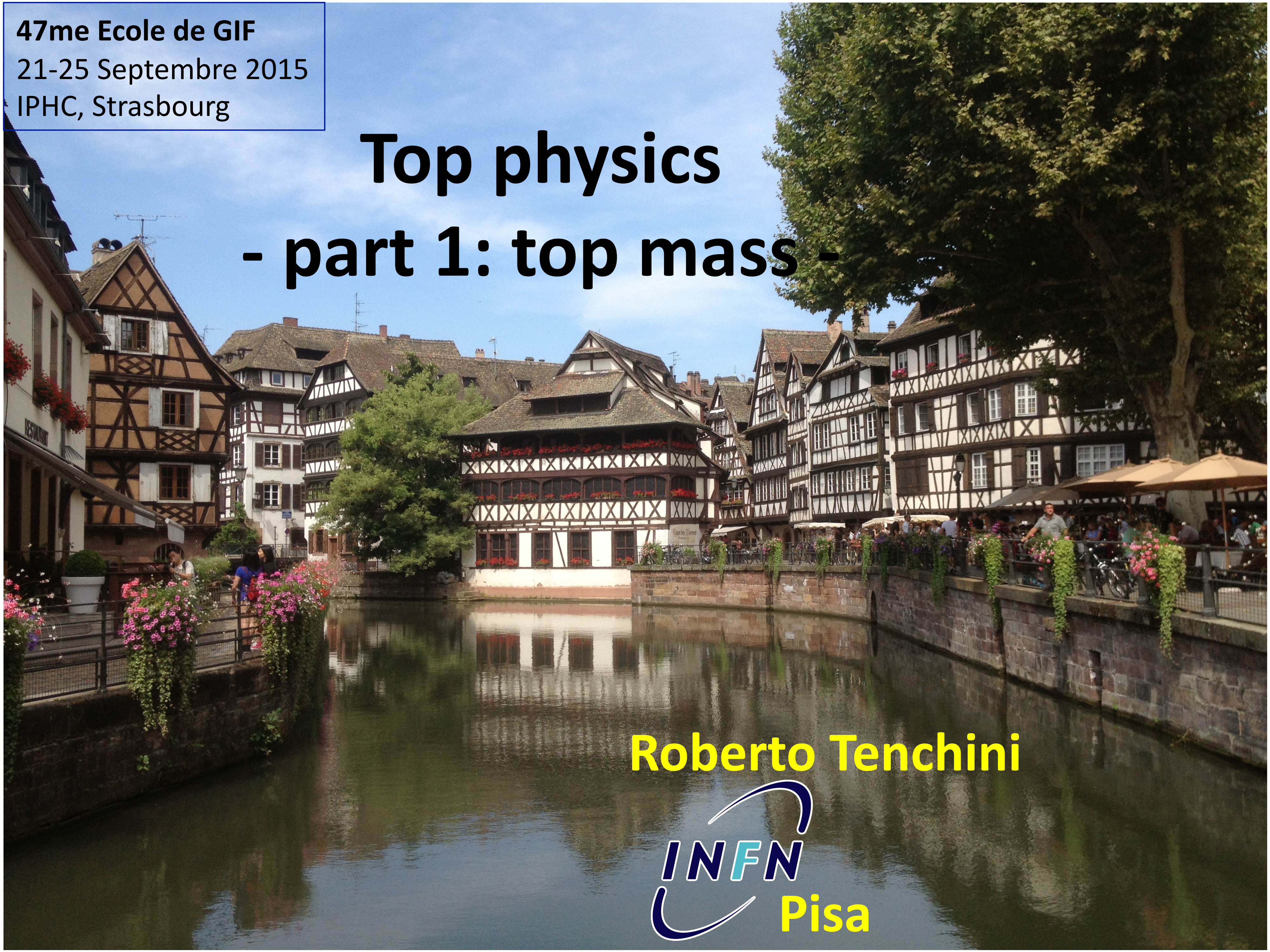
**47me Ecole de GIF**
21-25 Septembre 2015
IPHC, Strasbourg

# Top physics
# - part 1: top mass -




**Roberto Tenchini**

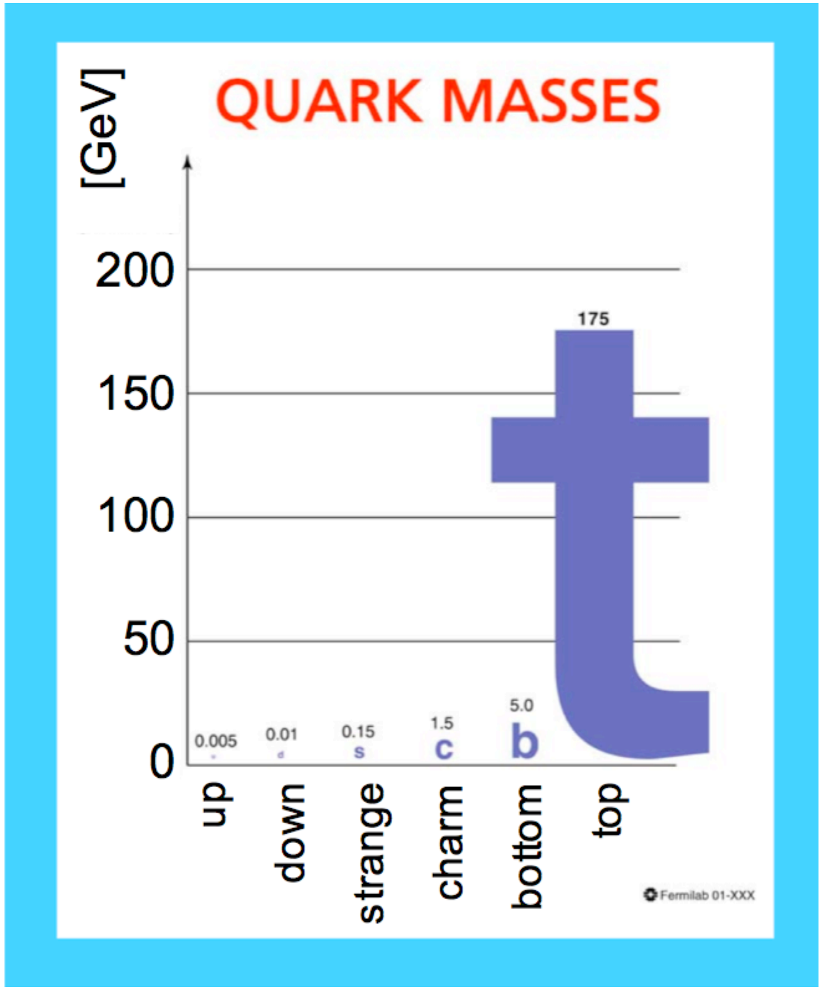
INFN Pisa

# 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*

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

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



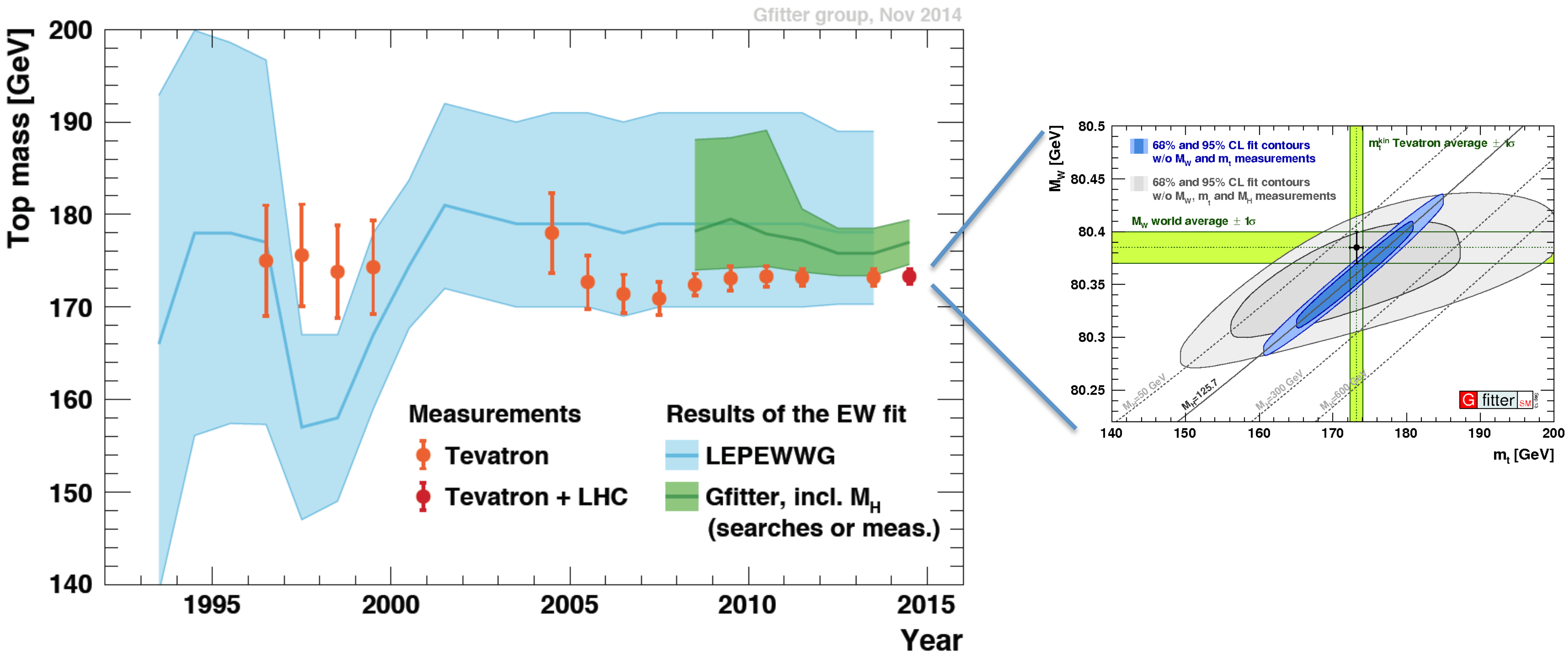
# Some consequences of the large top mass (the large top-Higgs Yukawa coupling)

- 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

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

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

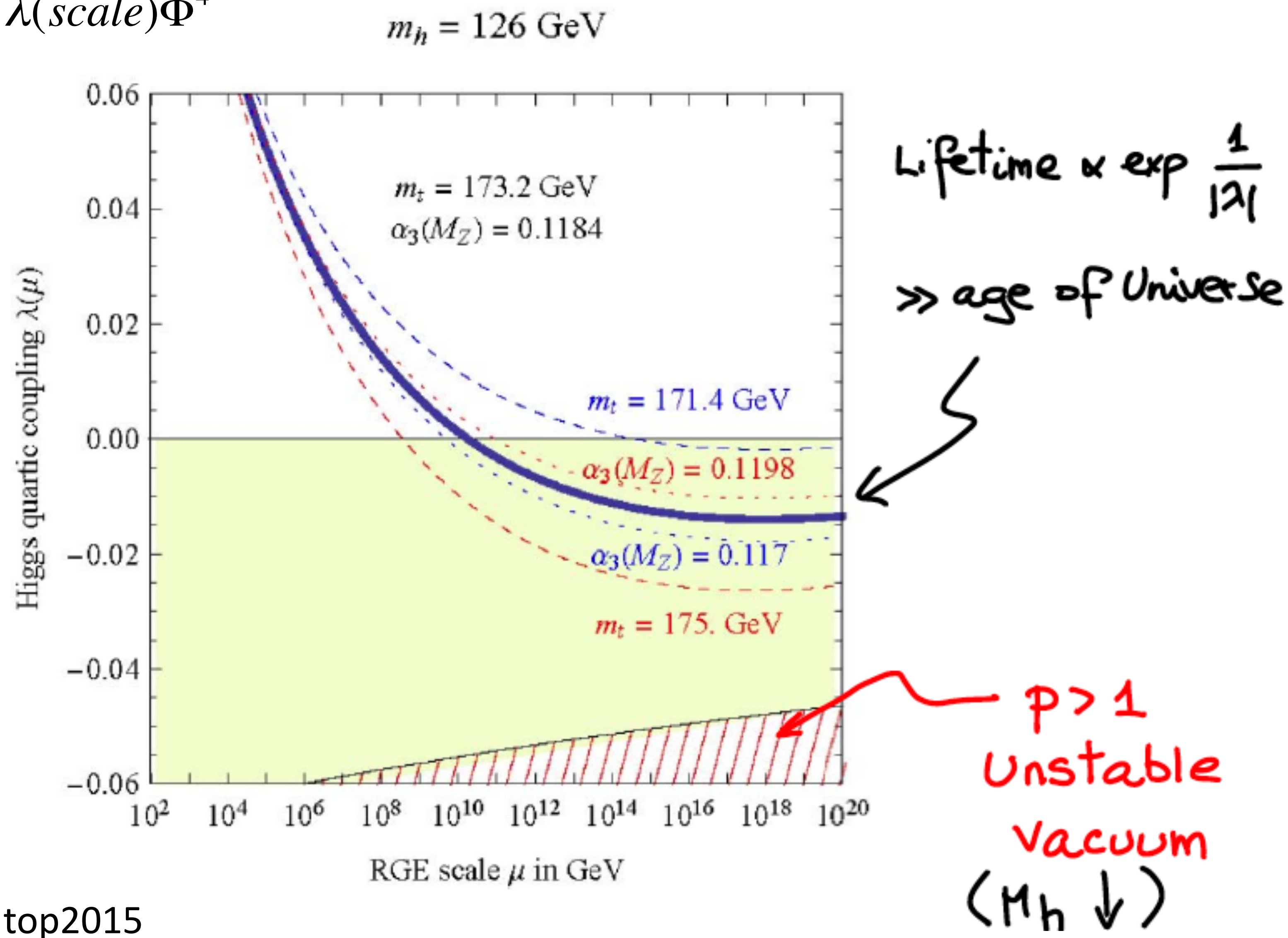
# Top mass and electroweak physics




Courtesy of Roman Kogler

# LIFE IN A METASTABLE VACUUM

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

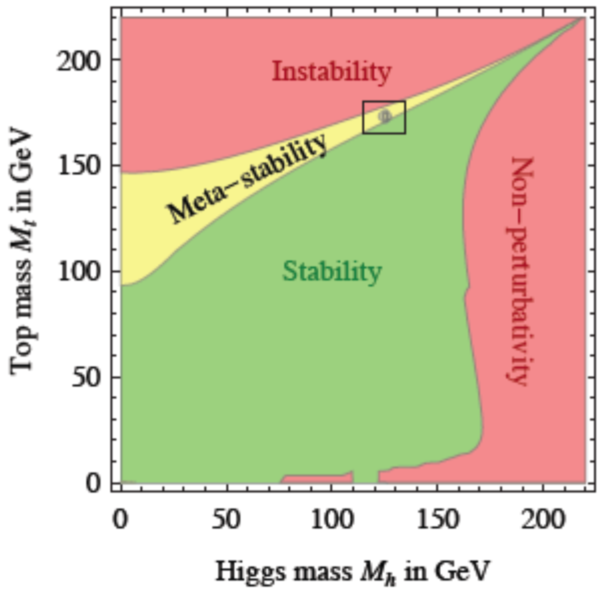


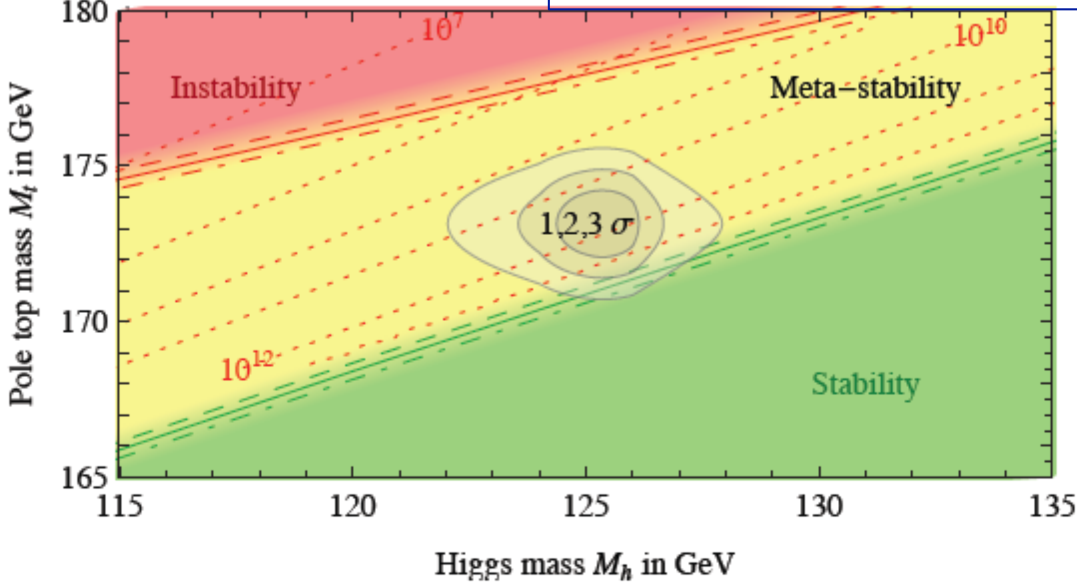

J.R. Espinosa at top2015

# 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

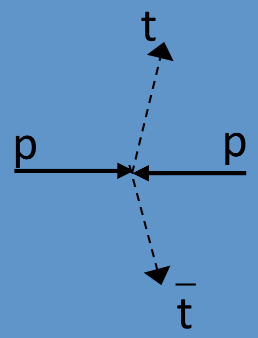


# TOP PRODUCTION AND DECAY: GETTING THE DATA SAMPLES

# Top Quark Production at the LHC

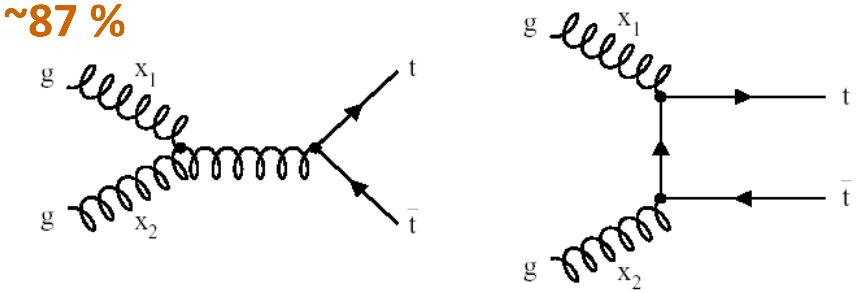
**top pairs**

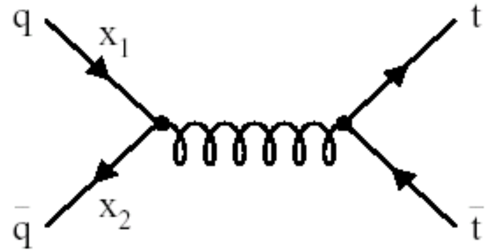



10 tt pairs per day @ Tevatron → 1 tt pair per second @ LHC

*qq →tt : 85%* *gg→tt : 87%*

**~87 %**

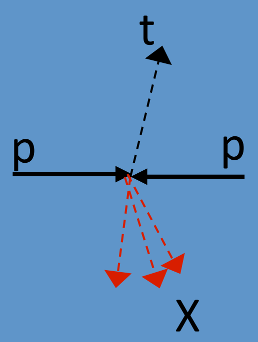


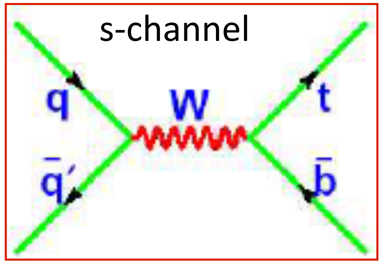

- NLO cross-section $\sigma^{NLO}$ = **232** pb at 8 TeV → ~2 M events/10fb$^{-1}$
- NNLO calculations now available, Czakon, Mitov (2013) arXiv:1303.6254

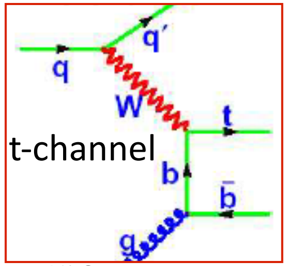
Some references (not a complete list!): (top pairs) N.Nason *et al.* Nucl.Phys. B303 (1988) 607, S.Catani *et al.* Nucl.Phys. B478 (1996) 273, M.Beneke *et al.* hep-ph/0003033, N.Kidonakis and R.Vogt, Phys.Rev. D68 (2003) 114014, W.Bernreuther et al. Nucl.Phys. B690 (2004) 81-137 (single-top) T.Stelzer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

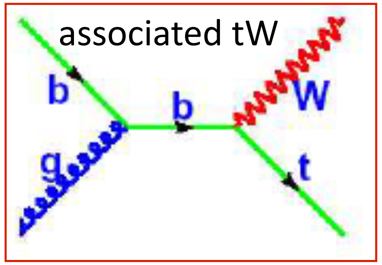
**single-top**




30 single-tops per minute @ LHC




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

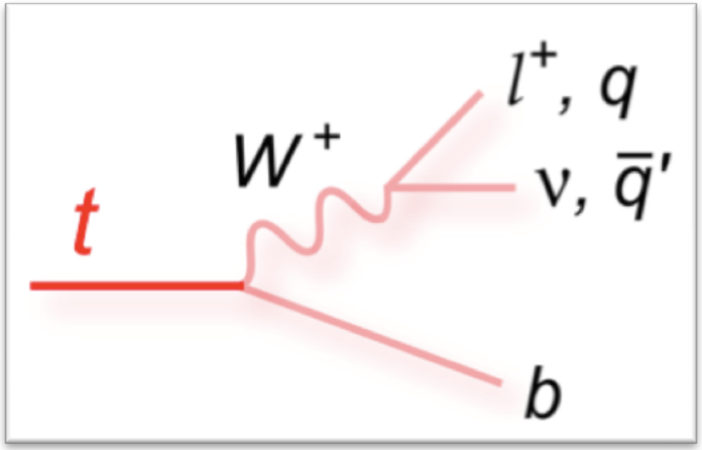
$\sigma^{NLO}$(total) 8 TeV = **112** pb

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

| s-channel | t-channel | associated tW | |
|---|---|---|---|
| $\sigma^{NLO}$ = 3.4 pb | $\sigma^{NLO}$ = 53 pb | $\sigma^{NLO}$ = 11 pb | →top production |
| $\sigma^{NLO}$ = 2.1 pb | $\sigma^{NLO}$ = 30 pb | $\sigma^{NLO}$ = 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**

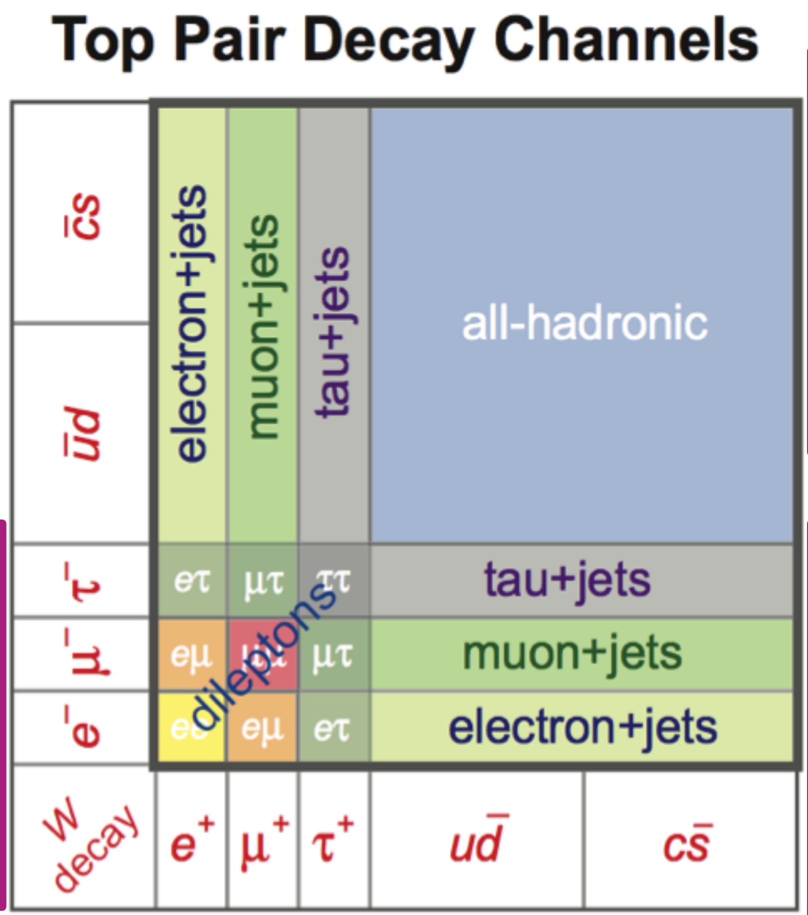
# ttbar topologies

**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:**
**- DETAILED EXAMPLE IN THE LEPTON+JETS – OTHER CHANNELS**
**- WHAT ARE WE MEASURING ?**
**- ALTERNATIVE METHODS**
**- DIFFERENTIAL TOP MASS**

# Methods for top mass measurement (1)

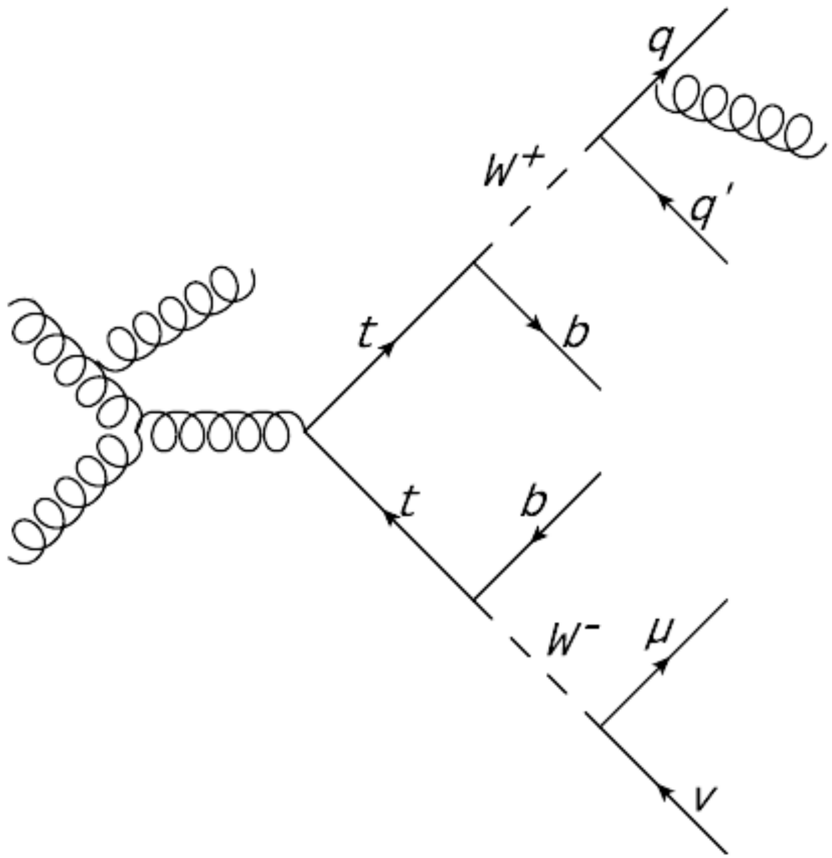
- *Standard methods* at hadron colliders: measure the top mass from the decay products in a specific **top pair decay channel**
  - from the simplest versions: measure invariant mass of, e.g. three jets in lepton+jets events
  - to the more sophisticated versions: use of the full event information to 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 / arXiv:1509.04044]

- Trigger for isolated muon [or electron] + jets ($pT > 24$ GeV [27 GeV])
- Exactly 1 isolated lepton with $p_T$ >33 GeV, $|\eta|<2.1$ (veto additional isolated e, μ)
- ≥ 4 "particle flow" jets (anti-kt , R = 0.5) with $p_T > 30$GeV, $|\eta|<2.4$
- 2 jets b-tagged among the 4 leading jets
- Composition:
  - 93% $\bar{t}t$, 4% W+jets, 2% single-top, 1% other
- 105000 events in 19.7 $fb^{-1}$ at 8 TeV selected

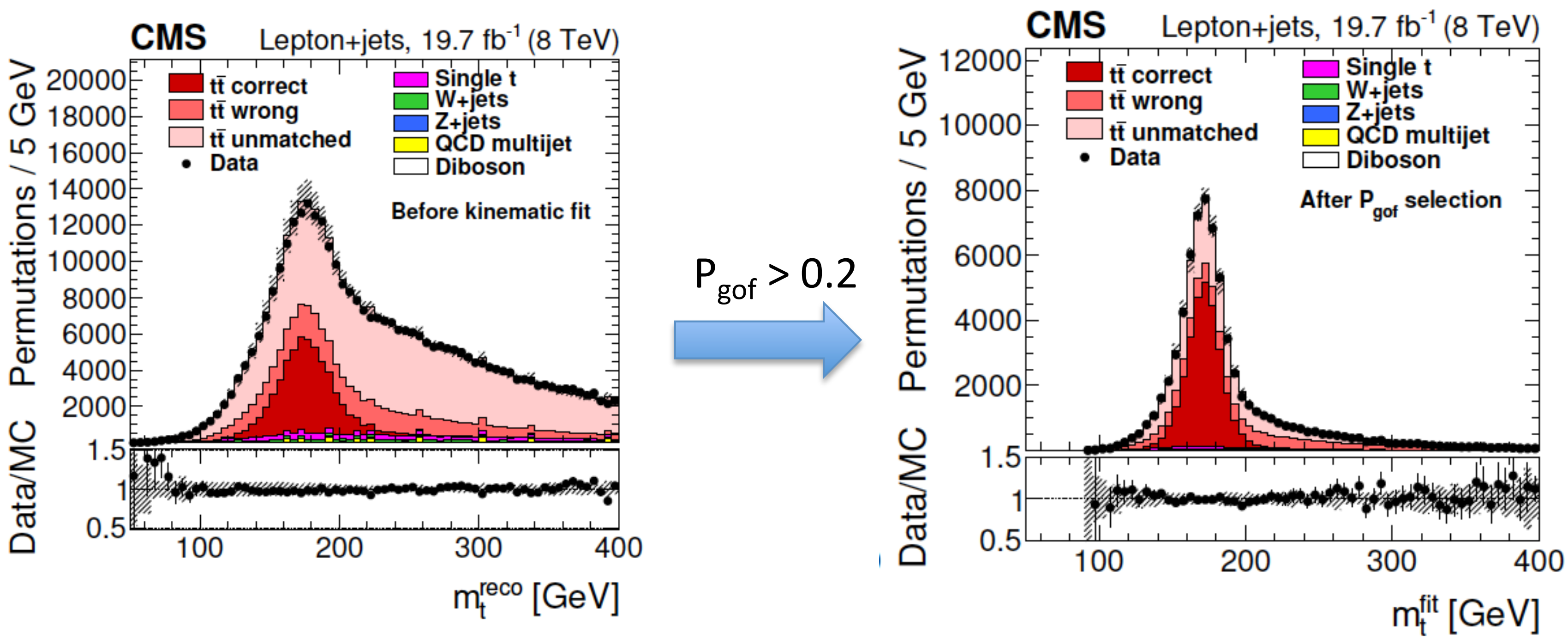



Compare with selections at Tevatron with full statistics: about 2500 events

# Event reconstruction

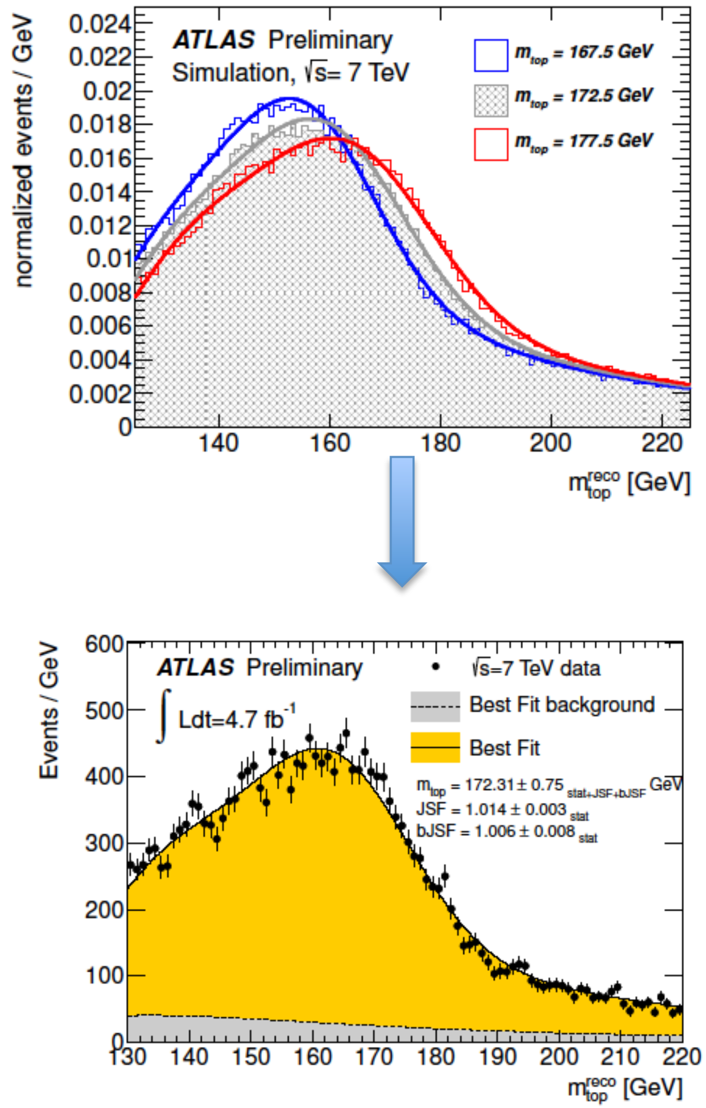
[example from CMS, TOP-14-001 / arXiv:1509.04044 ]

- 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 $P_{gof} > 0.2$
- 28295 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.**

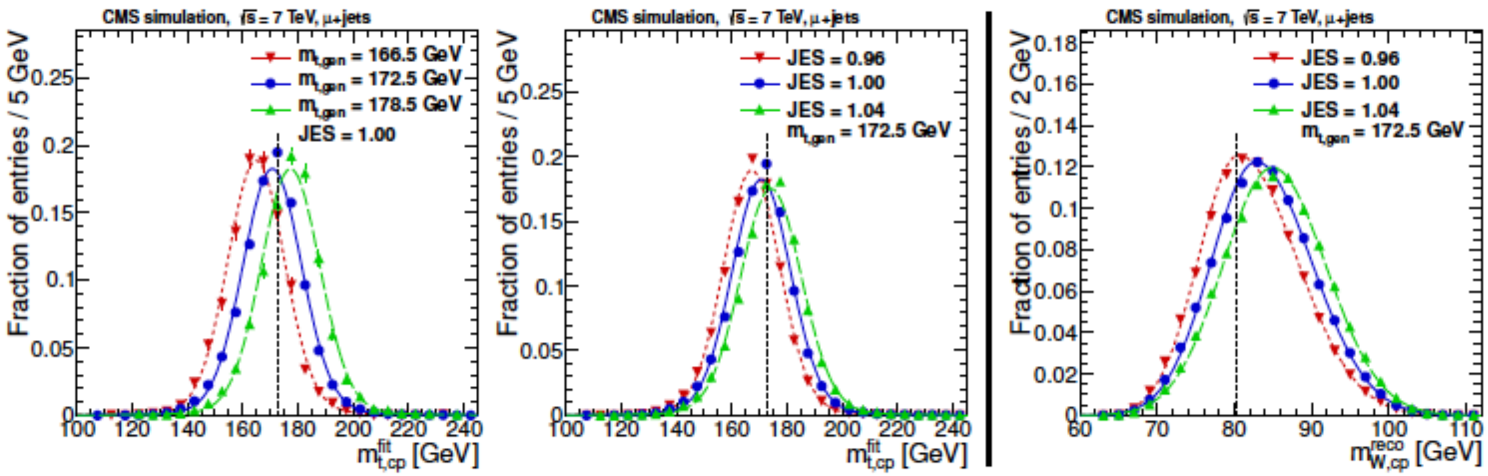


# Construct probability densities: ideogram method

[example from CMS, TOP-14-001 / arXiv:1509.04044 ]

- 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
- 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

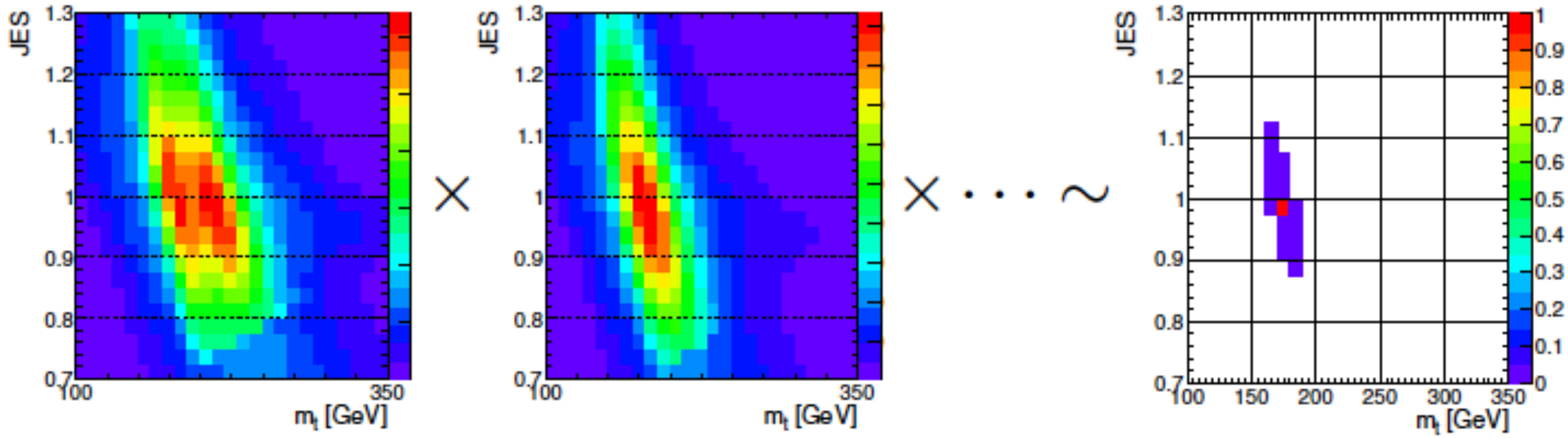
- Calculate likelihood for event with $n$ permutations, $j$ denotes *correct*, *wrong* and *unmatched* permutations

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

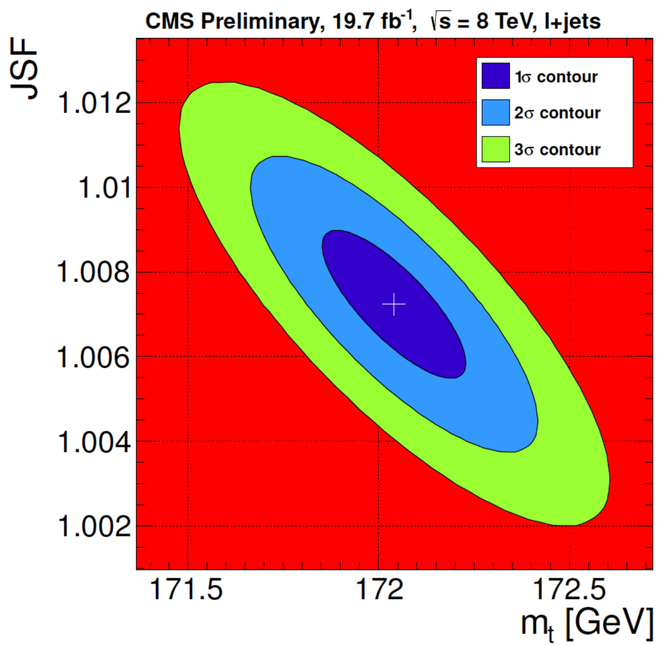
$$P\left(m_{t,i}^{fit}, m_{W,i}^{reco}|m_t, \text{JES}\right) = \sum_j f_j P_j\left(m_{t,i}^{fit}|m_t, \text{JES}\right) \cdot P_j\left(m_{W,i}^{reco}|m_t, \text{JES}\right)$$

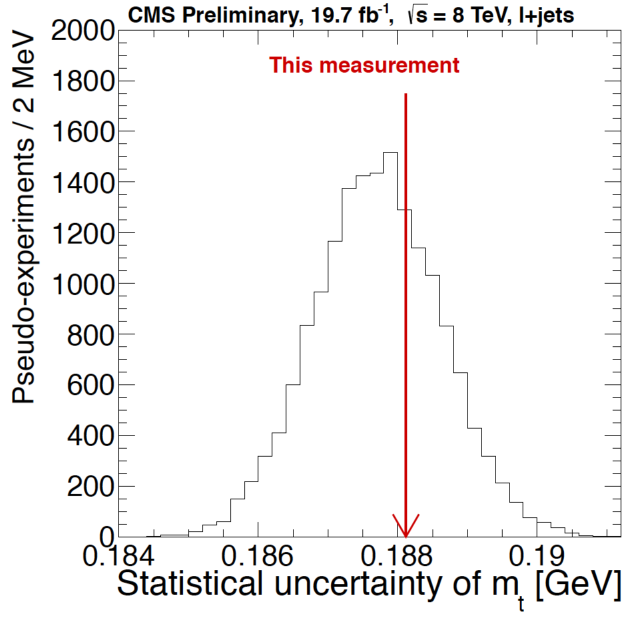
- Most likely $m_t$ and JES by maximizing

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



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



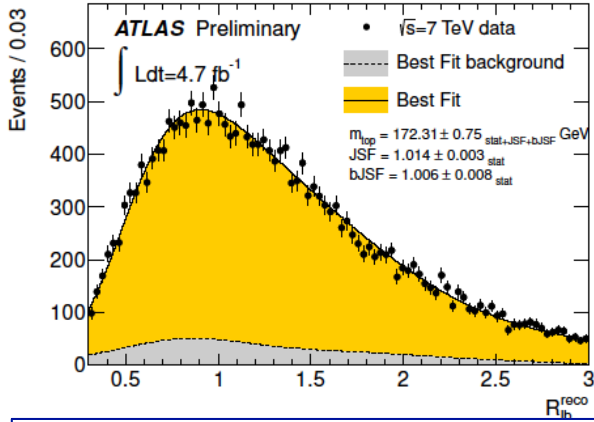




$$
\begin{aligned}
m_t &= 172.04 \pm 0.19\,(\text{stat.+JSF}) \pm 0.75\,(\text{syst.})\,\text{GeV}, \\
\text{JSF} &= 1.007 \pm 0.002\,(\text{stat.}) \pm 0.012\,(\text{syst.}).
\end{aligned}
$$

(Note: this was the preliminary result, kept for illustration, for the final measurement see arXiv:1509.04044)

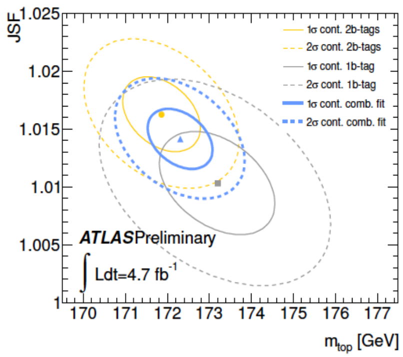
# Top mass fitting techniques and JES

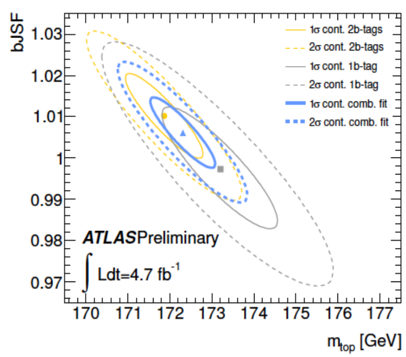
- The Jet Energy Scale is the most important source of experimental uncertainties, the W mass constraint is a powerful tool for light quark JES
- Can also find a variable sensitive to b-jet JES and constraint it in situ [ATLAS, CONF-2013-046] in this case b-tagging is used not only for jet classification,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




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

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

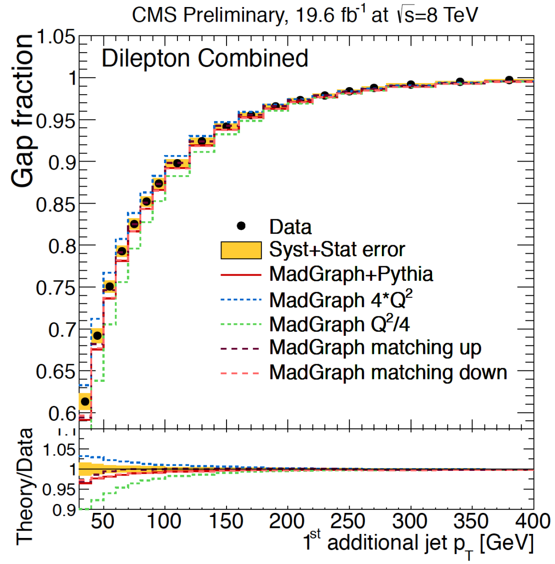


# Main sources of systematic uncertainties

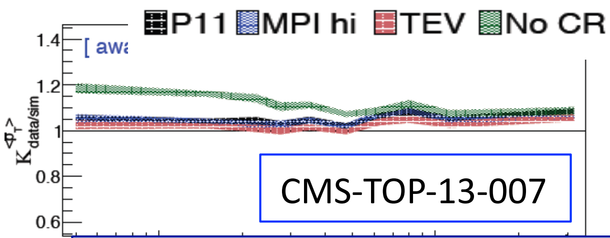
## [for l+jet measurements]

- 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-12-018




CMS-TOP-13-007

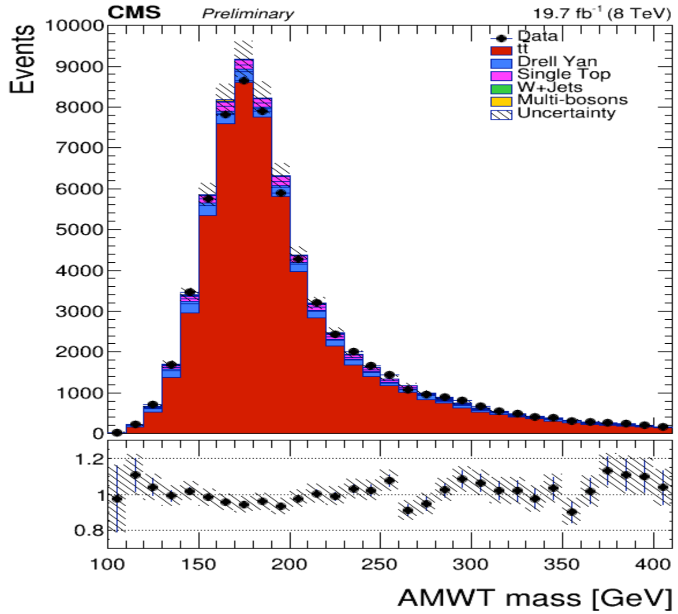
can use data to constrain generator modeling

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

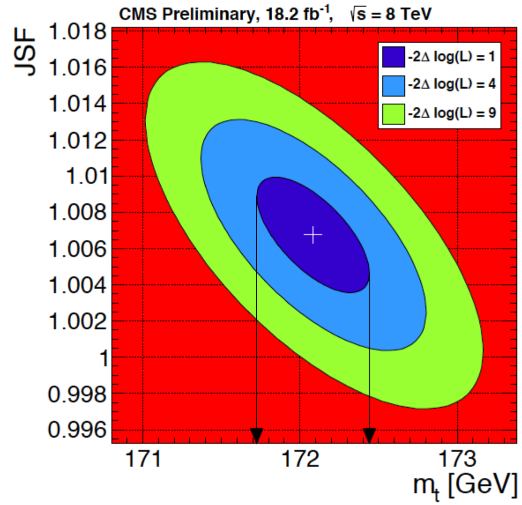
# A note on the other channels

- 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

CMS-TOP-2014-010




CMS-TOP-2014-002



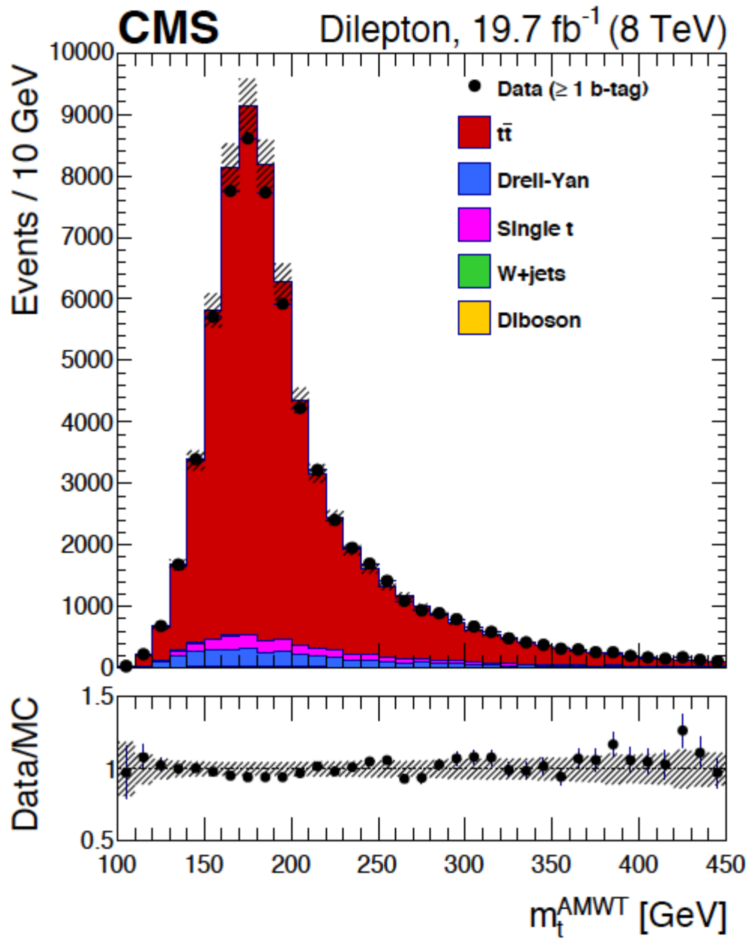
# top mass from dilepton reconstruction

- two charged leptons, two neutrinos, and two b quarks, resulting in 18 unknowns: three momentum components for each of the six final state particles.
- measure three-momenta of 2 charged leptons and 2 b-jets, plus 2 missing $E_T$ components, leaves 4 unknowns, solved with 4 constraints
  - $M_{l\nu}$ = 80.40 GeV (for both $W^+$, $W^-$ candidates)
  - $M_{Wb}$ = top mass for t and tbar candidates
- note that the system is not linear: up to 4 solutions, becomes 8 taking into account the b and bbar ambiguity, numerical methods are used to find the right solution

(e.g. L. Sonnenschein PRD 72, 095020 (2005)

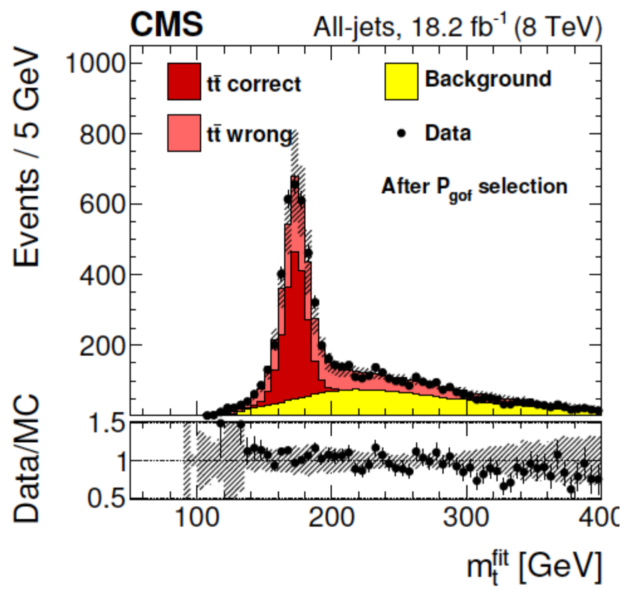
# top mass from dileptons (AMWT)

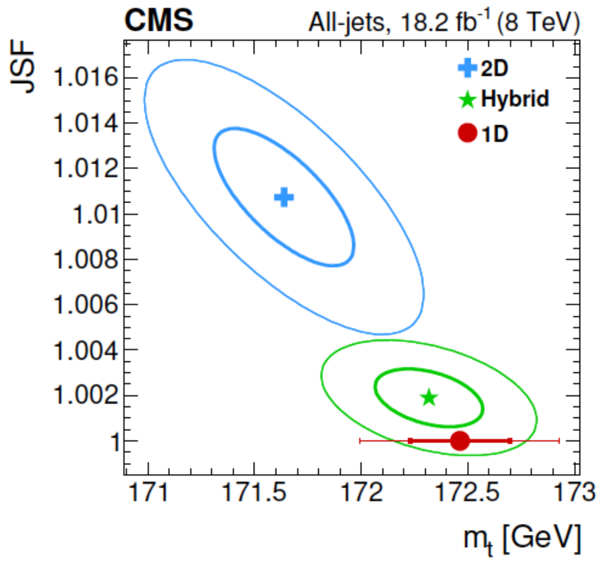
- For each event, scan solutions as a function of top mass and compute a weight from the matrix element summed over all possible initial partons taking into account the PDF
- Reconstruct many times according to momentum resolution and find the top mass value with maximum weight: $m^{AMW}_{Top}$



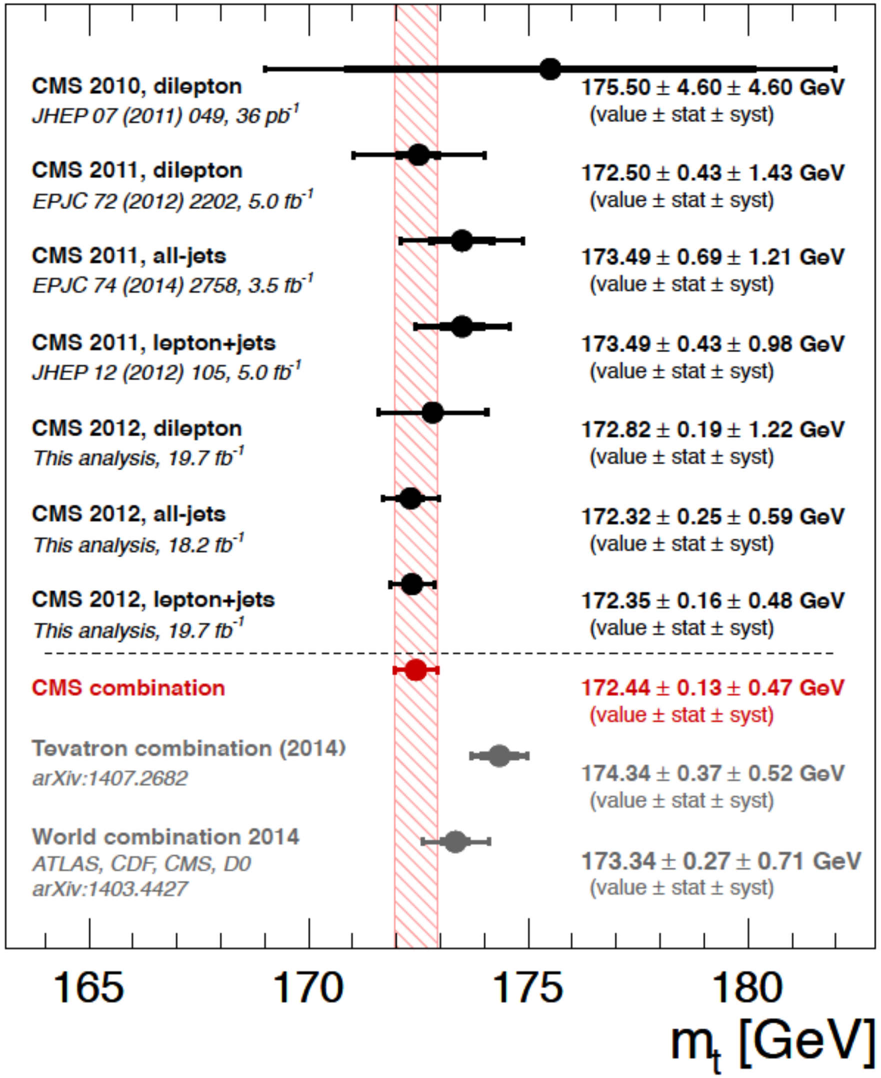
# top mass from fully hadronic events

- The two b-tagged jets are candidates for the bottom quarks, while the four untagged jets serve as candidates for the light quarks of the W boson decays.
- six possible parton-jet assignments per event and the assignment that fits best to the ttbar hypothesis based on the $\chi 2$ of the kinematic fit

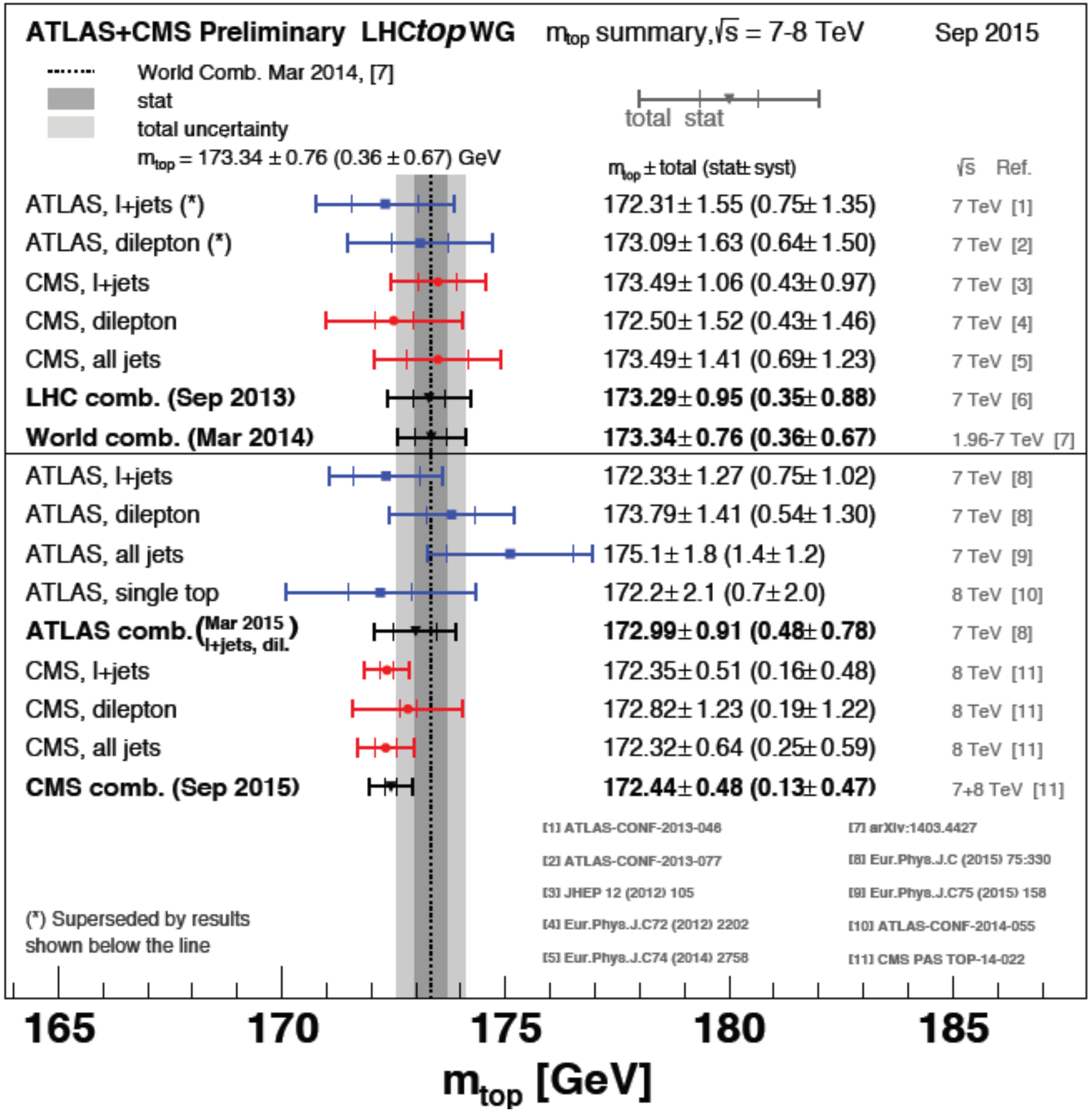


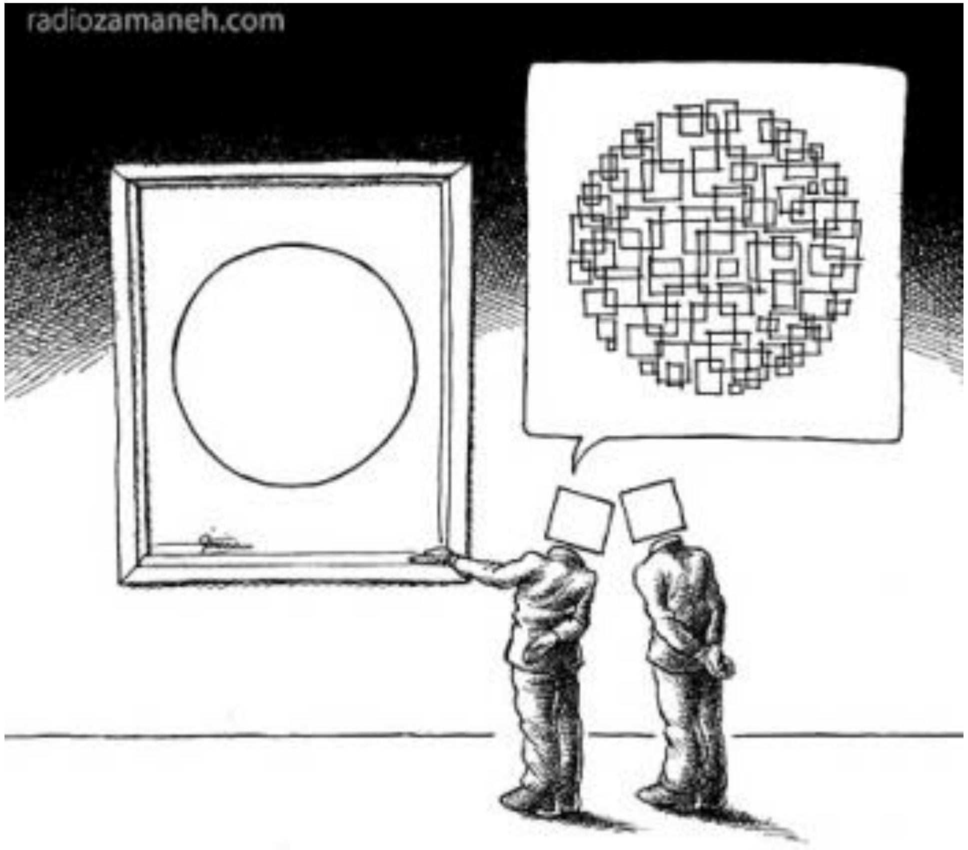
# Summary of the eight CMS $m_{top}$ "standard" measurements and their combination



# Grand LHC table



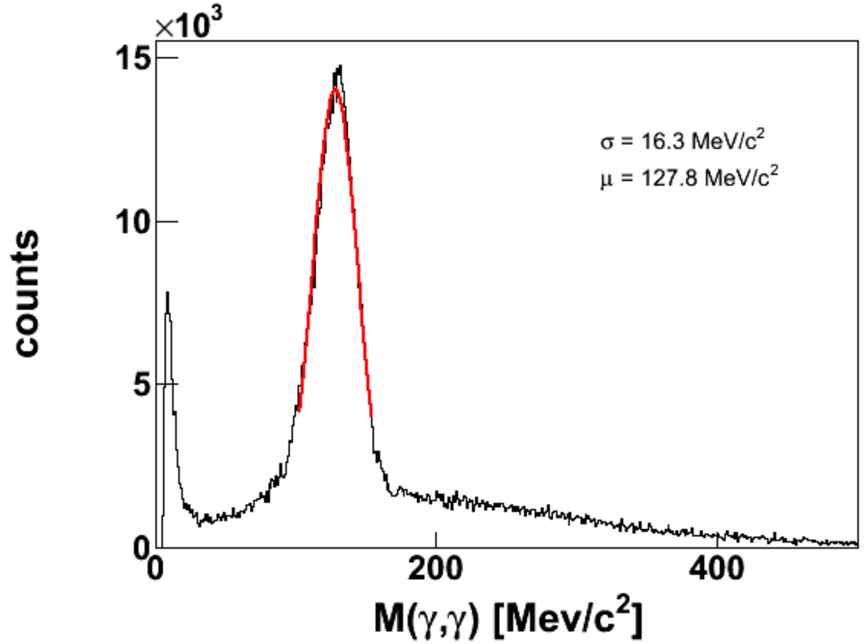
# INTERPRETATION OF TOP MASS MEASUREMENTS



# MEASURING A MASS FROM DECAYS PRODUCTS

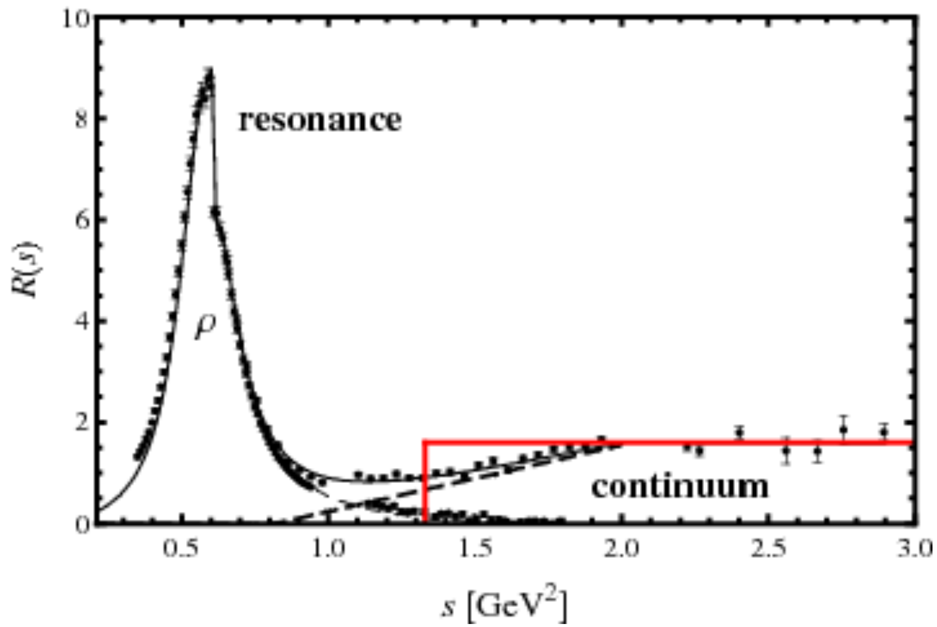
**TWO extreme cases**

$\pi^0$ mass from 2 photons




case 1. Experimental resolution much lower than natural width: the experiment provides a mass measurement

$\rho^0$ mass from 2 pions

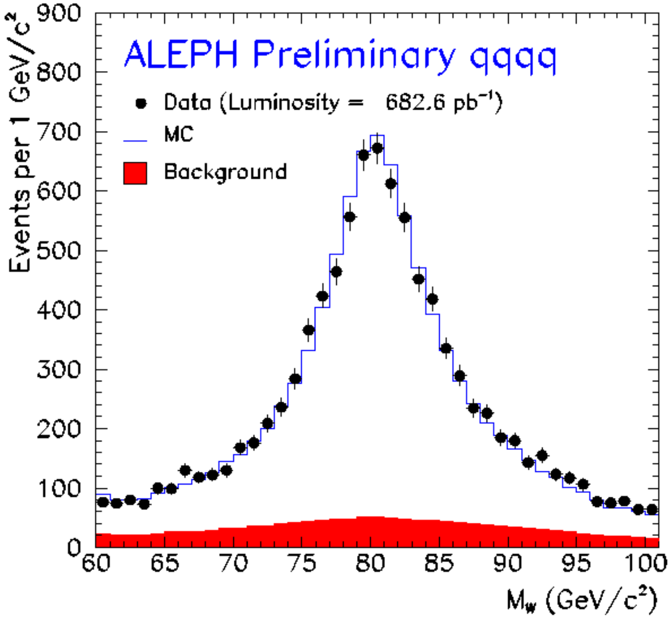


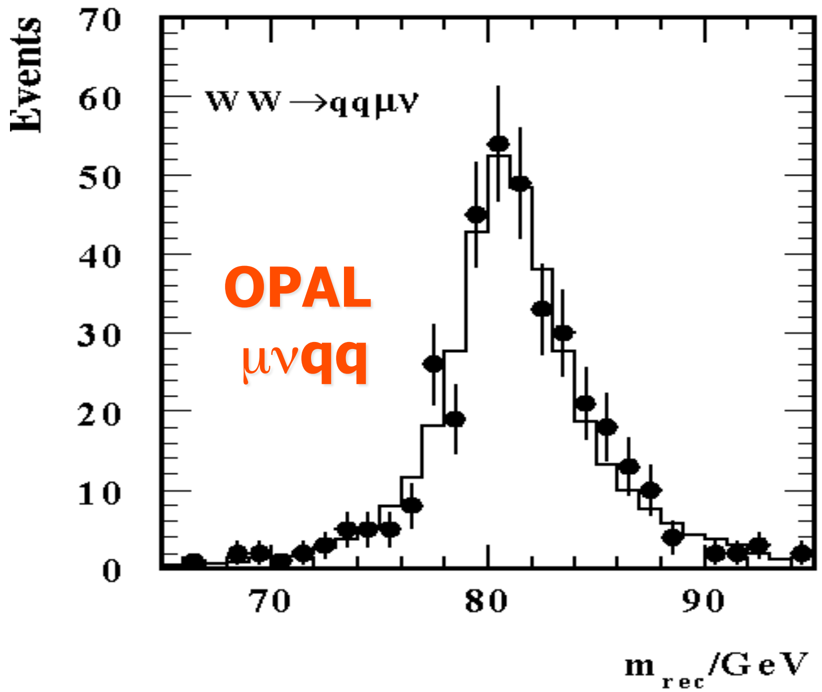

case 2. Experimental resolution much higher than natural width: the experiment provides data points to fit a resonance.

# MEASURING A MASS FROM DECAYS PRODUCTS

**Example of an intermediate case**

The W mass measured from the decay products: a Monte Carlo simulation, tuned at the Z, is used to extract the mass. The mass scheme used in the MC is relevant to interpret the measurement (e.g. Breit Wigner with fixed-width scheme (W) vs a running-width scheme (Z), difference of 27 MeV, sizeable given the precision)



# Issues in top mass interpretation

- There are three different issues related to the interpretation of current (and future !) measurements
  - top pole mass: higher order corrections to self energy (recent progress on this)
  - mass scheme used in simulation vs fixed order calculations (work ongoing, no reason to believe it cannot be solved)
  - color reconnection (the hard one, where experiments should concentrate)

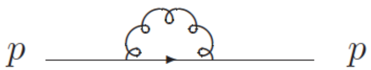
# top pole mass and higher order corrections

Electron

$$\frac{1}{p^2 - m^2} \qquad m = 0.511 \text{ MeV}$$

Quark

$$\frac{1}{p^2 - m^2}$$




Renormalized propagator: $S(p) = -\frac{i}{\not{p} - m_t^0 + \Sigma^R(p, m_t^0, \mu)}$

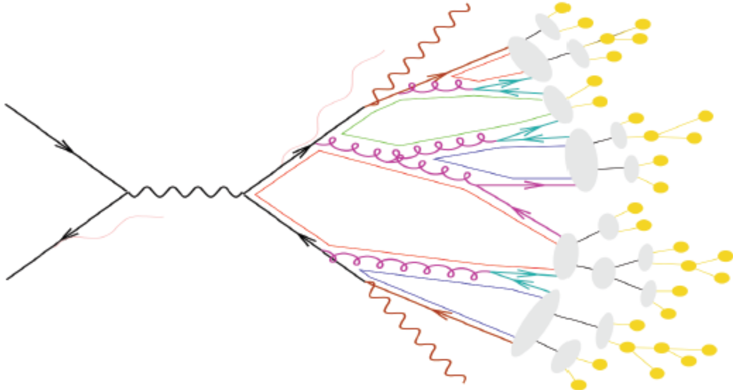
Marquard, A.V.Smirnov, V.A.Smirnov, Steinhauser, Feb.2015:

$$m_{t,\text{pole}} = m_{t,\overline{\text{MS}}} \left(1 + 0.4244\,\alpha_s + 0.8345\,\alpha_s^2 + 2.375\,\alpha_s^3 + (8.49 \pm 0.25)\alpha_s^4\right)$$

Recently computed: renormalon ambiguity < 100 MeV

# which mass scheme used by simulations ?

Parton showers: LO + soft/collinear (N)LLs + non-perturbative models



$$dP = \frac{\alpha_S}{2\pi}\, P(z)dz\, \frac{dQ^2}{Q^2}\, \Delta_S(Q^2_{\max}, Q^2)$$

$\Delta_S$ captures leading-log virtual corrections

Width effects are neglected

One calls 'Monte Carlo mass' the value of $m_t$ based on standard reconstruction methods

aMC@NLO includes off-shell and non-resonant effects, not yet NLO decays

Improvement in POWHEG: NLO top decays and approximate treatment of top width

Both aMC@NLO and POWHEG use the top-quark pole mass

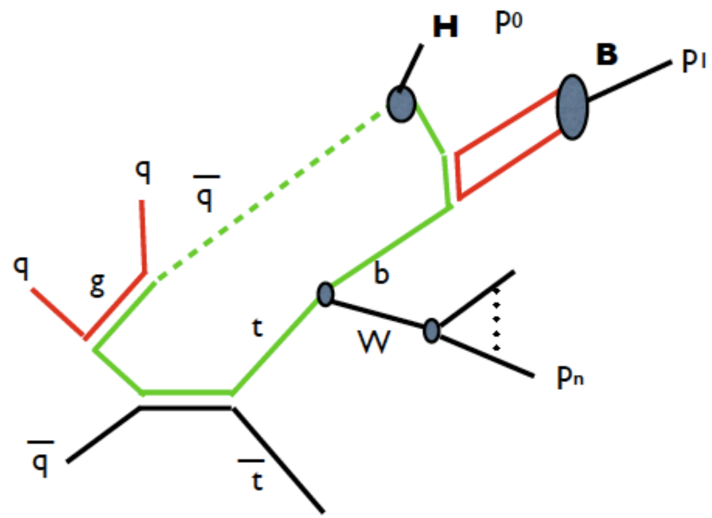
From G. Corcella – top2015

Work ongoing to relate "mc mass" to a well-defined calculation

# The real issue: top decay products have to (re)connect !

- **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
  - 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**

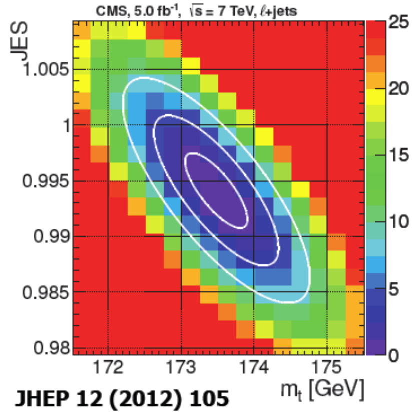



plot courtesy of Michelangelo Mangano

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

# 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

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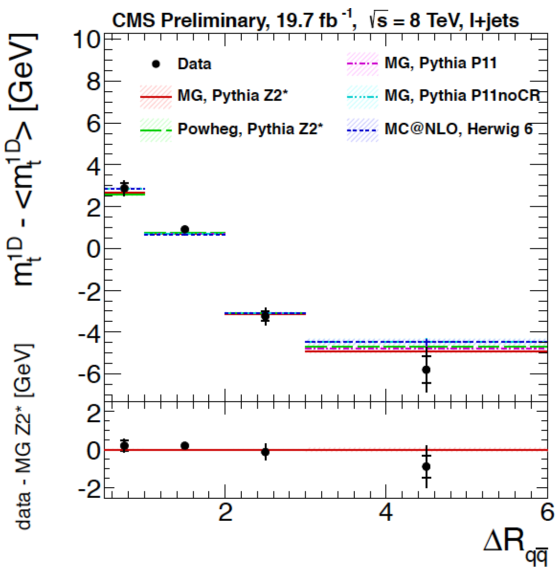
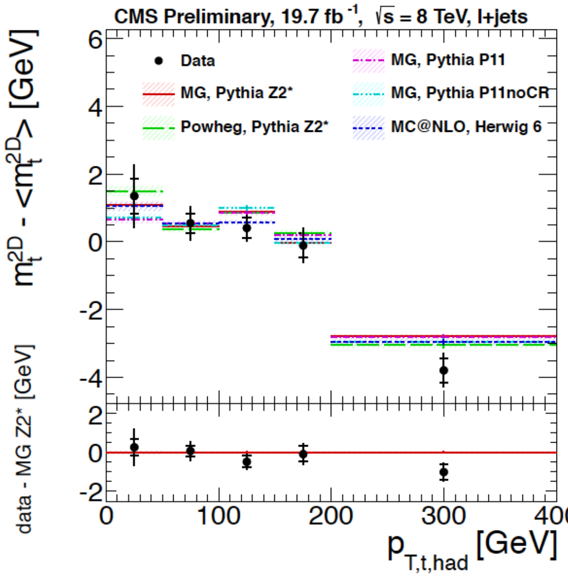
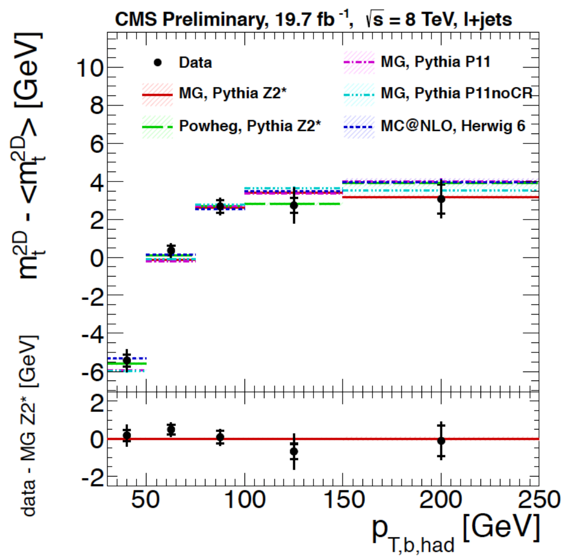
CMS-TOP-14-001



# Methods for top mass measurement (2)

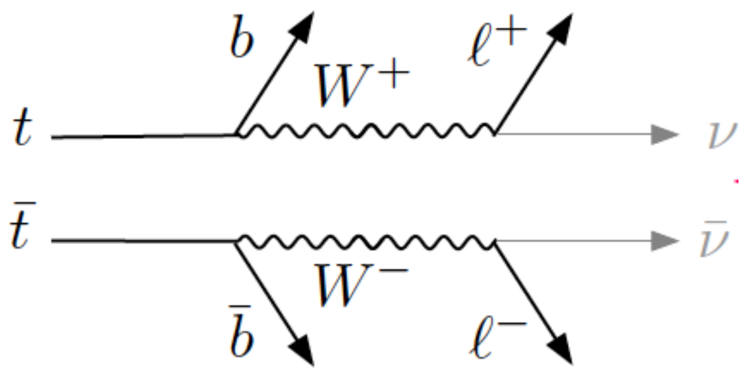
- Given the potential bias in measuring the top mass from its decay products, important to explore **alternative techniques**, e.g.
  - Measure the **decay length** (the boost) of B hadrons produced in top decays, the boost is related to the original top mass
  - Select **specific channels**, for example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

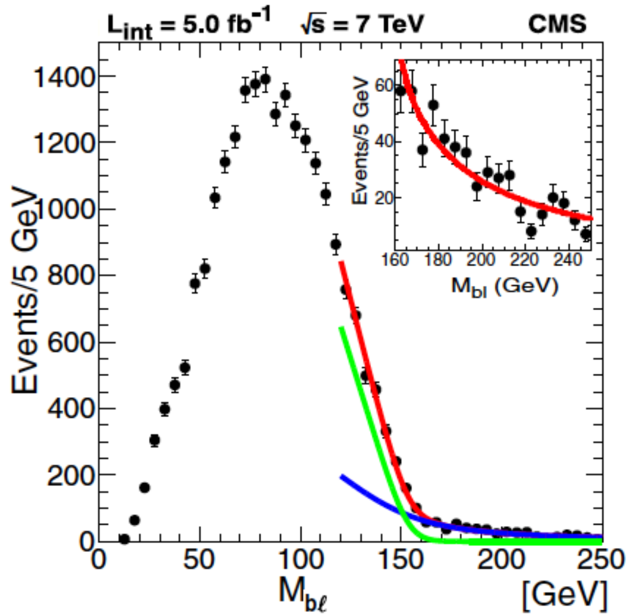
# TOP mass from alternative techniques

- 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

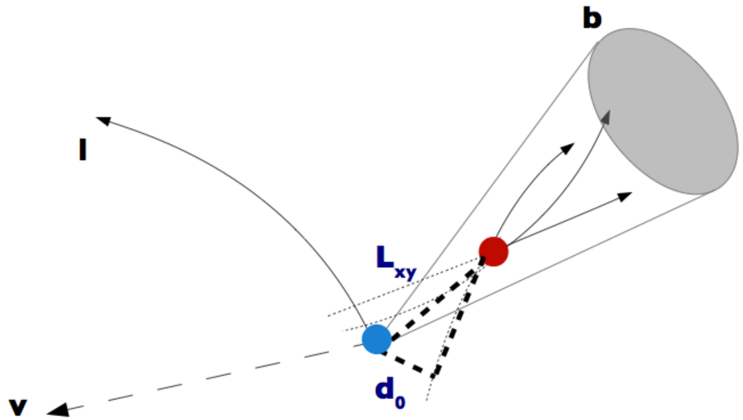
$$M_t = 173.9 \pm 0.9\,(\text{stat.})^{+1.6}_{-2.0}\,(\text{syst.})\,\text{GeV}$$



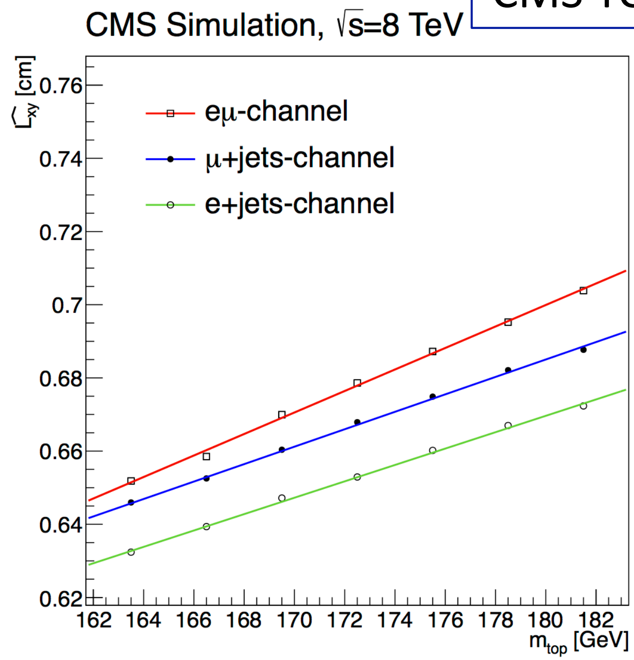



# Another example: top mass from the b decay length

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



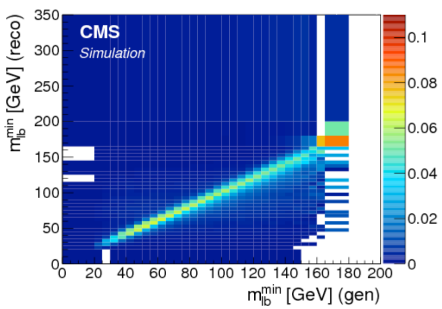

CMS TOP-12-030



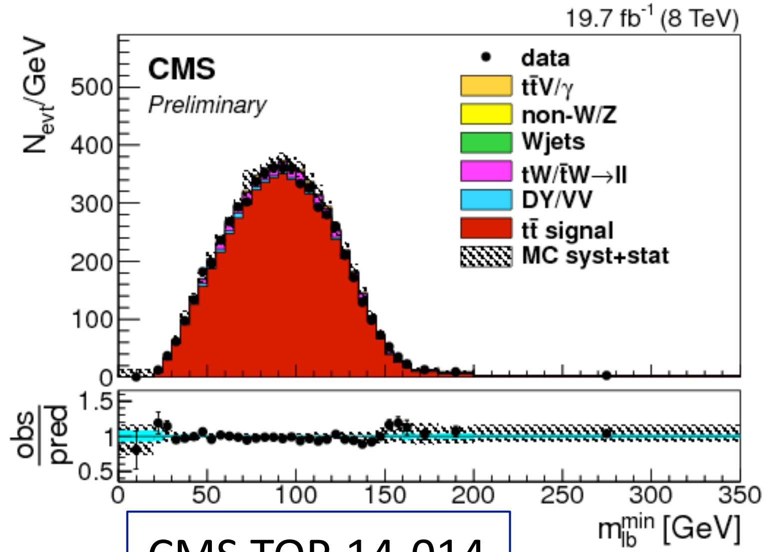

$m_t = 173.5 \pm 1.5\text{stat} \pm 1.3\text{syst} \pm 2.6p_t(\text{top})$ GeV

# Top mass from lepton-b invariant mass

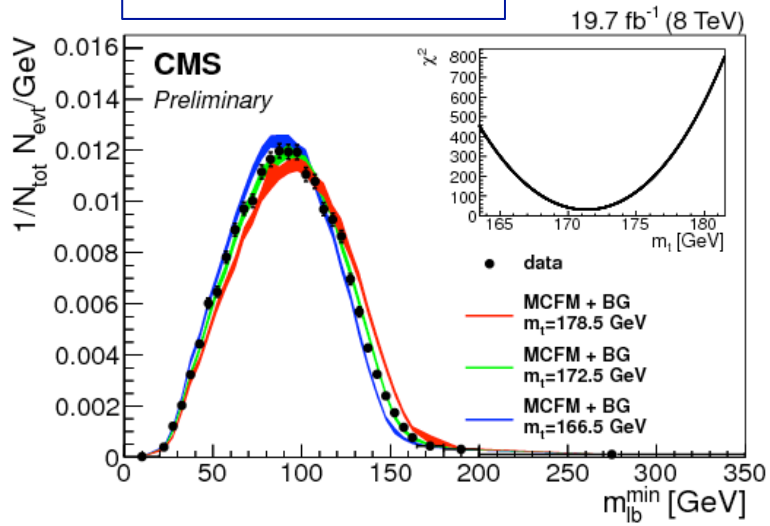
- Exploit high-purity dilepton event and compare directly to fixed-order calculations (NLO), which are available for $m_{lb}$
- Use unfolding method to compare directly with calculations




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



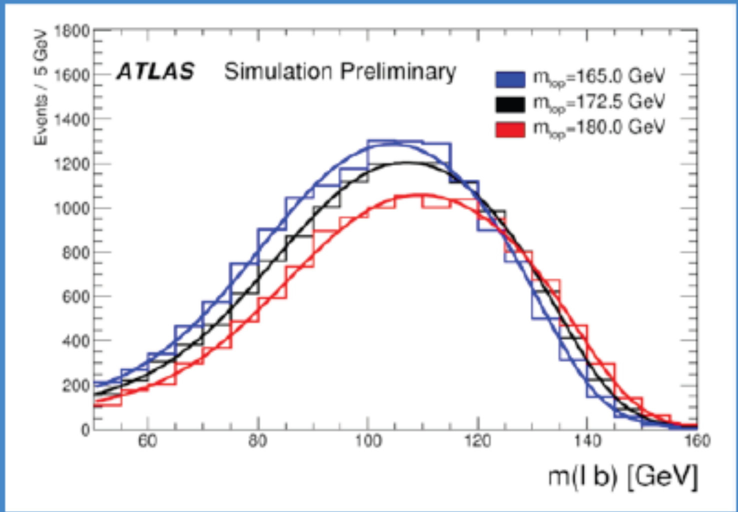

CMS TOP-14-014

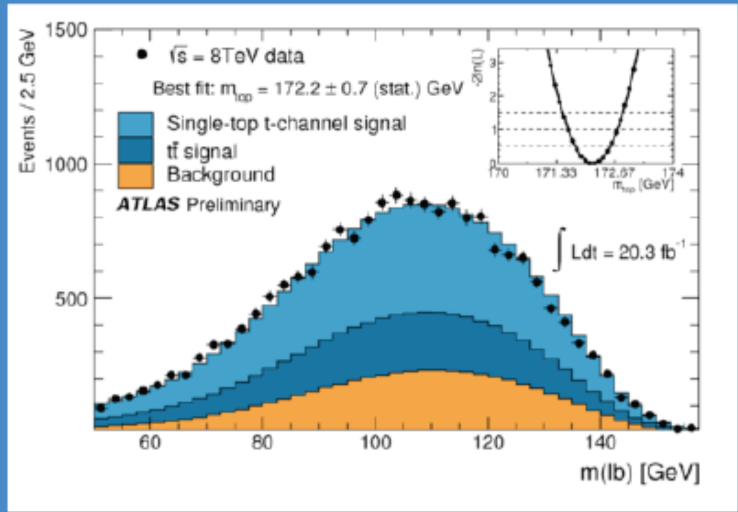


# $M_t$ with ATLAS: single top

*Template ($m_{lb}$)*
(8 TeV, 20.3 fb$^{-1}$)

ATLAS-CONF-2014-055




| syst | GeV |
|---|---|
| JES | 1.5 |
| hadronization | 0.7 |
| W+jets bckgd | 0.4 |

Use t-channel (σ=84 pb)
- 1 high-$p_T$ lepton, large MET
- >=2 high-$p_T$ jets, 1 btag

Neural Network selection

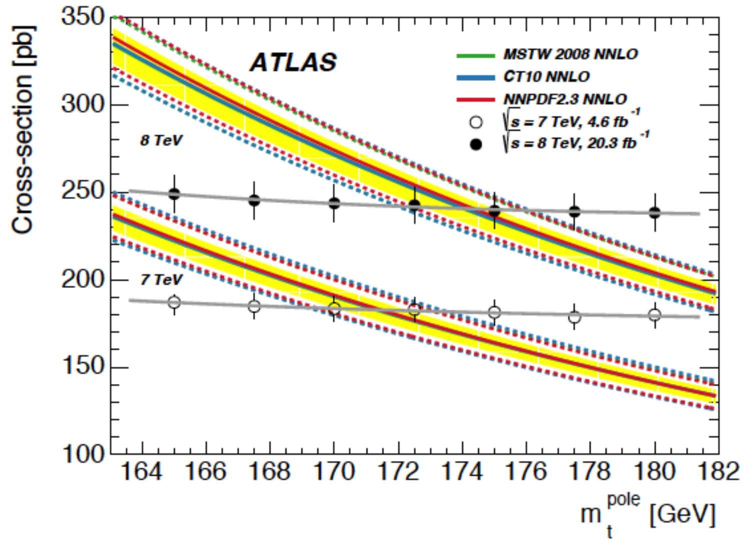
$M_t$=172.2±0.7(stat)±2.0(syst) GeV

$M_t$=172.2±2.1 GeV (±1.24%)

# 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 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 beam energy




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

# Extraction from differential cross-section

Alioli, Moch, Uwer, Fuster, Irles, Vos, EPJC73 (2013) 2438, arXiv:1303.6415

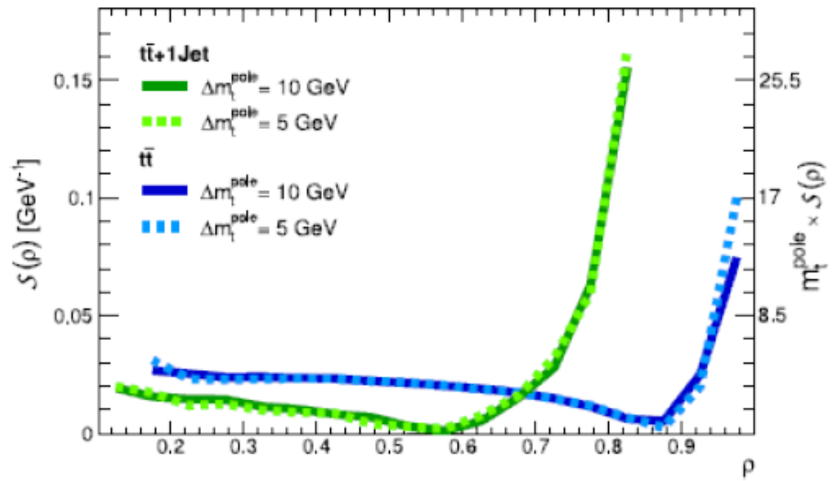
## Extraction from total cross section

Precision limited by poor sensitivity: $\Delta m/m \sim 0.2\ \Delta\sigma/\sigma$

$t\bar{t}$ threshold offers better sensitivity, but:

→ is limited to a very narrow region

→ requires description of bound state effects




$\rho\ \mu\ 1/m(t\bar{t})$ for top quark pairs

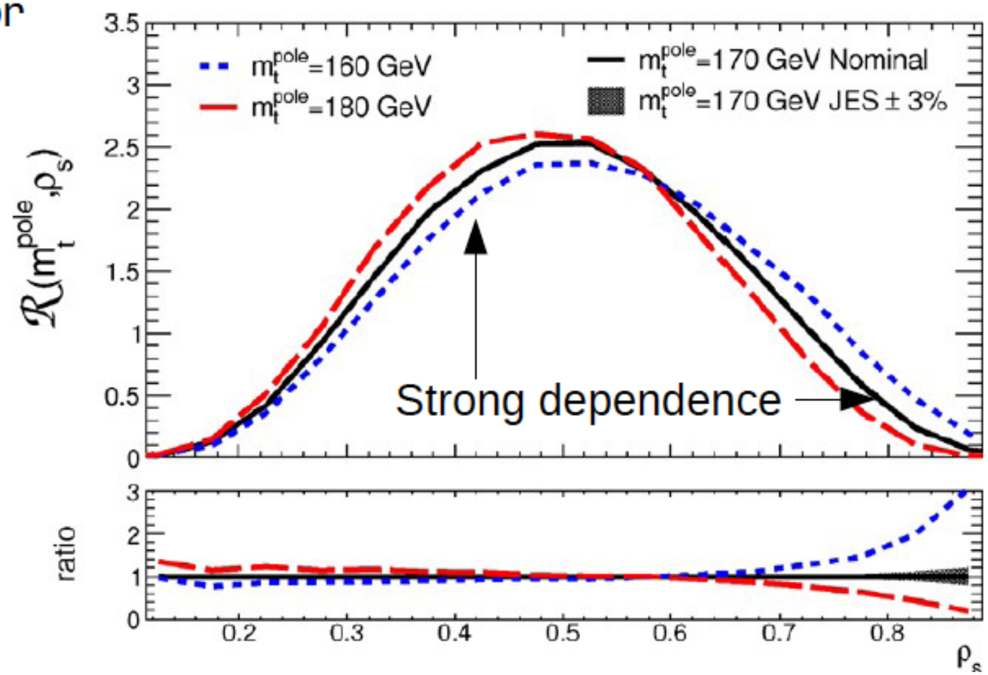
## Now consider the $t\bar{t}j$ cross-section

Sensitivity enhanced by mass-dependent radiation

Threshold effect spreads over large region

Infer mass from (normalized) shape

of $\rho = 1/m(t\bar{t}j)$ distribution




$\rho\ \mu\ 1/m(t\bar{t}j)$ for associated $t\bar{t}j$ production

→ *1 at threshold*

→ *0 for boosted production*

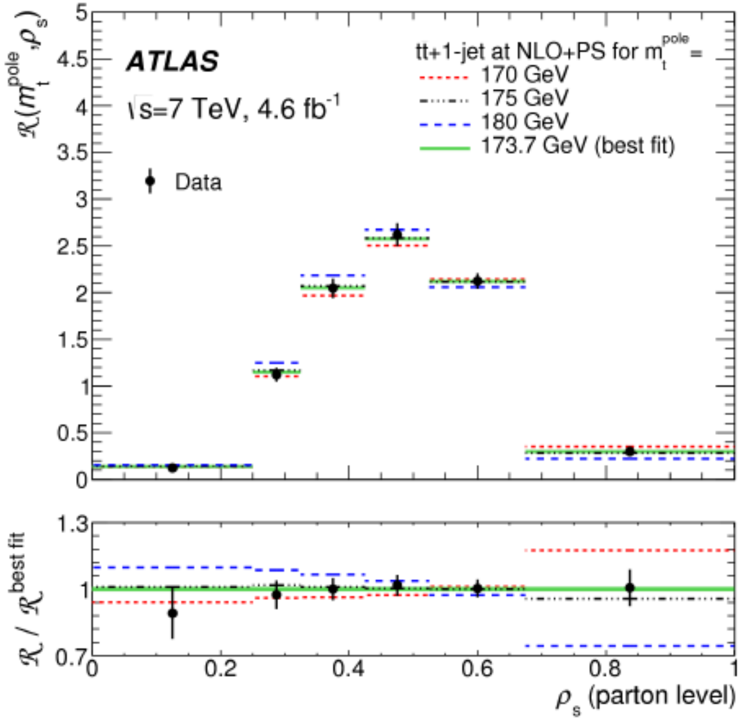
# ATLAS: Top quark mass from tt + 1 jet events

ATLAS, arXiv:1507.01769

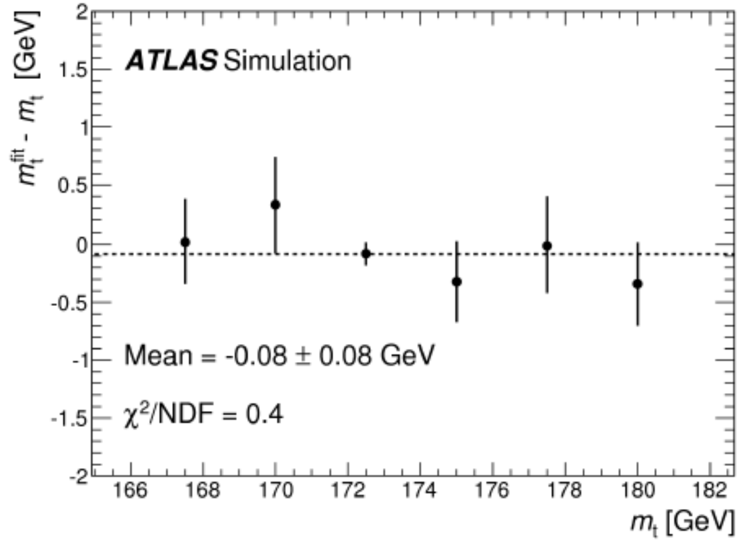
Unfold normalized differential cross-section at 7 TeV to parton-level

Fit with $t\bar{t}$ + 1 jet NLO+PS theory

Mass scheme fixed in NLO calculation
(difference NLO vs. NLO+PS ~ 300 MeV)

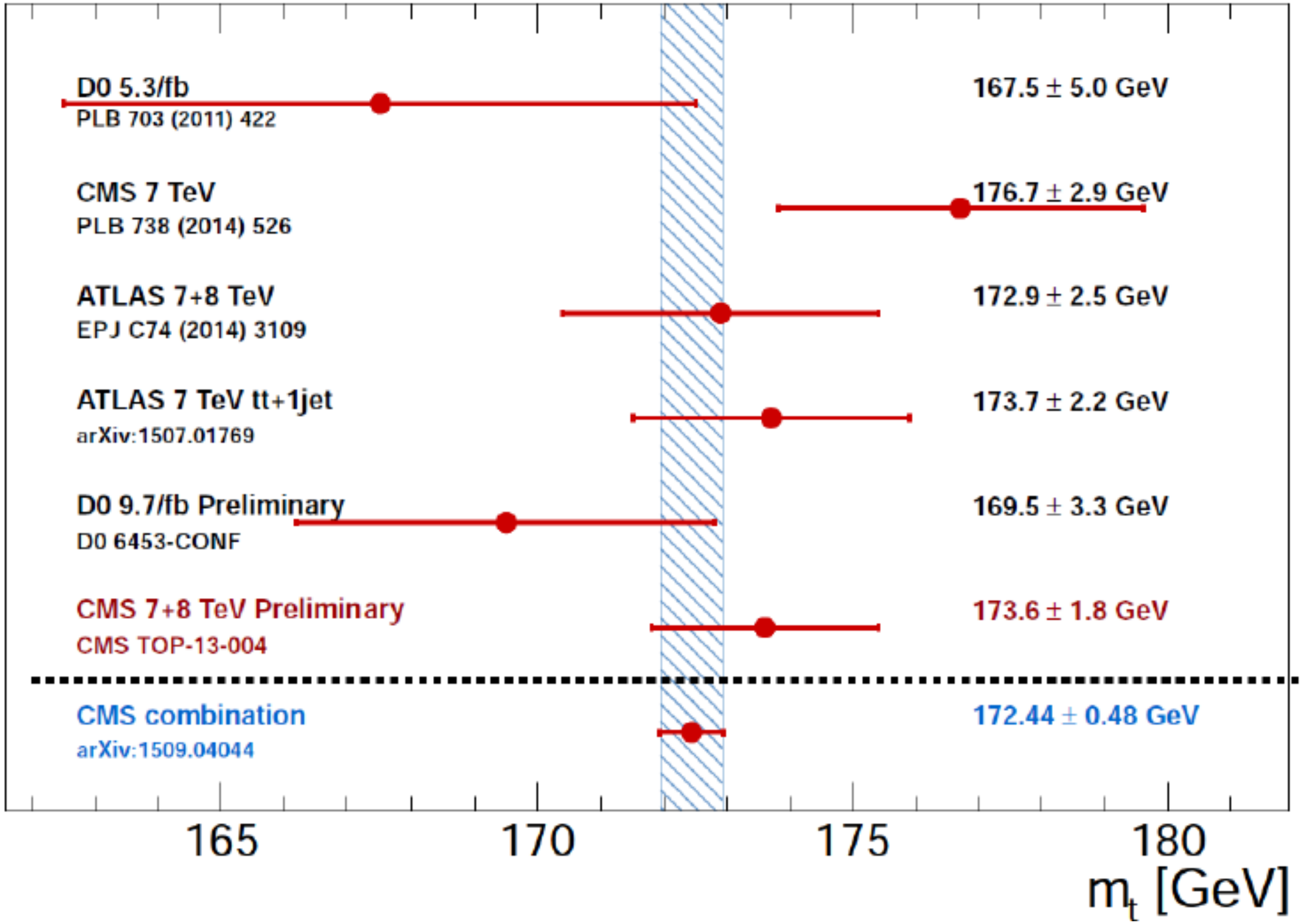



Negligible MC mass dependence in the correction of the normalized differential cross-section



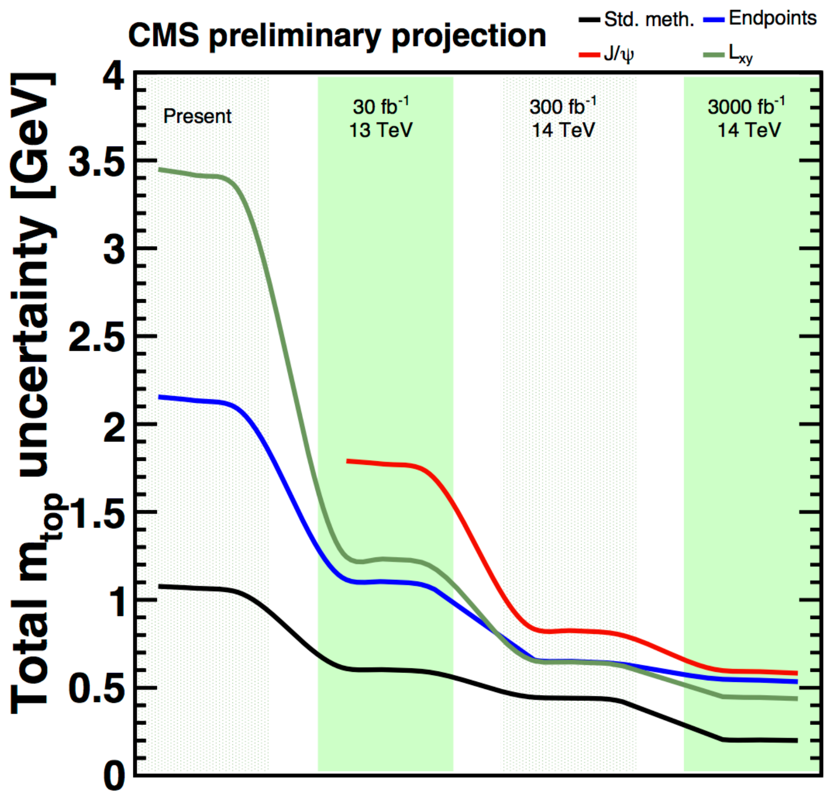

$$M_t^{pole} = 173.7 \pm 2.2 \text{ GeV}$$

# Top mass extraction from cross section measurements



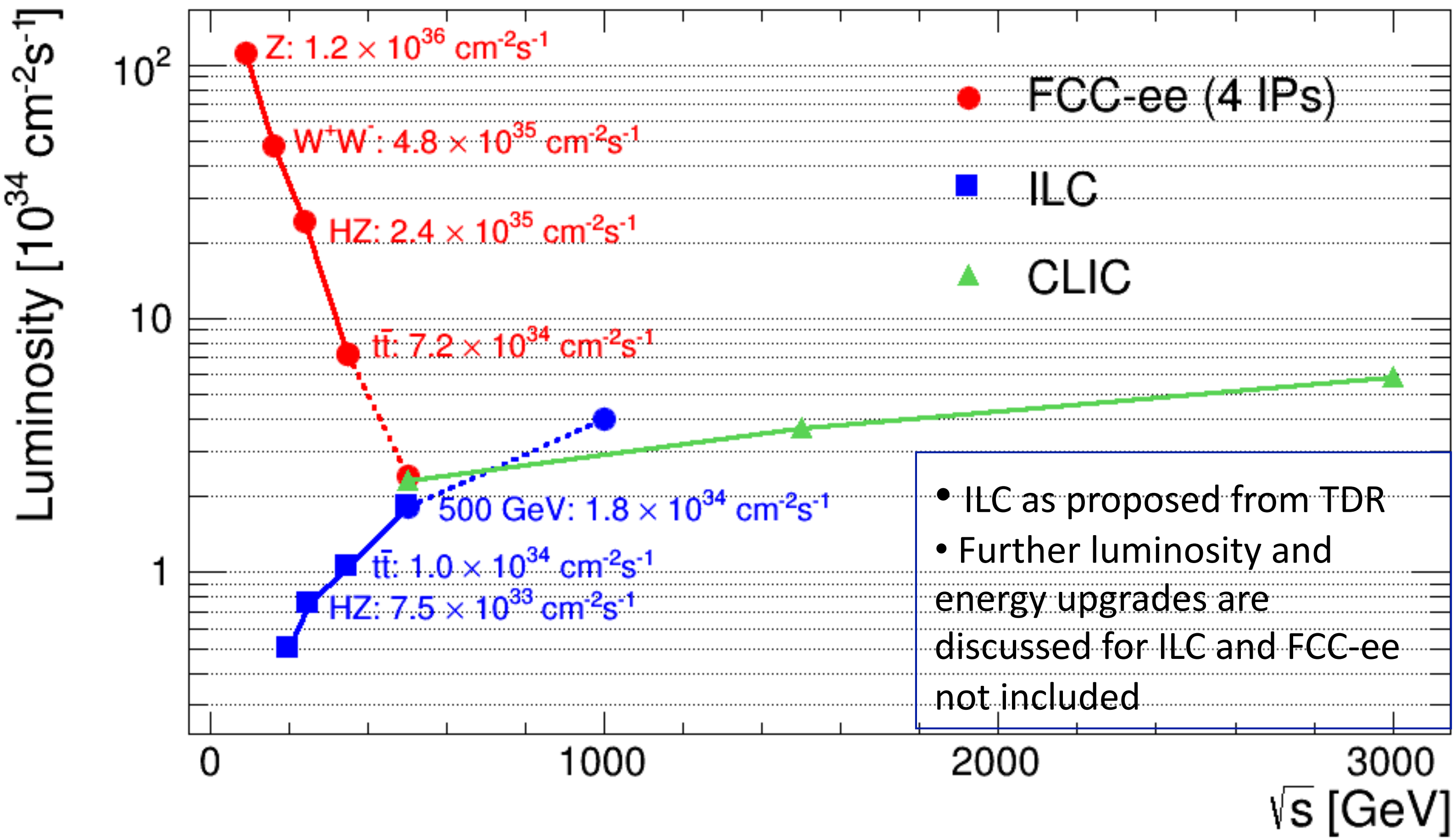
# Prospects for top mass at the LHC

- 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

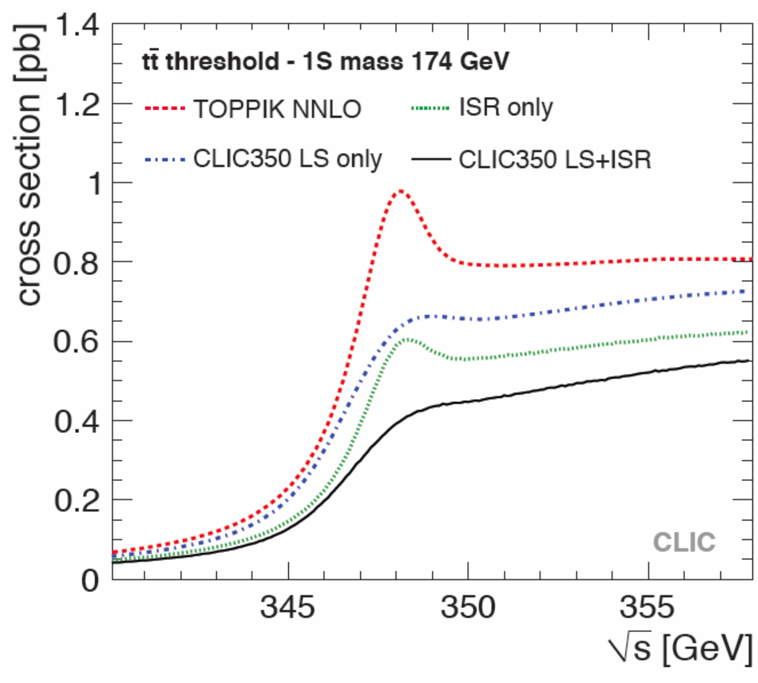
# Prospects at future $e^+e^-$ Colliders: Linear and Circular

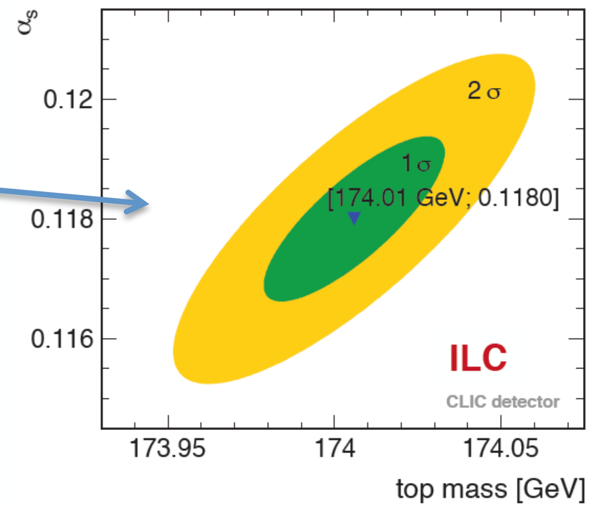



TLEP physics study group: arXiv:1308.6176

# 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 $\alpha_s$ , **top width** and top-Higgs **Yukawa coupling** (with high statistics 2D / 3D fits possible)

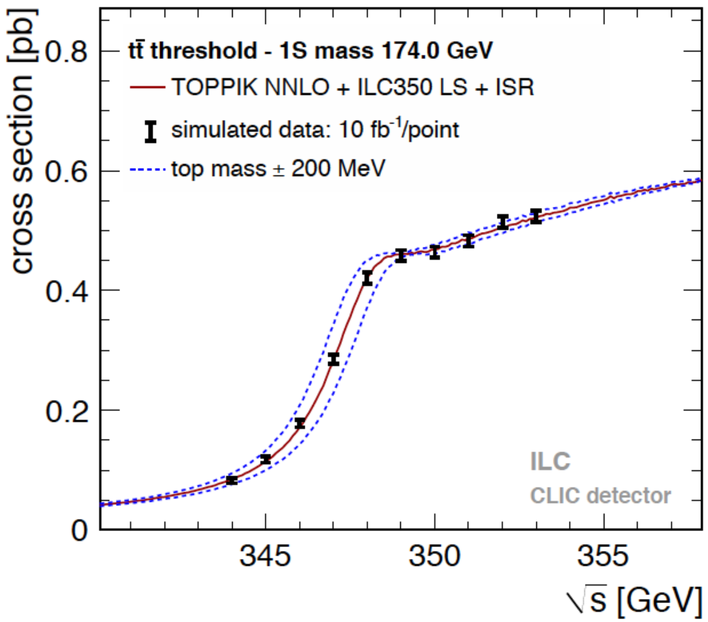


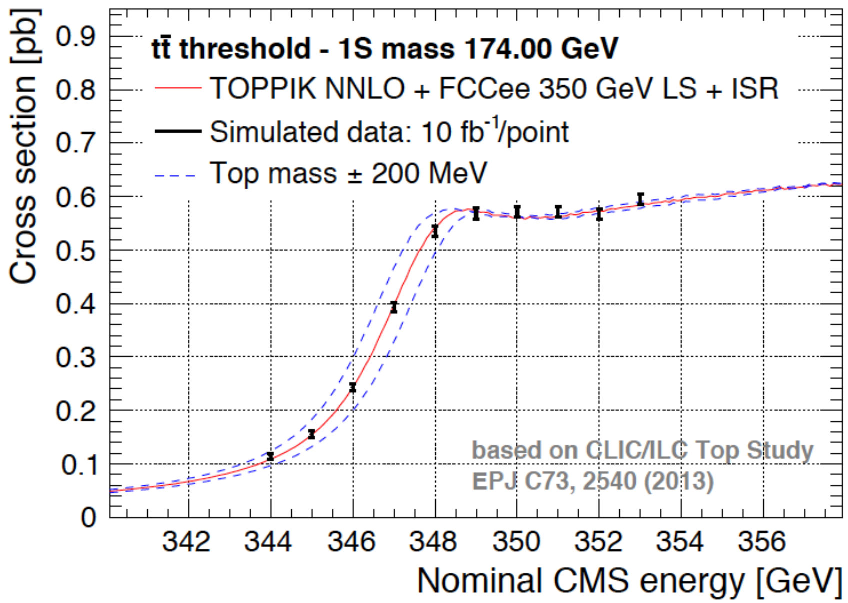



# e+e- at 350 GeV: threshold scan

- 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

# Conclusion of part 1

- Top mass 2014 world average 173.34±0.76 GeV, current LHC best measurement 172.35±0.16±0.48 GeV
- Recent progress on top mass interpretation
- High statistics at LHC offers a unique opportunity of studying the robustness of top mass determination based on top decay products
  - data-based constraints on systematics
  - differential measurements
  - alternative techniques
- We need e+e- colliders to reach precisions in the range 100 MeV → 10 MeV

# BACKUP SLIDES

# top – antitop mass difference: a CPT test

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