Top-quark, Higgs boson and beyond the Standard Model

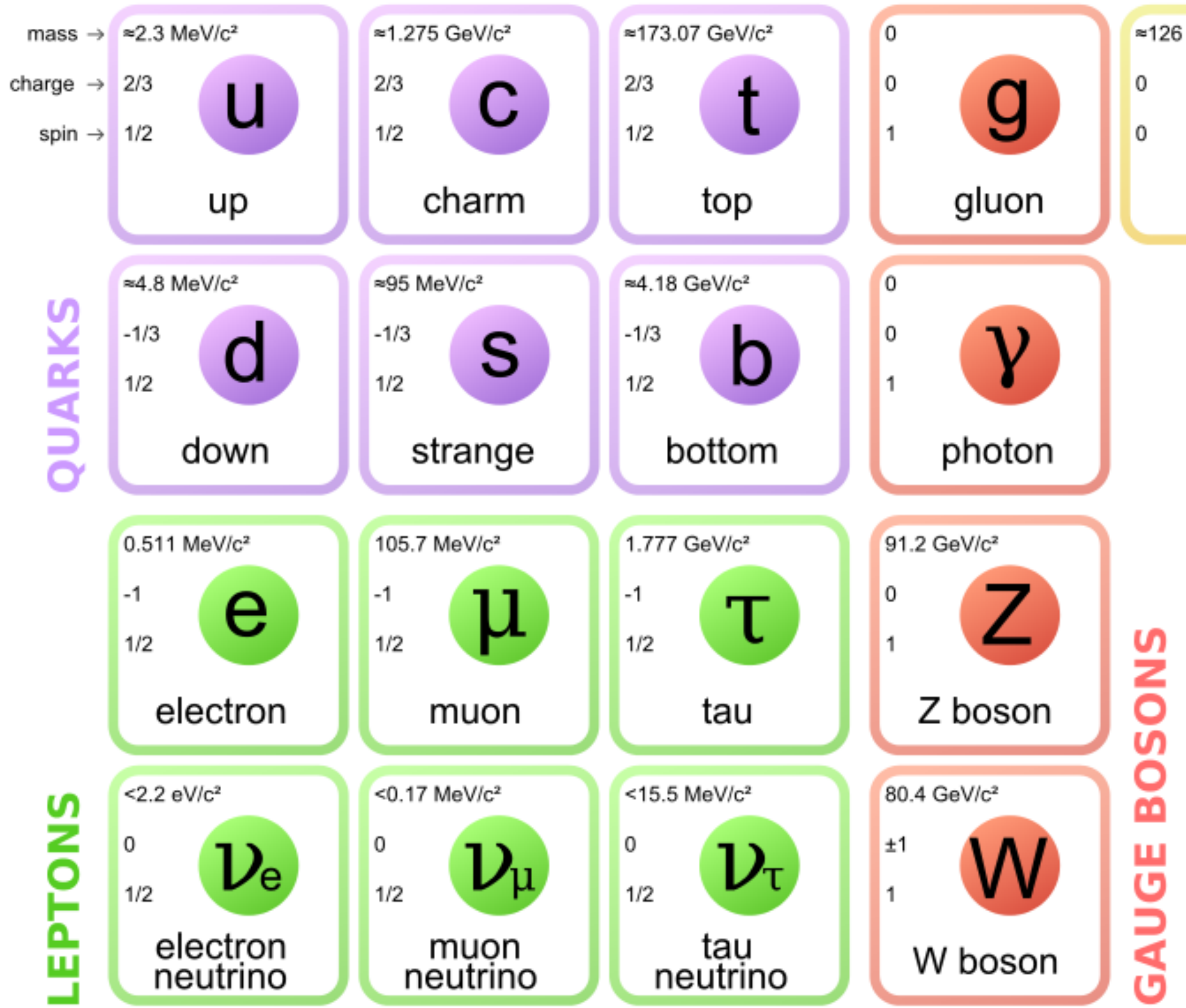
W. H. Bell

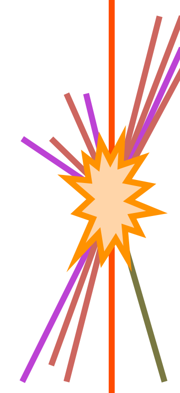
Université de Genève

Overview

- Standard Model : particles and cross-sections
- The ATLAS detector
- Standard Model measurements
  - Cross-section overview
  - ttbar cross-section
- Fiducial measurements of ttbar processes
  - ttbar and additional jets
  - New observables
- Standard Model Higgs
  - Electroweak fits
  - Production & decay
  - Vacuum instability
  - VH to b bbar + X measurements
- Conclusions & outlook

Standard Model

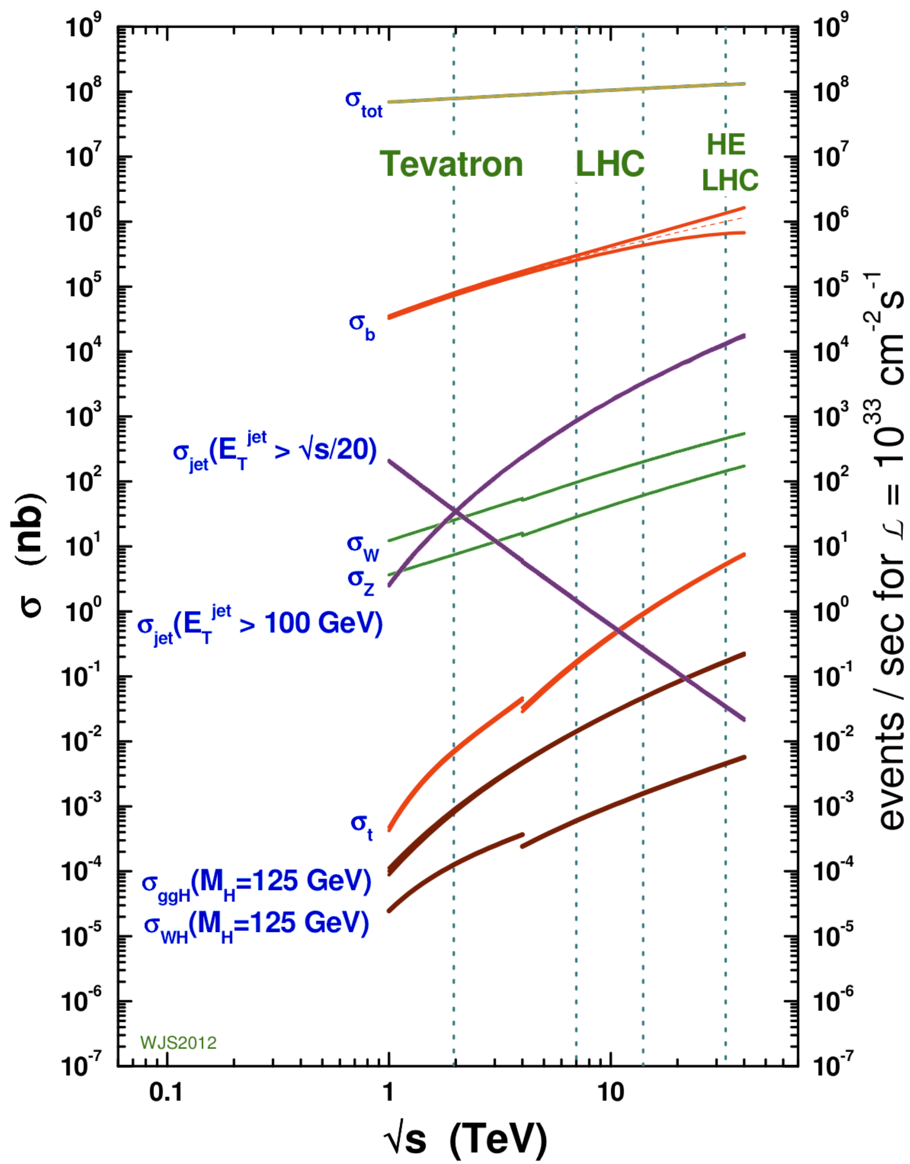




Beyond the Standard Model

- Looking beyond the Standard Model (SM) requires precision measurements.
  - New processes may be hidden within uncertainties.
    - E.g. stealth stop search
  - For example, additional measurements of top-quark and Higgs processes will help to determine stability of Higgs potential up to Planck scale (1.22×10^{19} GeV).
- Often cannot compare theoretical calculations directly to data.
  - Require phenomenological models to add soft and colinear radiation and describe other physics that cannot be calculated with perturbative QCD.

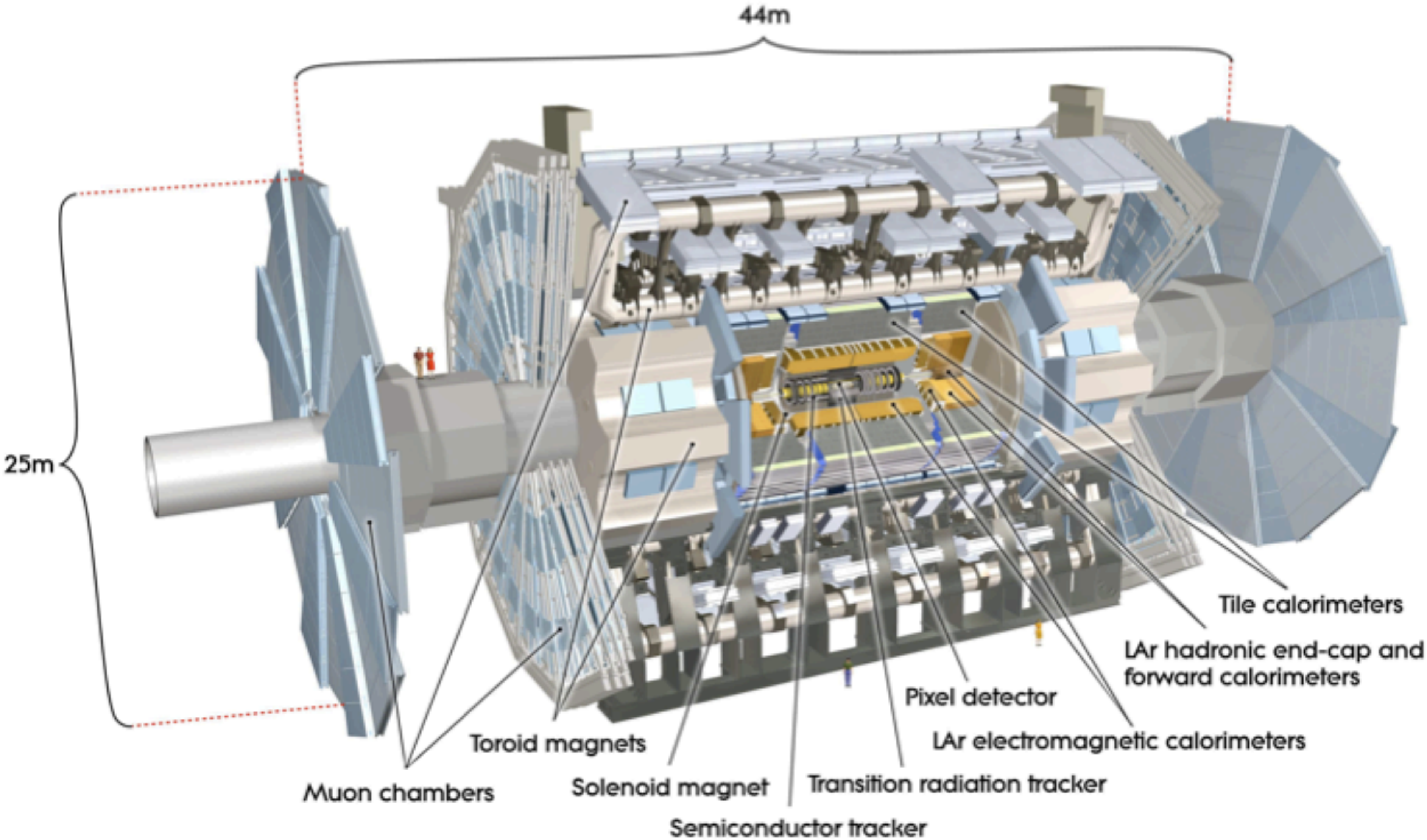
ppbar and *pp* cross-section



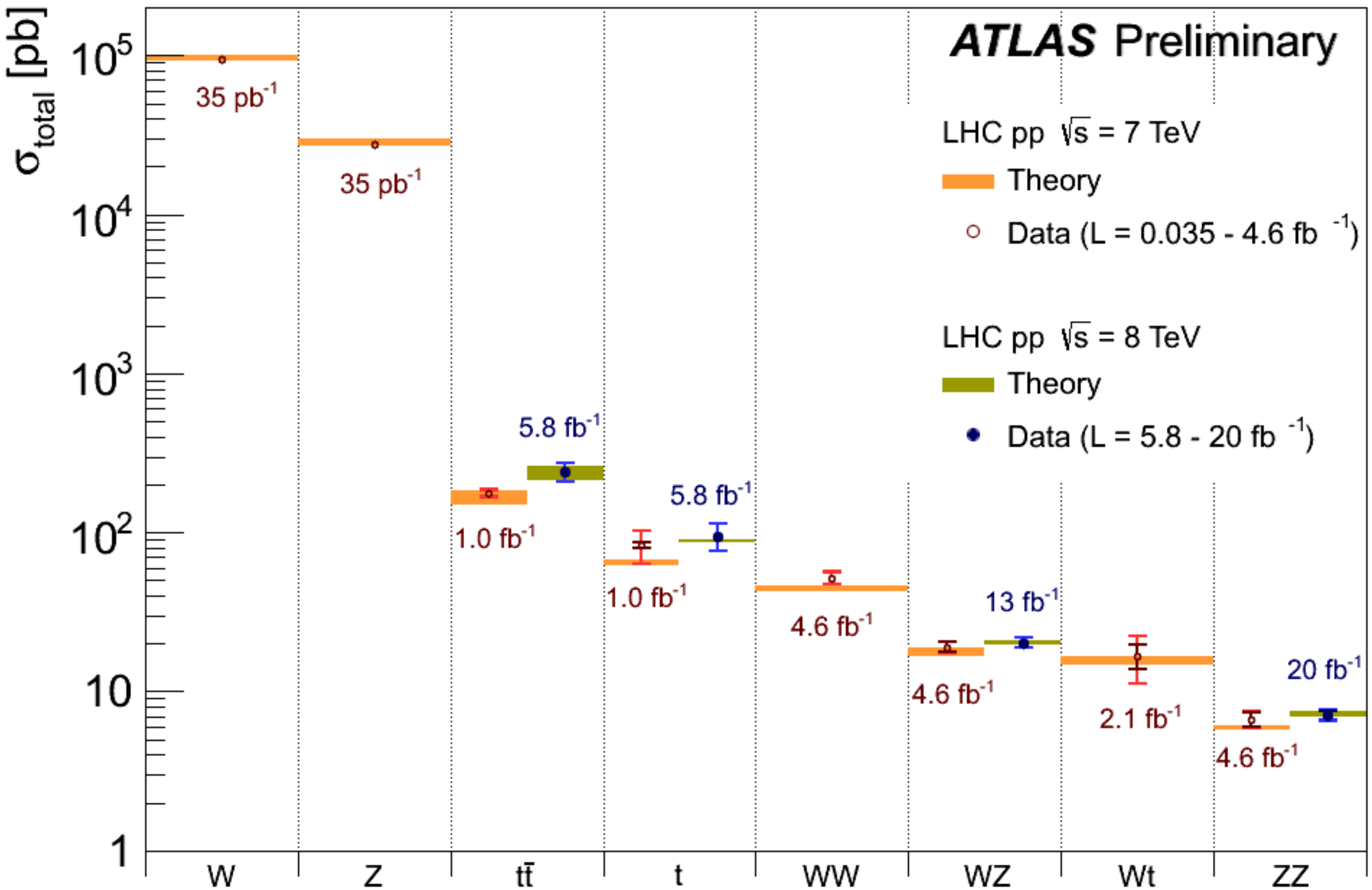
Production cross-sections

- Production cross-sections of SM processes span many orders of magnitude.
- Cross-sections rise as a function of centre-of-mass energy (√s).
- Higher energy LHC running will provide larger SM sample and higher search reach.

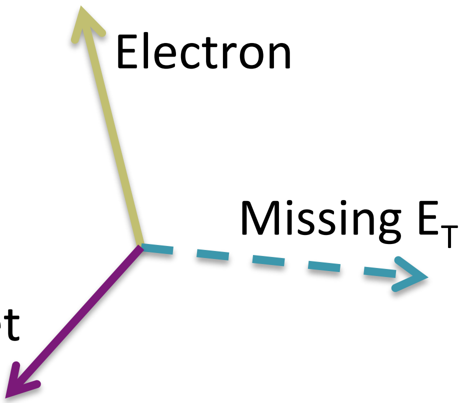
The ATLAS detector



Inclusive cross-sections: data and SM predictions

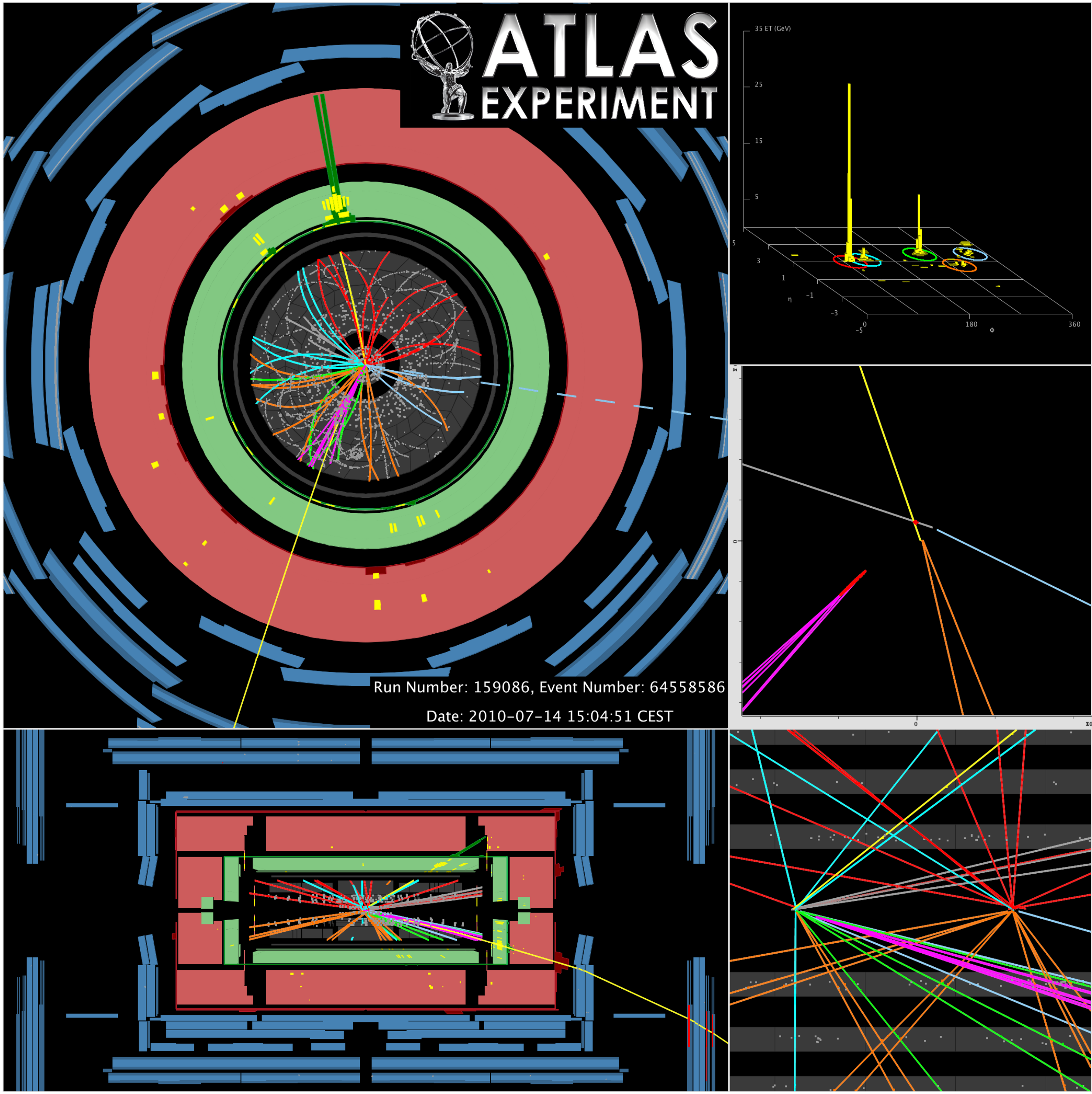


ttbar single-lepton event selection

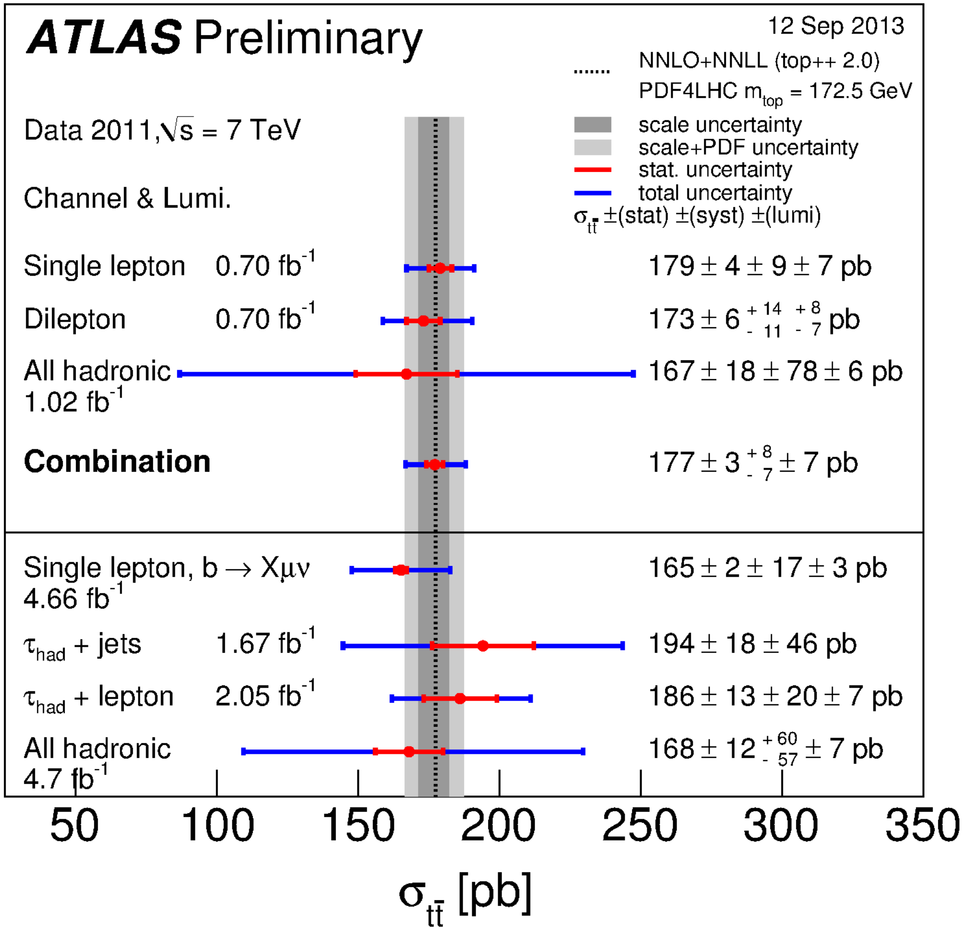


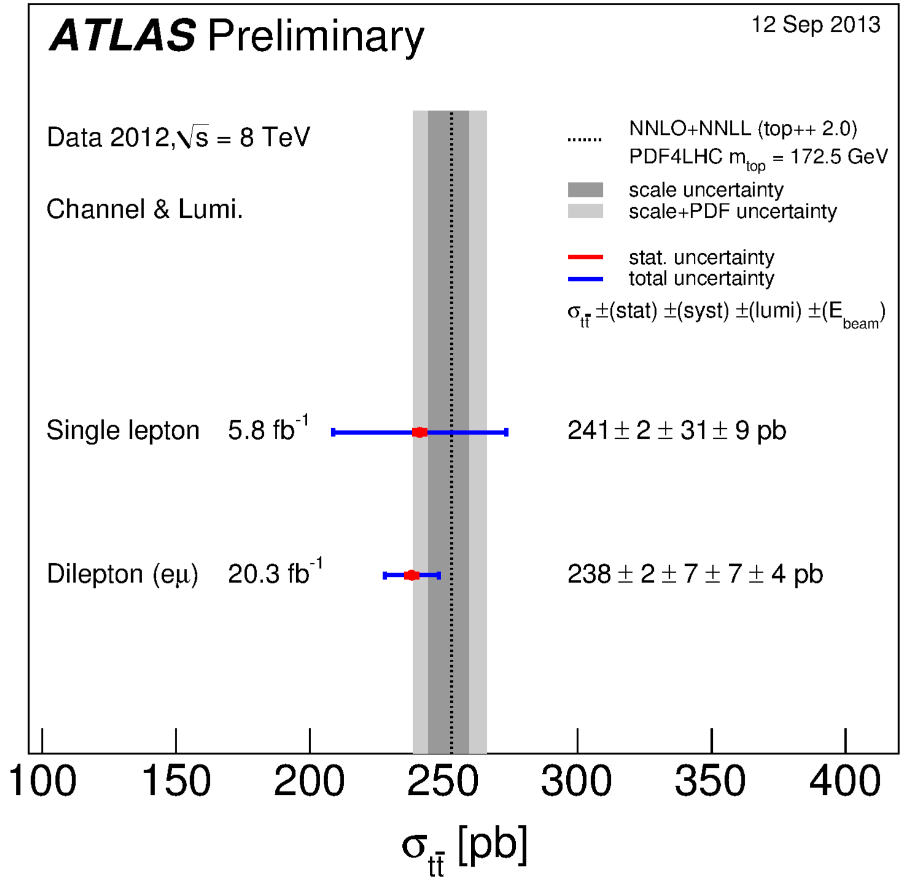
At least three or four jets reconstructed with the anti-k_t algorithm (0.4 radius parameter)

Missing energy vector from calorimeter energy deposits and muon term.

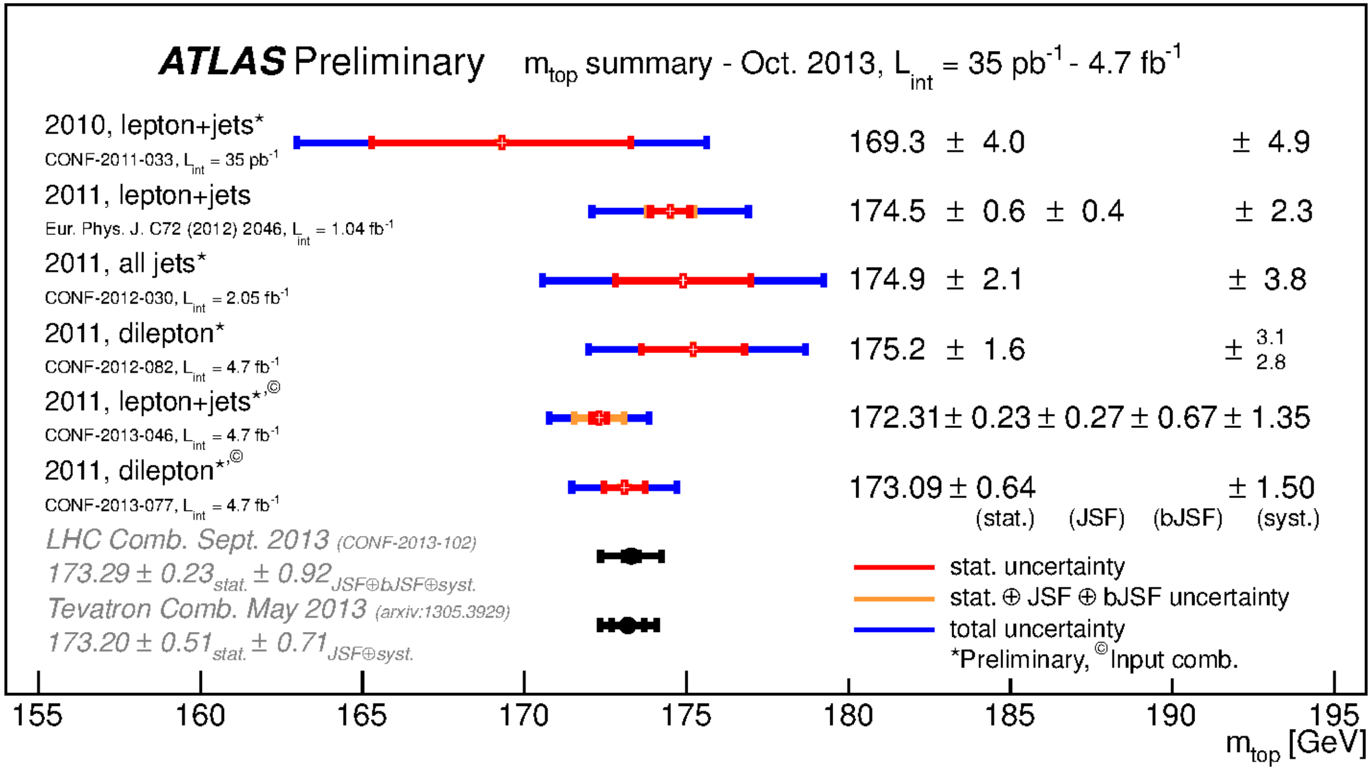


Top-quark inclusive production cross-section





Top-quark mass



ttbar inclusive production cross-section √s=8TeV

- eμ event selection
- Using exactly one (N_1) or exactly two (N_2) b-quark jets
- C_b – tagging correlation

$$
\begin{aligned}
N_1 &= L\sigma_{t\bar{t}}\, \epsilon_{e\mu} 2\epsilon_b (1 - C_b \epsilon_b) + N_1^{\mathrm{bkg}} \\
N_2 &= L\sigma_{t\bar{t}}\, \epsilon_{e\mu} C_b {\epsilon_b}^2 + N_2^{\mathrm{bkg}}
\end{aligned}
$$

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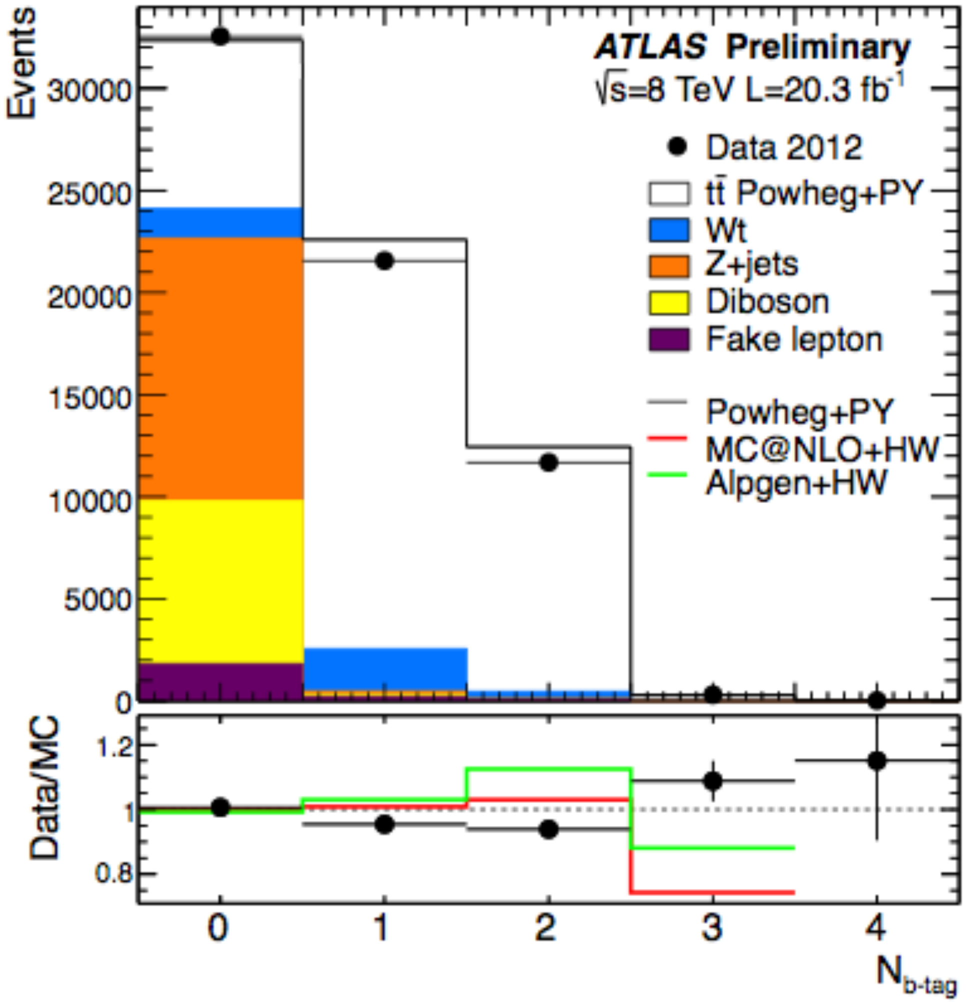
Ttbar cross-section using eμ √s=8TeV

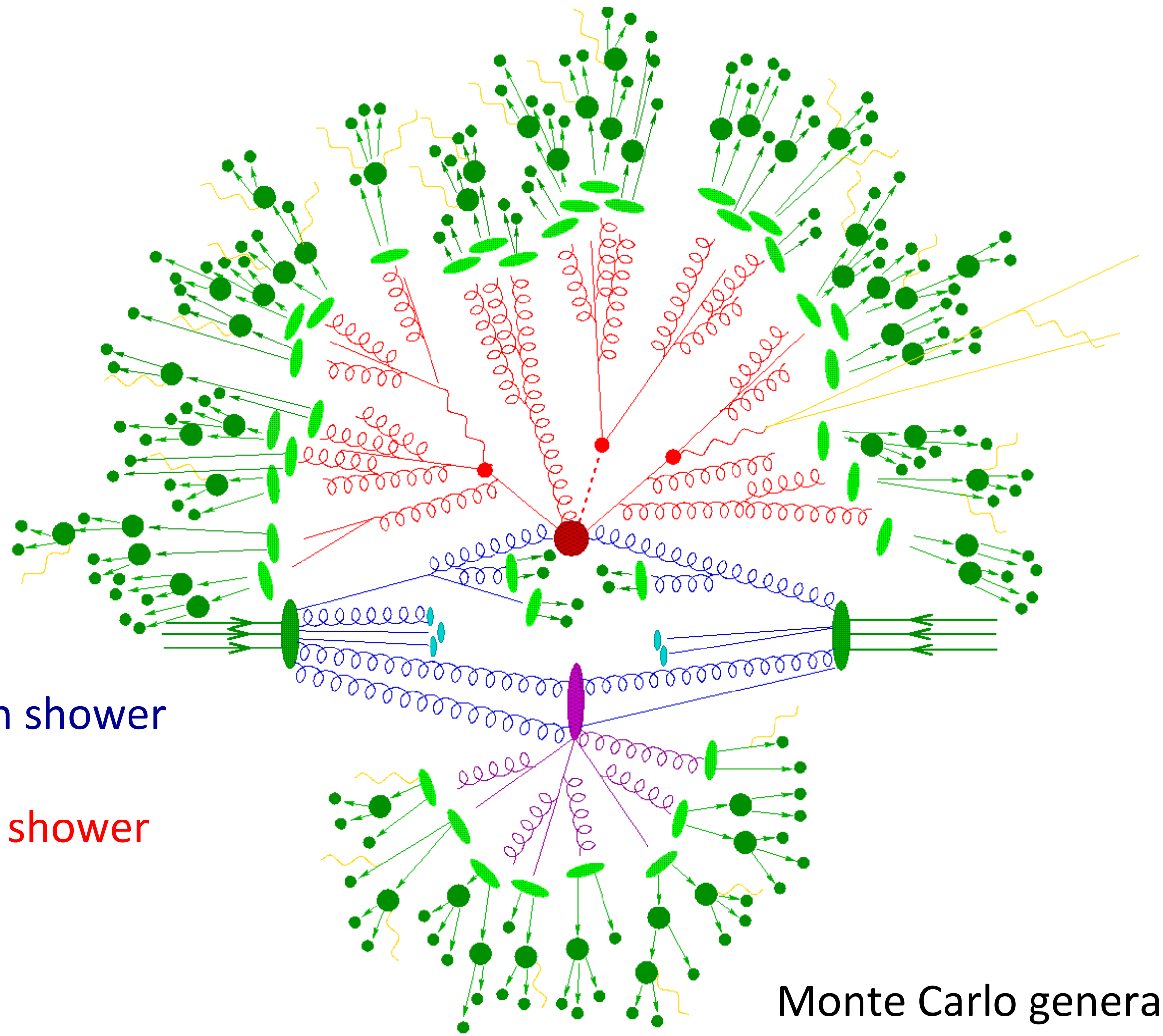


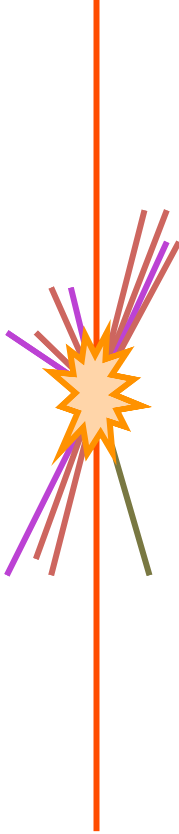
$$\sigma_{t\bar{t}} = 237.7 \pm 1.7\ (\text{stat}) \pm 7.4\ (\text{syst}) \pm 7.4\ (\text{lumi}) \pm 4.0\ (\text{beam energy})\ \text{pb}$$

Inclusive to fiducial

- Inclusive measurements
  - are convenient for comparisons with fixed order matrix element calculations
  - but can integrate in a lot of model dependencies.
    - For example, ttbar acceptance for e+jets or μ+jets is typically ~5%.
- Fiducial measurements
  - require parton shower and hadronisation.
    - Matching of fixed order calculations is often not available beyond NLO or LO.
  - unfold measured data, accounting for resolution affects rather than large acceptance corrections.

A proton-proton collision

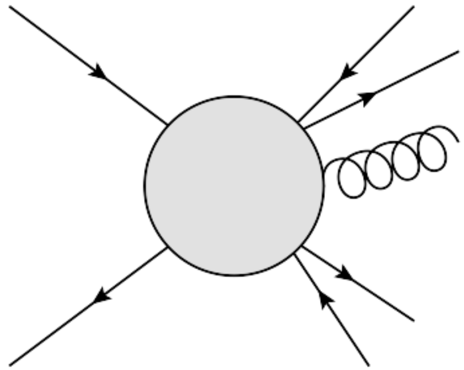




Initial state parton shower
Signal process
Final state parton shower
Fragmentation
Hadron decays
Beam remnants
Underlying event

Monte Carlo generator representation
Sherpa

Advanced MCs and observables



- More advanced Monte Carlo (MC) generators include decays in ME calculation.
  - No intermediate state bosons in event record.
- Careful design of observables needed to produce long term precision tests of SM.

Gap fraction observables

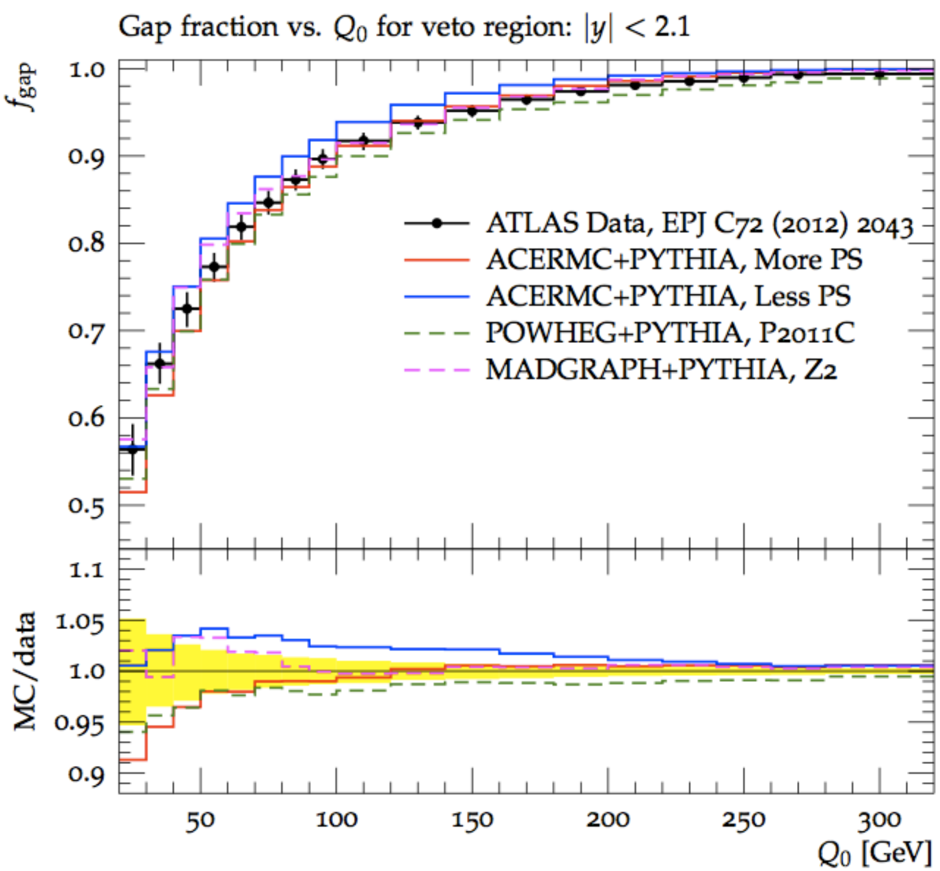
- Require dilepton event selection (ee,eμ,μμ)
- Two identified b-quark jets.
- Define the gap fraction
  - Events that do not contain an additional jet above threshold

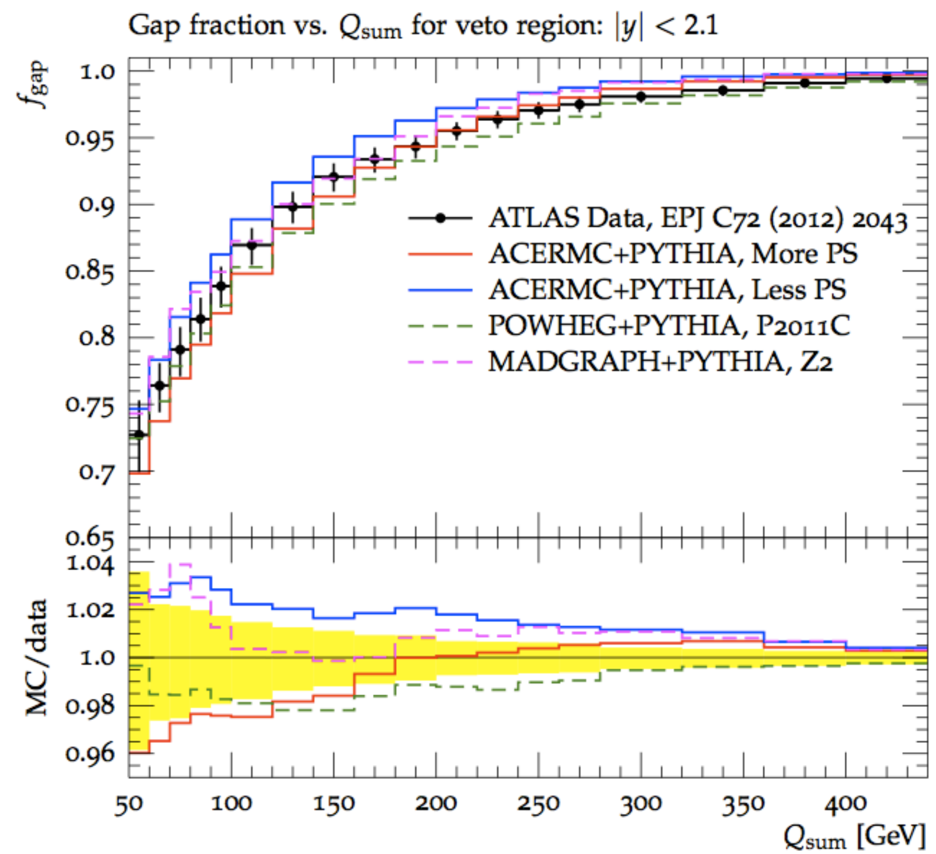
$$f(Q_0) = \frac{n(Q_0)}{N}$$

  - Events that do not contain jets with an energy sum above threshold

$$f(Q_{\rm sum}) = \frac{n(Q_{\rm sum})}{N}$$

ttbar gap fraction √s=7TeV





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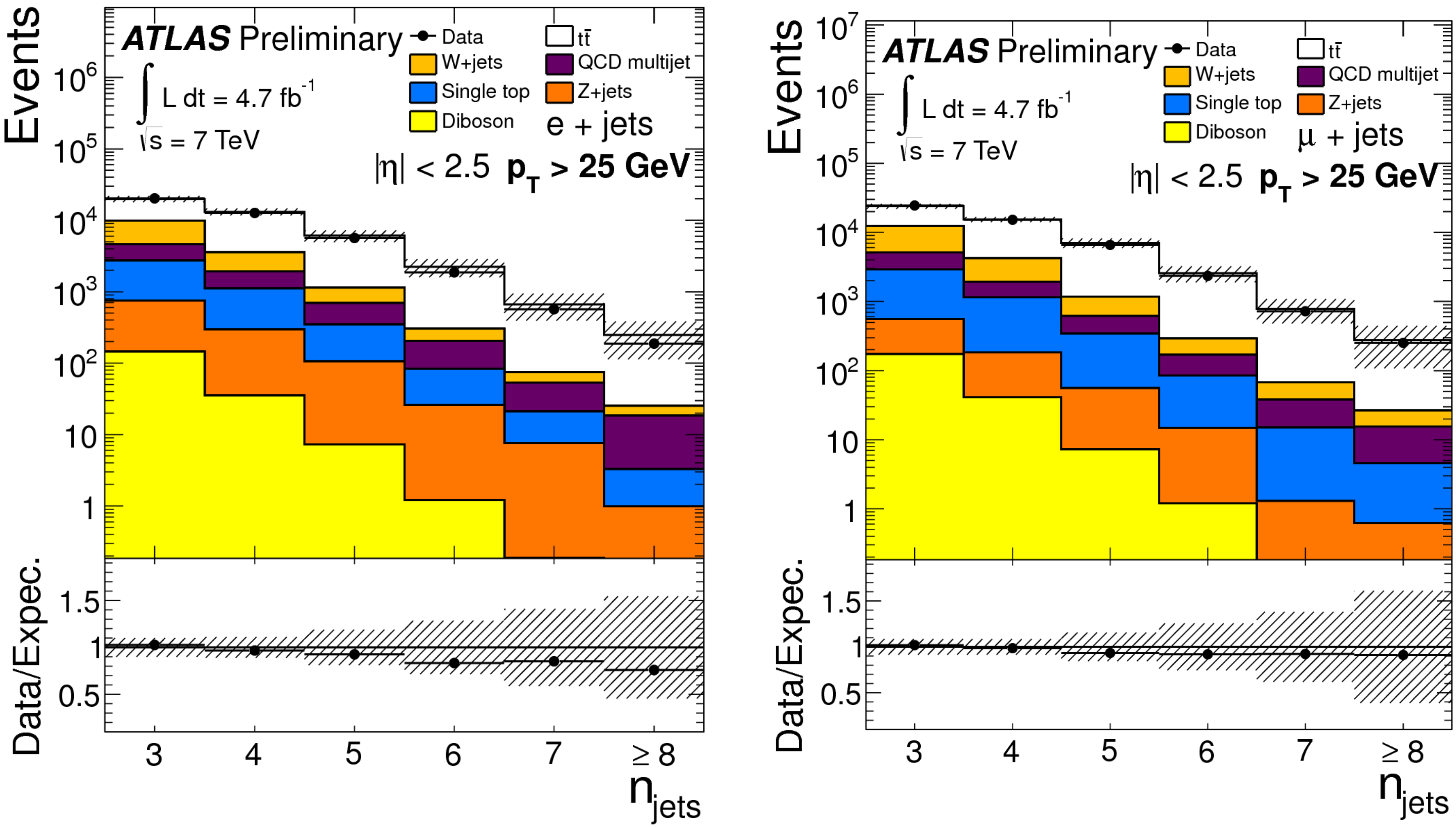
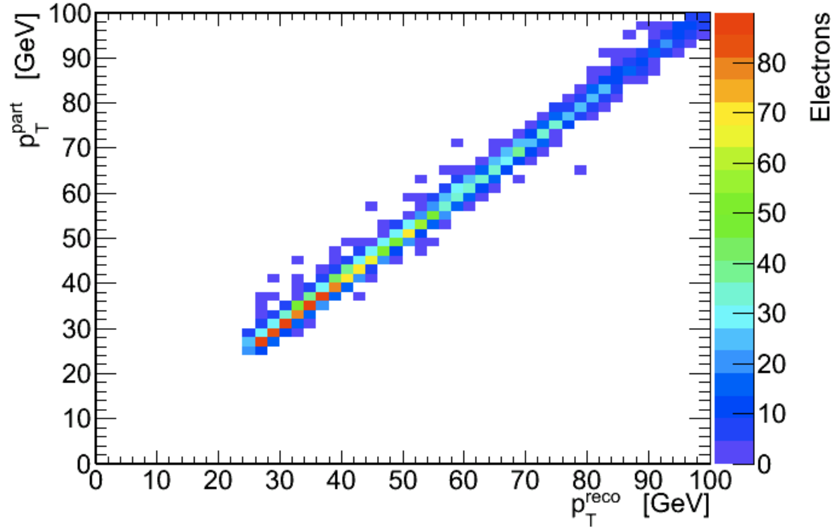
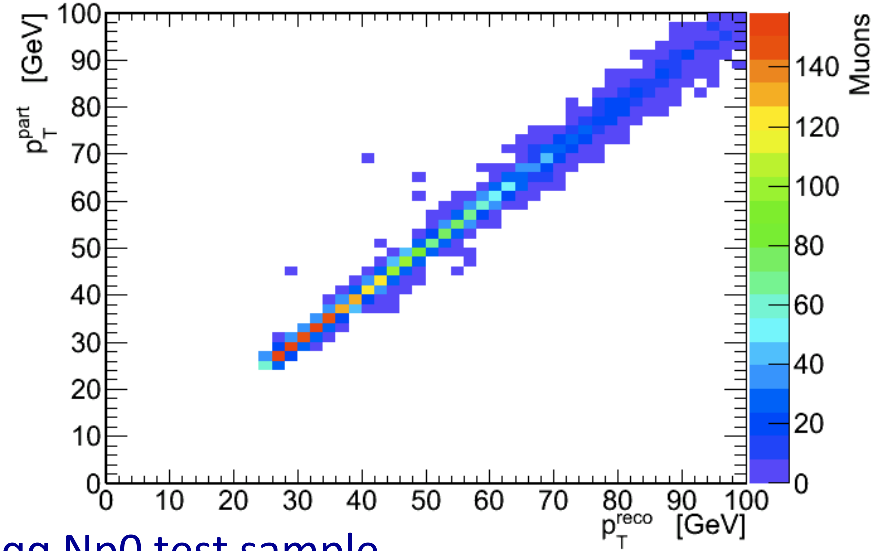
Single-lepton ttbar selection

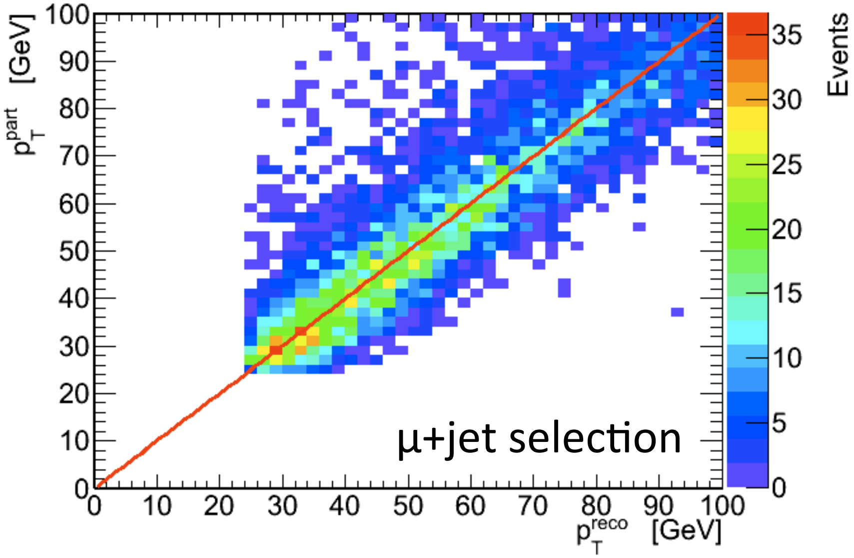


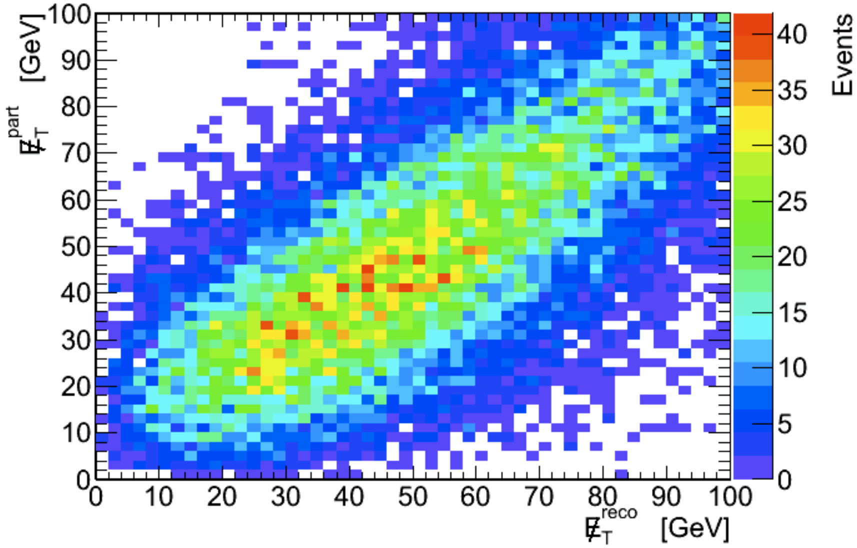
Object correlations after ΔR match





ALPGEN+HERWIG ttbar lnqq Np0 test sample





Correction & unfolding

$$\vec{N}_{part} = \vec{f}_{part!reco} M^{reco}_{part} \vec{f}_{reco!part} \vec{f}_{accpt} (\vec{N}_{reco} - \vec{N}_{bgnd})$$

where

$\vec{N}_{reco}$ Number of reconstructed jets with all reconstruction cuts. (Measured)

$\vec{N}_{bgnd}$ Number of background jets from W+jets, QCD, etc..

$\vec{f}_{accpt}$ Mean acceptance correction for everything except jet p_T cut.

$\vec{f}_{reco!part}$ Number of jets passing reconstruction, but failing particle-level selection.

M^{reco}_{part} Unfolding response matrix, used iteratively to converge towards data.

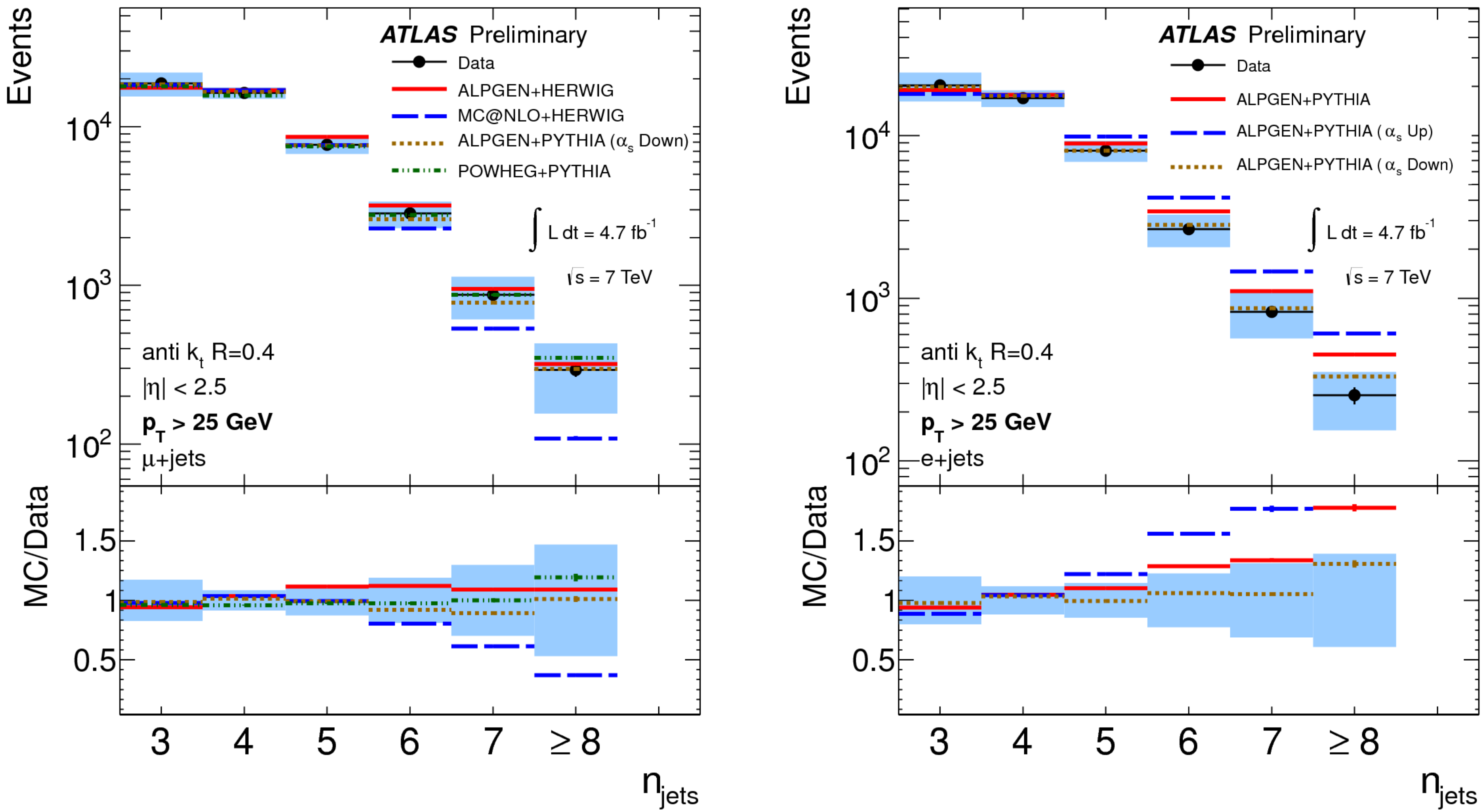
$\vec{f}_{part!reco}$ Correction for events that would have been accepted.

$\vec{N}_{part}$ Number of particle-level jets with all particle-level cuts. (True)

Example analysis: overview

1. Fill the reconstructed jet multiplicity ($Njets_{reco}$) from data.
2. Remove background contribution (W+jets, QCD, etc.)
   - Remove these bin-wise from $Njets_{reco}$
3. Correct for difference in acceptance between reconstructed and particle-level selection – all cuts accept jet p_T.
   - Assume all other terms enter just as a re-weighting of $Njets_{reco}$
   - Reweighting taken from MC – small correlation with Njets.
4. Remove jets which are reconstructed, but do not pass particle-level selection.
5. Unfold ($Njets_{reco}$ to $Njets_{part}$) – defined for event which pass particle and reconstruction-level selections.
6. Correct for events that were not reconstructed due to resolution effects.

ttbar and associated jets



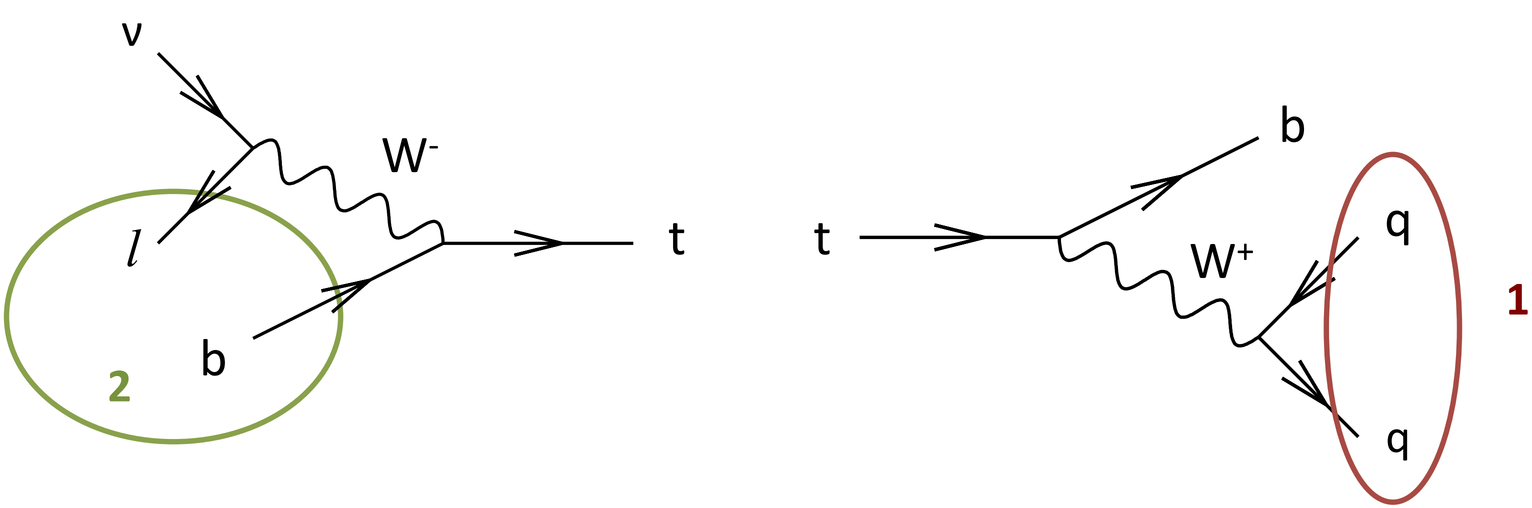
Ttbar+jets : systematic uncertainties

- Jet energy scale uncertainty 3—40%
- Background uncertainty 18%(3%) for low (high) multiplicities
- Initial/Final state radiation 1—6%
- Generators 1—6%

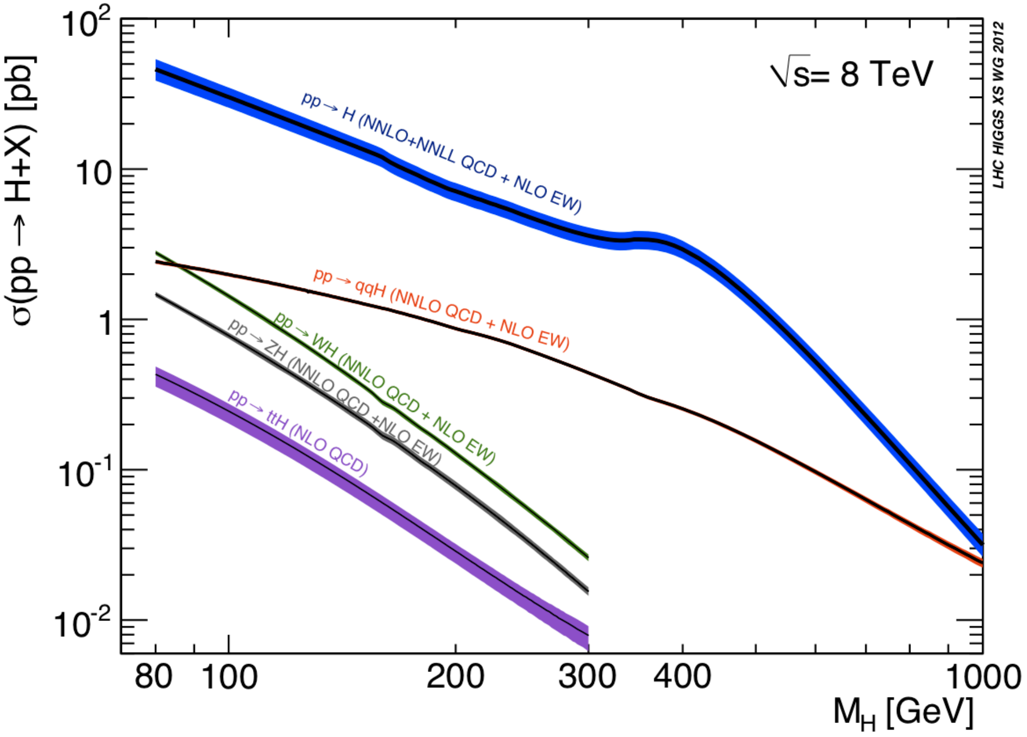
- JES uncertainty has since been reduced by evaluating each component part separately.

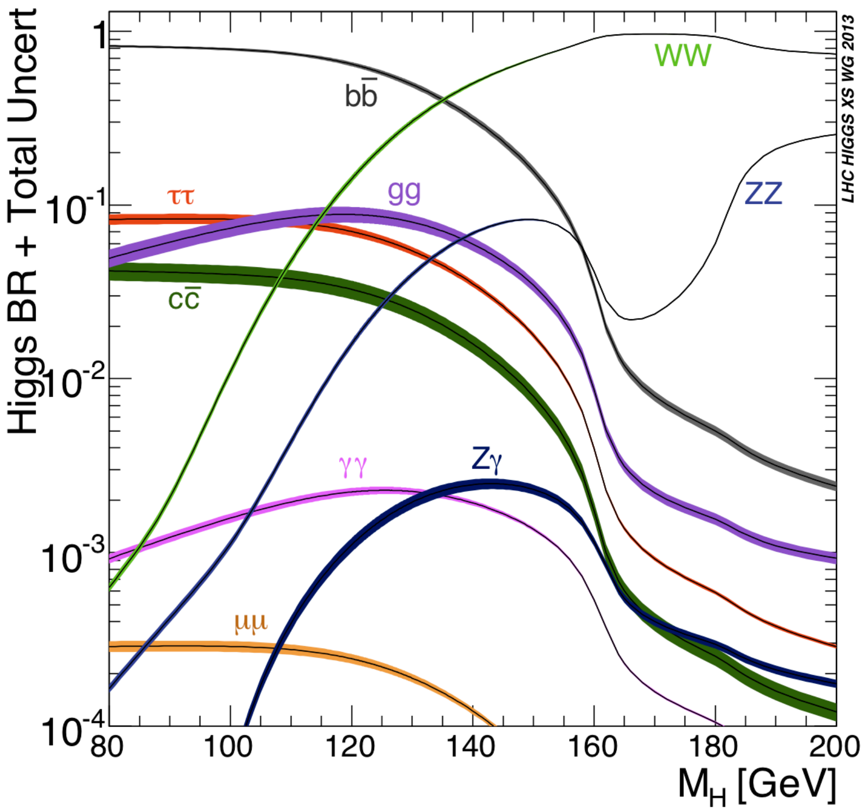
Pseudo-top

- Pseudo-top defined from recipe rather than kinematic fitter
  - Avoid Monte Carlo generator dependence.
  - Compare fixed order pQCD calculation with parton shower, within the kinematic range of the result.
- Define observable with particles and reconstructed objects.
  - Unfold from reconstructed observable to particle observable.
  - Observable must be well correlated, i.e. behave as a resolution

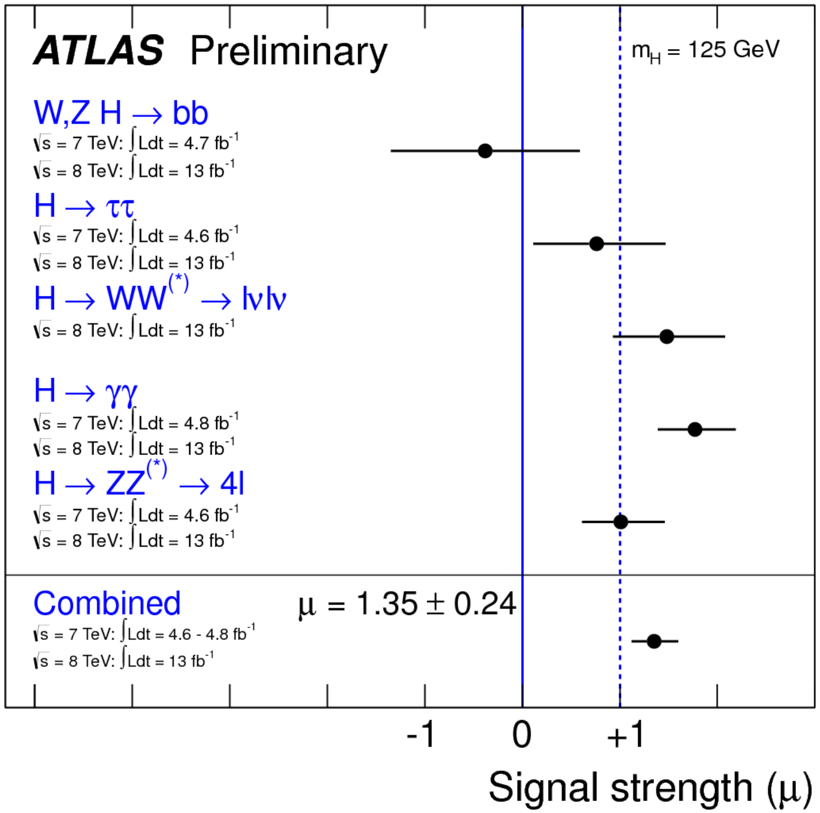


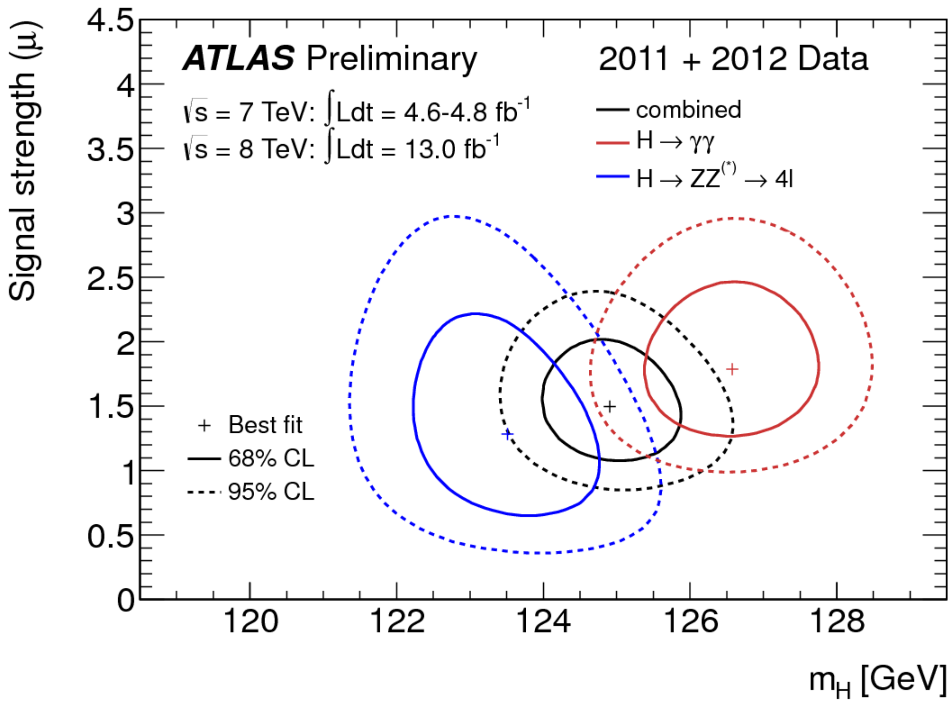
SM Higgs boson production and decay





Higgs boson cross-section combination

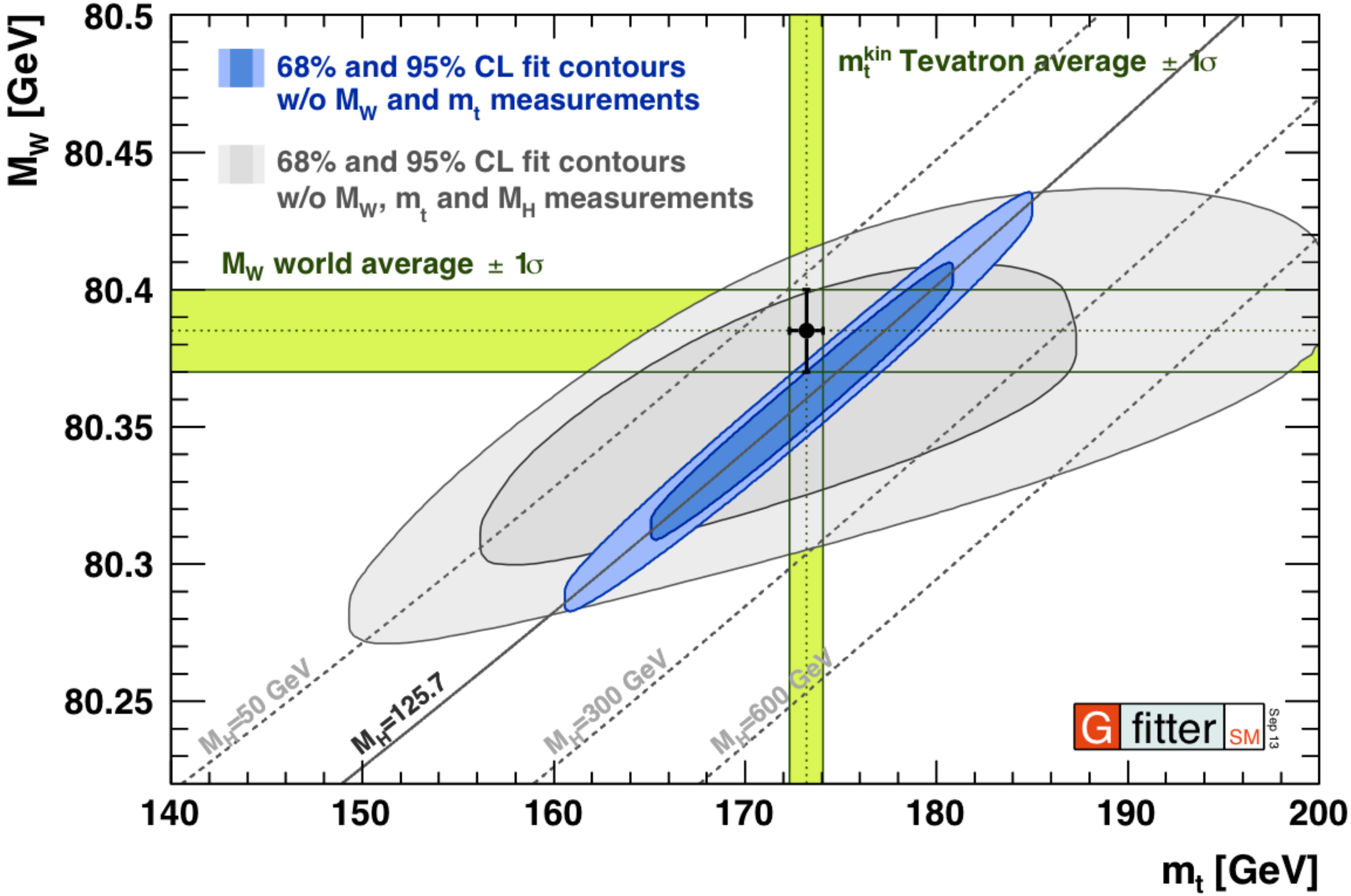




Electroweak fits

- Can indirectly predict the Higgs mass from electroweak data.
  - Extract information from Higgs loops affecting Z and W boson measurements.
- Assuming new boson is SM Higgs boson
  - Can over constrain the SM.
  - ATLAS and CMS measurements agree within 1.3σ of indirect determination (94^{+25}_{-22} GeV)

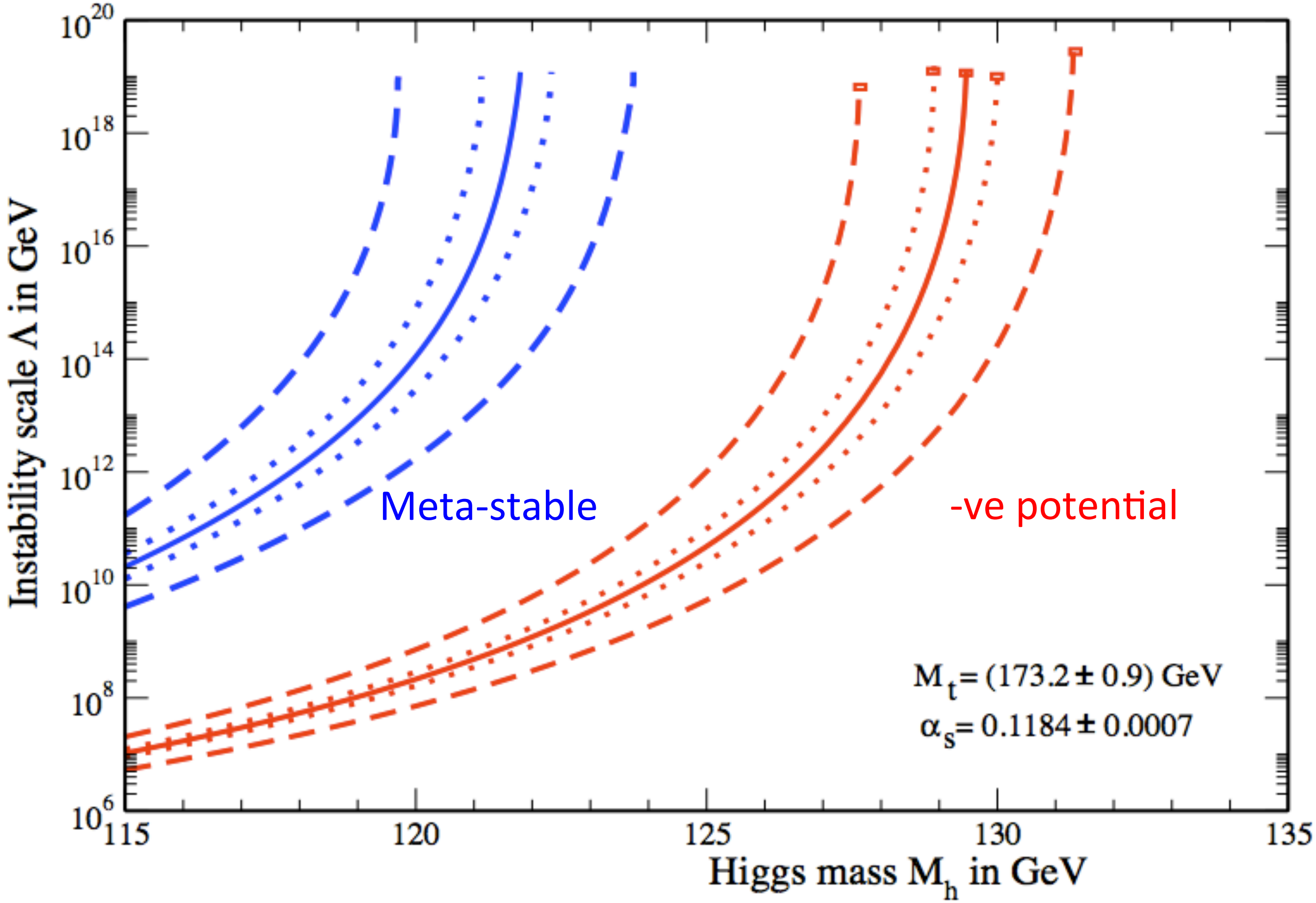
Electroweak fit of SM

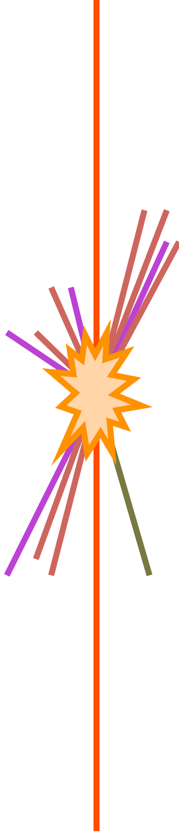


Higgs and hierarchy problem

- Light Higgs appears to be self-protected and self-tuned by spontaneous symmetry breaking [arXiv: 1305.6652v2]
  - No need to add extra symmetry to protect Higgs (e.g. SUSY)
- Possible to arrange cancellation of the quadratic divergence in the Higgs mass by imposing requirements on coupling constants of the theory [M. J. G. Veltman, Acta Phys. Polon. B 12 (1981) 437.]
- The quartic coupling runs slowly.
  - Becoming negative before the Planck scale.

Higgs instability : -ve potential

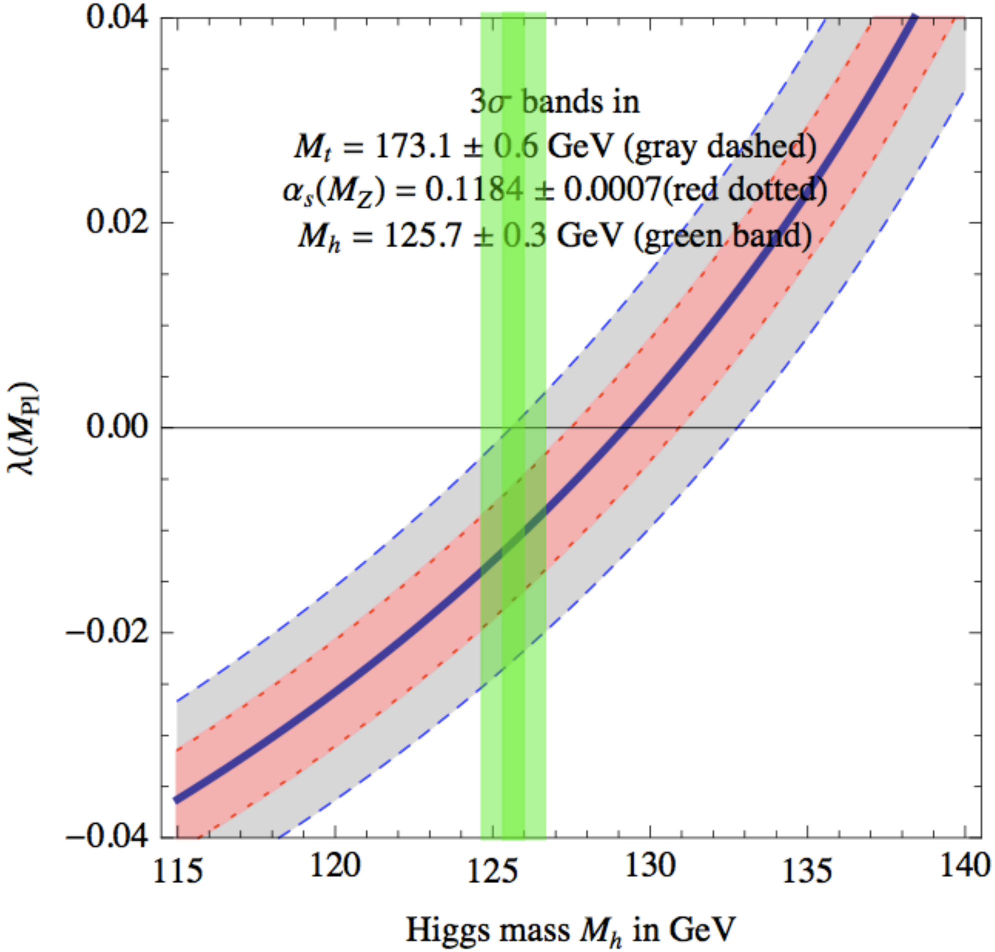




For best-fit values of m(t) and of α_s, the coupling becomes negative around 5×10^9 GeV

Phys.Lett. B709 (2012) 222-228

Higgs quartic coupling (λ) at Planck scale



arXiv:1205.6497v2

VH ➔ b bbar + x

- Higgs to b bbar – 58% BR for m_H = 125GeV
- Inclusive (H to b bbar) measurement not possible due to multijet background
- Instead use W/ZH to leptons and missing E_T
- Require b-tagging to select b-quark jets

VH ➔ b bbar + x

Object	0-lepton	1-lepton	2-lepton
Leptons	0 loose leptons	1 tight lepton + 0 loose leptons	1 medium lepton + 1 loose lepton
Jets	2 b-tags $p_{\mathrm{T}}^{\mathrm{jet}_1} > 45$ GeV $p_{\mathrm{T}}^{\mathrm{jet}_2} > 20$ GeV $+ \leq 1$ extra jets		
Missing E_T	$E_{\mathrm{T}}^{\mathrm{miss}} > 120$ GeV $p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV $\Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}) < \pi/2$ $\min[\Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet})] > 1.5$ $\Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, b\bar{b}) > 2.8$	$E_{\mathrm{T}}^{\mathrm{miss}} > 25$ Gev	$E_{\mathrm{T}}^{\mathrm{miss}} < 60$ GeV
Vector Boson	-	$m_{\mathrm{T}}^{W} < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV

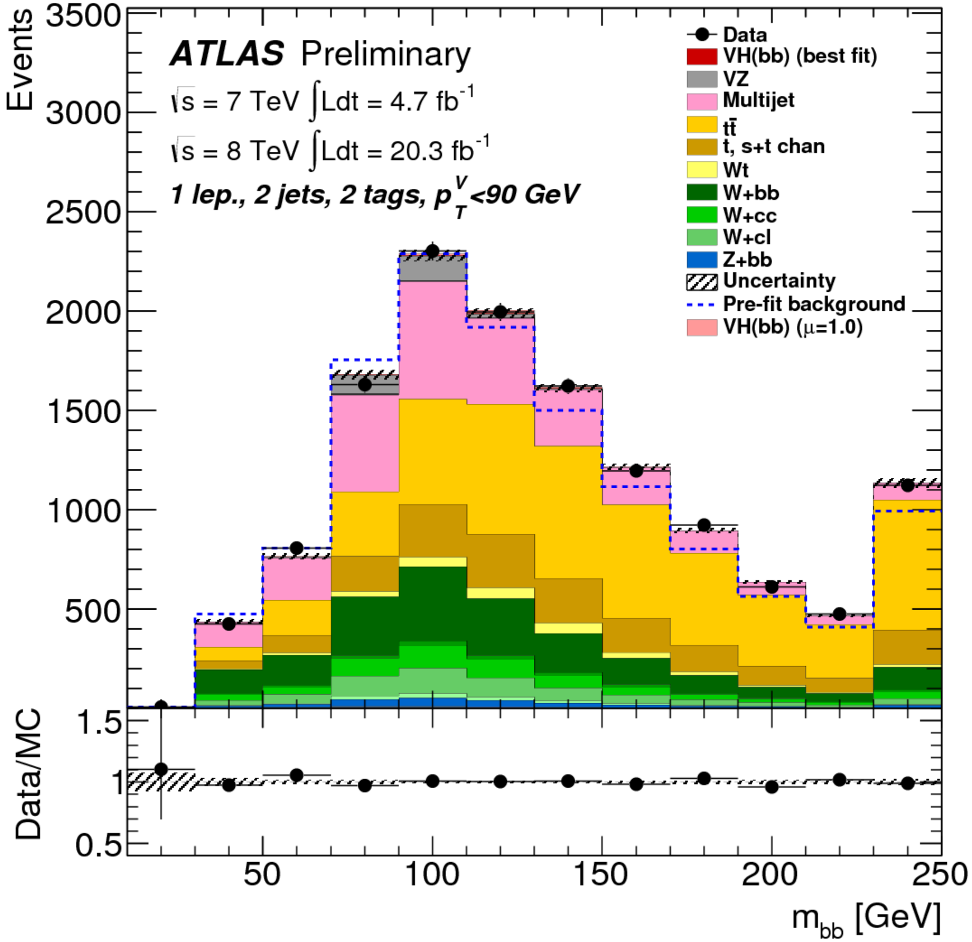
VH → b bbar + x

- For m_H = 125GeV 95% CL of 1.4 times SM expectation for

$$pp \rightarrow (W/Z)(H \rightarrow b\bar{b})$$

- The ratio of measured signal strength (μ) to SM is found to be

$$\mu = 0.2 \pm 0.5(\text{stat.}) \pm 0.4(\text{syst.})$$



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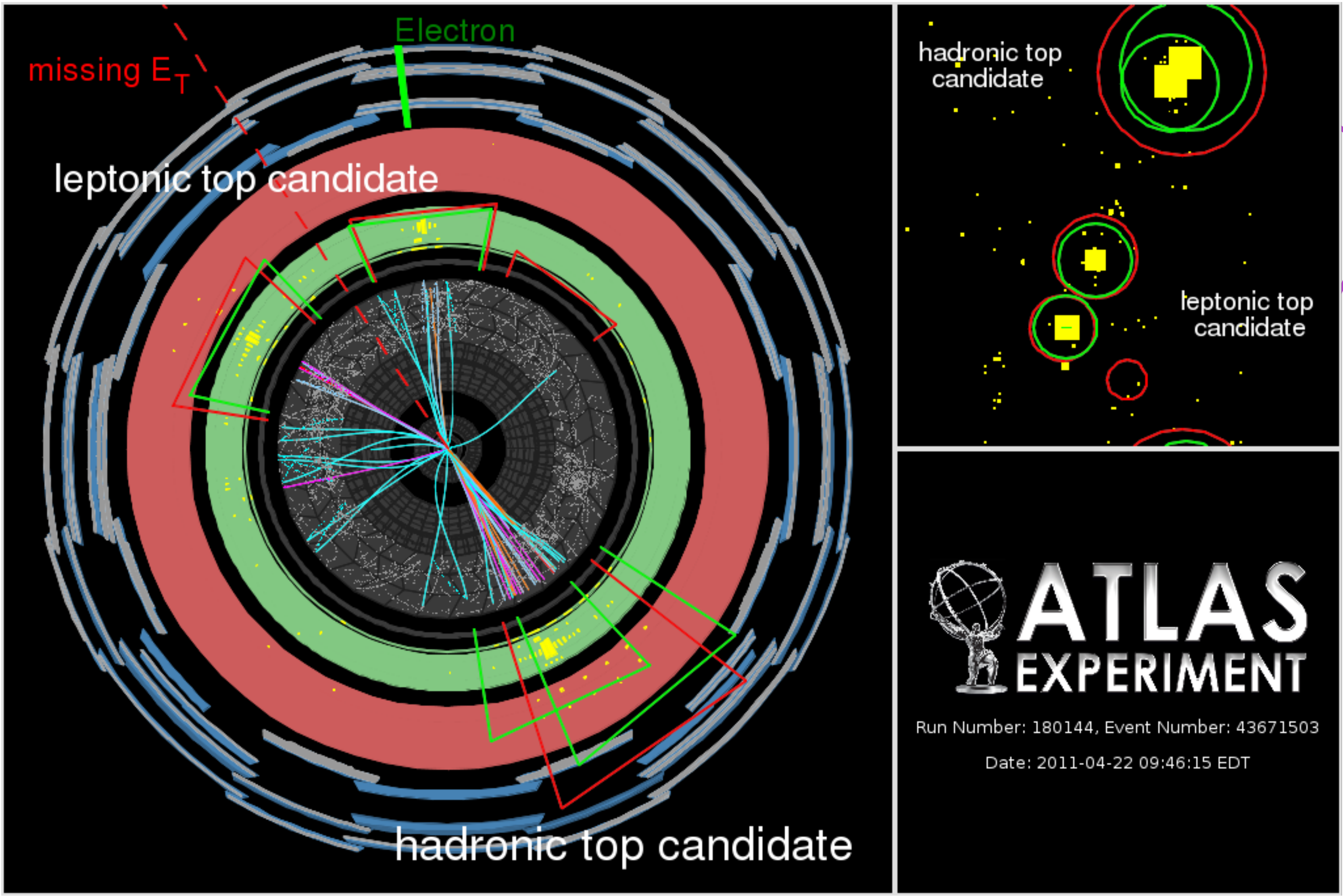
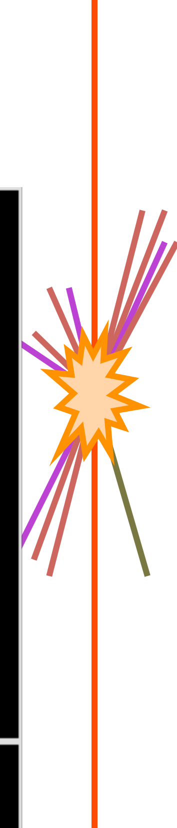
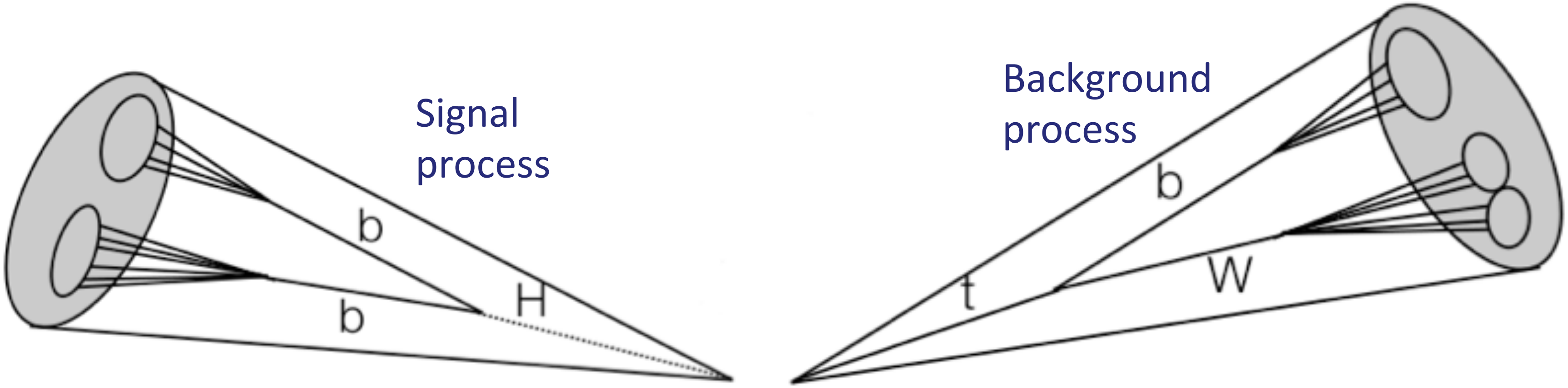
Boosted ttbar decay



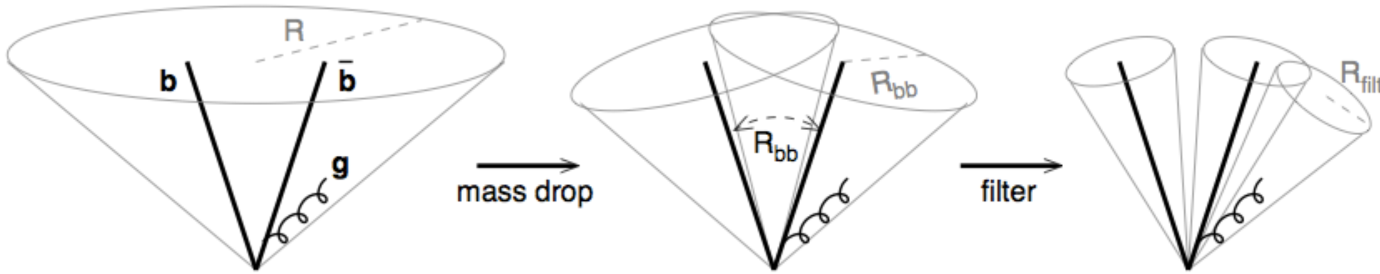


Boosted VH to bbar+X

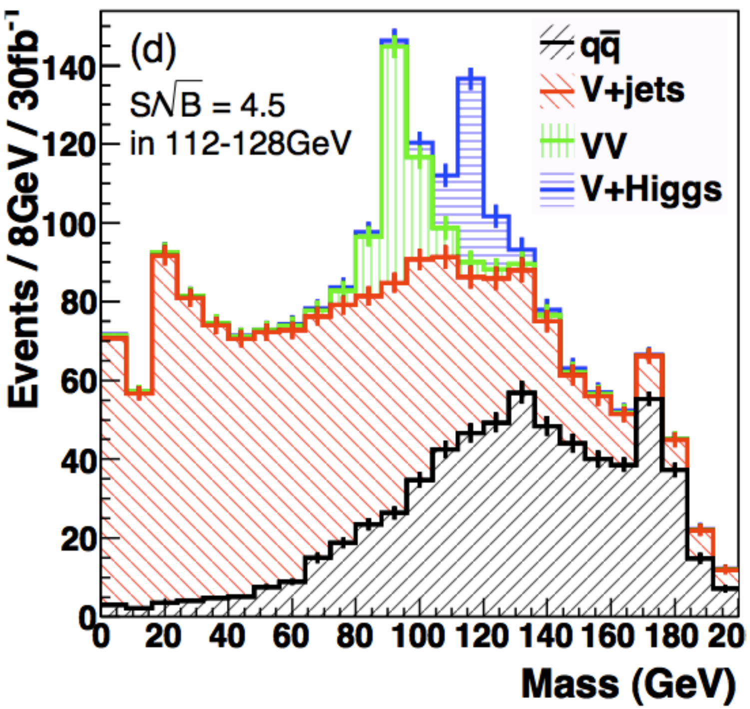
- With a large recoil emission, H and associated W or Z boson can become boosted.
  - b-quark jets are not longer easy to separate with small R jets.
    - Mini-isolation for leptons
  - Cluster decay products within large R jets.
    - Substructure then used to separate signal from background



Sub-structure analysis



- C/A jets with R = 1.2
  - p_T > 200GeV
  - Mass drop filter
- Luminosity of 30fb^{-1} @ 14TeV.



Phys.Rev.Lett.100:242001,2008 arXiv:0802.2470v2

Conclusions & outlook

- SM predictions agree with many inclusive and differential measurements.
  - Need to probe model dependencies: PDF, PS, matching
  - More experimental tests needed, e.g. ttbar+b bbar.
- Best fit using top-quark and Higgs masses leaves Higgs unstable at higher scales.
  - Precision measurements of Higgs and top mass needed.
  - Additional couplings at higher scales could stabilise the running of the quartic coupling term.
- Need conclusive measurements of Higgs decays to quarks.
  - Requires improved analysis techniques and higher energy LHC running.
- New physics couplings may be just around the corner.
  - Need to precisely determine if SM agrees with reality.

Unanswered questions

- Even if the Higgs field is/can be stabilised up to the Planck scale, several questions remain:
  - Magnitude of the masses?
  - Mixing parameters?
  - Grand unification with gravity?
- Still a lot to understand.