Top Quark Production and Mass

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Hadron Collider School – HASCO 2015
Georg-August-Universtät, Göttingen, Germany
19-24 July 2015

Plan for the Lectures

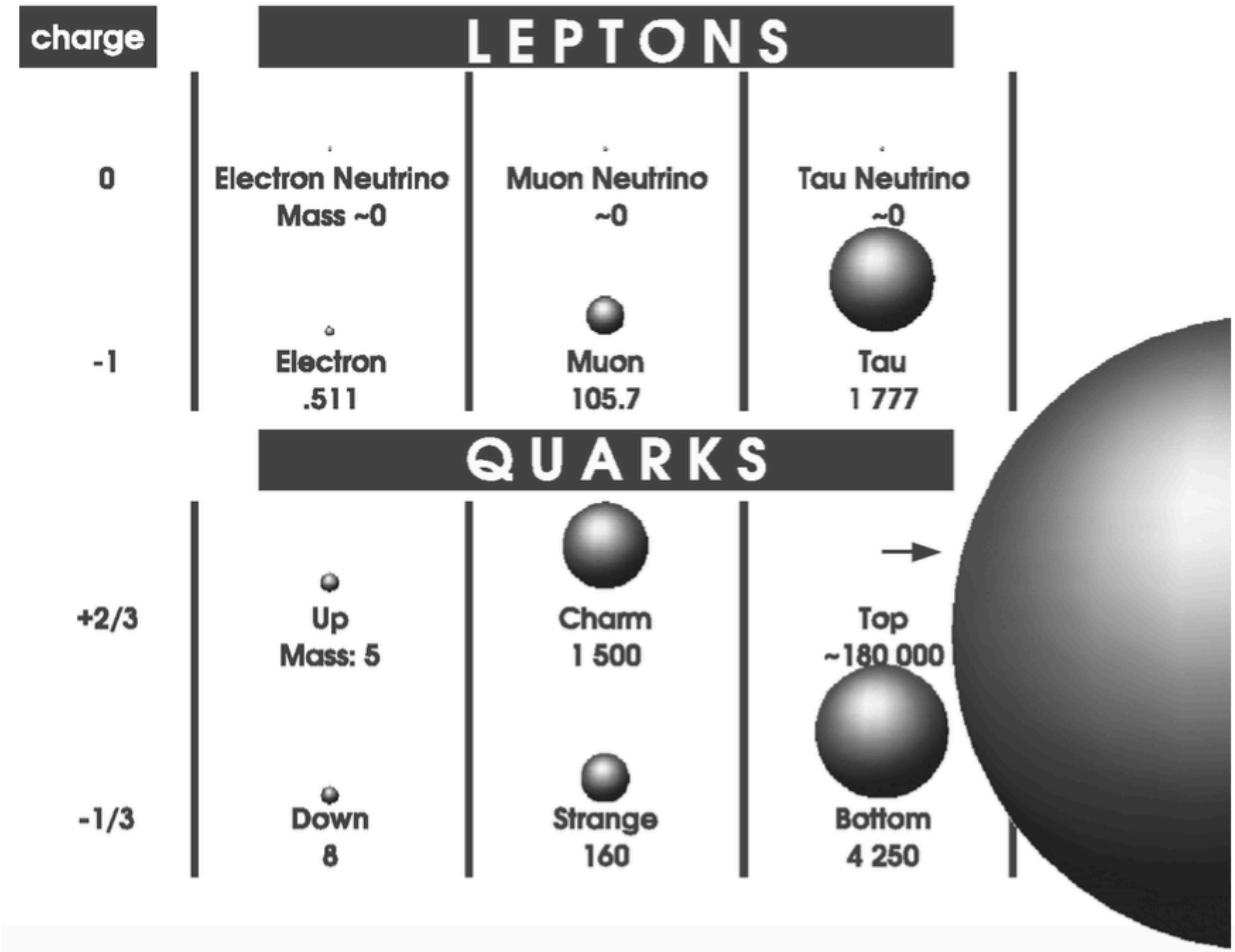
- Introduction, top quark production and mass: Efe Yazgan
- Top quark properties: Maria Moreno-Llacer

Example results/plots taken from top quark public pages of Tevatron and LHC experiments:

ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
CDF: http://www-cdf.fnal.gov/physics/new/top/top.html
D0: http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/

The Top Quark

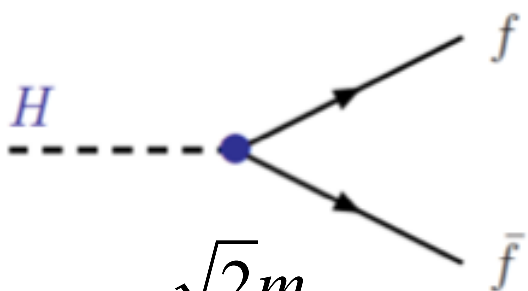
- The most massive particle known to date (m_t~173 GeV).



Quadt, EPJC 48, 835 (2006)

The Top Quark

- Very short lifetime (α M_t^{-3}) < hadronization time scale ~ $1/\Lambda_{QCD}$
  - Λ_{QCD}
    - typical scale for which α_s becomes very strong
    - ~1 fm ~ typical scale of a hadron (proton radius).
  - No hadronic bound states.
  - Quark properties are “directly” accessible.



$$y_t = \frac{\sqrt{2}m_t}{v} \cong 1$$

→ The largest Yukawa couplings among the fermions.

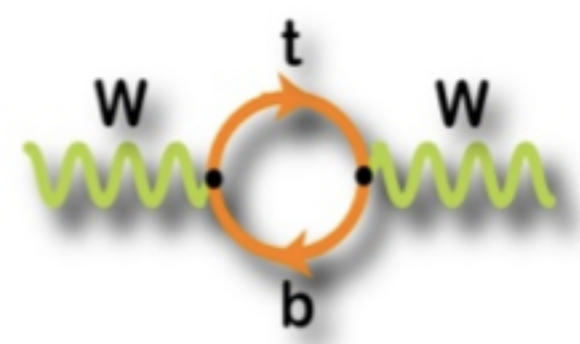
→ *Top quark might have a natural relation to EWSB.*

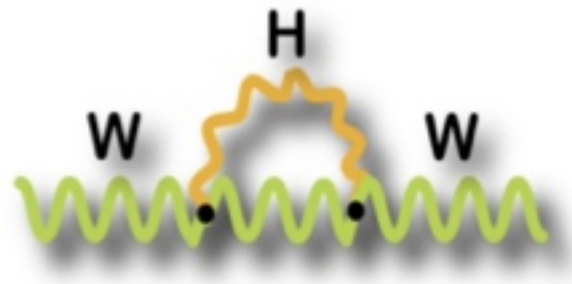
The only elementary high mass particle that has color → EWK, QCD and flavor physics.

Quantum Fluctuations Predicting the Existence of Top and Higgs

- **Heisenberg uncertainty principle** → *Particles can be created from nothing (for a very short period of time) w/o the necessary energy supply (virtual or off-mass-shell particle).*
- Top quark and the Higgs boson modify tree level SM processes through radiative corrections.
- *Indirect effect of the top quark (and Higgs) observable even if the collider energy is not sufficient to create the real particle.*

e.g.





HW: Read the Nobel lectures of 't Hooft and Veltman (1999)

$$\Delta\rho = (\rho - 1) \propto m_t^2$$

Propagator for fermions α 1/q
(Dirac equation)

$$\Delta\rho \propto \ln(m_H)$$

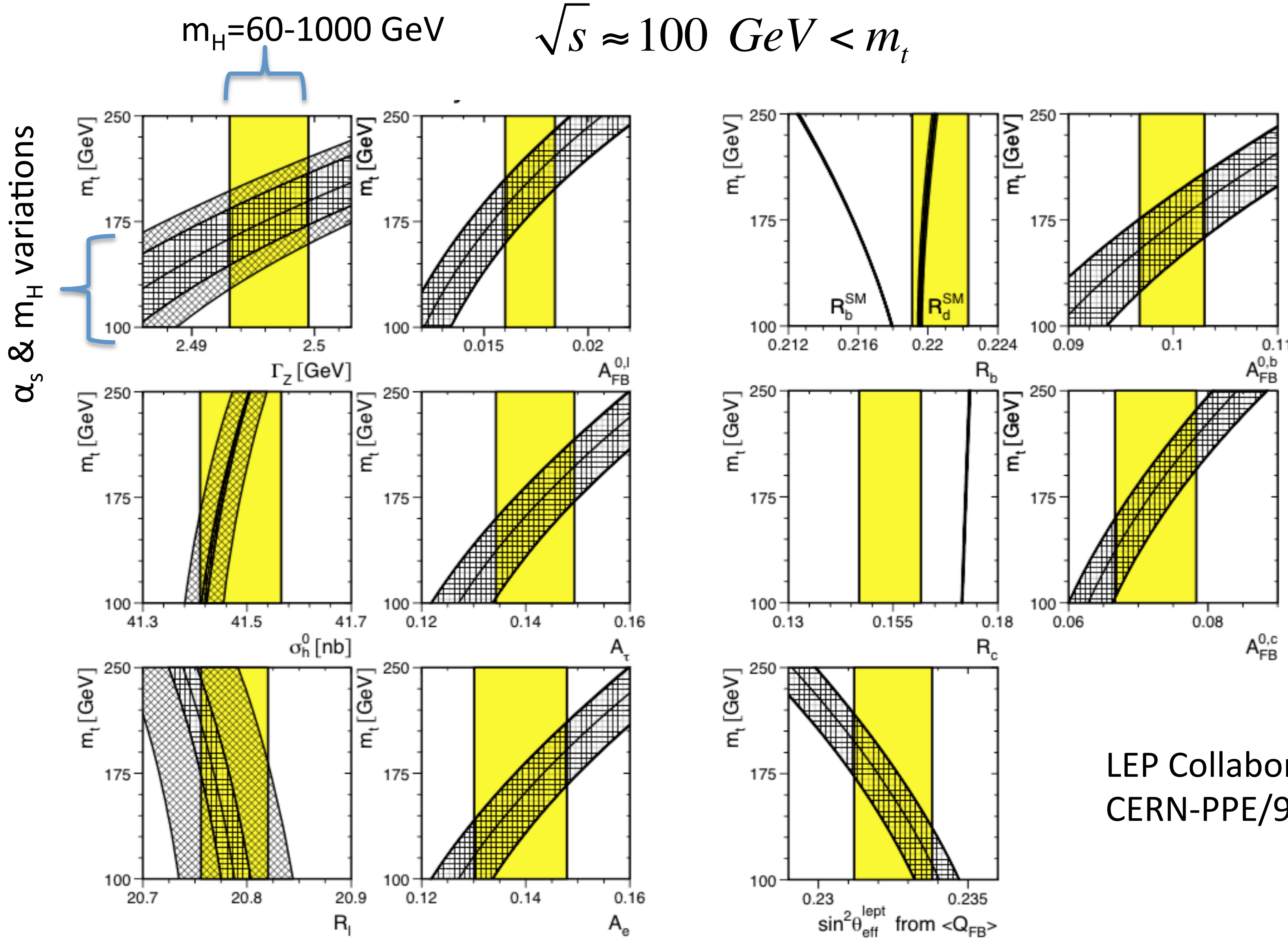
Propagator for boson α $1/q^2$
(Klein-Gordon equation)

$$M_W^2 = \rho\left(M_W^{tree-level}\right)^2 \quad \text{w/} \quad \rho = 1 + \Delta\rho_t + \Delta\rho_H$$

Veltman,
NPB 123, 89 (1977)

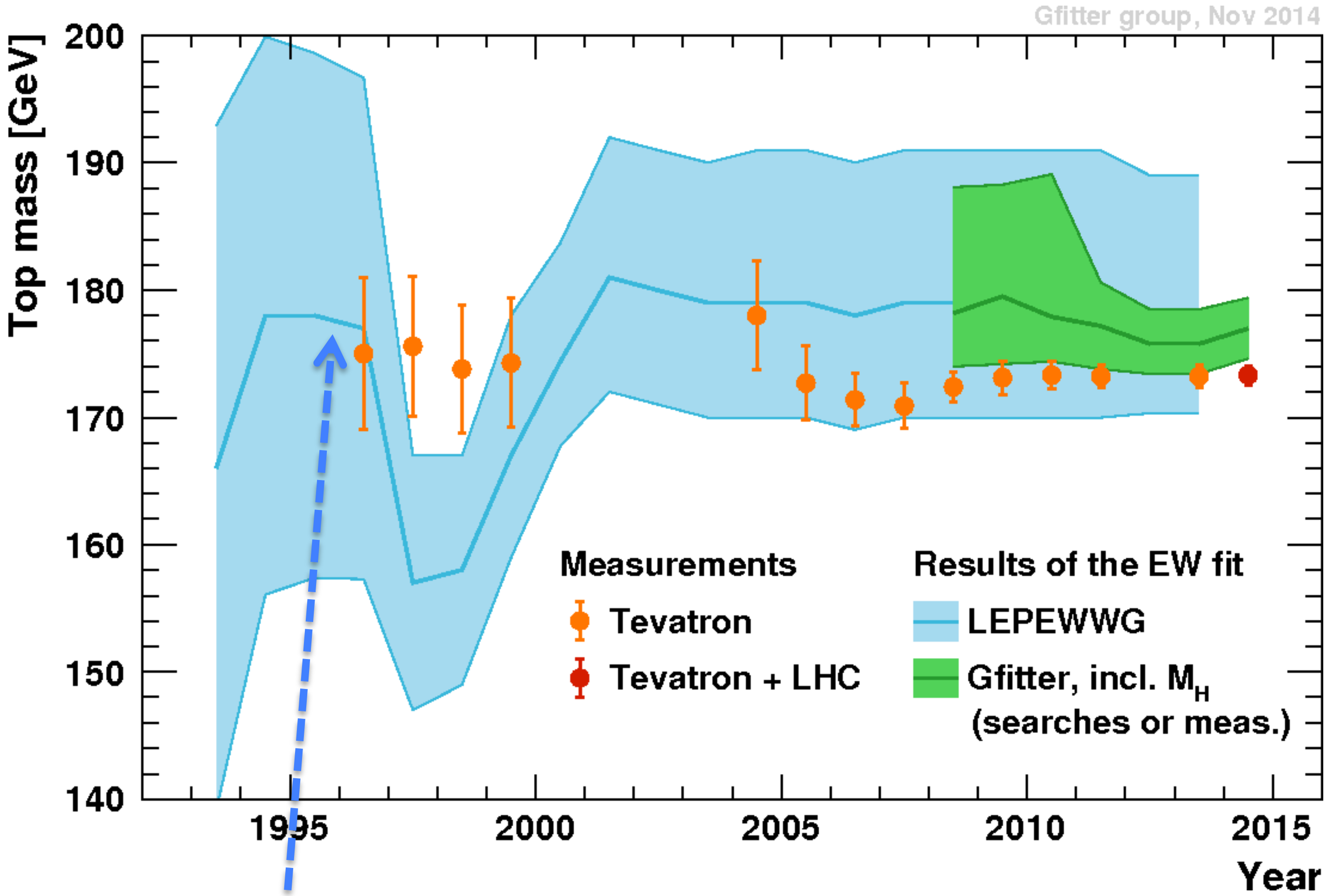
LEP (1995) vs SM predictions

$$\sqrt{s} \approx 100\ GeV < m_t$$



LEP Collaborations
CERN-PPE/95-172

- Z boson line shape and asymmetries compared to SM measurements vs top mass.
- LEP 1 prediction m_t = 173 + 13 – 10 GeV

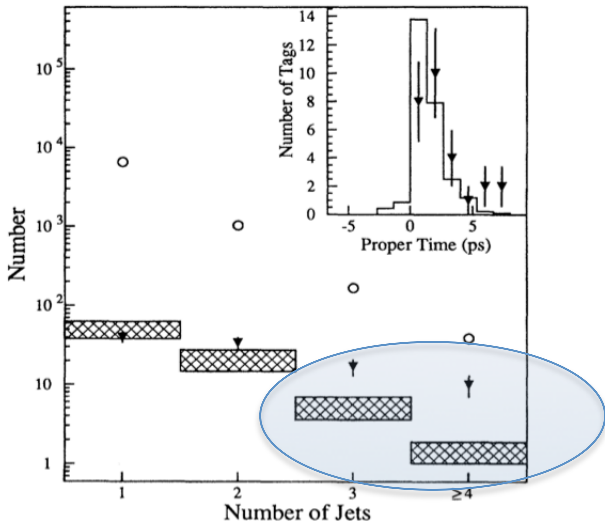


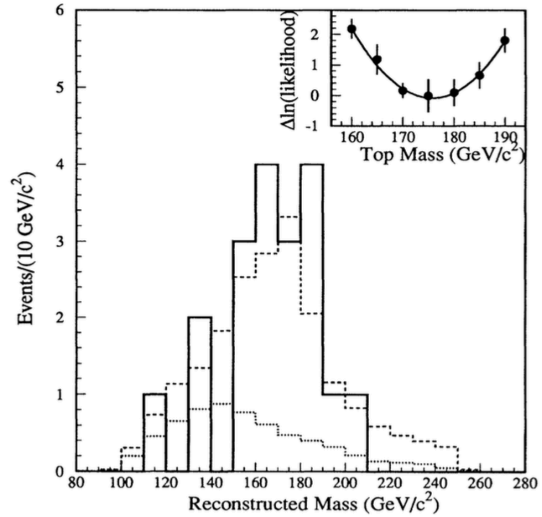
http://project-gfitter.web.cern.ch/project-gfitter/History/

- Quantum fluctuations showed the existence of the top quark and predicted its mass precisely before it was discovered. → Triumph of the SM.

The Discovery of the Top Quark

CDF, PRL 74, 2626 (1995)





Discovery at the Tevatron with O(10) events.

Signal consistent with

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

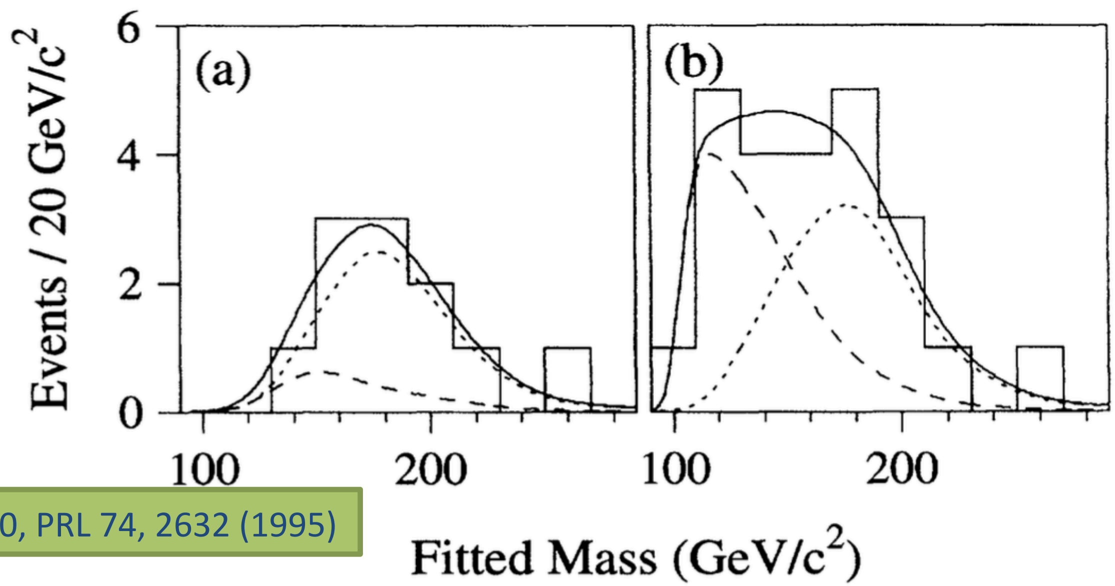
and inconsistent w/ the background prediction.

$$\sigma_{t\bar{t}}^{CDF} = 6.8^{+3.6}_{-2.4}\, pb$$

$$\sigma_{t\bar{t}}^{D0} = 6.4 \pm 2.2\, pb$$

$$m_t^{CDF} = 176 \pm 8(stat.) \pm 10(syst.)\ GeV$$

$$m_t^{D0} = 199^{+19}_{-21}(stat.) \pm 22(syst.)\ GeV$$

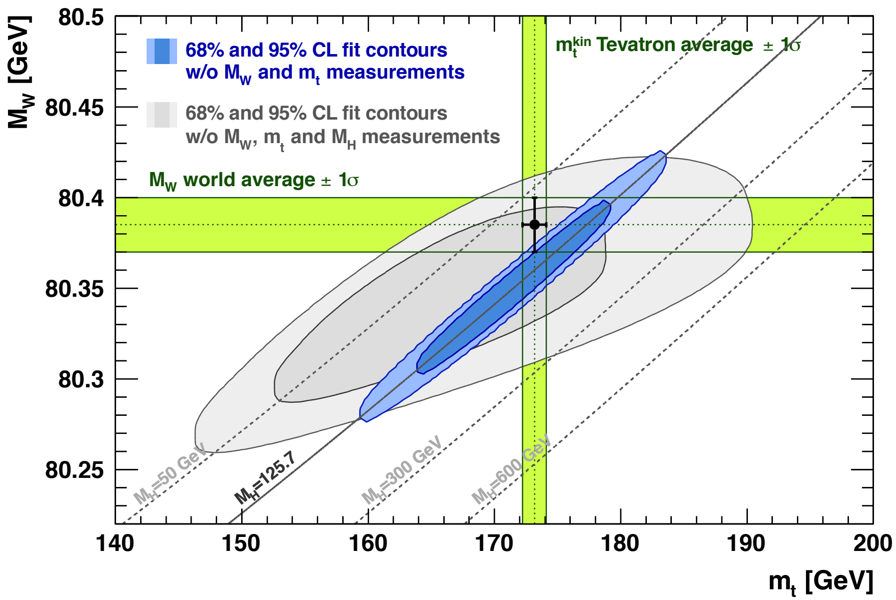


D0, PRL 74, 2632 (1995)

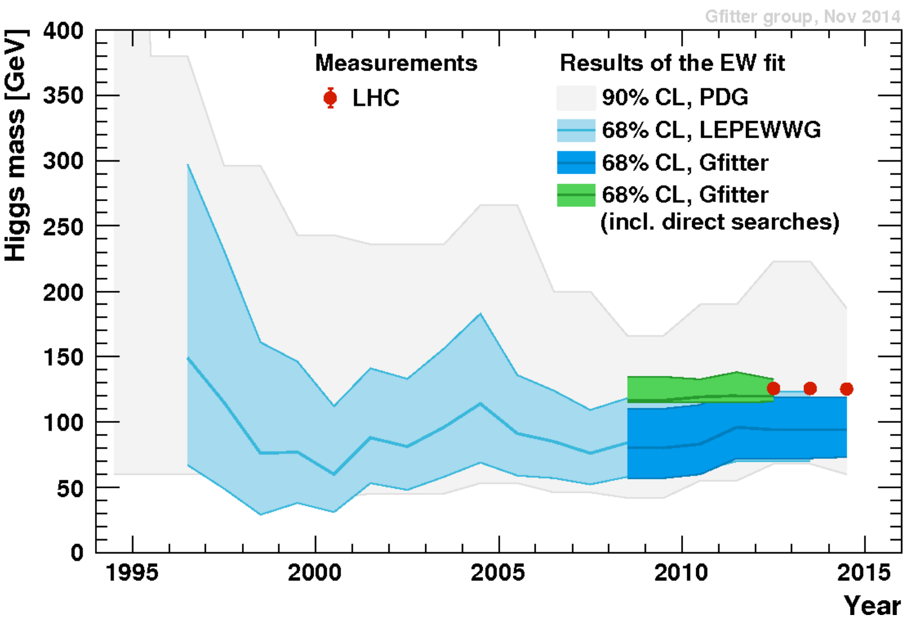
The Top Quark Mass

Electroweak fit before Higgs discovery: $m_H = 94^{+25}_{-22}\,GeV$ consistent with measured m_H within 1.3σ.

The Gfitter Group, M. Baak et al., EPJC 72, 2205 (2012)



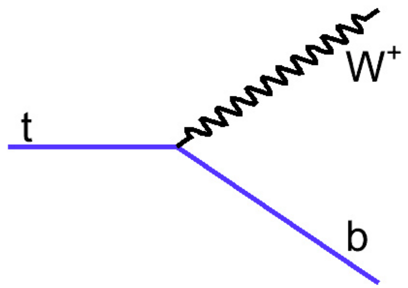
http://project-gfitter.web.cern.ch/project-gfitter/History/

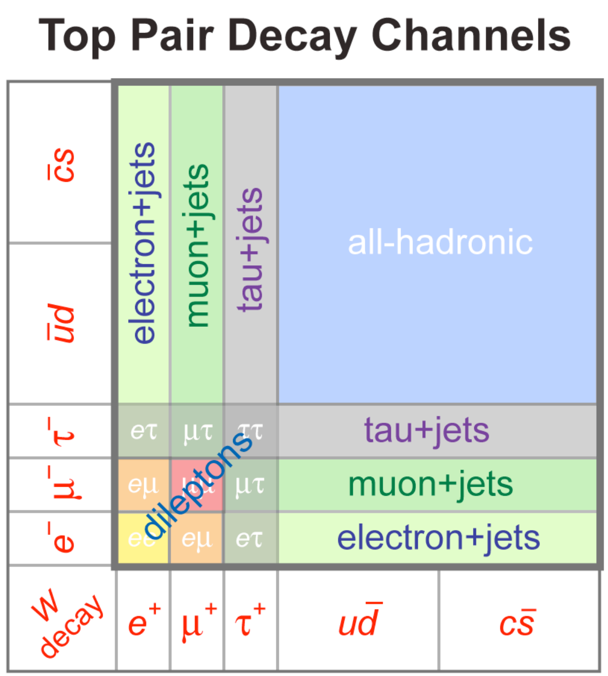


Quantum fluctuations showed the existence of the Higgs boson and predicted its mass precisely before it was discovered. → One of the most critical tests of the standard model!

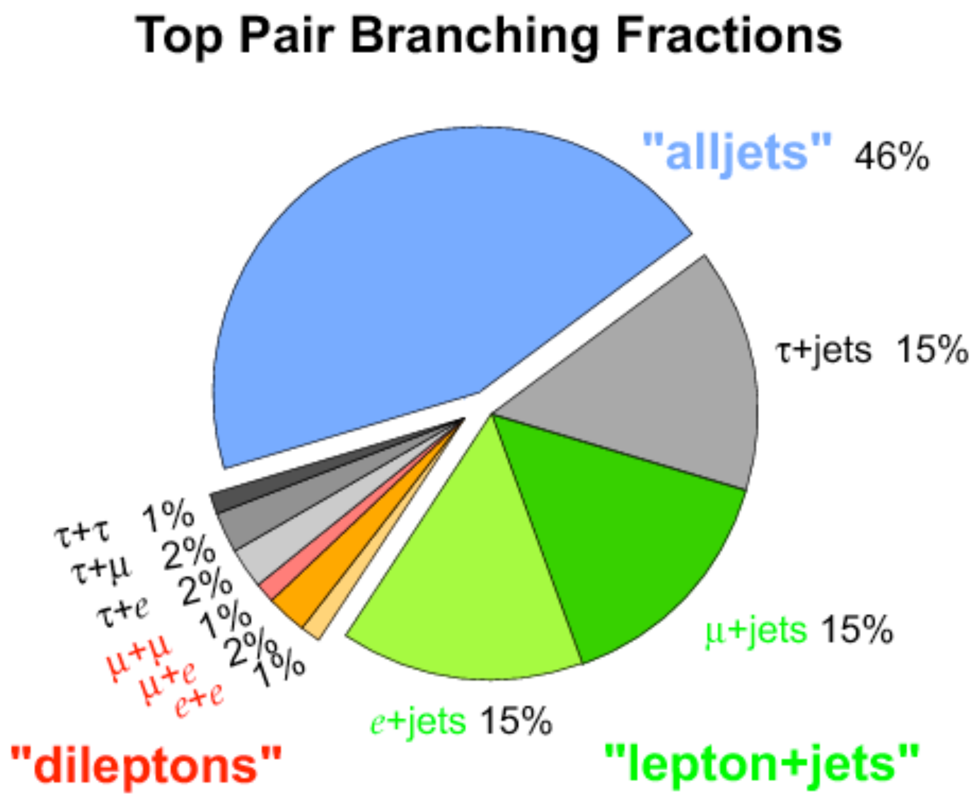
Top Quark Decays

Only quark with m > m_W and decays exclusively to Wb pairs.

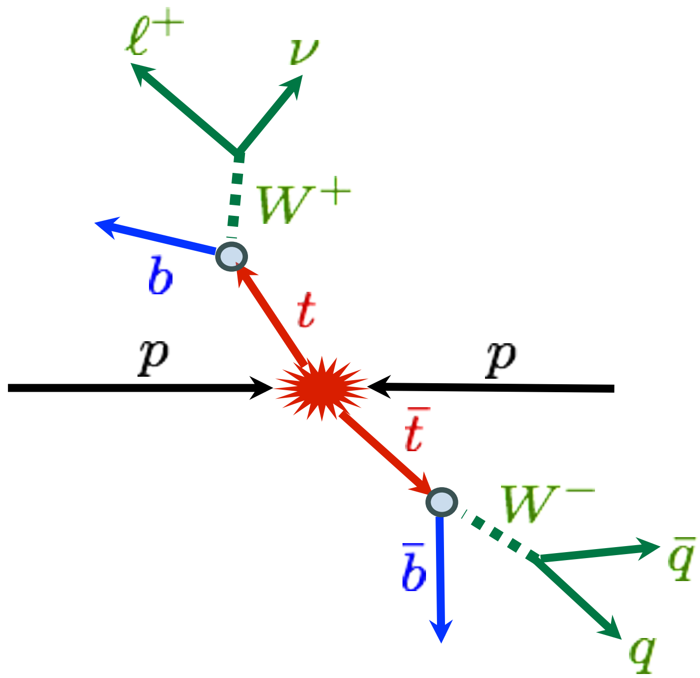




- $t\bar{t}$ decay channels are categorized by the W boson decay modes.

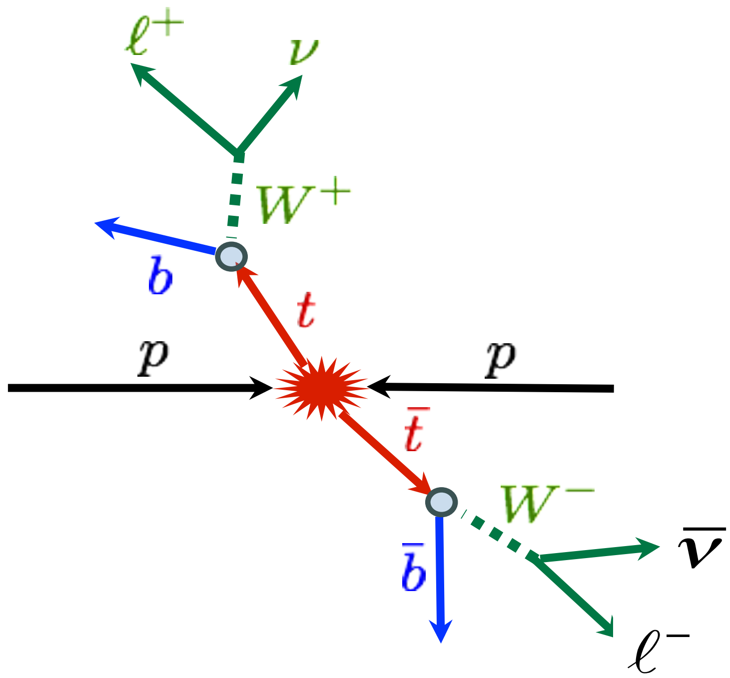


Top Quark Signatures and Backgrounds



- Lepton+jets channel
  - A high p_T lepton
  - $\geq$ 4 high p_T jets (2 of which are jets from b-decays)
  - Missing transverse energy
- Main backgrounds:
  - $t\bar{t}$ other, Single top, W+jets

Top Quark Signatures and Backgrounds

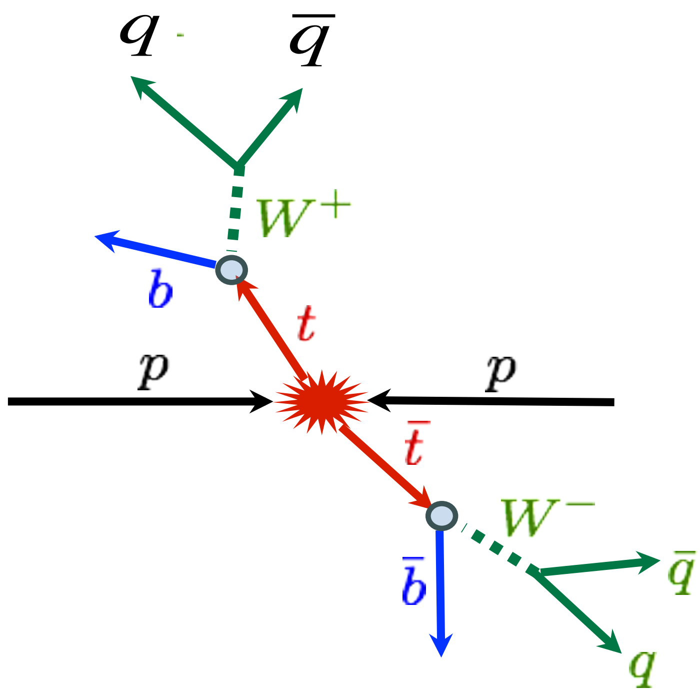


- Dilepton channel
  - Two high p_T leptons
  - ≥ 2 high p_T jets (2 of which are from b-decays)
  - Missing transverse energy

→ Fever number of events
→ But purer
→ Best channel: eμ

- Main backgrounds:
  - $t\bar{t}$ other
  - Single top
  - W/Z+jets

Top Quark Signatures and Backgrounds



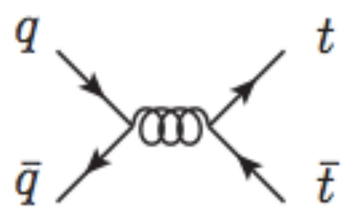
- All-hadronic channel
  - $\geq$ 6 high p_T jets (2 of which are from b-decays)

→ Possible to fully reconstruct the event (i.e. no neutrinos)
→ But larger uncertainties compared to other channels due to multiple jets
  → Jet energy scale and b-tagging.

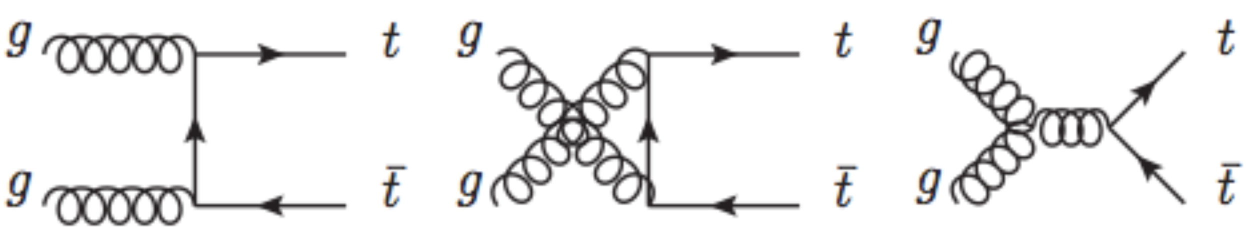
- Main backgrounds:
  - QCD multijets

Top Quark Pair Production

- $t\bar{t}$ pair production through QCD interactions: Dominant mechanism at hadron colliders.



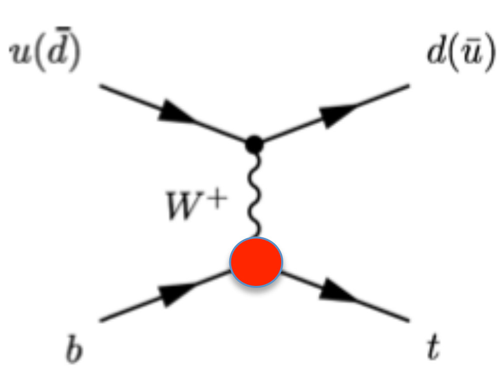
$q\bar{q}$ annihilation
~15% (LHC)
~85% (Tevatron)



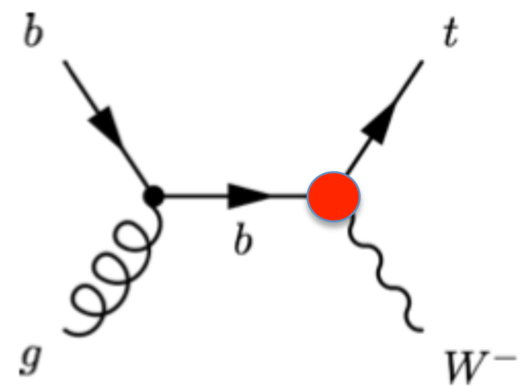
Gluon fusion
~ 85% (LHC)
~15% (Tevatron)

At LO QCD → $O(\alpha_s^2)$

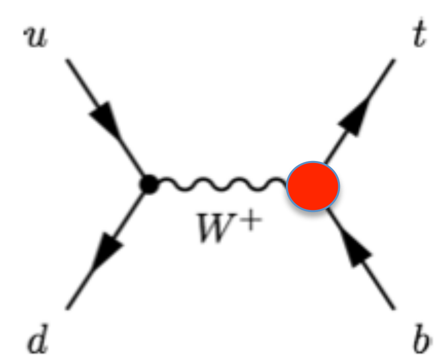
Single Top Quark Production



t-channel
(dominant process)

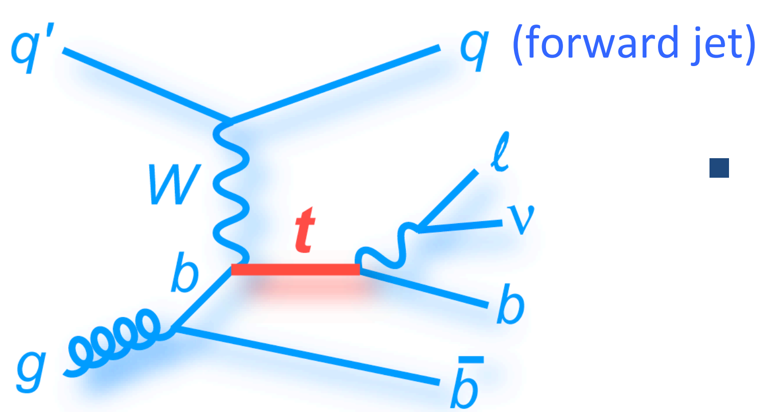


tW associated production



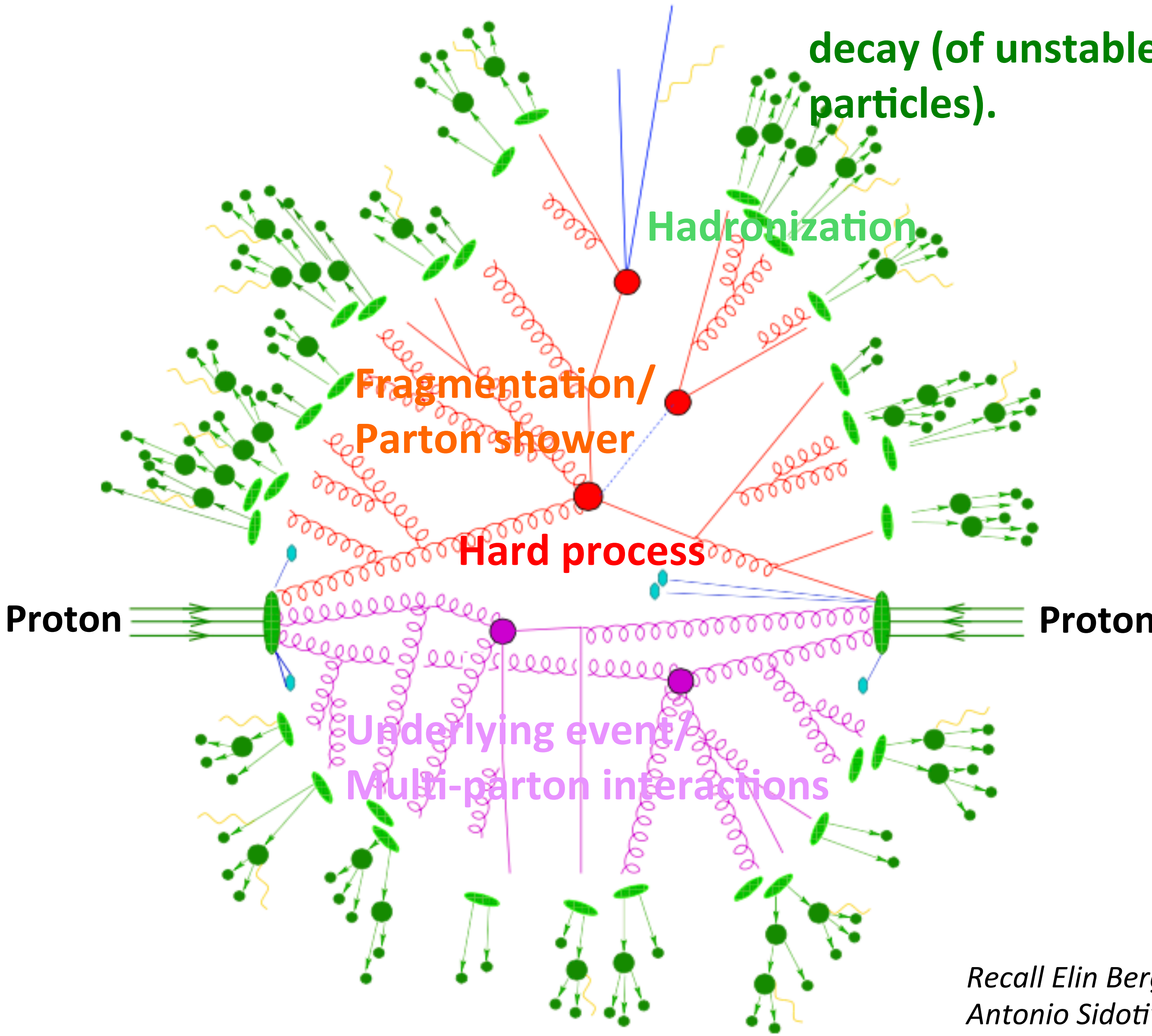
s-channel

- Single top quarks are produced through the electroweak interaction.
- First observed in 2009 by both Tevatron experiments (PRL 103 092002, PRL103 092001) using multivariate techniques.
- All production modes established now.



- t-channel
  - Main backgrounds: W+jets, $t\bar{t}$, QCD multijet

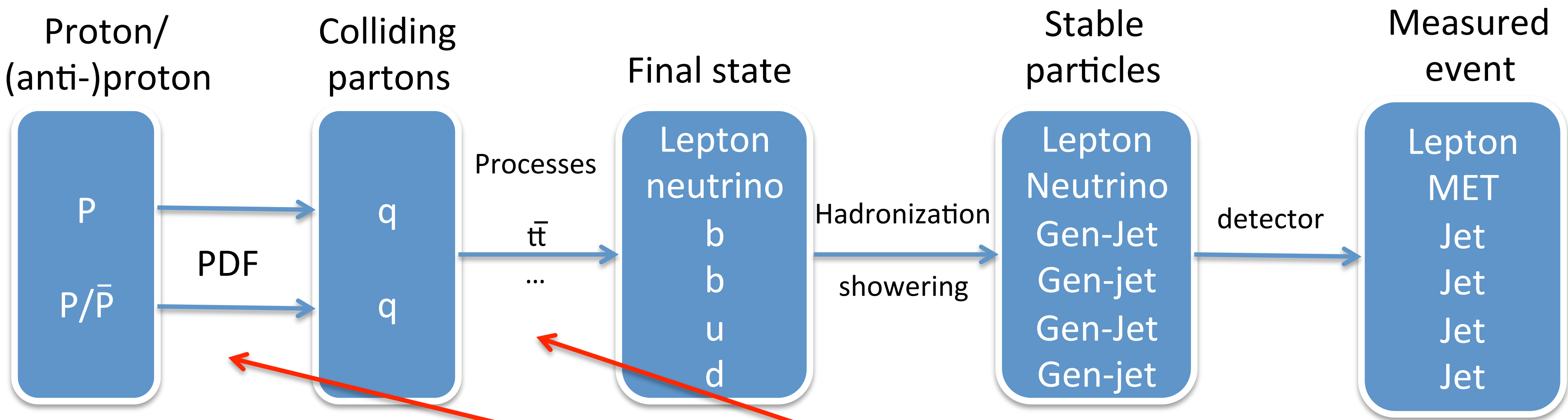
Top Quark Event Modeling



Recall Elin Bergeaas Kuutmann's & Antonio Sidoti's lectures.

Gleisberg et al. JHEP02 (2004) 056

Top Quark Event Modeling



$$\sigma_{pp\to t\bar{t}}\left(s,m_t\right)=\sum_{i,j=partons}\int dx_1\,dx_2 f_i^{pdf}\left(x_1,\mu_f^2\right)f_j^{pdf}\left(x_2,\mu_f^2\right)\hat{\sigma}_{ij\to t\bar{t}}\left(\hat{s},m_t,\mu_f,\mu_r,\alpha_s\left(\mu_r\right)\right)$$

Top Quark Event Modeling

$$\sigma_{pp\to t\bar{t}}(s,m_t) = \sum_{i,j=partons} \int dx_1\, dx_2 f_i^{pdf}(x_1,\mu_f^2) f_j^{pdf}(x_2,\mu_f^2) \hat{\sigma}_{ij\to t\bar{t}}(\hat{s},m_t,\mu_f,\mu_r,\alpha_s(\mu_r))$$

$\oplus$ showering/ & hadronization

Non-perturbative | *Perturbative in α_s*

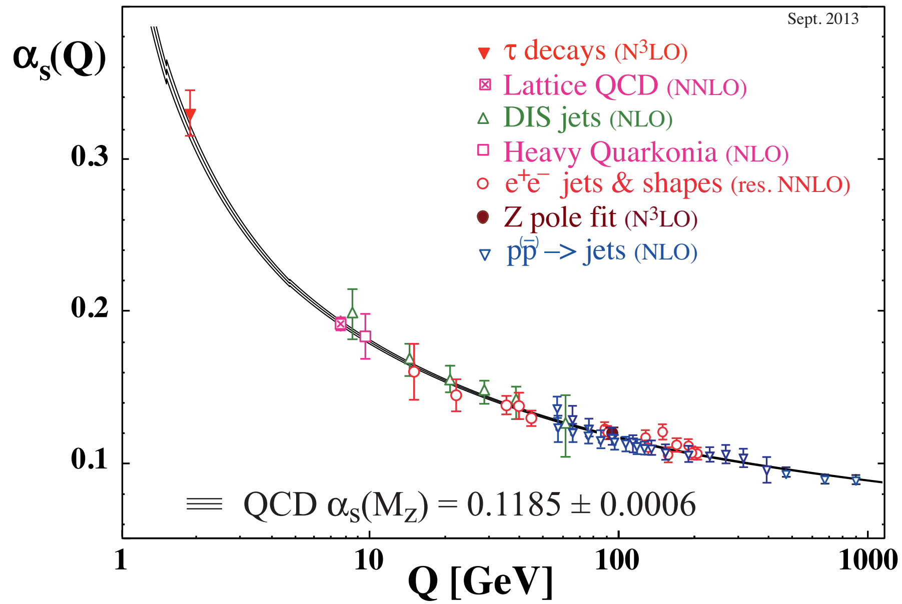
factorization ➔ $PDFs(x,\mu_f^2) \otimes \hat{\sigma}(\hat{s},m_t,\mu_f,\mu_r,\alpha_s(\mu_r))$

$p_T^{parton} < \mu_F$ | $p_T^{parton} > \mu_F$

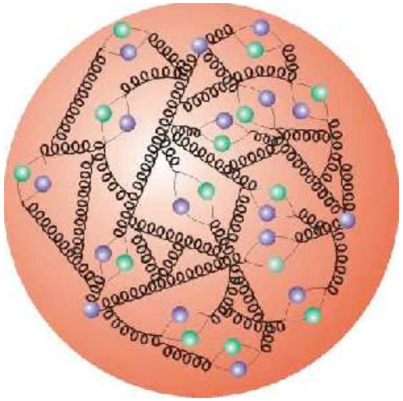
Recall Elin Bergeaas Kuutmann's & Antonio Sidoti's lectures.

$$\mu_f \sim Q \sim \sqrt{\hat{s}} \sim \sqrt{x_1 x_2 s}$$ *(Q: energy scale of the hard process)*

→ *inputs: m_t, α_s, and PDFs*



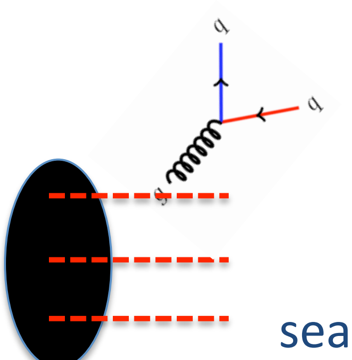
Nucleon Structure



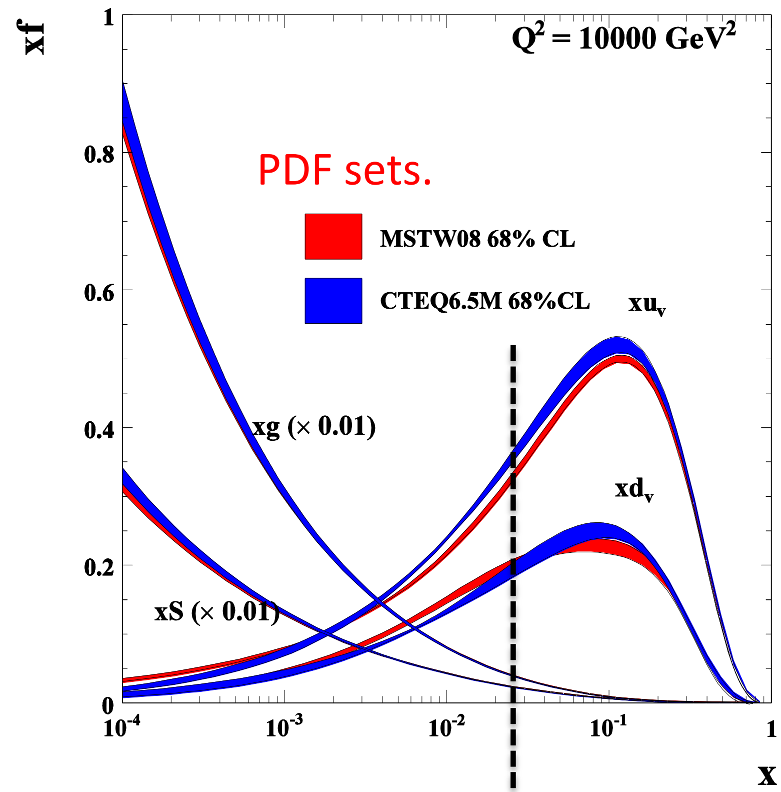
- Hadron collider = parton collider
- $f_i(x,Q^2)$ probability to find a parton to carry the fraction x of the longitudinal hadron momentum at the energy scale Q^2.
  - Intrinsic property of the nucleon → process independent.
  - Parametrized by PDF sets.

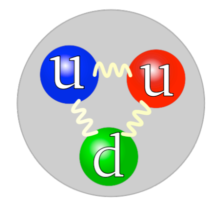
The quark sea:

Valence quarks emit gluons that in turn split into quark-antiquark pairs.



sea quarks dominate.



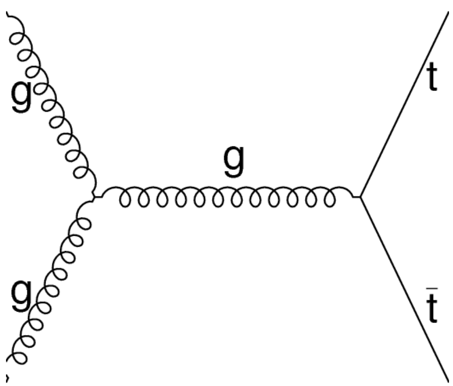


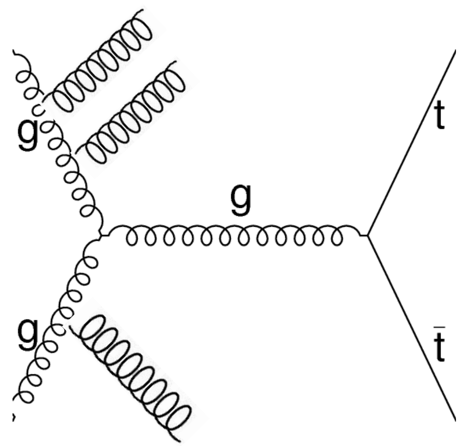
determine the quantum numbers of the hadron.

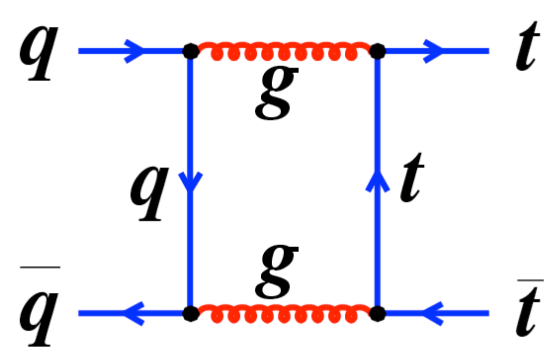
Valence quarks dominate.

Hard Process

- Calculation in perturbative QCD
  - LO → LO ME + Radiation from parton shower.
  - Multi-leg LO → LO + Additional partons in the hard process but no loops + radiation from parton shower.
  - NLO → LO + Additional partons in the hard process including loops (+ parton shower).







NLO and multi-leg LO need matching/merging to the parton shower.

Cross section Extraction

Total Inclusive cross section

→ count signal events:

$$\sigma = \frac{N_{obs} - N_{bkg}}{(A \times \varepsilon) \times B \times L}$$

A: Acceptance (depends on PDF, and other modeling uncertainties, e.g. renormalization and factorization scales)

ε: Selection efficiency for events in acceptance (affected by the errors in triggers and reconstruction)

L: Integrated luminosity

B: Branching ratio

Differential cross sections:

"Unfolded" to correct for detector effects (bin-to-bin migration) and acceptance

→ To particle or parton level

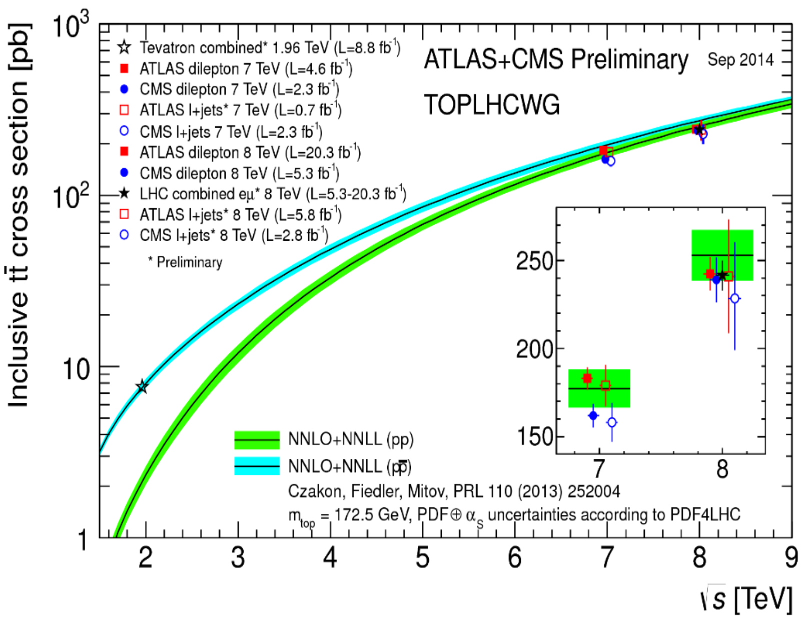
→ In full or fiducial phase space

Response matrix

$$\frac{1}{\sigma}\frac{d\sigma_i}{dX} = \frac{1}{\sigma}\frac{\sum_j R_{ij}^{-1}\left[N_{obs,j} - N_{bkg,j}\right]}{\Delta_i^X (A \times \varepsilon)_i}$$

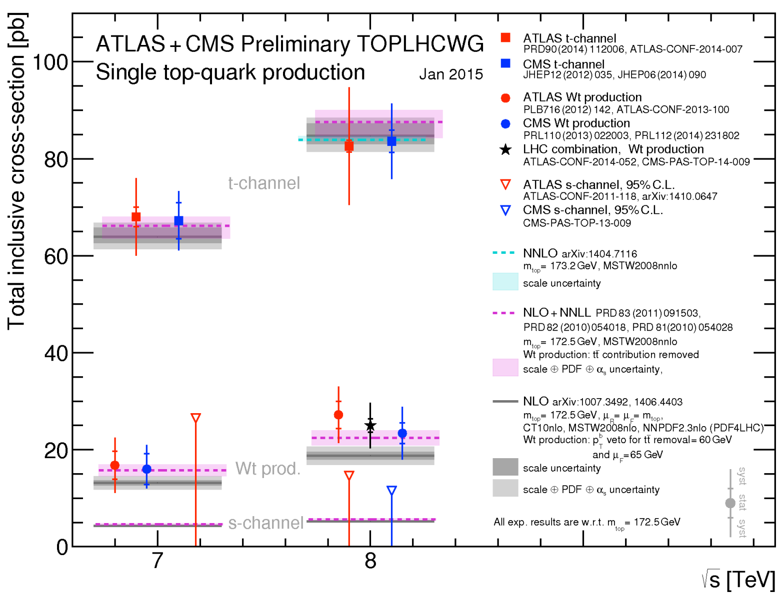
Bin width

Top Quark Production – Current Status



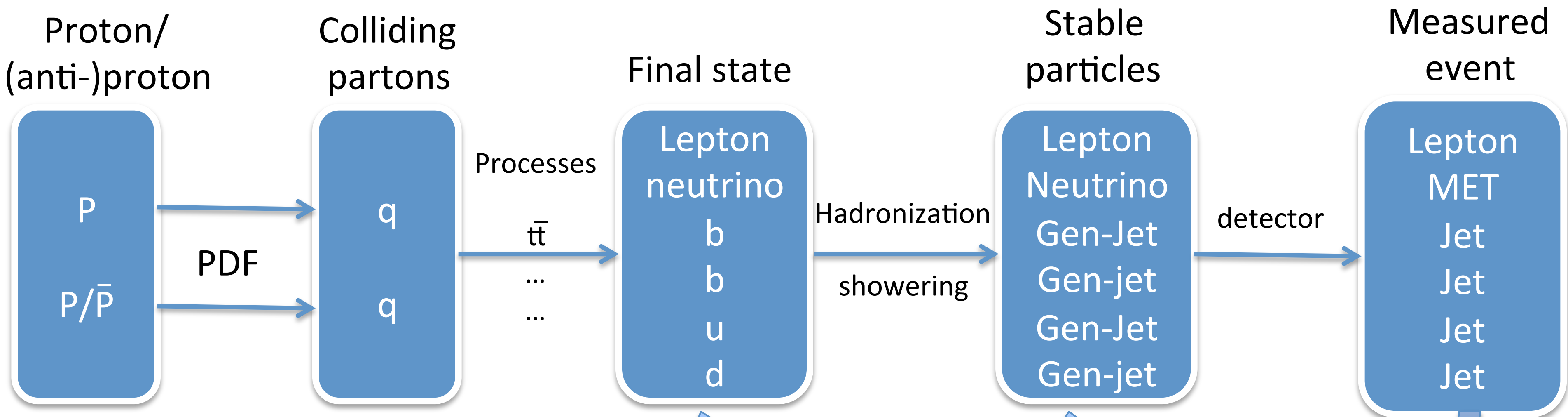
- Top pair cross sections at NNLO precision

$$\delta_{NNLO-theory} = 5.7\% \;>\; \delta_{e\mu} = 3.5\%$$

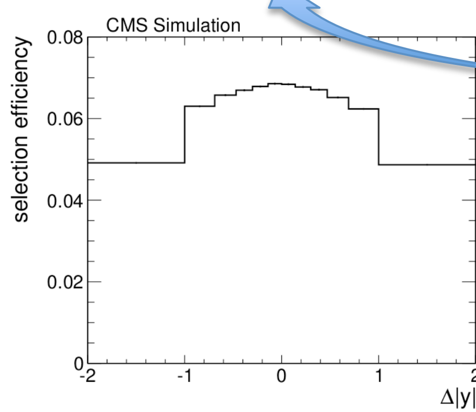


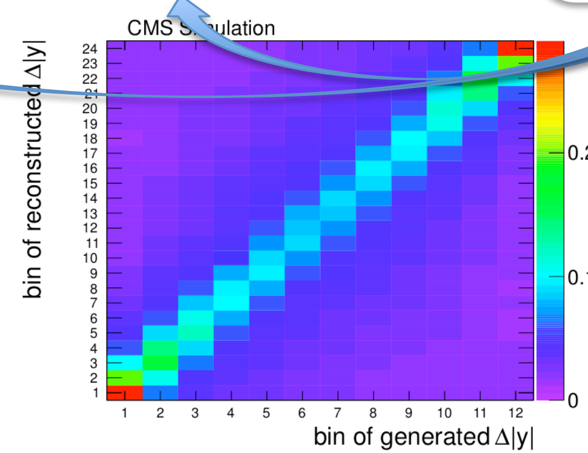
- Single top t-channel cross section at NNLO precision
  - theory uncertainty ~1%
  - Measurement uncertainty ~10%

Unfolding



The goal is to compare to theory predictions (at the particle/parton level).





Commonly used unfolding methods: iterative D'Agostini, SVD

selection efficiency
→ diagonal matrix

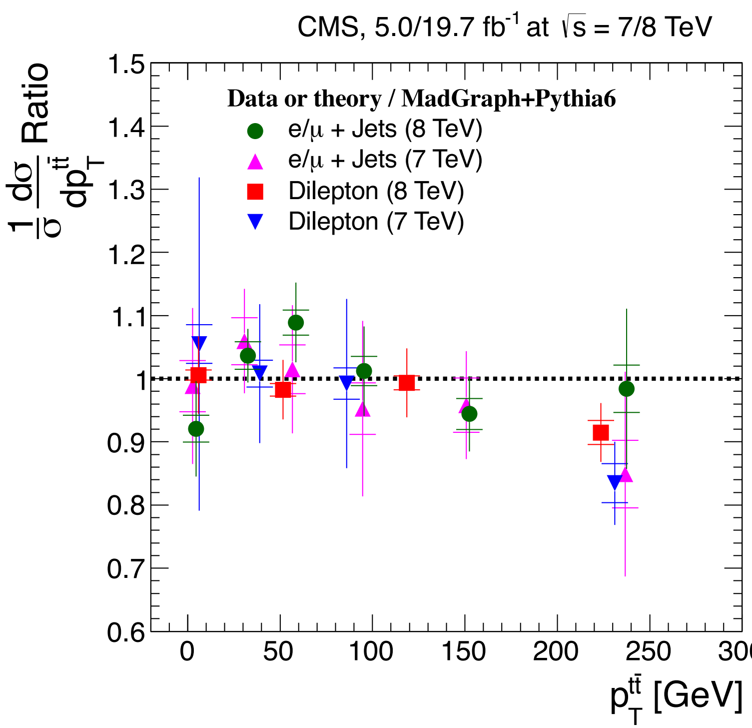
(non-diagonal)
bin migration matrix

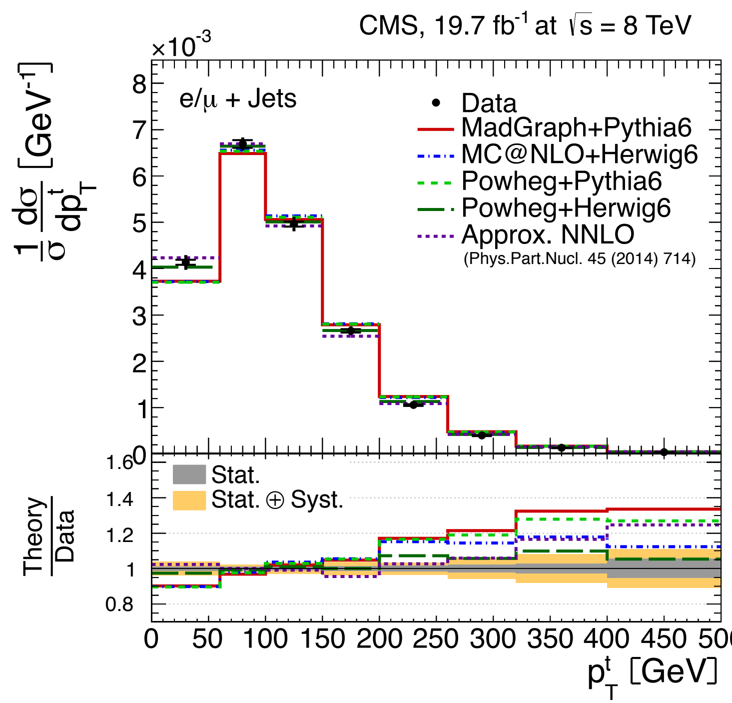
e.g., CMS-PAS-TOP-12-033

Top Pair Differential Cross Sections

- Test various levels of pQCD approximations for top quark production in different phase space regions.
- Test and tune MC models
- Test/improve PDF sets.
- Differential distributions from data are described reasonably well except top p_T.
- For all distributions trend is the same for 7 & 8 TeV and in lepton+jets and dilepton measurements.

arXiv:1505.04480



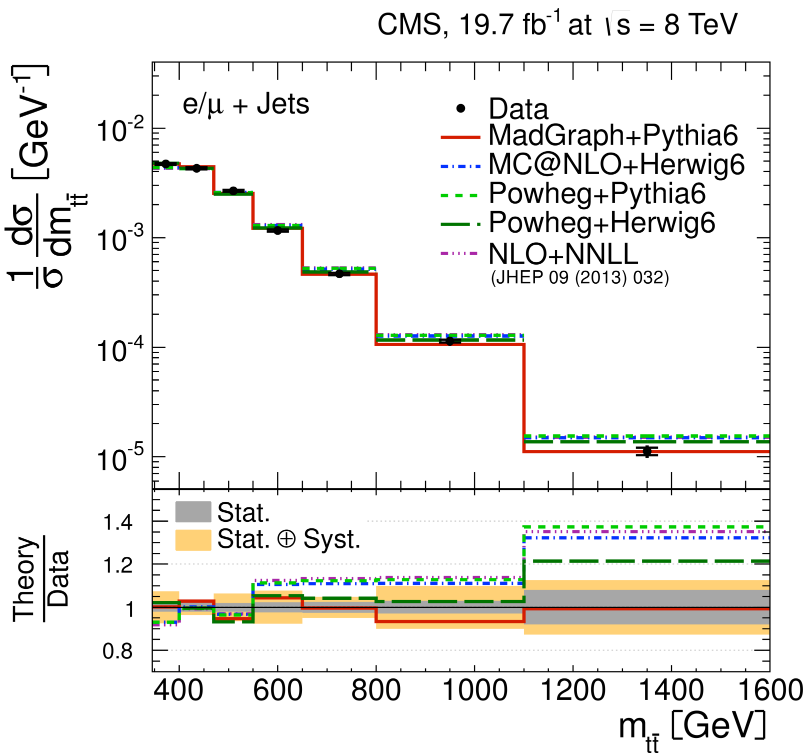


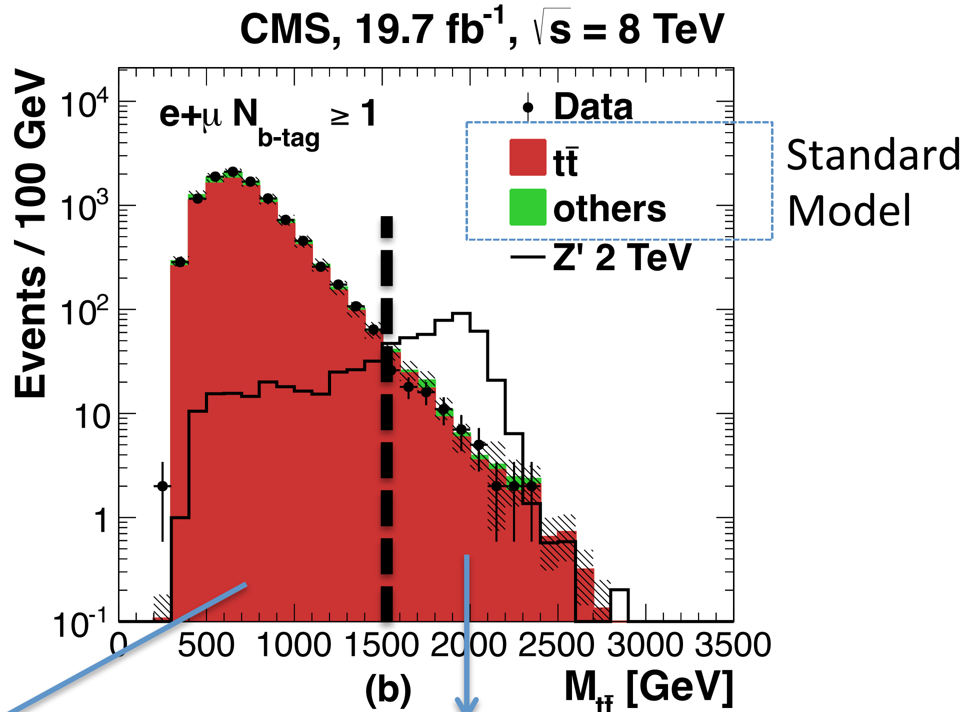
Top Pair Differential Cross Sections

- $M(t\bar{t}) \rightarrow$ resonances

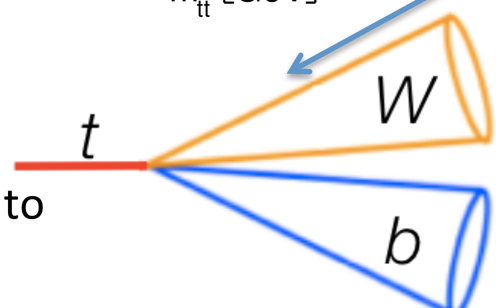
arXiv:1505.04480

PRL 111 (2014) 211804





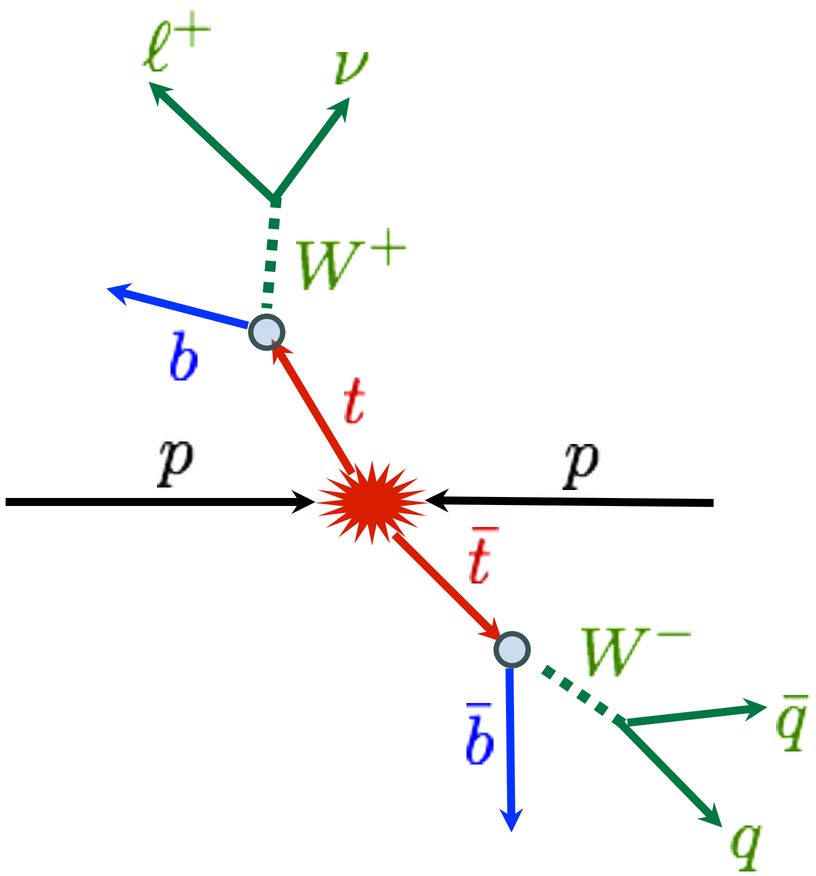
Boosted topology:
Each top quark is highly lorentz boosted
→ Decay products collimated



Resolved topology:
Each parton matched to
A single jet.

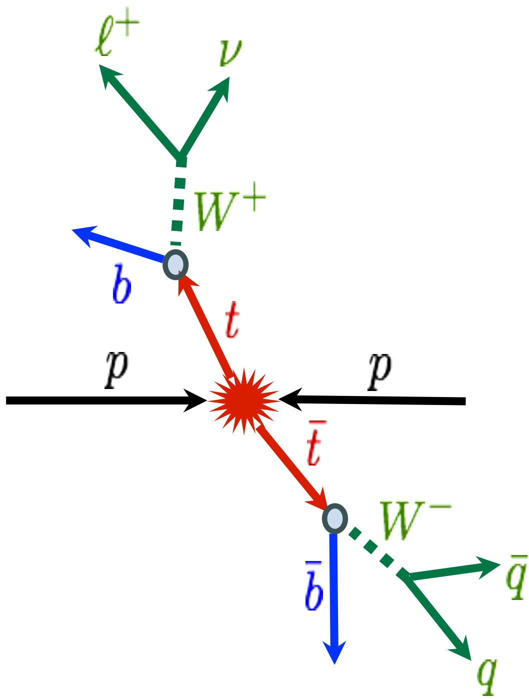
Top Mass Measurements

- Basic methods
  - Full invariant mass reconstruction → The most powerful and standard
  - Partial reconstruction using a variable correlated to top mass → less powerful but different systematic uncertainties
  - Indirect measurement through $t\bar{t}$ and $t\bar{t}$+jet cross sections, … → top quark pole mass

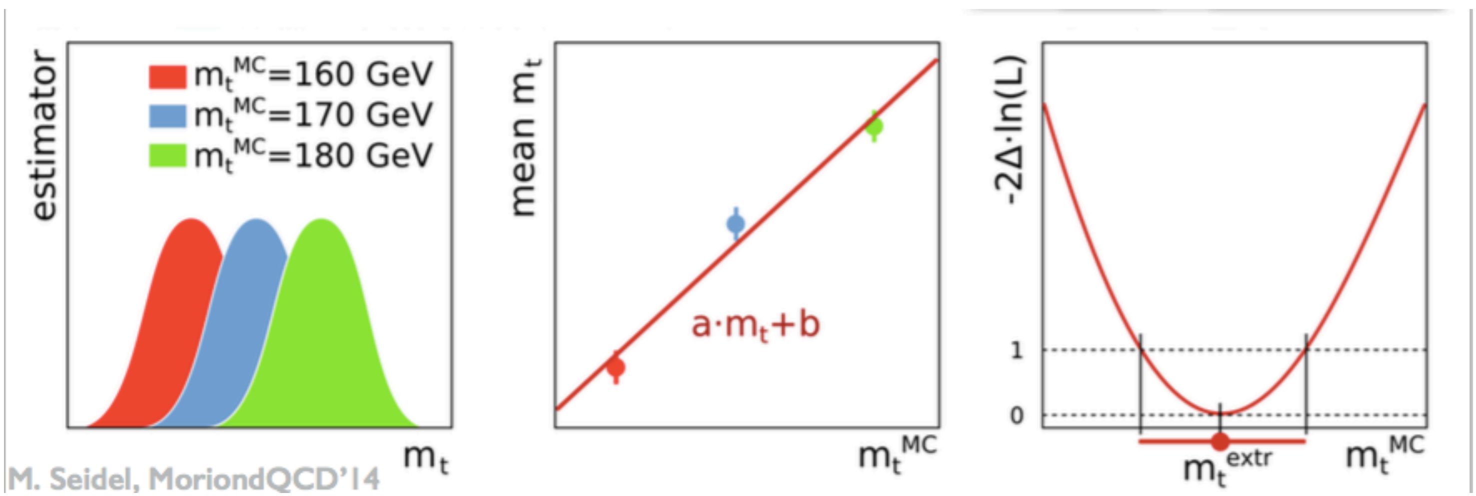


Full Mass Reconstruction

- General features:
  - Assign each jet to a top decay product (constrained kinematic fits)
  - Calibration of the method based on $m_t^{MC} = m_t^{meas}$
  - Determination of m_t^{MC} (and JES simultaneously) from data.



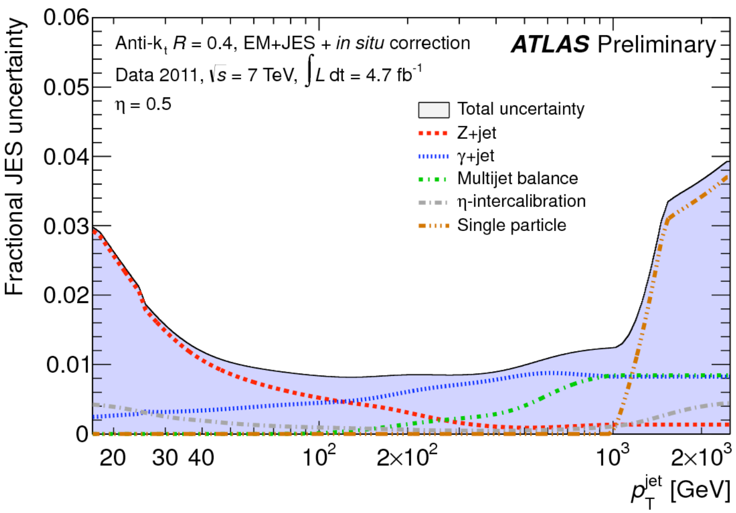
Main challenge: Jet reconstruction, Jet energy scale uncertainties, modeling.

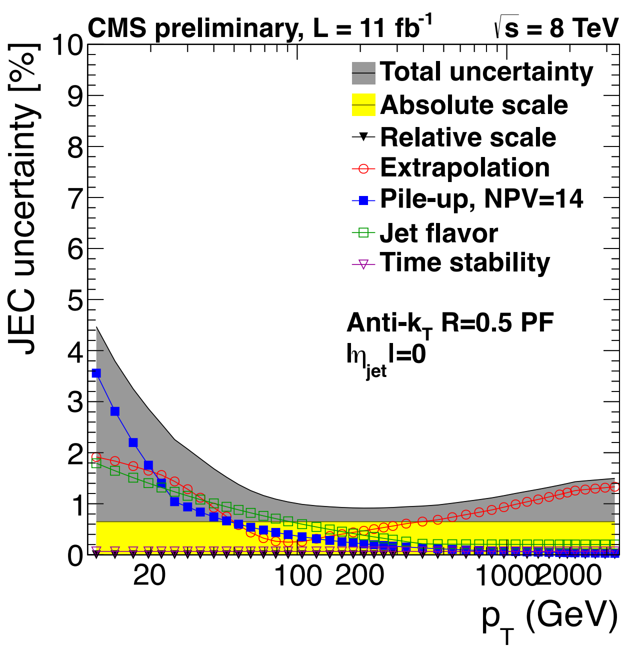


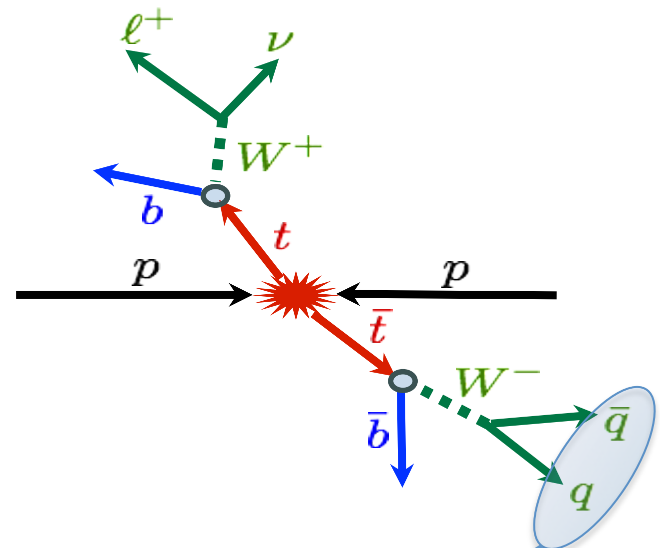
Full Mass Reconstruction Methods (Tevatron → LHC)

- Template Method → Simple and relatively fast
  - Compare data to MC distributions with different top mass values.
- Matrix element method → The most precise, but relatively slow, and only at leading order.
  - Event likelihood calculated from $t\bar{t}$ matrix element integrated in the full phase-space using the full event information.
- Ideogram method (lepton+jets/all-hadronic channels) → Very precise and fast
  - Combines the matrix element (in an approximate way) and template approaches
  - Analytical event likelihoods based on templates from simulation.
- \+ Dilepton Channel
  - Solve the under-constrained $t\bar{t}$ system

Jet Energy Scale Uncertainties







➔ JES calibration with dijet and γ/Z+jet events → ~1-3%

➔ <1% when complemented with in-situ JES calibration.

→ 2D method (Tevatron, CMS): fit JES factor (JSF) using W→jj (remaining uncertainty from different jet-flavors)

→ 3D method (ATLAS): 2D + fit relative b-to-light-jet scale (bJSF).

Systematic Uncertainties

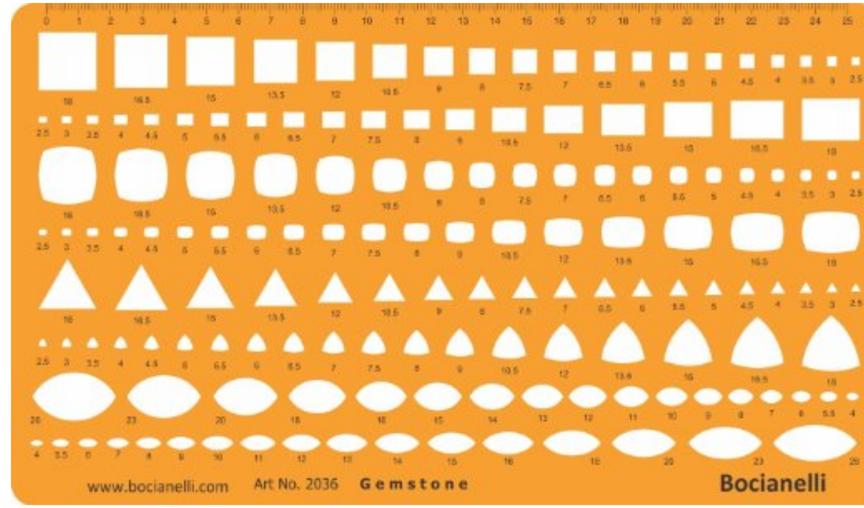
	δm_t^{2D} (GeV)	δJSF	δm_t^{1D} (GeV)
Experimental uncertainties			
Fit calibration	0.10	0.001	0.06
p_T- and η-dependent JES	0.18	0.007	1.17
Lepton energy scale	0.03	<0.001	0.03
MET	0.09	0.001	0.01
Jet energy resolution	0.26	0.004	0.07
b tagging	0.02	<0.001	0.01
Pileup	0.27	0.005	0.17
Non-$t\bar{t}$ background	0.11	0.001	0.01
Modeling of hadronization			
Flavor-dependent JSF	0.41	0.004	0.32
b fragmentation	0.06	0.001	0.04
Semi-leptonic B hadron decays	0.16	<0.001	0.15
Modeling of the hard scattering process			
PDF	0.09	0.001	0.05
Renormalization and factorization scales	0.12±0.13	0.004±0.001	0.25±0.08
ME-PS matching threshold	0.15±0.13	0.003±0.001	0.07±0.08
ME generator	0.23±0.14	0.003±0.001	0.20±0.08
Modeling of non-perturbative QCD			
Underlying event	0.14±0.17	0.002±0.002	0.06±0.10
Color reconnection modeling	0.08±0.15	0.002±0.001	0.07±0.09
Total	0.75	0.012	1.29

CMS-PAS-TOP-14-001

Template Method

ATLAS-CONF-2013-046

- 3D template method in the lepton +jets channel
- Kinematic fit (for top reconstruction and jet-parton combinations).

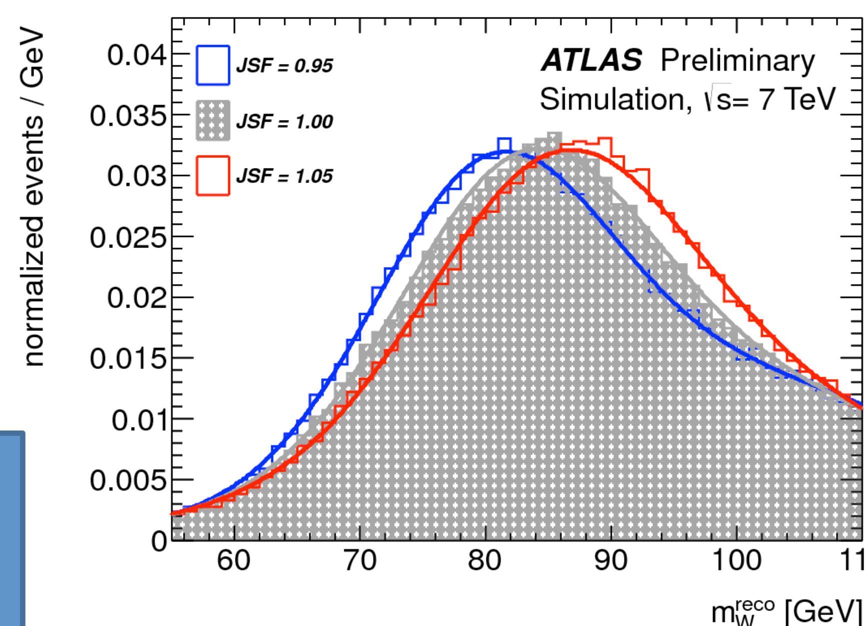


Simultaneously fit to the templates of

$$m_W^{reco}, R_{\ell b}^{reco} = \frac{p_T^{b_{had}} + p_T^{b_{lep}}}{p_T^{W_{jet1}} + p_T^{W_{jet2}}}, m_t$$

overall jet scale factor (JSF)

constrain overall relative bjet to light jet scale factor (bJSF)



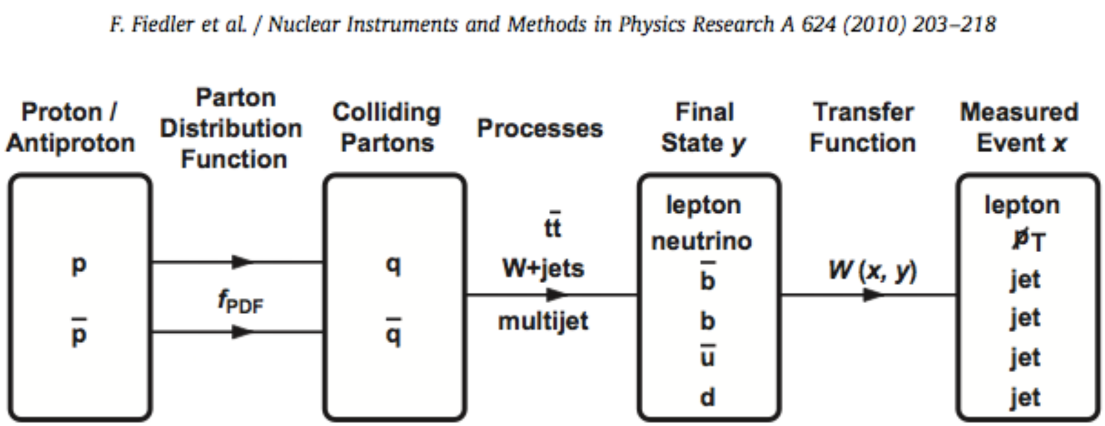
Matrix Element Method

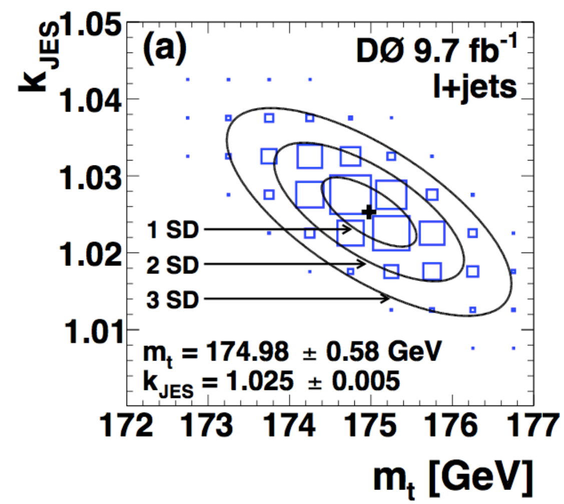
- The probability (or weight) of the observed event (x) to be produced and observed following the hypothesis H:

$$P(x \mid H) = \frac{1}{\sigma_{obs}} \int f_{pdf}(q_1) f_{pdf}(q_2) dq_1\, dq_2 \frac{(2\pi)^4 |M(y)|^2}{q_1 q_2 s} W(x, y, k_{JES}) d\Phi(y)$$

e.g. m_t

constrain using m_W





PRL 113, 032002 (2014)
http://arxiv.org/abs/1405.1756v2

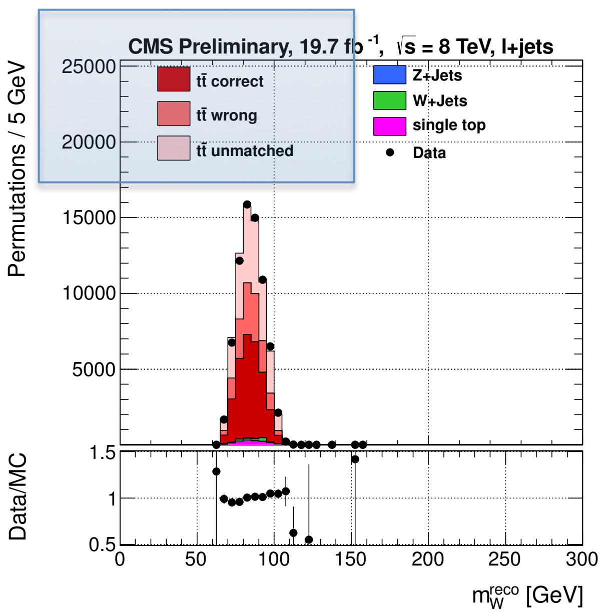
$$m_t = 174.98 \pm 0.58(stat + JES) \pm 0.49(sys)\ \ GeV$$

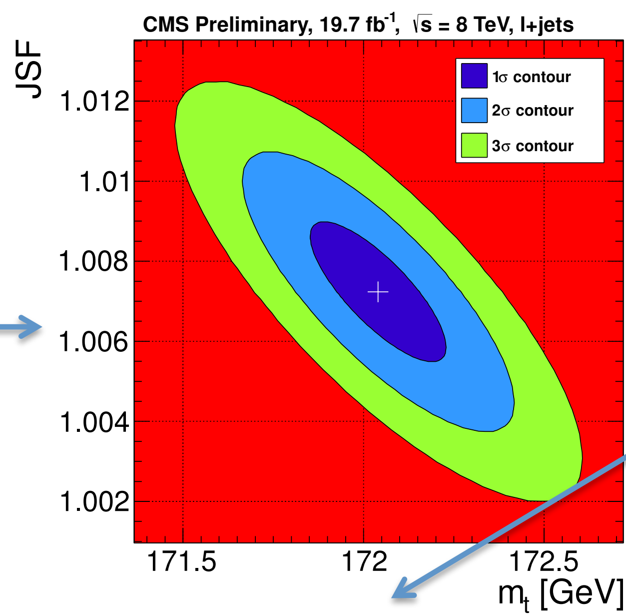
$$m_t = 174.98 \pm 0.76\ \ GeV$$

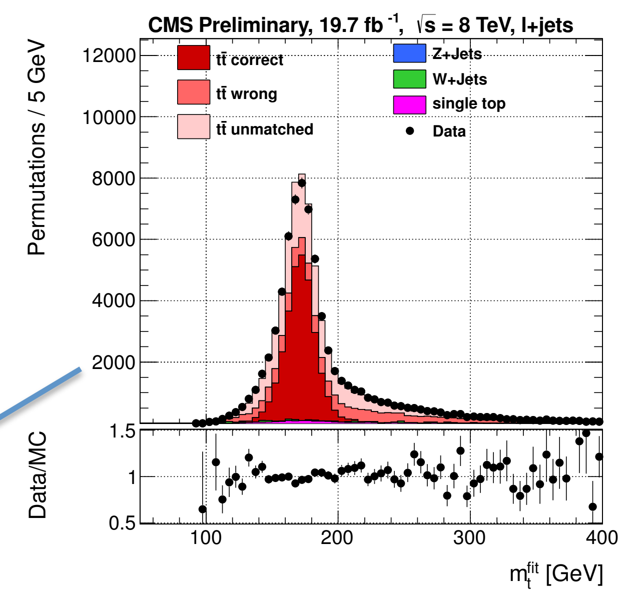
The Ideogram Method

→ Template method with multiple permutations (correct, wrong, unmatched) per event.
→ All different permutations taken into account with weights + include b-quark tagging.
→ Kinematic fit → improve mass reconstruction.

Determine m_t simultaneously with jet energy scale factor in a joint likelihood fit.





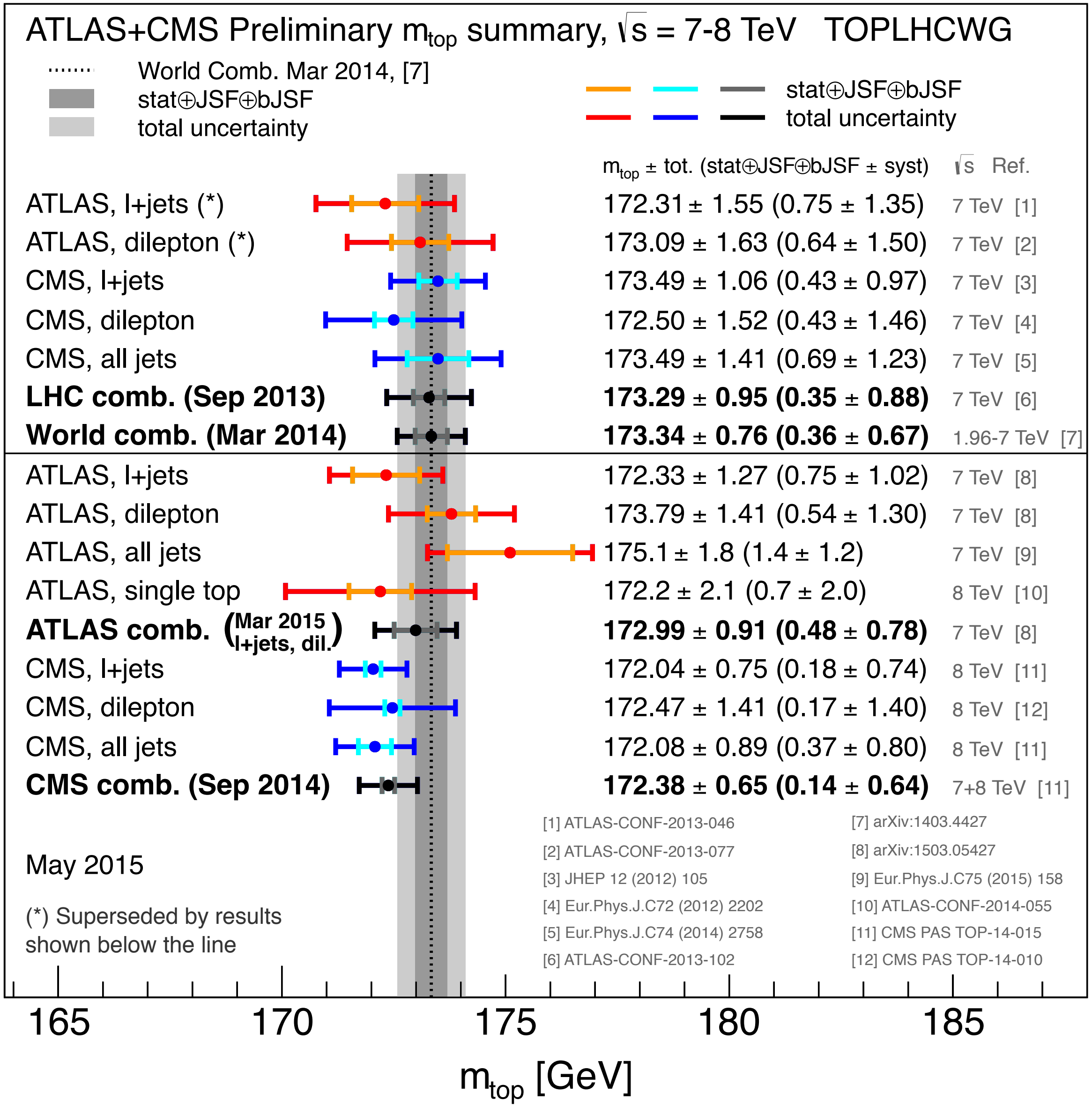


$$m_t = 172.04 \pm 0.19\,(\text{stat.+JSF}) \pm 0.75\,(\text{syst.})\,\text{GeV},$$
$$\text{JSF} = 1.007 \pm 0.002\,(\text{stat.}) \pm 0.012\,(\text{syst.}).$$

CMS-PAS-TOP-14-001

→ *First single measurement with < 1 GeV precision.*

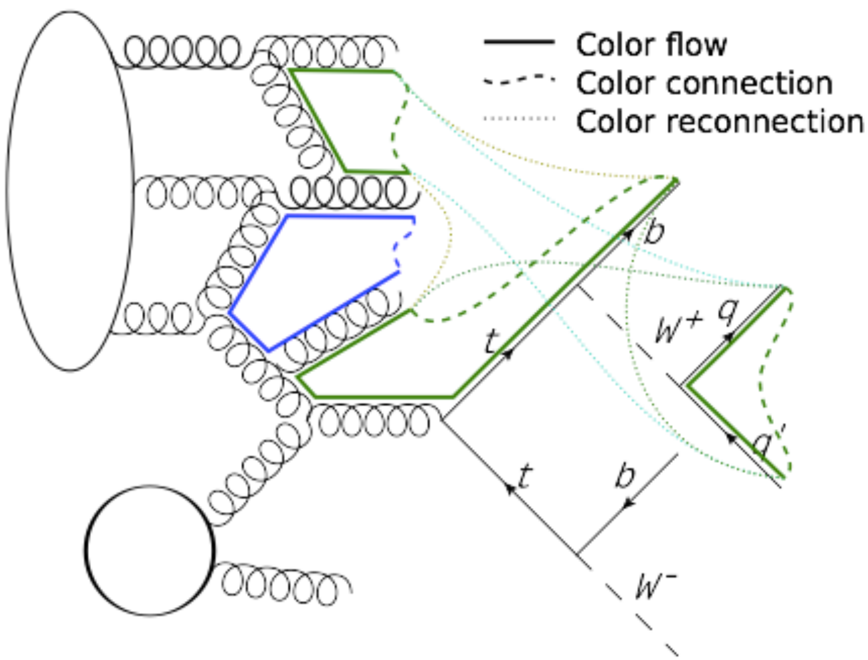
Top Quark Mass – Direct Measurements Summary



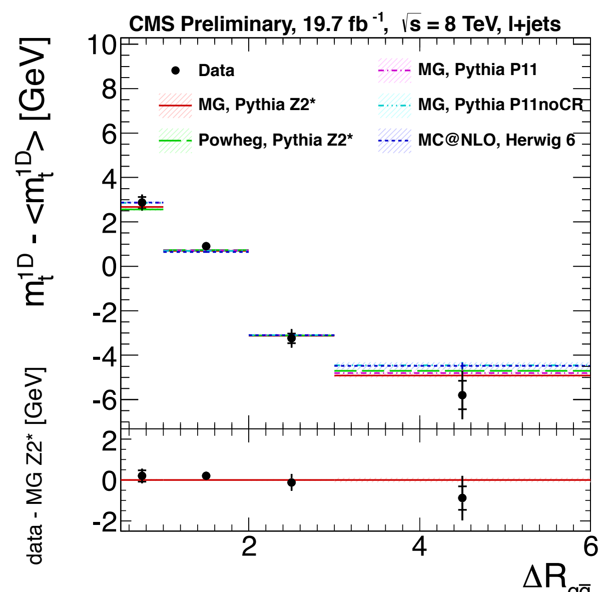
Dependence of Top Mass on Event Kinematics

CMS-PAS-TOP-14-001

- Interpretation of the top mass measurements is not straightforward for $\delta m_t \sim< 1$ GeV $\sim\Gamma_t$.
- Study model uncertainties.
  - some (non-)perturbative effects have different kinematic dependences.
  - Difficult to define a pole mass for an unstable and colored particle.



- Study variables sensitive to
  - color connection,
  - ISR/FSR,
  - b-quark kinematics.



No mis-modeling of data.

Alternative Top Quark Mass Measurements (CMS)

- Measurements with different/independent systematic uncertainties or with different m_t definitions.
- Top mass from
  - B-hadron lifetime [CMS-PAS-TOP-12-030]
  - b-jet kinematics from J/ψ [CMS-PAS-TOP-13-007]
  - kinematic endpoints [EPJC 73 (2013) 2494]
  - $t\bar{t}$ cross section [PLB 728, 496 (2014)]
  - $t\bar{t}$+1 jet [ATLAS-CONF-2014-053]
  - M_{lb} [CMS-PAS-TOP-14-014]
  - Single top quark event in t-channel [ATLAS-CONF-2014-055]
  - ….

Top Quark Mass - Definitions

- Free quarks not observable (confining property of QCD)
- All quarks except the top quark hadronize → Top quark mass theoretical framework dependent.
- Two common definitions:
  - Pole mass (See e.g. arXiv:9612329)
    - Perturbatively defined
    - Position of the pole in the renormalized quark propagator
    - "intuitive mass"
    - Suffers from ambiguities due to non-perturbative corrections.
  - "Running mass" ($m_t^{\overline{MS}}$)
    - Renormalization scale dependent.

Ambiguity of $O(\Lambda_{QCD})$

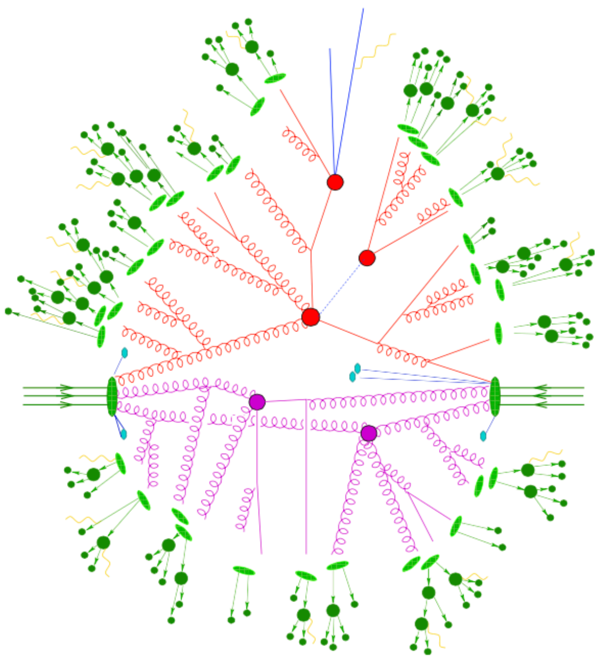
The two definitions can be related analytically:
e.g. see PLB482 (2000),99; arXiv:1212.4319

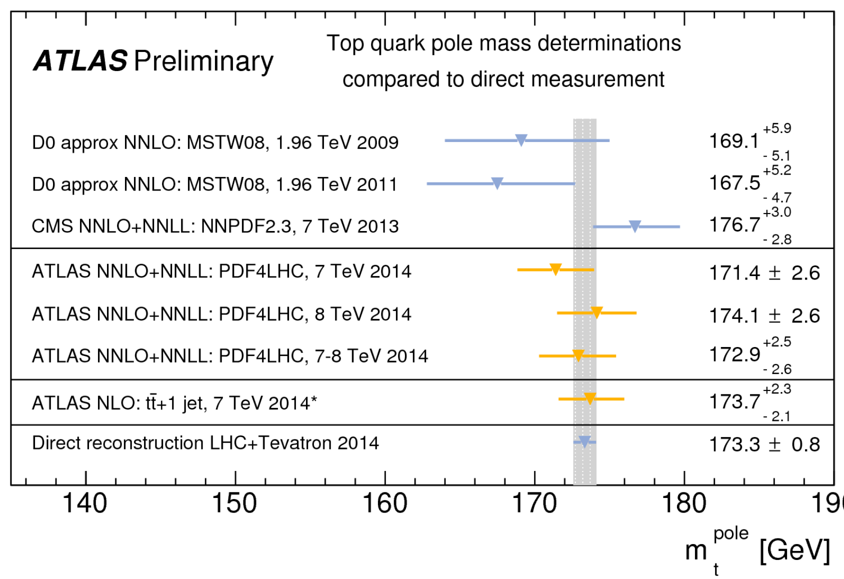
Top Quark Mass Definitions

- Monte Carlo Mass
  - No straightforward definition in ***direct top mass measurements***
  - Direct top quark measurements rely on the complicated relation between the experimental observable and m_t.
  - MEs at fixed order (LO or NLO) QCD + higher orders by parton showers

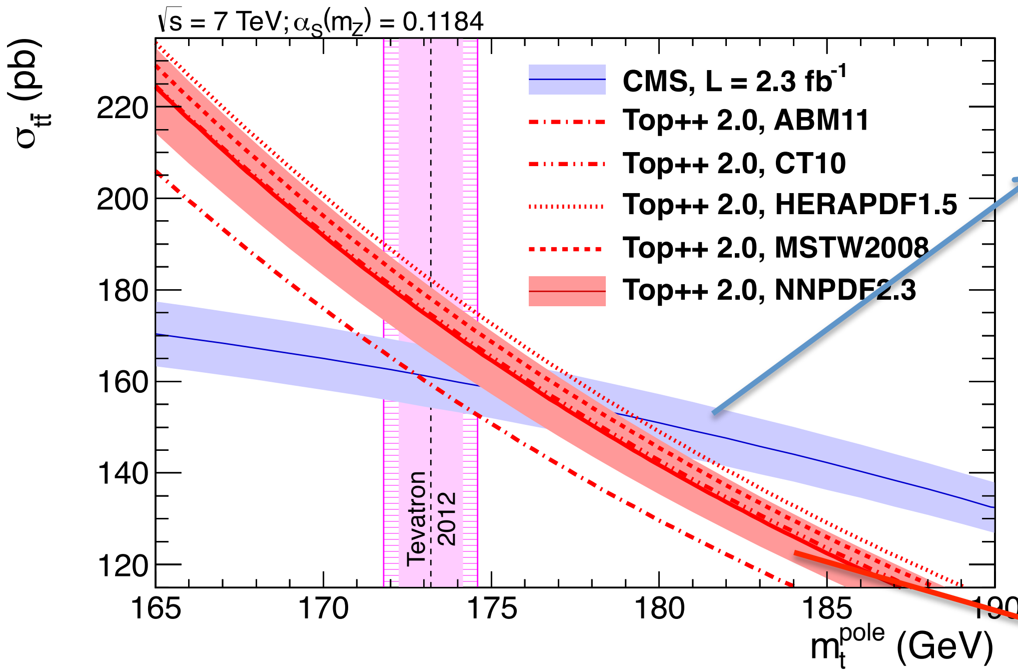
$$m_t^{MC} \neq m_t^{pole} \neq m_t^{MS} \neq m_t^{XX}$$

$$m_t^{pole} - m_t^{MC} \approx 1\ GeV$$





Fix $\alpha_s(m_Z)$ and PDF → Determine m_t^{pole}



Dependence due to efficiency and acceptance depending on m_t.

Recall: $\sigma = \dfrac{N_{obs} - N_{bkg}}{(A \times \varepsilon) \times B \times L}$

It is harder to produce heavier particles.

$$\sigma_{pp\to t\bar{t}}(s, m_t) = \sum_{i,j=partons} \int dx_1\, dx_2 f_i^{pdf}(x_1, \mu_f^2) f_j^{pdf}(x_2, \mu_f^2)\, \hat{\sigma}_{ij\to t\bar{t}}(\hat{s}, m_t, \mu_f, \mu_r, \alpha_s(\mu_r))$$

$$\boxed{m_t^{pole} = 176.7^{+3.0}_{-2.8}\, GeV}$$

→ ***Top mass at NNLO QCD.***

PLB 728, 496 (2014)
arXiv:1307.1907v3

Also see ATLAS, EPJ-C74 (2014) 3109

Dominant systematic uncertainties: measured $t\bar{t}$ cross-section and PDF.

Top Quark Pole Mass Determination from $t\bar{t}$+1 Jet Events

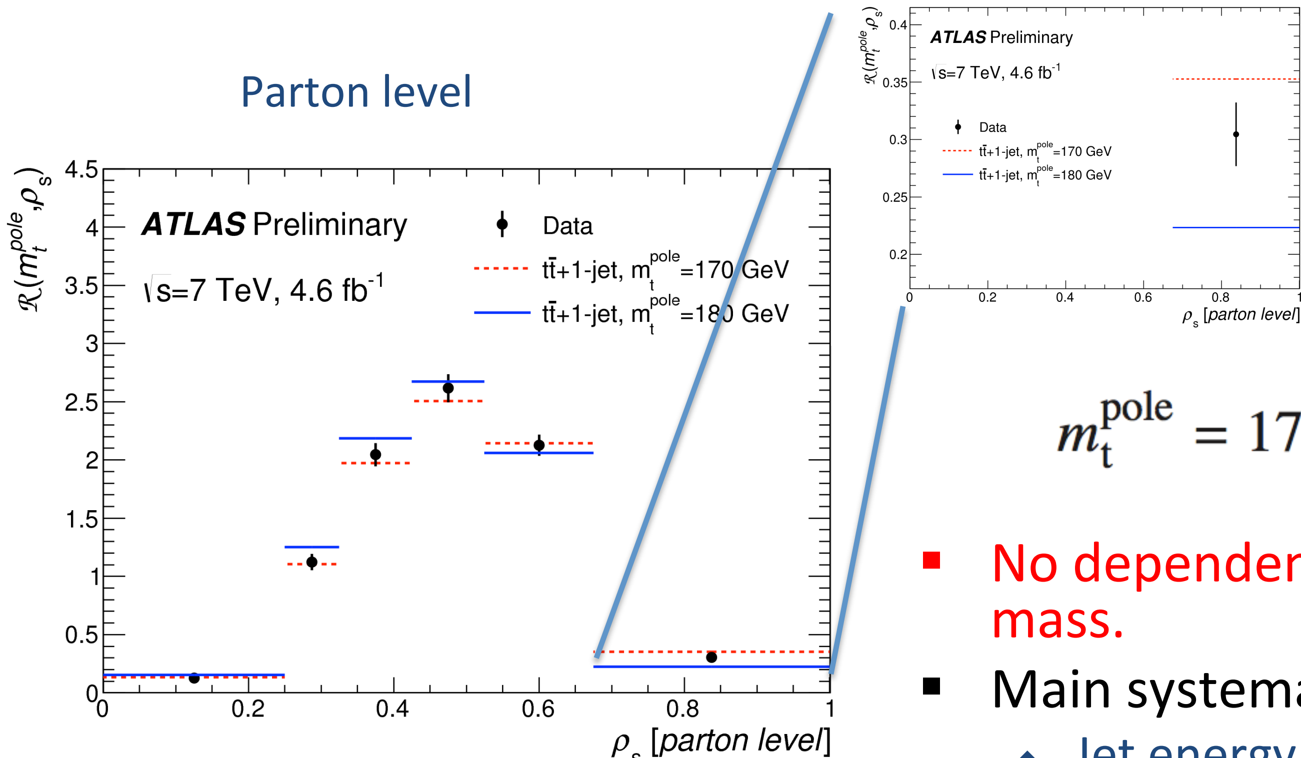
- $t\bar{t}$+1 jet system → gluon radiation depends on the quark mass.
- Pole mass at NLO from normalized cross section vs the invariant mass of the $t\bar{t}$+1jet system.

$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^{\text{pole}}, \rho_s),$$

where ρ_s is defined as

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}},$$

Parton level

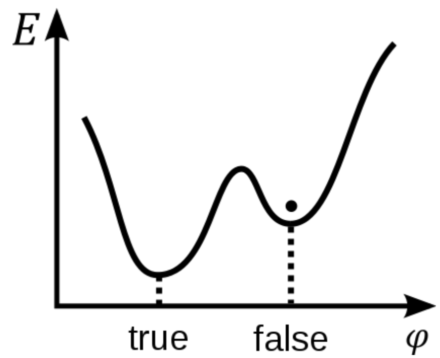


$$m_t^{\text{pole}} = 173.7 \,^{+2.3}_{-2.1} \text{ GeV}$$

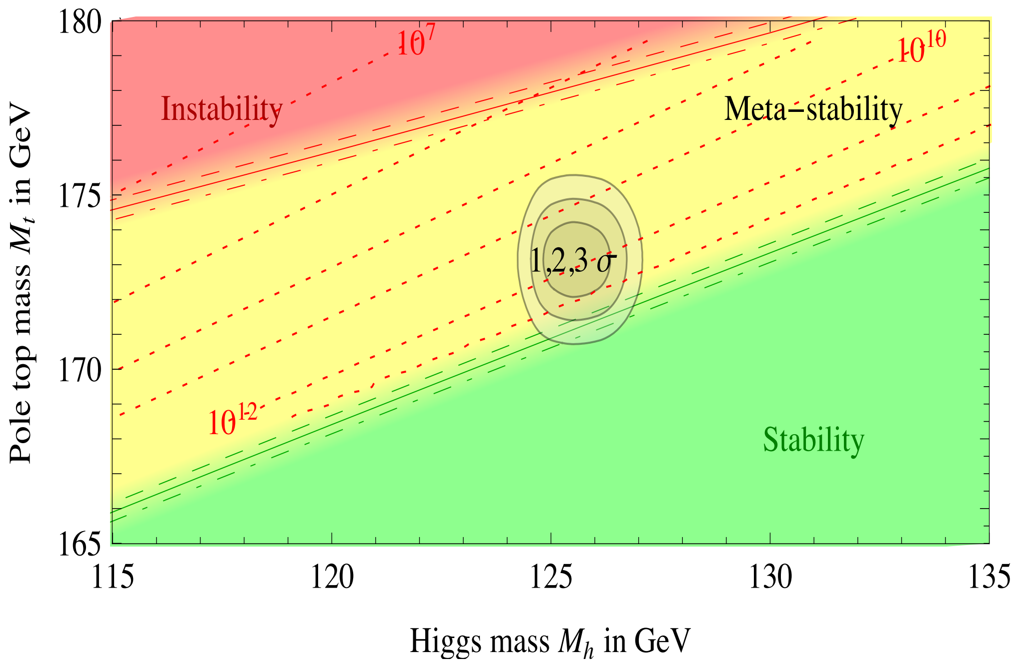
- No dependence on the input MC mass.
- Main systematic uncertainty sources:
  - Jet energy scale, QCD scales, ISR/FSR.

The Top Quark Mass and Vacuum Stability (Fate of the Universe)

- Input to theoretical studies of electroweak vacuum stability.



Degrassi, et. al. arXiv:1205.6497
JHEP 08 (2012) 098



Measured top and Higgs masses
→ SM valid up to the Planck scale?

Summary

- Top quark plays an important role in testing and understanding QCD, electro-weak, flavor and searches for new physics.
- Precise inclusive and differential cross section predictions and measurements.
- Top quark mass < 1 GeV precision.
  - Measurements pushing the limits of our understanding of the mass of the heaviest colored elementary particle.
  - Eventually (full LHC Run II data or a future electron-positron collider) top quark mass might tell us whether we are in a stable or a meta-stable universe.
- Almost all LHC Run I measurements dominated by systematics uncertainties.
  - LHC Run II focusing on
    - reducing these uncertainties through new type of measurements, improving modeling and theoretical calculations → better understand QCD and improve new physics searches using top quarks.
    - Single top and tt+X differential distributions.
    - tails of differential distributions (esp. with boosted top quarks).

Additional Slides

The Top Quark

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. **C38**, 090001 (2014) (URL: http://pdg.lbl.gov)

t

$I(J^P) = 0(\frac{1}{2}^+)$

Charge $= \frac{2}{3}\, e$ Top $= +1$

Mass (direct measurements) $m = 173.21 \pm 0.51 \pm 0.71$ GeV [a,b]
Mass ($\overline{\mathrm{MS}}$ from cross-section measurements) $m = 160^{+5}_{-4}$ GeV [a]
Mass (Pole from cross-section measurements) $m = 176.7^{+4.0}_{-3.4}$ GeV
$m_t - m_{\overline{t}} = -0.2 \pm 0.5$ GeV (S = 1.1)
Full width $\Gamma = 2.0 \pm 0.5$ GeV
$\Gamma(W b)/\Gamma(W q(q = b, s, d)) = 0.91 \pm 0.04$

t-quark EW Couplings

$F_0 = 0.690 \pm 0.030$
$F_- = 0.314 \pm 0.025$
$F_+ = 0.008 \pm 0.016$
$F_{V+A} < 0.29$, CL = 95%

t DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$W q(q = b, s, d)$				–
$W b$				–
$\ell \nu_\ell$ anything		[c,d] (9.4±2.4) %		–
$\gamma q(q=u,c)$		[e] $< 5.9 \times 10^{-3}$	95%	–
$\Delta T = 1$ weak neutral current ($T1$) modes				
$Z q(q=u,c)$	$T1$	[f] $< 2.1 \times 10^{-3}$	95%	–

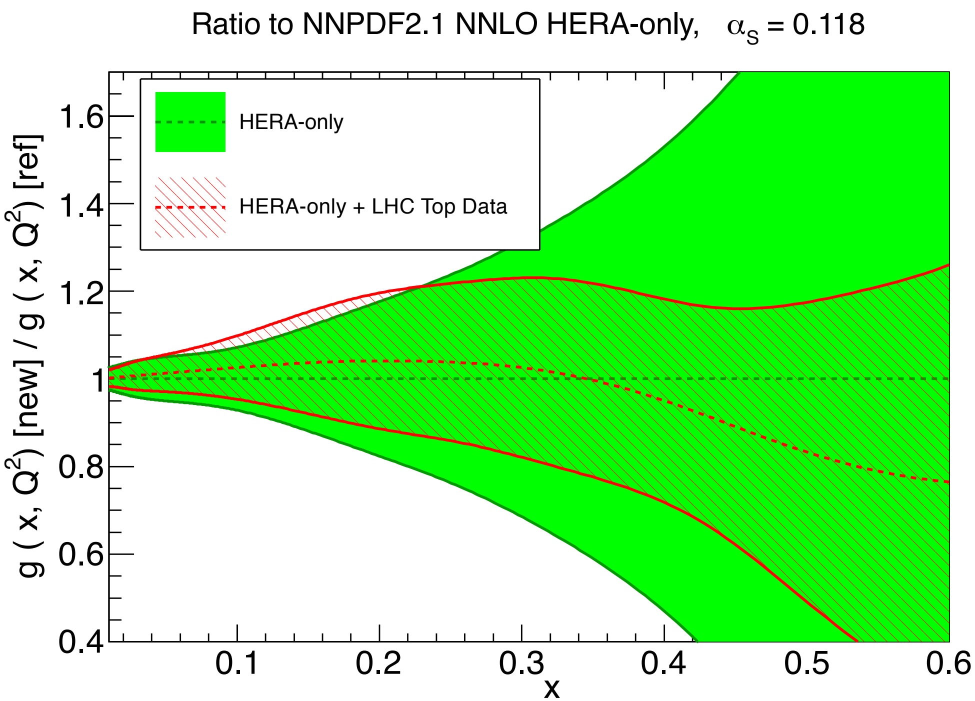
→ First observed at Tevatron proton-antiproton collider Run I (1992-1996) by CDF and D0 experiments.

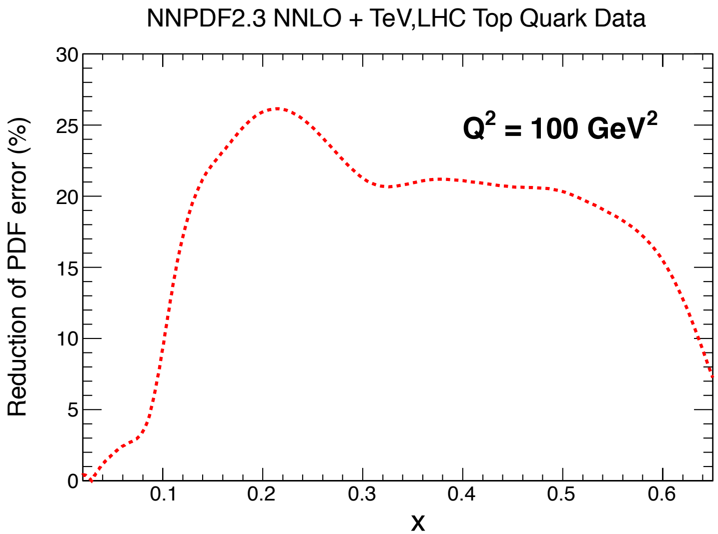
→*All properties obtained from colliders.*

Top-Z boson coupling established.
Top-Higgs boson coupling hasn't been directly observed yet.

Constraints on the gluon PDF from Top Pair Production

Czakon et al.
arXiv:1303.7215





Relative reduction of error due to the inclusion of top data in the PDF fit.

- LHC top quark production cross section data already providing significant constraints on gluon PDF at large x.
- Significant impact on predictions for the scalar boson, and BSM predictions (dominated by gg processes).

Top Pair Differential Distributions - Systematic Uncertainties

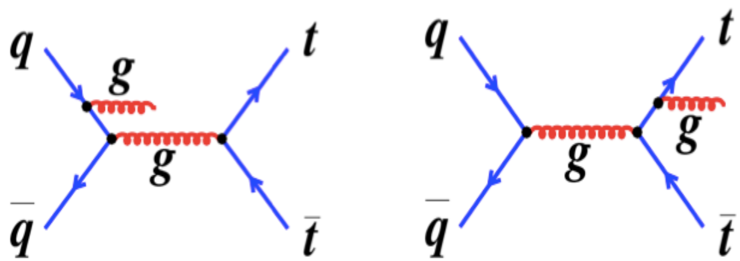
Table 1: Breakdown of typical systematic uncertainties for the normalized differential cross sections. The uncertainty on the jet-parton matching threshold is indicated as "ME-PS threshold". The medians of the distribution of uncertainties over all bins of the measurement are quoted. For the ℓ+jets channels, the background from Z+jets is negligible and included in the "Background (all other)" category.

Relative systematic uncertainty (%)				
Source	Lepton and b jet observables		Top quark and $t\bar{t}$ observables	
	ℓ+jets	dileptons	ℓ+jets	dileptons
Trigger eff. & lepton selec.	0.1	0.1	0.1	0.1
Jet energy scale	2.3	0.4	1.6	0.8
Jet energy resolution	0.4	0.2	0.5	0.3
Background (Z+jets)	—	0.2	—	0.1
Background (all other)	0.9	0.4	0.7	0.4
b tagging	0.7	0.1	0.6	0.2
Kinematic reconstruction	—	<0.1	—	<0.1
Pileup	0.2	0.1	0.3	0.1
Fact./renorm. scale	1.1	0.7	1.8	1.2
ME-PS threshold	0.8	0.5	1.3	0.8
Hadronization	2.7	1.4	1.9	1.1
Top quark mass	1.5	0.6	1.0	0.7
PDF choice	0.1	0.2	0.1	0.5

arXiv:1505.04480

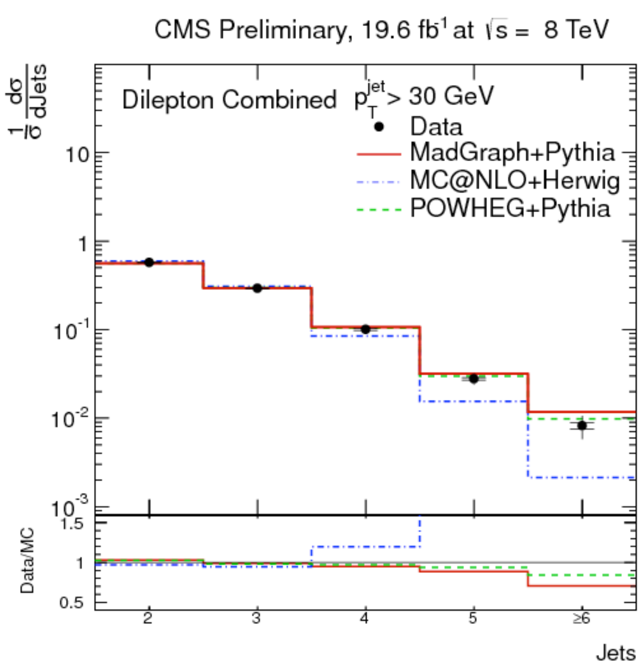
$t\bar{t}$ + jets

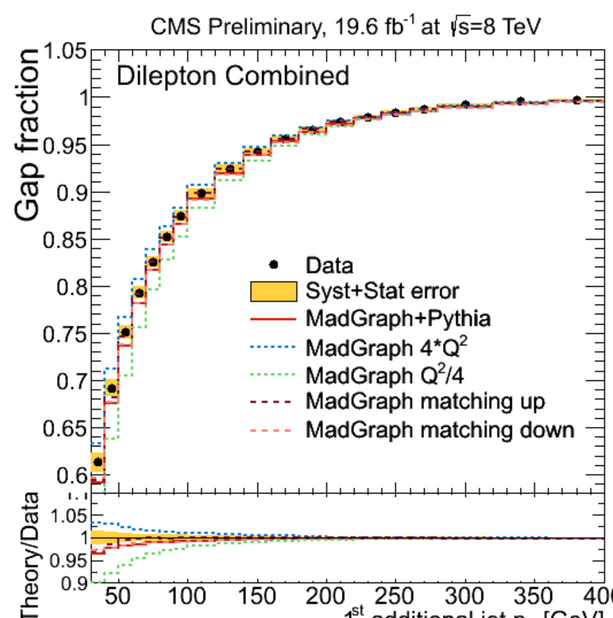
- At the LHC, $t\bar{t}$ events are usually accompanied by additional hard jets from initial or final state QCD radiation (ISR/FSR).
  - Test higher-order QCD calculations (ISR parameters, QCD scales, ..)
  - Improve model choices and uncertainties for coming measurements.



- $t\bar{t}$ + 1 and 2 jet calculations are available at NLO.
- $t\bar{t}$ + jets: background to H→$b\bar{b}$, ...

arXiv:1404.3171, CMS-PAS-TOP-12-041

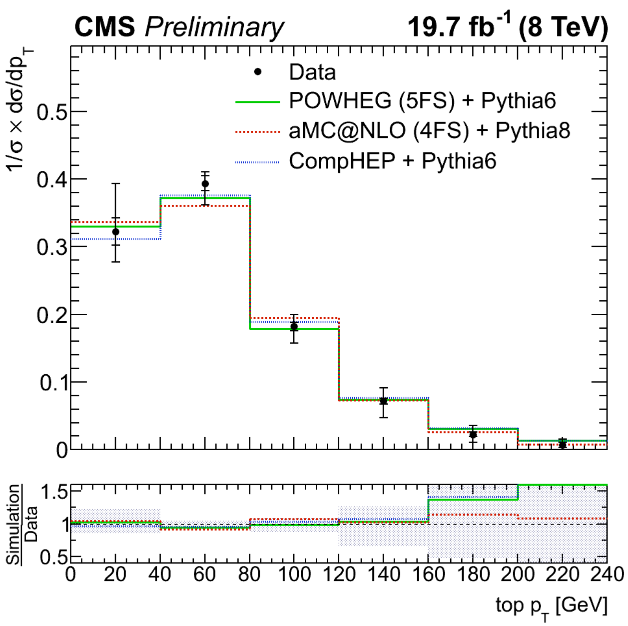


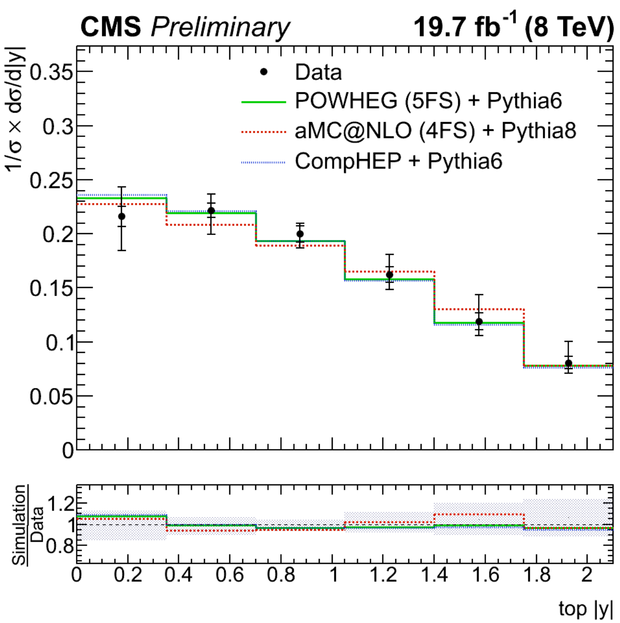


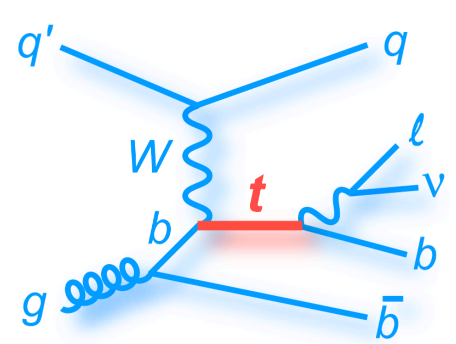
- "Gap fraction": fraction of events w/o additional jets above a threshold.
  - Alternative way to investigate jet activity from QCD radiation.

Differential Measurements in the single top t-channel

- Different implementations for b-quark modeling in the initial state for NLO generators.
- CompHep: combination of 2→2 and 2→3 processes based on the p_T spectrum of the second b quark (as an NLO approximation).
- Data distributions (corrected to parton level) are described well by both NLO and LO MCs + Pythia6.







CMS-PAS-TOP-14-004

The Ideogram Method

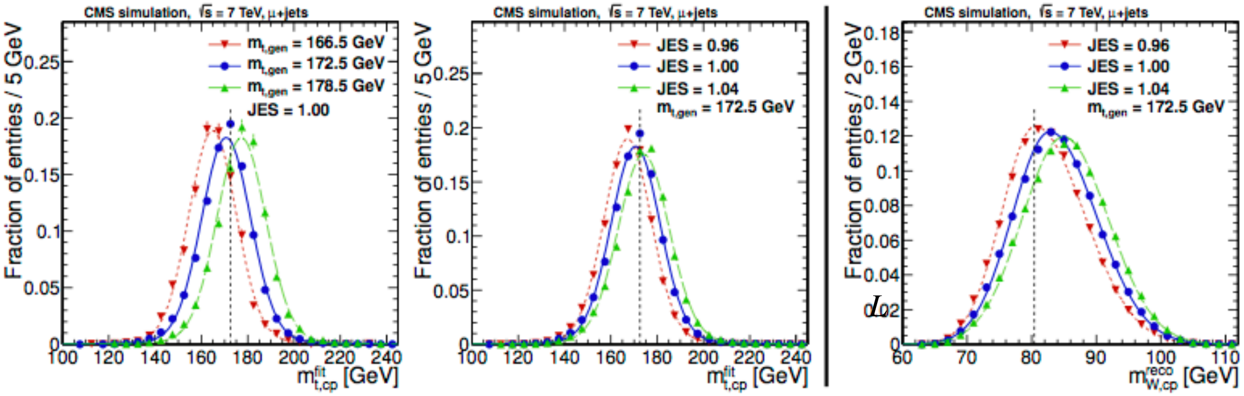
→ Template method with multiple permutations (correct, wrong, unmatched) per event.

→ All different permutations taken into account with weights + include b-quark tagging.

→ Kinematic fit → improve mass reconstruction.

CMS-PAS-TOP-14-001

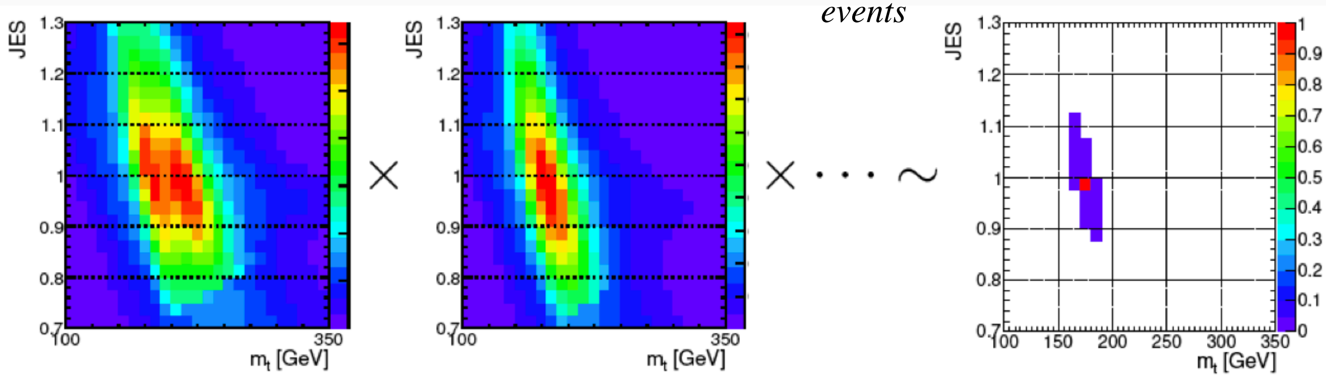
e.g., correct permutations:



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

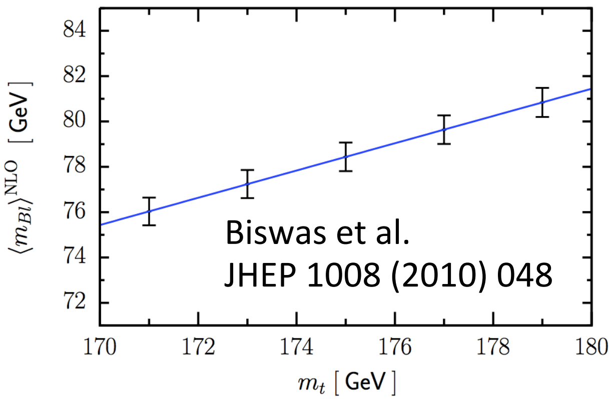
- Fits to analytical expressions
- Parameters of the fitted functions parameterized linearly in m_t, JES, and m_txJES.

Maximize $$L\left(m_t, JES \middle| sample\right) \sim \prod_{events} L\left(event \middle| m_t, JES\right)^{w(event)}$$



(event likelihoods) (sample likelihood)

Top quark mass from lepton-bjet Invariant Mass



- M_{lb} reconstructed and fitted to theory from MC simulation and fixed order QCD prediction → unambiguously defined pole mass.
- eμ channel for high precision.
- Select the permutation that minimizes the mlb in each event.

CMS-PAS-TOP-14-014

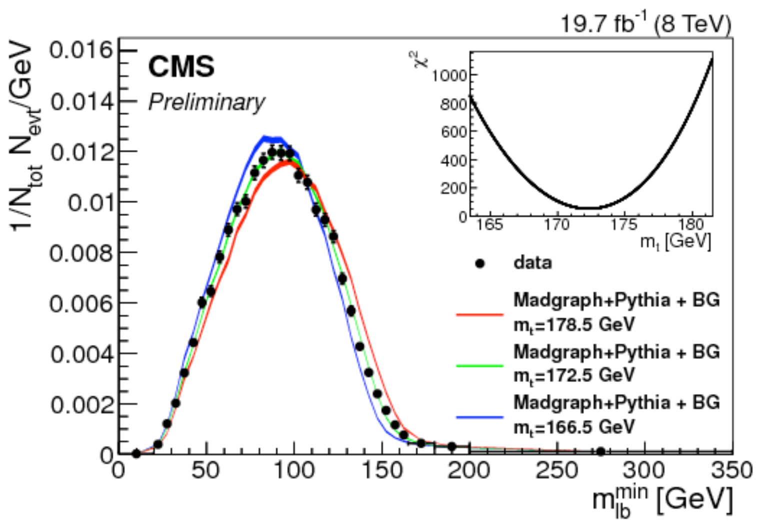
$$m_{lb}^2 = \frac{m_t^2 - m_W^2}{2}(1-\cos\theta_{lb})$$

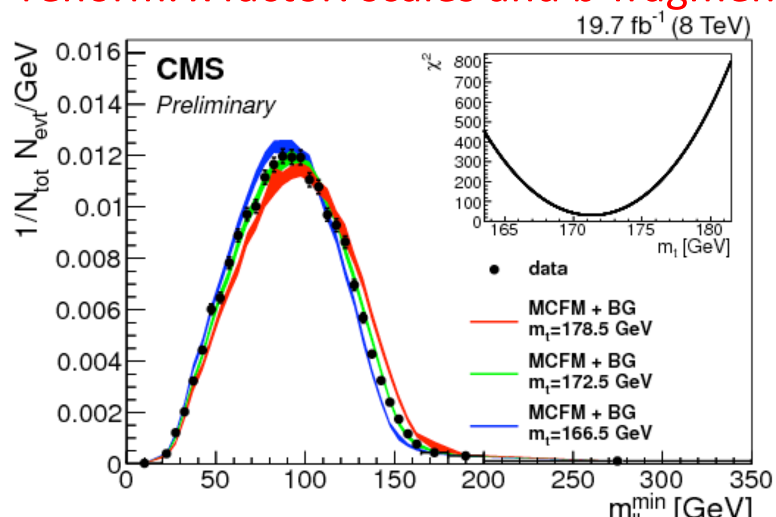
Endpoint at

$$\max(m_{lb}) \approx \sqrt{m_t^2 - m_W^2}$$

Prediction	Fit method	Fitted m_t [GeV] from m_{lb}^{min}
MADGRAPH+PYTHIA	shape+rate	$173.1^{+1.9}_{-1.8}$
MADGRAPH+PYTHIA	rate	$173.7^{+3.5}_{-3.4}$
MADGRAPH+PYTHIA	shape	$172.3^{+1.3}_{-1.3}$
MCFM (LO)	shape	$171.5^{+1.1}_{-1.1}$
MCFM (NLO)	shape	$171.4^{+1.0}_{-1.1}$

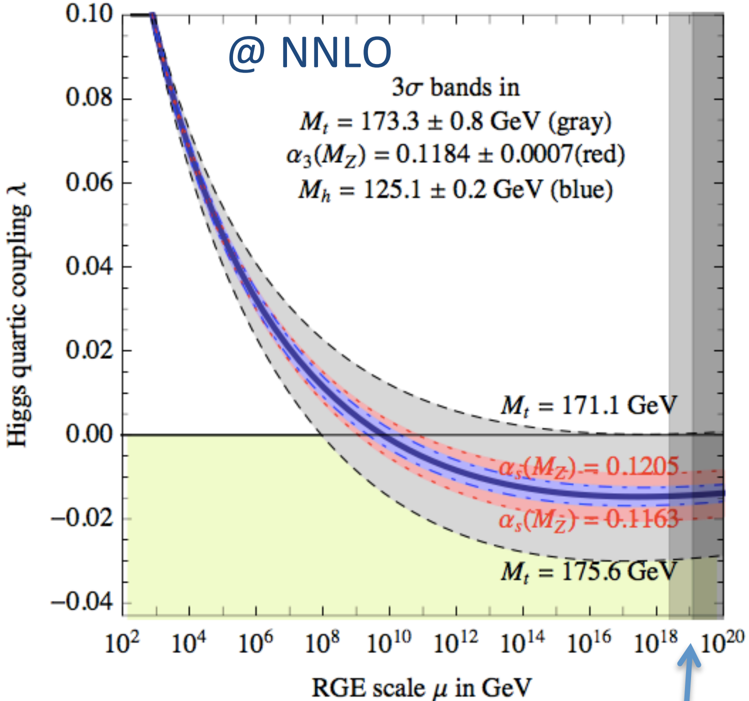
Main uncertainty sources:
renorm. x factor. scales and b-fragmentation.





The Top Quark Mass and Vacuum Stability (Fate of the Universe)

Degrassi, et. al. arXiv:1205.6497
JHEP 08 (2012) 098



Planck scale

- Measured m_H → λ (the quartic scalar coupling)

$$V^{\mathrm{eff}} \approx -\frac{1}{2}m^2(\mu)\phi^2(\mu) + \lambda(\mu)\phi^4(\mu) \sim \lambda(\mu)\phi^4(\mu)$$

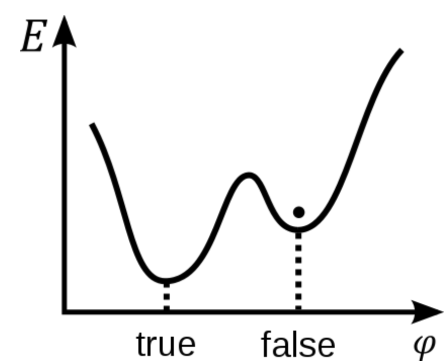
for

$\phi(\mu) >> v$

stability

meta-stability

v: electroweak minimum



Measured top and Higgs masses
→ SM valid up to the Planck scale?