Top Properties at CMS

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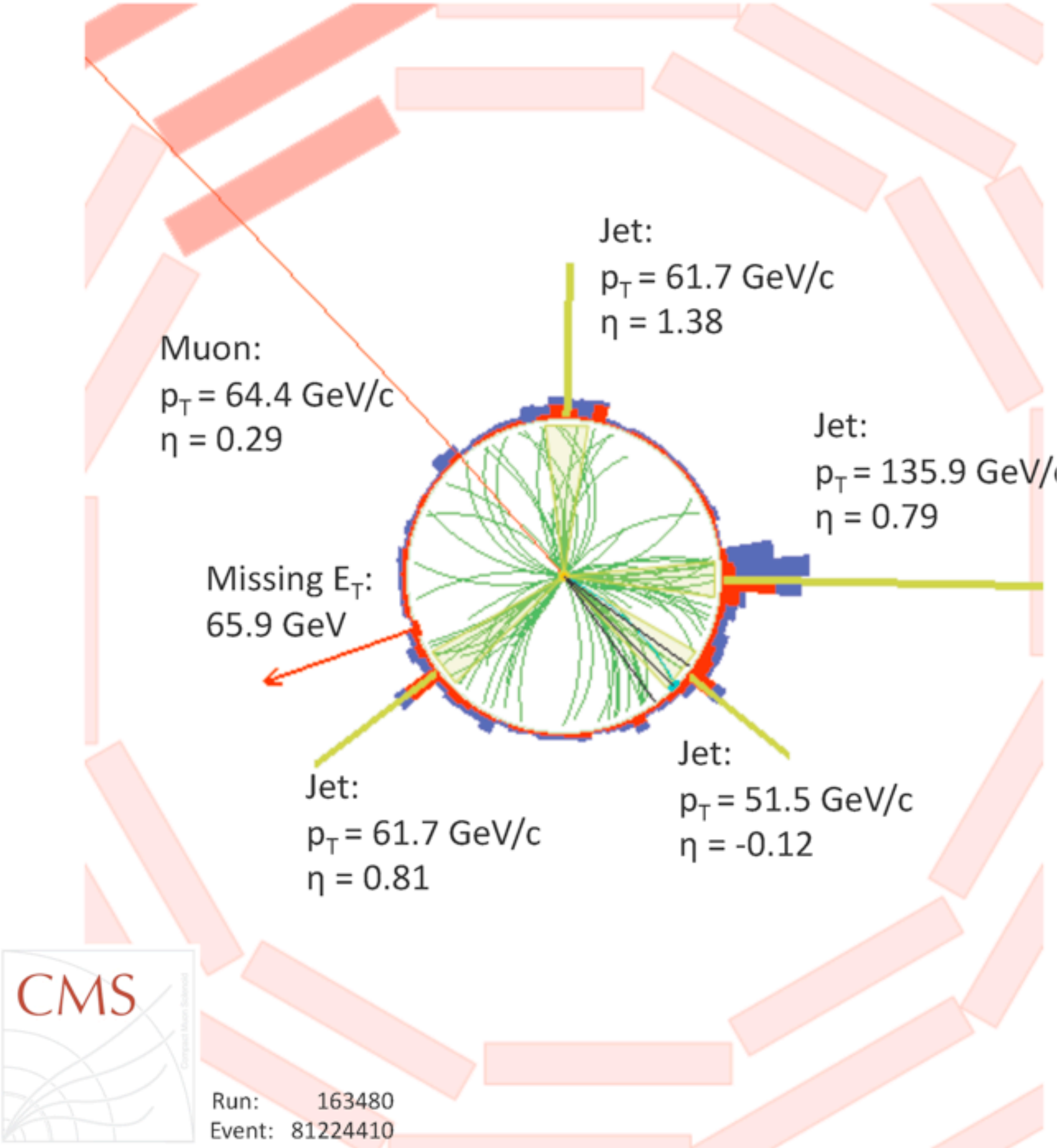
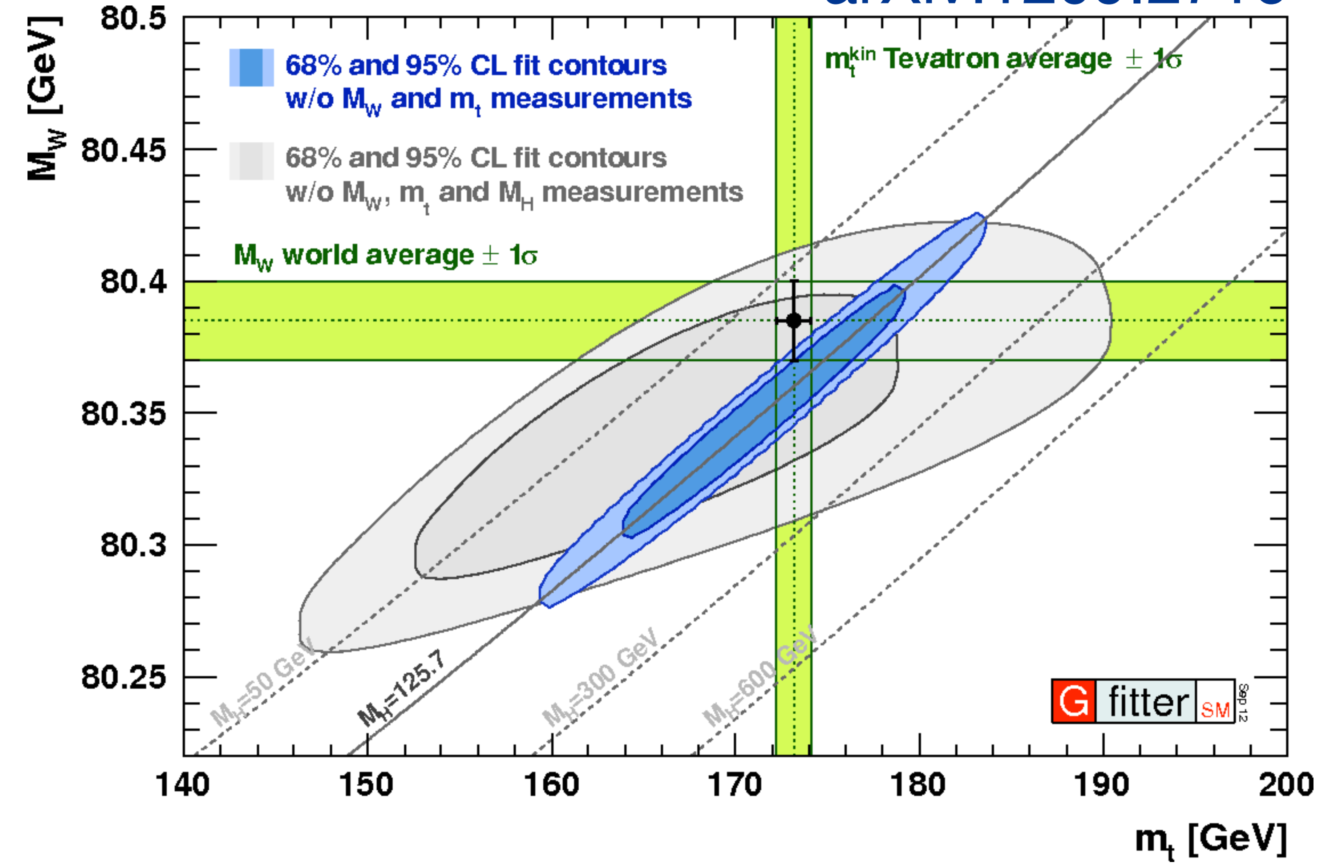
Les Rencontres de Physique de la Vallée d'Aoste



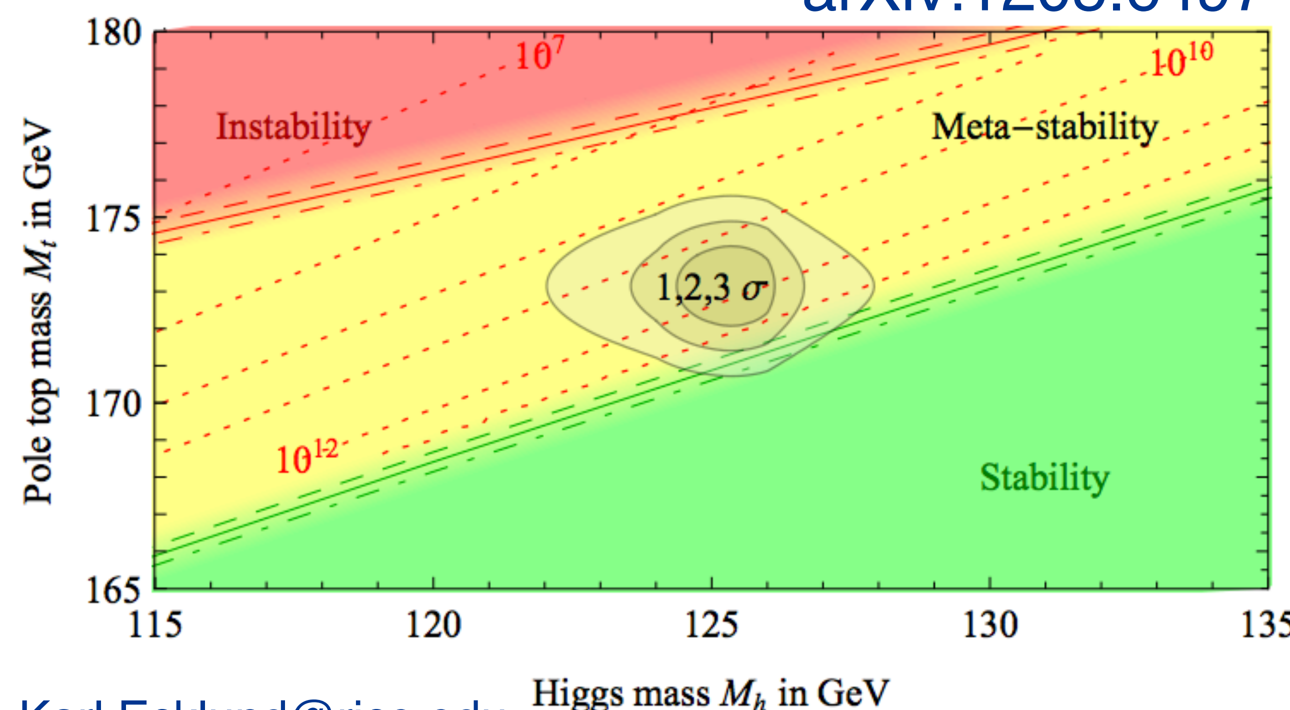
Motivation for Top Properties

- Top is heaviest quark
  - may play an unusual role
- Is top a SM quark?
  - in addition to production
  - measurement of properties, mass, and couplings
- Top mass: Precision needed to test Electroweak theory given a Higgs-like boson at 125 GeV
  - Global consistency
  - EW vacuum stability!

arXiv:1209.2716



arXiv:1205.6497

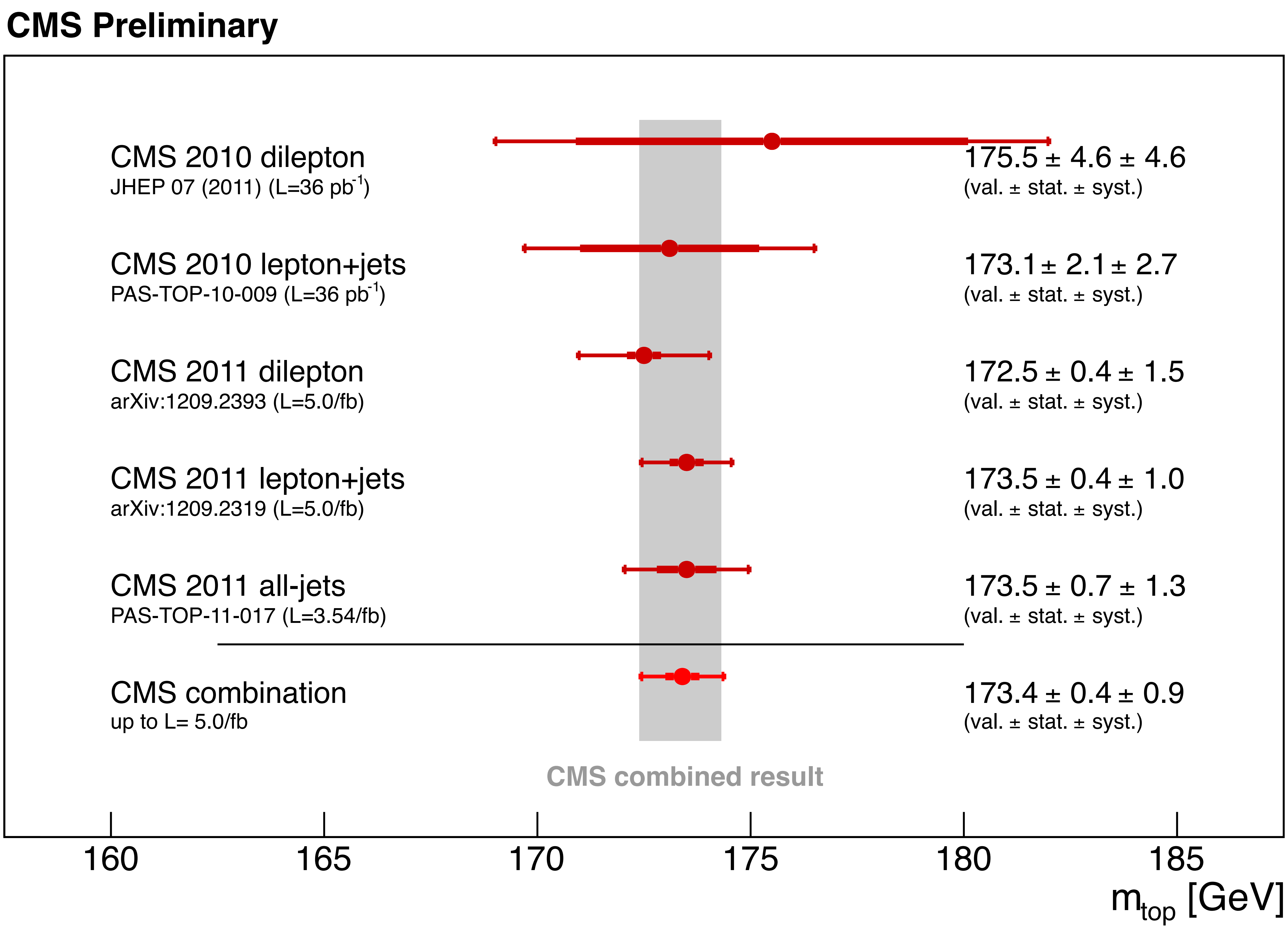


Outline

- Top mass
  - hadronic, semi-leptonic, dileptonic channels
  - (complementary techniques)
  - New! study of kinematic dependence for m_t measurement
- Top couplings
  - New! bottom quark content in top decay using t-tbar events: $|V_{tb}|$
  - Wtb couplings from W Helicity analysis
    - New! From t-tbar events in dilepton channel
    - New! From single top topologies

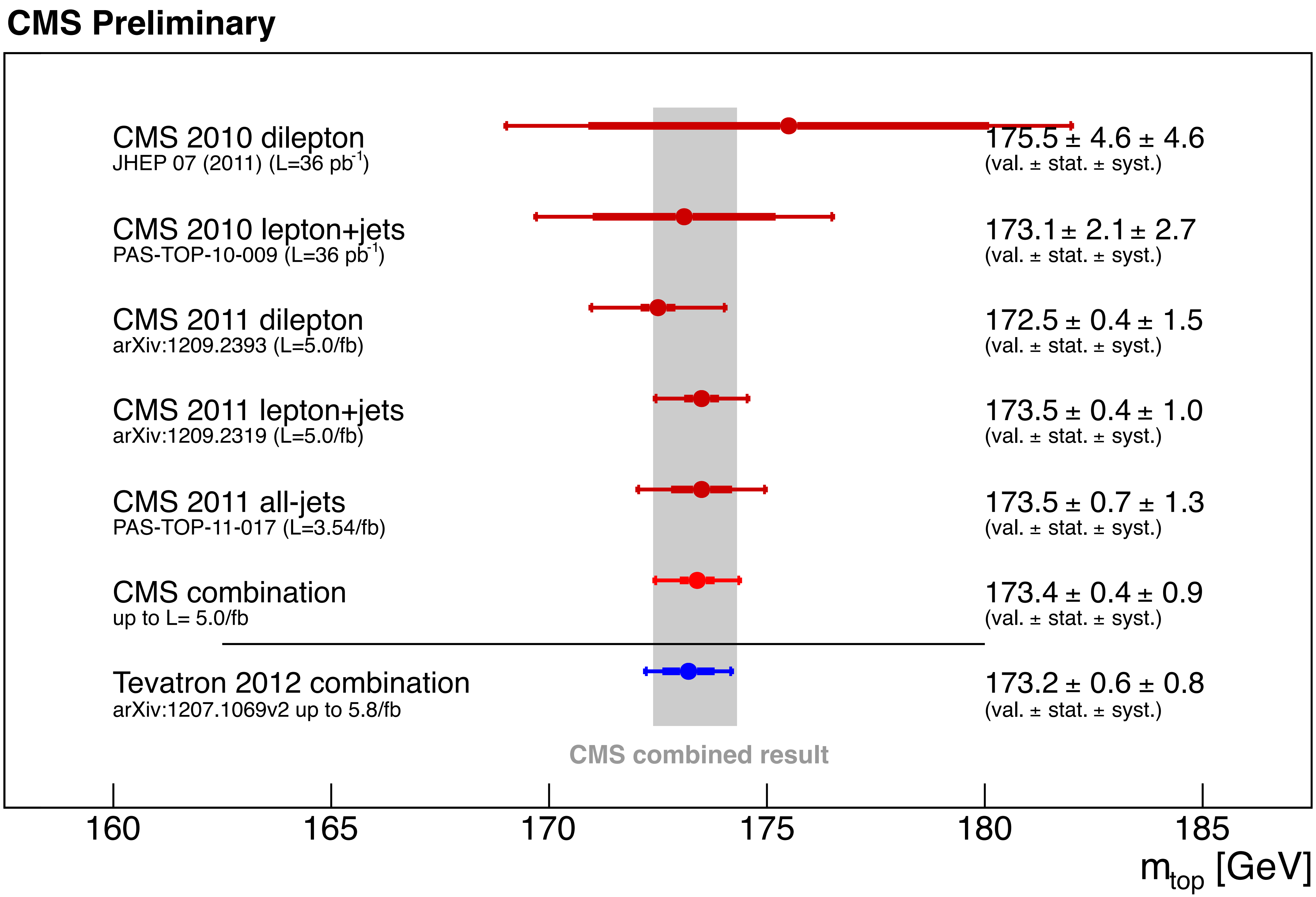
First public presentation at this conference!

CMS Mass Measurements



Most precise measurements in all channels

CMS Mass Measurements



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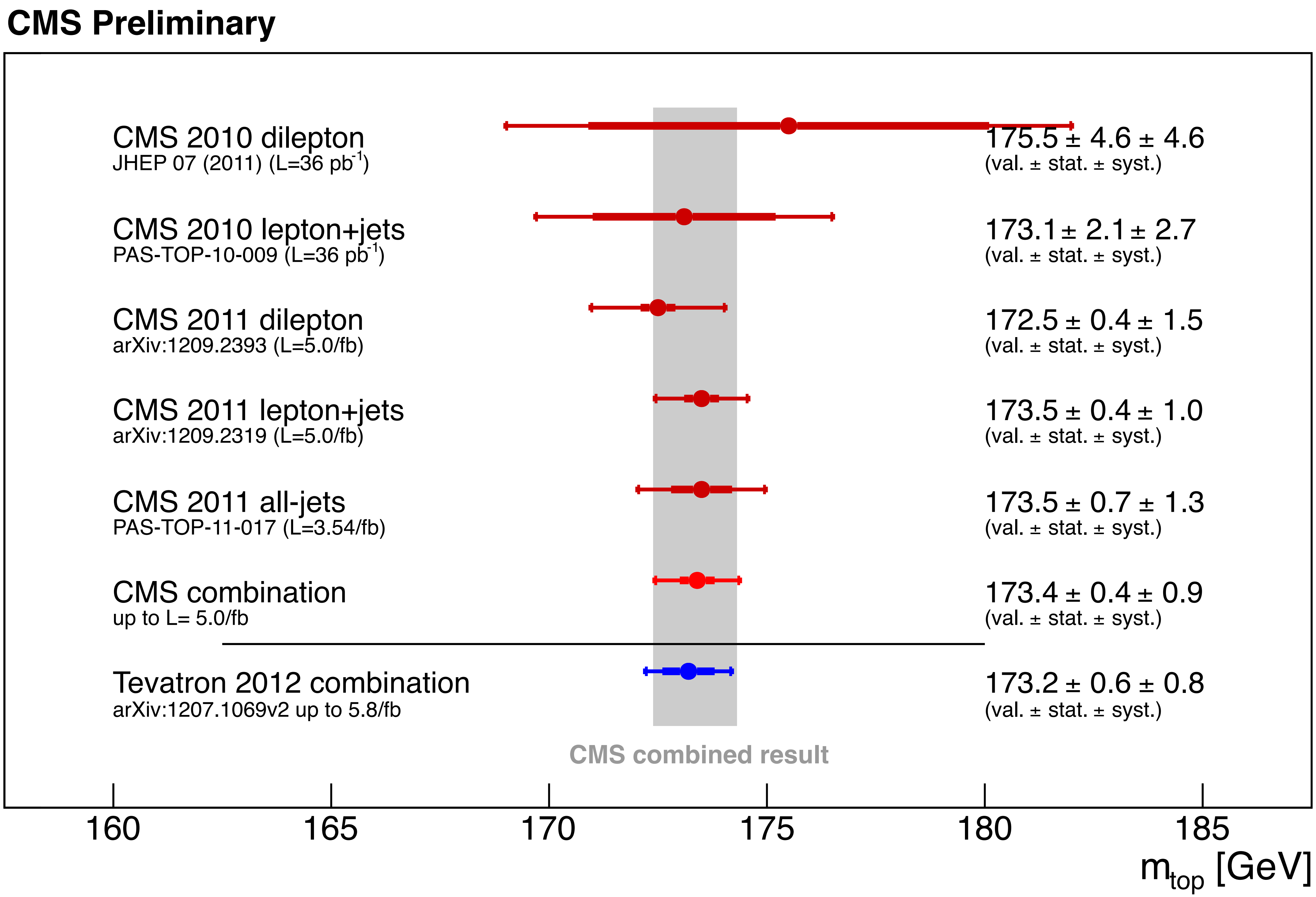
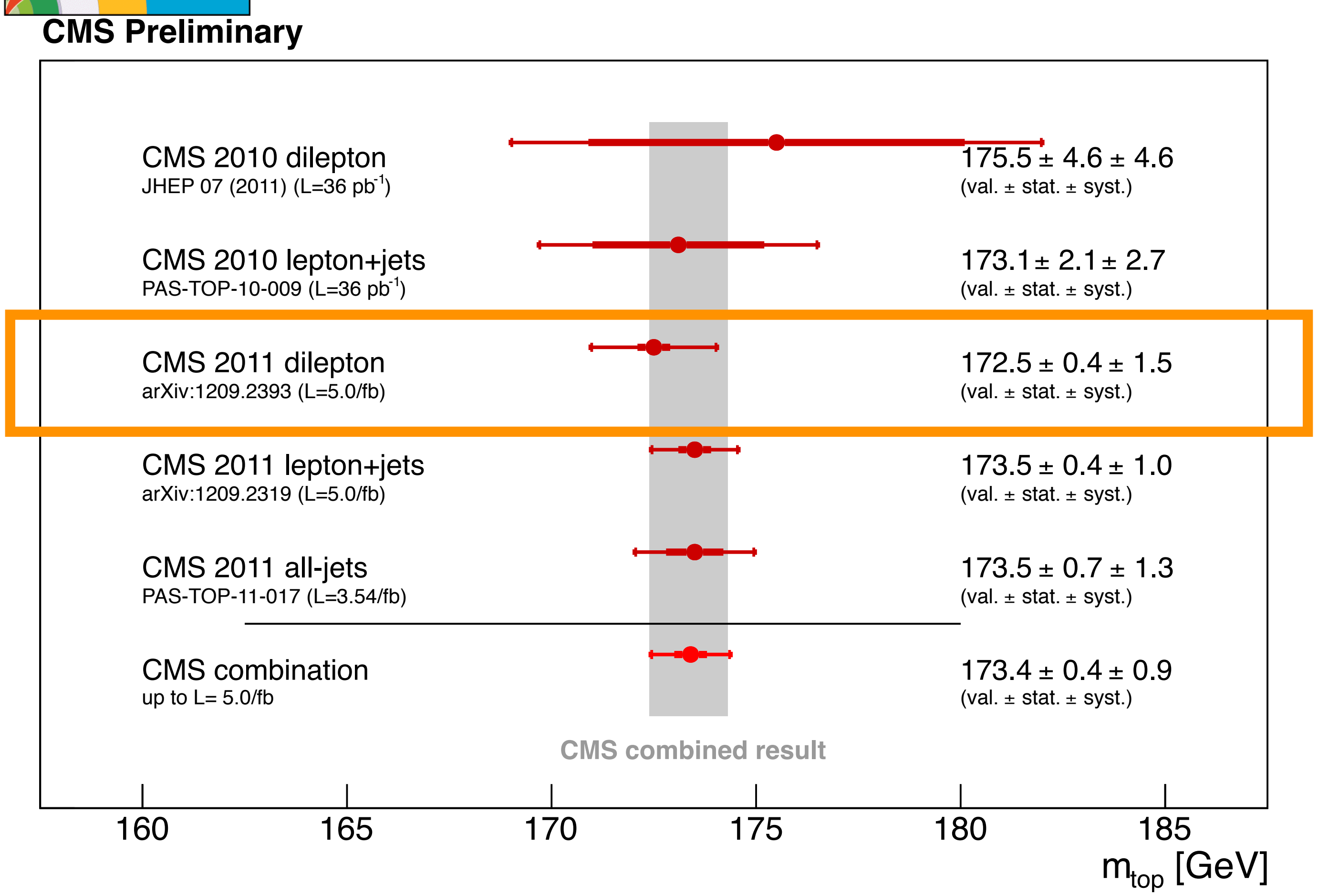


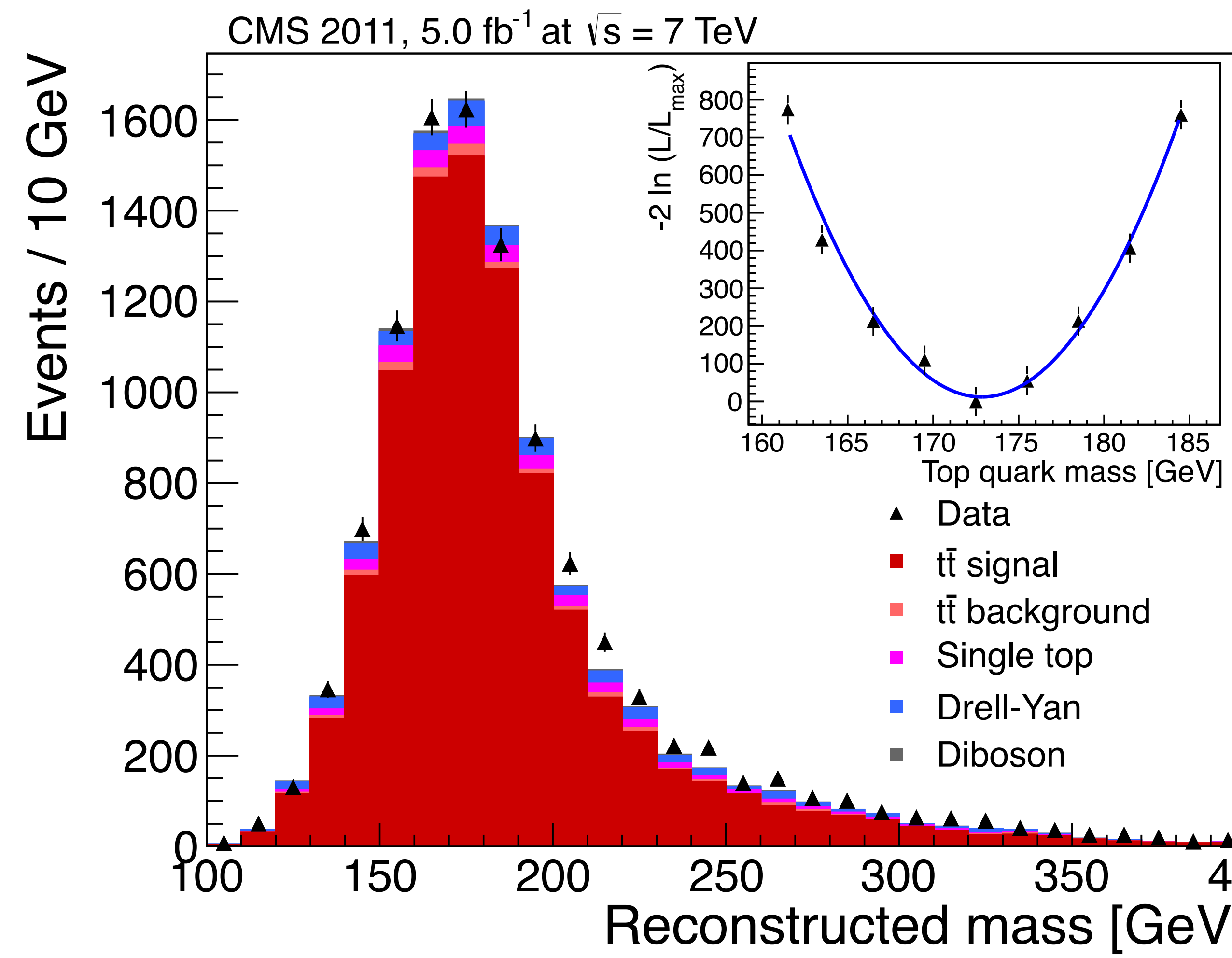
Precision of combination equal to Tevatron combination

EPJC 72 (2012) 2202

m_t in dilepton channel



9934 Events



- 5.0 fb^{-1} pp @ $\sqrt{s}$=7 TeV

$$t\bar{t} \rightarrow WbWb \rightarrow (\ell^+\nu_\ell b)(\ell^-\bar{\nu}_\ell b)$$

- Analytical Matrix Weighting Technique
  - take combination with largest weight w

$$w = \left\{\sum f(x_1)f(x_2)\right\} p(E^*_{\ell^+}|m_t)p(E^*_{\ell^-}|m_t)$$

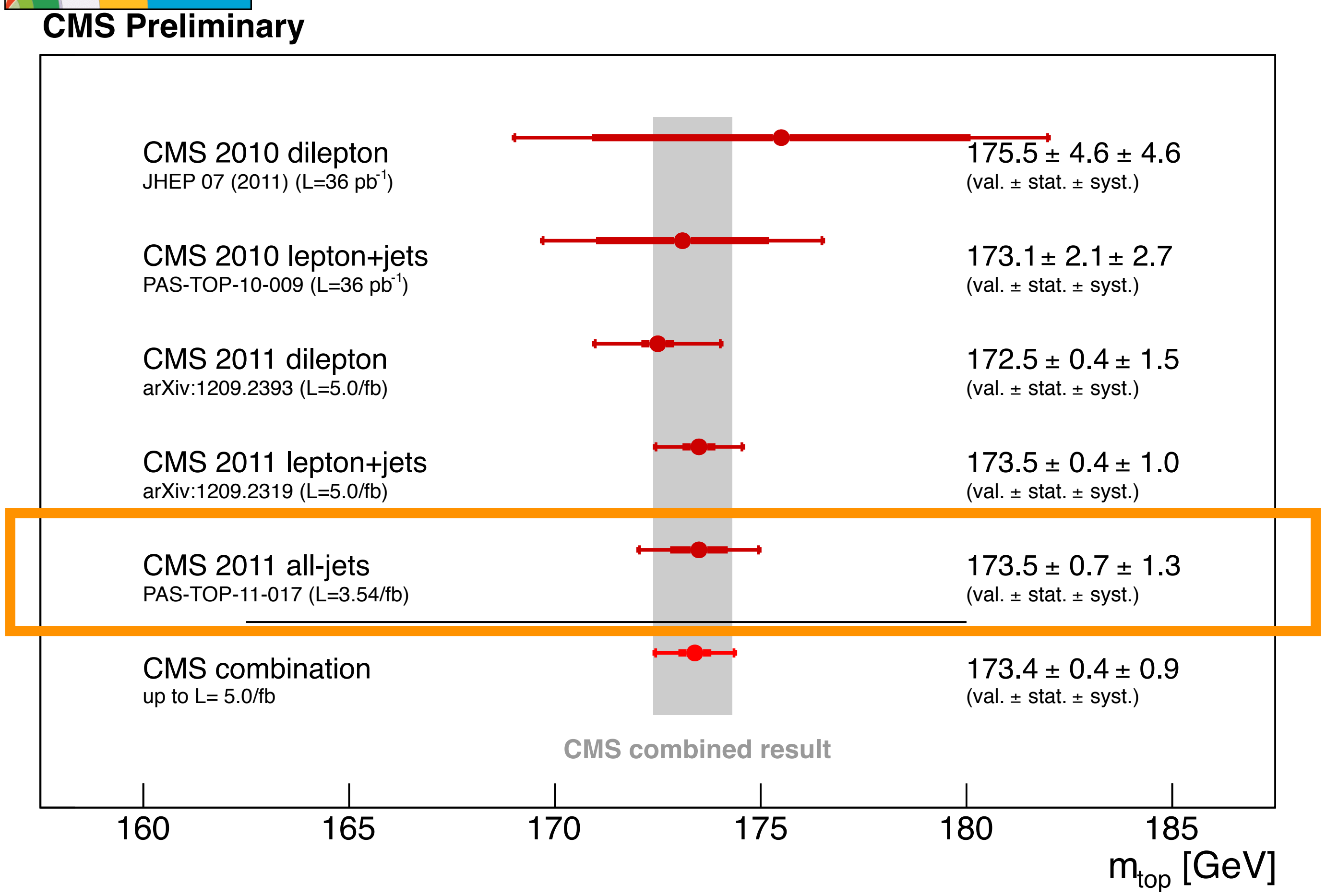
Sum over initial state partons uu, dd, gg

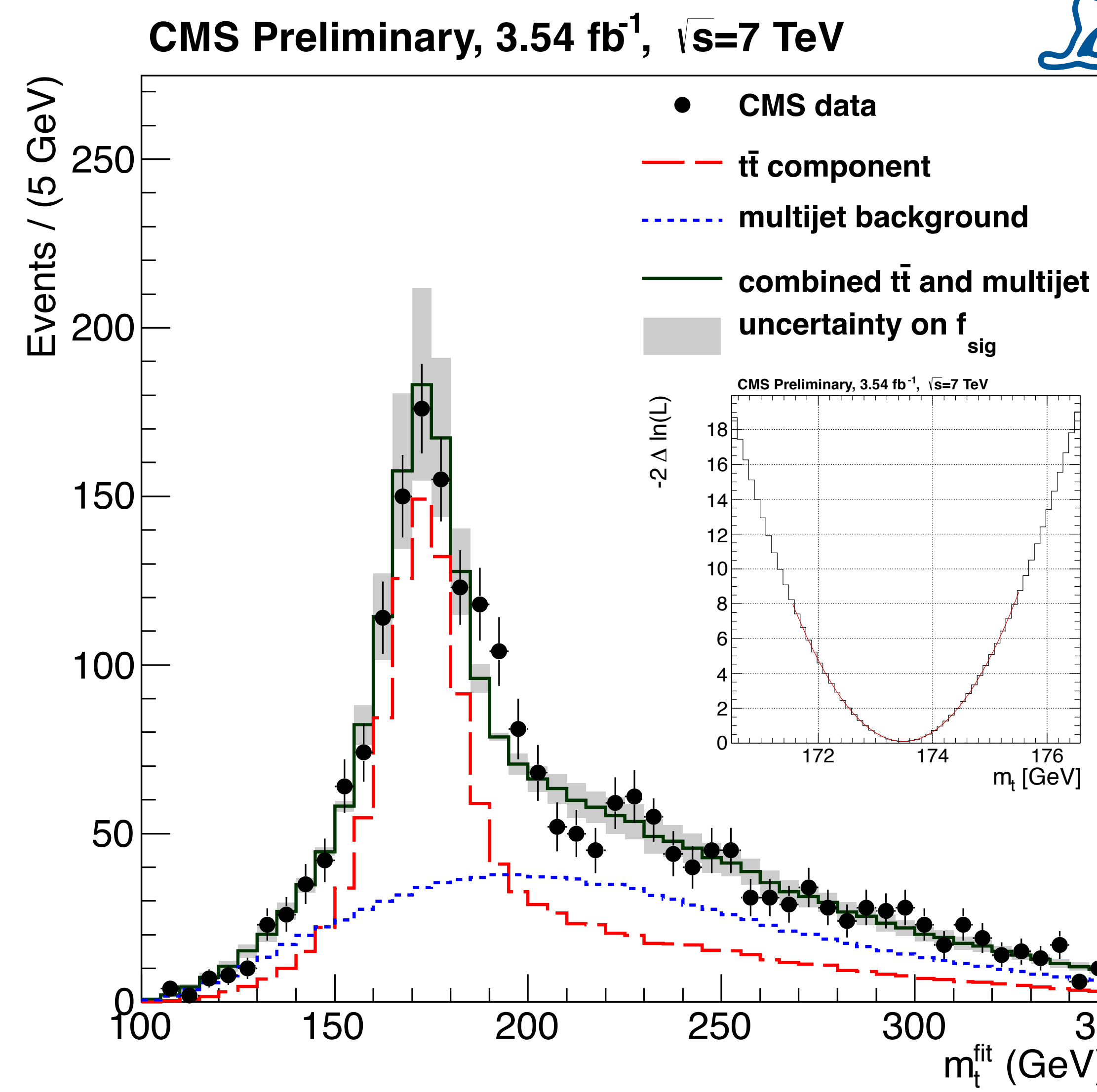
probability density for E_l in top rest frame

- Leading systematic uncertainties:
  - JES & flavor dependence
  - renormalization/factorization scale
- Best m_t measurement using dileptons

m_t=172.5 ± 0.4 (stat) ± 1.5 (syst) GeV

m_t from all hadronic channel



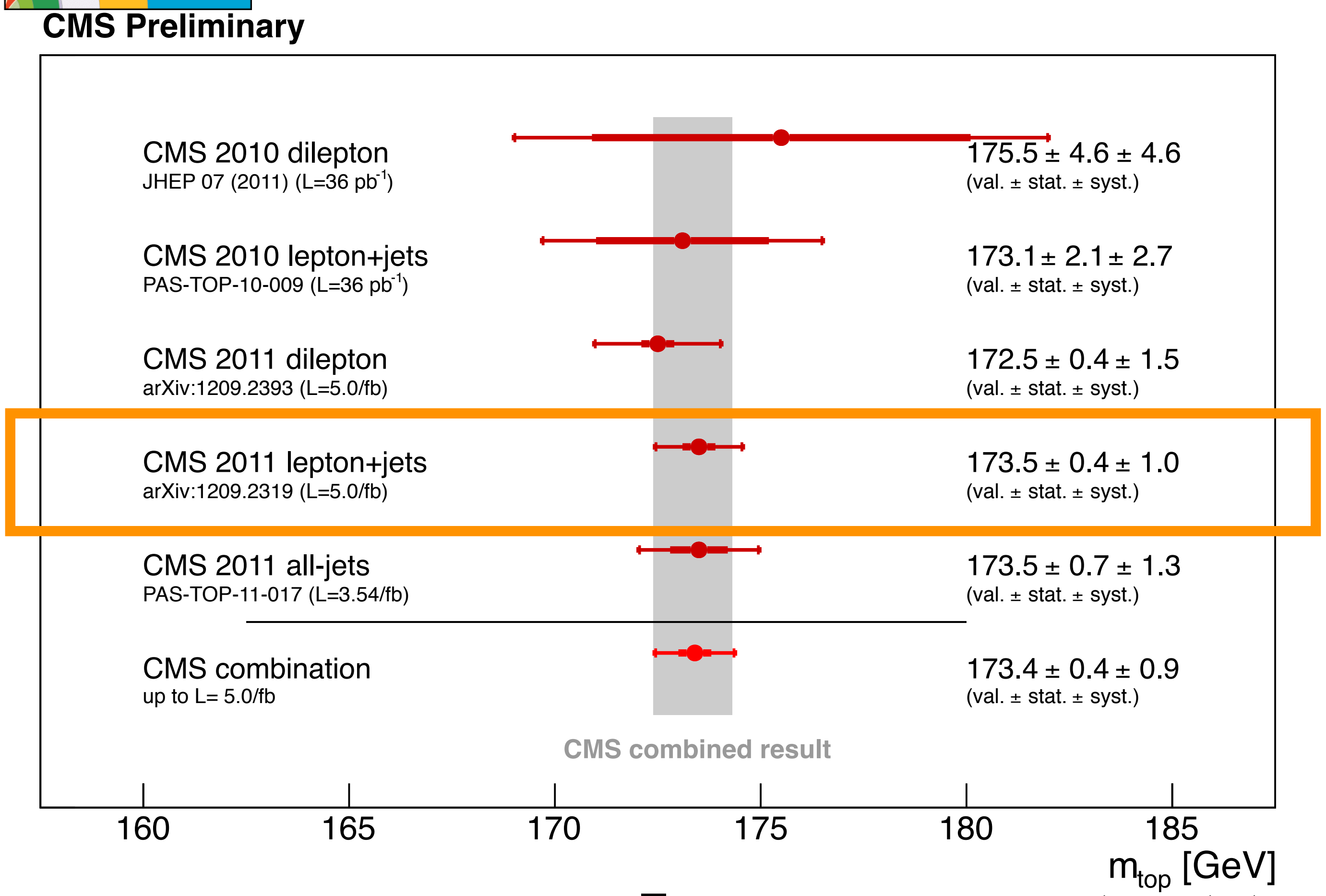


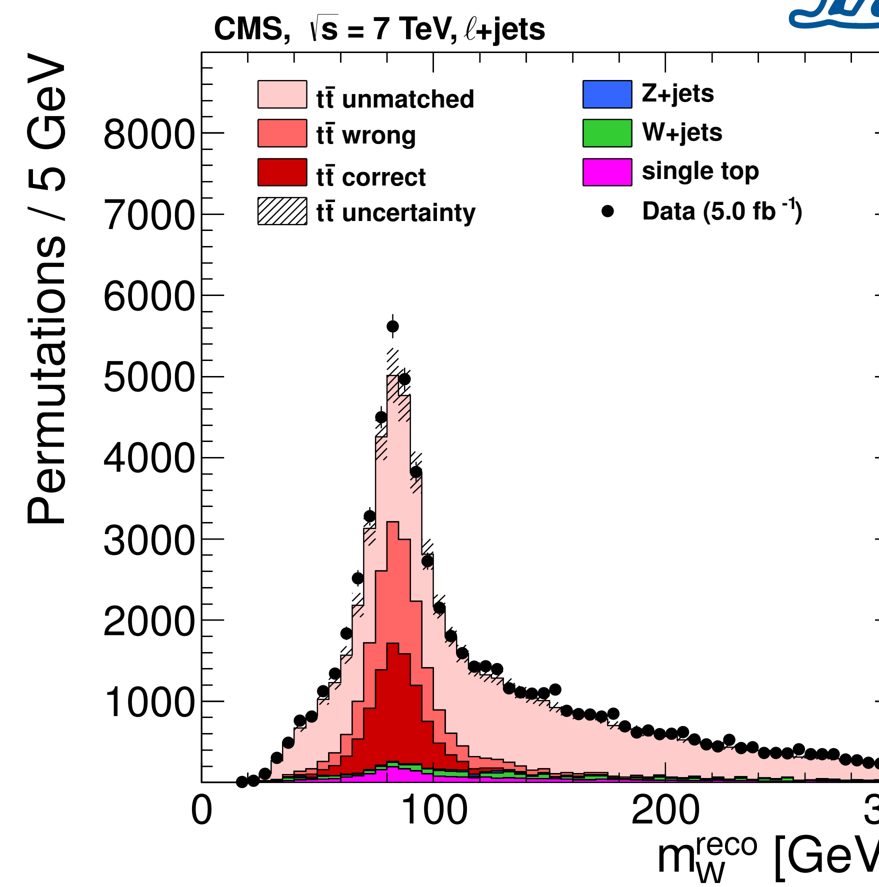
- At least 6 jets, two b-tagged
- Kinematic fit using m_W and m_t=m_{tbar} (3 dof)
  - improves jet-parton assignment & resolution
  - Require $P_{gof}(\chi^2)>0.09$
  - Take permutation with best χ^2
- Model multijets from data using event mixing in preselected sample
- Measure m_t with Ideogram method
  - analytic event-by-event likelihood calibrated using simulation
- JES dominant systematic (1.09 GeV)
- Most precise m_t using this channel

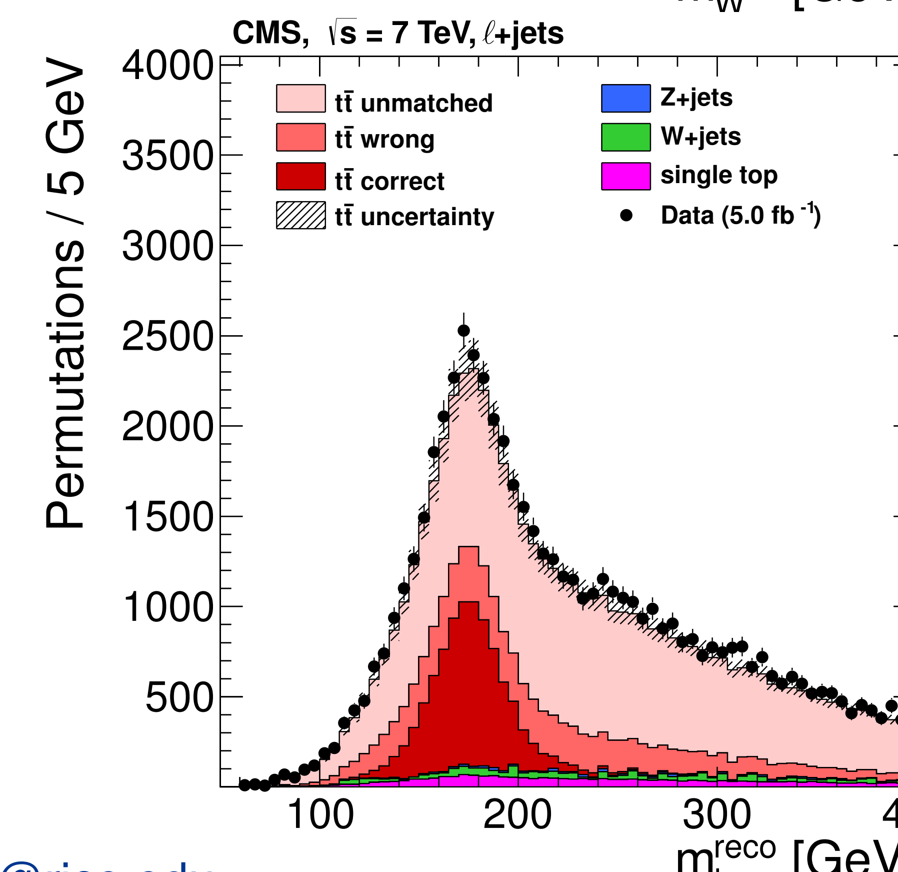
$$\boxed{m_t = 173.49 \pm 0.69(\mathrm{stat}) \pm 1.25(\mathrm{syst})}$$

JHEP 12 (2012) 105

m_t in l+jets channel 7 TeV

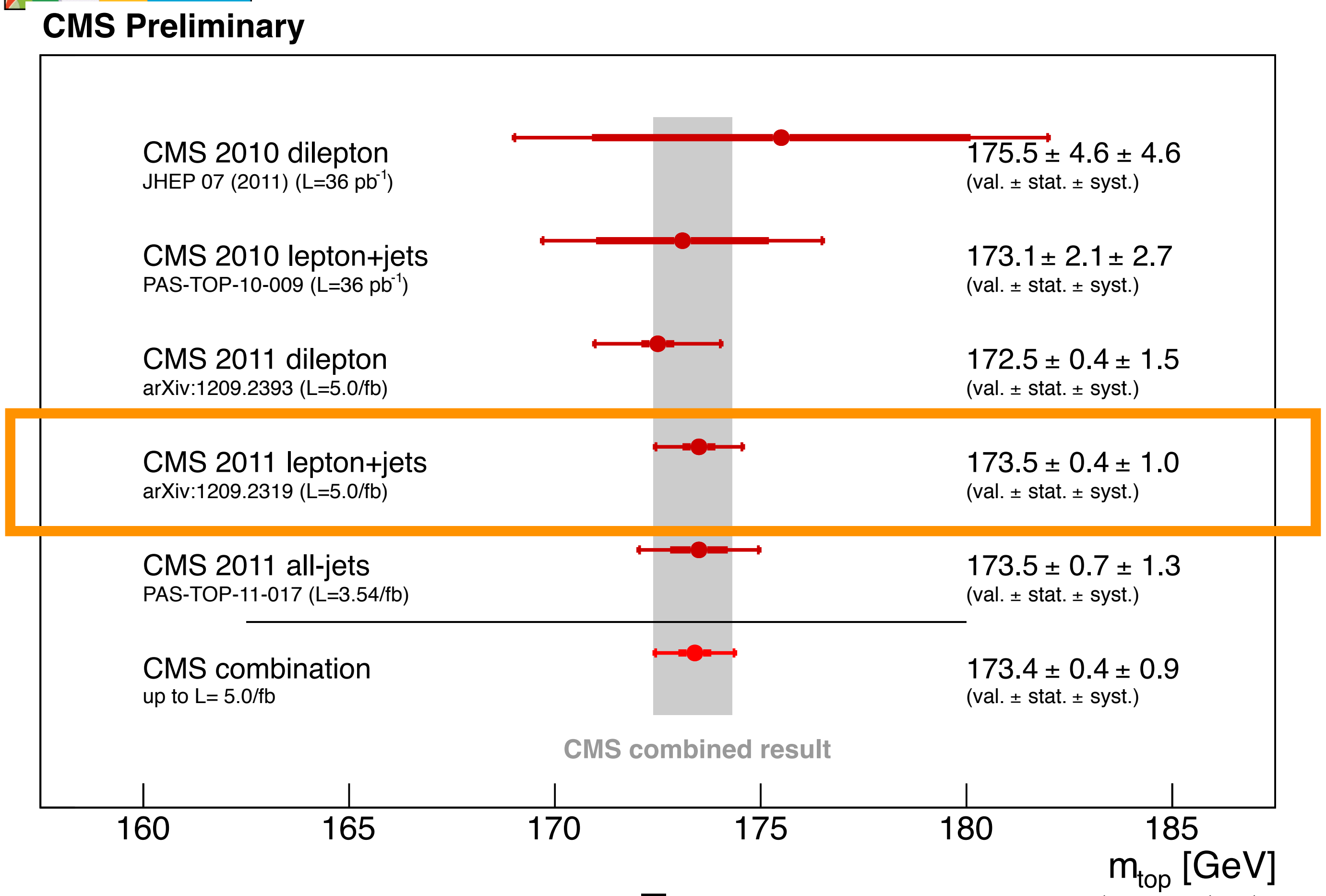


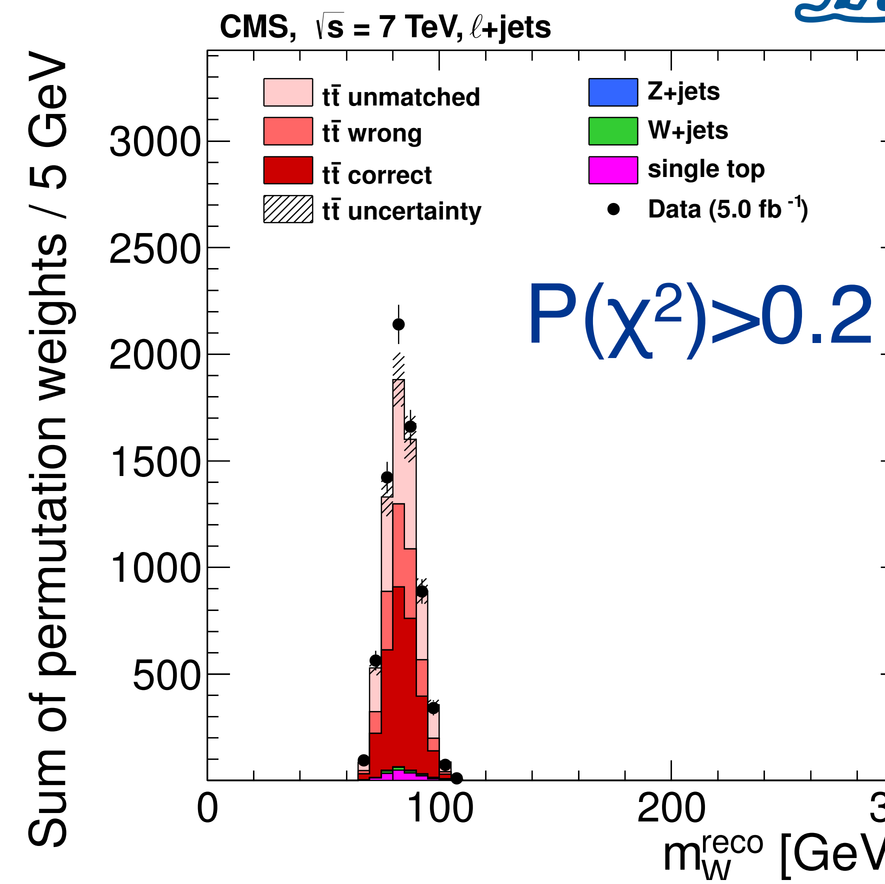


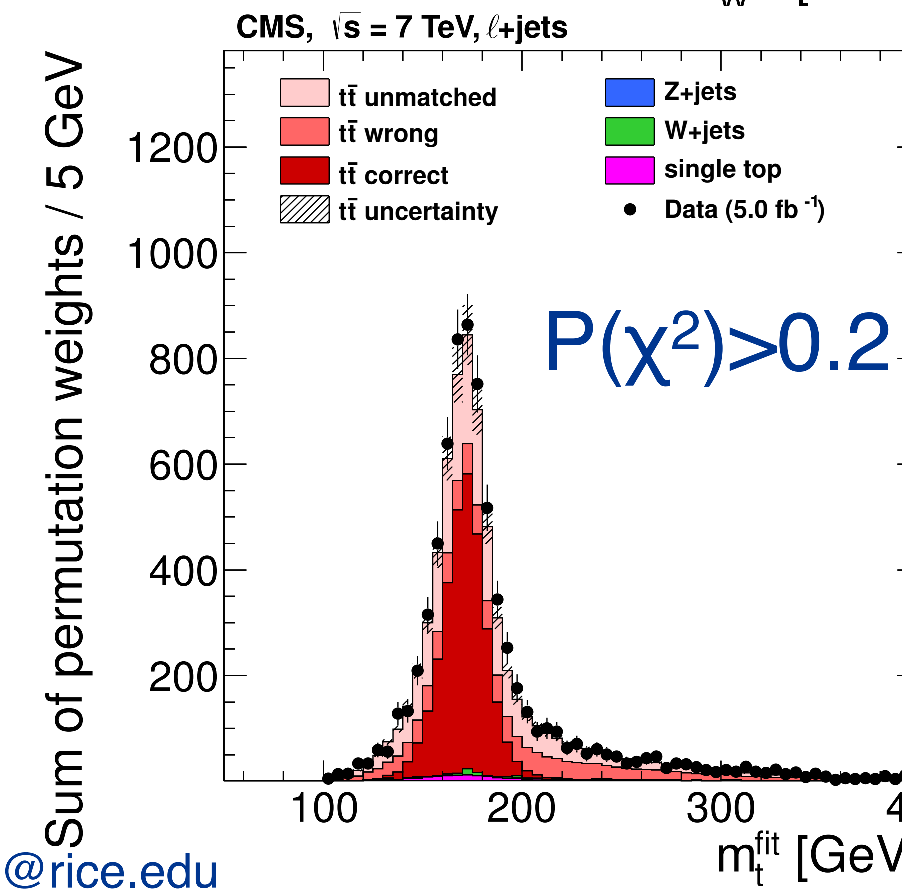


- Event Selection $t\bar{t} \to WbWb \to (\ell\nu b)(jjb)$
  - Exactly 1 $e^\pm$ or $\mu^\pm$ $|\eta|<2.1$, $p_T>30$ GeV
  - Four or more jets $p_T>30$ GeV & 2 b-tags
- Kinematic Fit (2 d.o.f.)
  - m_t free but require $m_t=m_{tbar}$ & $m_W=80.4$ GeV
  - Require $P_{gof}(\chi^2)>0.2$
  - correct permutations: 13%→44%
- Sample of 5174 events in 5.0 fb^{-1} pp @ $\sqrt{s}$=7 TeV

m_t in l+jets channel 7 TeV







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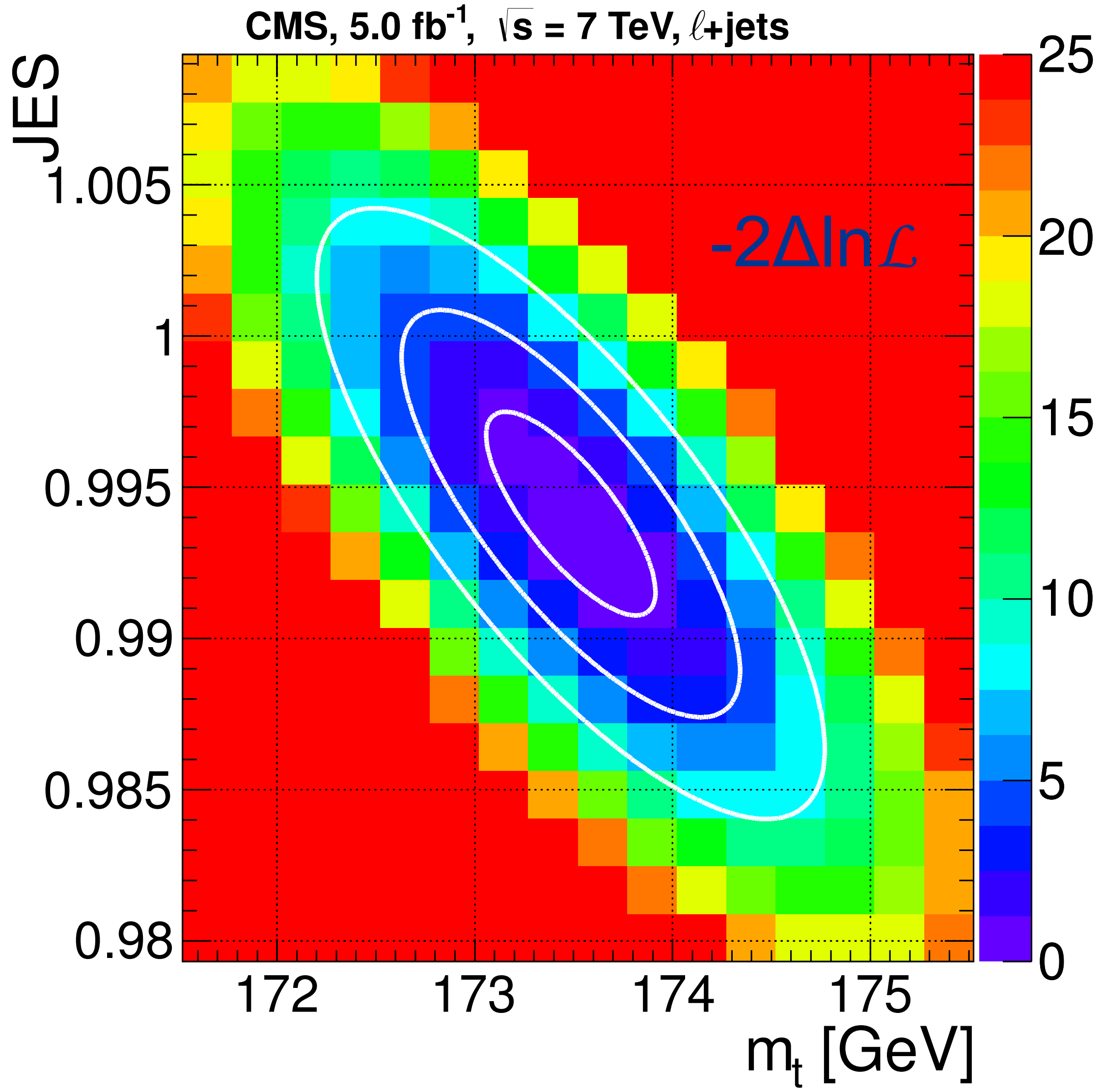
m_t in l+jets channel 7 TeV

$$\mathcal{L}(\text{sample}|m_t, \text{JES}) = \prod_{\text{events}} \left(\sum_{i=1}^{n} c P_{\text{gof}}(i) P(m_{t,i}^{\text{fit}}, m_{W,i}^{\text{reco}} | m_t, \text{JES}) \right)^{w_{\text{event}}}$$

- Ideogram method
  - Analytic Likelihood function
  - calibrated using simulation
- Jointly fit for m_t and light-flavor **J**et **E**nergy **S**cale
- Leading systematic uncertainties
  - color reconnection
  - b-jet energy scale



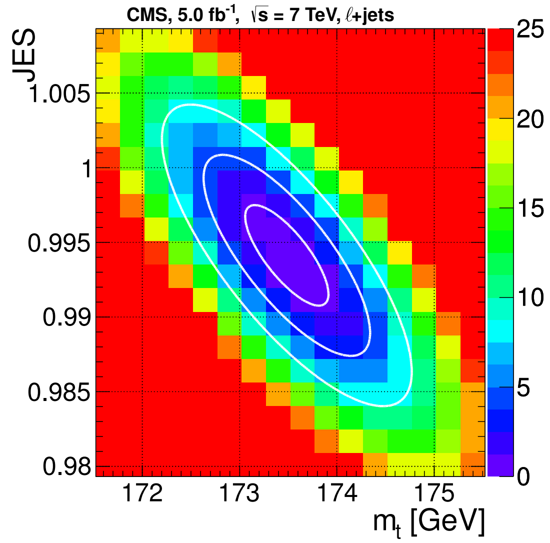
m_t=173.49 ± 0.43 (stat+JES) ± 0.98 (syst) GeV

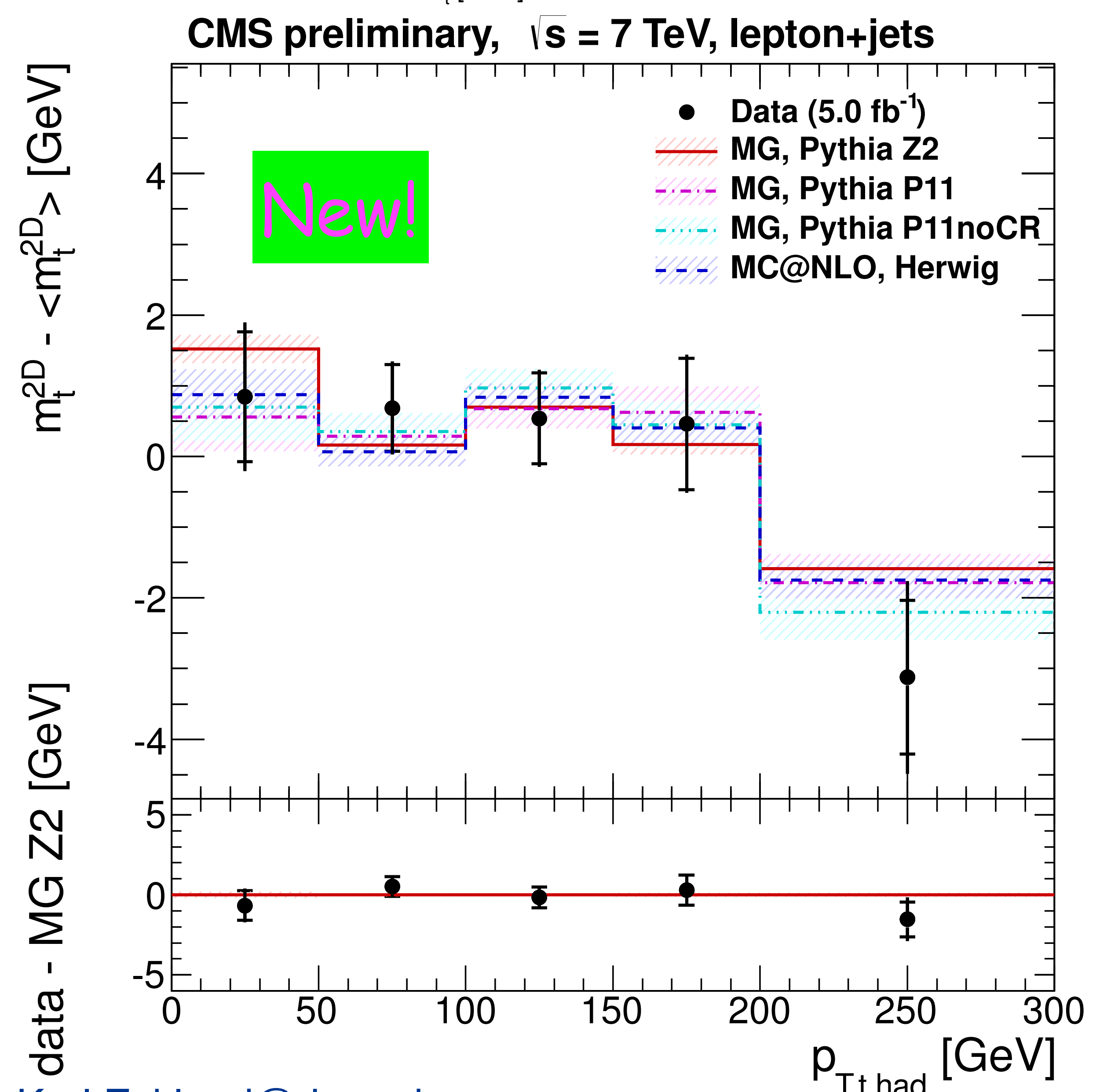
Best single analysis measurement of m_t!

Study of m_t dependence on kinematics

New!

- Investigation of possible biases on m_t through study of kinematic distributions
  - Color reconnection effects
  - Radiative effects ISR/FSR
  - b-quark kinematics
- Use same sample & technique as l+jets
  - 2D mass and JES fit
  - now binned in 12 variables
  - Shifts in m_t and JES studied
  - Compared to MC models
    - MadGraph+Pythia Z2,P11
    - MC@NLO+Herwig6

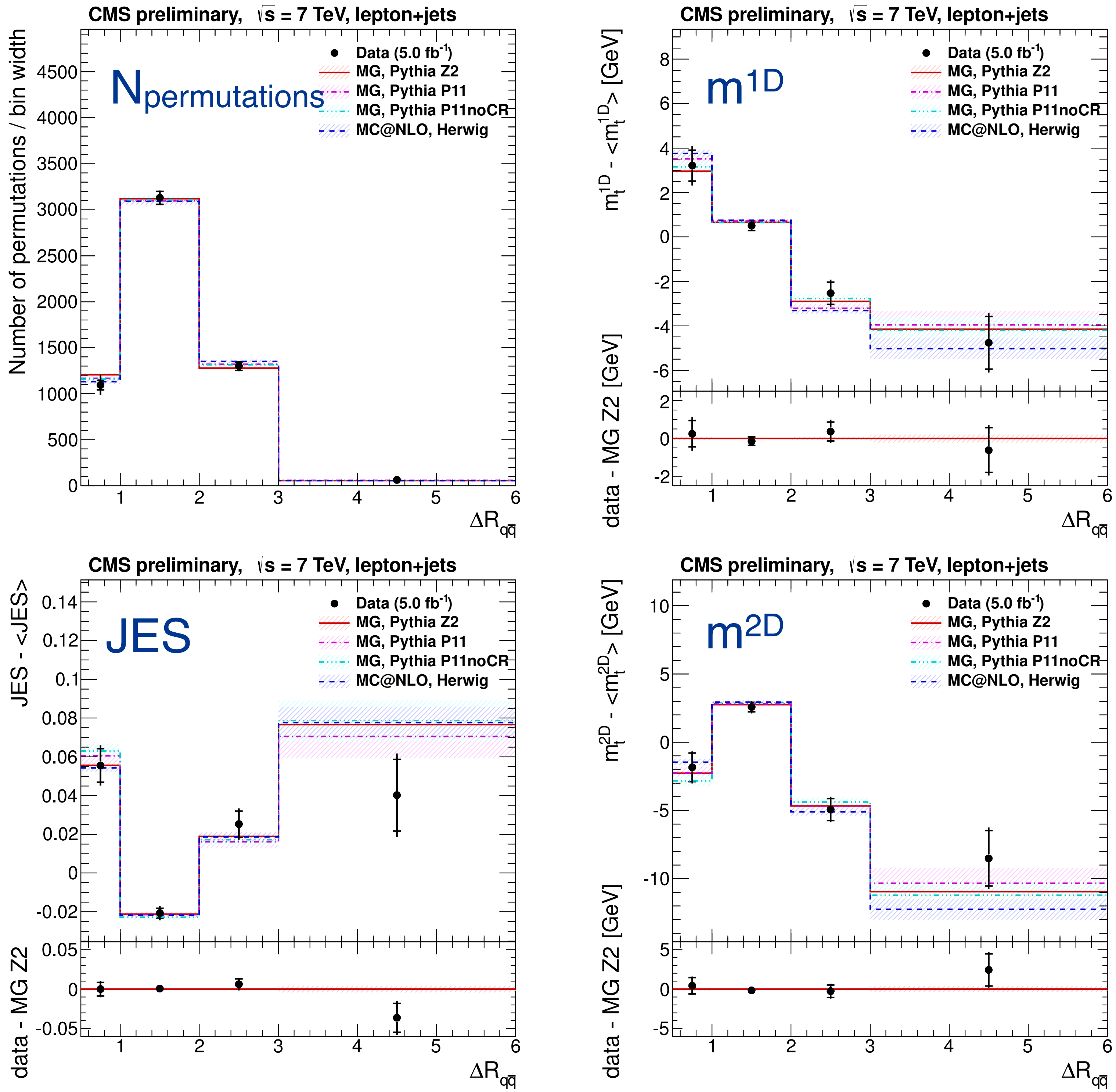




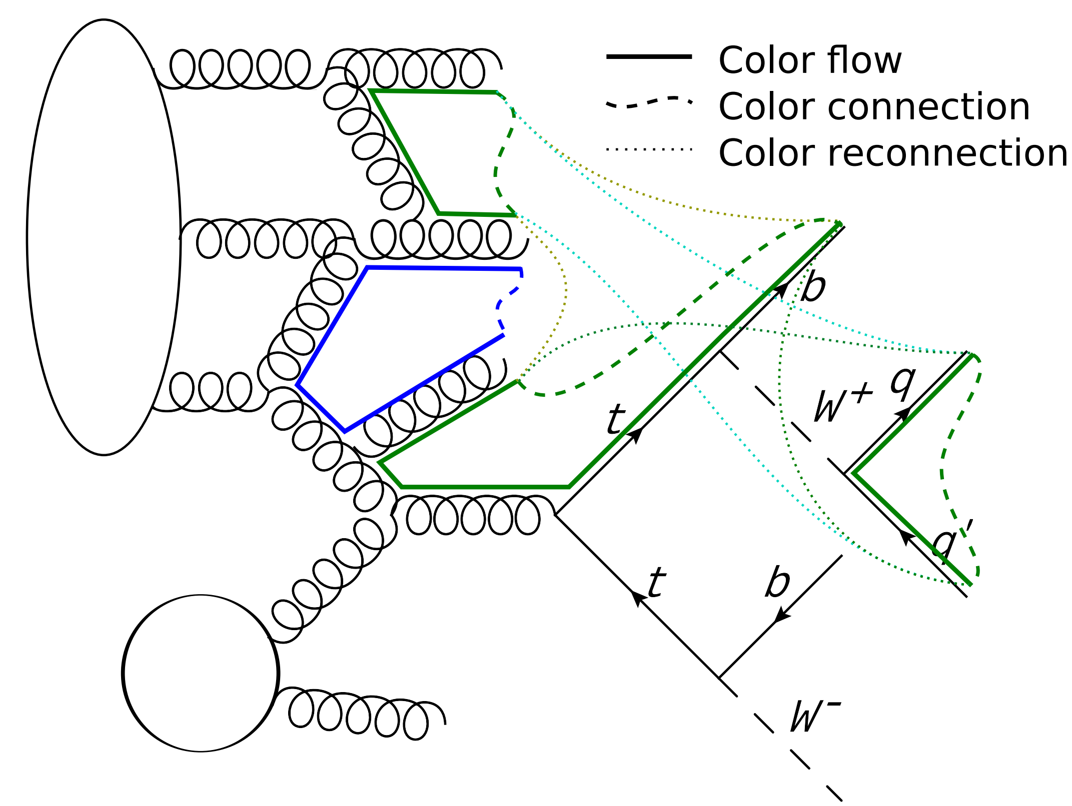
CMS PAS TOP-12-029

m_t and color reconnection

New!



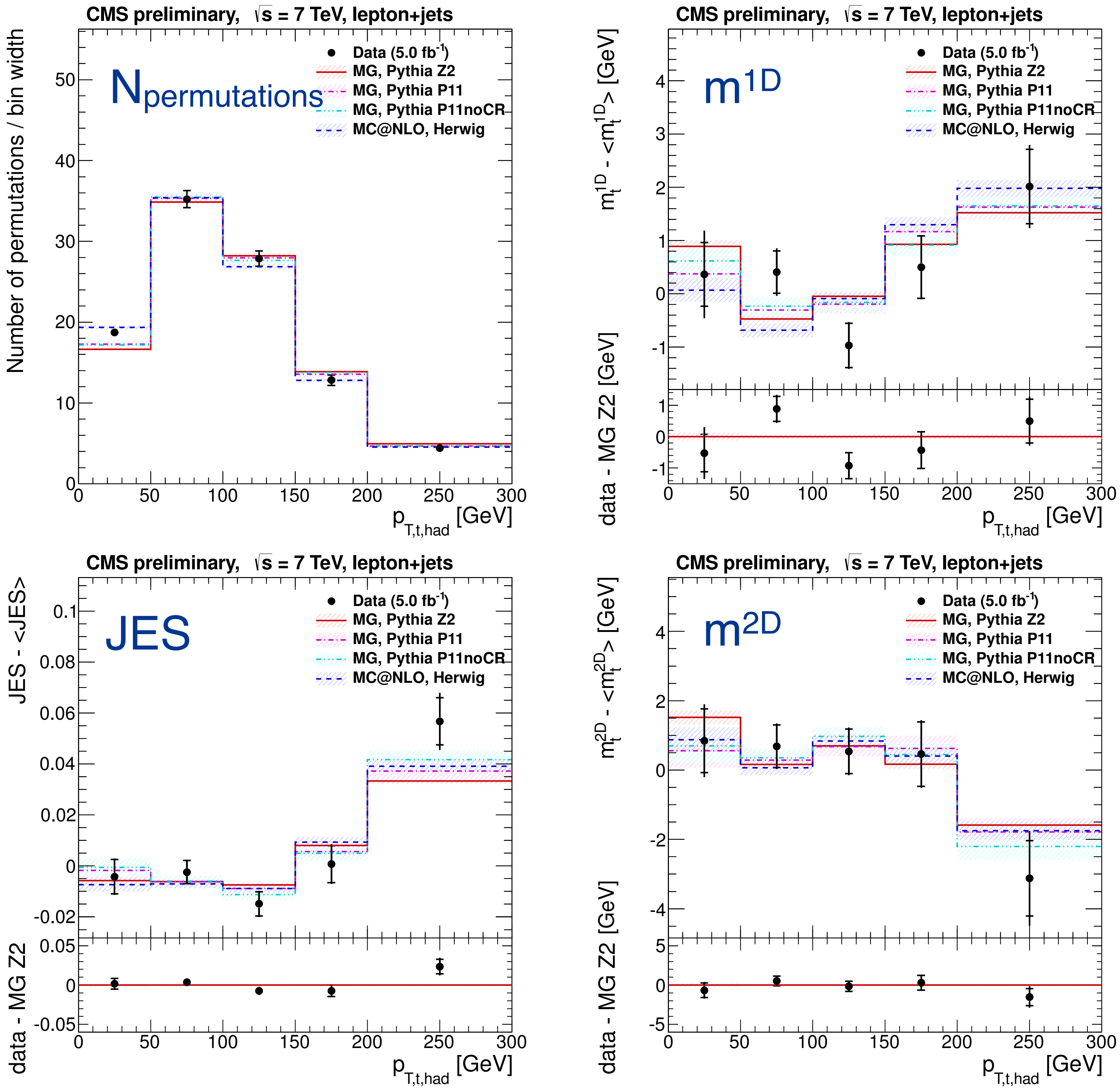
$\Delta R_{qq}=(\Delta\eta^2+\Delta\phi^2)^{1/2}$



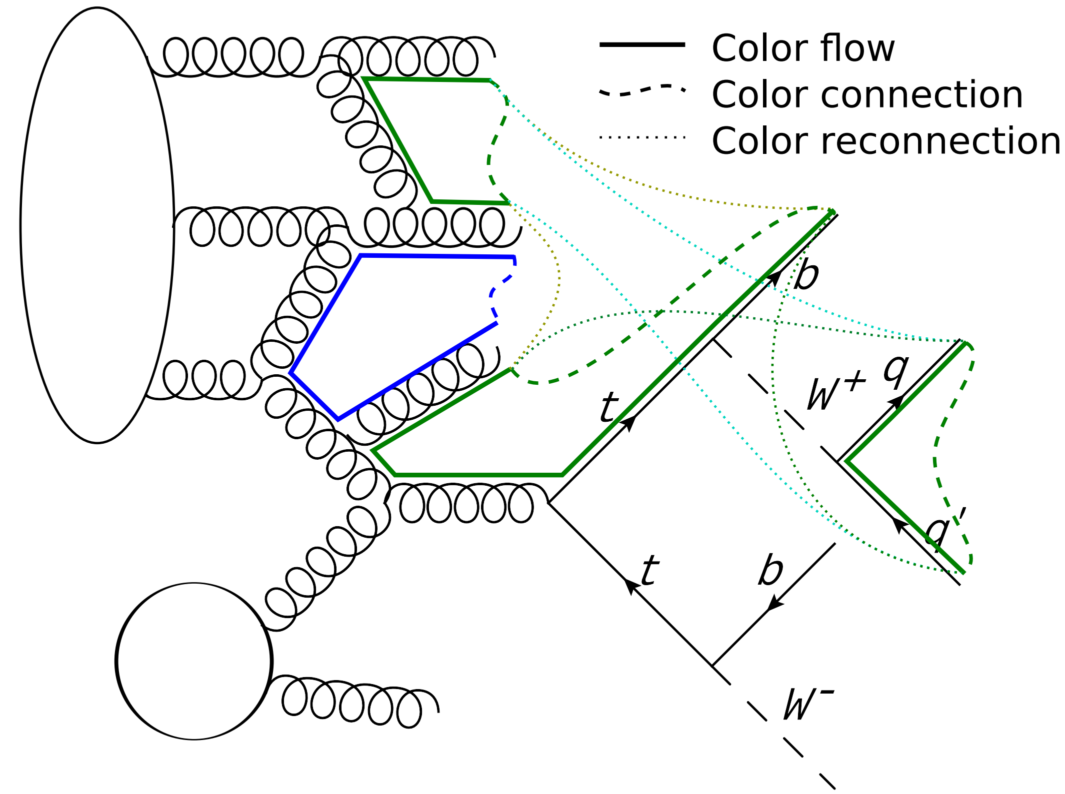
- Empirical model
  - finite probability for color reconfiguration
  - MadGraph+PYTHIA
  - MC@NLO+Herwig 6
- Largest systematic for l+jet m_t
  - Pythia P11 and P11noCR
- No sign of extreme effects here!

m_t and color reconnection

New!



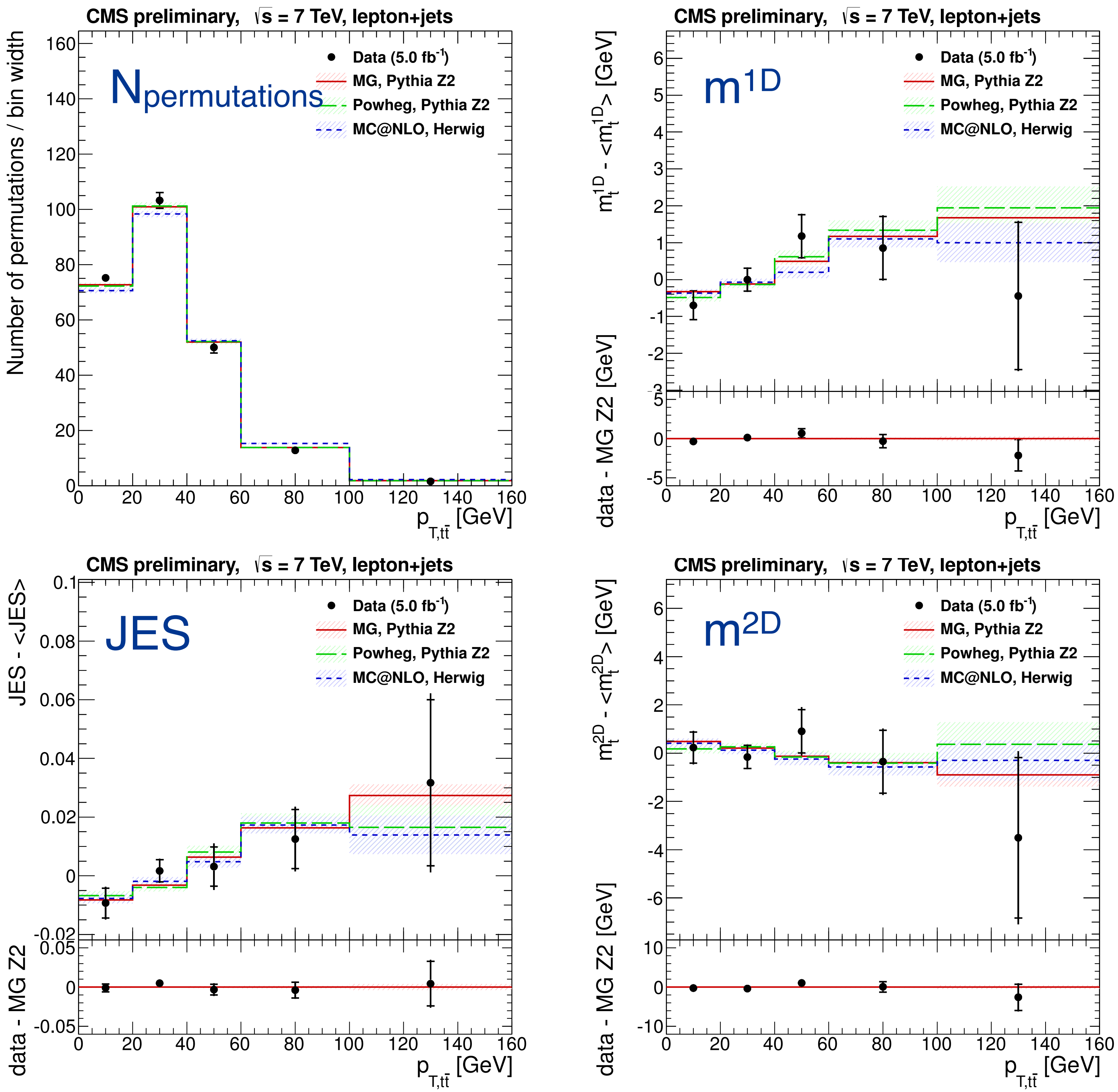
p_T hadronically decaying top

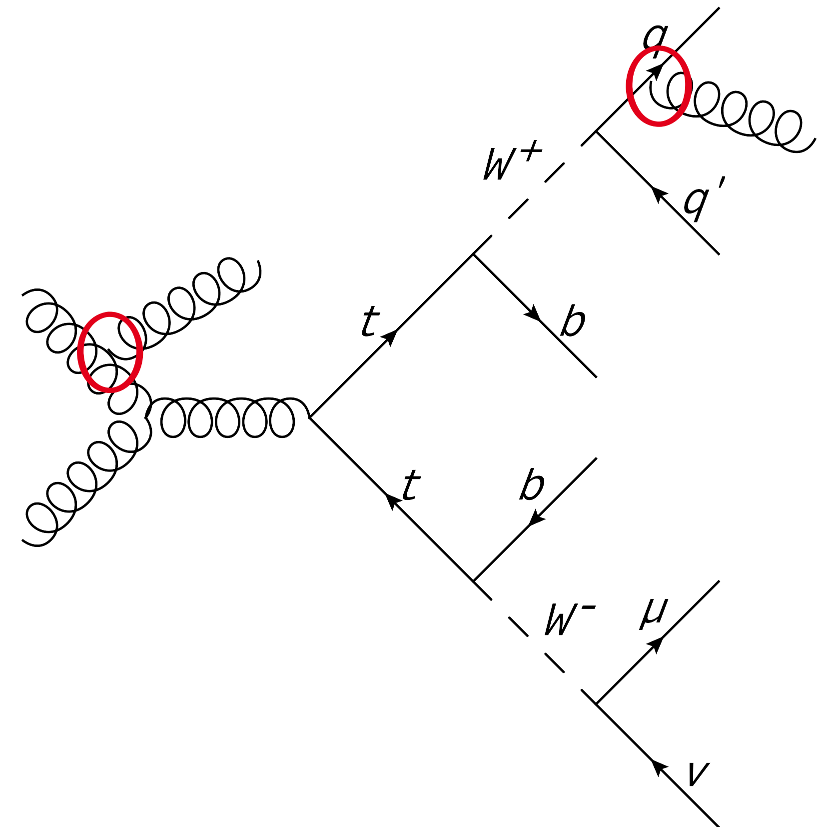


- MC@NLO best match for $N_{entries}$ for lowest p_T bin
- No significant dependence below 200 GeV
  - 2D fit compensates
  - Onset of jet merging at 200 GeV
- No sign of extreme effects here!
  - all MC models track well

m_t and initial/final state radiation

New!





- Measure of ISR
- Small dependence compensated by 2D fit

p_T top-antitop system

Study of m_t dependence on kinematics

New!

- 12 observables studied
- Global agreement is good:
  - χ^2=68.58/78 dof P=0.77
- All MC simulation codes & tunes following trends well within statistics
  - MadGraph+PYTHIA Z2, P11, P11noCR
  - POWHEG+PYTHIA Z2
  - MC@NLO+HERWIG

Observable	m_t^{1D} χ^2	JES χ^2	m_t^{2D} χ^2	Ndf	
$\Delta R_{q\bar{q}}$	1.01	3.41	1.49	3	Color reconnection
$\Delta\phi_{q\bar{q}}$	2.31	2.18	2.89	3	
$p_{T,t,had}$	9.40	7.83	2.41	4	
$\lvert\eta_{t,had}\rvert$	0.41	3.33	3.17	3	
H_T	3.18	1.19	2.24	4	ISR/FSR
$m_{t\bar{t}}$	2.52	2.98	2.25	4	
$p_{T,t\bar{t}}$	3.39	1.67	2.18	4	
Jet multiplicity	1.47	2.00	1.56	2	
$p_{T,b,had}$	0.81	2.35	2.17	4	B-jet kinematics
$\lvert\eta_{b,had}\rvert$	2.64	0.30	0.48	2	
$\Delta R_{b\bar{b}}$	4.87	2.61	8.01	3	
$\Delta\phi_{b\bar{b}}$	2.87	3.85	6.86	3	

Shown

- First mass measurement binned in kinematic variables
  - including variables suggested by theoretical community
- Based on single most precise measurement
- Results rule out extreme or dramatic effects
- Valuable input for interpretation of m_t measurements for EW fits
- Builds confidence in systematic & theoretical effects for m_t meas.

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"Street Cred" for precise m_t

- Valuable input for interpretation of m_t measurements for EW fits
- Builds confidence in systematic & theoretical effects for m_t meas.

CMS PAS TOP-12-035

New!

b content in top decay: $|V_{td}|$

- 16.7 fb^{-1} pp @$\sqrt{s}$=8 TeV
- $t\bar{t} \to WqWq \to (\ell^+\nu_\ell q)(\ell^-\bar{\nu}_\ell q)$
  - high purity sample 70-90%
  - two isolated leptons e or μ : p_T>20
  - at least two jets p_T>30
  - for ee, μμ: missing E_T > 40 GeV

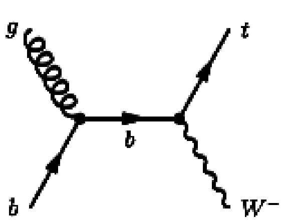
$$\mathcal{R} = \frac{\mathcal{B}(t \to Wb)}{\sum \mathcal{B}(t \to Wq)} = |V_{tb}|^2$$

3 Gen. SM

- Measure top only with kinematics & no b-tags
- Count b-tags to measure R

Estimate purity of sample N_{tt}/N_{evt} → Estimate number of t→Wq reconstructed → Compare number of b-tagged jets with expected

- Use kinematic info for data-driven Drell Yan estimate (dominant)
- Constrain single top tW from simulation



- Use M(lb) kinematics
- Categorize by # jets from top: 0, 1, 2

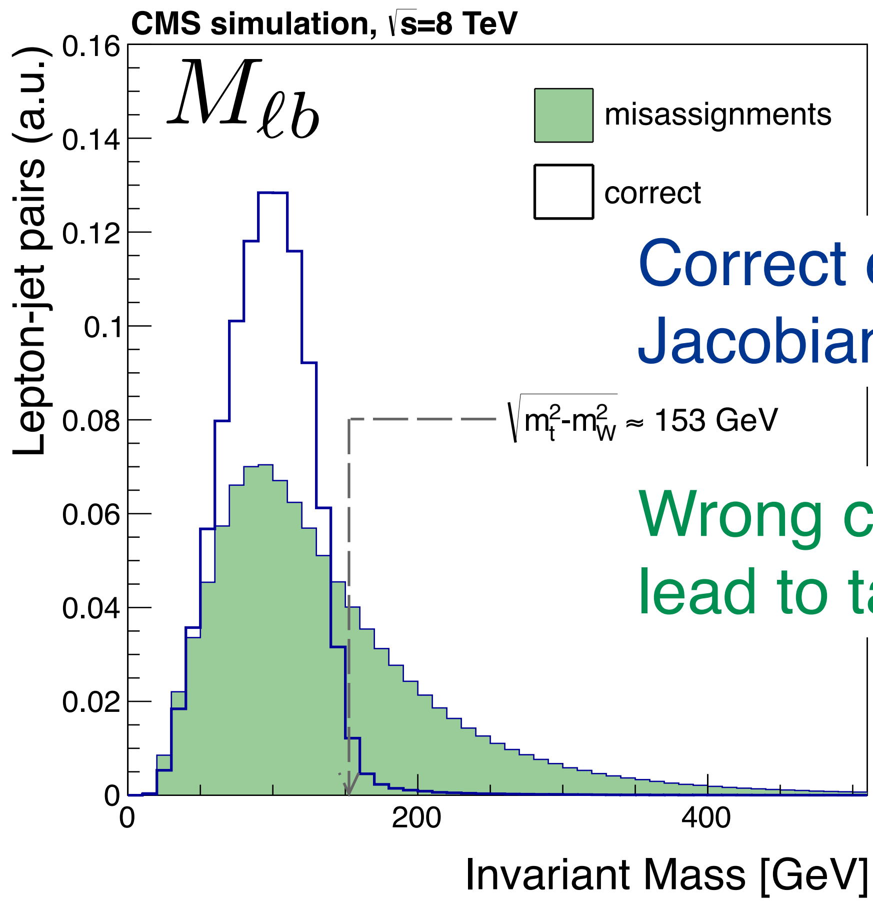
- Measure b-tag efficiency with independent sample of dijet events
- count b tags
- compare with data-driven probabilities

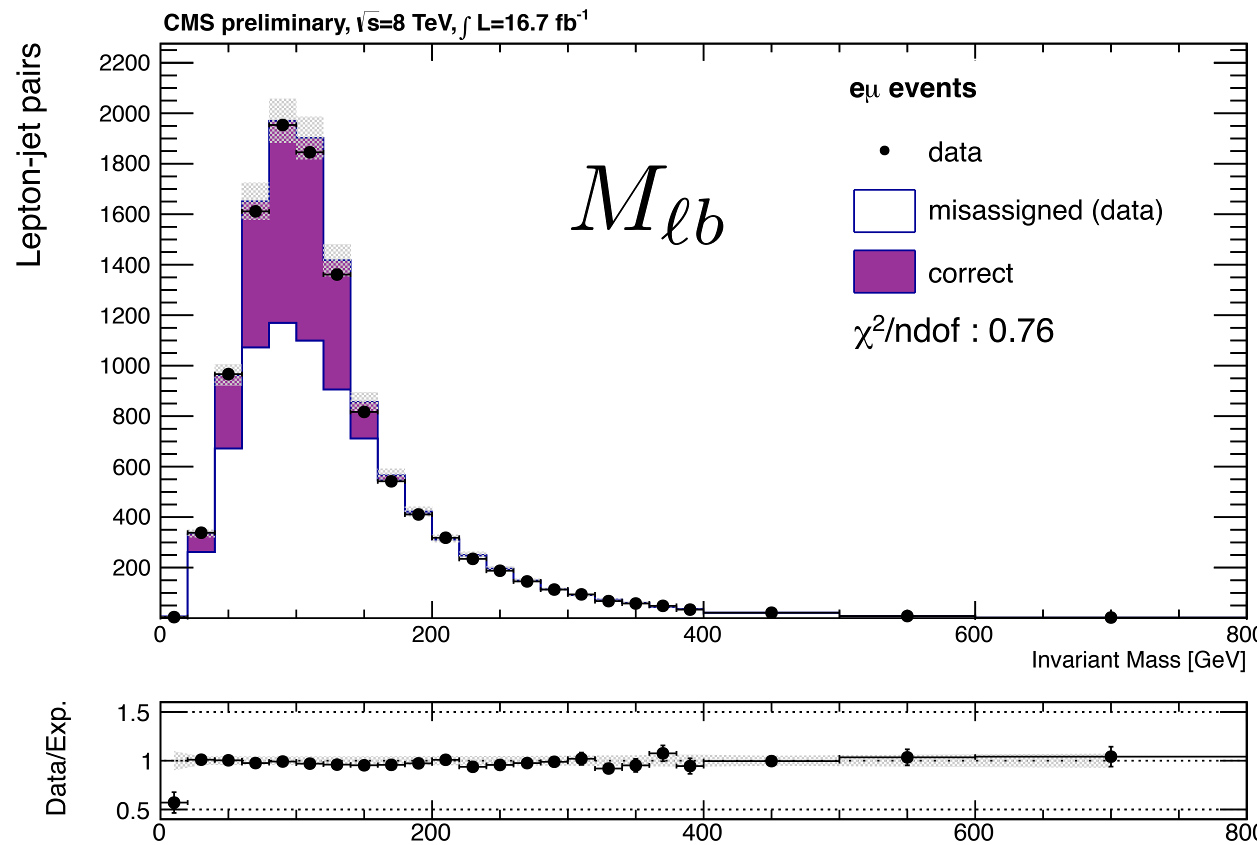
Fit for R from measured b-tag multiplicities using data-driven b-tag efficiency & probability functions

New!

b content in top decay: $|V_{td}|$

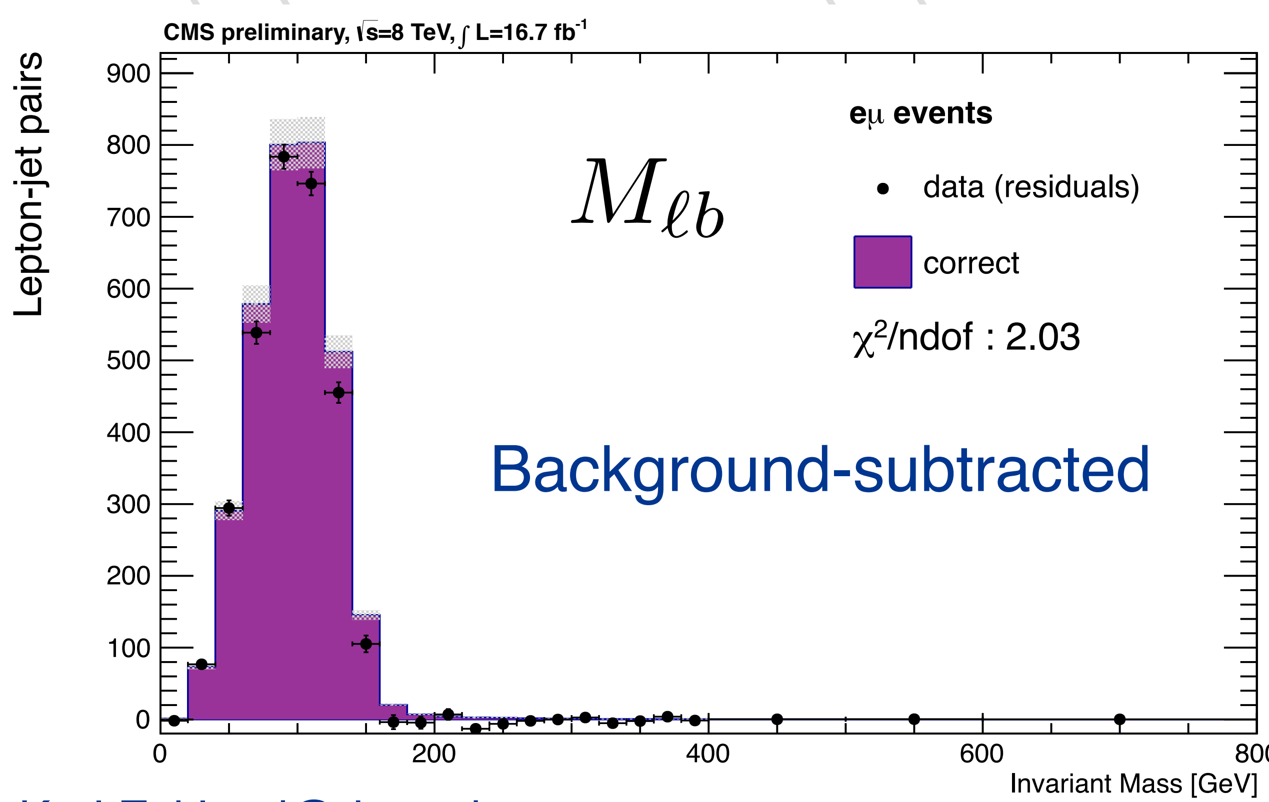
Counting correctly reconstructed $t \to Wq$ $ql\nu$





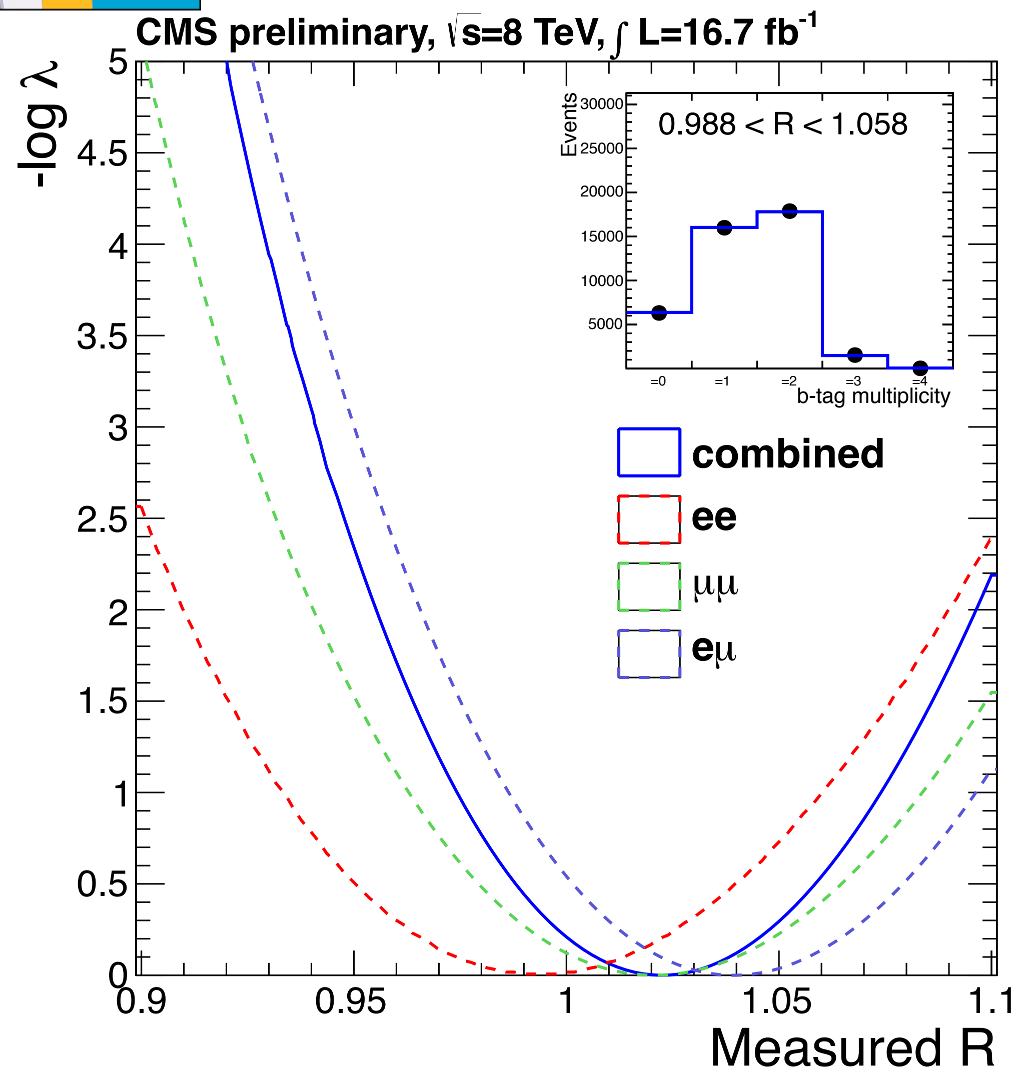
- Model combinatoric background with randomly rotated leptons
- Normalized to control region M>180 GeV

Category		$f^{MC}_{correct}$	$f^{data}_{correct}$	data/MC
ee	=2 jets	0.265 ± 0.002	$0.28 \pm 0.01 \pm 0.01$	$1.05 \pm 0.04 \pm 0.04$
	=3 jets	0.211 ± 0.002	$0.21 \pm 0.02 \pm 0.01$	$0.99 \pm 0.09 \pm 0.05$
	=4 jets	0.173 ± 0.002	$0.18 \pm 0.02 \pm 0.02$	$1.04 \pm 0.12 \pm 0.12$
$e\mu$	=2 jets	0.3475 ± 0.0009	$0.35 \pm 0.01 \pm 0.01$	$1.00 \pm 0.02 \pm 0.02$
	=3 jets	0.2539 ± 0.0008	$0.26 \pm 0.01 \pm 0.01$	$1.01 \pm 0.04 \pm 0.04$
	=4 jets	0.2114 ± 0.0010	$0.20 \pm 0.01 \pm 0.01$	$0.94 \pm 0.05 \pm 0.05$



New!

b content in top decay: $|V_{tb}|$



- Fit for R using analytic data-driven probability functions for number of tags in each category (36 total)
  - e.g. for 2 jets, 2 b-tags, 2 tops reconstructed

$$P = \mathcal{R}^2\varepsilon_b^2 + 2\mathcal{R}(1-\mathcal{R})\varepsilon_b\varepsilon_q + (1-\mathcal{R})^2\varepsilon_q^2$$

  - ε_b = b-jet tag efficiency ; ε_q = light flavor tag efficiency
  - measured in dijet events, (p_T,η) dependent

$$\mathcal{R} = 1.023^{+0.036}_{-0.034}$$

$$|V_{tb}| = 1.011^{+0.018}_{-0.017}$$

Feldman-Cousins

$\mathcal{R} > 0.945$ @ 95% CL

$|V_{tb}| > 0.972$ @ 95% CL

CMS PAS TOP-12-035

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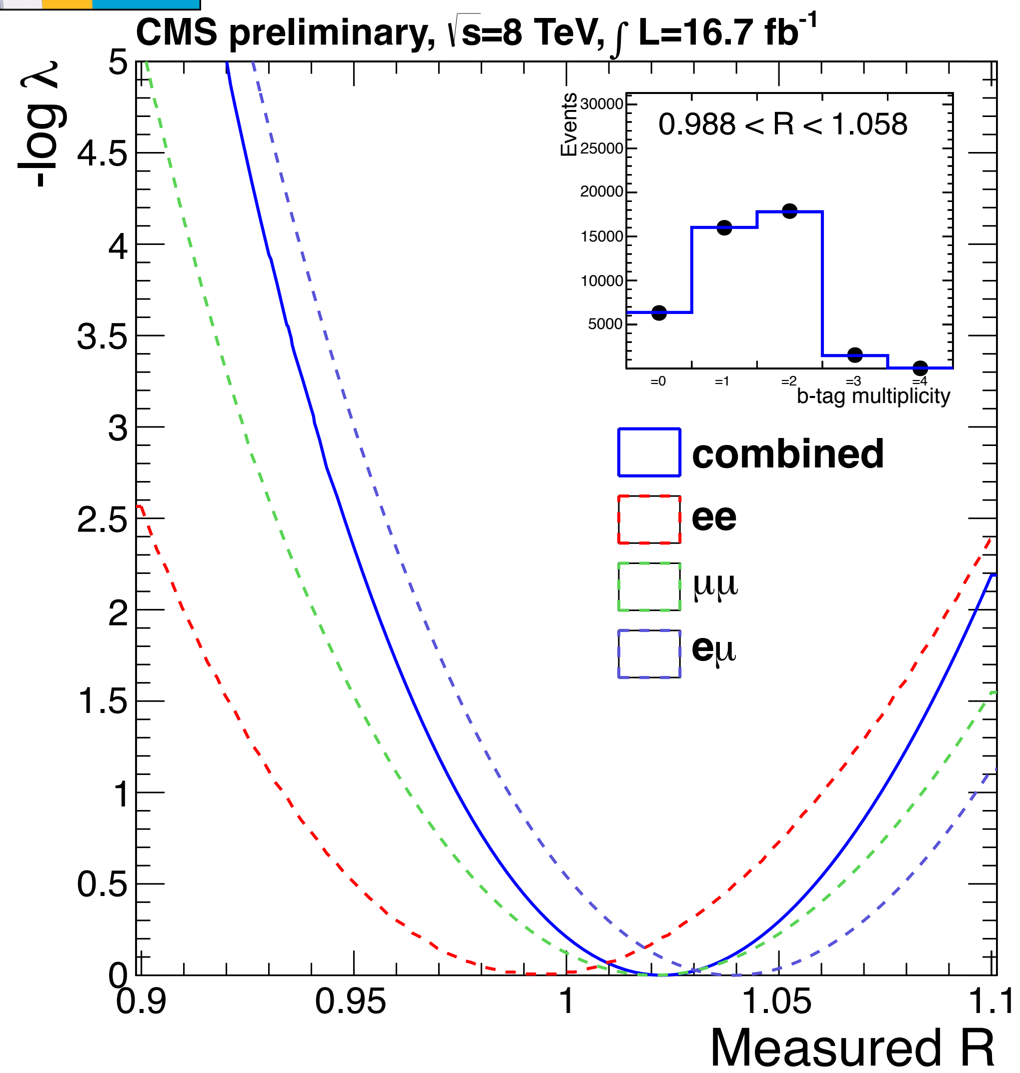
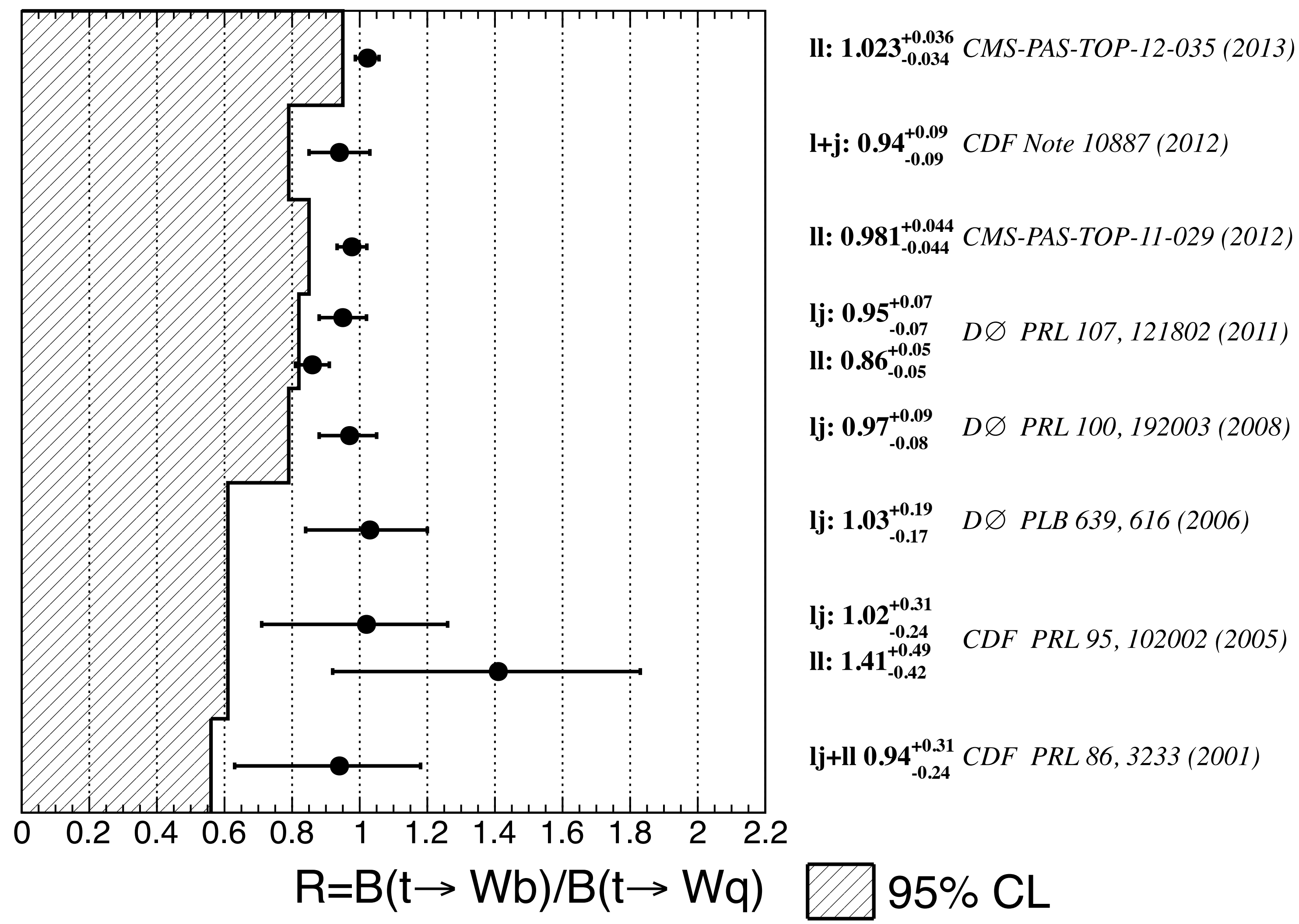
World's Best Measurement!





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Feldman-Cousins

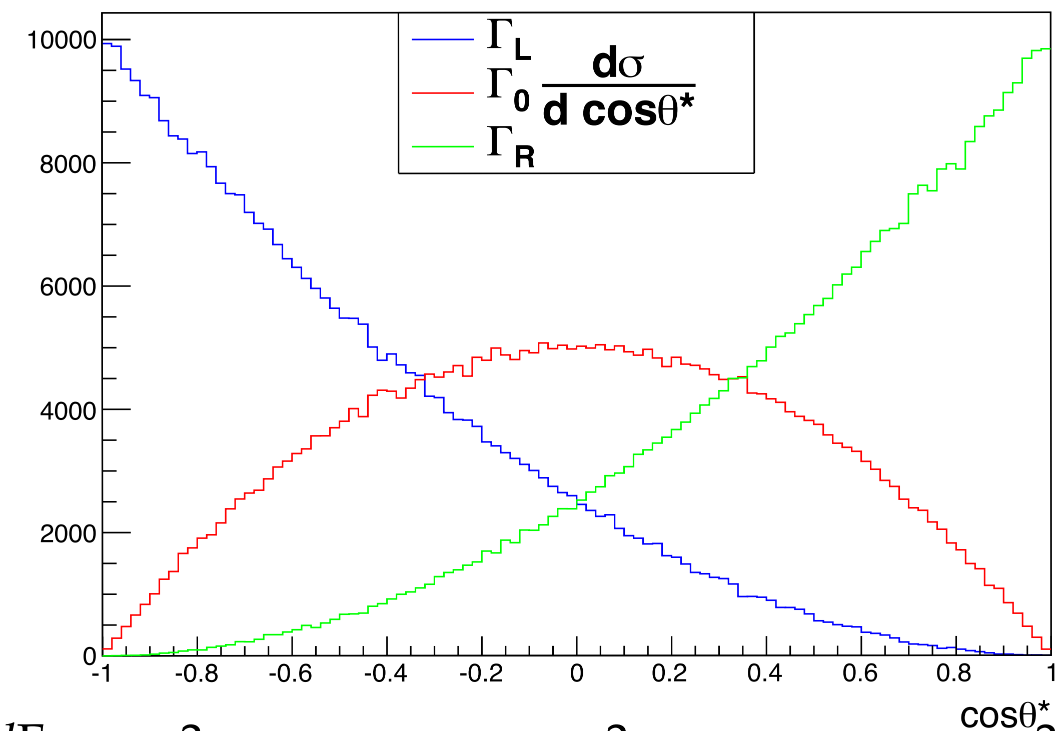
$\mathcal{R} > 0.945$ @ 95% CL

$|V_{tb}| > 0.972$ @ 95% CL

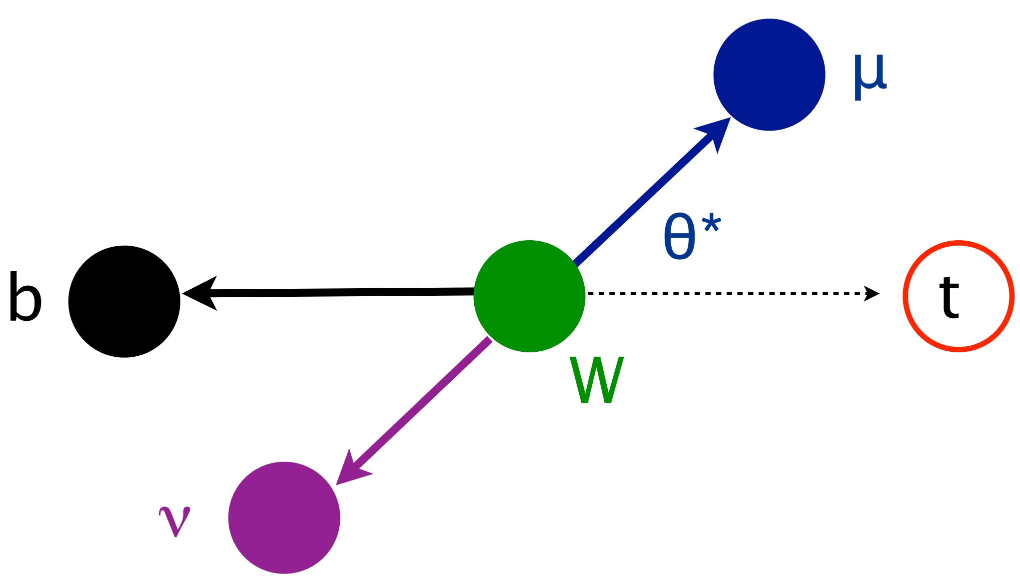
W Helicity in top decay

$$\mathcal{L}_{tWb}^{anom.} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW_{\mu}^{-} + H.C,$$

- Probe Wtb couplings from polarization of W in top decay t→Wb
- Helicity fractions:
  - Normalized partial widths for L,R,Longitudinal(0) polarized Ws
  - SM predictions (V-A):
    - F_0=0.687(5)
    - F_L=0.311(5)
    - F_R=0.0017(1)
- Analysis of helicity angle θ* distribution:
  - Direction of charged lepton in W rest frame with respect to W direction in top rest frame

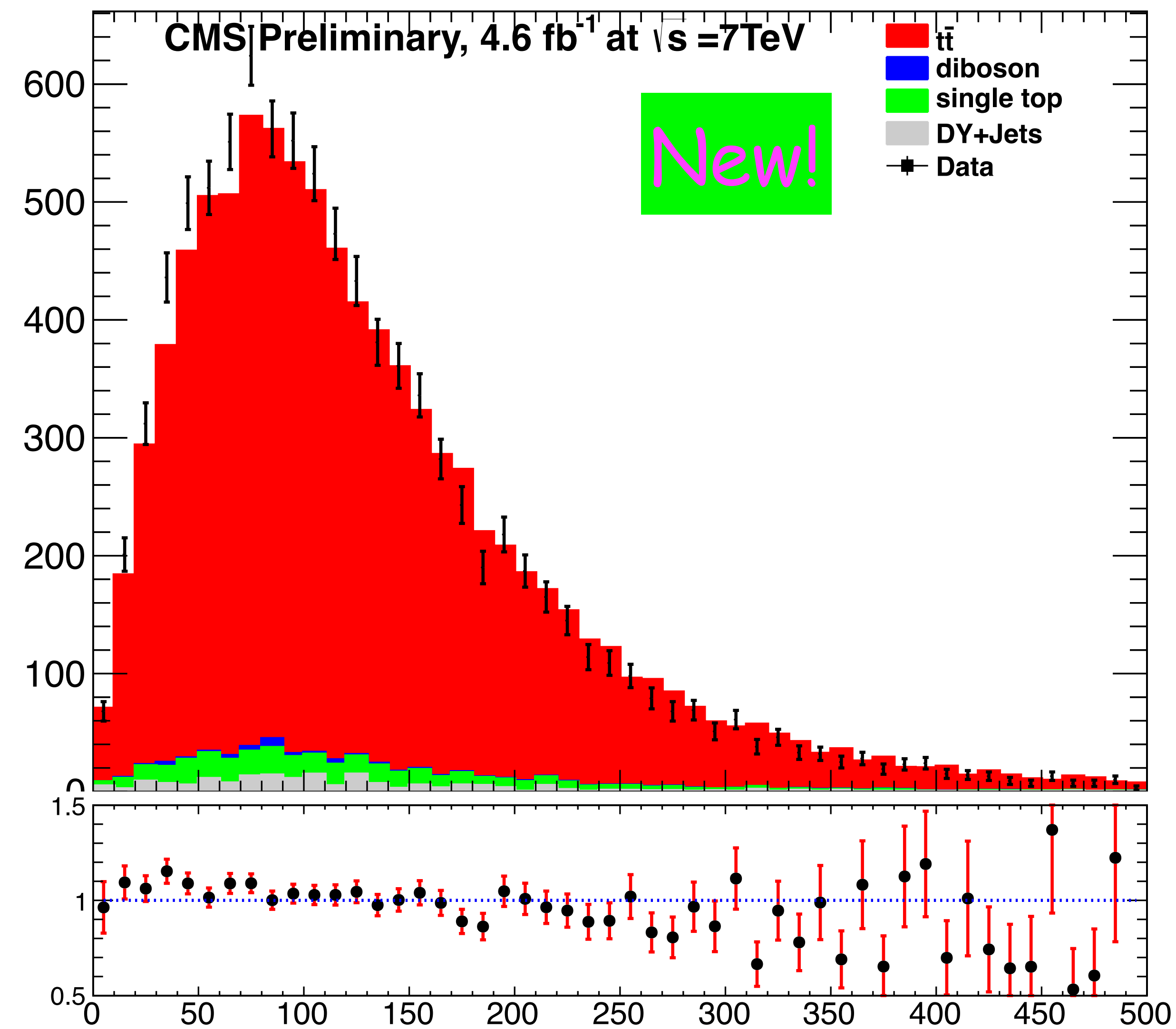


$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{8}(1+\cos\theta^*)^2 F_R + \frac{3}{4}\sin^2\theta^* F_0$$



W Helicity in t-tbar dilepton events

- pp@ 7 TeV 4.6 fb^{-1}
- Two isolated leptons e (μ)
  - p_T>20 GeV & IηI<2.5 (2.4)
  - opposite sign
- Suppress DY for same flavor
  - Veto Z: 76 < m(ll) < 106 GeV
- Require one b-tagged jet
- Missing transverse energy
  - E_T>30 (20) GeV ee, μμ (eμ)
- Top reconstruction
  - W mass constraint used for neutrino solutions
  - Take jet-parton permutation with smallest M(tt)



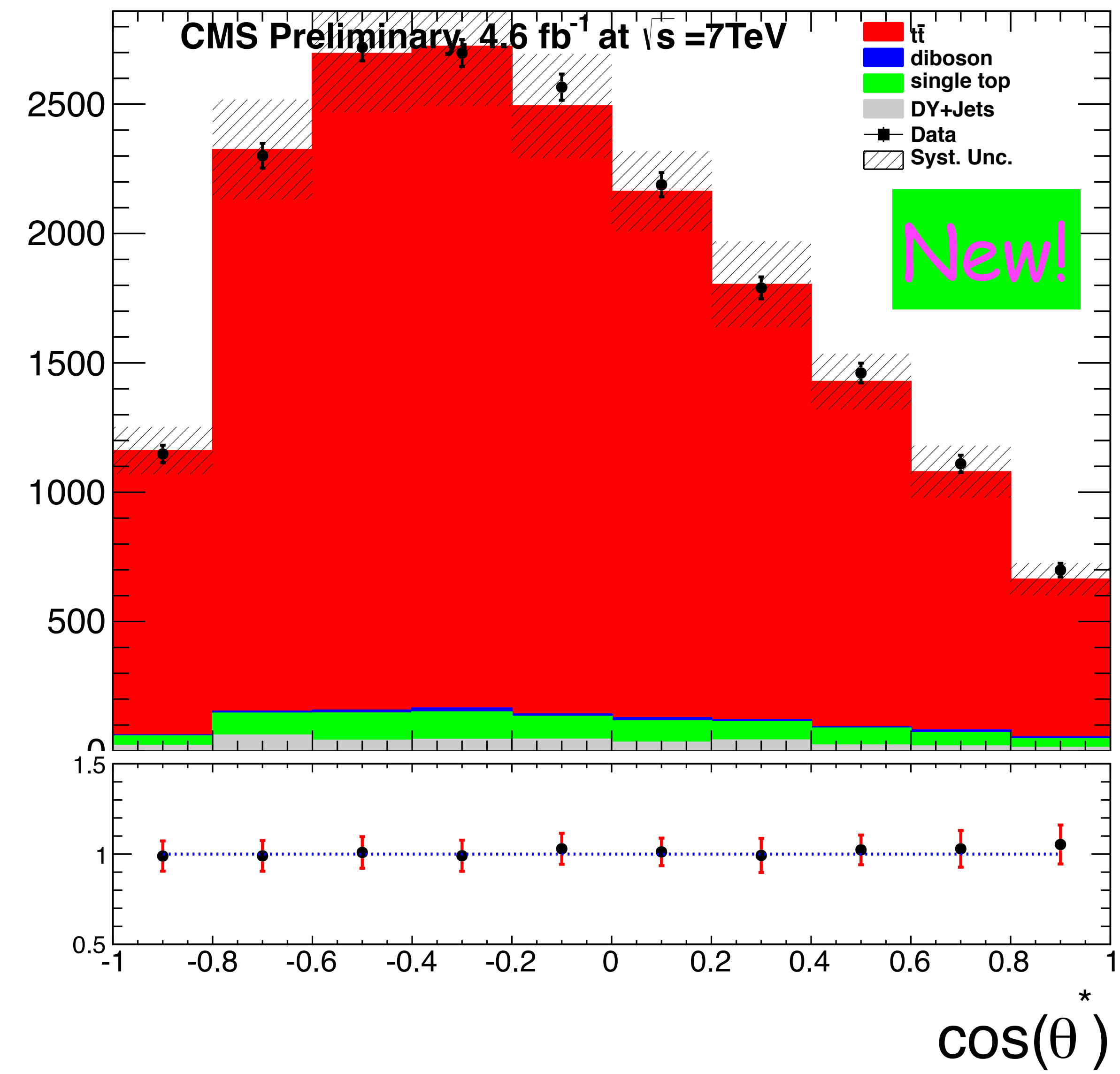
p_t of Top's in Top reconstruction

Reconstructed kinematics of top important for determination of cos θ* and fit for helicity fractions

W Helicity in t-tbar dilepton events

- Fit reconstructed cos θ* using reweighting method
  - takes into account resolution and efficiencies
  - Fit for F_L and F_0
  - Take F_R from unitarity constraint: $F_R+F_L+F_0=1$

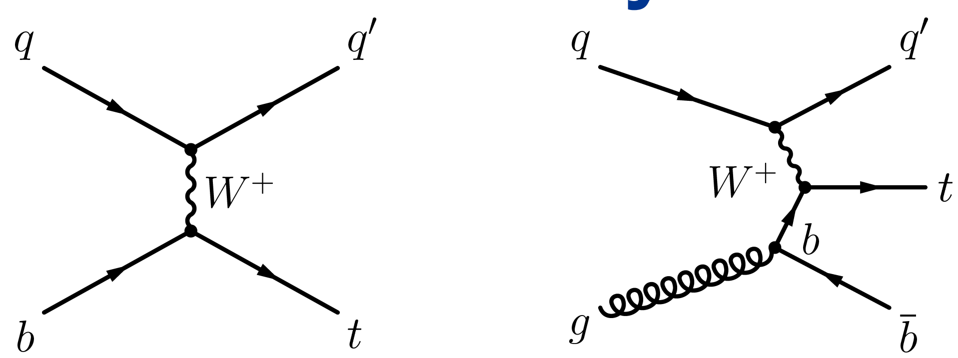
- Leading systematic uncertainties
  - top mass
  - top Q^2 scale in simulation



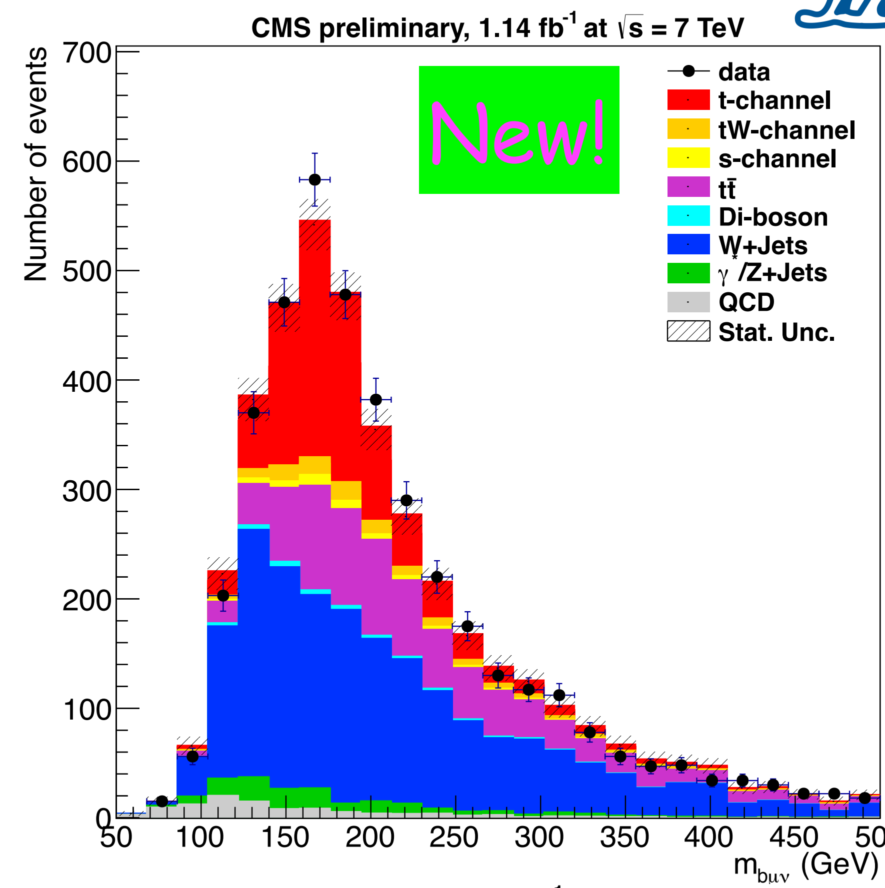
F_L= 0.288 ± 0.035 (stat) ± 0.050 (syst)
F_0= 0.698 ± 0.057 (stat) ± 0.063 (syst)
F_R= 0.014 ± 0.027 (stat) ± 0.055 (syst)

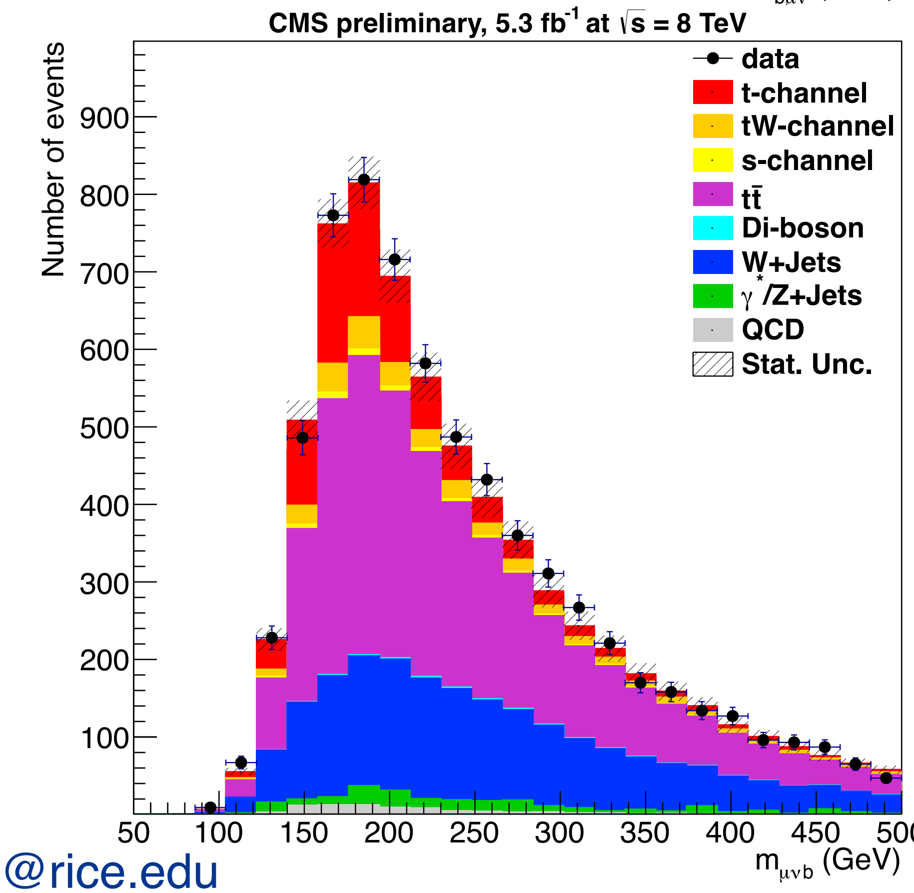
Consistent with SM expectations/V-A structure
Compatible with measurement in t-tbar l+jets (TOP-11-020)

W Helicity in Single Top Topologies

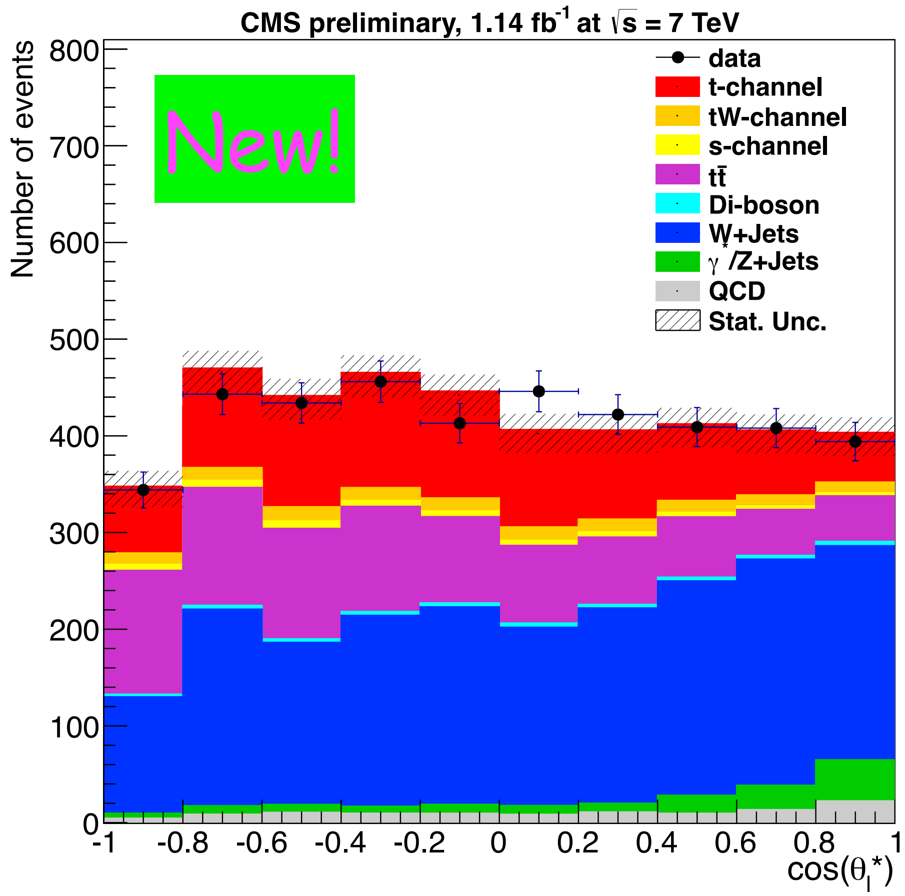


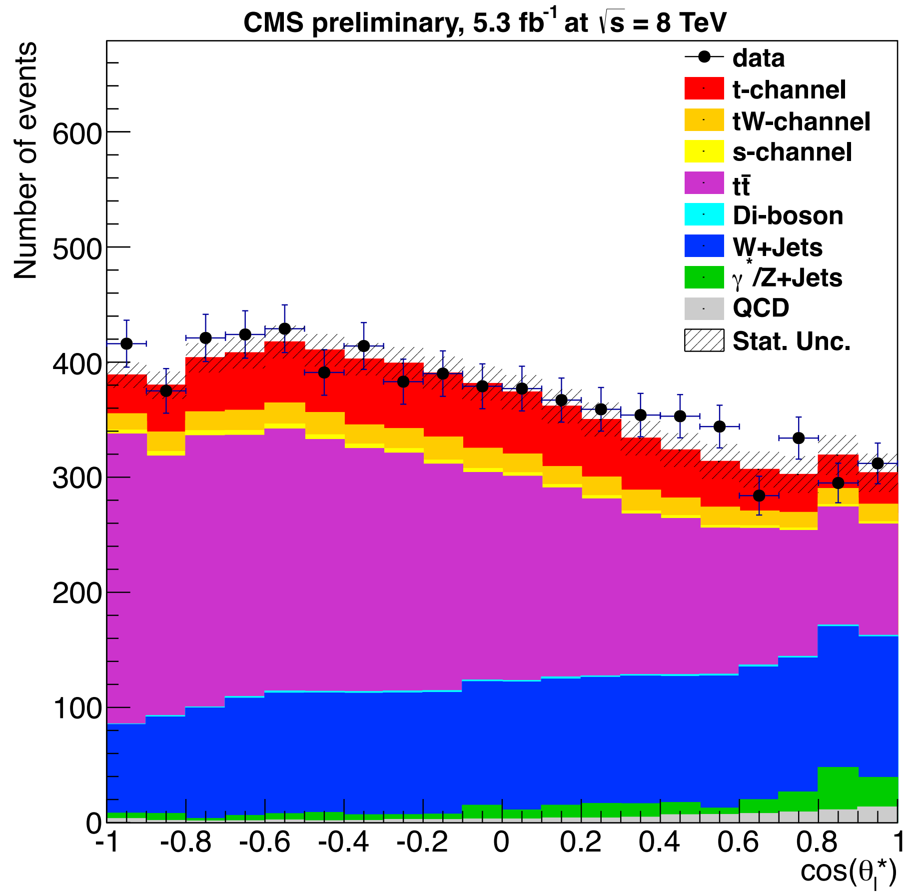
- W helicity fractions are also accessible in single top process
  - N.B. couplings in production & decay
- 7 TeV (1.14 fb^{-1}) & 8 TeV (5.3 fb^{-1})
- Selection: ($t \rightarrow Wb \rightarrow \mu\nu b$)
  - single isolated μ: |η|<2.1 & p_T>20 (26) GeV
  - exactly two jets: |η|<4.5 & p_T>30 (60) GeV
  - exactly one b-tagged jet
- Substantial backgrounds
  - t-tbar (MC simulation)
  - Data-driven W+jets from 0 b-tag
  - Data-driven QCD multijet

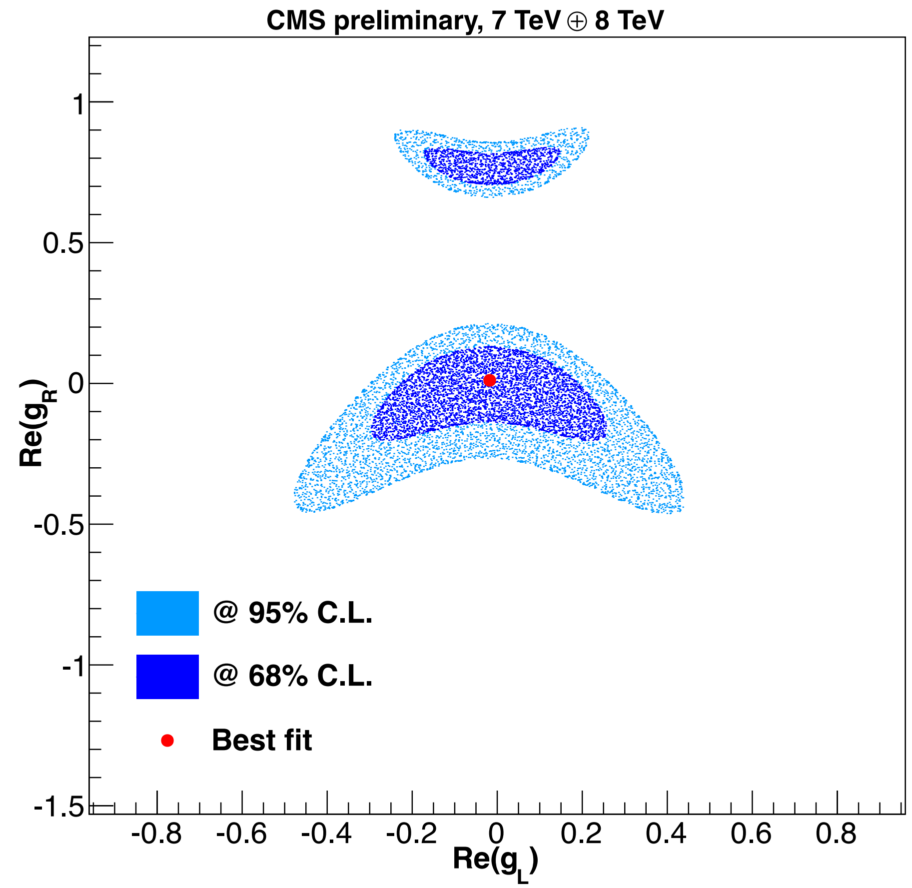




W Helicity in Single Top Topologies







Constraints on anomalous couplings (combination)

- Separate likelihood fits with reweighting method
  - also for decays of t tbar pairs
  - 2D (F_0,F_L) F_R from unitarity
- Systematic uncertainties
  - Q^2 scale & simulation
  - Jet Energy Scale & Resolution
  - W+jets shape

Combination 7&8 TeV:

F_L= 0.293 ± 0.069 (stat) ± 0.030 (syst)
F_0= 0.713 ± 0.114 (stat) ± 0.023 (syst)
F_R=-0.006 ± 0.057 (stat) ± 0.027 (syst)

Consistent with SM expectations/V-A structure
Compatible with measurements in t tbar

Other Results

Too many to present here

- Mass
  - JHEP 06(2012) 109 top-antitop mass difference
  - CMS PAS TOP-12-027 Top mass from endpoint (M_{T2})
- Properties
  - CMS PAS TOP-12-014 Associated production ttZ and ttW
    - Talk by R. Wallny earlier today
  - CMS PAS TOP-11-020 W Helicity in l+jet events
  - CMS PAS TOP-12-004 Spin correlations in t-tbar
  - CMS PAS TOP-12-016 Top polarization
  - Phys.Lett. B718(2012) 1252 Search for FCNC ($t \rightarrow Zq$) in $t\bar{t}$
  - CMS PAS TOP-11-031 Charge of top quark
  - CMS PAS HIG-12-035 Search for $t\bar{t}H$ production

Summary

- Top quark properties have been studied at CMS
  - Mass: precise measurement of high interest for electroweak fits (vacuum stability!)
  - Mass: theoretical effects from colored & unstable object investigated with study of m_t vs kinematic variables: New!
    - No sign of dramatic effects
    - Should aid interpretation of top mass measurements
  - Couplings - $|V_{tb}|$ compatible with 3 generation SM CKM New!
  - Couplings - W Helicity fractions from dilepton channel and single top topologies New! New!
    - as expected for V-A decay limits on anomalous couplings
- So far, top looks like a SM quark
- Outlook: Additional 8 TeV data analysis in progress

Backup Slides

EPJC 72 (2012) 2202

m_t in dilepton channel

- 5.0 fb^{-1} pp @ $\sqrt{s}$=7 TeV

$$t\bar{t} \rightarrow WbWb \rightarrow (\ell^+\nu_\ell b)(\ell^-\bar{\nu}_\ell b)$$

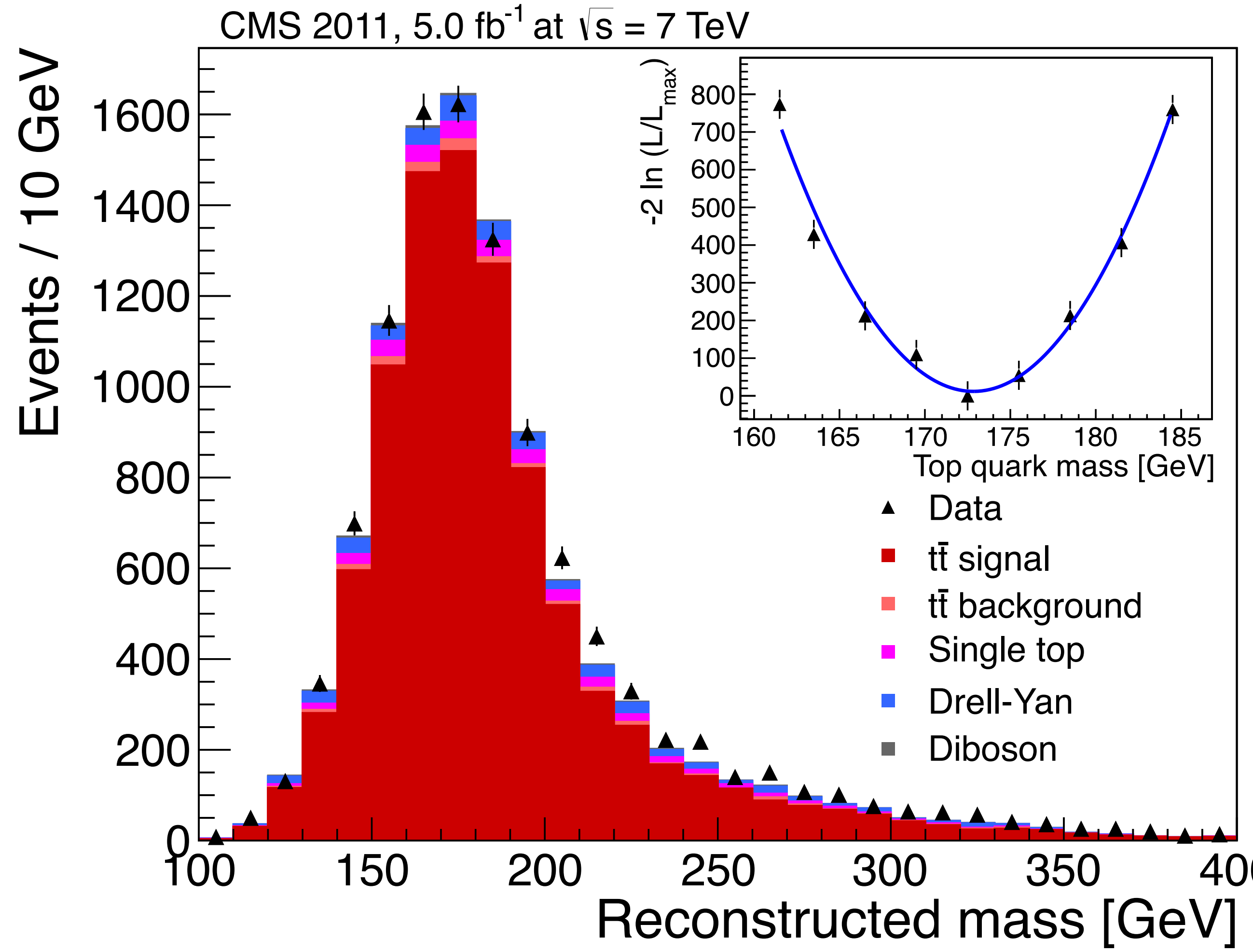
- High purity sample selected
  - Two opposite sign isolated leptons p_T>20 GeV $|\eta|$<2.4
  - Two jets p_T>30 GeV $|\eta|$<2.4
  - At least one b-tag
  - Missing E_T > 40 GeV to Reject DY (except eμ)
  - Veto Z peak 76 - 106 GeV
- Analytical Matrix Weighting Technique, scanning m_t
  - up to 8 kinematic solutions
  - combination with largest weight w taken as reconstructed top mass

$$w = \left\{\sum f(x_1)f(x_2)\right\} p(E^*_{\ell+}|m_t)p(E^*_{\ell-}|m_t)$$

Sum over initial state partons u$\underline{u}$ d$\underline{d}$ gg

probability density for E_l in top rest frame

9934 Events

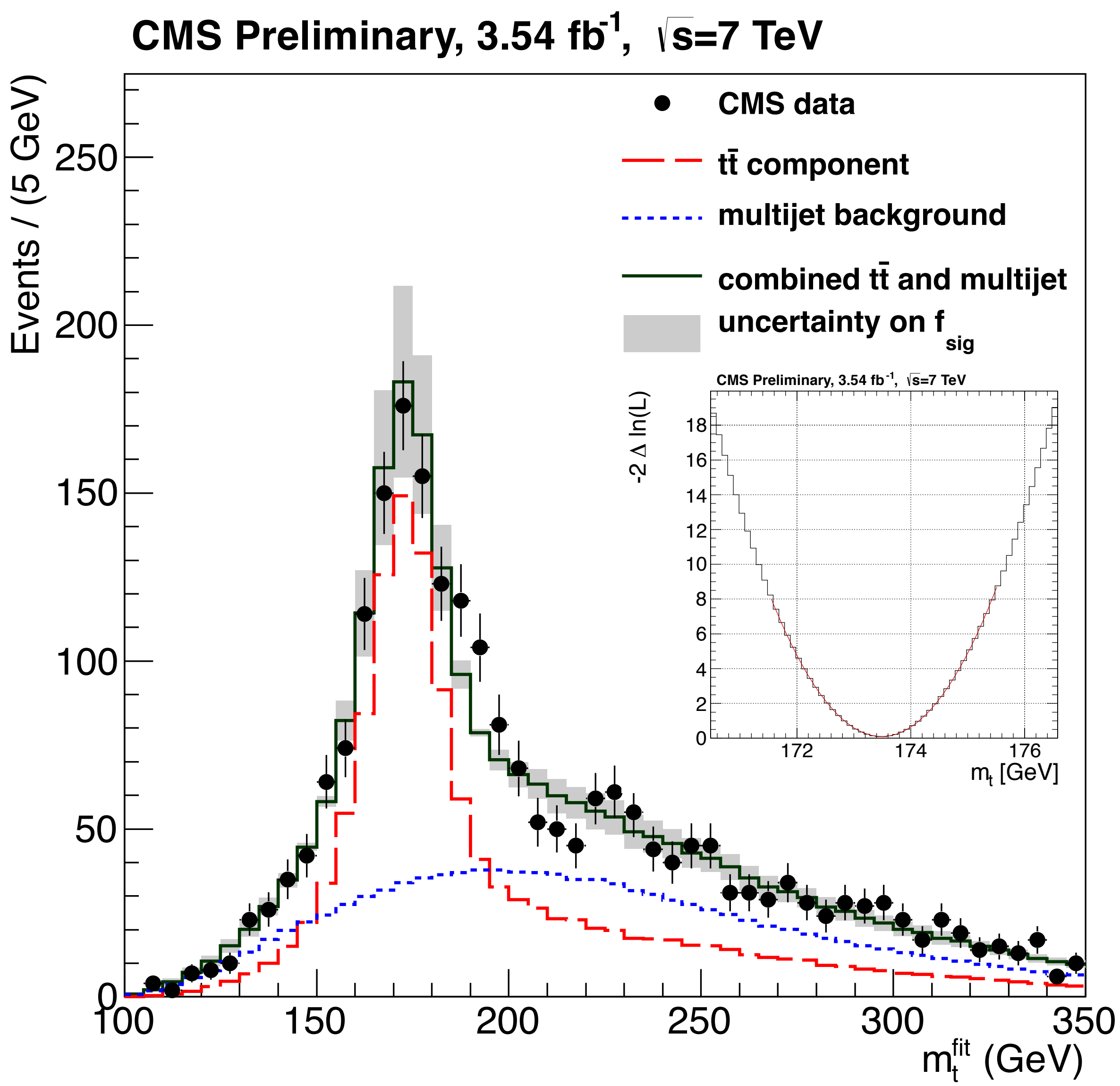


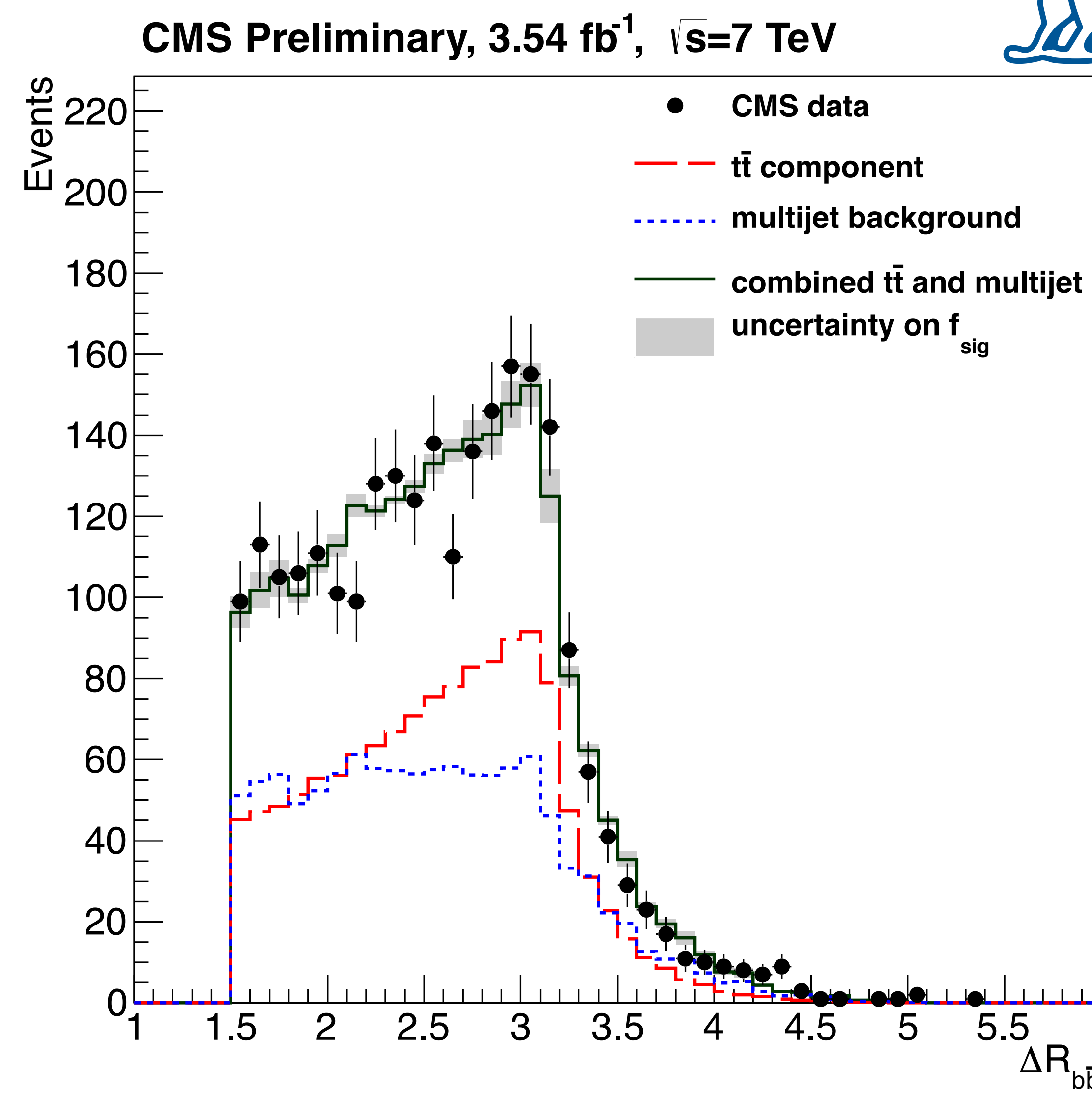
m_t=172.5 ± 0.4 (stat) ± 1.5 (syst) GeV

- Leading systematic uncertainties:
  - JES & flavor dependence
  - renormalization/factorization scale

CMS PAS TOP-11-017
m_t from all hadronic channel

- At least 6 jets, two b-tagged p_T>60,60,60,60,50,40,30 GeV …
- Choose permutation with best kinematic fit χ^2
- Suppress multijet background with ΔR_{bb}>1.5
- Model multijets from data using event mixing in preselected sample





- Mass measurement from Ideogram method (as l+jets)
  - calibrated on simulation
- JES dominant systematic (1.09 GeV)

$$\boxed{m_t = 173.49 \pm 0.69(\text{stat}) \pm 1.25(\text{syst})}$$

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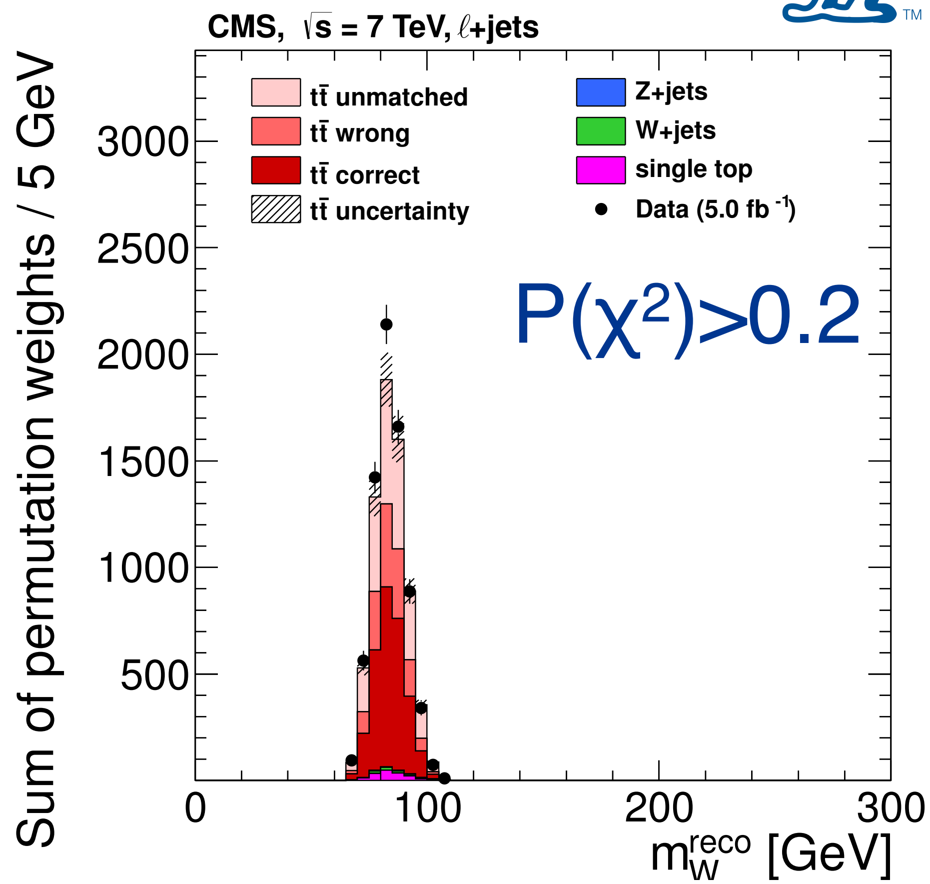
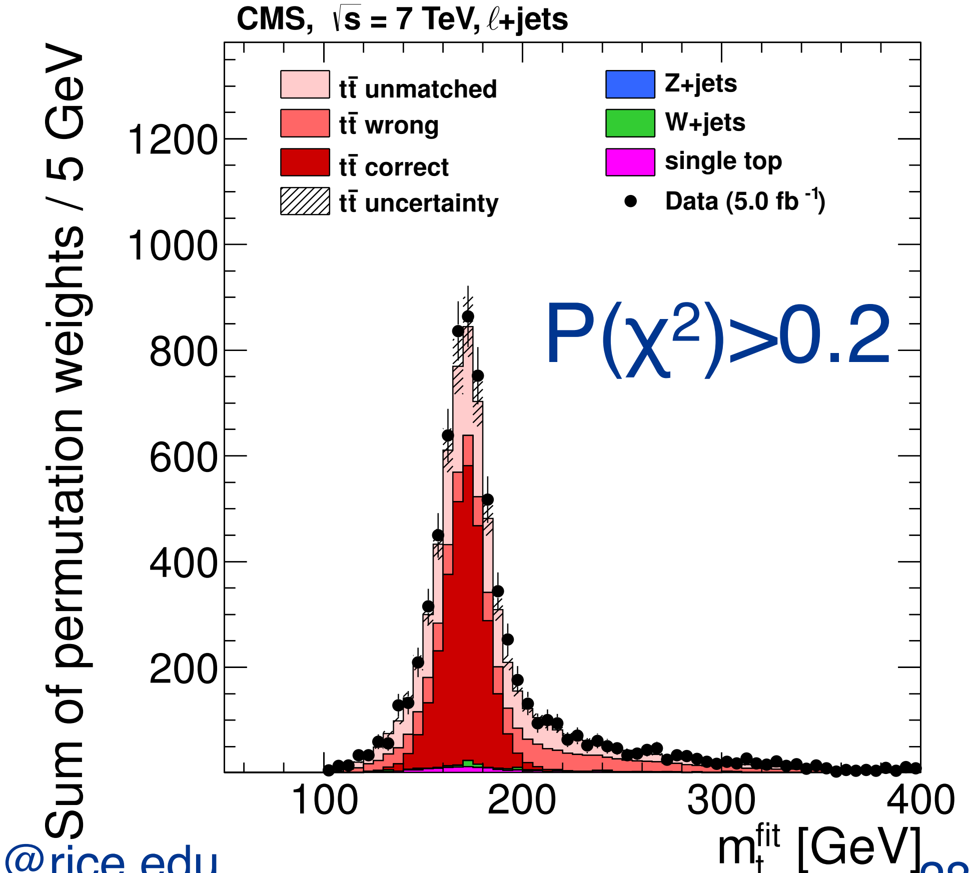
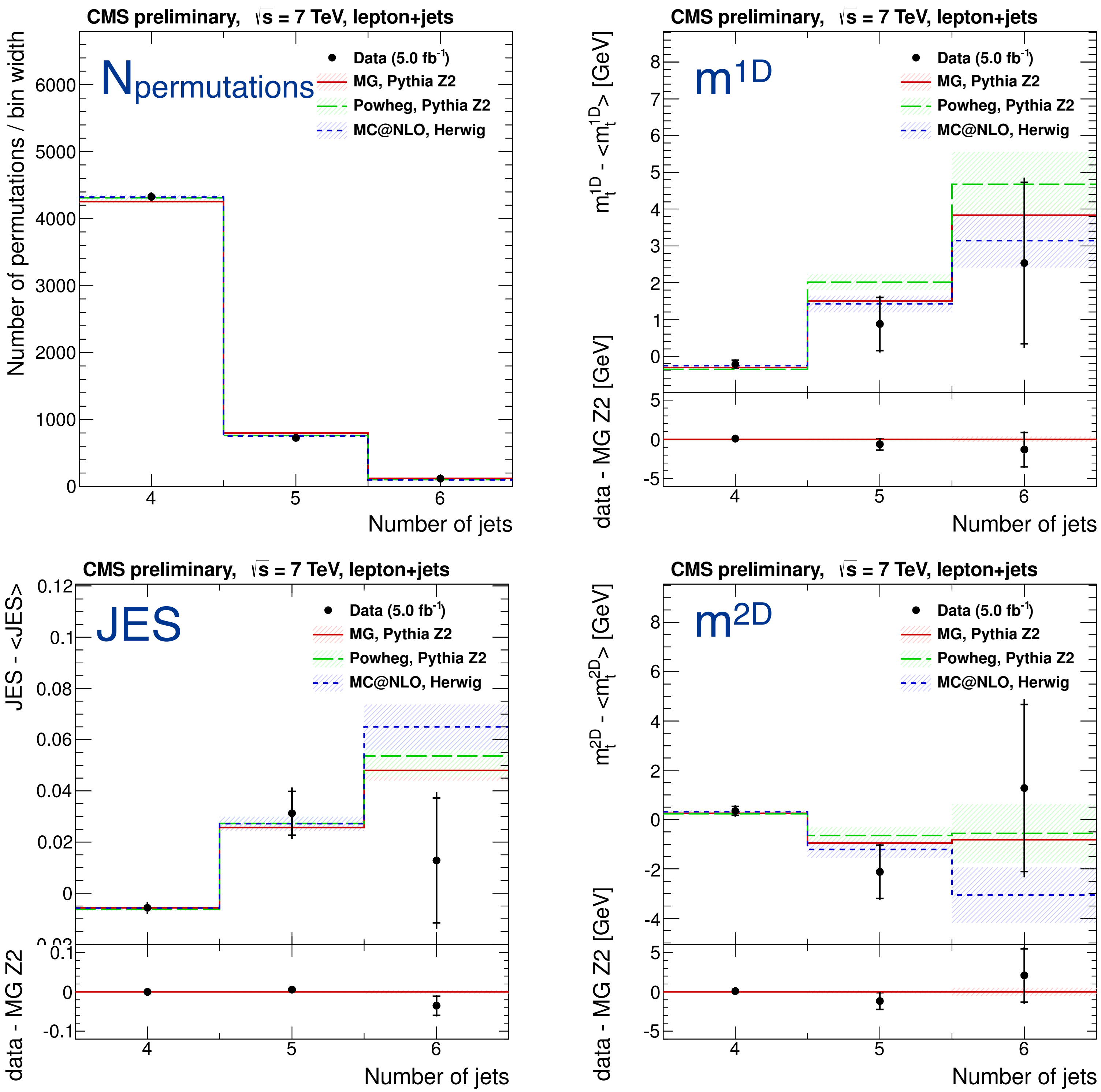
m_t in l+jets channel 7 TeV

- 5.0 fb^{-1} pp @ $\sqrt{s}$=7 TeV
- $t\bar{t} \rightarrow WbWb \rightarrow (\ell\nu b)(jjb)$
- Event Selection
  - Exactly 1 $e^{\pm}$ or $\mu^{\pm}$ $|\eta|<2.1$, $p_T>30$ GeV
  - Four or more jets $p_T>30$ GeV
  - Two b-tagged jets
- Kinematic Fit (2 d.o.f.)
  - improves kinematic resolution & parton-jet assignment
  - m_t free, $m_t = m_{tbar}$
  - W mass constraint 80.4 GeV
  - Require $P(\chi^2)>0.2$
  - correct permutations: 13%→44%
- Sample of 5174 events

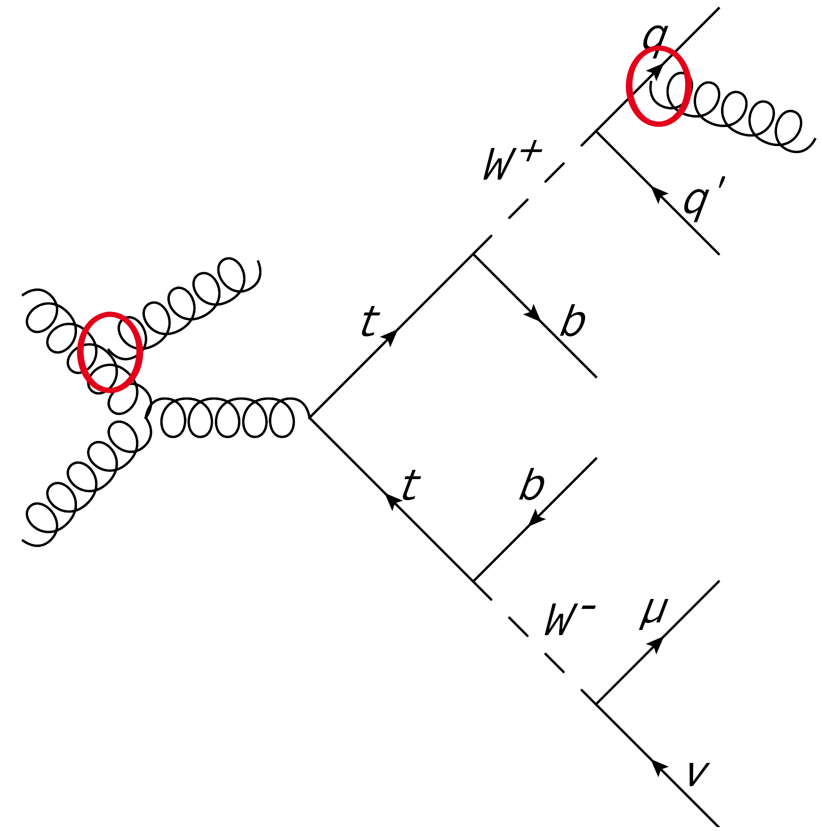




New! m_t and initial/final state radiation



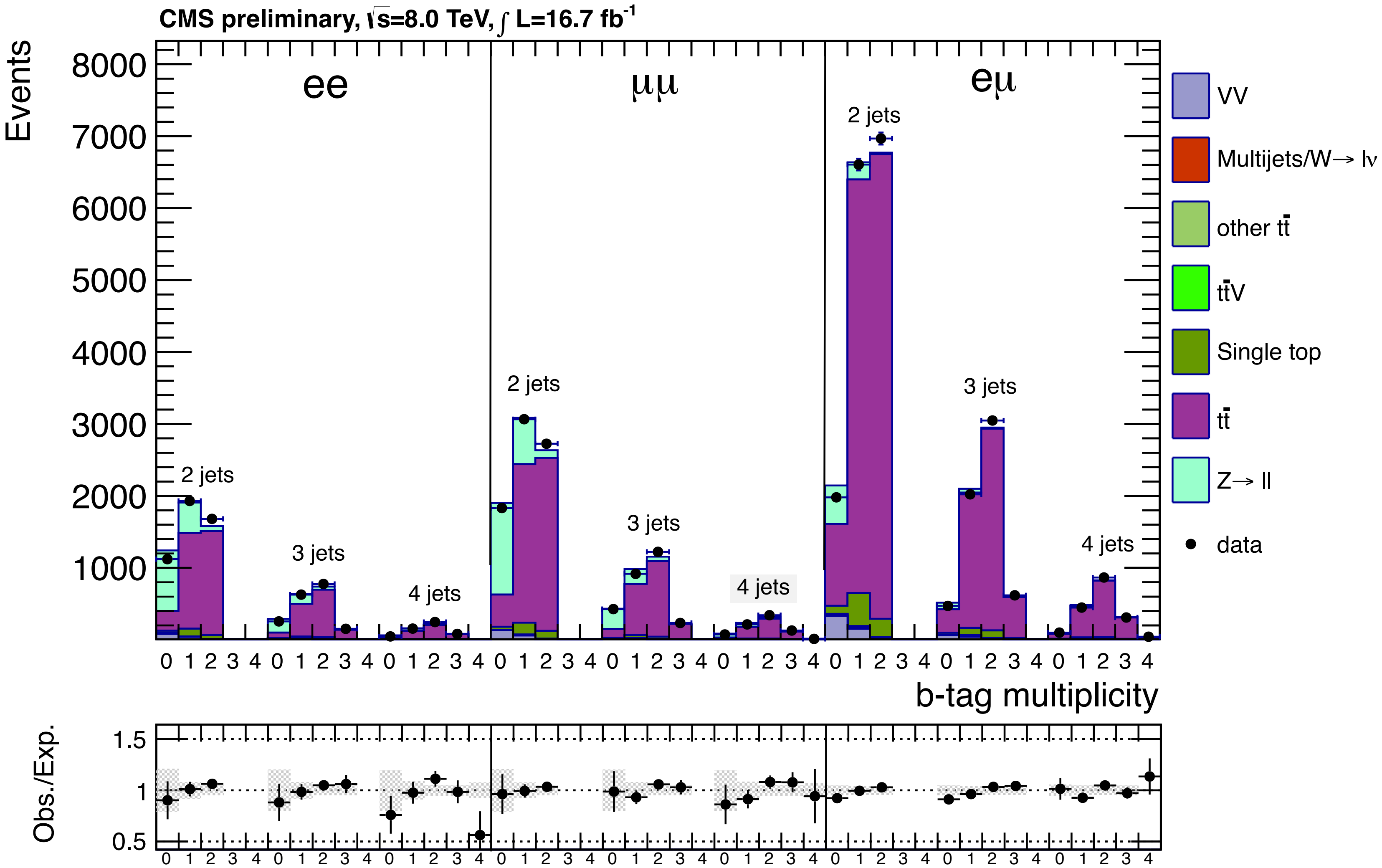
Number of Jets

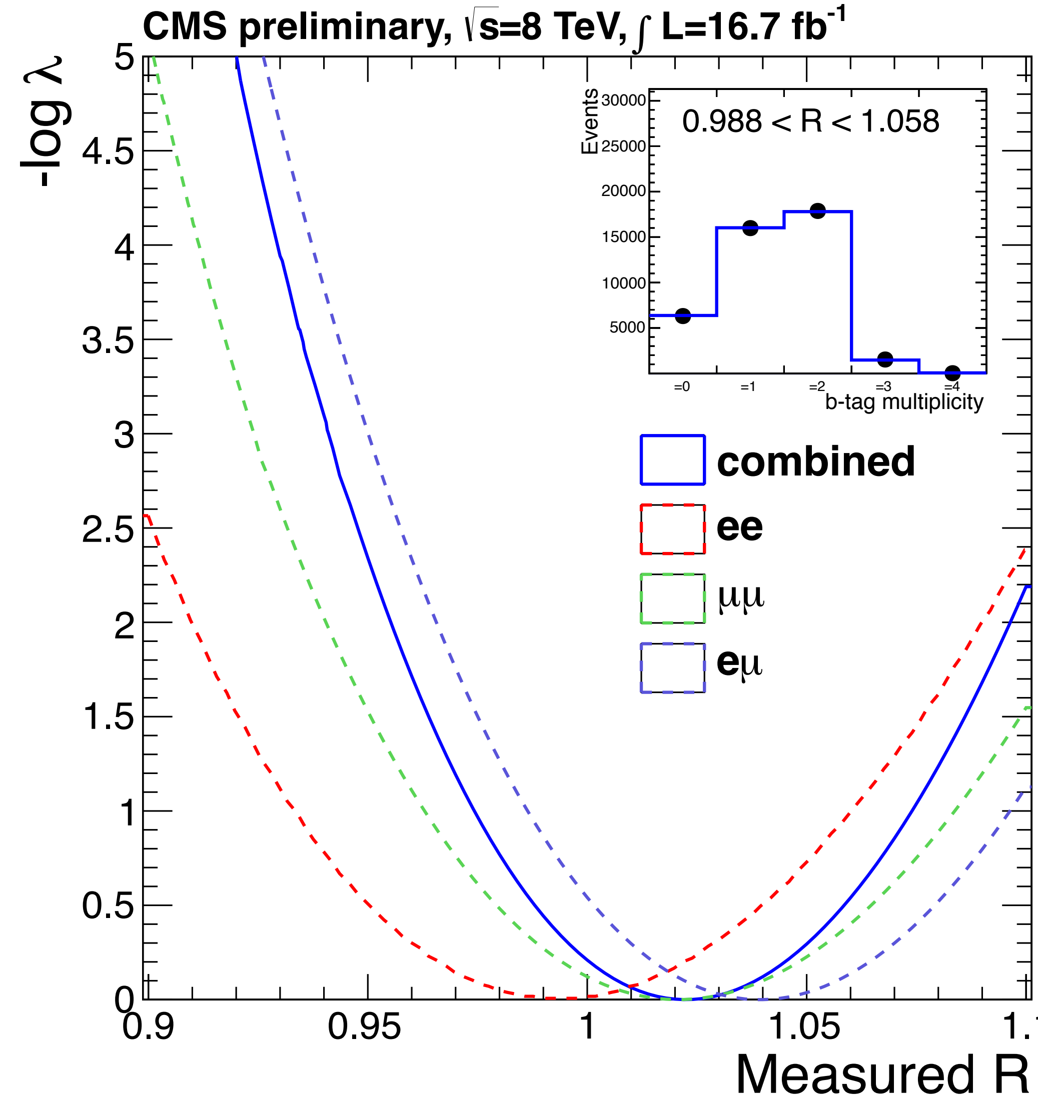


- Only jets p_T>30 GeV
- More jets, larger probability of picking high-p_T ISR

New!

b content in top decay: $|V_{tb}|$





- Fit for R using analytic data-driven probability functions for number of tags in each category (36 total)
  - e.g. for 2 jets, 2 b-tags, 2 tops reconstructed

$$P = \mathcal{R}^2\varepsilon_b^2 + 2\mathcal{R}(1-\mathcal{R})\varepsilon_b\varepsilon_q + (1-\mathcal{R})^2\varepsilon_q^2$$

  - ε_b = b-jet tag efficiency ; ε_q = light flavor tag efficiency
  - measured in dijet events, (p_T,η) dependent

$$\mathcal{R} = 1.023^{+0.036}_{-0.034}$$

$$|V_{tb}| = 1.011^{+0.018}_{-0.017}$$

Feldman-Cousins

$\mathcal{R} > 0.945$ @ 95% CL

$|V_{tb}| > 0.972$ @ 95% CL