight" b-tag
  - veto on "loose" b-tag (2D analysis)
  - veto on back-to-back jets (BDT analysis)

- W transverse mass > 40 (50) GeV for μ (e).

- top candidate reconstructed by imposing a constraint on the W mass



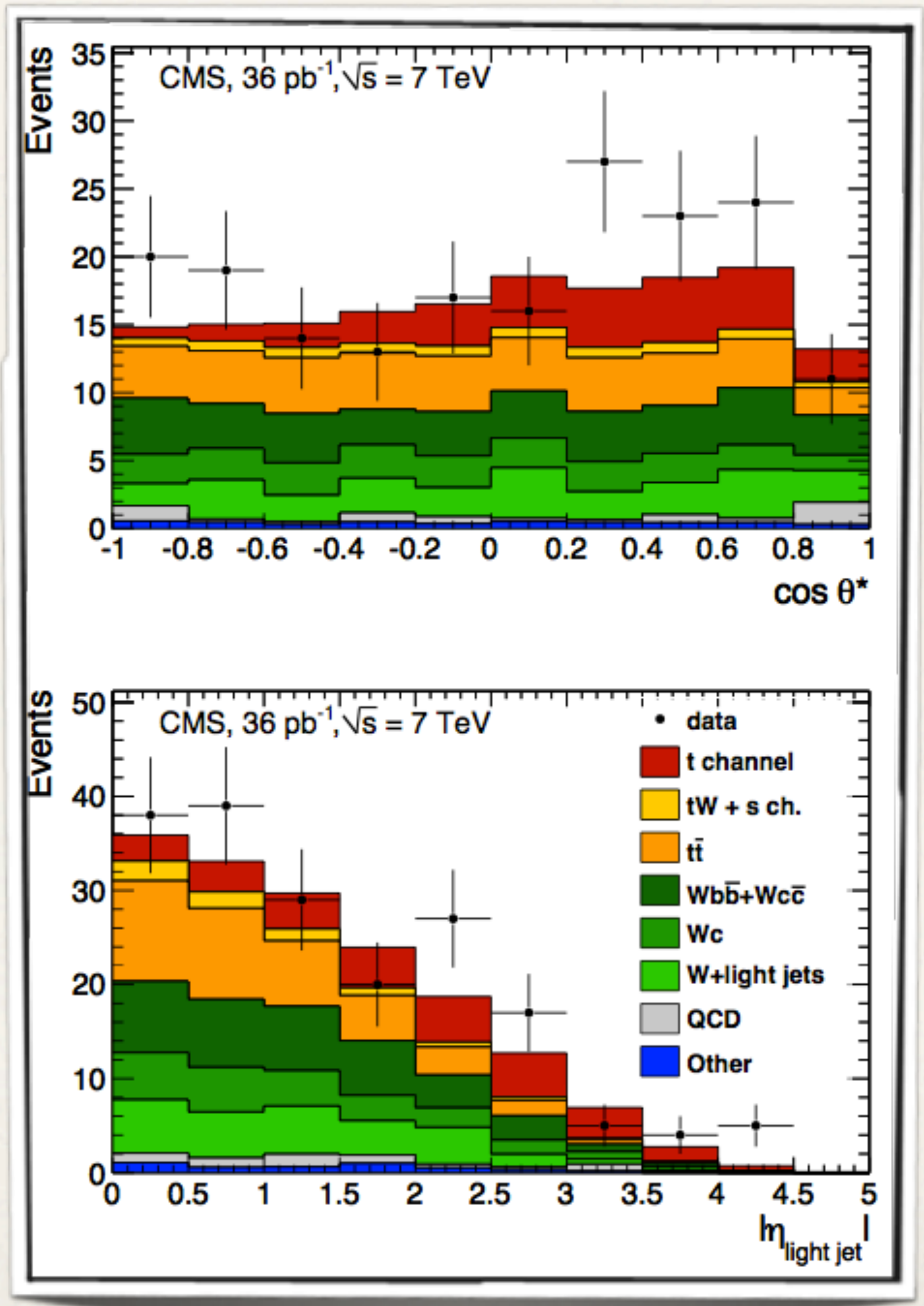
t-channel single top cross-section

2 complementary analyses: **2D template fit** (2D) and **Boosted Decision Tree** (BDT)

arXiv:1106.3052, subm. to PRL

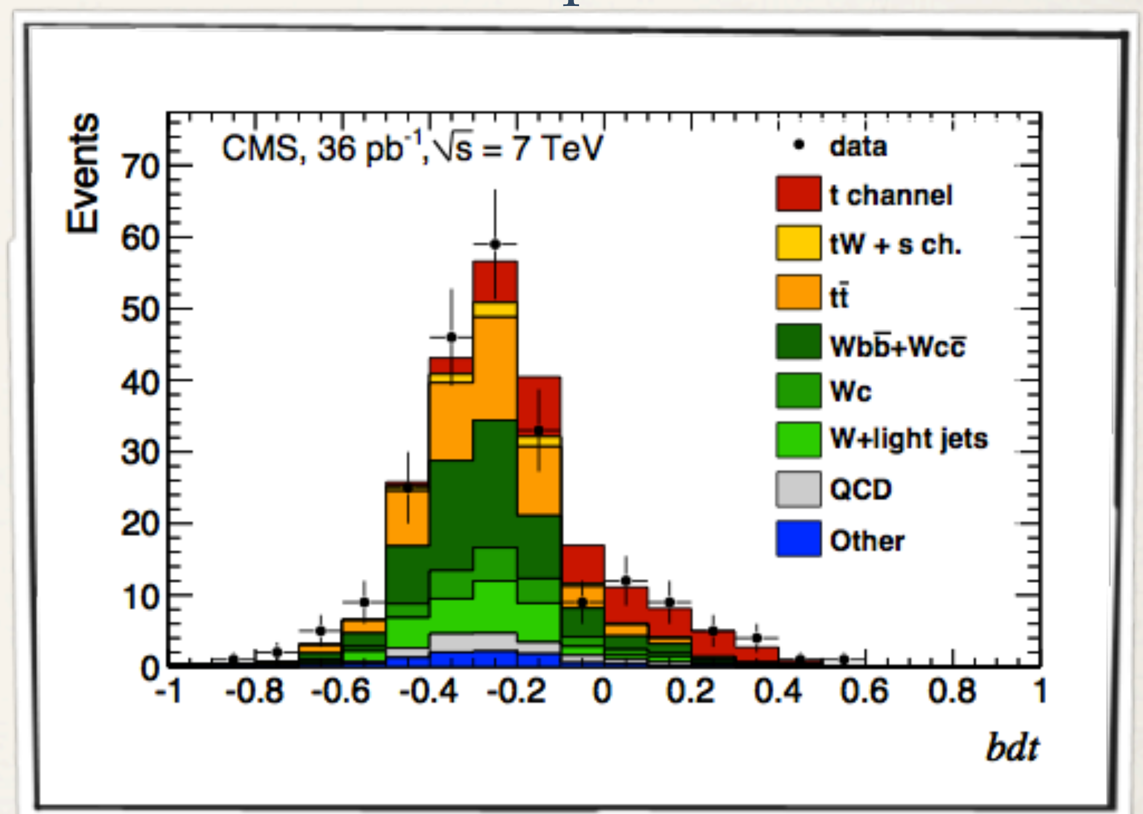
2D analysis, maximum likelihood fit to:

- **cos(θ*),** **θ*** angle between the lepton and the untagged jet.
- **$\eta_{\text{light jet}}$** of the untagged jet.



BDT analysis:

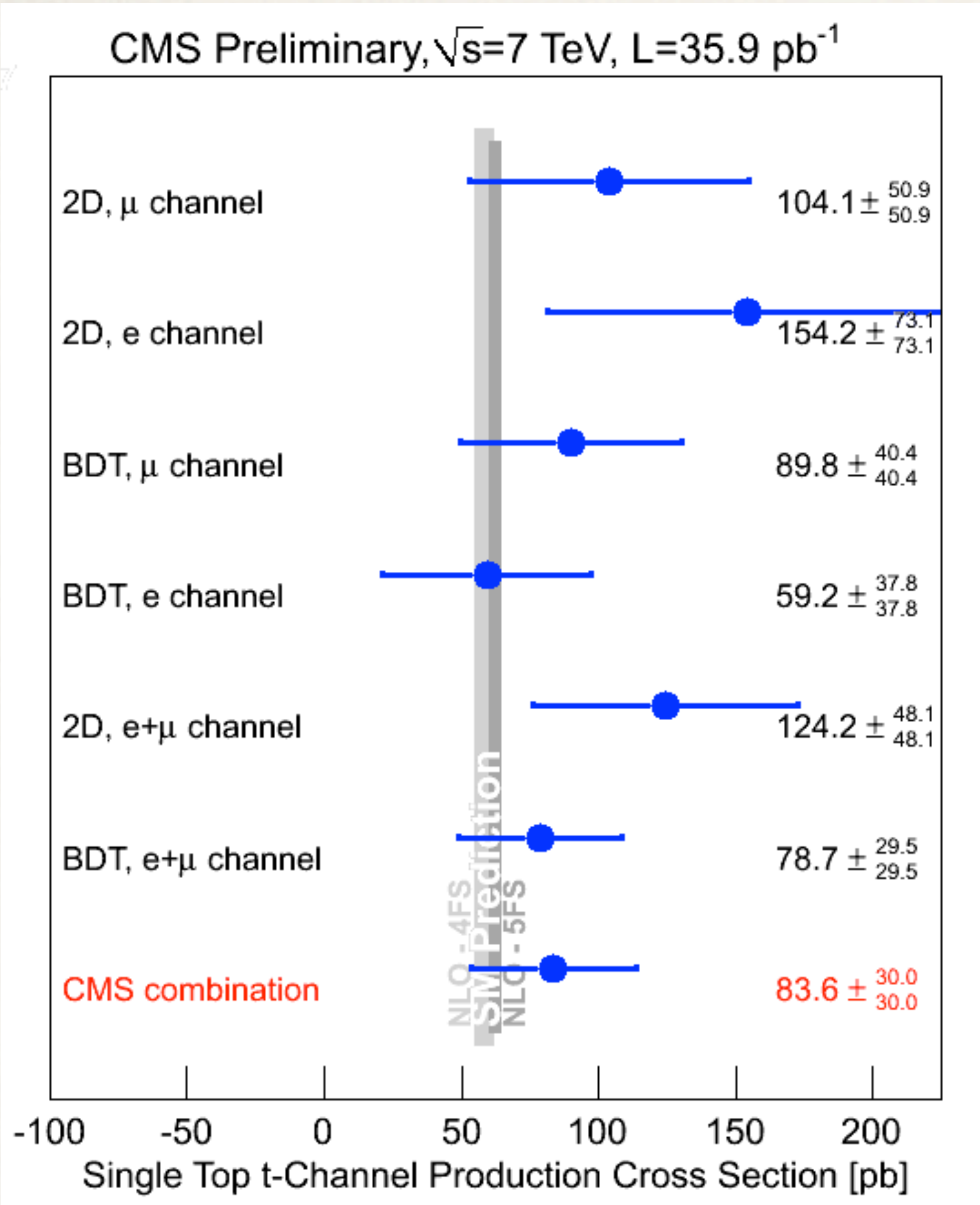
- based on 37 input observables
- cross-section extracted from fit to the BDT output.



Main systematics:

- b-tagging efficiency, signal model, factor./renorm. scale for W/Z+jets, JES.

t-channel single top cross-section



arXiv:1106.3052, subm. to PRL

2D and BDT combined Cross-section:

$$\sigma = 83.6 \pm 29.8(stat.+syst.) \pm 3.3(lumi.)$$

observed (predicted) sensitivity:

- 2D analysis: 3.7 (2.1) σ
- BDT analysis: 3.5 (2.9) σ

Test of the CKM unitarity:

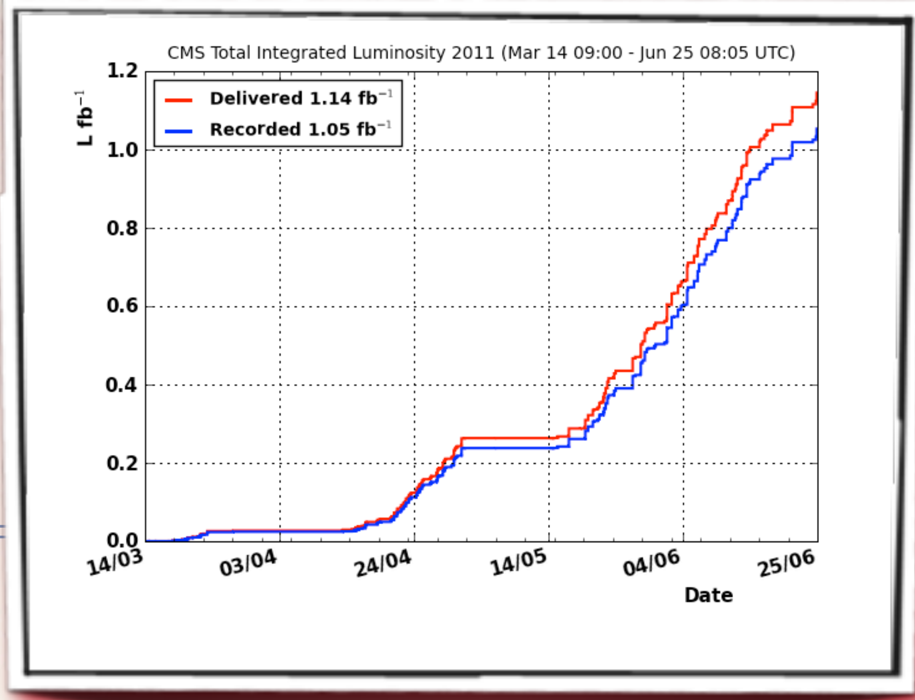
- use the prior knowledge that $0 \leq |V_{tb}|^2 \leq 1$
  - 2D analysis: $|V_{tb}| > 0.62$
  - BDT analysis: $|V_{tb}| > 0.68$

Confirmed Tevatron single top quark observation.

First single top cross-section measurement in pp collisions!

Reached 33% precision already, with only 2010 data!

Summary and Outlook



- Many CMS Top Physics results already in the first year of data taking!

  Impressive precision:
  - top pair production cross-section to 12 %
  - top mass to 2 %
  - t-channel Single Top cross-section to 33%

- Other CMS Top Physics results not covered in this talk:
  - top pair invariant mass
  - forward-backward charge asymmetry
  - like-sign top pairs

- 2011 dataset: factor of 30 integrated luminosity already now!

- Stay tuned for a wealth of novel results on Top Physics to appear very soon!

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

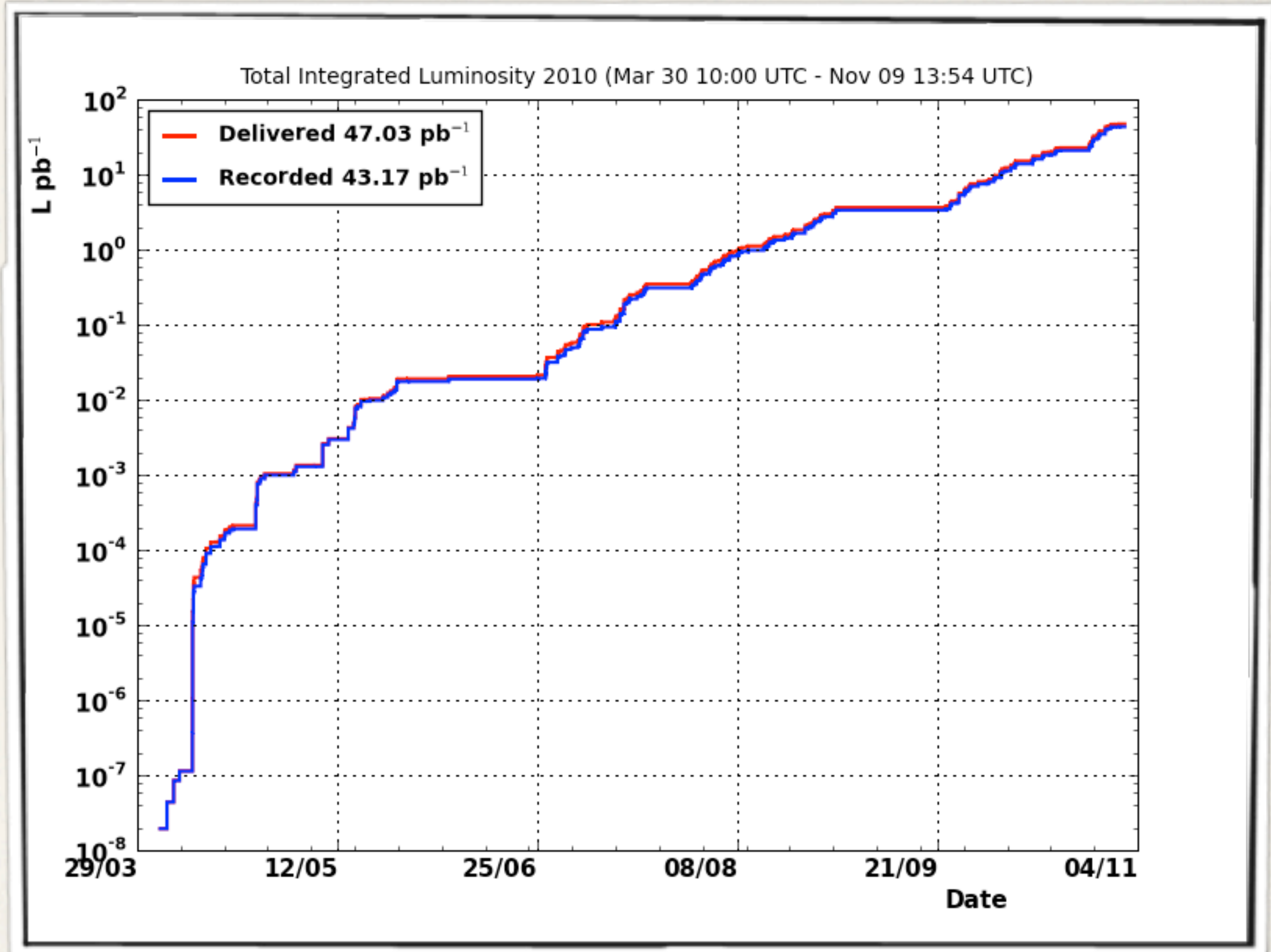
BACKUP

LHC p-p collisions at 7 TeV center-of-mass energy

The LHC

- LHC peak instantaneous luminosity: ~1200 x $10^{30} cm^{-2} s^{-1}$

data-taking period **recorded and certified by the CMS** experiment shown in this talk, corresponding to **36 pb^{-1}**



CMS performance: 92% average efficiency

MC Simulation and Theory uncertainties

- **Use MADGRAPH to simulate top signal and most important backgrounds (W/Z+jets)**
  - Matrix elements with up to 3 (tt) or 4 (W/Z) extra jets
  - ME+PS matching using MLM prescription
  - Scales set as
  - Cross sections rescaled to inclusive (N)NLO values
- **Dedicated samples to estimate modeling uncertainties, varying**
  - scale Q by factors 2.0 and 0.5
  - amount of ISR/FSR radiation
  - matching thresholds by factors 2.0 and 0.5
  - MC@NLO as alternate signal generator
- **Use data-driven backgrounds wherever possible**

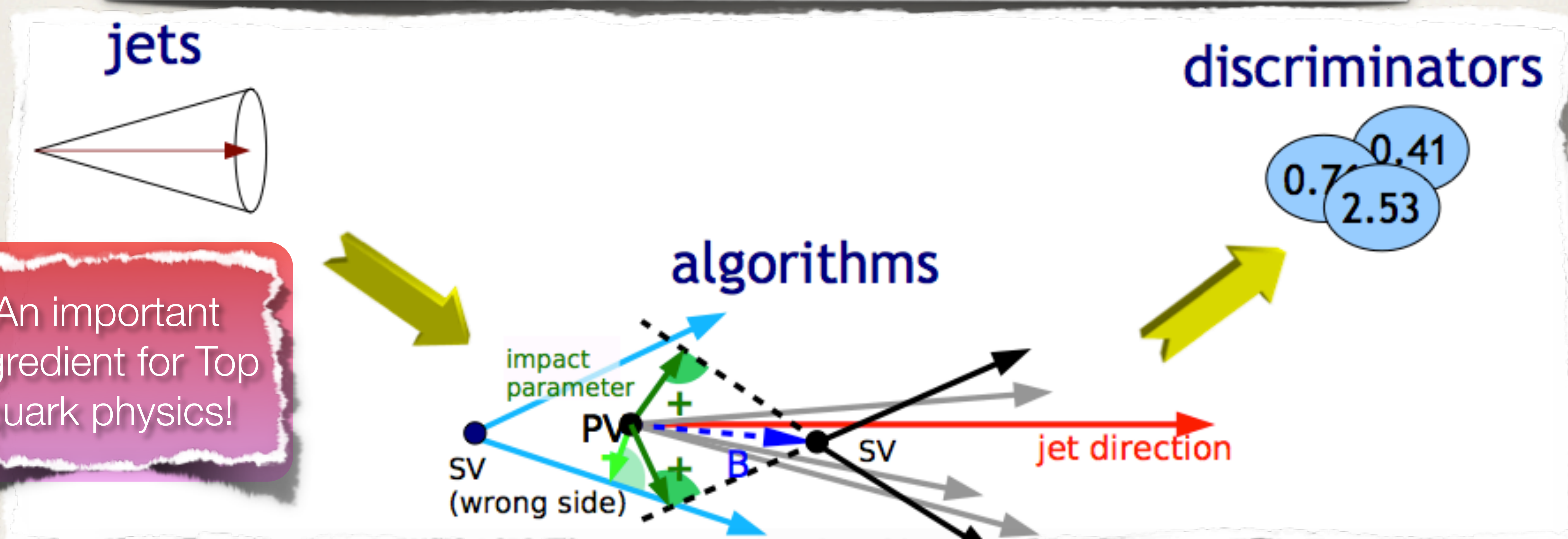
Total cross-section at 7 TeV:

- NLO (MCFM): $\sigma_{t\bar{t}}^{\mathrm{NLO}} = 158^{+23}_{-24}$ pb
- approx. NNLO
  - Kidonakis, PRD 82 (2010) 114030: $\sigma_{t\bar{t}} = 163^{+11}_{-10}$ pb
  - Langenfeld, Moch, Uwer, PRD80 (2009) 054009;
  - Aliev et al., CPC 182 (2011) 1034: $\sigma_{t\bar{t}} = 164^{+10}_{-13}$ pb

Enhancing the top-antitop signal by identifying b-jets: b-tagging

b-quarks significantly differ from light flavor quarks by:

- ✦ **mass:** m = 4.2 GeV;
- ✦ **lifetime:** τ ≈ 1.5 ps -> ~1.8 mm (at 20 GeV) before decay;
- ✦ **decay:** weak, mostly into c-quarks, **~20% decay into leptons**);
- ✦ **tracks:** high decay multiplicity, significant displacement;
- ✦ **Secondary vertices (SV):** tracks intersecting at a common vertex

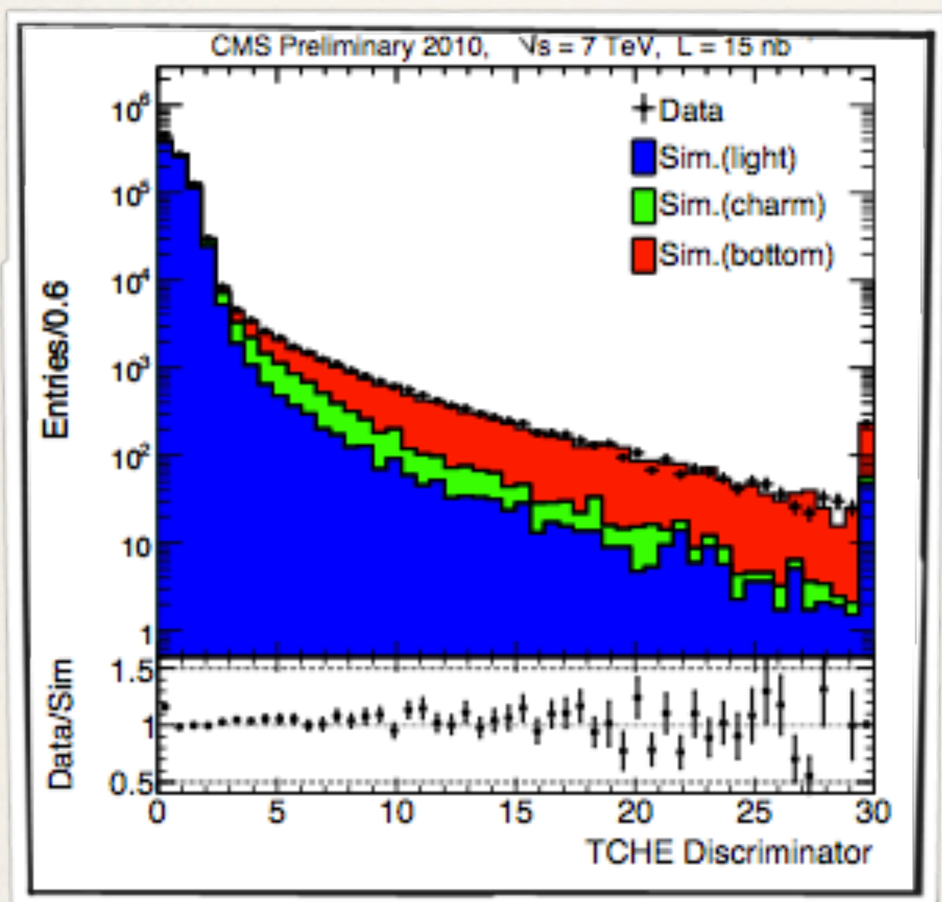


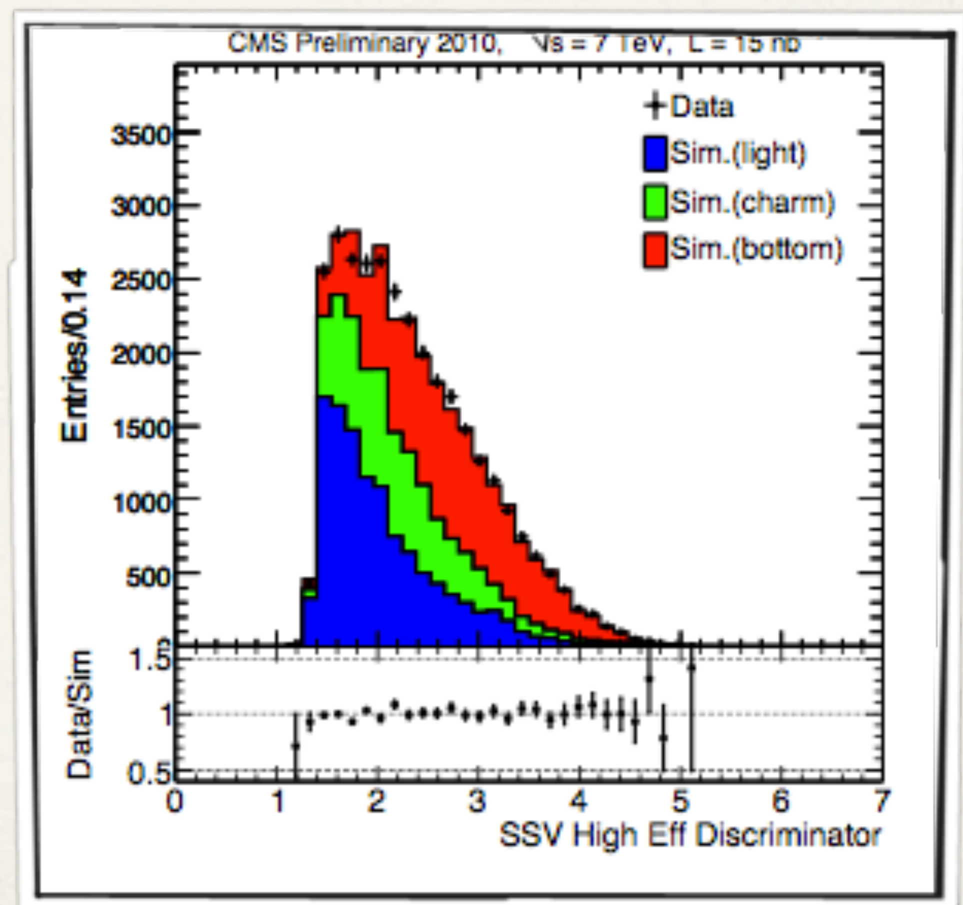
An important ingredient for Top quark physics!

Enhancing the top pair signal by identifying b-jets: b-tagging

CMS PAS BTV-10-001

- ✦ “Track counting” tagger: Uses Impact Parameter significance of the n-th track as discriminator;
- ✦ “Secondary Vertex” tagger: uses discriminator based on 3D flight distance;





- ✴ General good data-MC agreement;
- ✴ Differences are taken into account in analysis by applying a scale factor (very close to unity).