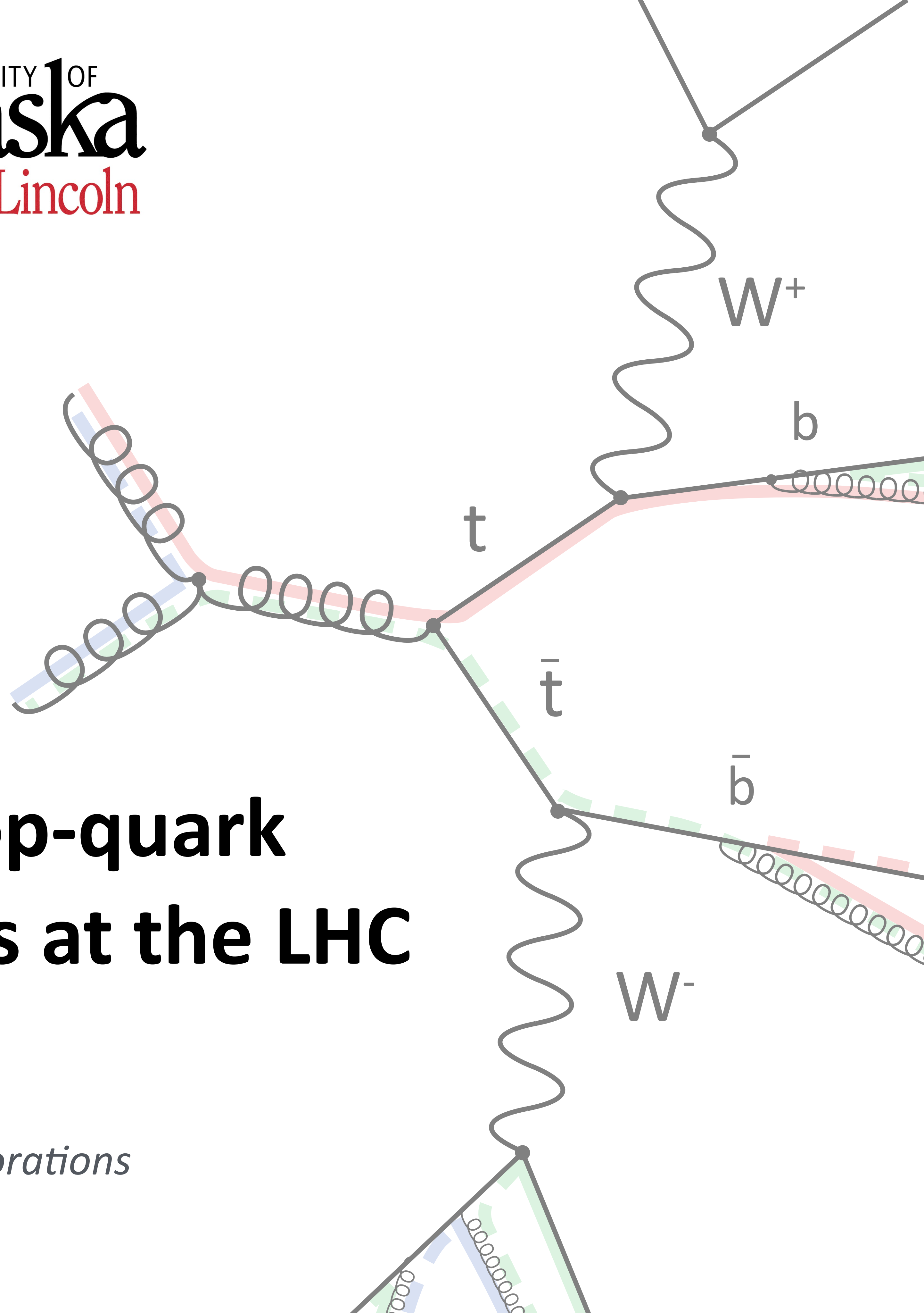
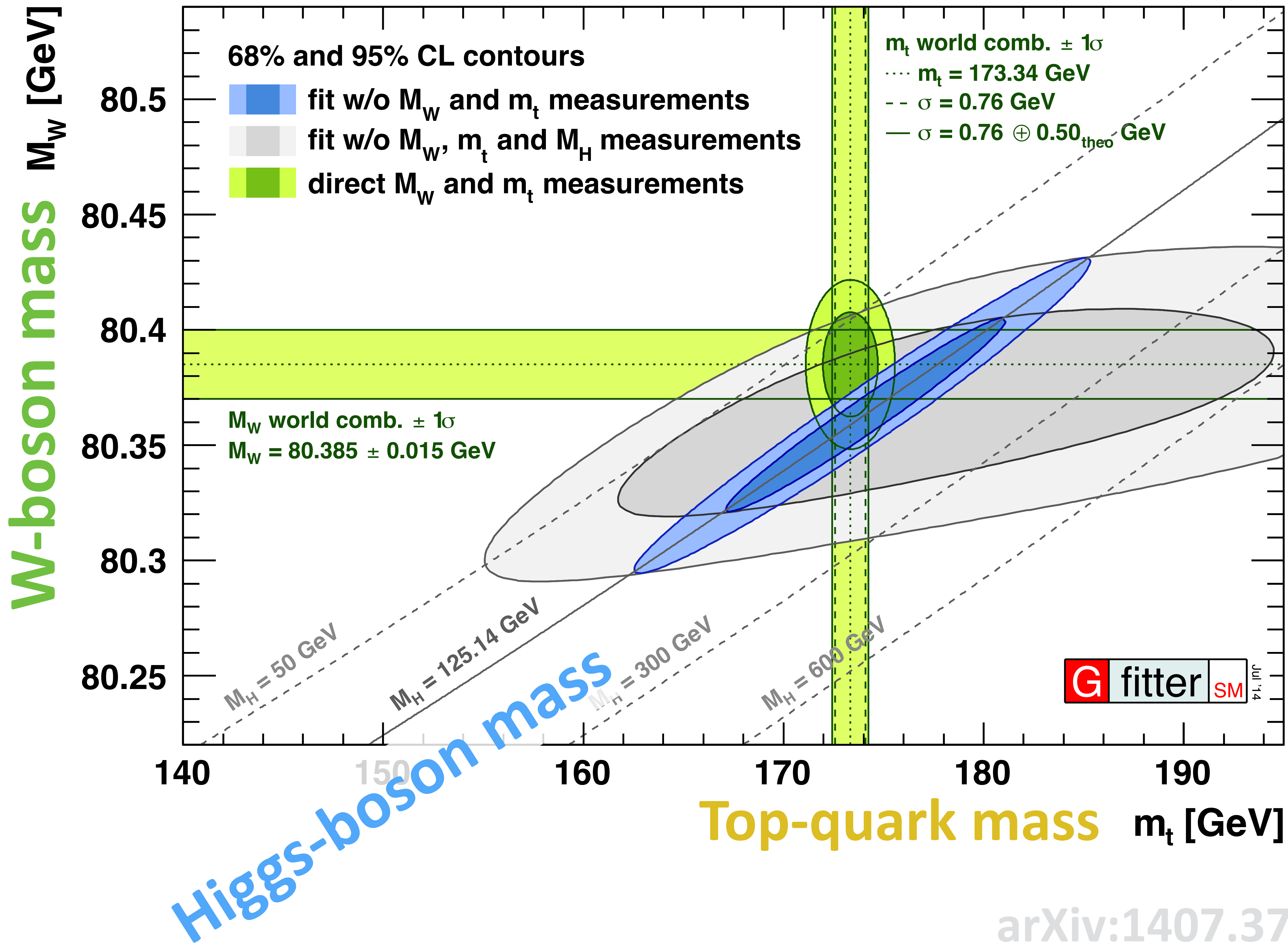
New methods for top-quark mass measurements at the LHC

Benjamin Stieger (UNL)
on behalf of the ATLAS and CMS collaborations
Moriond EW, March 15th 2016



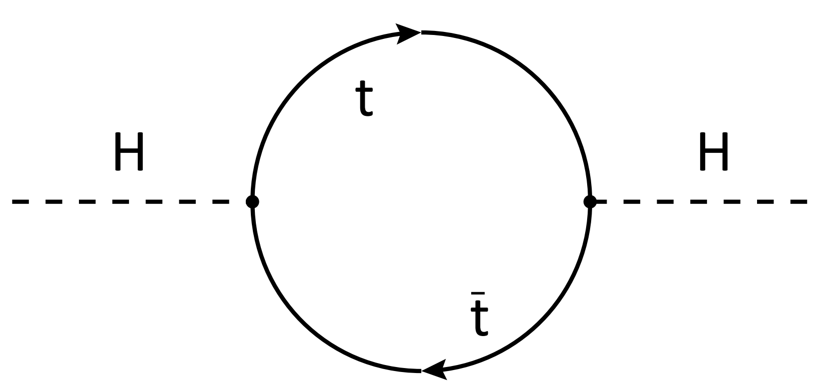
We can test the **self-consistency** of the Standard Model using the top-quark mass and other inputs



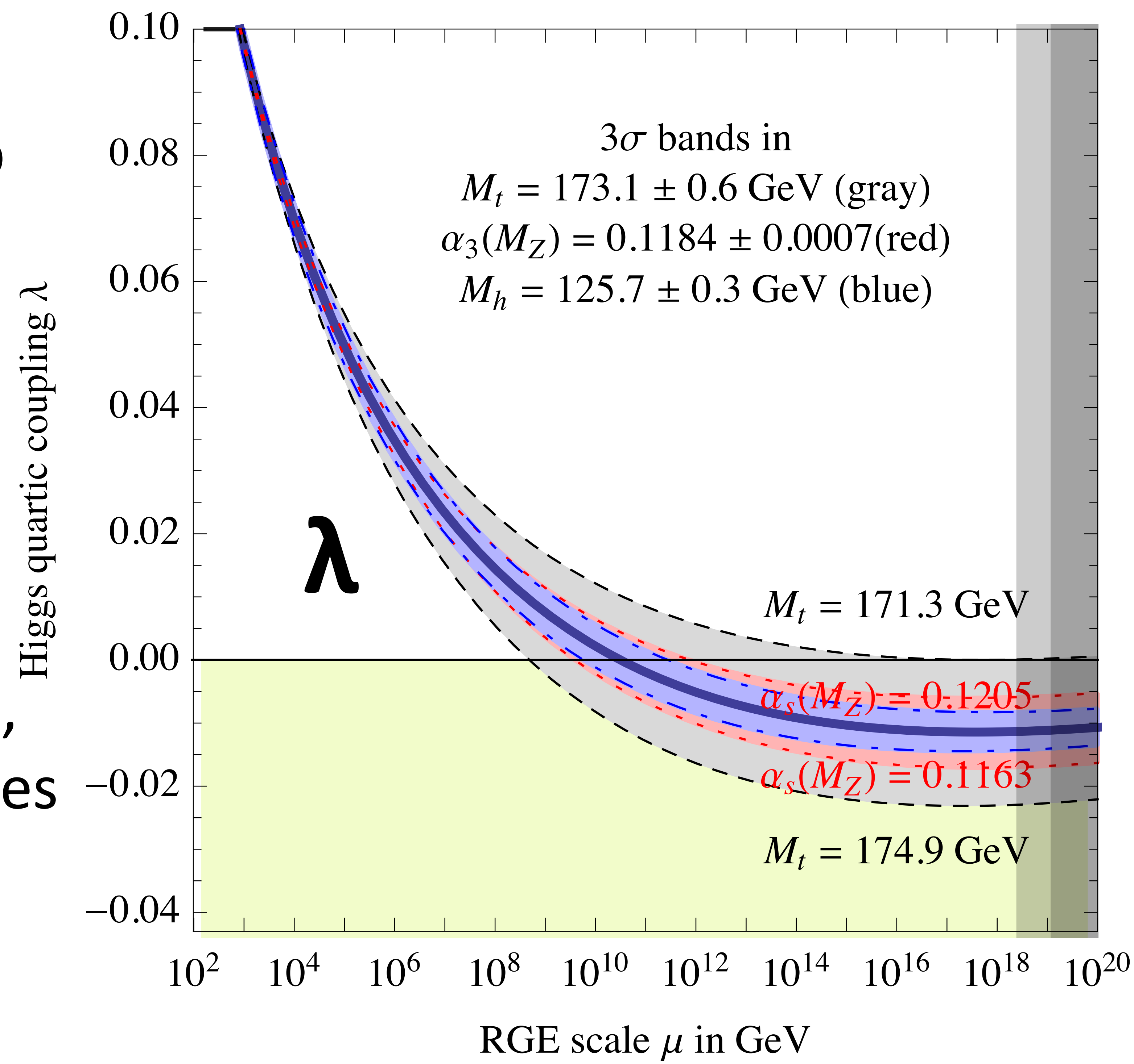
arXiv:1407.3792

Knowing the top-quark mass might just reveal the **fate of our universe**

- Evolution of Higgs quartic coupling λ depends on top mass

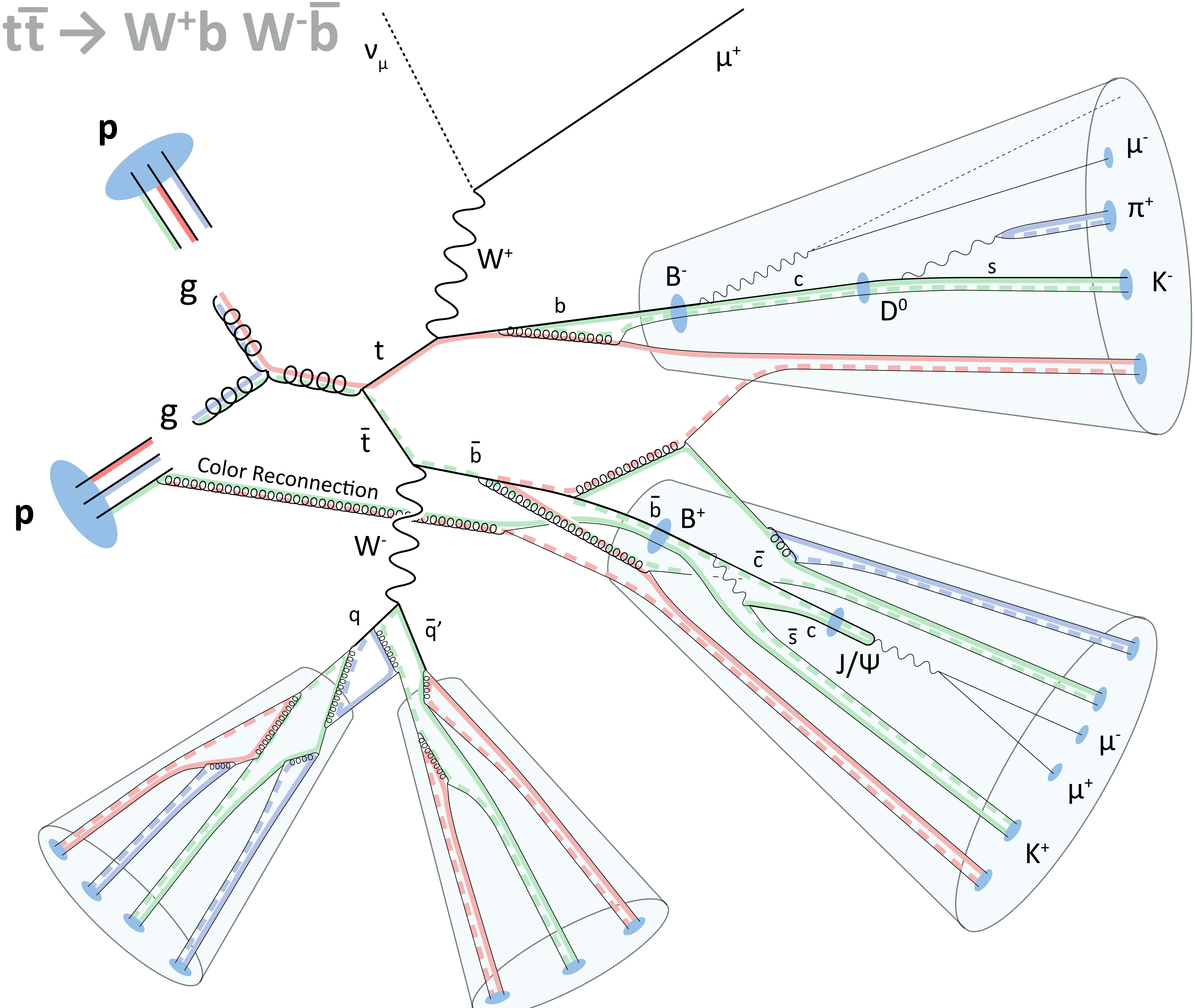


- When λ becomes negative, the Higgs potential becomes unbounded from below

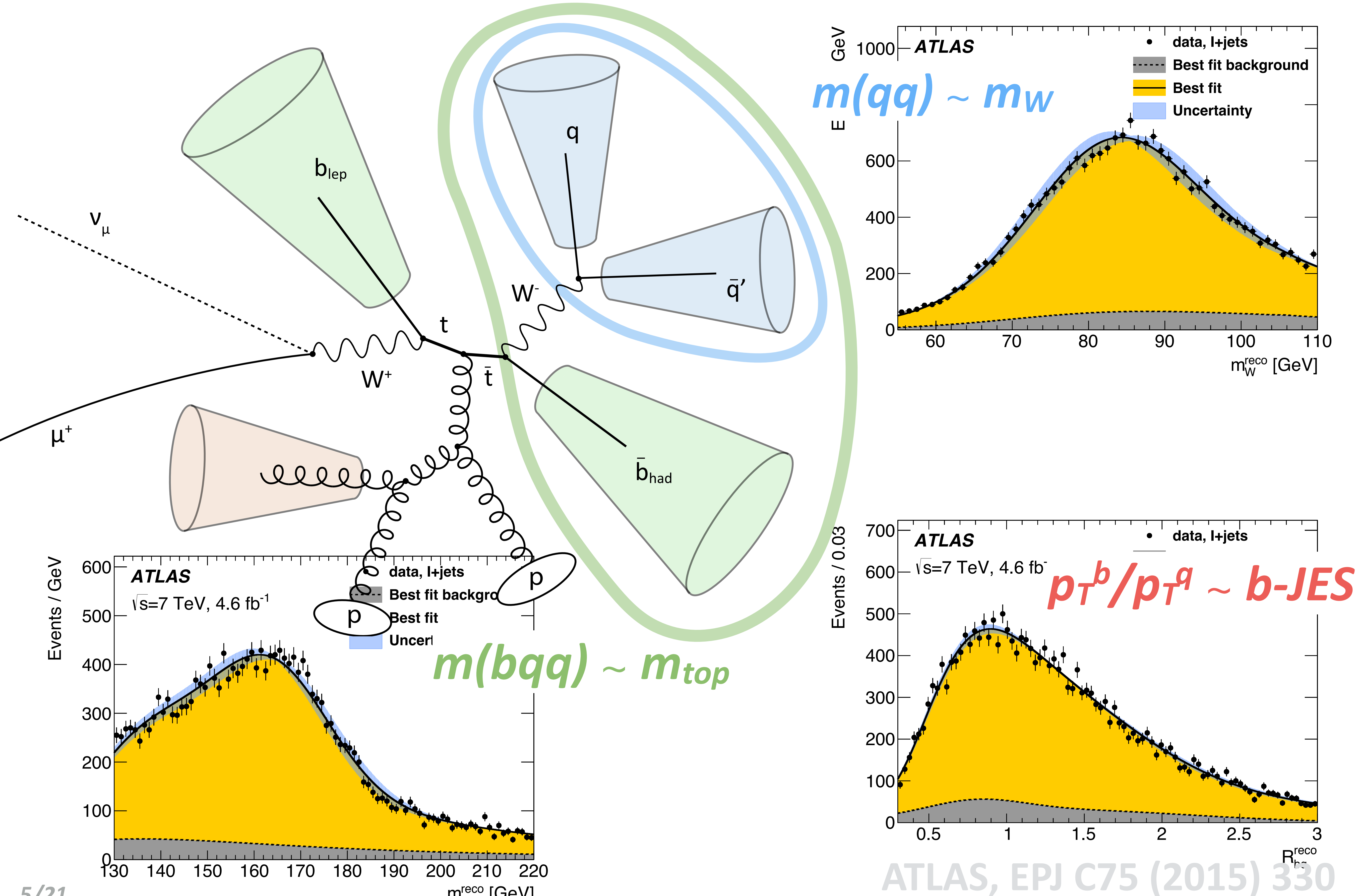


arXiv:1205.6497

$pp \rightarrow t\bar{t} \rightarrow W^{+}b\, W^{-}\bar{b}$



Extracting the top-quark mass in $t\bar{t}$ events



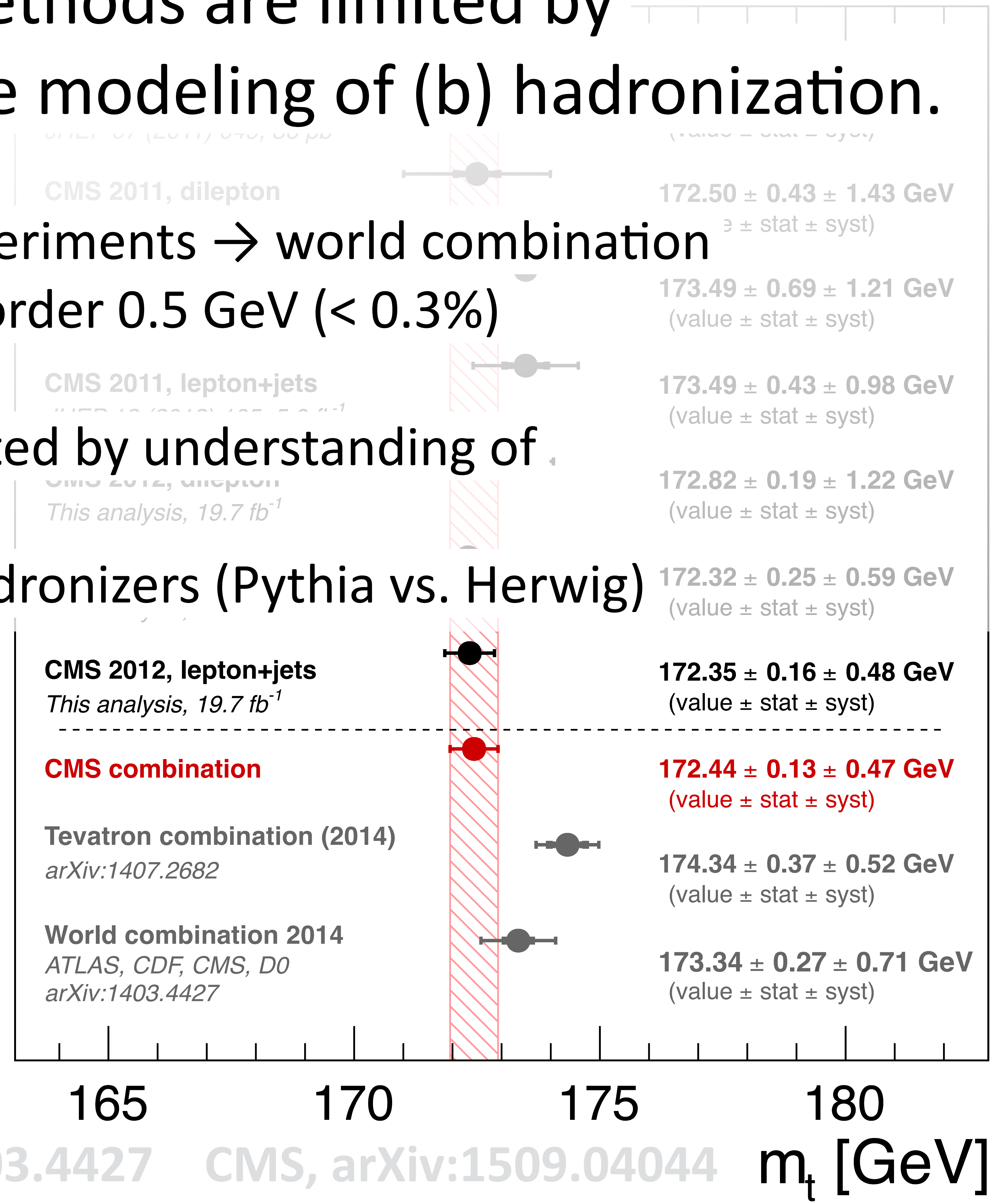
ATLAS, EPJ C75 (2015) 330

The most sensitive methods are limited by uncertainties from the modeling of (b) hadronization.

- Results from all four experiments → world combination
- Reaching a precision of order 0.5 GeV (< 0.3%)

- Precision ultimately limited by understanding of hadronization modeling
  - Compare different hadronizers (Pythia vs. Herwig)
  - Dedicated studies

- How can we improve?



World Comb.: arXiv:1403.4427 CMS, arXiv:1509.04044

Can we gain by approaching the problem differently?

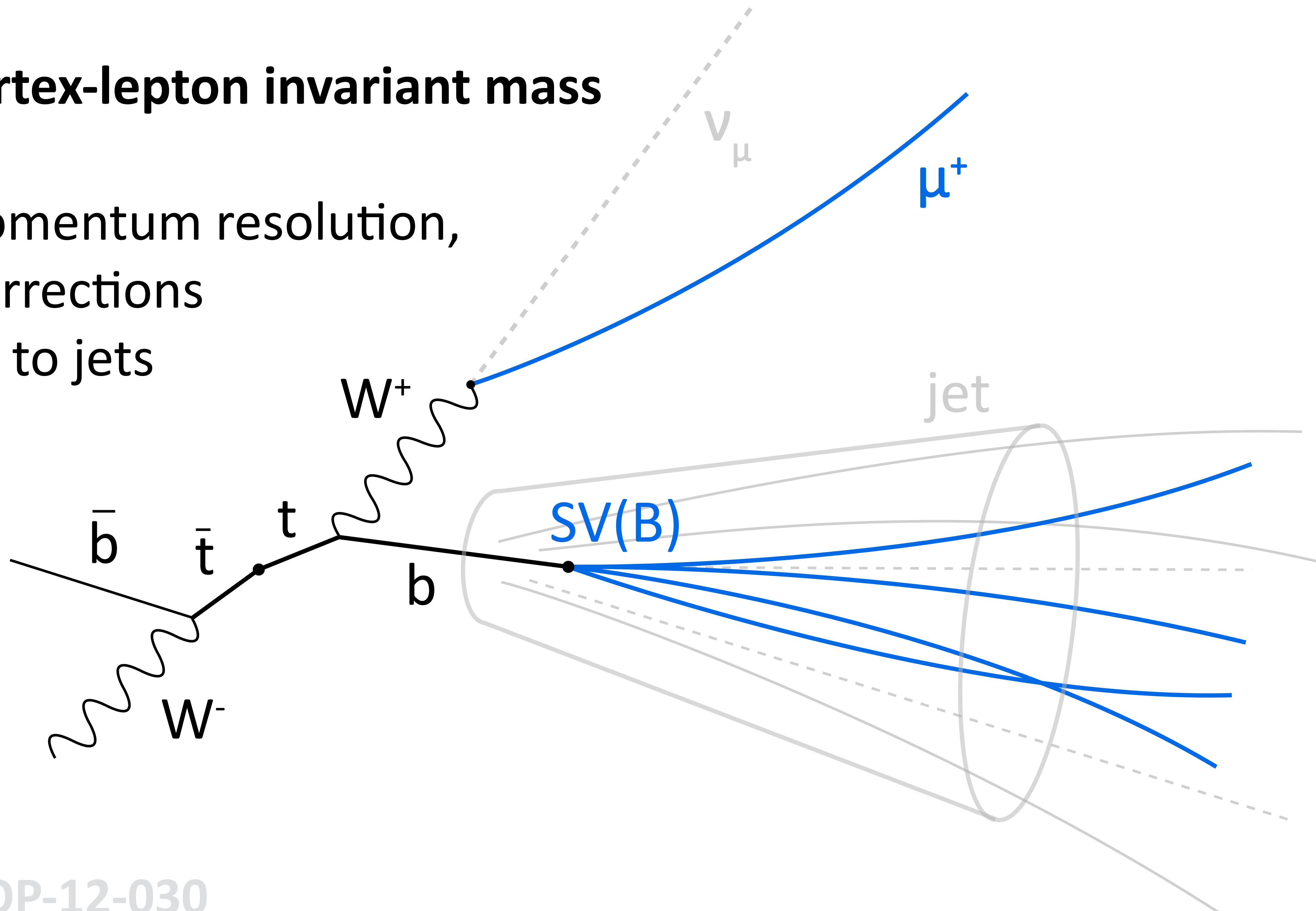
- Use experimentally clean(er) **observables**
  - Don't use jets, avoid hadronization issues
  - Alternative systematic sensitivities
  - Impact in combination with standard methods

- **Theoretically-calculable** observables
  - With some sensitivity to the mass
  - Basic example: inclusive production cross-section
  - Shapes of lepton-b invariant mass (m_{lb}), $t\bar{t}$+jet invariant mass (ρ_S)

- **Constrain modeling systematics** in the data—e.g.:
  - Hadronization: b fragmentation, semileptonic b hadron decays, …
  - Top quark p_T, scale uncertainties in differential cross sections
  - Underlying event

Reduce experimental uncertainties by using only charged tracks and leptons.

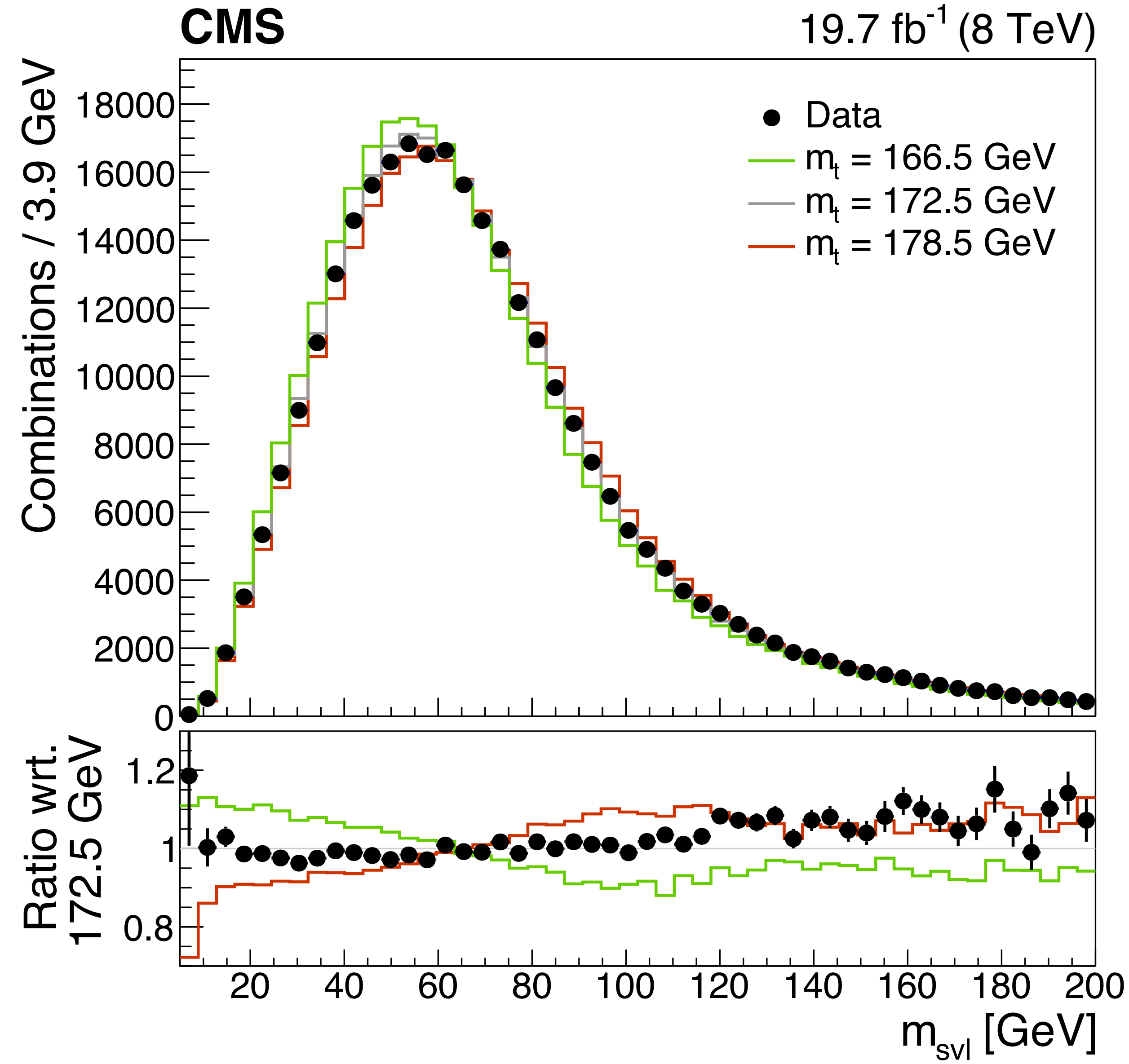
- Reconstruct **secondary vertex** from b-hadron decay
- Exploit **vertex-lepton invariant mass**
- Higher momentum resolution, smaller corrections compared to jets

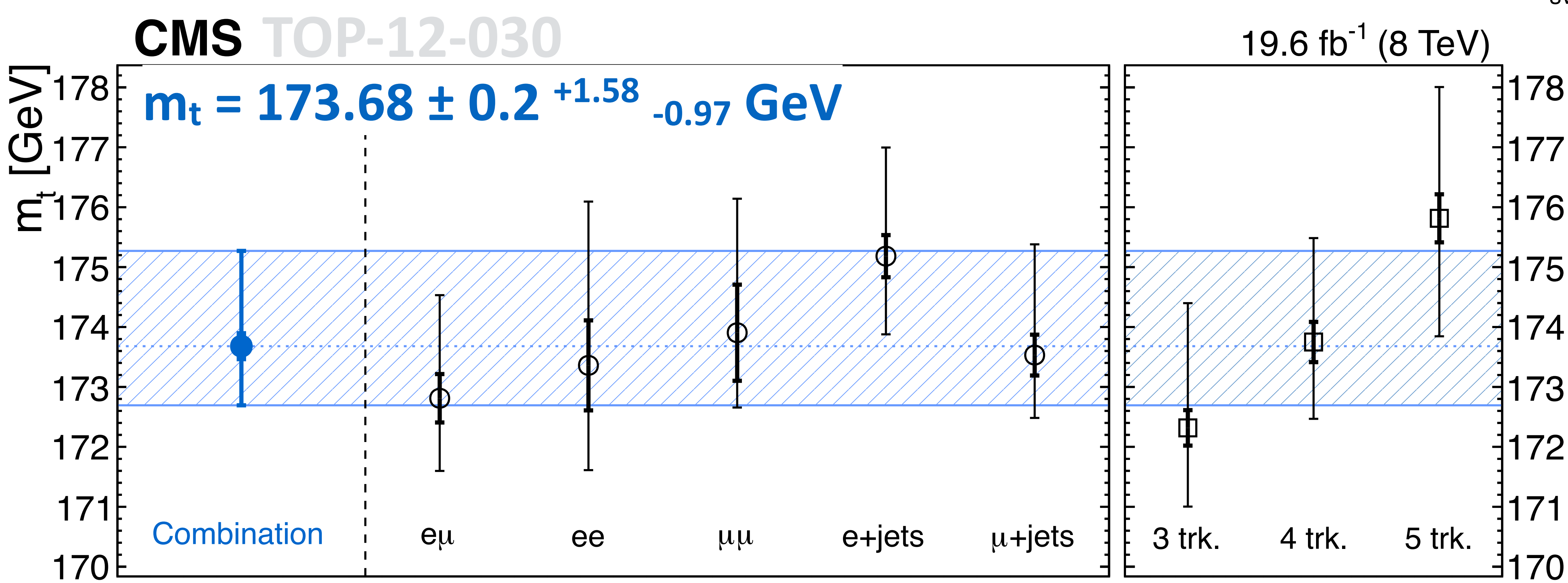


CMS TOP-12-030

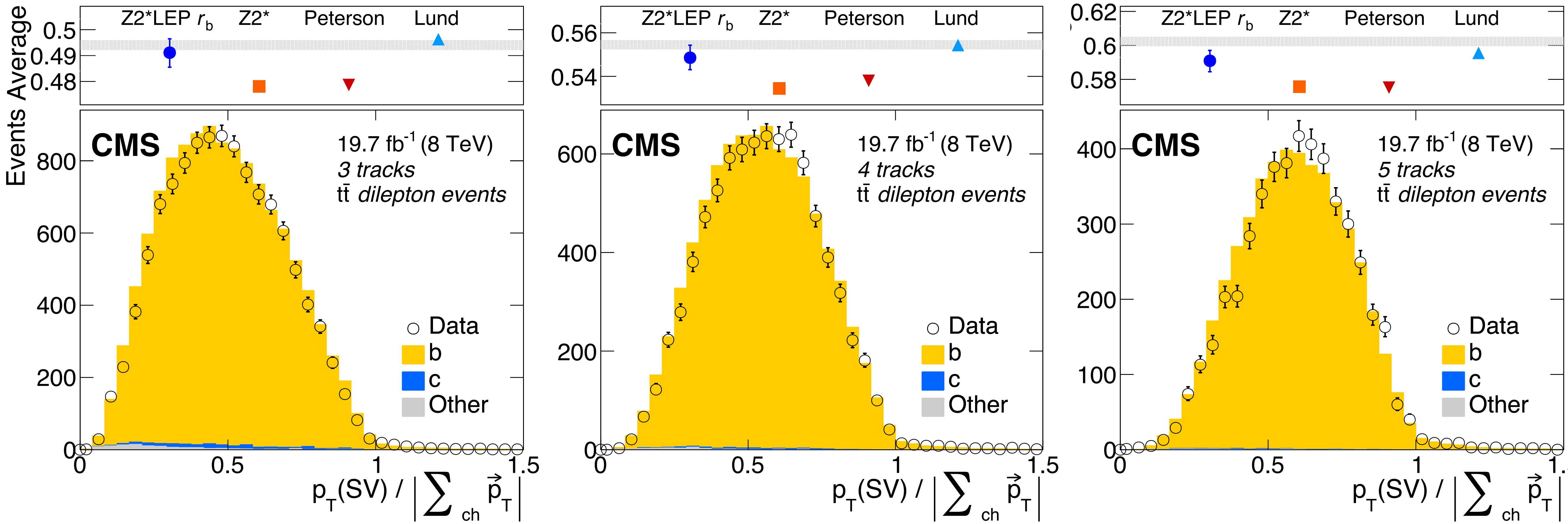
Lepton + Secondary Vertices

- Performed in bins of SV-track multiplicity
- Leading systematic uncertainties
  - b fragmentation ($^{+1.00}_{-0.54}$ GeV)
  - Top quark p_T ($^{+0.82}$ GeV)
  - (These are virtually negligible in standard measurements)
- Total experimental uncertainties < 500 MeV

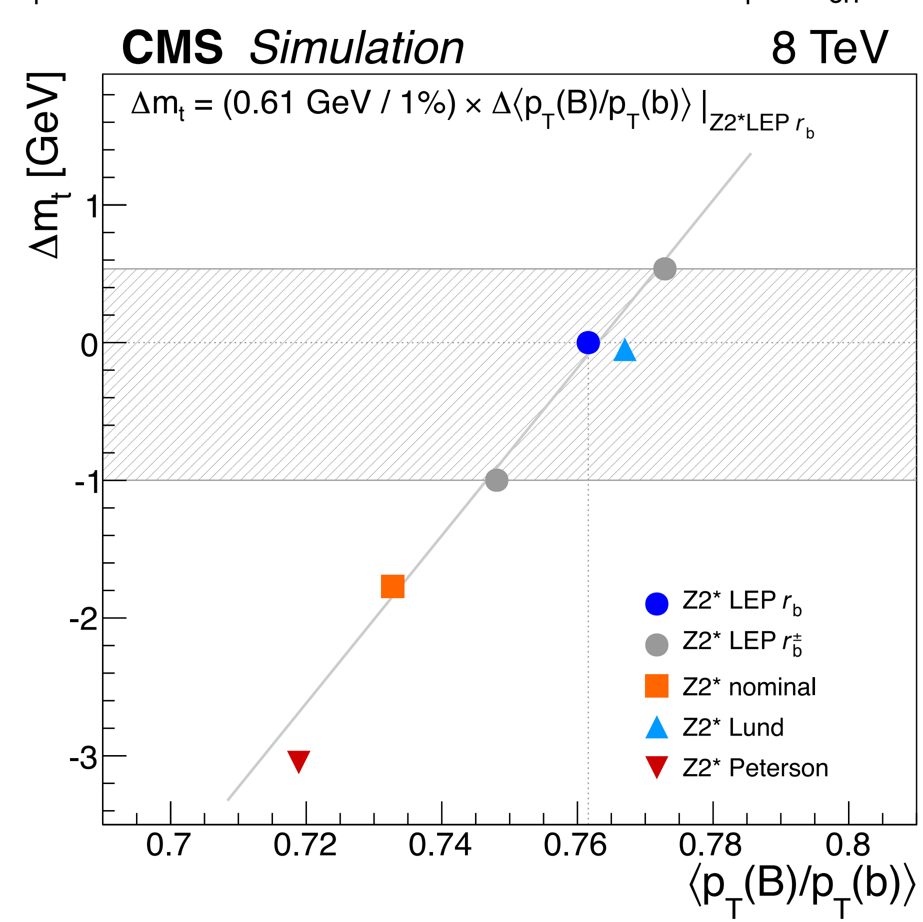




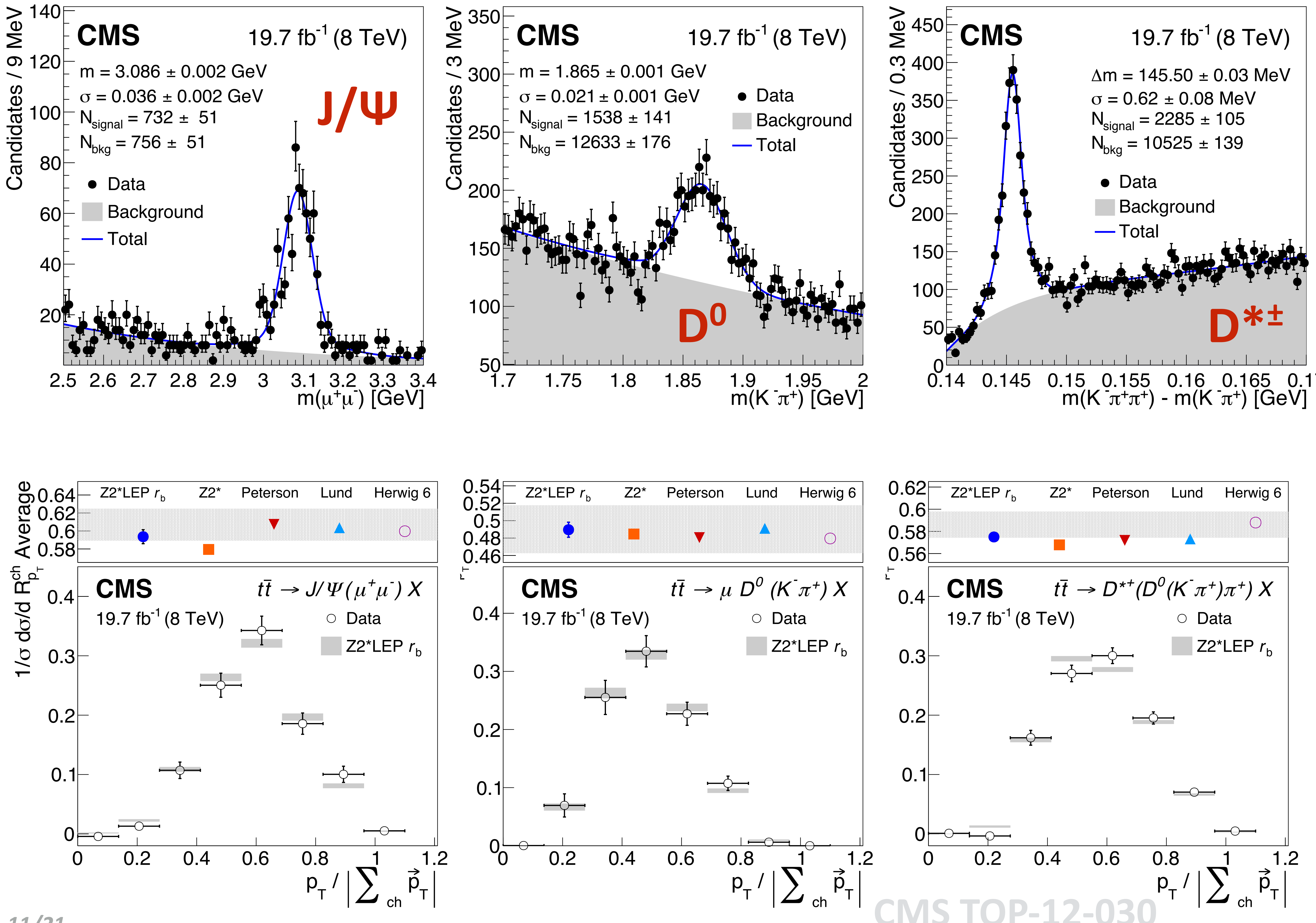
Studying b-quark fragmentation in the data



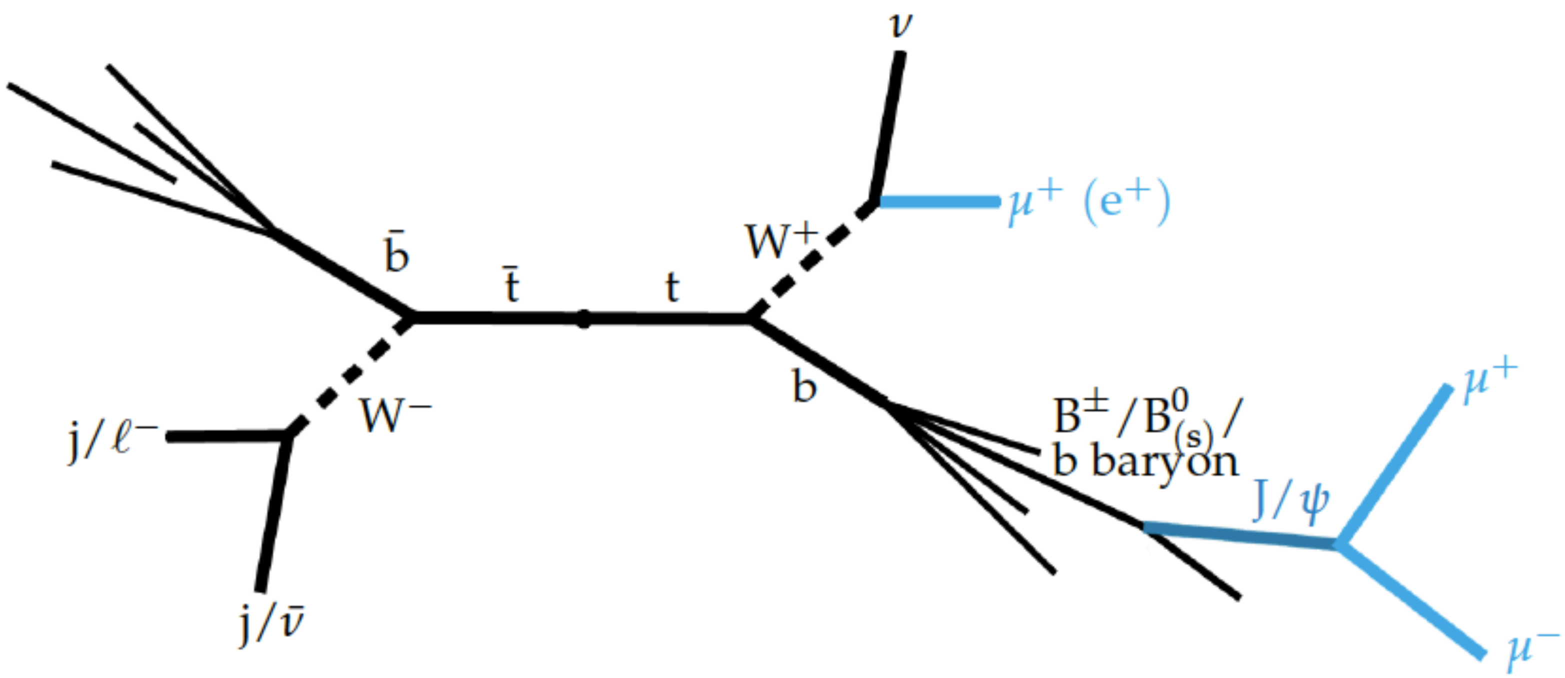
- Compare fraction of jet-momentum carried by secondary vertex for different fragmentation function shapes
  - Proxy for parton-to-hadron momentum transfer
- Dominant effect on measured top mass

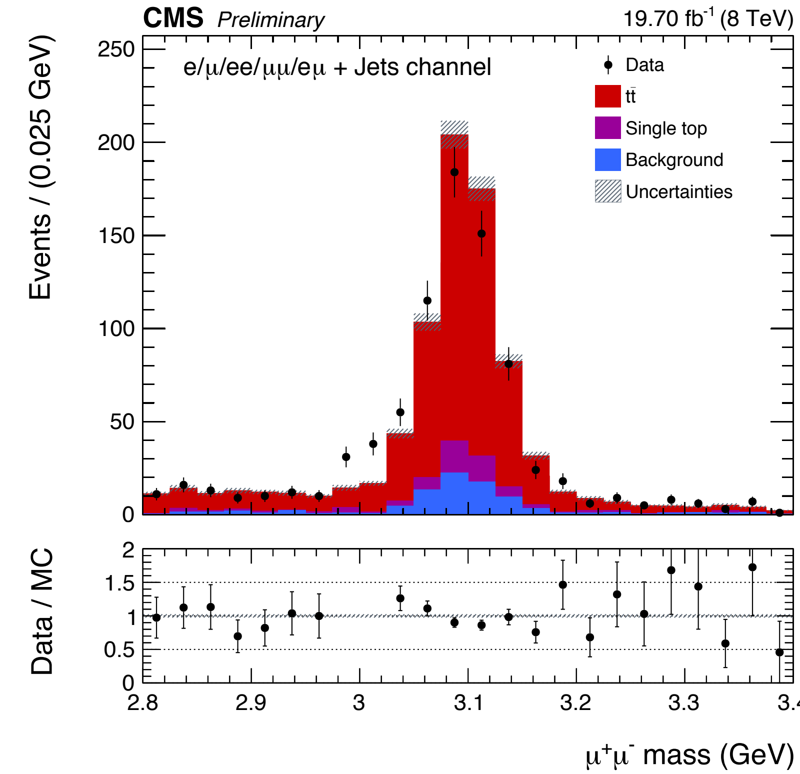


CMS TOP-12-030

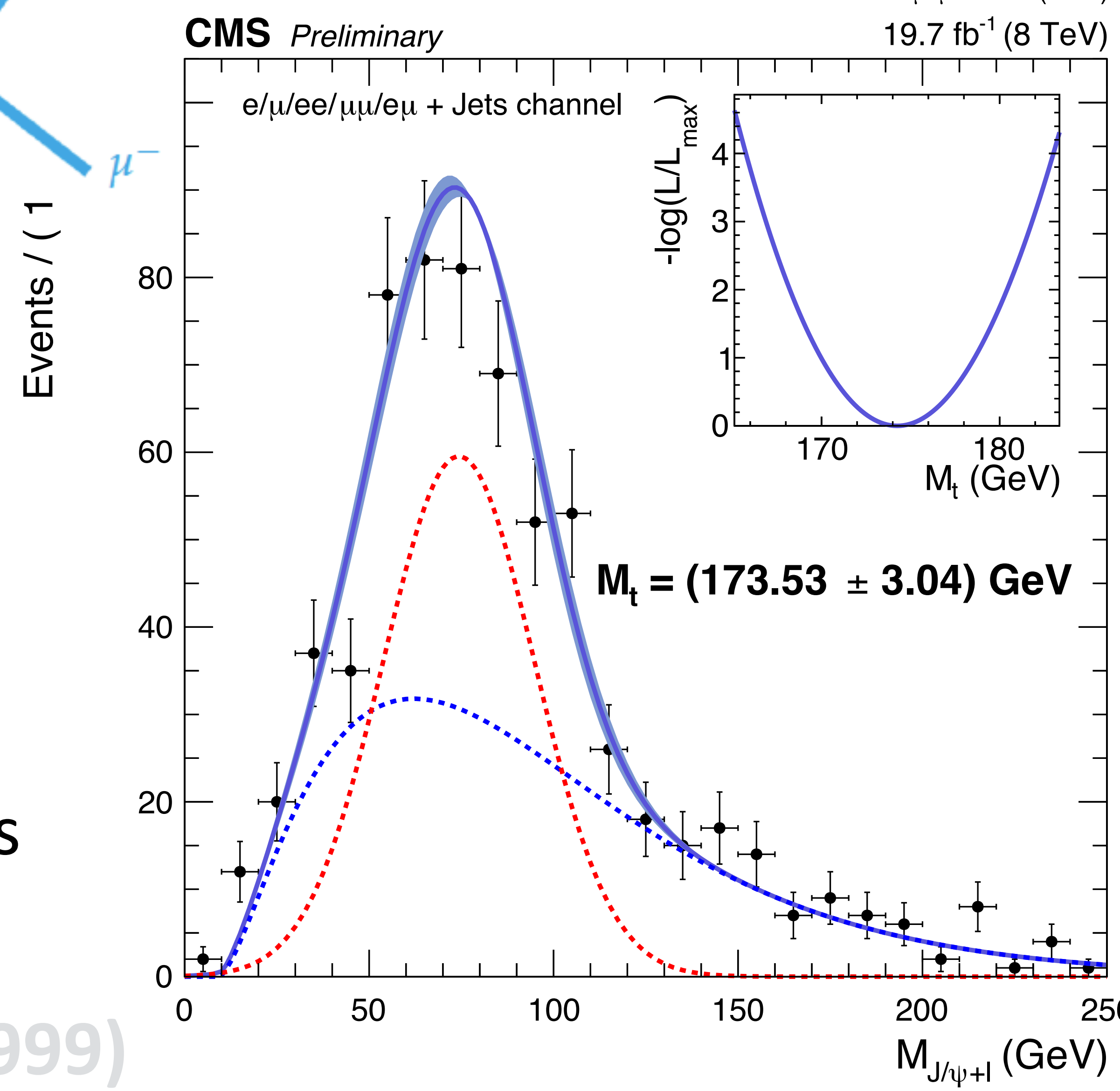

CMS 19.7 fb-1 (8 TeV)
m = 3.086 ± 0.002 GeV
σ = 0.036 ± 0.002 GeV
N_signal = 732 ± 51
N_bkg = 756 ± 51
J/Ψ
Data
Background
Total
Candidates / 9 MeV
m(μ+μ-) [GeV]
m = 1.865 ± 0.001 GeV
σ = 0.021 ± 0.001 GeV
N_signal = 1538 ± 141
N_bkg = 12633 ± 176
D0
Candidates / 3 MeV
m(K-π+) [GeV]
Δm = 145.50 ± 0.03 MeV
σ = 0.62 ± 0.08 MeV
N_signal = 2285 ± 105
N_bkg = 10525 ± 139
D*±
Candidates / 0.3 MeV
m(K-π+π+) - m(K-π+) [GeV]
Z2*LEP r_b
Z2*
Peterson
Lund
Herwig 6
Average
1/σ dσ/d R^ch_pT
tt̄ → J/Ψ(μ+μ-) X
tt̄ → μ D0 (K-π+) X
tt̄ → D*+(D0(K-π+)π+) X
Data
Z2*LEP r_b
pT / |Σ_ch p⃗T|
CMS TOP-12-030

Using charmed mesons might provide an even cleaner observable.

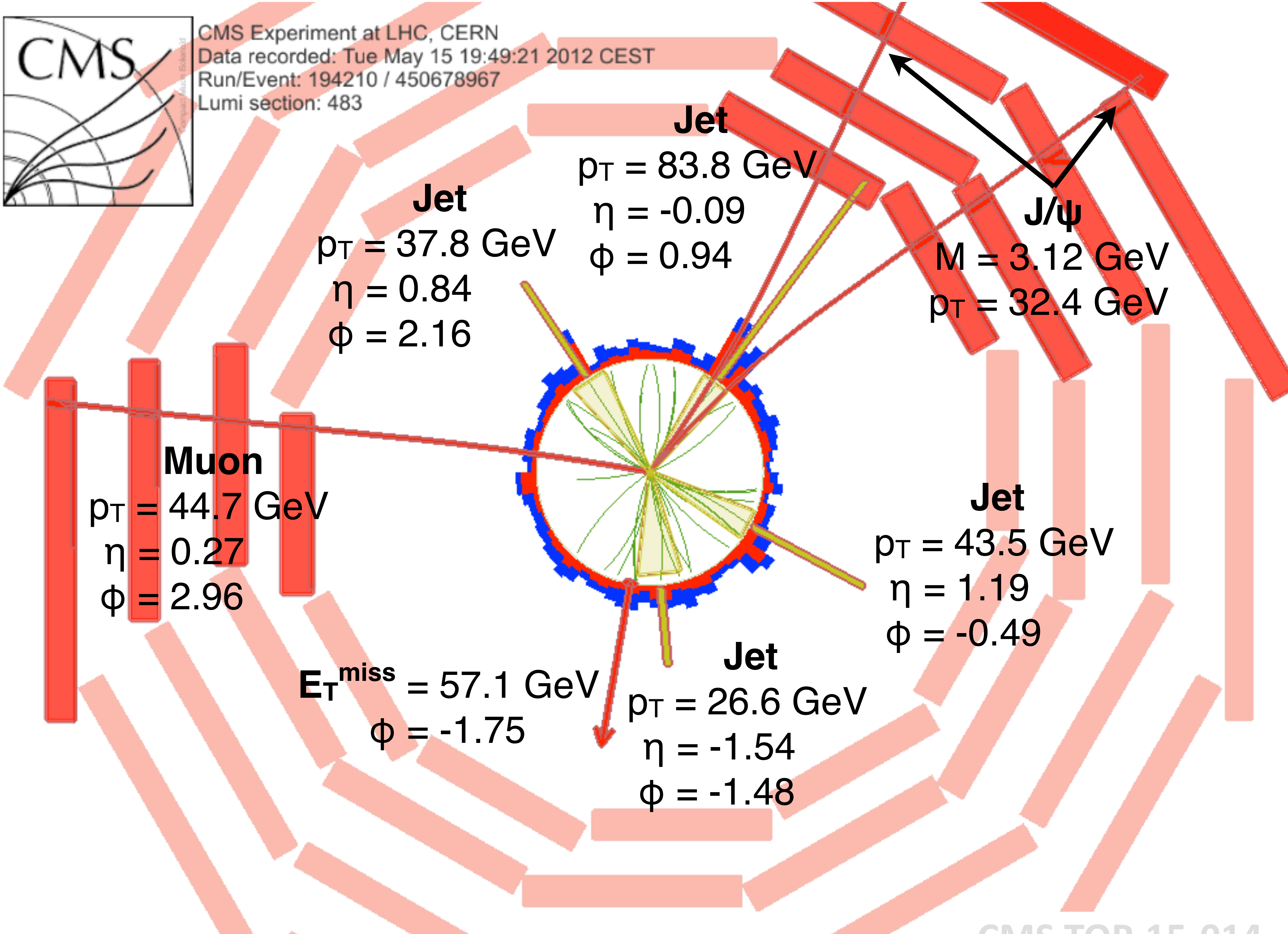




- **Lepton + J/Ψ** invariant mass
- Small branching fractions
  - 666 available events in 8 TeV dataset
  - Statistical uncertainty of 3.0 GeV
- However < 1 GeV syst. uncertainty
  - b-fragmentation ~0.3 GeV
  - Limited by top p_T modeling, QCD scales
  - Relevant exp. uncertainties < 100 MeV



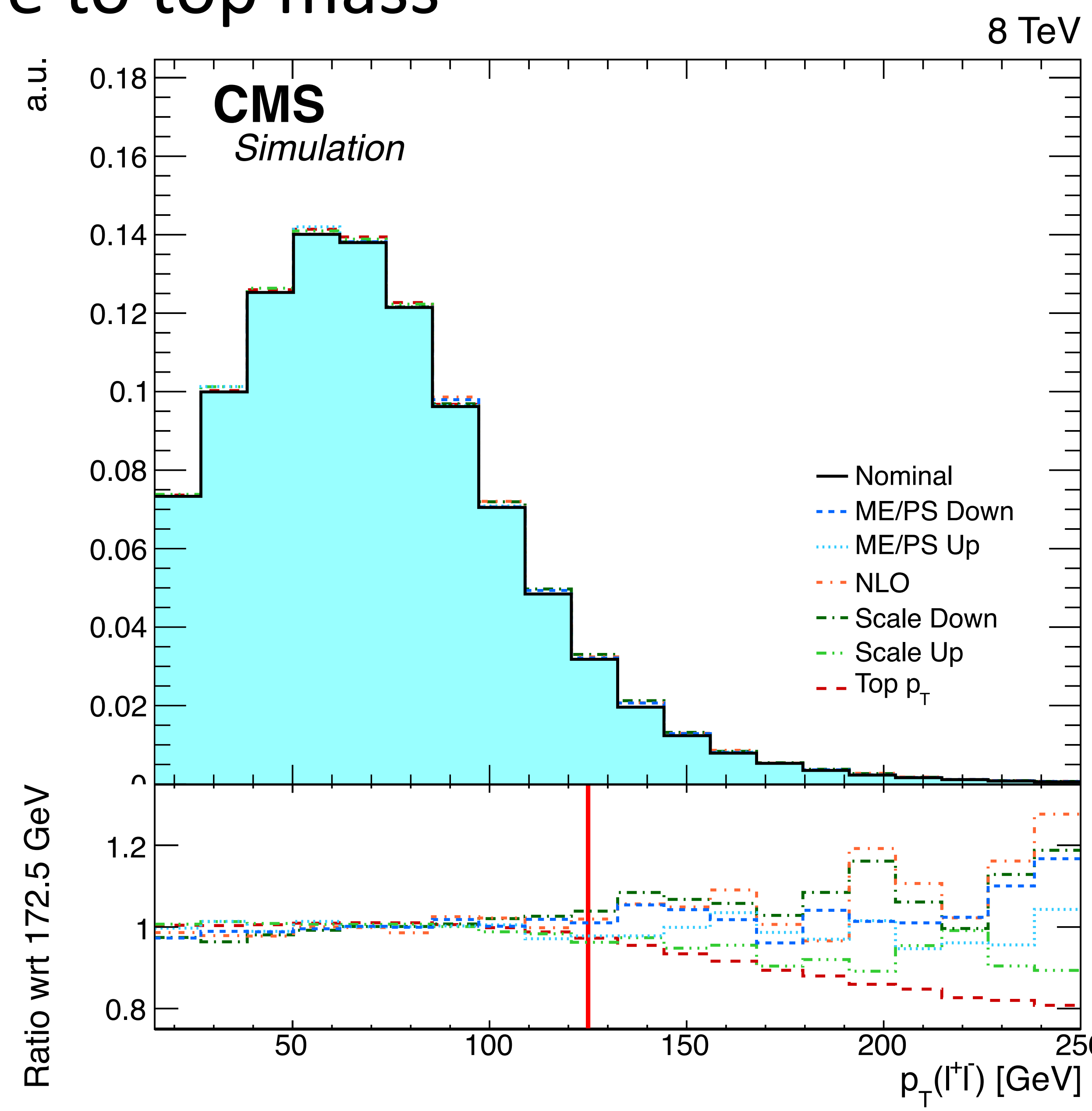
CMS TOP-15-014 Kharchilava (1999)



CMS TOP-15-014

Ideal case would be an experimentally-clean, mass-sensitive observable, that is theoretically calculable.

- Dilepton kinematics proposed by ***Frixione and Mitov (2014)***
- Found $p_T(l^+l^-)$ to be most sensitive to top mass



- Clean, but hampered by QCD scale uncertainties
  - Caveat: using only **leading-order MC** in Run I (8 TeV)
  - Furthermore, **top quark p_T mismodeling** has a large impact
  - Experimentally limited only by lepton momentum scale

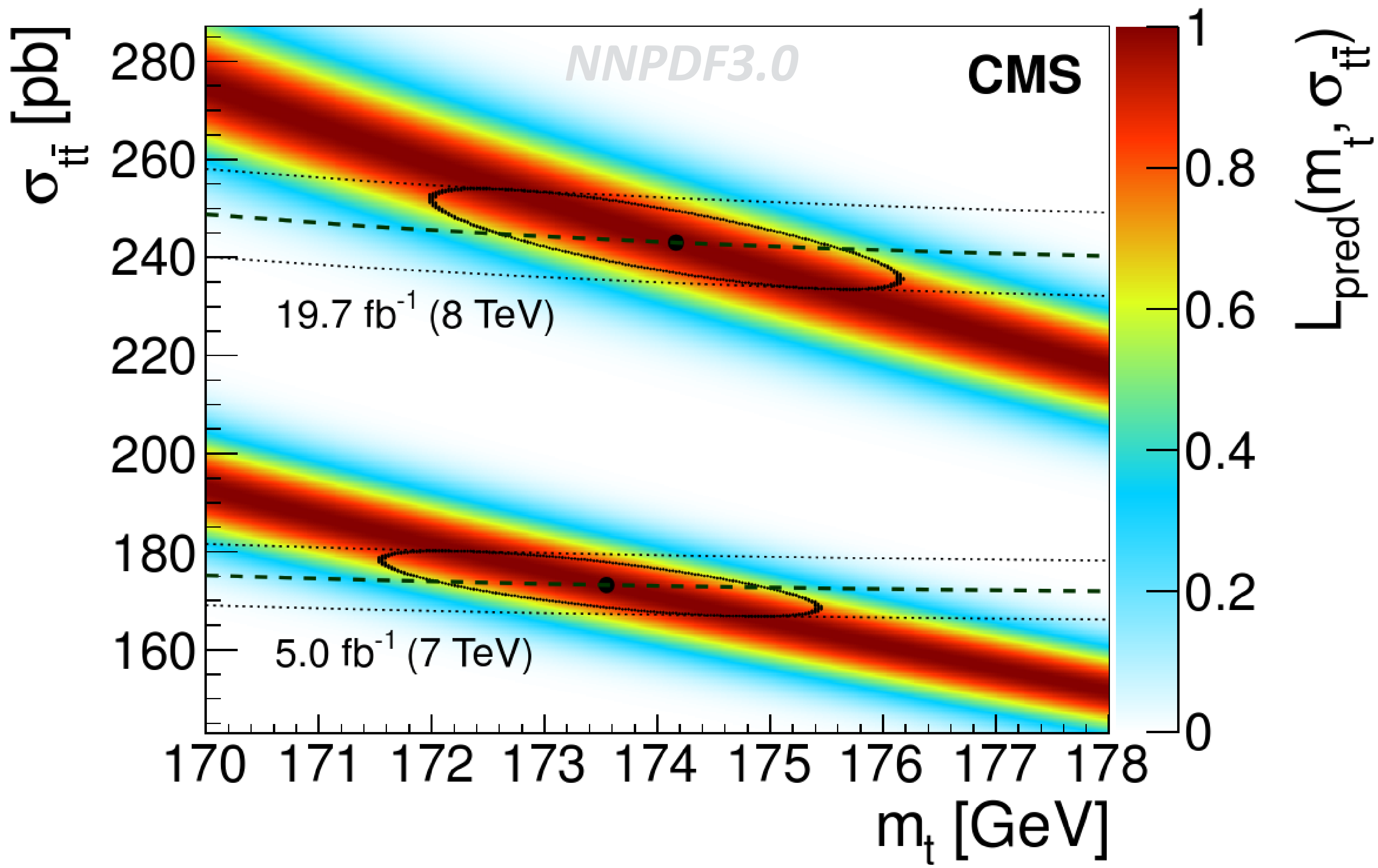
CMS (2016): $\mathbf{m_t = 171.7 \pm 1.1 \pm 0.5\ ^{+3.1}_{-2.5}\ ^{+0.8}\ GeV}$

(stat.) (exp.) (theo.) (top p_T)

CMS TOP-16-002

Can extract the top quark pole mass from the inclusive $t\bar{t}$ production cross-section.

- Mass-dependence can be calculated at NNLO
  - Acceptance depends on m_t as well
- Fixed value of α_S
- Ultimately limited by beam uncertainties: luminosity, energy



CMS (2016): **m_t = 173.8 $^{+1.7}_{-1.8}$ GeV** ATLAS, EPJ C74 (2014) 3109

ATLAS (2014): **m_t = 172.9 $^{+2.5}_{-2.6}$ GeV** CMS, arXiv:1603.02303

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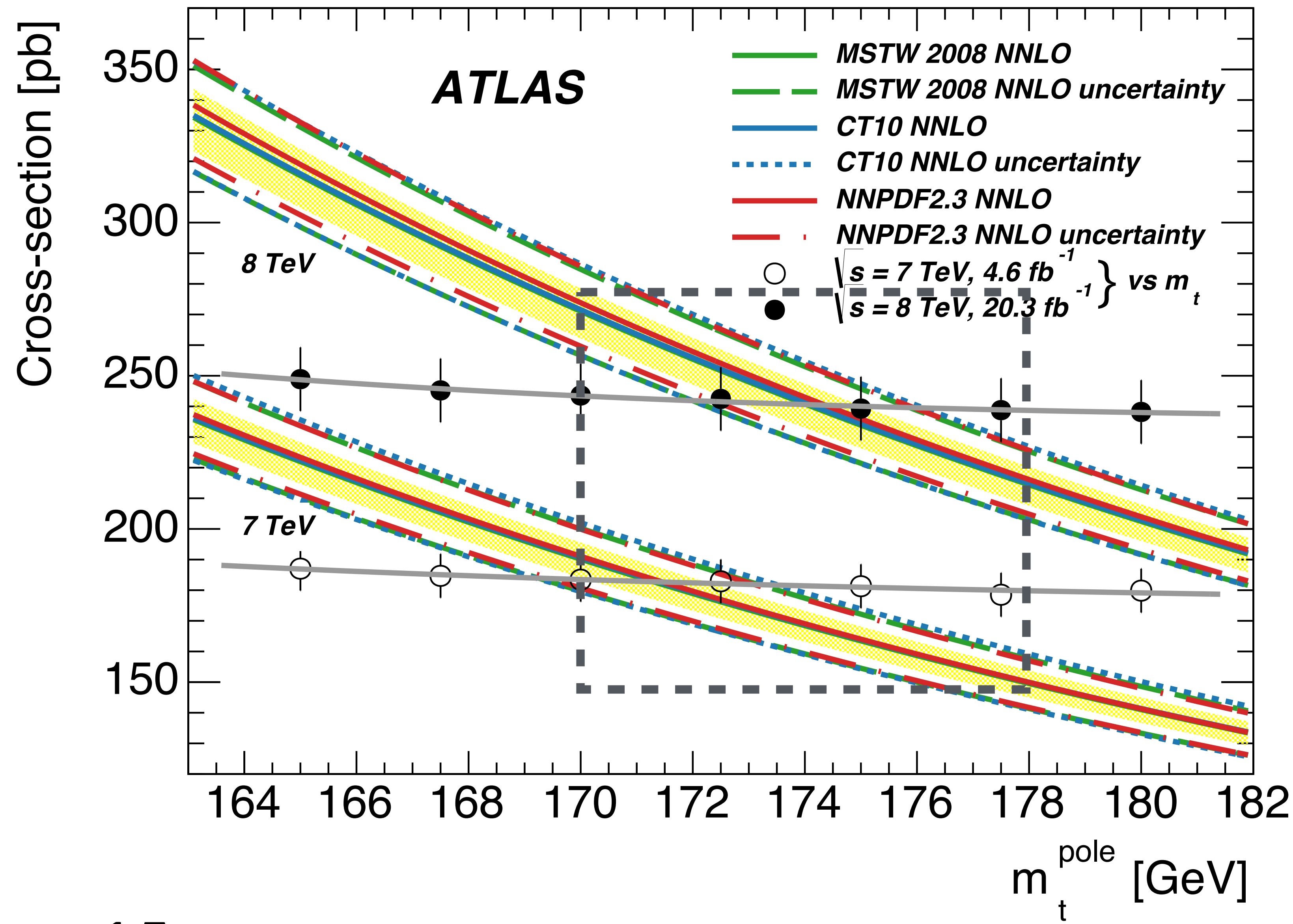

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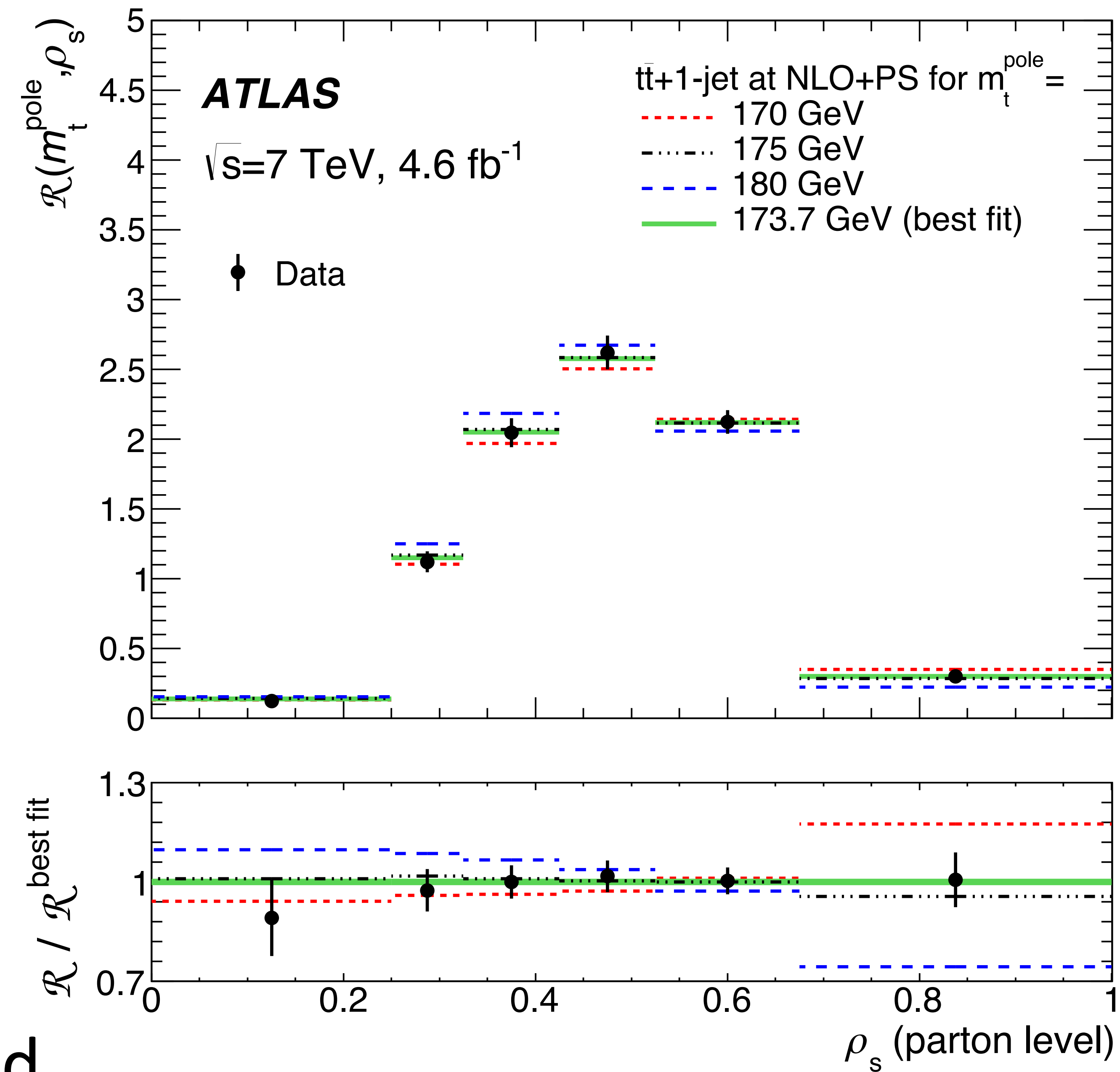
Shapes are potentially more sensitive, and not limited by beam uncertainties.

Alioli, Fuster, Moch, et al. (2013)

- Primary QCD radiation depends on top quark mass
  - Calculable at NLO
- Study $t\bar{t}$ events with at least one additional jet
  - Measure diff. cross section versus $\rho_S \propto 1 / m(t\bar{t}, \text{jet})$



- Independent of mass from cross section

- Unfolded distribution compared to NLO MC calculation to extract pole mass

$$\mathbf{m_t = 173.7\ ^{+2.3}_{-2.1}\ GeV}$$

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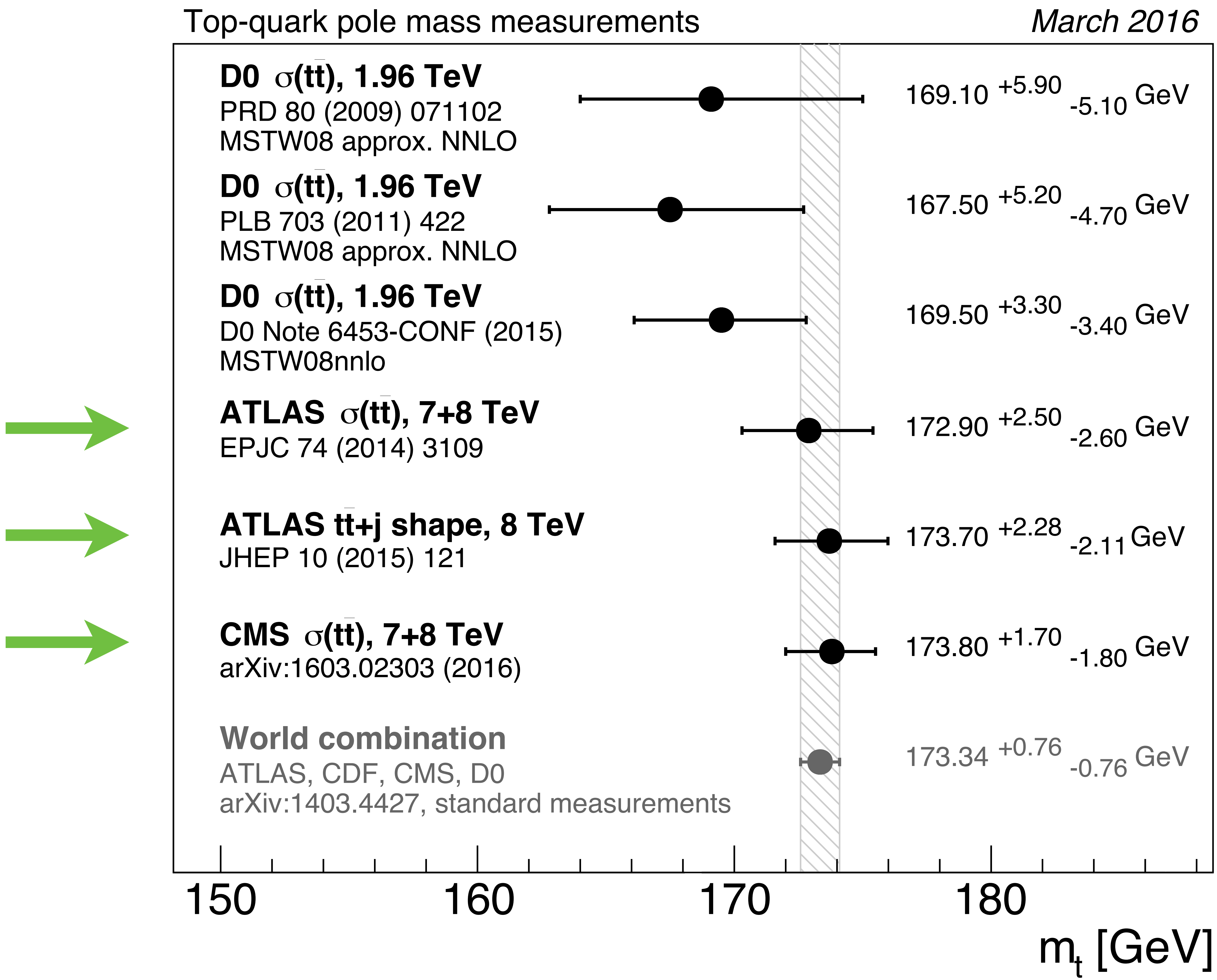
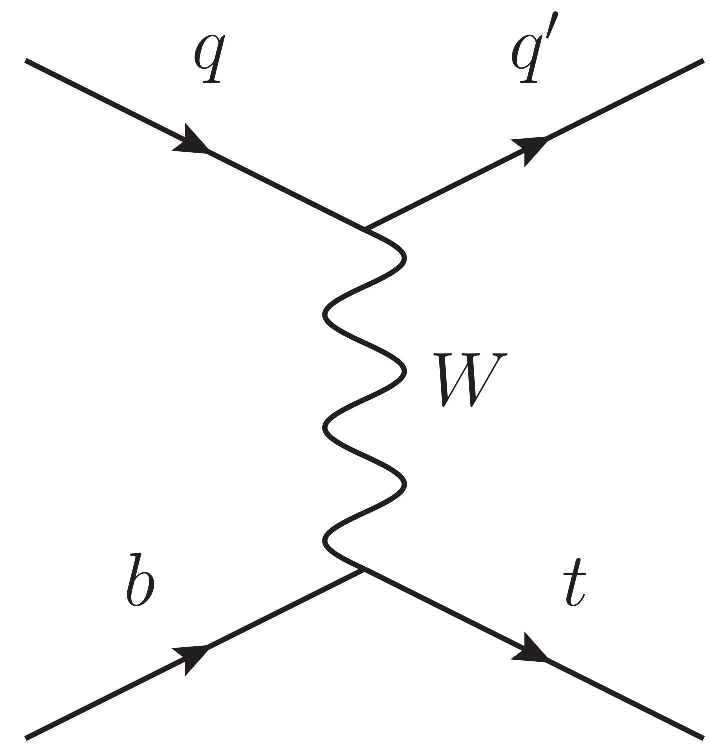
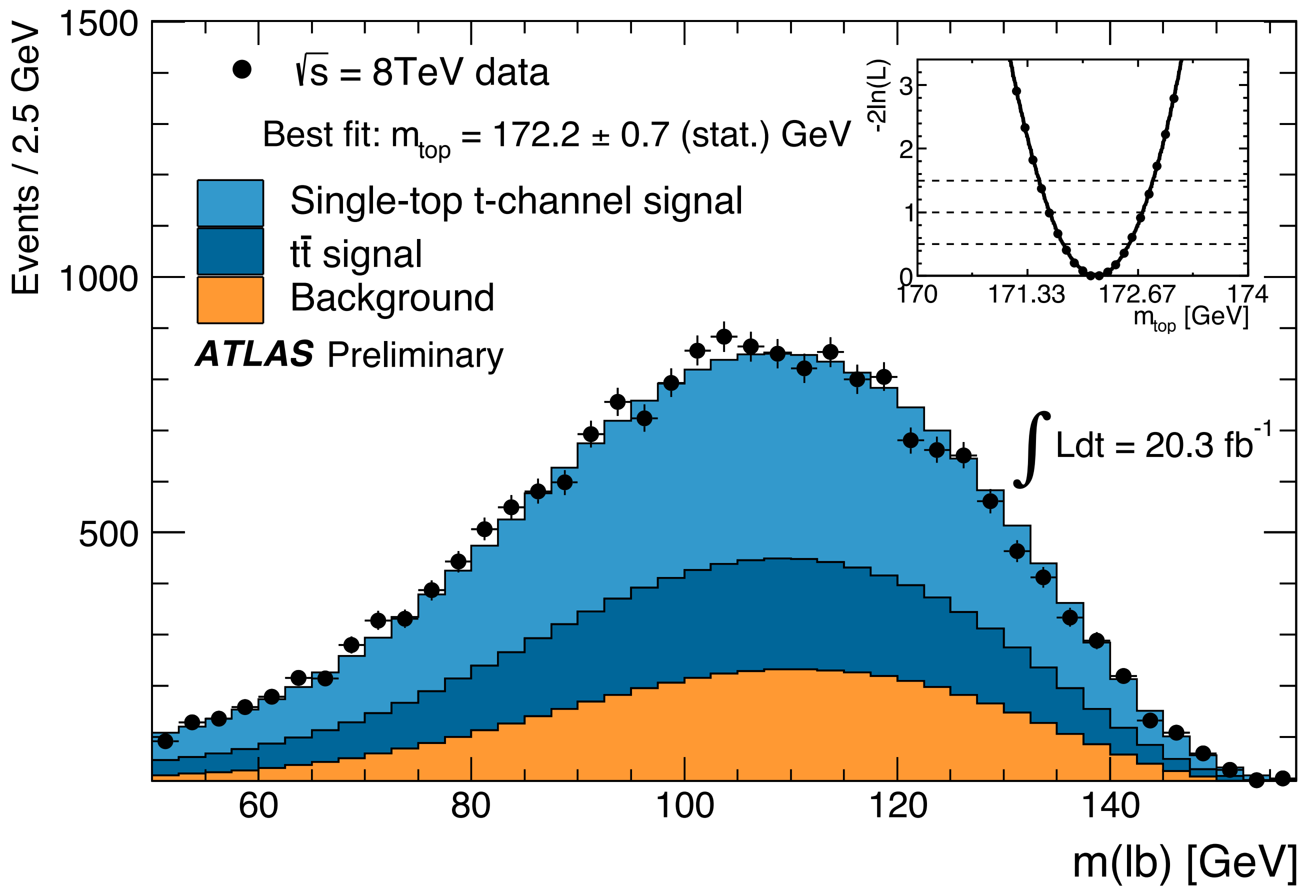
Pole mass measurements

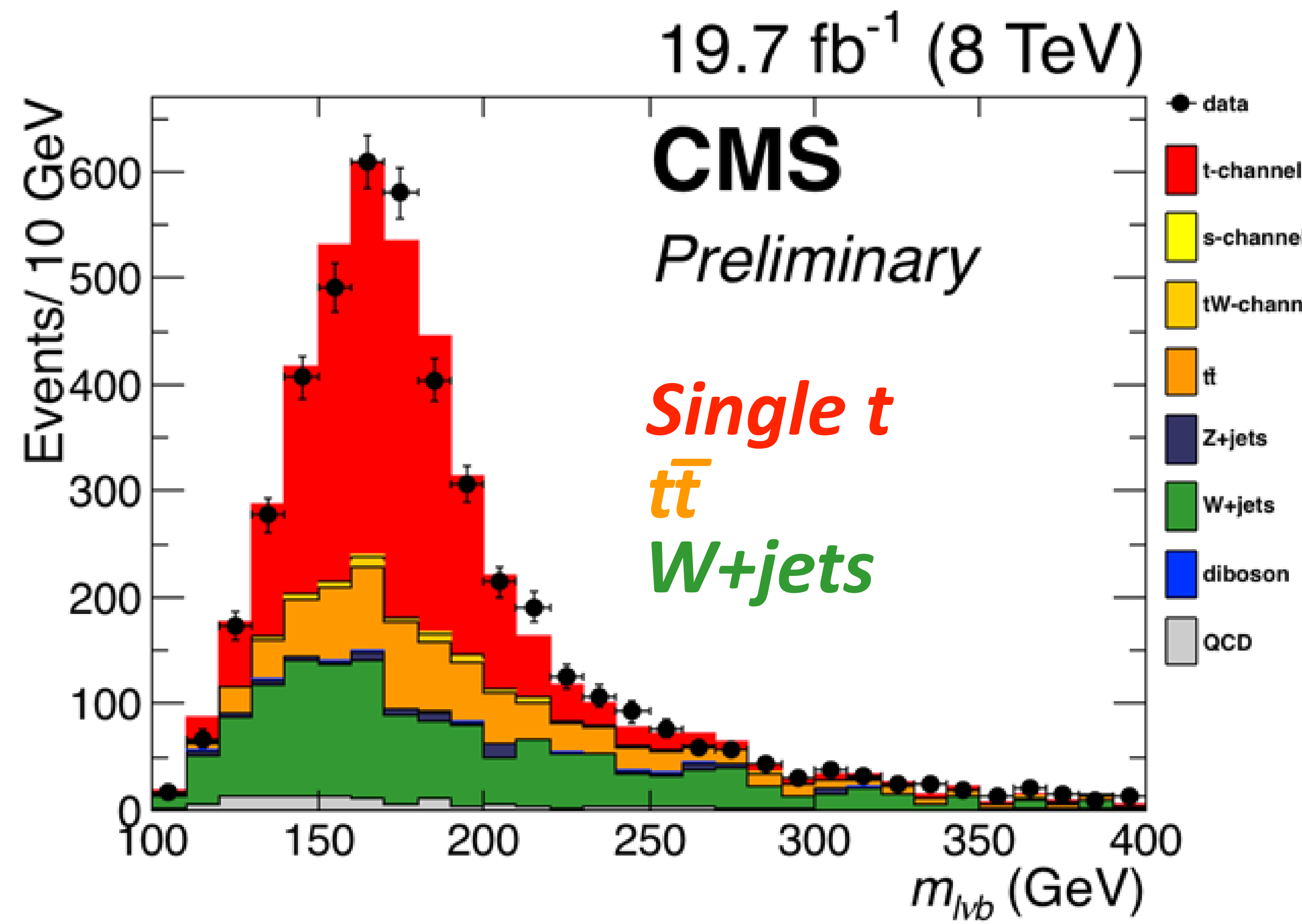


Analyses targeting alternative topologies can give further insights

- Single top production, EWK mediated
- Color reconnection
- Hard scattering, parton distributions







ATLAS (2014): $\mathbf{m_t = 172.2 \pm 2.1}$ **GeV** ATLAS CONF-2014-055

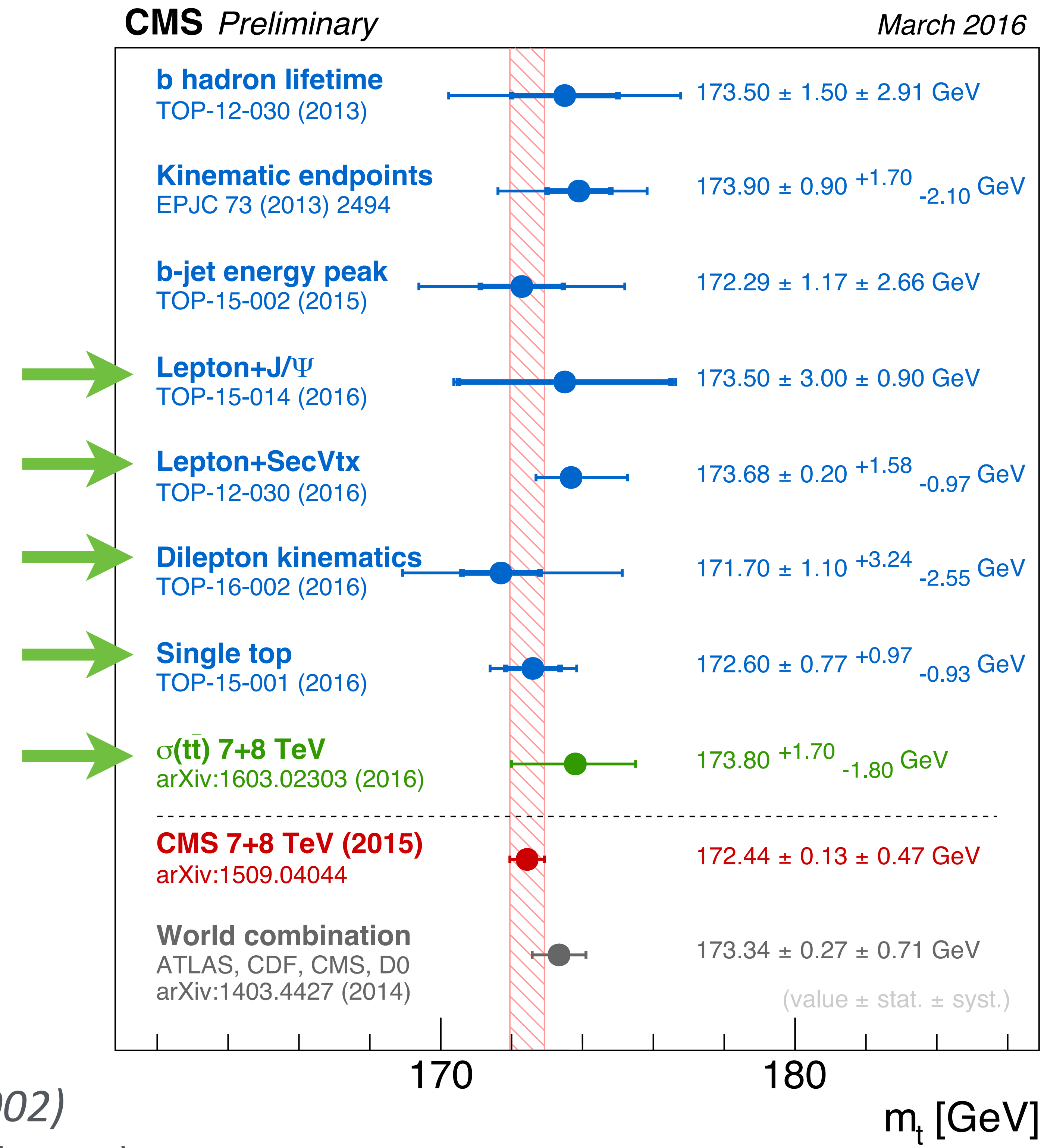
CMS (2016): $\mathbf{m_t = 172.6 \pm 1.2}$ **GeV** CMS TOP-15-001

- Sub 500 MeV precision from standard measurements
  - Challenging to advance further

- The precision is limited by our ability to model the signal
  - In particular related to the **b-quark hadronization**
  - On experimental side from influence in jet-energy scales

- Alternative methods can help tackle the issue from different sides and contribute to understanding of modeling

- Lot's of ideas and ongoing activity in the field, and lot's to look forward to with 13 TeV data



More results, e.g. on:

- *Standard measurements*
- *b-jet energy peak position (CMS, TOP-15-002)*
- *Kinematic endpoints (CMS, EPJ C73 (2013) 2494)*

CMS public results: *http://cms-results.web.cern.ch/cms-results/public-results/publications/*

ATLAS public results: *https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults*

Additional material

What are the dominant sources of systematics in standard methods?

Detector understanding

- Experimental
  - Jet energy response corrections

Signal modeling

- (b) hadronization modeling
- Hard-scattering process
  - μ_R/μ_F scales, signal kinematics

Lepton+jets channel	hybrid δm_t^{hyb} (GeV)
Experimental uncertainties	
Method calibration	0.04
Jet energy corrections	
– JEC: Intercalibration	+0.01
– JEC: In situ calibration	+0.12
– JEC: Uncorrelated non-pileup	−0.10
– JEC: Uncorrelated pileup	−0.04
Lepton energy scale	+0.01
E_T^{miss} scale	+0.04
Jet energy resolution	−0.03
b tagging	+0.06
Pileup	−0.04
Backgrounds	+0.03
Modeling of hadronization	
JEC: Flavor-dependent	
– light quarks (u d s)	+0.05
– charm	+0.01
– bottom	−0.32
– gluon	−0.08
b jet modeling	
– b fragmentation	<0.01
– Semileptonic b hadron decays	−0.16
Modeling of perturbative QCD	
PDF	0.04
Ren. and fact. scales	−0.09 ± 0.07
ME-PS matching threshold	+0.03 ± 0.07
ME generator	−0.12 ± 0.08
Top quark p_T	+0.02
Modeling of soft QCD	
Underlying event	+0.08 ± 0.11
Color reconnection modeling	+0.01 ± 0.09
Total systematic	0.48
Statistical	0.16
Total	0.51

arXiv:1509.04044 (CMS)

lepton+SV

CMS TOP-12-030

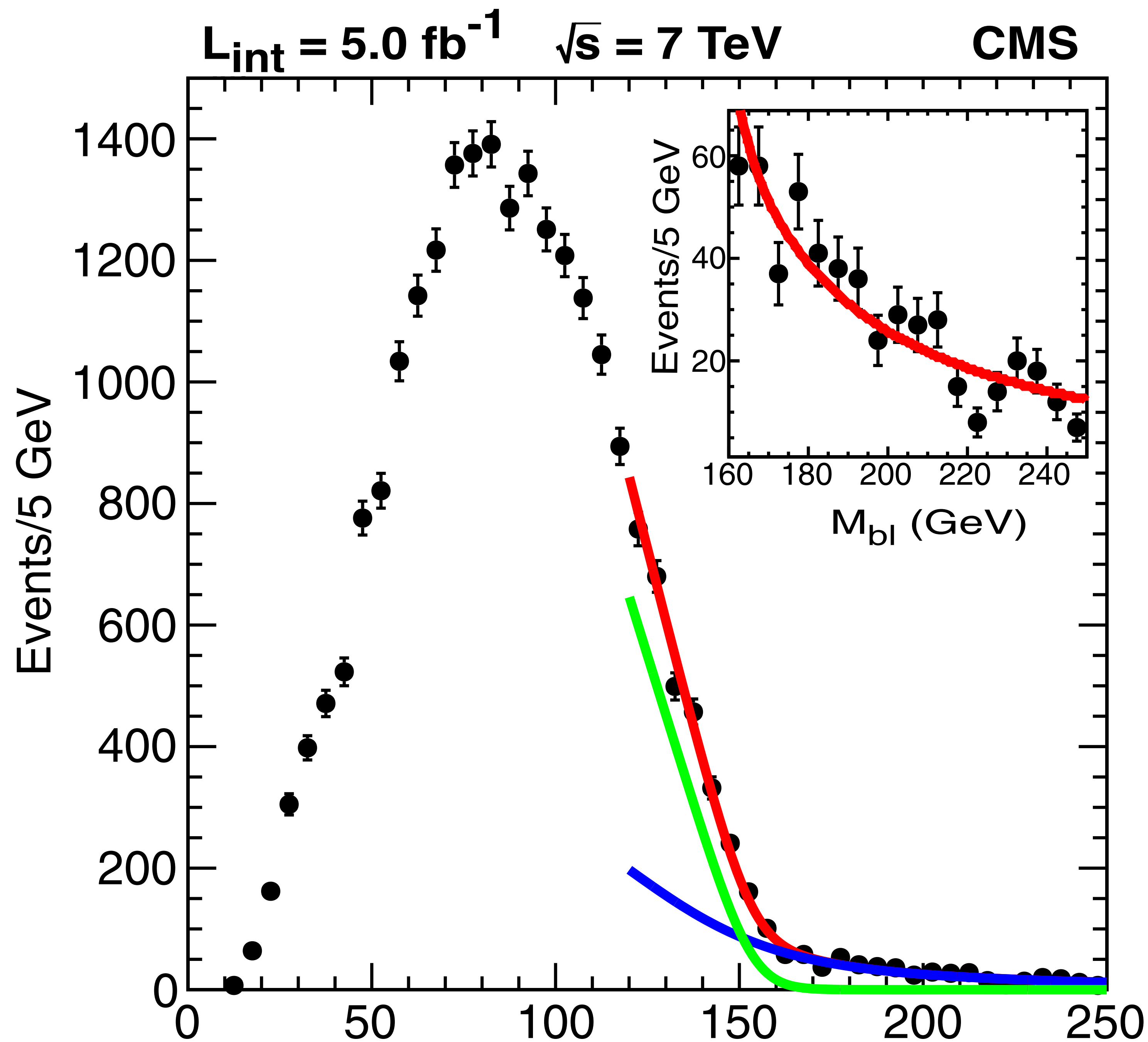
Source	Δm_t [GeV]	
Theoretical uncertainties		
μ_R/μ_F scales $t\bar{t}$	+0.22	−0.20
μ_R/μ_F scales t (*t*-channel)	−0.04	−0.02
μ_R/μ_F scales tW	+0.21	+0.17
Parton shower matching scale	−0.04	+0.06
Single top quark fraction	−0.07	+0.07
Single top quark diagram interference (*)	+0.24	
Parton distribution functions	+0.06	−0.04
Top quark p_T	+0.82	
Top quark decay width (*)	−0.05	
b quark fragmentation	+1.00	−0.54
Semileptonic B decays	−0.16	+0.06
b hadron composition (*)	−0.09	
Underlying event	+0.07	+0.19
Color reconnection (*)	+0.08	
Matrix element generator (*)	−0.42	
$\sigma(t\bar{t} + \text{heavy flavor})$	+0.46	−0.36
Total theoretical uncertainty	+1.52	−0.86
Experimental uncertainties		
Jet energy scale	+0.19	−0.17
Jet energy resolution	−0.05	+0.05
Unclustered energy	+0.07	−0.00
Lepton energy scale	−0.26	+0.22
Lepton selection efficiency	+0.01	+0.01
b tagging	−0.02	−0.00
Pileup	−0.05	+0.07
Sec.-vertex track multiplicity (*)	−0.06	
Sec.-vertex mass modeling (*)	−0.29	
Background normalization	< 0.03	
Total experimental uncertainty	+0.43	−0.44
Total systematic uncertainty	**+1.58**	**−0.97**
Statistical uncertainty	**±0.20**	

lepton+J/Ψ CMS TOP-15-014

Source	Value (GeV)
Experimental uncertainties	
Monte Carlo statistics	±0.22
Muon momentum scale	±0.09
Electron momentum scale	±0.11
Modeling of the J/ψ candidate mass distribution	+0.09
Jet energy scale	< 0.01
Jet energy resolution	< 0.01
Trigger efficiencies	±0.02
Background normalization	±0.01
Pileup	±0.08
Theoretical uncertainties	
ME generator	−0.37
Renormalization scale	$\{^{+0.12}_{-0.46}$
ME-PS matching threshold	$\{^{+0.12}_{-0.58}$
top quark transverse momentum	+0.64
b fragmentation	±0.30
Underlying event	±0.13
Color reconnection modeling	+0.12
Parton density functions	$\{^{+0.39}_{-0.11}$
Total	$\{^{+0.89}_{-0.94}$

Without relying on simulation, we can extract the top mass from the endpoints of kinematic distributions

- Endpoints depend on masses of particles involved in the decay
- Simultaneous fit of neutrino, W, and top masses
- Almost independent of simulation



m_t = 173.9 ± 0.9$_{stat}$ $^{+1.7}_{-2.1\ syst}$ GeV

Lepton+b-jet invariant mass [GeV]

CMS TOP-11-027 EPJ C73 (2013) 2494