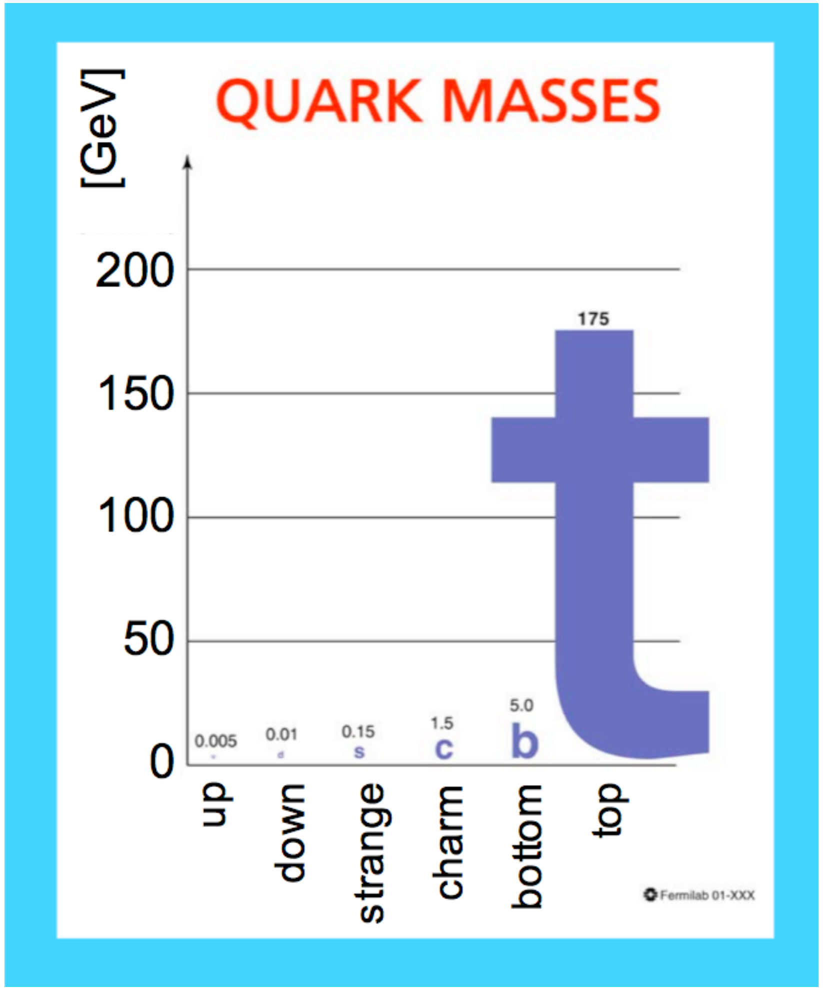
TOP

The sixth guy stands up !

- The up-like quark of the third family, the top quark, has **a mass comparable to a tungsten atom** !
- In other words, **the top – Higgs Yukawa coupling is large (≈1)**:
    - *top is a window to electroweak symmetry breaking*

$$Y = \sqrt{2}\,\frac{m_{top}}{\text{v.e.v.}(\sim 246\ \text{GeV})}$$

$$\Gamma(H \to f\bar{f}) = \frac{N_c g^2 m_f^2}{32\pi m_W^2}\beta^3 m_H$$

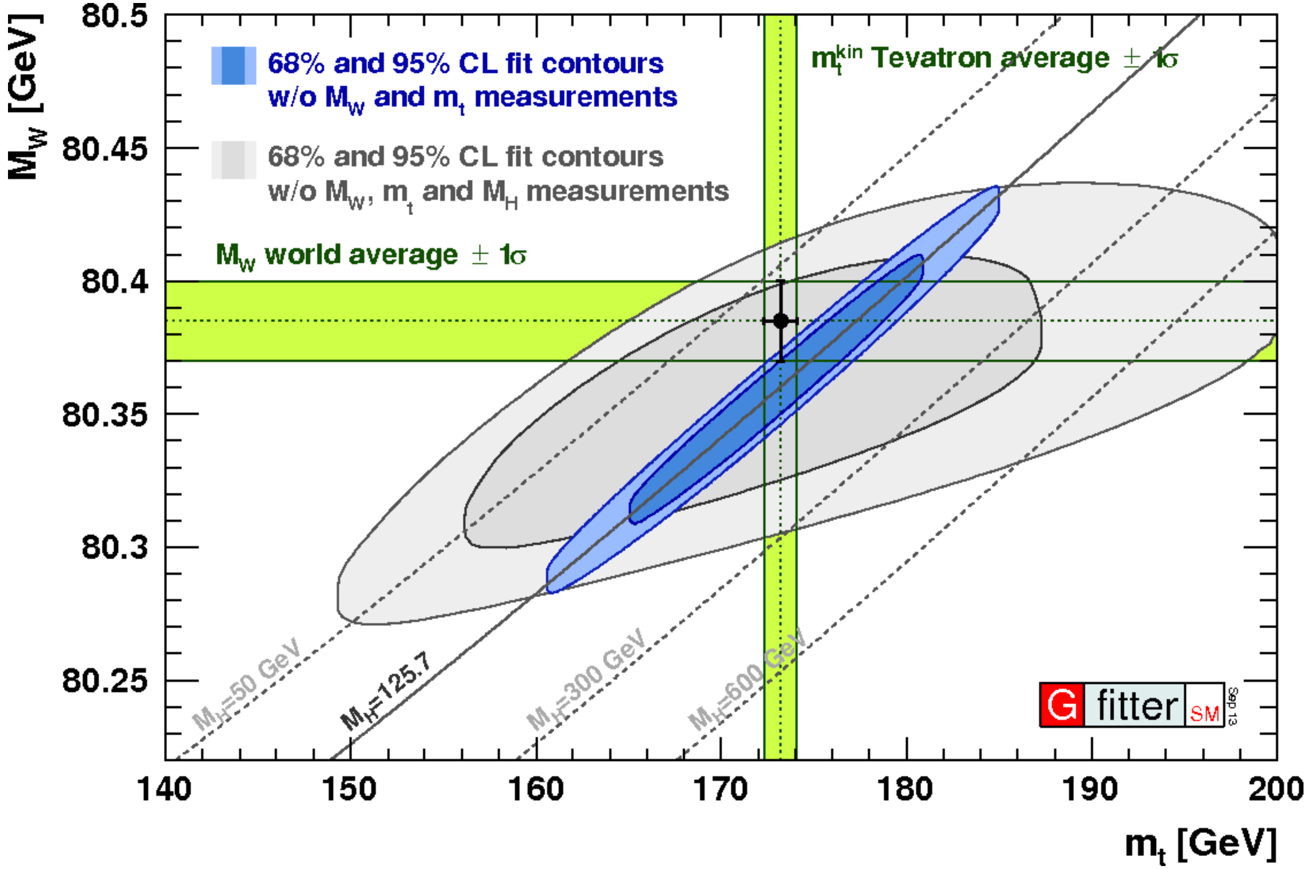


Some consequences of the large top mass (the large top-Higgs Yukawa coupling)

- Due to the non-decoupling properties of electroweak interactions (Veltman, 1977) the top quark gives large contributions to pure EWK radiative corrections $\approx G_F m_t^2$
- Very short lifetime: bound states are not formed, opportunity to study a free quark

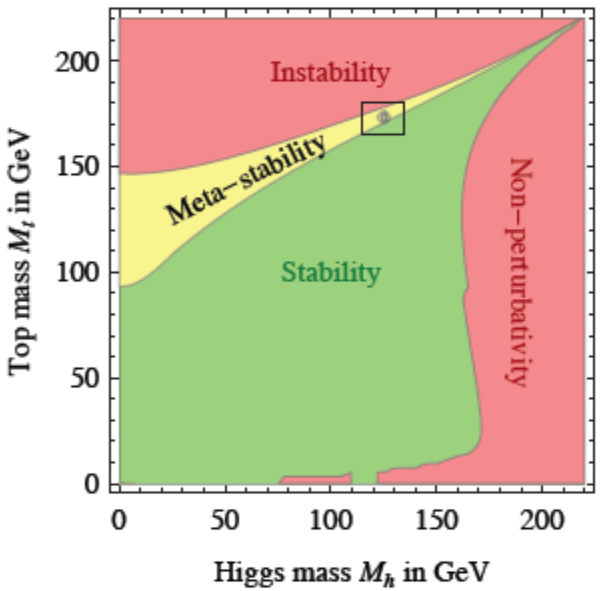
$\tau_{top} \simeq 0.4 \times 10^{-24}\, s$

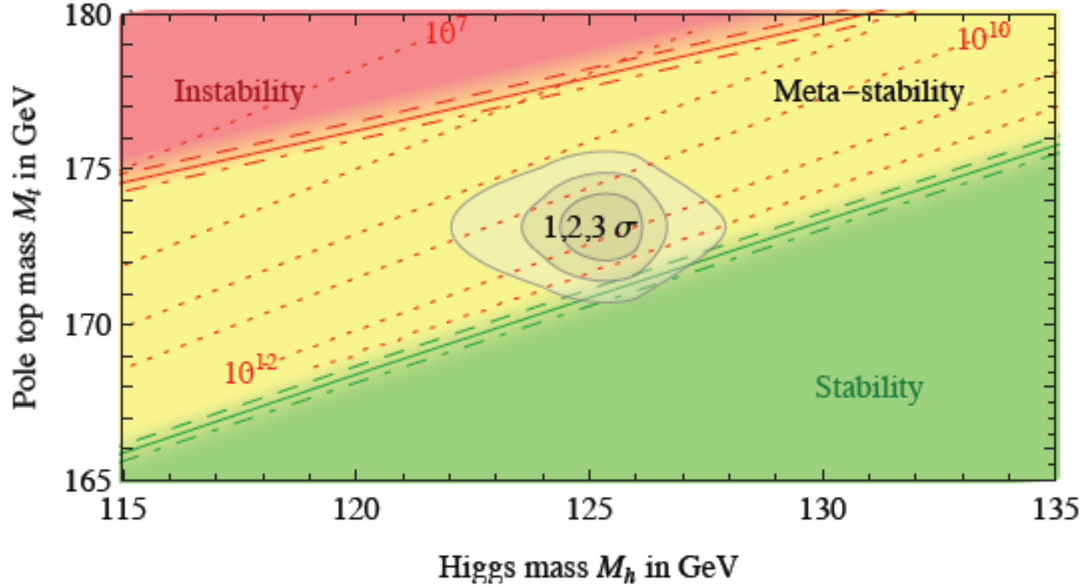
$$\Gamma(t \to bW) = \frac{G_F}{8\pi\sqrt(2)} m_t^3 |V_{tb}|^2 \approx 1.5\,\mathrm{GeV/c^2}.$$


68% and 95% CL fit contours
w/o M_W and m_t measurements
68% and 95% CL fit contours
w/o M_W, m_t and M_H measurements
M_W world average ± 1σ
m_t^kin Tevatron average ± 1σ
M_H=50 GeV
M_H=125.7
M_H=300 GeV
M_H=600 GeV
G fitter SM
Sep 13
M_W [GeV]
m_t [GeV]
80.5
80.45
80.4
80.35
80.3
80.25
140
150
160
170
180
190
200

Relation between top and Higgs masses and stability of the vacuum in our universe

Electroweak Vacuum → $V = \frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda(scale)\Phi^4$



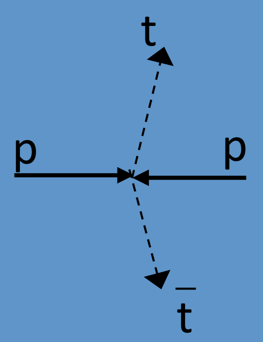


De Grassi et al. ArXiv:1205.6497

TOP PRODUCTION AND DECAY: GETTING THE DATA SAMPLES

Top Quark Production at the LHC

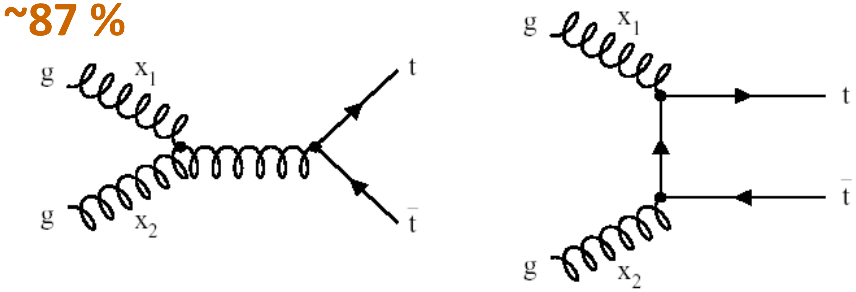
top pairs

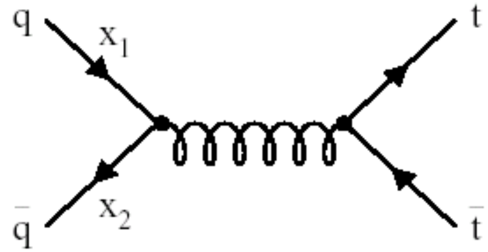


10 tt pairs per day @ Tevatron → 1 tt pair per second @ LHC

qq →tt : 85% *gg→tt : 87%*

~87 %

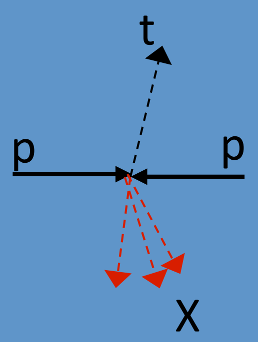




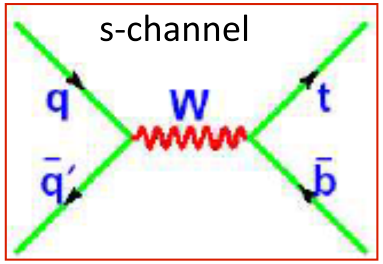
❖ NLO cross-section σ^{NLO} = **232** pb at 8 TeV ~2 M events/10fb^{-1}

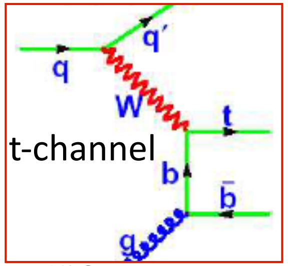
Some references (not a complete list!): (top pairs) N.Nason *et al.* Nucl.Phys. B303 (1988) 607, S.Catani *et al.* Nucl.Phys. B478 (1996) 273, M.Beneke *et al.* hep-ph/0003033, N.Kidonakis and R.Vogt, Phys.Rev. D68 (2003) 114014, W.Bernreuther et al. Nucl.Phys. B690 (2004) 81-137 (single-top) T.Stelzer et al. Phys.Rev. D56 (1997) 5919, M.C.Smith and S.Willenbrock Phys.Rev. D54 (1996) 6696, T.M.Tait Phys.Rev. D61 (2000) 034001

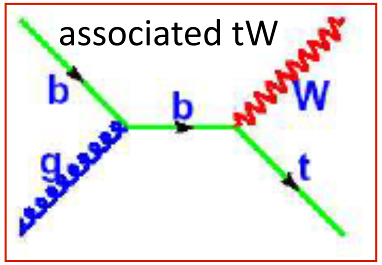
single-top



30 single-tops per minute @ LHC







σ^{NLO} = 3.4 pb σ^{NLO} = 53 pb σ^{NLO} = 11 pb →top production

σ^{NLO} = 2.1 pb σ^{NLO} = 30 pb σ^{NLO} = 11 pb →anti-top production

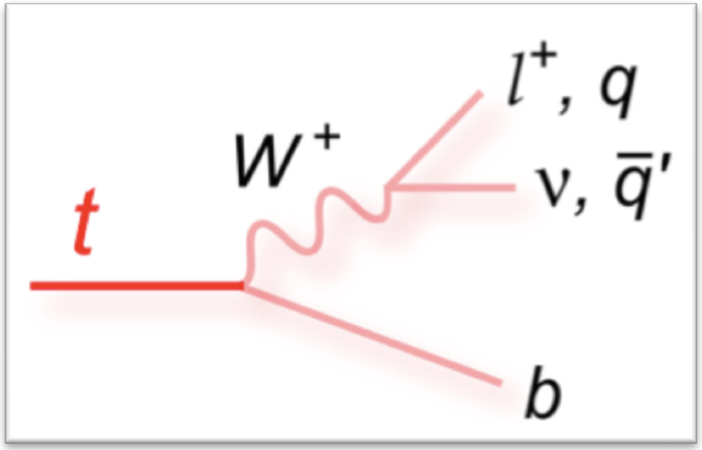
σ_{top} & $\sigma_{anti\text{-}top}$ not equal

σ^{NLO}(total) 8 TeV = **112** pb

~1 M events/10fb^{-1}

Top Quark decays

It decays almost excusively to Wb, from CKM elements V_{tu}, V_{ts}, V_{tb} :



$$\frac{BR(t \to Wb)}{BR(t \to Wq)} \approx 0.99825 \pm 0.00005$$

$$BR(t \to cZ, c\gamma, cg) \approx O(10^{-33})$$

W decays are used to classify top final states

Decay topologies for ttbar :

- Dileptonic
- Lepton+jets
- Fully hadronic

For single top measurements only W leptonic decays are used

ttbar topologies

Lepton + jets ≈ 34%

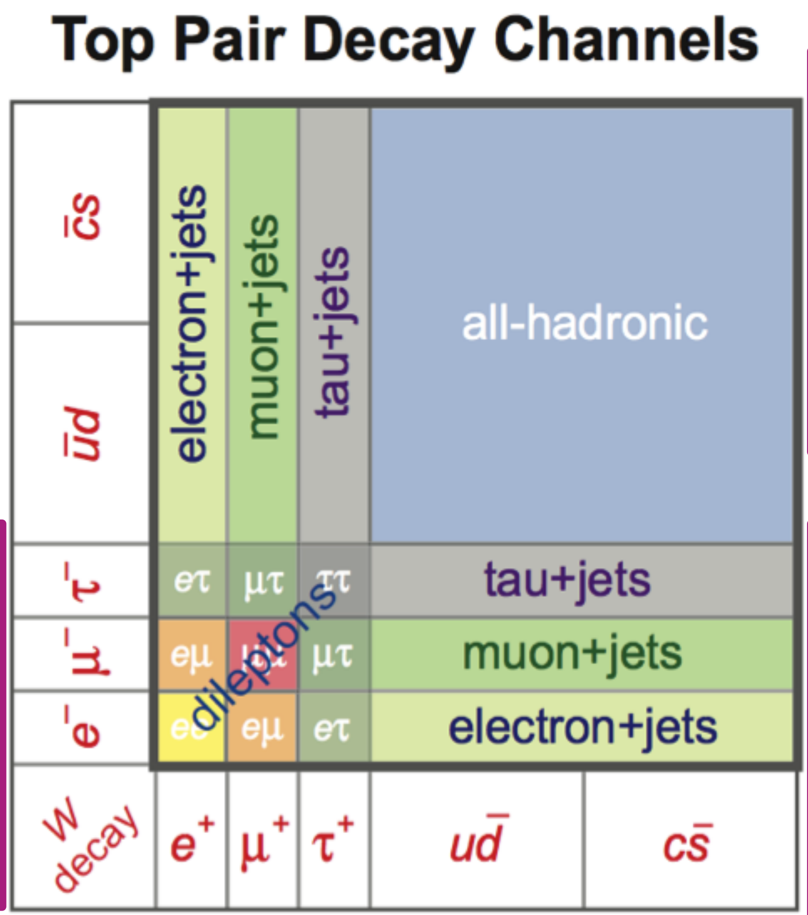
Low background

Main background:
W + jet

Dileptonic ≈ 6%

Very low background

main background:
Drell-Yan



Fully hadronic ≈ 46%

important background
from QCD multijet
events

Tau channels ≈ 14%

Important background
from W + jet, QCD,
other ttbar decays

Statistics with 20 fb-1 at 8 TeV

Channel	σ (NLO)	BR	Trigger eff	# Events
ttbar SL e mu	232	0.3	0.8	1 090 000
ttbar SL tau	232	0.15	0.5	340 000
ttbar DL (e, mu)	232	0.053	0.9	220 000
ttbar DL 1 tau	232	0.053	0.8	200 000
single top t-ch e mu	83	0.22	0.7	250 000
single top s-ch e mu	45.5	0.22	0.7	17 000
single top tW e mu	23	0.22	0.7	70 000

- **Typically two orders of magnitude more than final Tevatron statistics**
- Selection efficiencies not included !
- Trigger efficiency, **guesstimates** from present tables ... **(fully hadronic not included)**

EXPERIMENTAL METHODS FOR TOP MASS MEASUREMENTS:

- EXAMPLES IN THE LEPTON+JETS CHANNEL

- WHAT ARE WE MEASURING ?

- ALTERNATIVE METHODS

- DIFFERENTIAL TOP MASS

Methods for top mass measurement (1)

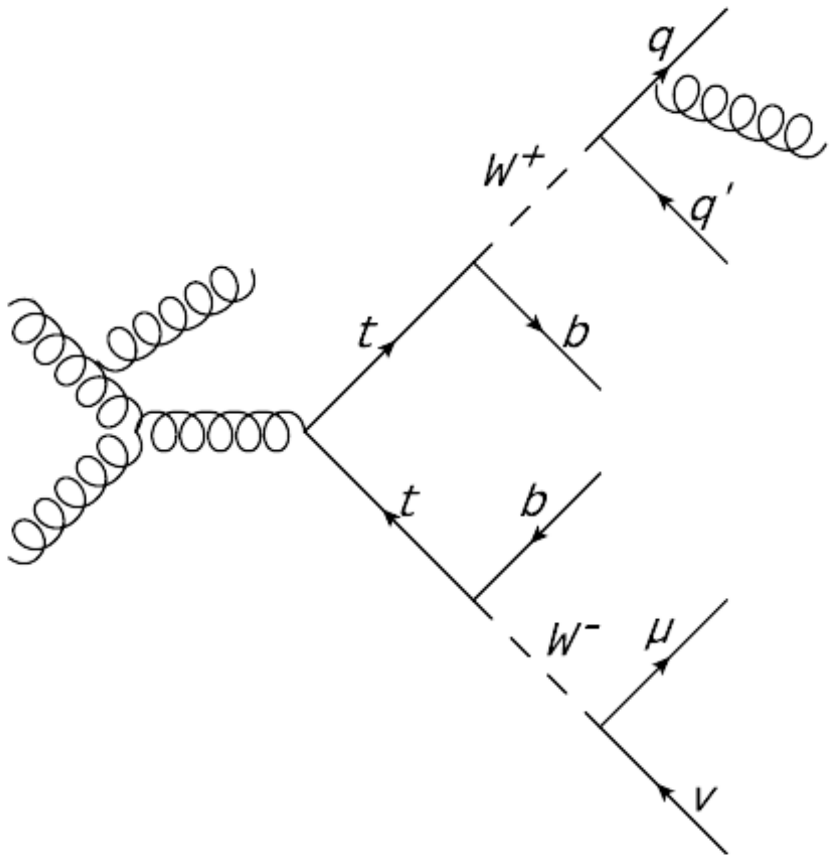
- *Standard methods* at hadron colliders: measure the top mass from the decay products in a specific **top pair decay channel**
  - from the simplest versions: measure invariant mass of, e.g. three jets in lepton+jets events
  - to the more sophisticated versions: use of the full event information to gain sensitivity, e.g. Matrix Element method
- The *standard methods* are the most precise with the current statistics
  - they are used in current LHC, Tevatron, World combinations
  - the top mass in EWK fits comes from these methods
- Crucial points for the *standard methods*
  - accurate calibration of physics objects, in particular Jet Energy Scale: use of kinematic fits for JES calibration in situ, e.g. use the W mass to constraint light quarks **jet energy scale (JES)** from two-jet invariant mass
  - associate measured objects (jets, leptons, missing E_T) to top candidate: e.g. use b-tagging to choose the right b-jet for the 3-jet combination

A couple of examples from the lepton+jets channel

Event selection: lepton+jets final state

[example from CMS, TOP-14-001 / JHEP 12 (2012) 105]

- Trigger for isolated muon or electron + jets (pT > 33 GeV)
- Exactly 1 isolated lepton with p_T >30 GeV, $|\eta|<2.1$ (veto additional isolated e, μ)
- ≥ 4 "particle flow" jets (anti-kt , R = 0.5) with p_T >30GeV, $|\eta|<2.4$
- 2 jets b-tagged among the 4 leading jets
- Composition:
  - 94% $\bar{t}t$, 2% W+jets, 3% single-top, 1% other
- 108000 events in 19.5 fb^{-1} at 8 TeV selected

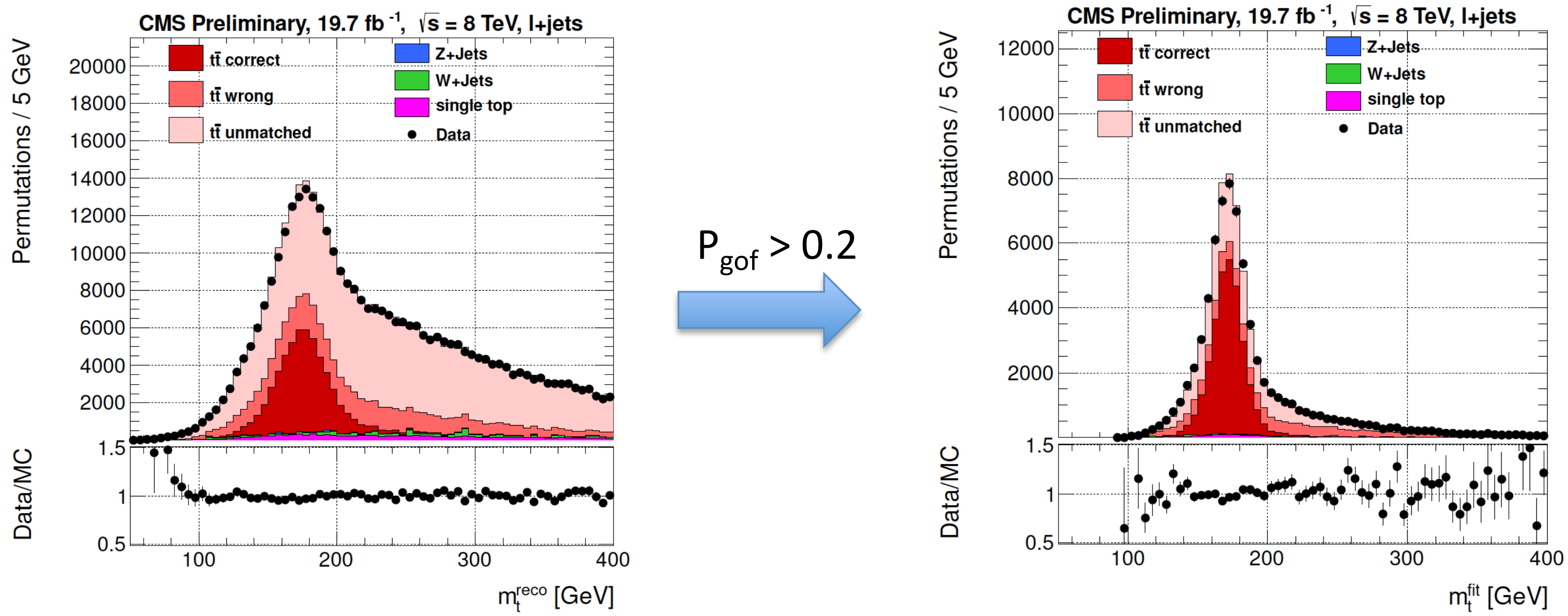


Compare with selections at Tevatron with full statistics: about 2500 events

Event reconstruction

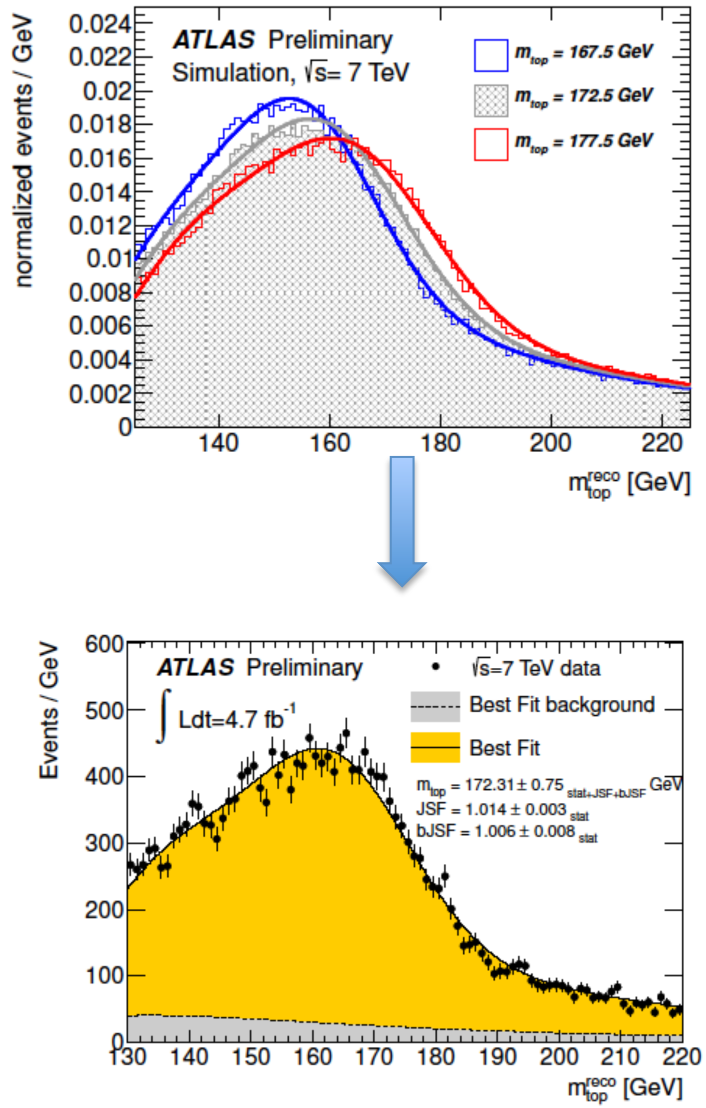
[example from CMS, TOP-14-001 / JHEP 12 (2012) 105]

- Assign 4 leading jets to partons from $t\bar{t}$ decay (obey b-tag)
  - Kinematic fit with constraints: m_W = 80.4 GeV, $m_t = m_{tbar}$
  - Weight each permutation by $P_{gof} = \exp-(1/2\chi^2)$, select $P_{gof} > 0.2$
- 28750 events in 19.7 fb^{-1} 2012 data (94% $t\bar{t}$, 44% correct perm.)



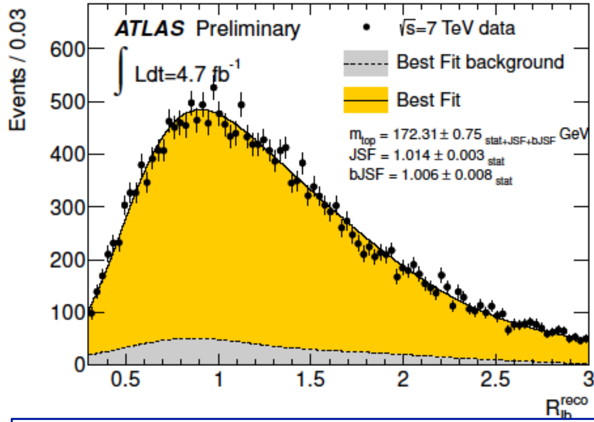
Top mass fitting techniques
[example from ATLAS, CONF-2013-046]

- Invariant mass distributions are distorted by
  - phase space constraints
  - detector resolution
  - wrong particle assignments to jets
  - backgrounds, pileup
  - selection cuts
- Need a MC simulation, tuned to data, to construct templates or probability densities
  - **important: at this stage the top mass definition in MC is not too relevant.**



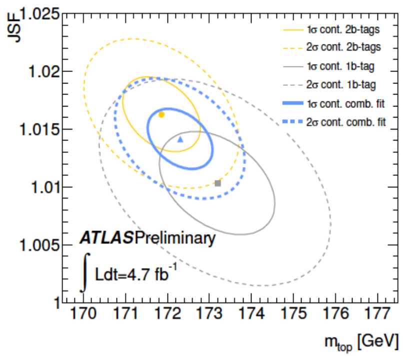
Top mass fitting techniques and JES

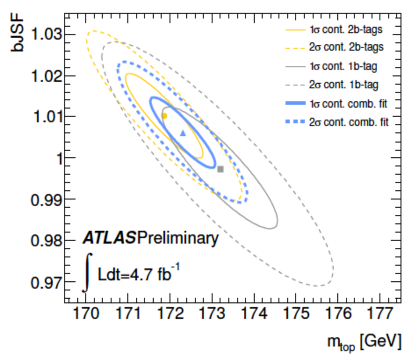
- The Jet Energy Scale is the most important source of experimental uncertainties, the W mass constraint is a powerful tool for light quark JES
- Can also find a variable sensitive to b-jet JES and constraint it in situ [ATLAS, CONF-2013-046] in this case b-tagging is used not only for jet classification, but also for JES determination
- Otherwise the simulation is used for b-jet JES, the impact of modeling assumption depends on the jet reconstruction technique



$$R_{\mathrm{lb}}^{\mathrm{reco,2b}} = \frac{p_{\mathrm{T}}^{b_{\mathrm{had}}} + p_{\mathrm{T}}^{b_{\mathrm{lep}}}}{p_{\mathrm{T}}^{W_{\mathrm{jet}_1}} + p_{\mathrm{T}}^{W_{\mathrm{jet}_2}}},$$

$$R_{\mathrm{lb}}^{\mathrm{reco,1b}} = \frac{p_{\mathrm{T}}^{b_{\mathrm{tag}}}}{(p_{\mathrm{T}}^{W_{\mathrm{jet}_1}} + p_{\mathrm{T}}^{W_{\mathrm{jet}_2}})/2}$$

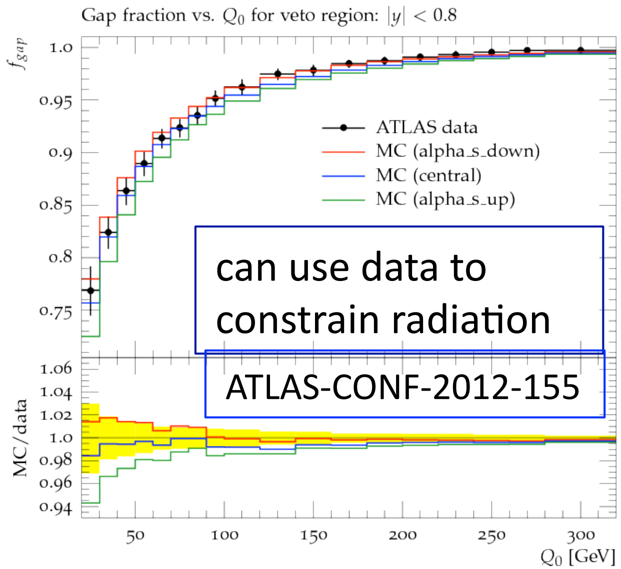


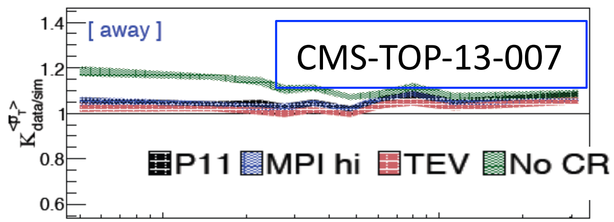


Main sources of systematic uncertainties

- Jet Energy Scale (depends on technique and jet reco, in situ statistical not included)
  - light jets, detector response [0.2-0.7 GeV]
  - b jets [0.1-0.6 GeV]
- Modeling of gluon radiation [0.3 – 0.45 GeV]
- Modeling of underlying event [0.1 – 0.2 GeV]
- Modeling of Colour Reconnection [0.2 – 0.5 GeV]
- Proton PDF [0.1 – 0.2 GeV]
- Hadronization, b-fragmentation (included also in JES) [0.3 -0.6 GeV]
- b-tagging [0.1 – 0.8 GeV]
- pileup modeling (included also in JES) (0.1-0.3 GeV)

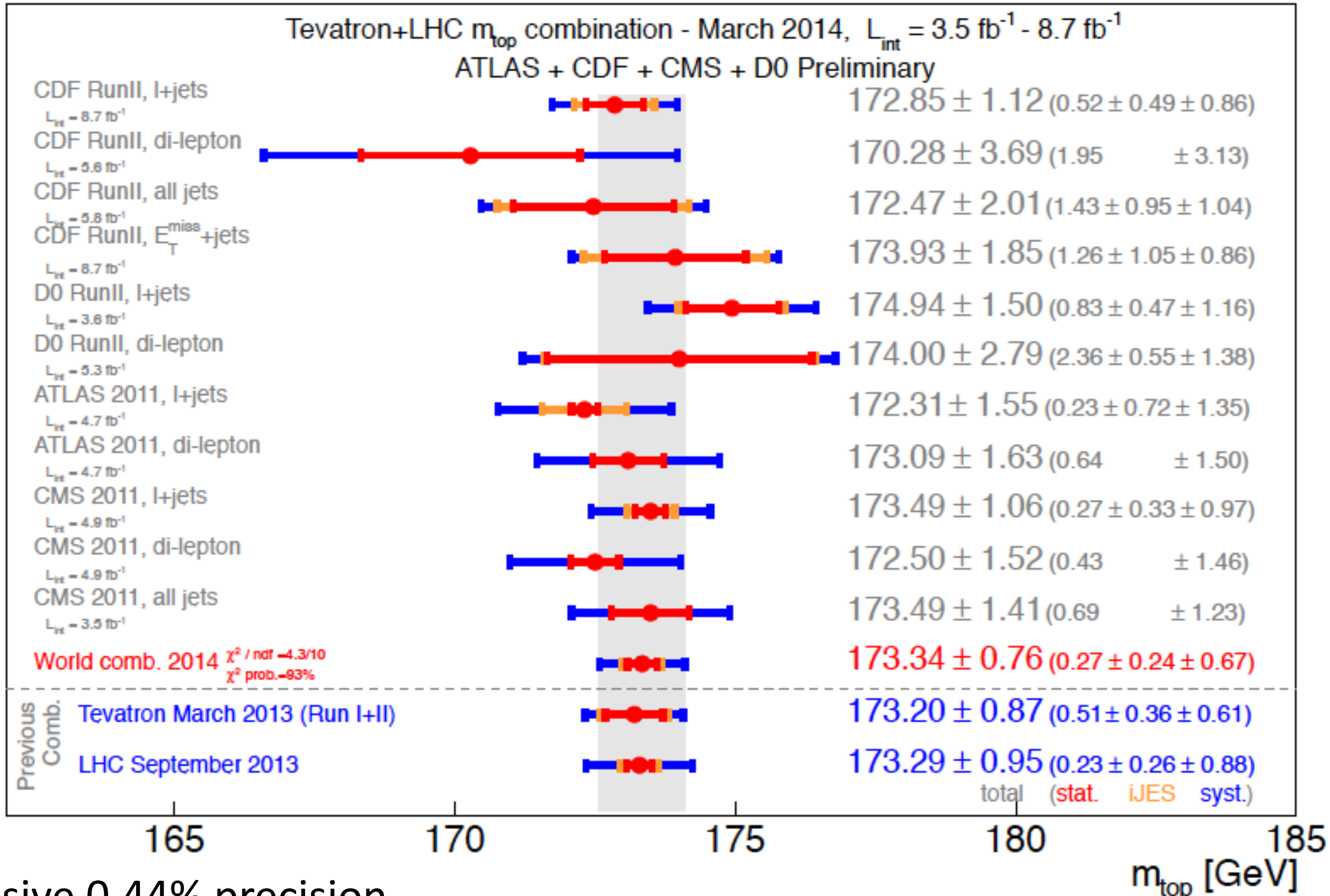
[The numbers are ranges for illustration only, more details in specific analysis and LHC combination notes]





can use data to constrain generator modeling

World combination of m_{top}

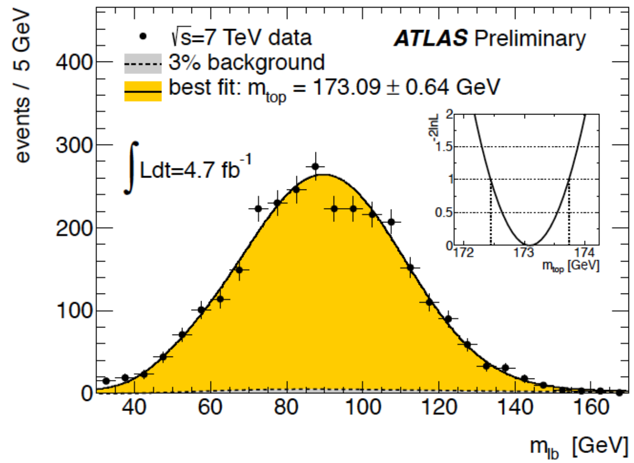


- An impressive 0.44% precision
- Some of the most precise measurements non included yet, e.g.
  - D0 full statistics, matrix element method, arXiv:1405.1756, m_t=174.98±0.76
  - CMS l+jets at 8 TeV, L=19.6 fb^{-1} CMS-TOP-2014-001, m_t=172.04±0.77

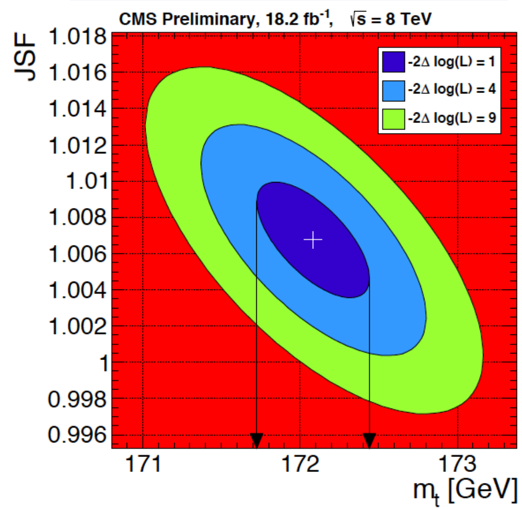
A note on the other channels at LHC

- The dilepton and all-hadronic decay channels provide and important cross check, given the difference in colour structure of the final state (next slide).
- The dilepton channel is kinematically underconstrained (2 ν's), but with low background
- The all-hadronic channel can profit of an accurate in-situ fit of the JES, already providing a result factor 2 better than Tevatron

ATLAS-CONF-2013-077



CMS-TOP-2014-002

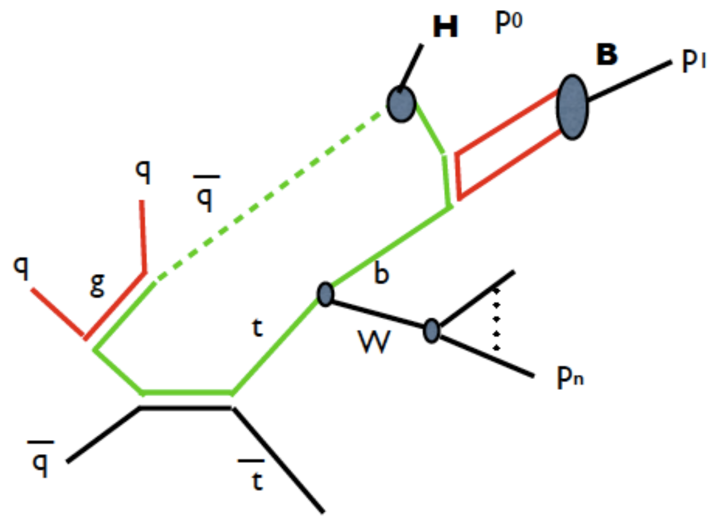


About measuring the top mass from its decay products

- **Top is a coloured fermion**, it decays before hadronizing, but the b quark from its decay must hadronize
  - **there is no way to assign final state particles only to the original top**, the concept is ill-defined as it is the use of a pole mass for a coloured particle
  - the effect is expected to be of the order of $\Lambda_{QCD} \approx 0.2$ GeV but the actual impact depends on the experimental method

1. **important to test variables sensitive to the final state definition**
2. **important to measure the mass with alternative techniques**

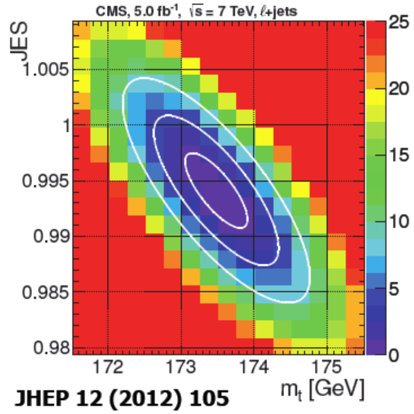
In prospect **1** and **2** will take advantage of the large LHC statistics



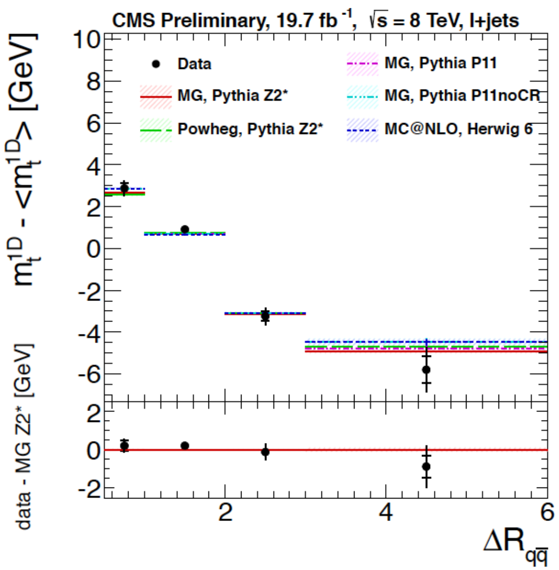
plot courtesy of Michelangelo Mangano

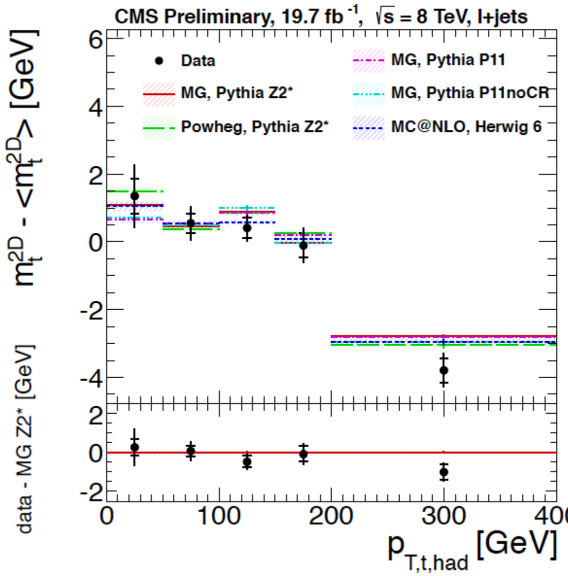
Dependence of Top Mass observable on event kinematics

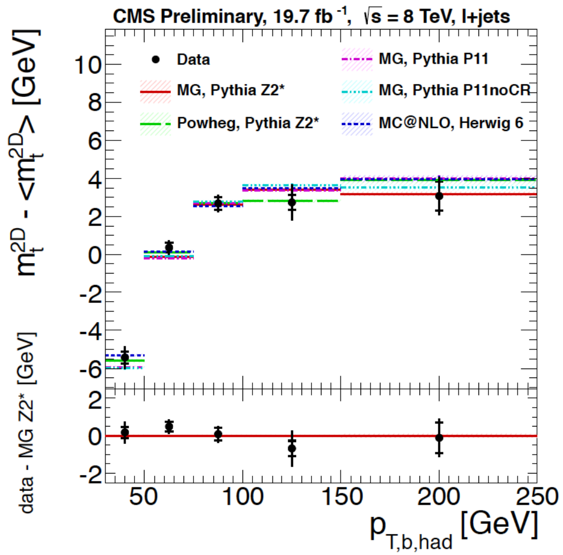
- test variables sensitive to the final state definition
  - kinematic dependence on final state properly modeled by MC? → 12 kinematic variables checked, related to Color Reconnection, ISR/FRS, b-jet kinematics
  - Good data/MC agreement rules out dramatic effects → need to pursue the study with Run 2 high statistics !!



CMS-TOP-12-029
CMS-TOP-14-001



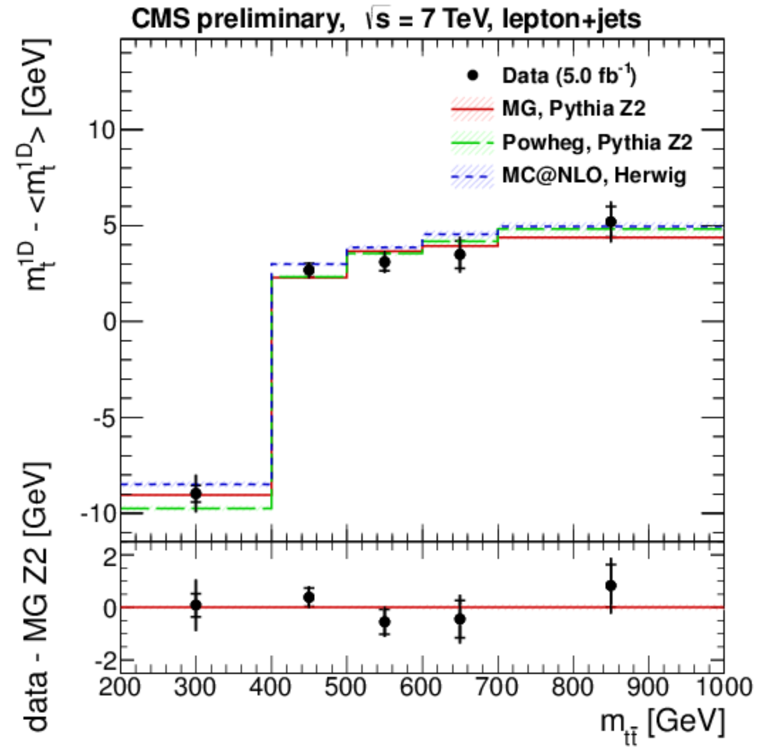




Dependence of Top Mass on Event Kinematics

CMS-PAS-TOP-12-029

	Fig.	Observable
color recon.	1	$\Delta R_{q\bar{q}}$
	2	$\Delta\phi_{q\bar{q}}$
	3	$p_{T,t,had}$
	4	$\lvert\eta_{t,had}\rvert$
ISR/FSR	5	H_T
	6	$m_{t\bar{t}}$
	7	$p_{T,t\bar{t}}$
	8	Jet multiplicity
b-quark kin.	9	$p_{T,b,had}$
	10	$\lvert\eta_{b,had}\rvert$
	11	$\Delta R_{b\bar{b}}$
	12	$\Delta\phi_{b\bar{b}}$



With the current precision, no mis-modelling found as function of variables related to color reconnection, ISR/FSR, b-quark kinematics.

Methods for top mass measurement (2)

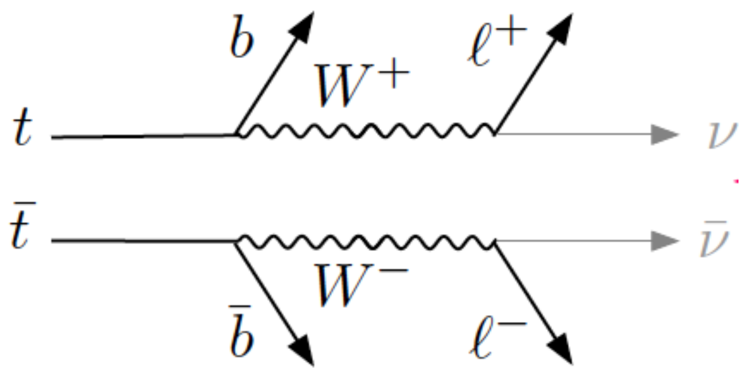
- Given the potential bias in measuring the top mass from its decay products, important to explore **alternative techniques**, e.g.
  - Measure the **decay length** (the boost) of B hadrons produced in top decays, the boost is related to the original top mass
  - Select **specific channels**, for example top with $W \rightarrow l\ \nu$ and $B \rightarrow J/\psi + X$ decays and measure the three-lepton invariant mass
  - Measure the **endpoint** of the lepton **spectrum** or other quantities in top decays
  - Measure the mass from single top events (great potential !)
- Alternative methods have typically larger statistical uncertainties, however at LHC we have large ttbar samples
  - Systematic uncertainties can be controlled with data, again large samples help.
- Another alternative: move away from properties of the decay products
  - **extract the top mass from the top cross section**

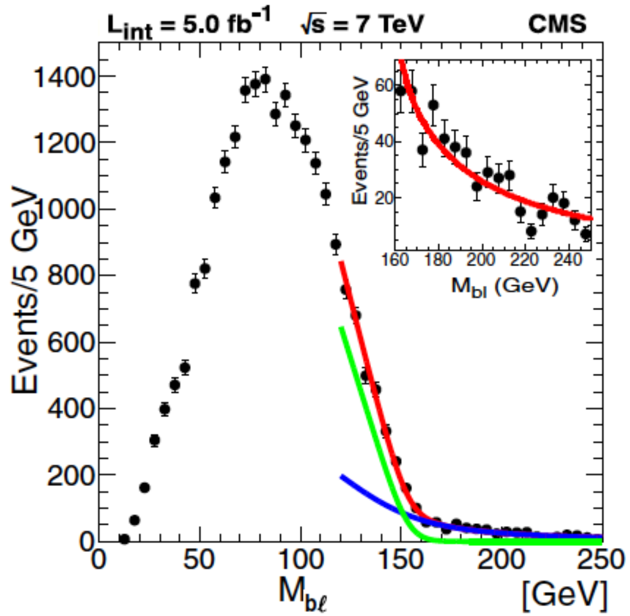
TOP mass from alternative techniques

- Example of a technique already yielding interesting precision: Endpoint method
- The shape of the signal can be computed analytically, background data-driven
- Use of MC limited to study underlying assumption: independent decay of two tops (color connections and reconnections violate this assumption)

arXiv:1304.7498

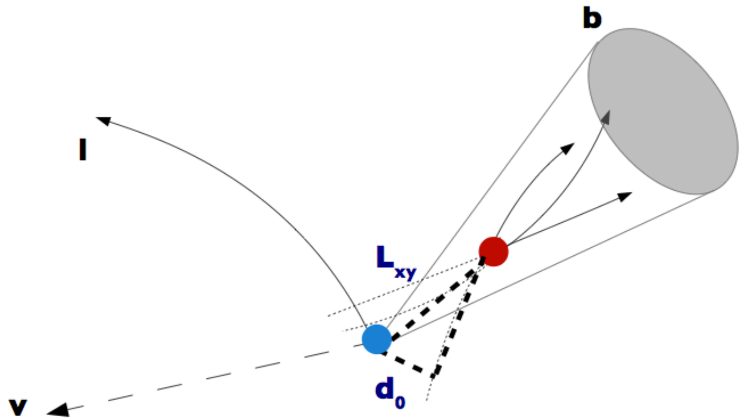
$$M_t = 173.9 \pm 0.9\,(\text{stat.})^{+1.6}_{-2.0}\,(\text{syst.})\,\text{GeV}$$



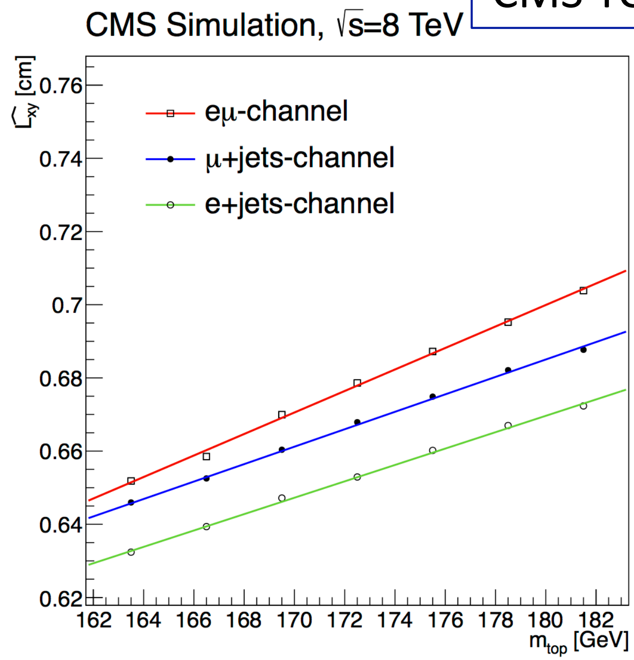


Another example: top mass from the b decay length

- The decay length of b hadrons from top decays is correlated to their boost, i.e. to the top mass



CMS TOP-12-030

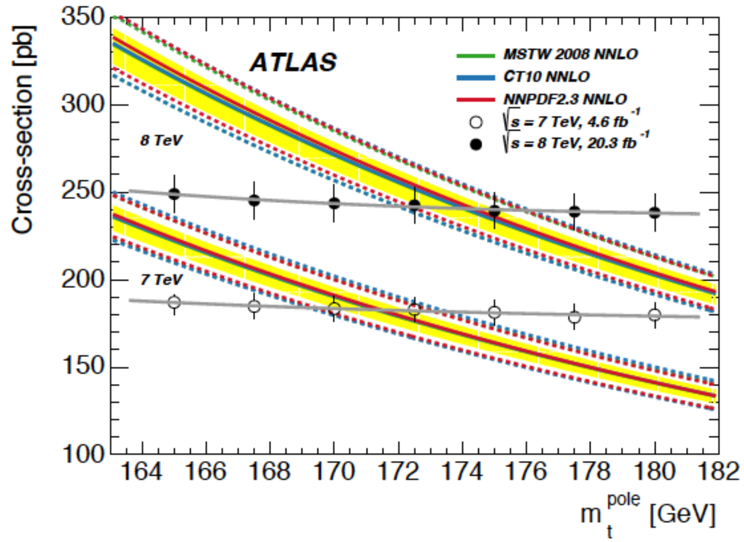


m_t = 173.5 ± 1.5stat ± 1.3syst ± 2.6p_t(top) GeV

ttbar cross section: mass interpretation

[example from ATLAS, arXiv:1406.5375]

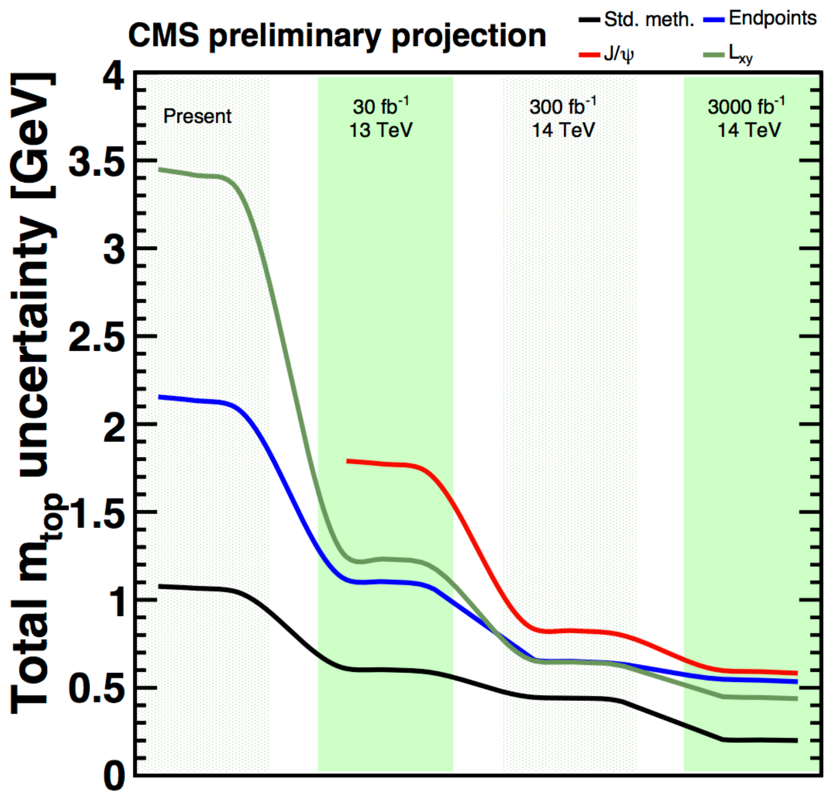
- Measure cross section in the most precise channel: dilepton eμ
- Use b-tagging and double tag method to avoid dependence on b-tag efficiency
  - interesting by-product: acceptance dependence on m_t is flat because of calibration of the jet acceptance in situ and cancelation with Wt background
- Use recent NNLO calculation of top pair cross section to extract m_t
- The method takes advantage of the excellent luminosity knowledge at LHC (~2%), which is also the long-term experimental limitation, together with the knowledge of the LHC beam energy



$$m_t = 172.9^{+2.5}_{-2.6}\ \text{GeV}$$

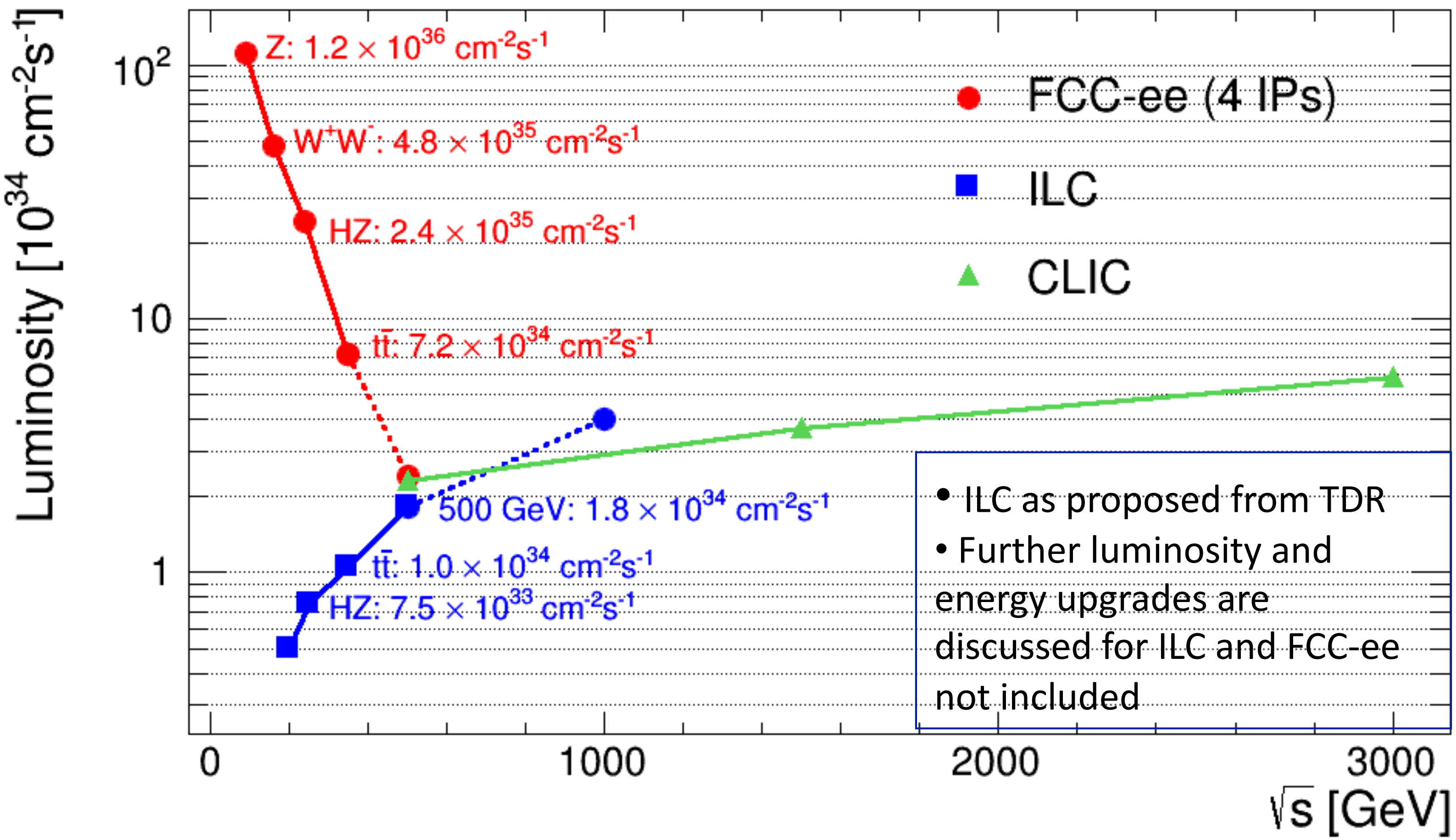
Prospects for top mass at the LHC

• There is potential to improve standard methods, taking advantage of the high statistics for, e.g., in-situ JES calibration, constraining models from differential studies, etc.
• There is even greater potential for alternative methods, most of the current systematic uncertainties can be reduced with higher statistics, e.g. top pt modeling, in-situ JES again
• Improvements on the cross section method are linked to improvements in the luminosity and beam energy uncertainties at LHC
• A optimistic view (maybe realistic give past experience at colliders !) of the evolution in precision is given in the picture



From CMS PAS FTR-13-017, prepared for the "European Strategy for particle physics" discussions

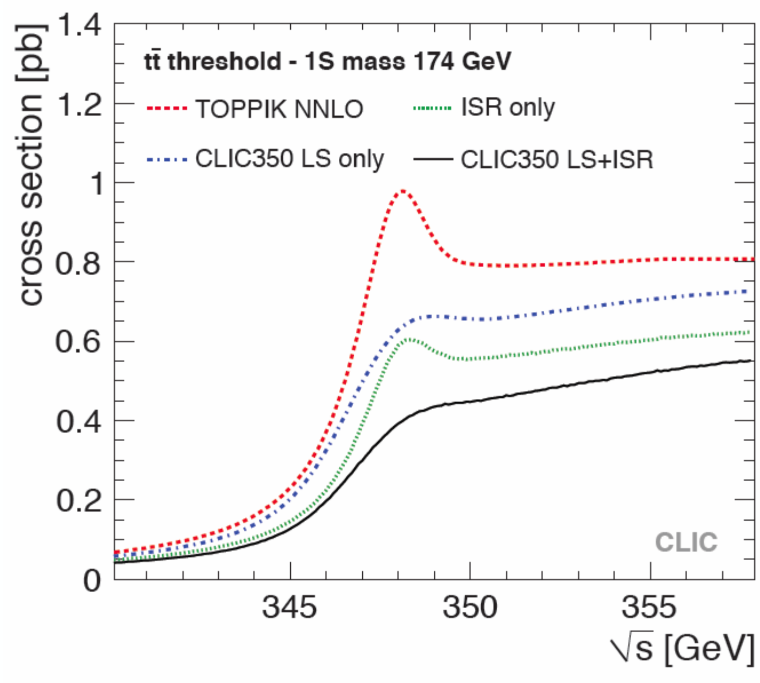
Prospects at future e^+e^- Colliders: Linear and Circular

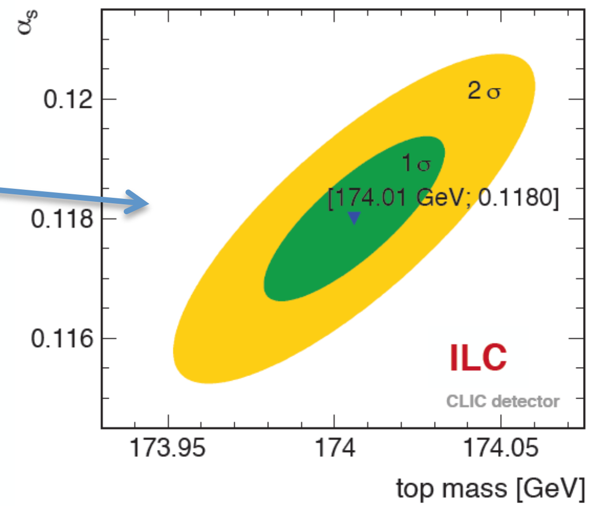


TLEP physics study group: arXiv:1308.6176

top mass from threshold scan

- Same conceptual advantage as cross section measurement at LHC, but experimentally dependent only on beam energy spectrum
- Other source of uncertainty is the modification of threshold lineshape related to α_s , **top width** and top-Higgs **Yukawa coupling** (with high statistics 2D / 3D fits possible)



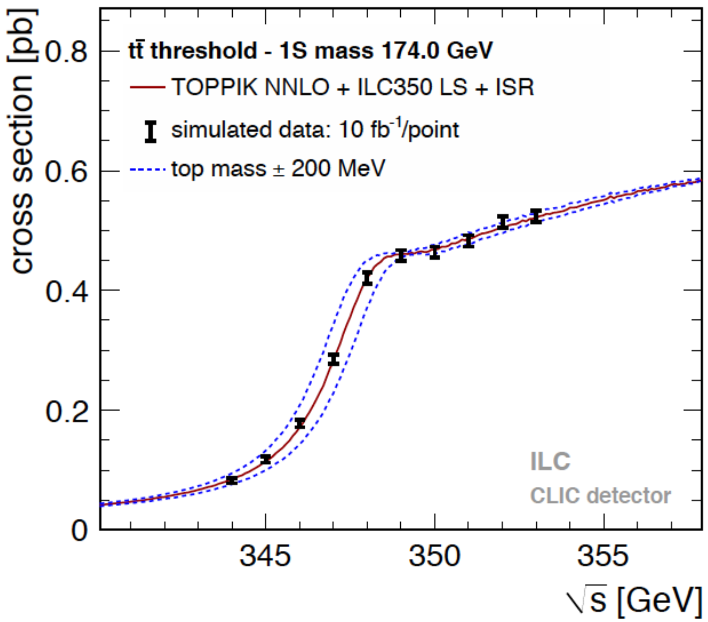


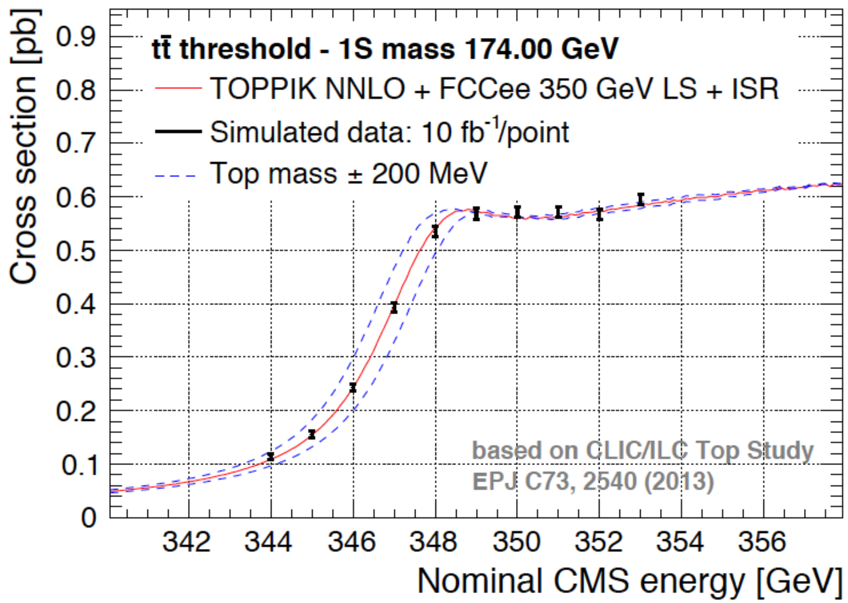
Eur. Phys. J. C73 (2013) 2530

e+e- at 350 GeV: threshold scan

- At ILC statistical uncertainty of 30 MeV with 10 fb-1 scan
- At FCC statistical uncertainty of 10 MeV expected - Advantage of a very low level of beamstrahlung at FCC
- Theoretical *current* uncertainty from higher order QCD contribution ~ 100 MeV

- Comparing ILC and FCCee - assuming identical detector performance





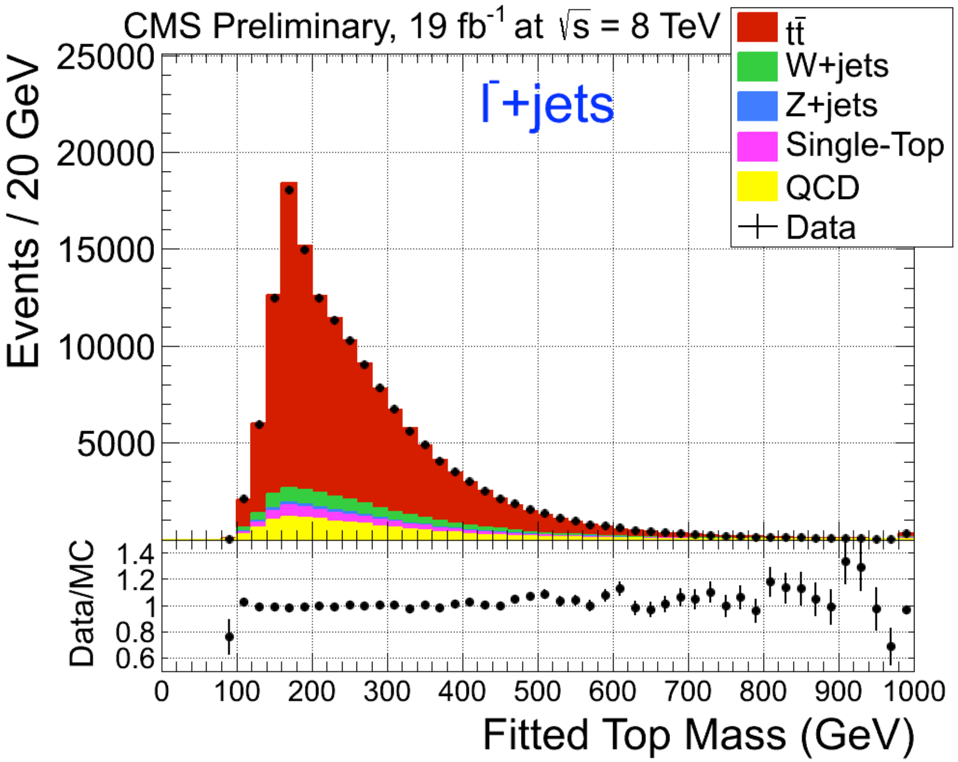
Simulated data points - same integrated luminosity

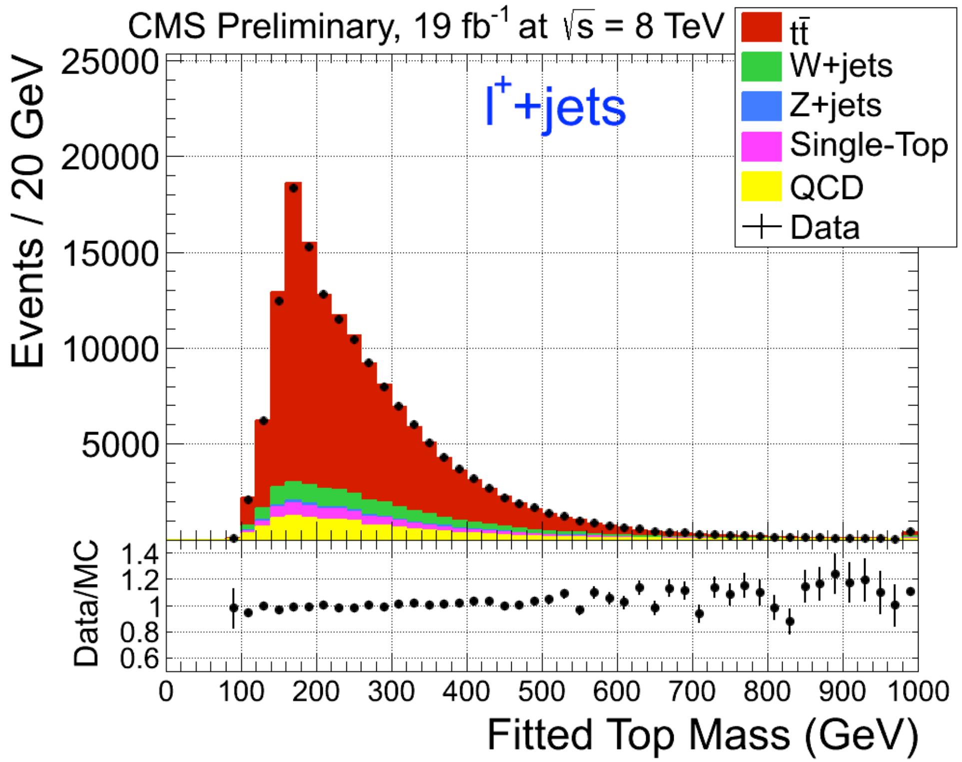
NB: Assuming unpolarized beams - LC beams can be polarized, increasing cross-sections / reducing backgrounds

From Frank Simon, presented at 7th TLEP-FCC-ee workshop, CERN, June 2014

top – antitop mass difference: a CPT test

$$\Delta m_{\mathrm{t}} = -272 \pm 196\ (\mathrm{stat.}) \pm 122\ (\mathrm{syst.})\,\mathrm{MeV}$$



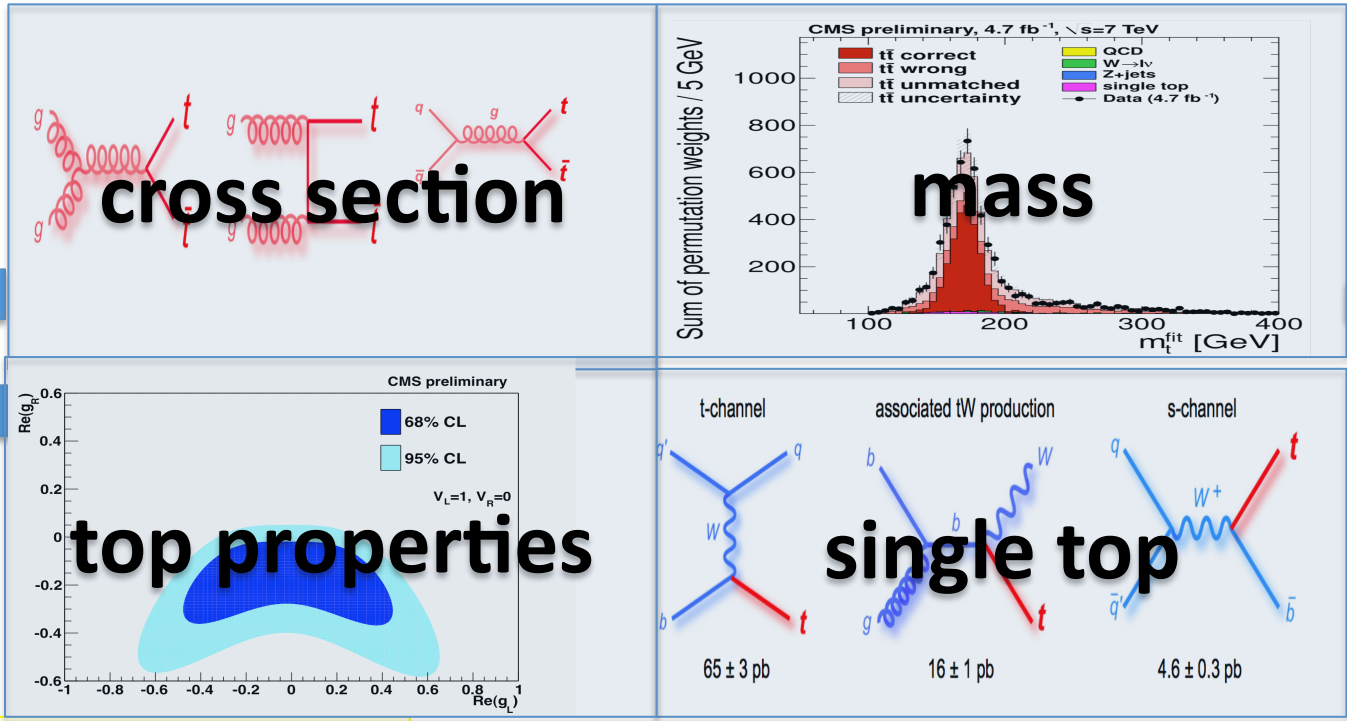


TOP AND HIGGS: NOT ONLY THE MASS

The top areas of study

Total and differential cross sections, Test of production mechanism(QCD, EWK), tt +jets production, measure PDF

Precision measurement of top mass, ΔM(t-tbar) (CPT test)



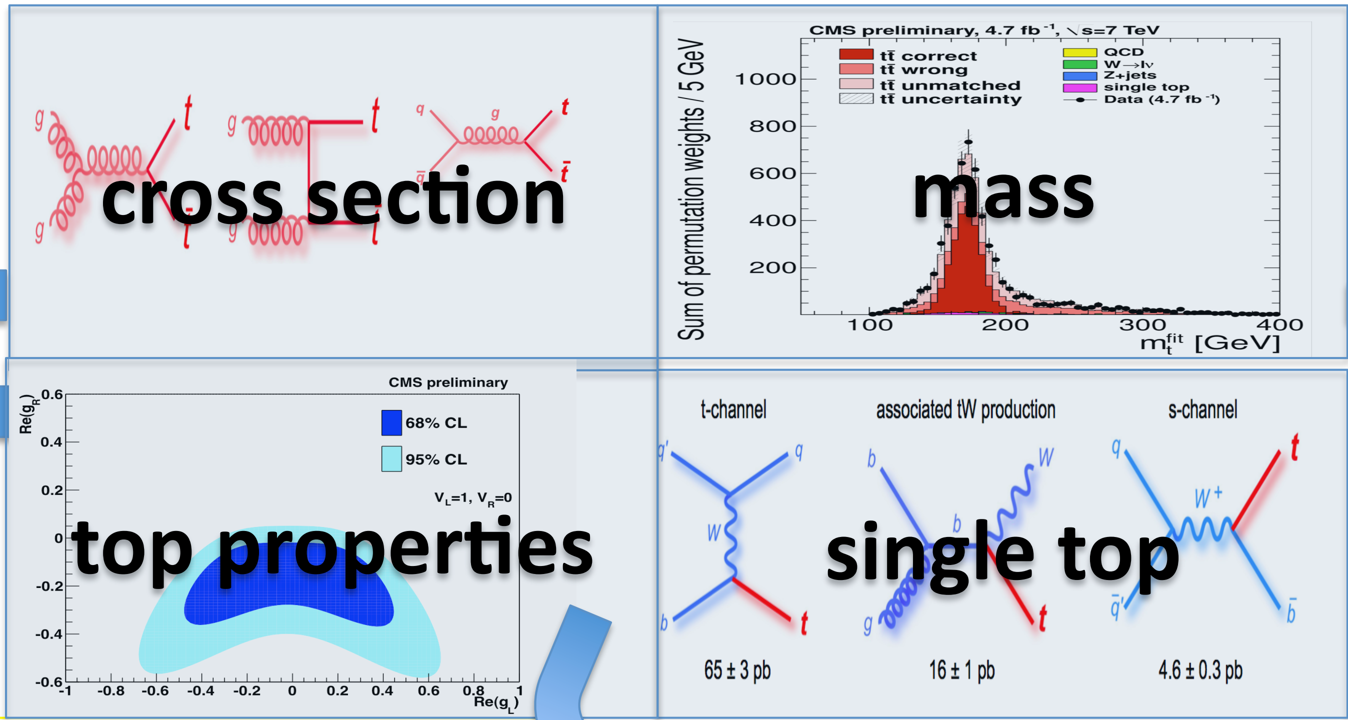
Couplings, branching ratios, charge, width, W helicity, spin correlations, charge asymmetry associated production (ttW, ttZ, ttH, tt+MET)

t, s and tW channels, EWK production properties, Vtb measurement, new physics in single top

The role of top in the Higgs era

ttbar is our monitoring for gluon gluon fusion !

Do we interpret the top mass correctly when we match top, W and Higgs Masses ?



Are top properties consistent with our view of electroweak symmetry breaking ?

Is there any sign of new physics in top production and decay ?

The ttbar cross section

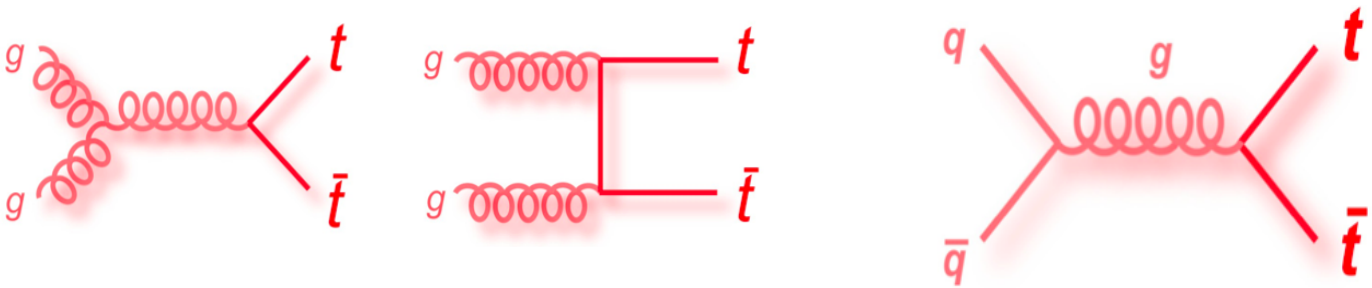
$$\sigma(s, m_t^2) = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2\, f_{h1}^{a}(x_1, \mu_f^2)\, f_{h2}^{b}(x_2, \mu_f^2)\, \hat{\sigma}_{ab}(\hat{s}, m_t, \alpha_s(\mu_f^2))$$

Parton combinations

PDF's

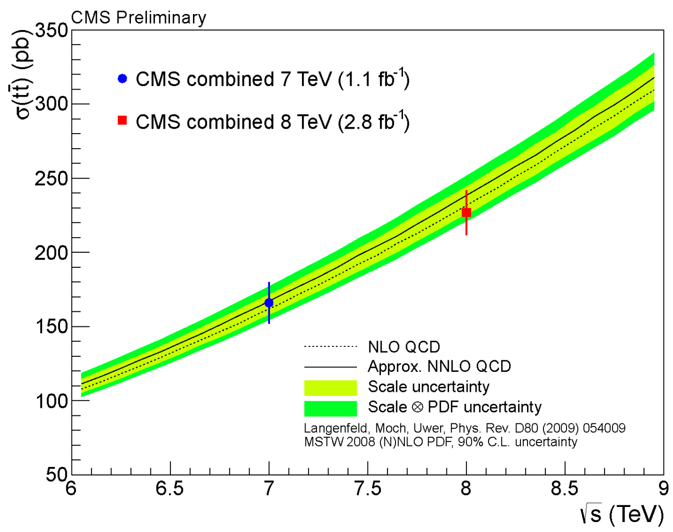
Momentum fraction with respect to the proton

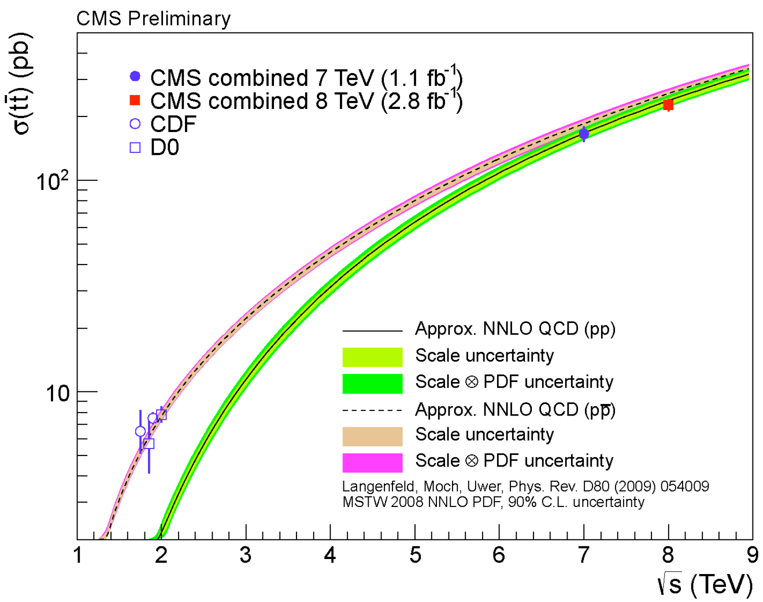
Cross section of the elementary process



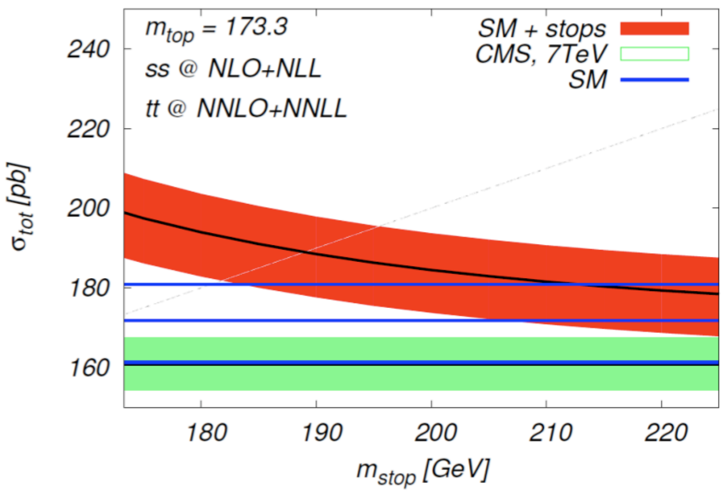
ttbar cross section at 7 and 8 TeV

- The cross section raises as foreseen
- Program of accurate measurement of the 8/7 TeV ratio (total and differential) and σ(tt)/σ(Z) for a precise test and PDF constraints





Interest for new physics: stealth stop !

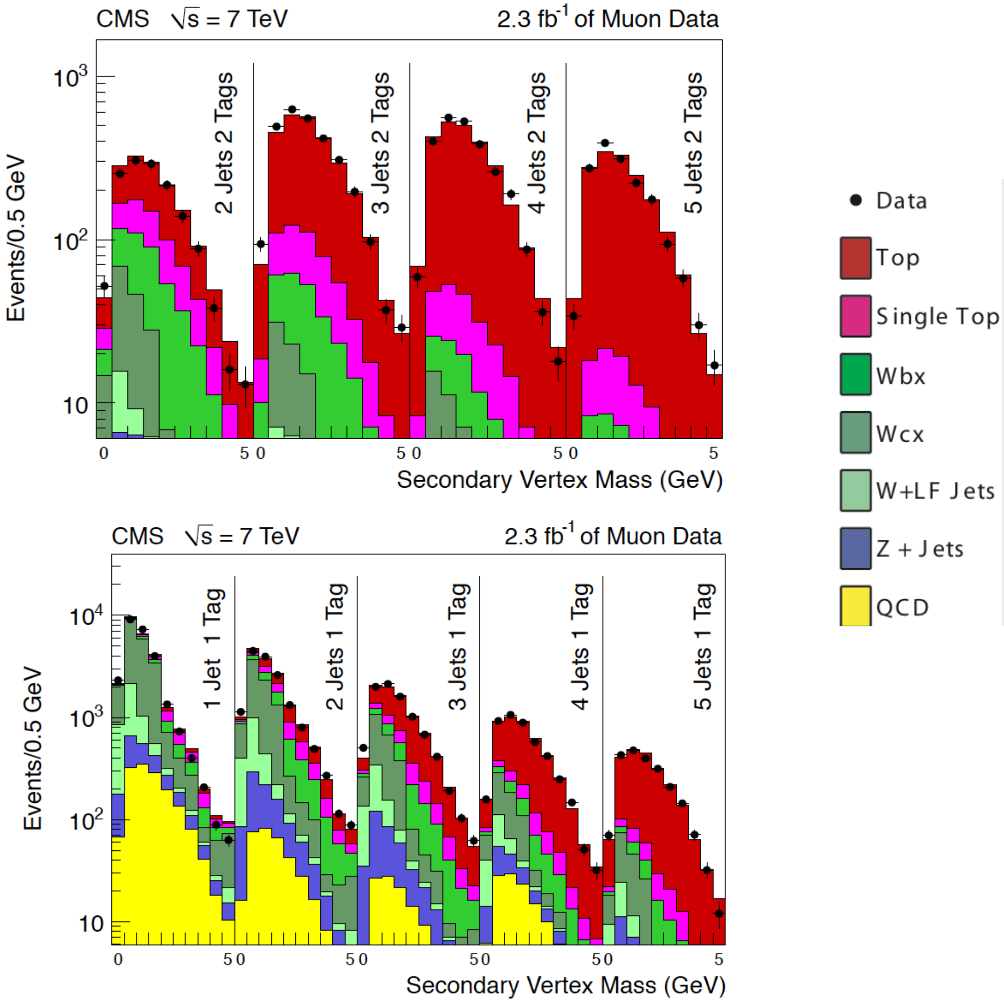


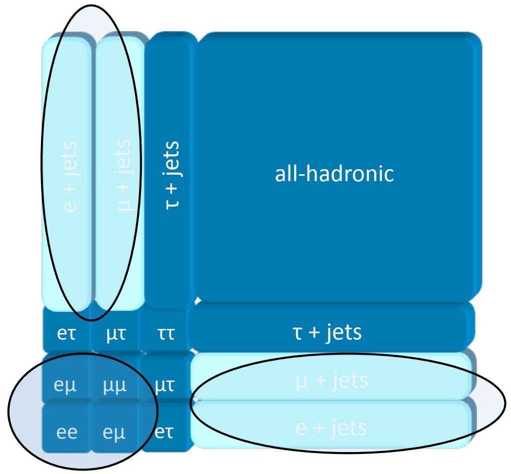
Selection of ttbar in the lepton+jets and dilepton channels

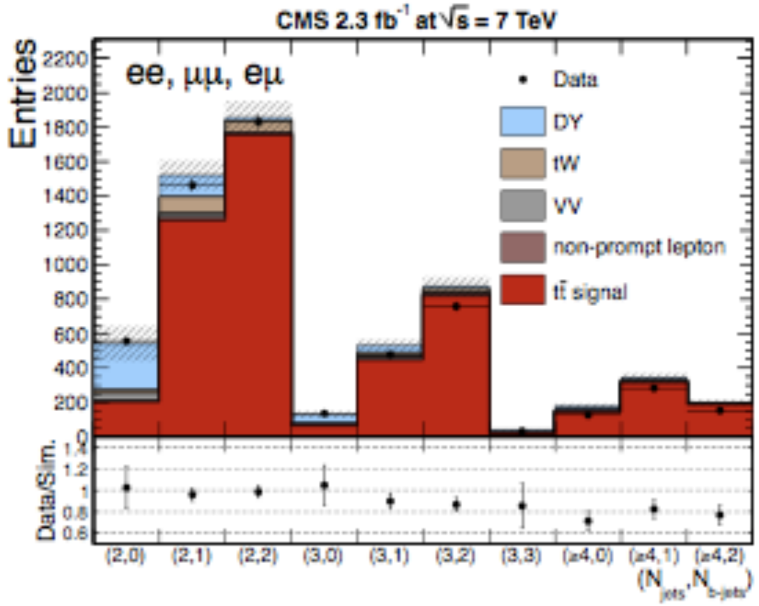
- Require one (or two) isolated leptons
- Lepton reconstruction and identification efficiency measured from data (Z→ ll) with tag-and-probe technique.
- Background measured from data using control samples
  - looser identification to get a background dominated sample and knowledge of tight-to-loose ratio for background leptons from another control sample
- B tagging used to further reduce the background

Leptons+jets and dileptons (e, μ)

- Excellent background control thanks to jet categorization, b tagging and in situ measurement of jet-energy scale



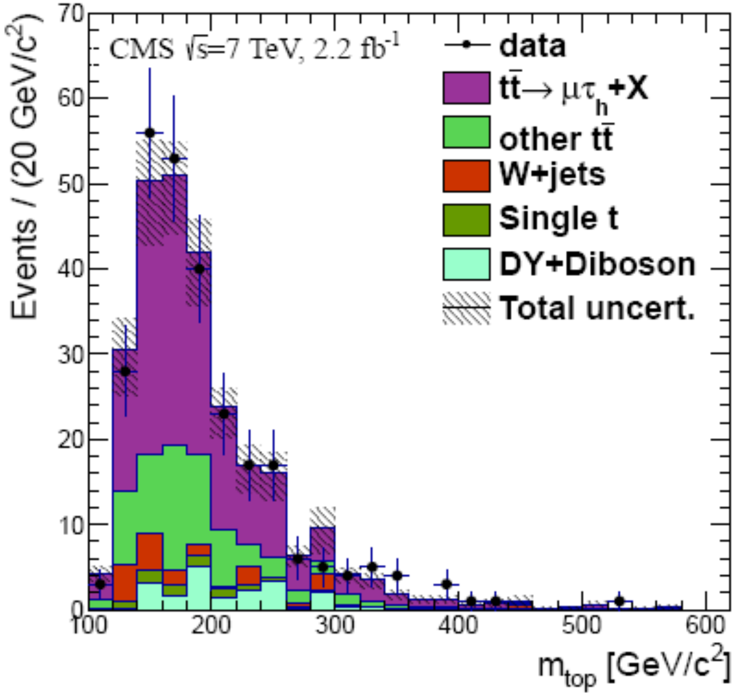




CMS TOP-11-005

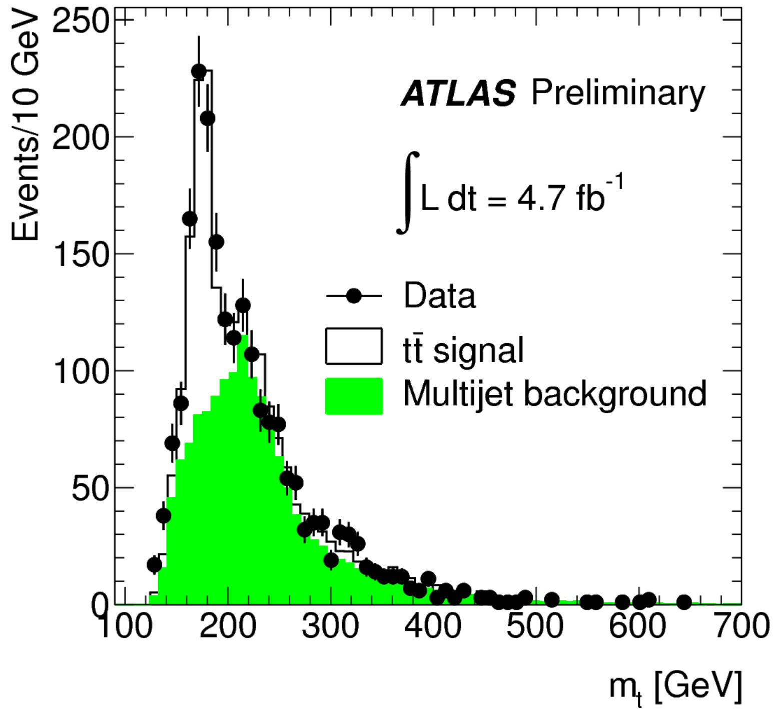
Other channels

$t\bar{t} \rightarrow \tau + \mu$



CMS arXiv:1203.6810

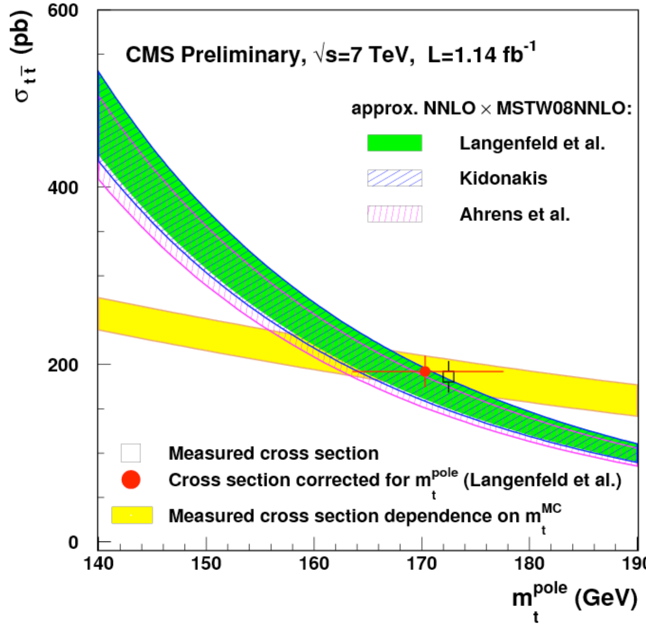
$t\bar{t} \rightarrow$ all hadronic

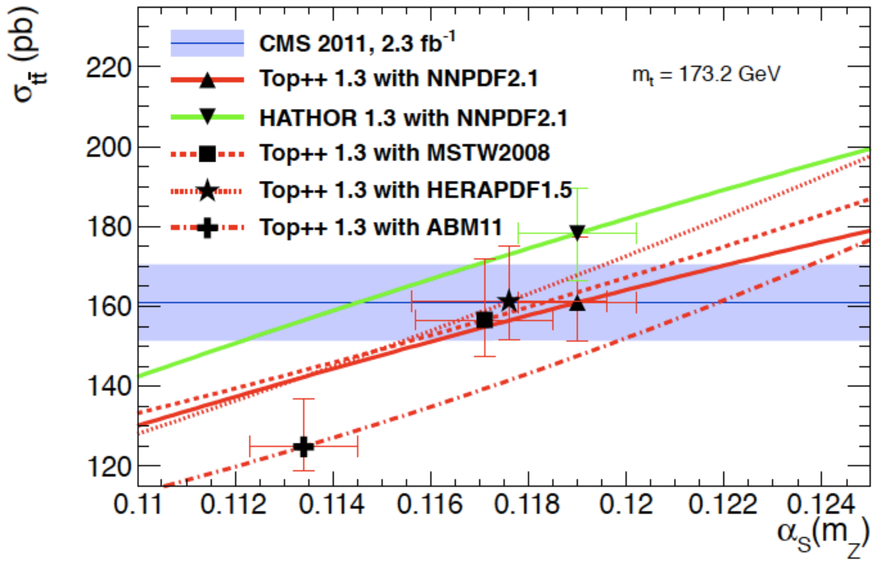


ATLAS CONF-2012-031

ttbar cross section interpretation

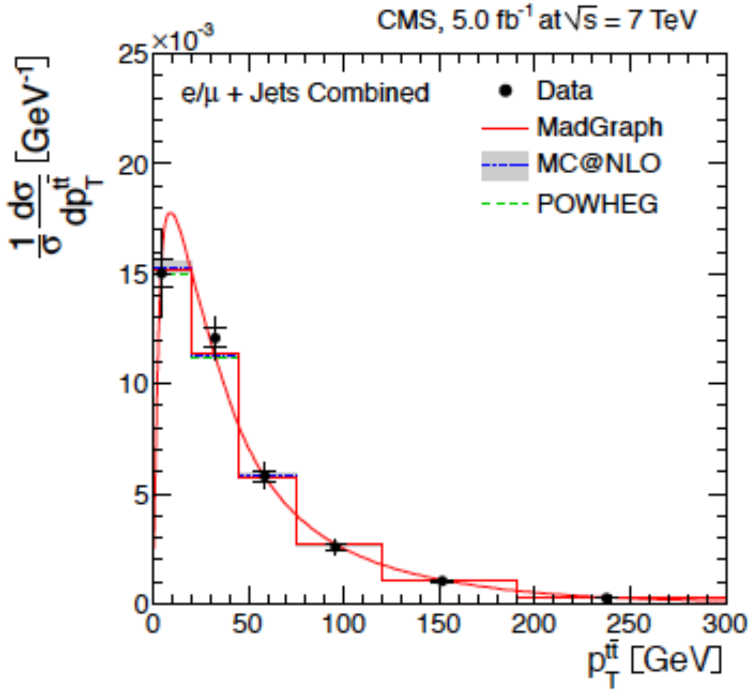
- Total cross section interpretation
  - as a measurement of the top mass (m_top= 176.7+3.8-3.4 GeV)
  - as a precise measurement of α_s [alphaS(mZ) = 0.1151+0.0033-0.0032 is extracted.]





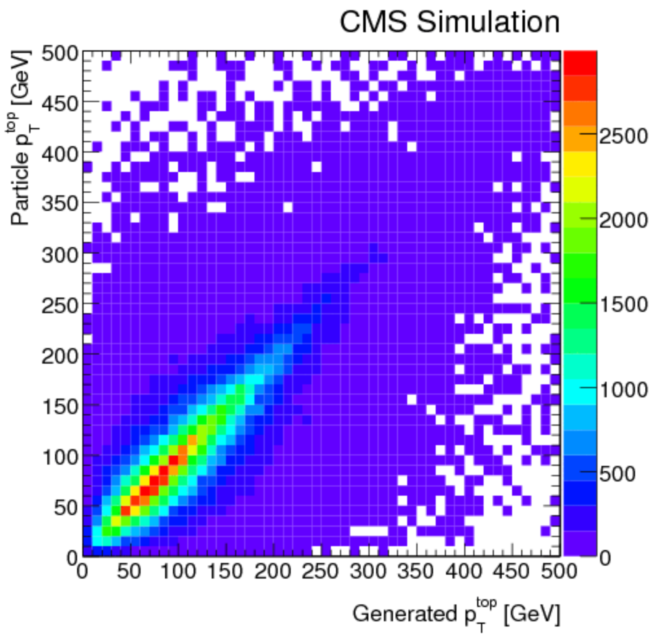
Differential cross sections

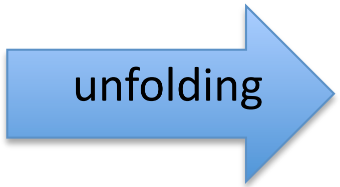
- Important measurements, they will play an important role for
  - i) investigate limitations of present MC (which QCD predictions and models describe our data best, in the search areas like high m(tt) and high multiplicities)
  - ii) provide independent interpretations (e.g. mass AND alpha_s from cross section)
  - Iii) sensitivity to high-x gluon (y(tt))

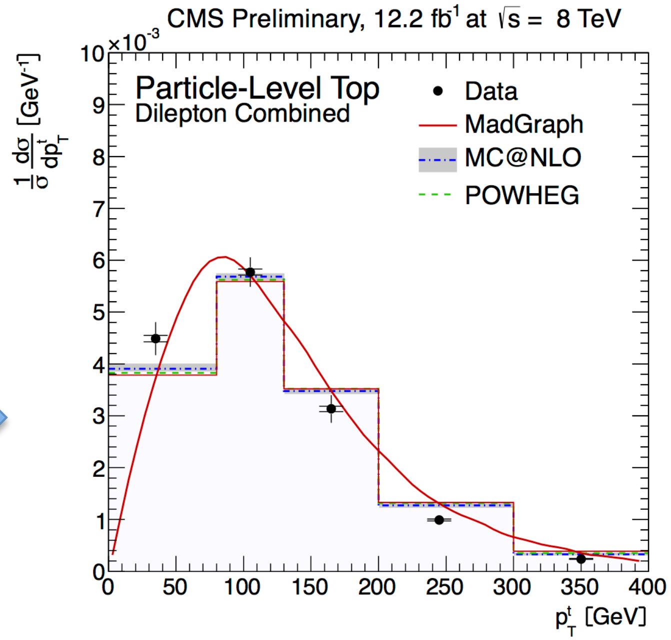


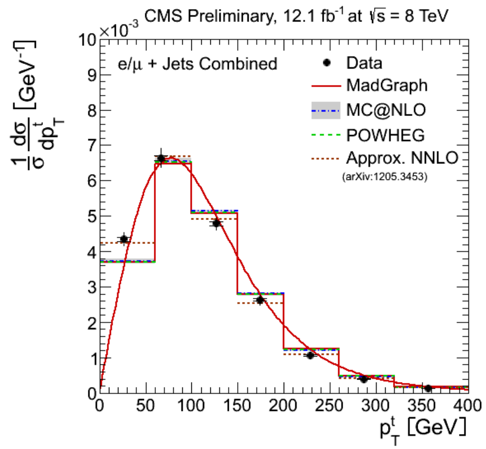
arXiv:1211.2220

Differential distributions and MC tuning already see discrepancies with respect to NLO generators !





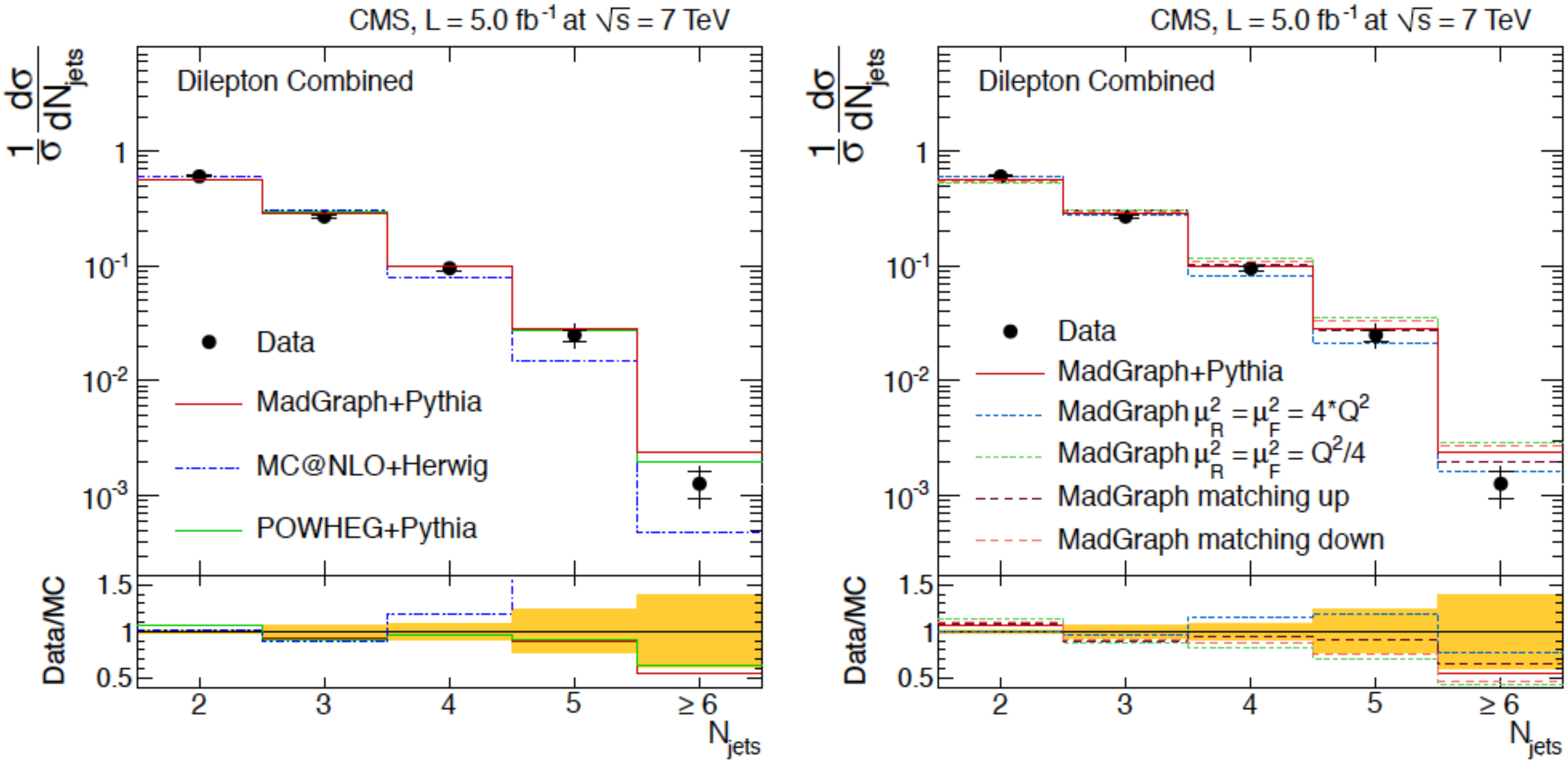




Ttbar and additional jets

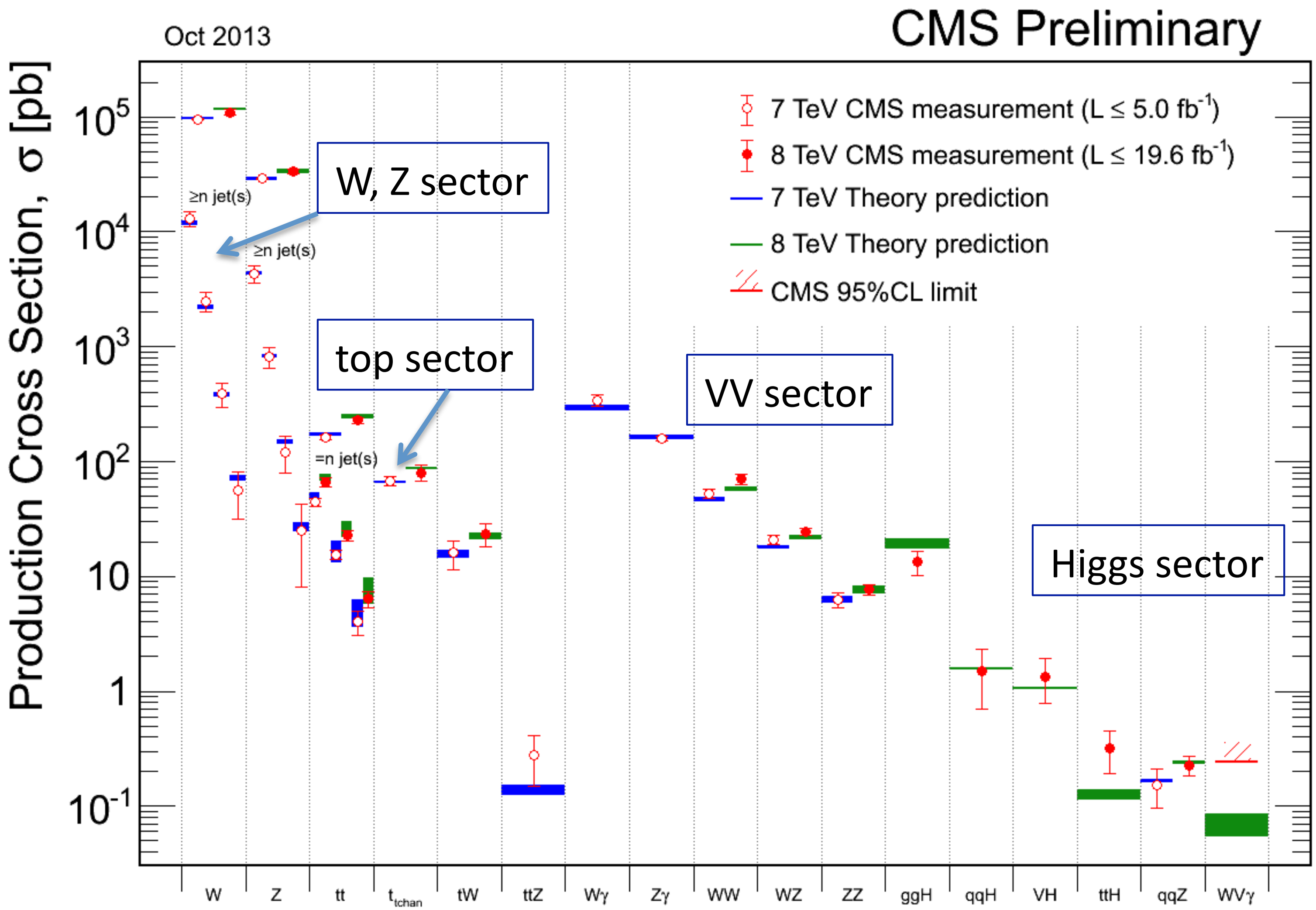
- Study of QCD radiation pattern

arXiv:1404.3171



Including top in the SM picture

Standard Model ? Terrific Model !

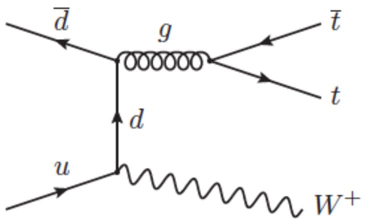


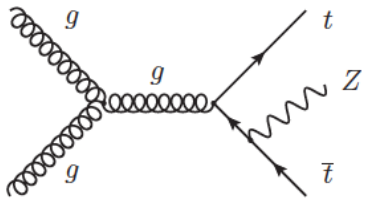
A few examples of other important topics in top physics

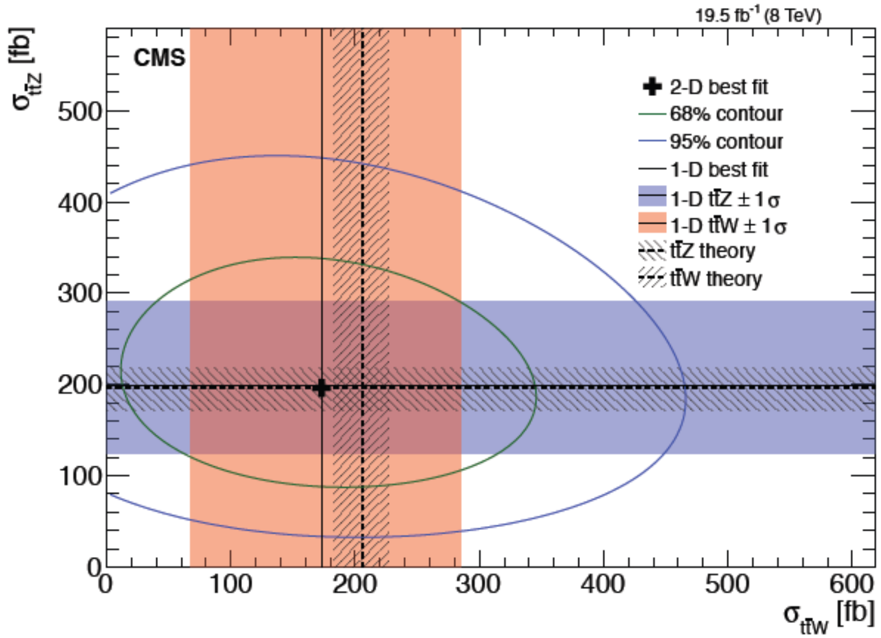
Rare processes: tt+X

- Important to measure low cross section processes
- Example: ttW and ttZ

(arXiv:1303.3239)

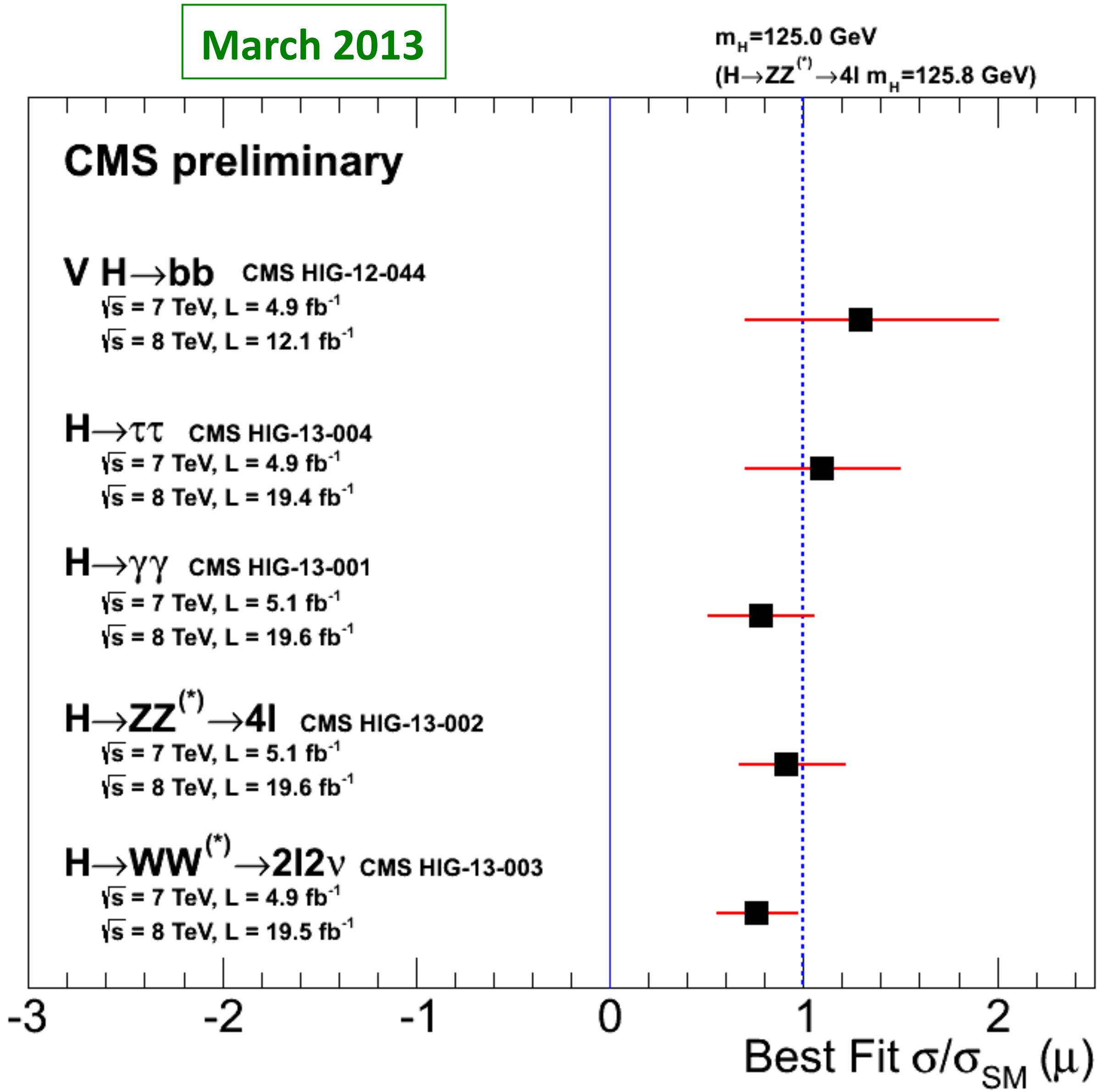






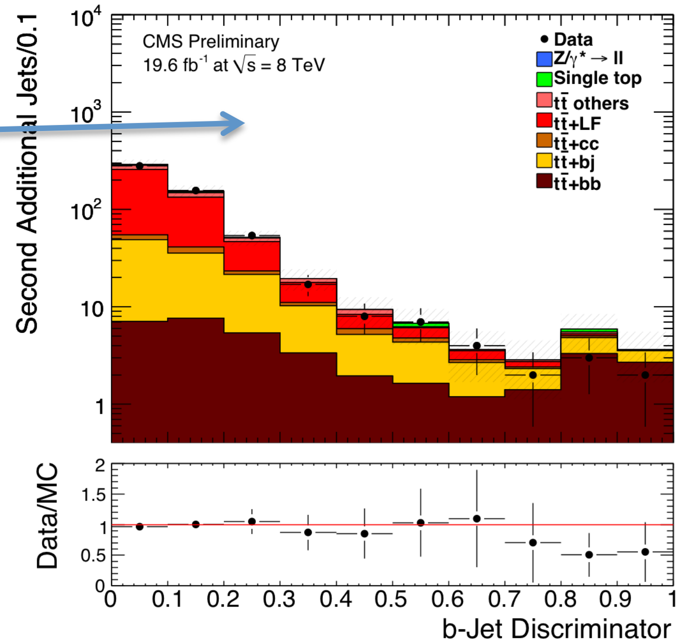
- Other processes tt+X
  - **Very important tt+bb and ttH**,
  - tt+MET , Four tops
  - tt+γ and interpretation as top charge measurement

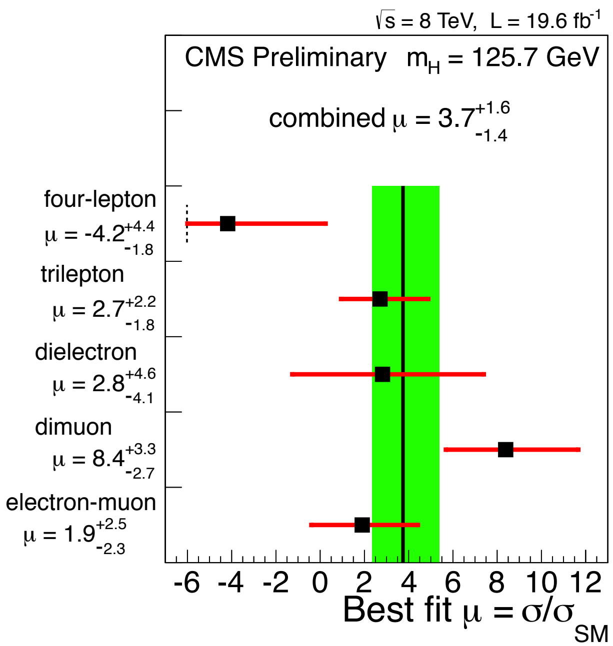
Higgs boson observation in various channels, what about coupling to top ?



Toward a direct measurement of the top-Higgs Yukawa coupling

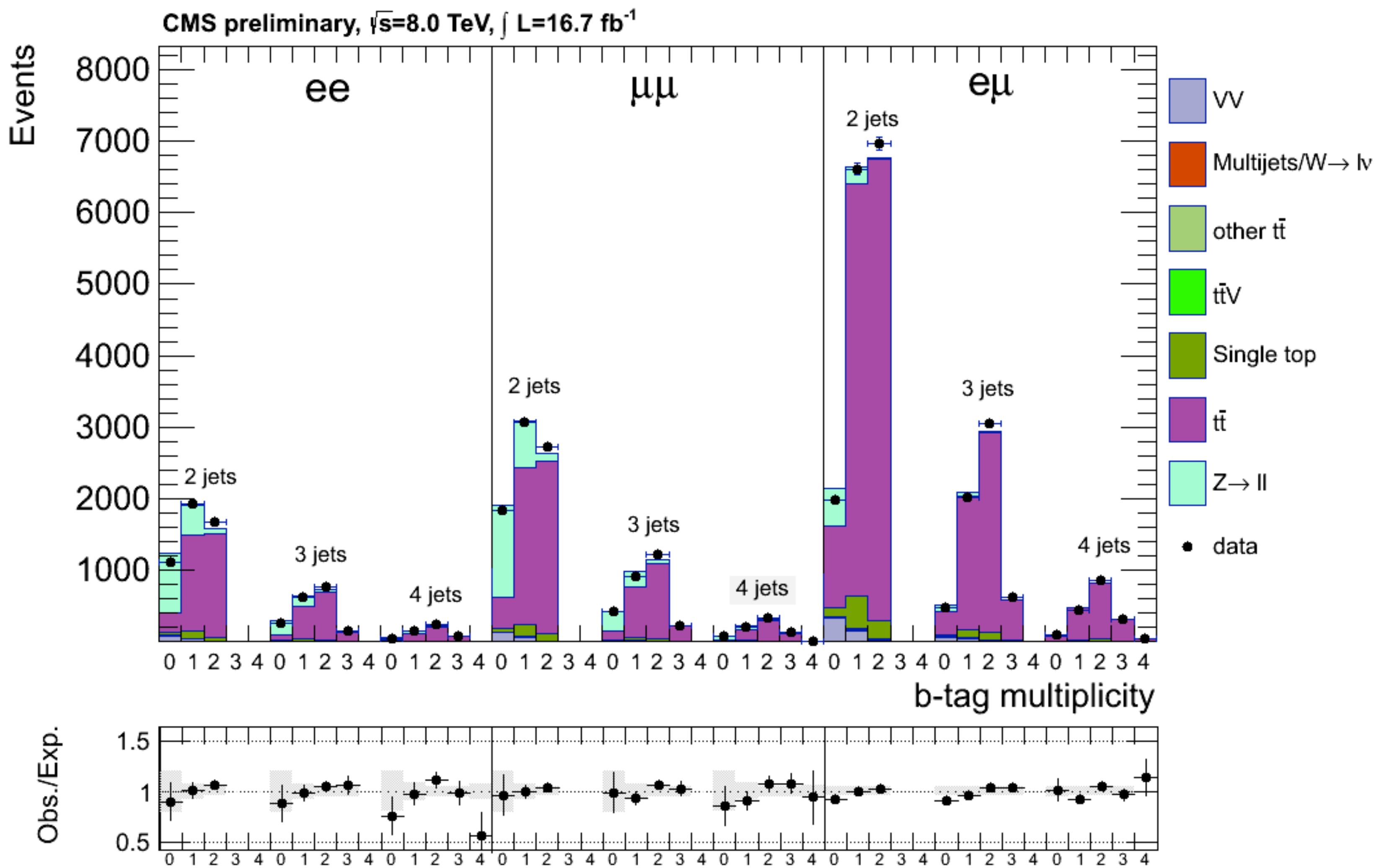
- First measurements of a typical background, ttbb
- From a recent ttH search in leptonic final states





TESTING TOP DECAYS

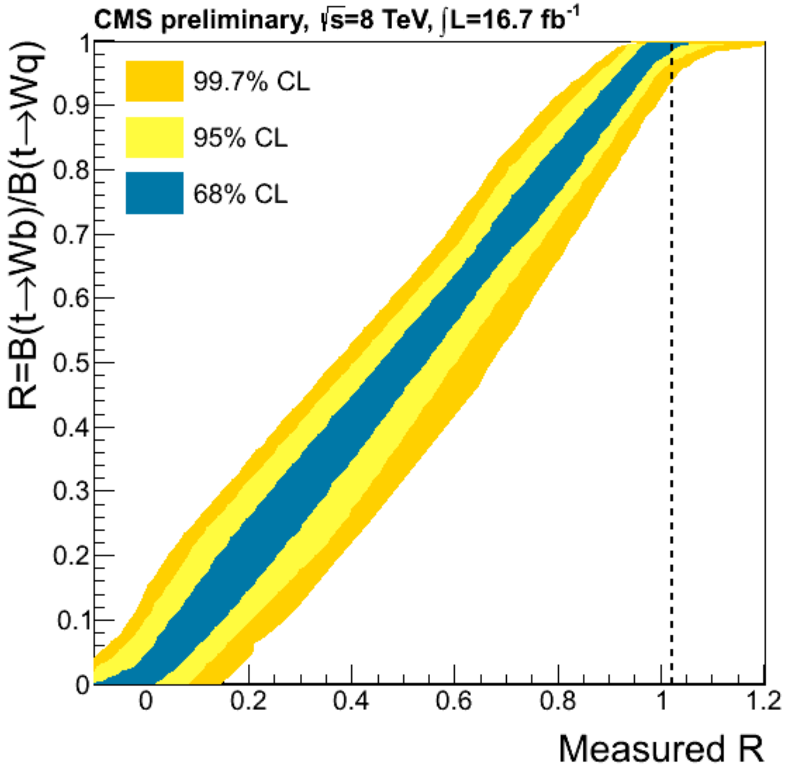
Measurement of the ratio
R=B(t → Wb) / B(t → Wq)

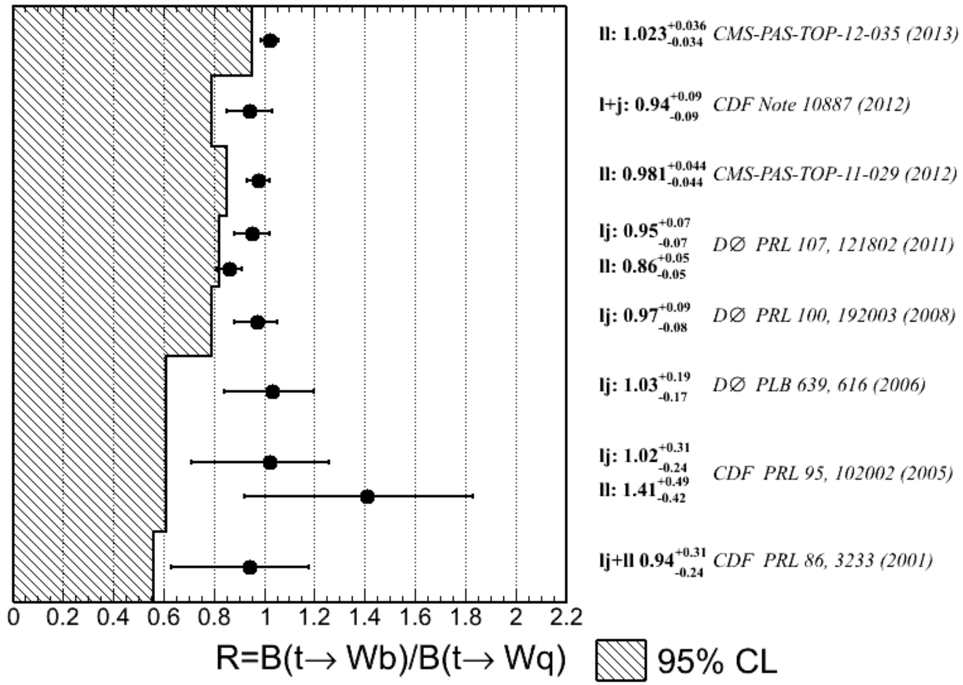


CMS TOP-12-035

Measurement of the ratio R=B(t → Wb) / B(t → Wq)

A lower limit R>0.945 at 95% CL is obtained after requiring that R≤1



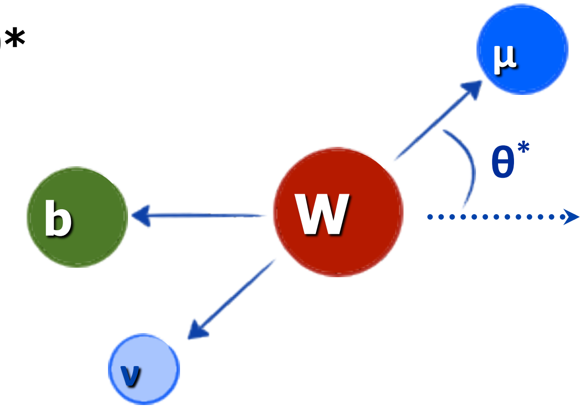


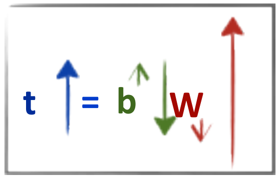
CMS TOP-12-035

W helicity in top decays

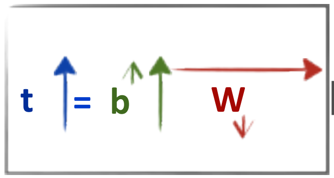
V-A SM nature of the tWb coupling can be probed using θ*

- compute cosθ* to measure contributions from different helicities
- $F_{0/L/R}$ relative contributions for SM are well known
- Different relative contrib. can indicate new physics
  - in SM only $V_L \neq 0$ and $g_R = g_L = V_R = 0$

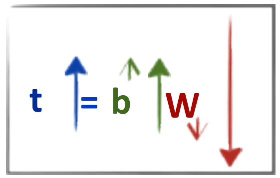




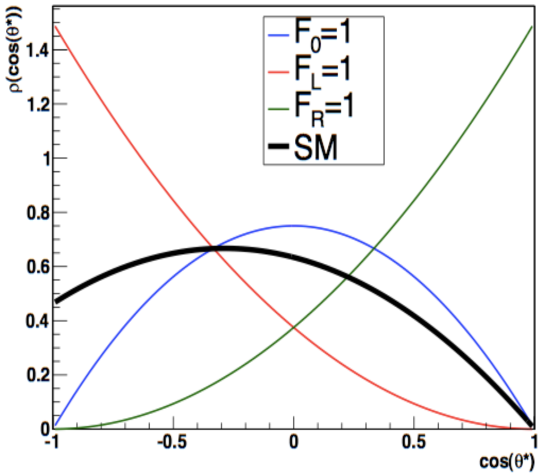
F_L [SM≃0.311]



F_0 [SM≃0.687]

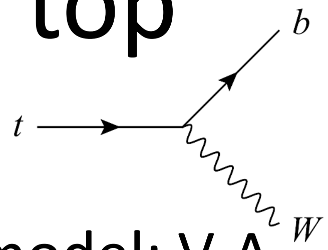


F_R [SM≃0.001]

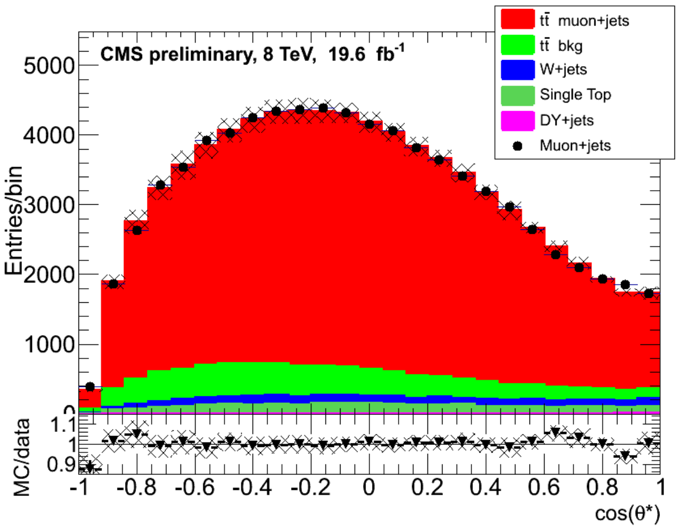


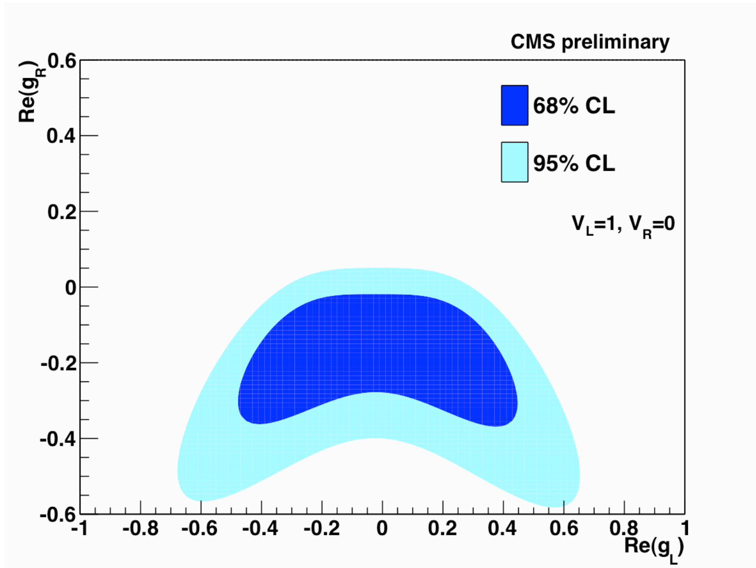
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)F_0 + \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{8}(1+\cos\theta^*)^2 F_R$$

The tWb vertex : W helicity in top decays



- The W helicity precisely predicted in the standard model: V-A structure of the decay
  - Longitudinal W polarization F0 ≈ 70%, **intimately related to the ewk breaking mechanism !**
  - Left polarization FL≈30%, Right pol FR ≈0





W helicity in top decays: results

ATLAS (l+jets + dilepton combined)
[JHEP 1206 (2012) 088]

- F_0 = 0.67 ± 0.03 (stat) ± 0.06 (syst)
- F_L = 0.32 ± 0.02 (stat) ± 0.03 (syst)
- F_R = 0.01 ± 0.01 (stat) ± 0.04 (syst)

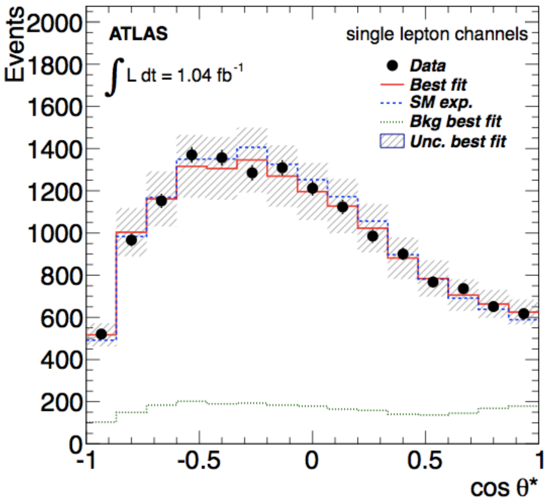
CMS (dilepton)
[CMS PAS TOP-12-15]

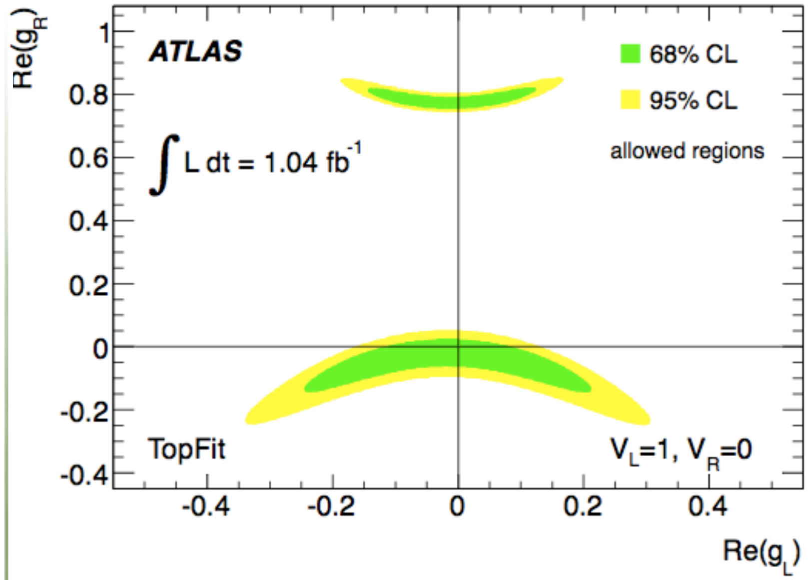
- F_0 = 0.698 ± 0.057 (stat) ± 0.063 (syst)
- F_L = 0.288 ± 0.035 (stat) ± 0.050 (syst)
- F_R = -0.014 ± 0.027 (stat) ± 0.055 (syst)

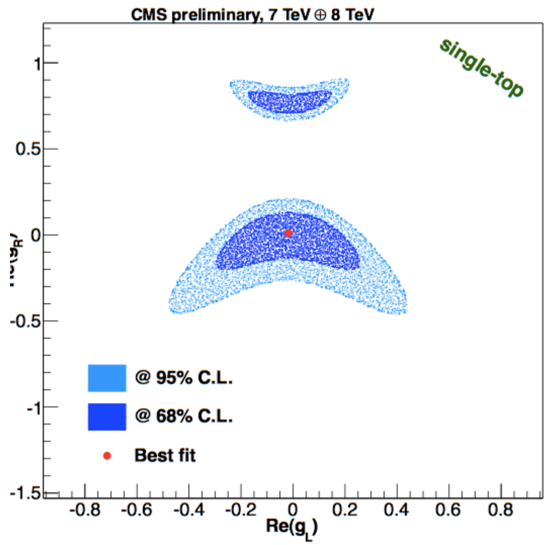
CMS (single top 7TeV + 8TeV)
[CMS PAS TOP-12-20]

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

Results compatible with SM



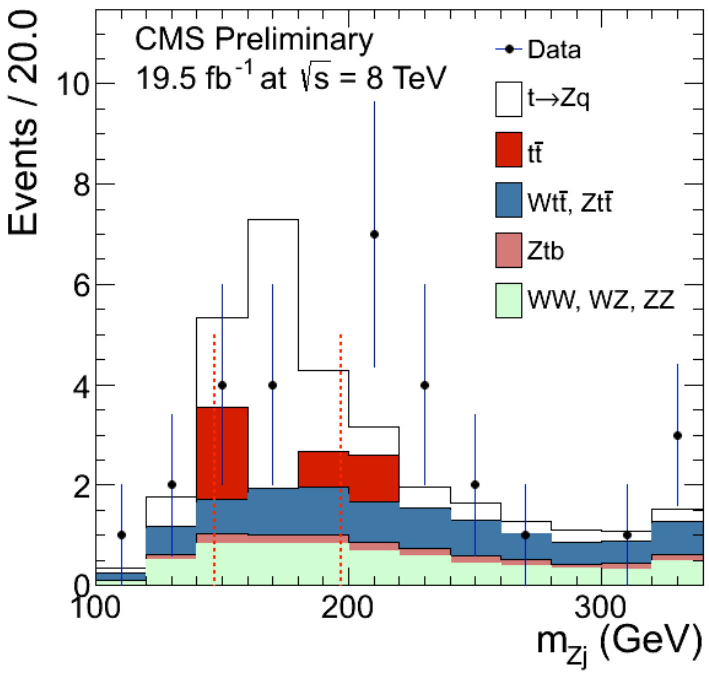


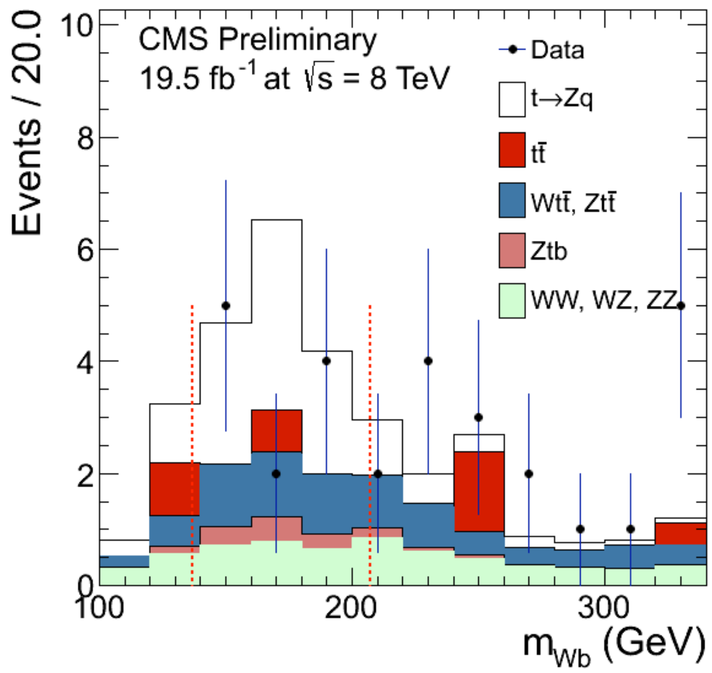


Used to probe anomalous couplings

Rare processes: limits on FCNC t→Zq

- FCNC searches have improved a lot with 20/fb
  - Current result from ttbar/trilepton searches: A t → Zq branching fraction greater than 0.07 % is excluded at the 95 % confidence level.



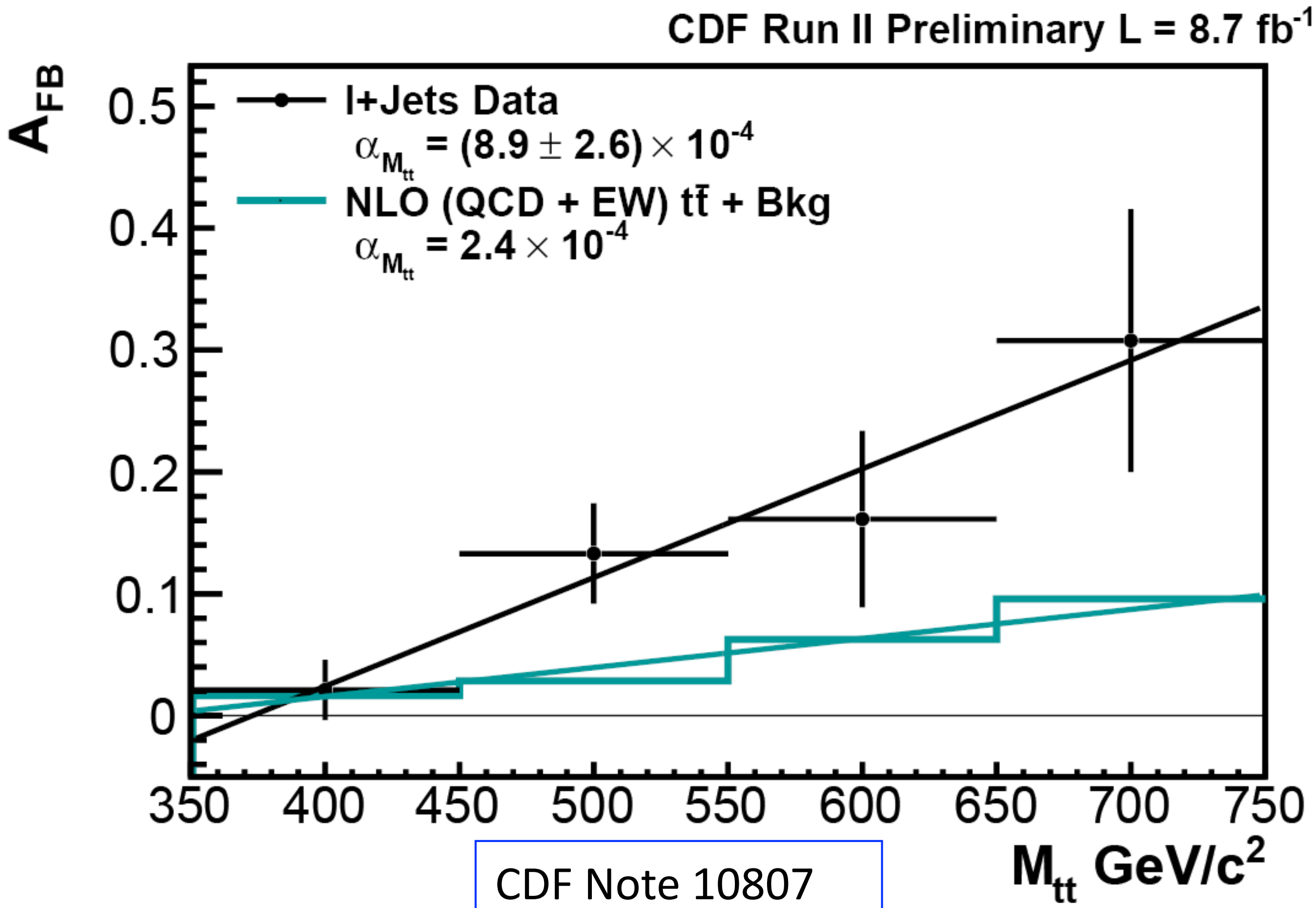


TESTING TOP PRODUCTION PROPERTIES

A discrepancy ? … A_{FB} in $p\bar{p}$

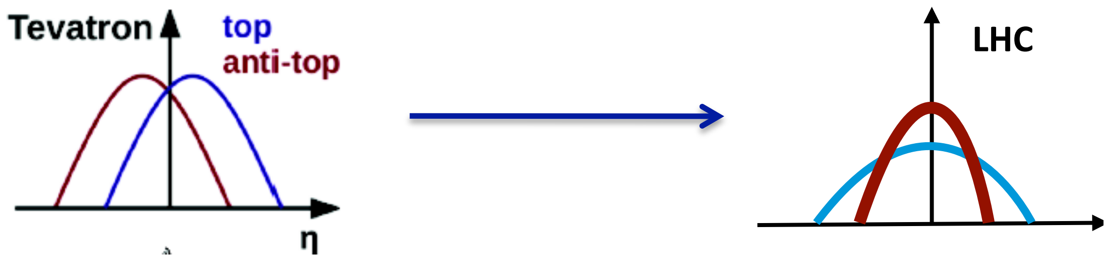
$$q\bar{q} \rightarrow t\bar{t}$$

- SM asymmetry from interference (higher order QCD ~ 7%)



CDF Note 10807

A_{FB} a LHC → charge asymmetry



$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

$$\Delta|y| = |y(t)| - |y(\bar{t})|$$

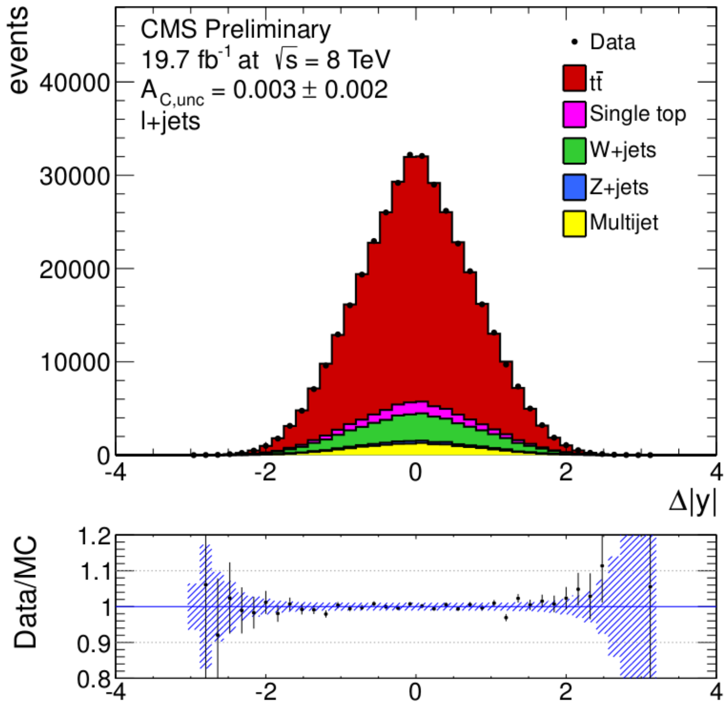
- top / anti-top rapidity asymmetry at LHC from quark-antiquark annihilation, gluon-gluon fusion, dominant process, intrinsically symmetric

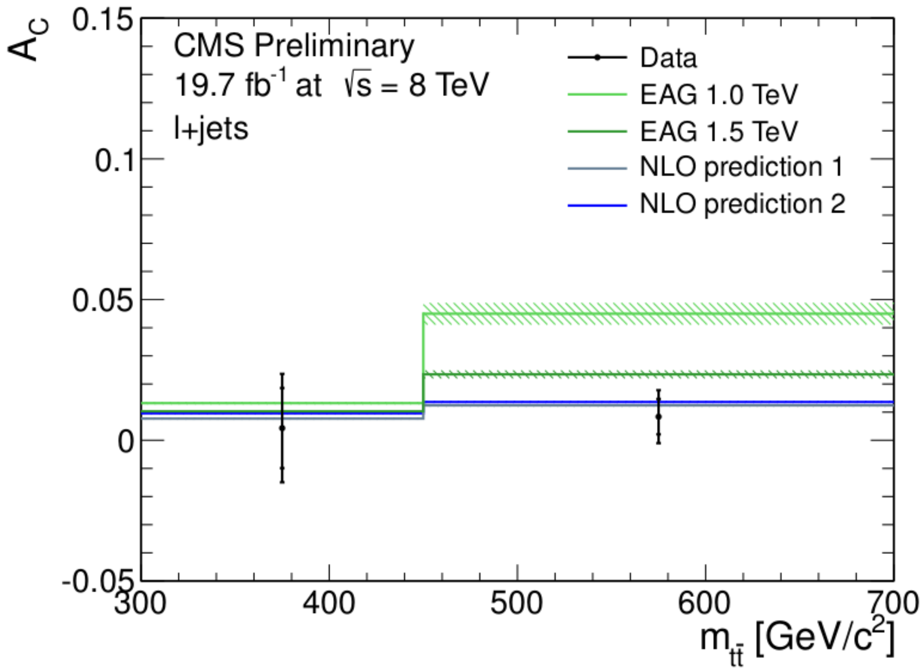
$$14\ \text{TeV}\ gg \rightarrow t\bar{t}\ (90\%),\ q\bar{q} \rightarrow t\bar{t}\ (10\%)$$

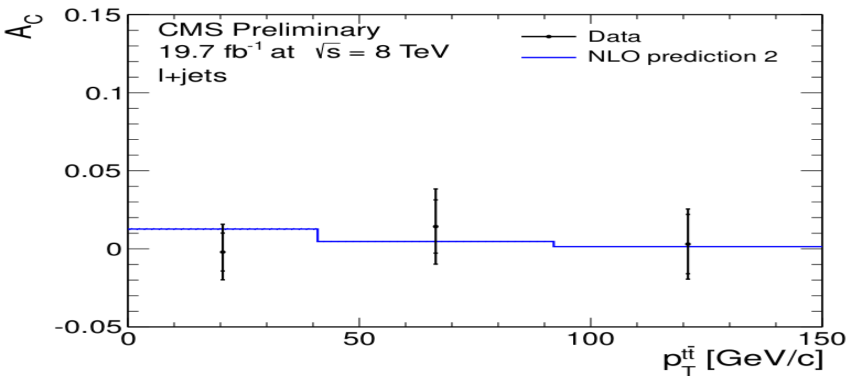
- **Important at LHC to study differential asymmetries**, to enhance new physics
  - **Sum of t and tbar rapidity to disentangle quark-antiquark and gluon-gluon fusion**
  - **ttbar invariant mass sensitive to new heavy states**
  - **Transverse momentum of the ttbar system sensitive to interference due to ISR**

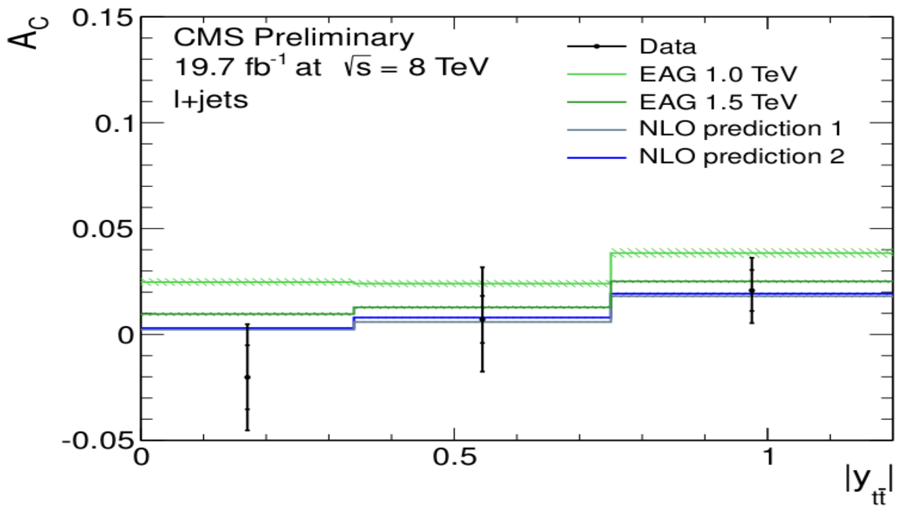
CMS PAS TOP-12-033

Charge asymmetry at LHC





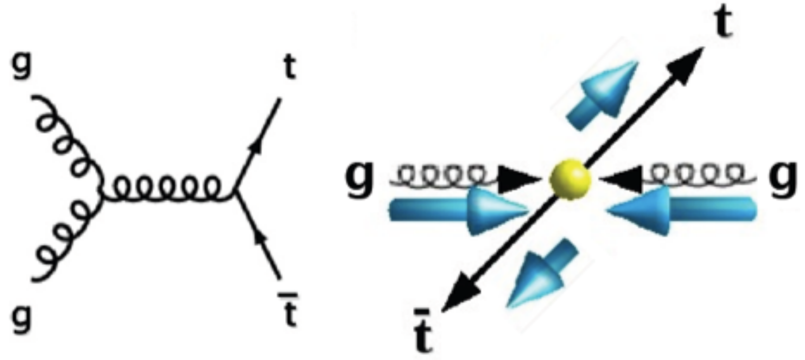




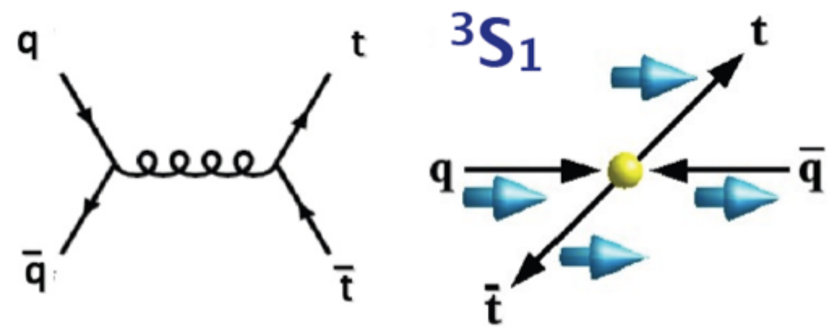
Spin correlations in ttbar

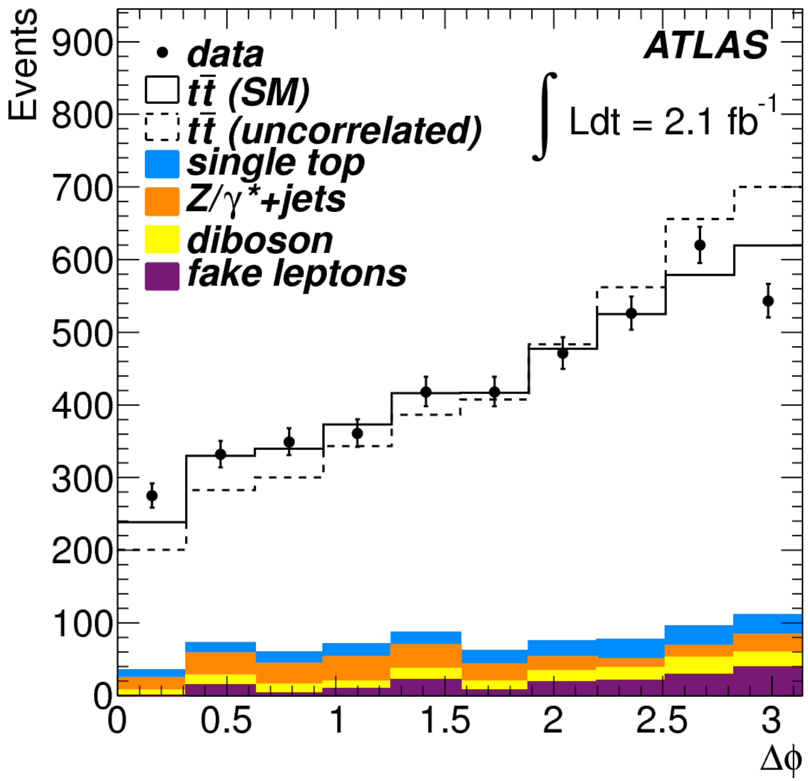
Another tool to investigate the production mechanism, possible only for the top quark
Investigating it now, but will become a precision tool with high statistics

gluon-gluon example at high boost

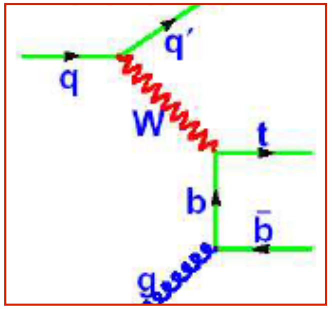


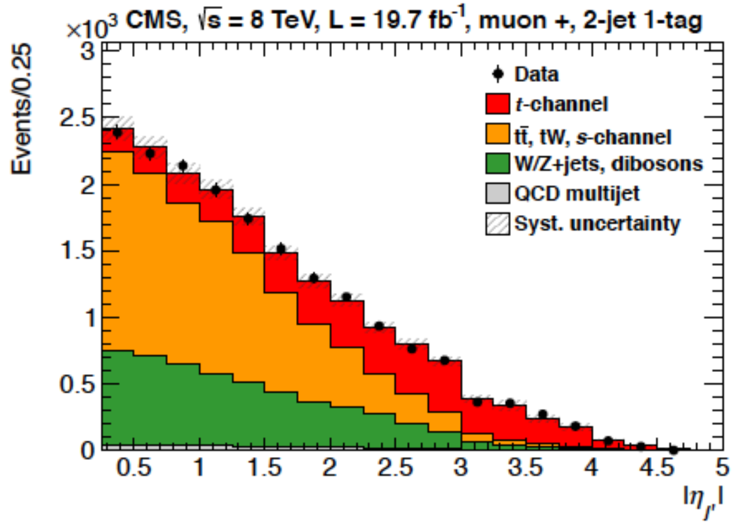
qqbar example at threshold

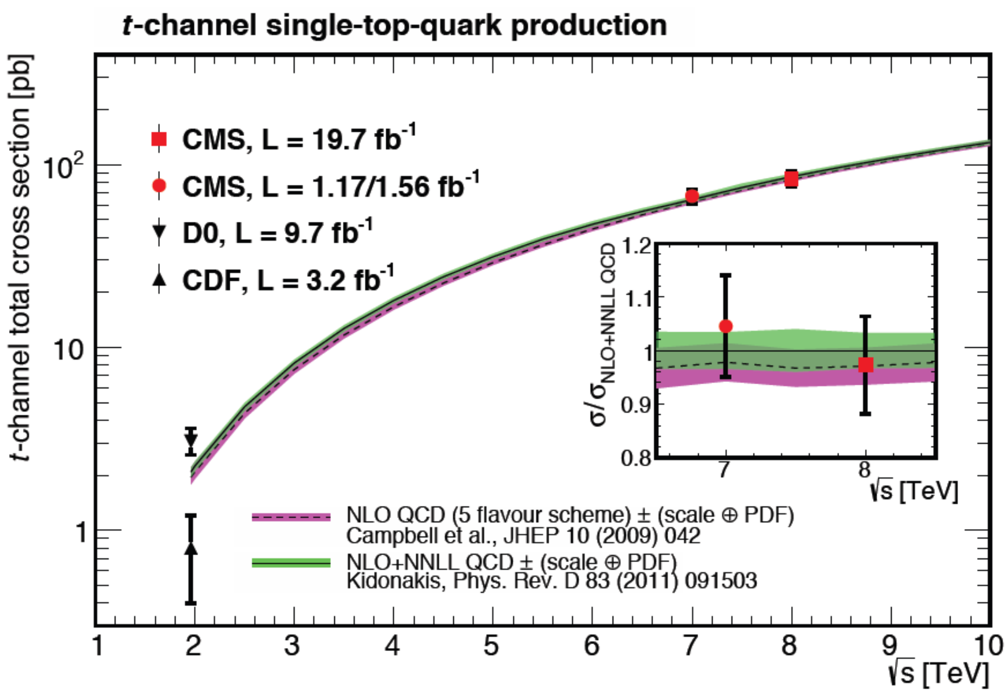


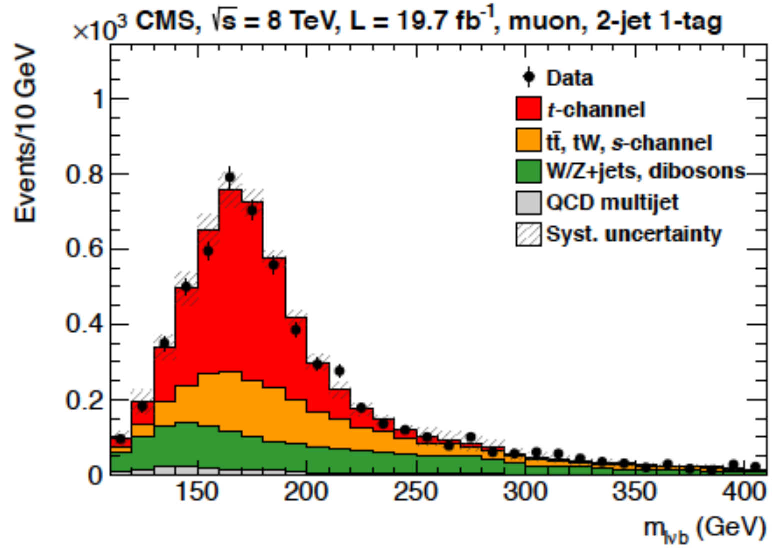


Single top t-channel



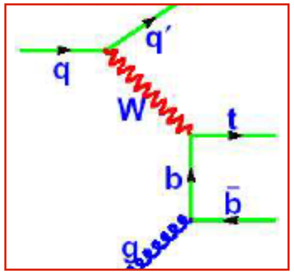


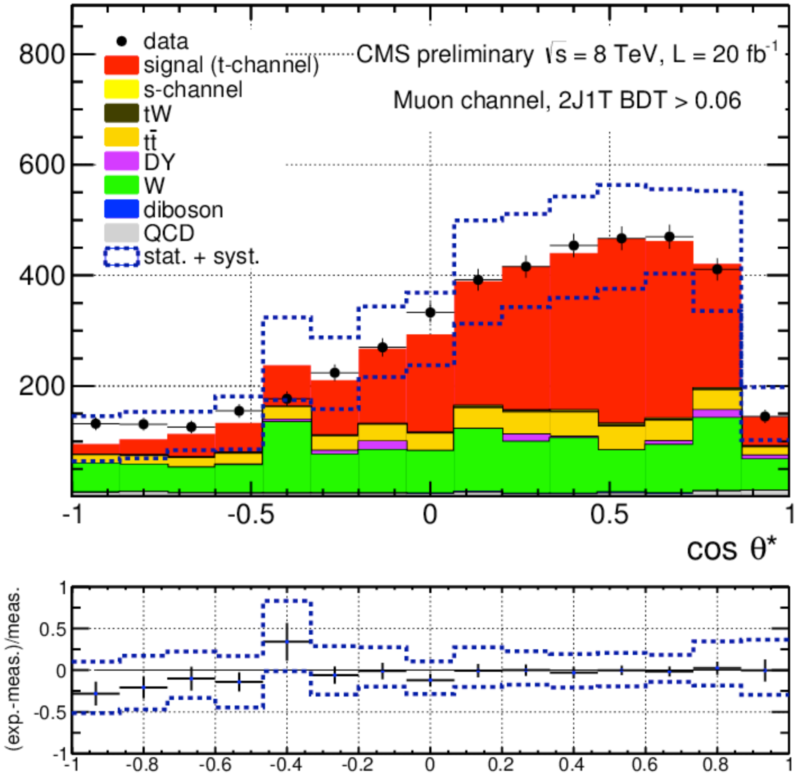


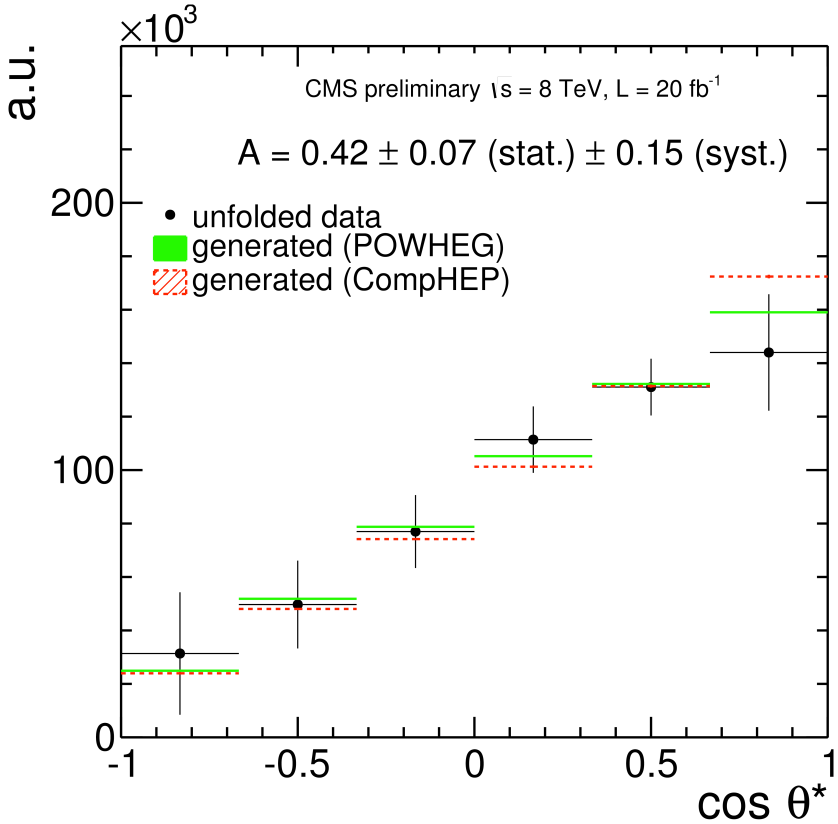


single top polarization in t-channel

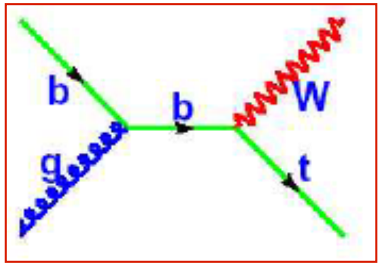
- V-A current, top 100% polarized !



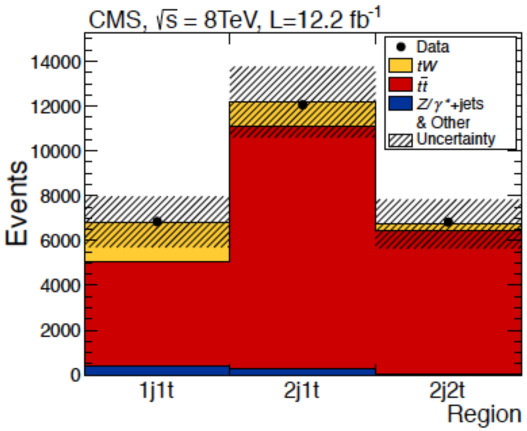


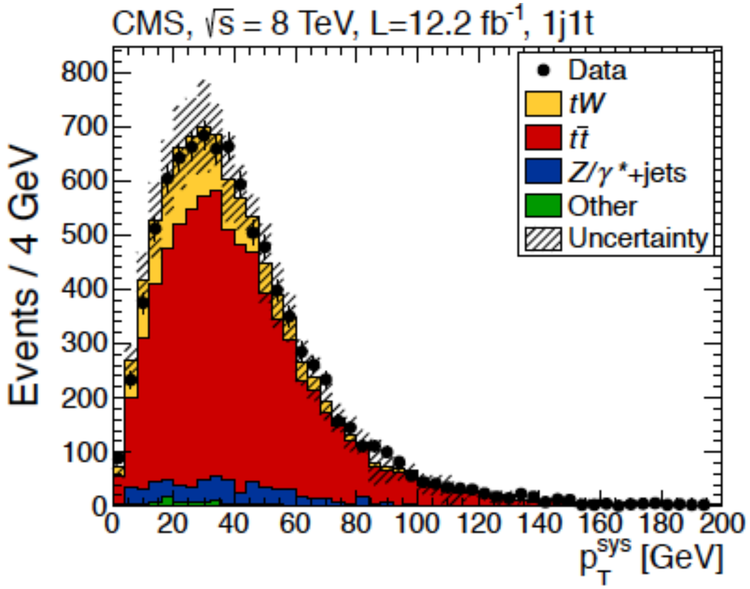


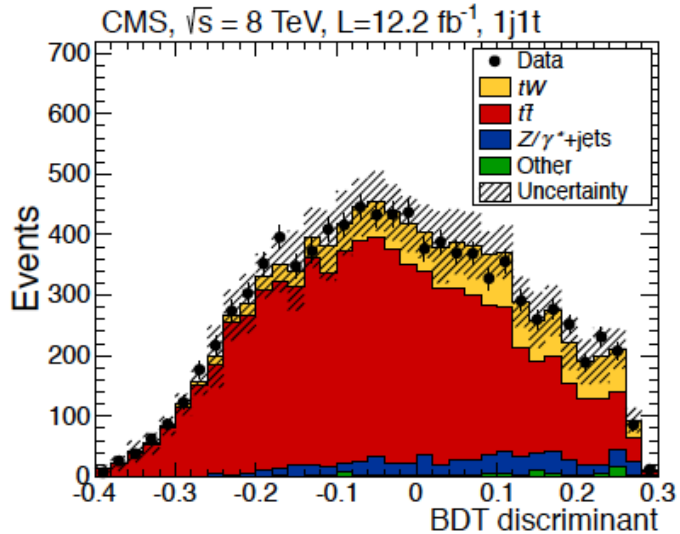
single top tW channel



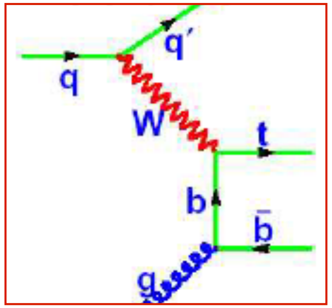
categorization important !

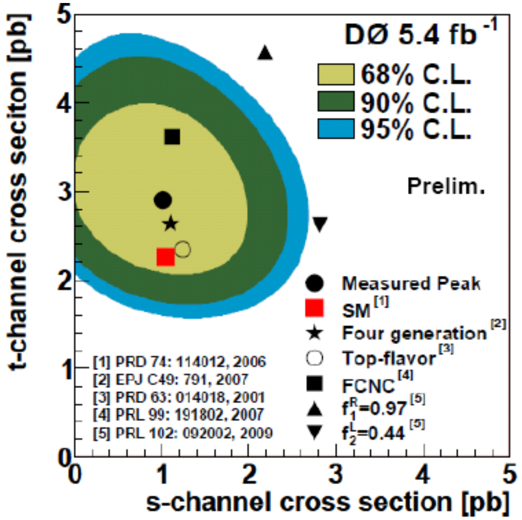


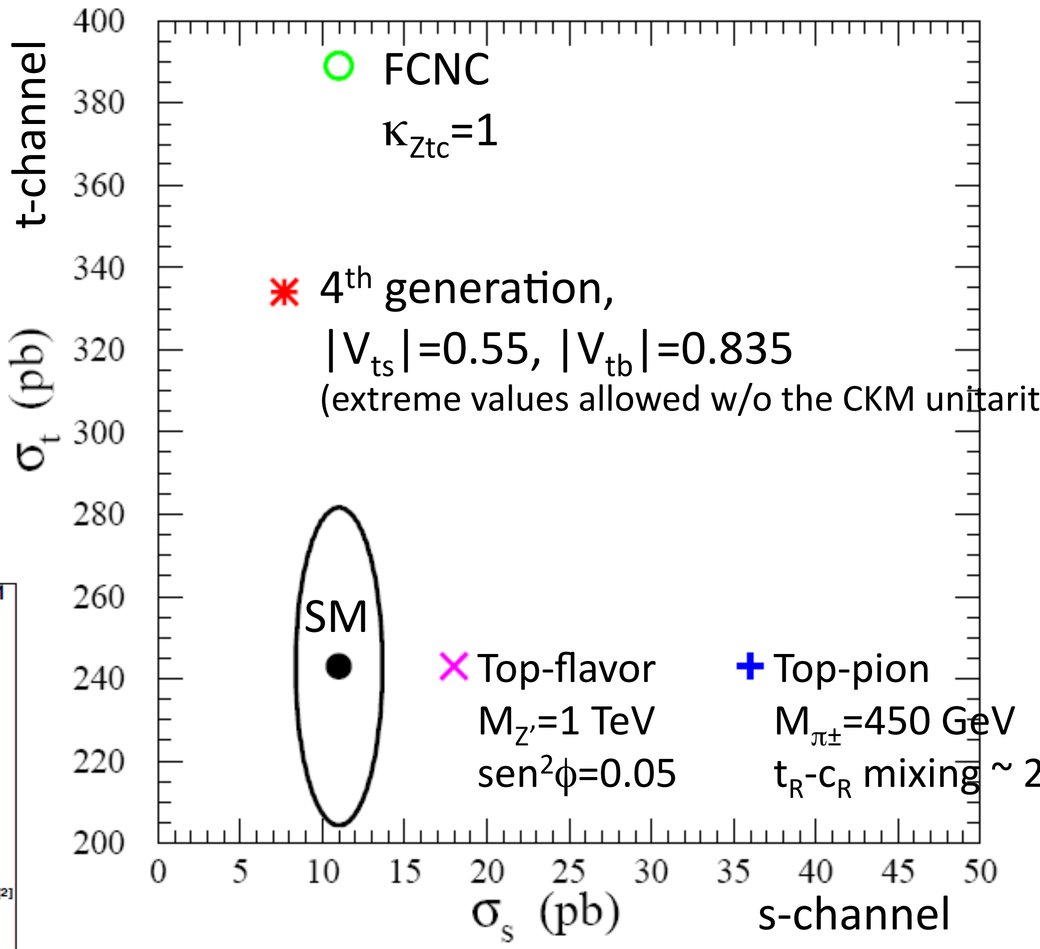




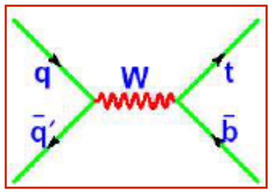
Single top in t and s channel sensitive to different aspects of New Physics (tW, too !)







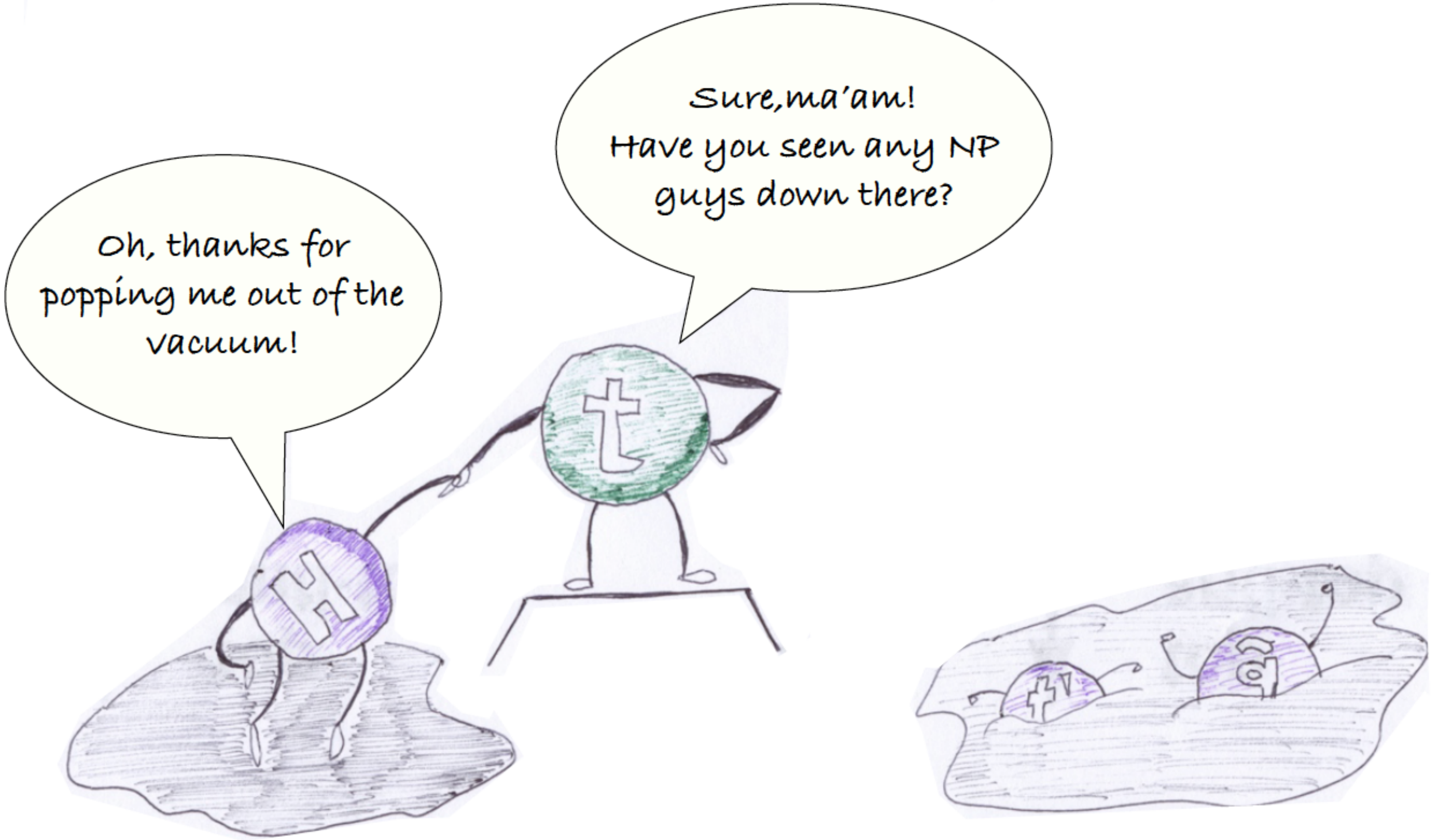
(plot for 14 TeV)



T.Tait, C.-P.Yuan, Phys.Rev. D63 (2001) 0140018

Conclusions

- **Top physics an important sector of electroweak-symmetry-breaking studies**
  - **A complement to direct Higgs measurements**
- After first three years of top-physics results **at the LHC-top-factory**, now entering a new phase
- **Entering uncharted territory in terms of (statistical) precision, use statistics as a tool to reduce systematic uncertainties**



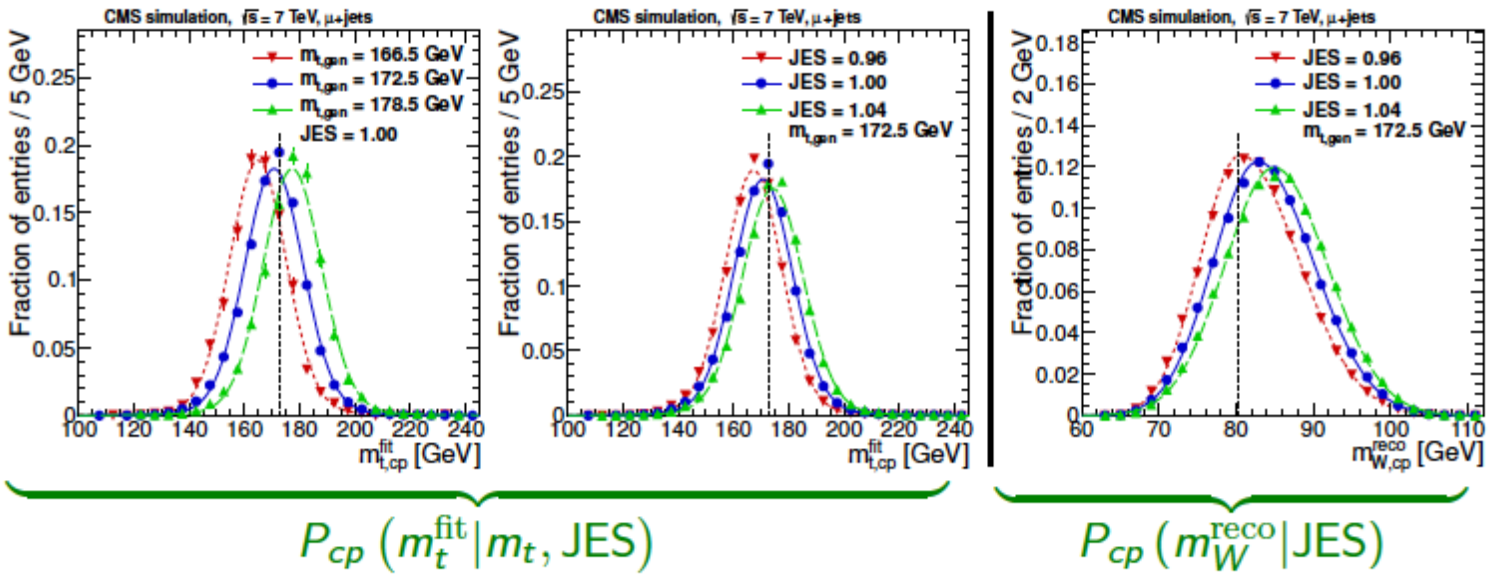
Courtesy of Fabio Maltoni

BACKUP

Ideogram method: probability densities

- Simulated samples with
  - 9 different top masses: 161.5–184.5 GeV
  - 3 different JES: 0.96, 1.00, 1.04
- Fit $m(top)_{fit}$, $m(W)_{reco}$ distributions with analytical expressions
- Parametrize linearly in m_t , JES, $m_t \times$ JES

Example: *correct permutations*



Ideogram method

- Calculate likelihood for event with n permutations, j denotes *correct*, *wrong* and *unmatched* permutations

$$\mathcal{L}(\text{event}|m_t, \text{JES}) = \sum_{i=0}^{n} P_{gof}(i)\, P\left(m_{t,i}^{fit}, m_{W,i}^{reco}|m_t, \text{JES}\right),$$

$$P\left(m_{t,i}^{fit}, m_{W,i}^{reco}|m_t, \text{JES}\right) = \sum_j f_j P_j\left(m_{t,i}^{fit}|m_t, \text{JES}\right) \cdot P_j\left(m_{W,i}^{reco}|m_t, \text{JES}\right)$$

- Most likely m_t and JES by maximizing

$$\mathcal{L}(m_t, \text{JES}|\text{sample}) \sim \prod_{\text{events}} \mathcal{L}(\text{event}|m_t, \text{JES})^{w_{\text{event}}}$$