Séminaires LAL
Orsay, 17th July 2015

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

INFN

Top physics results from CMS
(selected topics)

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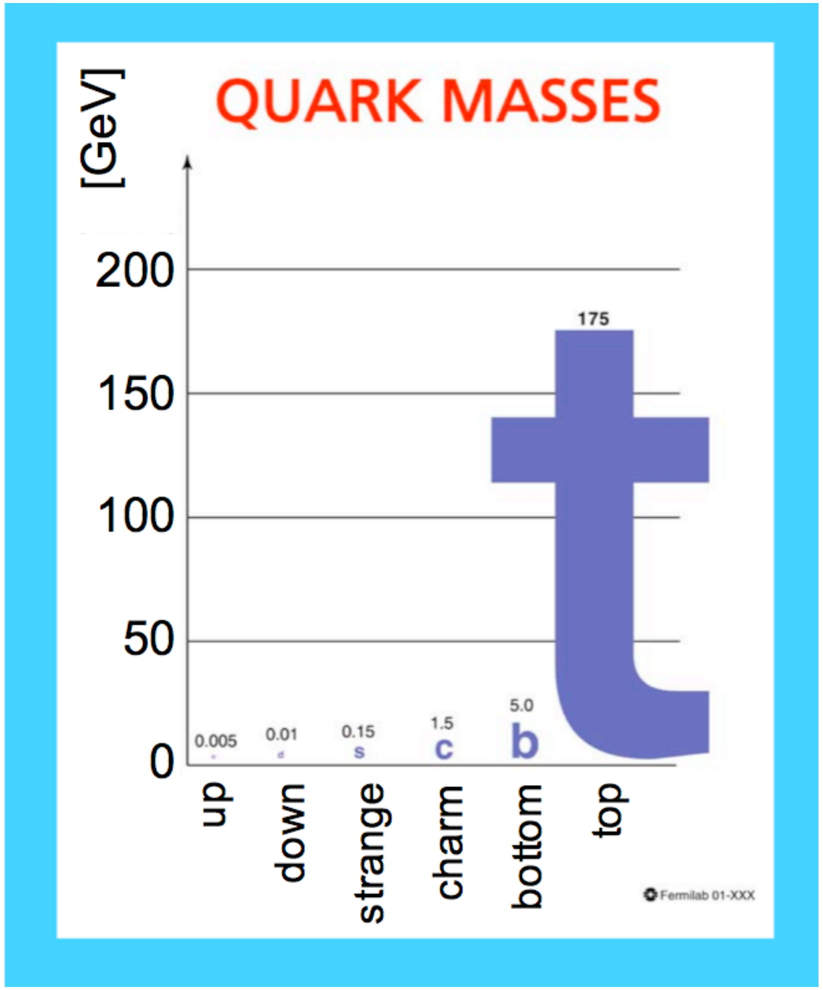
INFN Pisa

Its highness, the top quark

- 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*

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

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



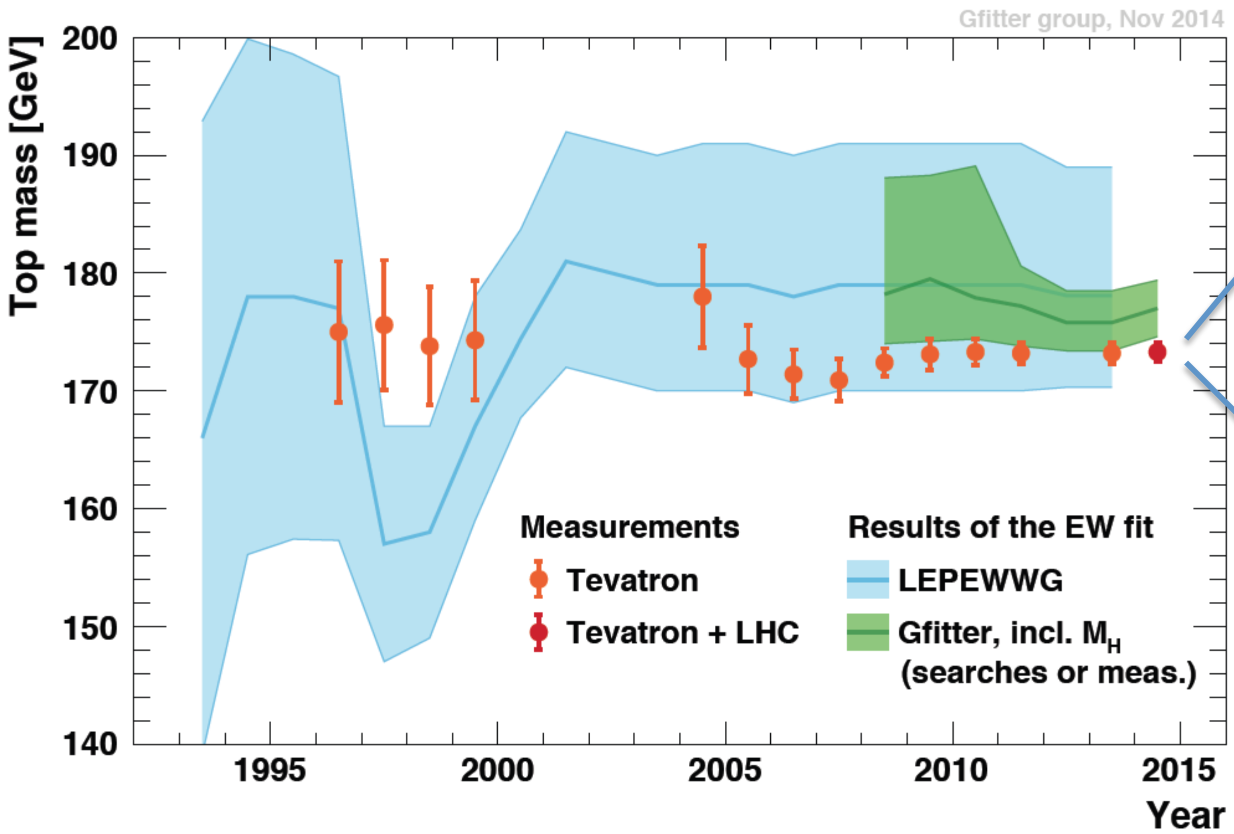
Some consequences of the large top mass (the large top-Higgs Yukawa coupling)

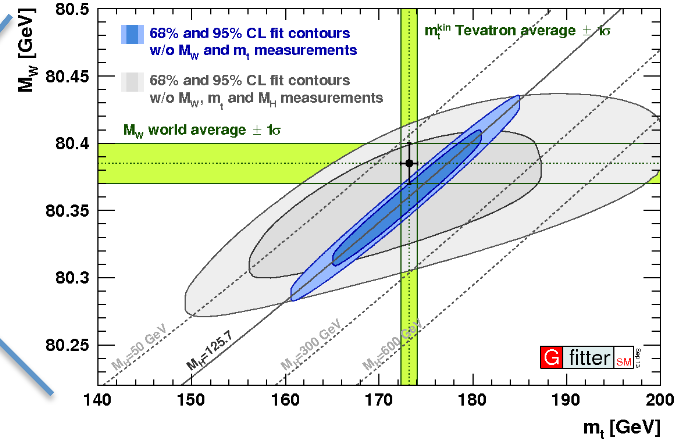
- Due to the non-decoupling properties of electroweak interactions (Veltman, 1977) the top quark gives large contributions to pure EWK radiative corrections $\approx G_F m_t^2$
- Very short lifetime: bound states are not formed, opportunity to study a free quark

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

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

Top mass and electroweak physics



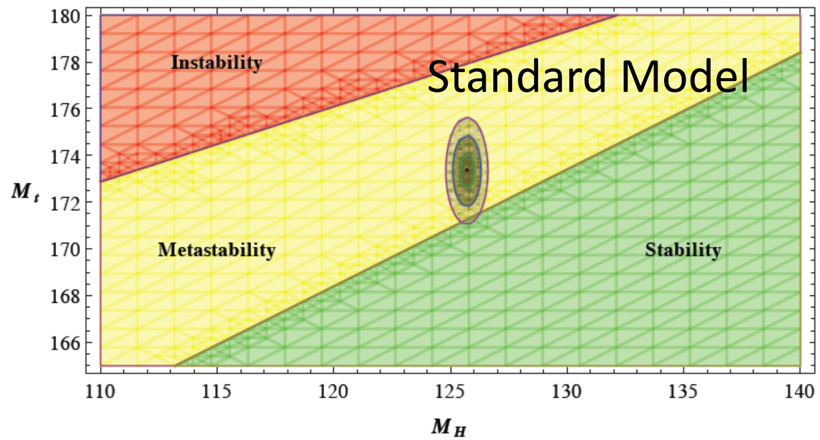


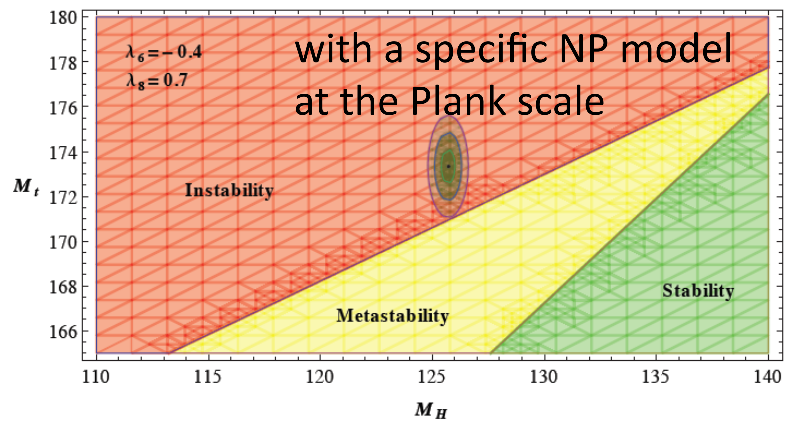
Courtesy of Roman Kogler

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

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

The fate of our universe, i.e. the stability of the EWK vacuum (Degrassi et al., arXiv:1205.6497), might not depend (only) on its mass, nevertheless the top mass value opens a window to new physics up to the Planck scale (Branchina et al., arXiv:1407.4112)

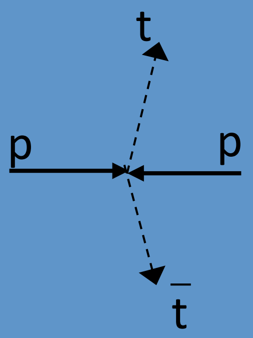




TOP PRODUCTION AND DECAY: GETTING THE DATA SAMPLES

Top Quark Production at the LHC

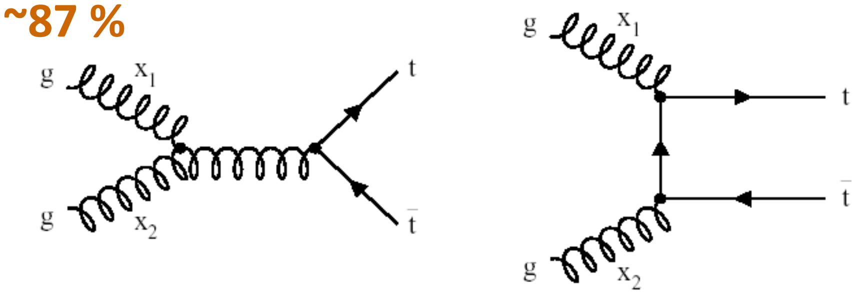
top pairs

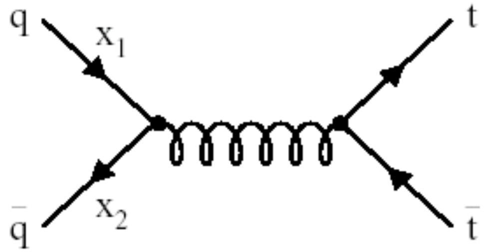


10 tt pairs per day @ Tevatron → 1 tt pair per second @ LHC

qq →tt : 85% *gg→tt : 87%*

~87 %

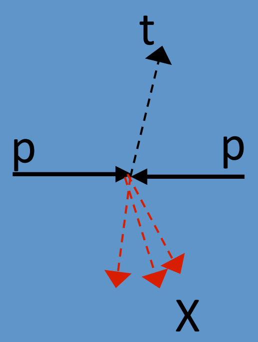




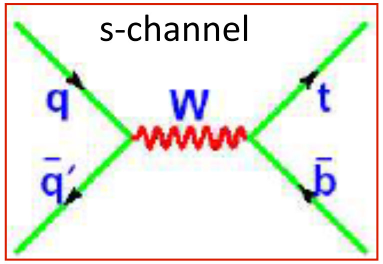
- NLO cross-section σ^{NLO} = **232** pb at 8 TeV ~2 M events/10fb^{-1}
- NNLO calculations now available, Czakon, Mitov (2013) arXiv:1303.6254

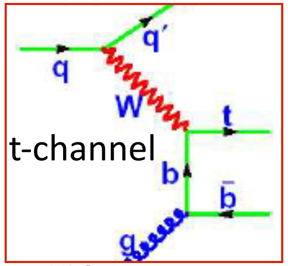
Some references (not a complete list!): (top pairs) N.Nason *et al.* Nucl.Phys. B303 (1988) 607, S.Catani *et al.* Nucl.Phys. B478 (1996) 273, M.Beneke *et al.* hep-ph/0003033, N.Kidonakis and R.Vogt, Phys.Rev. D68 (2003) 114014, W.Bernreuther et al. Nucl.Phys. B690 (2004) 81-137 (single-top) T.Stelzer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

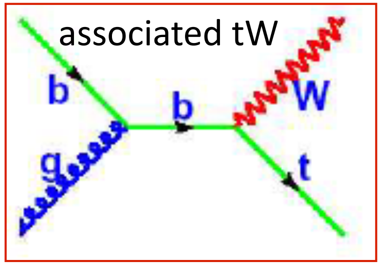
single-top



30 single-tops per minute @ LHC







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

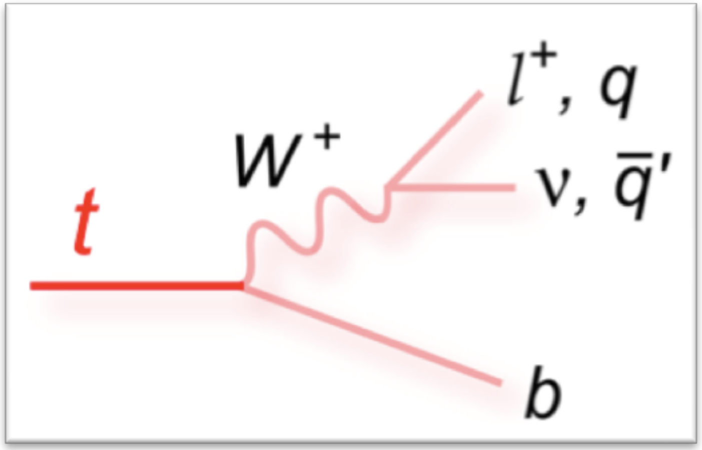
σ^{NLO}(total) 8 TeV = **112** pb

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

s-channel	t-channel	associated tW	
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

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%

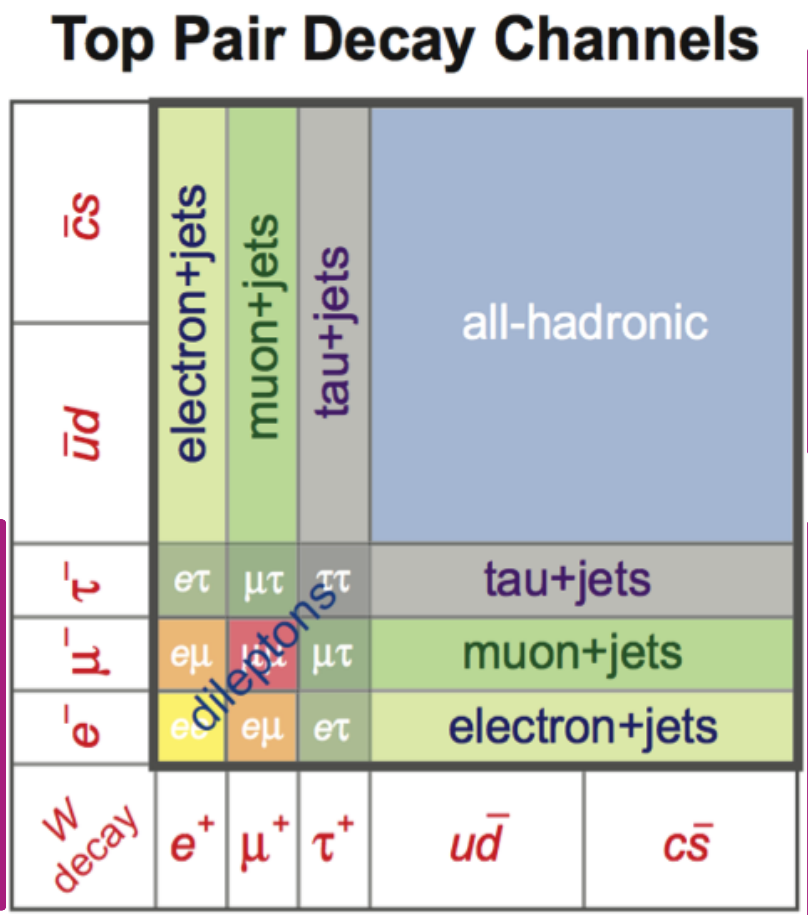
Low background

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:

- EXAMPLE IN THE LEPTON+JETS CHANNEL

- WHAT ARE WE MEASURING ?

- ALTERNATIVE METHODS

- DIFFERENTIAL TOP MASS

Methods for top mass measurement (1)

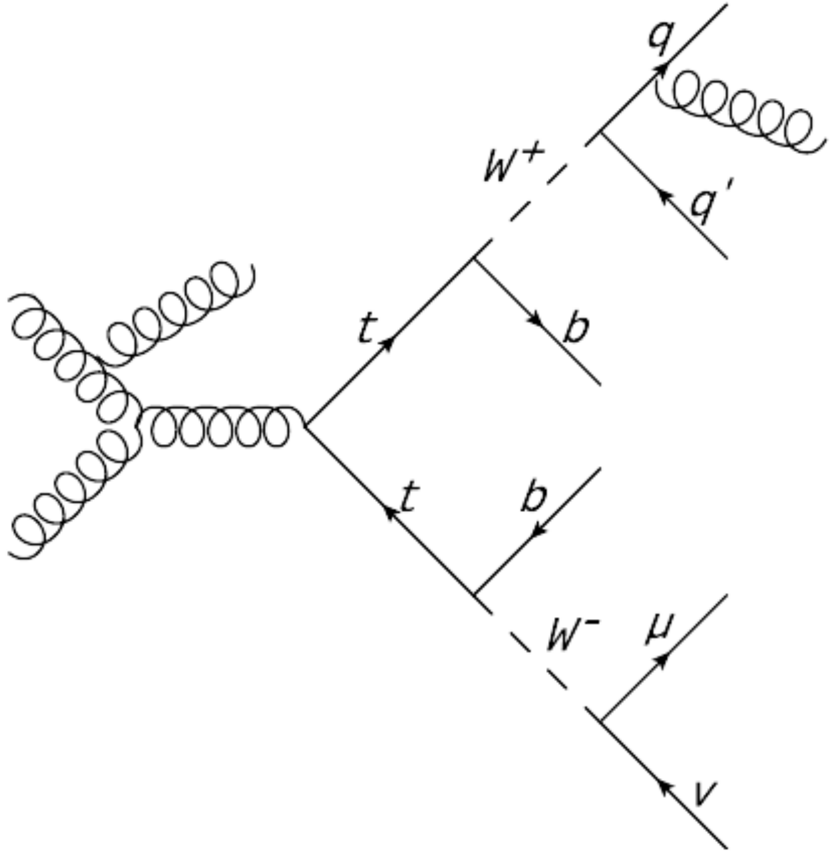
- *Standard methods* at hadron colliders: measure the top mass from the decay products in a specific **top pair decay channel**
  - from the simplest versions: measure invariant mass of, e.g. three jets in lepton+jets events
  - to the more sophisticated versions: use of the full event information to 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

An example 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 > 24 GeV [27 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

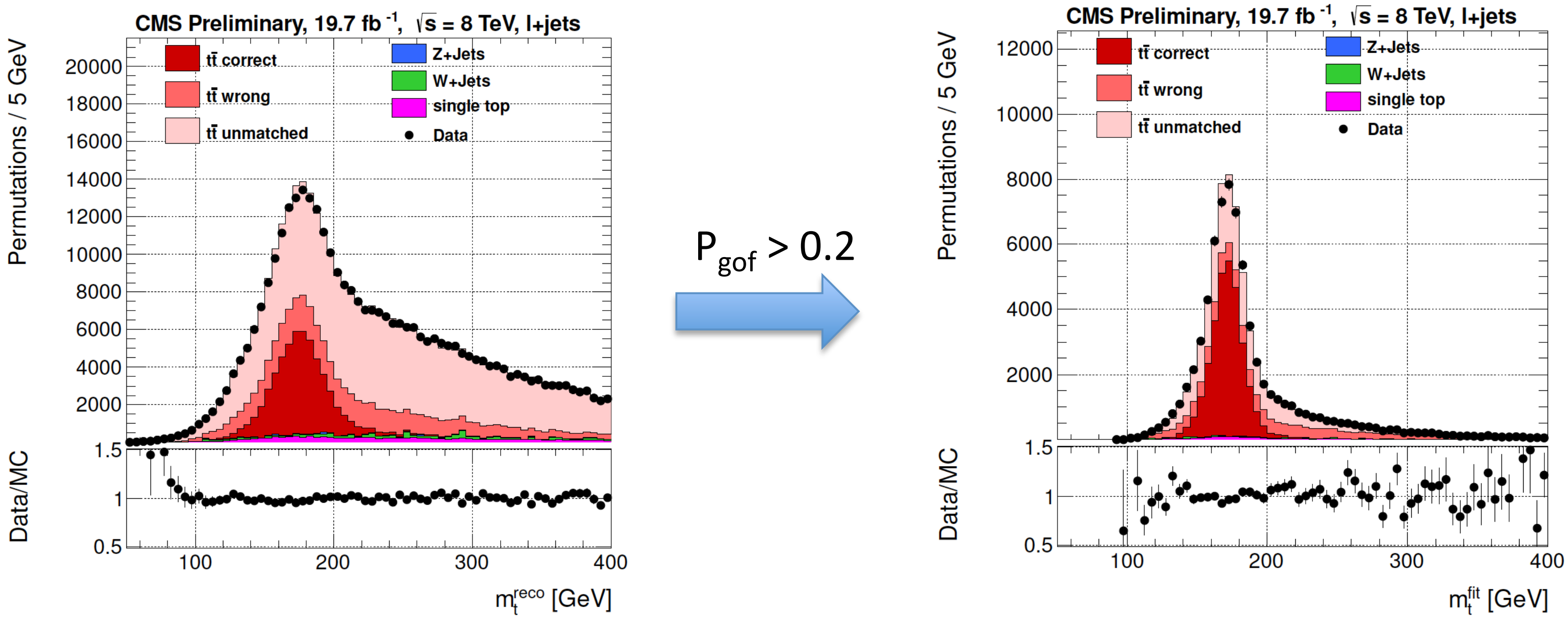


Compare with selections at Tevatron with full statistics: about 2500 events

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.)



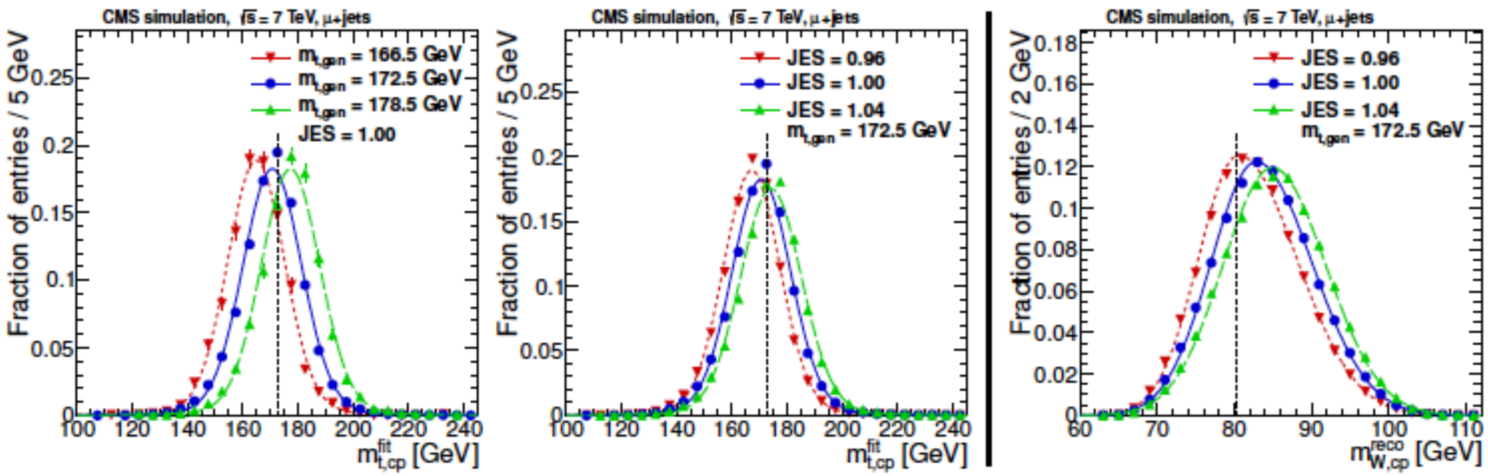
Top mass fitting techniques

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

Construct probability densities: ideogram method

- 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 × JES
- Take into account correct, wrong and unmatched permutations

Example: *correct permutations*



$P_{cp}\left(m_t^{\text{fit}} | m_t, \text{JES}\right)$ $P_{cp}\left(m_W^{\text{reco}} | \text{JES}\right)$

Ideogram method

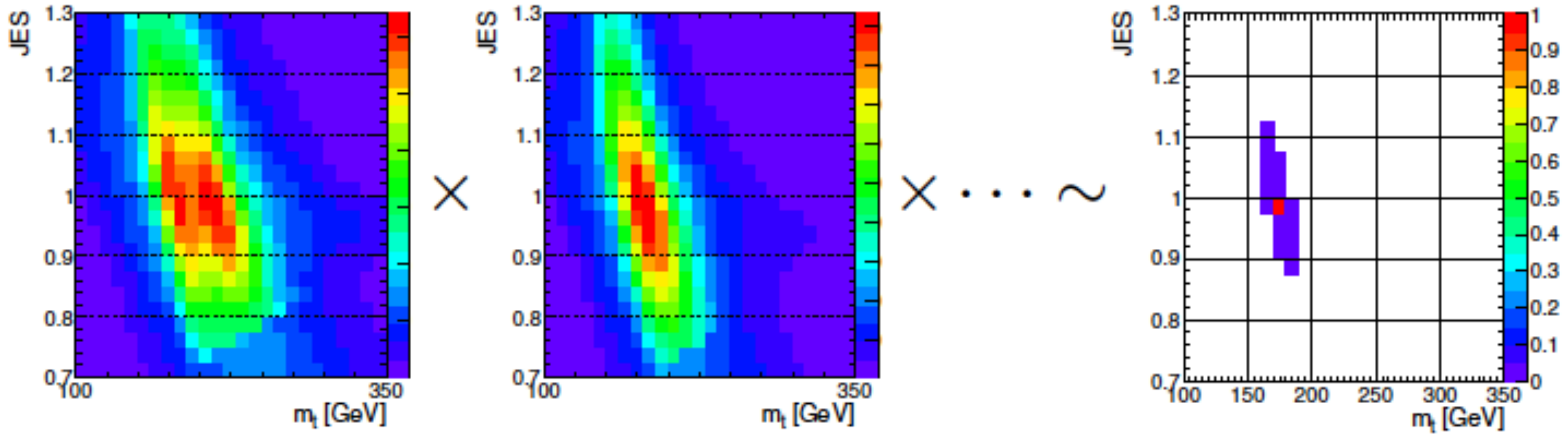
- Calculate likelihood for event with n permutations, j denotes *correct*, *wrong* and *unmatched* permutations

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

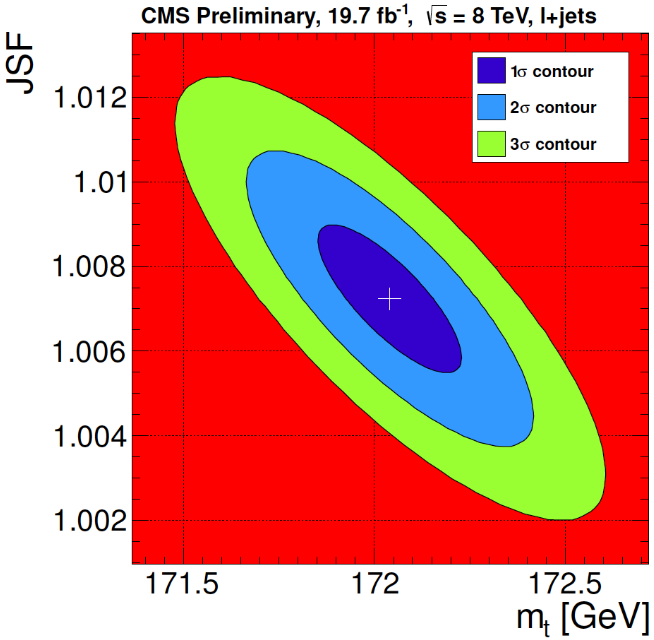
$$P\left(m_{t,i}^{fit}, m_{W,i}^{reco}|m_t, \text{JES}\right) = \sum_{j} f_j P_j\left(m_{t,i}^{fit}|m_t, \text{JES}\right) \cdot P_j\left(m_{W,i}^{reco}|m_t, \text{JES}\right)$$

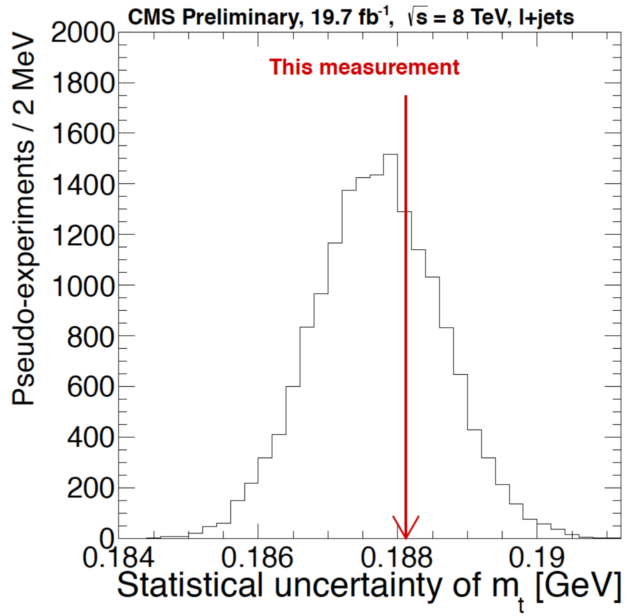
- Most likely m_t and JES by maximizing

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



Result for lepton+jet channel [TOP-14-001]



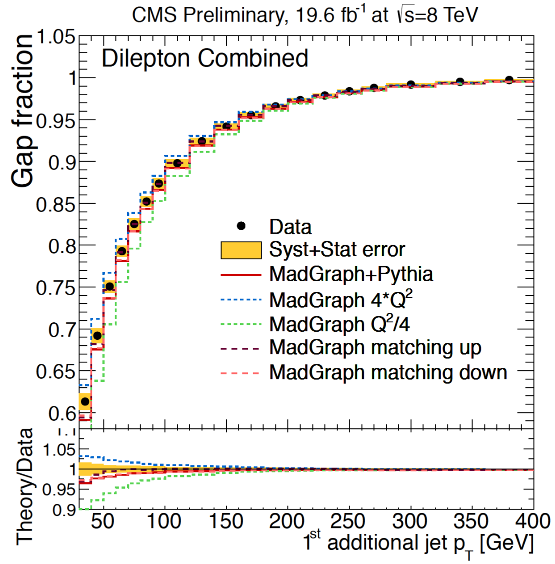


$$
\begin{aligned}
m_{\mathrm{t}} &= 172.04 \pm 0.19\,(\text{stat.+JSF}) \pm 0.75\,(\text{syst.})\,\text{GeV}, \\
\text{JSF} &= 1.007 \pm 0.002\,(\text{stat.}) \pm 0.012\,(\text{syst.}).
\end{aligned}
$$

Main sources of systematic uncertainties

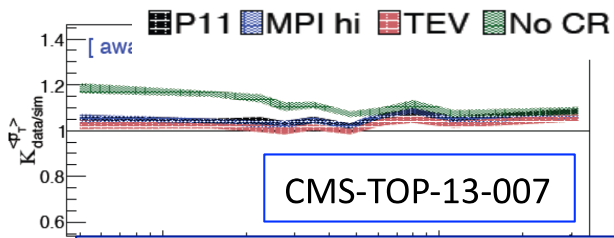
[for l+jet measurements]

- 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)



can use data to constrain radiation

CMS-TOP-12-014

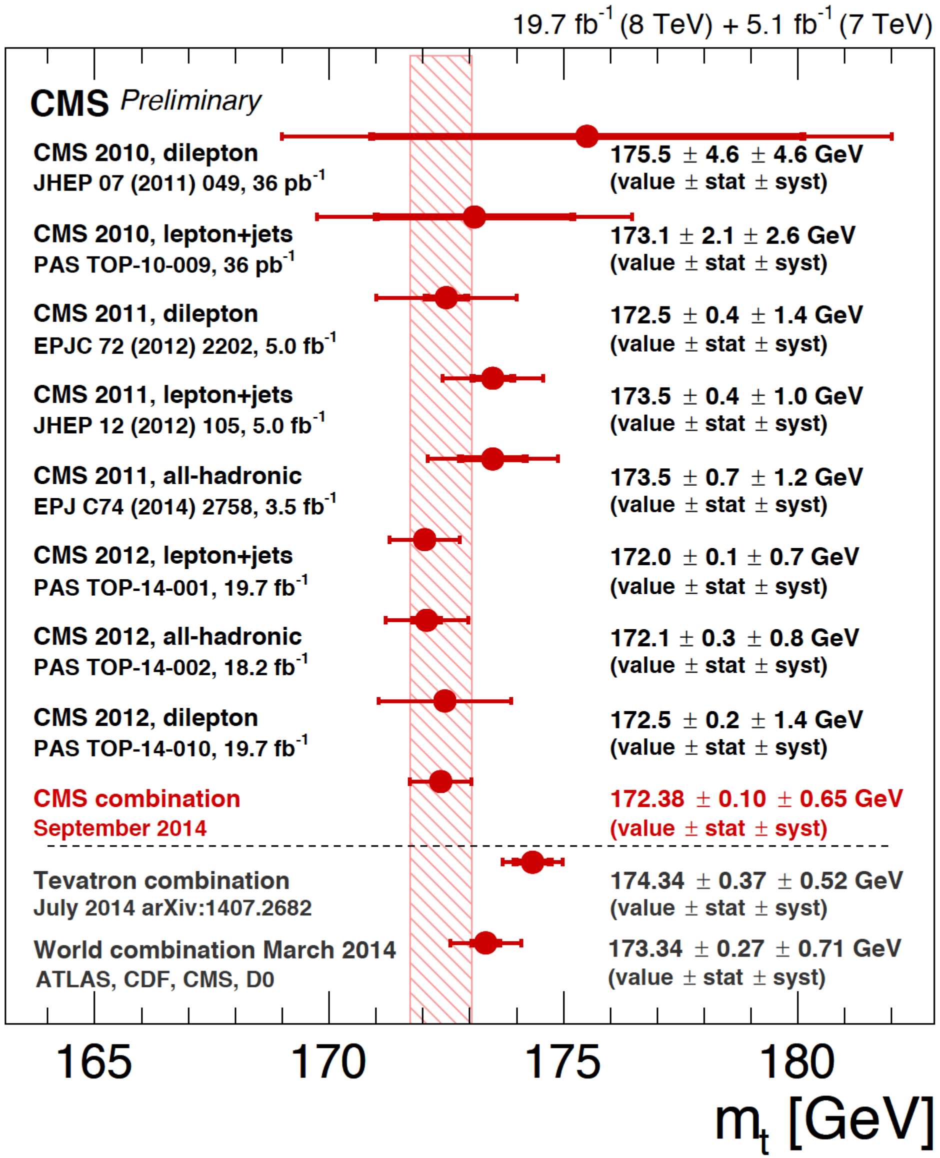


CMS-TOP-13-007

can use data to constrain generator modeling

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

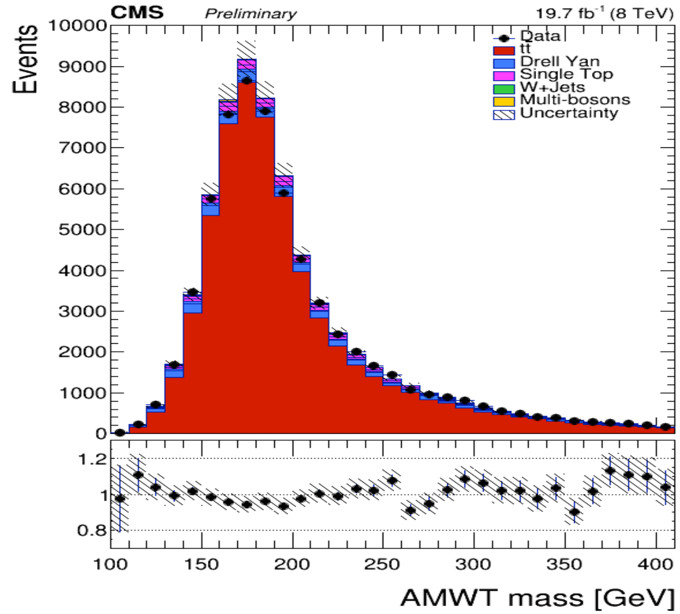
Summary of the eight CMS m_{top} "standard" measurements and their combination



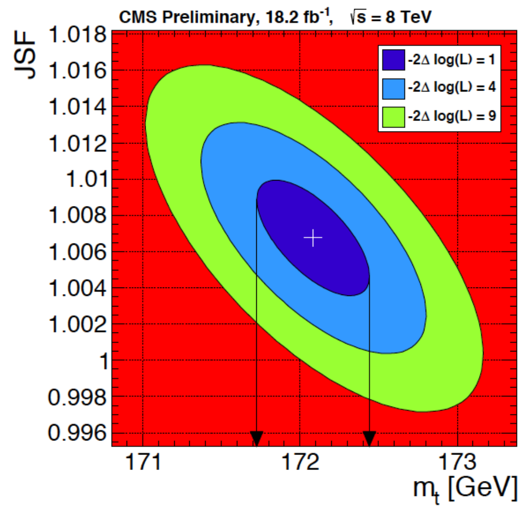
A note on the other channels

- 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

CMS-TOP-2014-010



CMS-TOP-2014-002

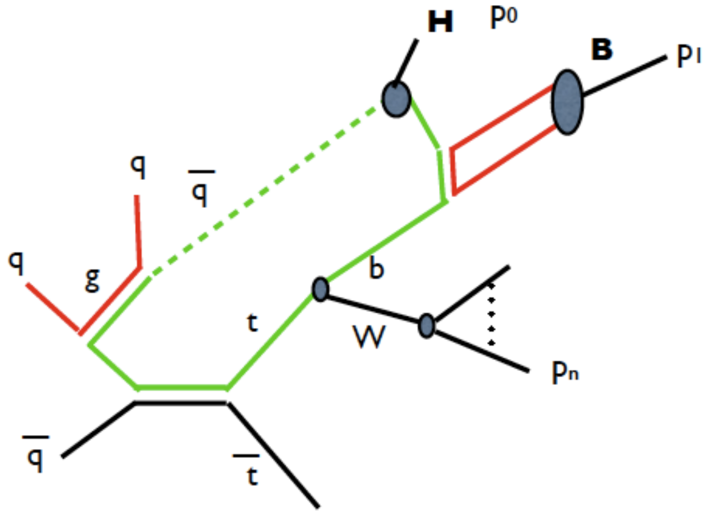


About measuring the top mass from its decay products

- **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 <u>the actual impact depends on the experimental method</u>

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

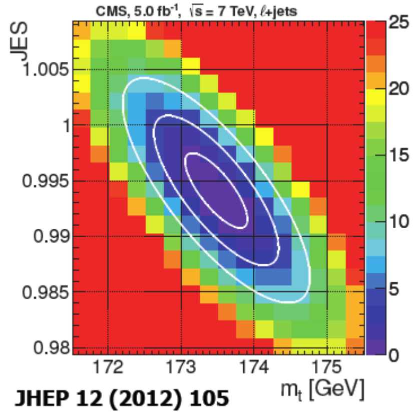
In prospect **1** and **2** will take advantage of the large LHC statistics



plot courtesy of Michelangelo Mangano

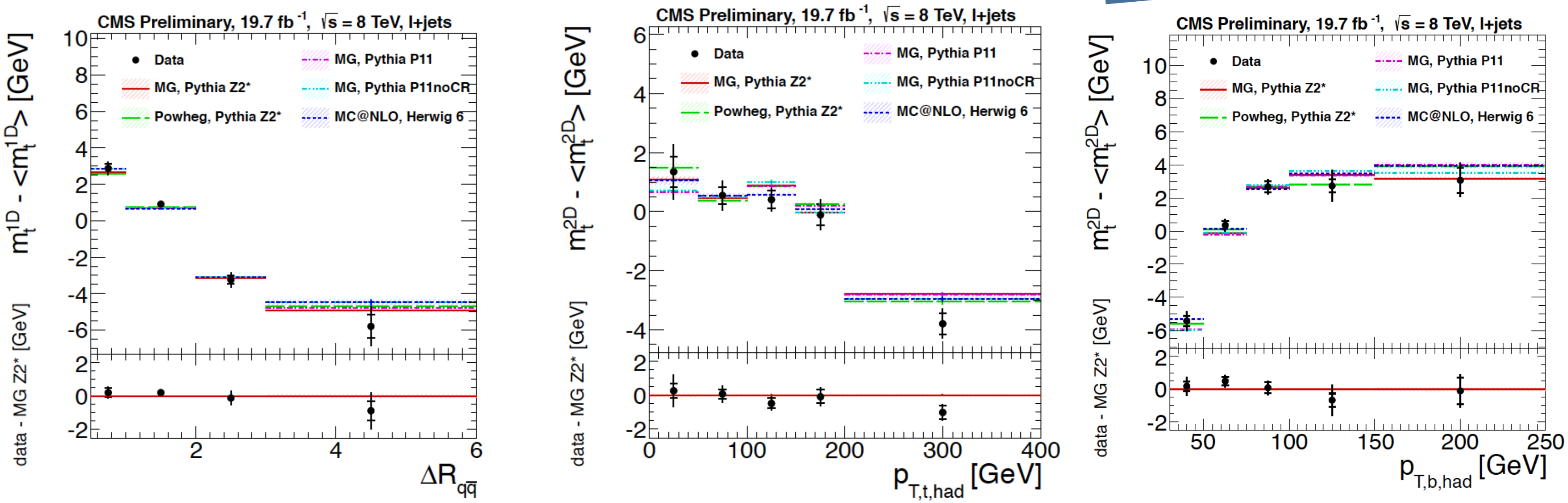
Dependence of Top Mass observable on event kinematics

- 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 !!



JHEP 12 (2012) 105

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



Methods for top mass measurement (2)

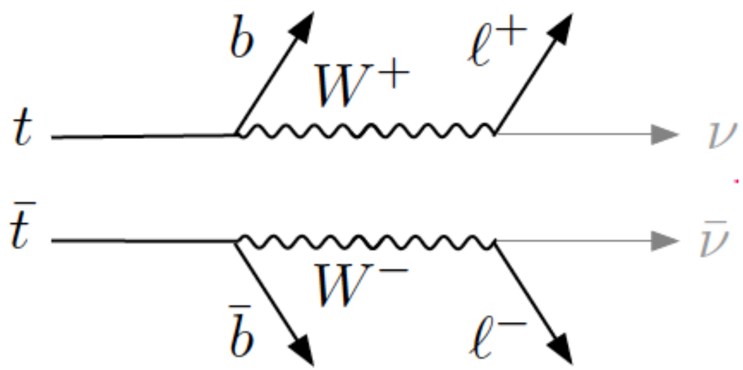
- Given the potential bias in measuring the top mass from its decay products, important to explore **alternative techniques**, e.g.
  - Measure the **decay length** (the boost) of B hadrons produced in top decays, the boost is related to the original top mass
  - Select **specific channels**, for example 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
- 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**

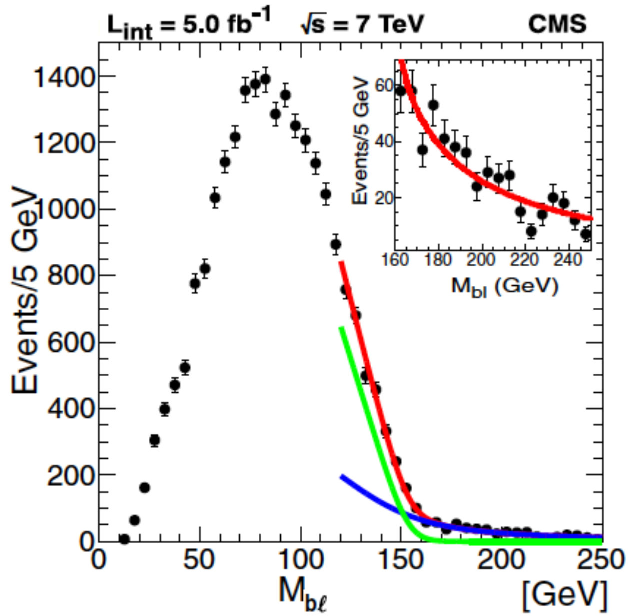
TOP mass from alternative techniques

- 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

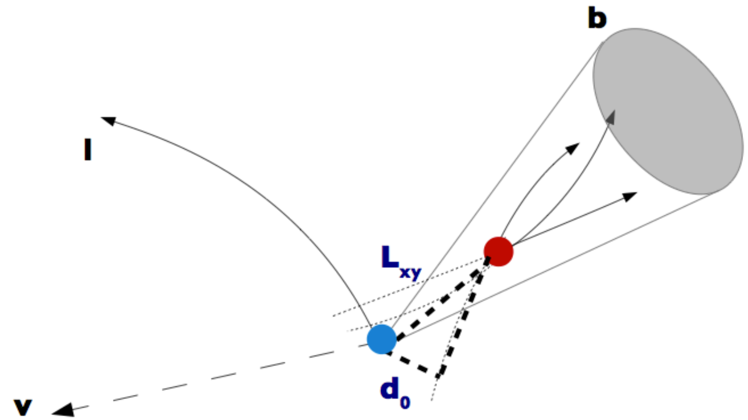
$$M_t = 173.9 \pm 0.9\,(\text{stat.})^{+1.6}_{-2.0}\,(\text{syst.})\,\text{GeV}$$



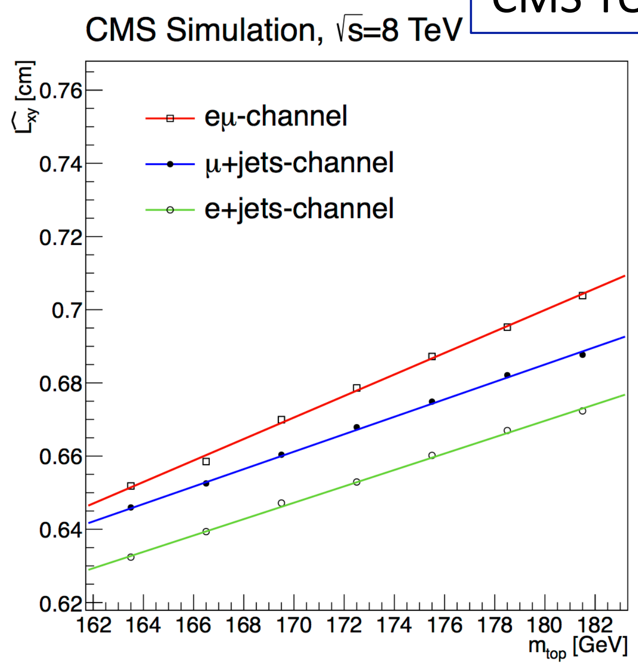


Another example: top mass from the b decay length

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



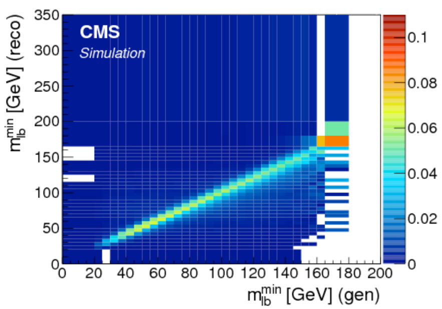
CMS TOP-12-030



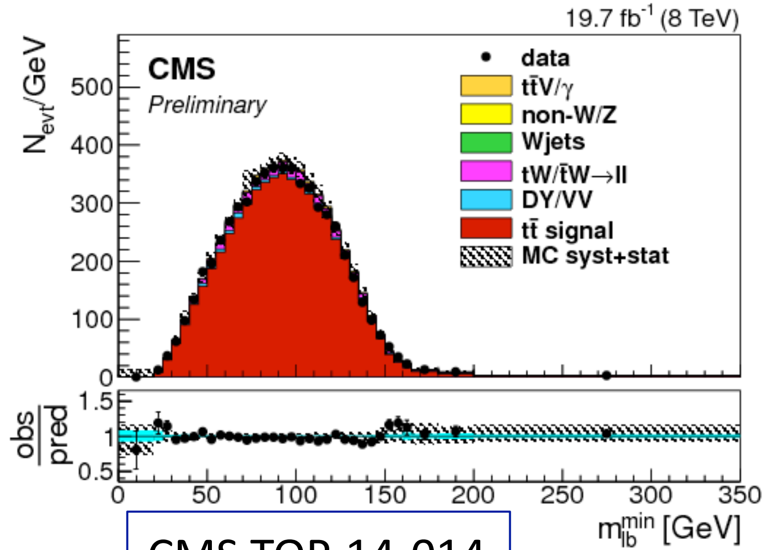
$m_t = 173.5 \pm 1.5stat \pm 1.3syst \pm 2.6p_t(top)$ GeV

Top mass from lepton-b invariant mass

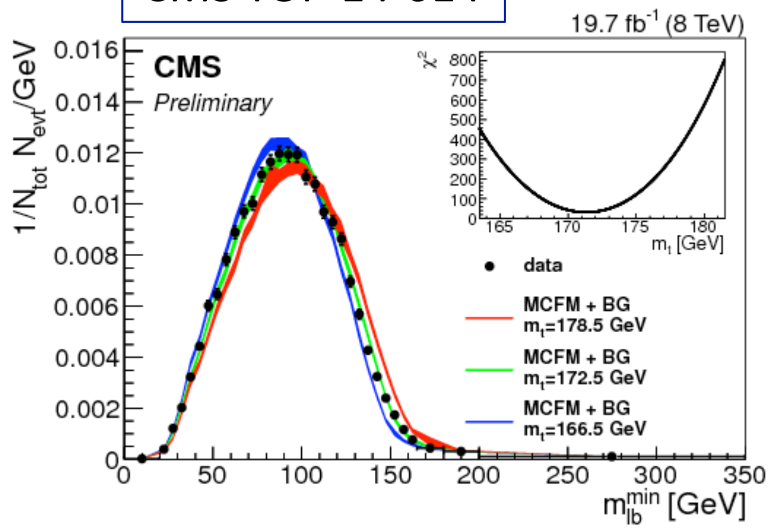
- Exploit high-purity dilepton event and compare directly to fixed-order calculations (NLO), which are available for m_{lb}
- Use unfolding method to compare directly with calculations



$$m_t = 171.4 \pm 0.4 \pm 1.0 \text{ GeV}$$



CMS TOP-14-014

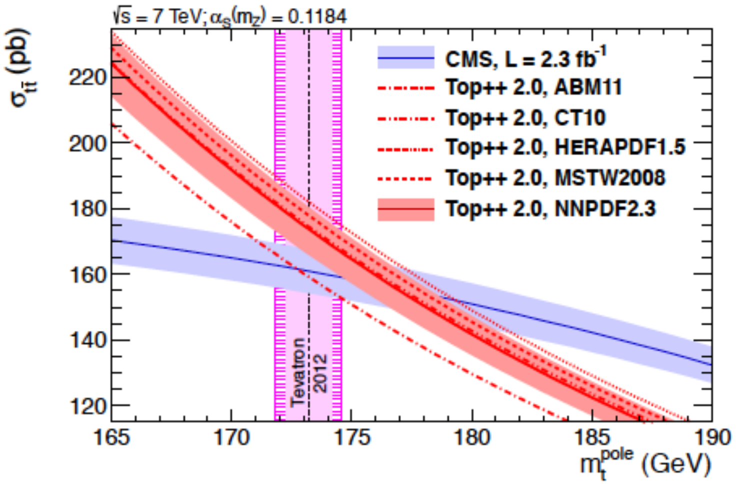


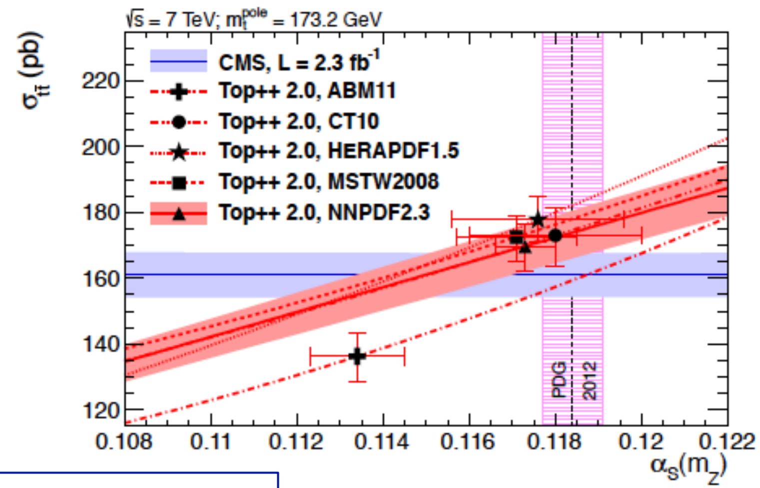
ttbar cross section: mass interpretation

[arXiv:1307.1908]

- Measure cross section in the most precise channel: dilepton eμ
- Use recent NNLO calculation (*) of top pair cross section to extract m_t
- Provides also a measurement of α_s
- 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

$$m_t = 176.7^{+3.0}_{-2.8}\ \text{GeV}$$

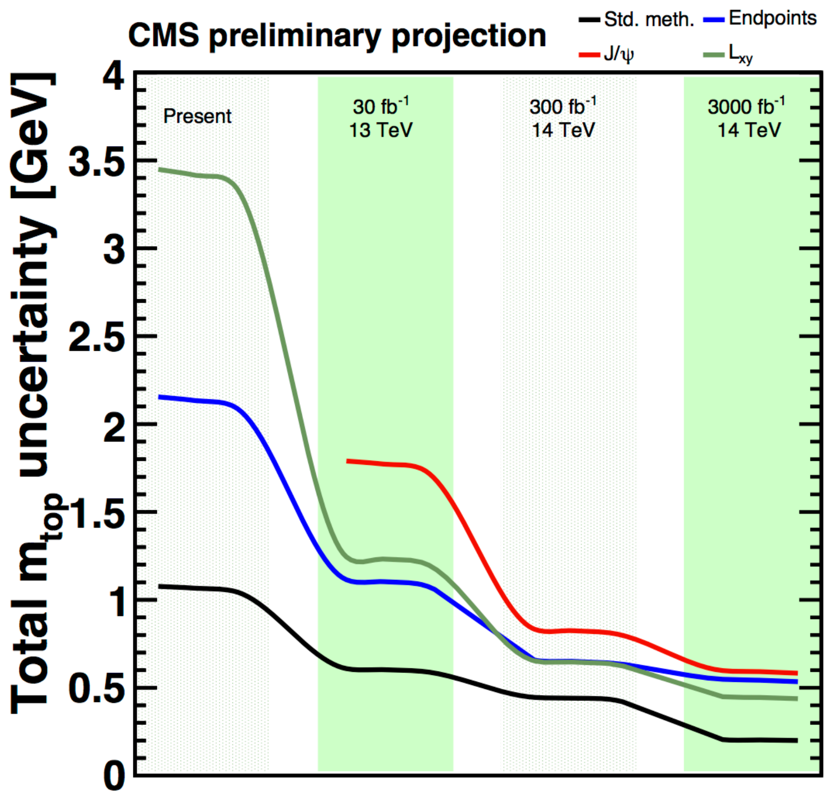




(*) Czakon, Fiedler, Mitov, (2013) arxiv:1303.6254, PRL 110.252004

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



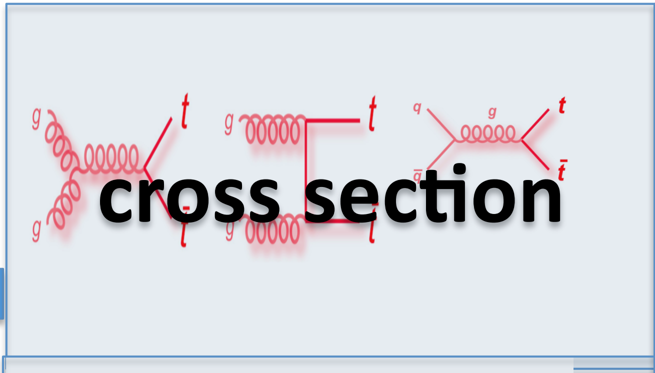
From CMS PAS FTR-13-017, prepared for the "European Strategy for particle physics" discussions

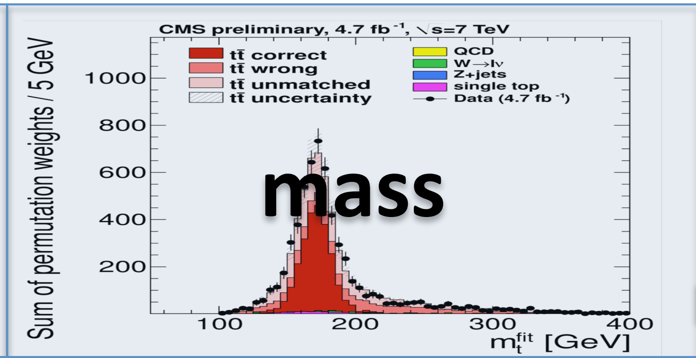
THE ROLE OF TOP IN THE HIGGS ERA: NOT ONLY THE MASS

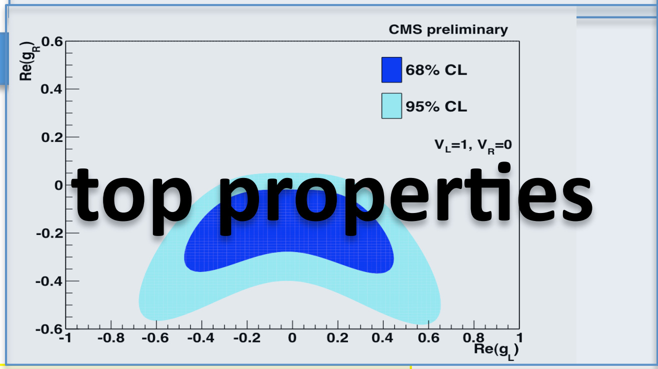
The top areas of study

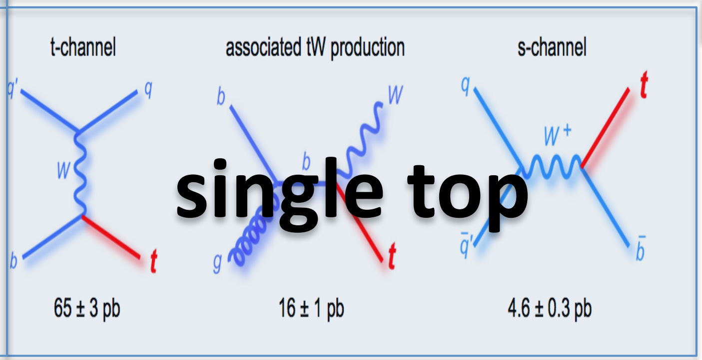
Total and differential cross sections, Test of production mechanism(QCD, EWK), tt +jets production, measure PDF

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









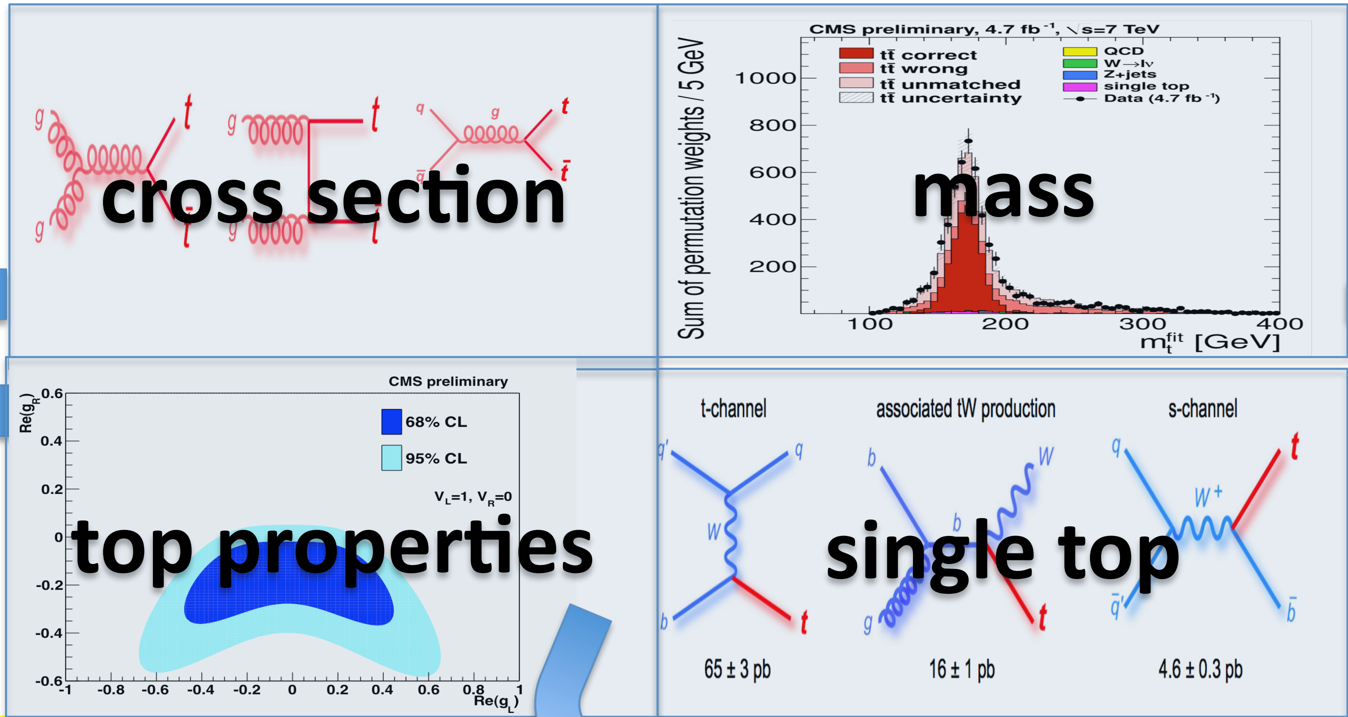
Couplings, branching ratios, charge, width, W helicity, spin correlations, charge asymmetry associated production (ttW, ttZ, ttH, tt+MET)

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 !

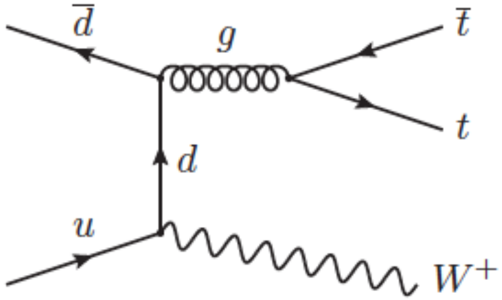
Do we interpret the top mass correctly when we match top, W and Higgs Masses ?

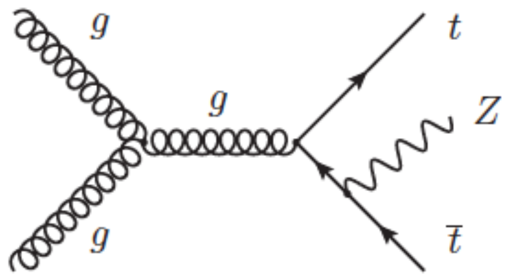


Are top properties consistent with our view of electroweak symmetry breaking ?

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

Associated production of top pair and **vector** boson



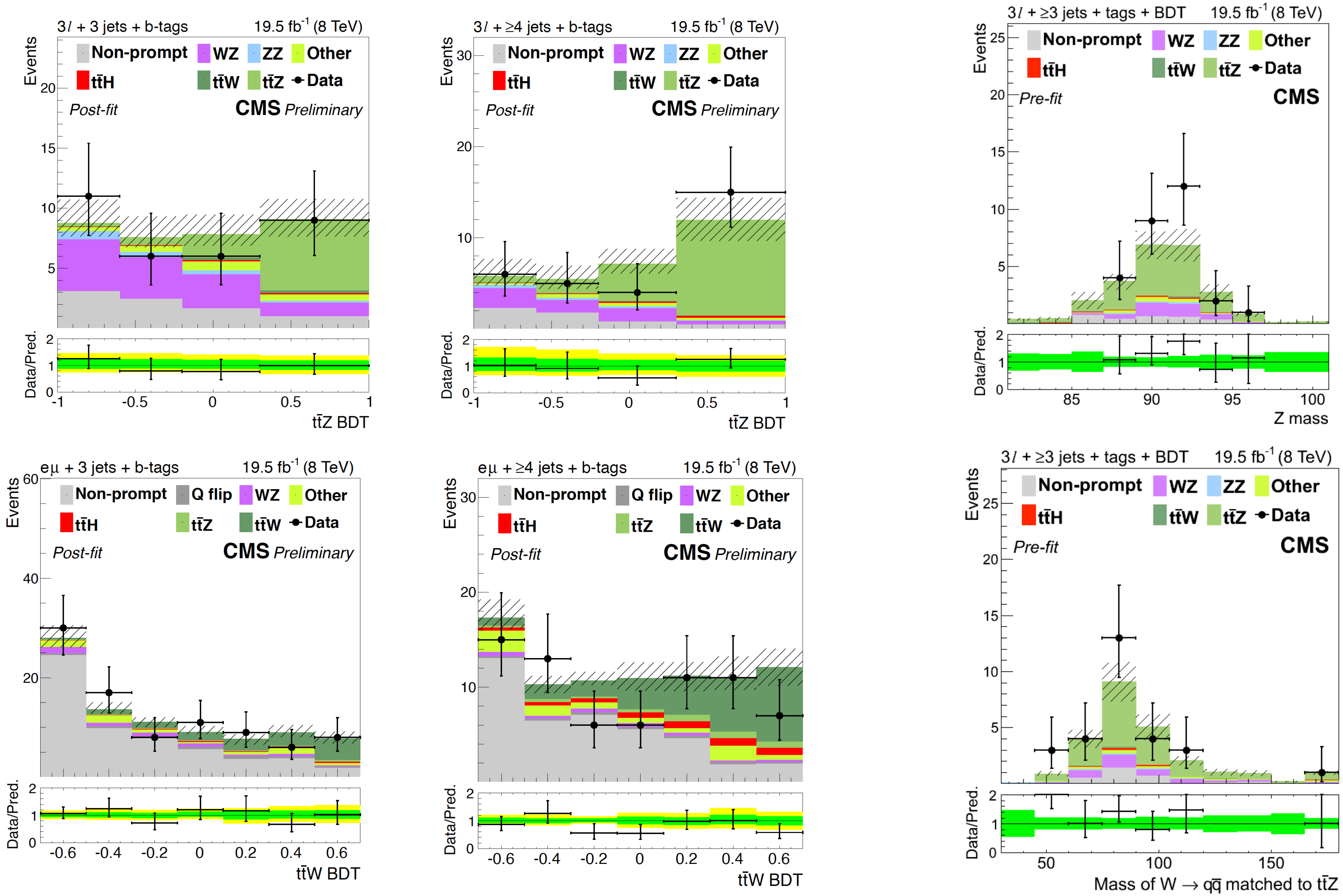


CMS TOP-14-021

- The ttZ process provides direct access to Z-top couplings
- Both ttW and ttZ processes can be altered by BSM physics
- Measured **ttW** and **ttZ** cross sections with 19.5 fb^{-1} of data collected at 8 TeV
- Measurement performed in multilepton (e or μ) final states
  - **ttZ measured in channels with two, three, or four leptons, with exactly one pair of same-flavor opposite-sign (OS) leptons close to the Z mass**.
  - **ttW measured in in channels with two same-sign (SS) leptons or three leptons, where no lepton pair is consistent with coming from a Z boson decay.**
  - **full or partial reconstruction of the ttW or ttZ system with a linear discriminant that matches leptons and jets to their parent particles using mass, charge, and b tagging information.**

CMS TOP-14-021

ttZ and ttW signals



CMS TOP-14-021

ttW e ttZ cross section measurements

	Cross section (fb)		Signal strength (μ)		Significance	
Channels	Expected	Observed	Expected	Observed	Expected	Observed
SS	203^{+88}_{-73}	414^{+135}_{-112}	$1.0^{+0.45}_{-0.36}$	$2.04^{+0.74(+1.52)}_{-0.61(-1.05)}$	3.44	4.89
3ℓ	203^{+215}_{-94}	210^{+225}_{-203}	$1.0^{+1.09}_{-0.96}$	$1.03^{+1.07(+2.39)}_{-0.99(-1.92)}$	1.03	1.03
SS + 3ℓ	203^{+84}_{-71}	382^{+117}_{-102}	$1.0^{+0.43}_{-0.35}$	$1.88^{+0.66(+1.35)}_{-0.56(-0.95)}$	3.54	4.81

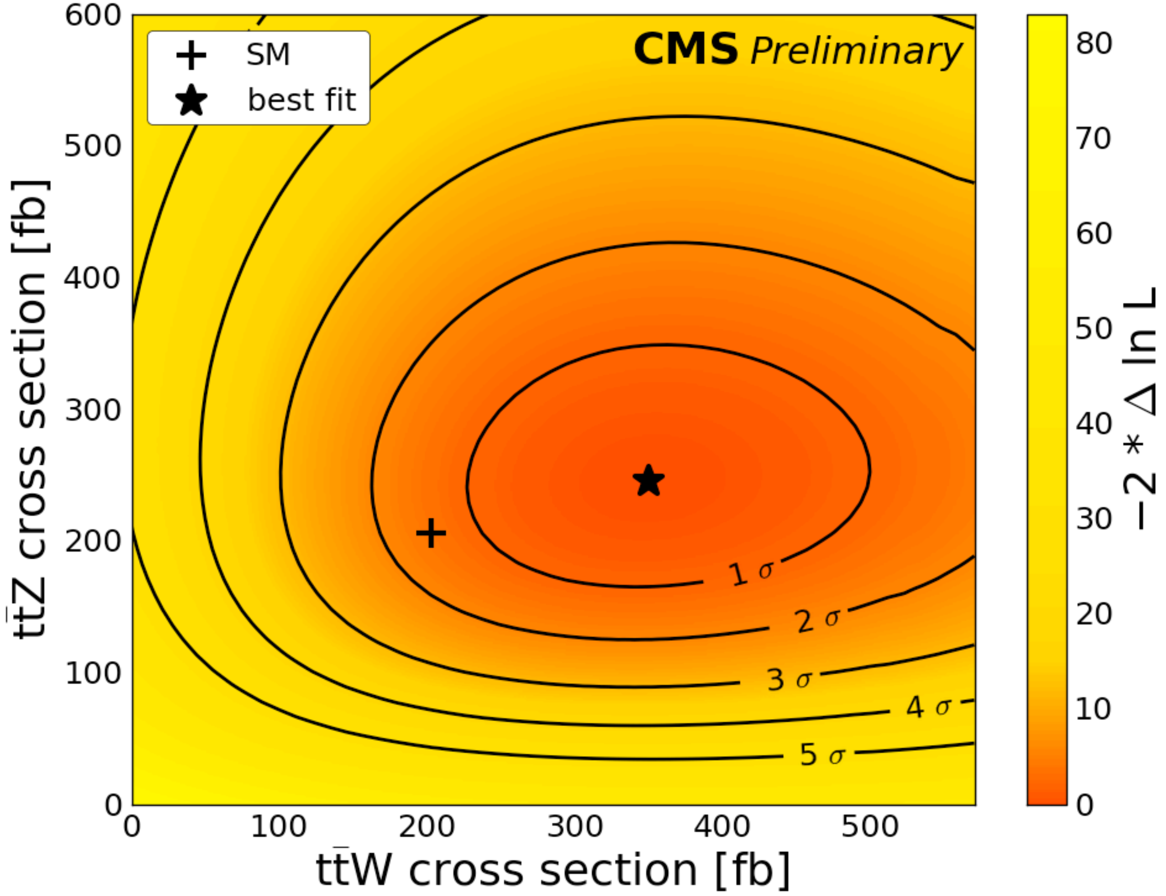
ttW

	Cross section (fb)		Signal strength (μ)		Significance	
Channels	Expected	Observed	Expected	Observed	Expected	Observed
OS	206^{+142}_{-118}	257^{+158}_{-129}	$1.0^{+0.72}_{-0.57}$	$1.25^{+0.76(+1.76)}_{-0.62(-1.16)}$	1.84	2.12
3ℓ	206^{+79}_{-63}	257^{+85}_{-67}	$1.0^{+0.42}_{-0.32}$	$1.25^{+0.45(+1.02)}_{-0.36(-0.62)}$	4.55	5.11
4ℓ	206^{+153}_{-109}	228^{+150}_{-107}	$1.0^{+0.77}_{-0.53}$	$1.11^{+0.76(+1.79)}_{-0.52(-0.86)}$	2.65	3.39
OS + 3ℓ + 4ℓ	206^{+62}_{-52}	242^{+65}_{-55}	$1.0^{+0.34}_{-0.27}$	$1.18^{+0.35(+0.79)}_{-0.29(-0.51)}$	5.73	6.44

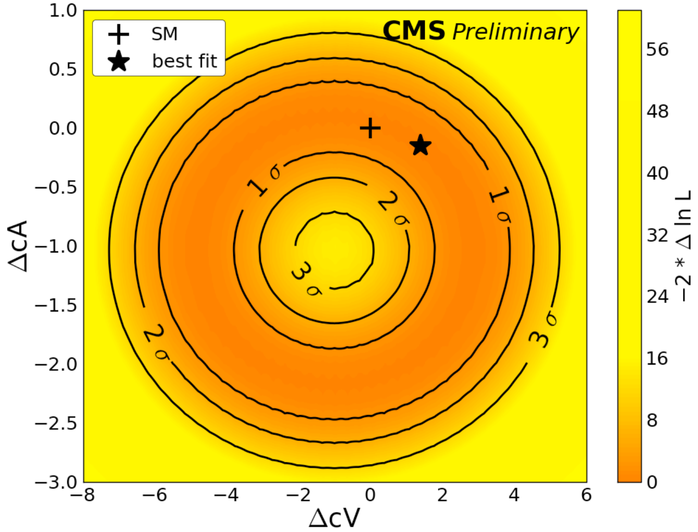
ttZ

CMS TOP-14-021

ttW e ttZ cross sections



ttZ couplings



Constraints on vector and axial couplings

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_1 + \frac{1}{\Lambda^2}\mathcal{L}_2 + \cdots$$
$$= \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_i (c_i \mathcal{O}_i + \text{h.c.}) + \frac{1}{\Lambda^2}\sum_i (c_i \mathcal{O}_i + \text{h.c.}) + \cdots$$

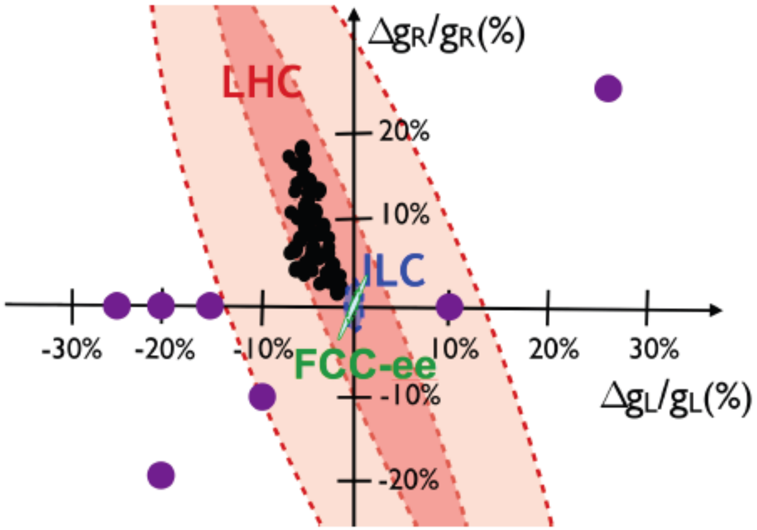
Constraints on dimension-6 operators

operator	best fit point(s)	1σ CL	2σ CL
$\bar{c}_{uB}$	-0.07 and 0.07	{-0.11, 0.11}	{-0.14, 0.14}
$\bar{c}'_{HQ}$	0.12	{-0.07, 0.18}	{-0.33, -0.24} and {-0.02, 0.23}
$\bar{c}_{HQ}$	-0.09 and 0.41	{-0.22, 0.08} and {0.24, 0.54}	{-0.31, 0.63}
$\bar{c}_{Hu}$	-0.47 and 0.13	{-0.60, -0.23} and {-0.11, 0.26}	{-0.71, 0.37}
$\bar{c}_{3W}$	-0.28 and 0.28	{-0.36, -0.18} and {0.18, 0.36}	{-0.43, 0.43}

The future of top-Z couplings

Stefania De Curtis et al., arXiv:1504.05407

P. Janot, JHEP 1504 (2015) 182



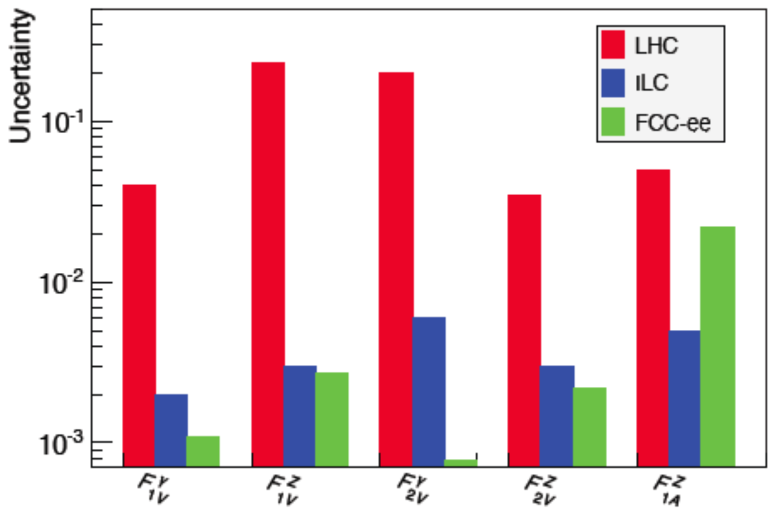
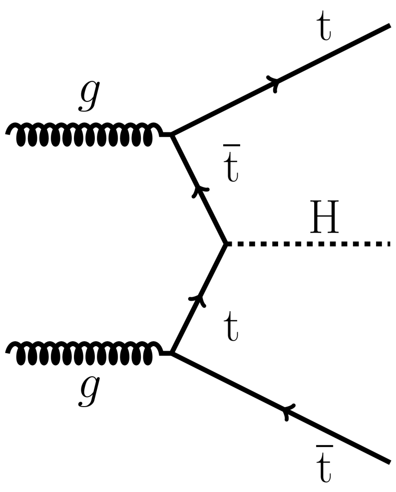


Fig. 17: *Left: Predicted deviations of Z couplings to t_L and t_R in various NP models [143, 148]. Also shown are the expected sensitivities of LHC (300 fb^{-1} and 3000 fb^{-1}), ILC and FCC-ee. Right: Comparison of statistical precisions on CP conserving axial and vector form factors expected at LHC with 300 fb^{-1} [145] at ILC500 with 500 fb^{-1} [147] and at FCC-ee with 2.4 ab^{-1} [142]. The FCC-ee (ILC) projections are obtained at $\sqrt{s} = 365\,GeV$ ($\sqrt{s} = 500\,GeV$). In the case of FCC-ee lepton-angular and energy distributions are used, while ILC projections are based on the use of beam polarization.*

from **White Paper of INFN-CSN1**, published in Frascati Physics Series, May 2015

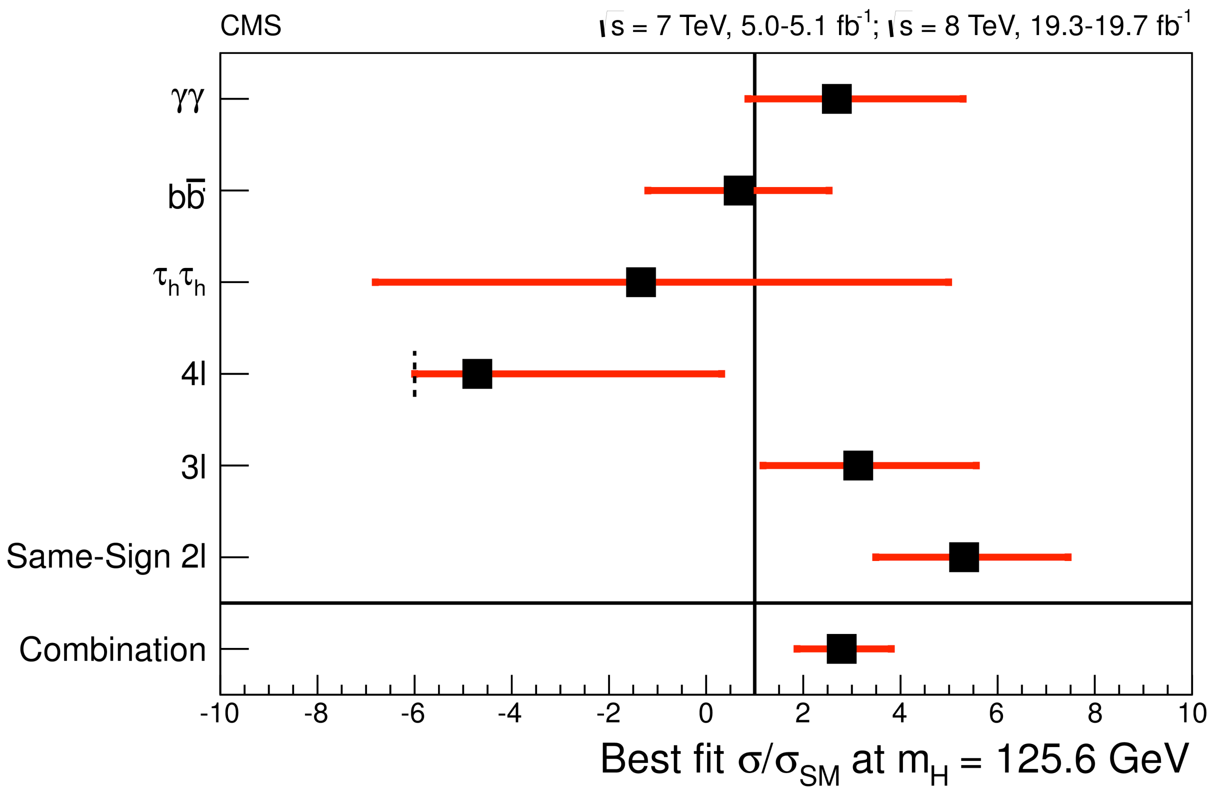
Associated production of top pair and **scalar** boson



CMS HIG-14-021

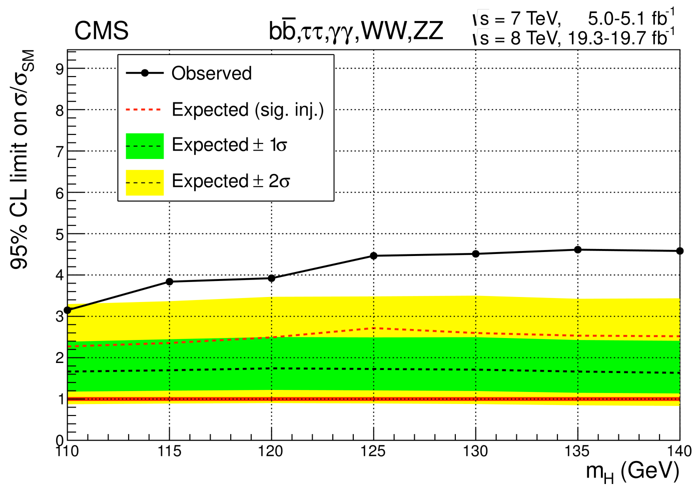
- The ttH process gives direct access to the top-Higgs Yukawa coupling.
- The process can be altered by BSM physics
- Searched with 5.1 fb^{-1} at 7 TeV and 19.7 fb^{-1} of at 8 TeV
- Measurement performed in several final states
  - top pair all hadronic, lepton+jets, dilepton
  - with H→hadrons, H→ leptons, H→ $\gamma\gamma$
  - categorization includes H→bb and H→ $\tau\tau$

Results for ttH search



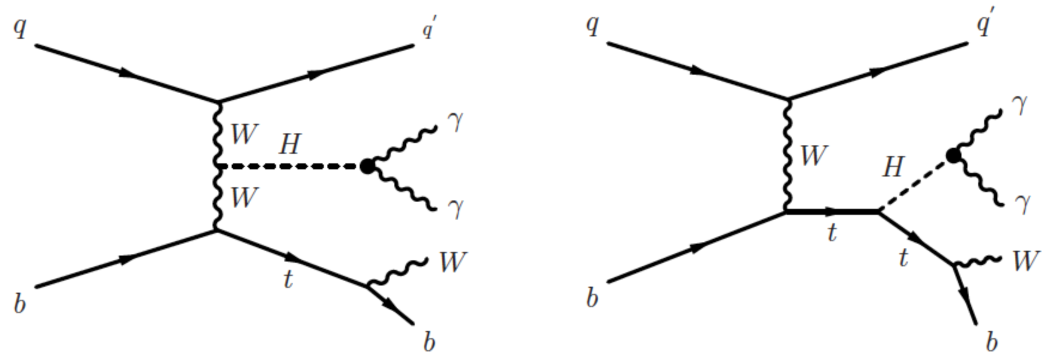
CMS HIG-14-021
JHEP 09 (2014) 087

μ=2.8±1.0 for an Higgs boson mass of 125.6 GeV



Associated production of single top and Higgs boson

CMS HIG-14-001



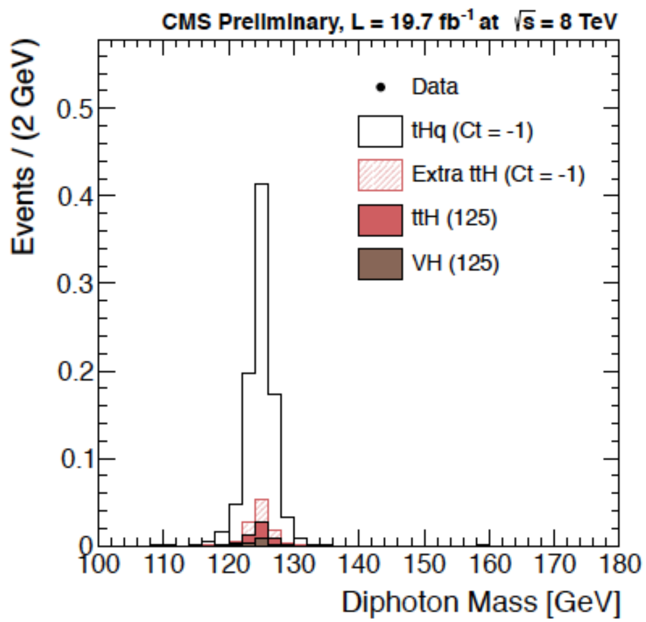
- Potentially gives the relative sign of the top-Higgs Yukawa coupling with respect to the Higgs-W coupling
- The two diagrams interfere destructively in the SM (σ=18 fb), but with flipped sign cross section increases by a factor 15
- Analysis performed in the H→γγ channel

$$\mathrm{tHq} \to (\mathrm{t} \to \mathrm{b}\ell\nu)(\mathrm{H} \to \gamma\gamma)q \quad \text{with } \ell = \mathrm{e}, \mu$$

CMS HIG-14-001

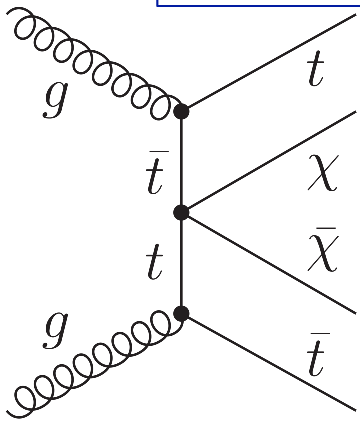
Results for tHq search

Zero events found: an observed 95% UL is set at 4.1 times the expected cross section with inverted Ct (= -1).

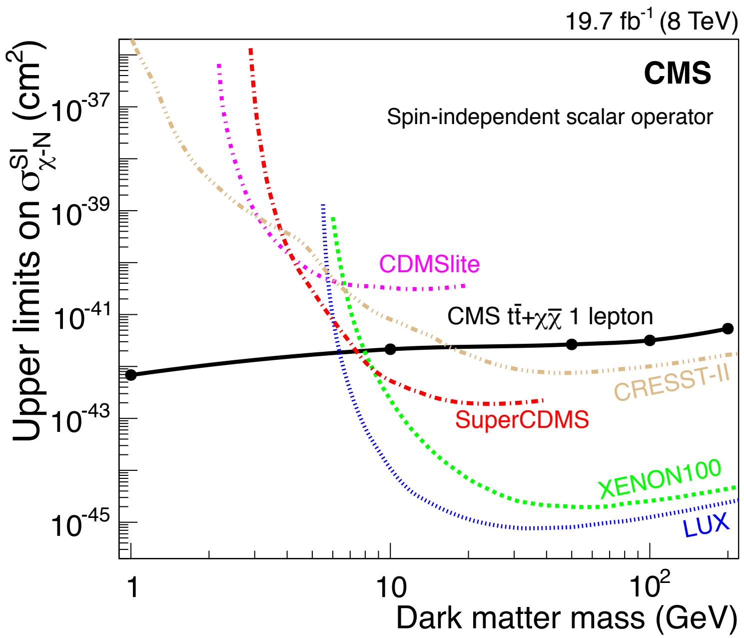


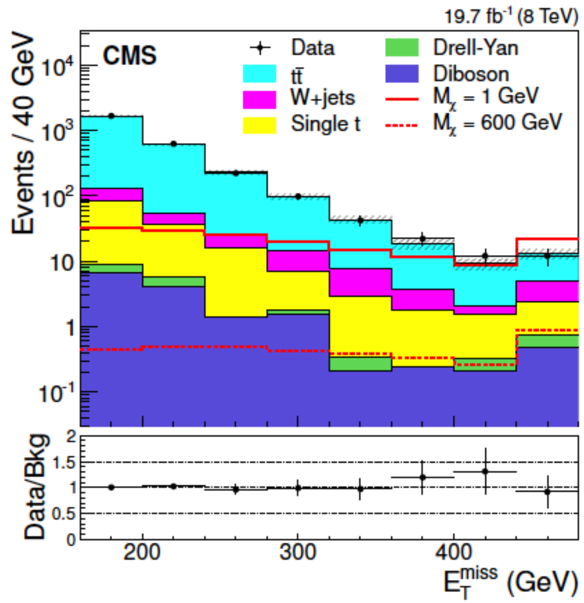
Search for Dark Matter produced in association with top pairs

JHEP 06 (2015) 221



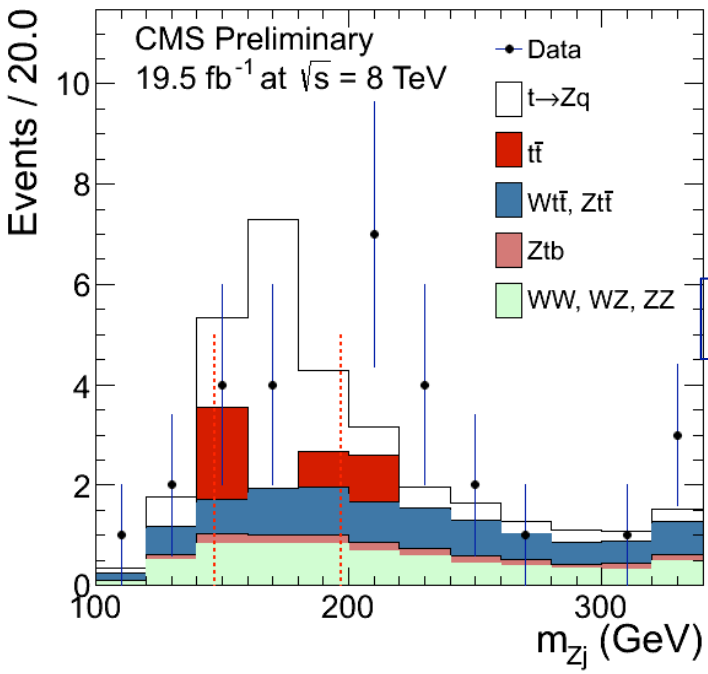
• Dark matter could couple to heavy fermions through contact interactions
• Search requires the presence of one lepton, multiple jets, and large missing transverse energy.



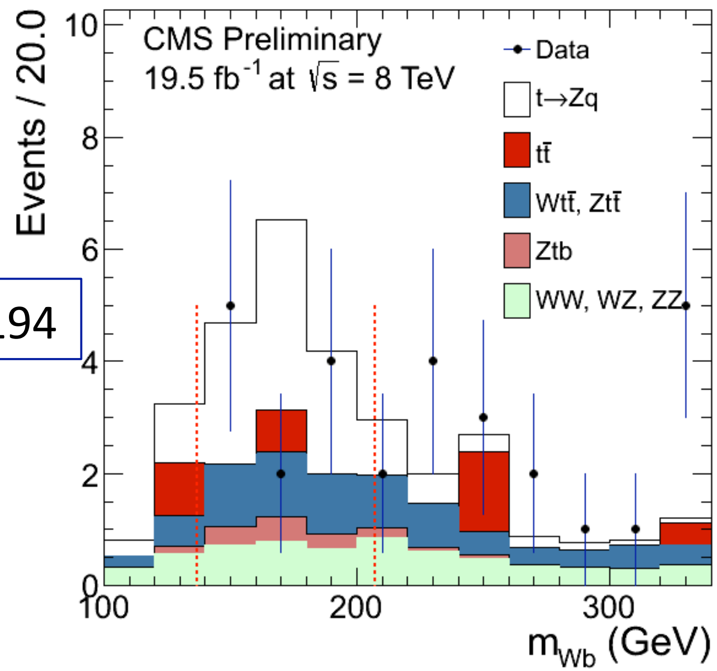


Rare top decays: limits on FCNC t→Zq, t→Hq

- FCNC searches requires statistics, promising for Run 2 and HL-LHC
  - Current result from ttbar/trilepton searches: **A t → Zq branching fraction greater than 0.07 % is excluded at the 95 % confidence level.**



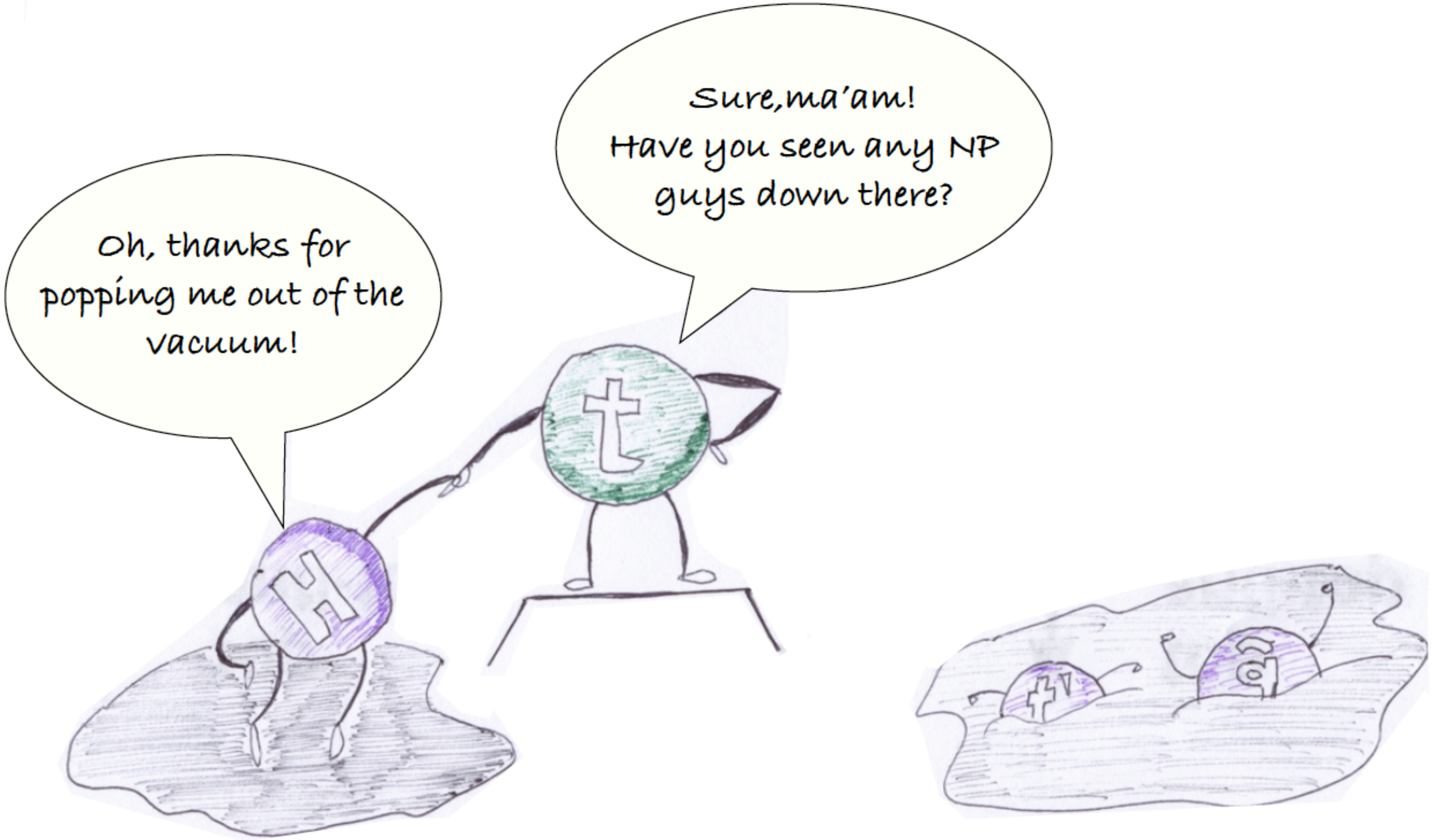
arXiv:1312.4194



  - Search **for t→Hc(u) decays with in the H→γγ channel gives 0.47(0.42)% at the 95% confidence level** [TOP-14-019]

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**

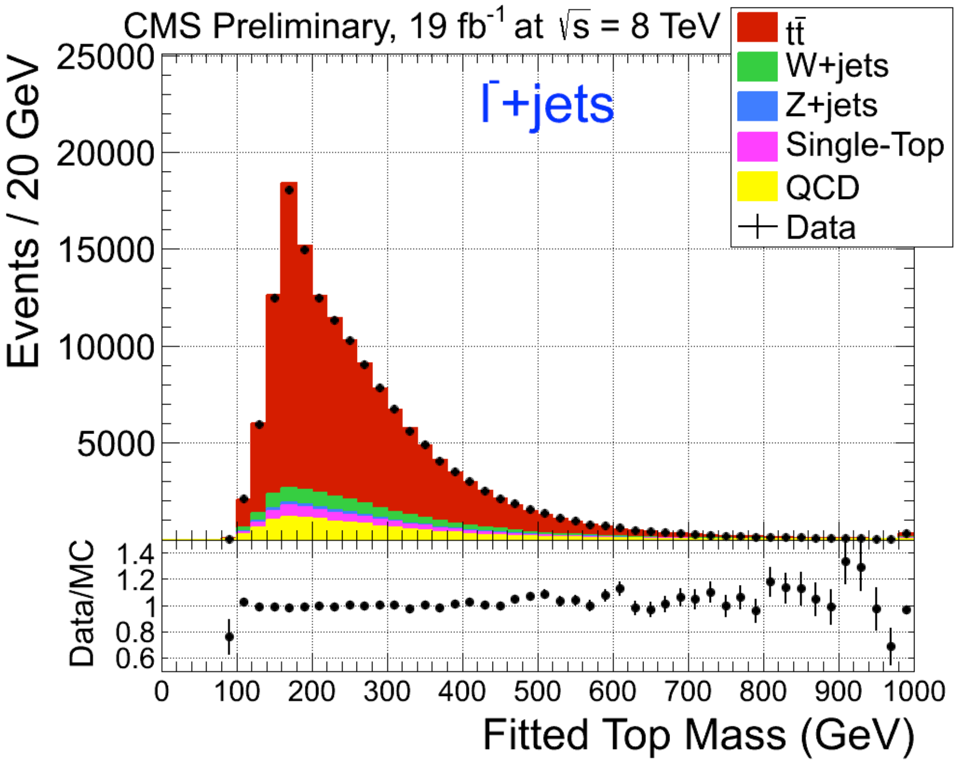


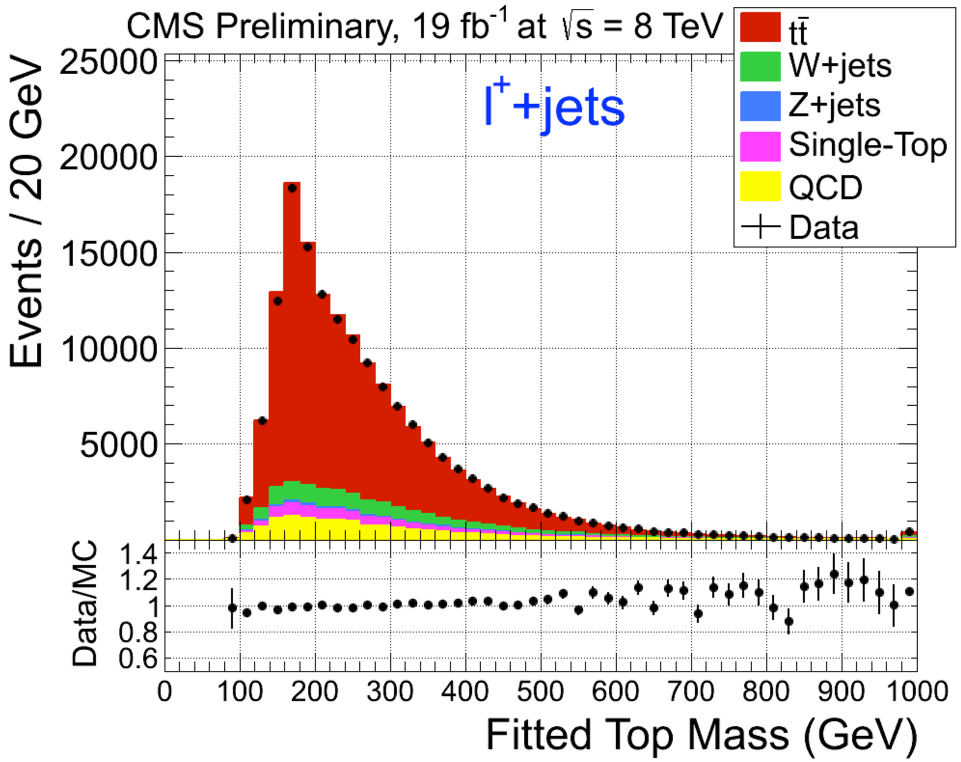
Courtesy of Fabio Maltoni

BACKUP SLIDES

top – antitop mass difference: a CPT test

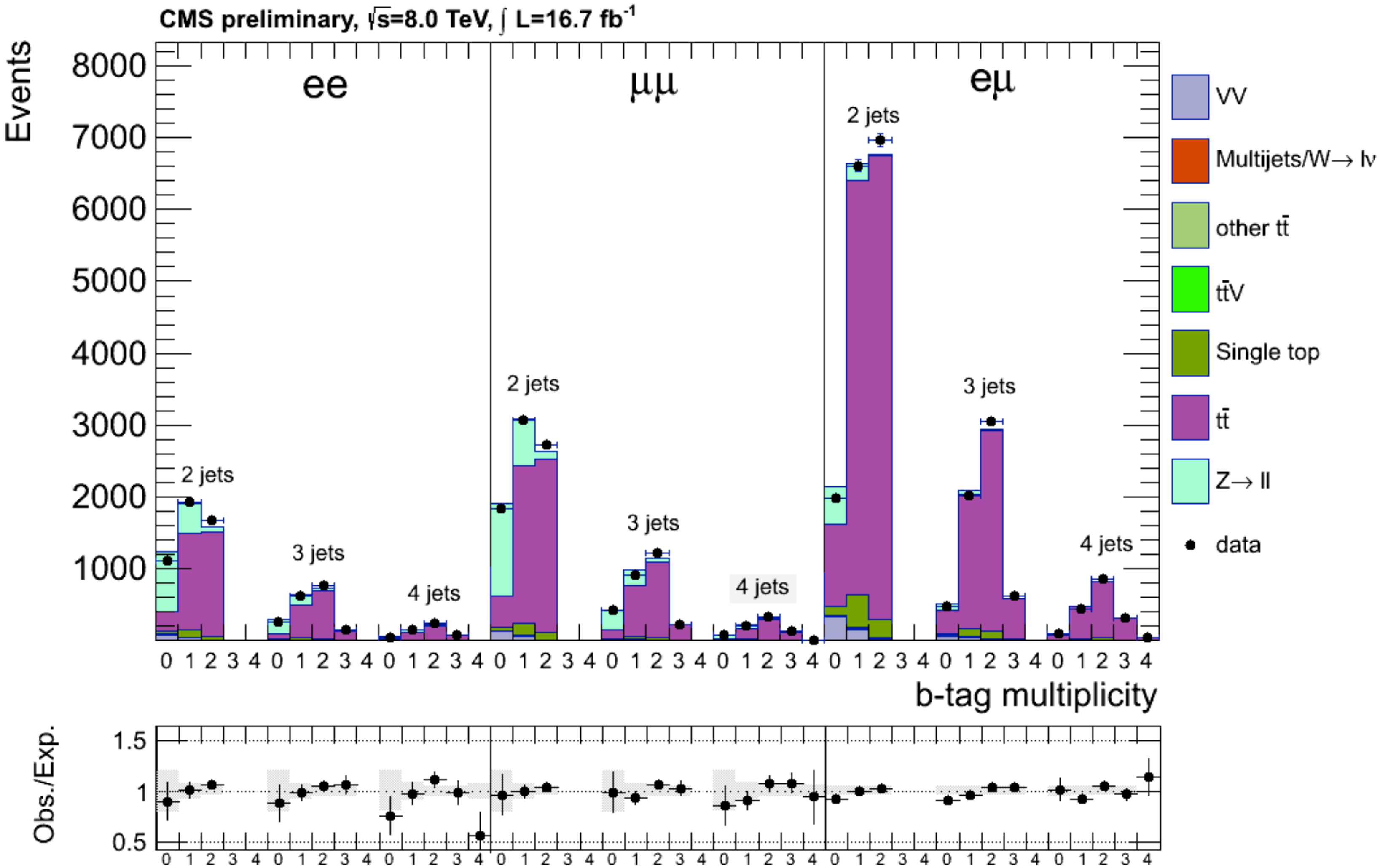
$$\Delta m_t = -272 \pm 196 \text{ (stat.)} \pm 122 \text{ (syst.) MeV}$$





TESTING TOP DECAYS

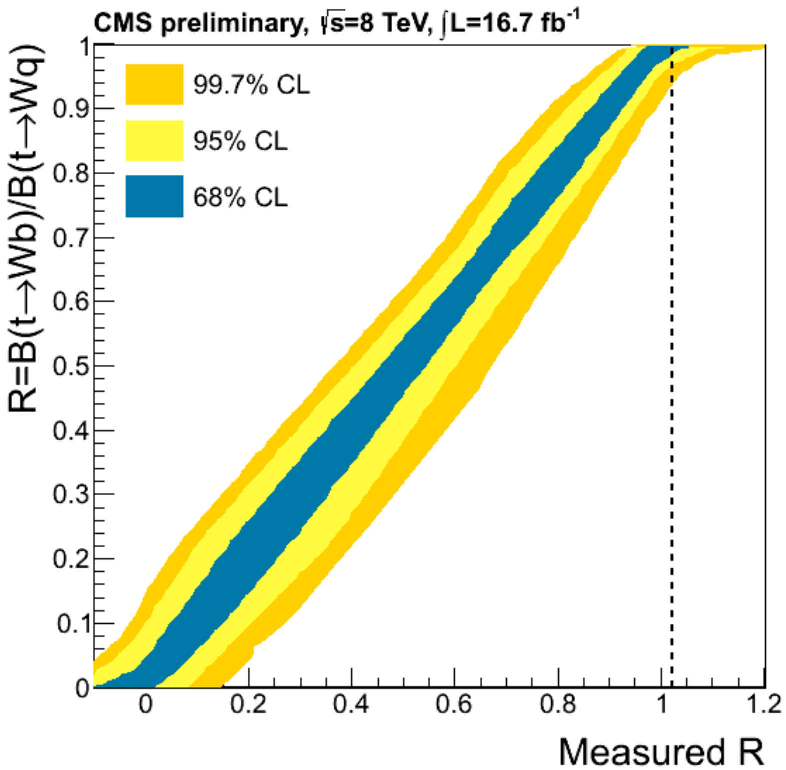
Measurement of the ratio R=B(t → Wb) / B(t → Wq)

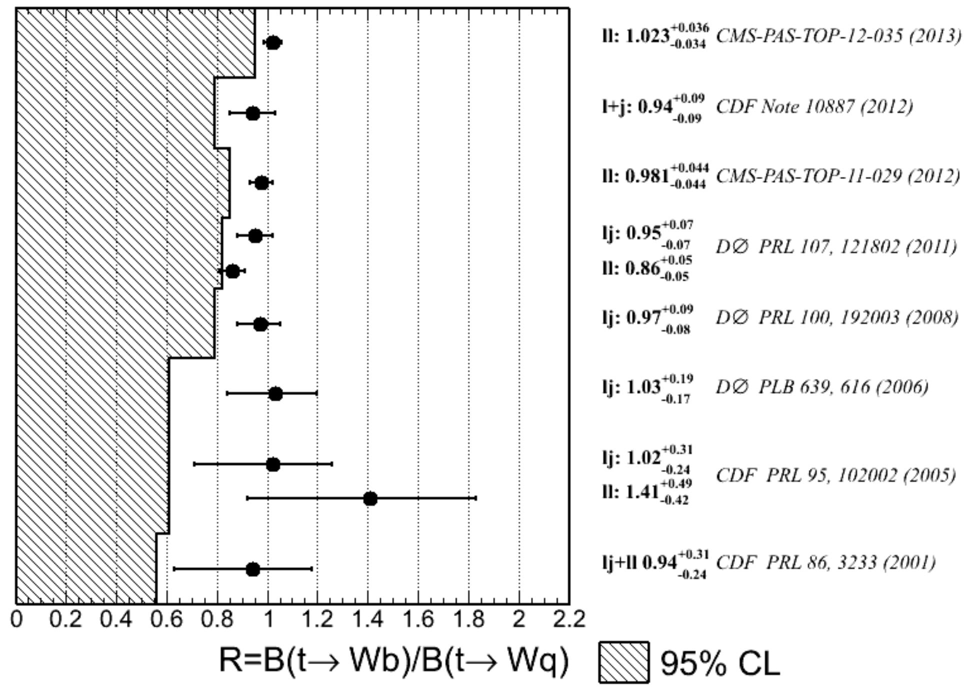


CMS TOP-12-035

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



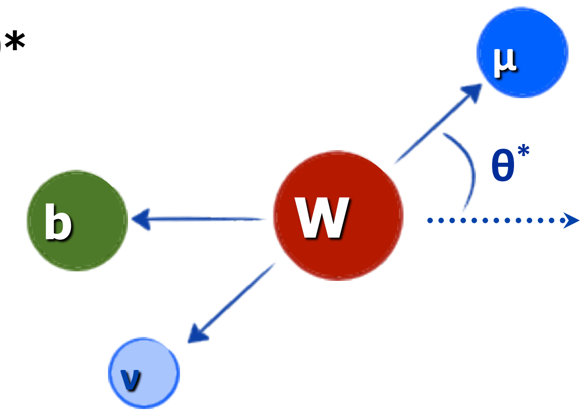


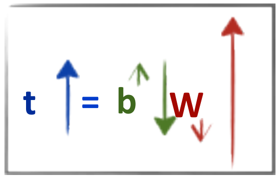
CMS TOP-12-035

W helicity in top decays

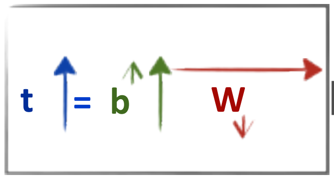
V-A SM nature of the tWb coupling can be probed using θ*

- 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 $g_R = g_L = V_R = 0$

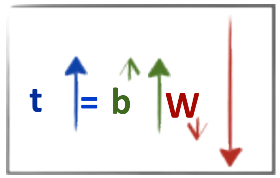




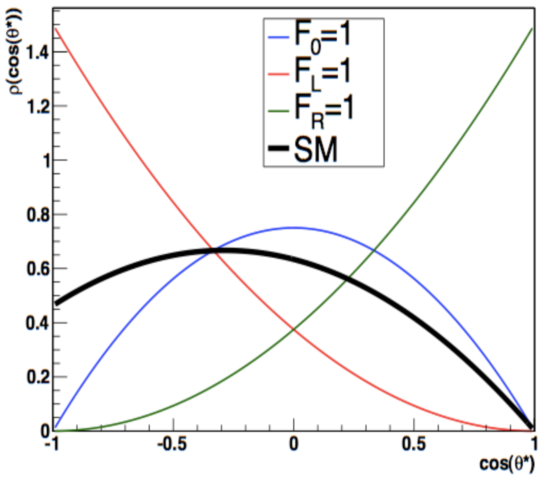
F_L [SM≃0.311]



F_0 [SM≃0.687]

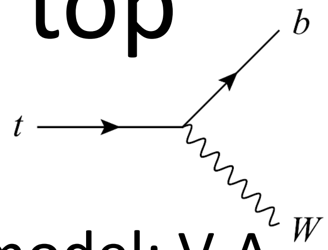


F_R [SM≃0.001]

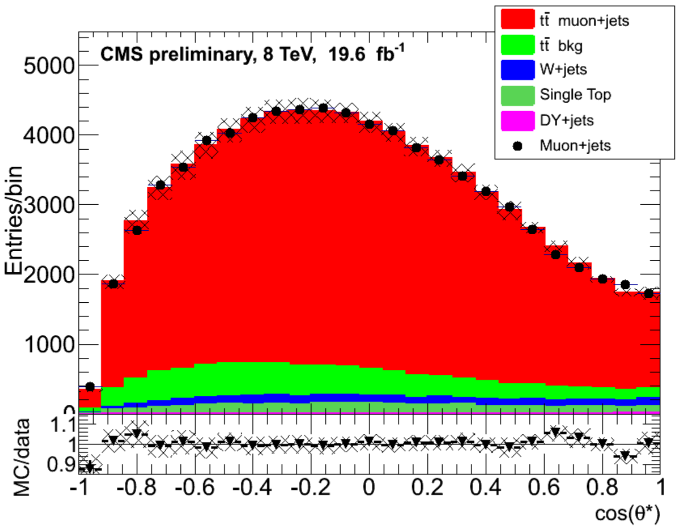


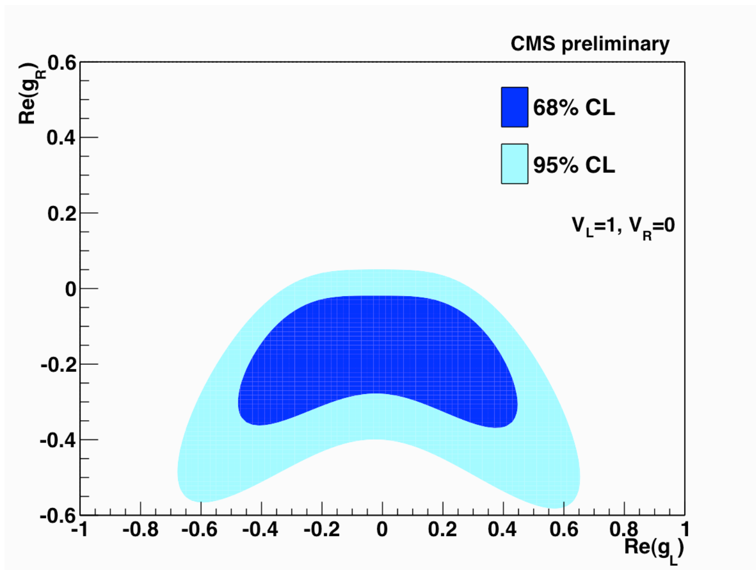
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)F_0 + \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{8}(1+\cos\theta^*)^2 F_R$$

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



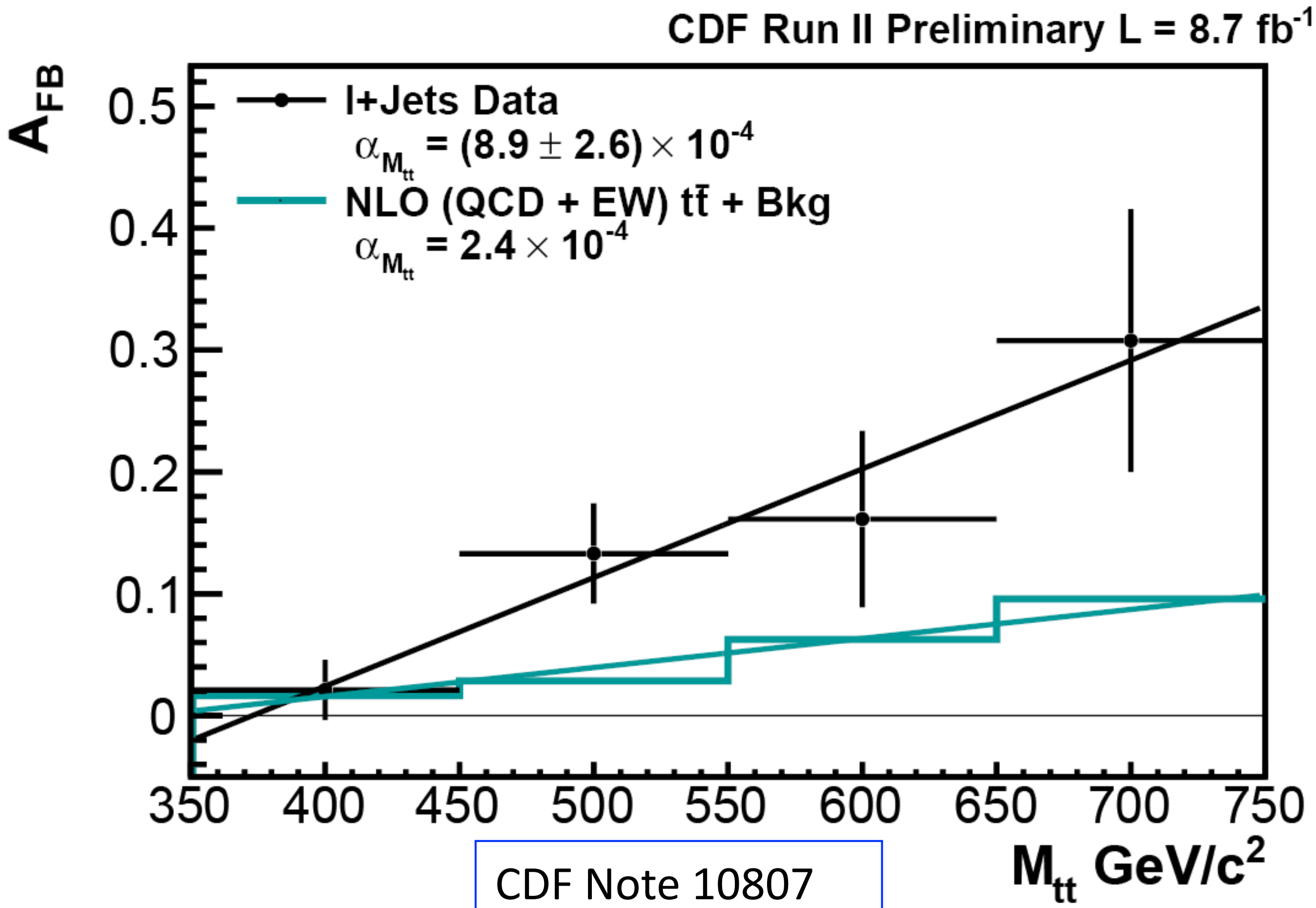


TESTING TOP PRODUCTION PROPERTIES

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

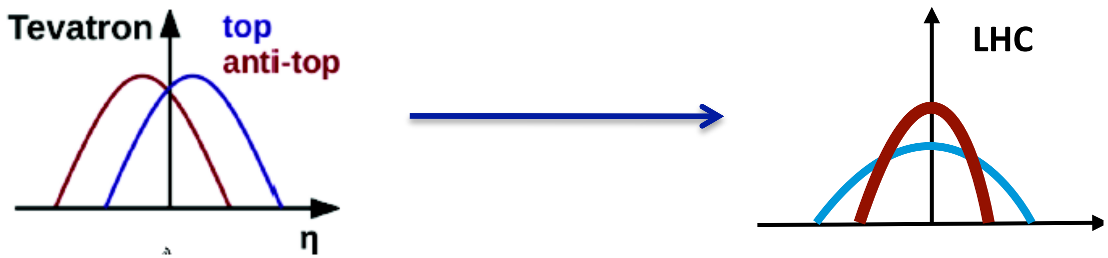
$$q\bar{q} \rightarrow t\bar{t}$$

• 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

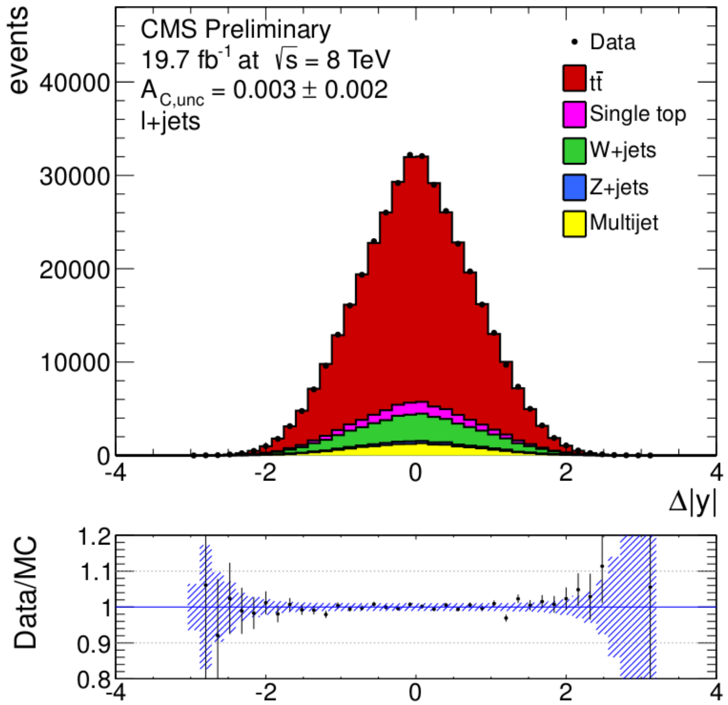
$$14\ \mathrm{TeV}\ gg \rightarrow t\bar{t}\ (90\%),\ q\bar{q} \rightarrow t\bar{t}\ (10\%)$$

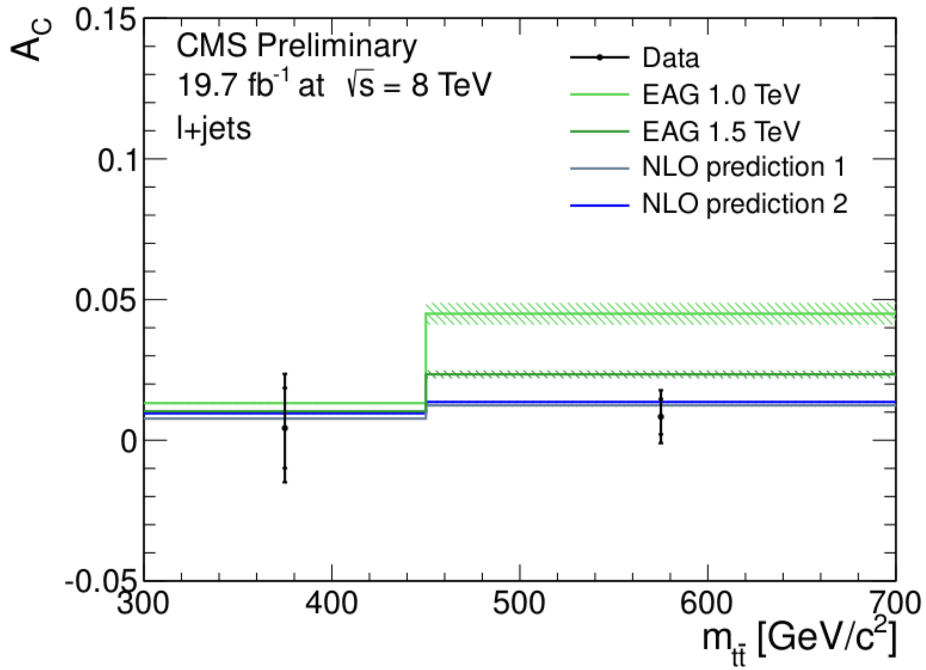
• **Important at LHC to study differential asymmetries**, to enhance new physics

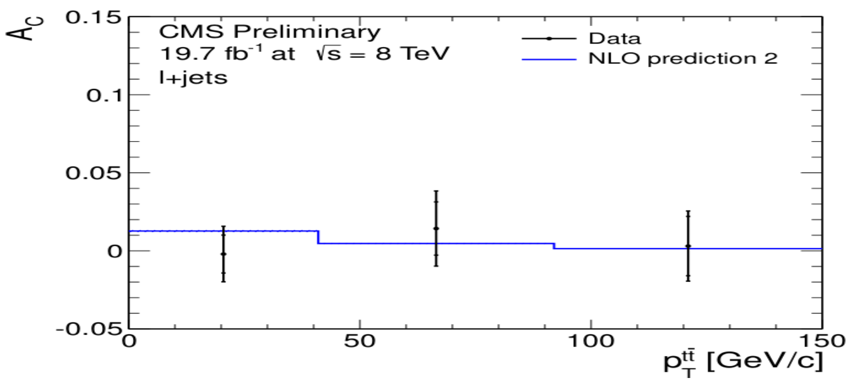
- **Sum of t and tbar rapidity to disentangle quark-antiquark and gluon-gluon fusion**
- **ttbar invariant mass sensitive to new heavy states**
- **Transverse momentum of the ttbar system sensitive to interference due to ISR**

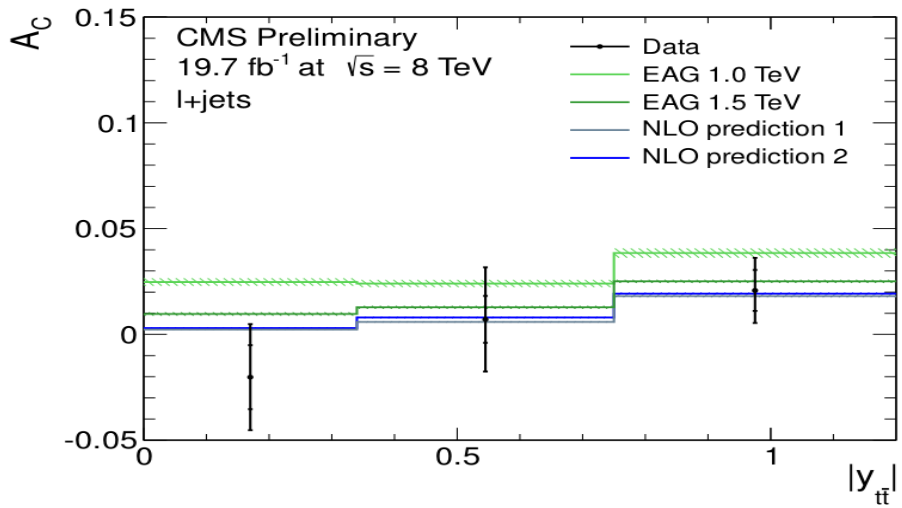
CMS PAS TOP-12-033

Charge asymmetry at LHC





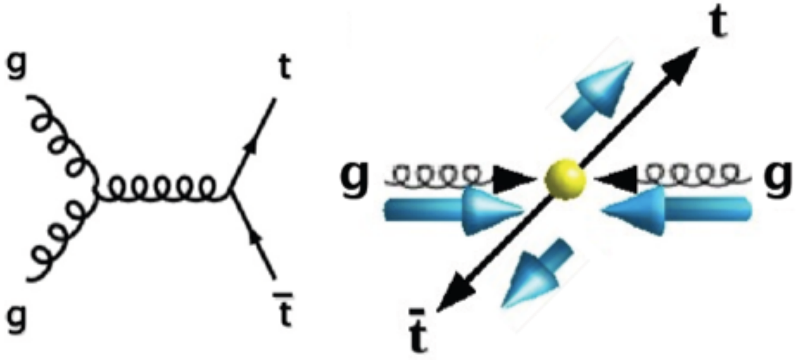




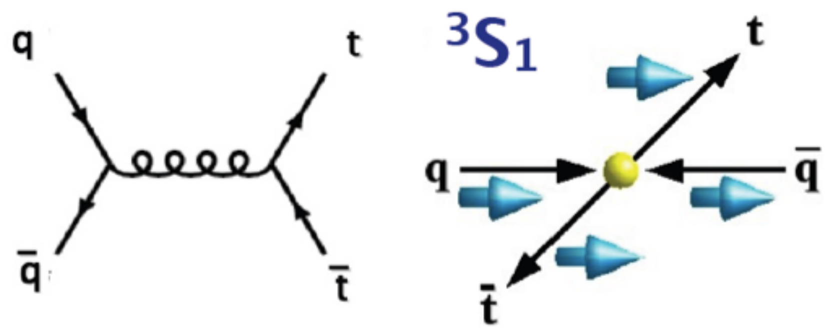
Spin correlations in ttbar

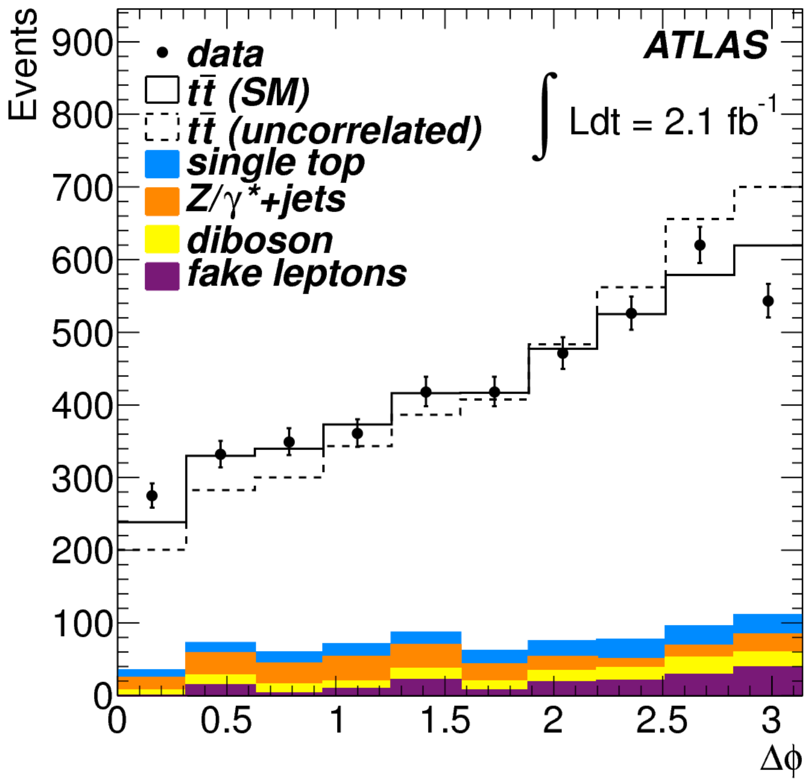
Another tool to investigate the production mechanism, possible only for the top quark
Investigating it now, but will become a precision tool with high statistics

gluon-gluon example at high boost

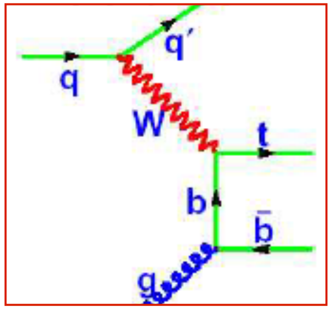


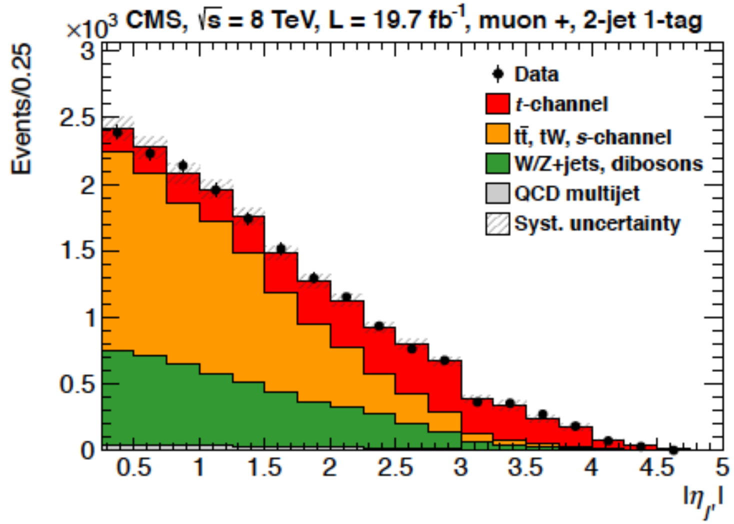
qqbar example at threshold

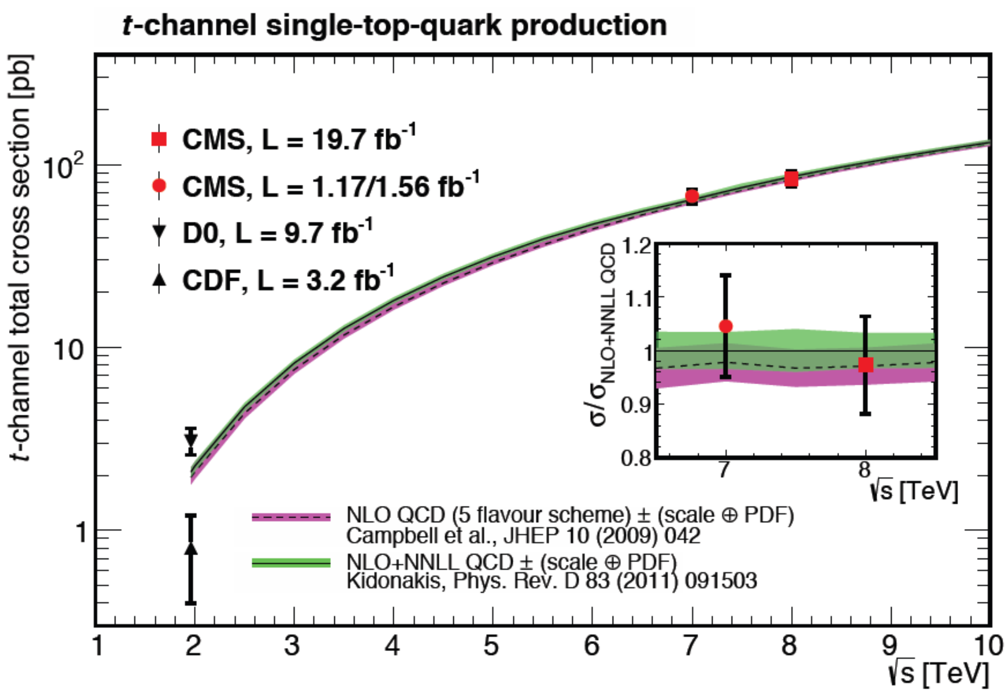


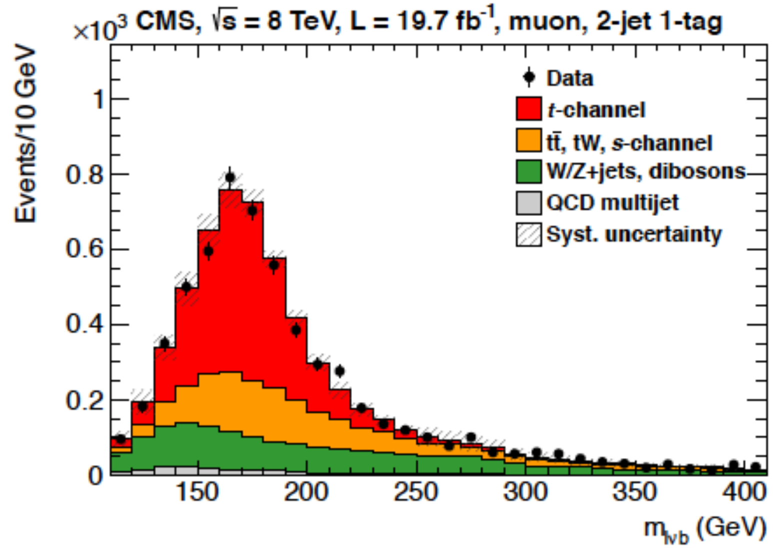


Single top t-channel



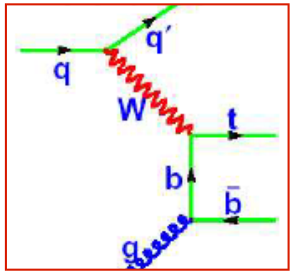


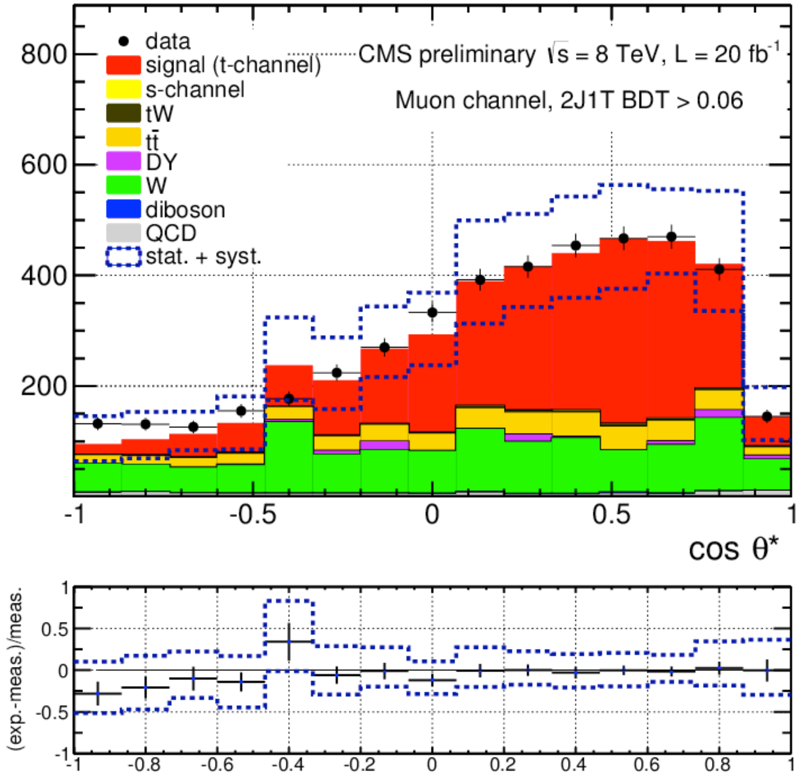


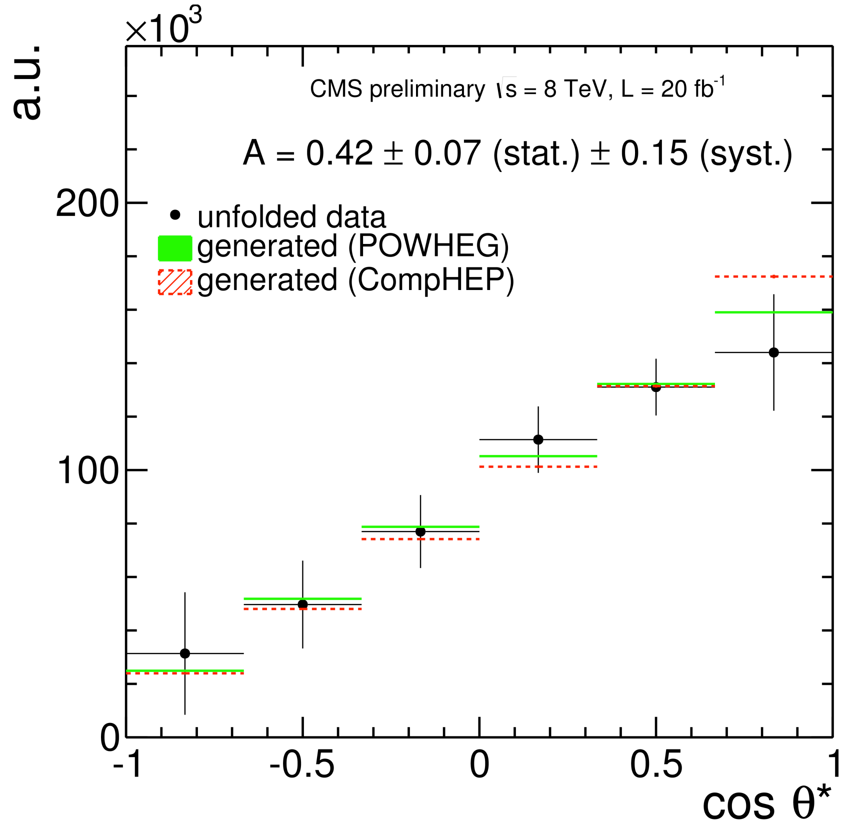


single top polarization in t-channel

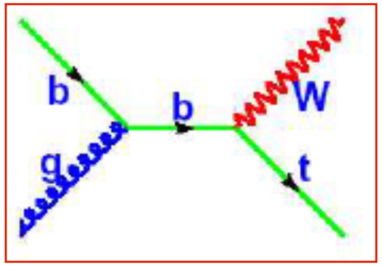
- V-A current, top 100% polarized !



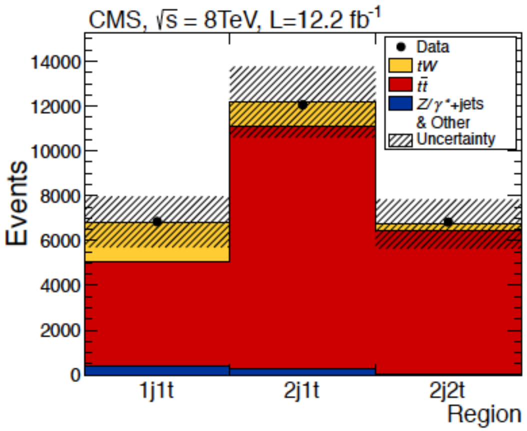


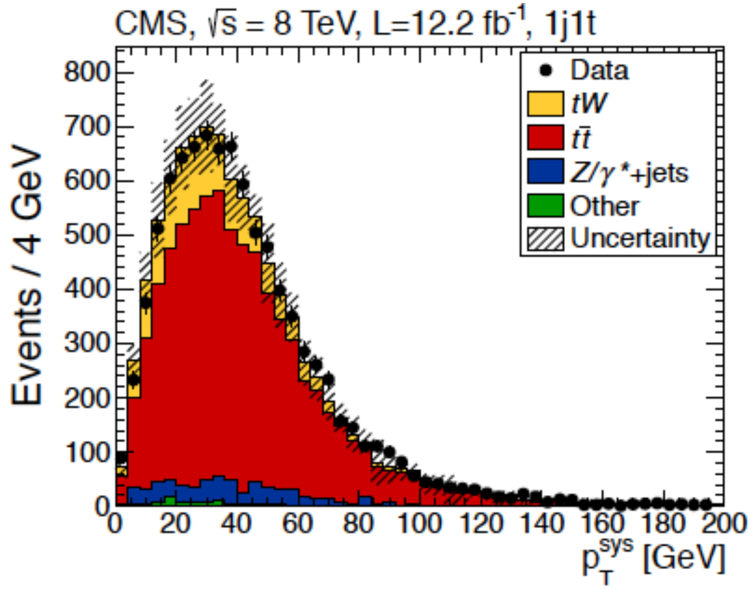


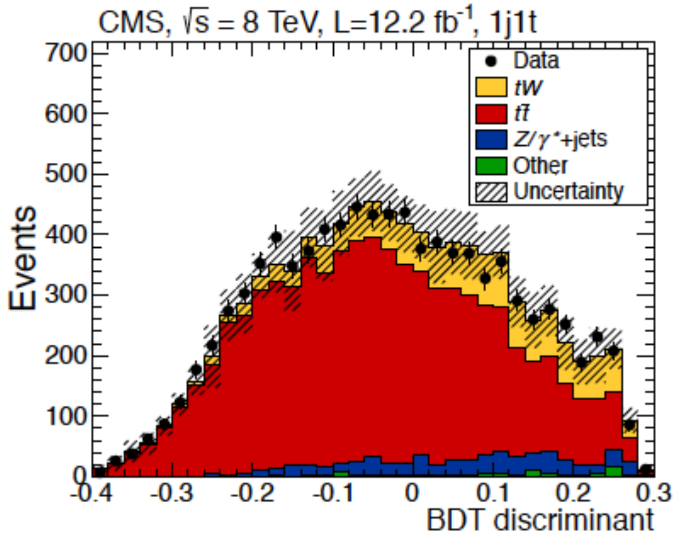
single top tW channel



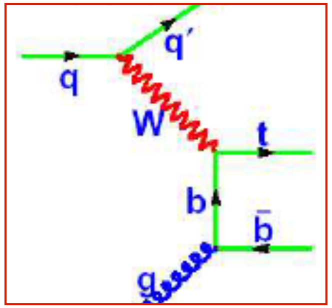
categorization important !

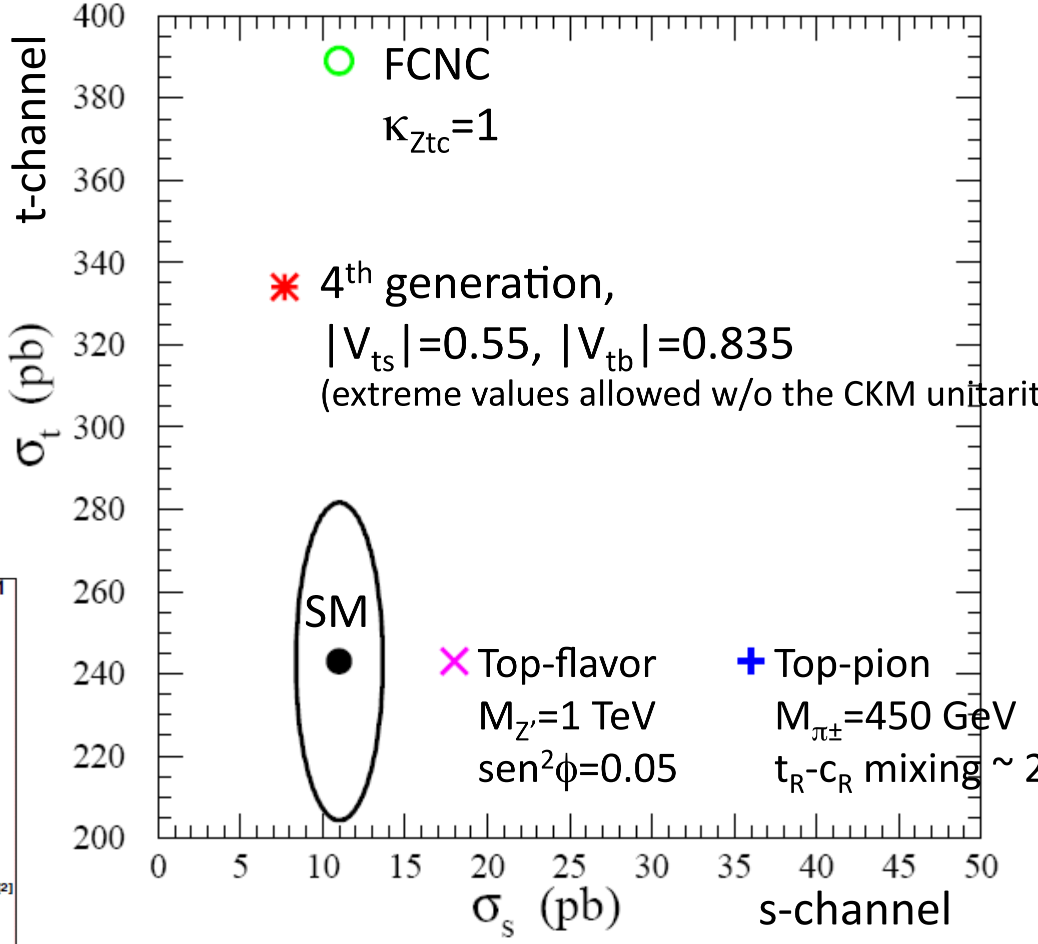




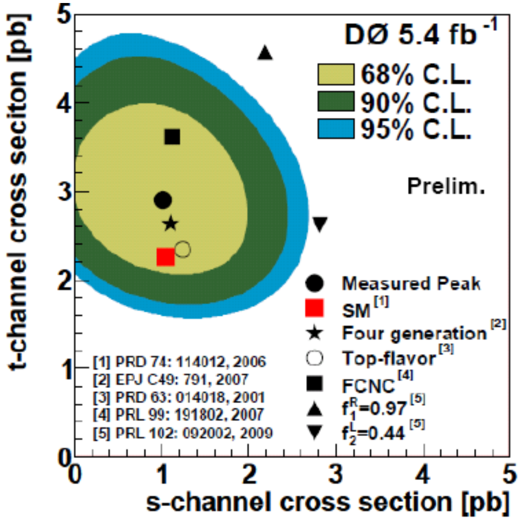


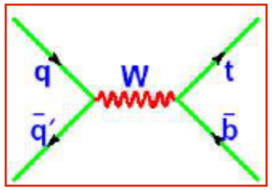
Single top in t and s channel sensitive to different aspects of New Physics (tW, too !)





(plot for 14 TeV)





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