Top quark pair production with taus or no leptons

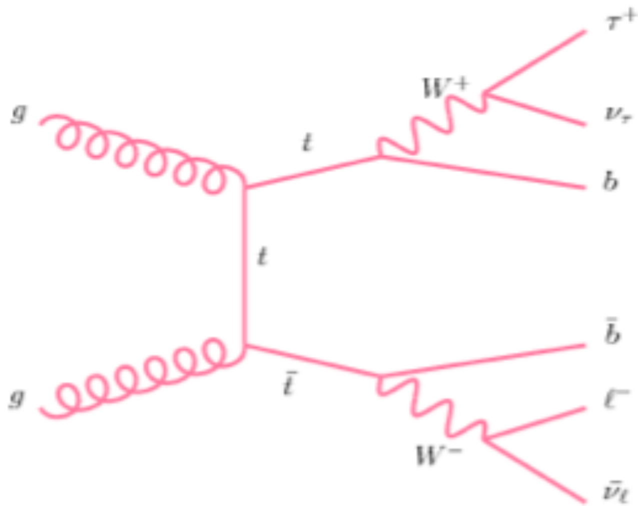
Michele Gallinaro

LIP Lisbon

(on behalf of the CDF, D0, ATLAS and CMS collaborations)

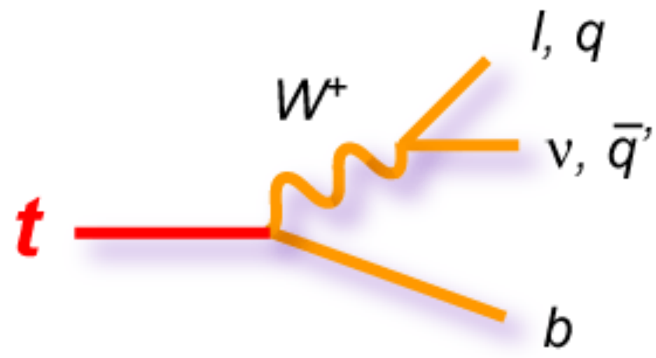
- ✓ Introduction
- ✓ Cross section measurements with taus
- ✓ All-hadronic cross section measurements

Taus/jets in top quark decays



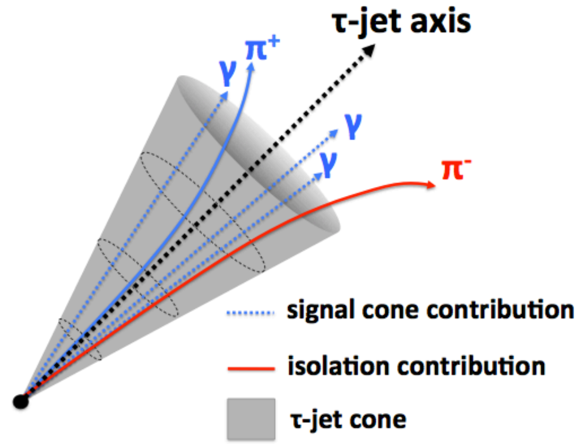
Channel	Signature	BR
Dilepton(e/μ)	$ee,\mu\mu,e\mu$ + 2*b*-jets	4/81
Single lepton	e,μ + jets + 2*b*-jets	24/81
All-hadronic	jets + 2*b*-jets	36/81
Tau dilepton	$e\tau$, $\mu\tau$ +2 *b*-jets	4/81
Tau+jets	τ + jets + 2*b*-jets	12/81

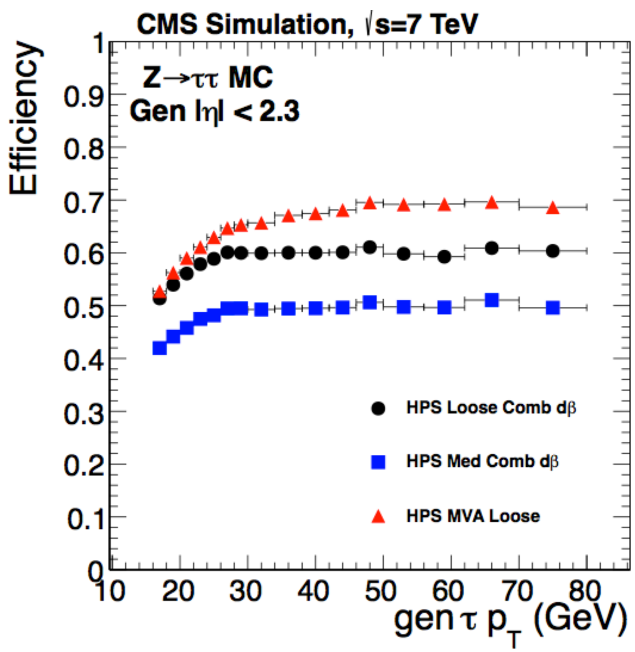
- Good fraction of all top quark decays
  - \`Tau dileptons' have same rate as e/μ dilepton channel
- Challenging (lower p_T than e or μ due to ν's)
- Involves exclusively 3rd generation quarks and leptons
- Probe new physics processes



Tau jet identification

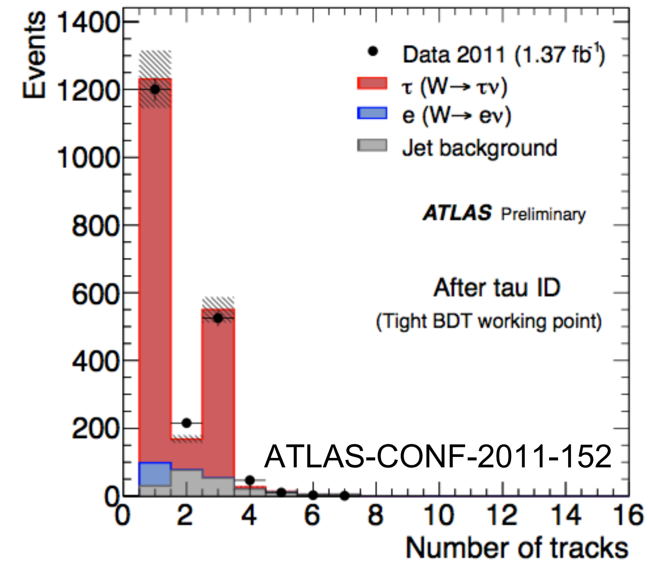
- Taus decay 65% to hadrons (i.e. jets) and 35% to leptons
  - narrow jet with few tracks
  - leptonic tau decays are similar to prompt leptons (lepton p_T is softer, 3-body decay)
- Hadronic tau decays
  - Main background from jets/electrons
  - Identified based on decay modes, charged hadrons, and ECAL deposits
- CMS: ``Hadron Plus Strips'' (HPS) algorithm
  - hadronic tau decays are reconstructed with Particle Flow (PF)
  - Uses photon conversion in tracker ($\gamma \rightarrow e^+e^-$)
  - Combines PF EM particles (γ,$e^\pm$) in "strips"
  - "strips" are combined with PF charged hadrons
  - Individual decay modes are reconstructed
- Fake Rate ~3% for 70% efficiency



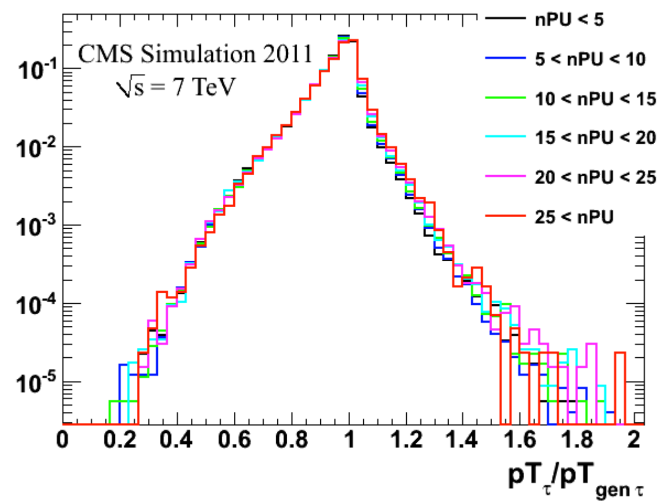


Tau jet identification (cont.)

- ATLAS tau-ID uses BDT
  - Select jets with 1,2, or 3 tracks (p_T>1 GeV, lead track p_T>4 GeV)
- Remove overlap with muon or electron
- Remove electrons misidentified as τ_{had} with BDT
- Another BDT to separate τ_{had} and jets



- determine eff/misID from Z/W decays:
  - BDT medium (ATLAS): τ eff.~63%, fake ~ 3%
- tau ID eff uncertainty: 5-6%



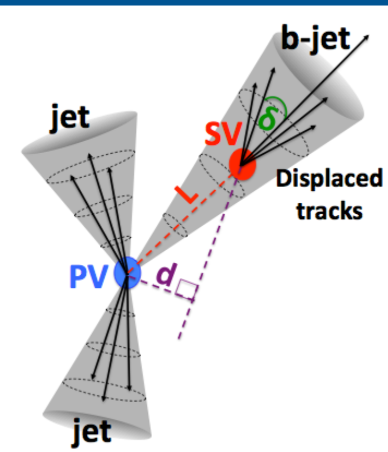
- Efficiency vs pileup: small dependence

b-tagging

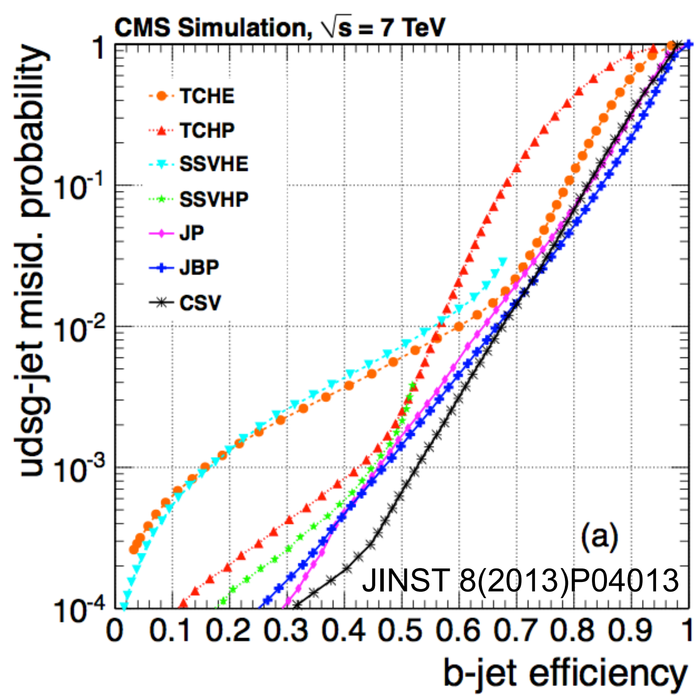
- Many algorithms deployed
- Good separation from light jets and c-jets
- Rely on long lifetime and high-mass of B-hadrons
- Relies on tracks with large impact parameter (IP)
  - Tracks ordered in decreasing IP significance (S_{IP})
  - Jet b-tagged if S_{IP} above threshold
  - For p_T=50-80 GeV, tag rate ~76% (mistag rate ~a few%)

(CMS)

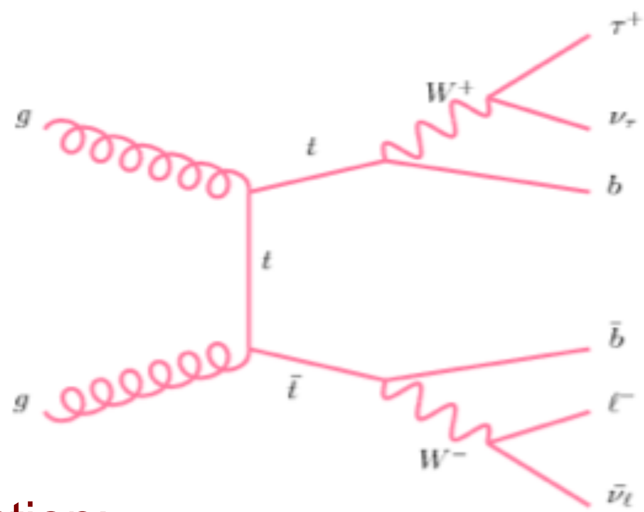
- Similar for ATLAS:
  - IP3D: track weights based on S_{IP}
  - SV1 reconstruct inclusive displaced vertex
  - JetFitter: reconstruct multiple vertices along b-hadron line
  - Advanced NN



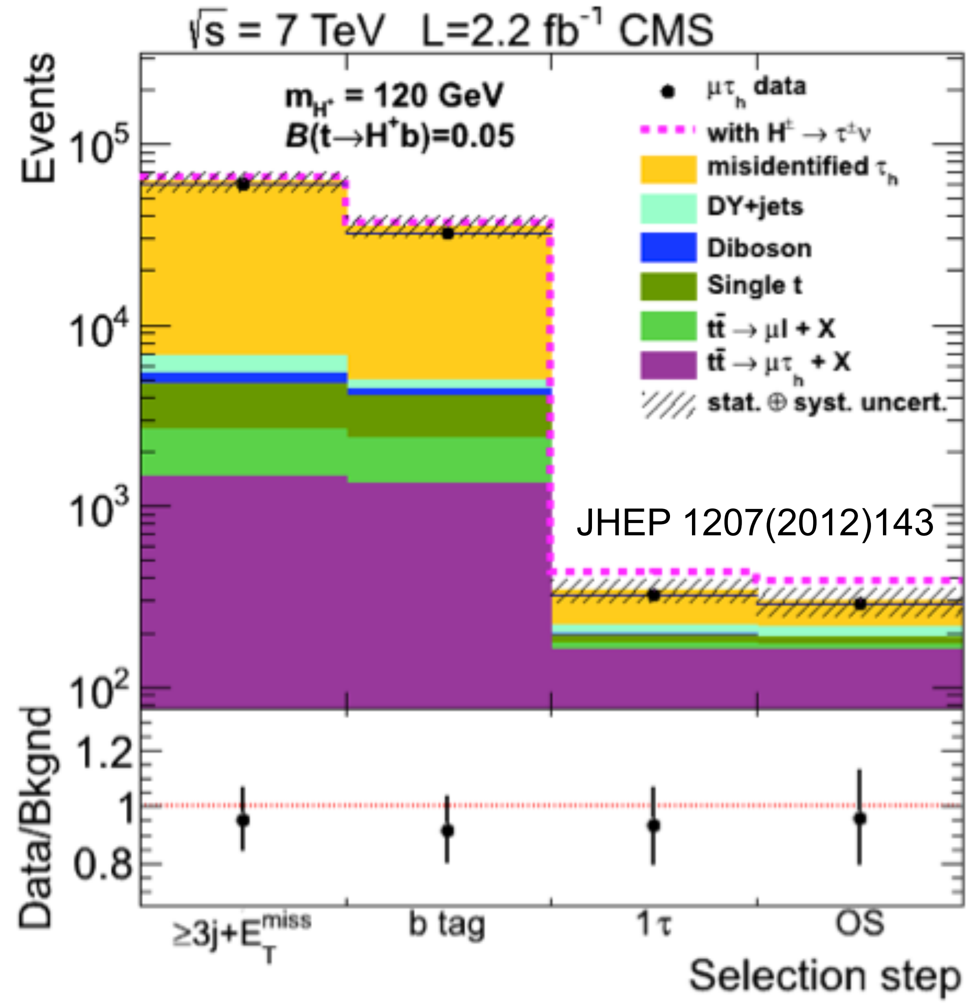
Operating points (CMS):
(tuned at jet p_T~80 GeV)
- Loose: 10% mistag
- Medium: 1% mistag
- Tight: 0.1% mistag



Tau+lepton final state

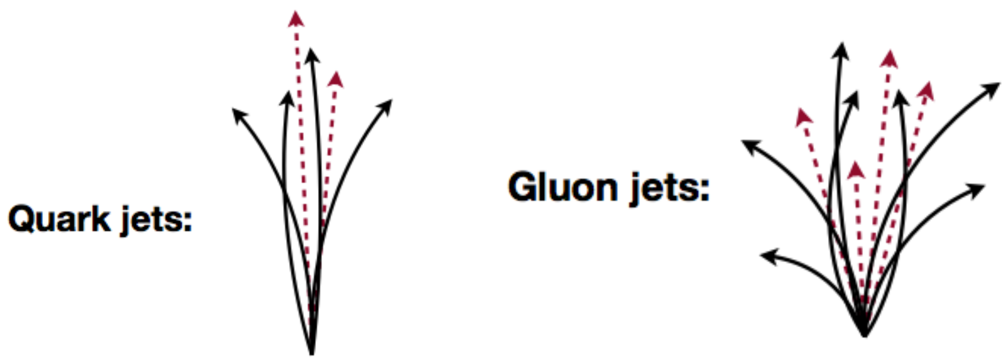


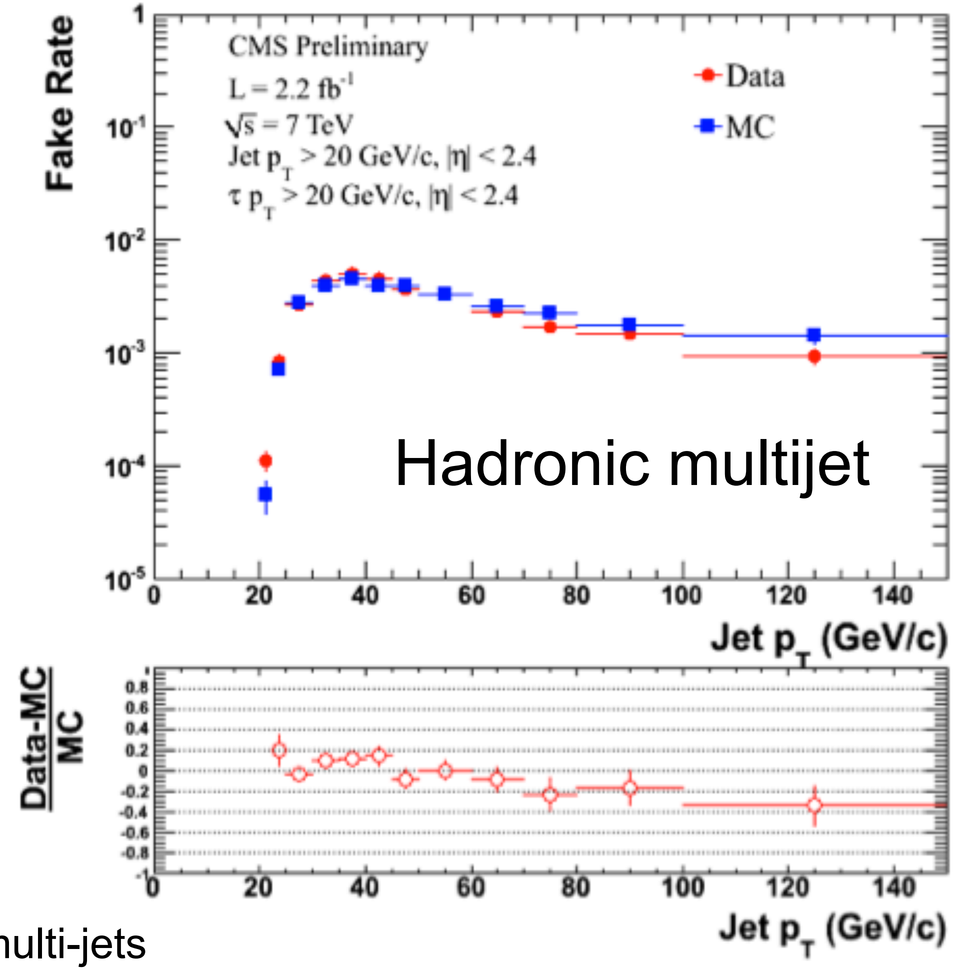
- Selection:
  - one isolated lepton (e/μ)
  - OS tau
  - at least two jets (one b-tagged)
  - MET
- Determine τ fakes from data
  - Expected to be dominated by quark/gluon jets
  - Estimate from multi-jet/W+jets, BDT: use data



Tau fake rate

- Main background from "fake" tau jets
- Background estimated from data:
  - Select "W+≥3 jets (1 lepton+MET+≥3 jets)
  - Apply to every jet the "jet→tau probability"
  - tau fake probability evaluated from data
  - Function of p_T, η, jet width
- Good agreement with expectations





Quark vs gluon jets:

- Different fake rates, different fractions in W+jet and multi-jets
- Gluon jets have higher multiplicities and softer constituents

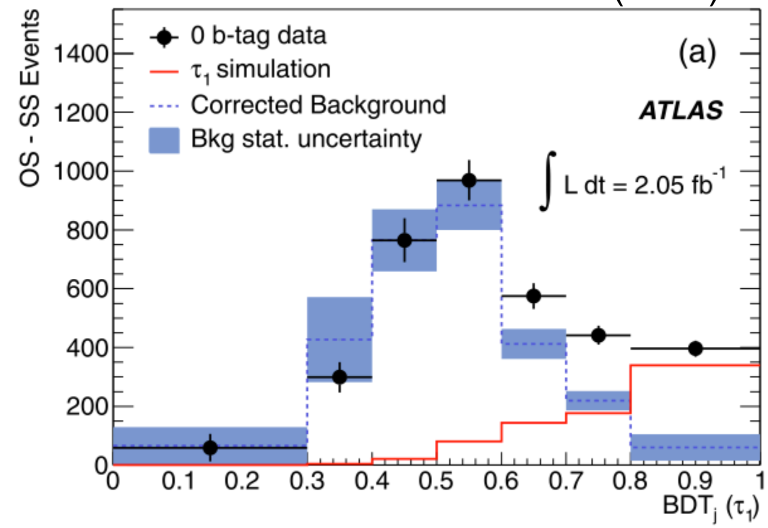
Alternative measurement: fit to BDT

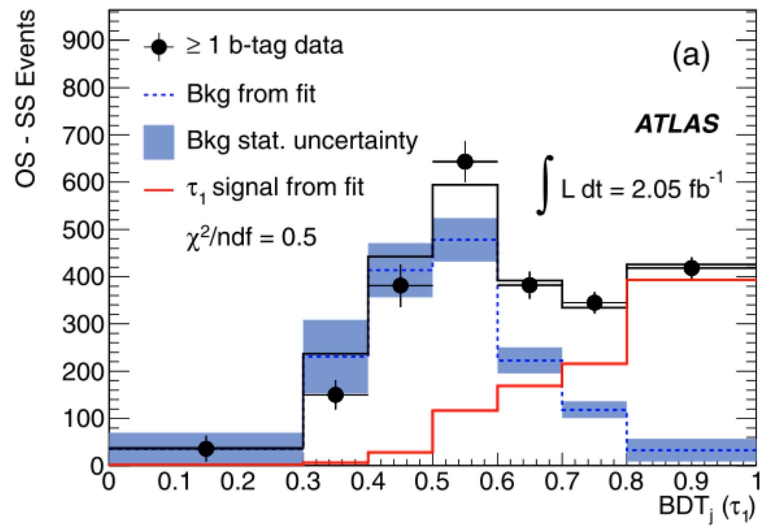
PLB 717(2012)89

Tau selection: use BDT to select τ_{had} vs *jet* vs *elec*

Measure cross section from fit to BDT

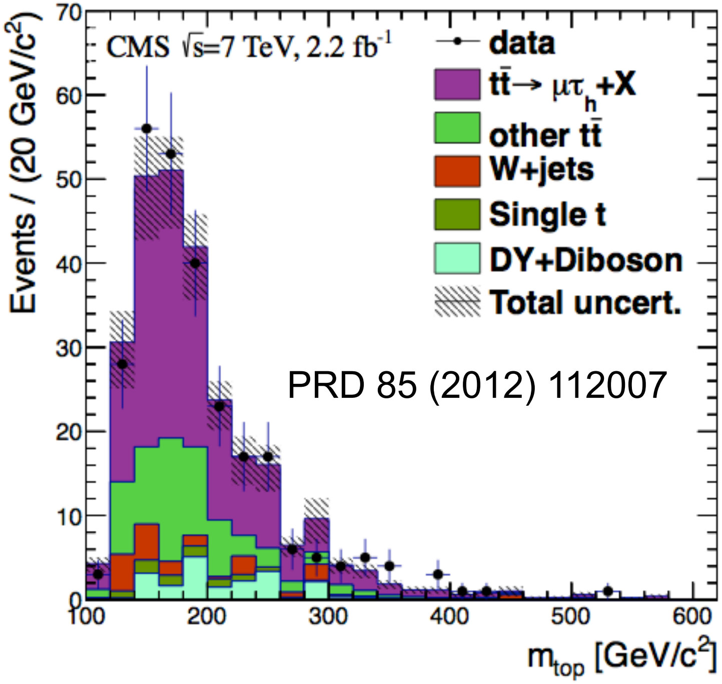
- Exploit SS sample in bkg estimate
- Signal and bkg templates from OS-SS distributions
  - gluon and b-bbar jet bkg contributions cancel out (approximately equal in OS/SS)
- Bkg: 0 b-jet selection to obtain fake τ_{had} template
  - Contribution of true τ_{had} evts is subtracted (MC)
  - Derived separately for 1- and 3-prongs
  - Apply MC correction for 0 b-jet to ≥1 b-jet extrapolation
- Signal: fit in ≥1b-tag data sample
  - Use fit to OS-SS BDT with signal+bkg templates
  - Shapes of templates are fixed



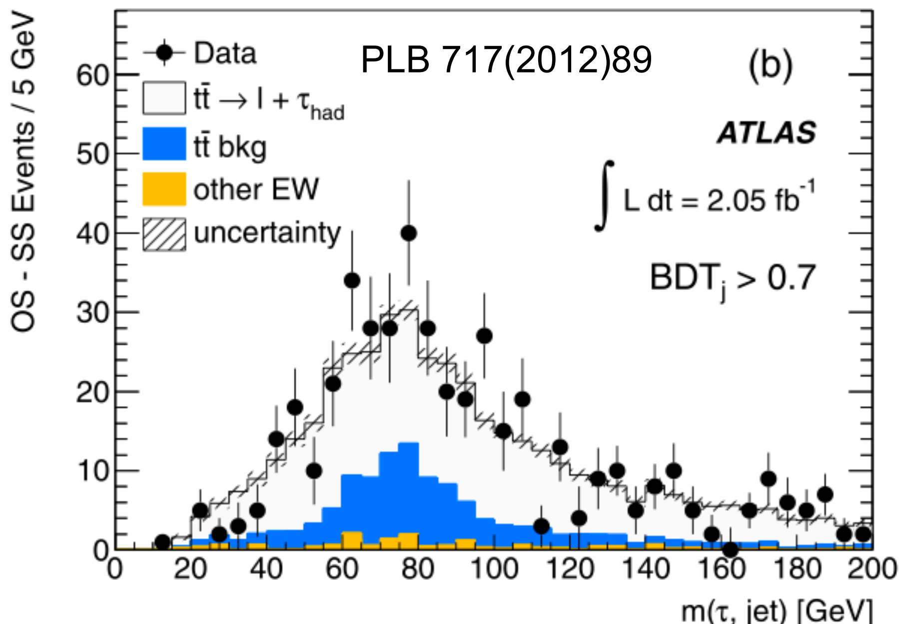


Cross section: tau+lepton channel

Reconstruct mass in ttbar events with taus



- Fit number of signal and bkg events



dominant syst.: τ fakes, b-tag

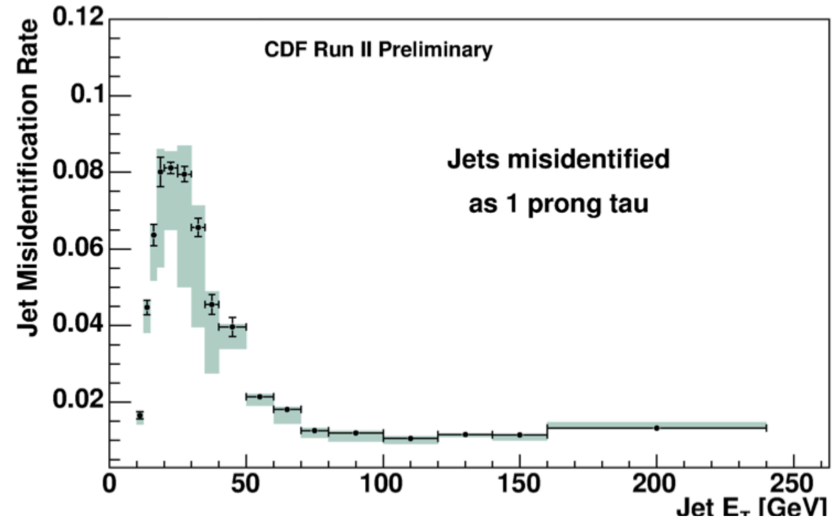
Good agreement between measurements and predictions

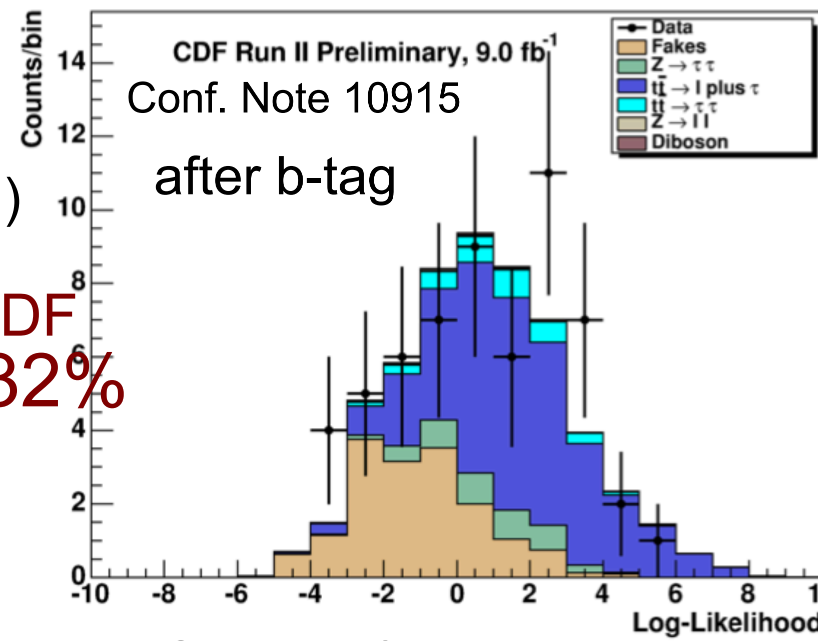
$\sigma_{t\bar{t}} = 186 \pm 13\,(\text{stat.}) \pm 20\,(\text{syst.}) \pm 7(\text{lumi.})\ \text{pb}$ ATLAS ±13%

$\sigma_{t\bar{t}} = 143 \pm 14(\text{stat.}) \pm 22(\text{syst.}) \pm 3(\text{lumi.})\ \text{pb}$ CMS ±18%

Tau dileptons and B($t \rightarrow \tau \nu b$)

- Cross section in tau+lepton final state
- Event selection:
  - 1 lepton, 1 tau (p_T^{LT}>4.5GeV), OS
  - ≥2 jets (≥1 b-tag)
  - MET>10 GeV
  - H_T>150 GeV
- Likelihood ratio discriminant: ln(LR)>0
  - Attempt to separate 1τ vs 2τ final states (w/LR')





CDF
±32%

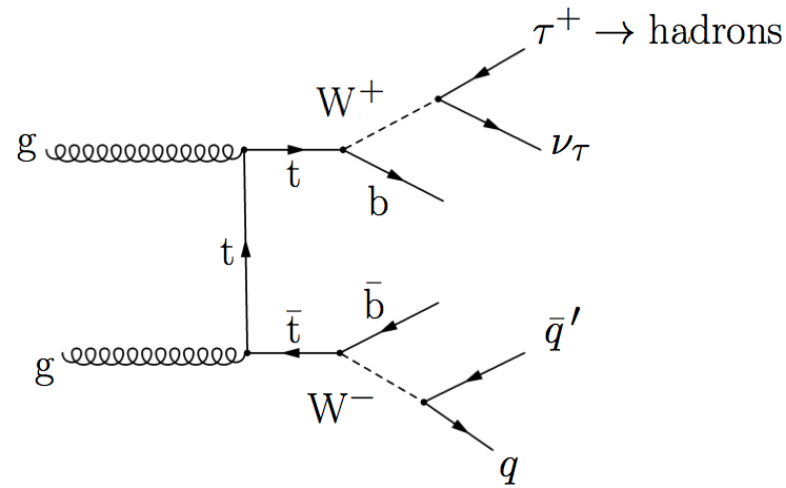
$$\sigma_{t\bar{t}} = 8.2 \pm 2.3(stat.)^{+1.2}_{-1.1}(syst.) \pm 0.5(lum.)\ \mathrm{pb}$$

$$BR(t \rightarrow \tau\nu b) = 0.098 \pm 0.022(stat.) \pm 0.014(syst.)$$

Tau+jets

- BR~15%
- Main background: QCD multi-jets, ttbar (all-had)

- Multi-jet trigger (+b or τ)
- Event selection:
  - one τ_h (>40 GeV) and at least 4/5 jets
  - ≥2 b-tagged jets
  - MET significance or MET
  - lepton veto

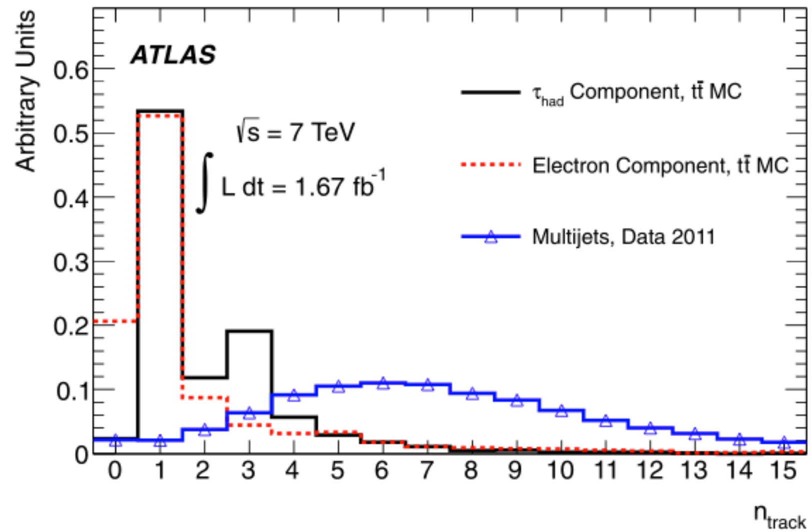


ATLAS

CMS

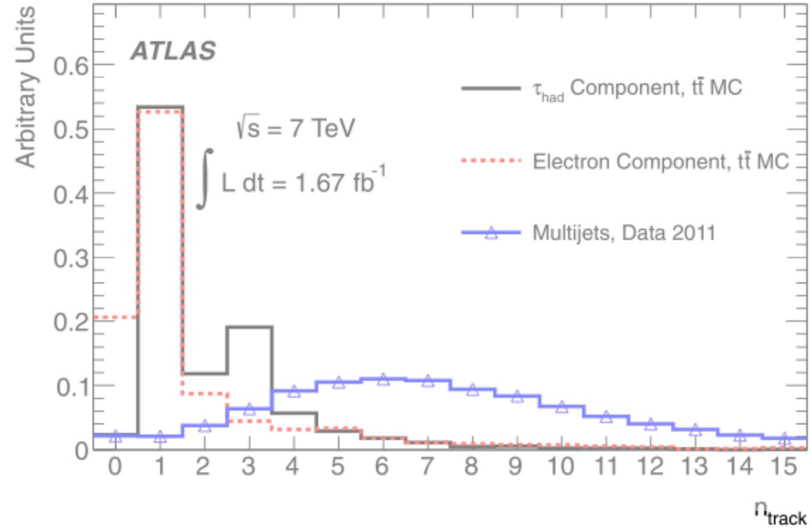
Extract signal

- fit number of tracks
  - 3-component fit (tau/el, q-jet, g-jet)
- signal template from MC
  - large bkg from misID electrons
- bkg template from sideband S_{MET}
- good separation btw signal/bkg

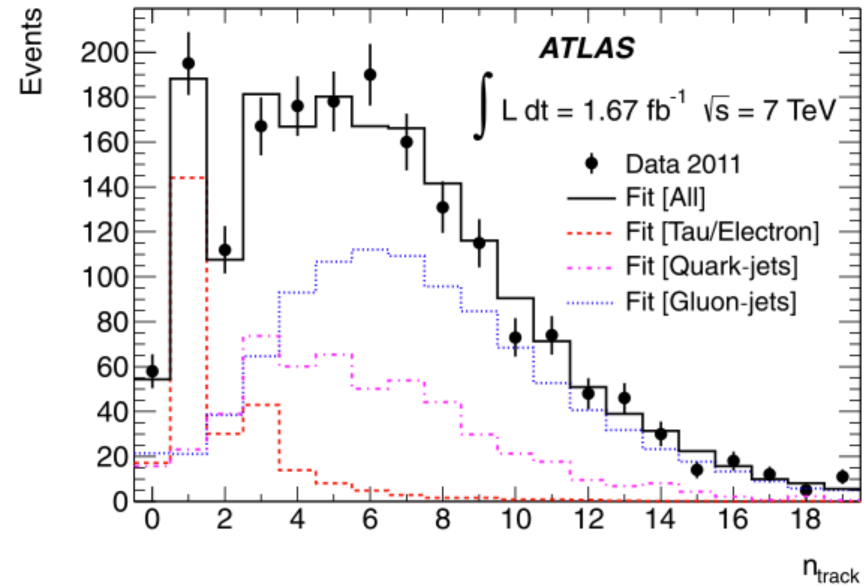


Likelihood fit

- fit number of tracks
  - 3-component fit (tau/el, q-jet, g-jet)
- signal template from MC
  - large bkg from misID electrons
- bkg template from sideband S_{MET}
- good separation btw signal/bkg

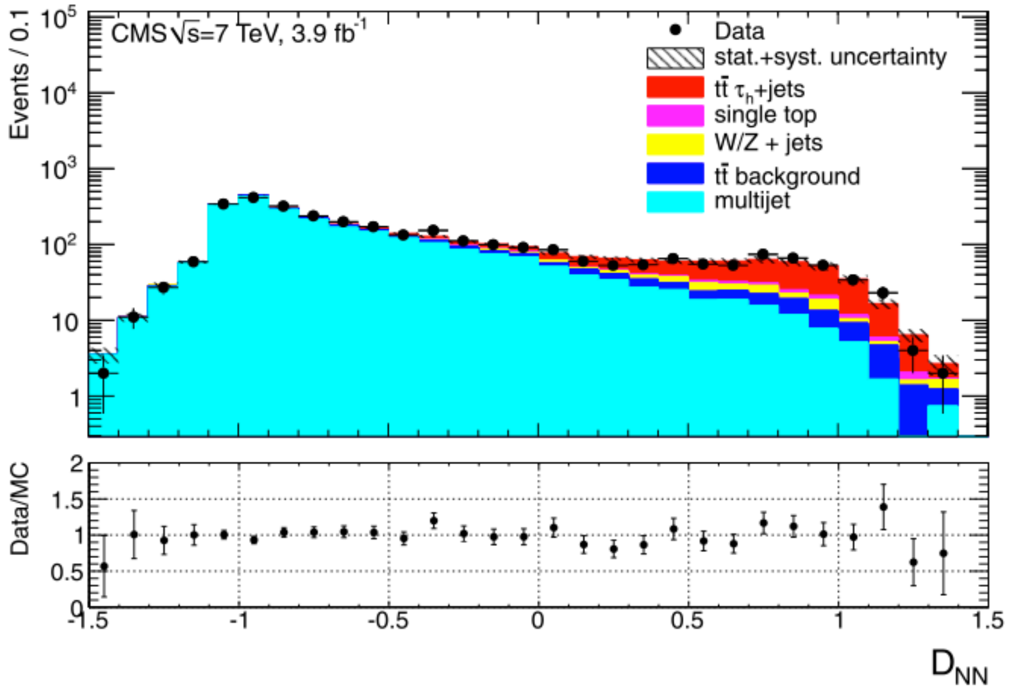


- Binned likelihood fit of n_{track}
  - soft constrain tau/ele and q-jet
  - stat unc determined from shape fit
  - pseudo-expts to determine syst unc
- Calculate number of events and measure cross section



Neural network

- Backgrounds
  - large QCD multi-jet bkg (~90%)
  - control sample from data (b-veto)
  - Other bkg from MC
- Training with simulated signal and multi-jet templates from data
- binned log-likelihood fit

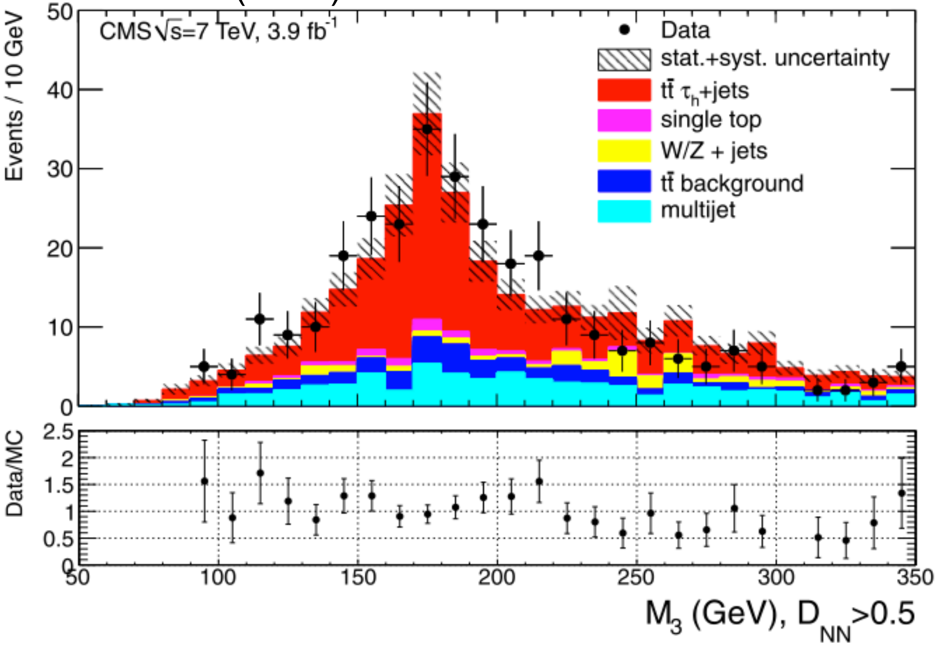


Source	Events
Signal $t\bar{t} \to \tau_h + \text{jets}$	$383 \pm 29\,(\text{fit})$
Multijet	$2392 \pm 29\,(\text{fit}) \pm 120\,(\text{syst.})$
Other $t\bar{t}$	$151 \pm 4\,(\text{stat.}) \pm 37\,(\text{syst.})$
W + jets	$62 \pm 8\,(\text{stat.}) \pm 14\,(\text{syst.})$
Single top	$41 \pm 1\,(\text{stat.}) \pm 8\,(\text{syst.})$
Z + jets	$21 \pm 2\,(\text{stat.}) \pm 4\,(\text{syst.})$
Total backgrounds	$2667 \pm 31\,(\text{stat.}) \pm 127\,(\text{syst.})$
Data	3050

Tau+jets final state

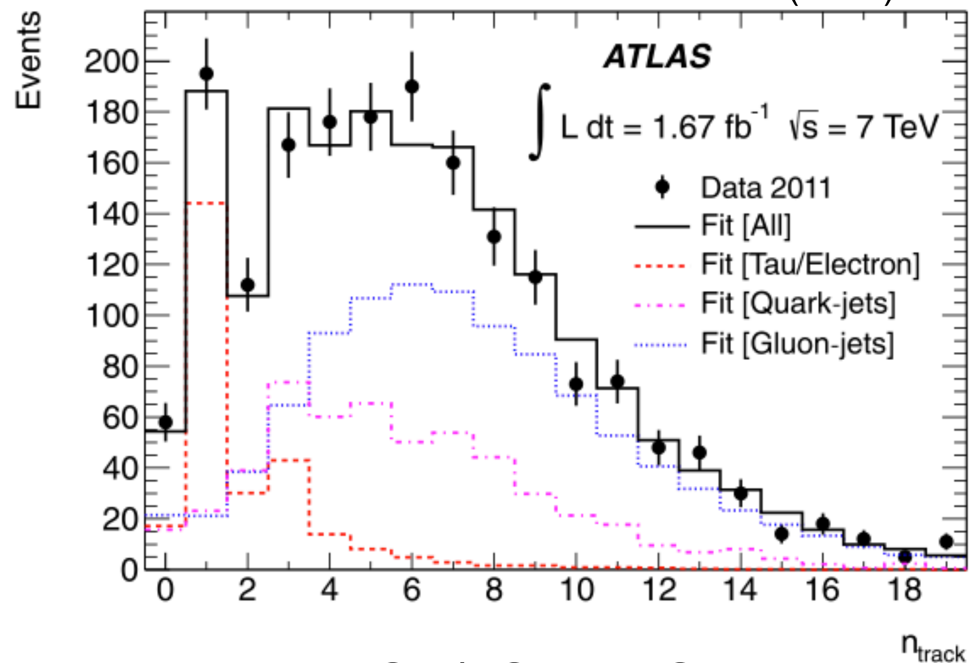
Yields: M_3 (inv mass of 3 highest p_T jets)

EPJC 73(2013)2386



Fit number of signal and bkg events

EPJC 73(2013)2328



dominant syst.: ISR/FSR, JES, τ ID

Good agreement between measurements and predictions

$$\sigma_{t\bar{t}} = 194 \pm 18 \text{ (stat.)} \pm 46 \text{ (syst.) pb}$$ ATLAS ±25%

$$\sigma_{\mathrm{t\bar{t}}} = 152 \pm 12\,\text{(stat.)} \pm 32\,\text{(syst.)} \pm 3\,\text{(lum.) pb}$$ CMS ±21%

Tau+jets

- Measure m_{top} and ttbar cross section
- Use NN to reduce multi-jet bkg
- Training from multi-jet data
- Optimize signal significance: $S_{exp}/\sqrt{S_{obs}}$
- Binned likelihood fit
- Measure cross section from #events:

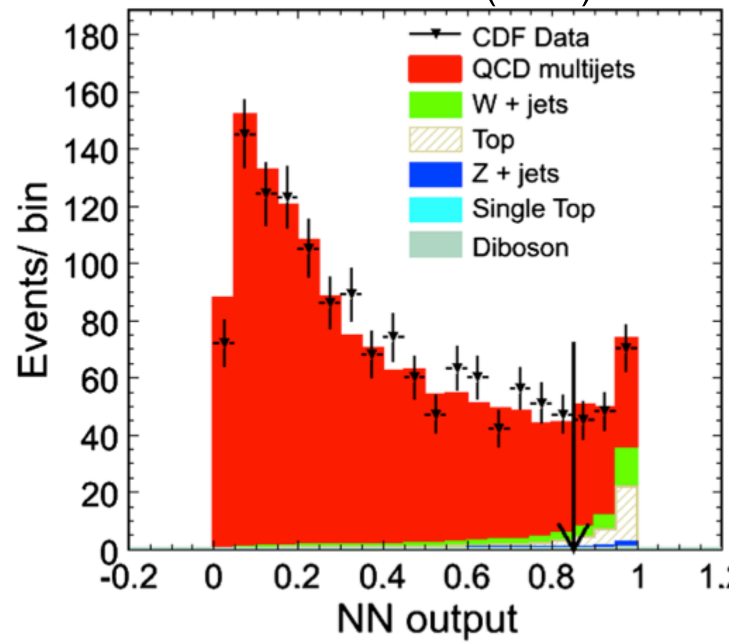
$$\sigma_{t\bar{t}} = 8.8 \pm 3.3(\text{stat}) \pm 2.2(\text{syst})\ \text{pb}$$

CDF
±45%

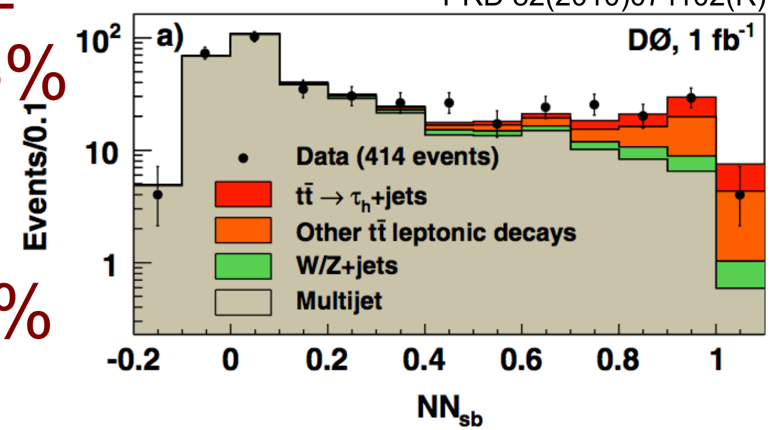
$$\sigma_{t\bar{t}} = 6.9^{+1.2}_{-1.2}(\text{stat})^{+0.8}_{-0.7}(\text{syst}) \pm 0.4(\text{lumi})\ \text{pb}$$

D0
±22%

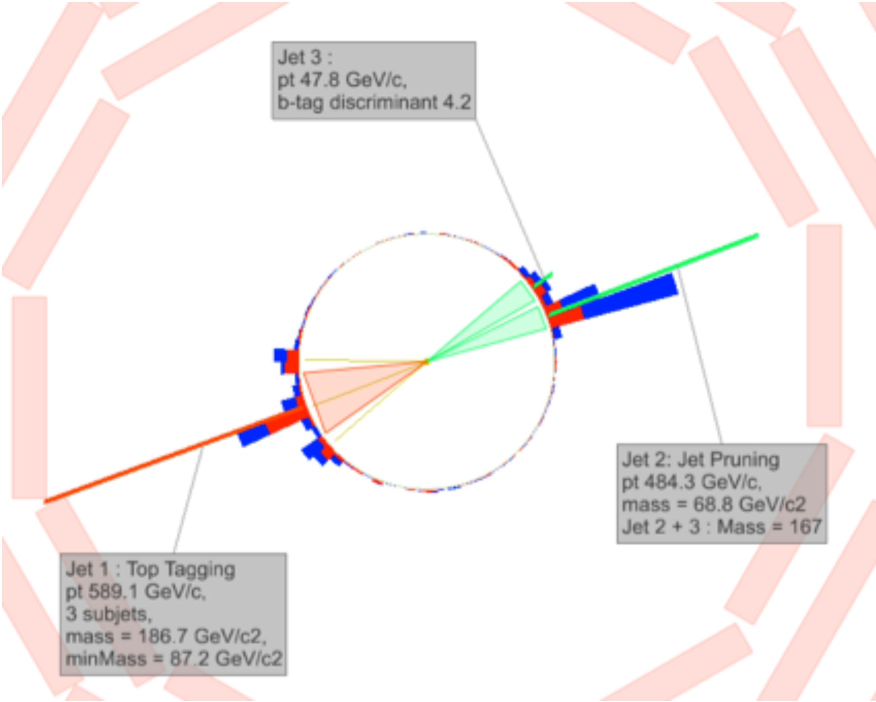
PRL 109(2012)192001



PRD 82(2010)071102(R)



All-hadronic channel

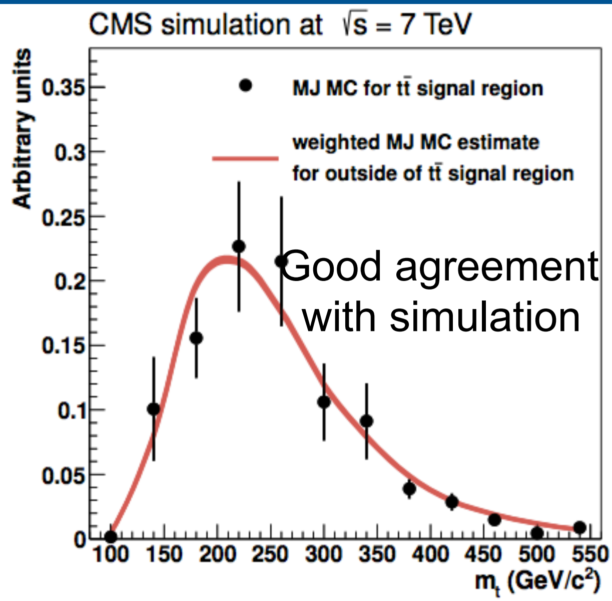


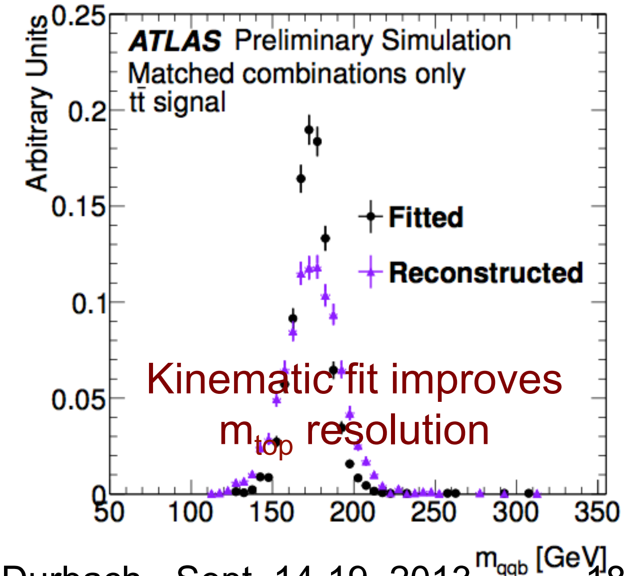
- Fully hadronic final state
- BR~46%
- Main background: multi-jets

- Six jets and no leptons in the final state
- Rely on multi-jet trigger
- Event selection
  - ≥6 jets
  - 2 b-tagged jets, ε_b~50-60%, mistag~0.1%
  - Kinematic fit exploits the topology of ttbar events
  - MET significance

Background and likelihood fit

- Reconstruct ttbar system from jets and fit with least χ^2 method
  - Reconstruct both W bosons
  - $m_{top1}=m_{top2}$ are free parameters
  - b-jets are taken as b-quark candidates
- Take permutation with smallest χ^2
- Derive mass templates from selected events after kinematic fit
- Templates are inputs for likelihood fit for cross section measurement
  - Signal and background templates
  - Multi-jet template from data (no b-tag)
  - Signal fraction is a free parameter
- Measure cross section

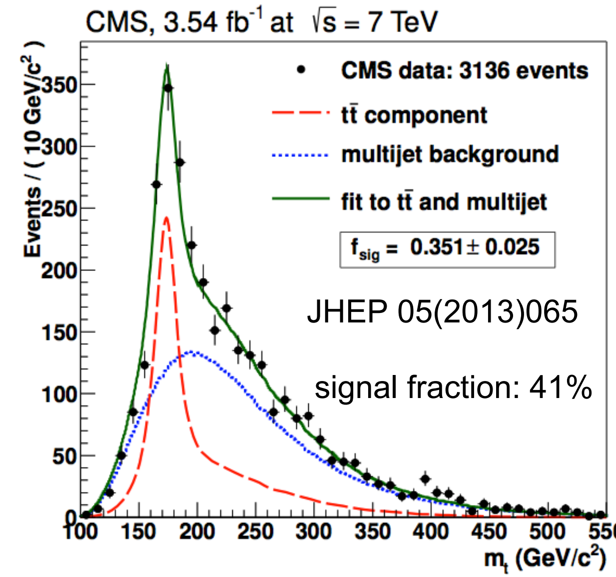




All hadronic

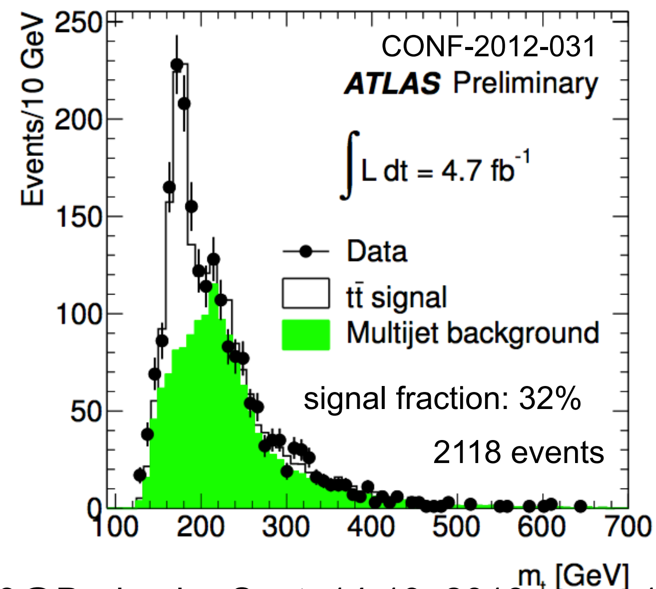
- Large BR, but large bkg
- Select at least 6 jets
  - b-tagging reduces combinatorics
- Top cross section from unbinned maximum likelihood to the reconstructed top mass
- Multijet QCD is main background (from data)
  - Use same selection without b-tag req.
  - Re-weigh mass spectrum from anti-tagged sample

Selection	Events	Fraction of $t\bar{t}$
At least 6 jets	786 741	0.02
At least two b-tags	21 783	0.18
Kinematic fit	3 136	0.41



dominant syst.: JES, b-tag

Fit top quark mass
(signal from generator, background data-driven)



ATLAS ±37%

$$\sigma(pp \rightarrow t\bar{t}) = 168 \pm 12\,(\text{stat.})\,^{+60}_{-57}\,(\text{syst.}) \pm 7\,(\text{lum.})\text{ pb}$$

$$139 \pm 10\,(\text{stat.}) \pm 26\,(\text{syst.}) \pm 3\,(\text{lum.})\text{ pb}$$

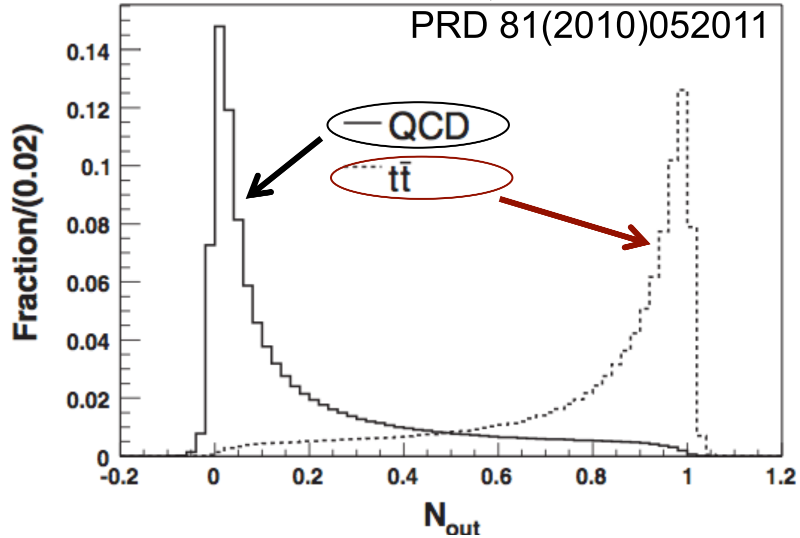
CMS ±20%

All-hadronic @ Tevatron

Similar selections:

- Select events with ≥6 jets
- ≥1(2) b-tag CDF(D0)
- kinematics + NN
- Signal fraction ~12/15% (D0/CDF)

CDF, 2.9 fb-1
PRD 81(2010)052011

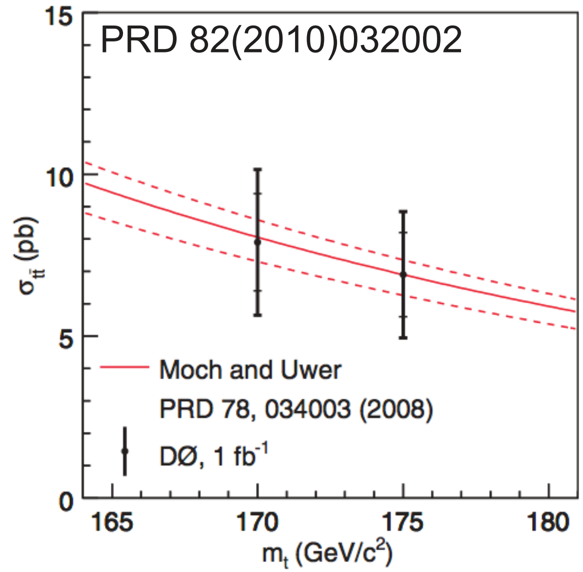


CDF ±16%

$$\sigma_{t\bar{t}} = 7.2 \pm 0.5(\text{stat}) \pm 1.0(\text{syst}) \pm 0.4(\text{lum})\ \text{pb}$$

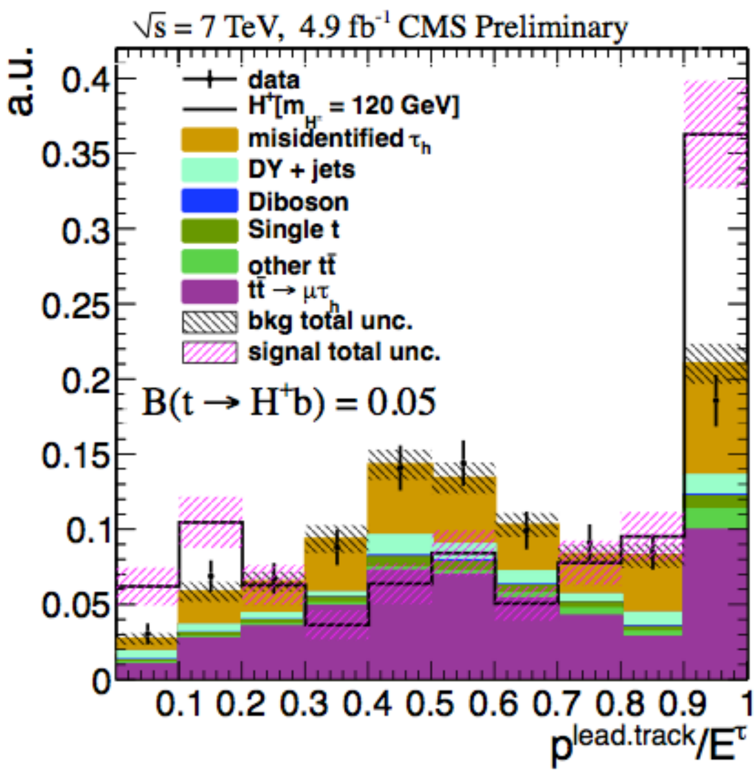
$$6.9 \pm 1.3\,(\text{stat}) \pm 1.4\,(\text{sys}) \pm 0.4\,(\text{lum})\ \text{pb}$$

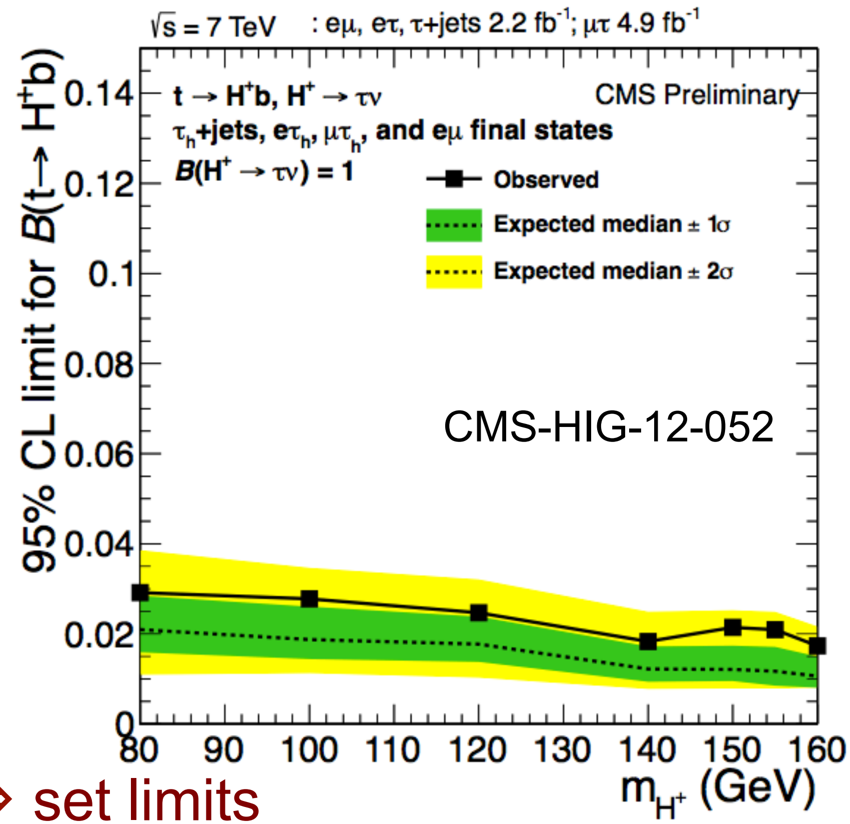
D0 ±28%



Is there a charged Higgs?

- If anomalous tau production in ttbar decays there may be contribution from charged Higgs





Yields in agreement with expectations ⇒ set limits

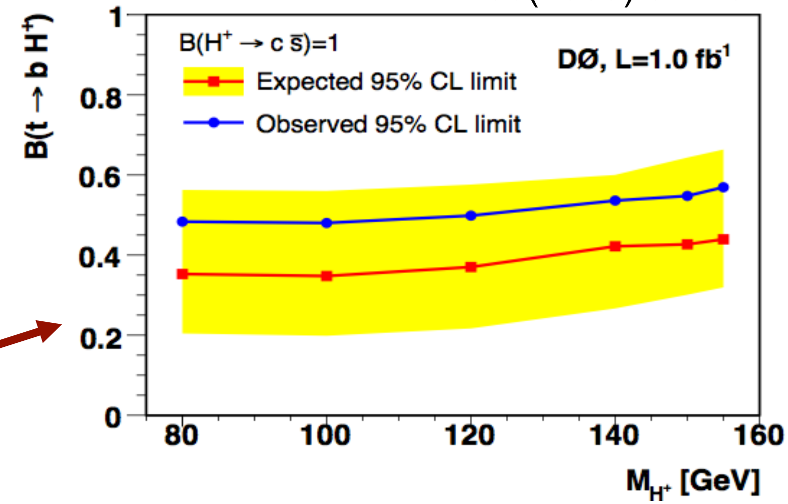
$80 < m_{H^+} < 160$ GeV. $\boxed{BR(t \to H^+ b) < 2-3\%}$

Cross section ratios

Many systematic unc. cancel in the ratio
Study of cross section ratios
⇨sensitive to BSM

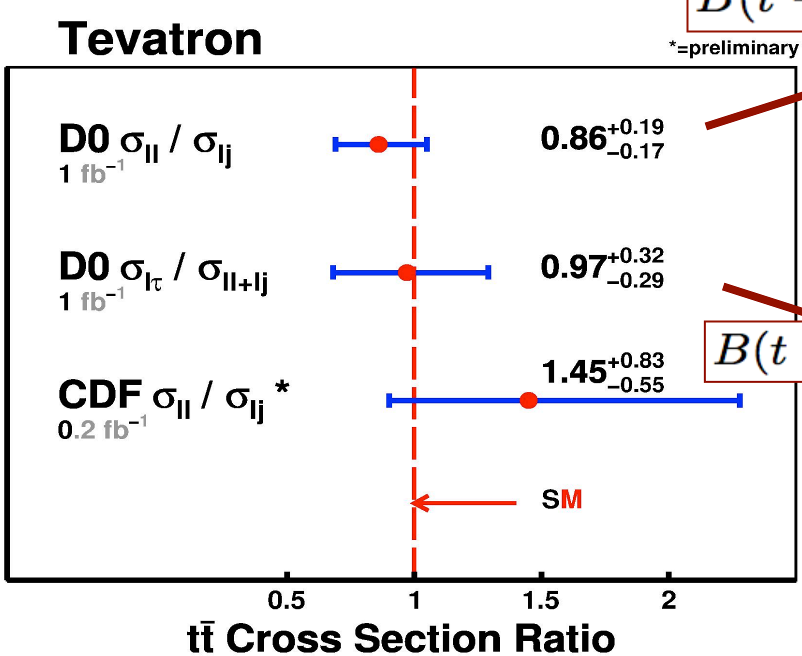
1. BR(l+jets)/BR(ll)
2. BR(l+tau)/BR(ll)

PRD 80(2009) 071102



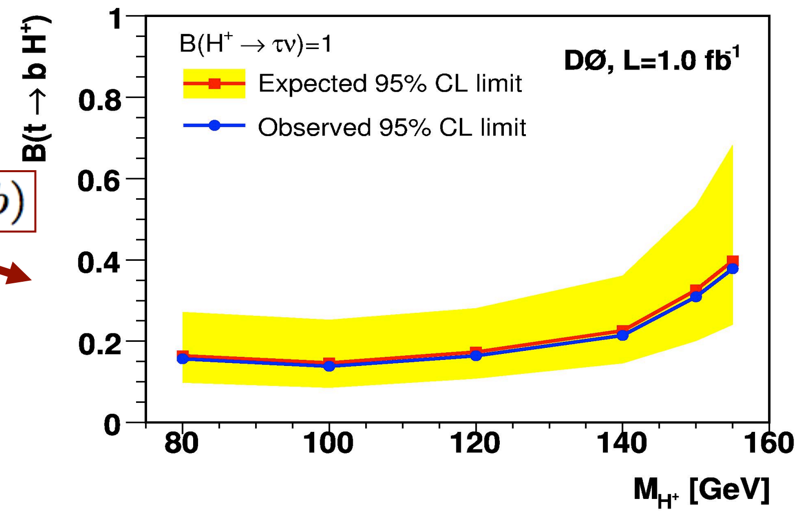
$B(t \to H^+ b \to c\bar{s}b)$

lept.+jets



$B(t \to H^+ b \to \tau^+ \nu b)$

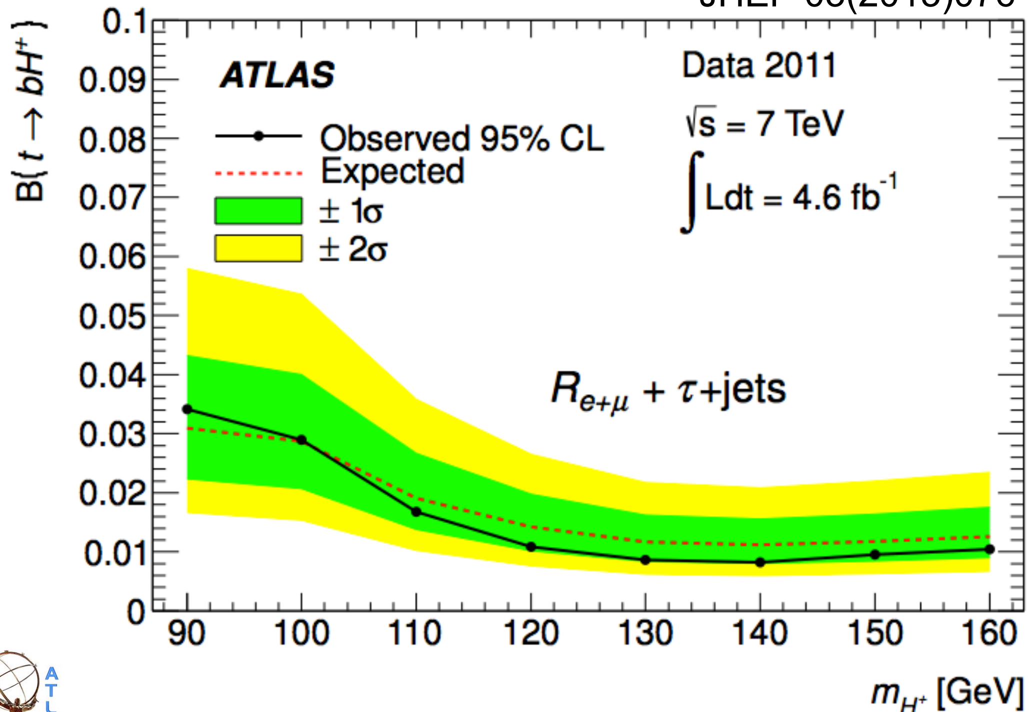
tau leptons

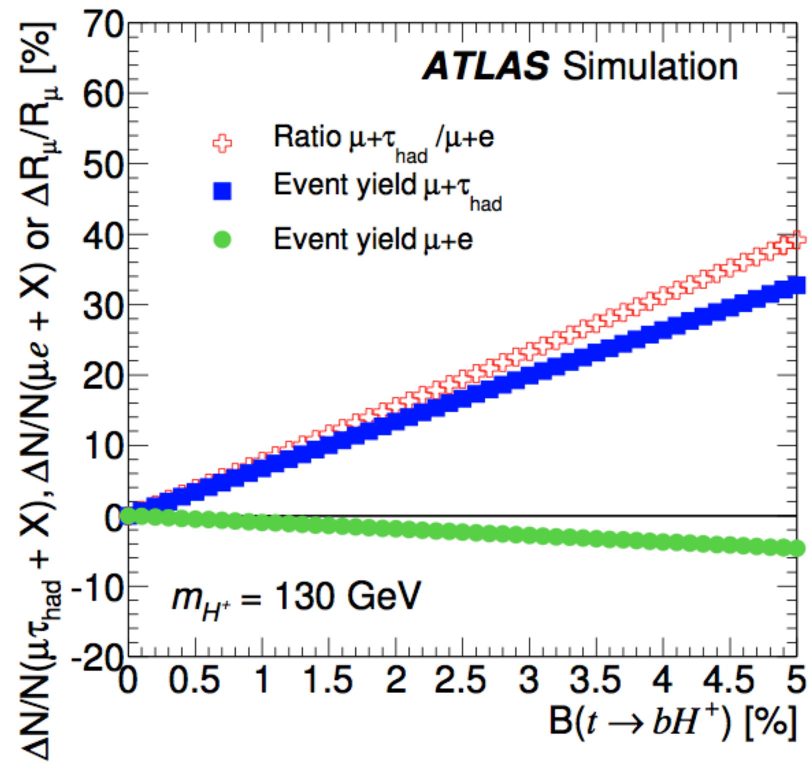


Combination of more channels

- Search for charged Higgs boson
- Use τ_{had}+lep and τ_{had}+jets final states
  - compare to eμ yields
- Search for anomalous decays

JHEP 03(2013)076





Set limits on:

$$\boxed{\mathcal{B}(t \to bH^+)}$$

Charged Higgs (cont.)

ATLAS-CONF-2013-090

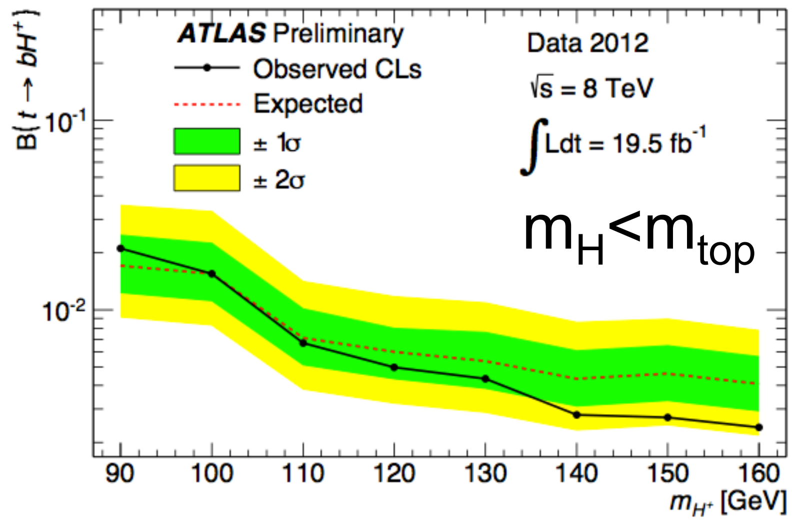
Search in τ_{had}+jet final state

- Light charged Higgs:

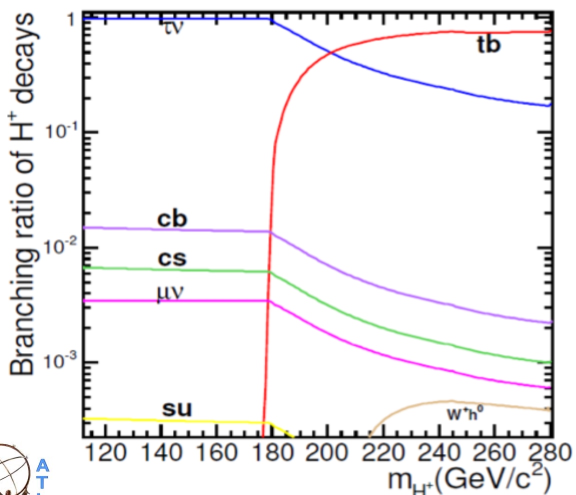
$$t\bar{t} \to [H^+ b]\,[W^- \bar{b}] \to [(\tau^+ + \nu_\tau) b]\,[q\bar{q}\bar{b}]$$

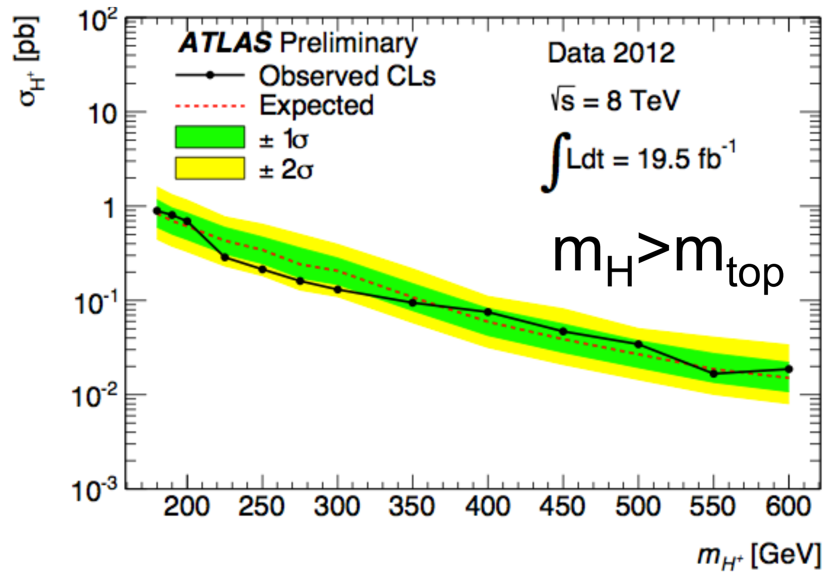
- Heavy charged Higgs

$$gg \to [\bar{t}b]\,[H^+] \to [(q\bar{q}\bar{b})b]\,[\tau^+ + \nu_\tau]$$



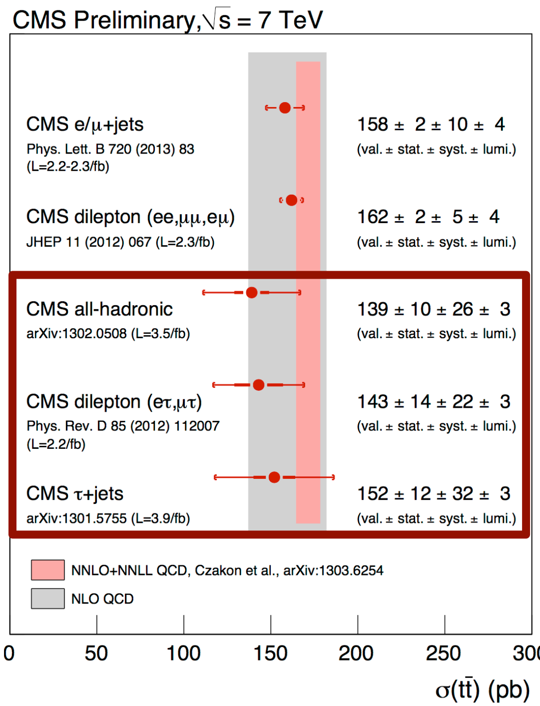
- Caveat: assume $B(H^+ \to \tau\nu) = 1$

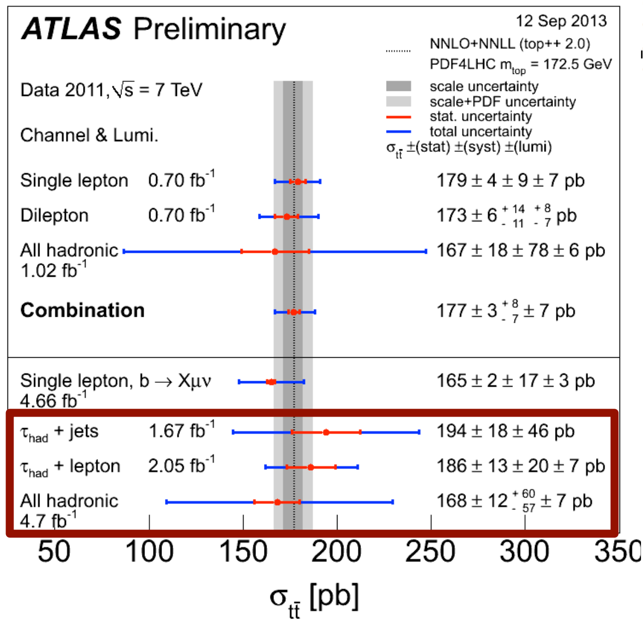


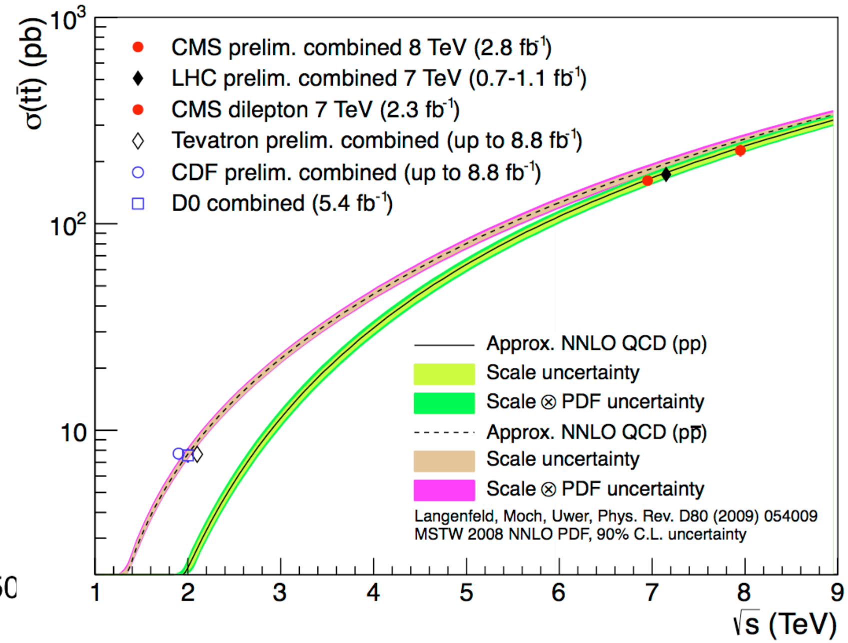


Summary

- Measurements involving taus or no leptons
- Sensitive to BSM searches
- Uncertainties dominated by systematics







⇒ Good agreement with SM expectations

backup

Tau dilepton: systematic uncertainties

CMS

- Misidentified taus
  - 13% (10%) for $e\tau$ ($\mu\tau$)
- Tau ID
  - 6%
- JES/JER/MET
  - 6%
- b-jet tagging/mistag
  - 5%

ATLAS

- b-tagging
  - 8-9%
- ISR/FSR
  - 4-5%
- Tau ID
  - 3%
- JES/JER/MET
  - 2-3%

Tau+jets: systematic uncertainties

CMS

- JES
  - 11%
- τ_{had} ID
  - 9%
- Trigger
  - 7%
- τ_{had} energy correction
  - 7%
- output fit and MC stat
  - 8%

ATLAS

- ISR/FSR
  - 15%
- evt generator
  - 11%
- b-tagging
  - 9%
- Hadronisation model
  - 6%
- JES
  - 5%

All hadronic: systematic uncertainties

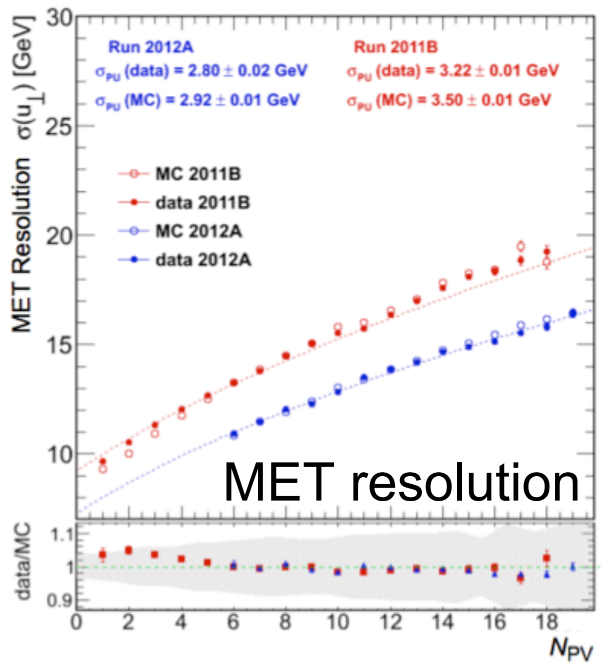
CMS

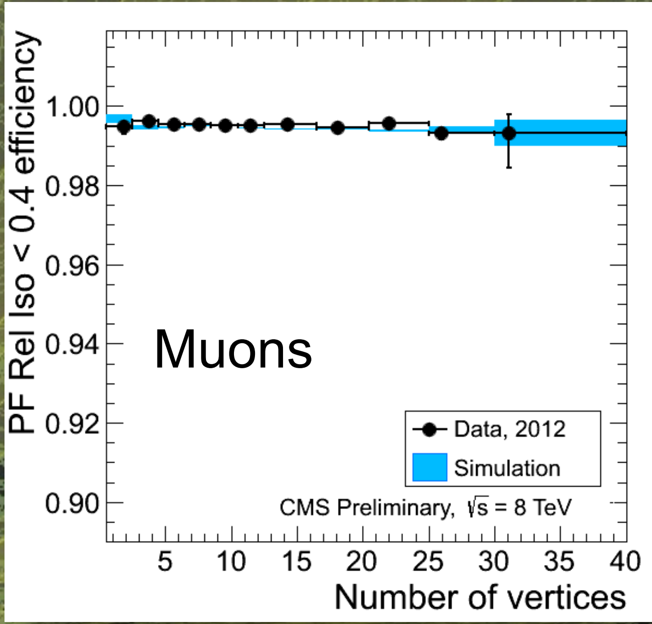
- JES
  - 10%
- Background
  - 9%
- b-tagging
  - 6%
- Total
  - 20%

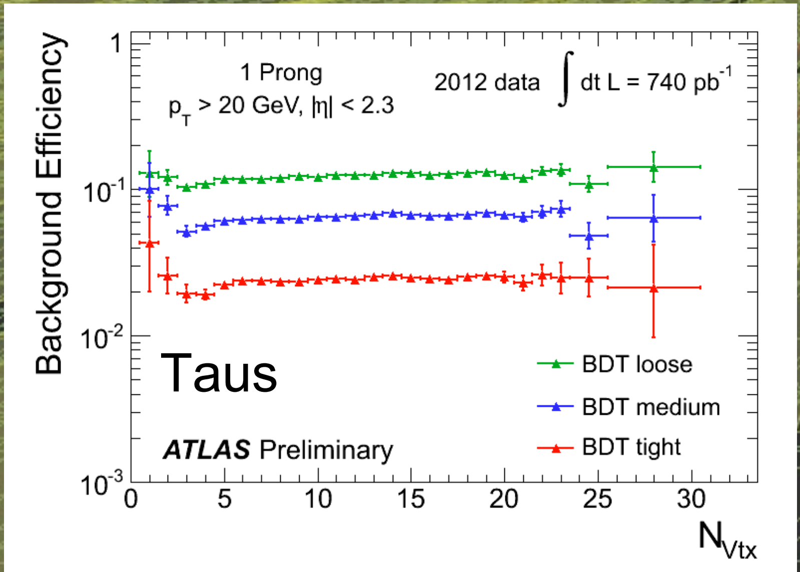
ATLAS

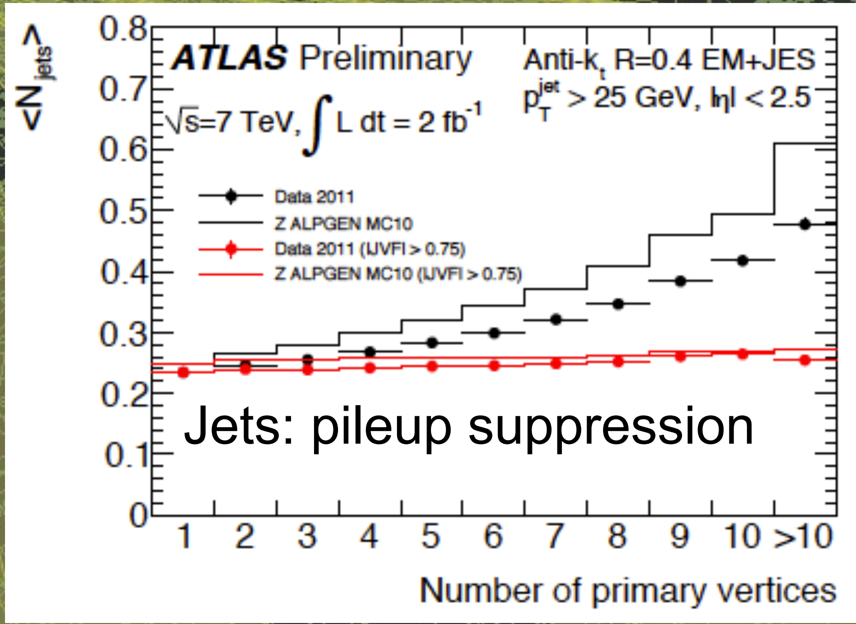
- JES
  - +20/-11%
- b-tagging
  - 17%
- ISR/FSR
  - 17%
- Shower/hadron model
  - 13%
- Multi-jet trigger
  - 10%
- Total
  - +36/-34%

Pile-up

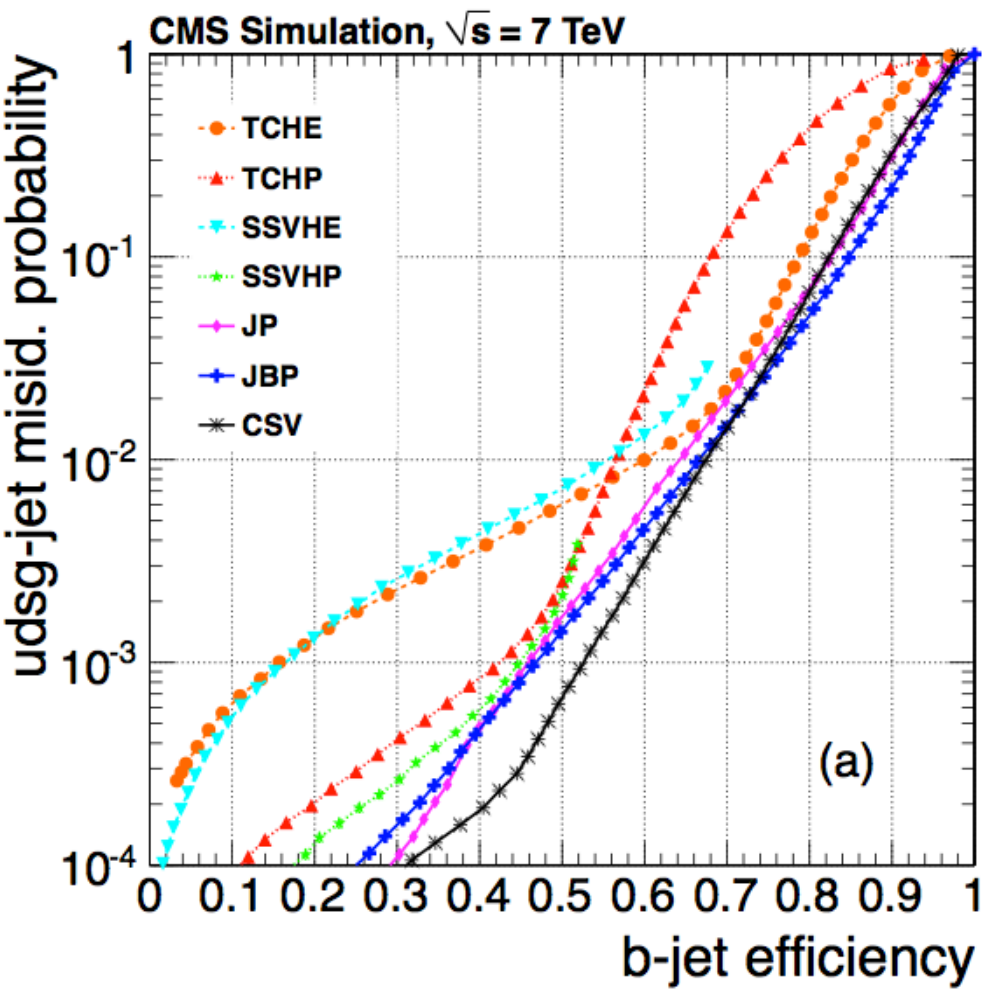

Run 2012A
σ_{PU} (data) = 2.80 ± 0.02 GeV
σ_{PU} (MC) = 2.92 ± 0.01 GeV
Run 2011B
σ_{PU} (data) = 3.22 ± 0.01 GeV
σ_{PU} (MC) = 3.50 ± 0.01 GeV
MC 2011B
data 2011B
MC 2012A
data 2012A
MET Resolution $\sigma(u_\perp)$ [GeV]
MET resolution
data/MC
N_{PV}

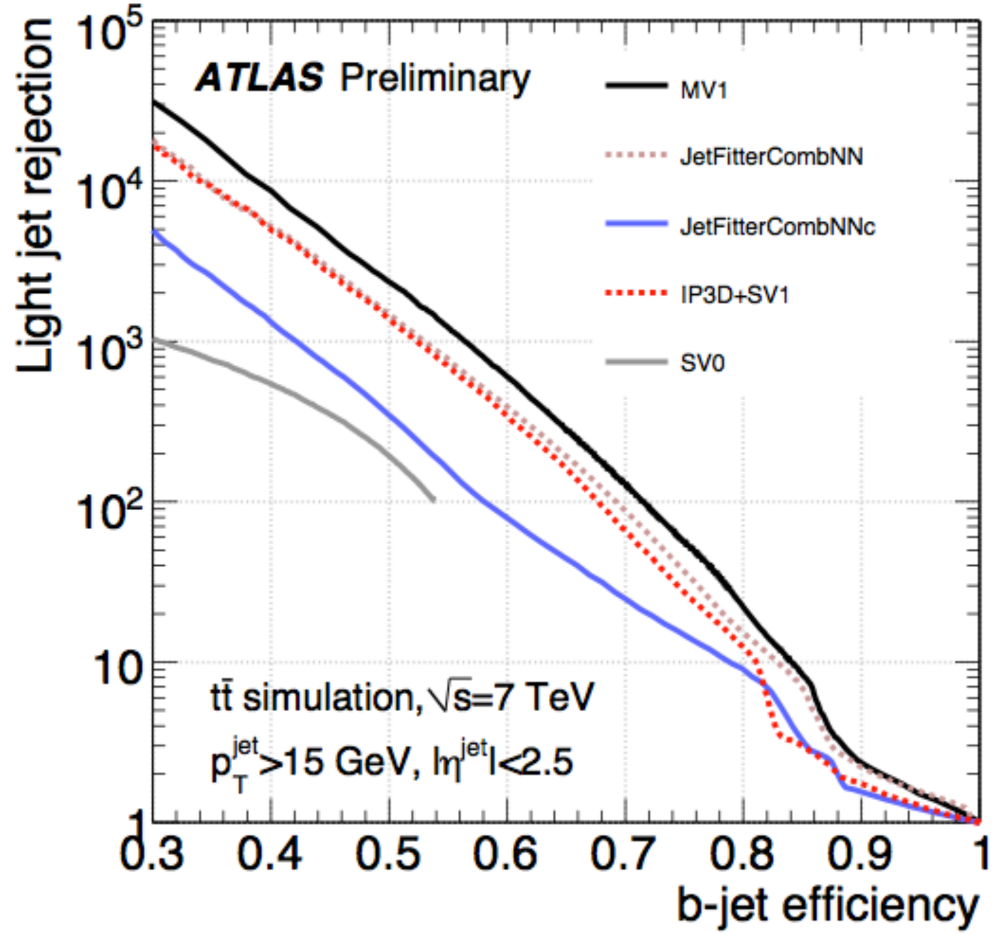

PF Rel Iso < 0.4 efficiency
Muons
Data, 2012
Simulation
CMS Preliminary, $\sqrt{s}$ = 8 TeV
Number of vertices


1 Prong
p_T > 20 GeV, $|\eta|$ < 2.3
2012 data $\int$ dt L = 740 pb^{-1}
Background Efficiency
Taus
BDT loose
BDT medium
BDT tight
ATLAS Preliminary
N_{Vtx}

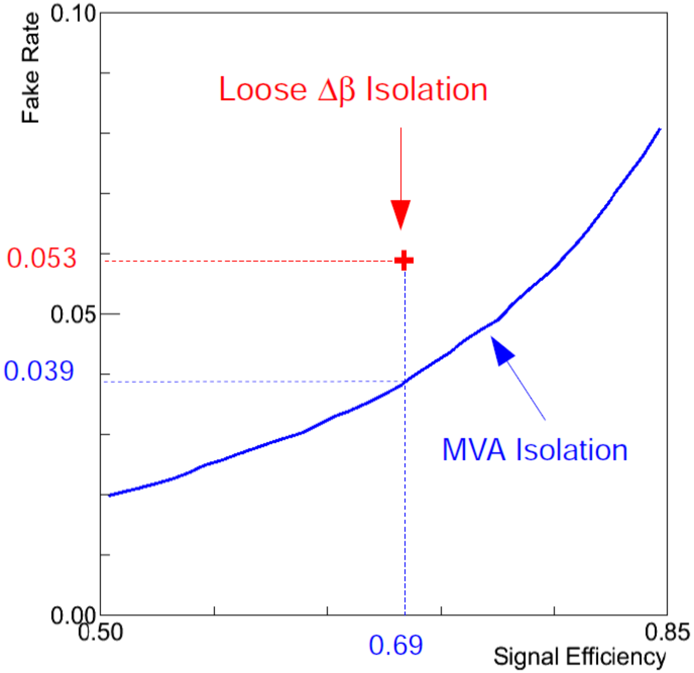

ATLAS Preliminary
Anti-k_t R=0.4 EM+JES
p_T^{jet} > 25 GeV, $|\eta|$ < 2.5
$\sqrt{s}$=7 TeV, $\int$ L dt = 2 fb^{-1}
Data 2011
Z ALPGEN MC10
Data 2011 (|JVF| > 0.75)
Z ALPGEN MC10 (|JVF| > 0.75)
Jets: pileup suppression
$\langle N_{jets} \rangle$
Number of primary vertices

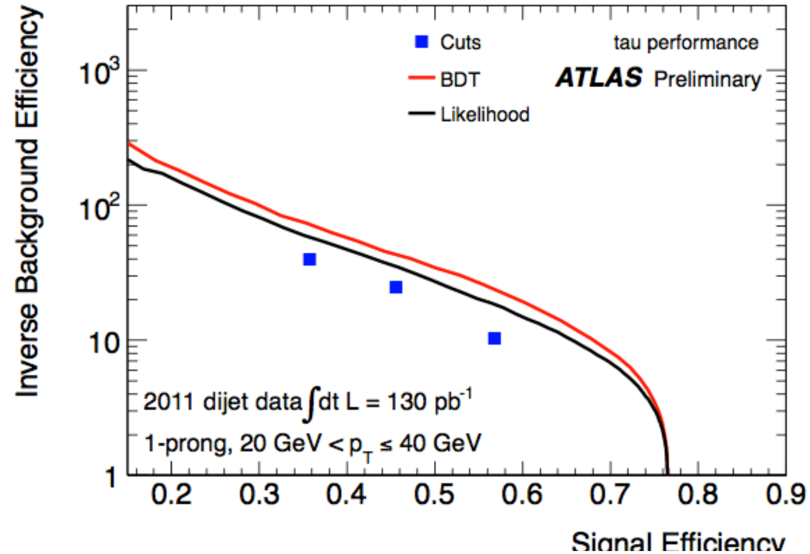
b-tagging performance





Tau identification





Algorithm	QCD	
	MC (%)	Data/MC
HPS "loose"	1.0	1.00 ± 0.04
HPS "medium"	0.4	1.02 ± 0.06
HPS "tight"	0.2	0.94 ± 0.09

Algorithm	Fit data
HPS "loose"	0.70 ± 0.15
HPS "medium"	0.53 ± 0.13
HPS "tight"	0.33 ± 0.08

ID method	Tau ID efficiency	Jet mis-ID probability
cut-based loose	$0.87 \pm 0.02 \pm 0.02$	0.221 ± 0.008
cut-based medium	$0.79 \pm 0.02 \pm 0.03$	0.081 ± 0.007
cut-based tight	$0.65 \pm 0.02 \pm 0.03$	0.025 ± 0.006
likelihood loose	$0.70 \pm 0.02 \pm 0.02$	0.085 ± 0.008
likelihood medium	$0.46 \pm 0.02 \pm 0.03$	0.046 ± 0.006
likelihood tight	$0.27 \pm 0.01 \pm 0.02$	0.021 ± 0.004
BDT loose	$0.81 \pm 0.02 \pm 0.03$	0.085 ± 0.008
BDT medium	$0.63 \pm 0.02 \pm 0.03$	0.029 ± 0.006
BDT tight	$0.42 \pm 0.01 \pm 0.03$	0.012 ± 0.004