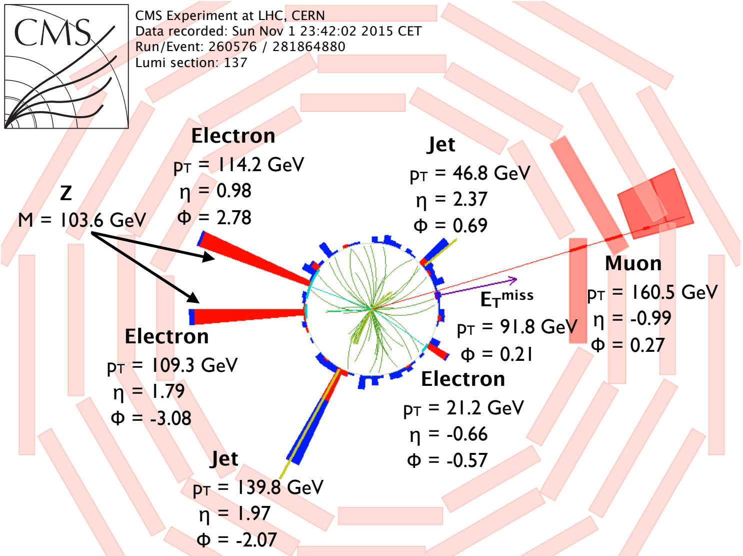
中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Top Quark Physics

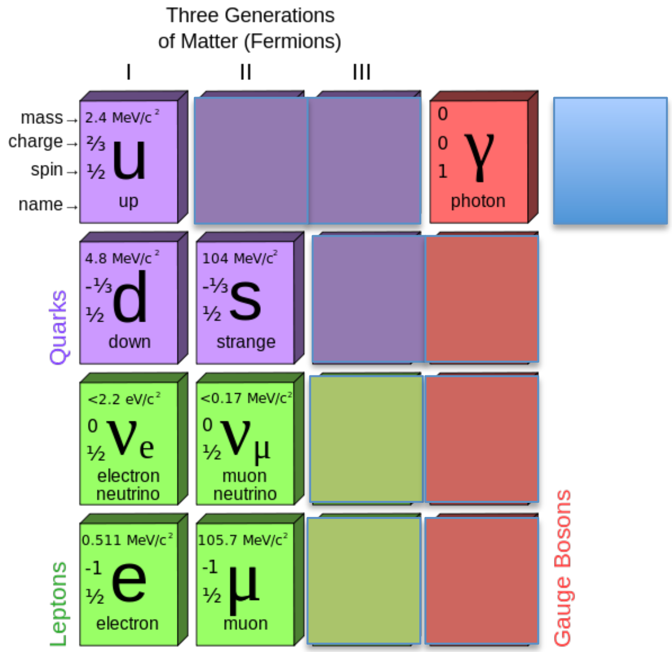
Efe Yazgan

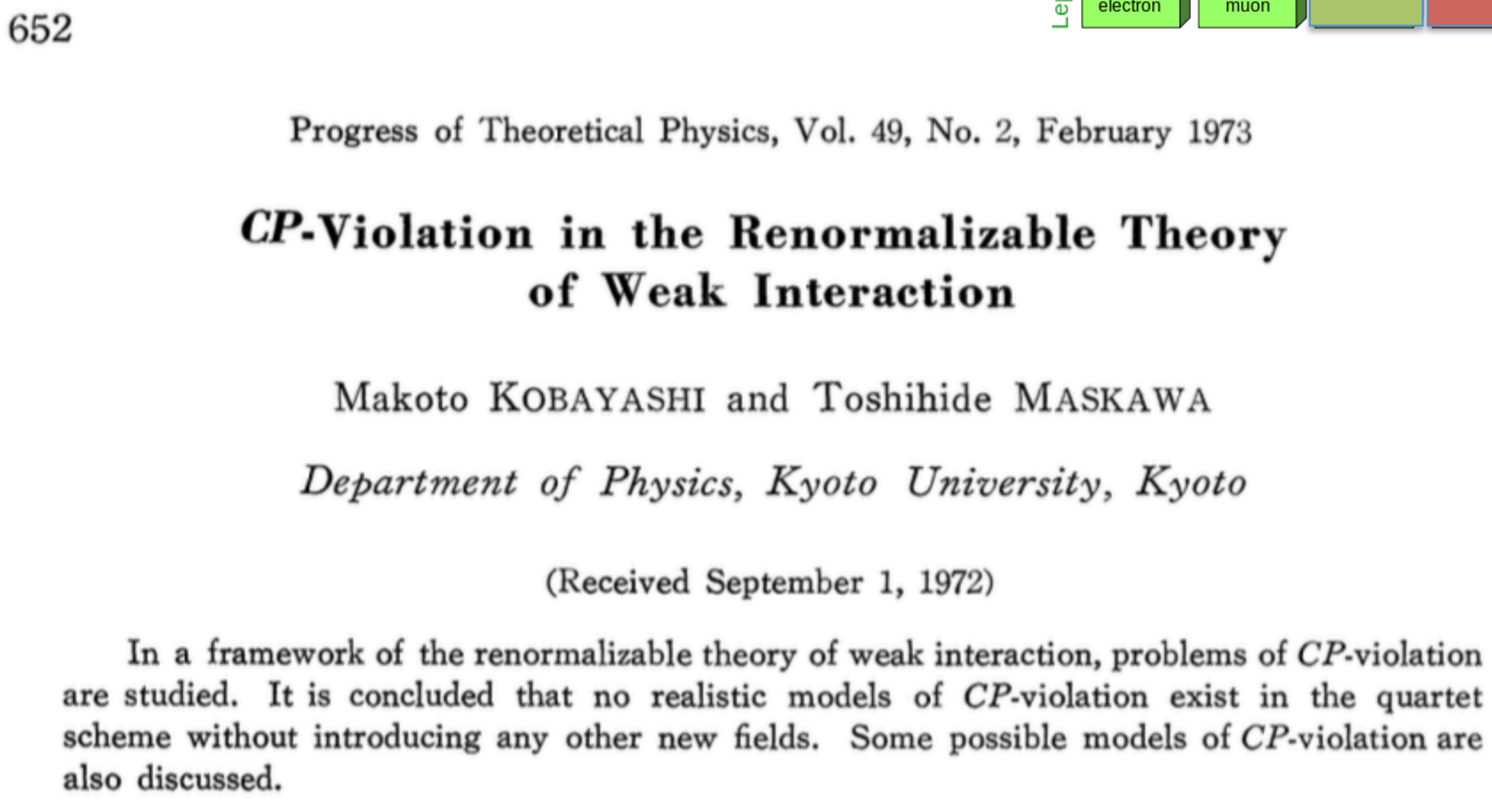
efe.yazgan@cern.ch



Hadron Collider School – HASCO 2017
Georg-August-Universtät, Göttingen, Germany
19 July 2017

Top Quark (through the six-quark model) Predicted in 1973





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Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

Second Argument for the Existence of the Top Quark: Weak Isospin of b Quark and its Partner

- b-quark discovered ('77) in E288 experiment and its iso-spin is measured.
- To complete the third generation → the weak isospin partner of the b-quark.

Standard Model in 1978

BQ

*Special Issue

Forty years ago: Fermilab scientists announce discovery of BOTTOM QUARK

Leon Lederman coaxed quark number 5 to come out and play

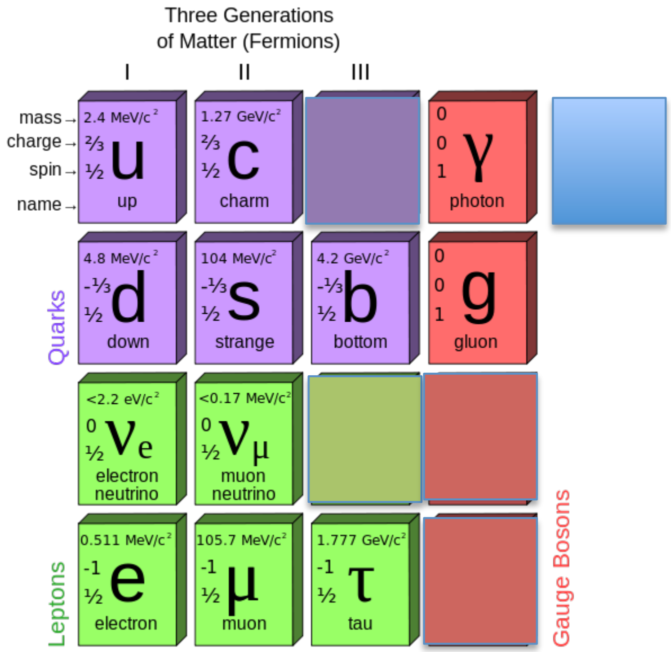
1977: **Heaviest** particle ever seen contains a **bottom**

John Yoh: The Upsilon 9.5 was ***REAL***

JUNE 2017

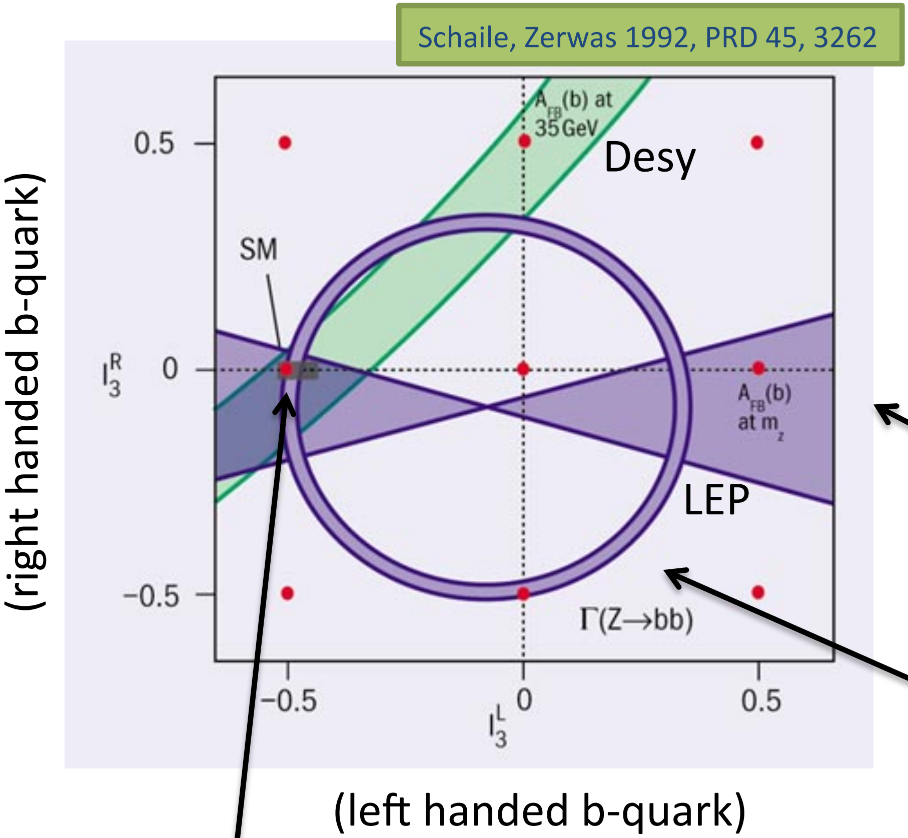
40th Anniversary Issue

WELCOME TO BQ'S FIRST VIDEO-ENHANCED ISSUE *BQ LIVE!*



http://news.fnal.gov/2017/06/forty-year-anniversary-bottom-quark-discovery-announcement/

Second Argument for the Existence of the Top Quark: Weak Isospin of b Quark and its Partner



Schaile, Zerwas 1992, PRD 45, 3262

V→ vector coupling
A → Axial coupling

If V_e, A_e known
→ Extract couplings of the b-quark using A_{FB} and Γ measurements.

$$A_{FB}^{m_Z}(b) = \frac{3}{4}\frac{2V_eA_e}{V_e^2 + A_e^2}\frac{2V_bA_b}{V_b^2 + A_b^2}$$

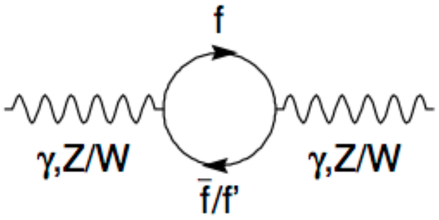
$$\Gamma\left(Z \rightarrow b\bar{b}\right) = \frac{G_F M_Z^3}{2\sqrt{2}\pi}\left(V_b^2 + A_b^2\right)$$

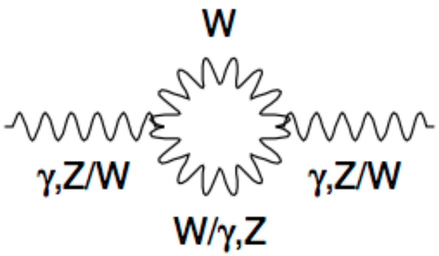
All measurements meet at:
$[I_3^L, I_3^R] = [-1/2, 0]$

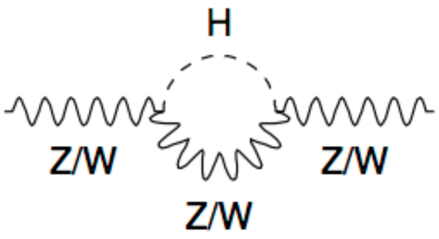
→ Isospin partner with
$[I_3^L, I_3^R] = [+1/2, 0]$ should exist.

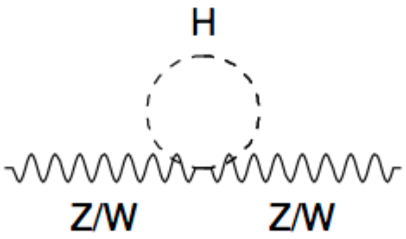
Quantum Fluctuations Seeing Invisible Particles

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

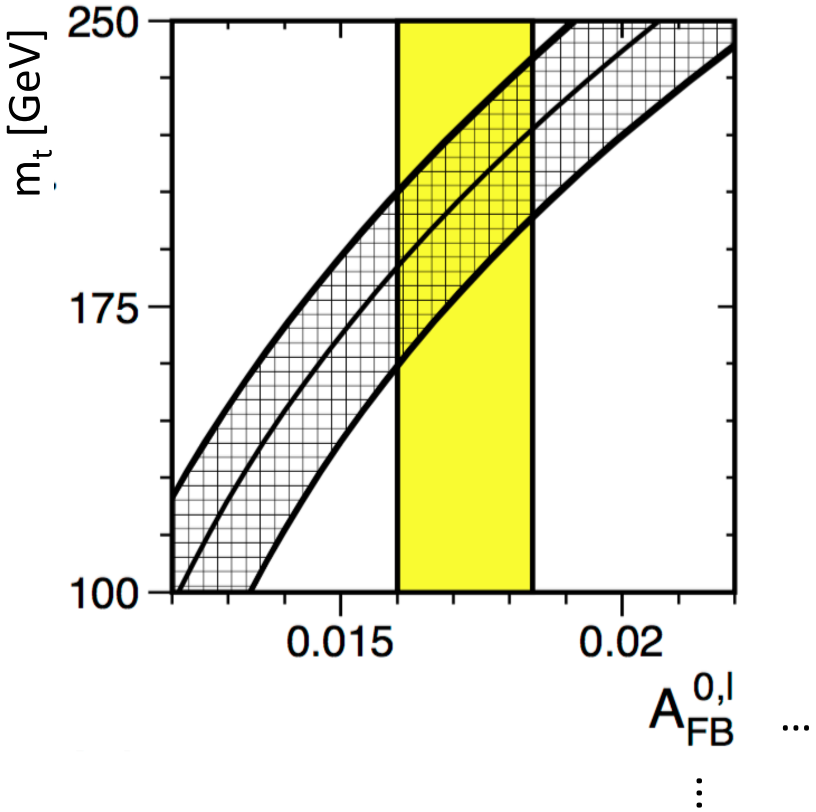


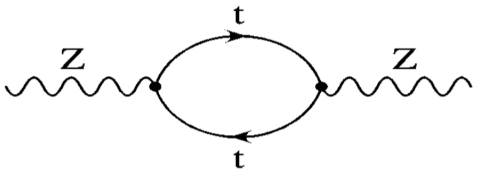






Top Quark's Effect at $\sqrt{s} \approx 100\ GeV < m_t$



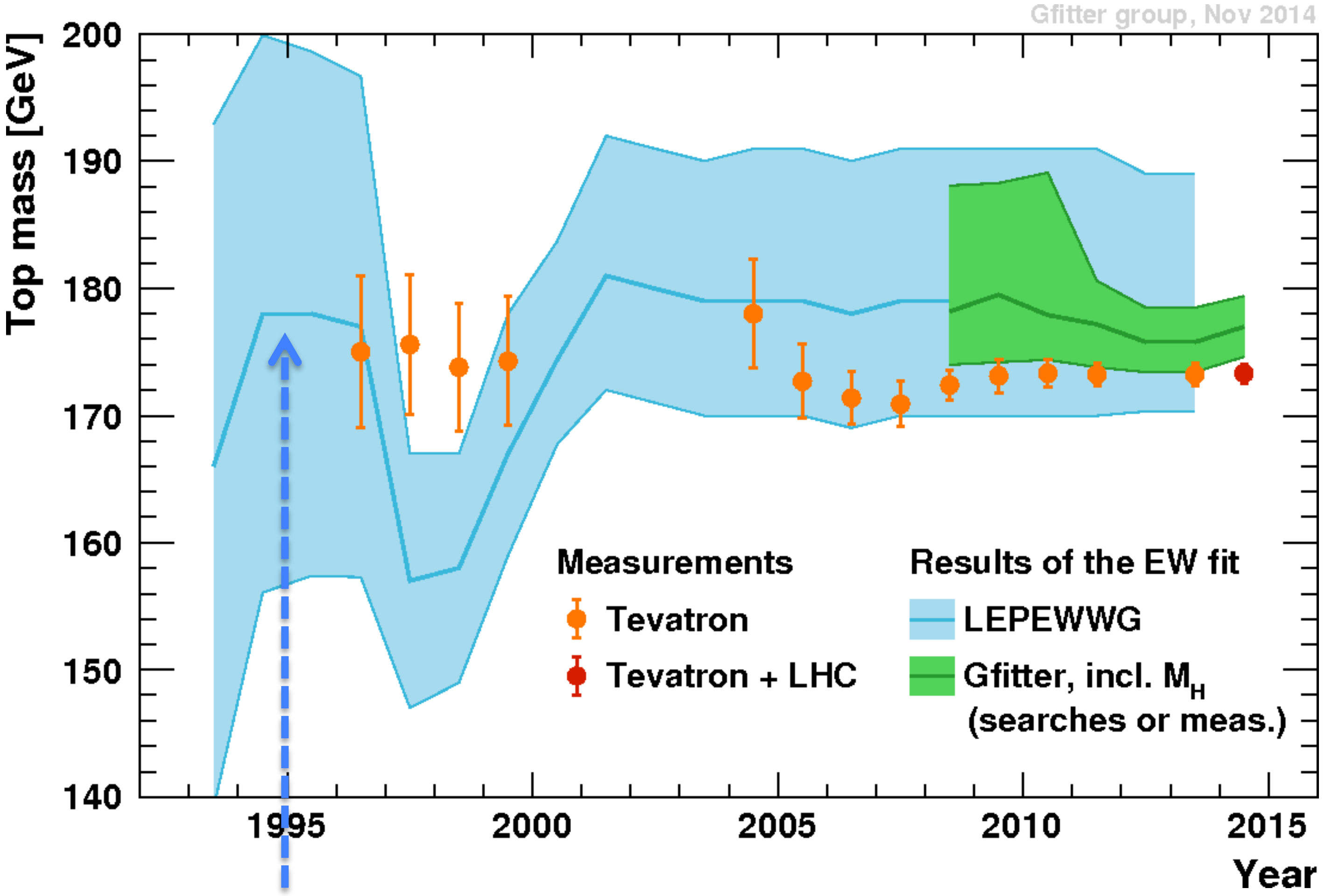


LEP 1 prediction:

$$\boxed{m_t = 173^{+13}_{-10}\,GeV}$$

LEP Collaborations CERN-PPE/95-172

One of the most critical tests of the standard model!



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

- Indirect measurements showed the existence of the top quark and predicted its mass precisely before it was discovered.

Third Argument for the Existence of the Top Quark: Anomaly Cancellation

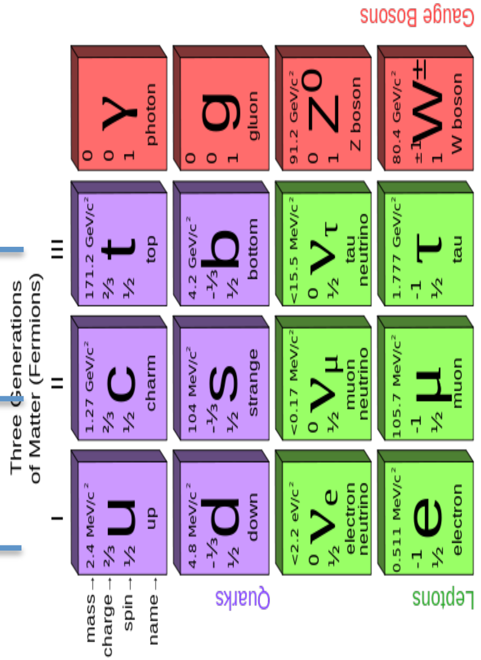
- Sum of electric charges in a family is zero.

color

$$\sum_i q_i = (q_u + q_d)x3 + q_e + q_{\nu_e} = \left\{\left(\frac{2}{3}\right)+\left(-\frac{1}{3}\right)\right\}x3 + (-1) + (0) = 0$$

$$\sum_i q_i = (q_c + q_s)x3 + q_\mu + q_{\nu_\mu} = \left\{\left(\frac{2}{3}\right)+\left(-\frac{1}{3}\right)\right\}x3 + (-1) + (0) = 0$$

$$\sum_i q_i = (\boxed{q_t} + q_b)x3 + q_\tau + q_{\nu_\tau} = \left\{\boxed{\left(\frac{2}{3}\right)}+\left(-\frac{1}{3}\right)\right\}x3 + (-1) + (0) = 0$$



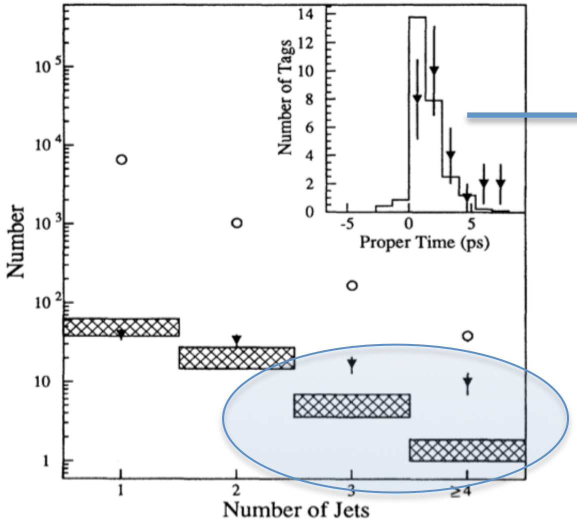
➔ A quark with charge +2/3 should exist.

e.g. see Y. Nagashima, Elementary particle physics Volumes 1 and 2

The Discovery of the Top Quark at the Tevatron

CDF, PRL 74, 2626 (1995)

with O(10) events.



lepton+jets events

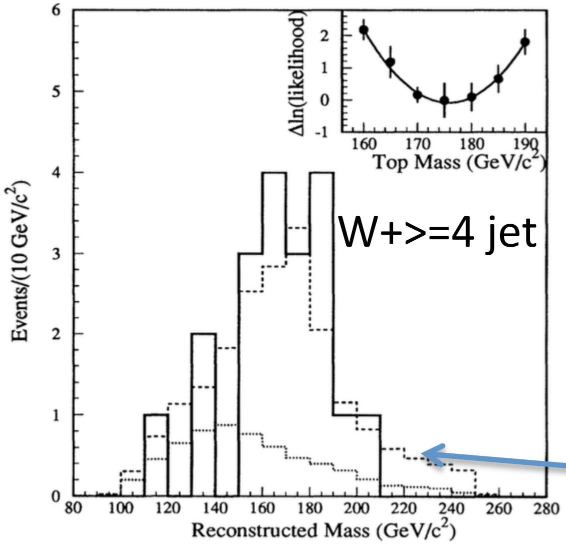
Decay lifetime of secondary vertex tags for W+>=3 jet events.

→Consistent with the prediction for b decays from ttbar simulation.

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

and inconsistent w/ the background prediction.

Circles:
Before b-tagging



W+>=4 jet

$$\sigma_{t\bar{t}}^{CDF}\left(\sqrt{s}=1.8\ TeV\right)=6.8_{-2.4}^{+3.6}\,pb$$

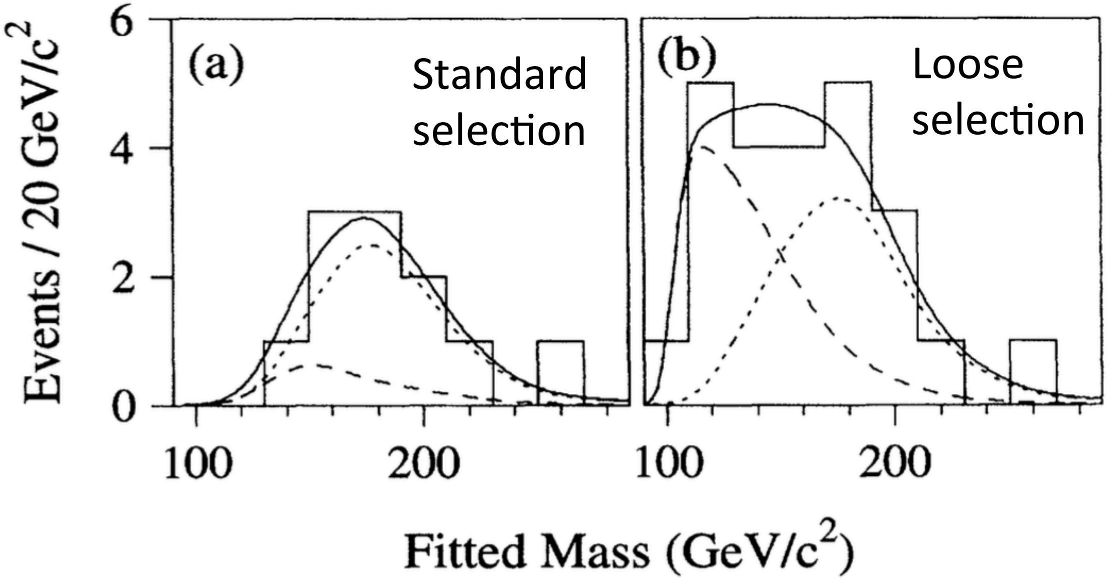
$$m_t^{CDF}=176\pm 8(stat.)\pm 10(syst.)\ GeV$$

Dashed:
Background+ ttbar simulation

The Discovery of the Top Quark at the Tevatron

D0, PRL 74, 2632 (1995)

with O(10) events.



Signal consistent with

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

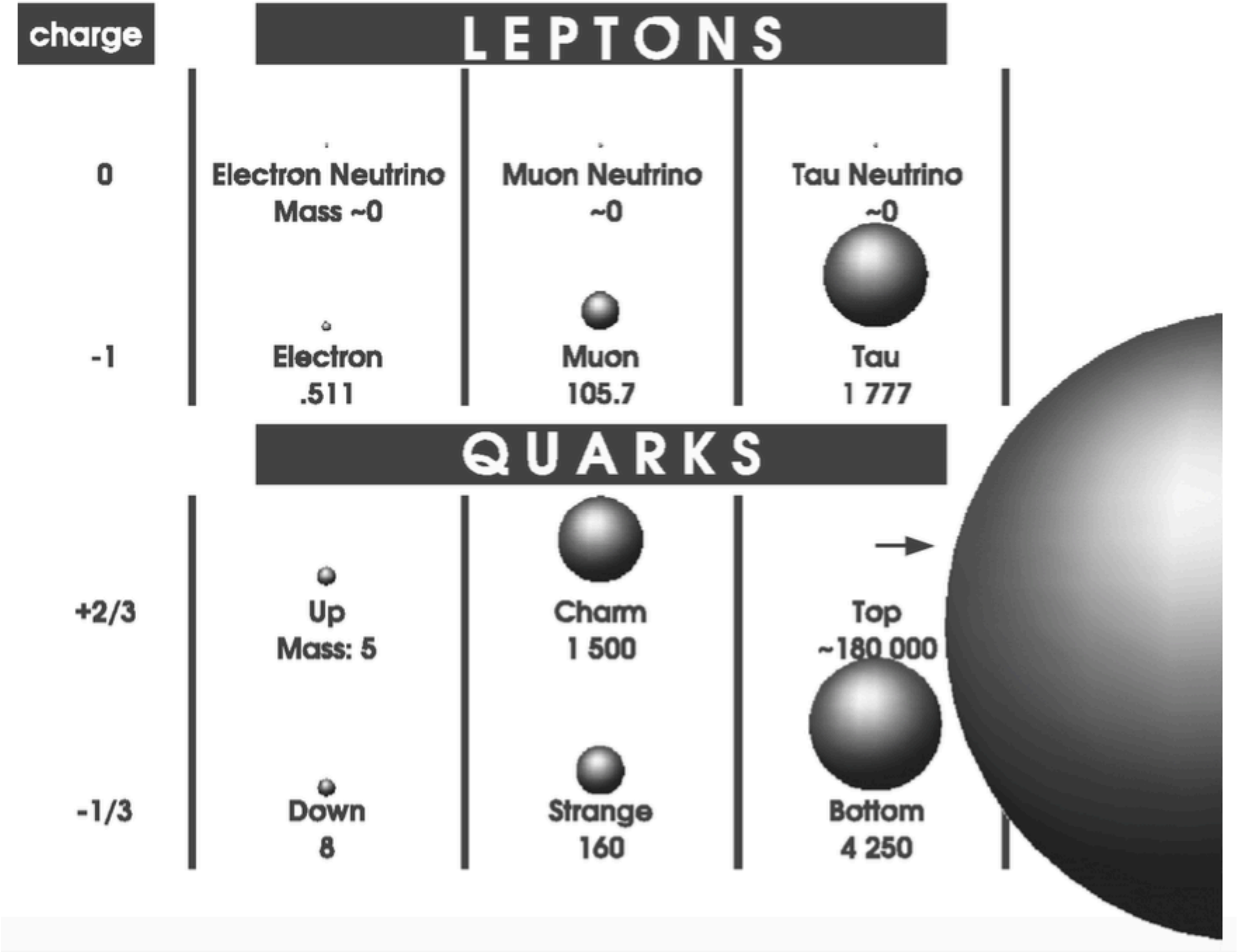
and inconsistent w/ the background prediction.

$$\sigma_{t\bar{t}}^{D0}\left(\sqrt{s} = 1.8\ TeV\right) = 6.4 \pm 2.2\, pb$$

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

The Top Quark

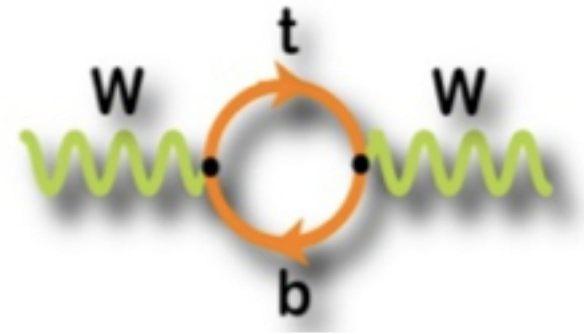
- The most massive particle known to date (m_t~173 GeV).

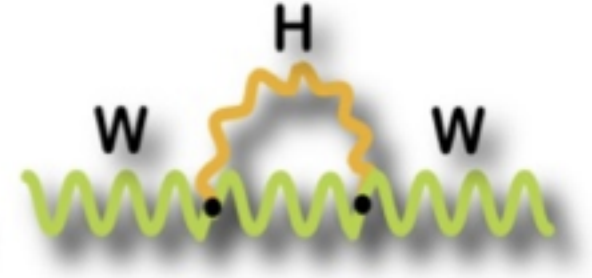


Quadt, EPJC 48, 835 (2006)

Quantum Fluctuations → Higgs Boson

e.g.





HW: Read the Nobel lectures of ‘t Hooft and Veltman (1999)

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

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

Propagator for fermions α 1/q
(Dirac equation)

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

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

Veltman,
NPB 123, 89 (1977)

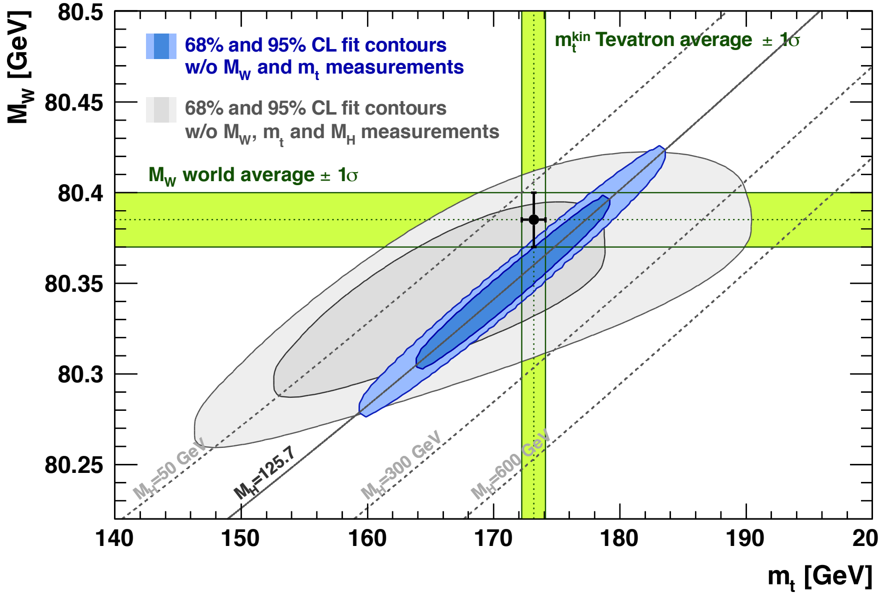
$$\Delta\rho_t \sim G_F m_t^2$$

$$\Delta\rho_H \sim G_F m_W^2 \log\frac{m_H^2}{m_W^2}$$

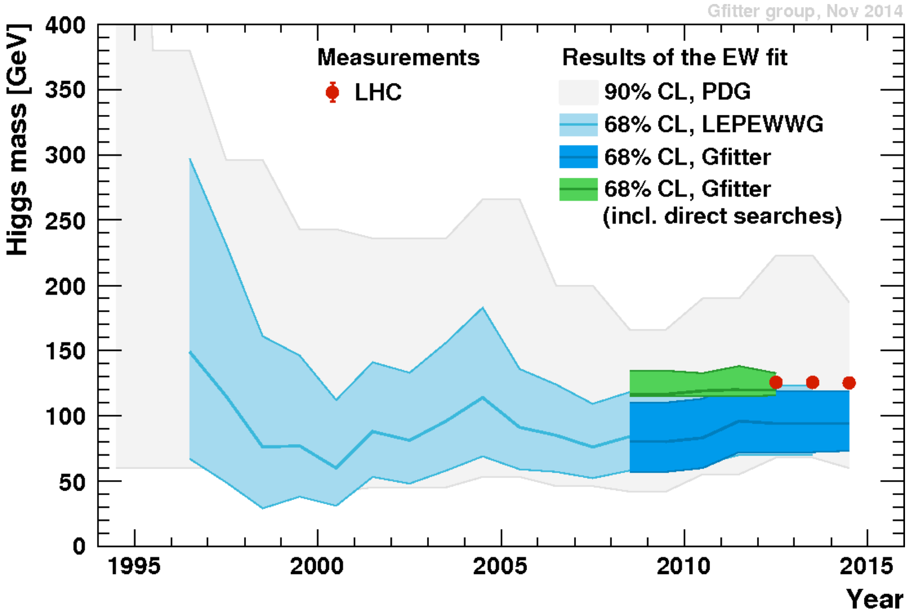
Precision Measurements of Top and W → Higgs

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/

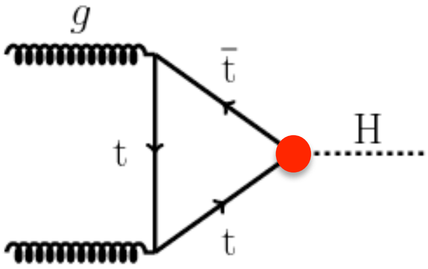


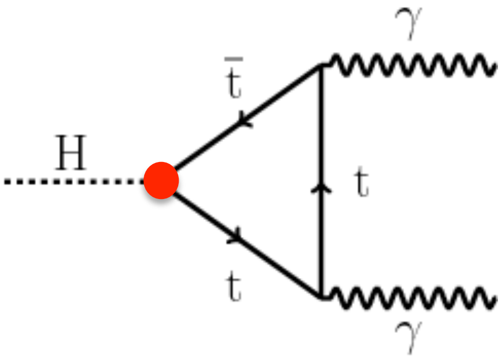
Quantum fluctuations showed the existence of the Higgs boson and predicted its mass precisely before it was discovered.

The most critical test of the standard model!

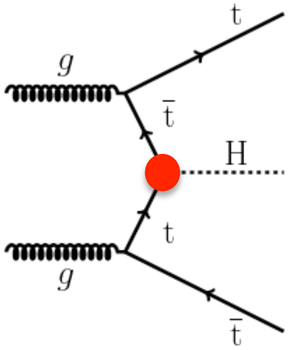
Top – Higgs Coupling
Test fermion mass generation

Indirect

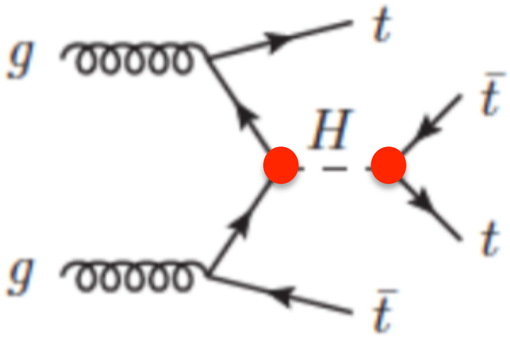




direct



$t\bar{t}H$



Higgs-induced
Four-top

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

→ The largest coupling among the fermions – special role in electroweak symmetry breaking?

→ No direct measurement of top-Higgs coupling yet.

Top Quark Properties

- Top quark has a very short lifetime

$$\tau_t = \frac{1}{\Gamma_t} \sim 0.5\times10^{-24}\,s < \frac{1}{\Lambda_{QCD}} < \frac{m_t}{\Lambda_{QCD}^2} \sim 3\times10^{-21}\,s << \tau_b \sim 10^{-12}\,s$$

$$\tau_t < \tau\left(hadronization\right) < \tau\left(spin-decorrelation\right) << \tau_b$$

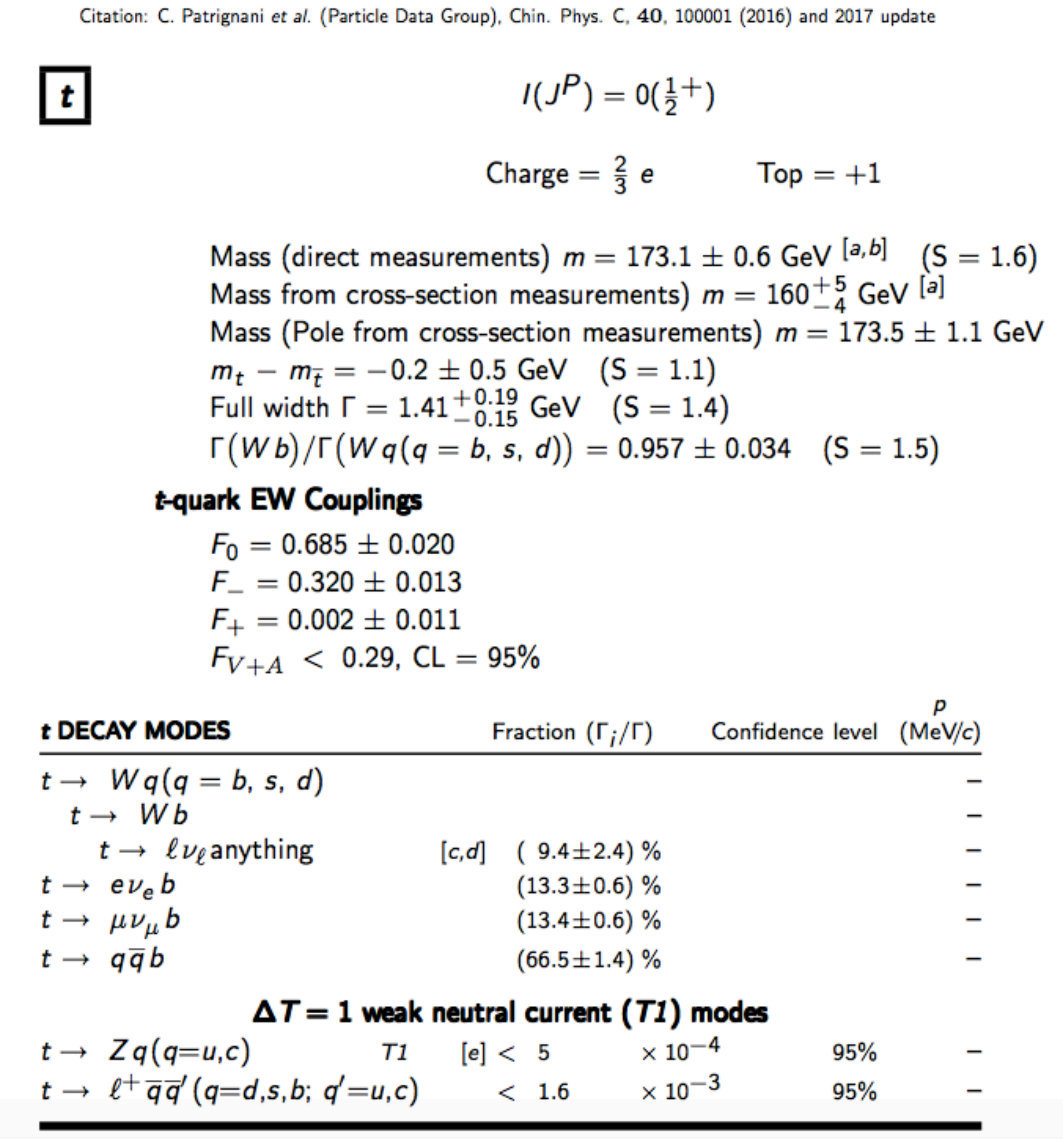
Λ_{QCD}:
→ scale for which α_s becomes very strong
→ ~1 fm scale of a hadron (proton radius)

No hadronic bound states

Spin effects propagate to decay products.

→Behaves like a bare quark
→Top quark properties "directly" accessible (mass, V_{tb}, spin, charge, y_t, …)

Top Properties



Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

t

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

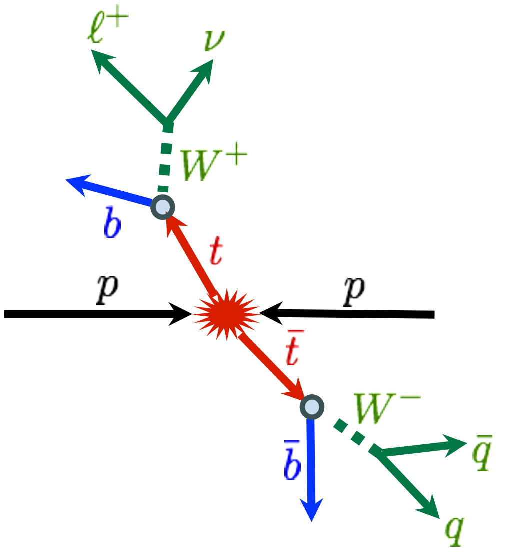
Charge = $\frac{2}{3}\,e$ Top = +1

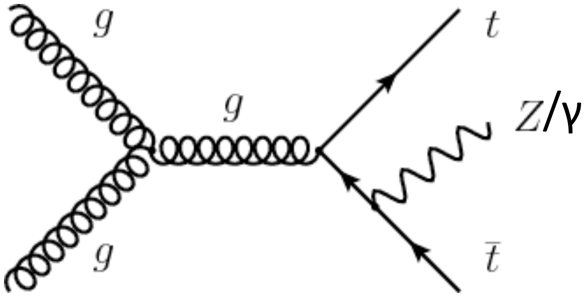
Mass (direct measurements) $m = 173.1 \pm 0.6$ GeV [a,b] (S = 1.6)
Mass from cross-section measurements) $m = 160^{+5}_{-4}$ GeV [a]
Mass (Pole from cross-section measurements) $m = 173.5 \pm 1.1$ GeV
$m_t - m_{\bar{t}} = -0.2 \pm 0.5$ GeV (S = 1.1)
Full width $\Gamma = 1.41^{+0.19}_{-0.15}$ GeV (S = 1.4)
$\Gamma(Wb)/\Gamma(Wq(q = b,\ s,\ d)) = 0.957 \pm 0.034$ (S = 1.5)

t-quark EW Couplings

$F_0 = 0.685 \pm 0.020$
$F_- = 0.320 \pm 0.013$
$F_+ = 0.002 \pm 0.011$
$F_{V+A} < 0.29$, CL = 95%

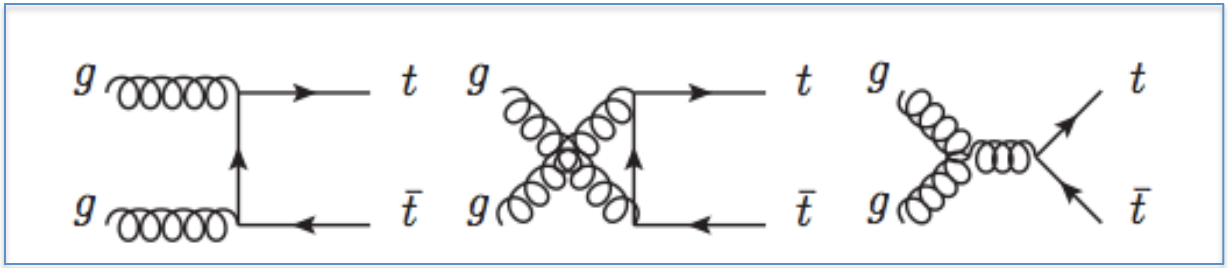
t DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$t \to Wq(q = b,\ s,\ d)$				–
$t \to Wb$				–
$t \to \ell\nu_\ell$ anything	[c,d]	(9.4±2.4) %		–
$t \to e\nu_e b$		(13.3±0.6) %		–
$t \to \mu\nu_\mu b$		(13.4±0.6) %		–
$t \to q\bar{q}b$		(66.5±1.4) %		–
$\Delta T = 1$ weak neutral current ($T1$) modes				
$t \to Zq(q{=}u,c)$	$T1$ [e]	< 5 $\times 10^{-4}$	95%	–
$t \to \ell^+\bar{q}\bar{q}'(q{=}d,s,b;\ q'{=}u,c)$		< 1.6 $\times 10^{-3}$	95%	–

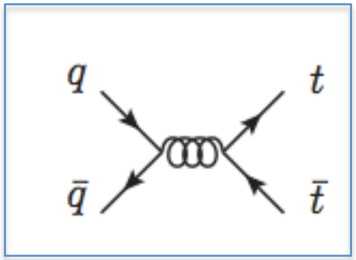




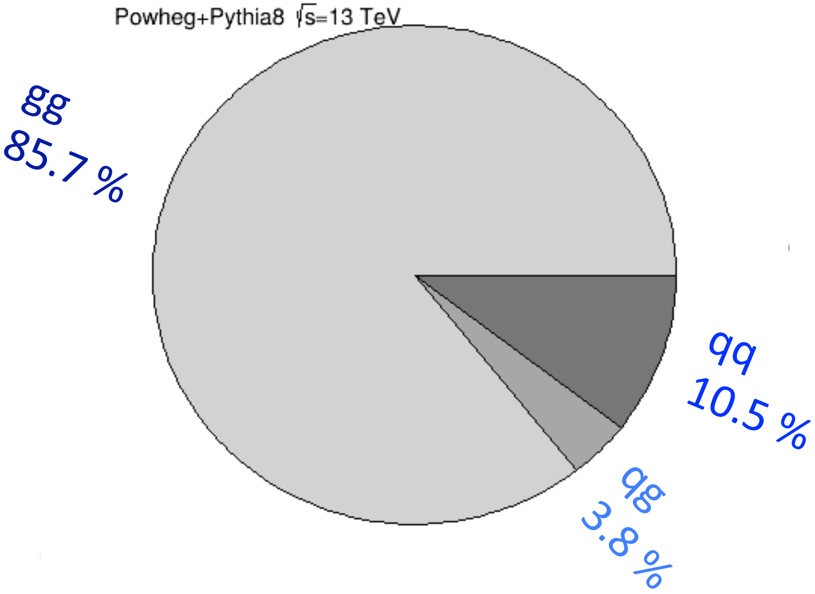
+ Cross sections, asymmetries, spin correlation, …

Top pair production through QCD interactions.



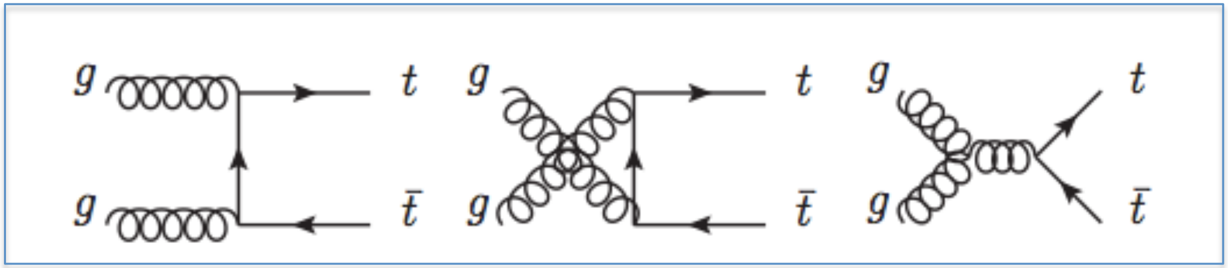


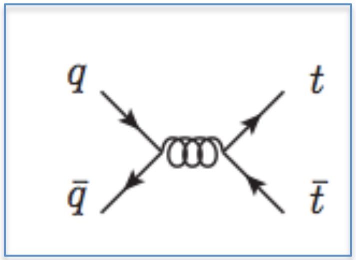
$$\sigma\left(t\bar{t}\right) \sim 830\ \ pb\ \ @\ \ 13\ TeV \qquad \sigma_{t\bar{t}}^{13TeV} \sim 3\times\sigma_{t\bar{t}}^{8TeV}$$



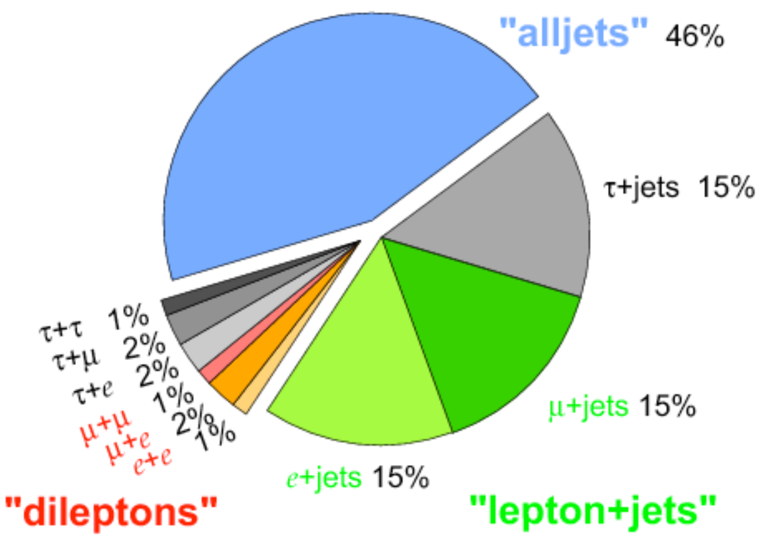
- Sensitive to PDFs, α_s, m_t
- Backgrounds to Higgs and many new physics searches

Top pair production through QCD interactions.

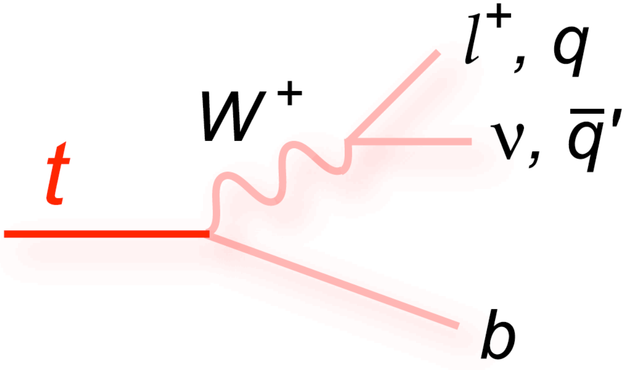




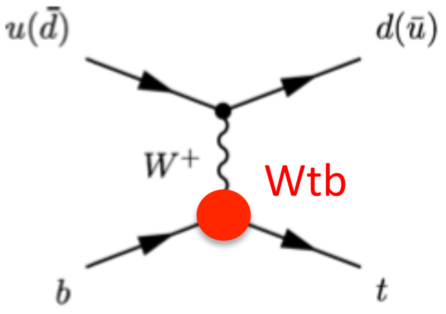
$$\sigma\left(t\bar{t}\right) \sim 830\ \ pb\ \ @\ \ 13\ TeV \qquad \sigma_{t\bar{t}}^{13TeV} \sim 3 \times \sigma_{t\bar{t}}^{8TeV}$$


Top Pair Branching Fractions

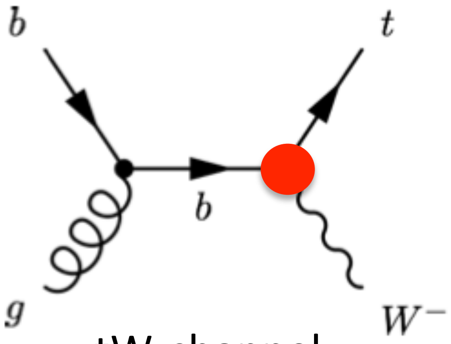
$$m_t > m_W$$



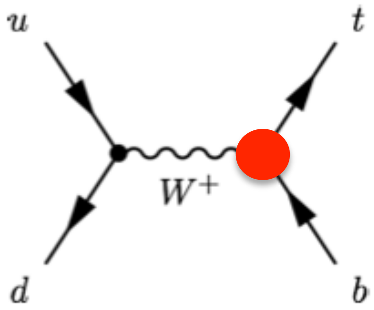
Electroweak single top production



t-channel
~220 pb



tW-channel
~72 pb

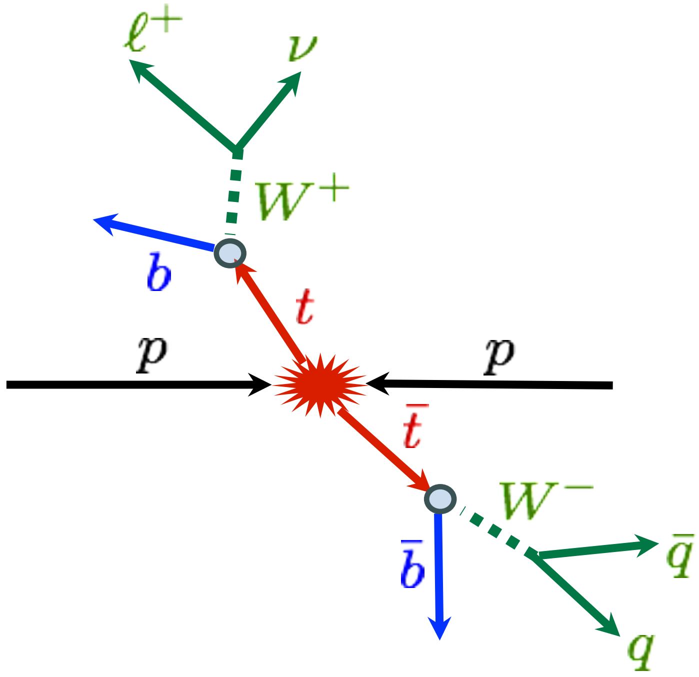


s-channel
~10 pb

$$\sigma_{t-chan}^{13TeV} \sim 2.5 \times \sigma_{t-chan}^{8TeV}$$

- Sensitive to Wtb vertex (V-A coupling), b- and u/d-PDFs.
  - V-A coupling: cross sections, W boson and top quark polarizations.
- Backgrounds to Higgs and many searches

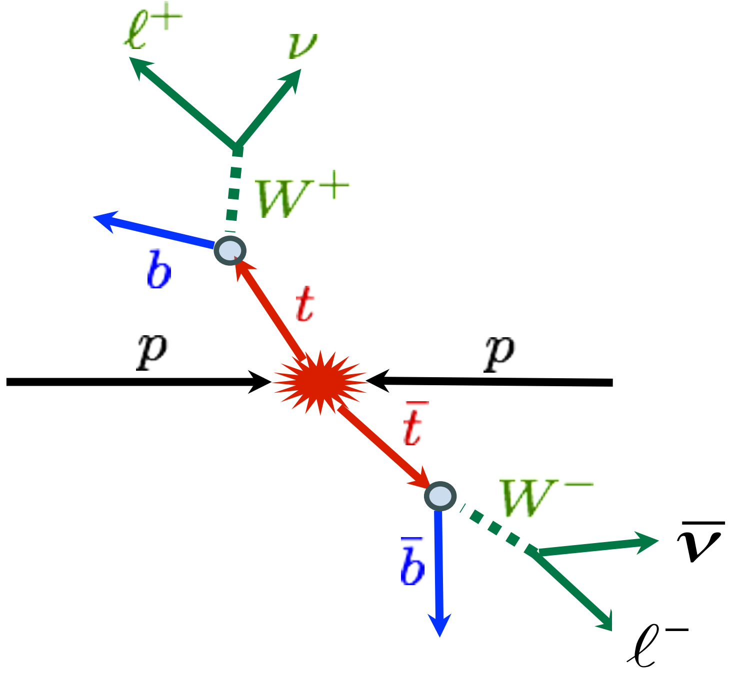
Top Quark Signatures and Backgrounds



- Lepton+jets channel
  - A high p_T lepton
  - ≥ 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

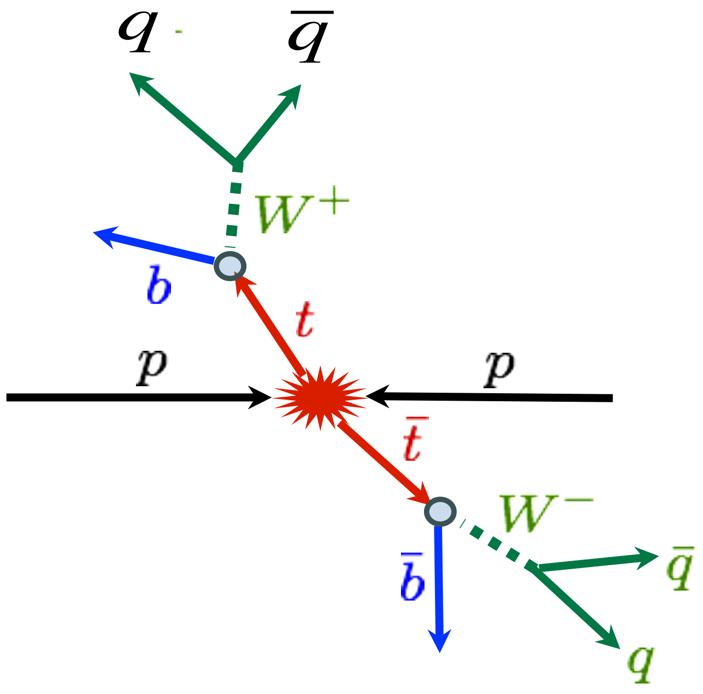


- Dilepton channel
  - Two high p_T leptons
  - ≥ 2 high p_T jets (2 of which are from b-decays)
  - Missing transverse energy

→ 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
  - ≥ 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

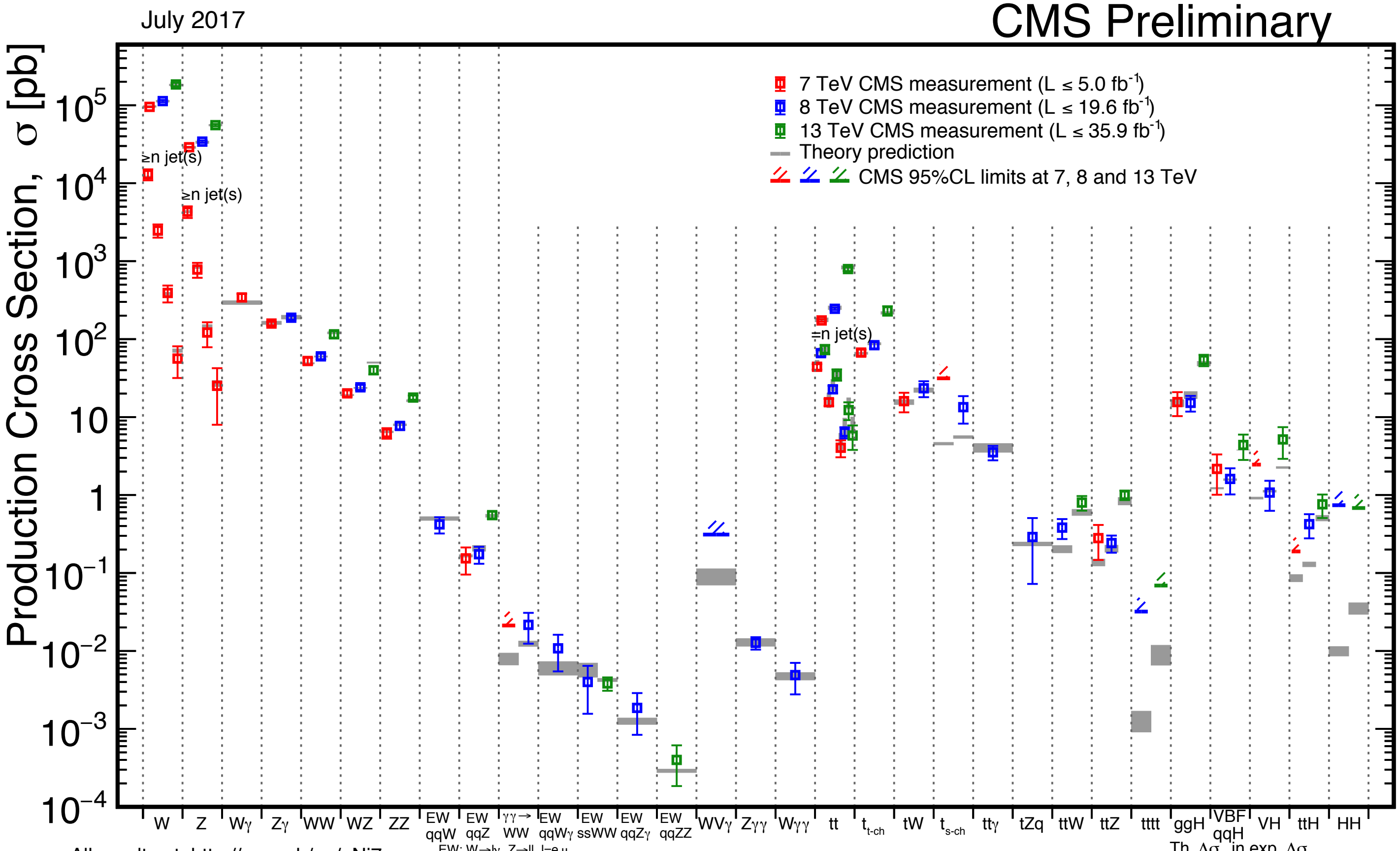
~Plan for the rest of the Lectures

- Top quark production and Event Modelling
- Boosted top
- Questions/Discussion & Break
- Top quark mass measurements
- Questions/Discussion & Break
- Asymmetry measurements
- ttbar spin Correlation
- Top quark couplings
- Questions/Discussion

Example results/plots taken from top quark public pages of Tevatron and LHC experiments (experimental view and most examples from CMS):

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/

SM (Top Quark) Measurements



All results at: http://cern.ch/go/pNj7

- Test SM with more precise and complex calculations.
- Look for and constrain new physics effects through radiative corrections.
- Improve predictions in phase-space regions for new physics searches (top as background).

Cross section Extraction

Total Inclusive cross section
→ count signal events:

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

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

Cross section Extraction

Total Inclusive cross section
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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

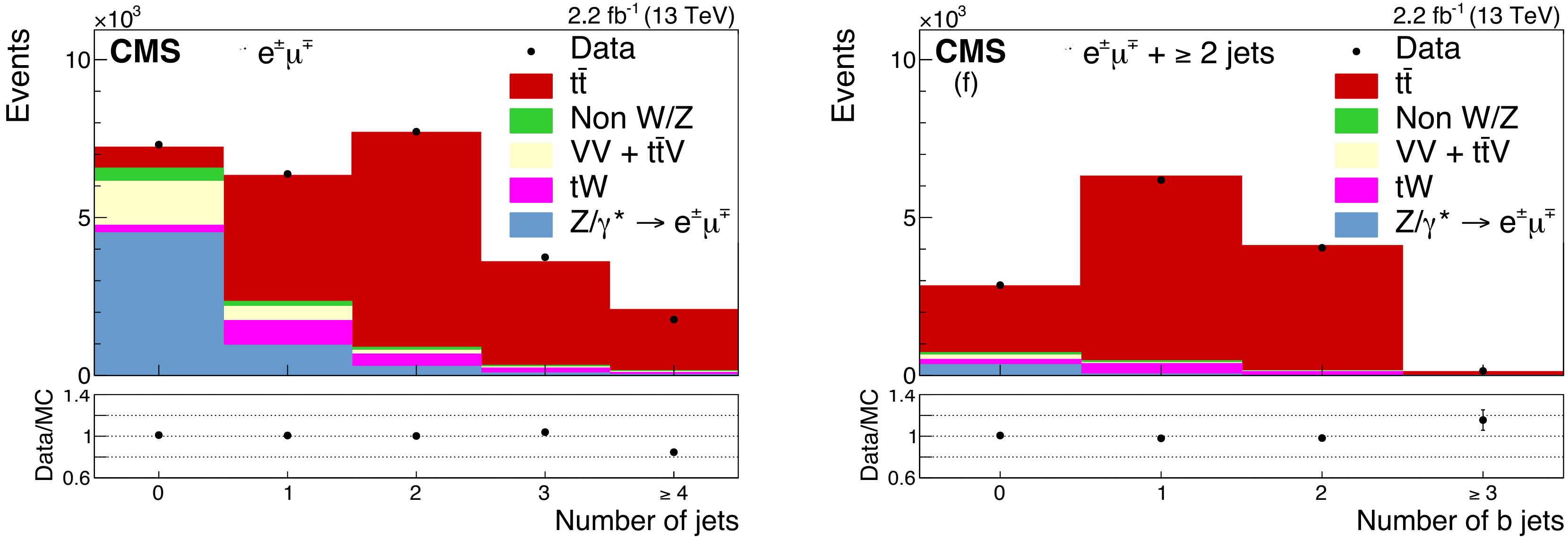
→ In full or fiducial phase space

Response matrix

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

Bin width

Top Pair Cross Section at √s = 13 TeV in the eμ Channel



- Cut and count
  - Select eμ pair with >= 2 jets and >=1 b-tag

http://dx.doi.org/10.1140/epjc/s10052-017-4718-8

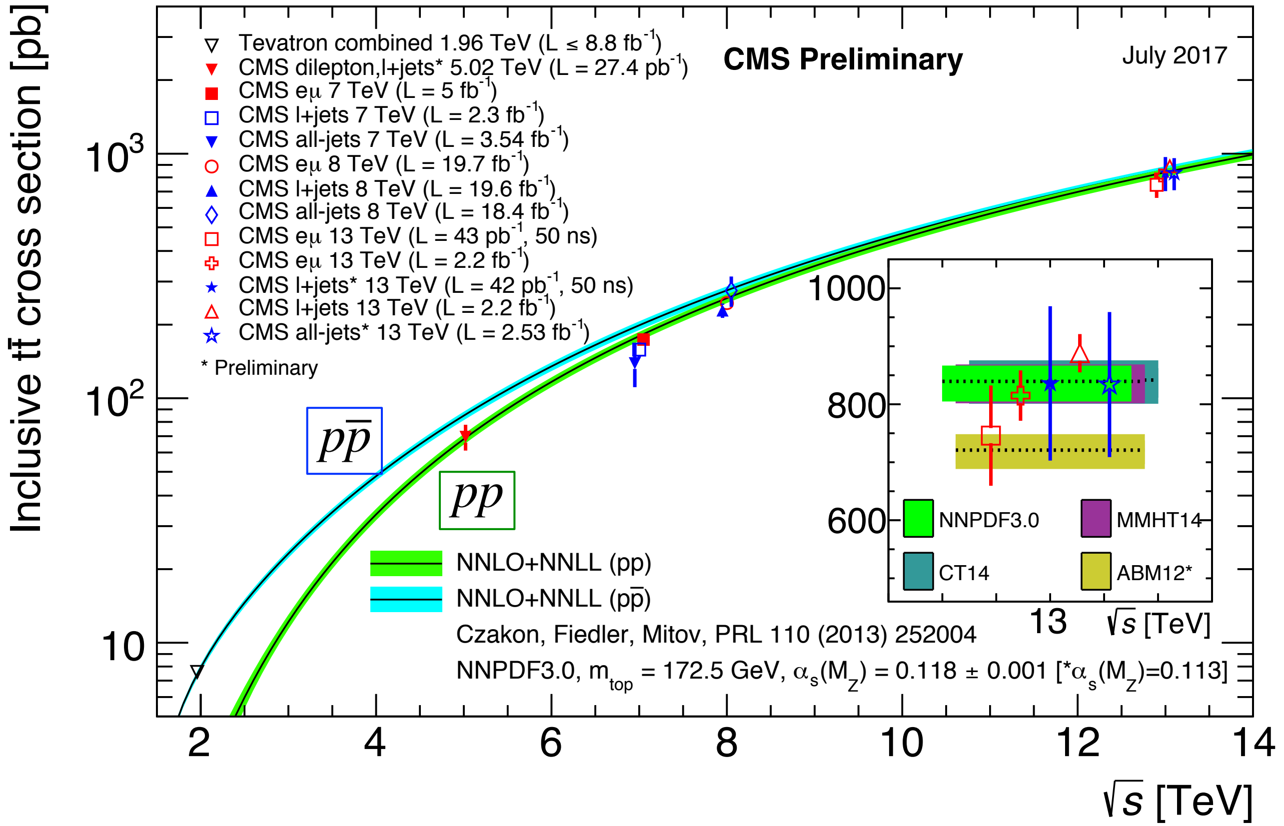
$$\sigma_{t\bar{t}}\left(m_t = 172.5\ GeV\right) = 815 \pm 9\boxed{\left(stat\right)} \pm 38\boxed{\left(syst\right)} \pm 19\boxed{\left(lumi\right)}\ \ pb$$

→ Consistent with NNLO+NNLL prediction and other measurements from ATLAS and CMS.

→ Already dominated by systematic uncertainties:

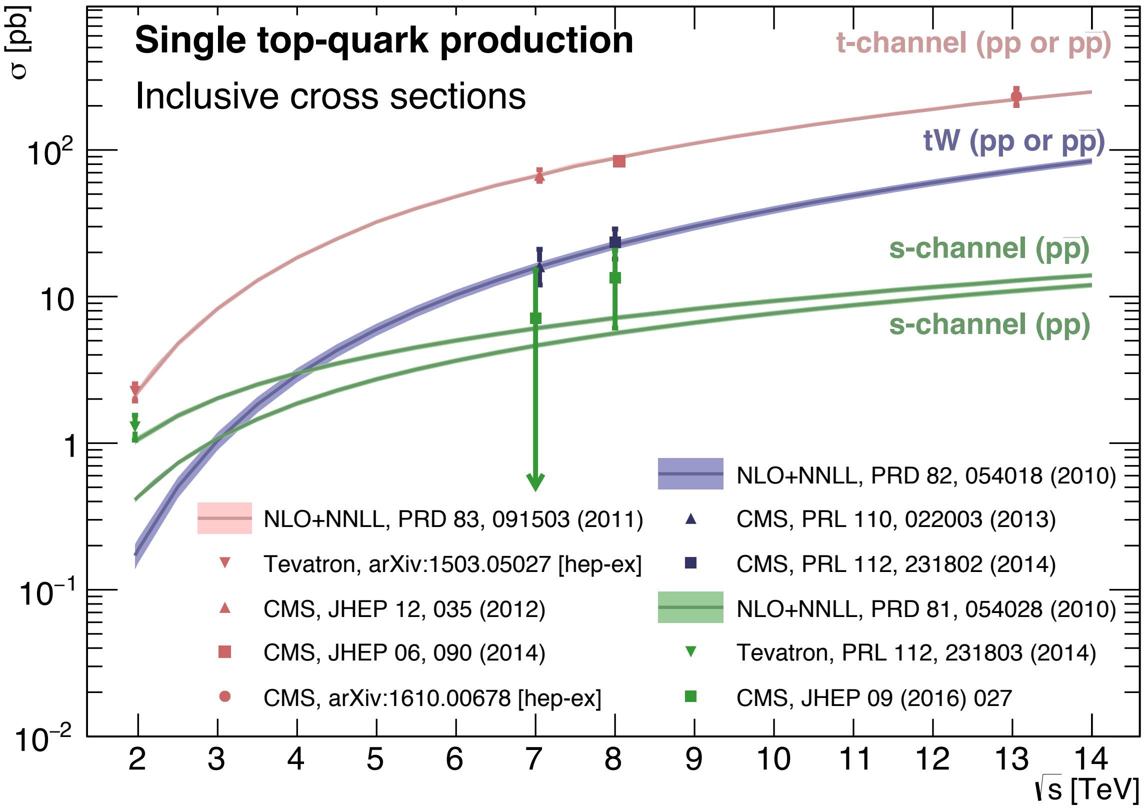
- → Luminosity, efficiencies, jet energy scale
- → Effect of generator choice on acceptance (POWHEG vs MG5_aMC@NLO)

Production Cross Sections from √s = 2 to 13 TeV



- Top quark pair cross section measurements at NNLO+NNLL precision: ~5.5%.
  - ◆ 13 TeV top pair cross section measurements: already at NNLO + NNLL precision
    - ~3.9% (l+jets) arXiv:1701.06228
    - ~5.3% (dilepton) EPJC 77 (2017) 172
  - ◆ Run I legacy measurement precision: ~3.5% (eμ channel) JHEP 08 (2016) 029

Single Top Cross Sections – Current Status



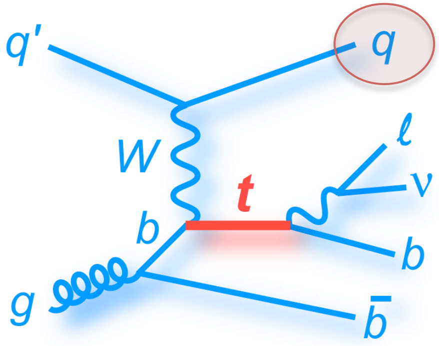
- All single top quark production modes measured at Run I.

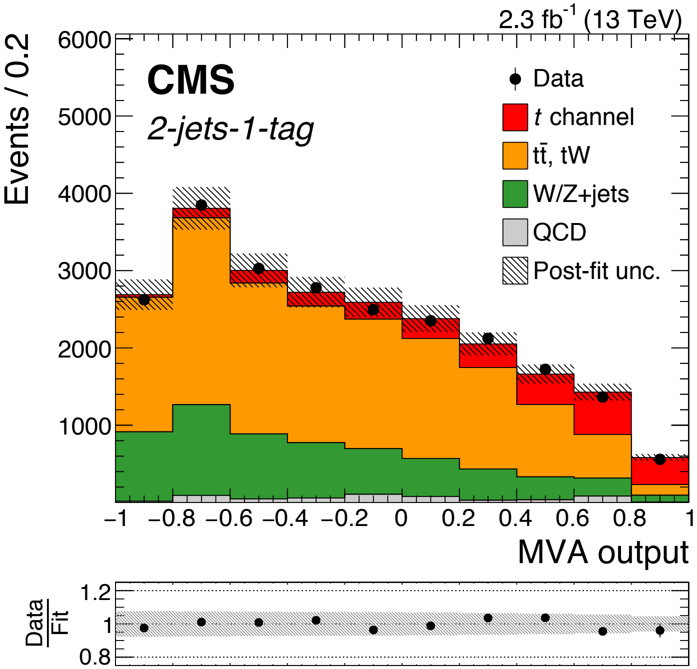
- Single top t-channel cross section at NNLO precision
  - Theory uncertainty ~1%
  - Measurement uncertainty
    - ~10% at 8 TeV (with 20 fb^{-1})
    - ~13% at 13 TeV (with 2.3 fb^{-1}) *arXiv:1610.00678*

Single Top Cross Section at √s = 13 TeV

TOP-16-003

- Event selection: 1 μ, 2 or 3 jets, 1 or 2 b-jets.
- Signal from binned likelihood fits to MVA discriminators with η_j, $m_{l\nu b}$, m_{jb}, $m_T(W)$, … in different categories.





$$\sigma_{t-ch.}\left(t+\bar{t}\right)=238\pm13\left(stat\right)\pm12\left(\exp\right)\pm26\left(theo\right)\pm5\left(lumi\right)\;\; pb=238\pm32\,pb$$

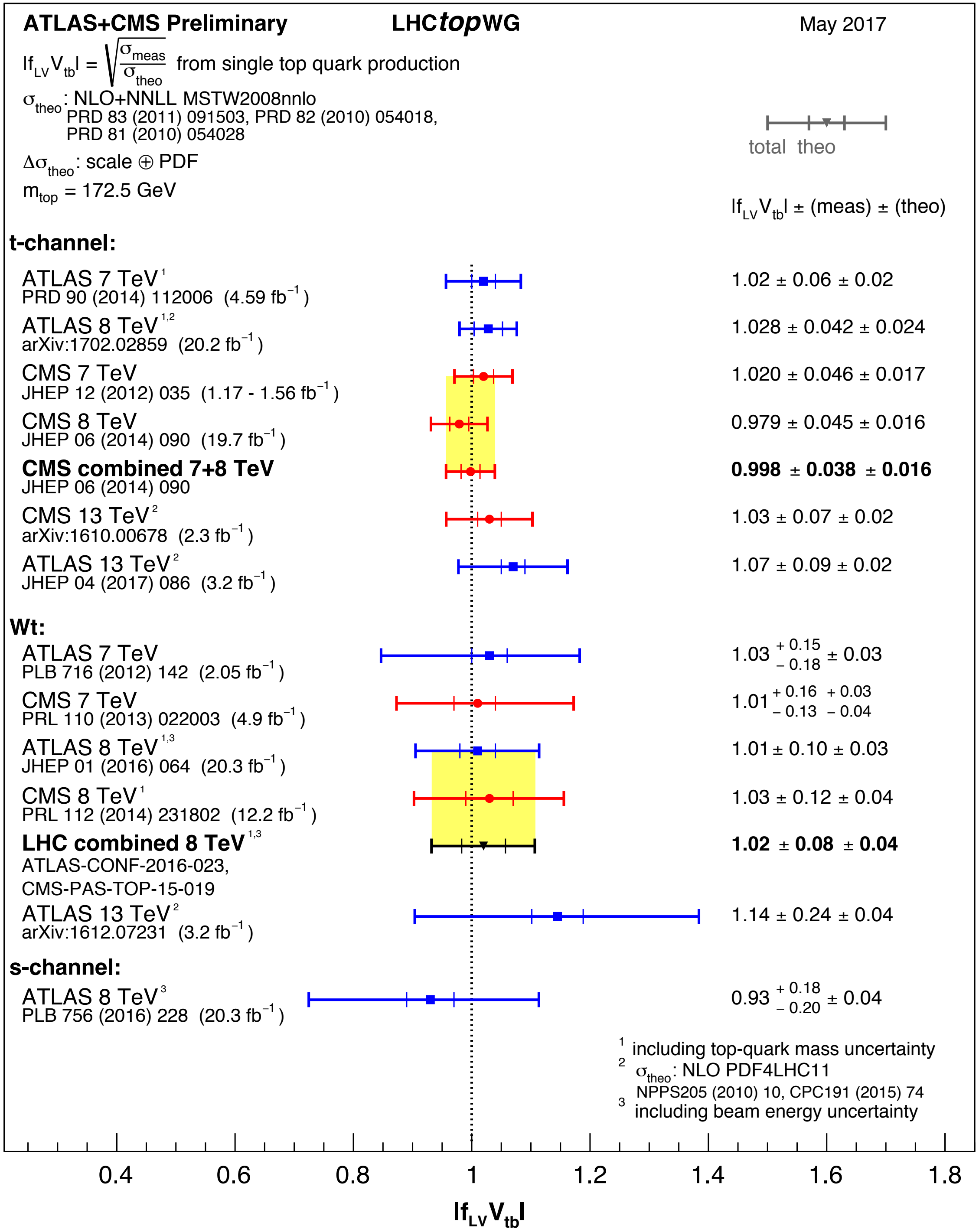
$$\left|V_{td}\right|,\left|V_{ts}\right|<<\left|V_{tb}\right|,\mathrm{Br}\cong1$$

$$\rightarrow\left|f_V^L V_{tb}\right|=\sqrt{\frac{\sigma_{t-ch.}}{\sigma_{t-ch.}^{theo.}}}=1.05\pm0.07\left(\exp\right)\pm0.02\left(theo\right)$$

M. Aliev et al. arXiv:1007.1327

Result dominated by signal modelling and QCD scale uncertainties.

7+8 TeV → $\delta_{|Vtb|}$=4%

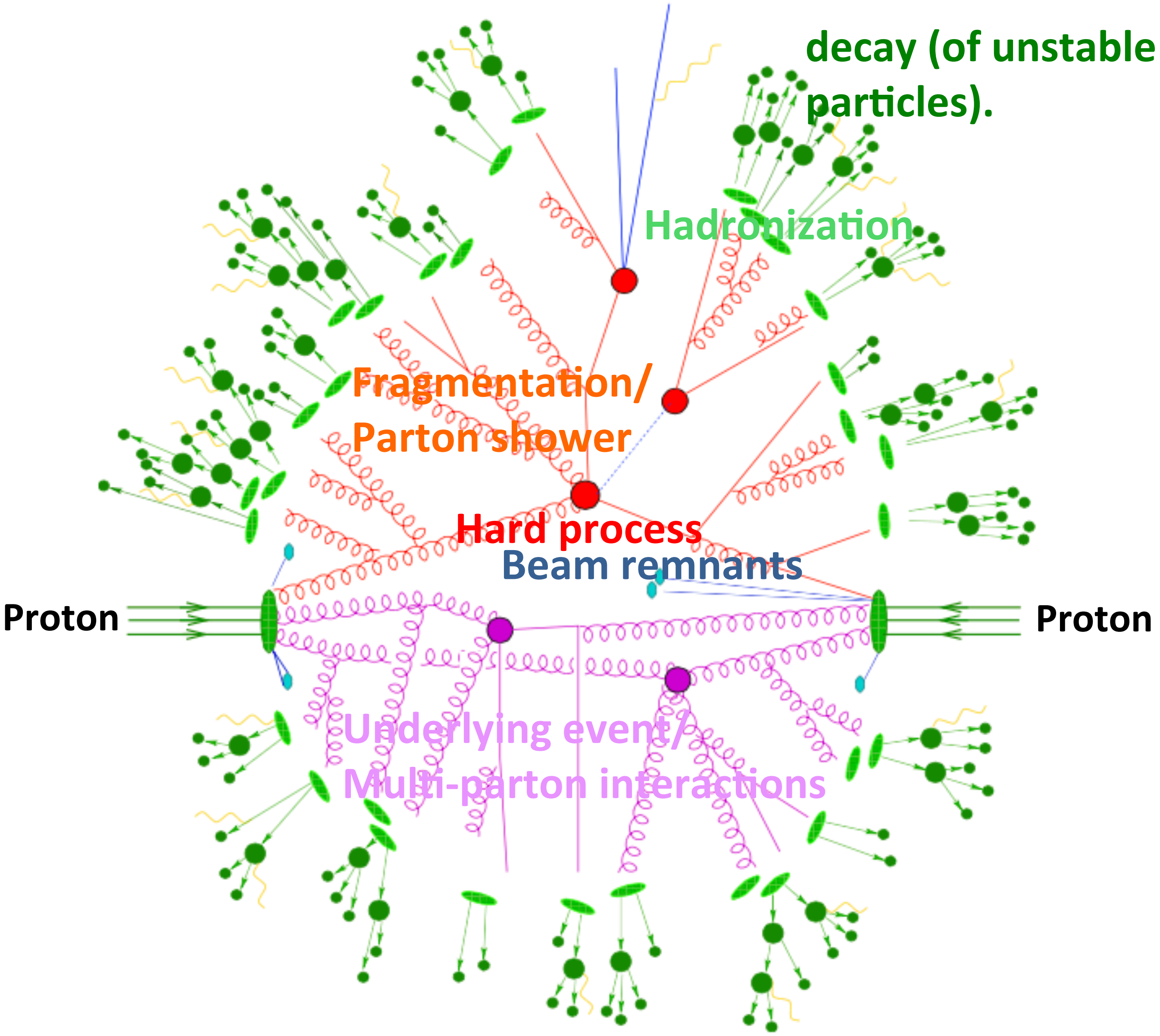


- CKM matrix element Vtb all consistent with SM.

Improving Uncertainties

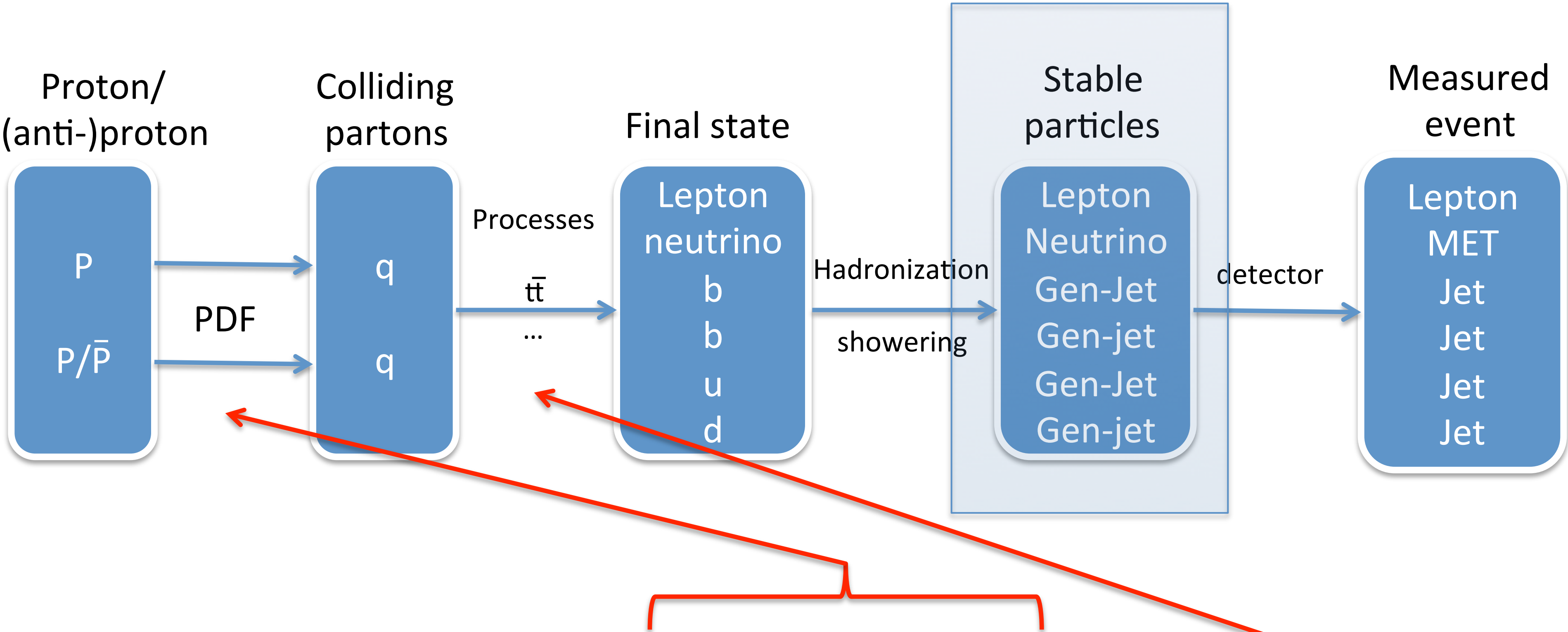
- Contributions to total uncertainty spread of over many different sources
- Some experimental uncertainties will improve with time
  - Statistical uncertainties
  - Lepton id and isolation
  - Jet energy scale
  - …
- Theory uncertainties can partially be tested and improved with measurements
  - Hadronization
  - Top quark pT modelling
  - …

(Top Quark) Event Modeling



Gleisberg et al. JHEP02 (2004) 056

(Top Quark) Event Modeling



Proton/ (anti-)proton

P

P/P̄

PDF

Colliding partons

q

q

Processes

$t\bar{t}$

…

Final state

Lepton
neutrino
b
b
u
d

Hadronization

showering

Stable particles

Lepton
Neutrino
Gen-Jet
Gen-jet
Gen-Jet
Gen-jet

detector

Measured event

Lepton
MET
Jet
Jet
Jet
Jet

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

Top Quark Event Modeling

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

$\oplus$ Underlying event,
showering/
& hadronization

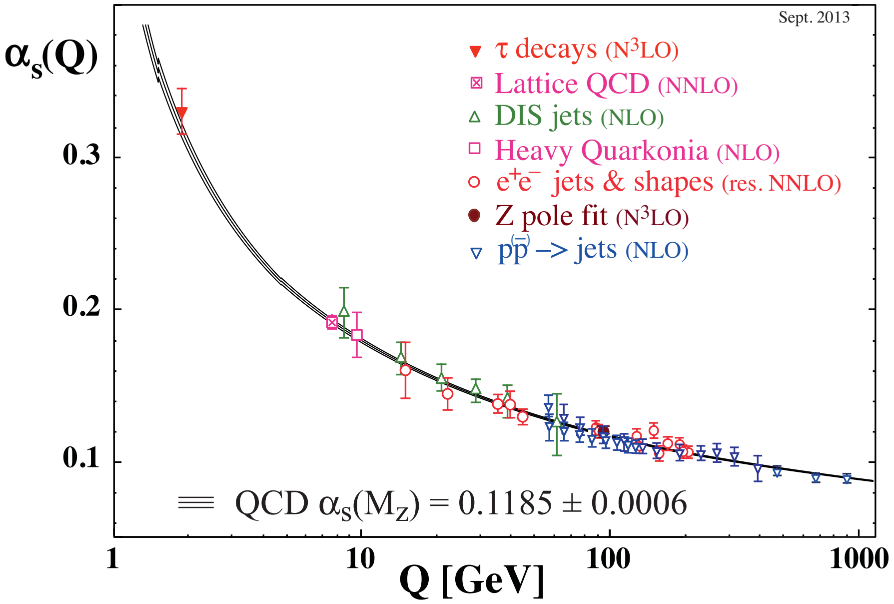
Non-perturbative | *Perturbative in α_s*

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

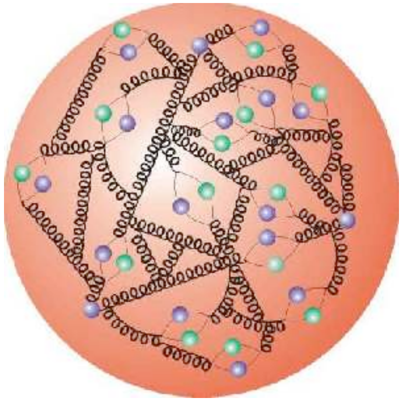
$p_T^{parton} < \mu_F$ | $p_T^{parton} > \mu_F$

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

→ inputs: m_t, α_s, and PDFs



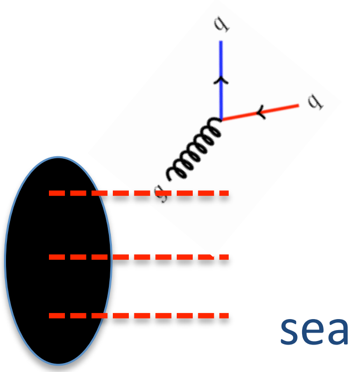
Nucleon Structure



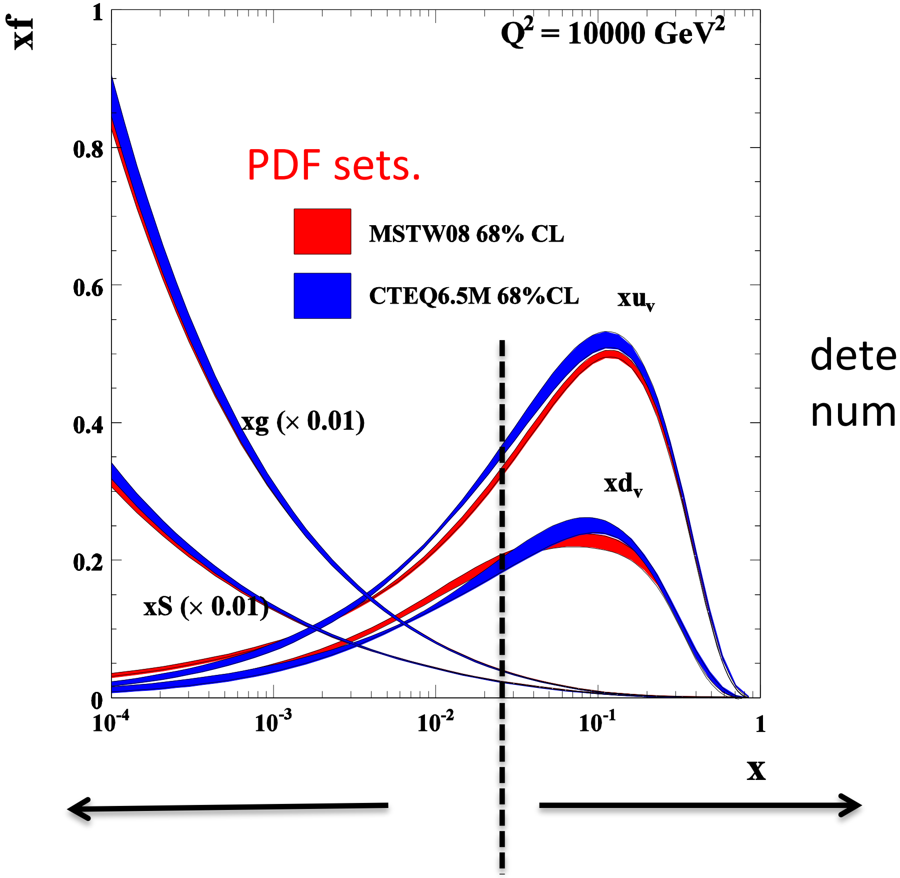
- Hadron collider = parton collider
- $f_i(x,Q^2)$ probability to find a parton to carry the fraction x of the longitudinal hadron momentum at the energy scale Q^2.
    - Intrinsic property of the nucleon → process independent.
    - Parametrized by PDF sets.

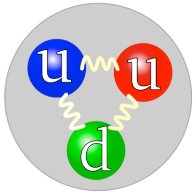
The quark sea:

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



sea quarks dominate.



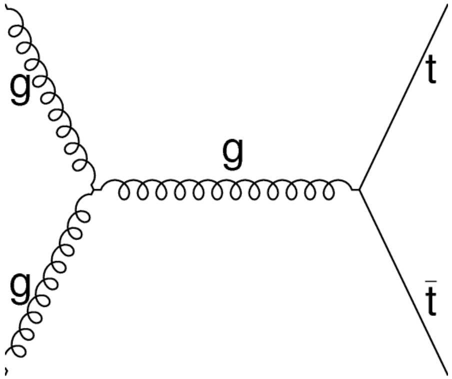


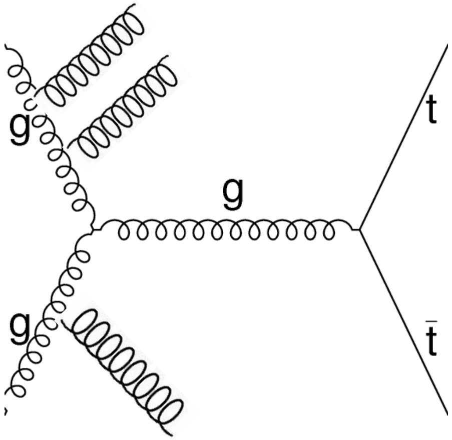
determine the quantum numbers of the hadron.

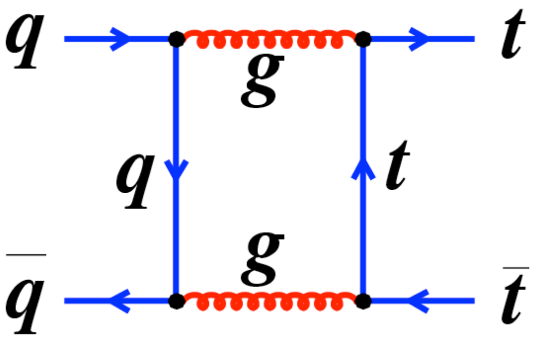
Valence quarks dominate.

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).





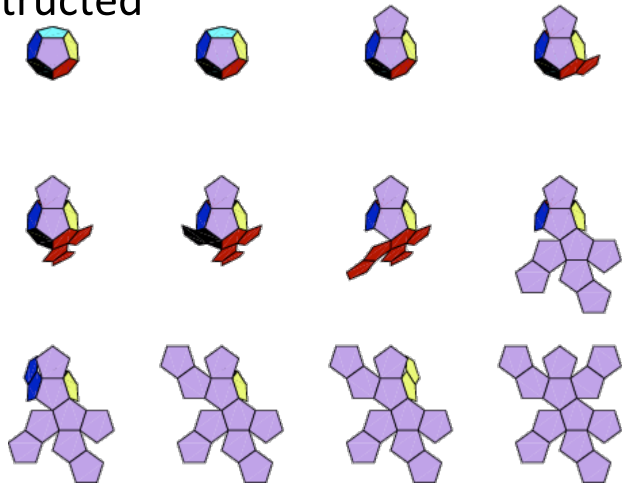


NLO and multi-leg LO need matching/merging to the parton shower.

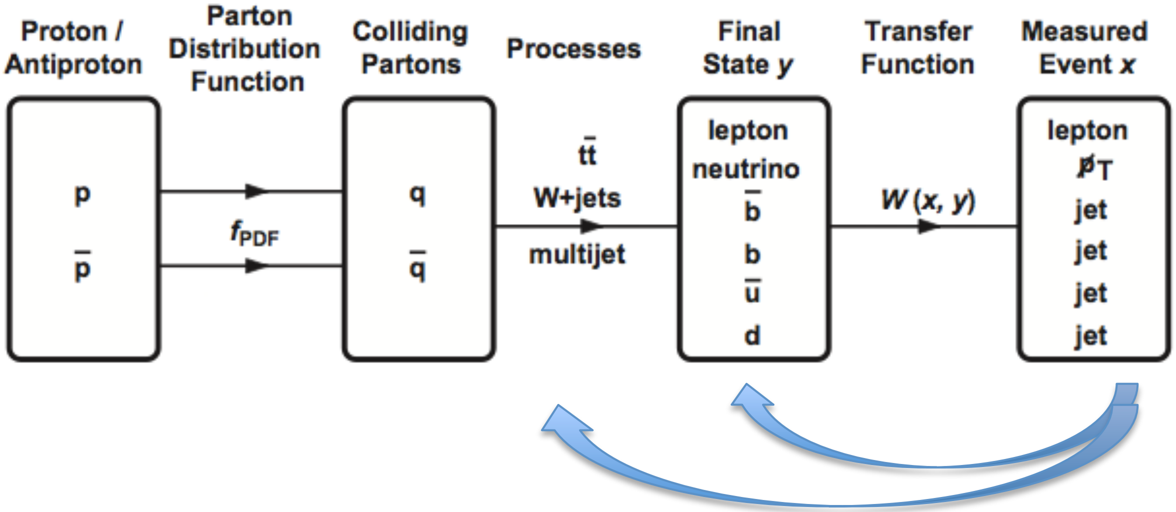
Unfolding

To be able to have the data usable in future and/or by anyone to test new models, or settings, or ideas, unfolding procedure corrects for experiment and monte carlo specific effects.

reconstructed level

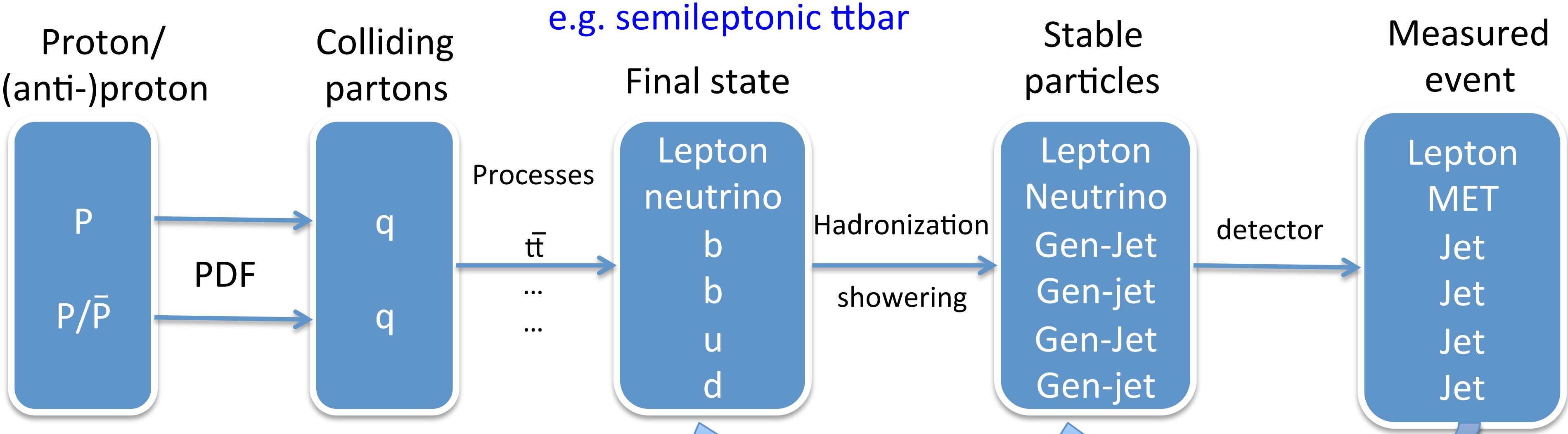


parton/particle level



Unfolding

e.g. semileptonic ttbar



Proton/ (anti-)proton

P

P/P̄

PDF

Colliding partons

q

q

Processes

tt̄

…

…

Final state

Lepton
neutrino
b
b
u
d

Hadronization

showering

Stable particles

Lepton
Neutrino
Gen-Jet
Gen-jet
Gen-Jet
Gen-jet

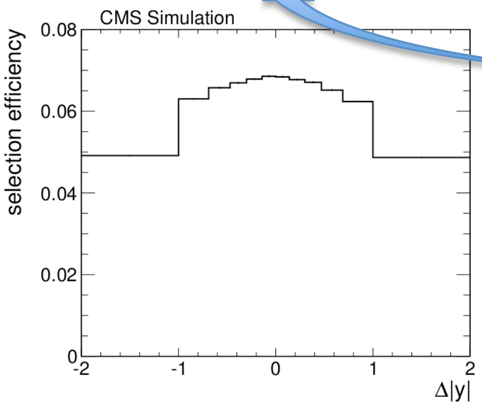
detector

Measured event

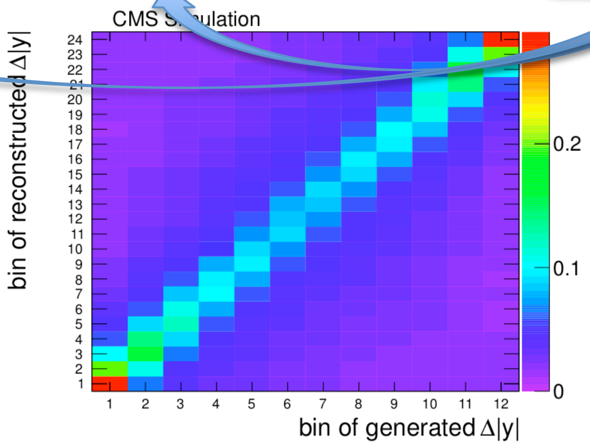
Lepton
MET
Jet
Jet
Jet
Jet

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



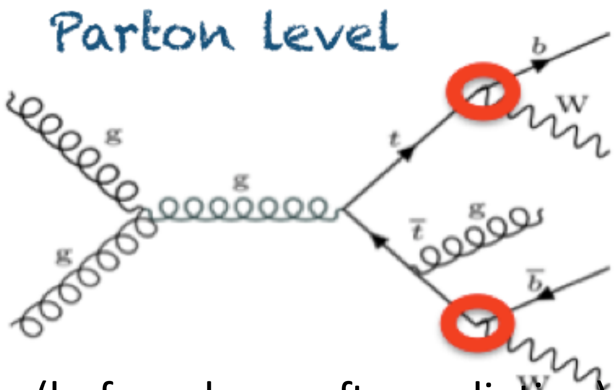
(non-diagonal)
bin migration matrix

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

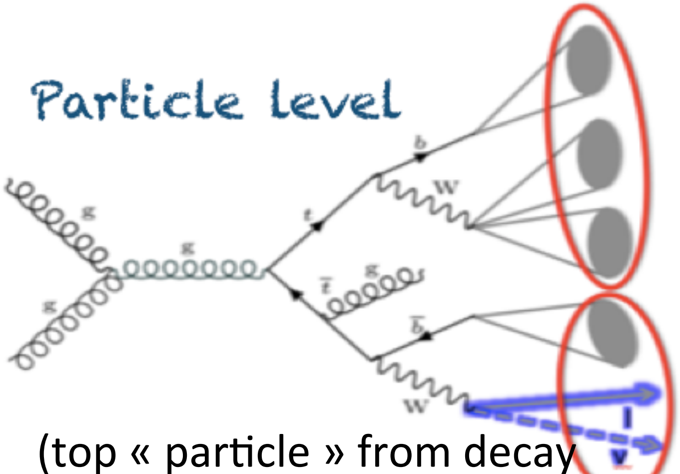
Improving uncertainties: Object Definitions for Top Particle

CMS-NOTE-2017-004

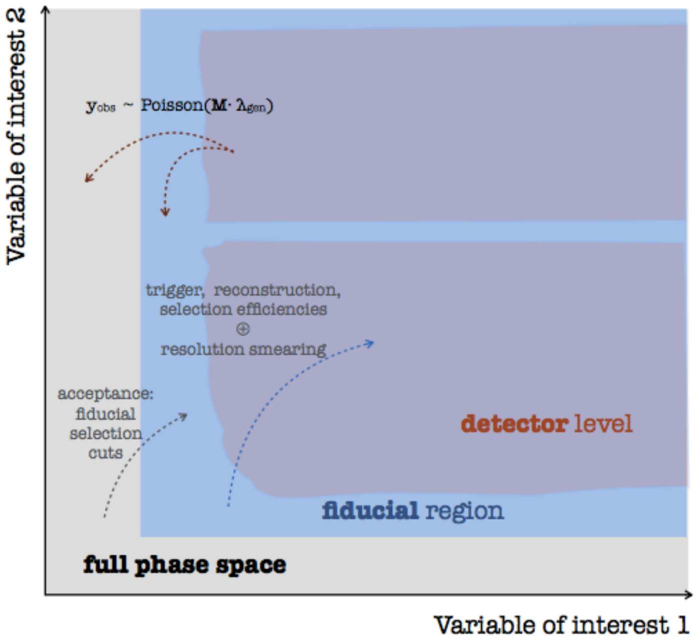
- Top quark simulations
  - at NLO+PS
  - finite width of the top quark for off-shell production and interference with the backgrounds.
  - Parton level top ill-defined.
  - Construct tops only from observed final-state = particle level top.
    - *fundamental aspect of performing current and future measurements of top quark differential production cross sections*



(before decay after radiation)



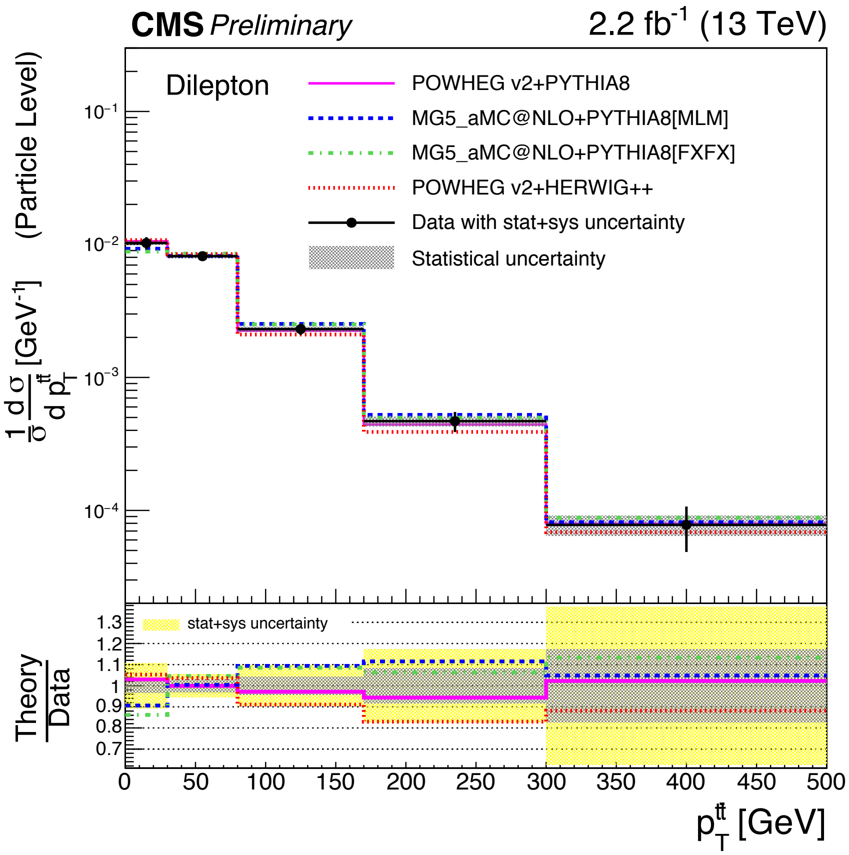
(top « particle » from decay products after hadronization)

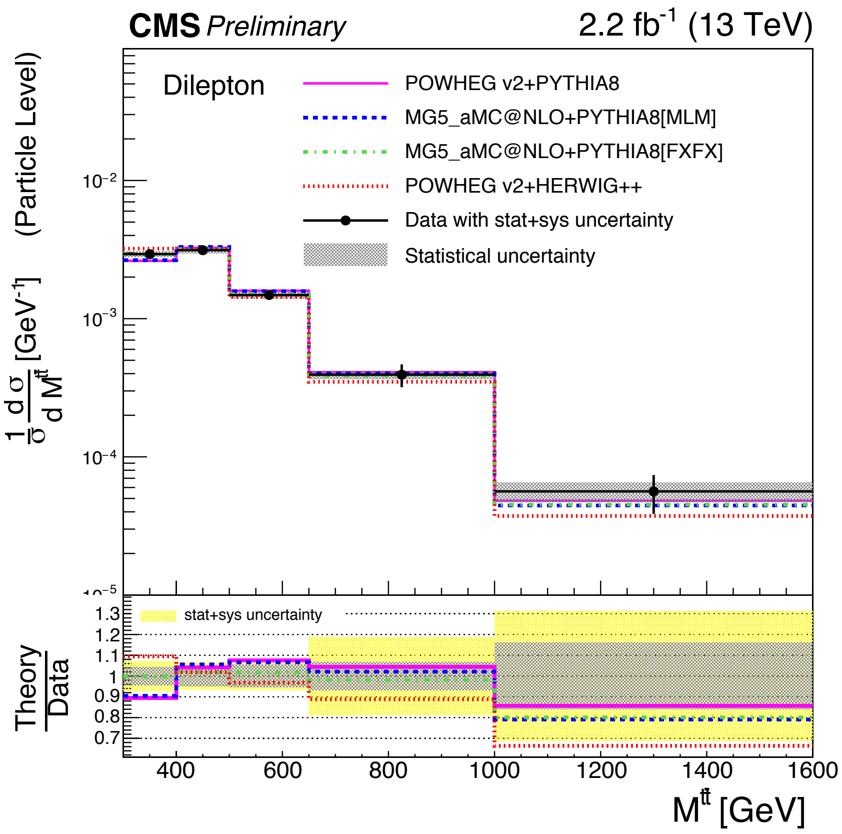


Top Quark Pair Differential Cross Sections

- Test QCD description of the top quark (both as signal and background)
- Test and tune new MCs (NLO ME + LO PS MC)

CMS-PAS-TOP-16-007



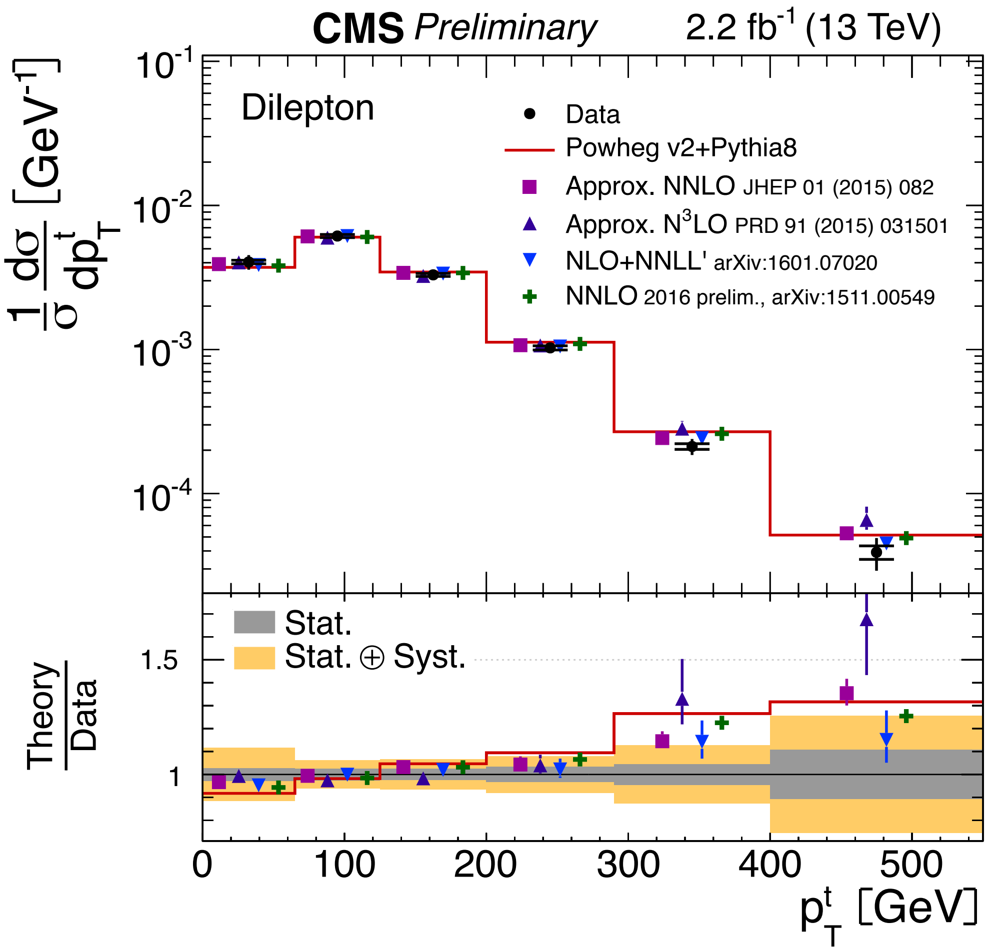


- Differential distributions described reasonably well by NLO MCs at particle level [TOP-16-007], at parton level and NNLO calculations [TOP-16-011, arXiv:1610.04191 (Accepted by PRD)]

The Top Quark p_T

- LHC Run I « discovery »: harder spectrum in LO/NLO + PS predictions than in data (also observed in run II)
  - NNLO+NNLL: significantly better description.

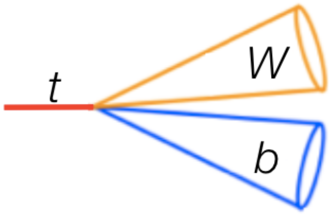
CMS-PAS-TOP-16-011



Boosted Top Pair Production

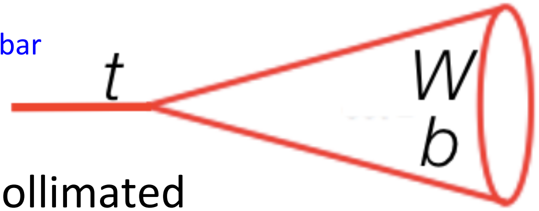
arXiv:1605.00116

Resolved topology:
Each parton matched
to a single jet.



High top p_T or high m_{ttbar}

Boosted topology:
→ Decay products collimated

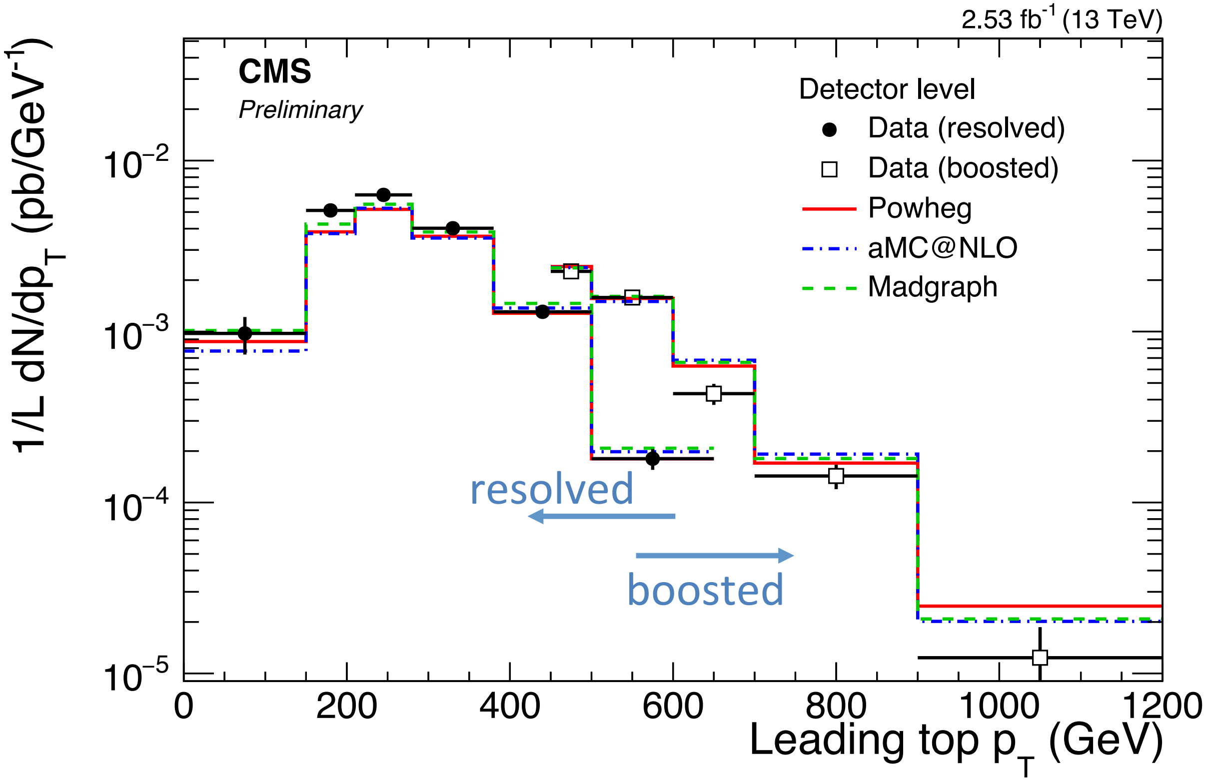


"fat jet", R=0.8

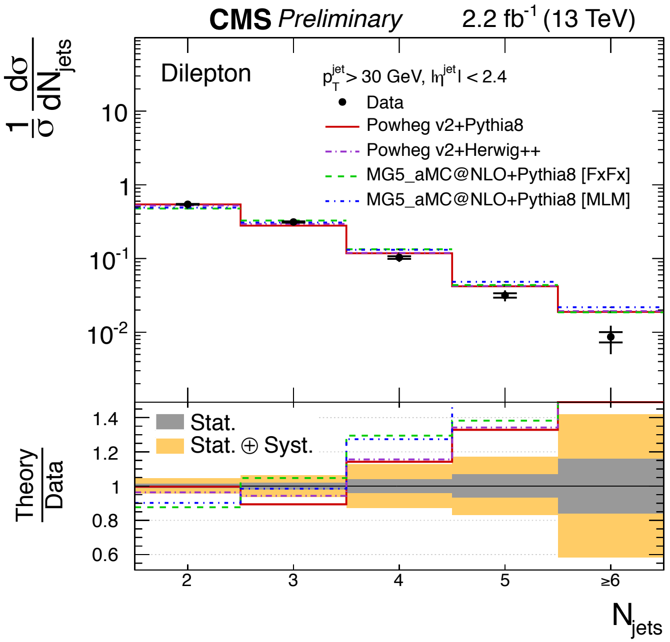
Similar behavior at Run II and in boosted top.

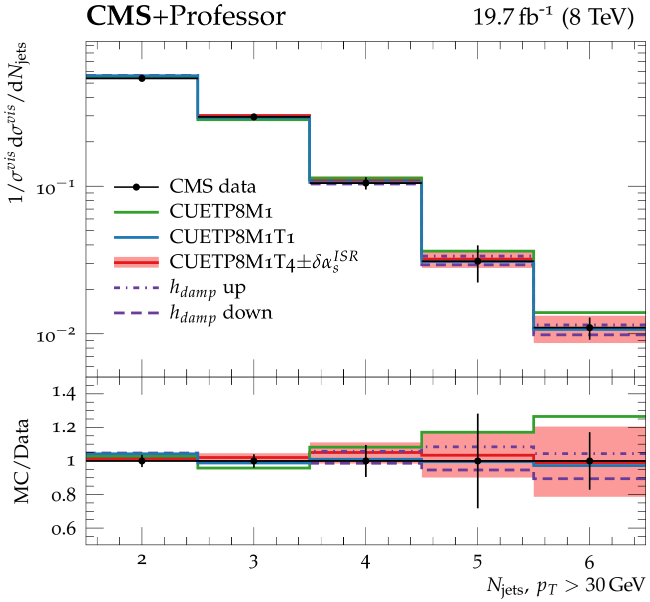
CMS-PAS-TOP-16-013

$m_{jet} \sim m_{top}$



Jet Multiplicity in Top Quark Pair Events





- Predictions overshoot the data for large jet multiplicities when out of the box parameters are used (in Monash-based tunes: α_s^{ISR}=0.1365)
- Effect also observed with 8 TeV data.

CMS-PAS-TOP-12-041 (dilepton 8 TeV),
CMS-PAS-TOP-16-011 (dilepton 13 TeV),
CMS-PAS-TOP-16-008 (l+jets 13 TeV)

CMS-PAS-TOP-16-021

Tune α_s^{ISR} using 8 TeV ttbar Njets and jet pT data —>

$$\alpha_s^{ISR} = 0.1108^{+0.0145}_{-0.0142}$$

$$h_{damp} = 1.581^{+0.658}_{-0.585} \times m_t$$

➔ Significantly lower strong coupling
➔ Consistent with PDG world average (0.118)

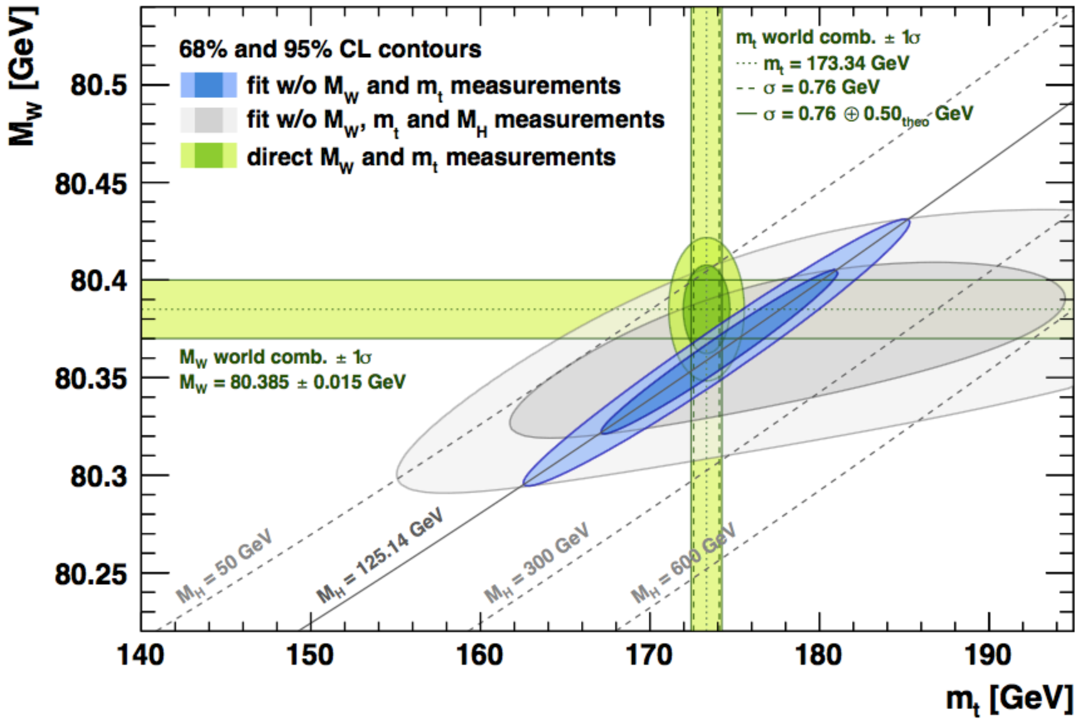
$$\alpha_s^{ISR} = 0.115^{+0.021}_{-0.019}$$

http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP-12-041/index.html#AddFig

QUESTIONS
&
BREAK

Top Quark Mass

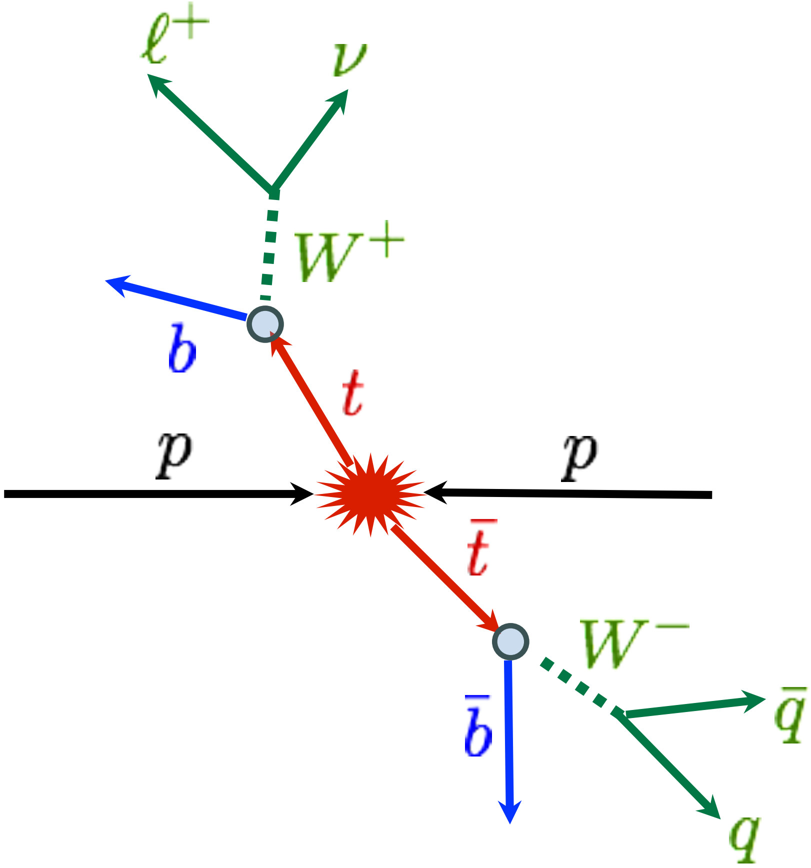
- A fundamental free parameter of the SM
- Check consistency of SM with high precision
- Check consistency of SM at very high energy scales
- m_t α y_t → The largest coupling among the fermions – special role in electroweak symmetry breaking?



arXiv: 1407.3792

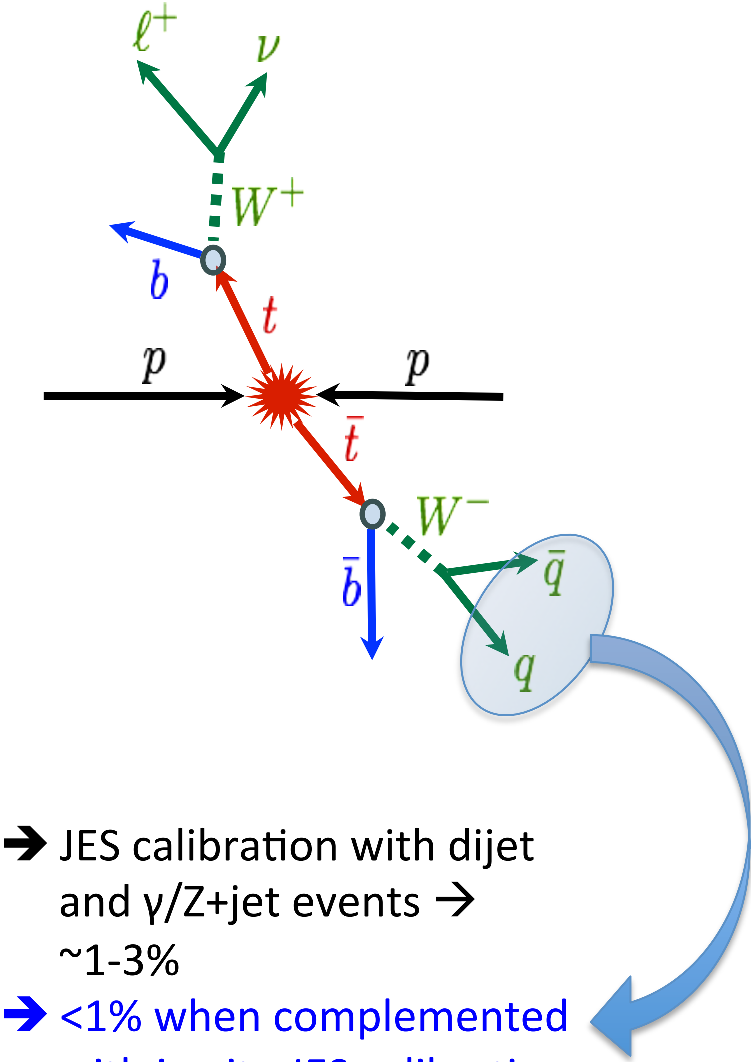
Top Mass Measurements

- 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

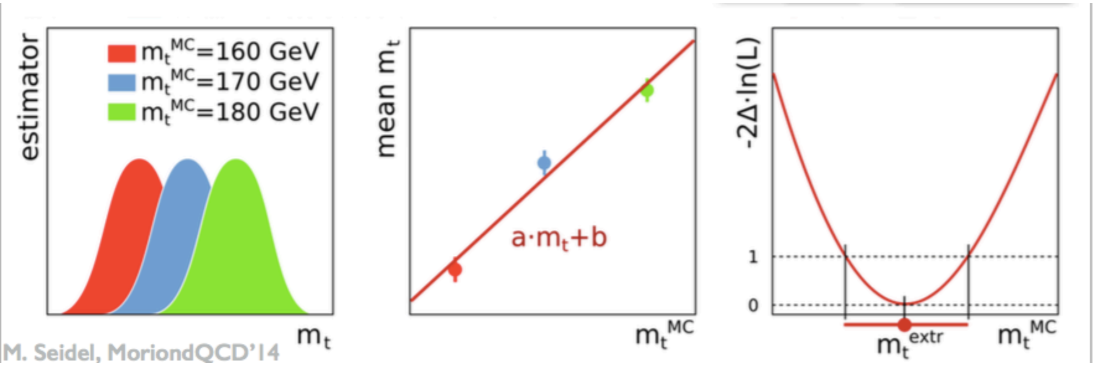


Full Mass Reconstruction

- General features:
  - Assign each jet to a top decay product (constrained kinematic fits)
  - Fit to templates
  - 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.



M. Seidel, MoriondQCD'14

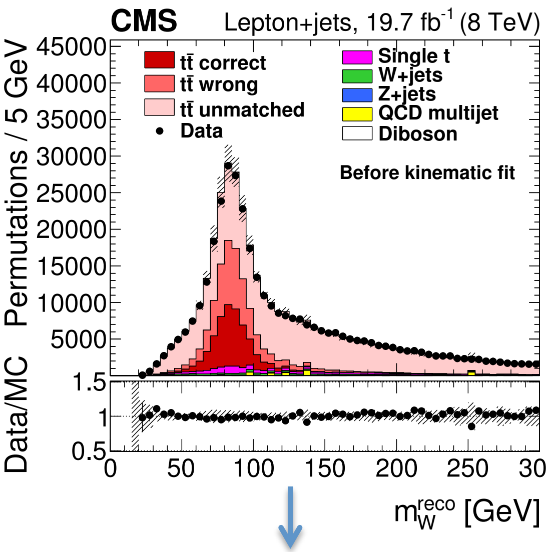
➔ JES calibration with dijet and γ/Z+jet events → ~1-3%

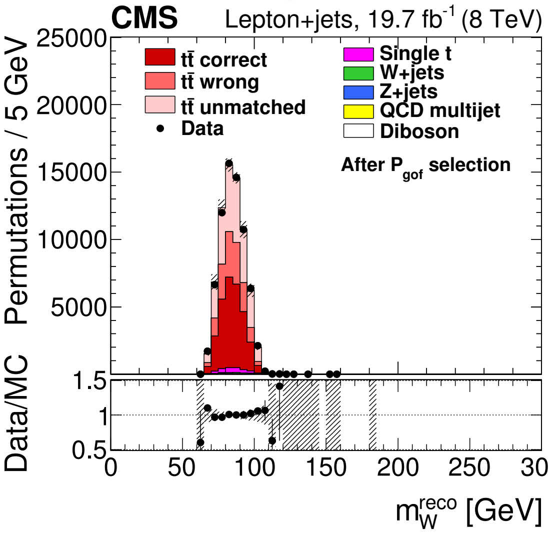
➔ <1% when complemented with in-situ JES calibration.

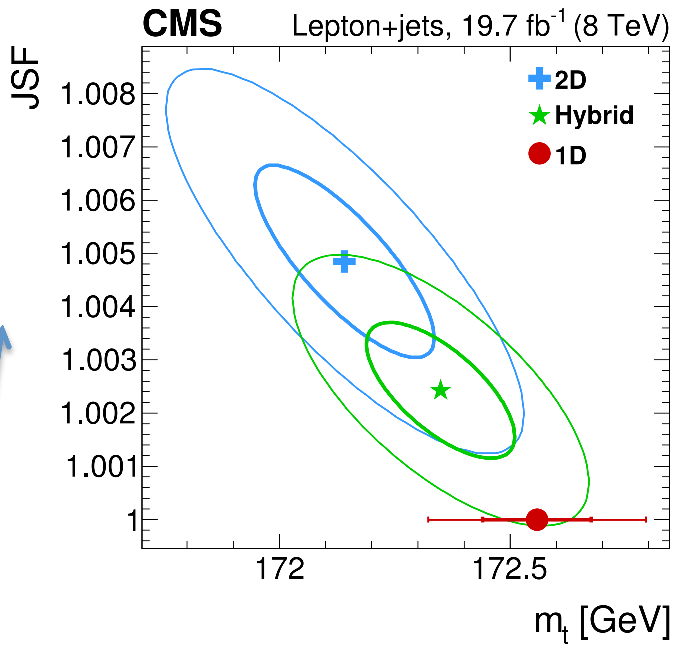
E.g. Full Mass reconstruction: The Ideogram Method

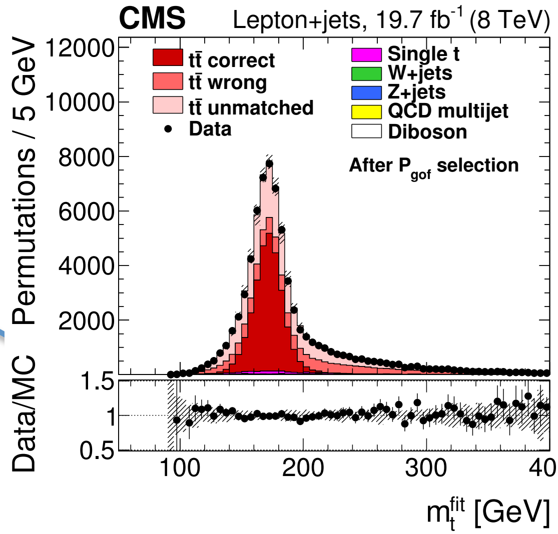
- Template method with multiple permutations (correct, wrong, unmatched) per event.
- All different permutations taken into account.
- Kinematic fit → improve mass reconstruction.

arXiv: 1509.04044

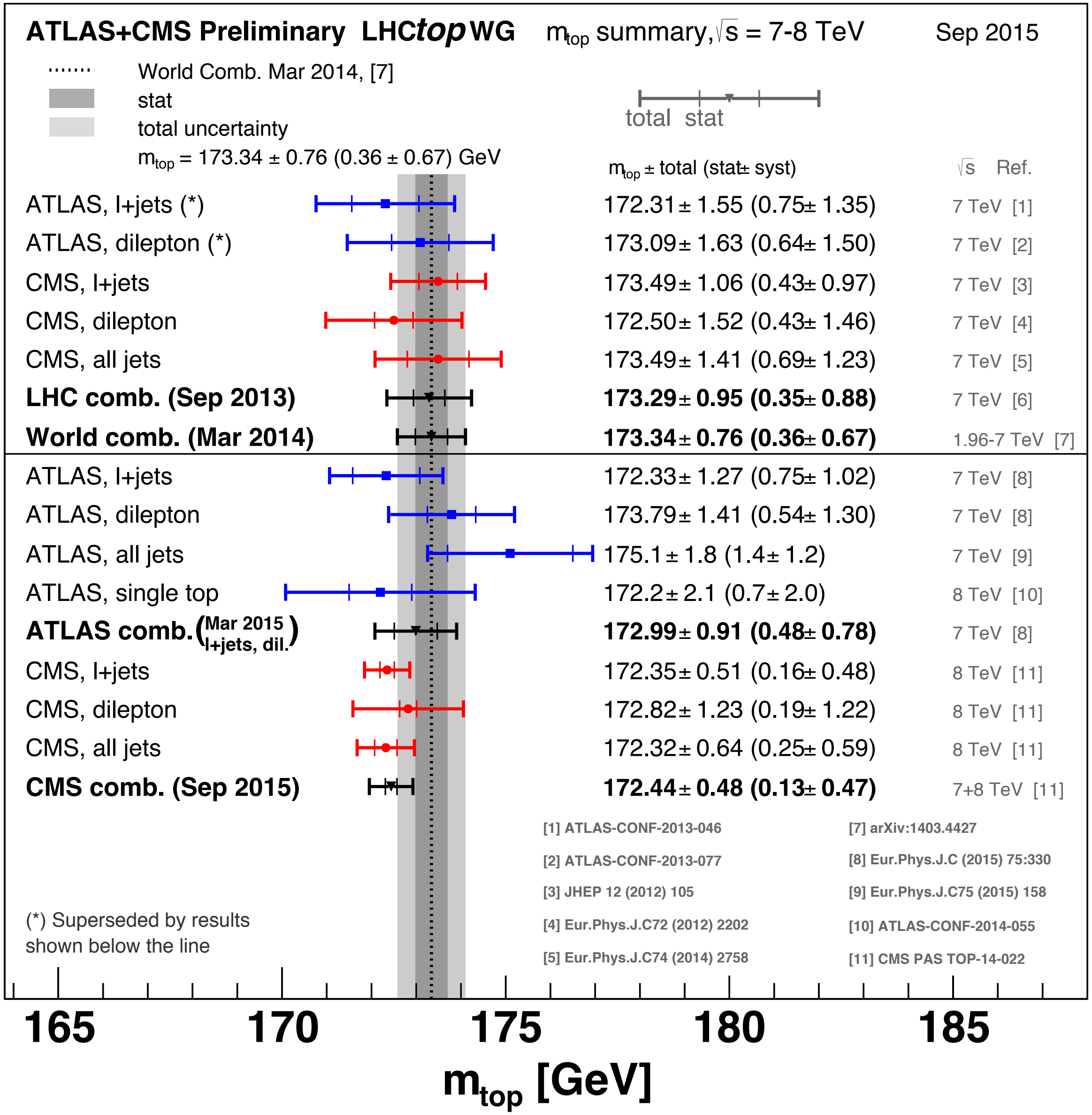








Summary of Top Mass Measurements using full Mass reconstruction

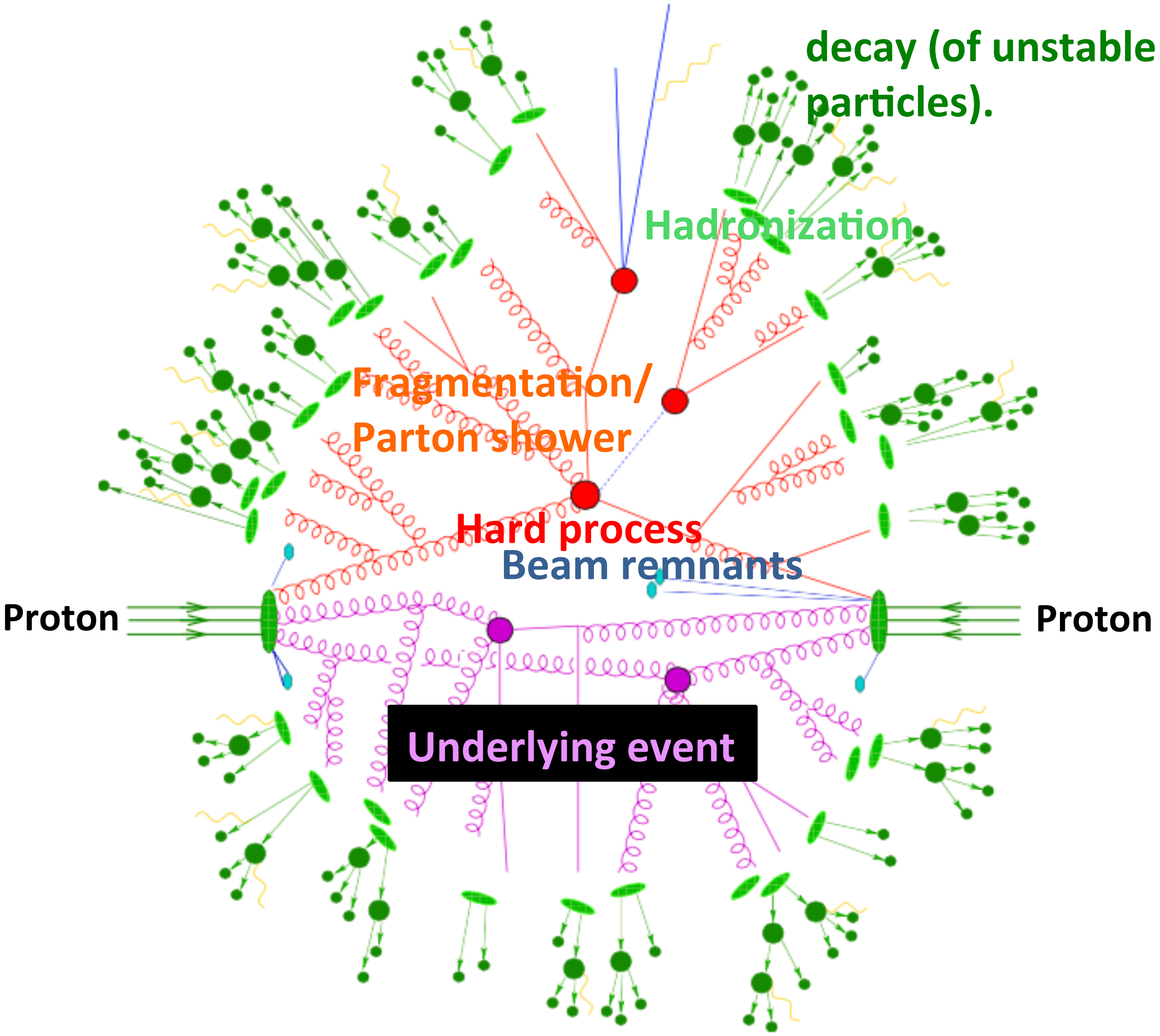


- Precision 0.3% ~ $2\Lambda_{QCD}$
- Dominant systematic uncertainties: flavor-dependent JEC and b jet modeling.

Improving Top Mass Measurements

- Dedicated measurements and theory studies to improve modeling.
- Alternative measurements displaying different aspects of systematics
- Use observables with a well-defined mass definition in pQCD: σ(ttbar), m(lb), m(tt,jet), …
- And alternative topologies.

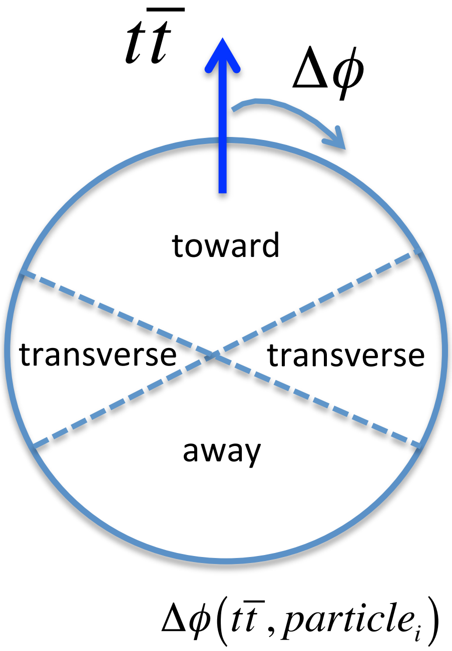
Underlying Event in ttbar Events

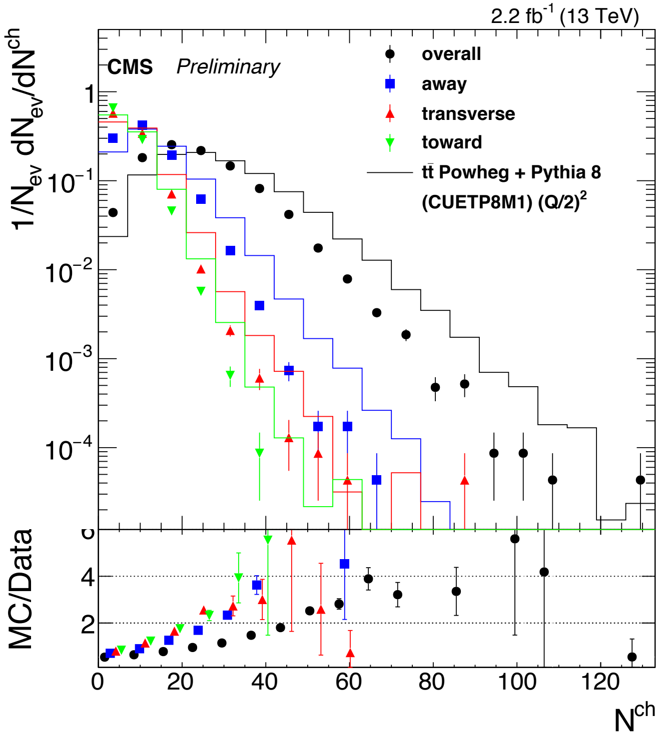


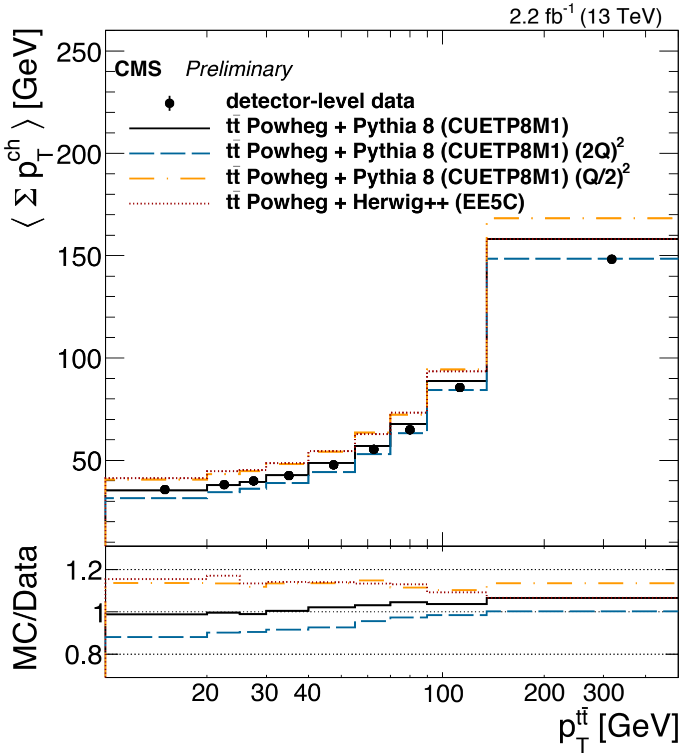
A First Look at Underlying Event in ttbar Events at √s = 13 TeV

- Charged particle activity through N^{ch}, Σp_T^{ch}, $<p_T^{ch}>$ vs p_T(ttbar) and N_{jets}.

CMS-PAS-TOP-15-017







→ Fair agreement between Powheg+P8 CUETP8M1 tune predictions.

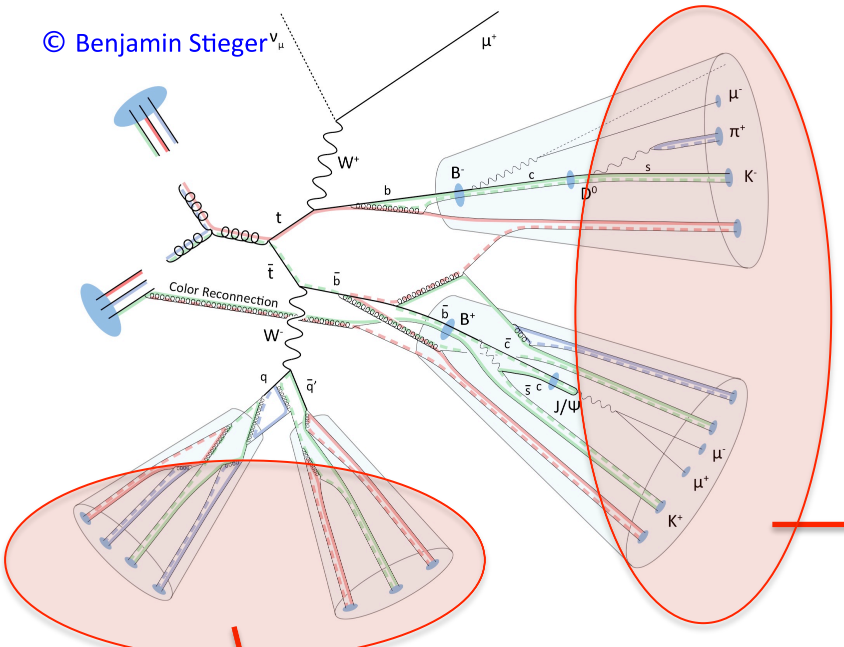
→ UE is sensitive QCD scales.

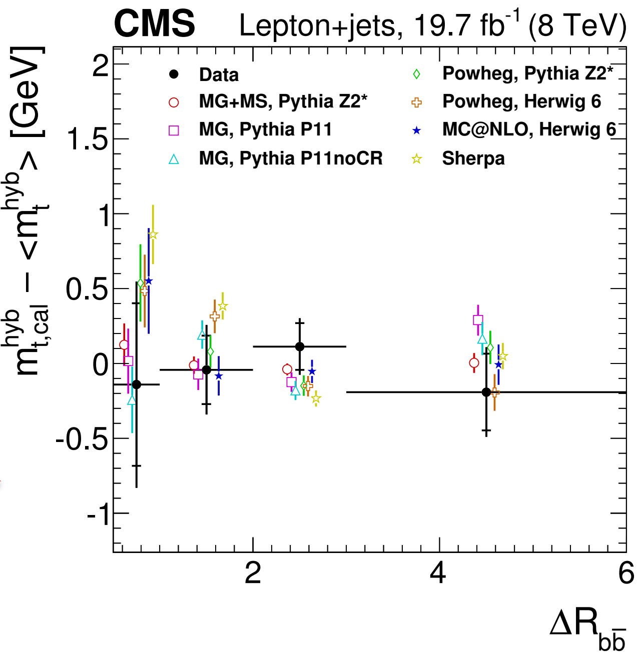
→ UE supposed to be universal but a complete measurement of UE in ttbar events may lead to more precise top mass with better understood systematics.

(non-)perturbative effects that have different kinematic dependences?

Phys. Rev. D 93 (2016) 072004

© Benjamin Stieger

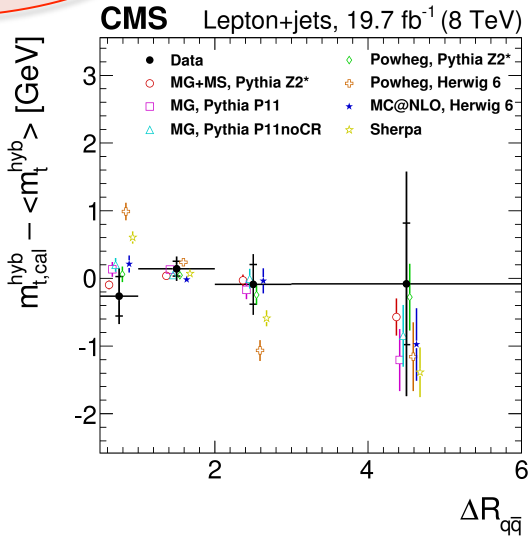




$\Delta R_{q\bar{q}}$
$p_T^{t,had}$
CR

$m_{t\bar{t}}$
$p_T^{t\bar{t}}$
N_{jets}
ISR/FSR

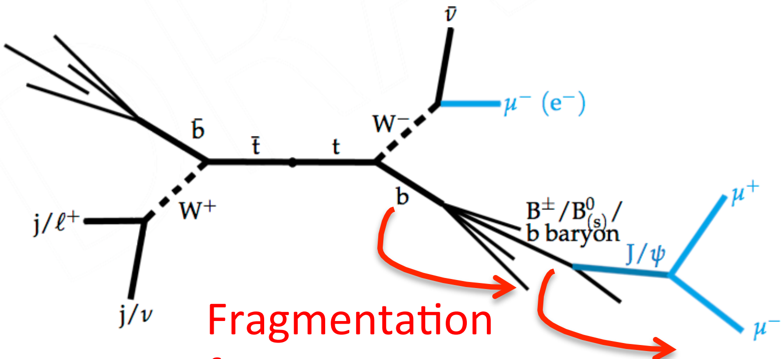
$p_T^{b,had}$
$|\eta^{b,had}|$
$\Delta R_{b\bar{b}}$
b. kin



- Study 8 variables sensitive to color reconnections, ISR/FSR, b-quark kinematics.
- *No indication of a kinematic bias.*
- *Statistics not yet enough to further constrain some of the alternate ttbar models.*

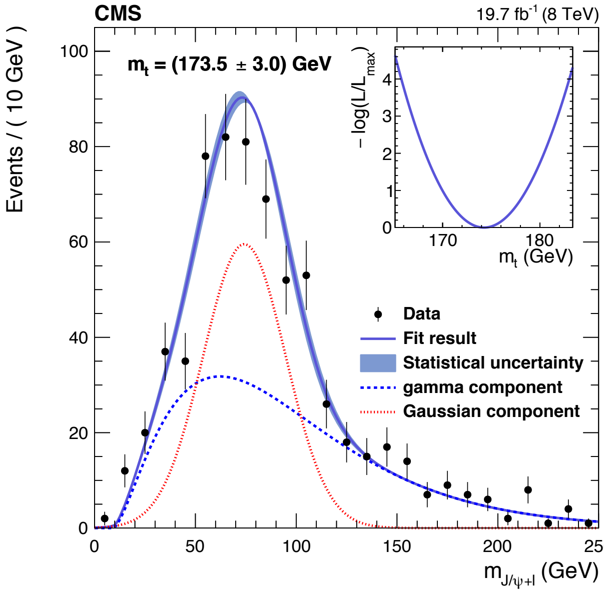
Top Quark Mass in ttbar Events with a J/ψ

- Use the correlation between the 3-prong leptonic mass and the top quark mass. CMS, CERN-LHCC 92-003, 1992



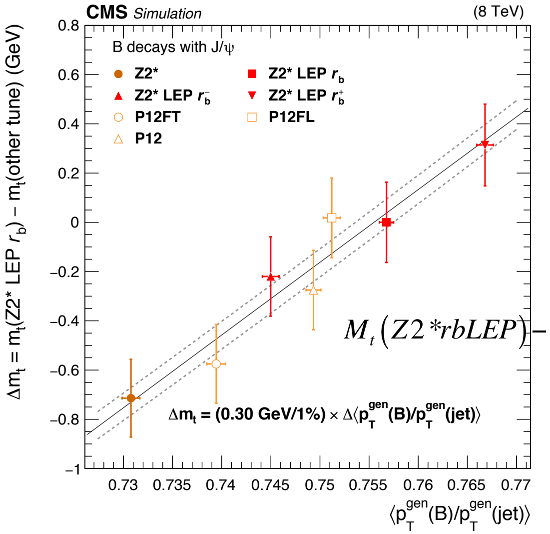
Fragmentation function

Precisely known from B factories



arXiv:1608.03560

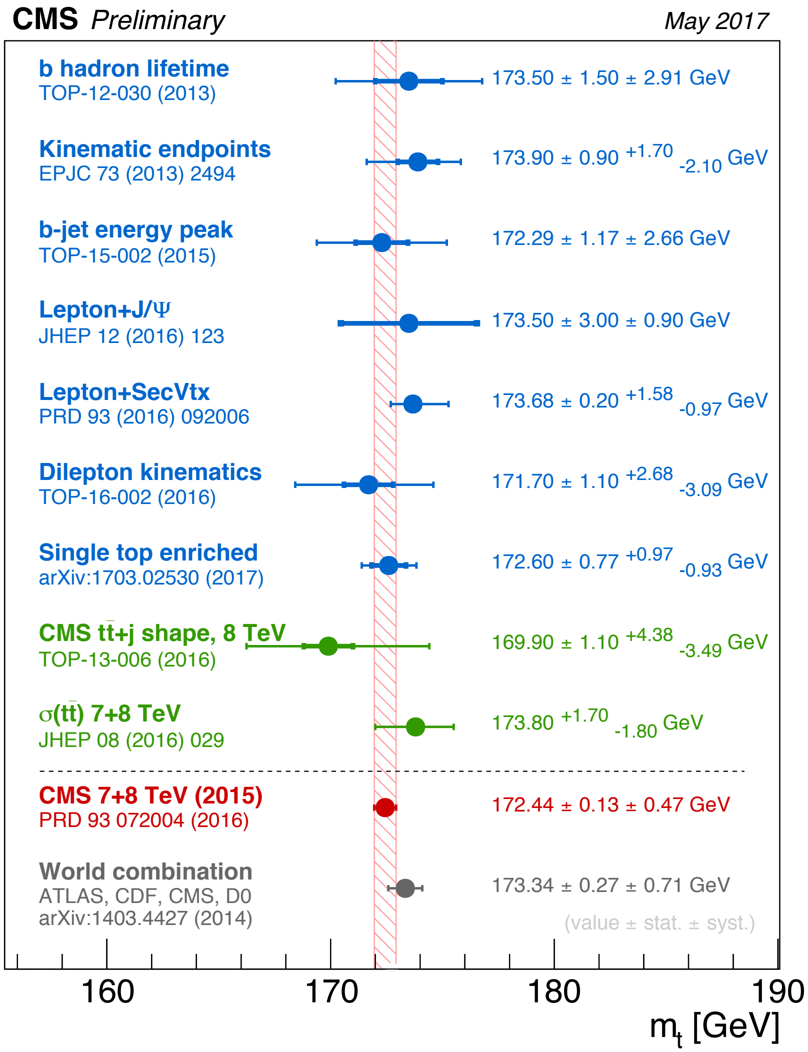
	δ [GeV]
Small number of events; BR=3.2×10^{-4}	3
Minimal experimental uncertainties	0.10
b quark fragmentation modeling	0.30 →
Top pT	~ 0.65
ME/PS matching	~ 0.55
QCD scales	~ 0.45



$$M_t(Z2^*rbLEP) - M_t(Z2^*) = -0.71$$

Average fragmentation

Summary of Alternative (Indirect) Top Mass Measurements



- So far, all the top mass definitions tested with CMS data look consistent within uncertainties
    - Many different techniques and observables have been explored at 8 TeV in all channels.
- Looking forward to further understand this parameter with LHC Run II data.

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)

    $$\sqrt{p^2} = m_t - i\Gamma_t/2$$

    - Perturbatively defined
    - Position of the pole in the renormalized quark propagator
    - "intuitive mass" (directly related to the production rate of ttbar pairs)
    - Suffers from ambiguities due to non-perturbative corrections.
    - Ambiguity of $\sim\Lambda_{QCD}$
  - "Running (or short distance mass) mass" (m_t^{MSbar})
    - Renormalization scale dependent.

The two definitions can be related analytically with an uncertainty $<\sim\Lambda_{QCD}$

e.g. see Marquard et al. PRL 114 (2015) 142002

Top Quark Mass Definitions

- Monte Carlo Mass
  - No straightforward definition in standard 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

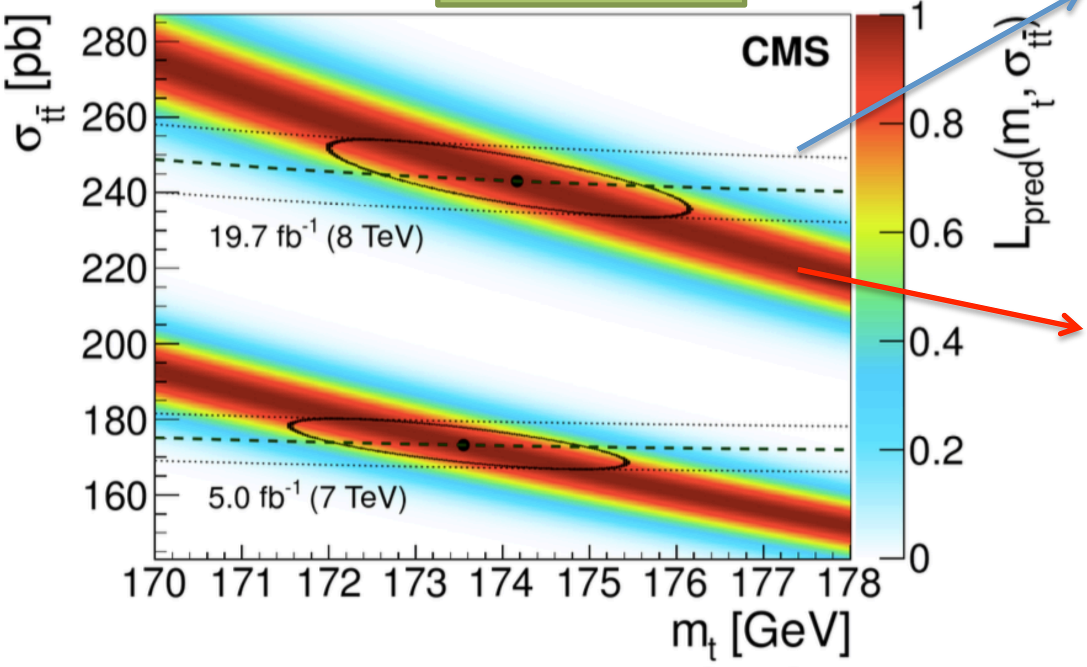
$$m_t^{MC} \neq m_t^{pole} \neq m_t^{MS} \neq m_t^{XX}$$

Top Quark Pole Mass from ttbar Production Cross Section: Fix $\alpha_s(m_Z)$ and PDF → Determine m_t^{pole}

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

- Full phase space cross sections at parton level with full Run-I data at 7 and 8 TeV in the most precise channel (eμ) (done also at RunII).
- Minimize theory x experimental likelihoods.

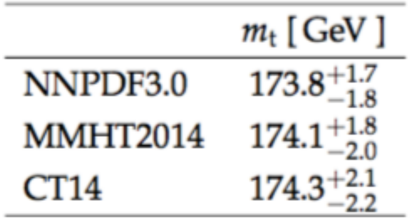
arXiv:1603.02303



Dependence due to efficiency and acceptance depending weakly on m_t.

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

It is harder to produce heavier particles.



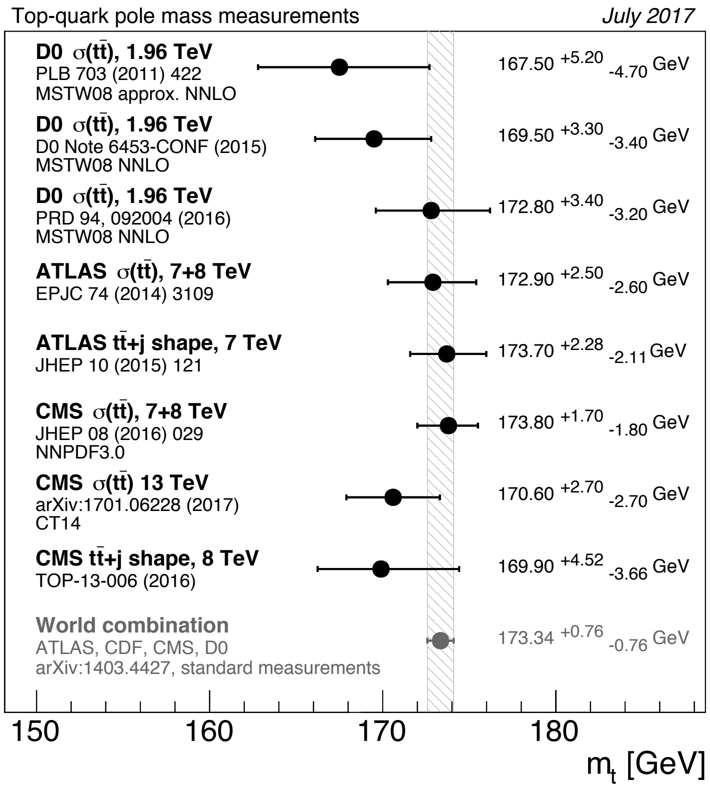
	m_t [GeV]
NNPDF3.0	$173.8^{+1.7}_{-1.8}$
MMHT2014	$174.1^{+1.8}_{-2.0}$
CT14	$174.3^{+2.1}_{-2.2}$

Dominant uncertainties: Luminosity, beam energy

Top Quark Mass Definitions

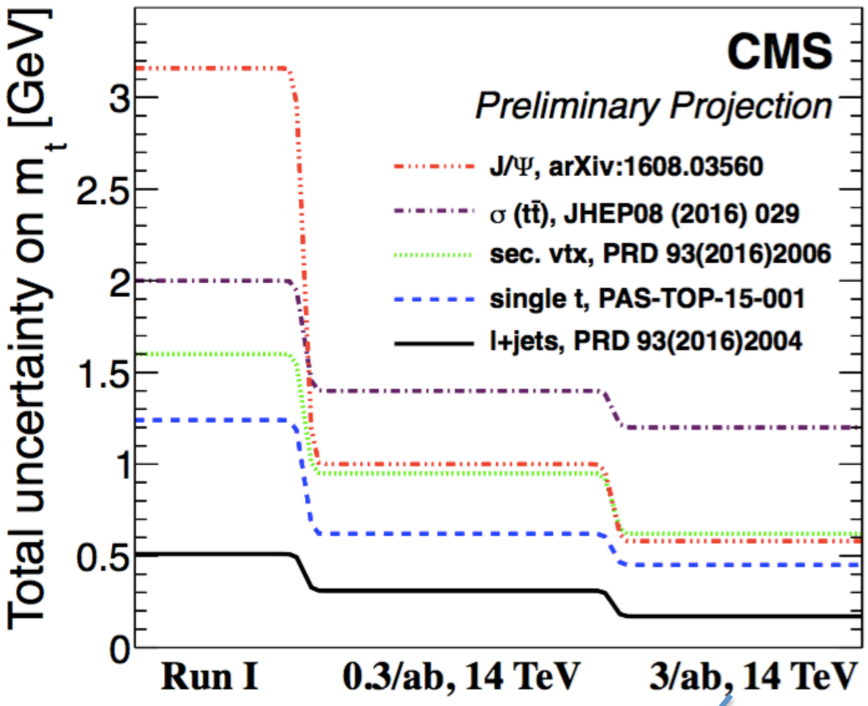
- Monte Carlo Mass
  - No straightforward definition in standard top mass measurements
  - Direct top quark measurements rely on the complicated relation between the experimental observable and m_t.
  - MEs at fixed order (LO or NLO) QCD + higher orders by parton showers

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



- With the current precision, top-quark pole mass measurements consistent with the standard measurements.

Top Mass Projected to HL-LHC



CMS-DPS-AN-16-286 following the method
In CMS-FTR-13-007

- Run I: Measurements dominated by systematic uncertainties except J/ψ.
- Assume same same physics performance maintained despite a severe pileup.
- Potential reduction of the trigger efficiency of up to a factor 3 balanced by increase of ttbar cross section.

- Direct top mass measurements → precision < 0.1%.
- All measurements limited especially by modeling uncertainties.
- Many improvements in understanding of the systematic uncertainties expected
  - Hadronization, top p_T, underlying event, …

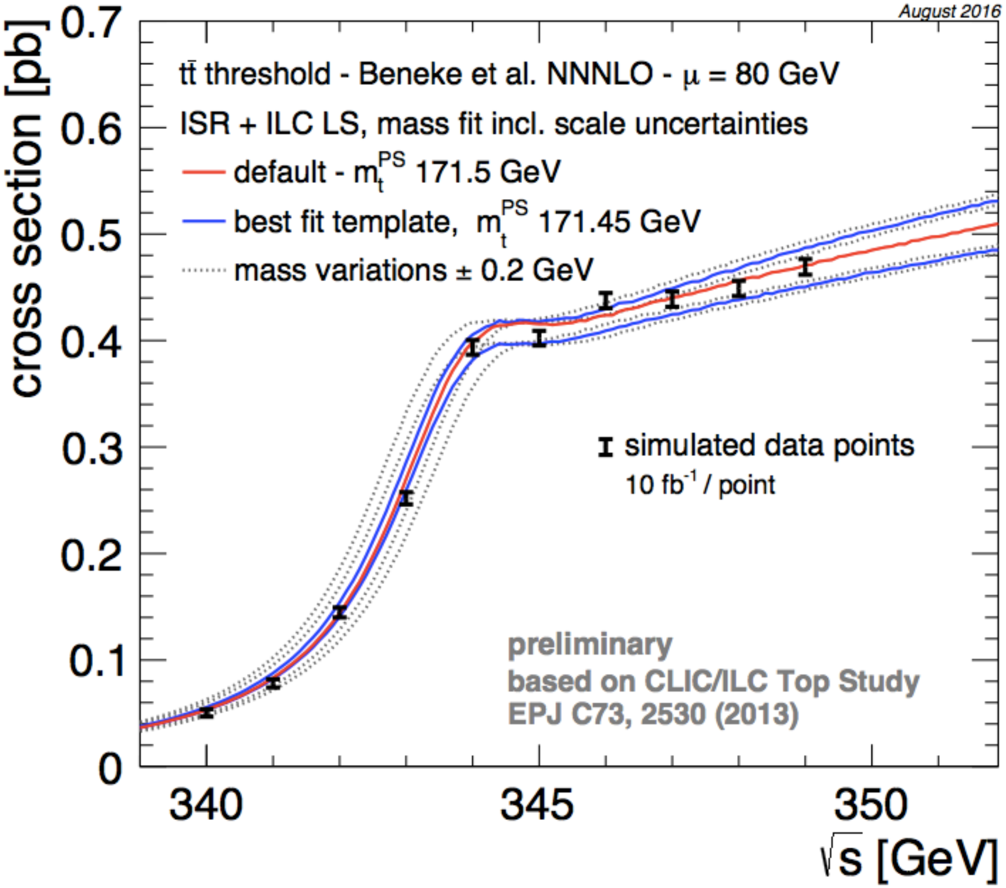
Top Quark Mass at Future Colliders

If √s <~ 350, no top physics except some with single top.

- Future lepton colliders
  - Linear
    - ILC: 250-500-1000 GeV
    - CLIC: 380-1500-3000 GeV
  - Circular → maximum collision energy fixed
    - FCC-ee: 90-160-240-350-370 GeV
    - CEPC: 250 GeV
- Future (hadron) colliders
  - HE-LHC: 27 TeV
  - FCC-hh: 100 TeV
  - SPPC: 100 TeV
  - LHeC: e+e- beam:60 GeV
    - + p beam (HL-LHC): 7 TeV → √s = 1.3 TeV
    - + p beam (HE-LHC): 13.5 TeV → √s = 1.8 TeV
    - + p beam (FCC-hh): 50 TeV → √s = 3.5 TeV

Top Quark Mass from Threshold Scan

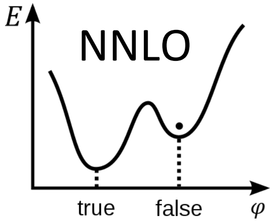
- HL-LHC: Direct top mass measurements → precision < 0.1% ~ 200 MeV.



- Cross section vs √s depends on m_t, Γ_t, α_s, y_t.
- Well-defined top quark mass.
- Statistical uncertainty ~<20 MeV.
- Scale uncertainty ~40 MeV.

F. Simon, 1611.03399
M. Vos et al. arXiv:1604.08122

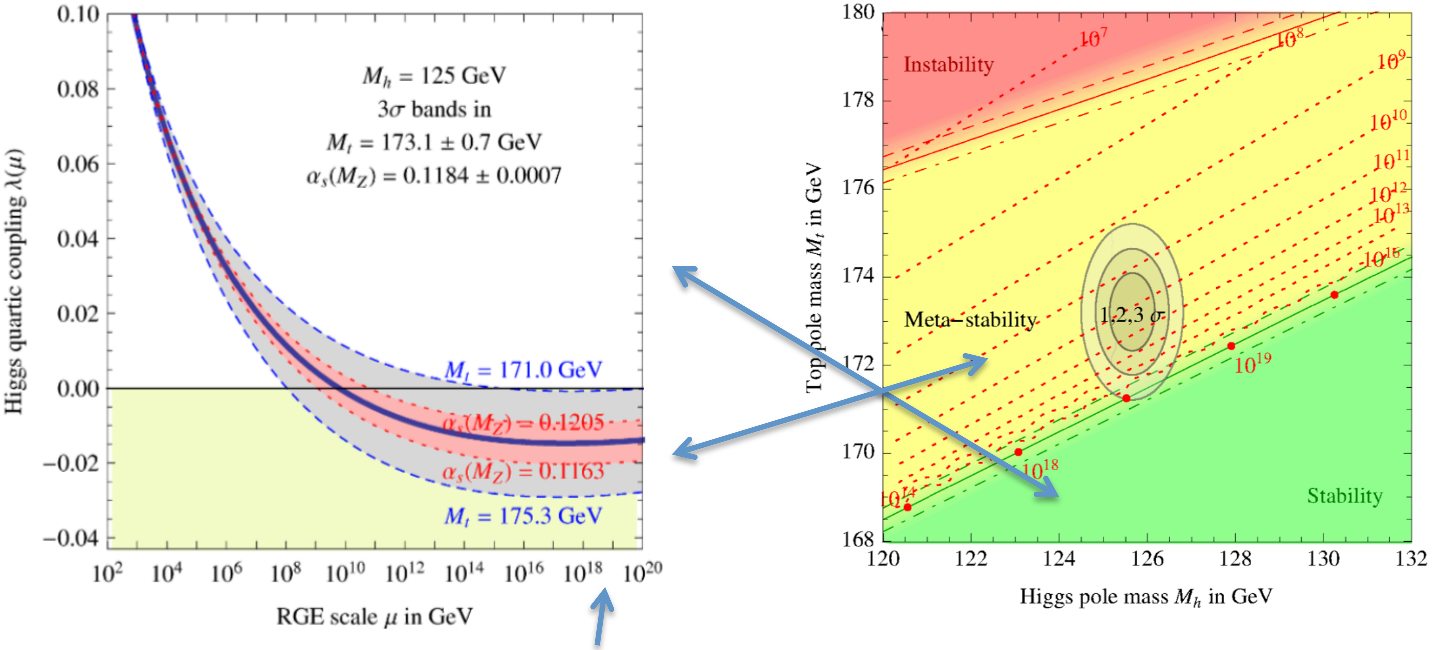
The Top Quark Mass and the Electroweak Vacuum



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

when $\phi(\mu) \gg v$

v: electroweak minimum



Planck scale

- The measured values of the top quark and the higgs boson mass
  - SM is consistent and could be valid up to Planck scale.
  - Vacuum may be Meta-stable.

Degrassi et al. JHEP 08 (2012) 098, arXiv:1405.6852

Top Width

- One of the less tested top quark property.
- Inversely related to top's lifetime.
- Γ_t(NLO) = 1.35 GeV (assuming m_t=173.3 GeV and α_s=0.118)

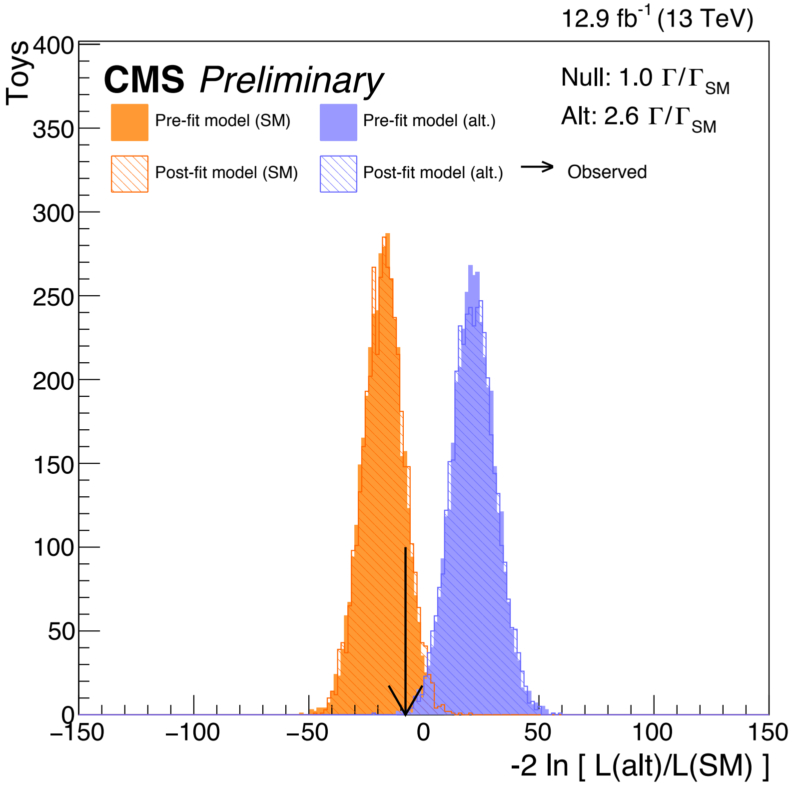
→ Reconstruct M_{lb} from ttbar and tW decay events w/ two charged leptons and w/ up to 2 jets.

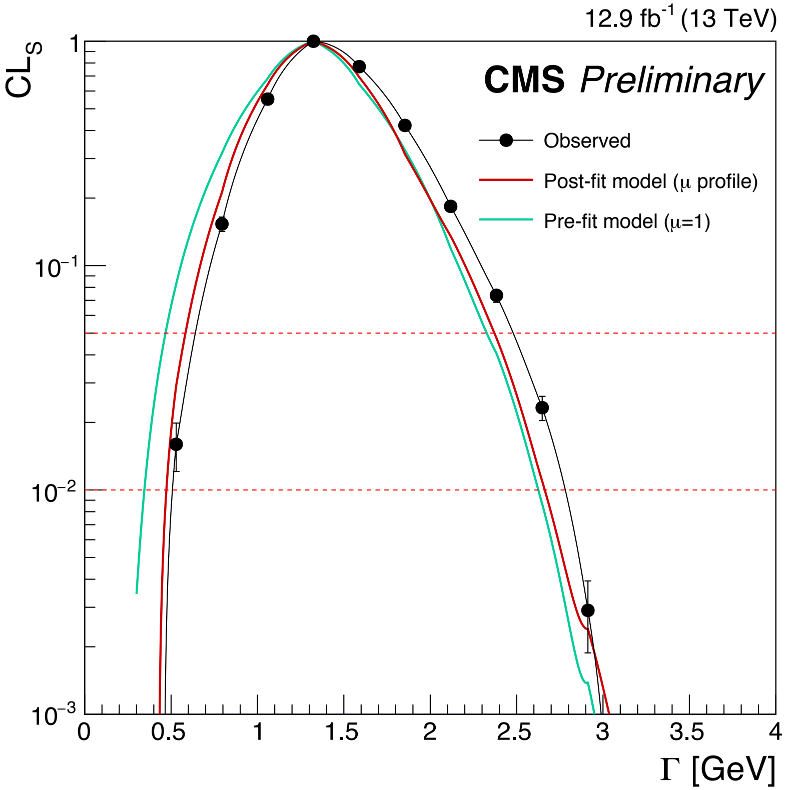
→ Binary hypothesis tests.

$$0.6 \leq \Gamma_t \leq 2.5\ GeV\ \ @\ \ 95\%\ CL$$

TOP-16-019

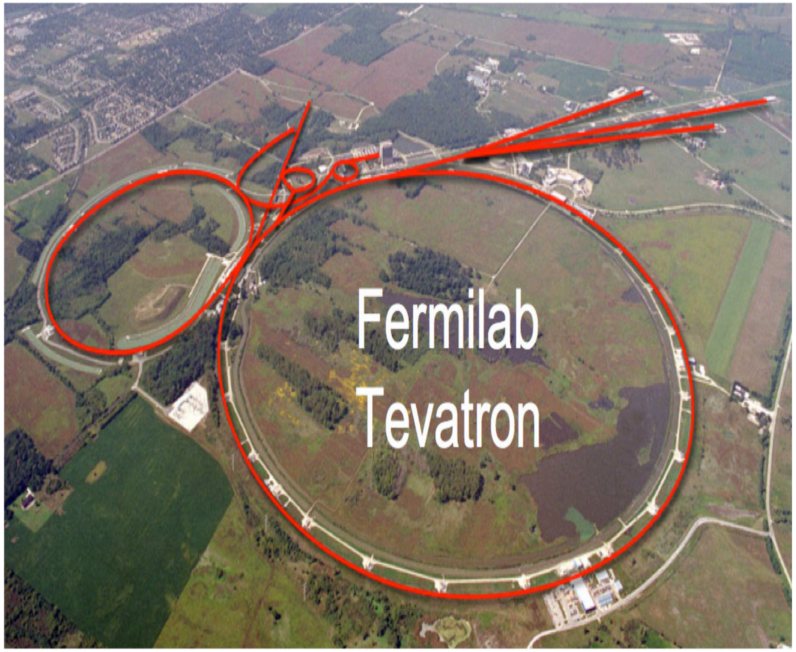
$$0.6 \leq \Gamma_t \leq 2.4\ GeV\ \ for\ m_t = 172.5\ GeV$$

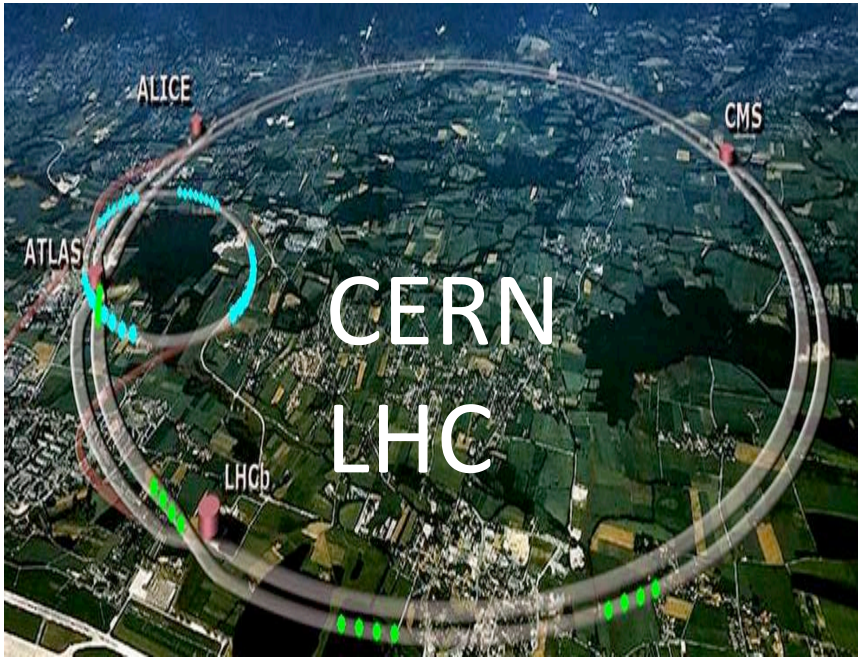




QUESTIONS
&
BREAK

Asymmetries at Hadron Colliders





$P\bar{P}$ collider

Parity → changes the direction of proton and anti-proton
Charge → changes the direction of proton and anti-proton

CP symmetric $\sigma_{total} = \bar{\sigma}_{total}$
not C and P symmetric separately

PP collider

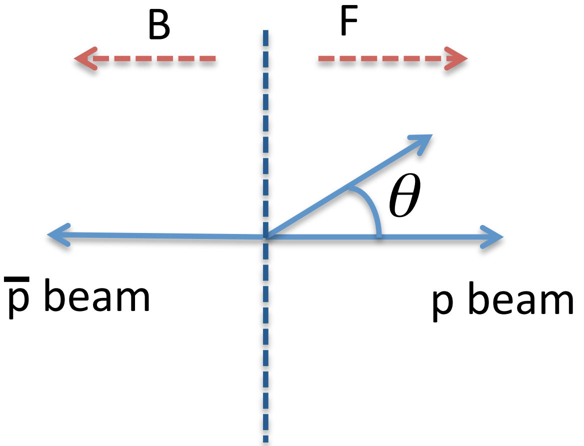
Parity → changes nothing
Charge → Makes LHC an anti-proton collider.

Not CP symmetric $\sigma_{total} \neq \bar{\sigma}_{total}$
not C symmetric but P symmetric.

Asymmetries at Hadron Colliders

$P\bar{P}$ collider (Tevatron)

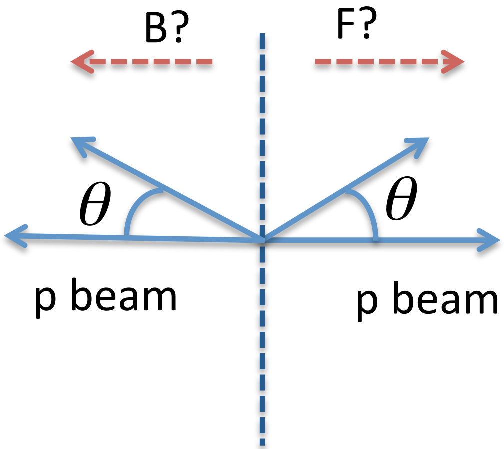
Parity asymmetric



Allows the definition of a forward (backward) hemisphere based on the P direction.

PP collider (LHC)

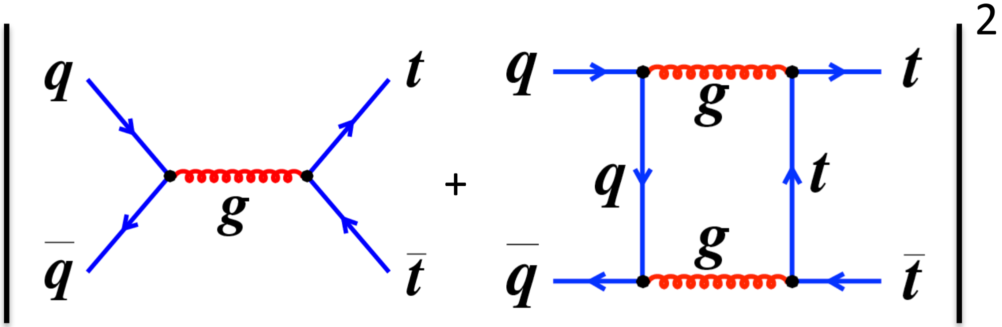
Parity symmetric

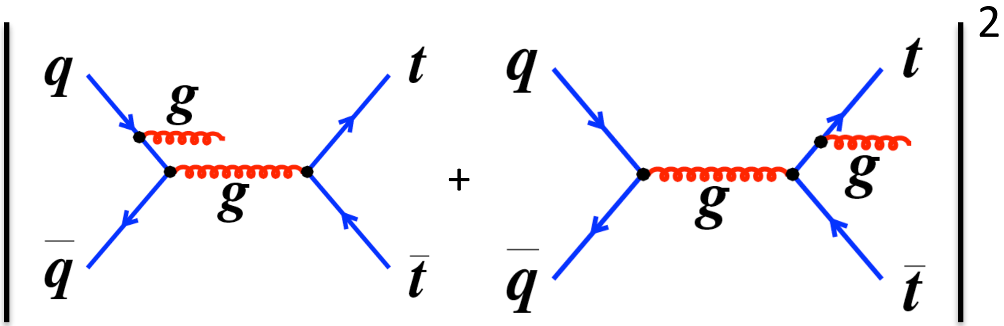


Does not allow the definition of a forward (backward) hemisphere based on the P direction, unless we consider the Parton Distribution Functions (PDFs.)

Asymmetry from Interference - $t\bar{t}$

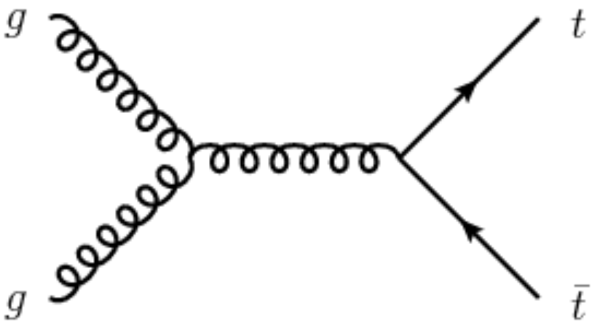
Interference: tree-level + box diagrams
(positive asymmetry)





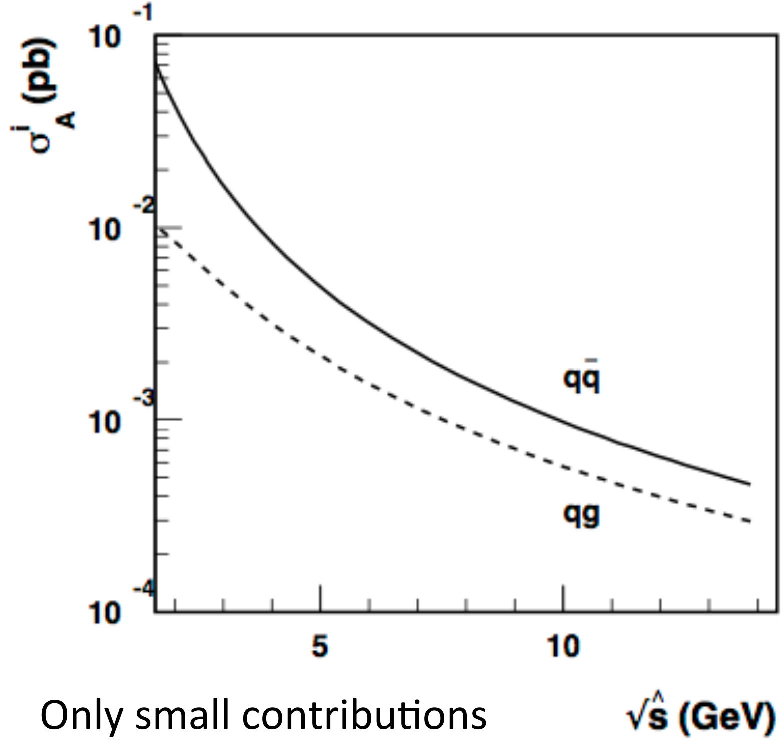
Interference: ISR+FSR
(negative asymmetry)

- No asymmetry at LO
- No asymmetry from gluon fusion
- At NLO: Interferences between q$\bar{q}$ diagrams

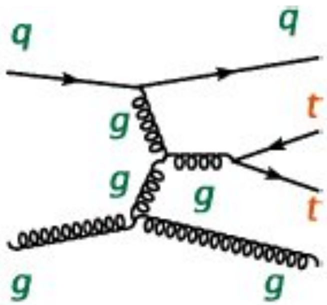


Asymmetry from Interference - tt̄

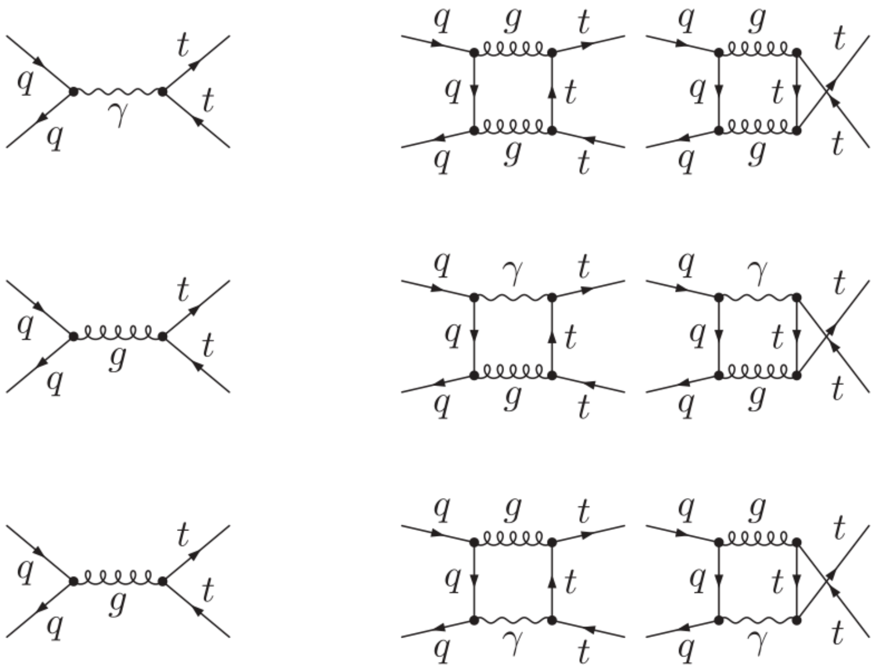
Kuhn & Rodrigo,
PRD 59 (1999) 054017



- Only small contributions from quark-gluon scattering

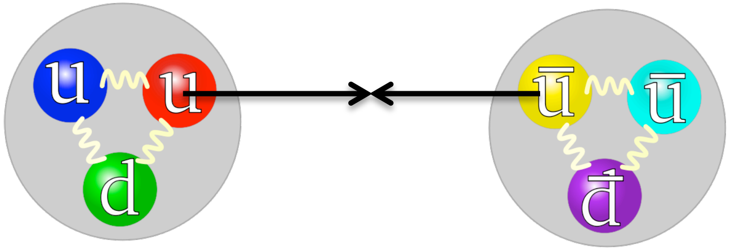


Hollik & Pagani
PRD 84 (2011) 093003

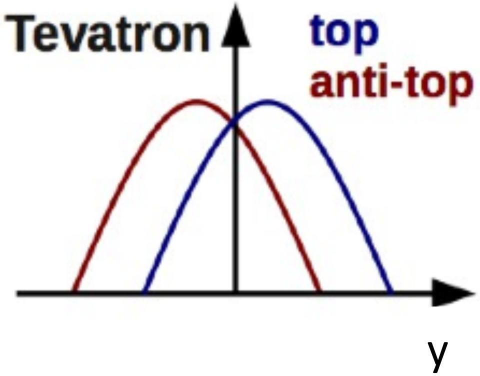


- Significant (~25%) contributions from QCD-electroweak interference terms.

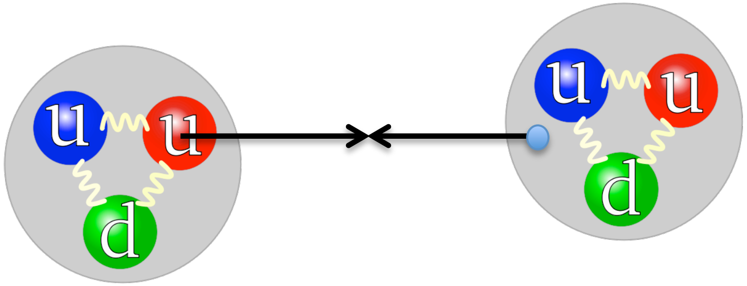
Asymmetry from Interference - $t\bar{t}$



Tevatron: annihilation of two valence quarks (PDF symmetric).

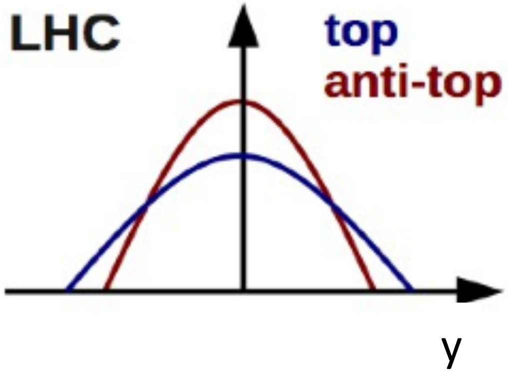


Forward-backward asymmetry (A_{FB})



LHC: annihilation of one valence and a sea anti-quark (PDF asymmetric) and moreover gluon fusion dominates.

→ much smaller asymmetry.

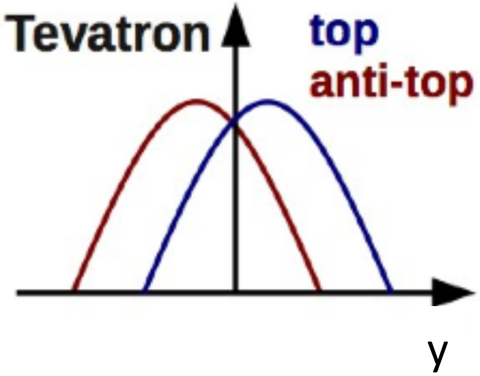


Charge asymmetry (A_C)

On average, P(valence quark) > P(sea anti-quark)
→ top quark rapidity broader than the anti-quark rapidity

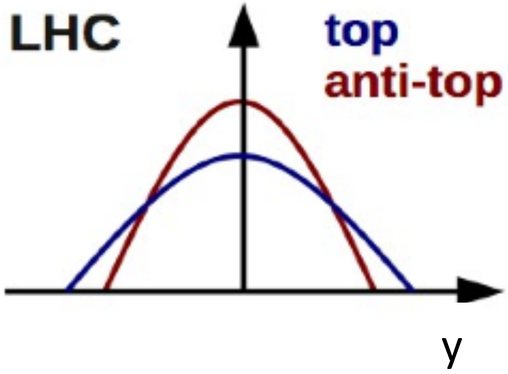
→ any large asymmetry will indicate the existence of new physics.

Asymmetry from Interference - tt̄



Forward-backward asymmetry (A_{FB})

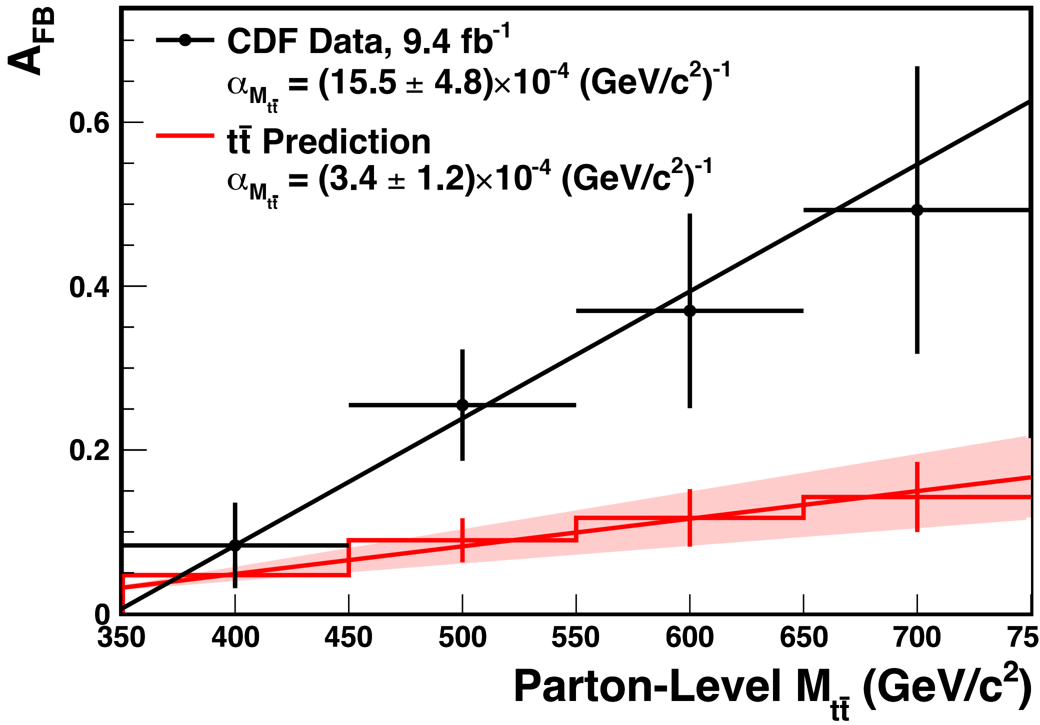
$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}, \quad \Delta y = y_t - y_{\bar{t}}$$



Charge asymmetry (A_C)

$$A_{FB} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}, \quad \Delta|y| = |y_t| - |y_{\bar{t}}|$$

tt Asymmetry at the Tevatron: Deviations from SM First Reported in 2009 by CDF and D0



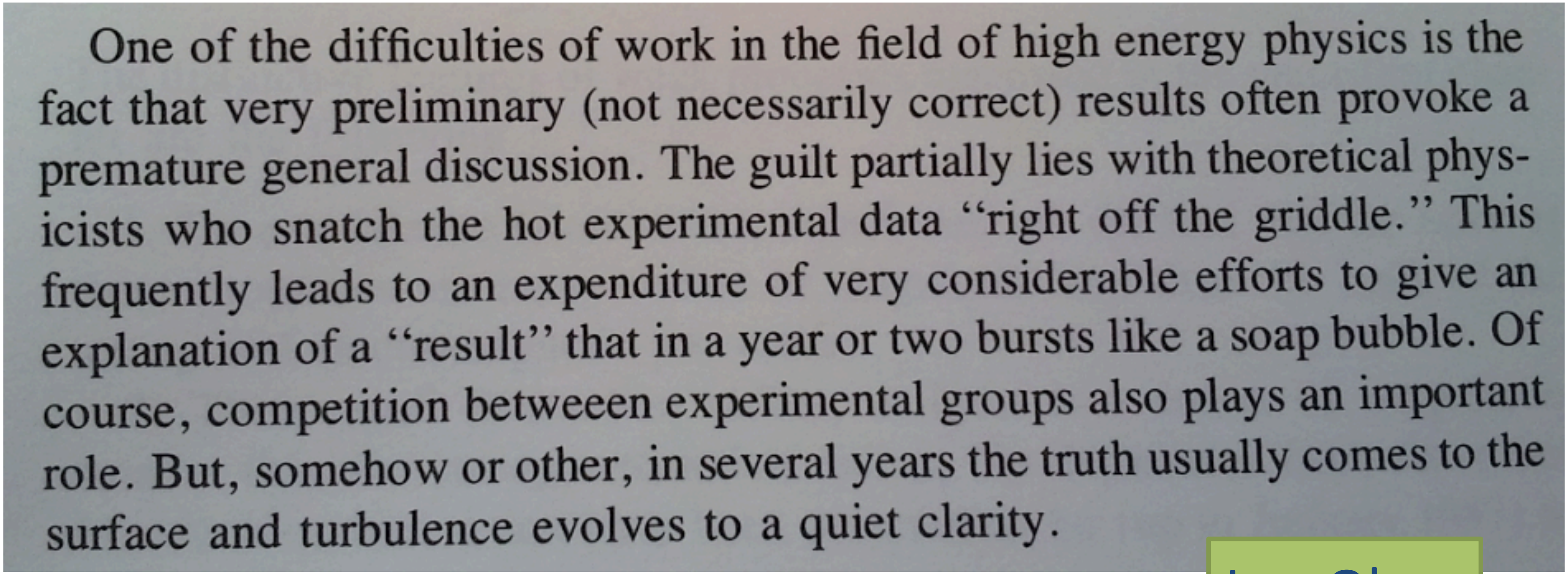
arXiv:1211.1003
PRD 87, 092002 (2013)

Inclusive A_{FB}: ~2σ deviation
$A_{FB}(m_{t\bar{t}}>450$ GeV): ~3σ

- Statistical fluctuation?
  - results dominated by statistical uncertainties
- Missing theory effect?
  - calculations were only at the lowest order
- Mistake in the measurement method?
- Missing uncertainties?

➔ If none,
may be new physics?

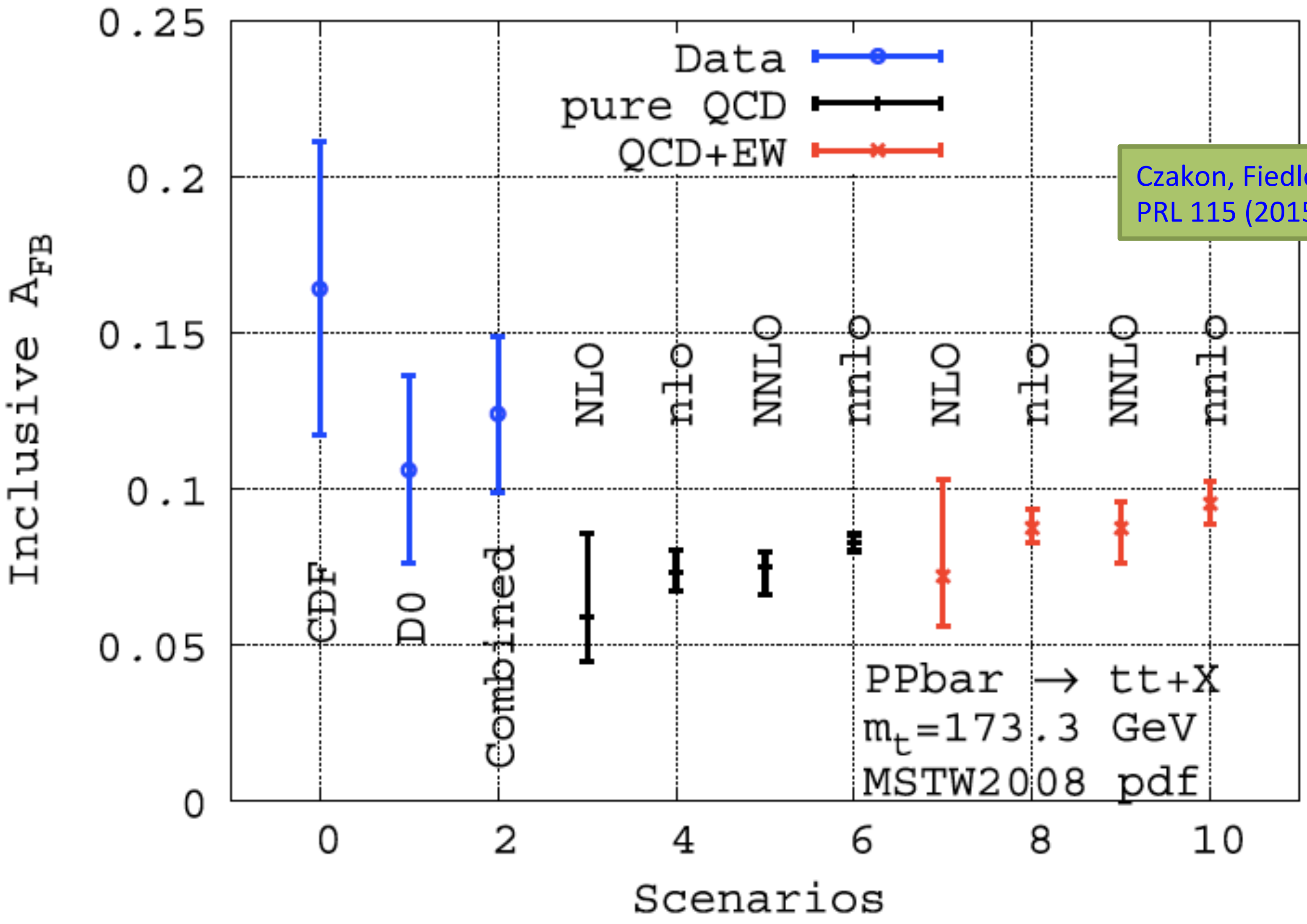
(but > 100 papers with
New physics interpretation)



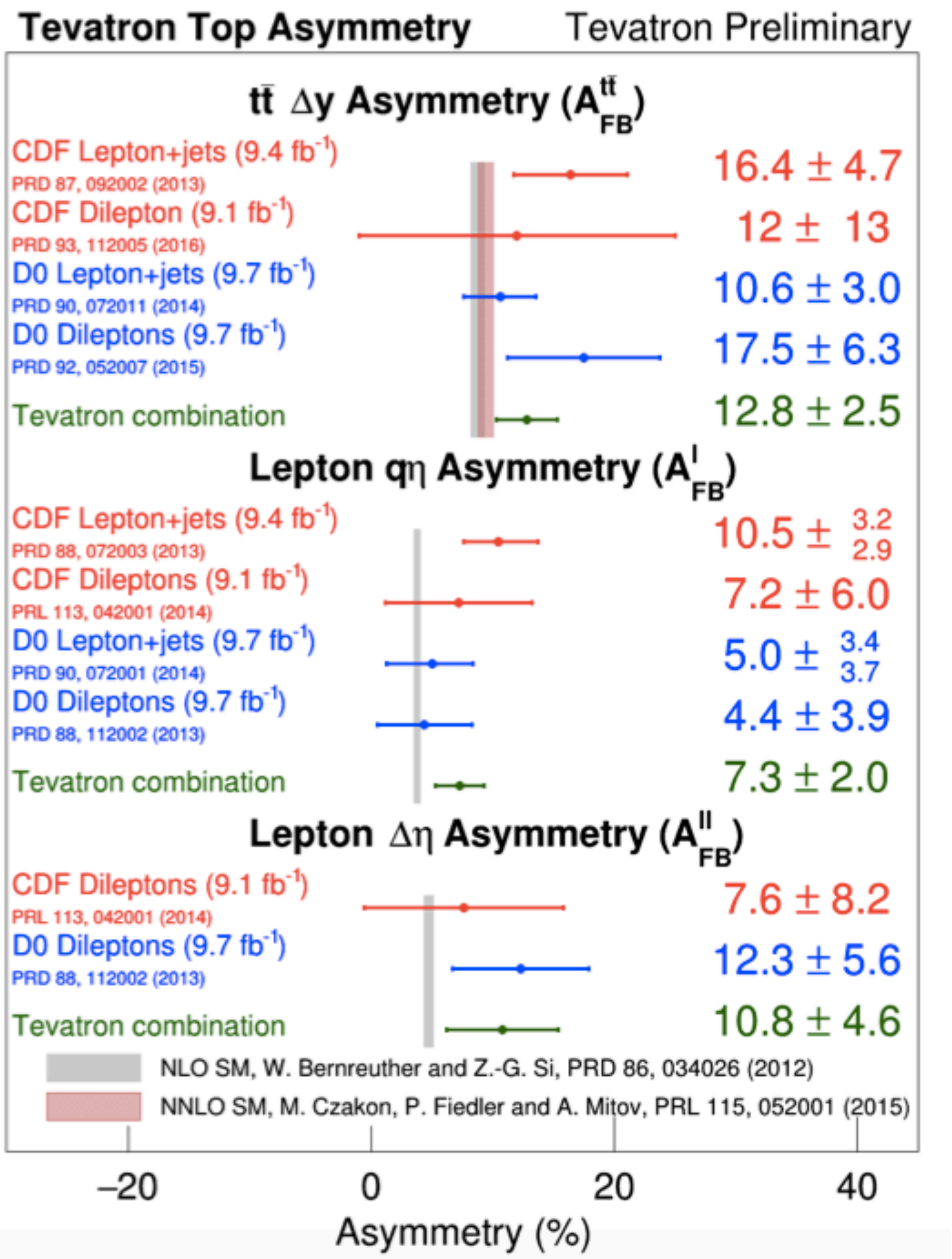
One of the difficulties of work in the field of high energy physics is the fact that very preliminary (not necessarily correct) results often provoke a premature general discussion. The guilt partially lies with theoretical physicists who snatch the hot experimental data "right off the griddle." This frequently leads to an expenditure of very considerable efforts to give an explanation of a "result" that in a year or two bursts like a soap bubble. Of course, competition betweeen experimental groups also plays an important role. But, somehow or other, in several years the truth usually comes to the surface and turbulence evolves to a quiet clarity.

Lev Okun

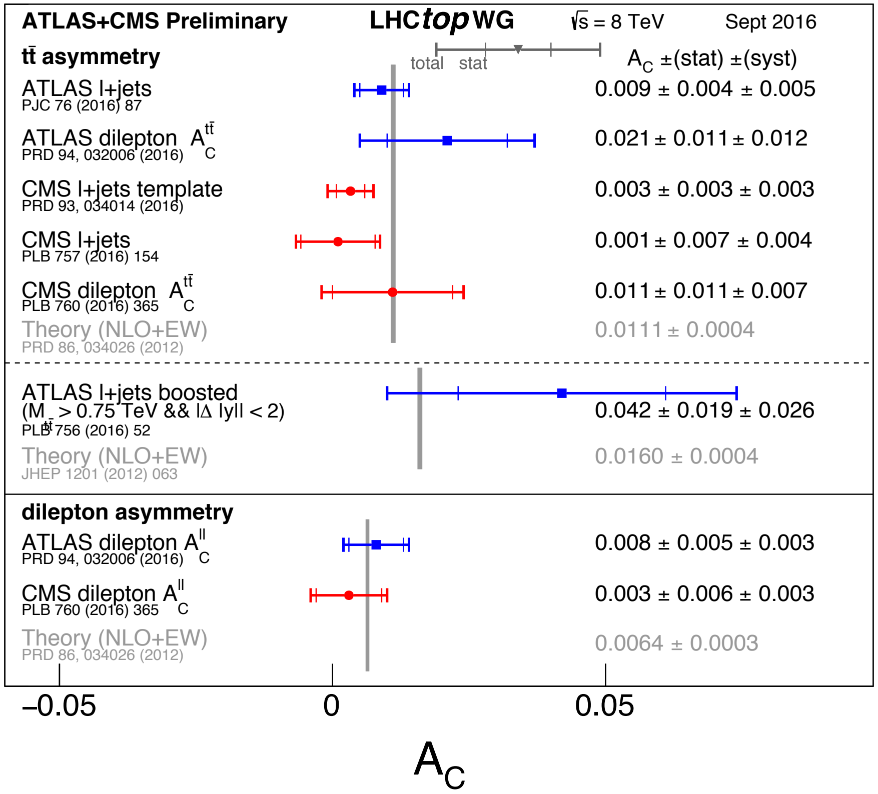
tt Asymmetry at the Tevatron @ 2015



Czakon, Fiedler, Mitov
PRL 115 (2015) 052001

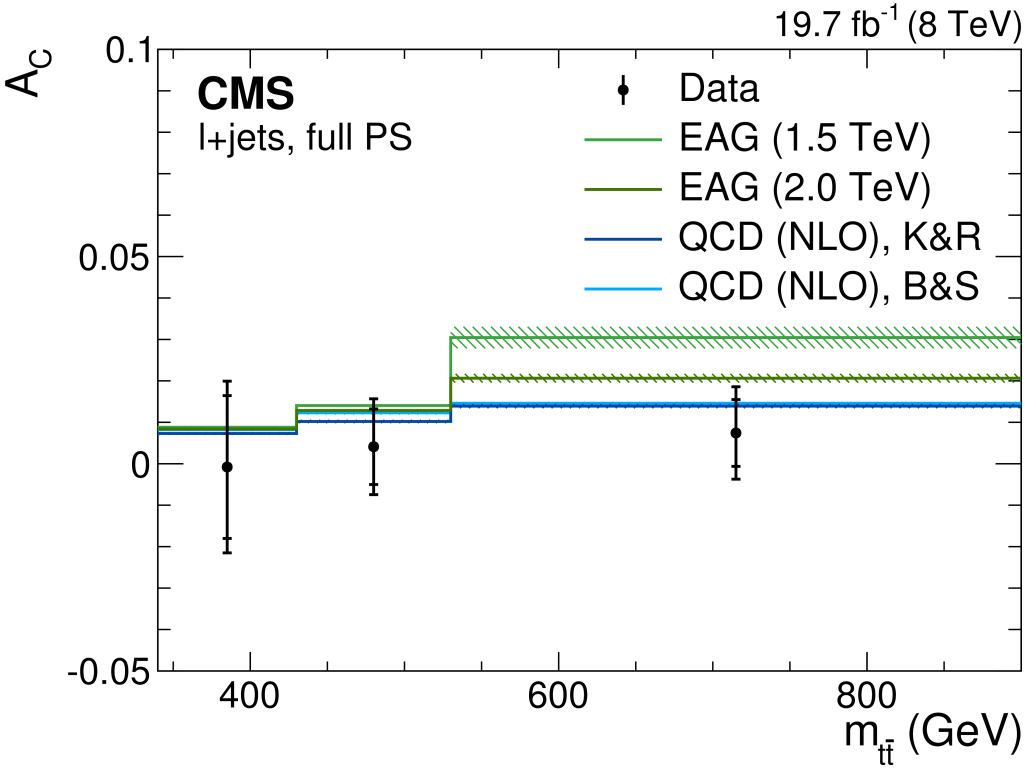


Fermilab-conf-16-386-ppd



- + bbbar asymmetry measurements consistent with LO predictions (LHCb arXiv: 1406.4789).

$t\bar{t}$ Asymmetry at the LHC

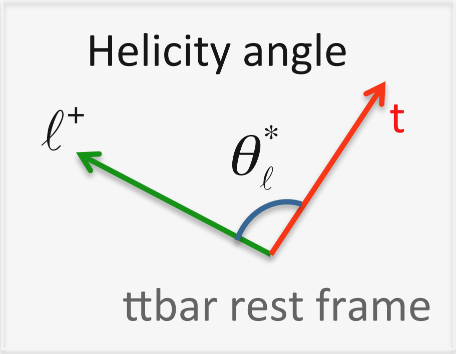


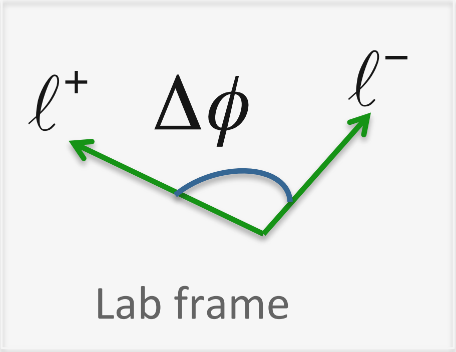
arXiv:1507.03119

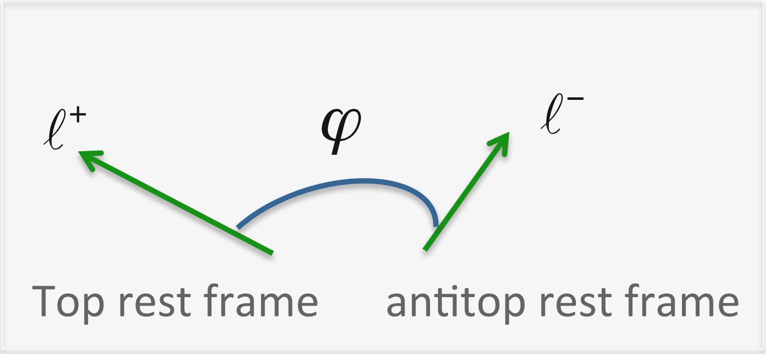
- M >~450 GeV, A_c ~2σ below predictions from EFT with new physics scale of 1.5 TeV.

ttbar production: Tops are unpolarized but heavy quark spins are correlated

Angles with or without top quark reconstruction:



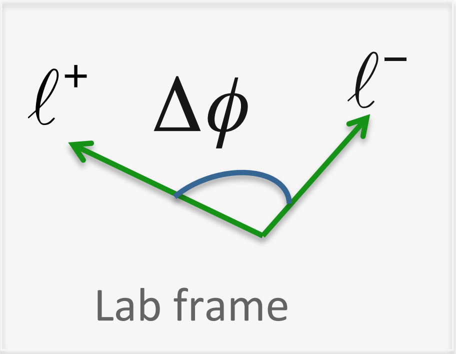




Or a multivariate method using more information from the events; e.g. Matrix Element Method:

$$P\left(x_i \middle| H\right) = \frac{1}{\sigma_{obs}} \int f_{PDF}\left(q_1\right) f_{PDF}\left(q_2\right) dq_1 dq_2 \frac{\left(2\pi\right)^4 \left|M\left(y,H\right)\right|^2}{q_1 q_2 s} W\left(x,y\right) d\Phi_6$$

Top Quark Spin Correlations - Dilepton Channel

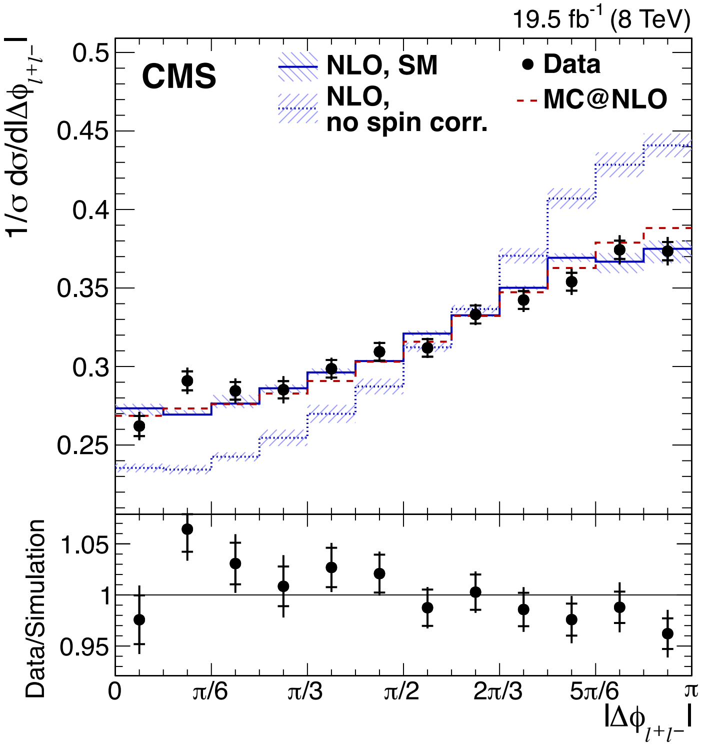


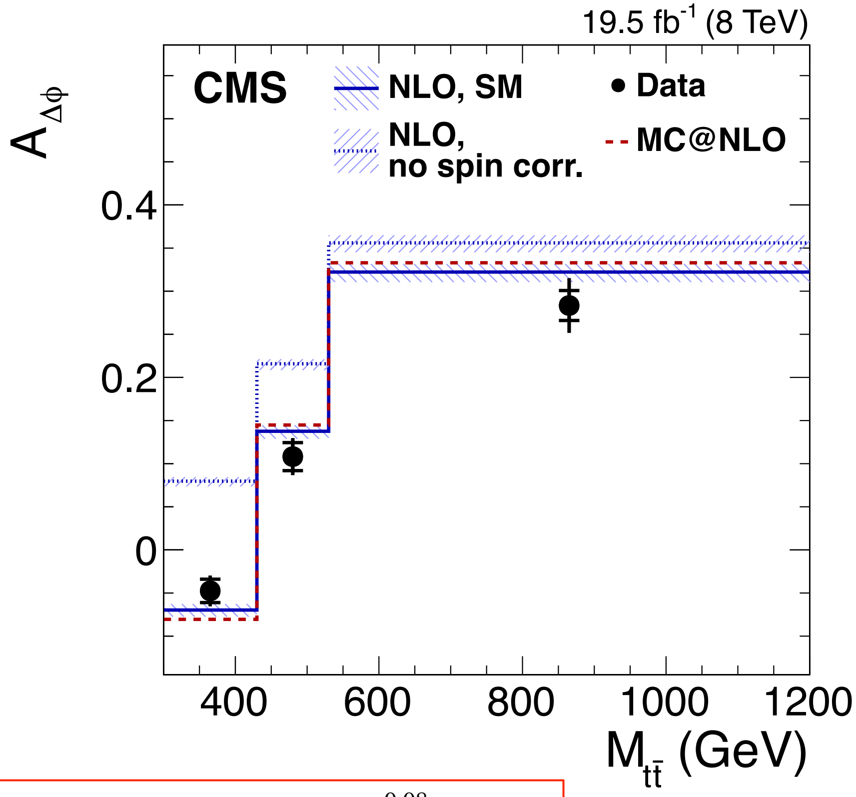
PRD 93 (2016) 052007

Δϕ distribution becomes flatter when tops are correlated.

$$A_{\Delta\phi} = \frac{N\left(\left|\Delta\phi_{\ell^+\ell^-}\right| > \pi/2\right) - N\left(\left|\Delta\phi_{\ell^+\ell^-}\right| < \pi/2\right)}{N\left(\left|\Delta\phi_{\ell^+\ell^-}\right| > \pi/2\right) + N\left(\left|\Delta\phi_{\ell^+\ell^-}\right| < \pi/2\right)}$$

$$f \equiv \frac{N_{SM}}{N_{SM} + N_{non-SM}}, \quad f_{SM} = 1$$



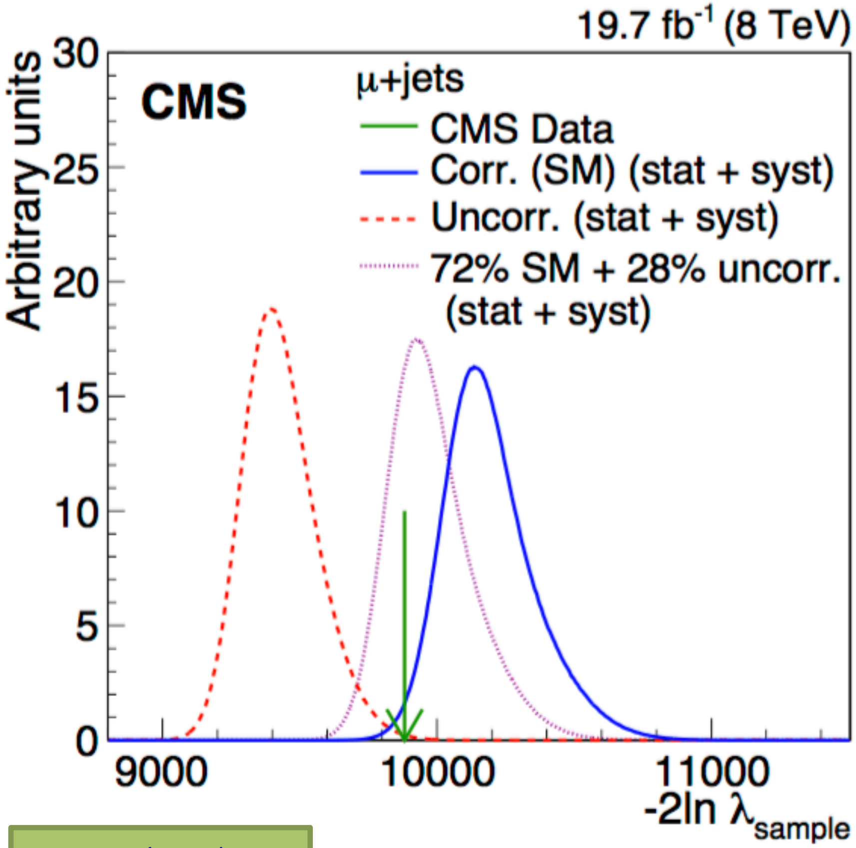


$$\boxed{f_{SM}\left(from\ A_{\Delta\phi}\quad vs\quad M_{t\bar{t}}\right) = 1.12 \pm 0.06(stat) \pm 0.08(syst)^{+0.08}_{-0.11}(theor)}$$

$t\bar{t}$ Spin Correlations – Lepton+Jets Channel

Leading order ME method to calculate event likelihoods for SM and uncorrelated hypotheses (H) using MadWeight *JHEP 12 (2010) 068*

$$P\left(x_i \middle| H\right) = \frac{1}{\sigma_{obs}} \int f_{PDF}\left(q_1\right) f_{PDF}\left(q_2\right) dq_1 dq_2 \frac{\left(2\pi\right)^4 \left|M\left(y,H\right)\right|^2}{q_1 q_2 s} W\left(x,y\right) d\Phi_6$$



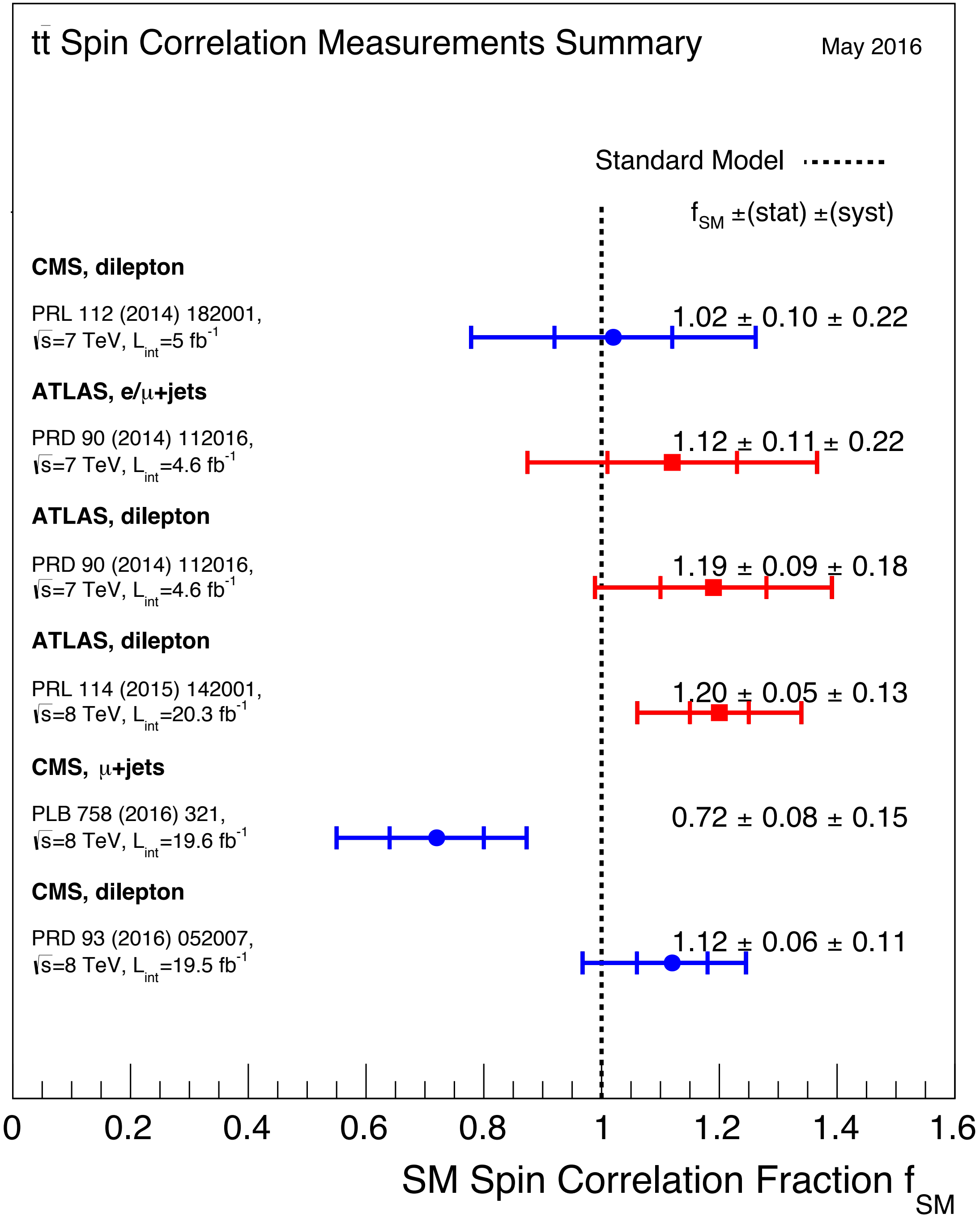
PLB 758 (2016) 321

$$\rightarrow -2\ln\lambda = -2\ln\frac{P\left(H_{non-SM}\right)}{P\left(H_{SM}\right)}$$

$$\boxed{f = 0.72 \pm 0.08\left(stat\right)^{+0.15}_{-0.13}\left(syst\right)}$$

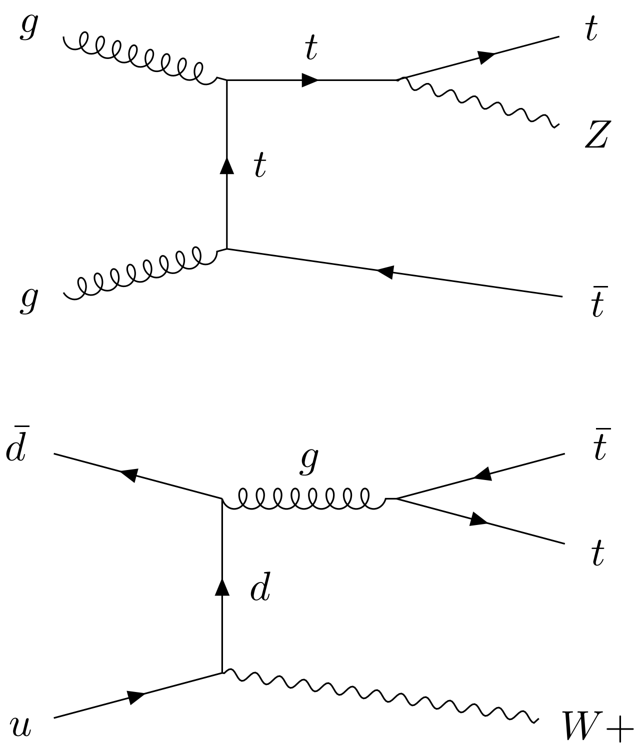
Most precise result in l+jets to-date

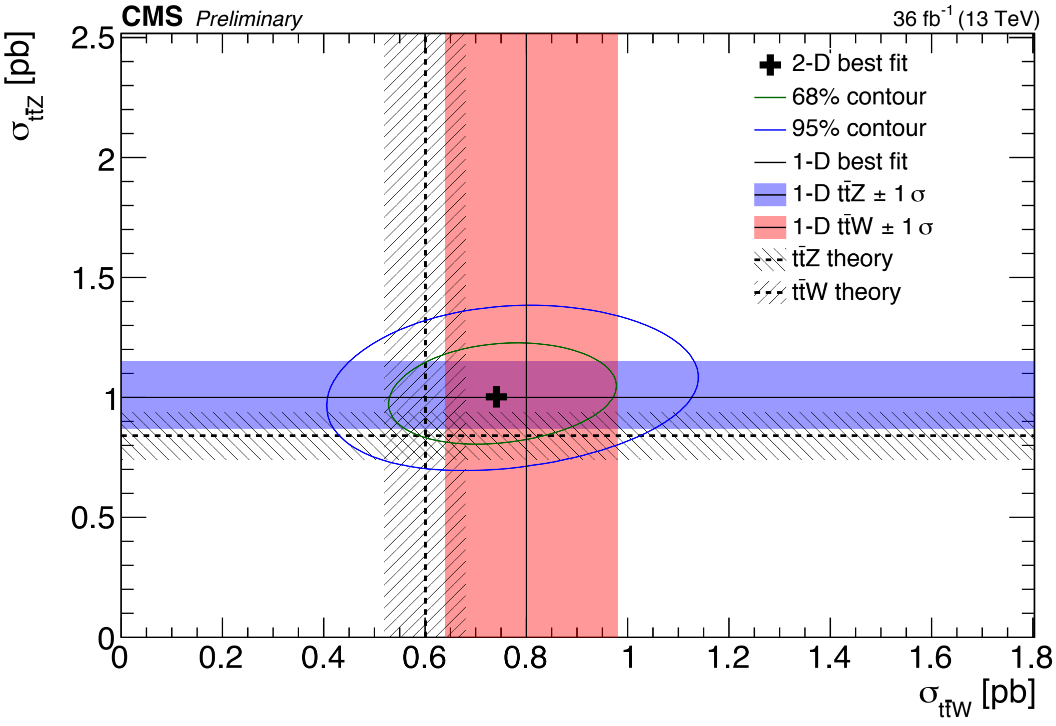
Dominated by:
JES, QCD scale, top quark mass


tt̄ Spin Correlation Measurements Summary
May 2016
Standard Model
f_SM ±(stat) ±(syst)
CMS, dilepton
PRL 112 (2014) 182001, √s=7 TeV, L_int=5 fb⁻¹
1.02 ± 0.10 ± 0.22
ATLAS, e/μ+jets
PRD 90 (2014) 112016, √s=7 TeV, L_int=4.6 fb⁻¹
1.12 ± 0.11 ± 0.22
ATLAS, dilepton
PRD 90 (2014) 112016, √s=7 TeV, L_int=4.6 fb⁻¹
1.19 ± 0.09 ± 0.18
ATLAS, dilepton
PRL 114 (2015) 142001, √s=8 TeV, L_int=20.3 fb⁻¹
1.20 ± 0.05 ± 0.13
CMS, μ+jets
PLB 758 (2016) 321, √s=8 TeV, L_int=19.6 fb⁻¹
0.72 ± 0.08 ± 0.15
CMS, dilepton
PRD 93 (2016) 052007, √s=8 TeV, L_int=19.5 fb⁻¹
1.12 ± 0.06 ± 0.11
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
SM Spin Correlation Fraction f_SM

Top Quark Couplings

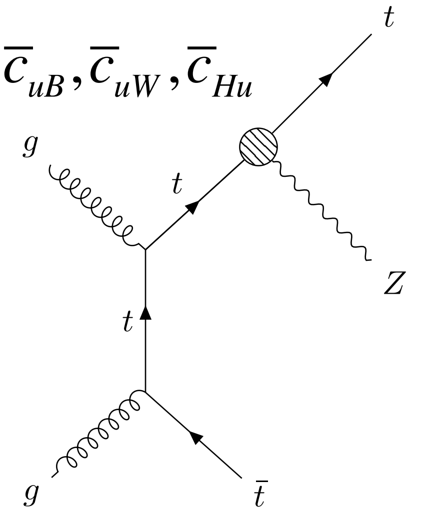
- ttZ and ttγ → Direct access to top-electroweak couplings.
- ttW and ttZ: important backgrounds for top-Higgs coupling measurements.
- ttZ/W and ttγ measured and limits on anomalous couplings, four-top production and ttH have been placed.

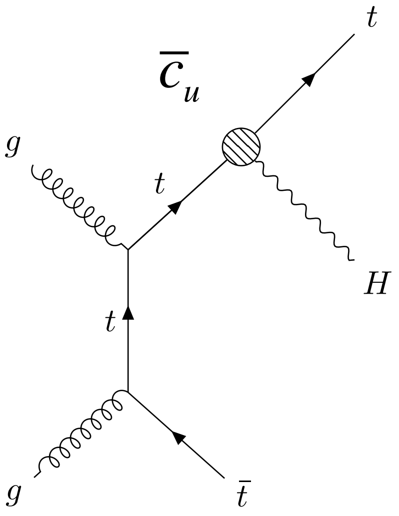


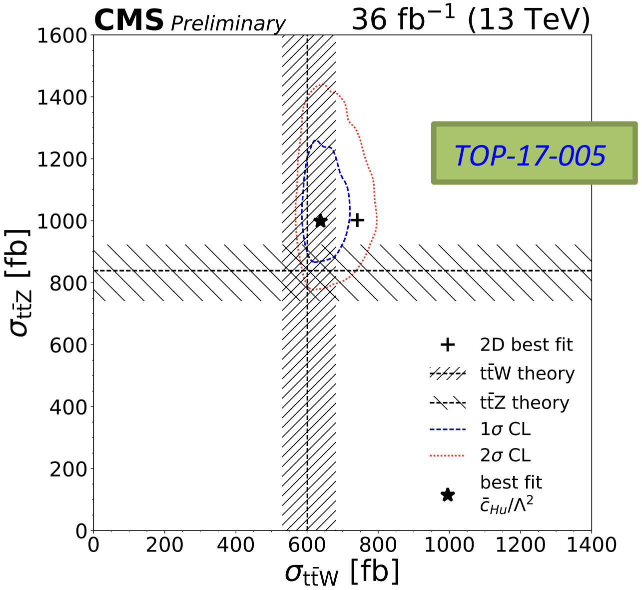


TOP-17-005

Top Quark Couplings







- Effective field theory
- Model independent search for NP at energy scales not accessible by experiments.
- Extend the SM Lagrangian with higher-order operators.
- Series expansion in 1/Λ (Λ = energy scale of new physics).
- c_i & c_j : Wilson coefficients parametrize the strength of the new physics interactions.

https://arxiv.org/abs/1008.4884

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_i c_i \mathcal{O}_i + \frac{1}{\Lambda^2}\sum_j c_j \mathcal{O}_j + \cdots$$

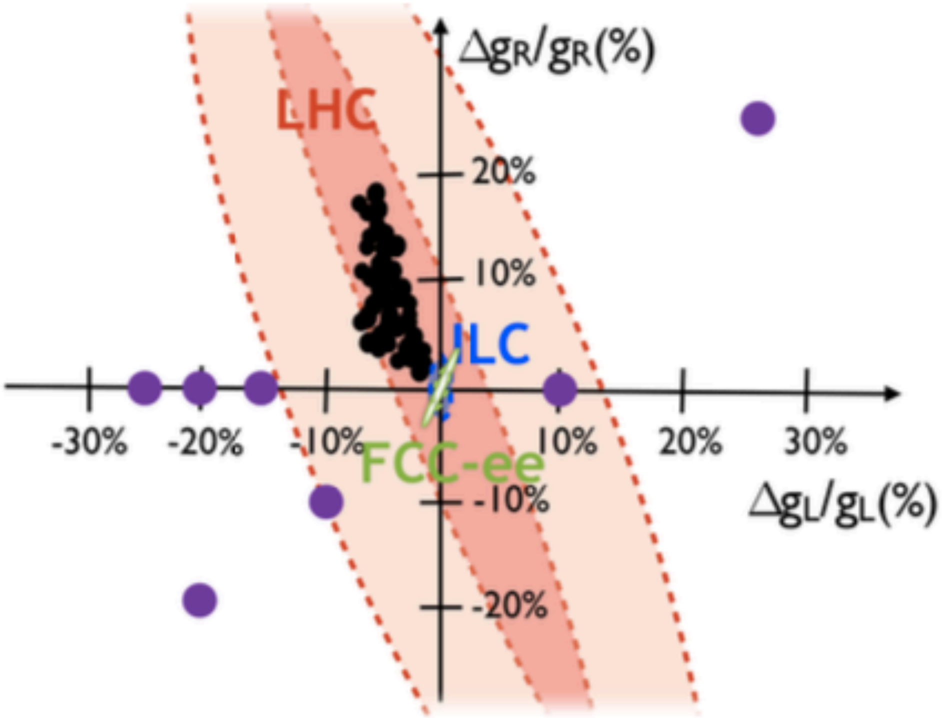
dim-4

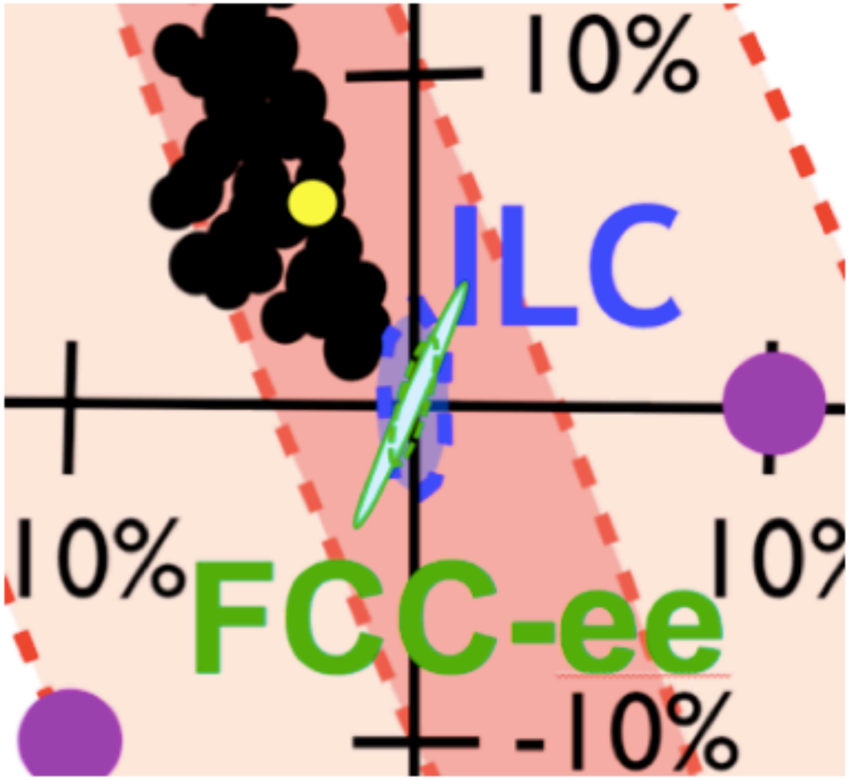
Dim-5 operators

Dim-6 operators

(59 independent operators)

Top-Z Coupling

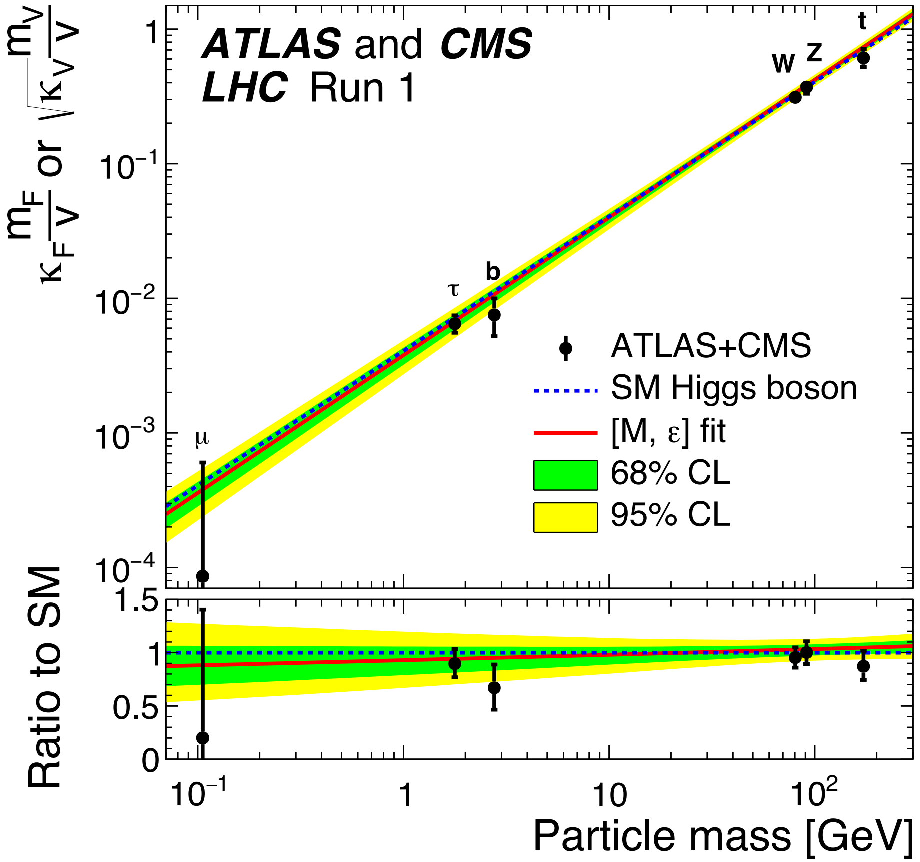




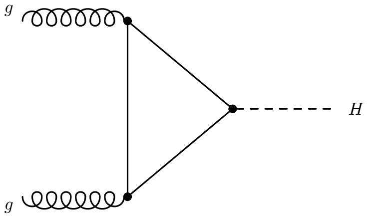
arxiv:1703.01626

- Zt_Lt_L and Zt_Rt_R couplings
- Purple points: various new physics model predictions.

Top-Higgs Coupling

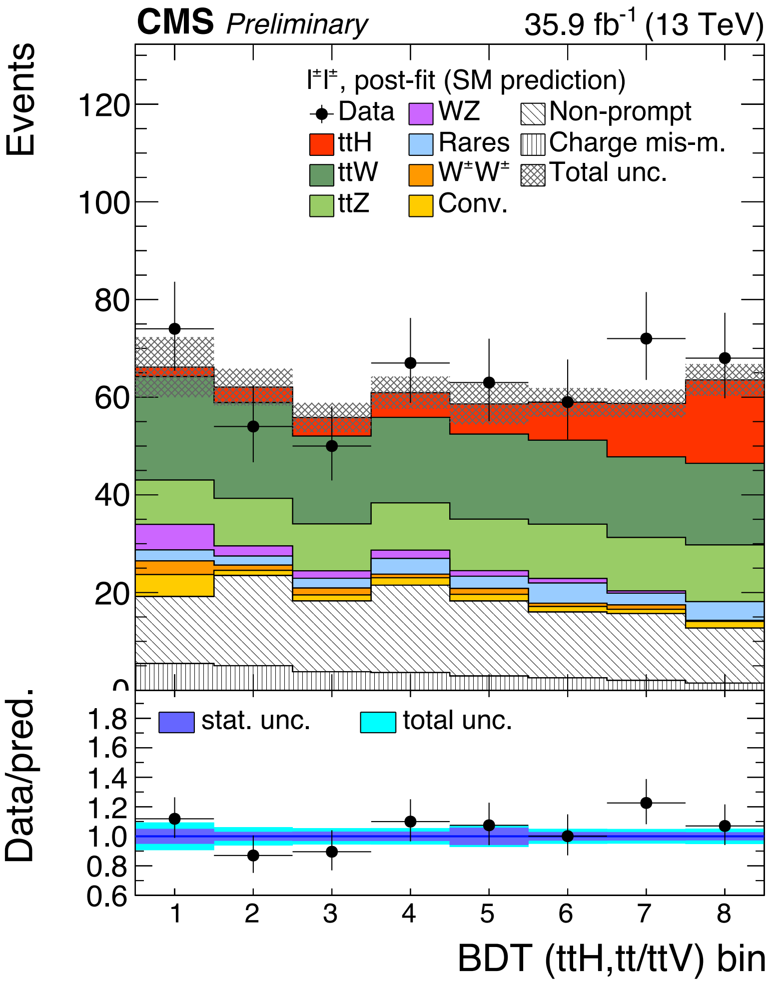


JHEP 08 (2016) 045



- κ framework → use simple coupling modifiers (k=1 → SM)
- Top-higgs coupling compatible with SM within <~ 1 σ
- All couplings compatible with SM within <~ 2 σ

ttH Evidence

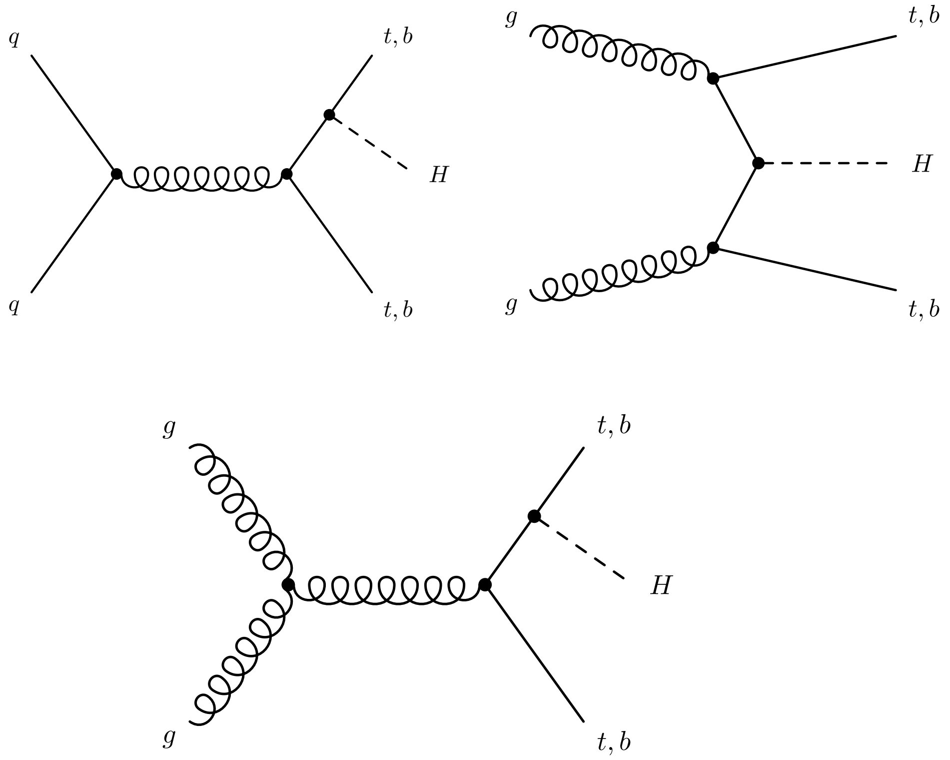


$$ttH, H \to WW^*, ZZ^*, \tau\tau$$

- → At least one of the top quarks decays leptonically
- → Select two leptons with same charge
- → 3 leptons or
- → 4 leptons
- → And 1 b tag

CMS-PAS-HIG-17-004

~3.3 σ



Anomalous Top-Gluon Interaction

PRD 93 (2016) 052007

- SM: dipole moments generated radiatively and are very small.
- BSM: dipole moment couplings can occur at tree level.

Anomalous interaction from a heavy-particle exchange ($M > m_t$) :

$$\mathcal{L}_{eff} = -\frac{\tilde{\mu}_t}{2}\bar{t}\sigma^{\mu\nu}T^a t G^a_{\mu\nu} - \frac{\tilde{d}_t}{2} i\sigma^{\mu\nu}\gamma_5 T^a t G^a_{\mu\nu}.$$

Chromo magnetic dipole moment

CP conserving

$$D = D_{SM} + \mathrm{Re}\left(\hat{\mu}_t\right) D_{NP}$$

$$-0.053 < \mathrm{Re}\left(\hat{\mu}_t\right) < 0.026 \quad @95\% \ C.L.$$

Chromo electric dipole moment

CP violating

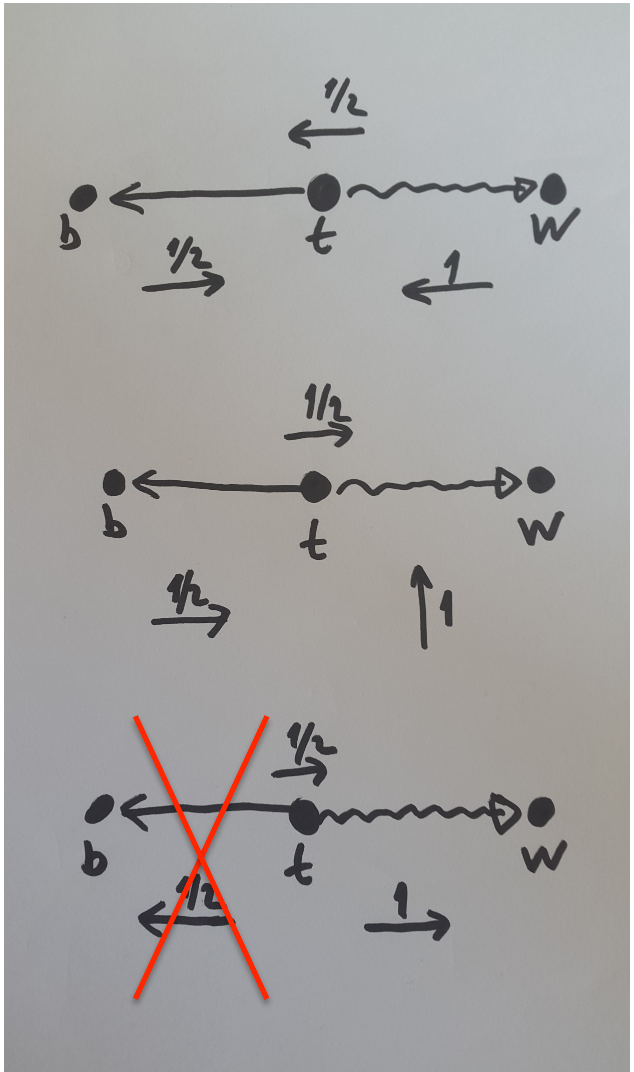
$$P^{CP-violating} = \mathrm{Im}\left(\hat{d}_t\right) P_{NP}^{CP-violating}$$

$$-0.068 < \mathrm{Im}\left(\hat{d}_t\right) < 0.067 \quad @95\% \ C.L$$

Bernreuther & Si,
PLB 725 (2013) 115
PLB 744 (2015) 413

W Boson Polarization

- Wtb vertex → electroweak V-A structure.
- W helicity fractions (F_X) sensitive to the Wtb vertex structure.



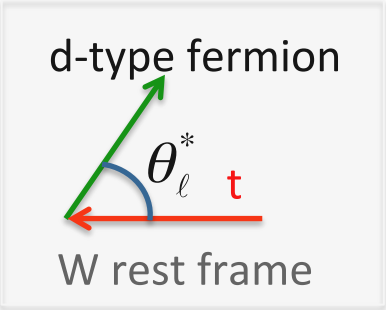
Left-handed
(negative helicity)

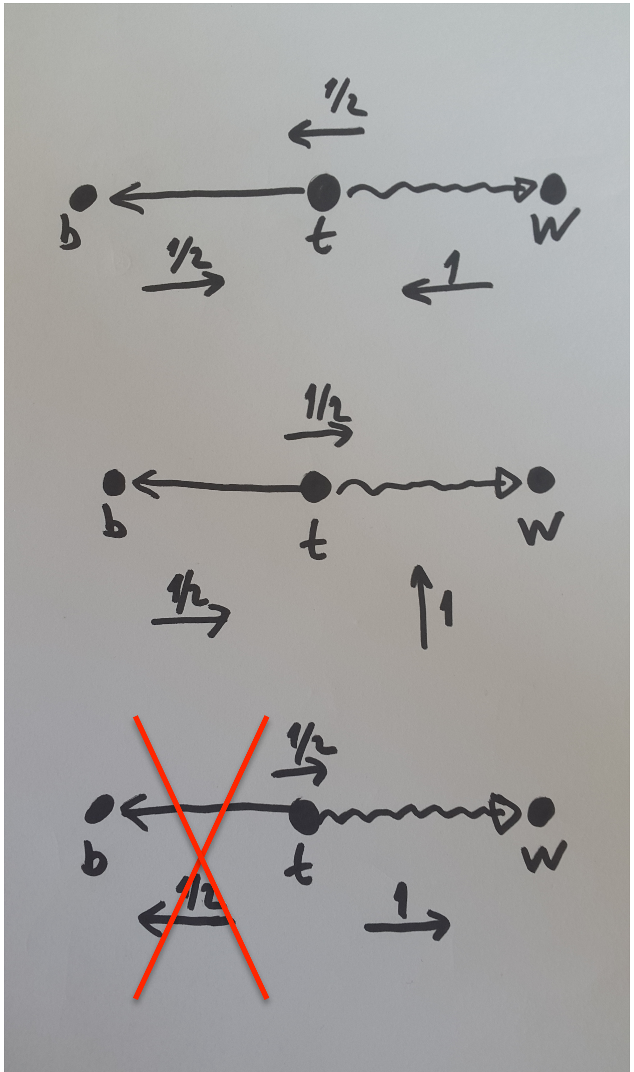
longitudinal
(zero helicity)

Right-handed
(positive helicity)

Massless b-quark always left-handed and top quark left or right handed → Angular momentum conservation: Top quark decay to a right-handed W boson is forbidden.

W Boson Polarization





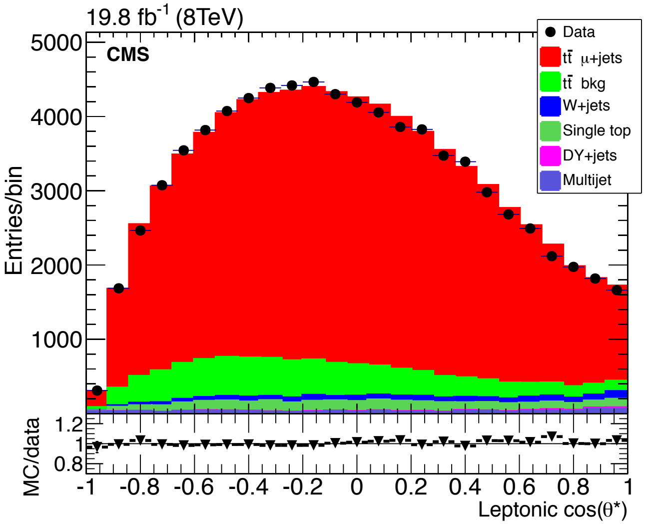
$$\frac{d\sigma}{d\cos\theta^*} \approx \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{4}\left(\sin\theta^*\right)^2 F_0 + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R$$

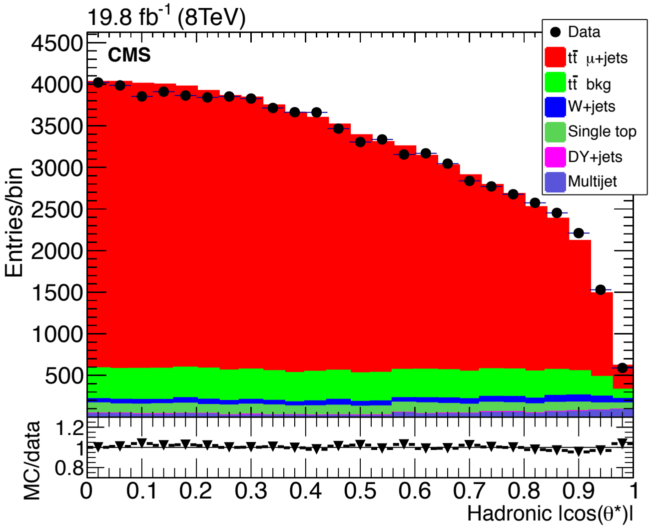
F_L~0.3	F_0~0.7	F_R~0
Left-handed (negative helicity)	longitudinal (zero helicity)	Right-handed (positive helicity)

Top quark prefers to couple more to longitudinally polarized W bosons.

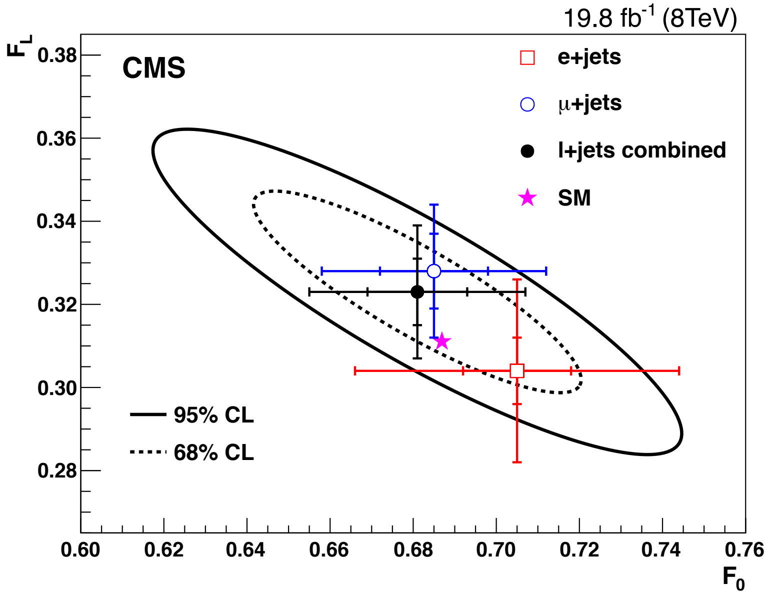
Higher orders (at NNLO QCD) with $m_b \neq 0$ modify the helicity fractions by ~2%.

W Boson Polarization





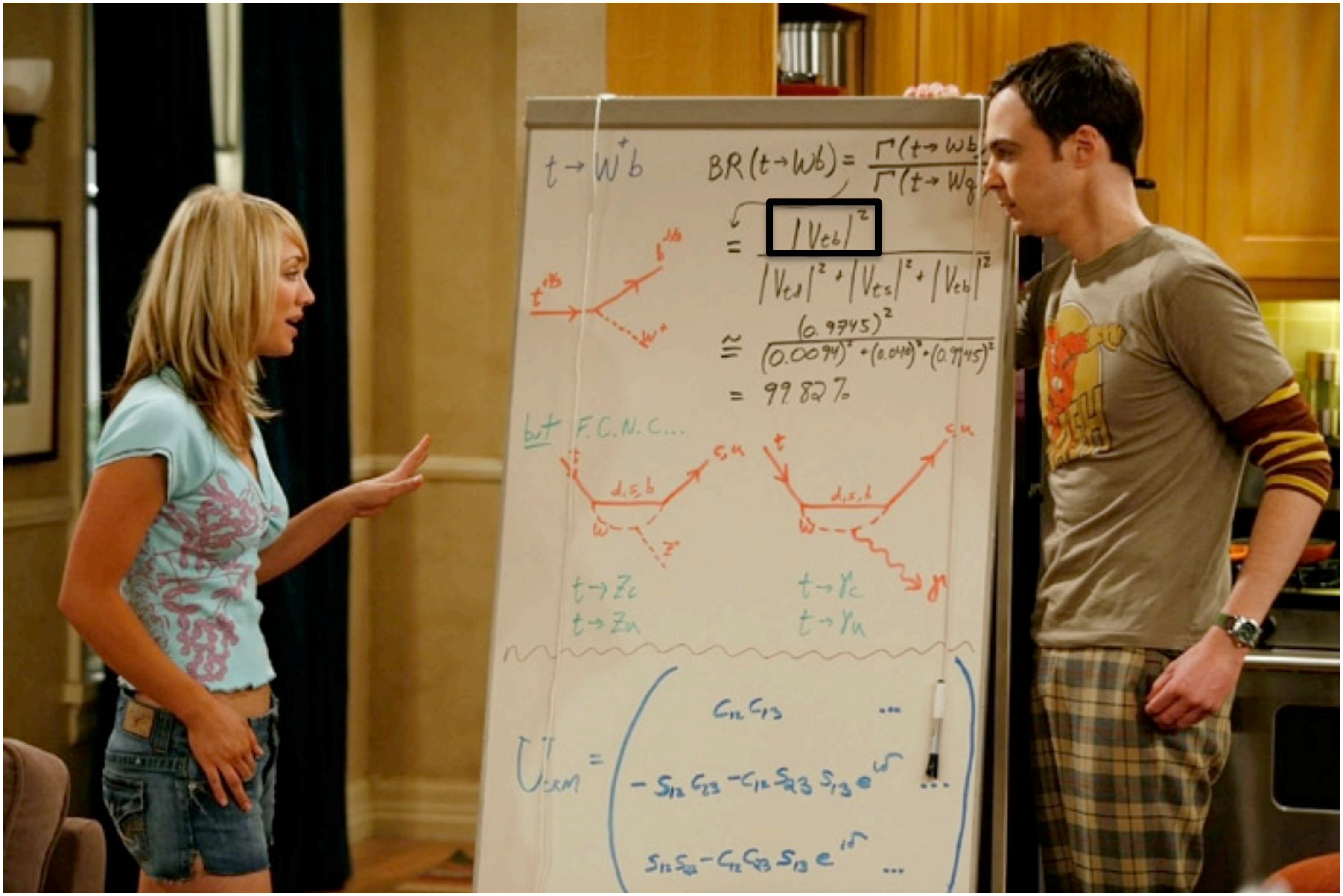
e/μ + 4 jets (2 b-tagged)



$$F_0 = 0.681 \pm 0.012(stat) \pm 0.023(syst)$$
$$F_L = 0.323 \pm 0.008(stat) \pm 0.014(syst)$$
$$F_R = -0.004 \pm 0.005(stat) \pm 0.014(syst)$$

Dominant uncertainties: Top quark mass and QCD scales.

CMS-PAPER-TOP-13-008, submitted to PLB


t → W⁺ b
BR(t→Wb) = Γ(t→Wb) / Γ(t→Wq)
= |Vtb|² / |Vtd|² + |Vts|² + |Vtb|²
≅ (0.9745)² / (0.0094)² + (0.049)² + (0.9745)²
= 99.82%
but F.C.N.C...
d, s, b
t → Zc
t → Zu
t → γc
t → γu
U_CKM =
c12 c13 ...
− s12 c23 − c12 s23 s13 e^iδ ...
s12 s23 − c12 c23 s13 e^iδ ...

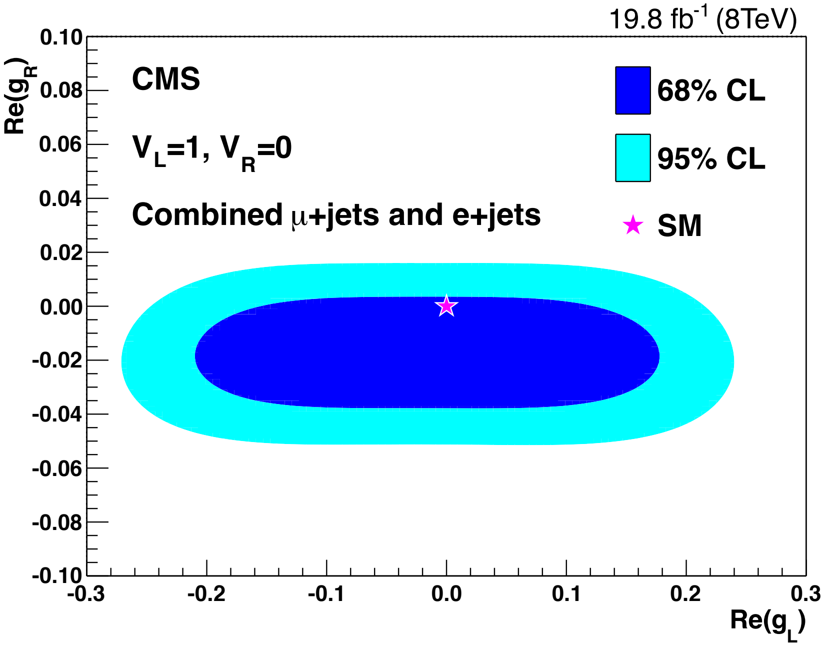
W Boson Polarization

- Wtb: magnitude determined by $|V_{tb}|$.
- BSM contributions to Wtb vertex modify helicity fractions.
- In the effective operative framework:

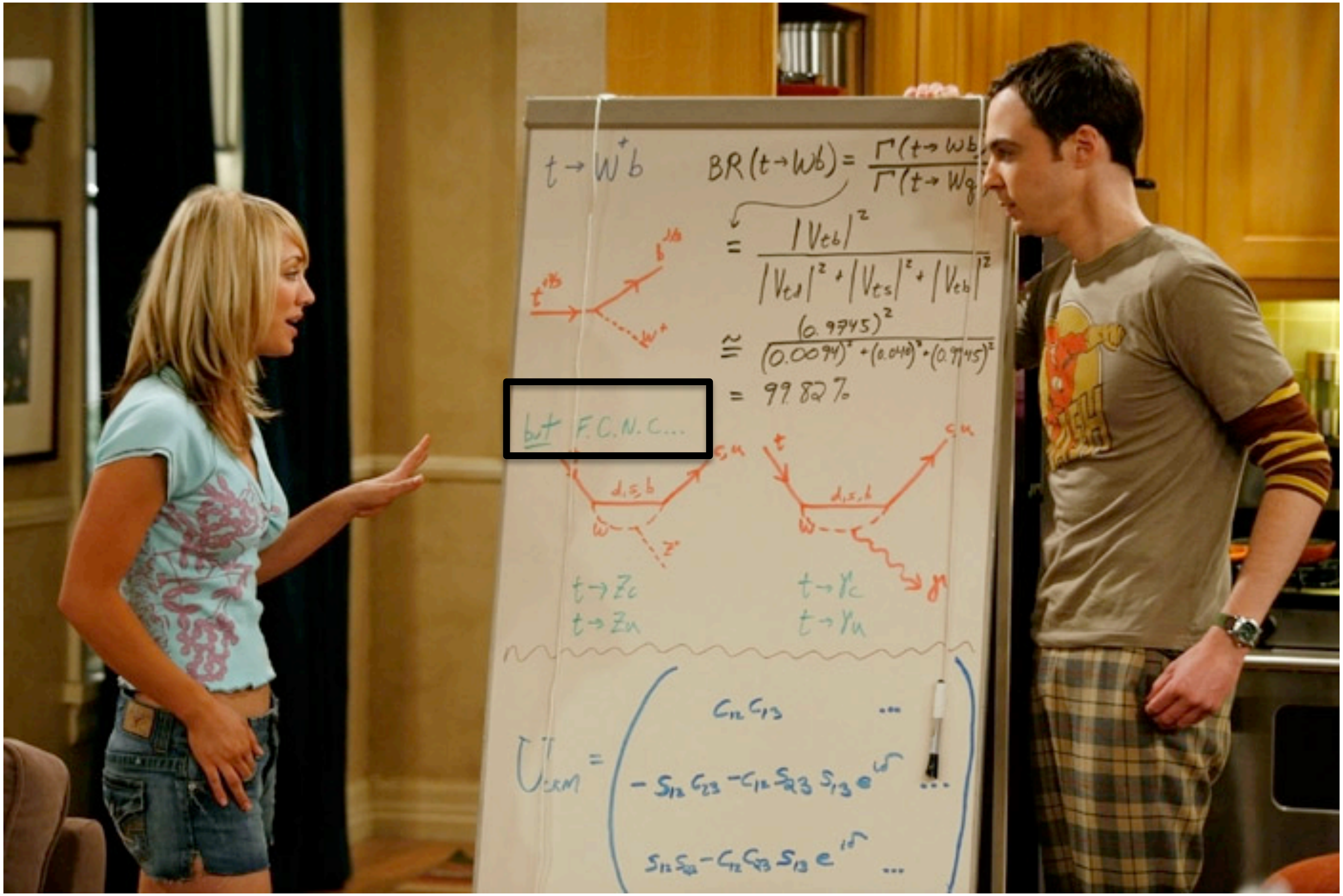
$$\begin{aligned}\mathcal{L}_{Wtb} &= -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W_{\mu}^{-} \\ &\quad -\frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right) t\, W_{\mu}^{-} + \text{h.c.}\end{aligned}$$

$$SM:\ V_L = V_{tb} \approx 1$$

$$V_R = g_L = g_R = 0$$

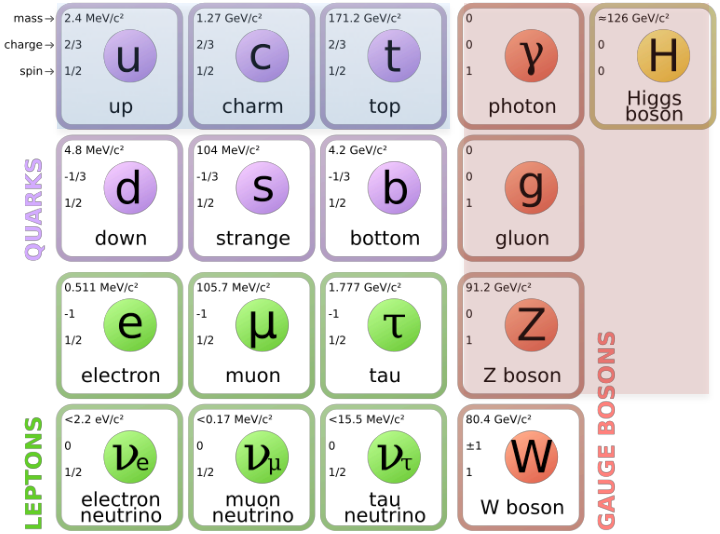


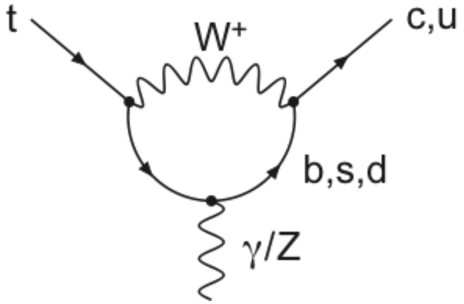
CMS-PAPER-TOP-13-008, submitted to PLB

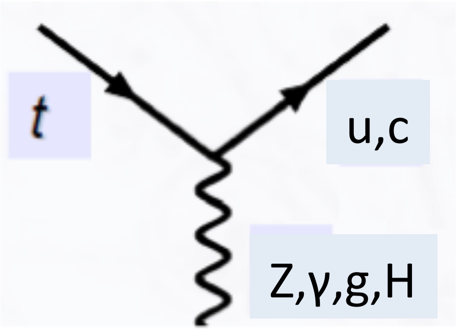

t → W⁺b
BR(t→Wb) = Γ(t→Wb) / Γ(t→Wq)
= |Vtb|² / (|Vtd|² + |Vts|² + |Vtb|²)
≅ (0.9745)² / ((0.0094)² + (0.049)² + (0.9745)²)
= 99.82%
t⁺²/³
b⁺¹/³
W⁺
but F.C.N.C...
t
c,u
d,s,b
W
Z⁰
γ
t→Zc
t→Zu
t→γc
t→γu
U_CKM =
c₁₂c₁₃ ...
−s₁₂c₂₃ − c₁₂s₂₃s₁₃e^{iδ} ...
s₁₂s₂₃ − c₁₂c₂₃s₁₃e^{iδ} ...

Flavor Changing Neutral Currents

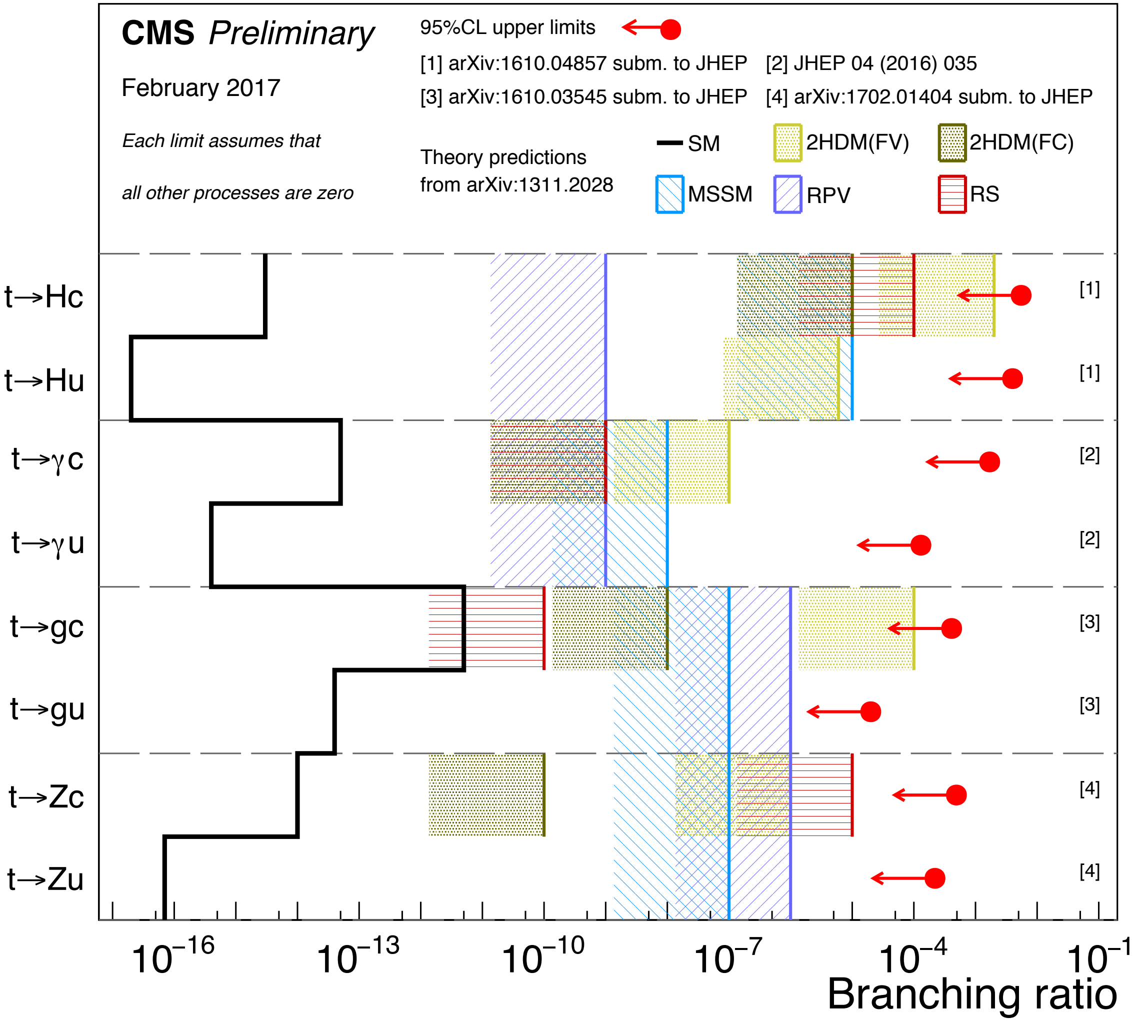
- SM: Forbidden at tree level
- Suppressed at higher orders due to GIM mechanism.
- Occurs only at the level of loop corrections with $\mathcal{B}(t\rightarrow Xq)\sim 10^{-15}\text{-}10^{-10}\%$
- BSM $\mathcal{B}(t\rightarrow Xq)\sim 10^{-7}\text{-}10^{-1}\%$
- Measurements$\sim 10^{-2}\text{-}1\%$







FCNC



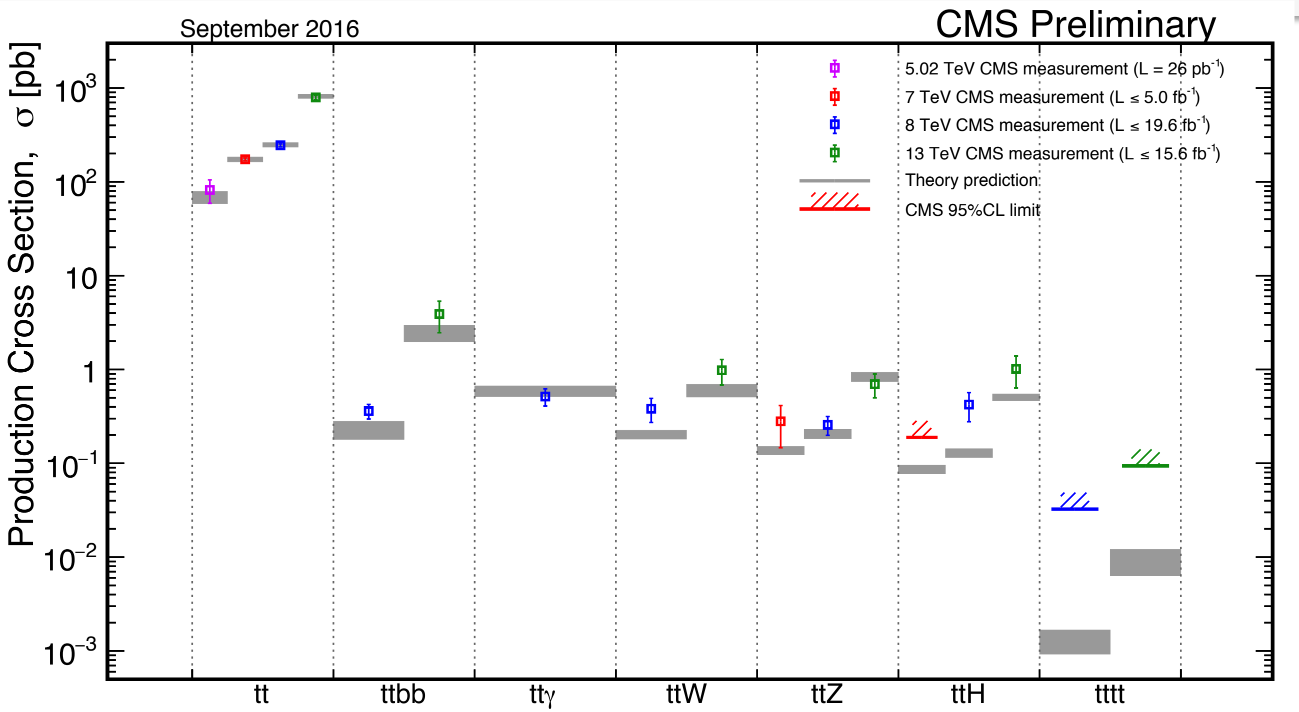
- No sign of FCNC in ttbar and single top
- Measurements statistics dominated.

Summary

- Top quark plays an important role in precision measurements and new particles searches.
- Top re-discovered at the LHC.
- Most LHC Run I measurements dominated by systematic uncertainties.
  - σ_{tt} < 4% better than NNLO accuracy
  - m_t with ~500 MeV precision.
  - Precise properties measurements and constraints on anomalous couplings.
- So far, all results in agreement with SM predictions.
  - And no evidence of any invisible particles.

LHC Run II

- Inclusive ttbar cross section already at NNLO precision.
- Single top t-channel precisely established.
- In both cases starting to probe differential spectra to understand new MCs
- Establish couplings to all bosons in Run II.
- Direct or indirect indications of new physics?



All results at: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Closing

- "A measurement that cannot be done accurately, can never be divorced from politics and must therefore generate mythologies. The more such shades of meaning there are, the less scientific the discussion becomes. Accurate measurement in this sense is scientific law, and a milieu in which accurate measurement is impossible is lawless.
- The need for precision, in turn, redoubles the need for that other great Greek tradition, open discussion for ideas and ruthless separation of meaningful things from meaningless ones. Precision alone does not guarantee good law…"
  - "A different Universe", R. B. Laughlin

QUESTIONS