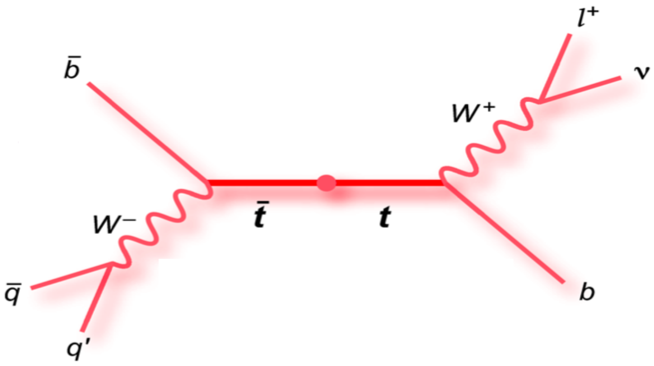
TOP QUARK PHYSICS (II)

Top quark production cross section

Mass measurements

Single Top

Searches of New Physics



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Summer student lectures
15. August 2013

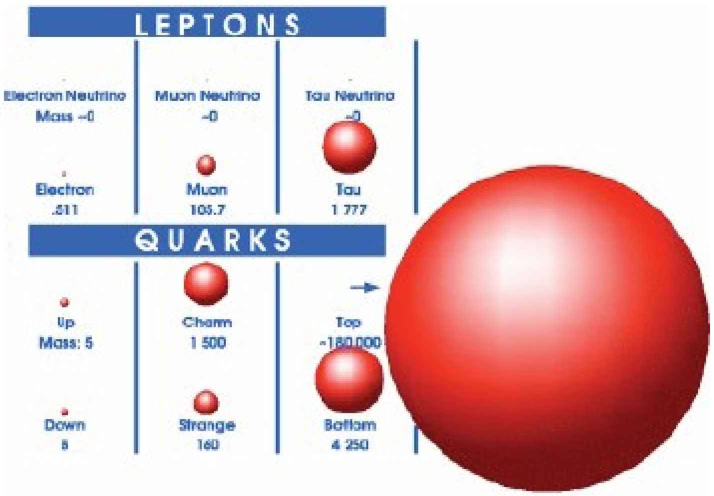
HELMHOLTZ
GEMEINSCHAFT

DESY

Outline

- Introduction
- History of the Top Quark Search and Discovery
- Tools for Top Physics
- Top properties: asymmetries, correlation, polarization

- Top quark production cross section
- Mass measurement
- Single top quark
- (Some) Searches for New Physics



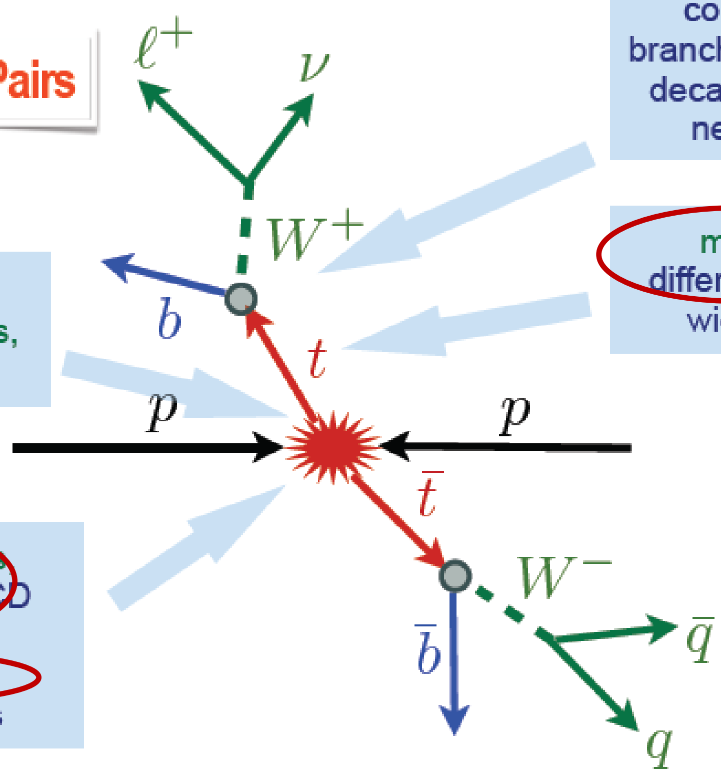
Overview of Top Analyses

Top Quark Pairs

couplings, V_{tb}, branching ratios, rare decays, W-helicity, new particles

mass, mass difference, charge, width, lifetime

asymmetries, spin correlations, color flow



cross sections, kinematics, QCD parameters, resonances, new particles

- Production
- Properties
- Single Top

EWK Single-Top Production

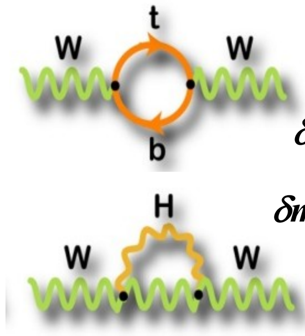
s, t, tW channel production, properties, couplings

What´s so special about top?
(Summary for the ones waking up now)

Special role in the electroweak (EWK) sector and in QCD

- Heaviest elementary particle known
  - The Higgs couples preferentially to top

$$y_t = \frac{\sqrt{2}m_t}{v} \approx 1$$

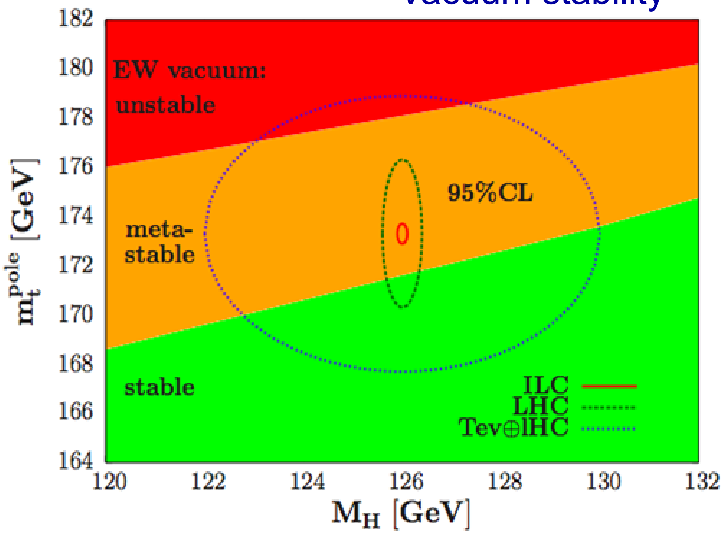


$\delta m_W \propto m_t^2$

$\delta m_W \propto \ln(m_H)$

- Sensitive to Higgs mass through EWK loop corrections
  - Top mass is related to the fate of the Universe

Vacuum stability



- Decays before hadronising: "bare" quark

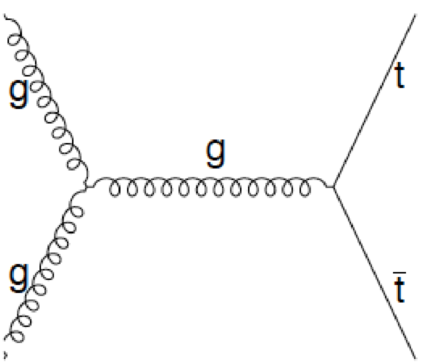
  $\tau \sim 5 \times 10^{-25}$ s << $1/\Lambda_{QCD}$

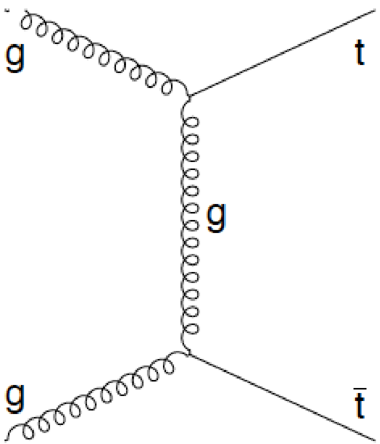
➔ A tool for precise tests of Standard Model (SM)

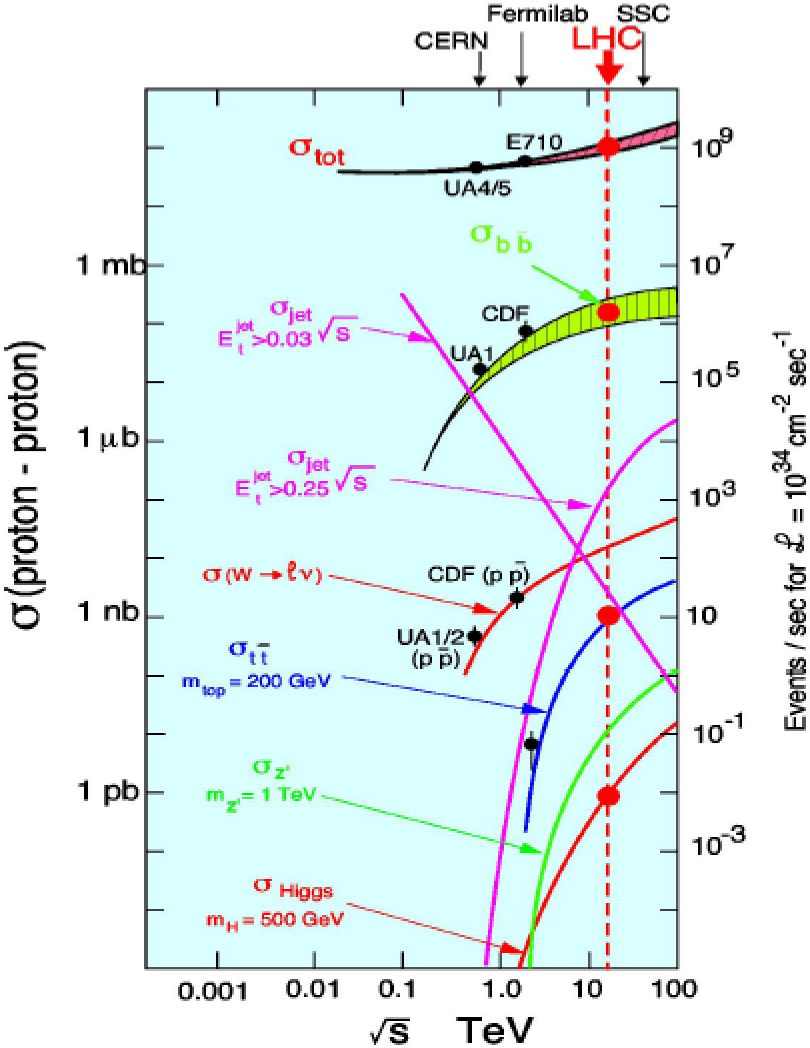
- Special role in various beyond SM extensions
  - New physics may preferentially couple/decay to t
  - Major source of background for many searches

➔ A sensitive probe to New Physics

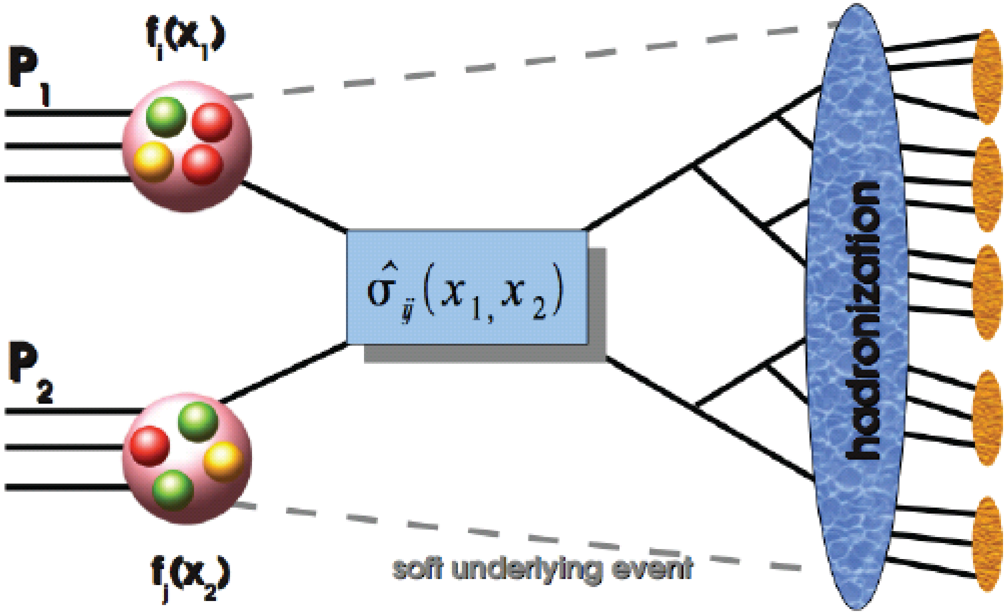
Top-quark pair (differential) cross section measurements







Cross section in hadron-hadron scattering



$$\sigma = \sum_{i,j=q,\bar{q},g} \int dx_1\, dx_2\, f_i(x_1, Q^2) \cdot \bar{f}_j(x_2, Q^2) \cdot \hat{\sigma}(Q^2)$$

Sum over incoming partons i, j

Momentum fraction for incoming parton

PDF for incoming parton i

"partonic" cross section

Cross section measurement

Cross section are conceptually simple…

$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bgd}}{\varepsilon_{t\bar{t}} \cdot \int L dt}$$

Data driven methods or MC

Eff(data/MC)*Acceptance(MC)

…the devil is in the details!

What fraction of tt events are retained after selection

Luminosity: How many proton-collisions?

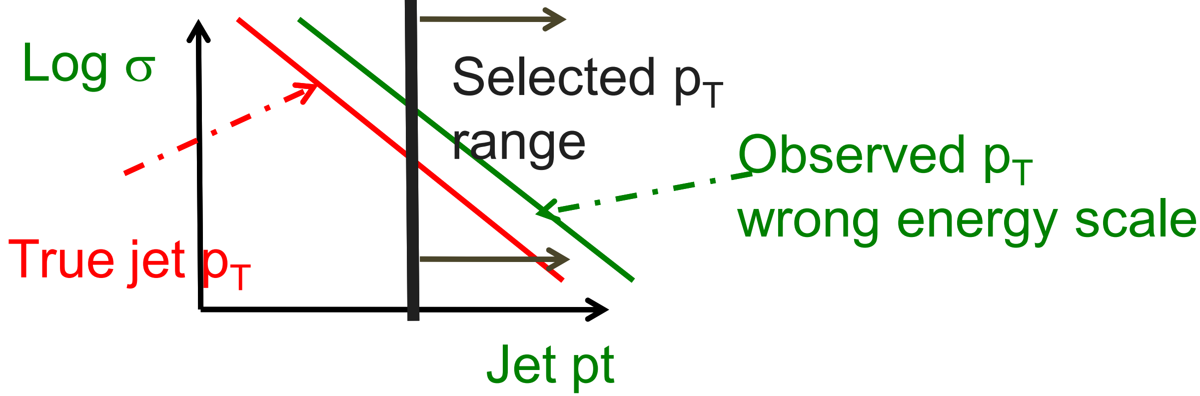
Why should we?

- Test of theoretical calculation, QCD with massive quarks
- Search for new physics

How to measure a cross section?

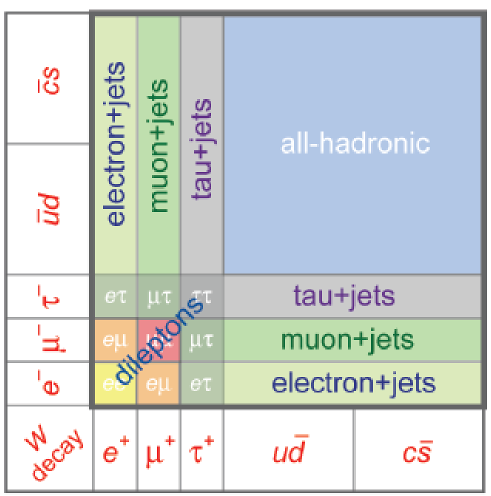
Experimental precision depends on how well
- background, efficiency, luminosity can be controlled

Key issue determine efficiency



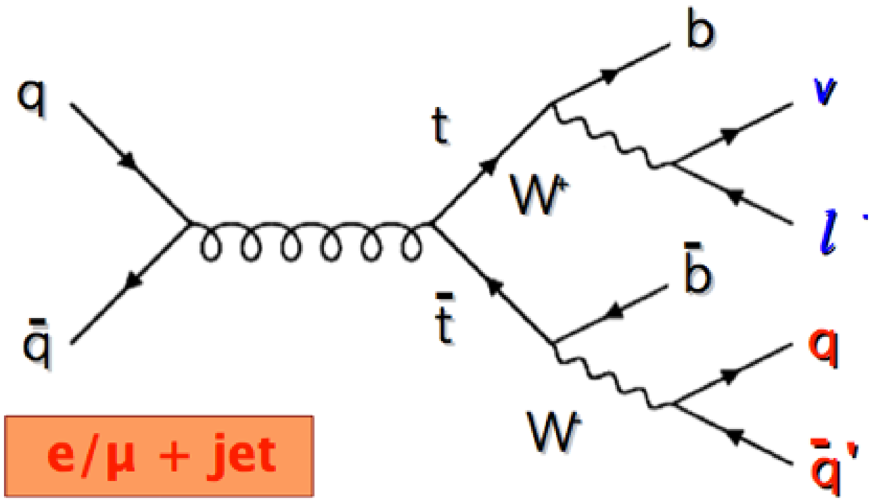
Largest uncertainties:
- Jet energy scale
- bottom identification
- Background yield
- Jets from QCD
- selection efficiency e, μ,.....

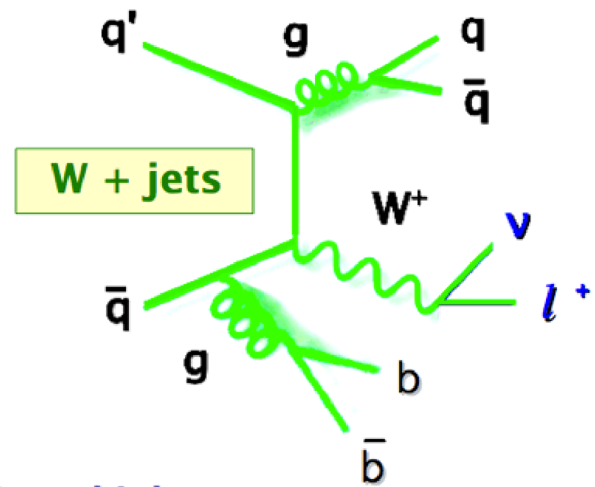
Experimental uncertainty ~ 10%
(depends on the channel)
Luminosity uncertainty ~ 4.4 %



ttbar measured in all decay channels (except ττ)

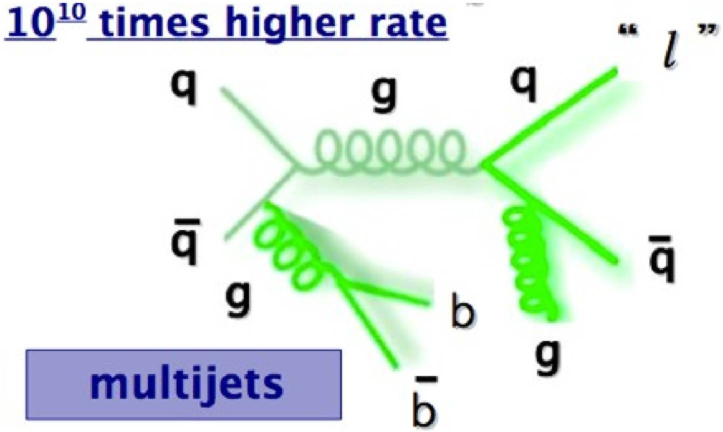
Lepton+Jets signatures

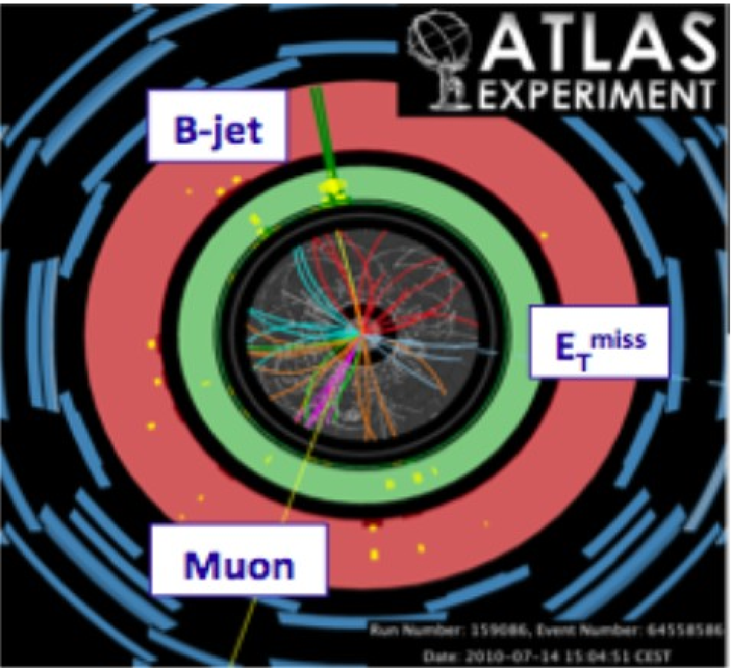




3000 times higher rate

10^{10} times higher rate

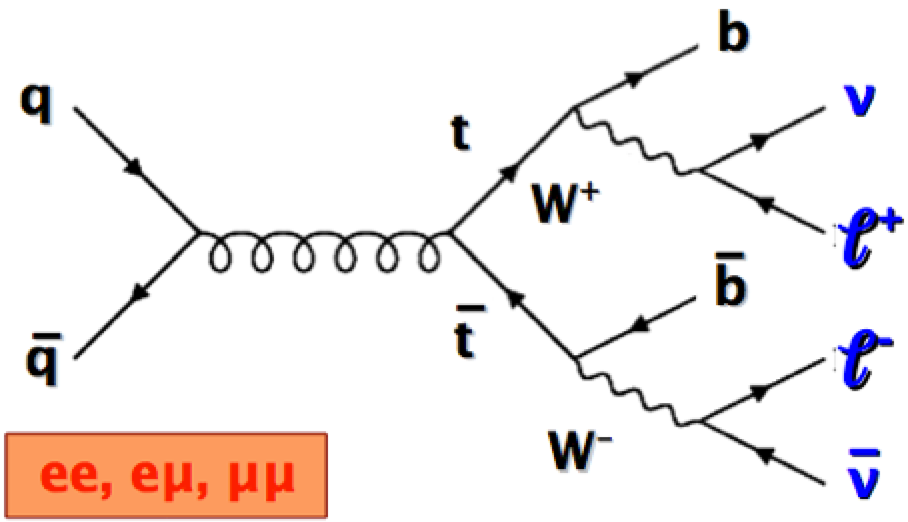


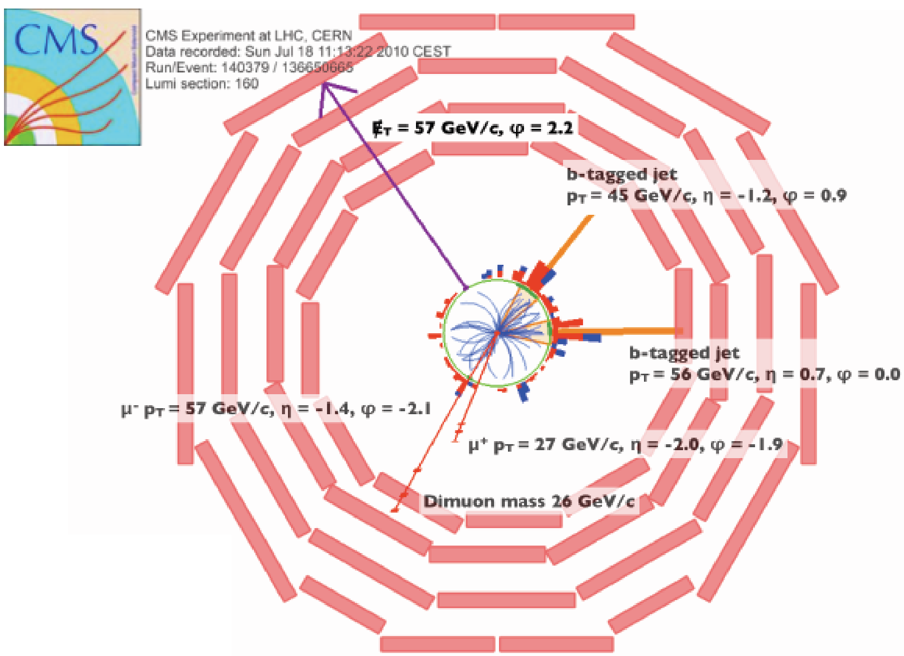


- BR~30%
- Moderate background

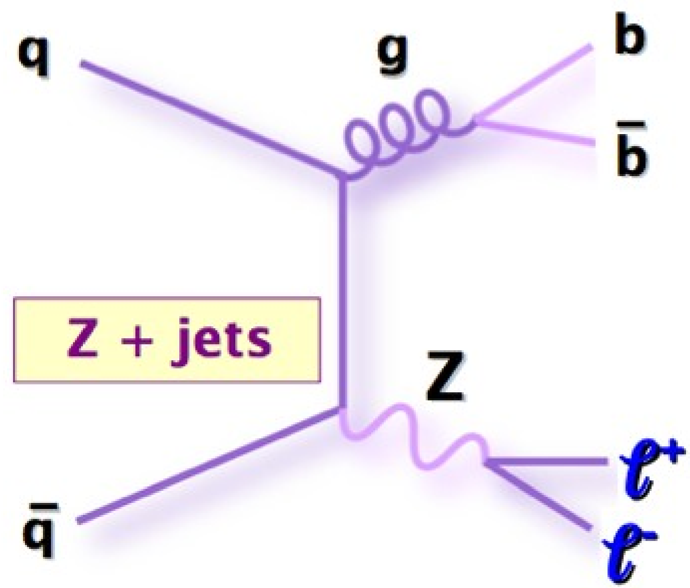
One lepton + at least three jets + MET, B-tag jets

Dilepton signatures





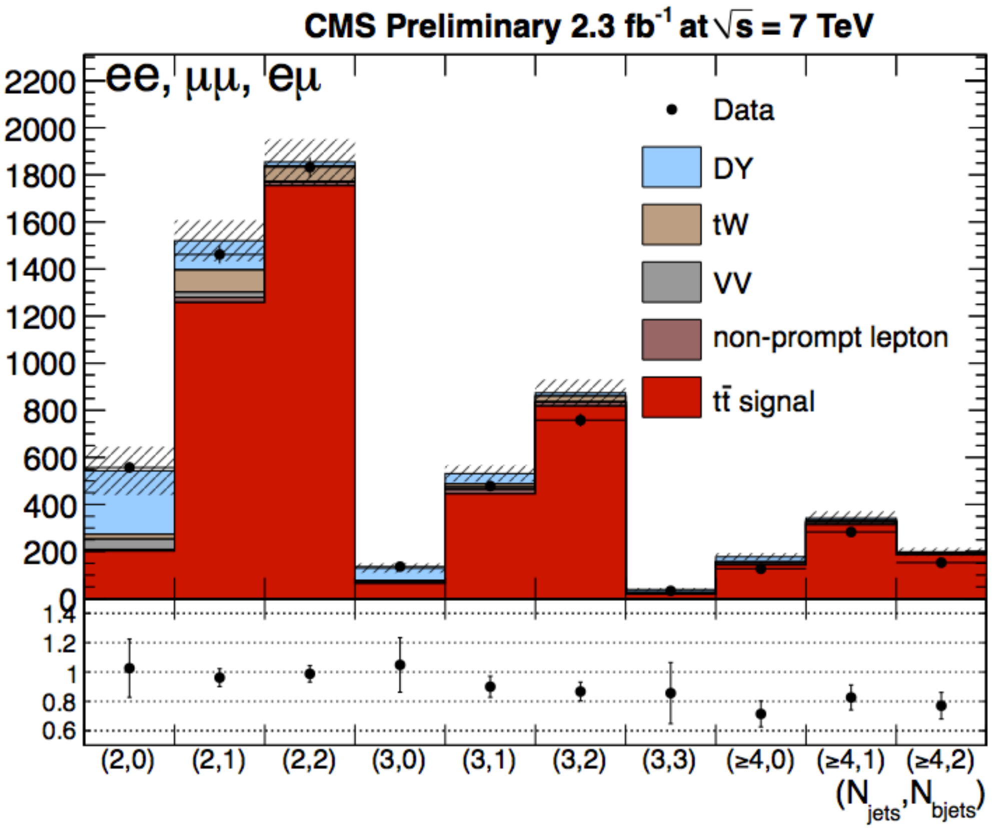
300 times higher rate



- Less statistics (BR~5%)
- Less background

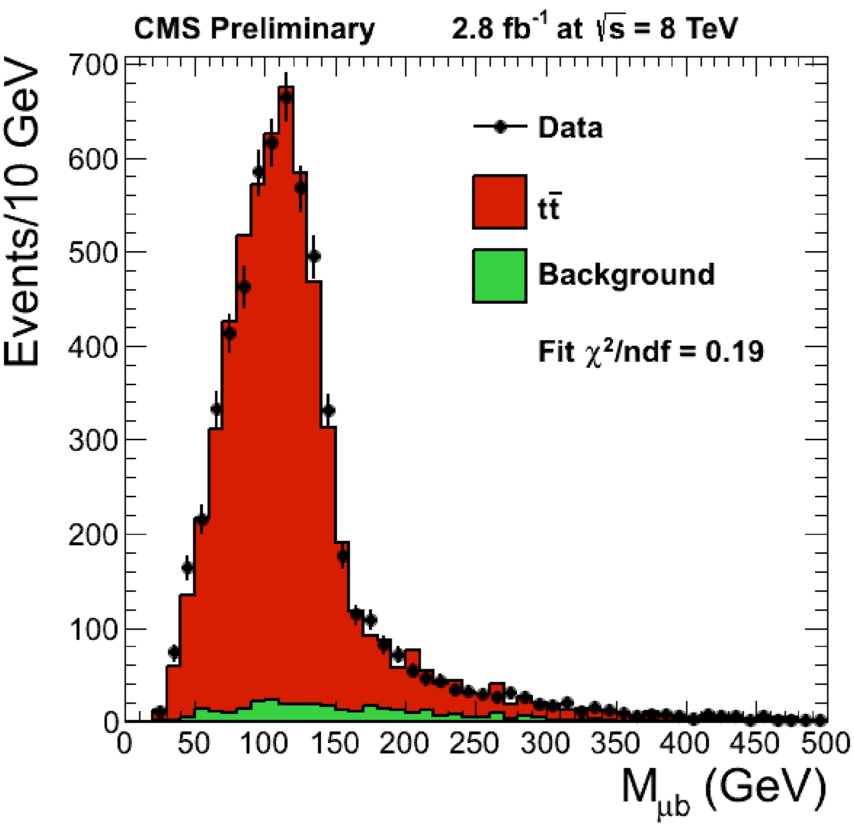
Two leptons + at least two jets + MET
More kinematic variables

Selection

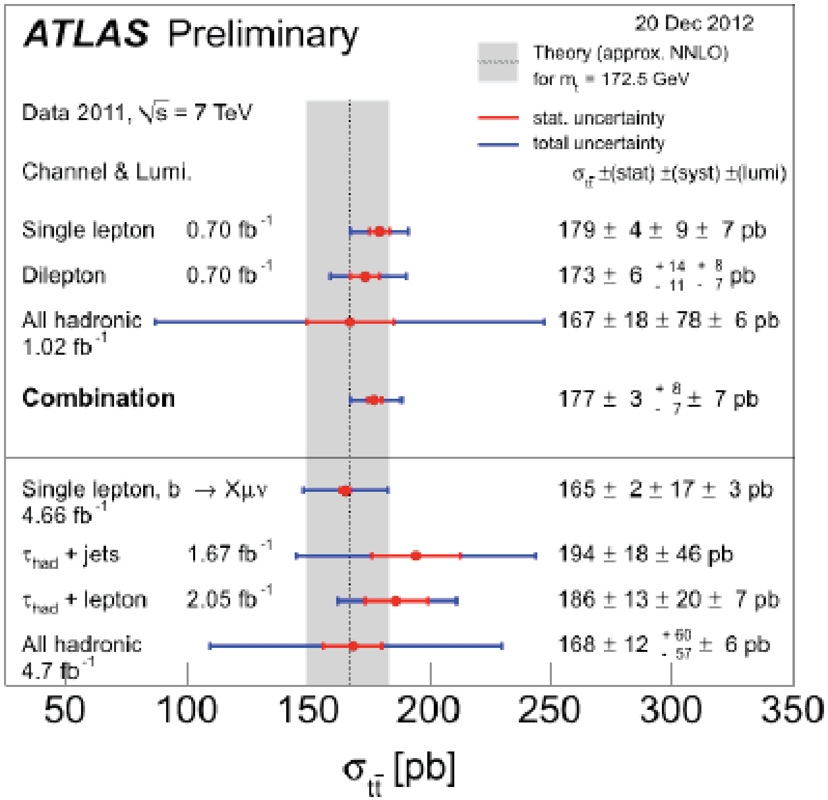


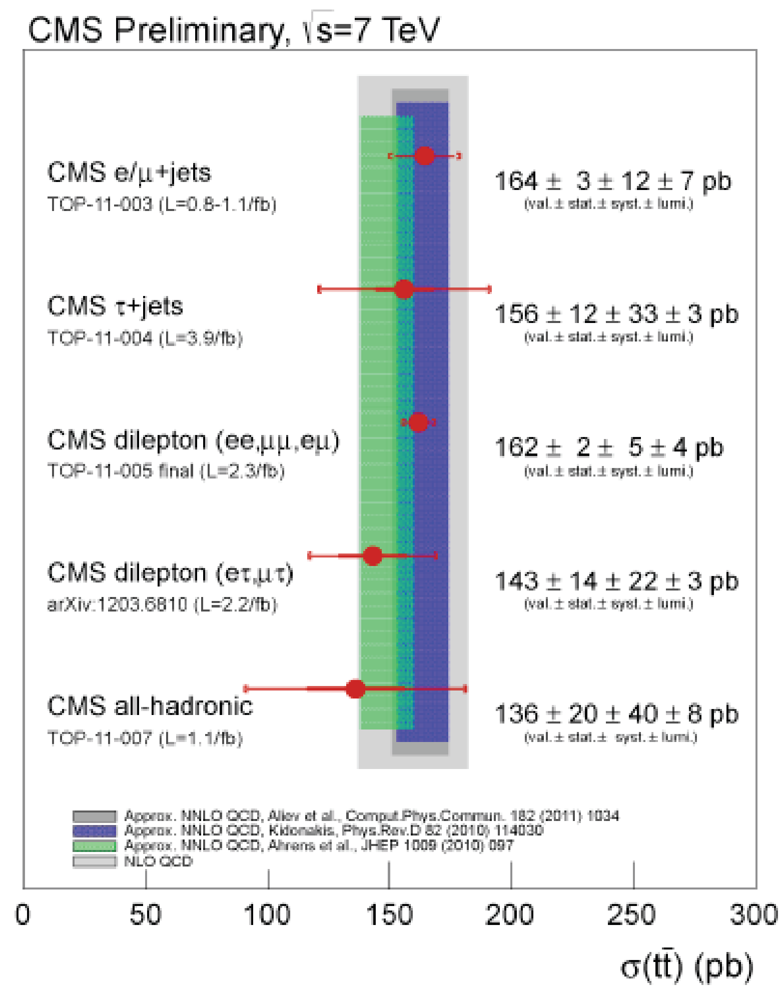
Dilepton

Lepton+jets



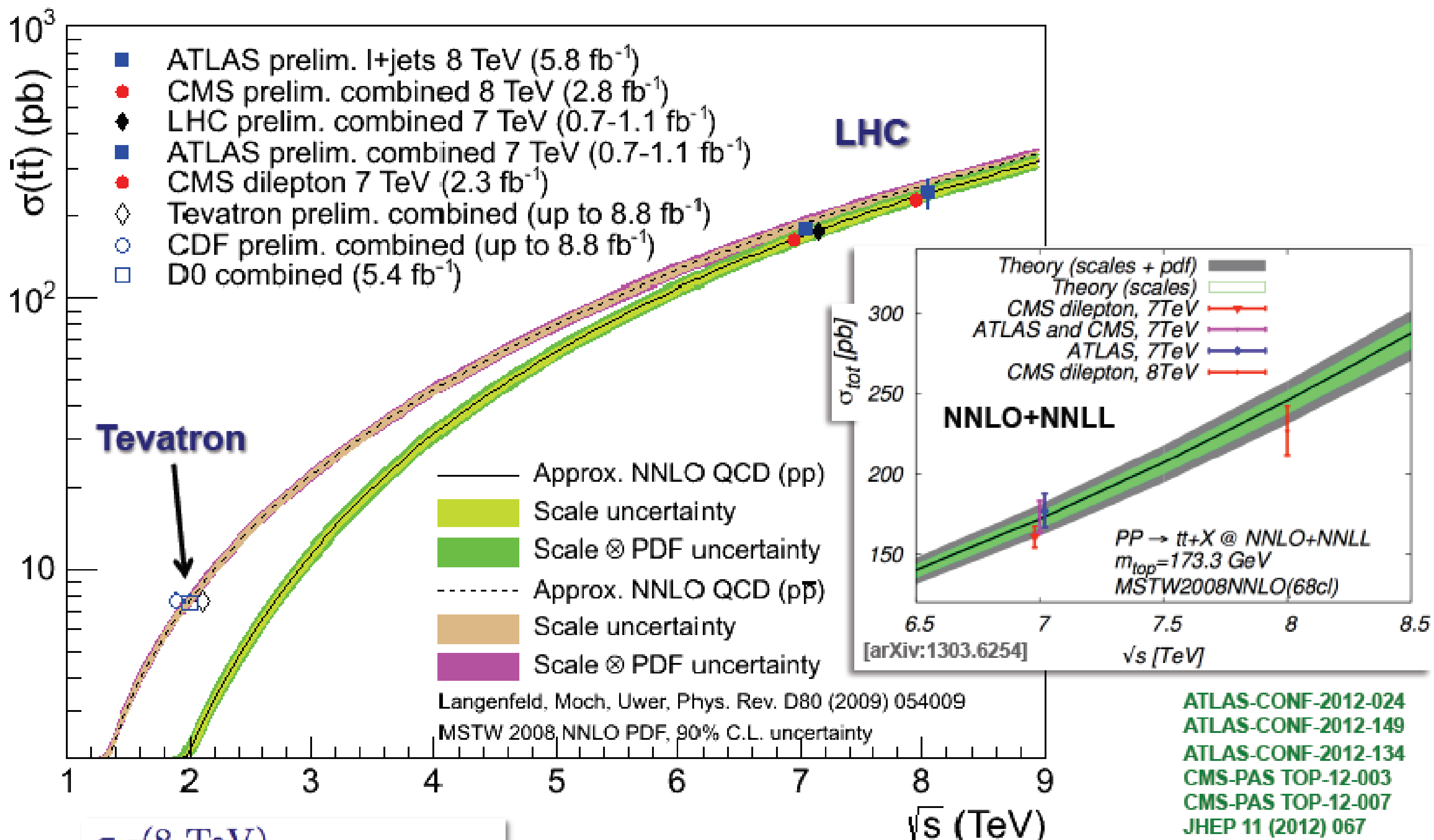
Top cross section at 7 TeV





Good agreement between measurements and predictions for all decay modes

Current status



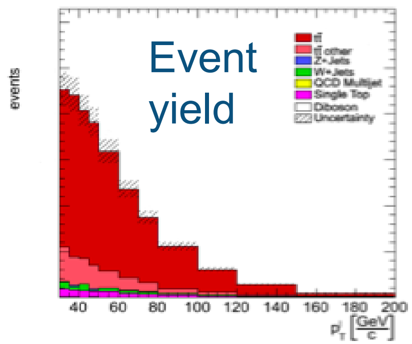
$$\frac{\sigma_{t\bar{t}}(8\ \mathrm{TeV})}{\sigma_{t\bar{t}}(7\ \mathrm{TeV})} = 1.41 \pm 0.11$$

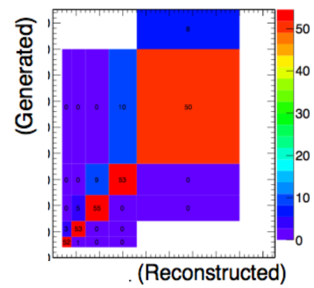
[exp. (theory) uncerts. uncorrel (correl), in agreement with arXiv:1303.7215]

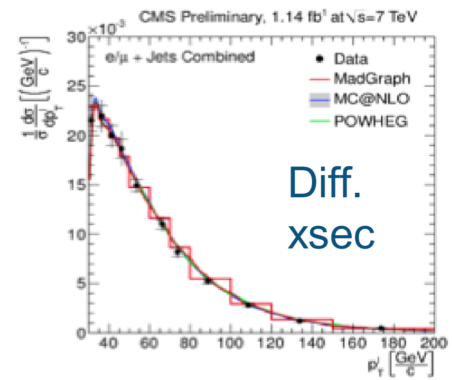
ATLAS-CONF-2012-024
ATLAS-CONF-2012-149
ATLAS-CONF-2012-134
CMS-PAS TOP-12-003
CMS-PAS TOP-12-007
JHEP 11 (2012) 067

Top-pair differential cross section

- Precise tests of pQCD, tuning & validation of MC models, constrains on BSM effects
- Measure $\sigma(t\bar{t})$ as a function of several kinematic variables for different observables: top, top pairs, (b)-jets, leptons, lepton pairs, E_T^{miss}, …







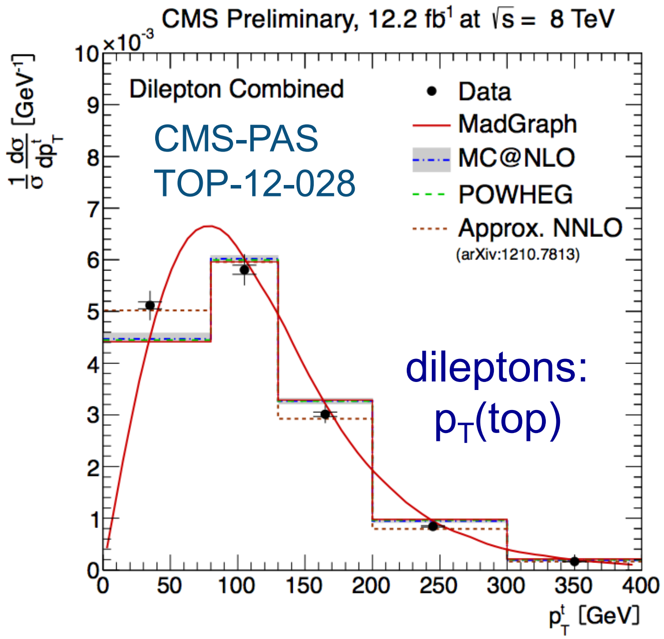
$$\frac{1}{\sigma}\frac{d\sigma^i}{dX} = \frac{1}{\sigma}\frac{N^i_{\text{Data}} - N^i_{\text{BG}}}{\Delta^i_X \epsilon^i L}$$

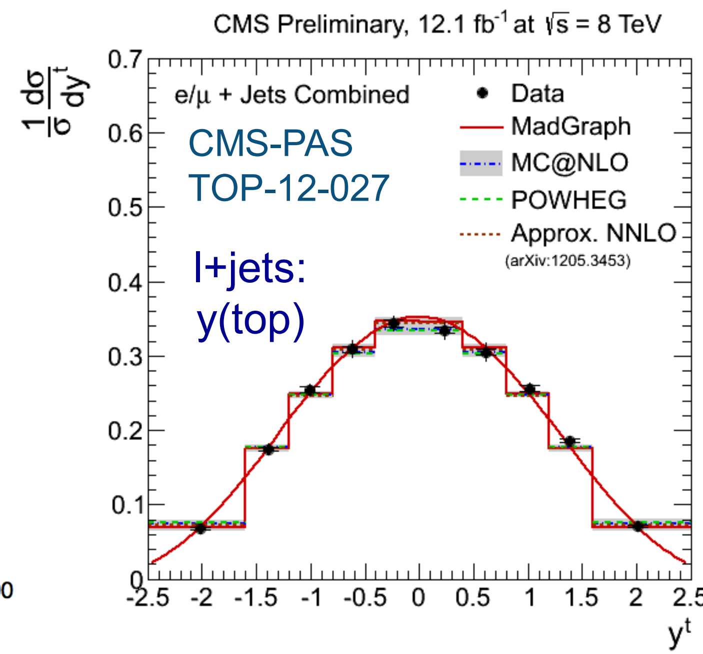
L = integrated luminosity
Δ^i_X = bin width for variable X
ε^i = efficiency and acceptance

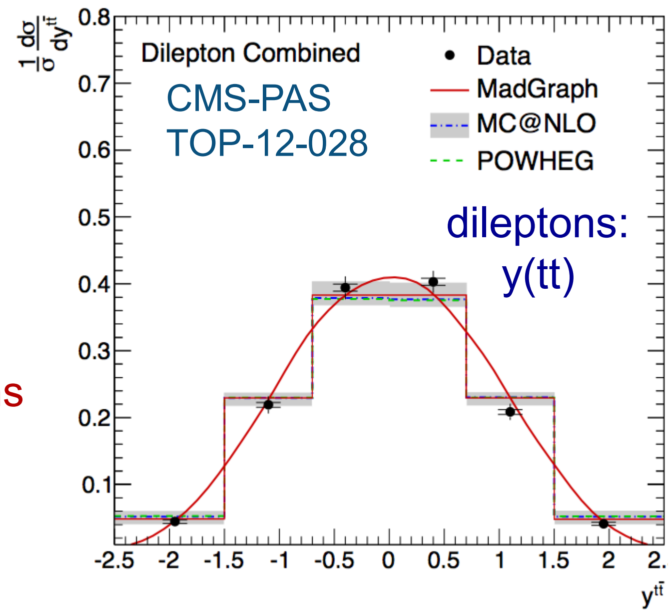
- Corrected for detector effects (finite experimental resolution)
- Normalised to inclusive cross section in corresponding phase space
  - Only shape uncertainties contribute

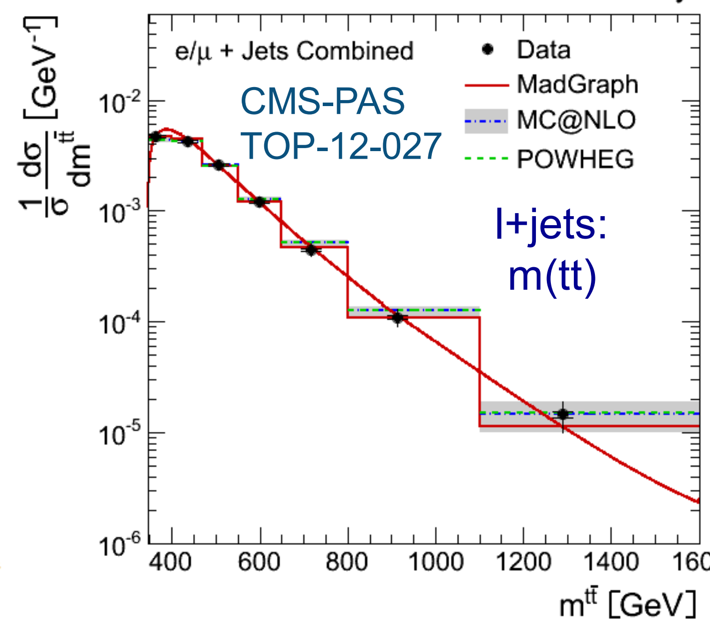
Top-pair differential cross section

- Full kinematic reco. of the tt system
- Comparison to different predictions
  - Softer top p_T in data, better described by approx. NNLO
  - approx. NNLO → p_T/y(top)
- In general, good agreement btw:
  - Dilepton and lepton+jet channel
  - data and predictions





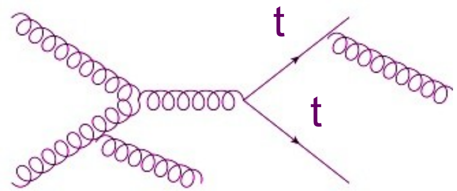




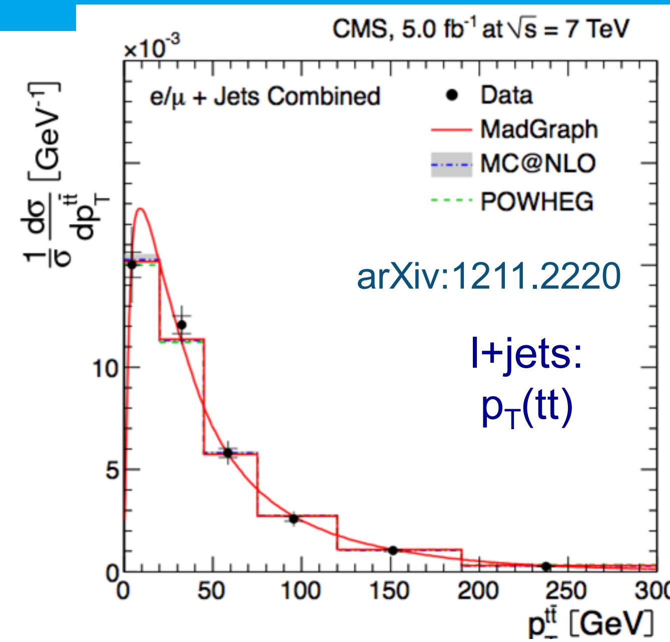
Constraining QCD radiation using ttbar events

At LHC, the fraction of $t\bar{t}$ events produced with additional hard jets from initial (final) state radiation is high

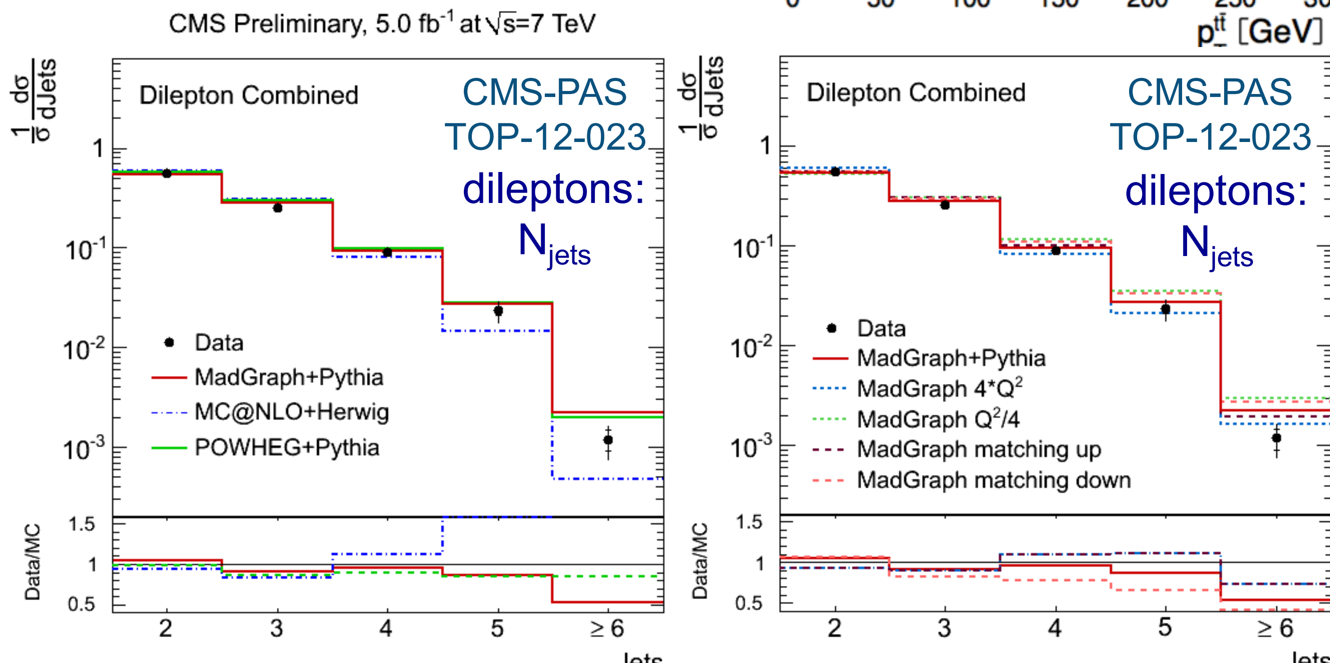
- Typically, large uncertainty due to radiation modelling in MC
  - Help tuning MC models with measurements



- Anomalous production of $t\bar{t}$+jets could reveal new physics
- Background for $t\bar{t}$+H and many BSM searches

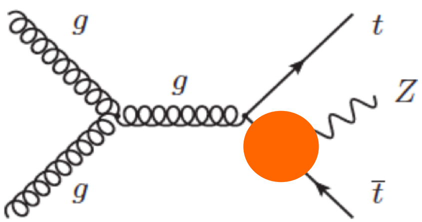


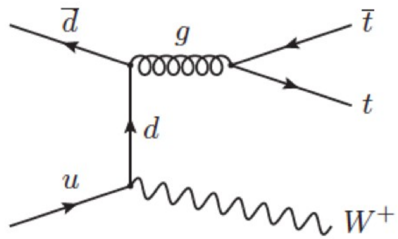
In general, good agreement between data and predictions

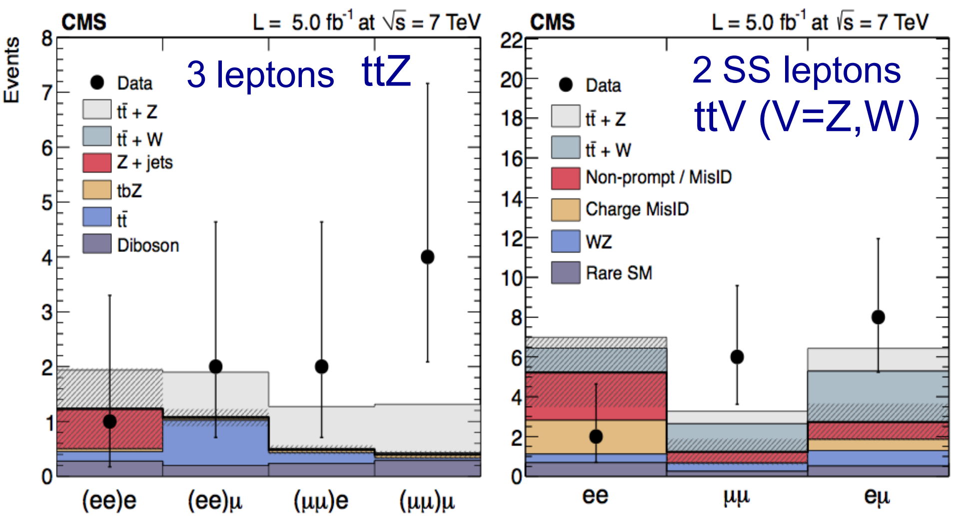


Top Pair Associated Production

- ttbar+W/Z are rare processes in SM measure couplings to bosons
  - Important bg for BSM searches





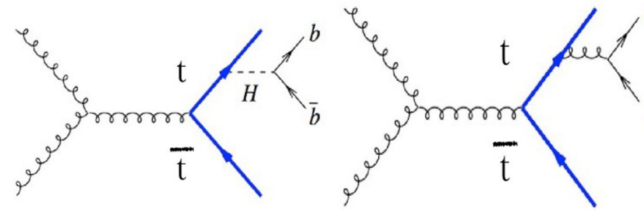


$$\sigma_{t\bar{t}Z} = 0.28^{+0.14}_{-0.11}\,(\text{stat.})\ {}^{+0.06}_{-0.03}\,(\text{syst.})\,\text{pb}$$ (3.3σ)

$$\sigma_{t\bar{t}V} = 0.43^{+0.17}_{-0.15}\,(\text{stat.})\ {}^{+0.09}_{-0.07}\,(\text{syst.})\,\text{pb}$$ (3σ)

Consistent with NLO calculations

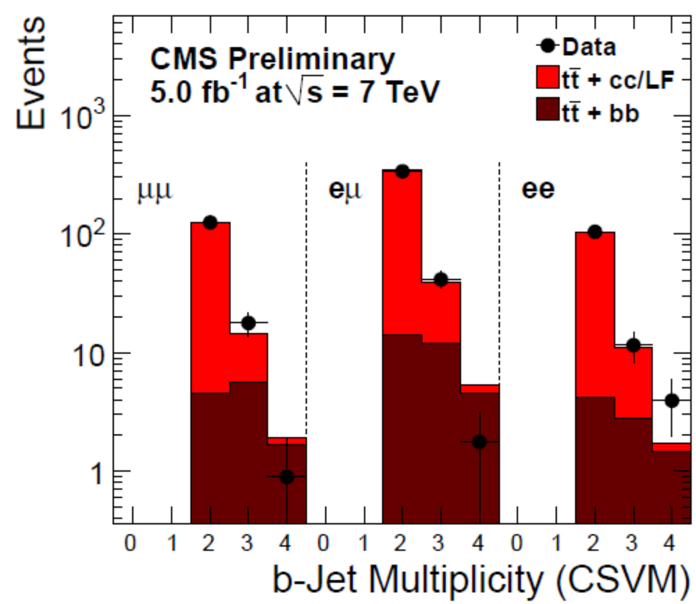
[JHEP 07 (2012) 052, JHEP 11 (2012) 056]



tt̄+bb̄: Ratio of light flavor to b-flavored jets (dilepton final state)

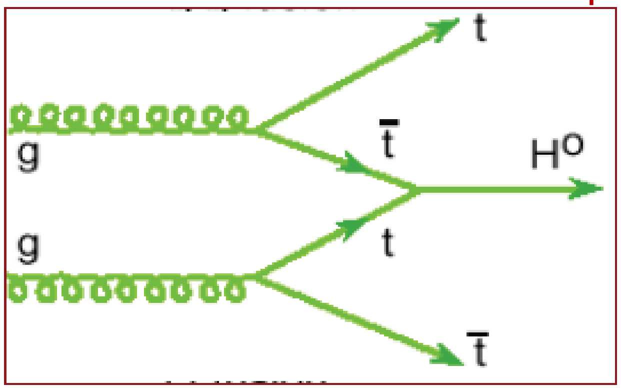
- important background to tt̄H search

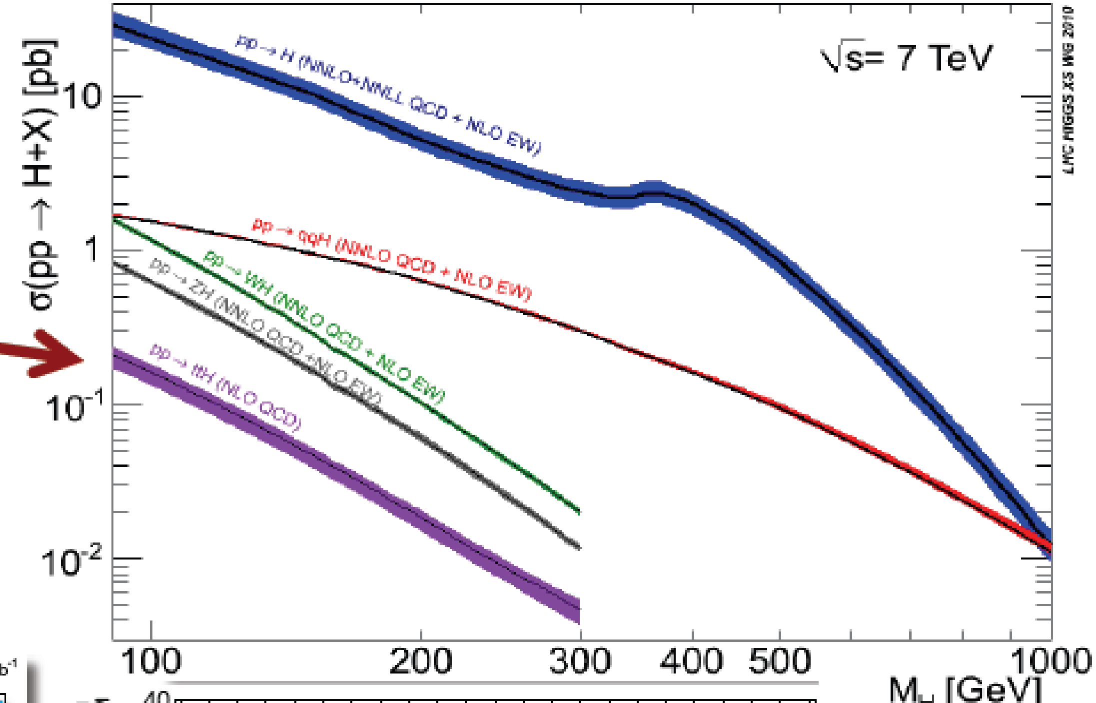
$$\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)} = 3.6 \pm 1.1_{stat} \pm 0.9_{syst}\%$$

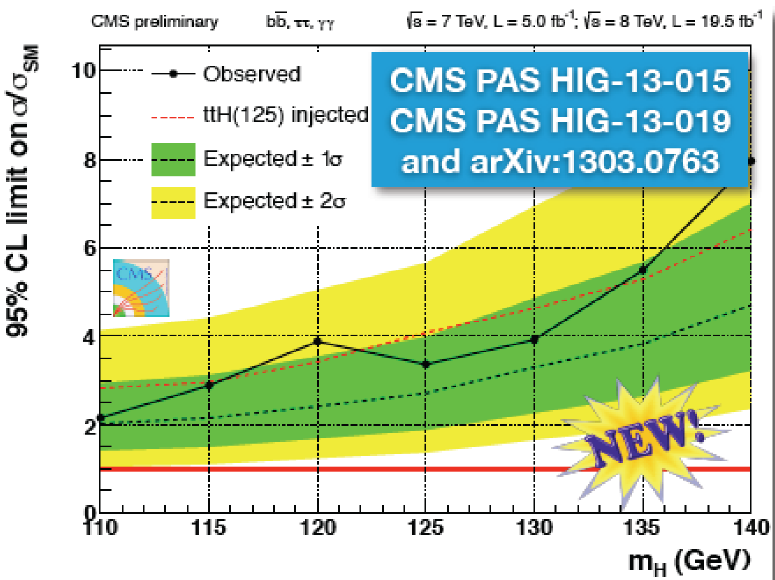


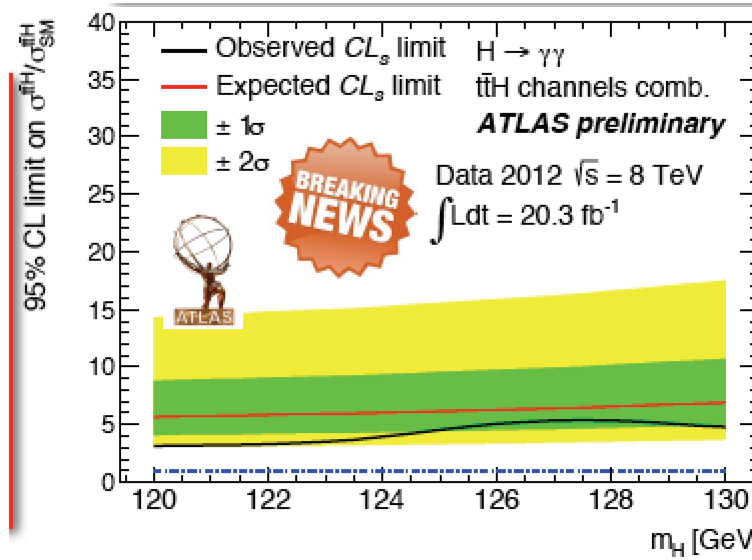
Top Pair Associated Production with Higgs

- ttbar produced in association with H
  - ttbar is a “clean” tag
- Direct measurement of H couplings

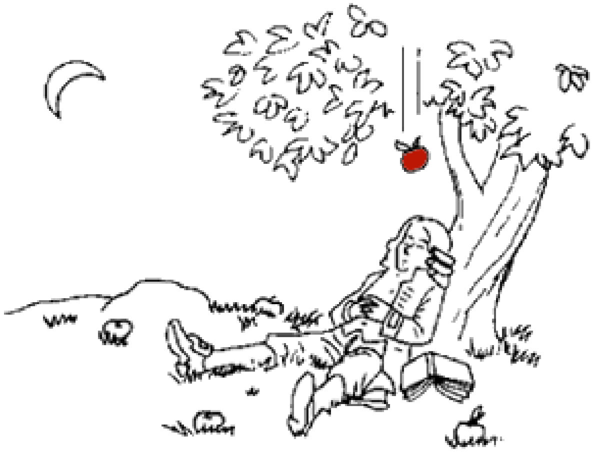






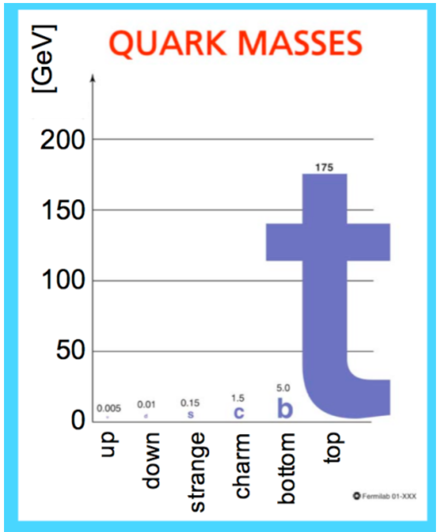


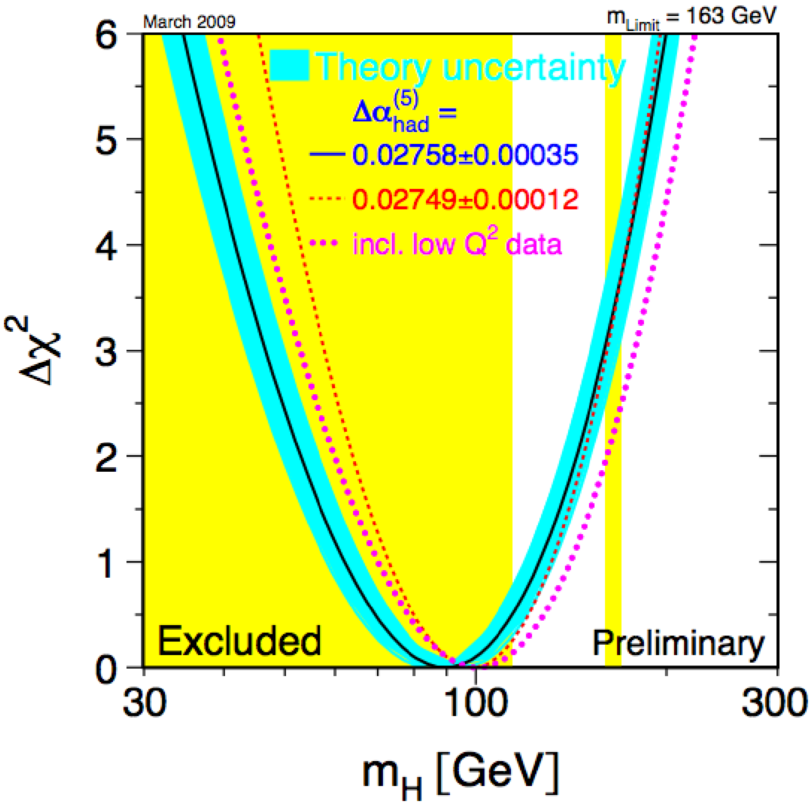
Top-quark pair mass measurements



Top Mass Measurements

- Top quark mass is a fundamental parameter of the SM
  - Known with good accuracy from the Tevatron: 173.20±0.87 GeV
  - Indirect constraint on the Higgs boson mass via EW corrections
- Only fermion with the mass of the order of EWSB scale
- Measuring precisely Mw and mtop
  - Test consistency of SM
  - Search for new Physics





Which mass are we measuring?

$$\mathcal{L} = \ldots - \bar{\psi} M \psi \left(1 + \frac{H}{v}\right) \ldots$$

> Fundamental parameter of the SM, not an observable -> scheme-dependent

- Pole mass: viewing top as a free parton
- MS mass ('running mass')

$$m_{pole} = \overline{m}(\overline{m}) \left(1 + \frac{4}{3}\frac{\overline{\alpha}_s(\overline{m})}{\pi} + 8.28 \left(\frac{\overline{\alpha}_s(\overline{m})}{\pi}\right)^2 + \cdots \right) + O(\Lambda_{QCD})$$

- Mass as defined in MC (´MC mass'): typically LO or NLO, different from pole mass or MS mass
- Difference between pole mass and MS mass ~10 GeV

> Determining m_{top}:

- Direct methods: full reconstruction of tt events, depend on MC
- Indirect methods: use the dependence of the top mass on the other variables (e.g. cross-section)

NB. Relation of measured m_{top} to well-defined mass not straightforward!

Direct measurement of the top mass

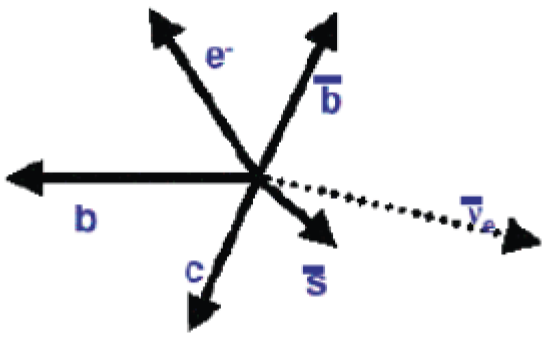
Lepton+jets

- undetected neutrino
  - P_x and P_y from E_T conservation
  - 2 solutions for P_z from $M_W = M_{l\nu}$
- leading 4-jet combinatorics
  - 12 possible jet-parton assignments
  - 6 with 1 b-tag
  - 2 with 2 b-tags
  - ISR + FSR

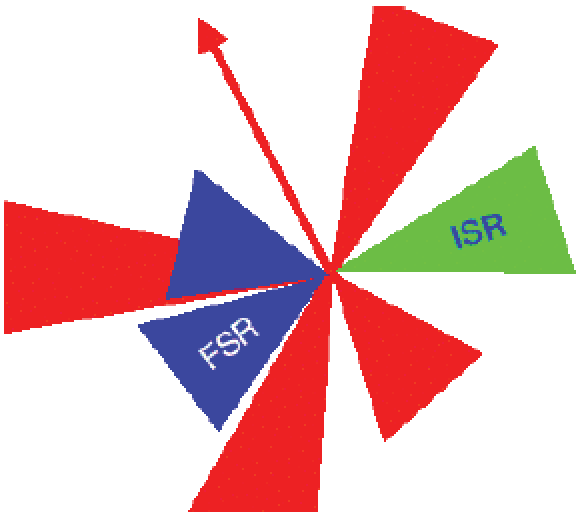
Dileptons

- (less statistics)
- two undetected neutrinos
- less combinatorics: 2 jets (+ISR/FSR)

LO final state:

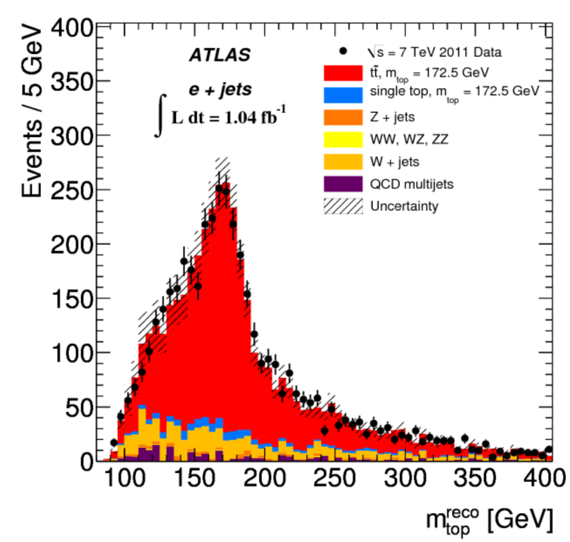


experiment sees:

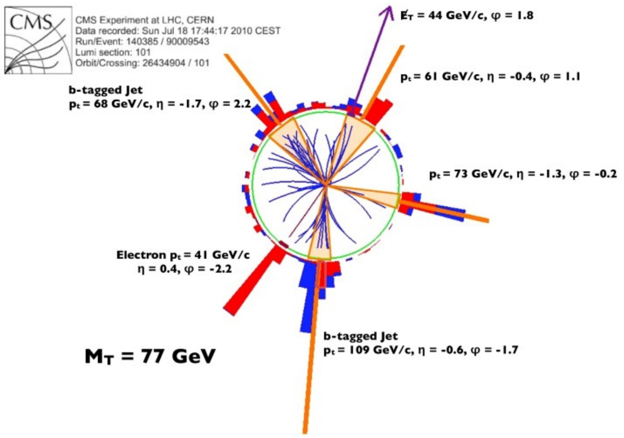


Mass in the lepton+jets channel

- Best channel (for now) to measure top quark mass
  - Compromise between large branching ratio (BR=30%) and a good background rejection
- Well defined final state (1 lepton, one neutrino, 2 b-jets, W->qq')



$$M^2 = (\sum_{\text{jet } i} E_{\text{jet } i} + E_l + E_\nu)^2 - (\sum_{\text{jet} i} \tilde{p}_{\text{jet} i} + \tilde{p}_l + \tilde{p}_\nu)^2$$



The problems:

- **How to get the z – component of ν**
- **Out of 4 (or more) jets: which jet belongs to which top?**
- **What is the energy scale of jets (and electrons)**

$p_z(\nu)$? Which jets?

$p_z(\nu)$? Constraint from W mass

$$\mathbf{M_W^2} = (\mathbf{E_l} + \mathbf{E_\nu})^2 - (\mathbf{p_x}(\mathbf{l}) + \mathbf{p_x}(\nu))^2 - (\mathbf{p_y}(\mathbf{l}) + \mathbf{p_y}(\nu))^2 - (\mathbf{p_z}(\mathbf{l}) + \mathbf{p_z}(\nu))^2$$

$$\mathbf{E}_\nu = \sqrt{\mathbf{p_x^2}(\nu) + \mathbf{p_y^2}(\nu) + \mathbf{p_z^2}(\nu)}$$

- Quadratic equation ➔ 2 solutions
- physics: in 70% the solution with smaller p_z correct

Which jets belongs to which top quark?

Two aspects: if more than 4 jets (ISR) – mostly jets with highest p_T

- 4 jets ➔ 4 possible assigments
- ($j_A j_B J_C / j_D$, $j_A j_B j_D / j_C$, ...)
- Note: if b – jets identified, reduced to 2 possibilities

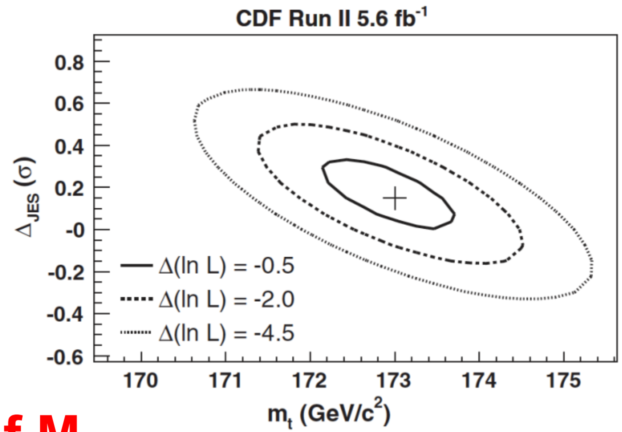
Important constraints
- mass (jjj) = mass(jlν) (= M_t)
- mass (jj) = M_W

Jet Energy Scale

- Measure signals in calorimeter ➔ derive jet energy
- Implies uncertainty! ➔ relates directly to top mass

$$M^2 = (\sum_{jet\ i} E_{jet\ i} + E_l + E_\nu)^2 - (\sum_{jeti} \tilde{p}_{jeti} + \tilde{p}_l + \tilde{p}_\nu)^2$$

- Top – quarks offer “self calibration“
- M(jj) has to be equal M_W ➔ change JES such that fulfilled

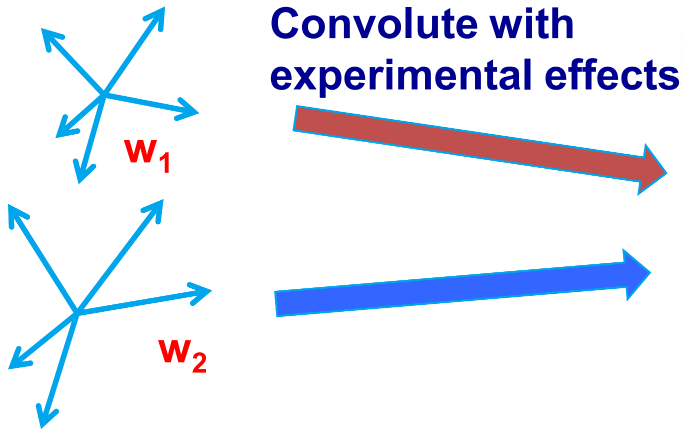


- Still the (slightly) dominant uncertainty of M_t

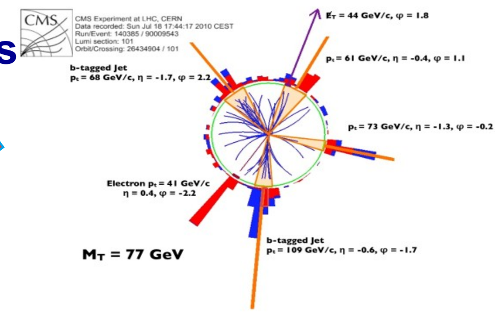
Combining all the information…

Theoretical pred with M_1(top)

Theoretical pred with M_2(top)

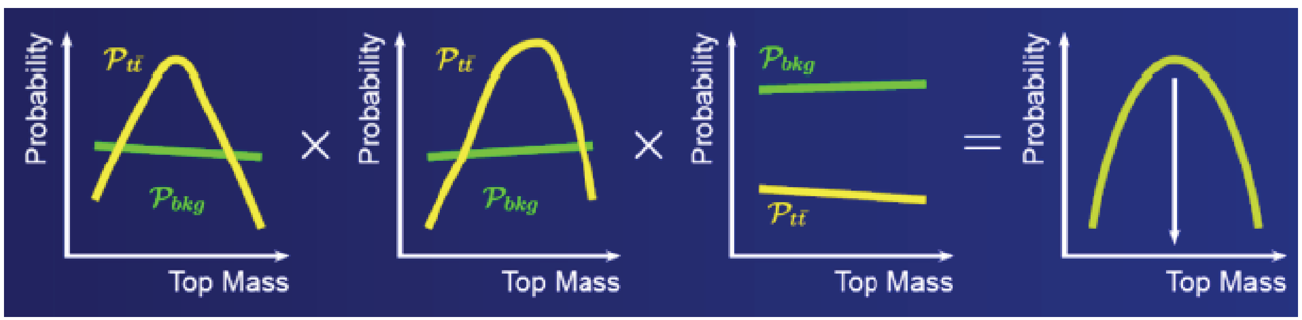


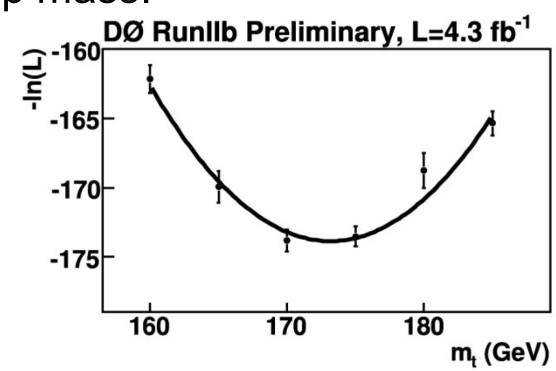
Convolute with experimental effects



> Matrix method

- Calculate probability for event to be top or BG, depending on top mass.
- Multiply event probabilities to obtain most likely mass





> Templates

- Use variables strongly correlated with top mass
- Compare data to MC generated with different top mass: extract mass using a maximum likelihood fit to data.

Top mass in lepton+jets

JHEP 12 (2012) 105

Simultaneous measurement of top mass and JES:

1 isolated μ/e, $\geq$ 4 jets, 2 b-tagged jets

- Reconstruct top mass from kinematic fit → m_t^{fit}
- W from reconstructed 2-jet invariant mass (handle on JES) → m_W^{reco}
- For each event, calculate the likelihood that m_t^{fit} and m_W^{reco} are consistent with a given top mass and JES factor
- 2D fit over all events to extract the top mass and JES:

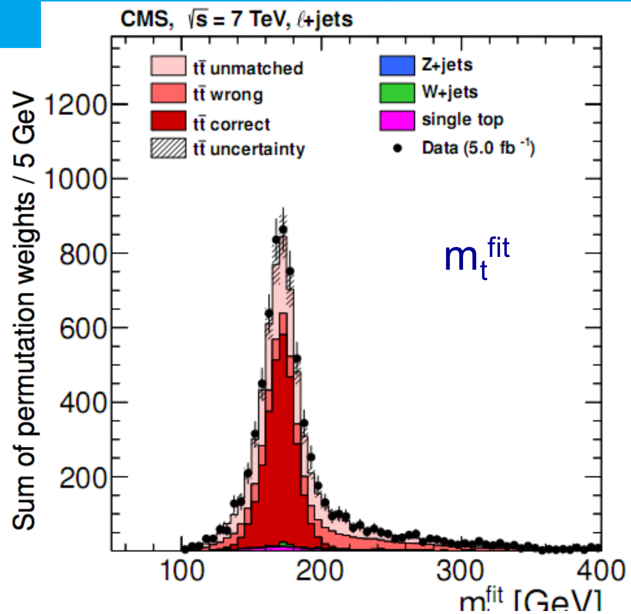
(< 1% precision !)

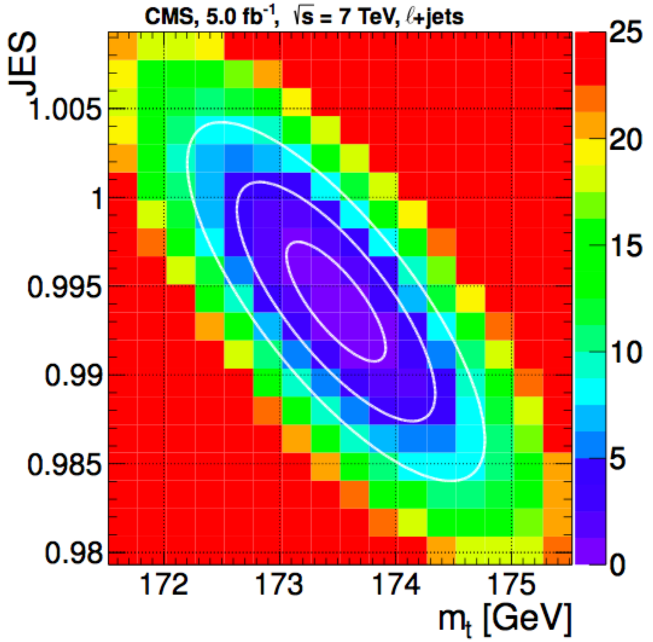
$$m_t = 173.49 \pm 0.43\,(\text{stat.+JES}) \pm 0.98\,(\text{syst.})\,\text{GeV}$$

$$\text{JES} = 0.994 \pm 0.003\,(\text{stat.}) \pm 0.008\,(\text{syst.})$$

- Most precise individual mass measurement ever !
- Consistent with world average

Main systematics: b-JES, colour reconnection



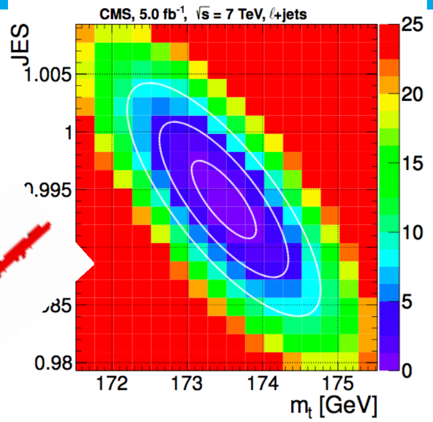


M_{top} dependence on kinematics

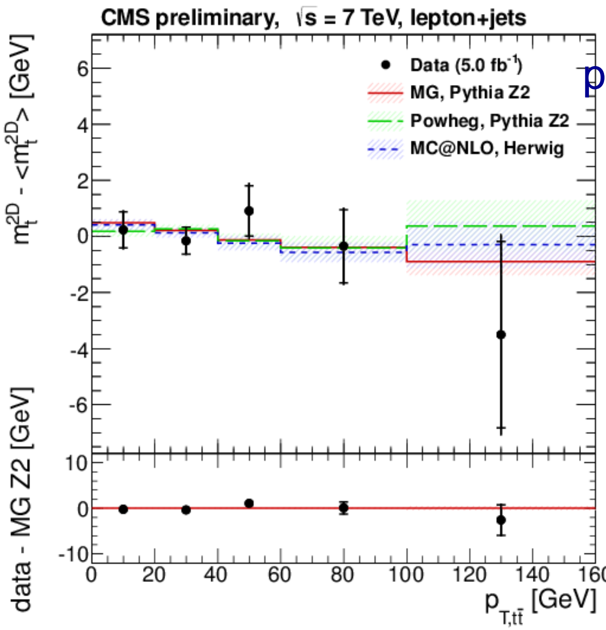
CMS-PAS TOP-12-029

> How does the measured m_t relate to the one needed for theoretical calculations ?

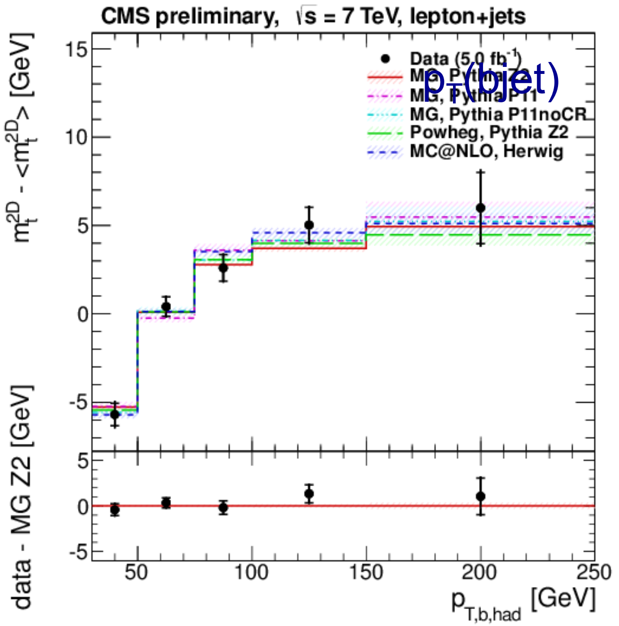
- Relation contains (non)perturbative corrections, expected to depend on event kinematics
  - •ISR/FSR radiation, …
- Is this kinematic dependence properly modelled in simulation?



Sensitive to ISR/FSR



b-quark kinematics

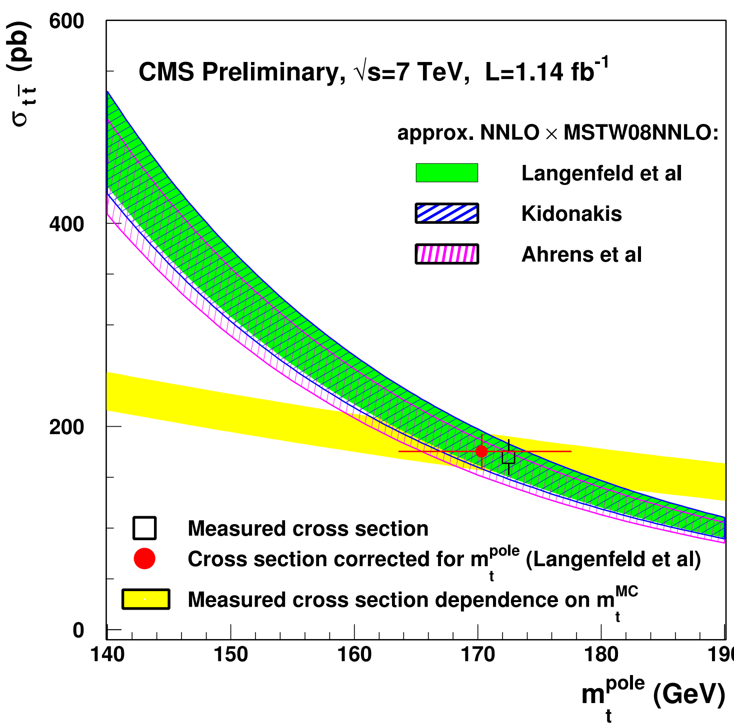


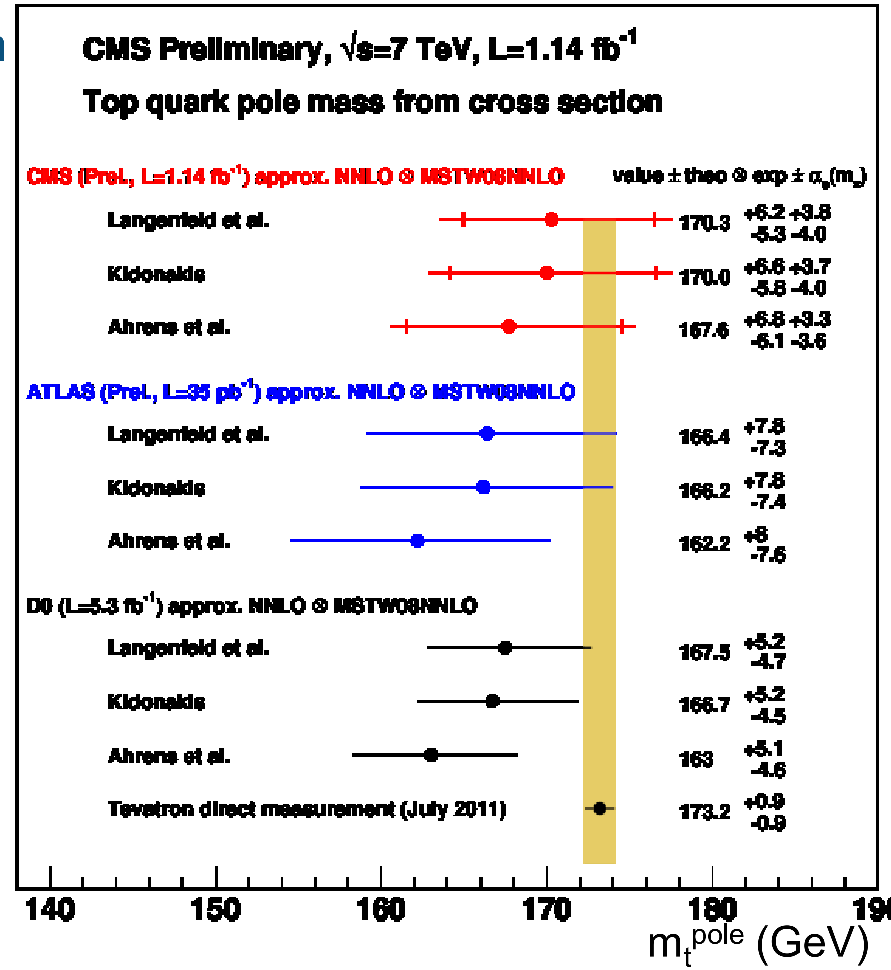
Good agreement between data and predictions; more data needed !

Top mass from cross section (indirect measurement)

Mass dependence of predicted cross section allows determining m_t from measured $\sigma(t\bar{t})$

- Remember: $\sigma(t\bar{t}) = f\,(m_{top}, \alpha_S, \text{PDFs})$
- Extract pole or $\overline{\text{MS}}$ mass from measured cross section in dileptons
- Most probable mass results from joint likelihood: theory □ experiment



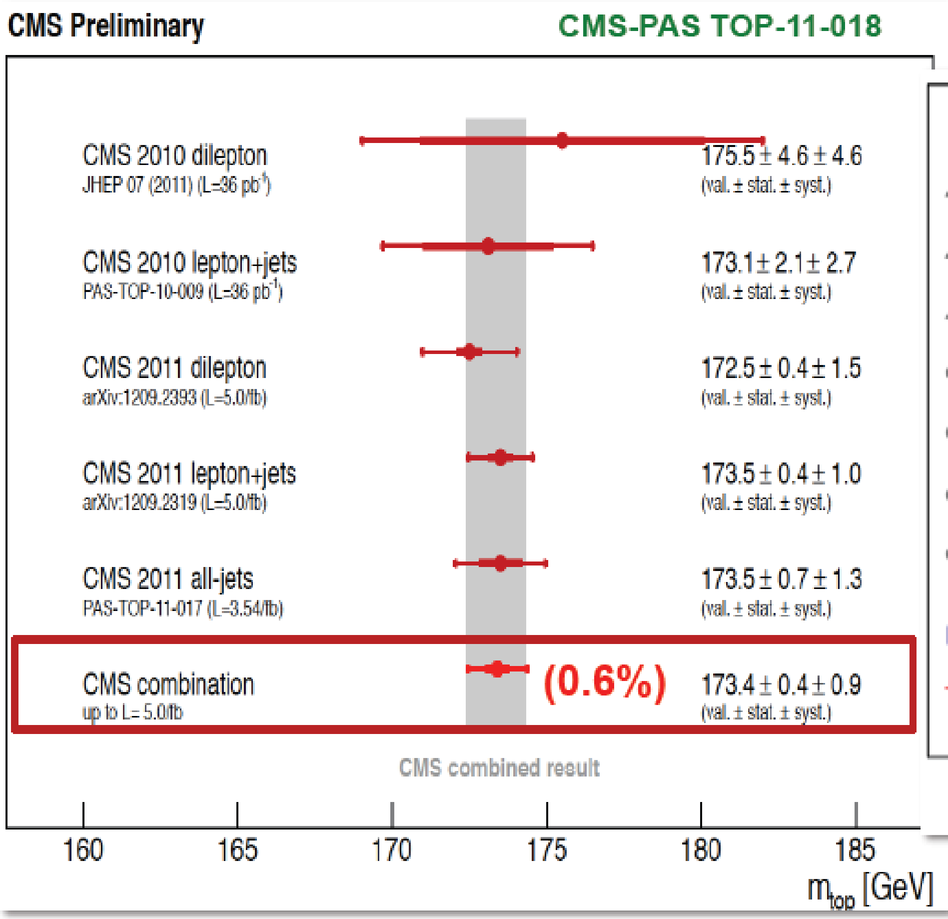


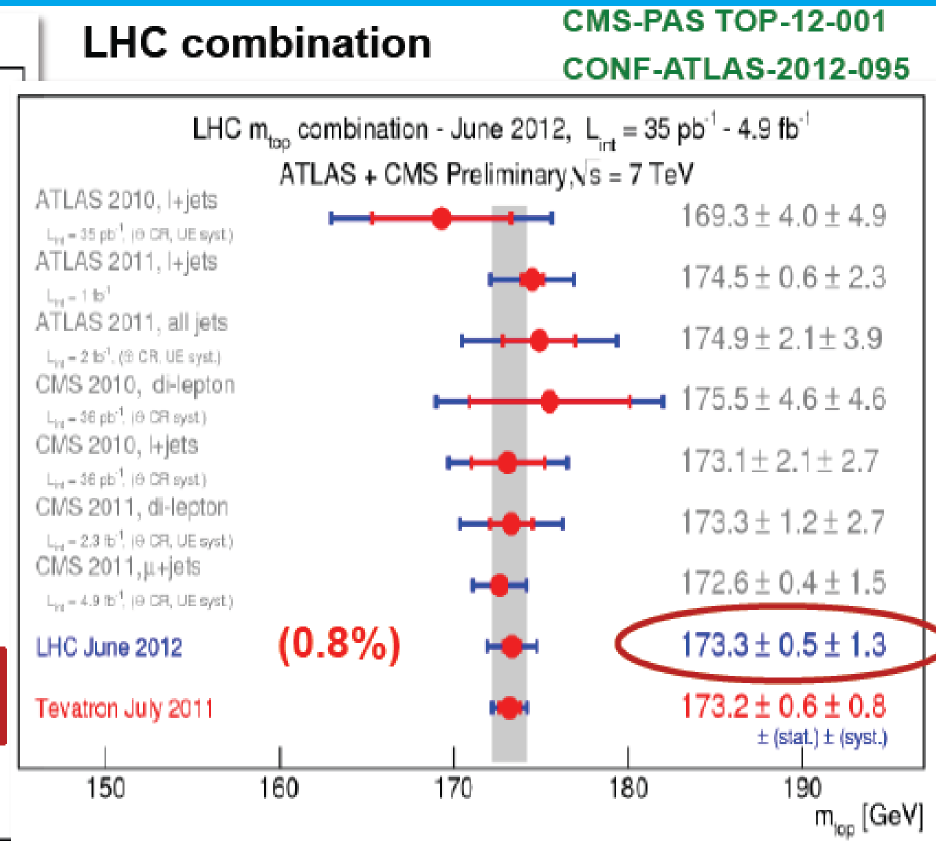
Good agreement btw different calculations & experiments

Imminent update using full NNLO & most precise $\sigma(t\bar{t})$

Main syst: uncert. of the measured $\sigma(tt)$, PDF, α_S

Summary of Top Mass Results





NB: Missing most up-to-date CMS and ATLAS results

Tevatron: m_t = 173.20 ± 0.87 GeV (0.5% !)

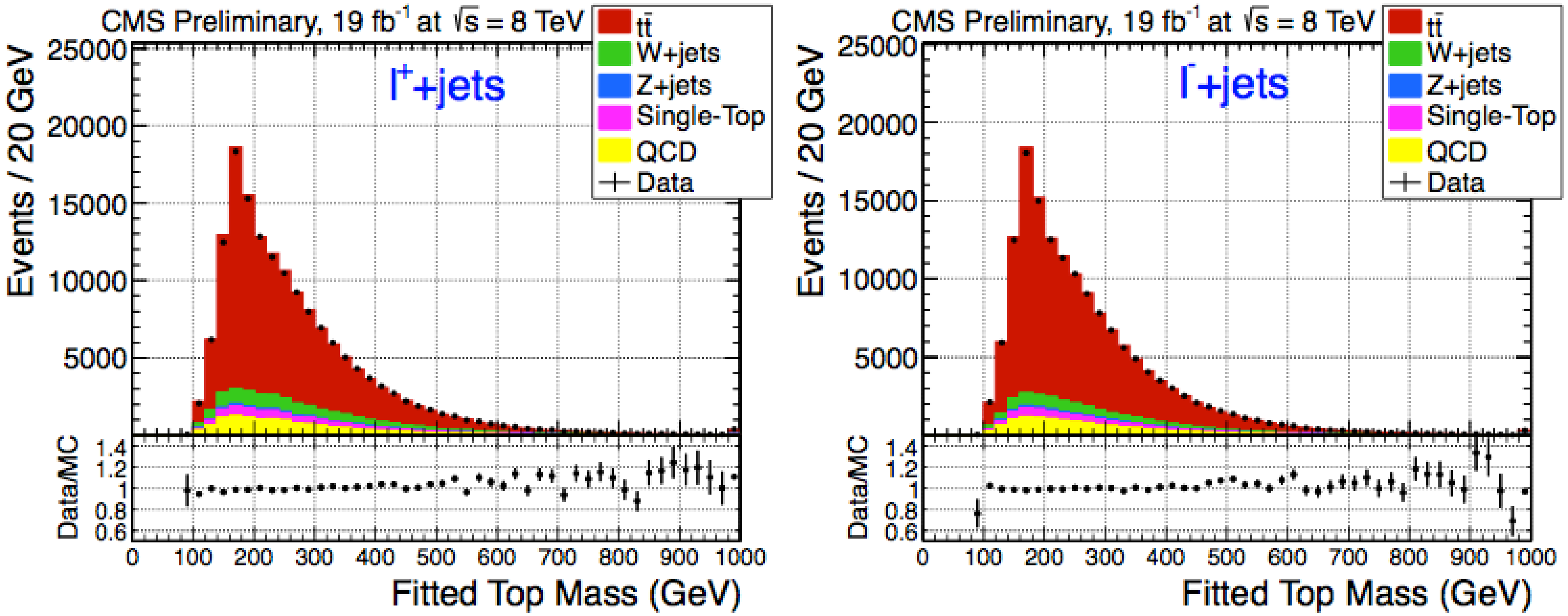
CDF Conf Note 10976
D0 Conf Note 6381

Measurements in l+jets and dilepton channels now competitive with the corresponding ones at Tevatron

Precision of combination similar to Tevatron combination

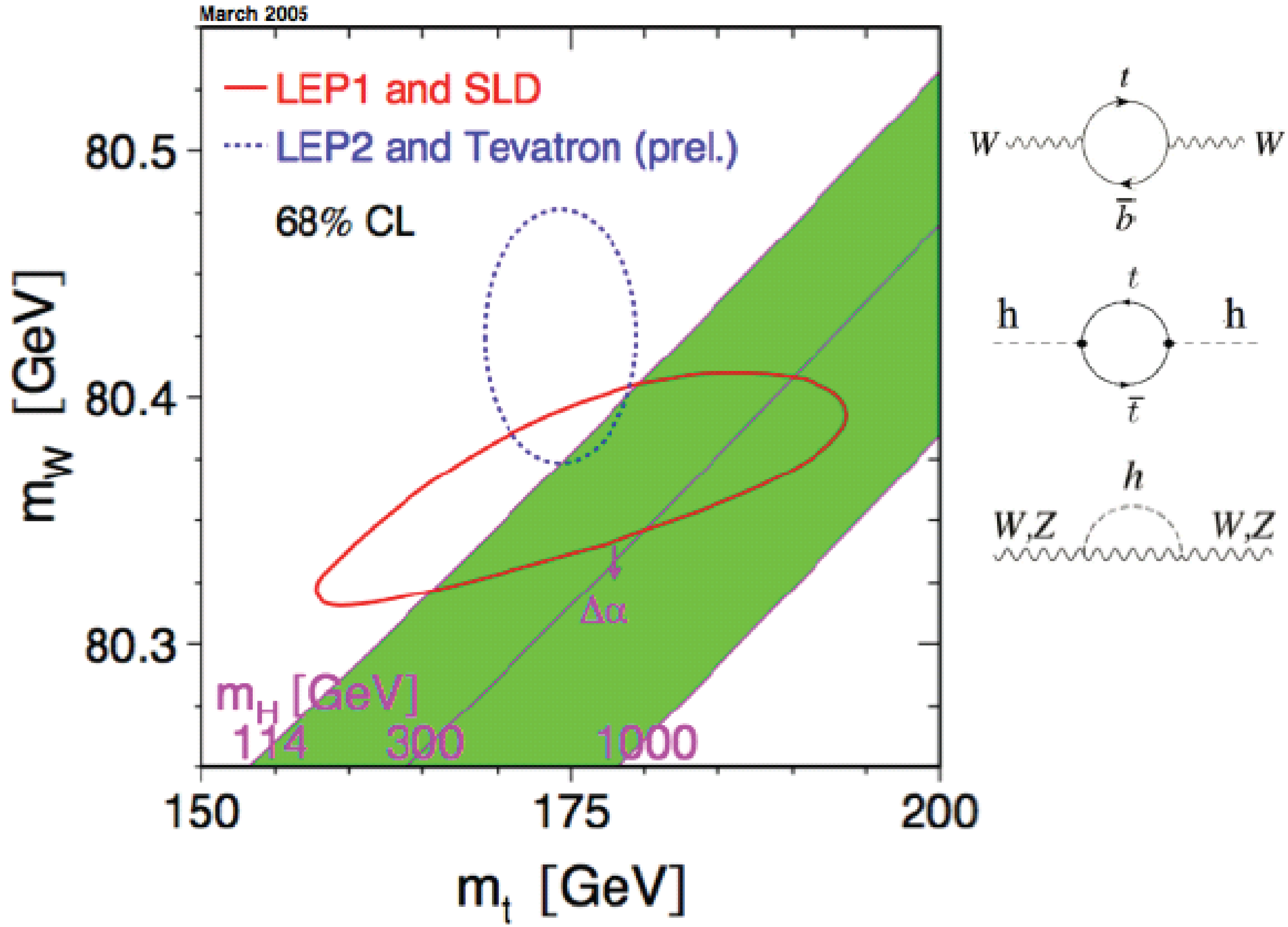
Top Mass Difference

- CPT invariance ⇒ mass of particle=mass of anti-particle
- Top quark decays before hadronizing ⇒ Δm can be measured directly
- Use lepton+jet final state: use μ+jet ttbar events: positive/negative muons (L=1.1/fb)
  - Compare mass measured from μ+/μ- +jets
  - Use hadronic side

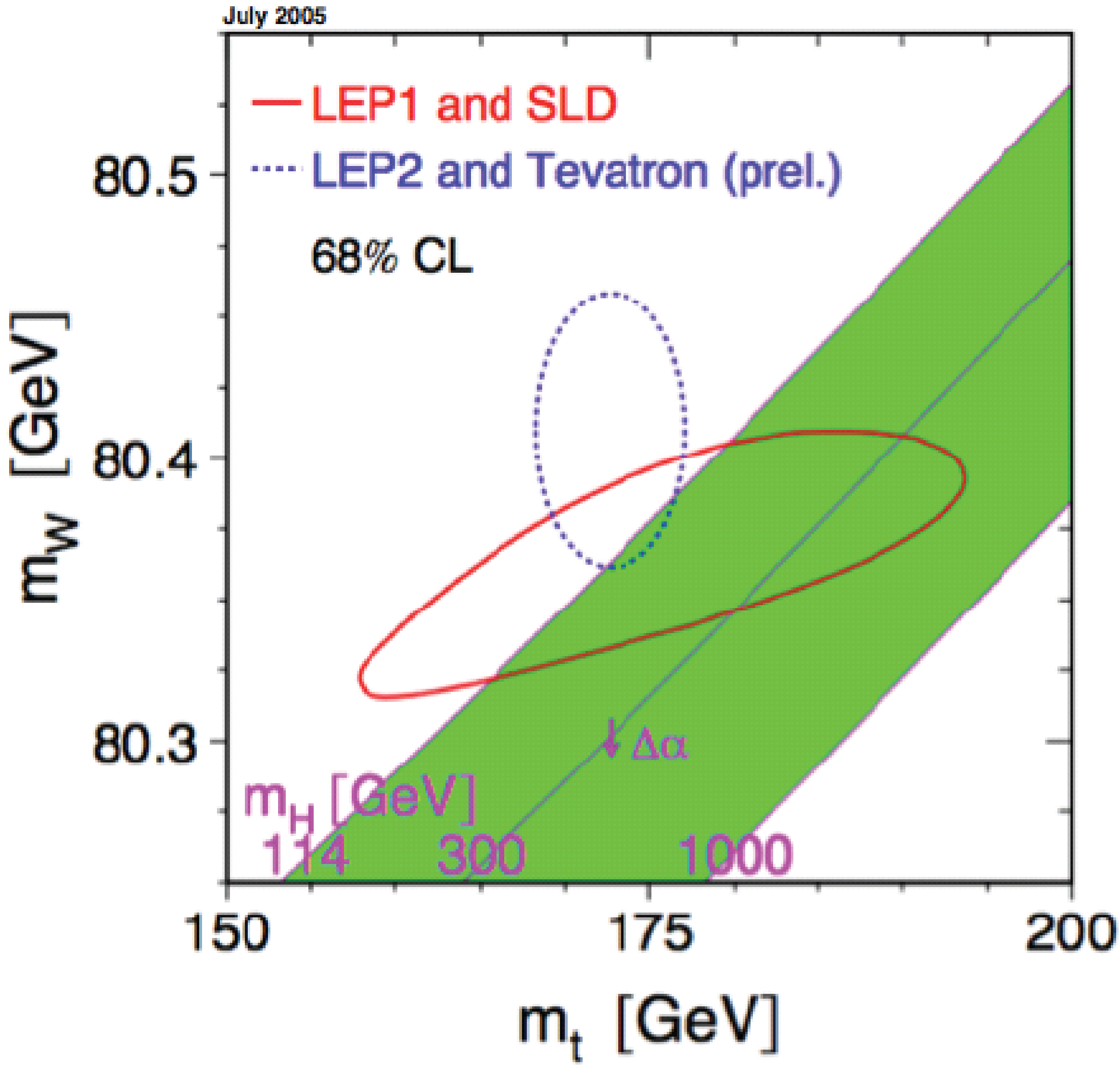


$$\Delta m_t = m_t^{had} - m_{\bar{t}}^{had} = -272 \pm 196\ (stat.) \pm 121\ (syst.)\ MeV$$

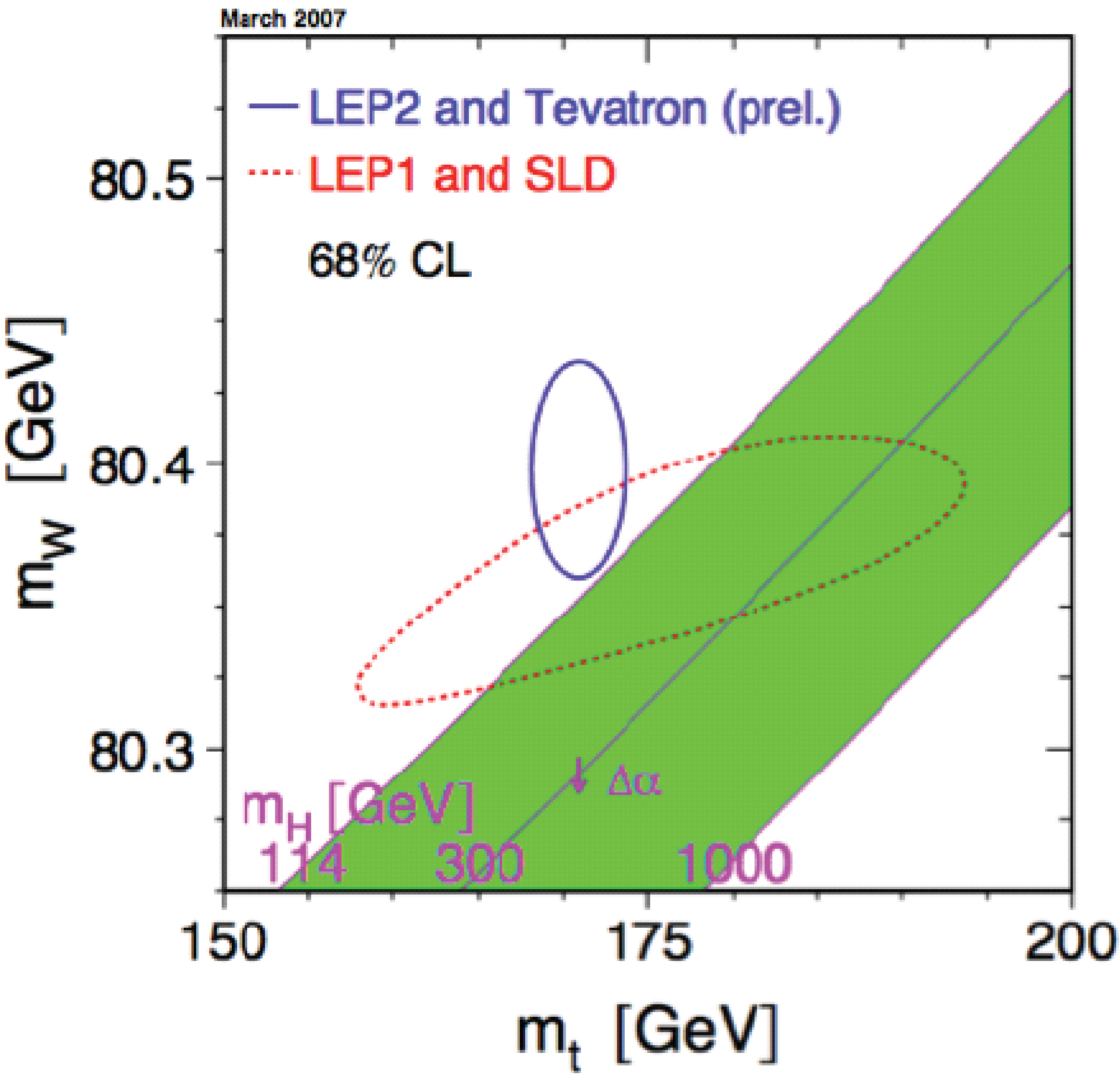
History Mtop vs Mw



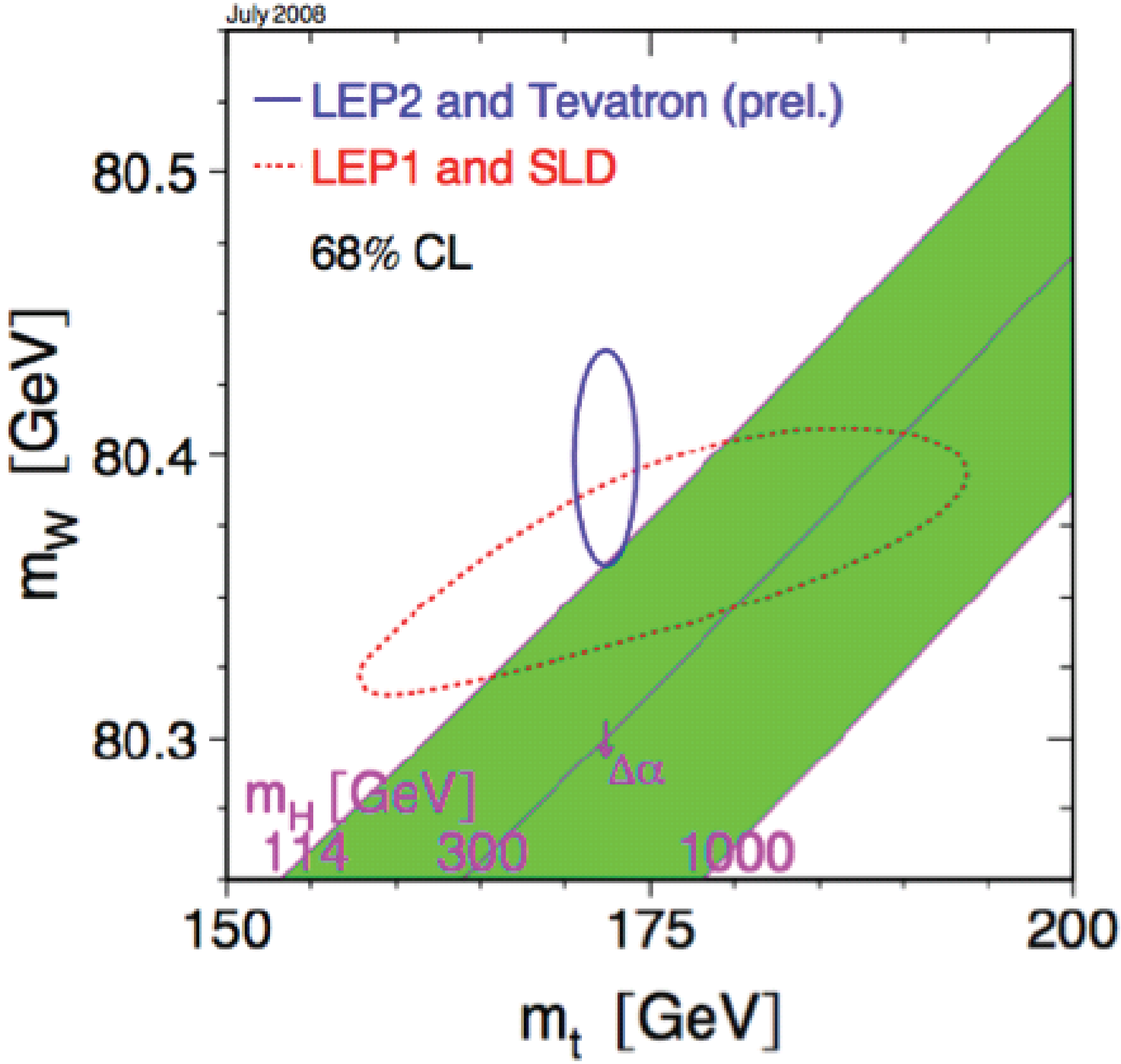
History Mtop vs Mw



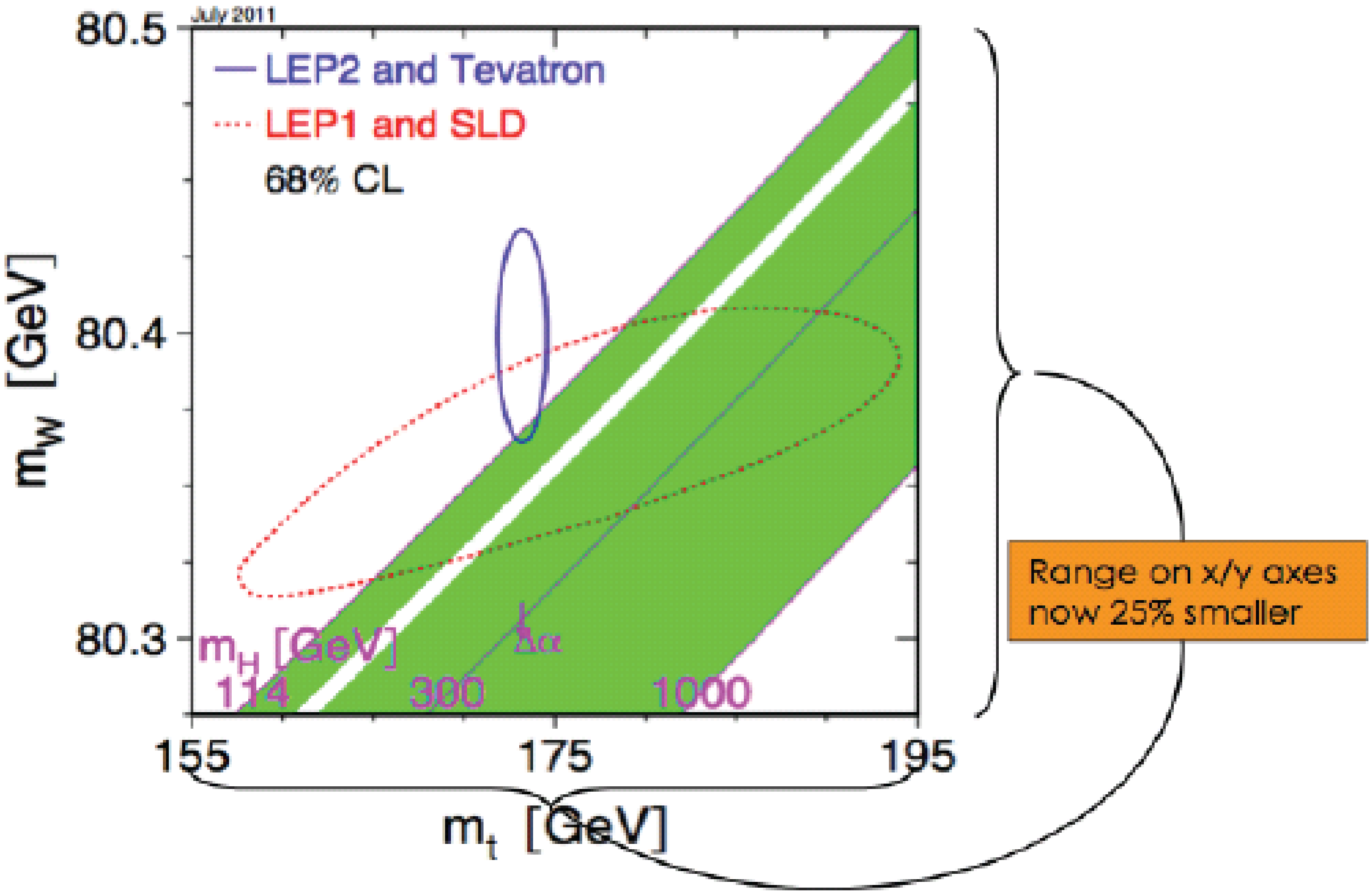
History Mtop vs Mw



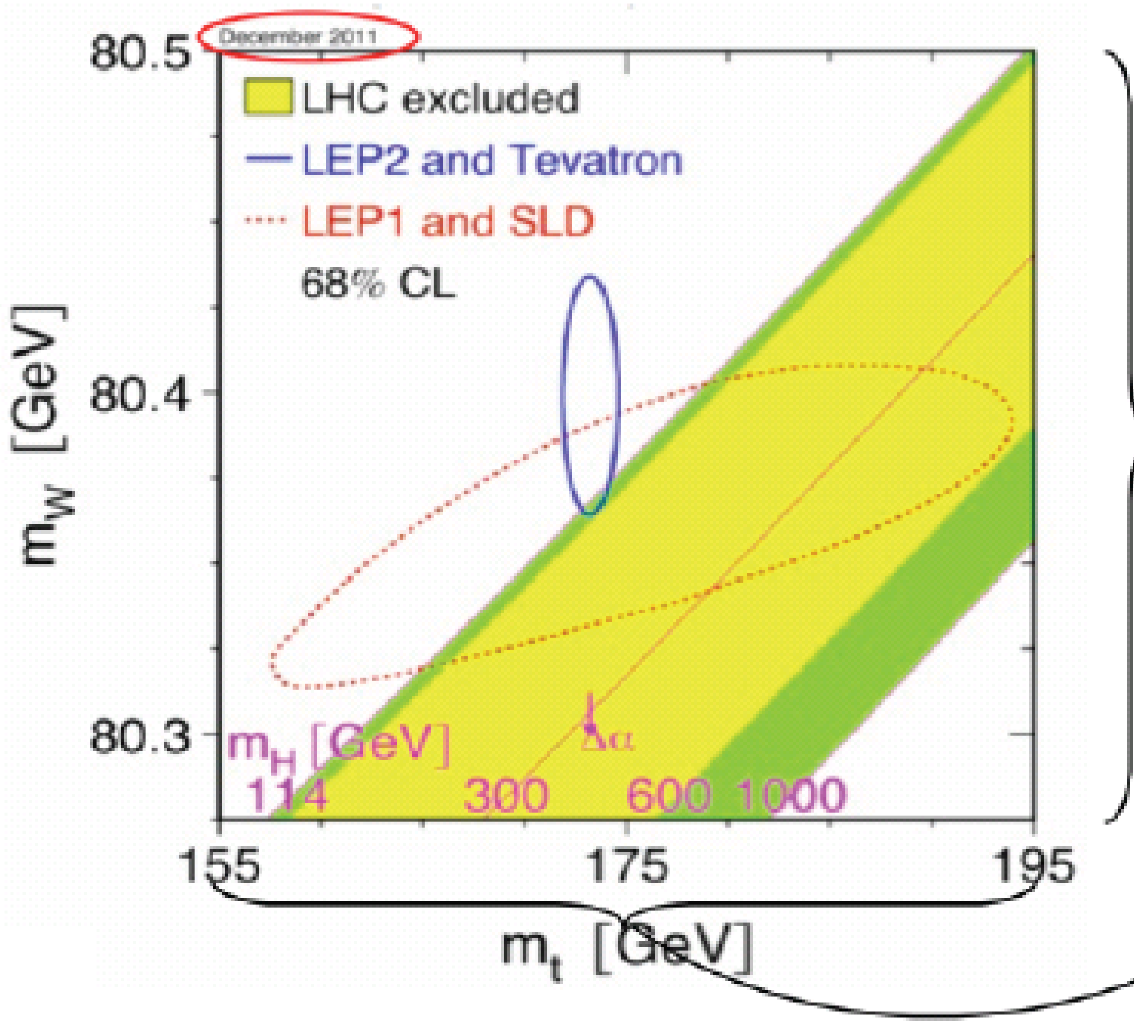
History Mtop vs Mw



History Mtop vs Mw

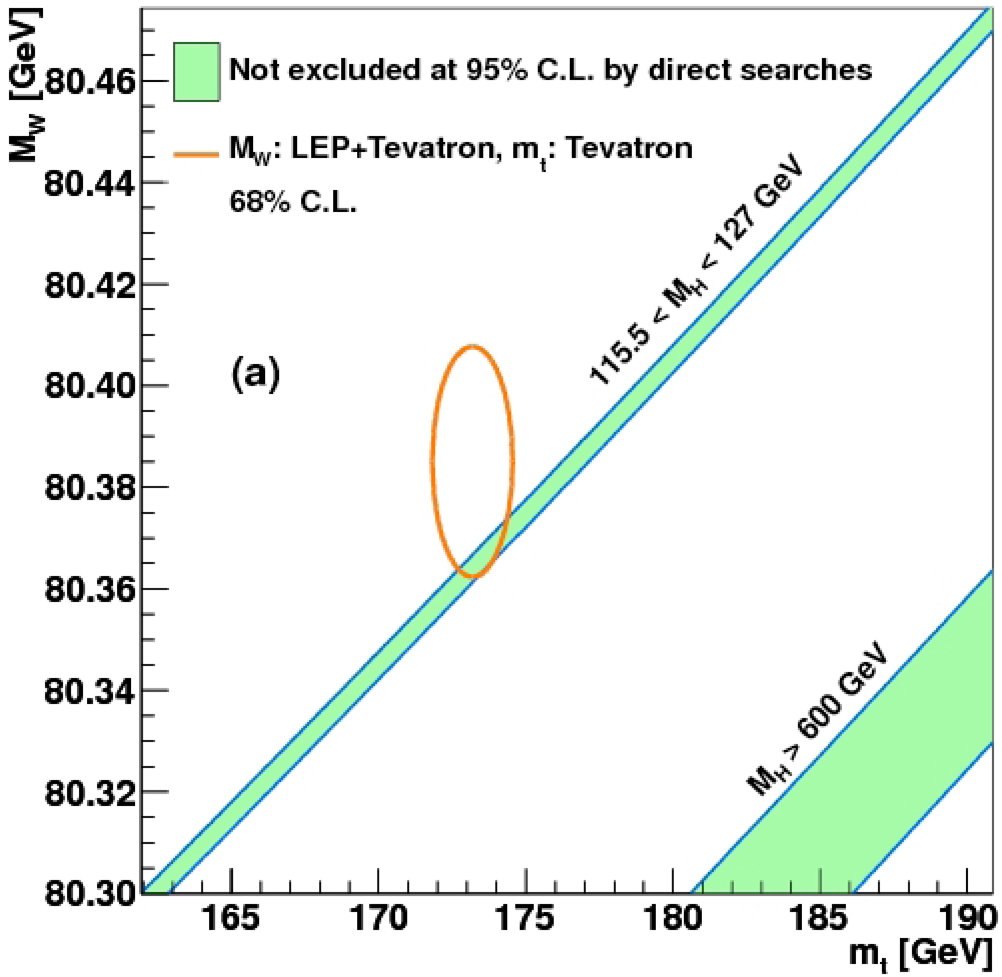


History Mtop vs Mw



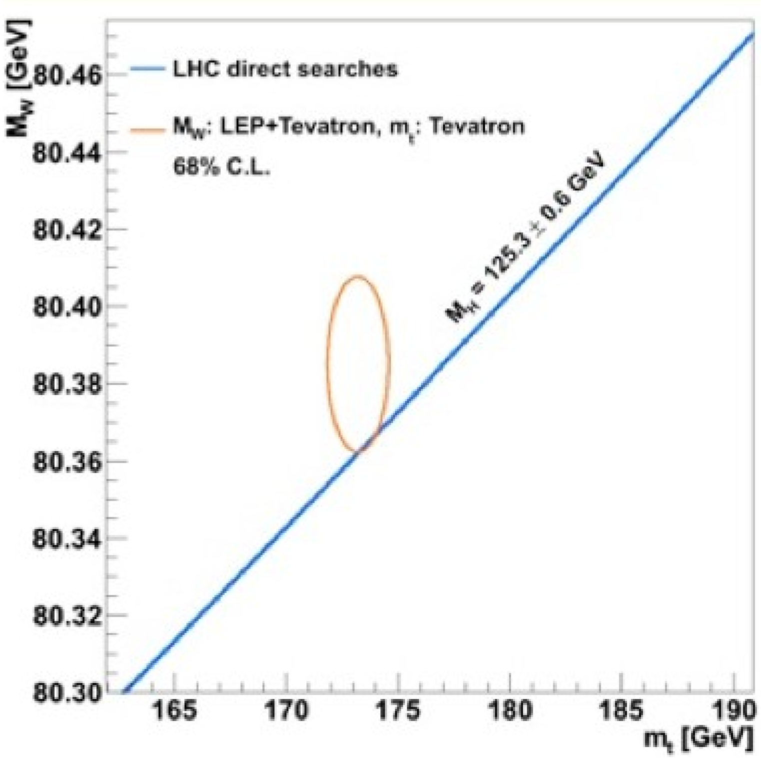
Range on x/y axes now 25% smaller

History Mtop vs Mw



History Mtop vs Mw

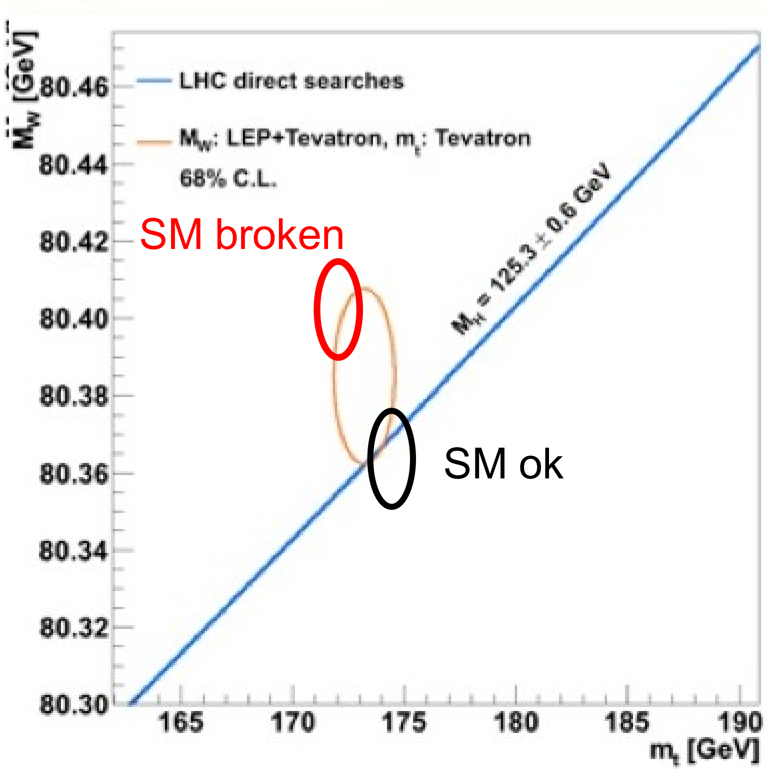
July 2012



> Standard Model is self-consistent

History M_{top} vs M_W

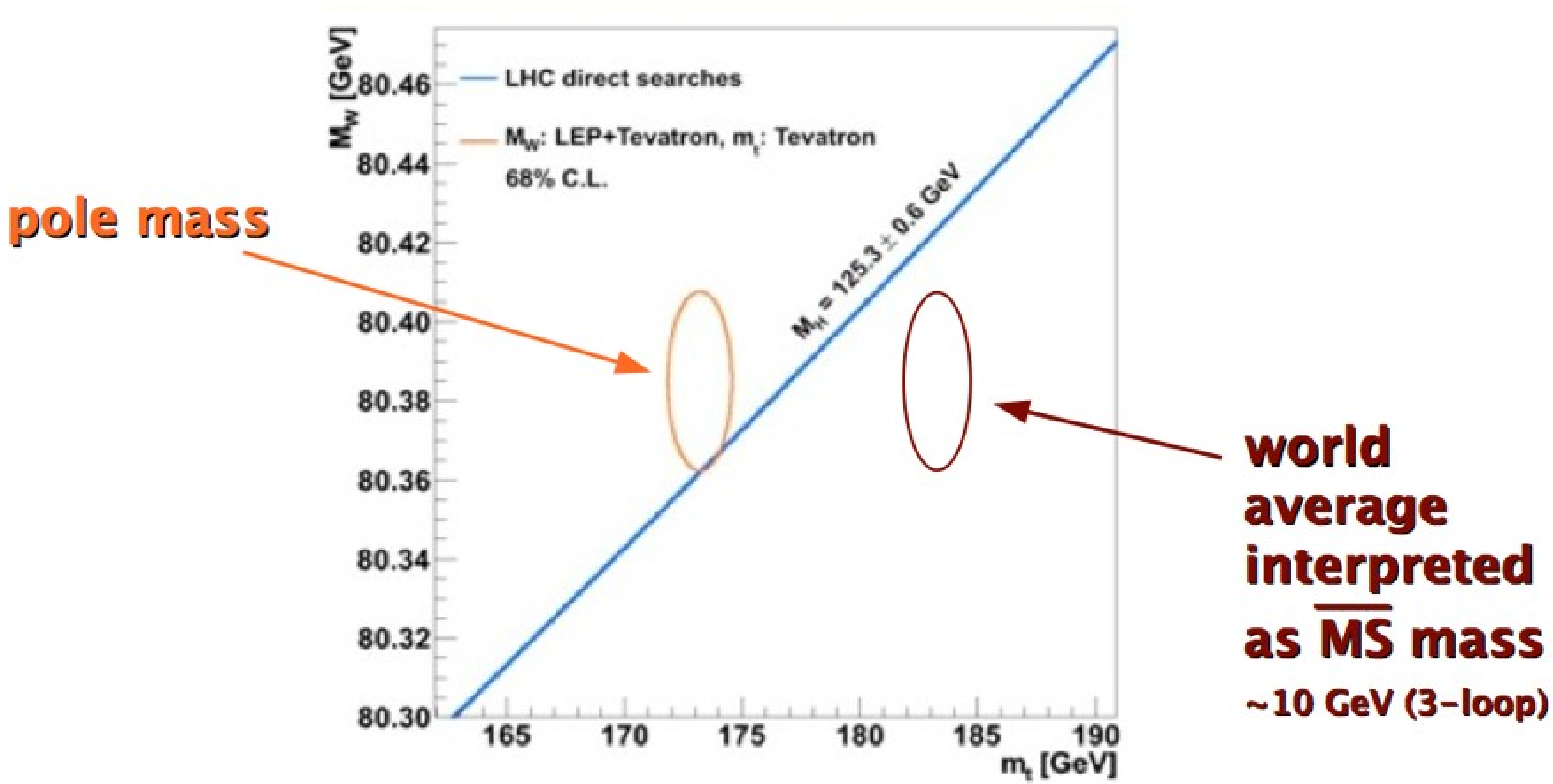
July 2012



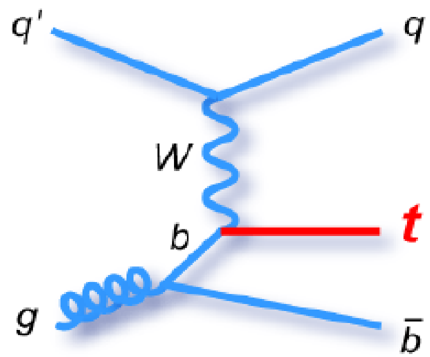
future:
Δ(mW)=15 MeV
Δ(mt)=1 GeV

> improved W mass measurement is critical

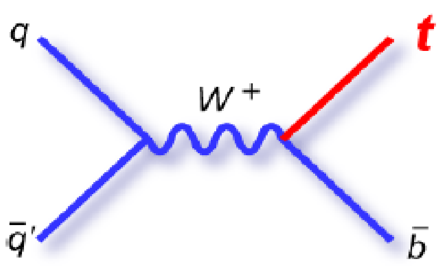
What mass do we measure?



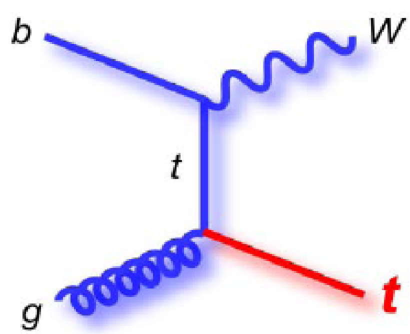
Single Top



t-channel



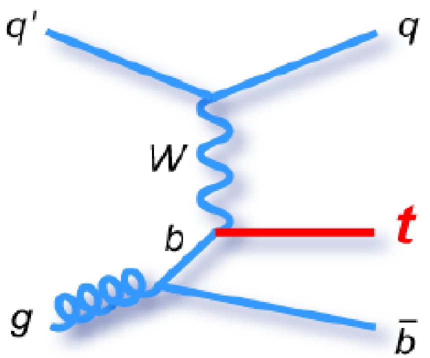
s-channel



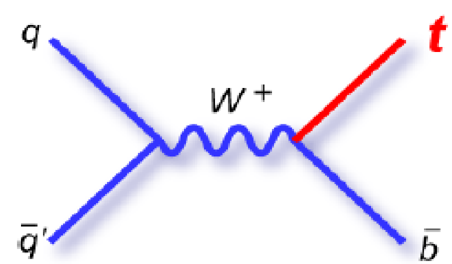
tW-channel

Single top quark production

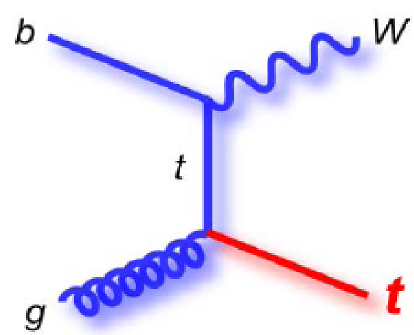
- At hadron colliders top quarks mostly produced in pairs, via strong interaction
- **Single top quarks produced via weak interaction**
- Three main modes:



t-channel



s-channel



tW-channel

Predictions	t-channel (σ_{tqb})	s-channel (σ_{tb})	tW-channel
Tevatron	**2.26 pb**	**1.04 pb**	**0.28 pb**
LHC (7 TeV)	**64.6 pb**	**4.6 pb**	**15.7 pb**

N. Kidonakis, Phys. Rev. D 83, 091503(R) (2011); Phys. Rev. D 81, 054028 (2010); Phys. Rev. D 82, 054018 (2010)

- LHC much more gluons than in Tevatron – different relative rates

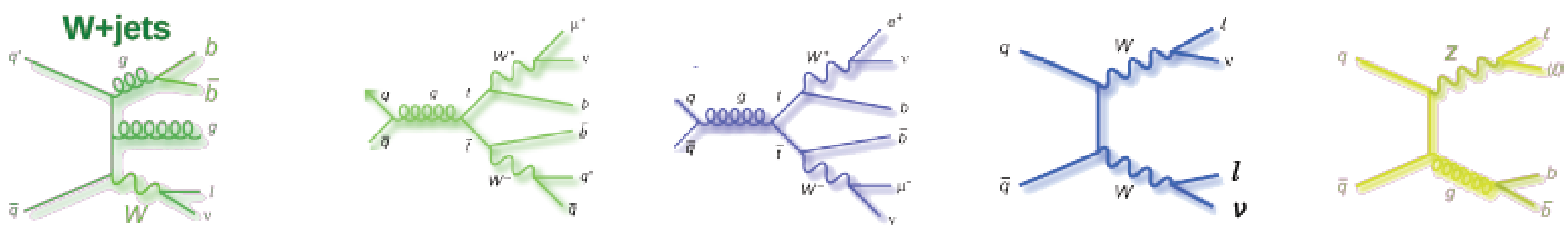
Single Top Quark Production

- Cross section proportional to $|V_{tb}|^2$, test unitarity of CKM
- Sensitivity to b-PDF and u/d-PDF

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Are sensitive to many models of new physics (new particles, FCNC, Anomalous couplings)
- Large backgrounds (W+jets, tt, QCD)

Backgrounds:



W+jets | top quark pairs | Diboson and Z+jets

Single top at a glance

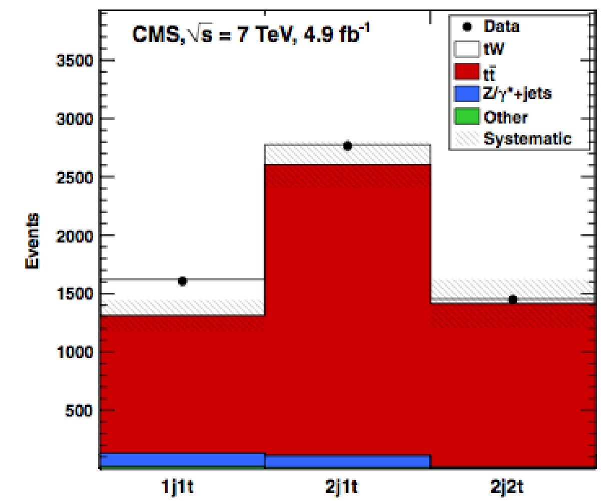
Phys.Rev.D74:114012,2006 http://arxiv.org/abs/1210.7813v2 JHEP 0809:127,2008

σ [pb]	t-channel	tW	s-channel	ttbar
Tevatron (1.96 TeV)	2.26 (±0.12)	0.28 (±0.06)	1.04 (±0.0[illegible])	7.14 (+0.76-0.86)
LHC (7 TeV)	65.9 (+2.1-0.7) (+1.5-1.7)	15.6 (±0.4) (+1.[illegible])	4.56 (±0.07) (+0.18-0.17)	163 (+7-5)(±9)
LHC (8 TeV)	87.2 (+2.8 -1.0) (+2.0 -2.2)	22.2 (±0.6) (±1.4)	5.55 (±0.08) (±0.21)	234 (+10-7)(±12)

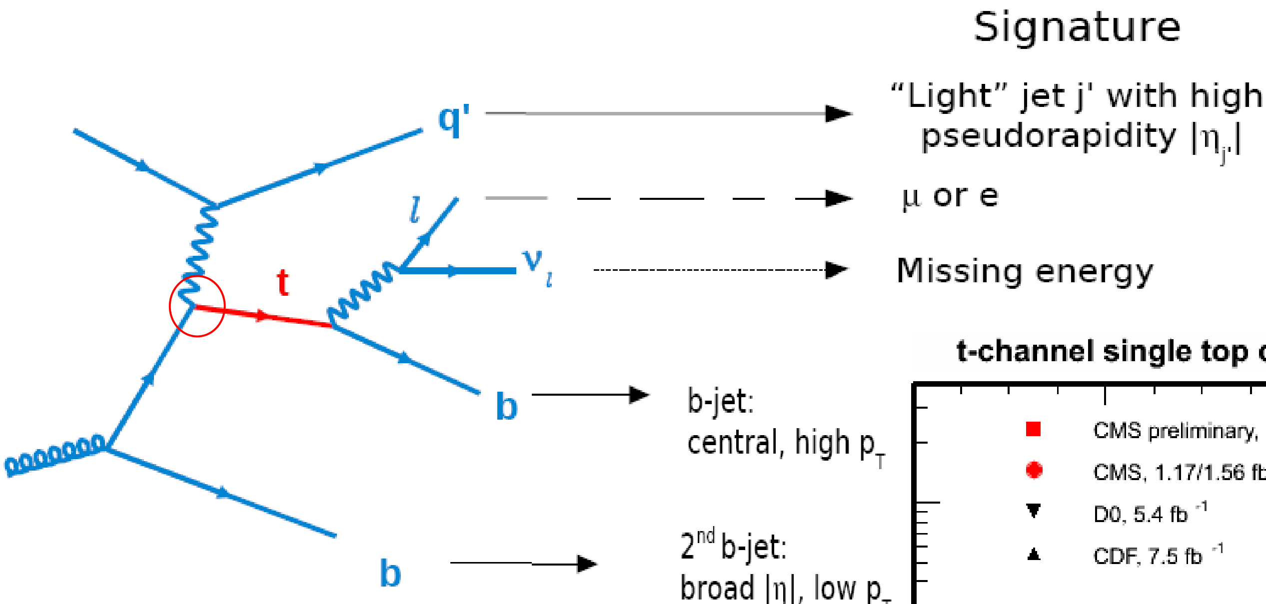
Discovered (t-channel, Tevatron) | Not accesible (tW, Tevatron) | Evidence (s-channel, Tevatron) | Evidence (tW, LHC 7 TeV) | Discovered (t-channel, LHC)

- t-channel has the largest cross-section at the LHC and the Tevatron, discovered and understood at the Tevatron and the LHC (milestone)
- s-channel at LHC: so far upper limit
- tW associated production: ATLAS and CMS reported evidence at 7TeV, CMS reached 4σ with full 7TeV dataset

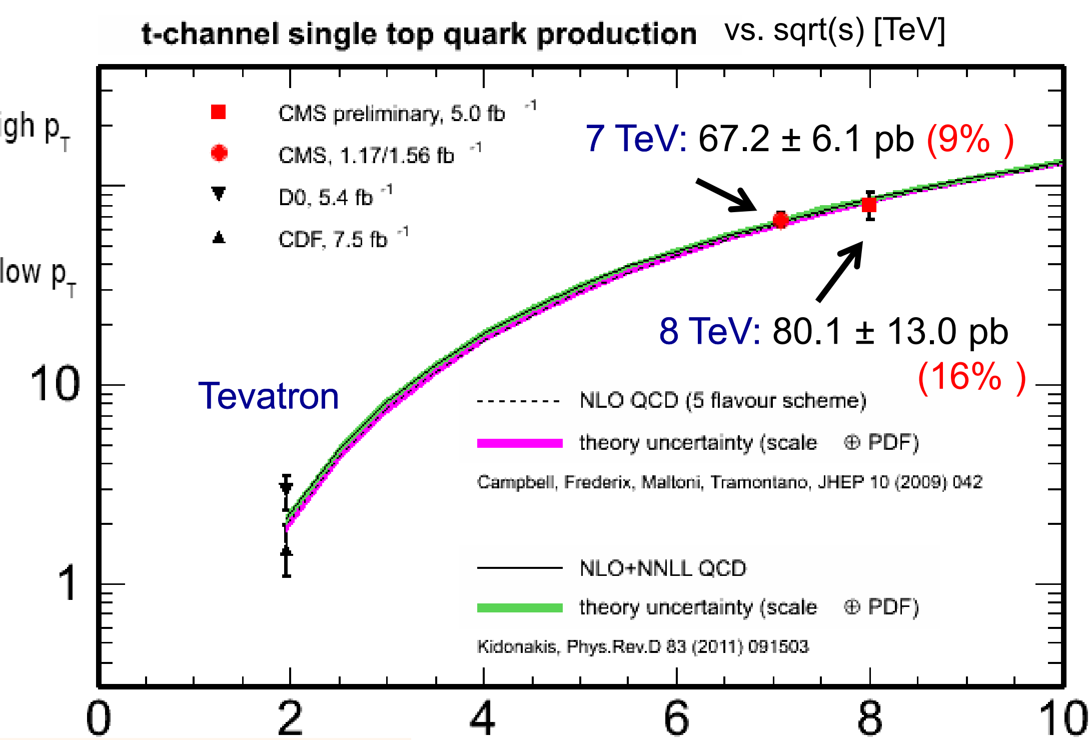
Phys. Rev. Lett. 110, 022003 (2013)



Single Top Observation: t-channel



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



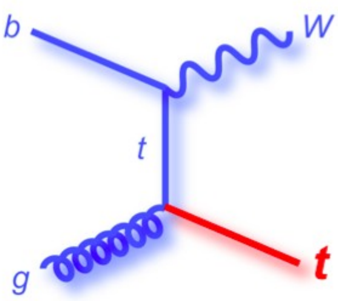
- Typically apply multivariate techniques (NN, BDT) using full event properties to maximize sensitivity

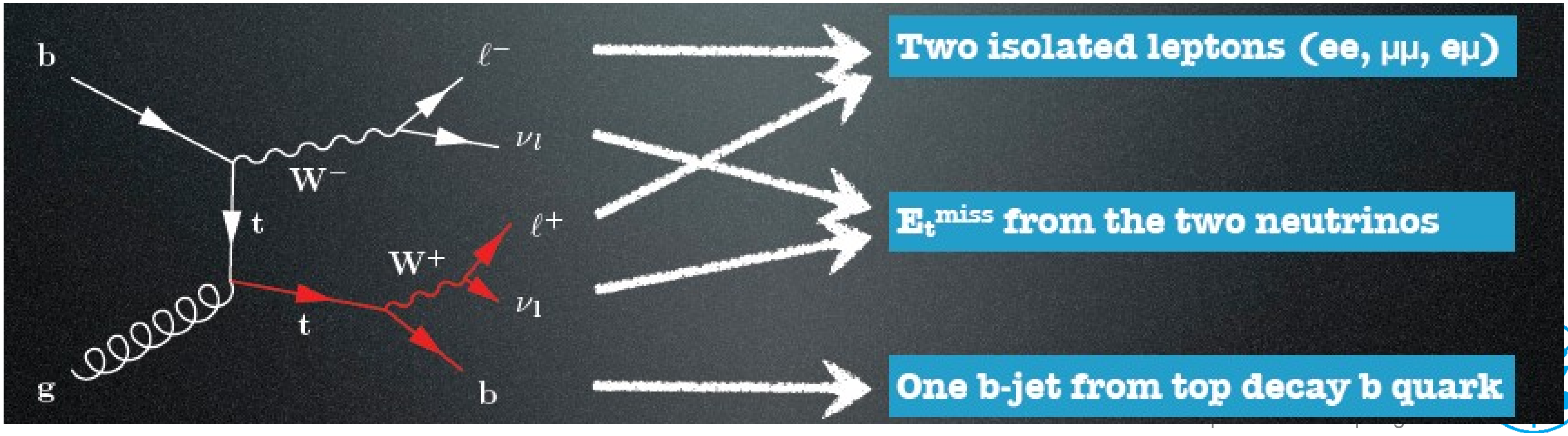
All measurements consistent with SM predictions

JHEP 12 (2012) 035
CMS-PAS TOP-12-011

tW-channel

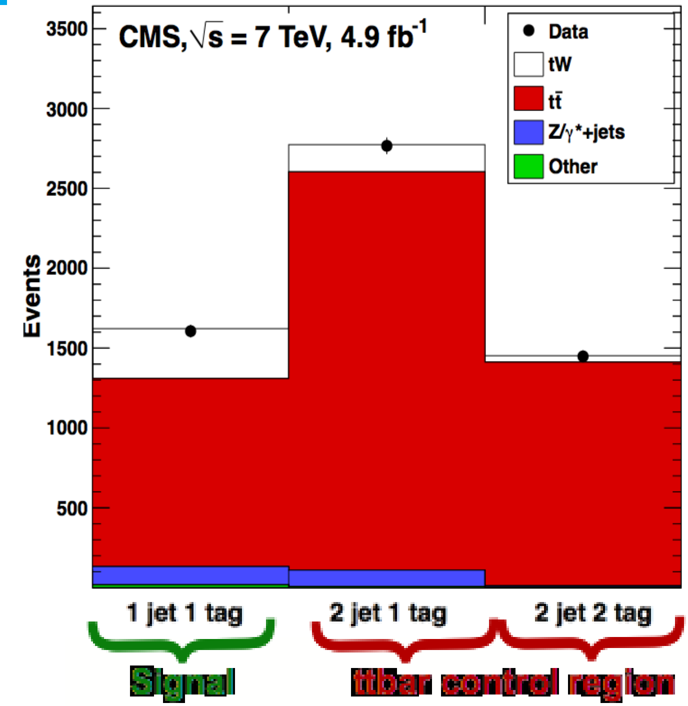
- The tW associated production was never studied before the LHC
- Good/bad news: looks like ttbar; easy to observe, but much ttbar background, small production rate and large backgrounds
- Shares final state with important searches
  - Higgs (HWW), SUSY
- Sensitive to new physics affecting the Wtb vertex (but not to new particles)
- Select dilepton events





Observation of *W-t* associated production

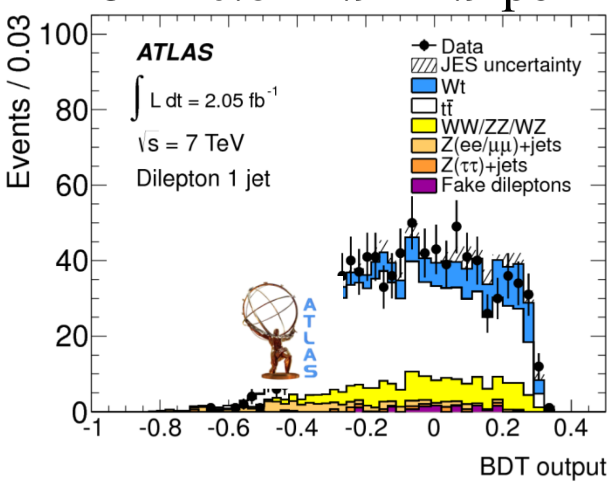
- Cross section from binned likelihood fit to multivariate (BDT) output in signal and sideband regions

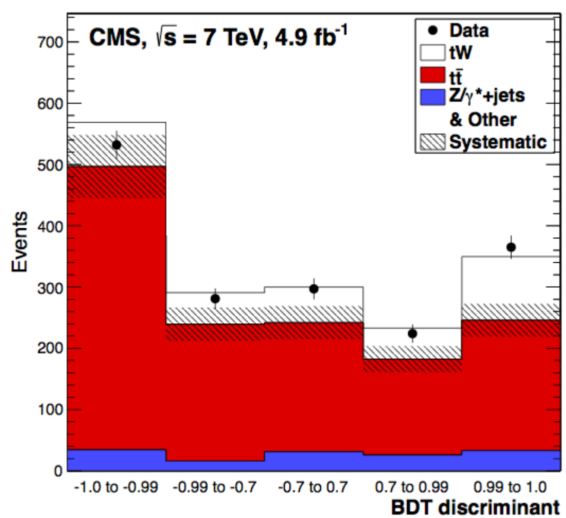


(3.3σ significance)

PLB 716 (2012) 142

$$\sigma = 16.8 \pm 2.9 \pm 4.9 \text{ pb}$$





CERN-PH-EP-2012-266
Submitted to PRL

$$\sigma = 16 \pm^{5}_{4} \text{ pb}$$

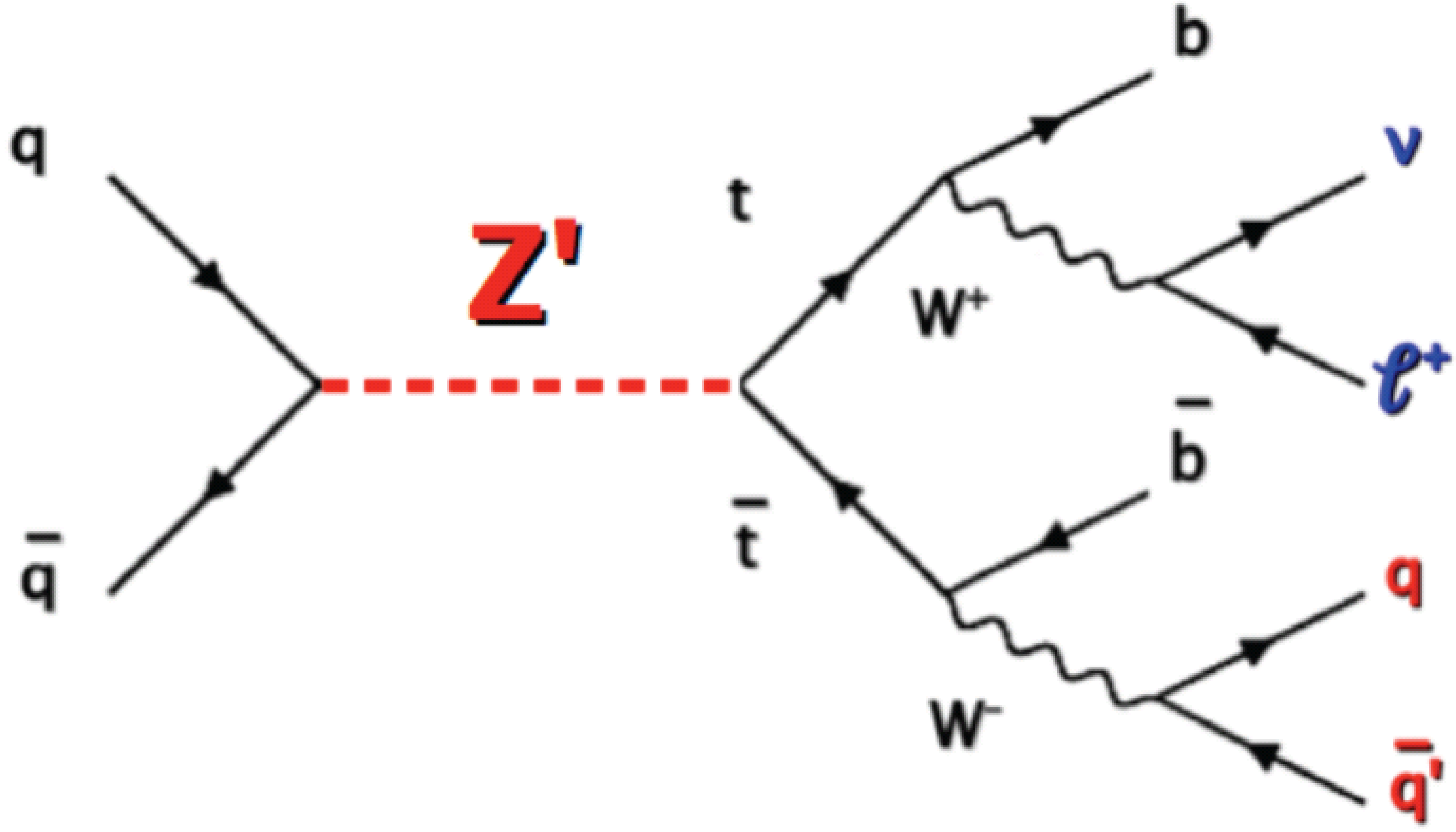
(4.0σ significance)

(6.0σ significance with 8TeV data!)

Searches in Top Production and Decay

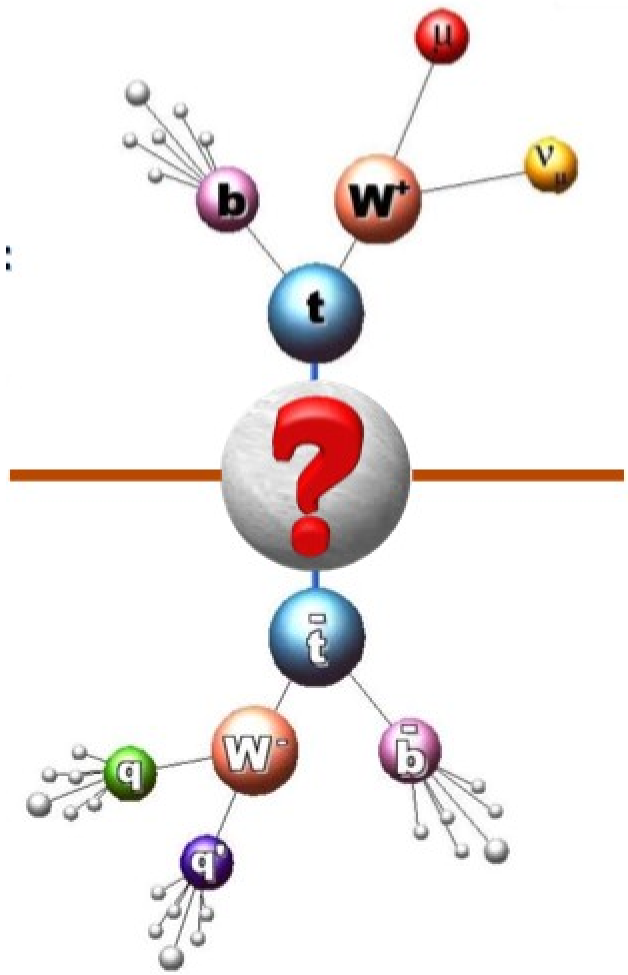
(some examples…)

Searches in Top Production



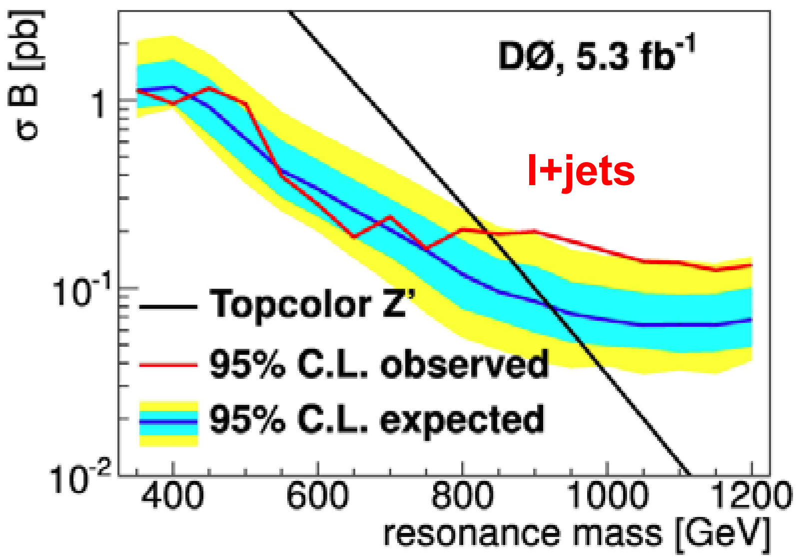
Top quark pair resonance

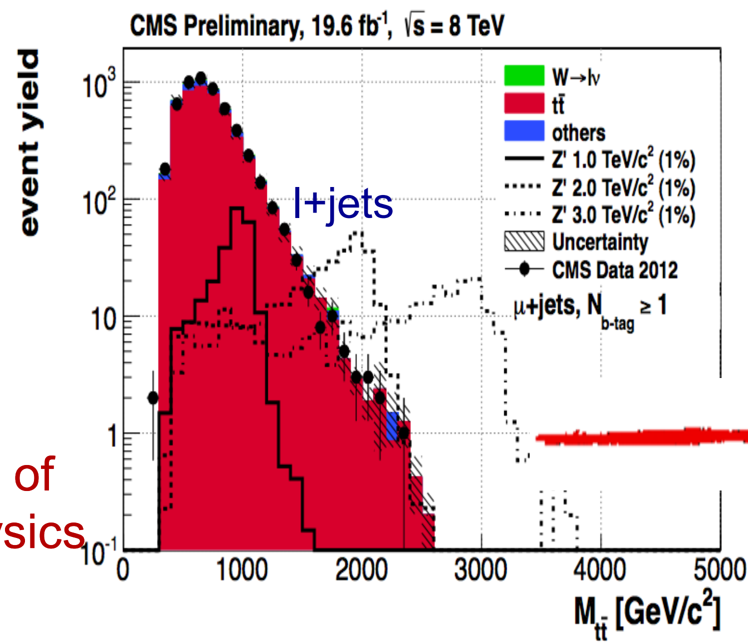
- > No resonance expected in SM
- > Why is Top so heavy?
  - new physics?
  - is third generation ‘special’?
  - couples predominantly to third generation quarks
- > Top is relatively unknown experimentally
- > Experimental check
  - search for a bump in the invariant mass spectrum

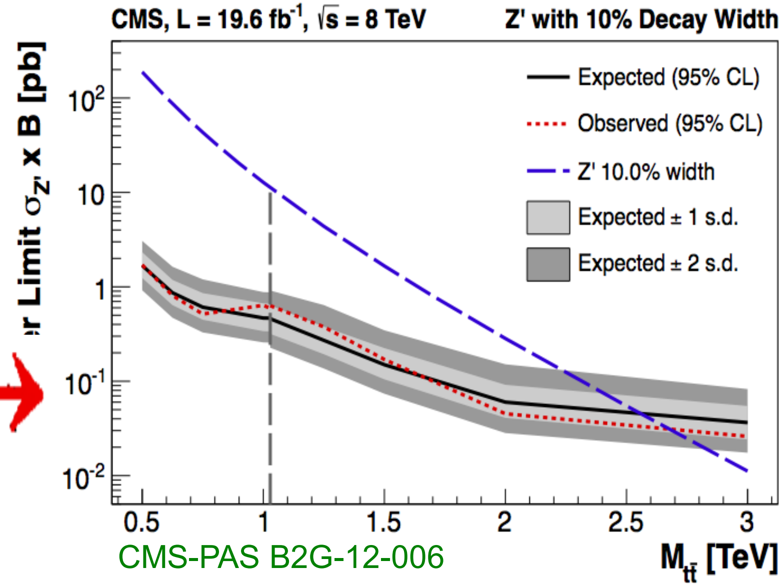


Search for heavy resonances

- Search for massive neutral bosons decaying via a ttbar quark pair
- Presence of new particles decaying into top pairs → distortion in m(tt) spectrum !
- Use dilepton/lepton+jet final states (electron and muon)
- Systematics include shape (JES, b-tag, theory model) and rates (eff. bkg yields)



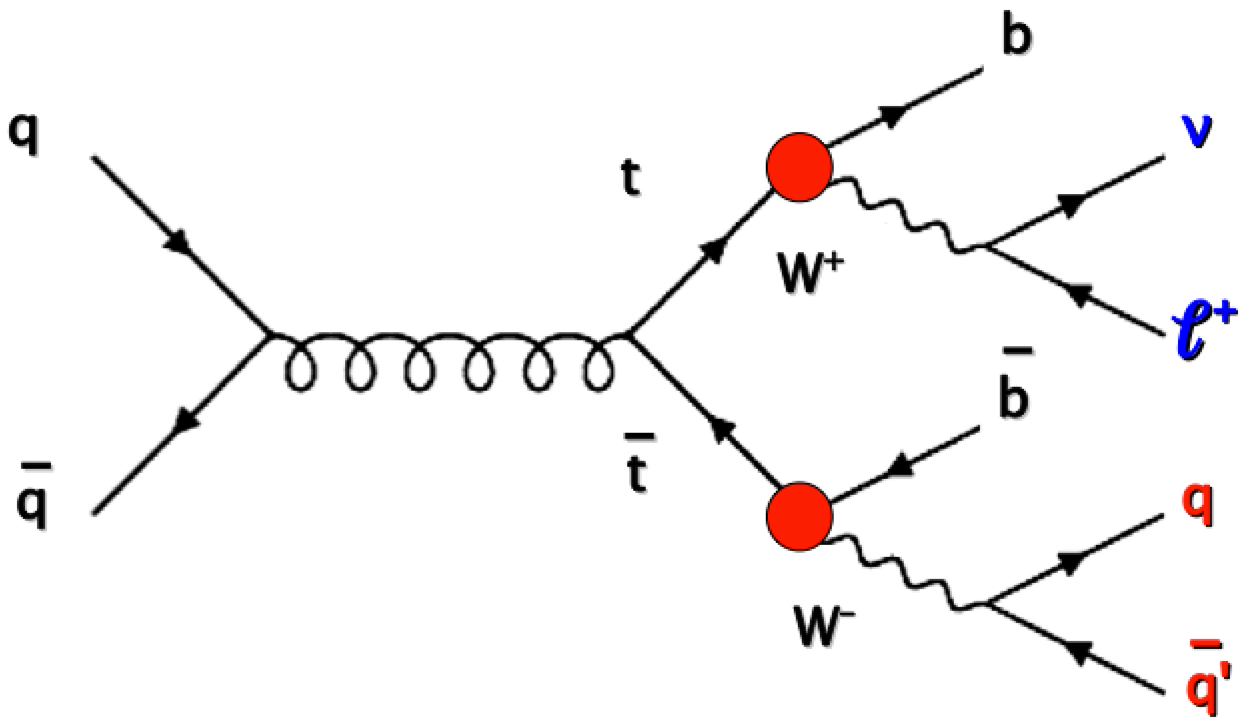




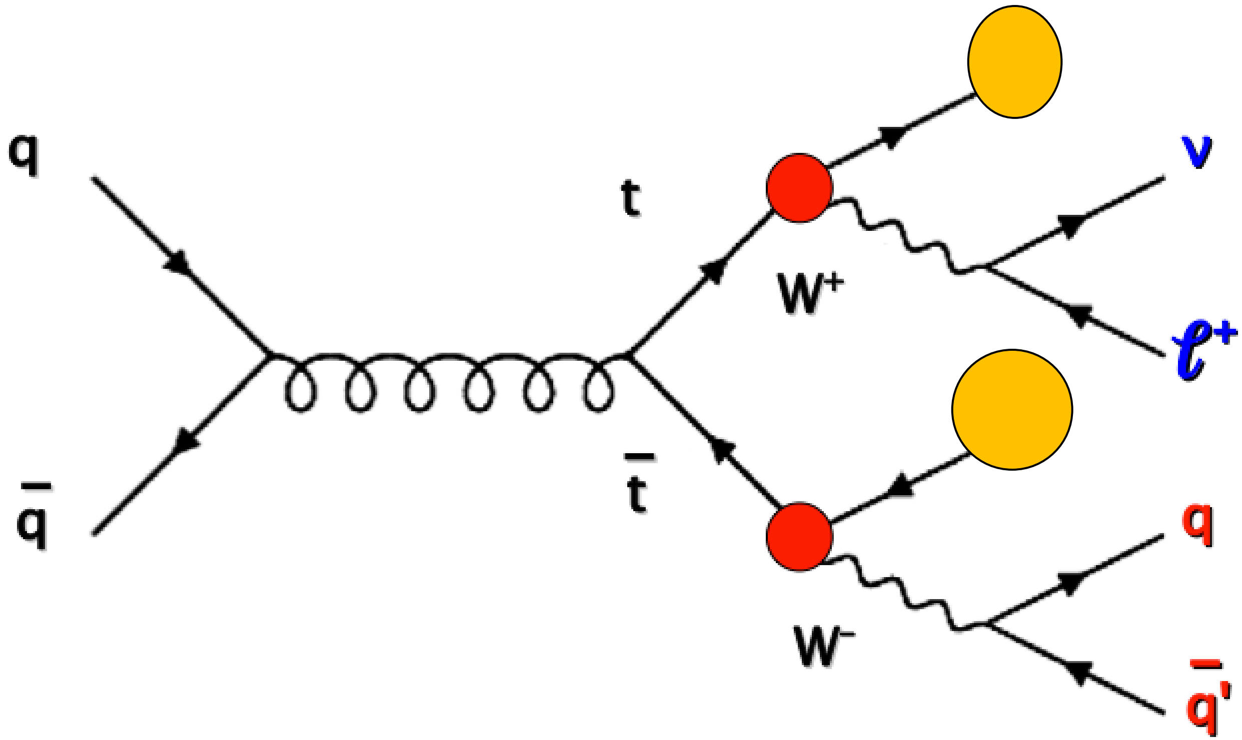
No hints of new physics so far ☹

CMS-PAS B2G-12-006

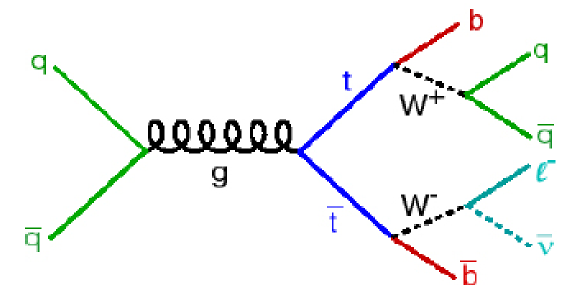
Searches in top decays



Searches in top decays: b disapearence



Top quark decays



top decay t→Wb, but really 100%?

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Indirect measurement using the CKM matrix:
  - Elements |Vub| and |Vcb| measured to be very small from decay of B mesons
  - Unitarity and only three generations implies |Vtb| is 0.998 @ 90% CL
- With top quark samples we can measure it directly as "R":

$$R = \frac{B(t \to Wb)}{B(t \to Wq)}$$

Standard Model:

$$R_{SM} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = |V_{tb}|^2 = 1$$

unitarity of CKM matrix

beyond SM:

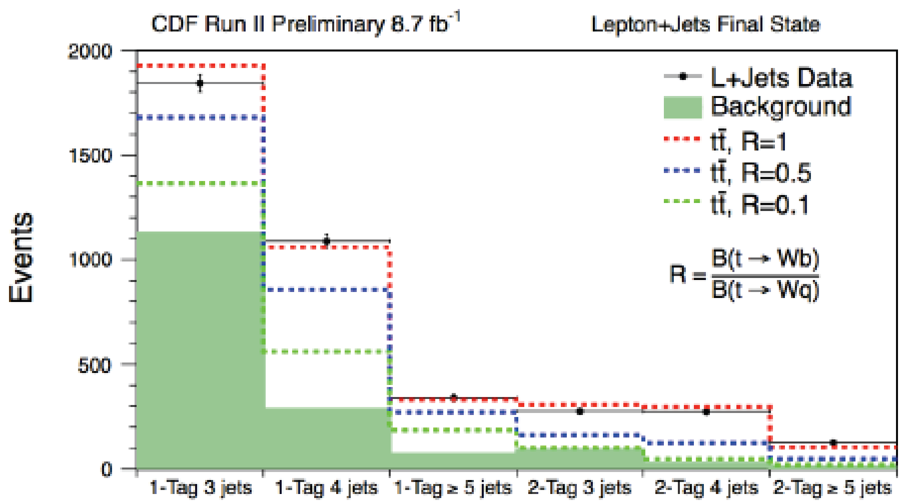
R ≠ 1

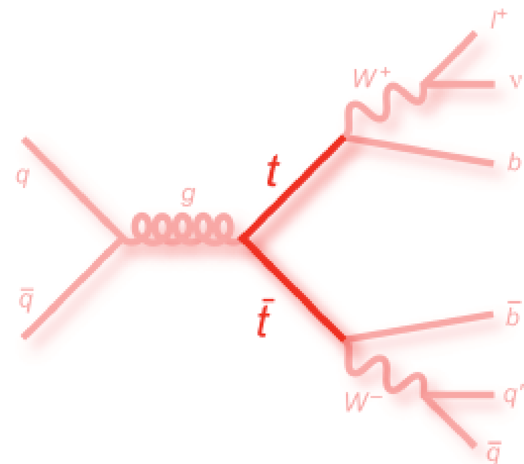
e.g. decay into 4th generation quark: R<1
sensitive to b disappearance

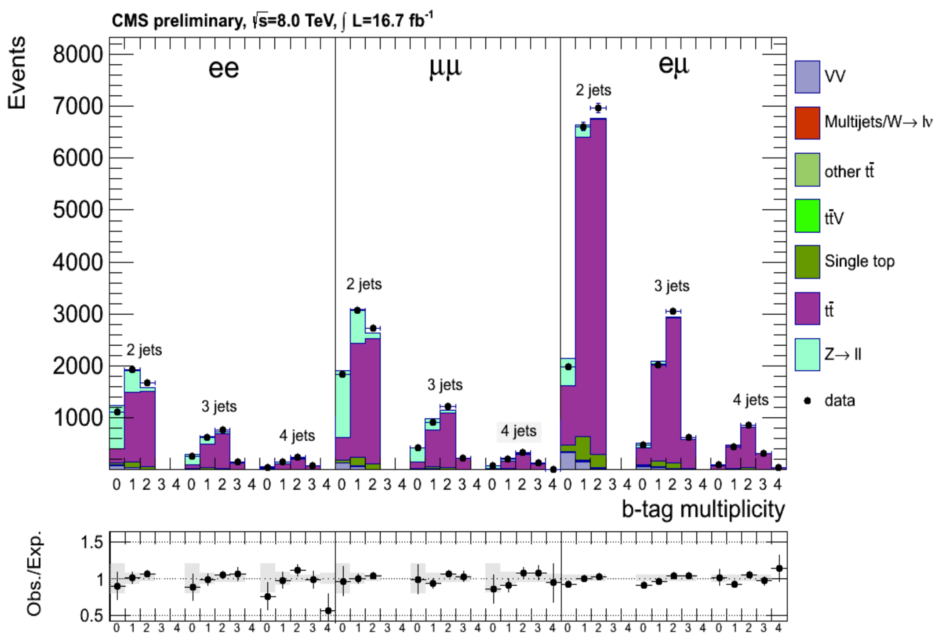
probability

Measuring of branching fractions

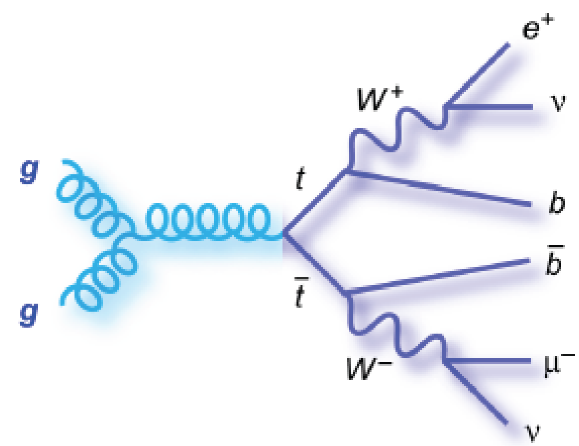
> R changes with the number of “b-tagged jets”





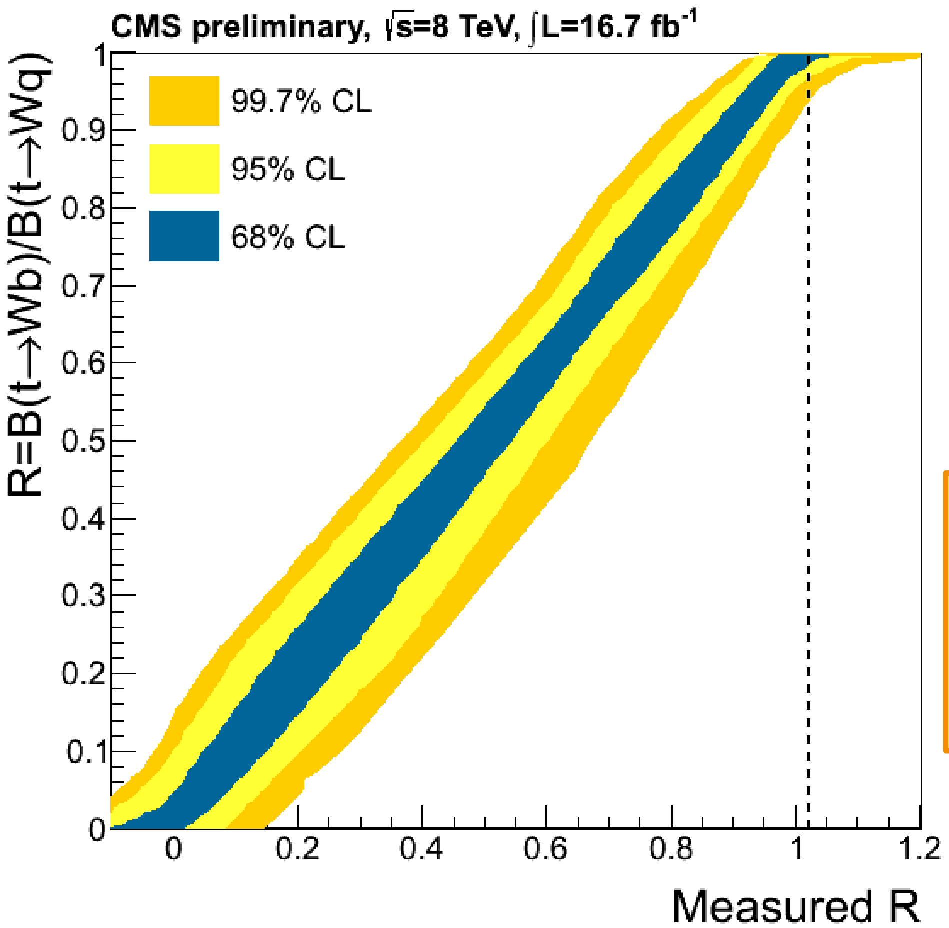


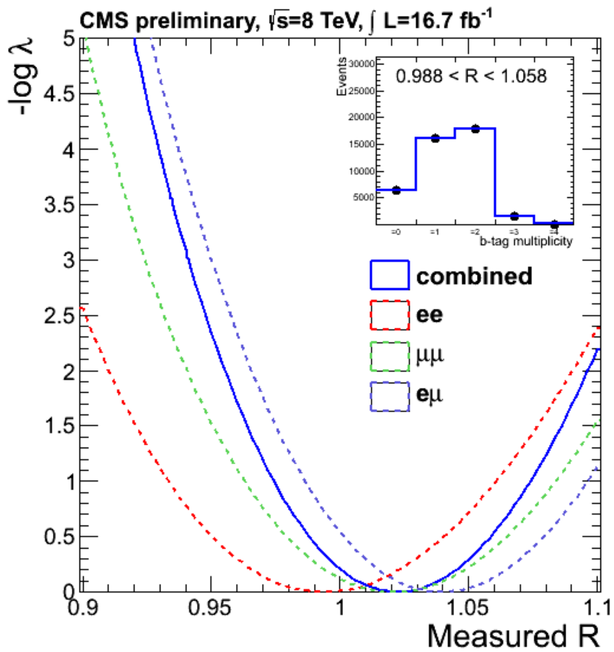
R=1



Measuring of branching fractions

> R changes with the number of "b-tagged jets"



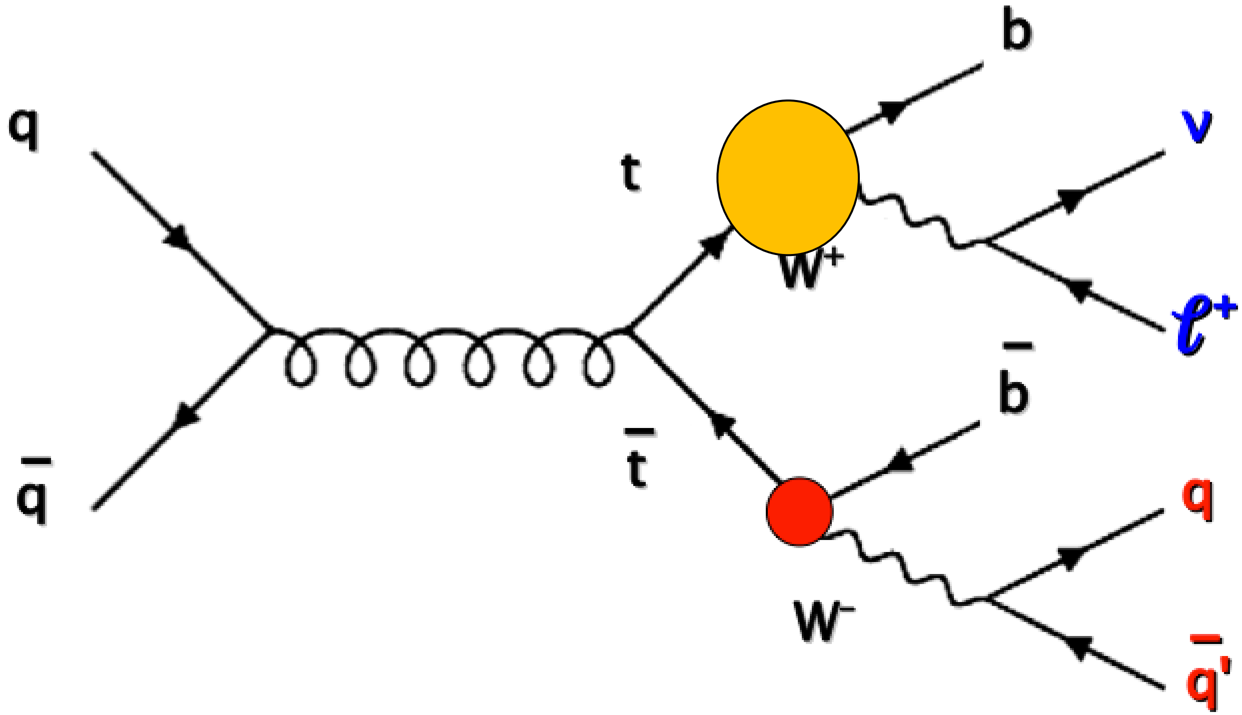


- $R=1.023^{+0.036}_{-0.034}$(stat+syst)

Assuming unitarity of the CKM matrix and its three-generation structure, the matrix element:

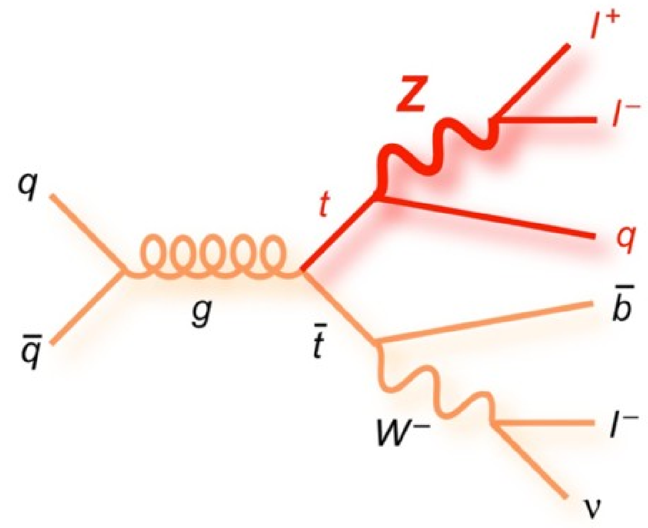
- $|V_{tb}|=1.011^{+0.018}_{-0.017}$(stat.+syst.)

Searches in top decays: W disapearence



Search FCNC in Top Quark Decays (Flavor Changing Neutral Currents)

$$\mathcal{L}_{FCNC} = \frac{e}{2\sin\theta_W \cos\theta_W} \bar{t}\gamma_\mu(v_Z - a_Z\gamma_5)qZ^\mu + h.c.$$



- In the SM flavour changing neutral currents (FCNC) are forbidden at tree level and much smaller than the dominant decay mode ($t \rightarrow bW$) at one loop level
- BSM models predict higher BR for top FCNC decays → powerful probe for new physics

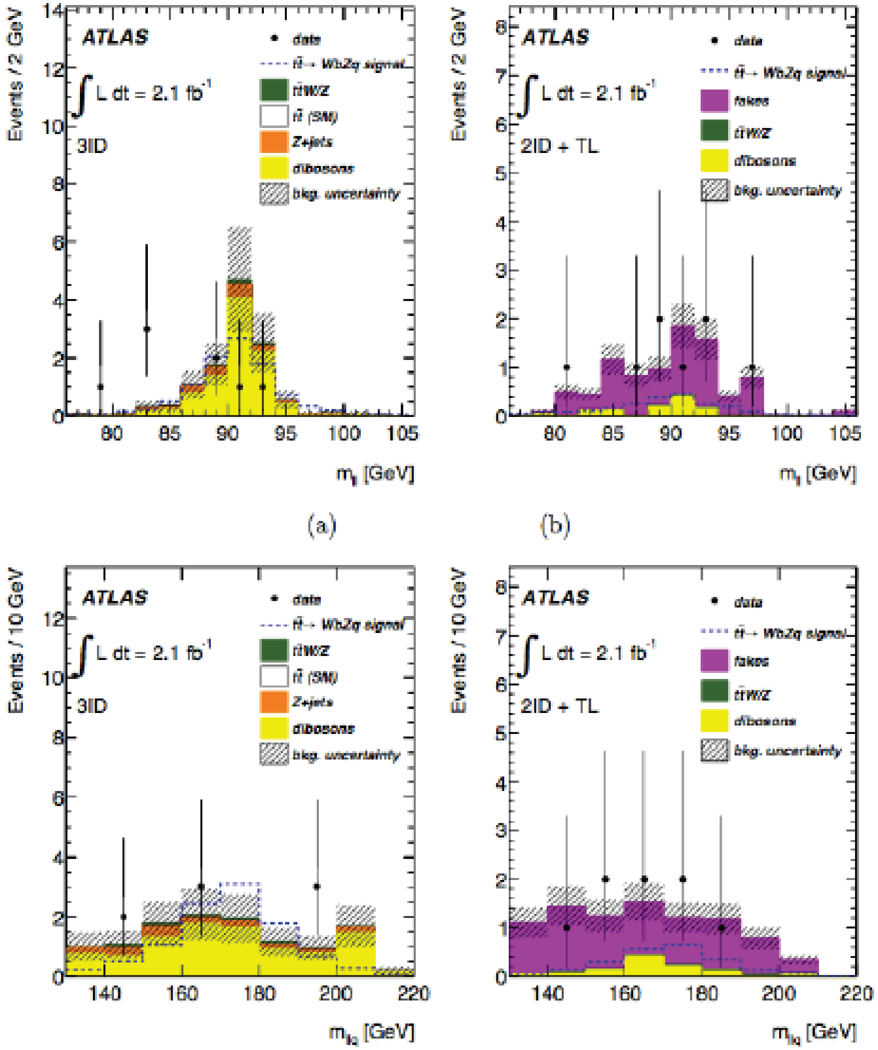
Search FCNC in Top Quark Decays

3 ID selection

- p_T (1st)>25 GeV

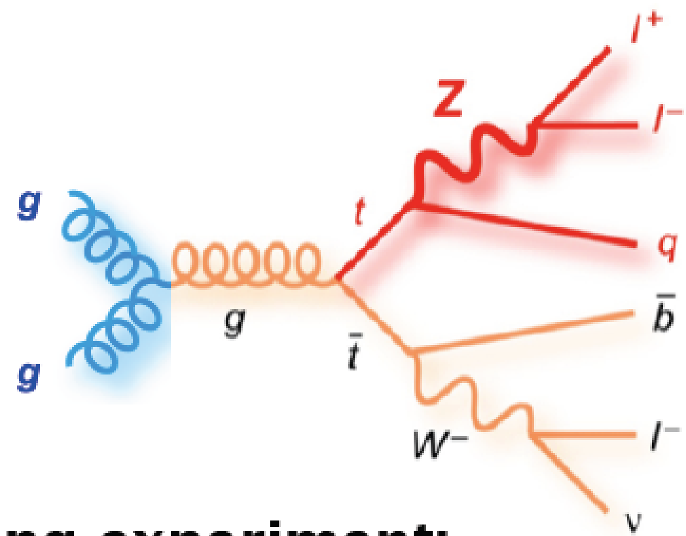
2ID+TL selection

- 2ID + 'track lepton', p_T (TL)>25GeV



$t\bar{t} \longrightarrow qZ\ bW \longrightarrow qll\ bl\nu$

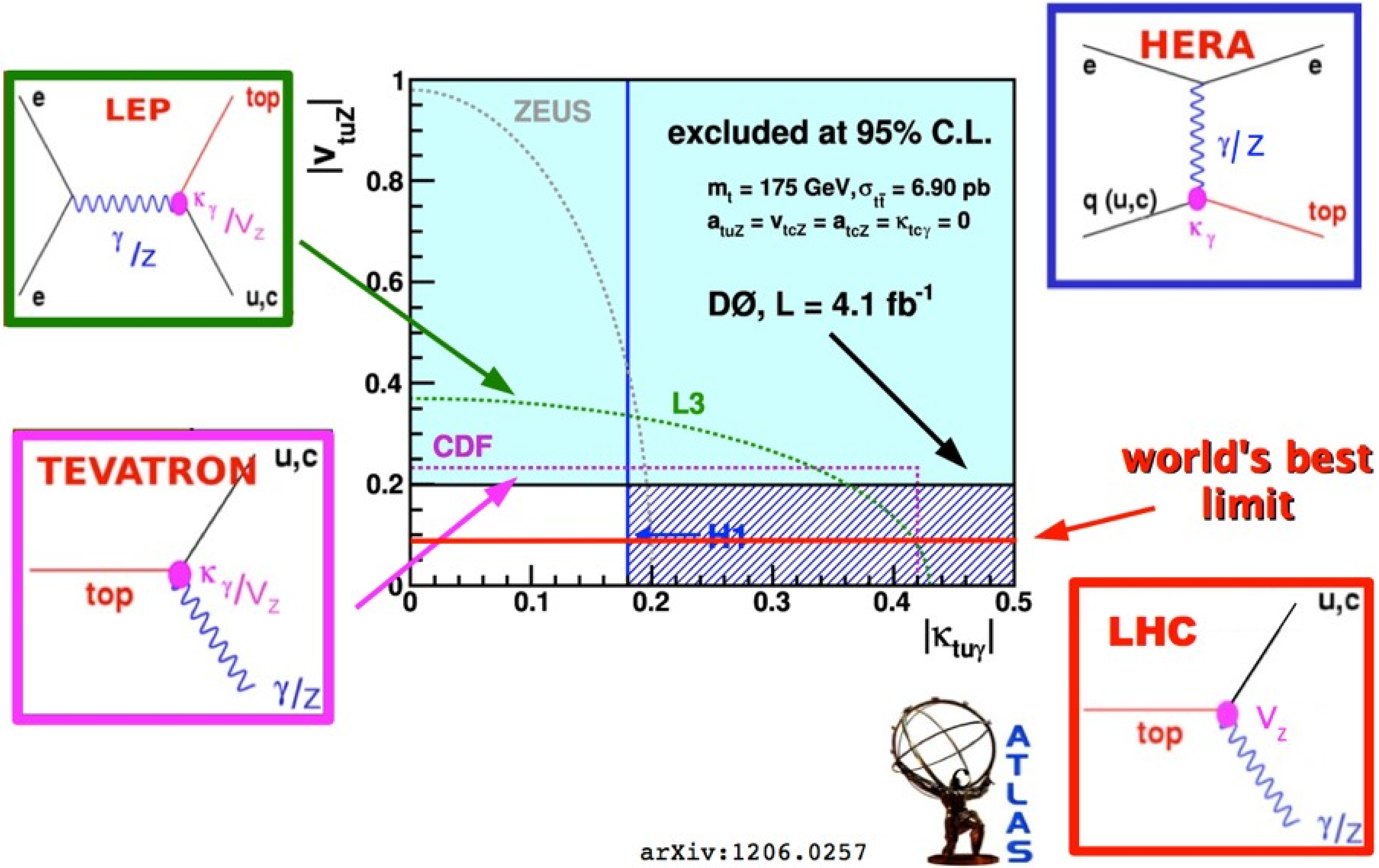
- 3 leptons (p_T > 20 GeV)
- 2 same flavour $|m(l^+l^-) - m(Z)| < 15$ GeV
- E_T^{miss} > 20 GeV, >= 2 jets (p_T>25 GeV)



counting experiment:

B(t→Zq)<0.73% (0.93% expected)

Search FCNC in Top Quark Decays



arXiv:1206.0257

Summary and outlook*

* “We´re nearly done, yeahhh!”

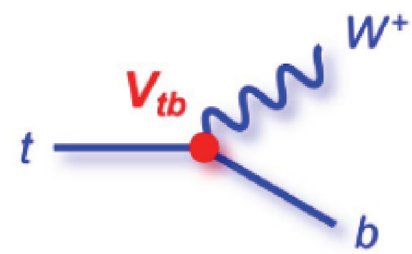
Summary

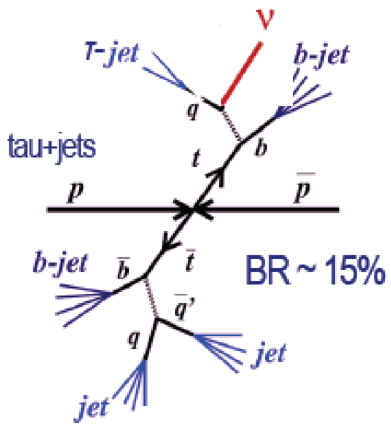
- We are in the middle of the precision top physics era
  - top pair cross section (4% LHC)
  - Vtb (8% Tevatron)
  - top mass (0.5% Tevatron, 0.8% LHC)
  - differential cross sections
- New processes: t-channel single top (observation), Wt (evidence), ttZ (evidence), …
- New properties: spin correlations (observation), top polarisation, color flow, jet veto, ...
- Many stringent searches for new physics

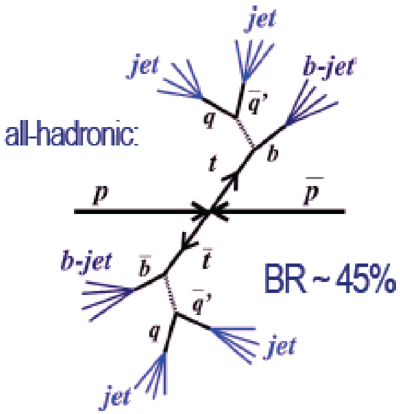
→ good agreement with SM
→ tremendous success of the whole field

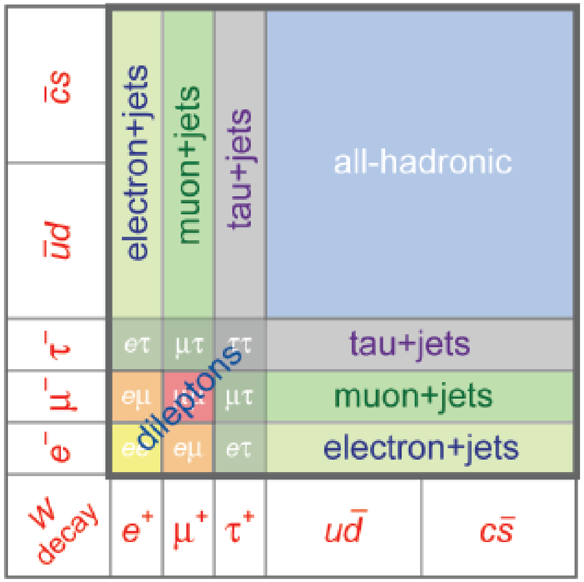
Back up

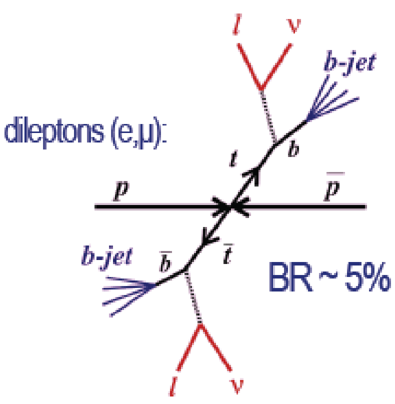
$t\bar{t}$ Event Signatures

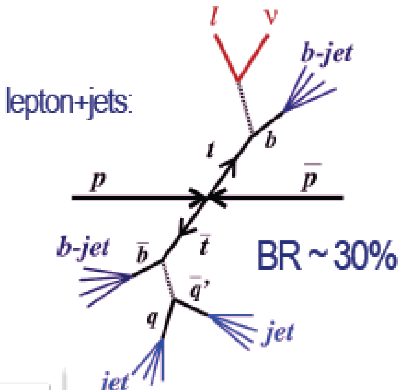












All experiments have measured $t\bar{t}$ in all decay channels (except $\tau\tau$)