Top Quark Physics

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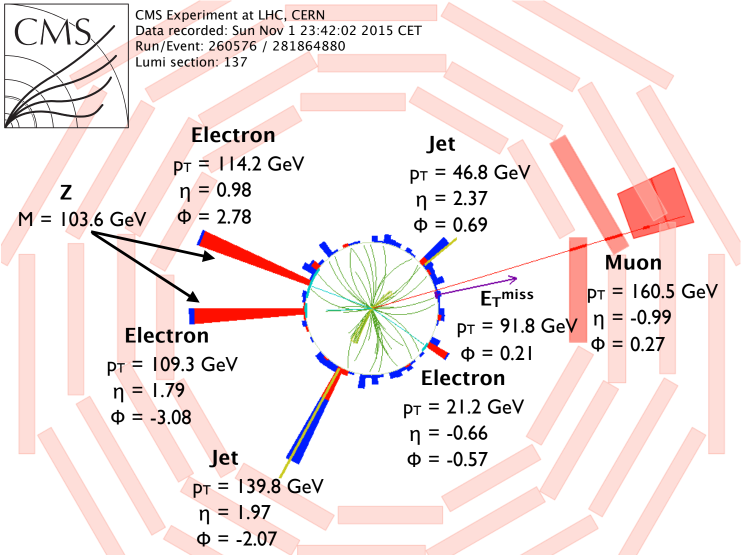
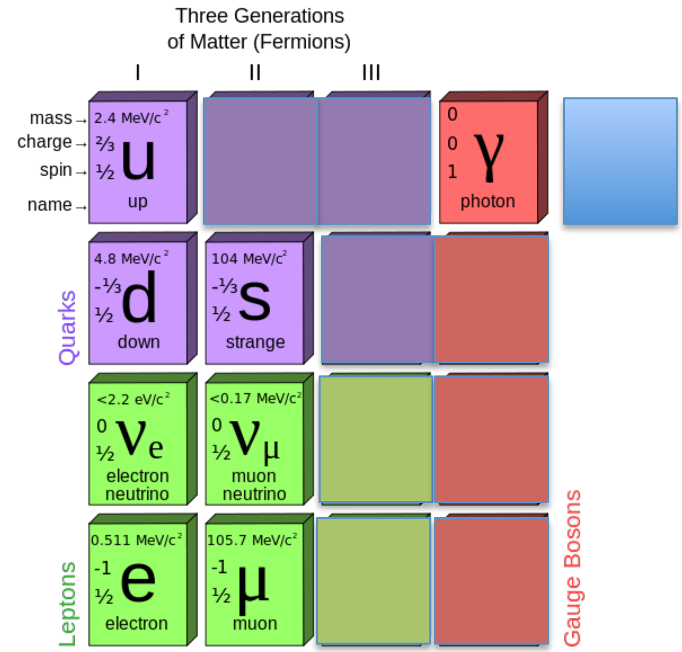


Hadron Collider School – HASCO 2016
Georg-August-Universtät, Göttingen, Germany
19-24 July 2016

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



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

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

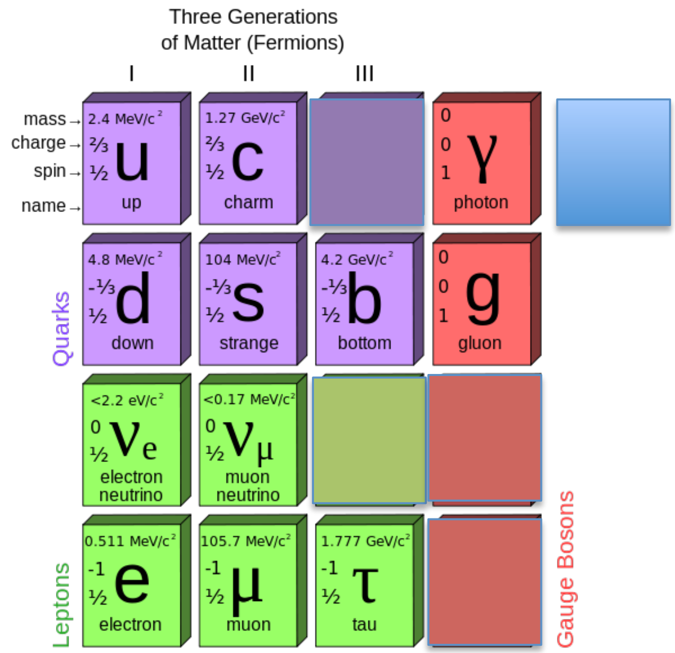
Department of Physics, Kyoto University, Kyoto

(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.

Standard Model in 1978

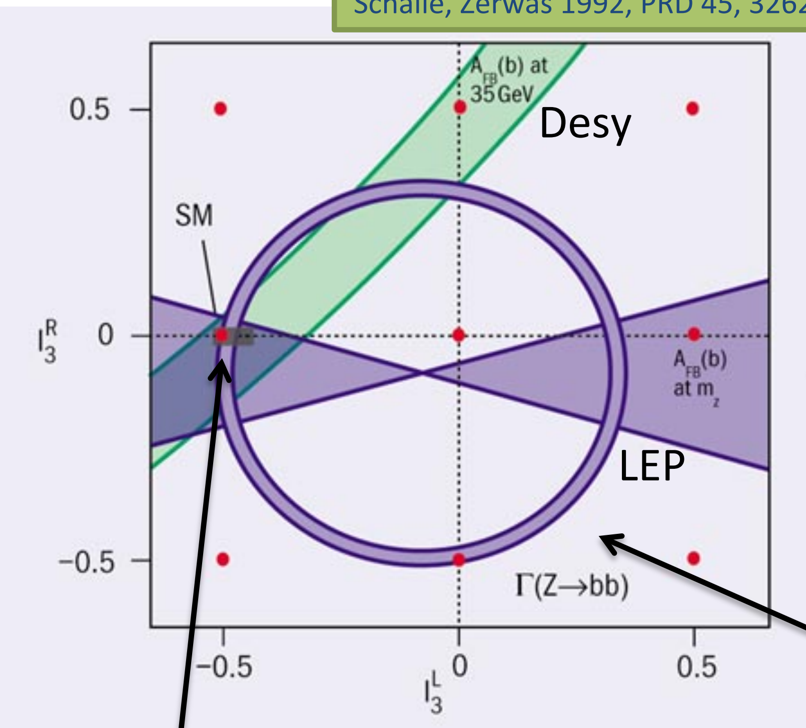
- b-quark discovered ('77) and its iso-spin is measured.
- To complete the third generation → the weak isospin partner of the b-quark.



Weak Isospin of b Quark and its Partner

Schaile, Zerwas 1992, PRD 45, 3262

(right handed b-quark)



(left handed b-quark)

V→ vector coupling
A → Axial coupling

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

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

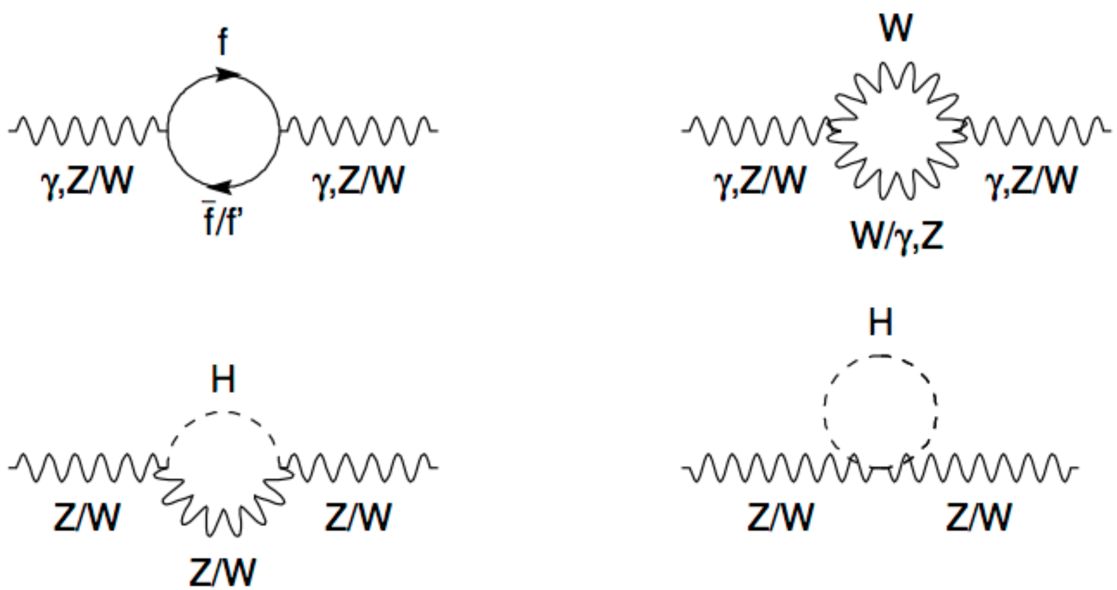
$$\Gamma(Z \to b\bar{b}) = \frac{G_F M_Z^3}{2\sqrt{2}\pi}(V_b^2 + A_b^2)$$

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

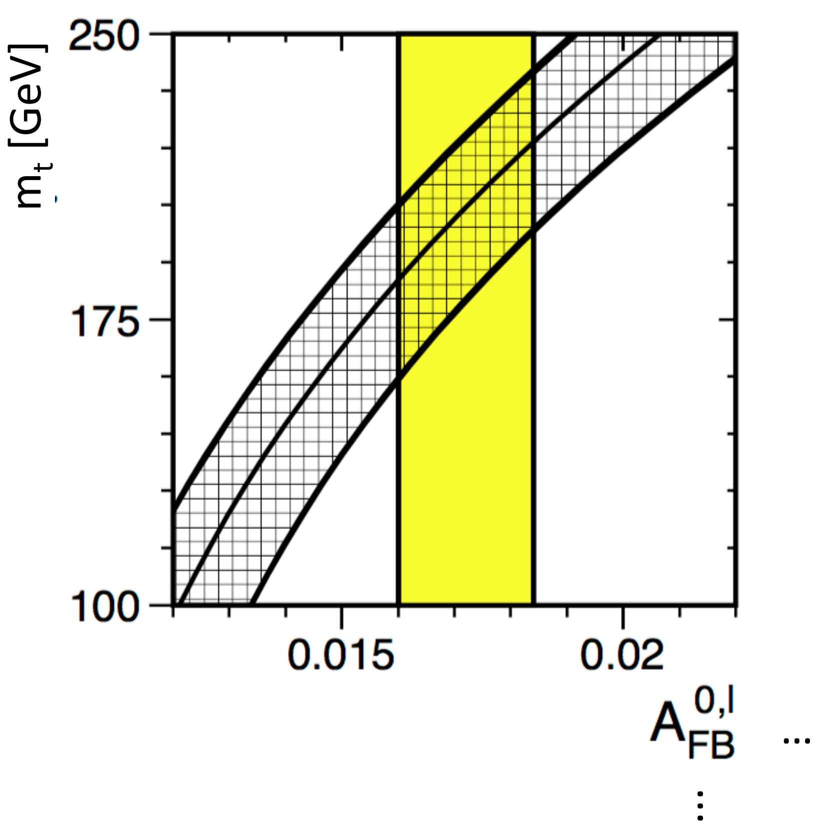
→ Isospin partner with
$[I_3^L, I_3^R] = [+1/2, 0]$ should exist.

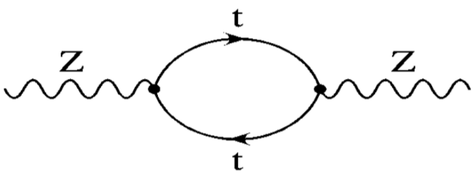
Quantum Fluctuations Seeing Invisible Particles

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



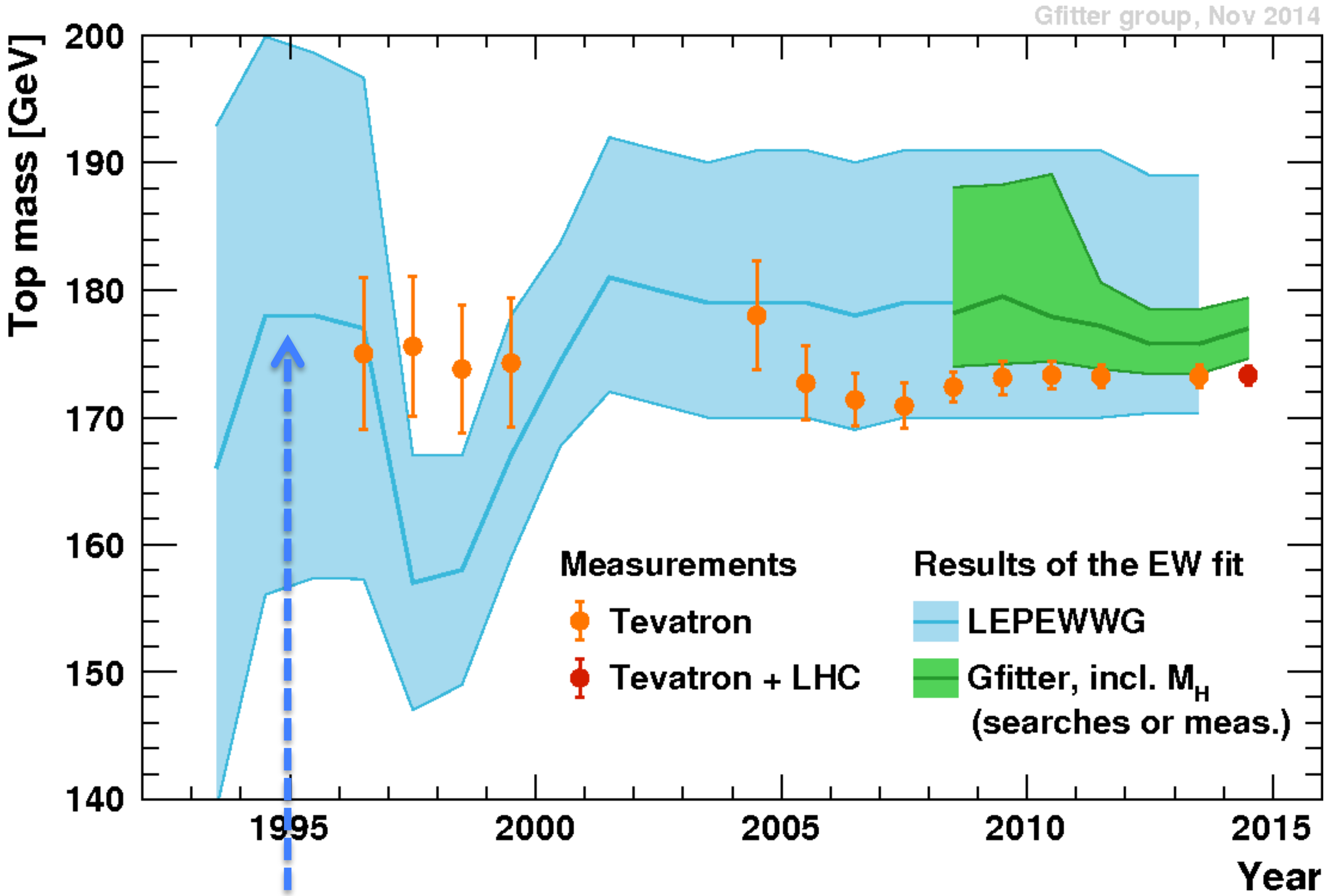


LEP 1 prediction:

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

LEP Collaborations CERN-PPE/95-172

One of the most critical tests of the standard model!



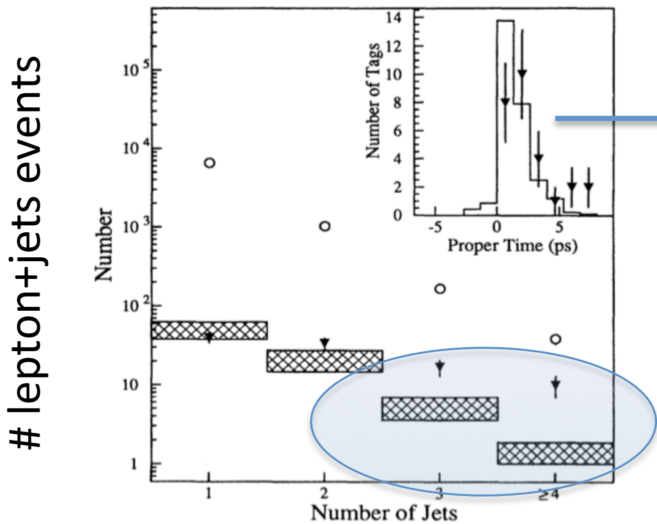
http://project-gfitter.web.cern.ch/project-gfitter/History/

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

The Discovery of the Top Quark at the Tevatron

CDF, PRL 74, 2626 (1995)

with O(10) events.

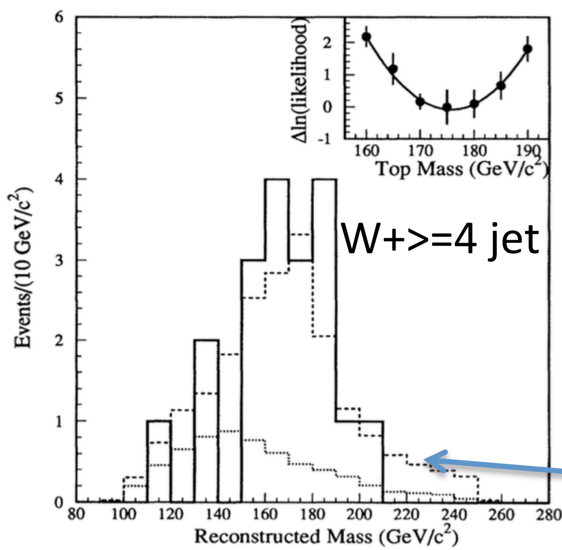


Circles:
Before b-tagging

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

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

Signal consistent with $t\bar{t} \rightarrow W^+ b W^- \bar{b}$
and inconsistent w/ the background prediction.



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

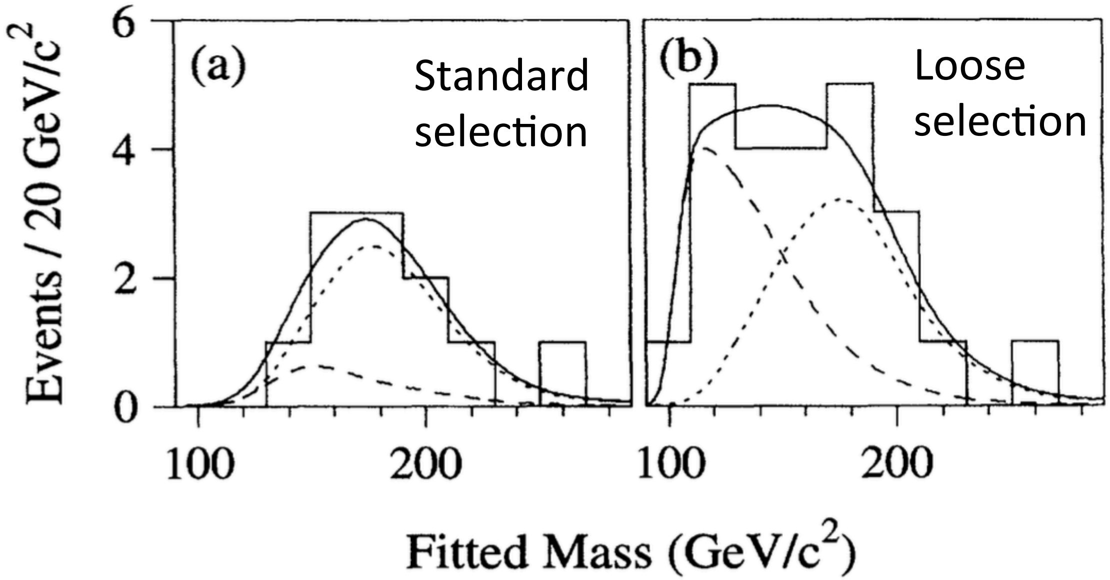
$$m_t^{CDF} = 176 \pm 8(stat.) \pm 10(syst.)\ GeV$$

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

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

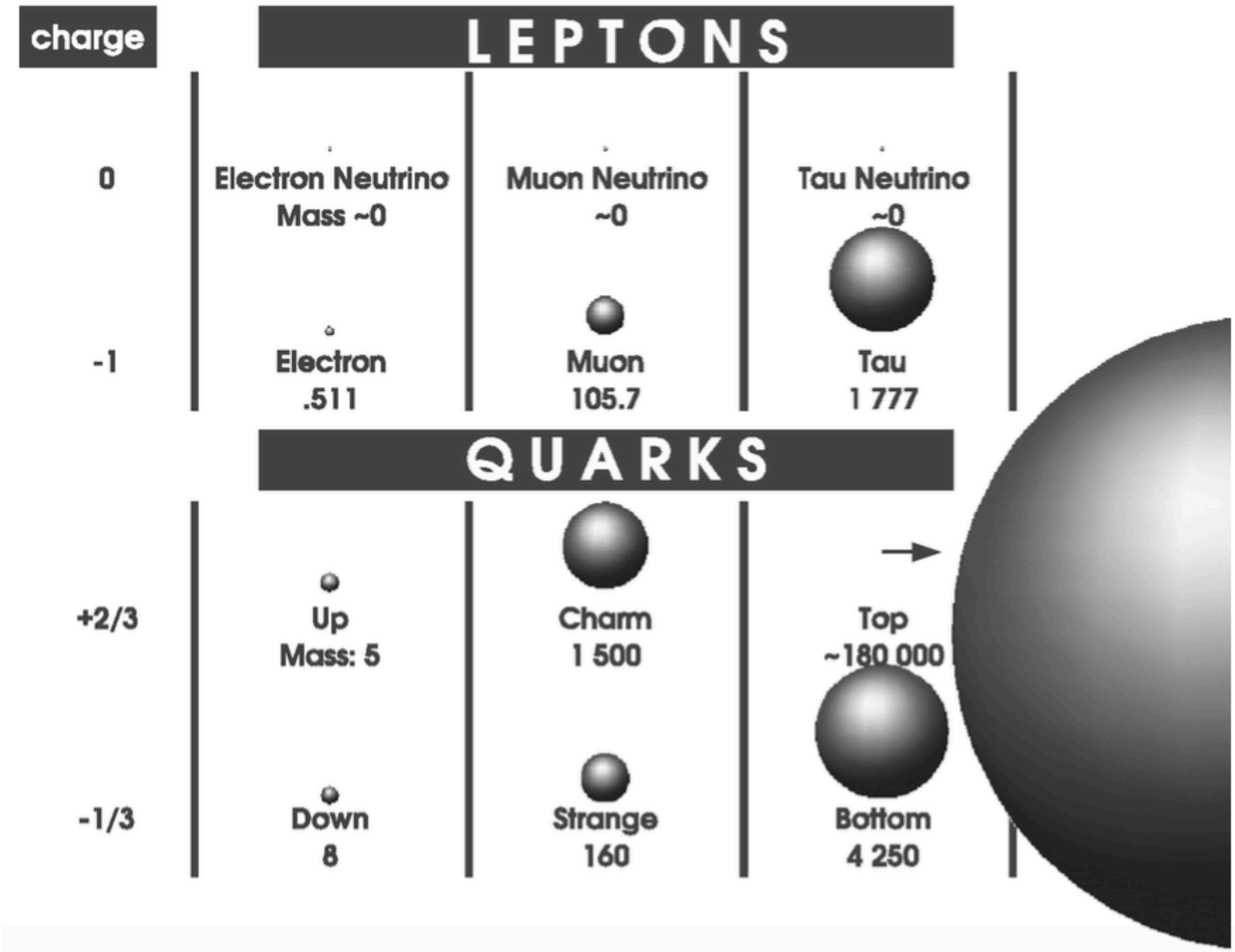
and inconsistent w/ the background prediction.

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

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

The Top Quark

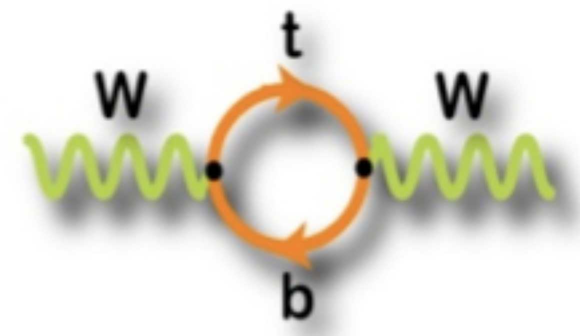
- The most massive particle known to date (m_t~173 GeV).

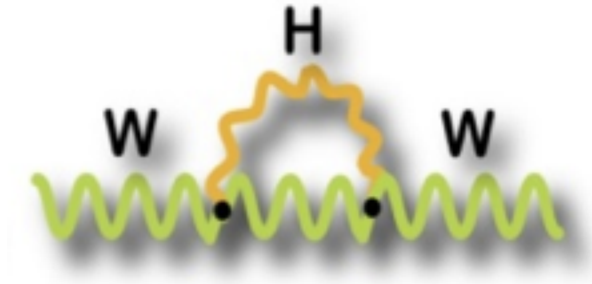


Quadt, EPJC 48, 835 (2006)

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)

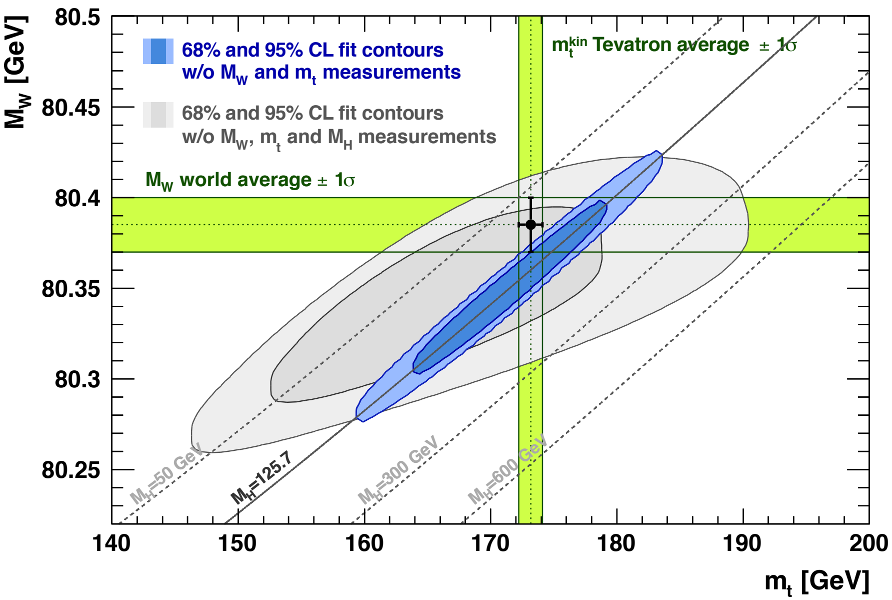
$$\Delta\rho_t \sim G_F m_t^2$$

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

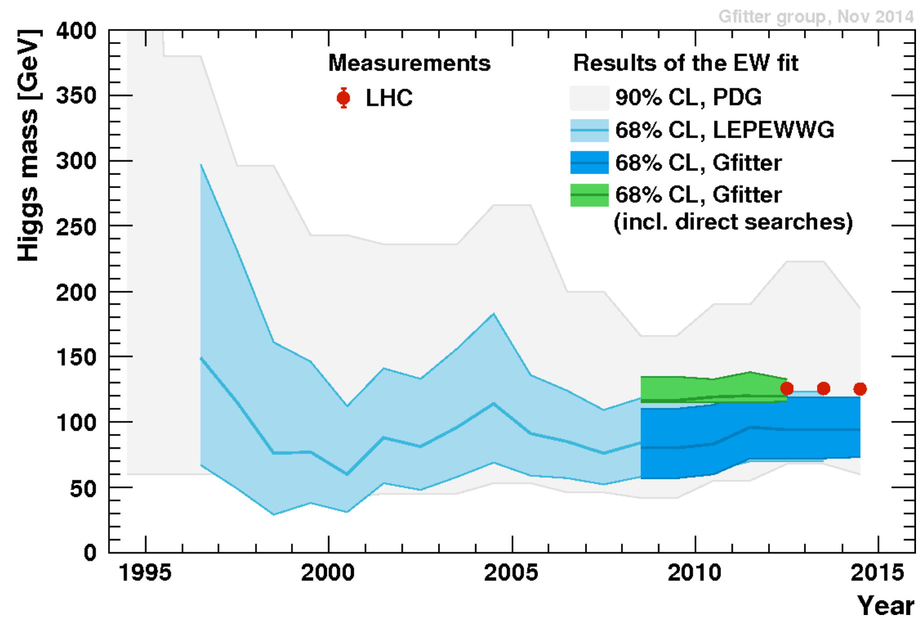
Precision Measurements of Top and W → Higgs

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/

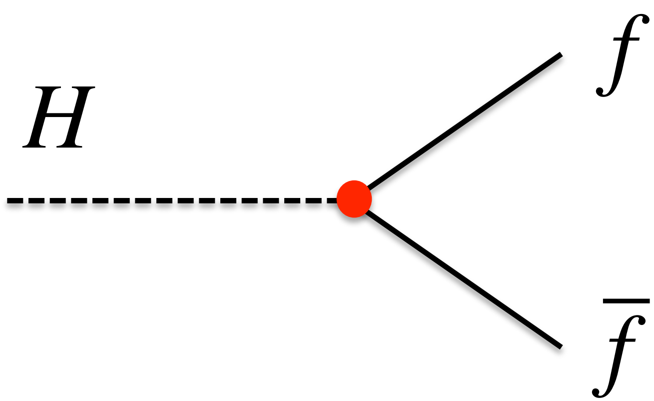


Quantum fluctuations showed the existence of the Higgs boson and predicted its mass precisely before it was discovered.

The most critical test of the standard model!

Top Quark Yukawa Coupling

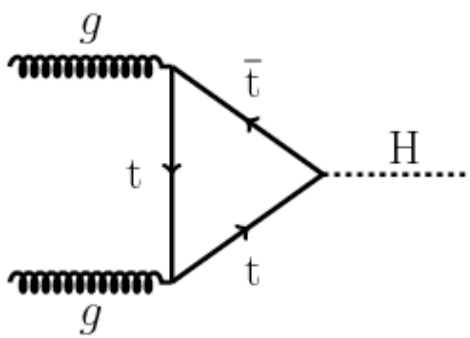
The largest among the fermions – special role in electroweak symmetry breaking?

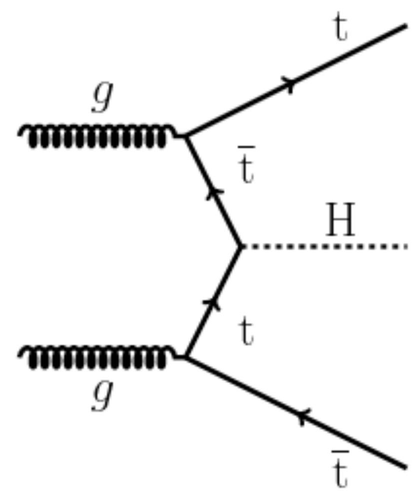


$$y_t = \frac{\sqrt{2}m_t}{v} \cong 1$$

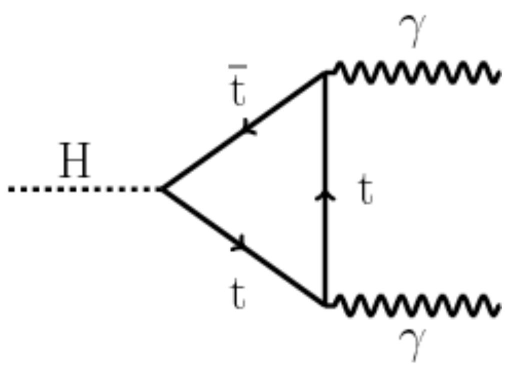
→ Top-Higgs boson coupling hasn't been directly measured yet.

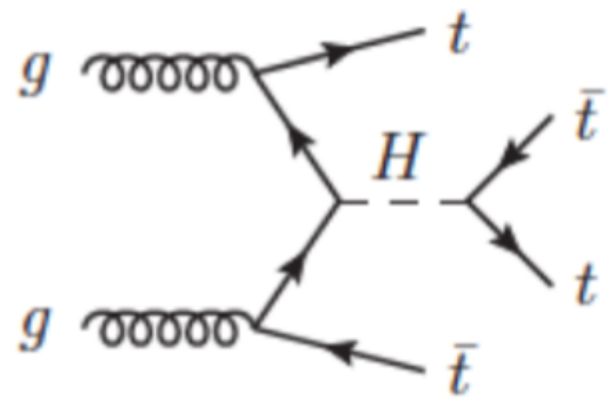
Top – Higgs Coupling
Test fermion mass generation





$t\bar{t}H$





Four-top

Indirect

direct

Top Quark Properties

- Top quark has a very short lifetime

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

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

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: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014) and 2015 update

http://pdg.lbl.gov/2015/tables/contents_tables.html

t

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

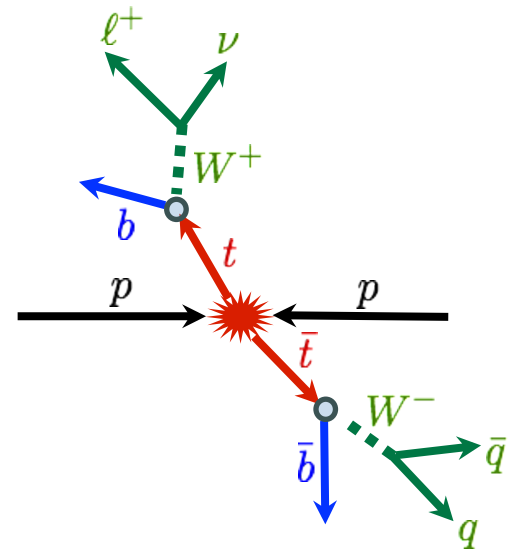
Charge $= \frac{2}{3}\,e$ Top $= +1$

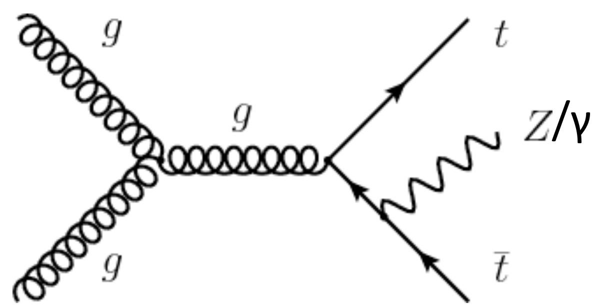
Mass (direct measurements) $m = 173.21 \pm 0.51 \pm 0.71$ GeV [a,b]
Mass ($\overline{\mathrm{MS}}$ from cross-section measurements) $m = 160^{+5}_{-4}$ GeV [a]
Mass (Pole from cross-section measurements) $m = 174.6 \pm 1.9$ GeV
$m_t - m_{\overline{t}} = -0.2 \pm 0.5$ GeV (S = 1.1)
Full width $\Gamma = 1.41^{+0.19}_{-0.15}$ GeV (S = 1.4)
$\Gamma(W\,b)/\Gamma(W\,q(q = b,\, s,\, d)) = 0.957 \pm 0.034$ (S = 1.5)

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%

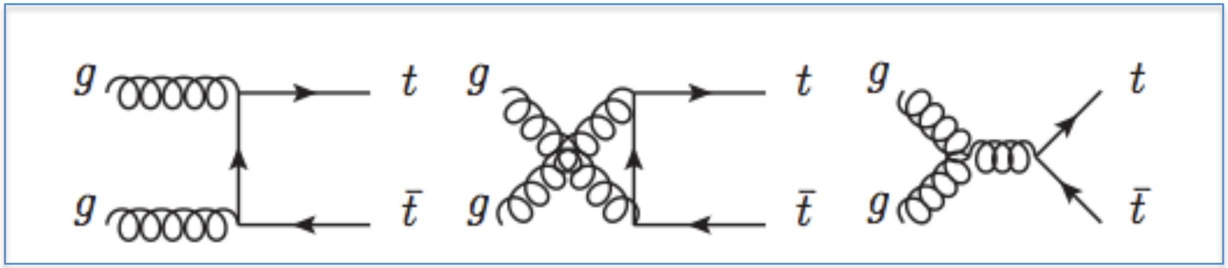
t DECAY MODES		Fraction (Γ_i/Γ)		Confidence level	p (MeV/c)
$t \to W\,q(q = b,\, s,\, d)$					–
$t \to W\,b$					–
$t \to \ell\nu_\ell$anything	[c,d]	(9.4±2.4) %			–
$t \to \gamma\,q(q{=}u,c)$	[e]	< 5.9	$\times 10^{-3}$	95%	–
$\Delta T = 1$ weak neutral current (T1) modes					
$t \to Z\,q(q{=}u,c)$ T1	[f]	< 5	$\times 10^{-4}$	95%	–
$t \to H\,q$		< 5.6	$\times 10^{-3}$	95%	–
$t \to \ell^+\,\overline{q}\,\overline{q}'(q{=}d,s,b;\; q'{=}u,c)$		< 1.6	$\times 10^{-3}$	95%	–

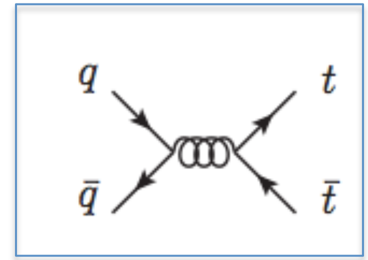




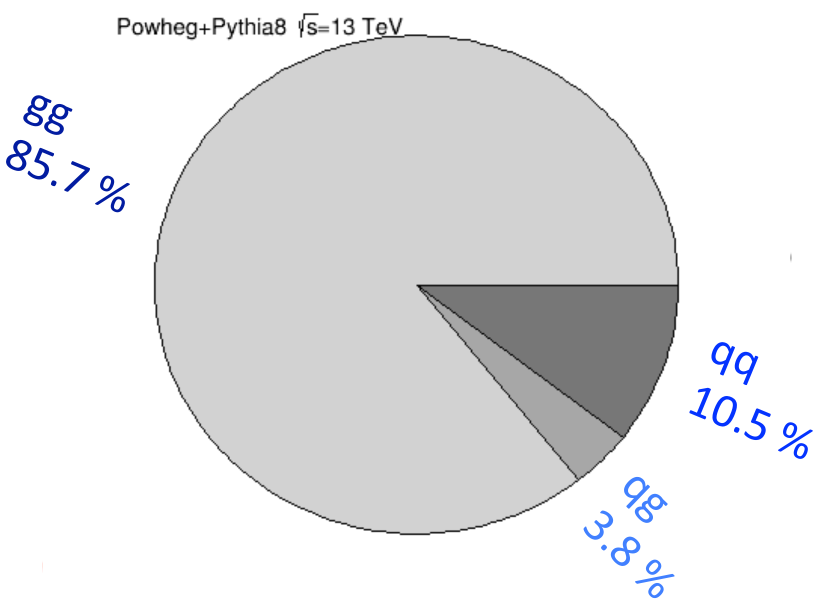
+ Cross sections, asymmetries, spin correlation, …

Top pair production through QCD interactions.



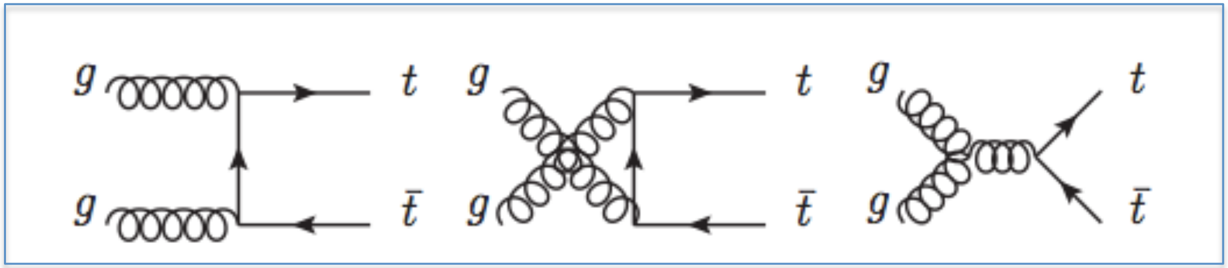


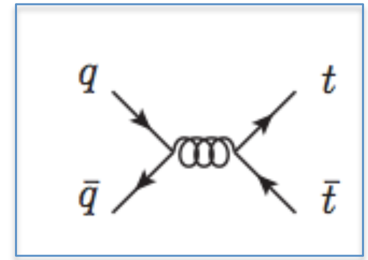
$$\sigma(t\bar{t}) \sim 830\ \ pb\ \ @\ \ 13\ TeV \qquad \sigma_{t\bar{t}}^{13TeV} \sim 3 \times \sigma_{t\bar{t}}^{8TeV}$$



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

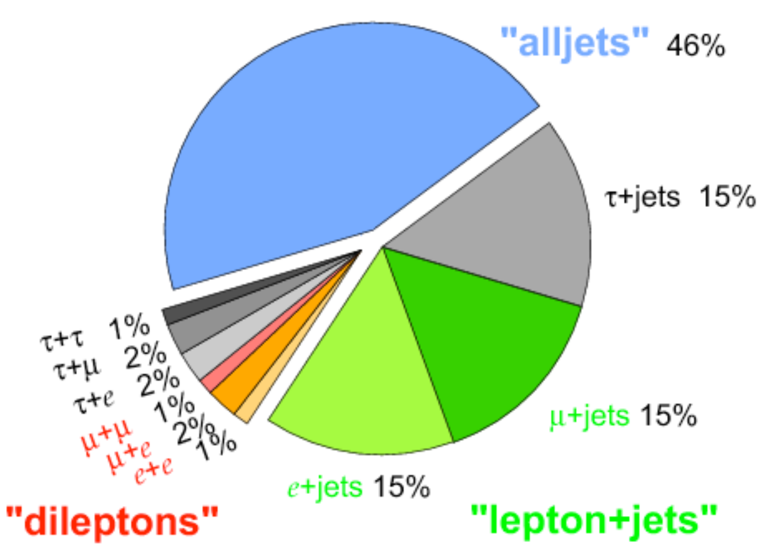
Top pair production through QCD interactions.



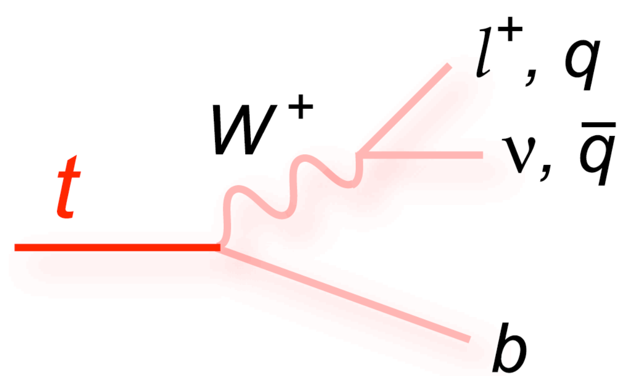


$$\sigma\left(t\bar{t}\right) \sim 830 \ \ pb \ \ @ \ \ 13 \ TeV \qquad \sigma_{t\bar{t}}^{13TeV} \sim 3 \times \sigma_{t\bar{t}}^{8TeV}$$

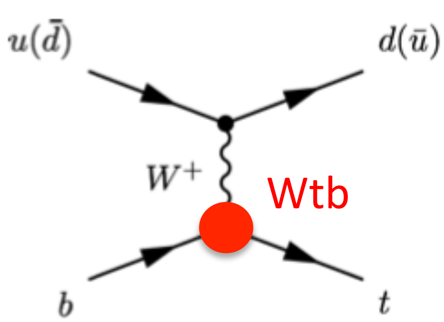
Top Pair Branching Fractions



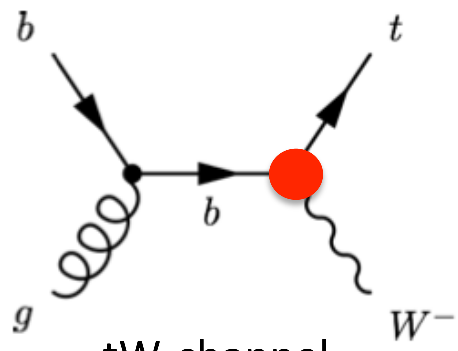
$$m_t > m_W$$



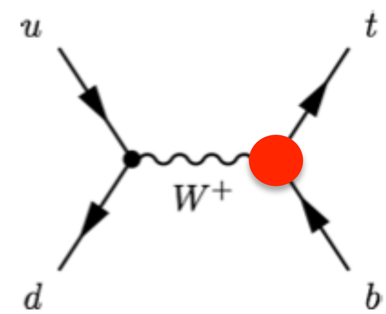
Electroweak single top production



t-channel
~220 pb



tW-channel
~72 pb

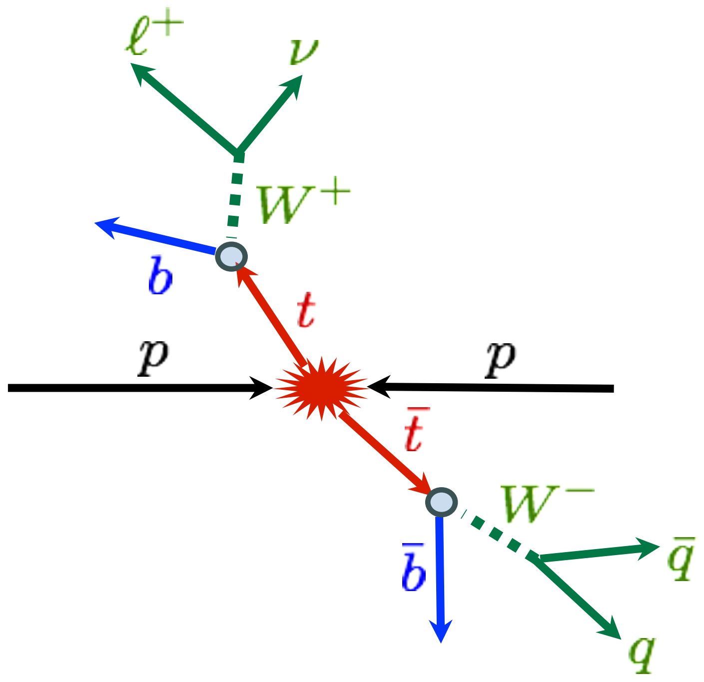


s-channel
~10 pb

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

- 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

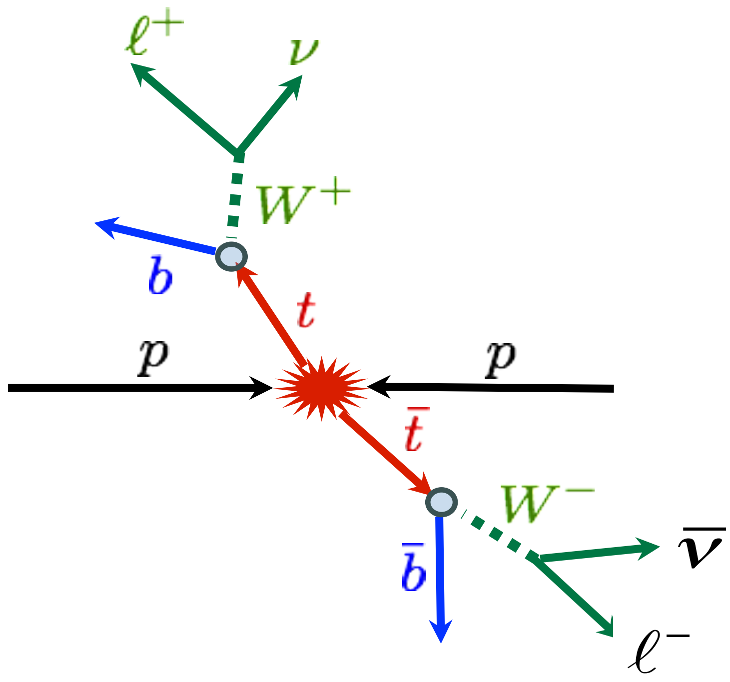
Top Quark Signatures and Backgrounds



- 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

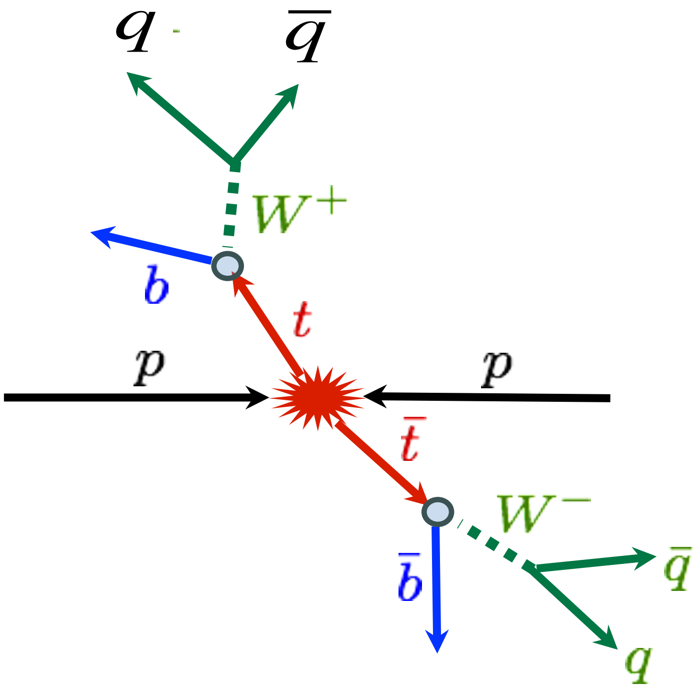


- Dilepton channel
  - Two high p_T leptons
  - ≥ 2 high p_T jets (2 of which are from b-decays)
  - Missing transverse energy

→ 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 Lectures

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

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/

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

Cross section Extraction

Total Inclusive cross section
→ count signal events:

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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:

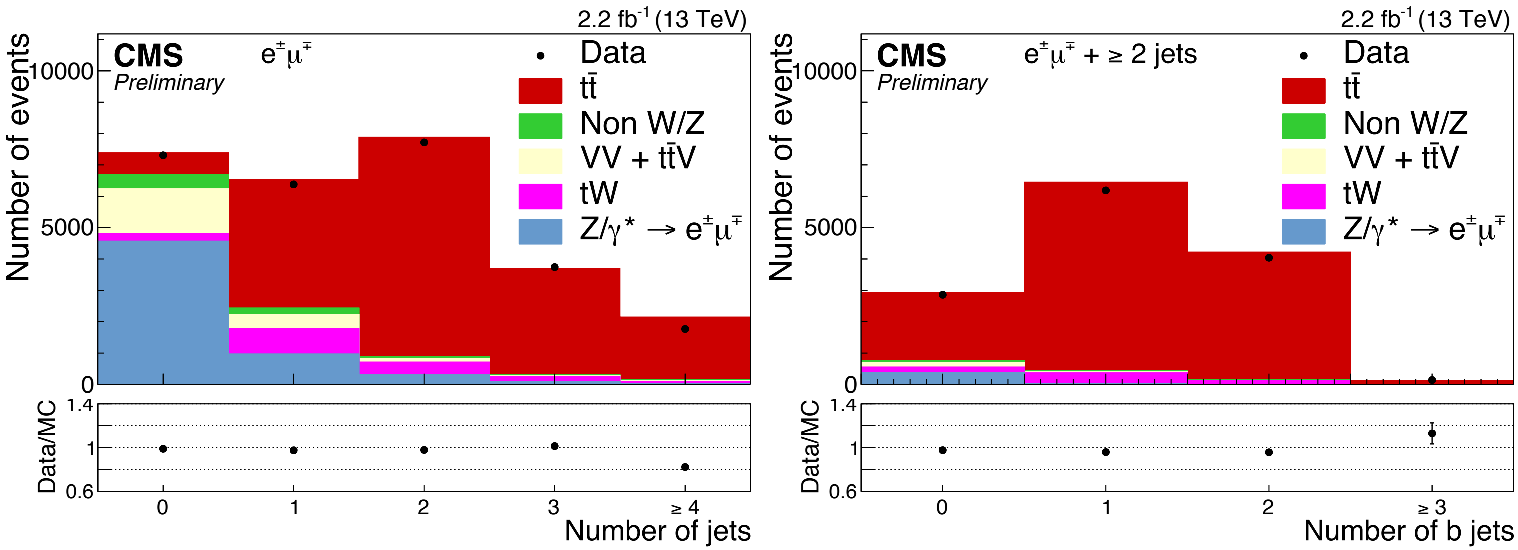
"Unfolded" to correct for detector effects (bin-to-bin migration) and acceptance
→ To particle or parton level
→ In full or fiducial phase space

Response matrix

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

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

TOP-16-005

$$\sigma_{t\bar{t}}\left(m_t = 172.5\ GeV\right) = 793 \pm 8\left(stat\right) \pm 38\left(syst\right) \pm 21\left(lumi\right)\ pb$$

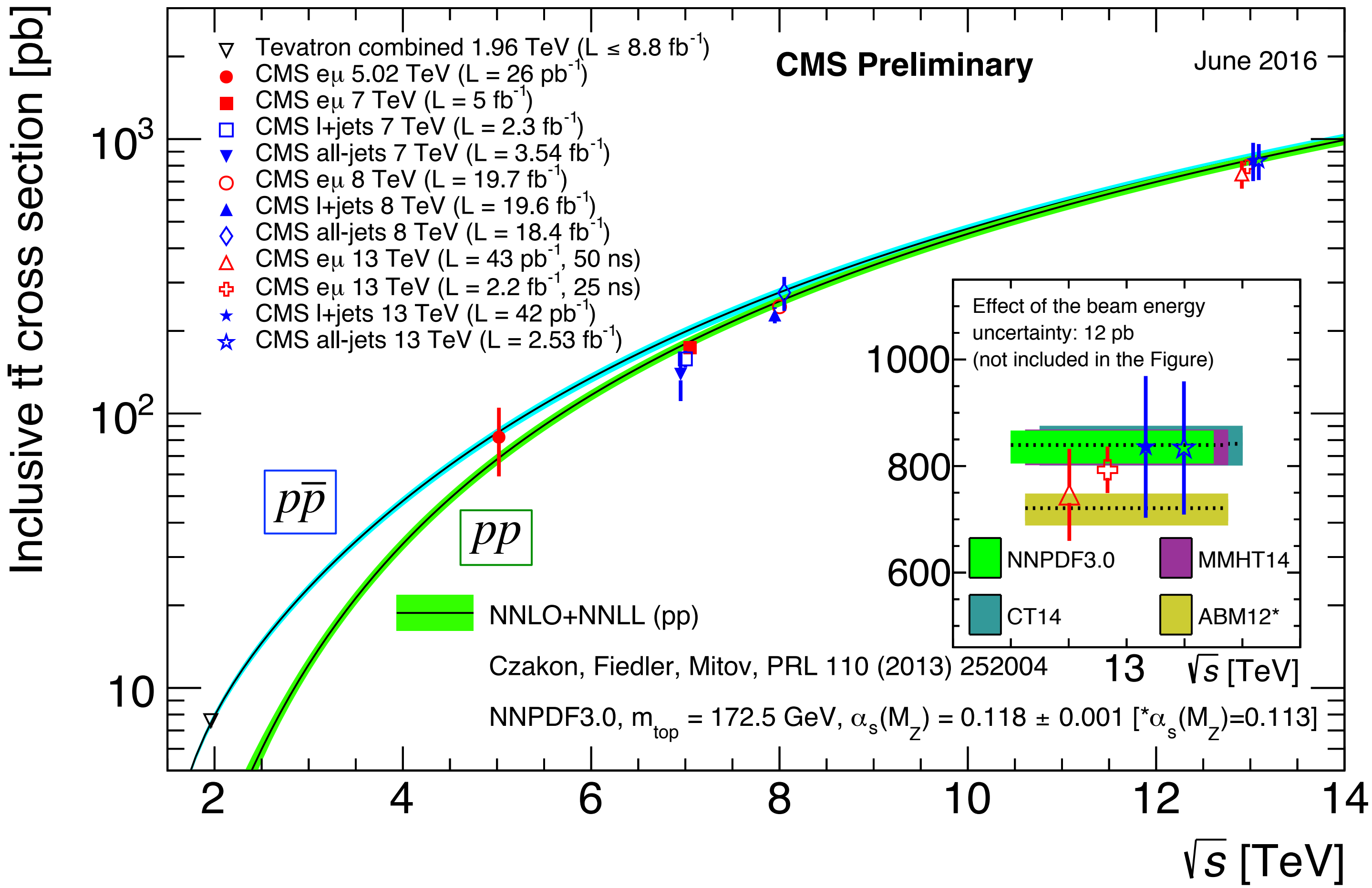
→ Consistent with NNLO+NNLL prediction and other measurements from ATLAS and CMS.

→ Already dominated by systematic uncertainties:

→ Luminosity, efficiencies, jet energy scale

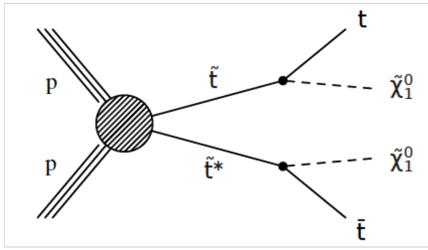
→ Effect of generator choice on acceptance (POWHEG vs MG5_aMC@NLO)

Production Cross Sections from √s = 2 to 13 TeV



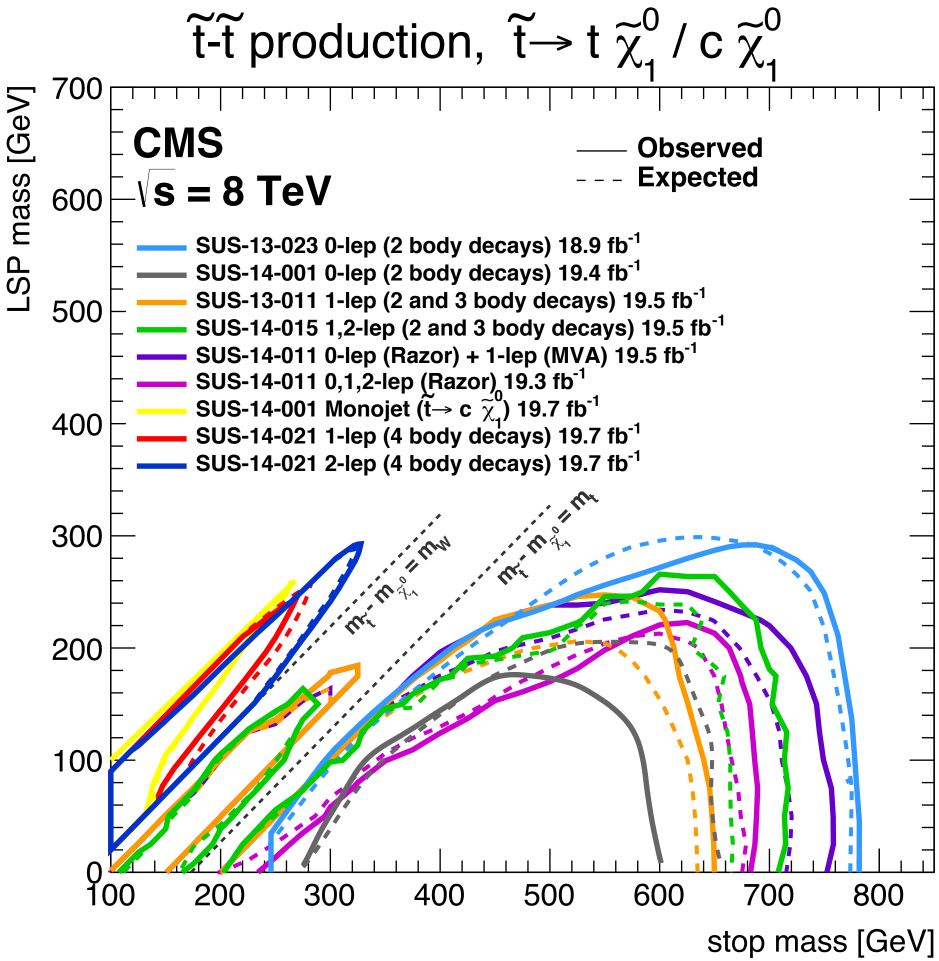
- eμ channel
  - 13 TeV top pair cross section measurements: already at NNLO + NNLL precision.
  - Run I legacy measurement precision: ~3.5%. arXiv:1603.02303

Top Squark Pair Production



$m(\tilde{t}) \approx m(\tilde{\chi}_1^0) + m_t \rightarrow \sigma_{t\bar{t}}$ (and ttbar spin correlations)

more sensitive than standard SUSY searches for low $m(\tilde{\chi}_1^0)$ and $m(\tilde{t}) \approx m_t$



Simplified model with two parameters:

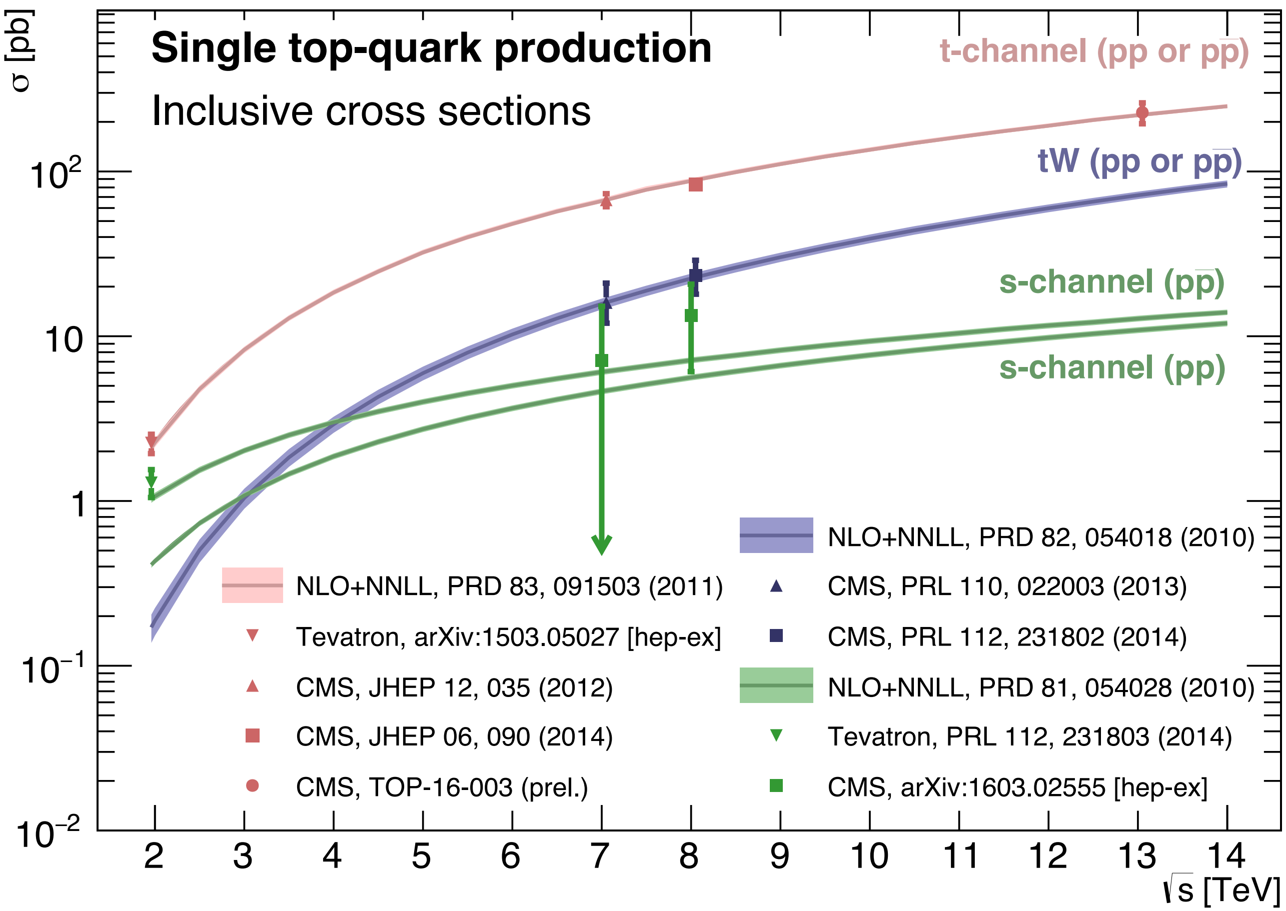
$$m(\tilde{t}), m(\tilde{\chi}_1^0)$$

arXiv:1603.02303

$$m(\tilde{t}; \tilde{\chi}_1^0 = 1\ GeV) > 189\ GeV$$

$$m(\tilde{t}; \tilde{\chi}_1^0) \notin 185-189\ GeV$$

Single Top Cross Sections – Current Status



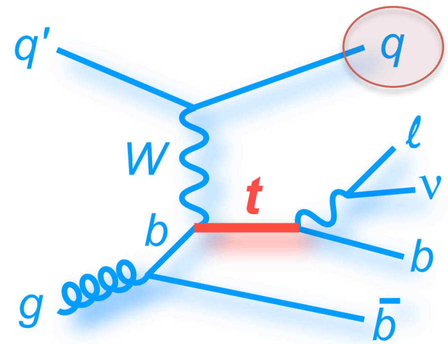
- All single top quark production modes measured at Run I.

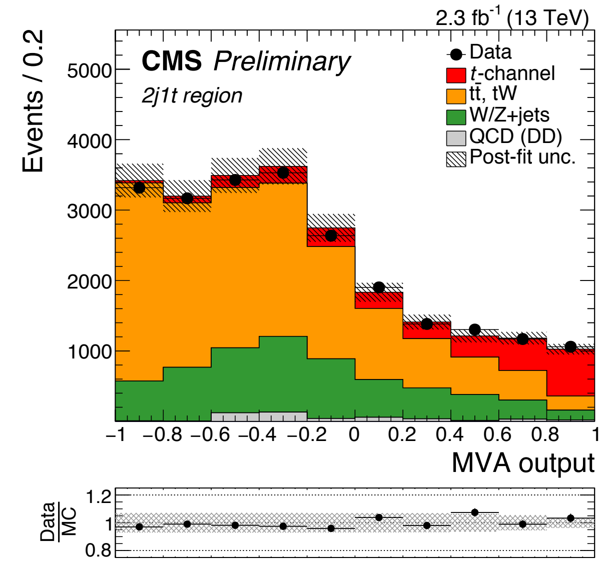
- Single top t-channel cross section at NNLO precision
  - Theory uncertainty ~1%
  - Measurement uncertainty
    - ~10% at 8 TeV (with 20 fb^{-1})
    - ~15% at 13 TeV (with 2.3 fb^{-1})

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.





$$\sigma_{t\text{-}ch.}(t+\bar{t}) = 227.8 \pm 9.1(stat) \pm 14.0(\exp)^{+28.7}_{-27.7}(theo) \pm 6.2(lumi)\ \ pb = 227.8^{+33.7}_{-33.0}\, pb$$

$$|V_{td}|, |V_{ts}| << |V_{tb}|, \mathrm{Br} \cong 1$$

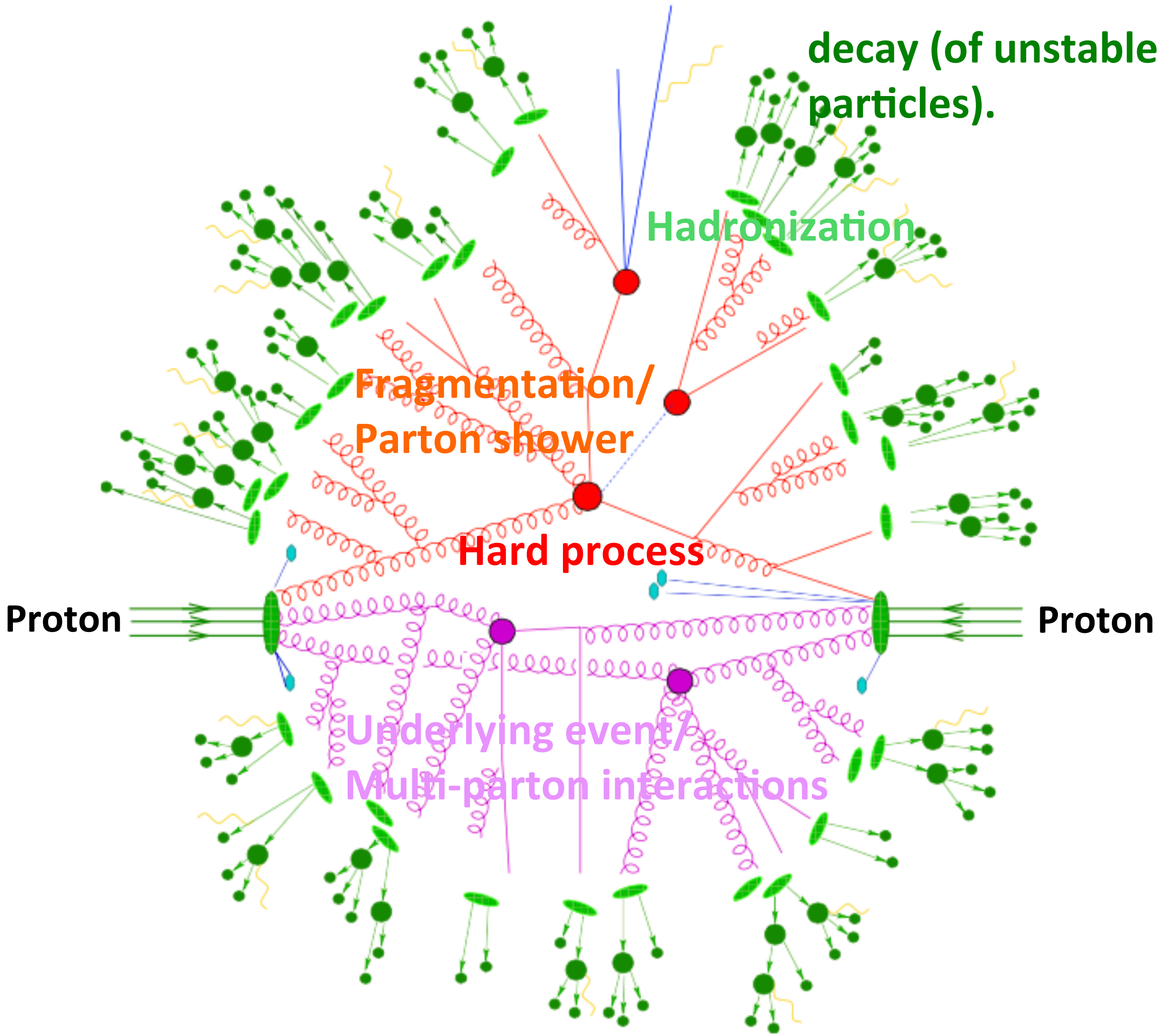
$$\rightarrow |f_V^L V_{tb}| = \sqrt{\frac{\sigma_{t-ch.}}{\sigma^{theo.}_{t-ch}}} = 1.02 \pm 0.07(\exp) \pm 0.02(theo)$$

M. Aliev et al. arXiv:1007.1327

Result dominated by signal modelling and QCD scale uncertainties.

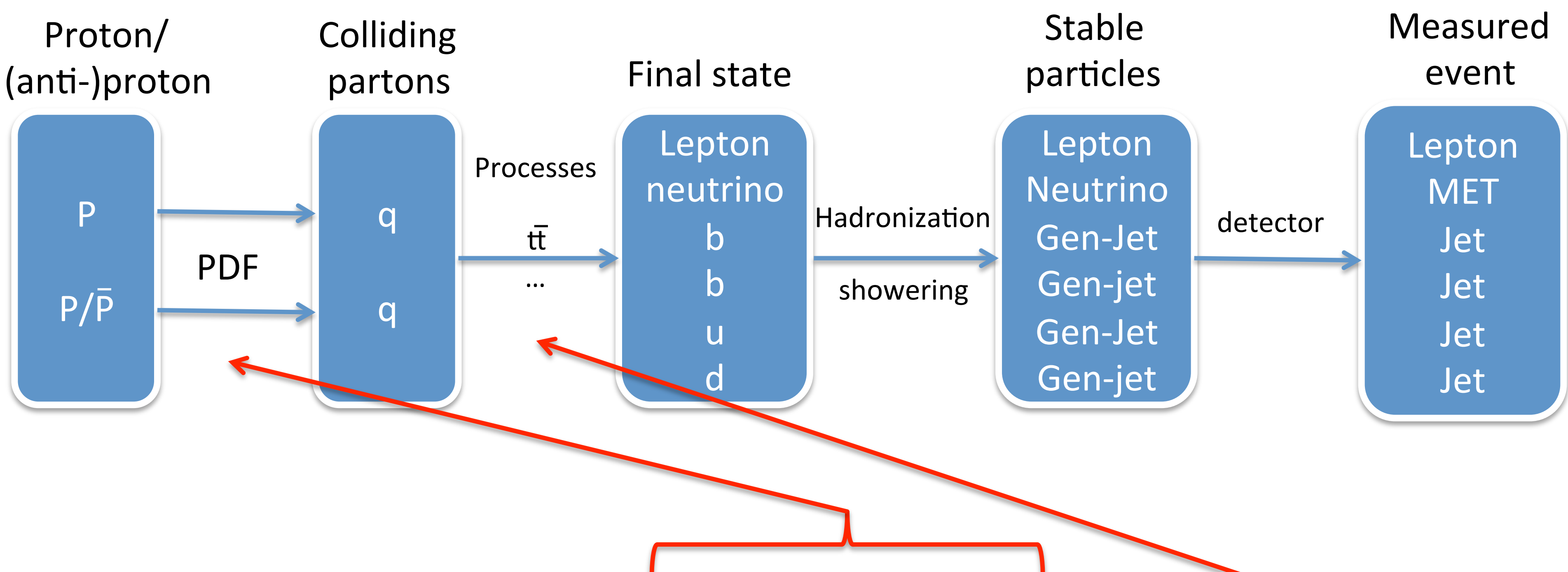
7+8 TeV → $\delta_{|V_{tb}|}$=4%

(Top Quark) Event Modeling



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

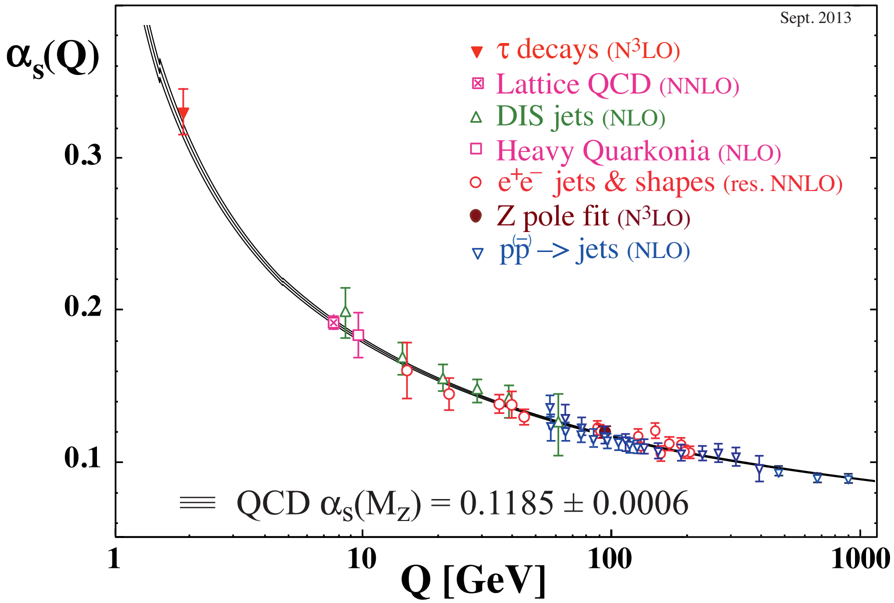
Non-perturbative | *Perturbative in α_s*

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

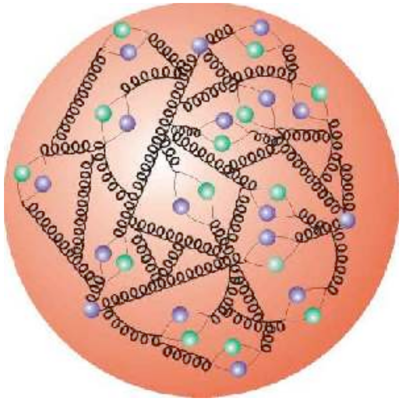
$p_T^{parton} < \mu_F$ | $p_T^{parton} > \mu_F$

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

→ inputs: m_t, α_s, and PDFs



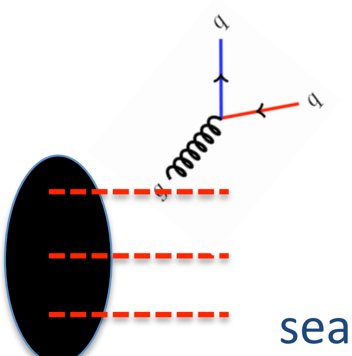
Nucleon Structure

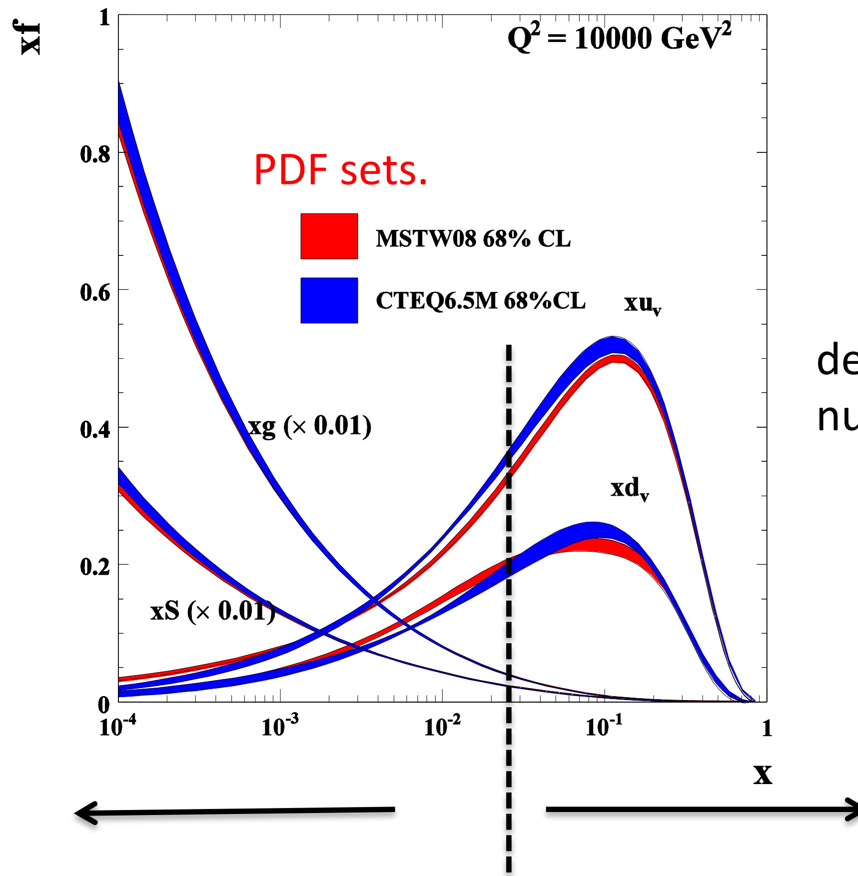


- Hadron collider = parton collider
- $f_i(x,Q^2)$ probability to find a parton to carry the fraction x of the longitudinal hadron momentum at the energy scale Q^2.
  - Intrinsic property of the nucleon → process independent.
  - Parametrized by PDF sets.

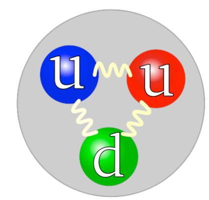
The quark sea:

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





sea quarks dominate.

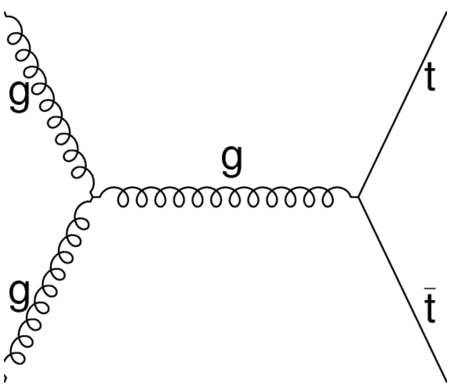


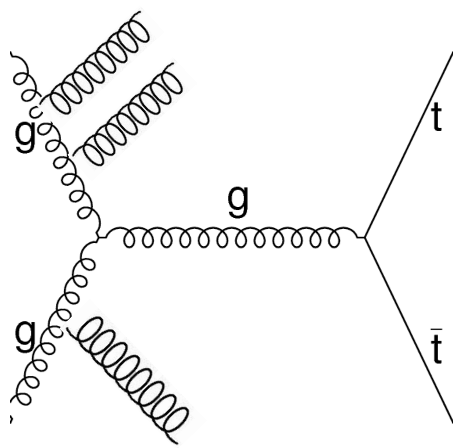
determine the quantum numbers of the hadron.

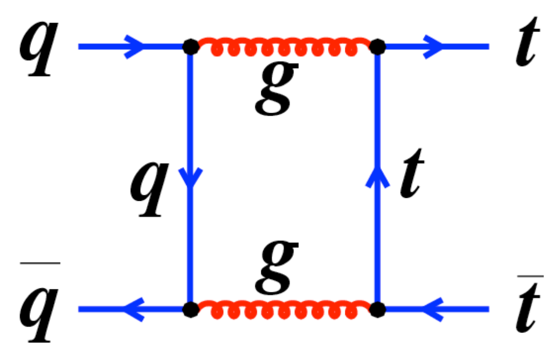
Valence quarks dominate.

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).

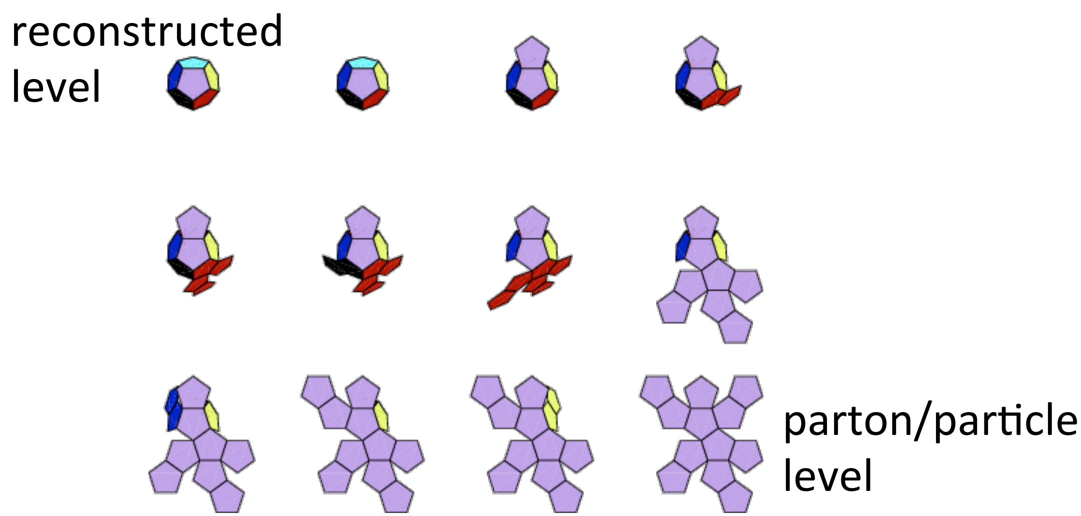


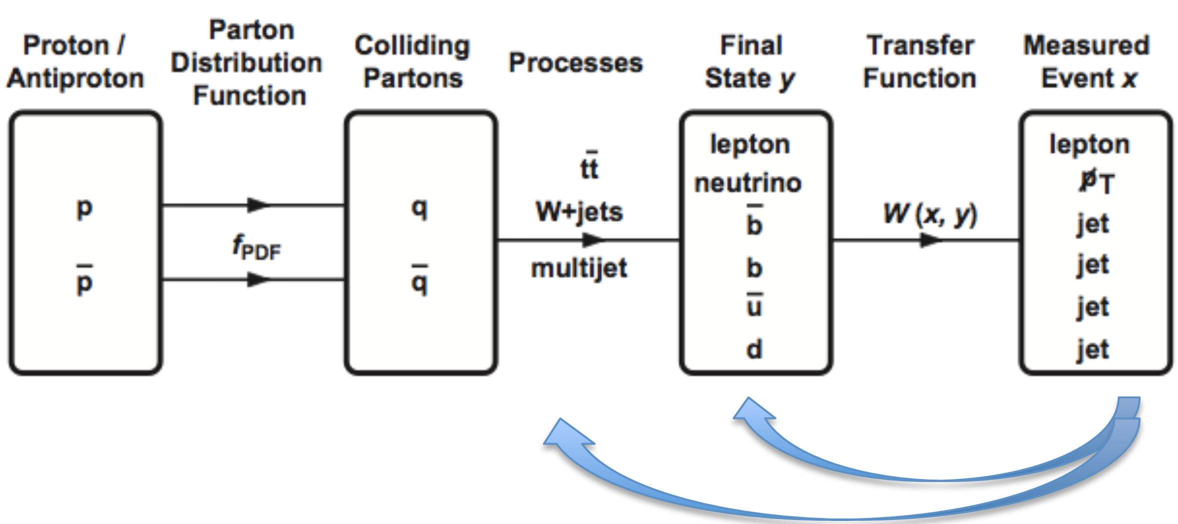




NLO and multi-leg LO need matching/merging to the parton shower.

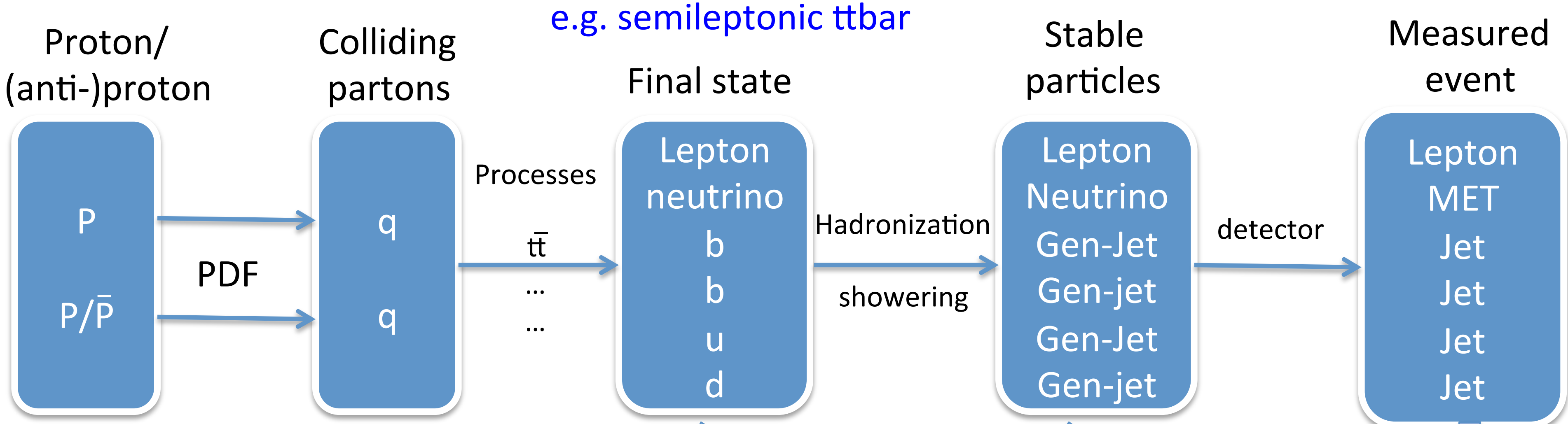
Unfolding


reconstructed
level
parton/particle
level

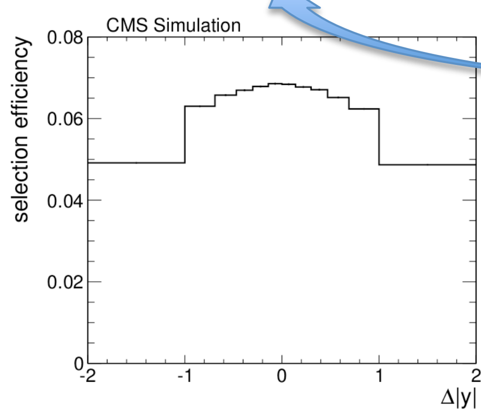

Proton /
Antiproton
Parton
Distribution
Function
Colliding
Partons
Processes
Final
State y
Transfer
Function
Measured
Event x
p
p̄
f_{PDF}
q
q̄
$t\bar{t}$
W+jets
multijet
lepton
neutrino
b̄
b
ū
d
W (x, y)
lepton
$\not{p}_T$
jet
jet
jet
jet

Unfolding

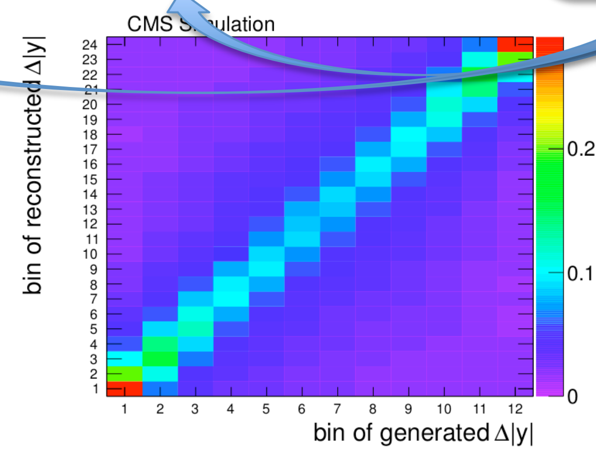
e.g. semileptonic ttbar



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



selection efficiency
→ diagonal matrix



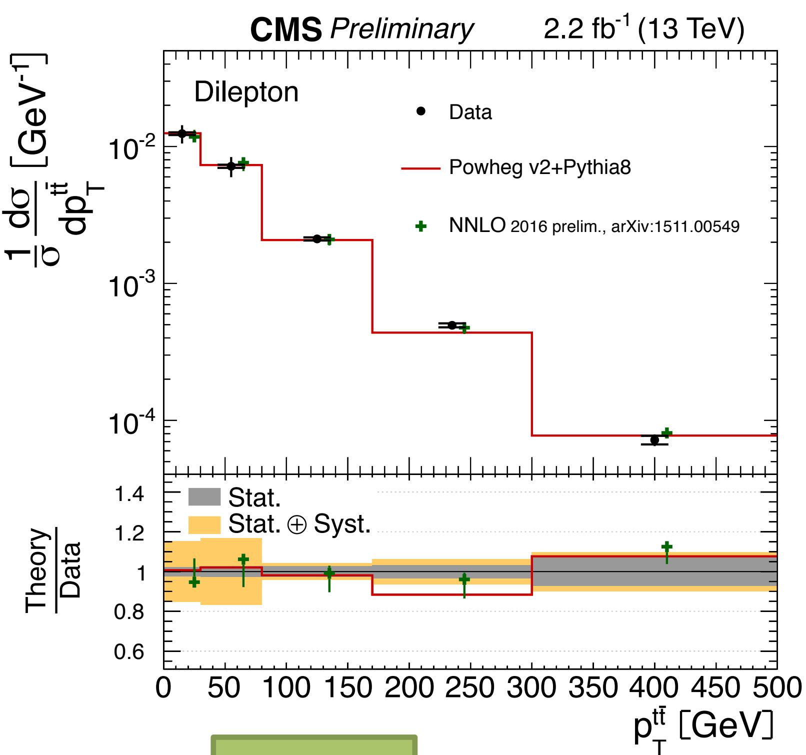
(non-diagonal)
bin migration matrix

Commonly used unfolding methods:
iterative D'Agostini, SVD

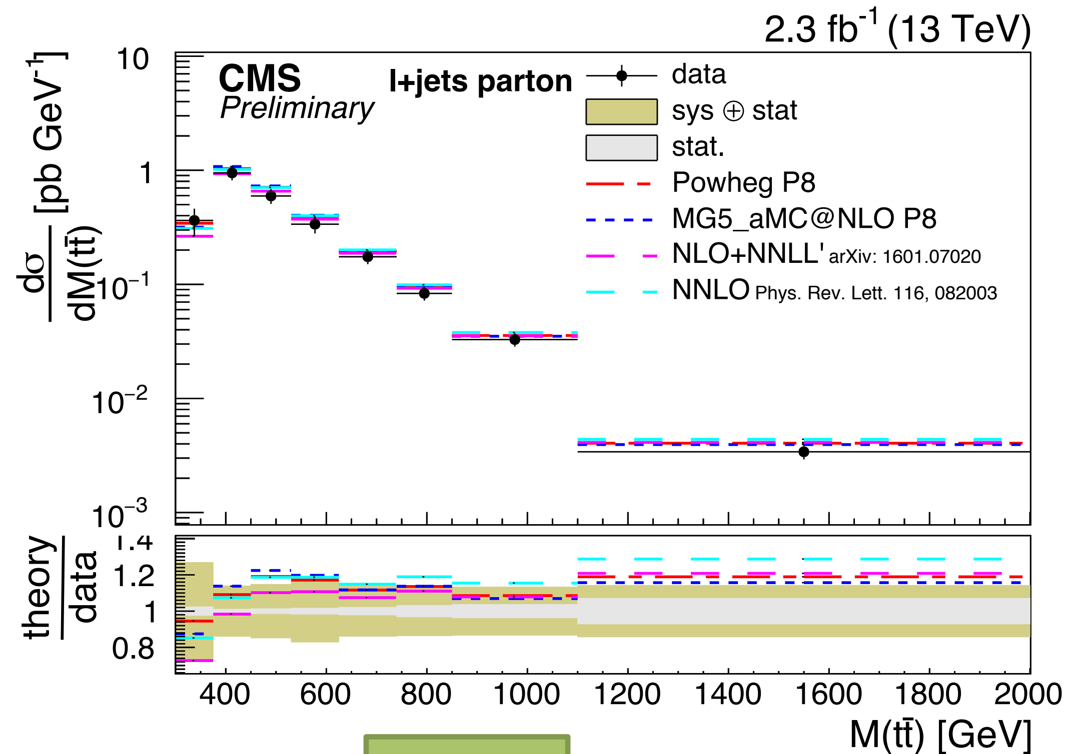
e.g., CMS-PAS-TOP-12-033

Top 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)



TOP-16-011

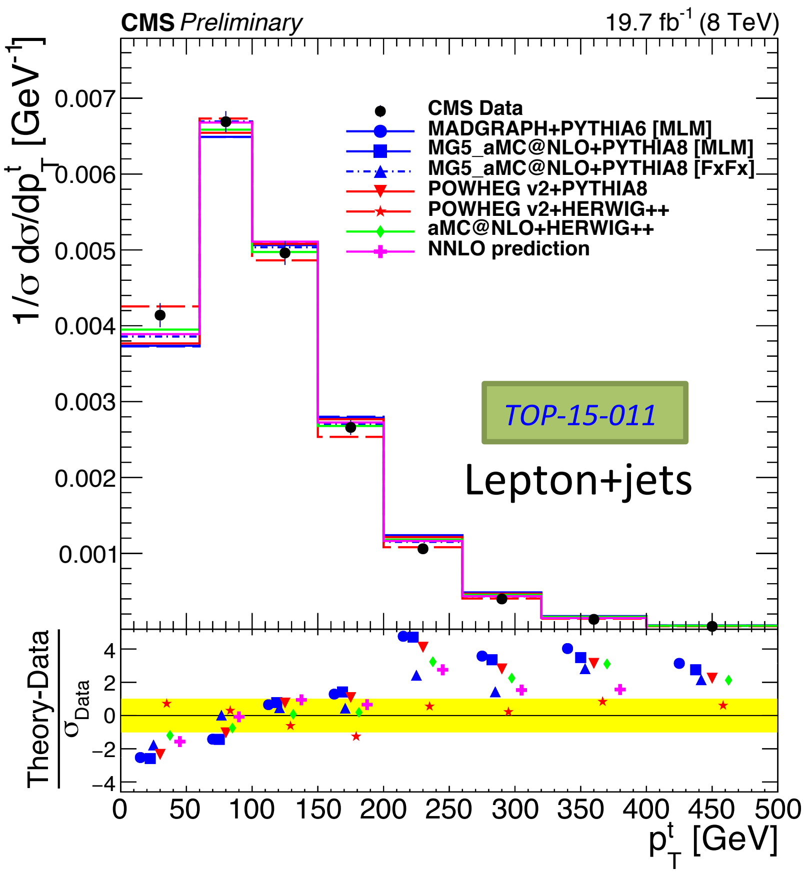


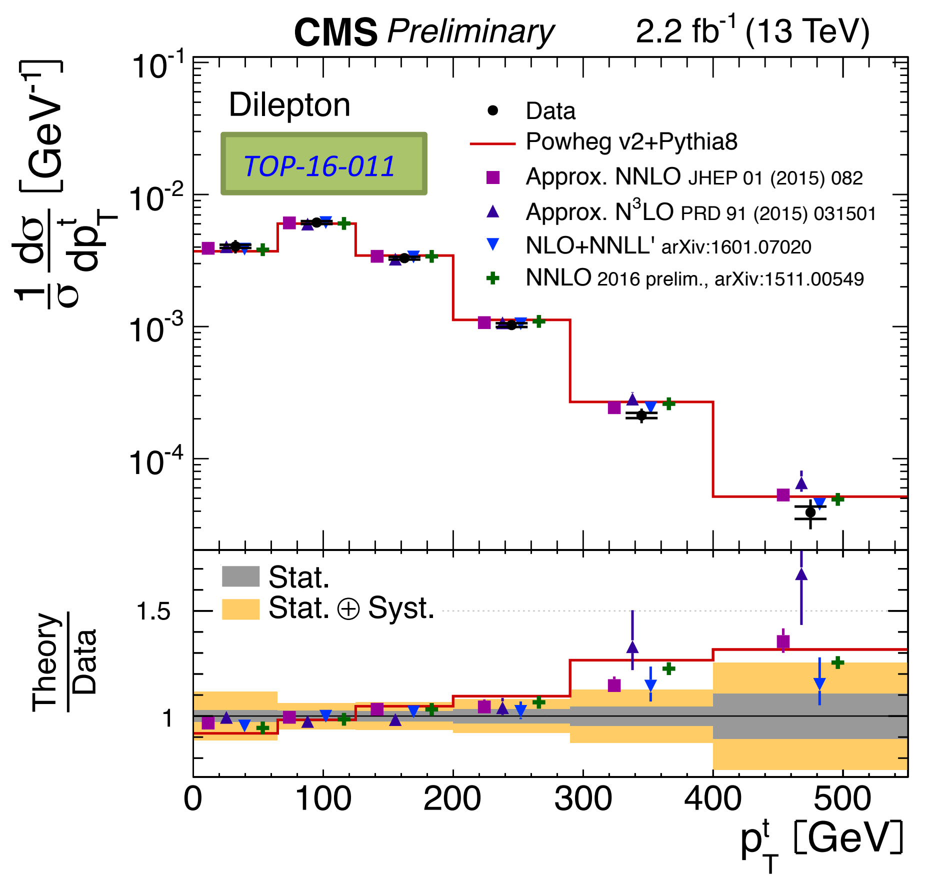
TOP-16-008

- Differential distributions described reasonably well.

The Top Quark p_T

- LHC Run 1 “discovery”: harder spectrum in LO/NLO+PS predictions than in data.
  - NNLO+NNLL → significantly better description of top p_T.
- First results at 13 TeV: similar behavior.

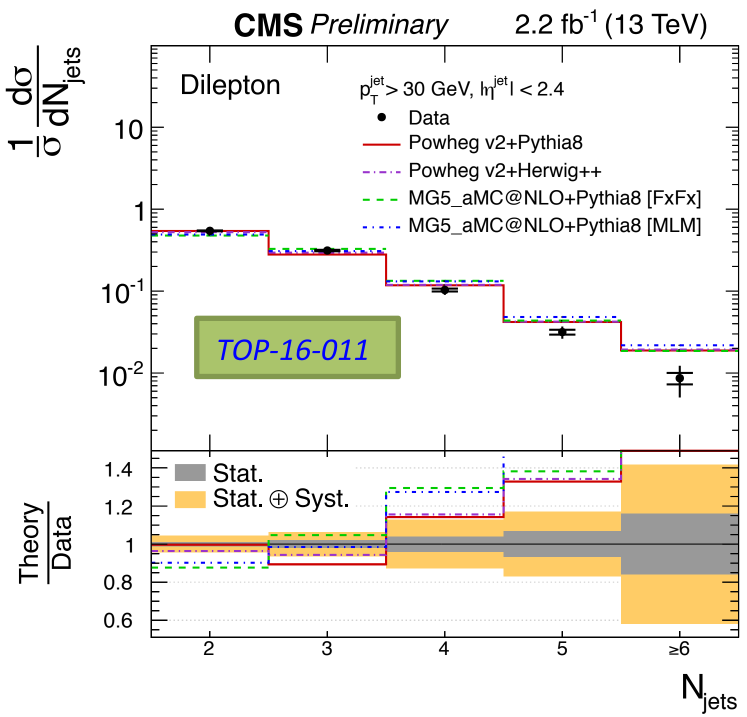


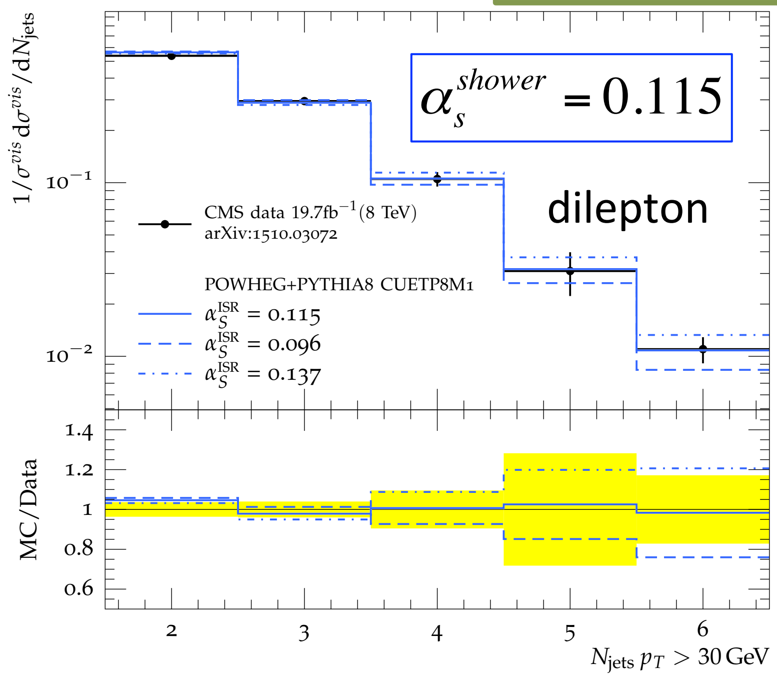


Jet Multiplicity at √s = 13 TeV

- Low jet multiplicities → Sensitive to Matrix element and matching to parton shower.
- High jet multiplicities → parton shower
- tt+jets important background to ttH.

arXiv:1510.03072;
Rivet: CMS_2015_I1397174





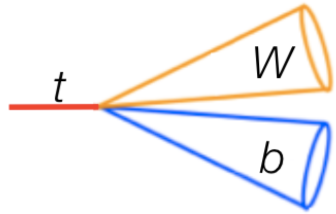
- New ME generator + PS codes in Run II
- Predictions overshoot the data for jet large multiplicities when out of the box parameters are used (in Monash-based tunes).
- First fix: α_s^{shower}

Monash Tune: Skands, Carrazza, Rojo, EPJ C 74 (2014) 1

Boosted Top Pair Production

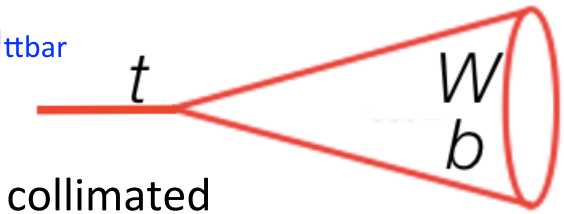
arXiv:1605.00116

Resolved topology:
Each parton matched
to a single jet.



High top p_T or high m_{ttbar}

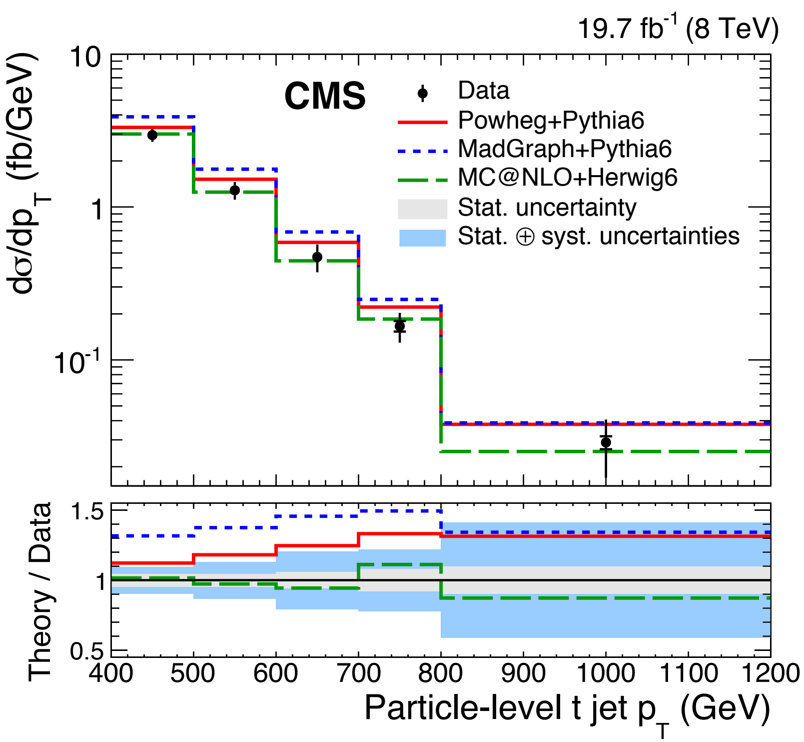
Boosted topology:
→ Decay products collimated

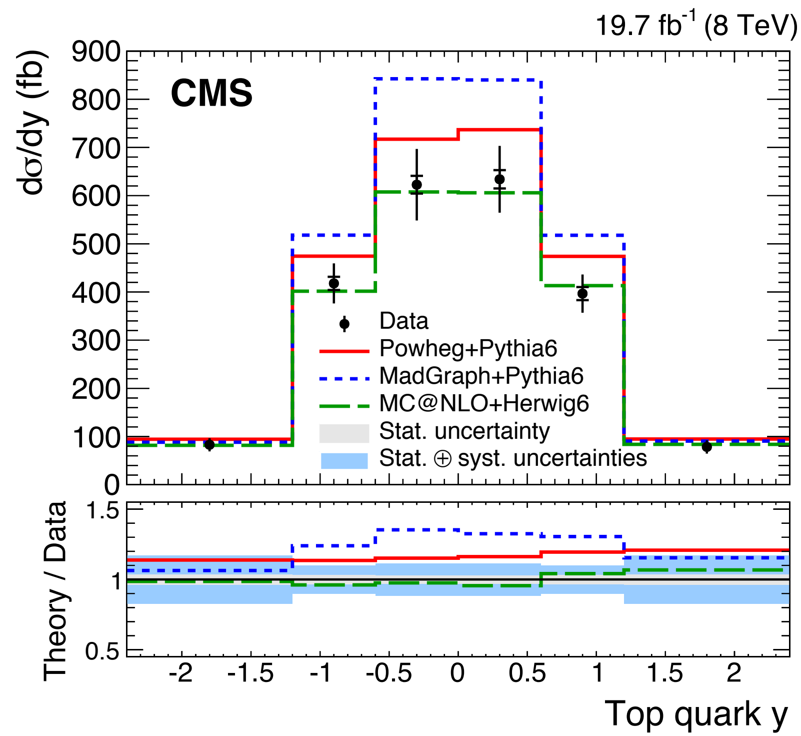


"fat jet", R=0.8

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

- Measurements at parton and particle levels.





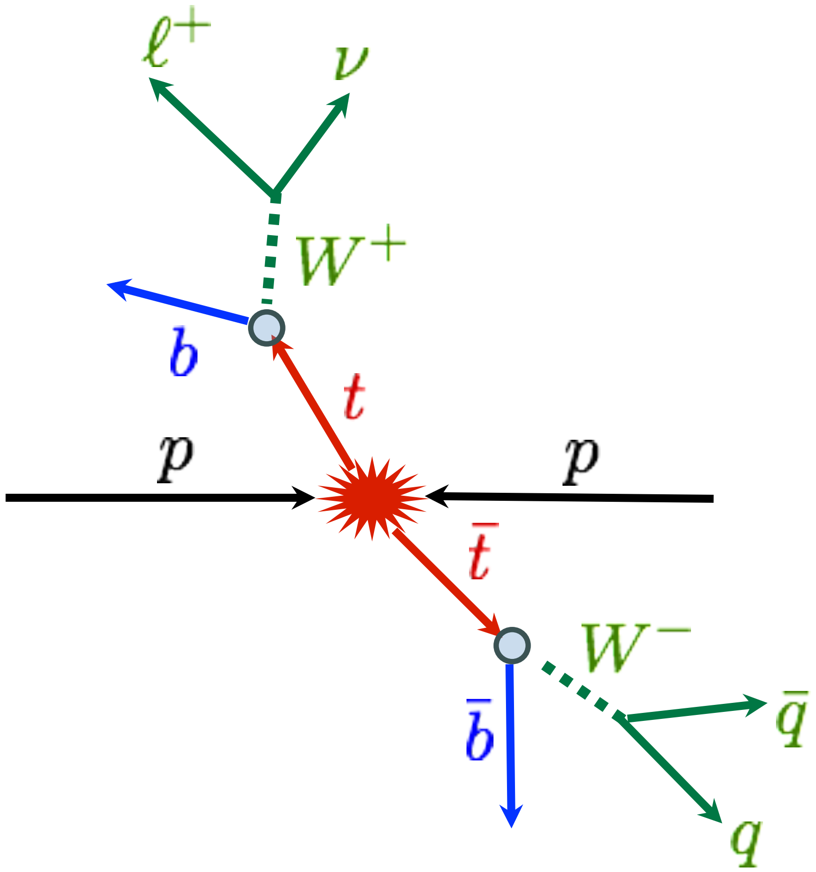
QUESTIONS

&

BREAK

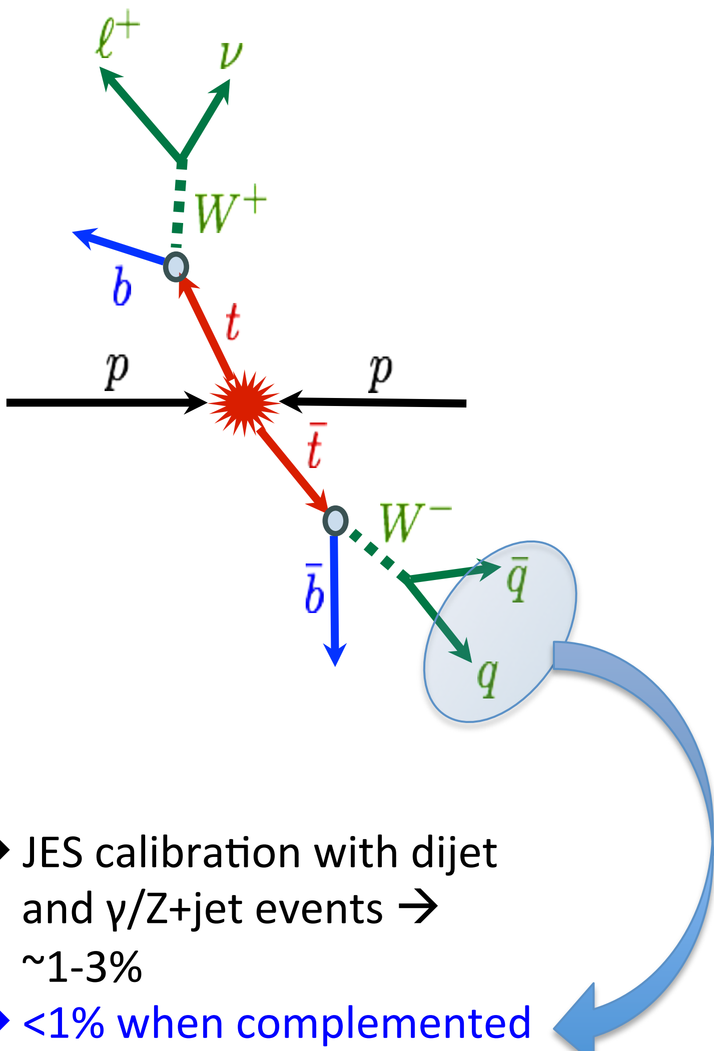
Top Mass Measurements

- 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

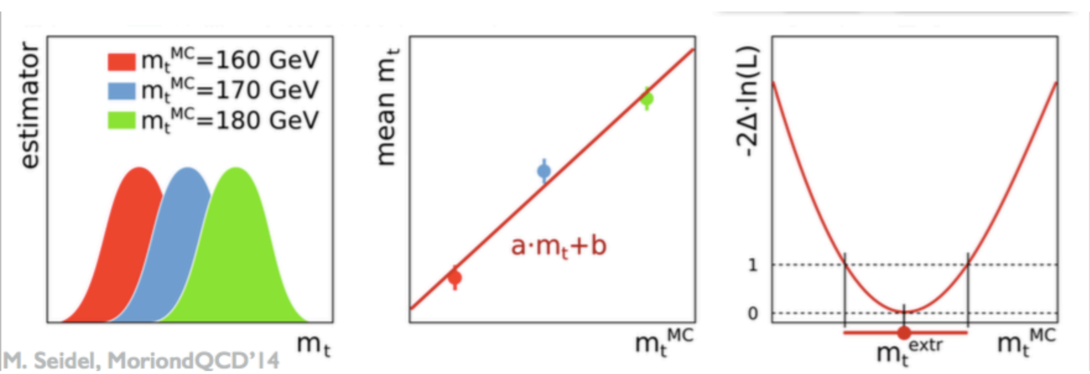


Full Mass Reconstruction

- 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.



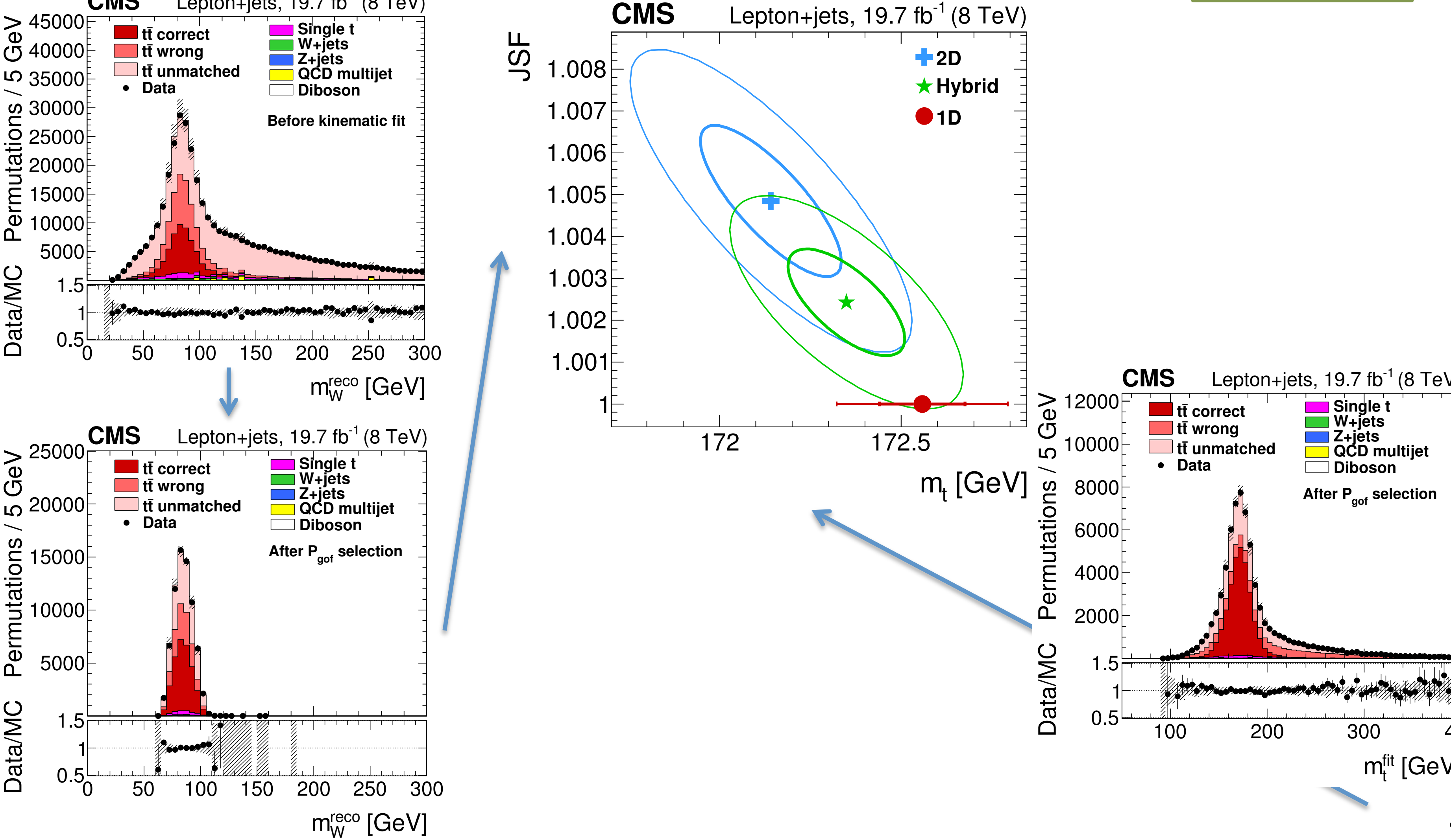
→ JES calibration with dijet and γ/Z+jet events → ~1-3%

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

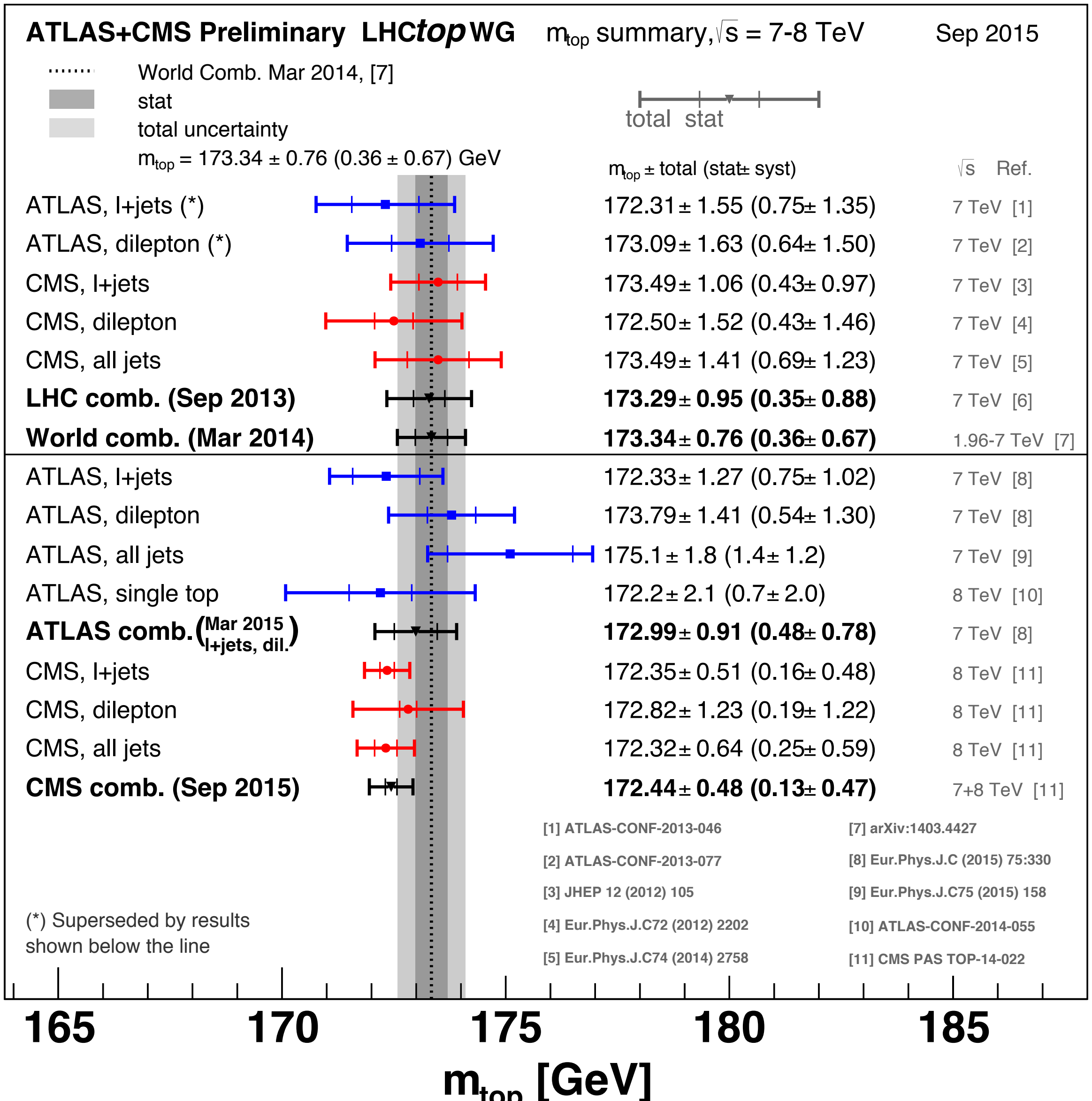
E.g. Full Mass reconstruction: The Ideogram Method

- 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



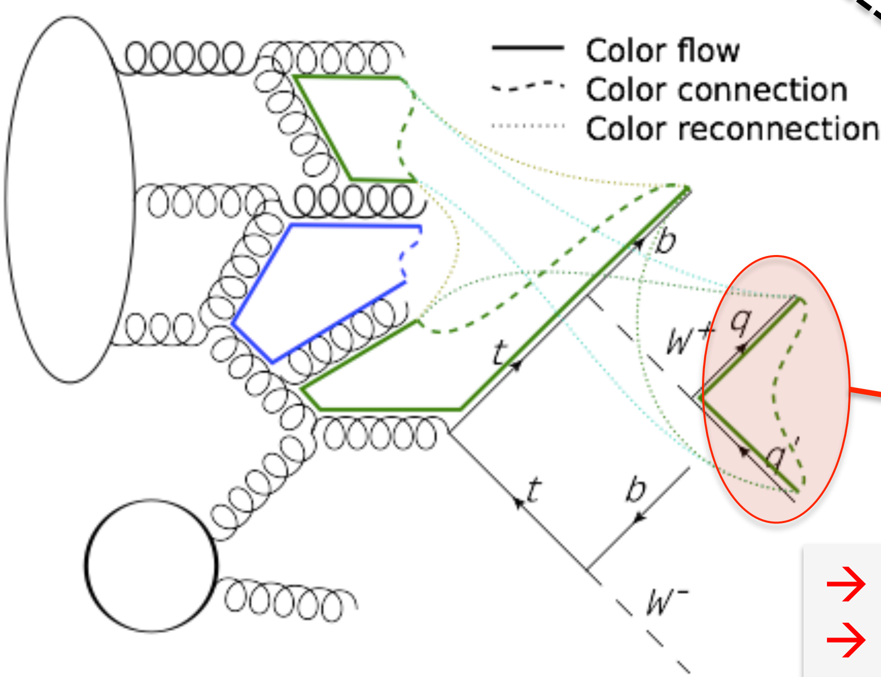
- Precision 0.3% ~ $2\Lambda_{QCD}$
- Dominant systematic uncertainties: flavor-dependent JEC and b jet modeling.

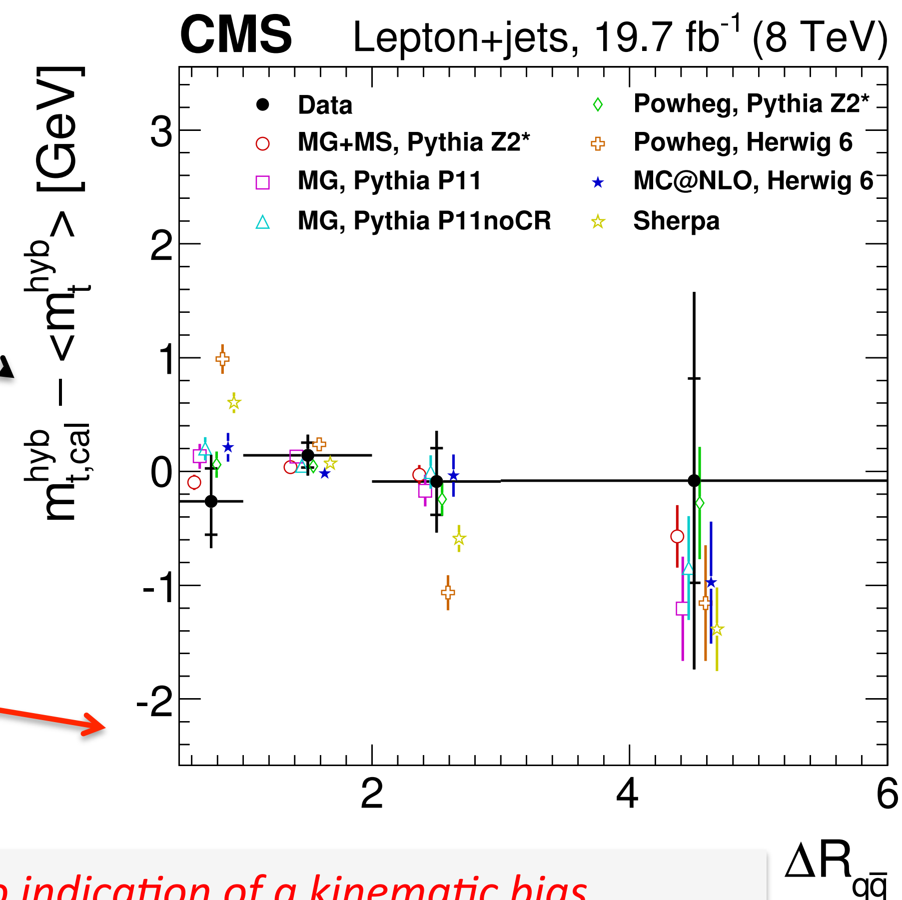
(non-)perturbative effects that have different kinematic dependences?

arXiv:1509.04044

- Study observables sensitive to color reconnections, ISR/FSR, b-quark kinematics.

Measurement calibrated in each bin – Average from the inclusive measurement.





→ *No indication of a kinematic bias.*
→ *Statistics not yet enough to constrain further some of the alternate ttbar models.*

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 ~Λ_{QCD}
  - "Running (or short distance mass) mass" (m_t^{MSbar})
    - Renormalization scale dependent.

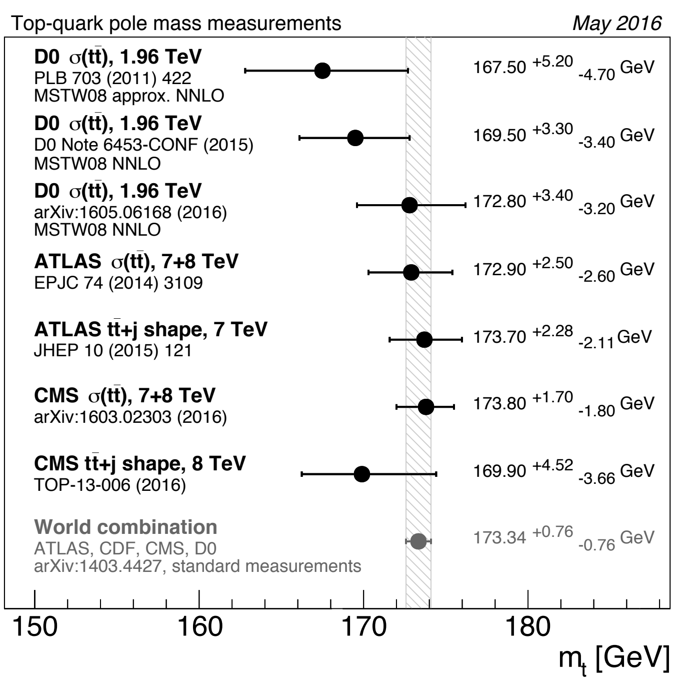
The two definitions can be related analytically with an uncertainty <~Λ_{QCD}

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

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

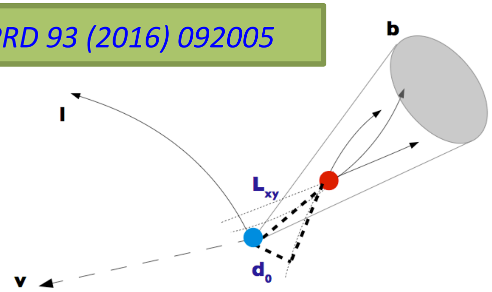


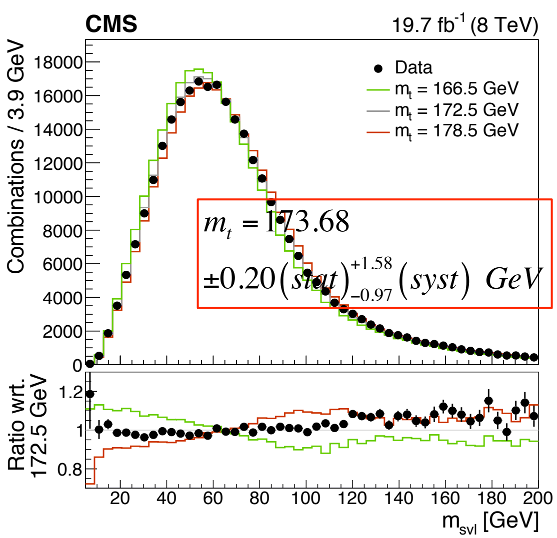
- With the current precision, top-quark pole mass measurements consistent with the standard measurements.

Recent Alternative Top Quark Mass Measurements

Invariant mass of the secondary vertex w/ >= 3 tracks + lepton.

PRD 93 (2016) 092005





Minimal experimental uncertainties.
Large dependence on fragmentation modeling.

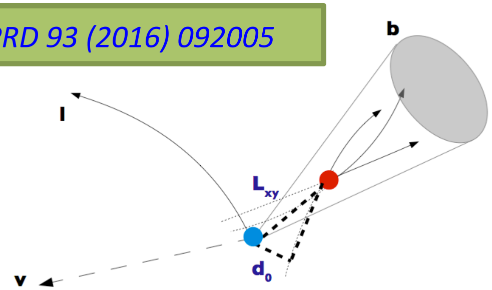
M_{svtx} mass:
b fragmentation

Recent Alternative Top Quark Mass Measurements

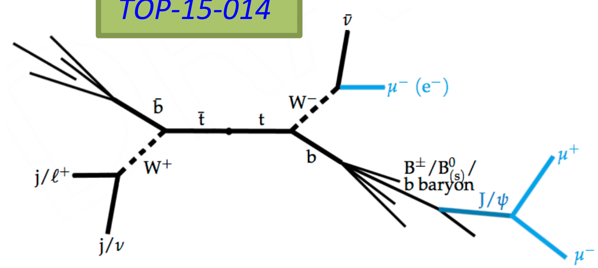
Invariant mass of the secondary vertex w/ >= 3 tracks + lepton.

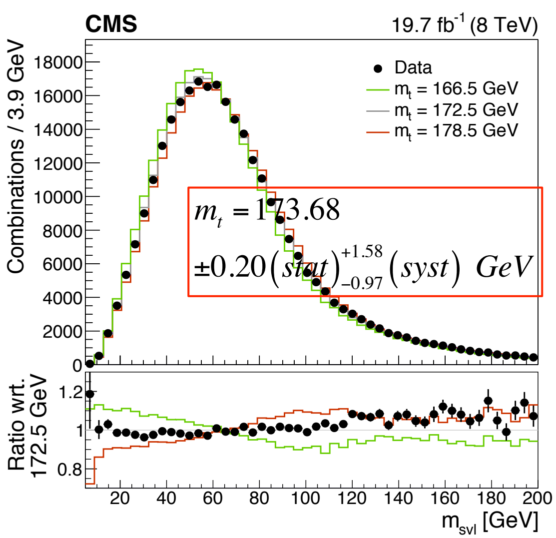
J/Ψ+lepton mass

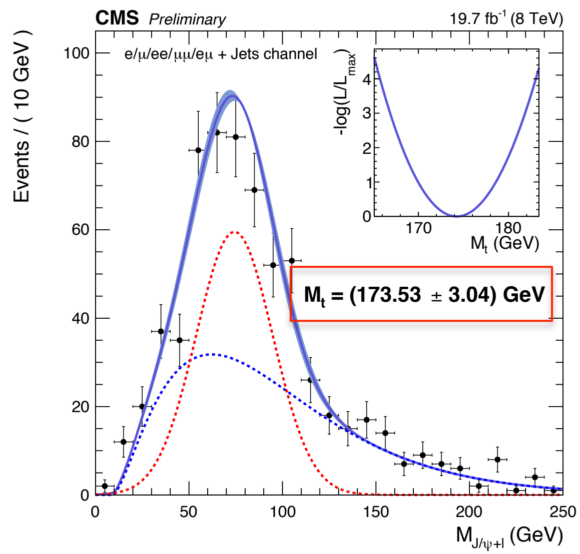
PRD 93 (2016) 092005



TOP-15-014







Minimal experimental uncertainties.
Large dependence on fragmentation modeling.

M_{svtx} mass:
b fragmentation

J/Ψ+lepton mass:
Result statistically limited

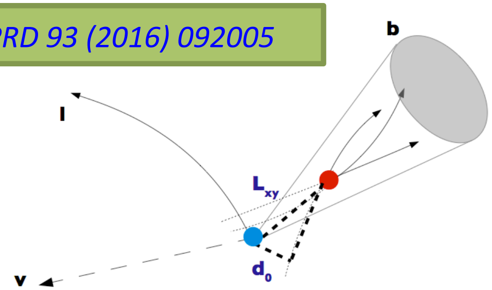
Recent Alternative Top Quark Mass Measurements

Invariant mass of the secondary vertex w/ >= 3 tracks + lepton.

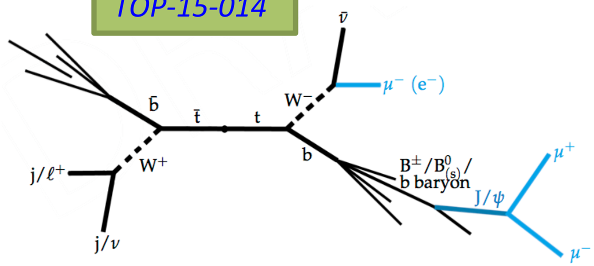
J/Ψ+lepton mass

$M_{l\nu b}$ in single top topology

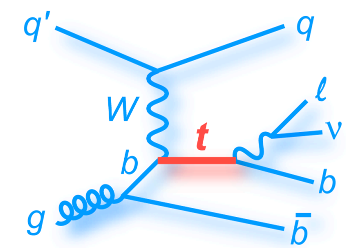
PRD 93 (2016) 092005

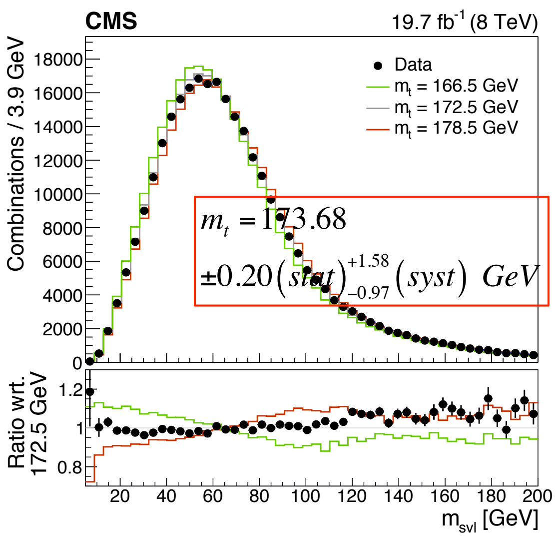


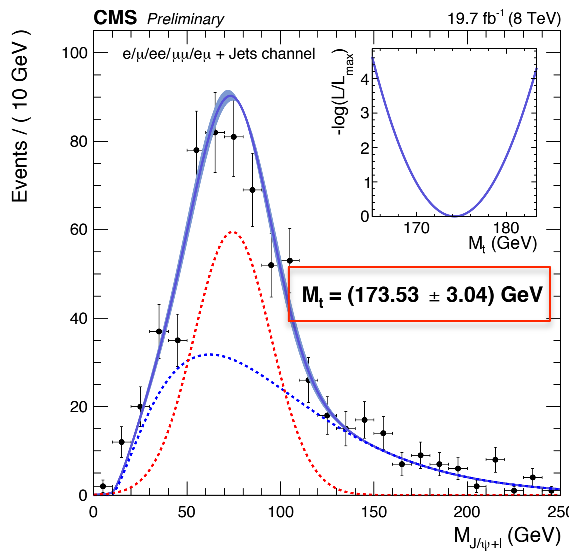
TOP-15-014

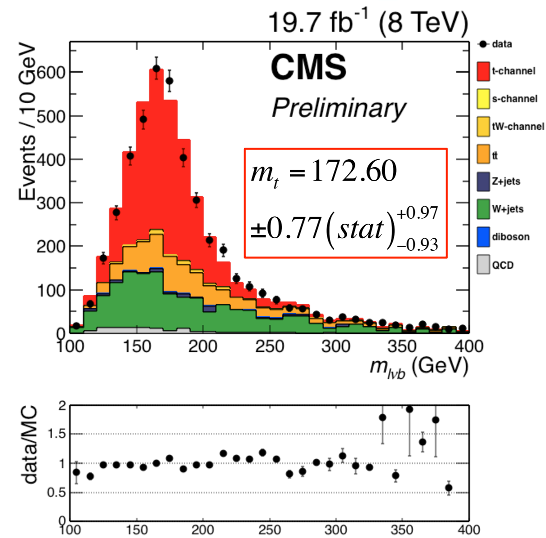


TOP-15-001









Minimal experimental uncertainties.
Large dependence on fragmentation modeling.

M_{svtx} mass:
b fragmentation

J/Ψ+lepton mass:
Result statistically limited

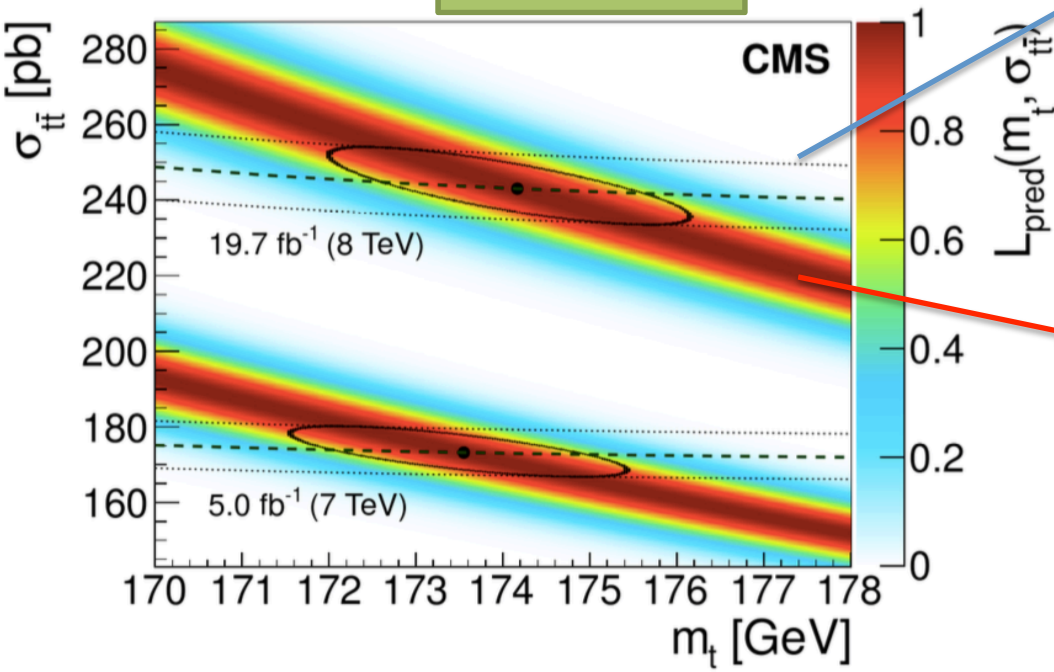
Alternative event topology
Partially uncorrelated systematics
Different color flow→ check for "unknown" syst.

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).
- Minimize theory x experimental likelihoods.

arXiv:1603.02303



Dependence due to efficiency and acceptance depending weakly on m_t.

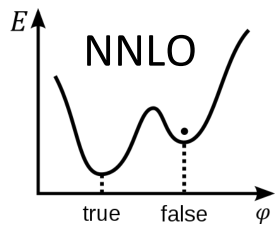
Recall: $\sigma = \dfrac{N_{obs} - N_{bkg}}{(A\times\varepsilon)\times B\times L}$

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

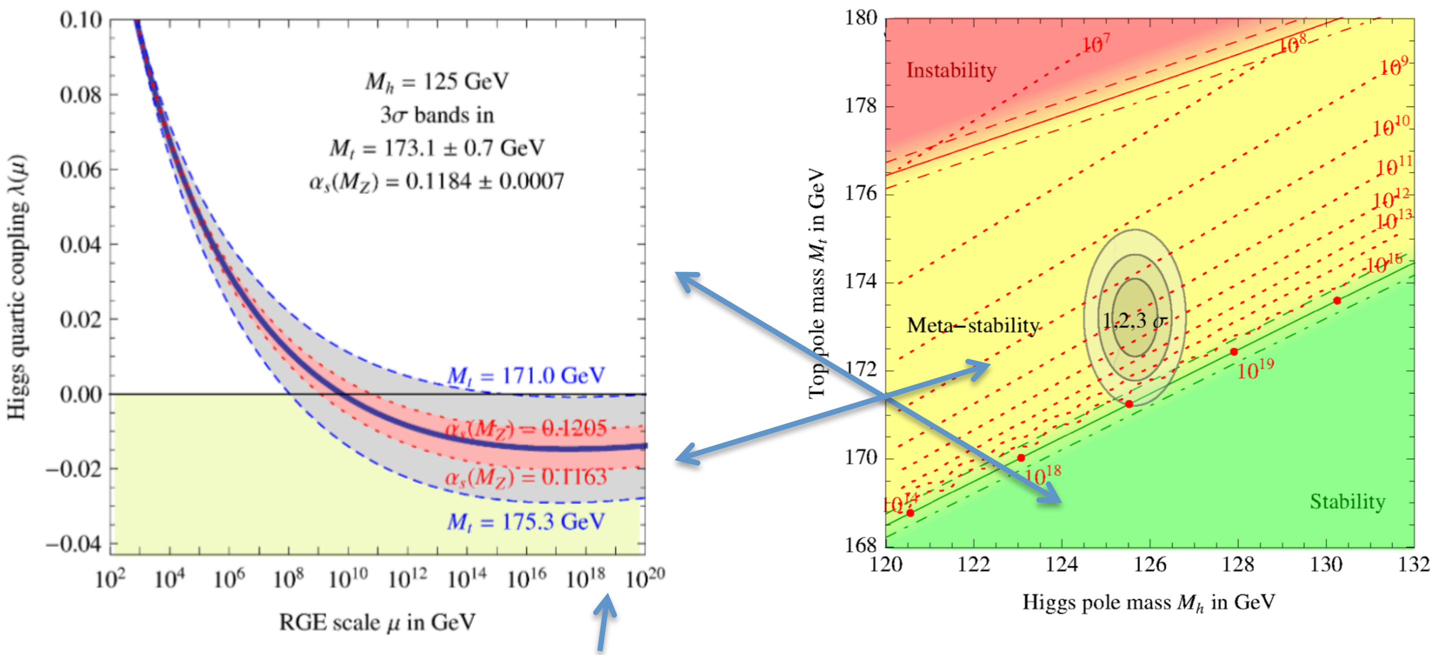
The Top Quark Mass and the Electroweak Vacuum



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

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

v: electroweak minimum

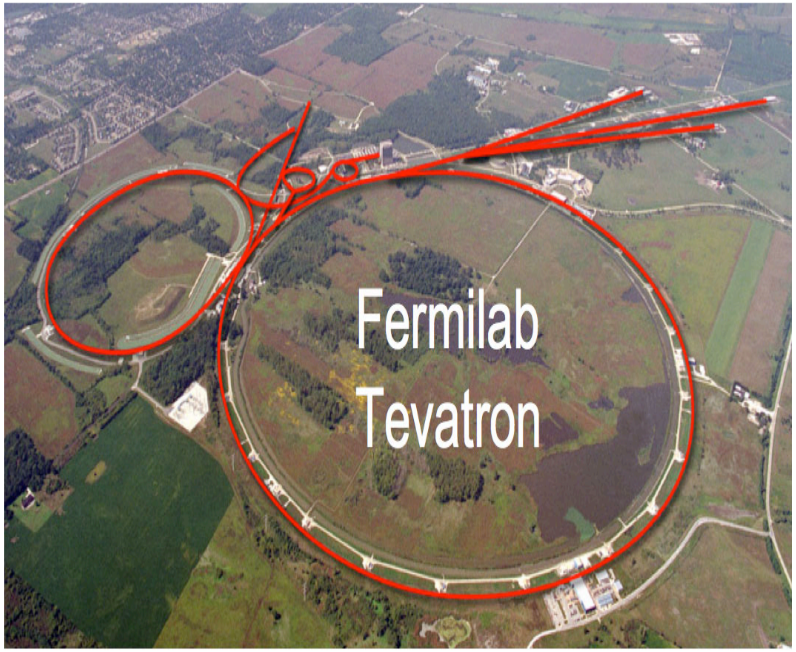


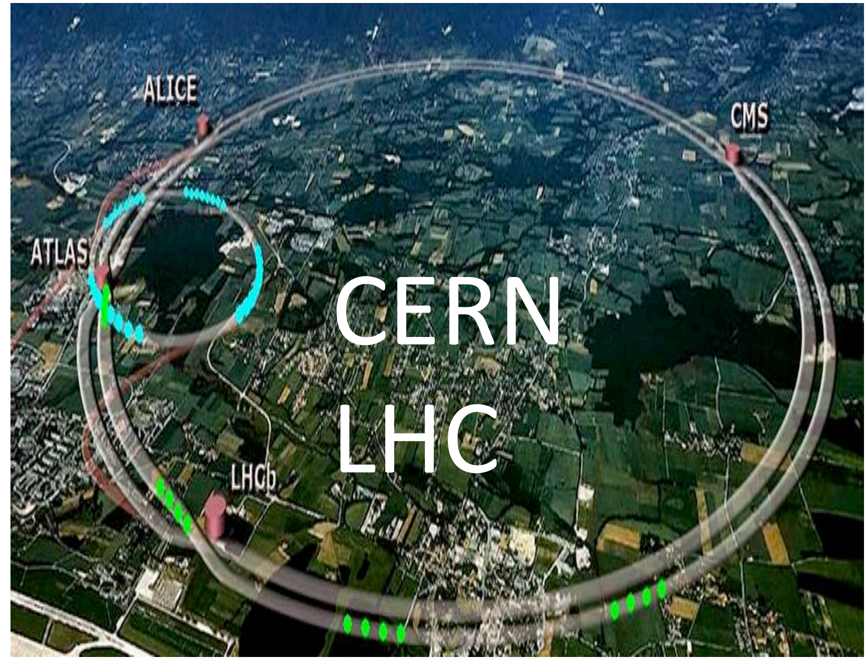
Planck scale

- 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

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

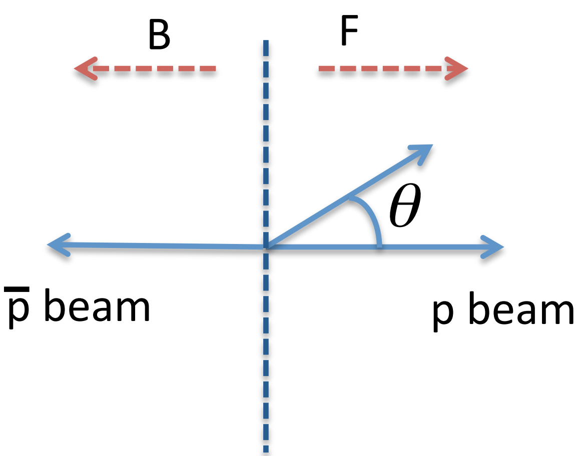
Parity → changes nothing
Charge → Makes LHC an anti-proton collider.

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

Asymmetries at Hadron Colliders

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

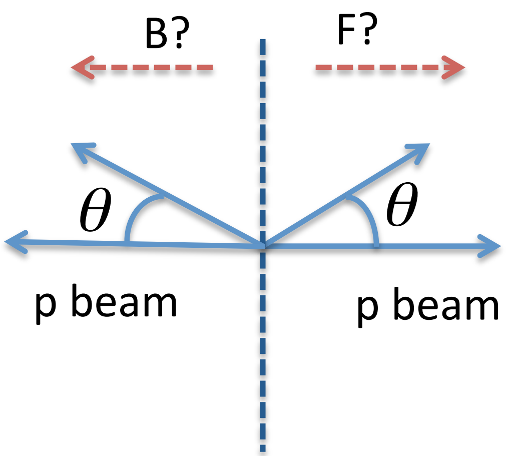
Parity asymmetric



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

PP collider (LHC)

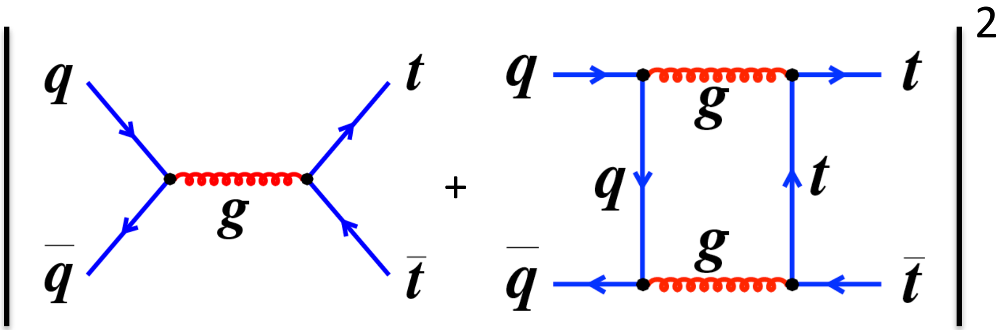
Parity symmetric

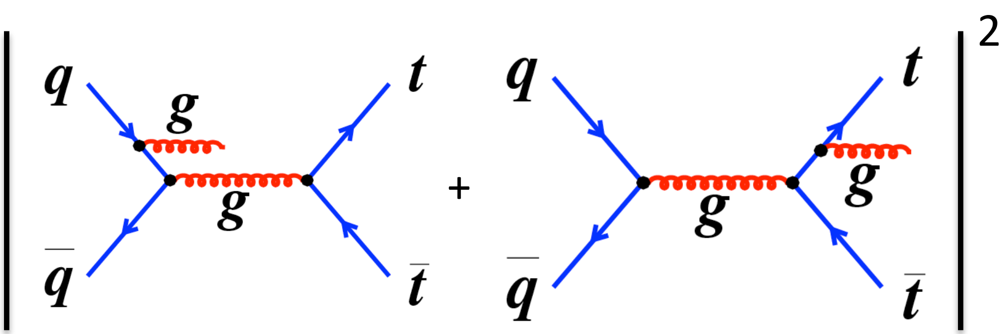


Does not allow the definition of a forward (backward) hemisphere based on the P direction, unless we consider the Parton Distribution Functions (PDFs.)

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

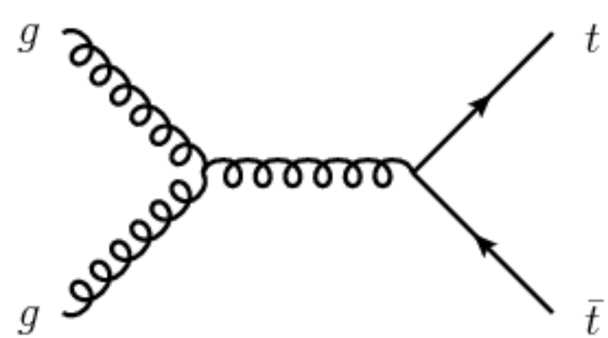
Interference: tree-level + box diagrams
(positive asymmetry)





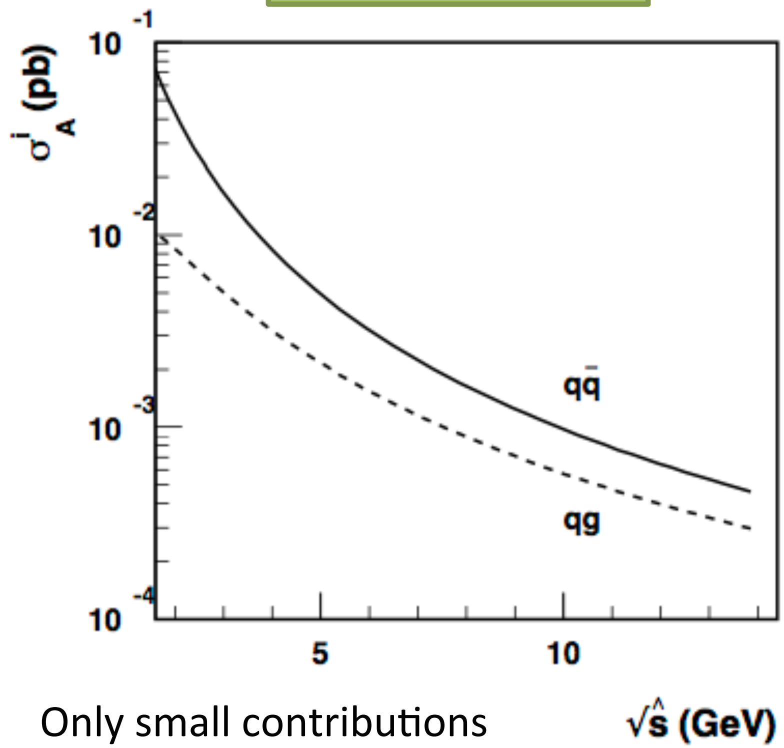
Interference: ISR+FSR
(negative asymmetry)

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

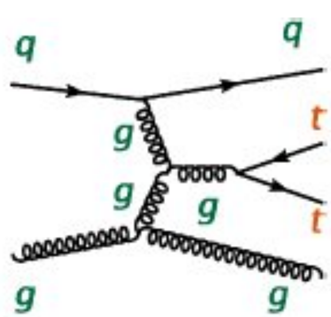


Asymmetry from Interference - $t\bar{t}$

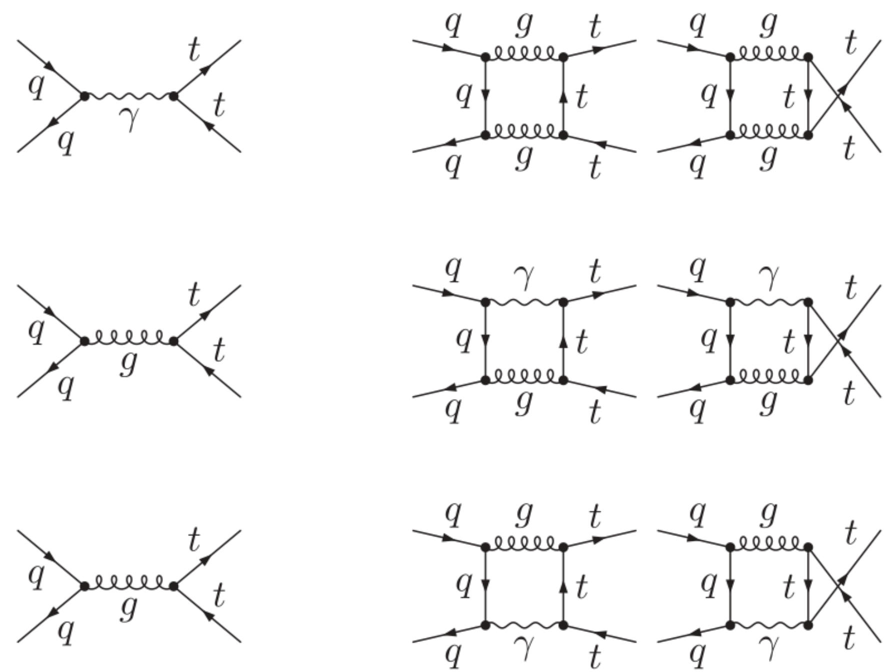
Kuhn & Rodrigo,
PRD 59 (1999) 054017



- Only small contributions from quark-gluon scattering

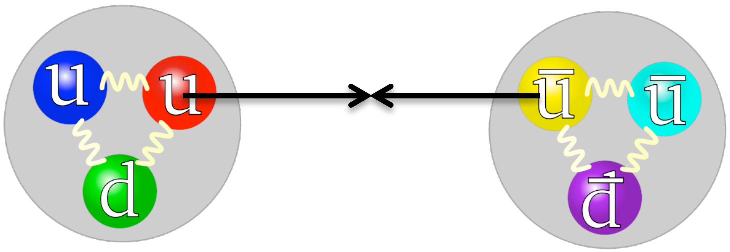


Hollik & Pagani
PRD 84 (2011) 093003

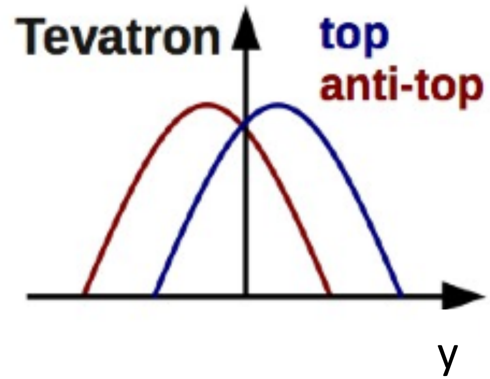


- Significant (~25%) contributions from QCD-electroweak interference terms.

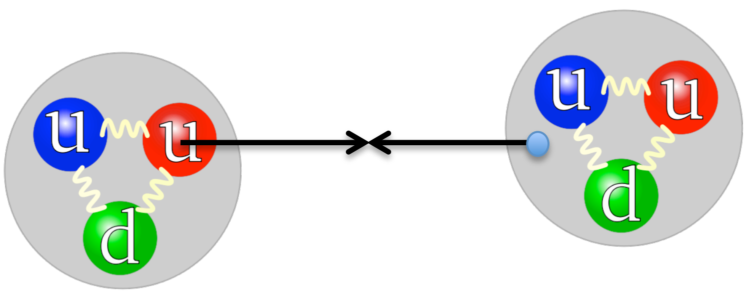
Asymmetry from Interference - $t\bar{t}$



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

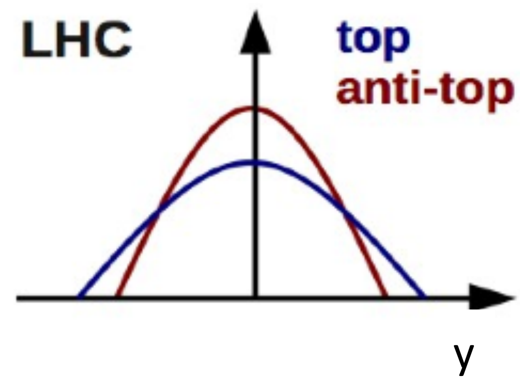


Forward-backward asymmetry (A_{FB})



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

→ much smaller asymmetry.

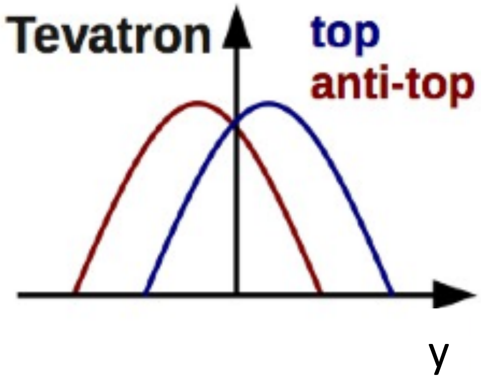


Charge asymmetry (A_C)

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

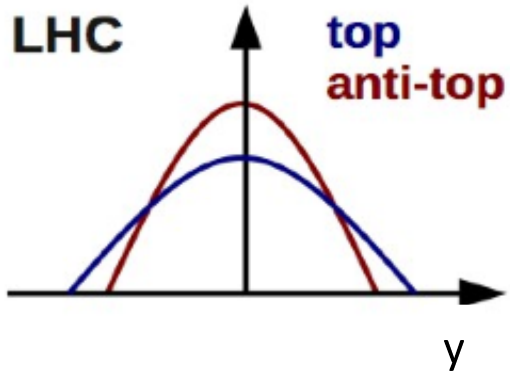
→ any large asymmetry will indicate the existence of new physics.

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



Forward-backward asymmetry (A_{FB})

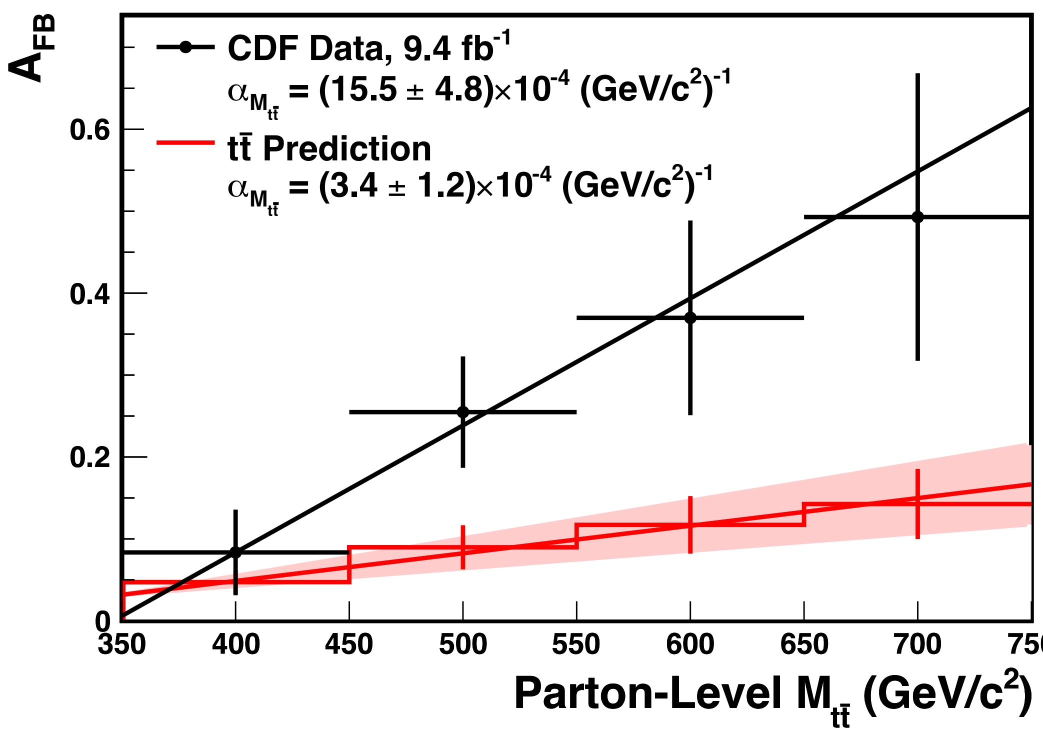
$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}, \ \Delta y = y_t - y_{\bar{t}}$$



Charge asymmetry (A_C)

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

$t\bar{t}$ Asymmetry at the Tevatron: Deviations from SM First Reported in 2009 by CDF and D0



arXiv:1211.1003
PRD 87, 092002 (2013)

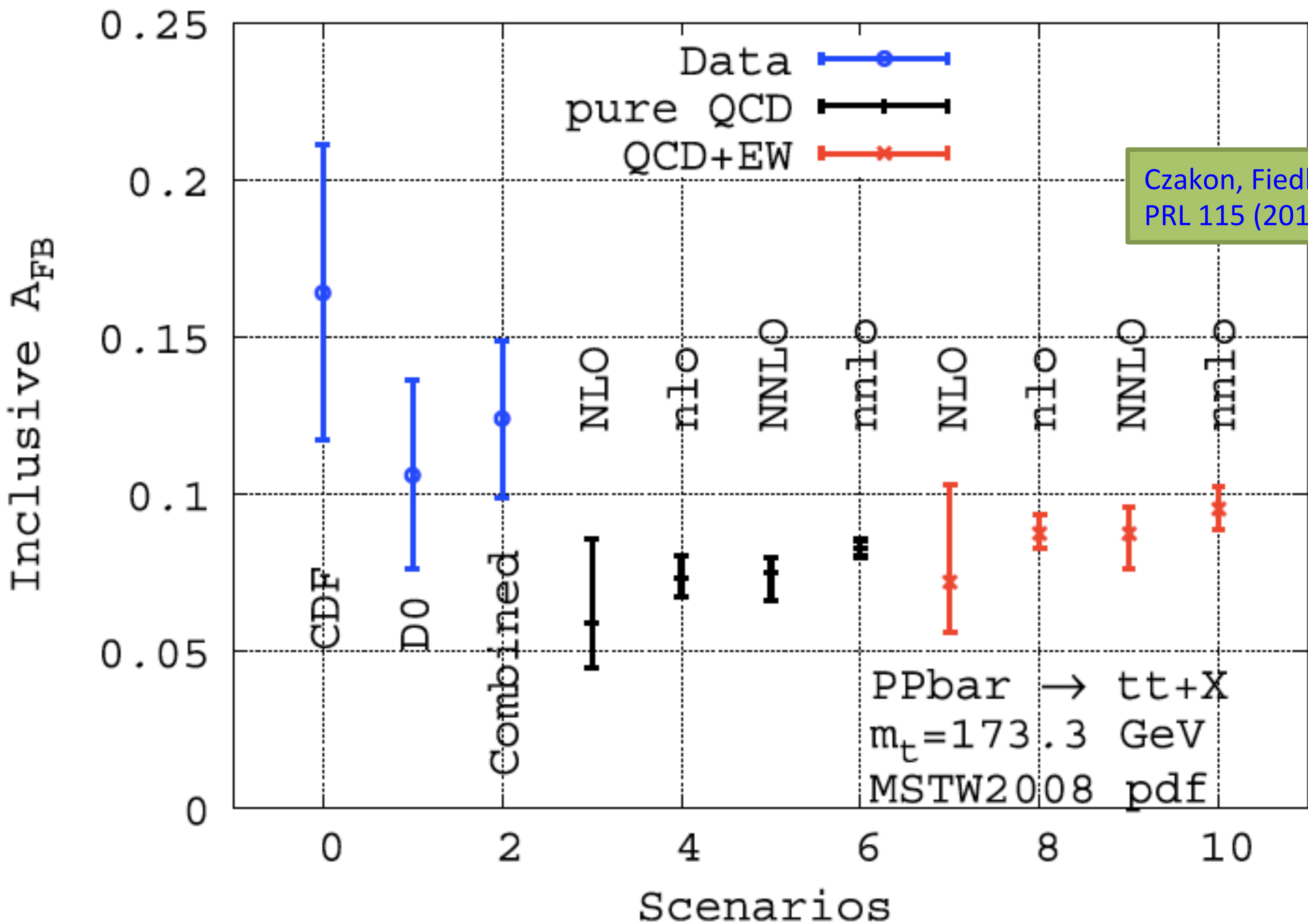
Inclusive A_{FB}: ~2σ deviation
$A_{FB}(m_{t\bar{t}}>450$ GeV): ~3σ

- 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?

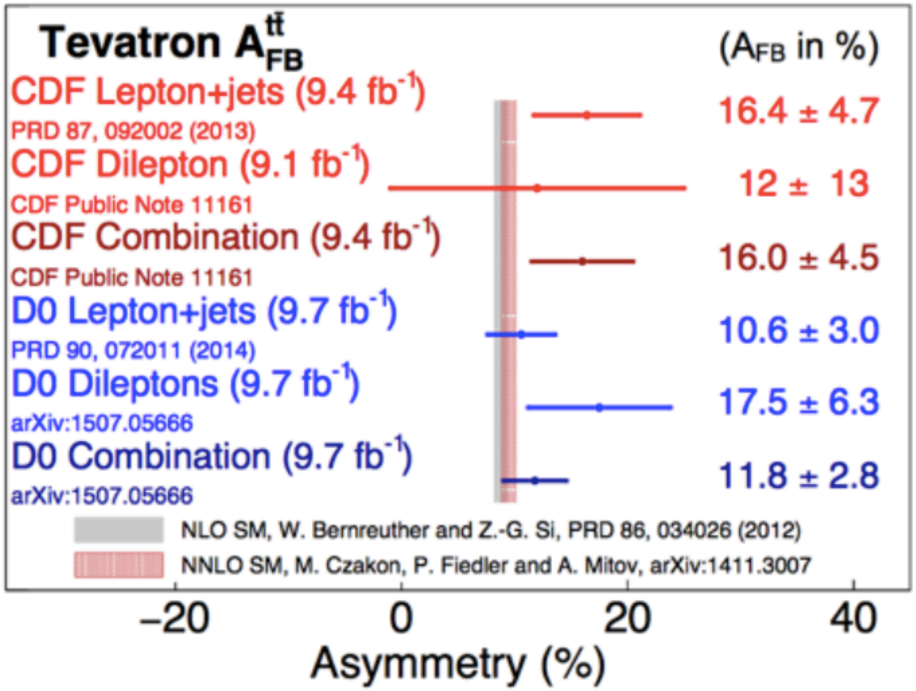
(but > 100 papers with New physics interpretation)

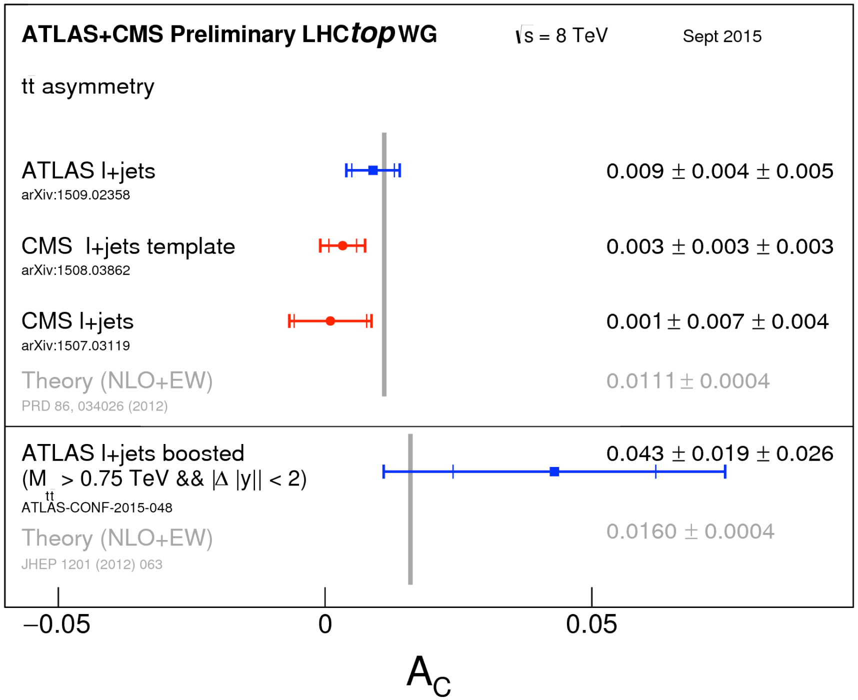
tt Asymmetry at the Tevatron @ 2015



Czakon, Fiedler, Mitov
PRL 115 (2015) 052001

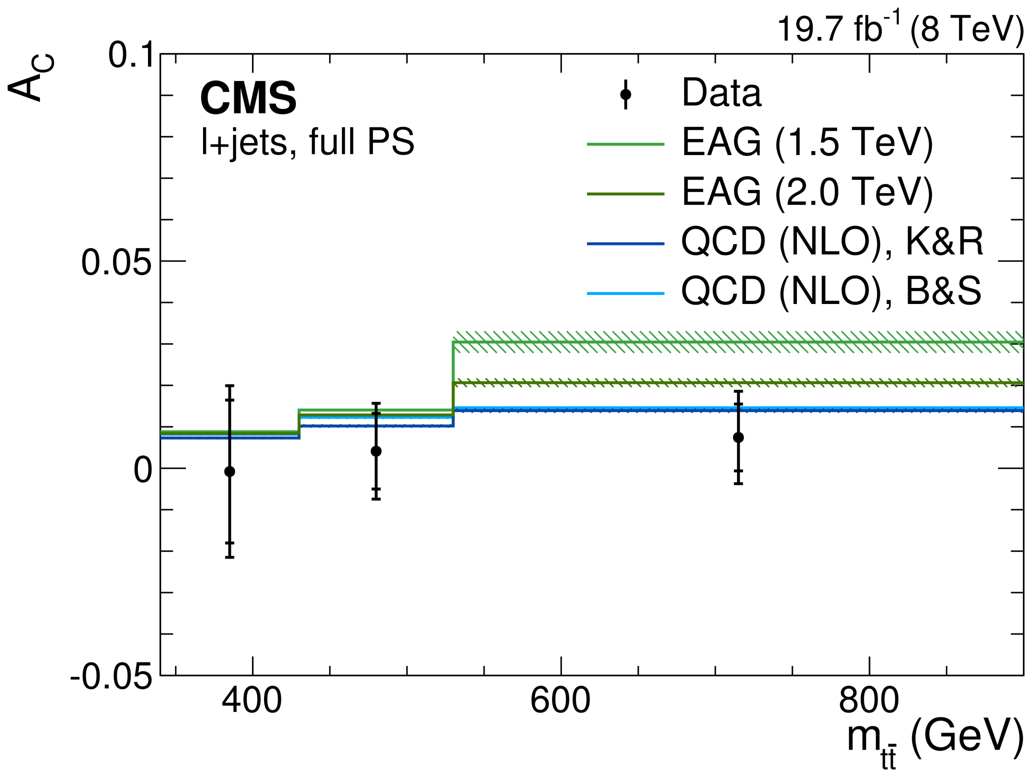
$t\bar{t}$ Asymmetry at the Tevatron and LHC





- $b\bar{b}$ asymmetry measurements consistent with LO predictions (LHCb arXiv:1406.4789).

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

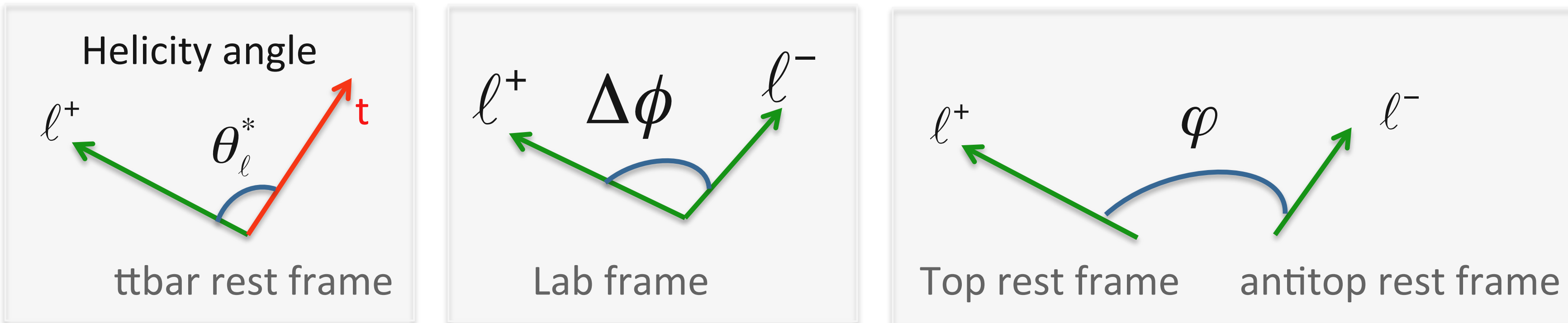


arXiv:1507.03119

- 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:

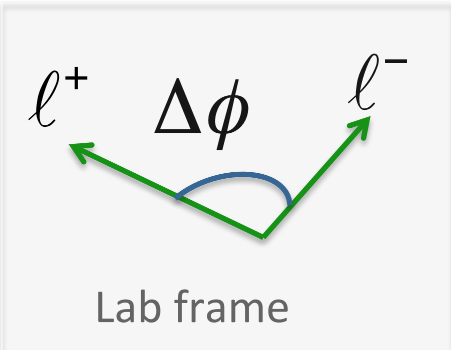


Or a multivariate method using more information from the events; e.g. Matrix Element Method:

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

Top Quark Spin Correlations - Dilepton Channel

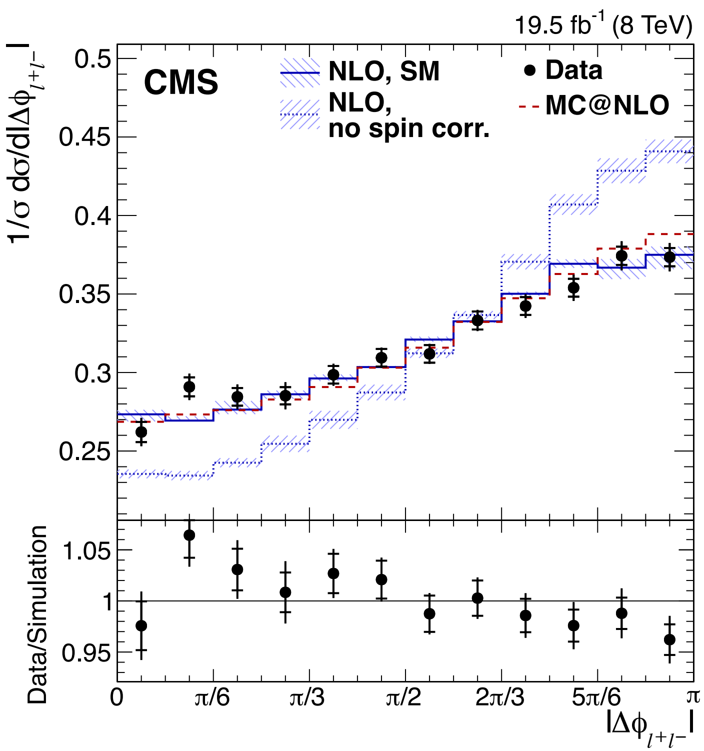
PRD 93 (2016) 052007

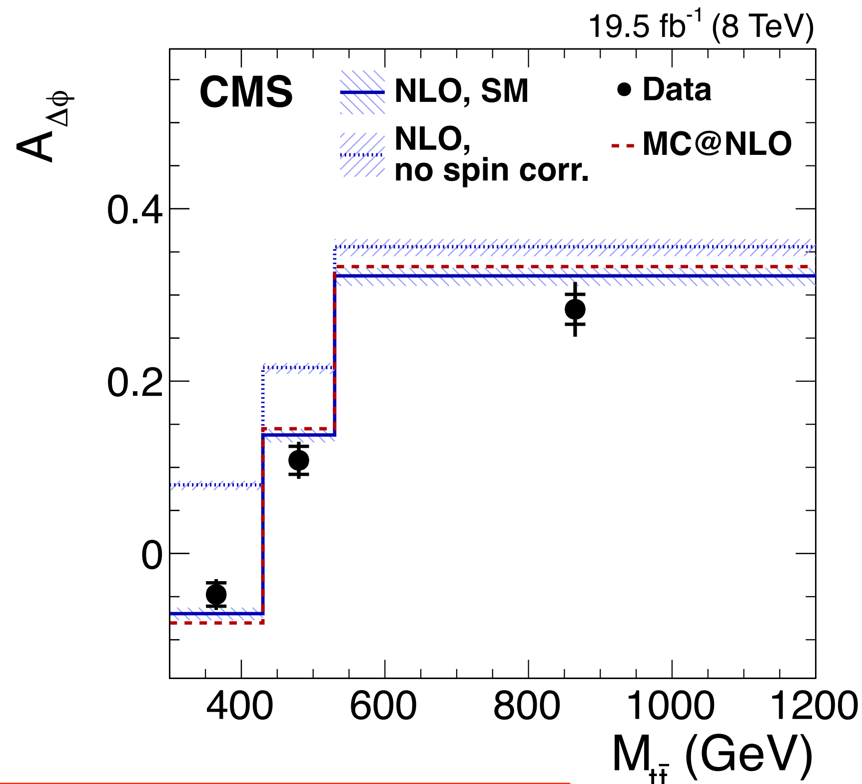


Δϕ distribution becomes flatter when tops are correlated.

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

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



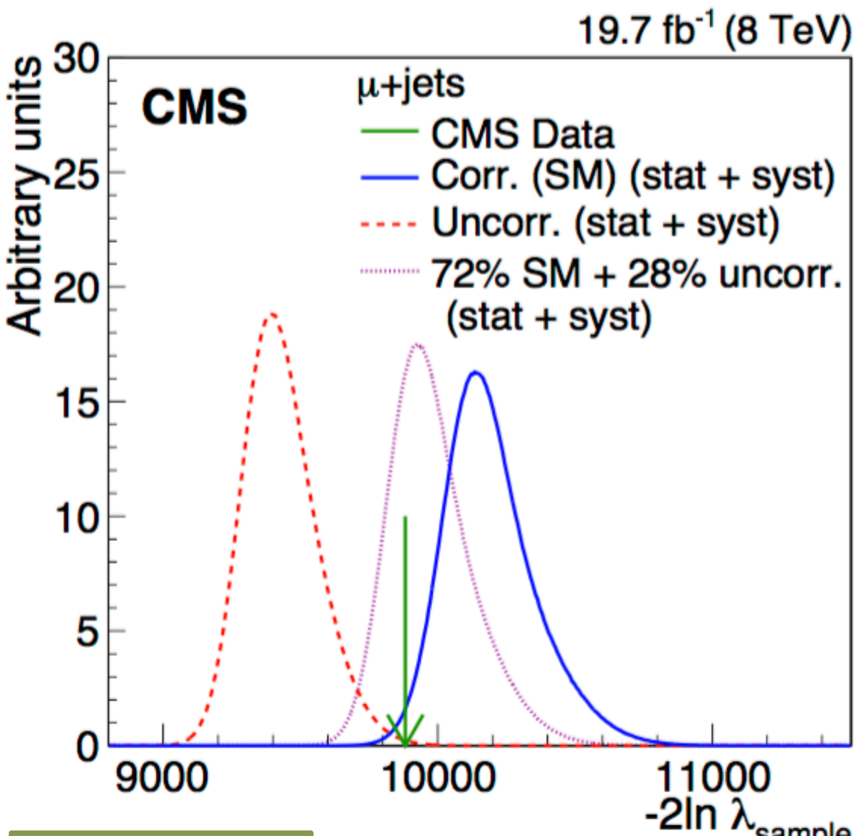


$$f_{SM}\left(from\ A_{\Delta\phi} \quad vs \quad M_{t\bar{t}}\right) = 1.12 \pm 0.06\left(stat\right) \pm 0.08\left(syst\right)^{+0.08}_{-0.11}\left(theor\right)$$

$t\bar{t}$ 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

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



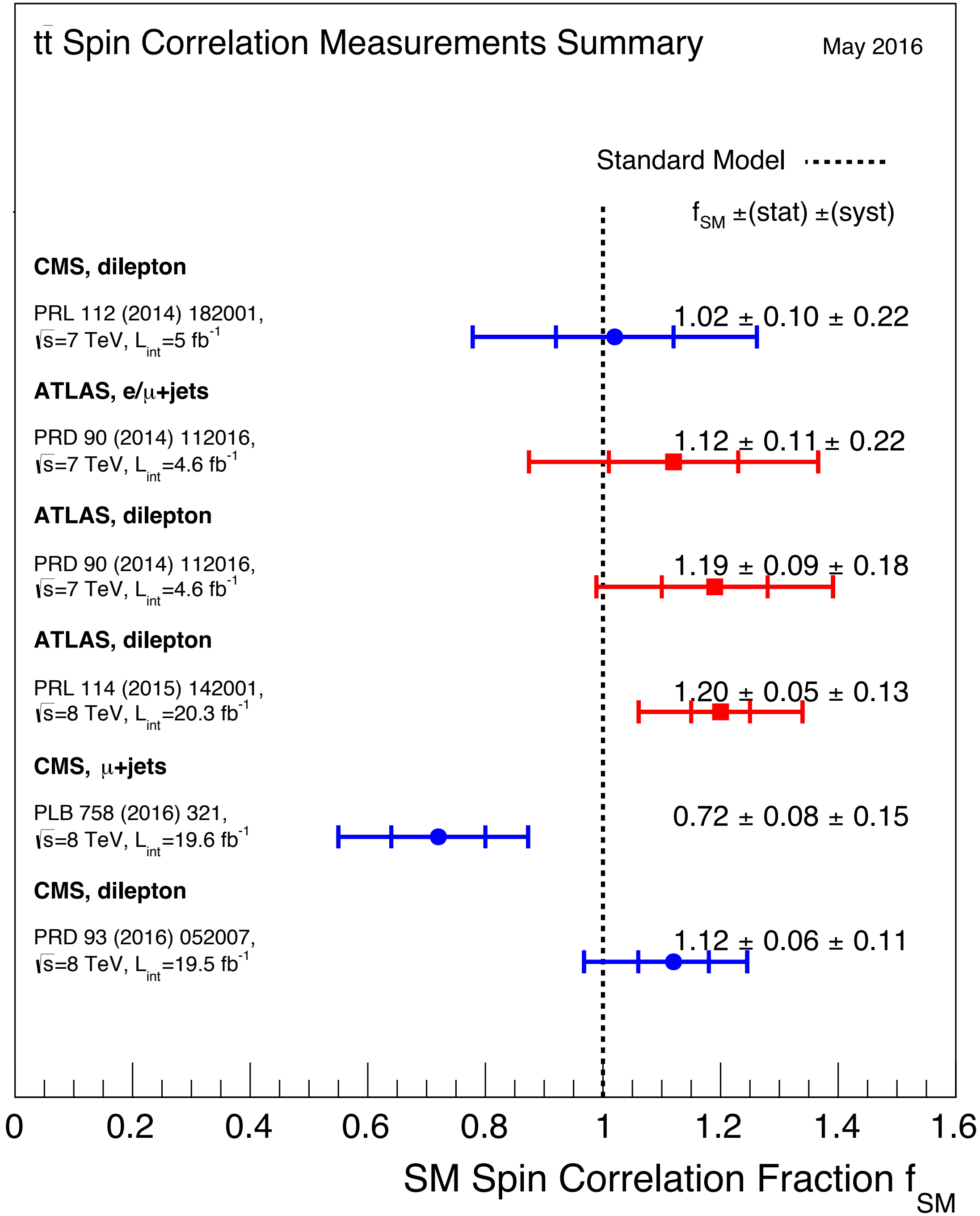
$$\rightarrow -2\ln\lambda = -2\ln\frac{P\left(H_{non-SM}\right)}{P\left(H_{SM}\right)}$$

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

Most precise result in l+jets to-date

Dominated by:
JES, QCD scale, top quark mass

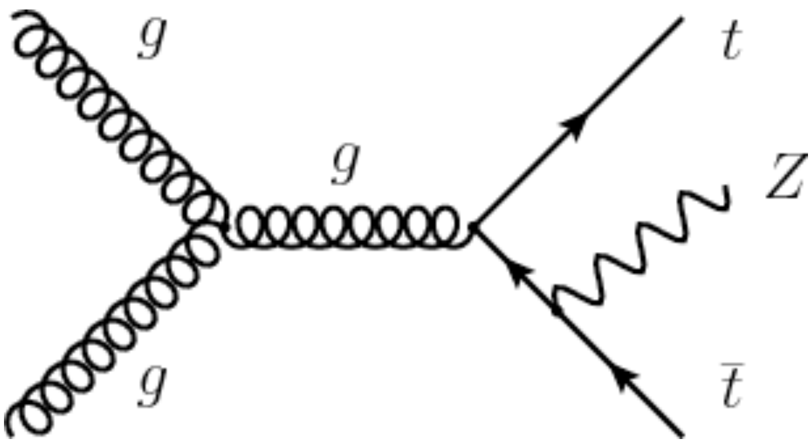
PLB 758 (2016) 321



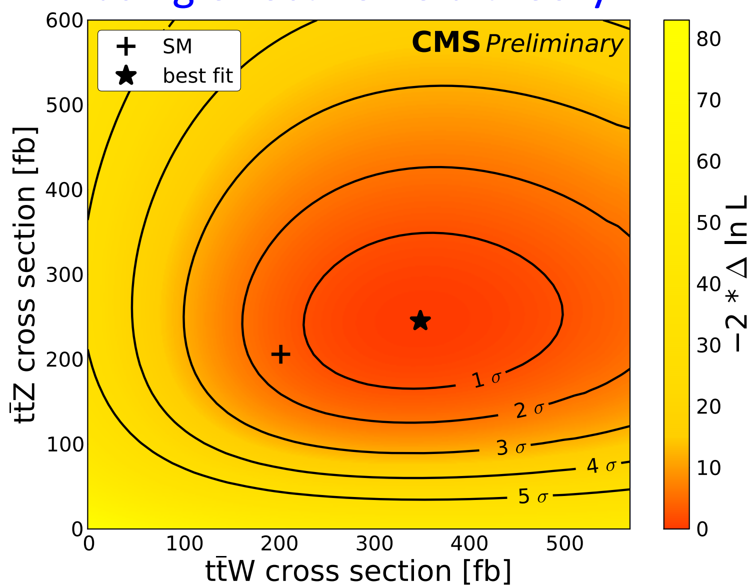
$t\bar{t}$ Spin Correlation Measurements Summary
May 2016
Standard Model
f_{SM} ±(stat) ±(syst)
CMS, dilepton
PRL 112 (2014) 182001,
$\sqrt{s}$=7 TeV, L_{int}=5 fb^{-1}
1.02 ± 0.10 ± 0.22
ATLAS, e/μ+jets
PRD 90 (2014) 112016,
$\sqrt{s}$=7 TeV, L_{int}=4.6 fb^{-1}
1.12 ± 0.11 ± 0.22
ATLAS, dilepton
PRD 90 (2014) 112016,
$\sqrt{s}$=7 TeV, L_{int}=4.6 fb^{-1}
1.19 ± 0.09 ± 0.18
ATLAS, dilepton
PRL 114 (2015) 142001,
$\sqrt{s}$=8 TeV, L_{int}=20.3 fb^{-1}
1.20 ± 0.05 ± 0.13
CMS, μ+jets
PLB 758 (2016) 321,
$\sqrt{s}$=8 TeV, L_{int}=19.6 fb^{-1}
0.72 ± 0.08 ± 0.15
CMS, dilepton
PRD 93 (2016) 052007,
$\sqrt{s}$=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 at 8 TeV.



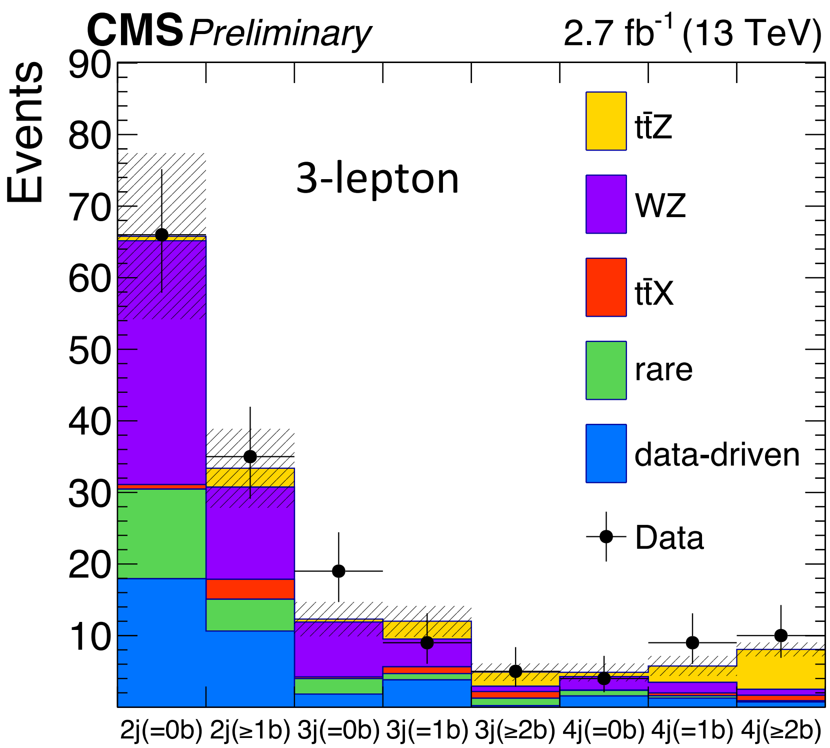
Constraints o the axial and vector components of the top-Z coupling using effective field theory.



Top Quark Couplings

TOP-16-009

- Run II:
  - σ(ttZ)@13 TeV → ~4 x σ(ttZ)@8 TeV
  - ttZ cross section from 3-lepton and 4-lepton final states.
  - Exploit jet and b-jet multiplicities to enhance the signal.

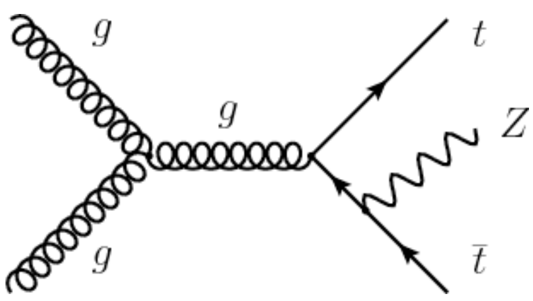


Expected significance: 3.1 SD
Observed significance: 3.6 SD

$$\sigma_{t\bar{t}Z} = 1065^{+352}_{-313}(stat)^{+168}_{-142}(syst)\ fb$$

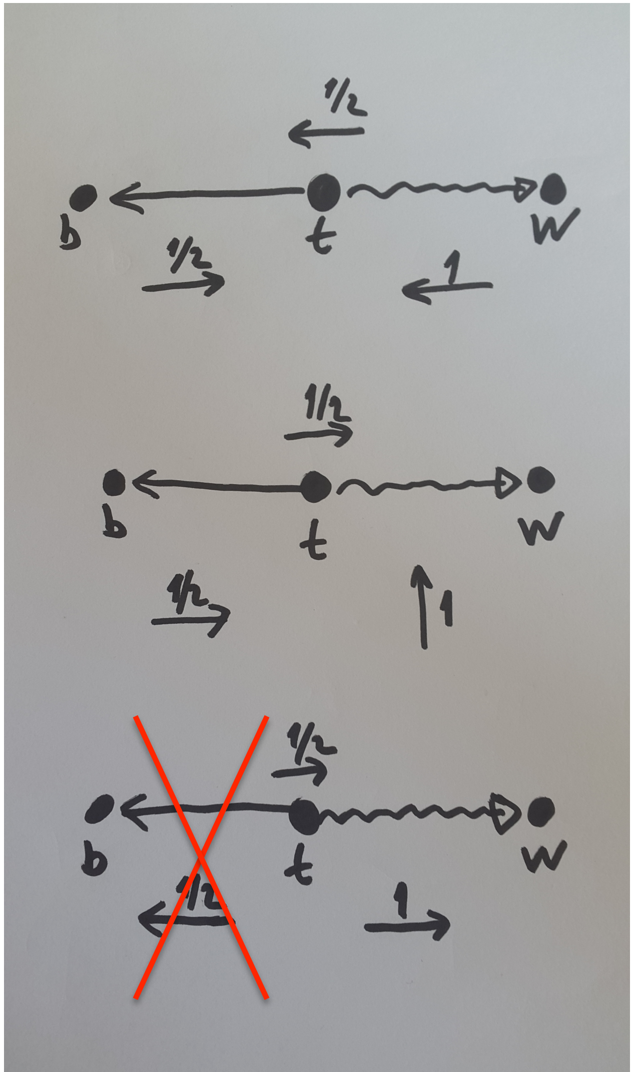
$$\sigma^{NLO}_{t\bar{t}Z} = 839.3^{+80}_{-92}(scale) \pm 25(pdf) \pm 25(\alpha_s)\, fb$$

Frixione et al. arXiv:1504.03446; Alwall et al. arXiv:1405.0301



W Boson Polarization

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



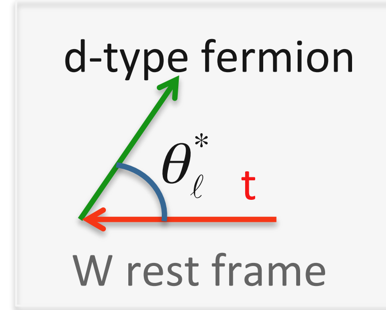
Left-handed
(negative helicity)

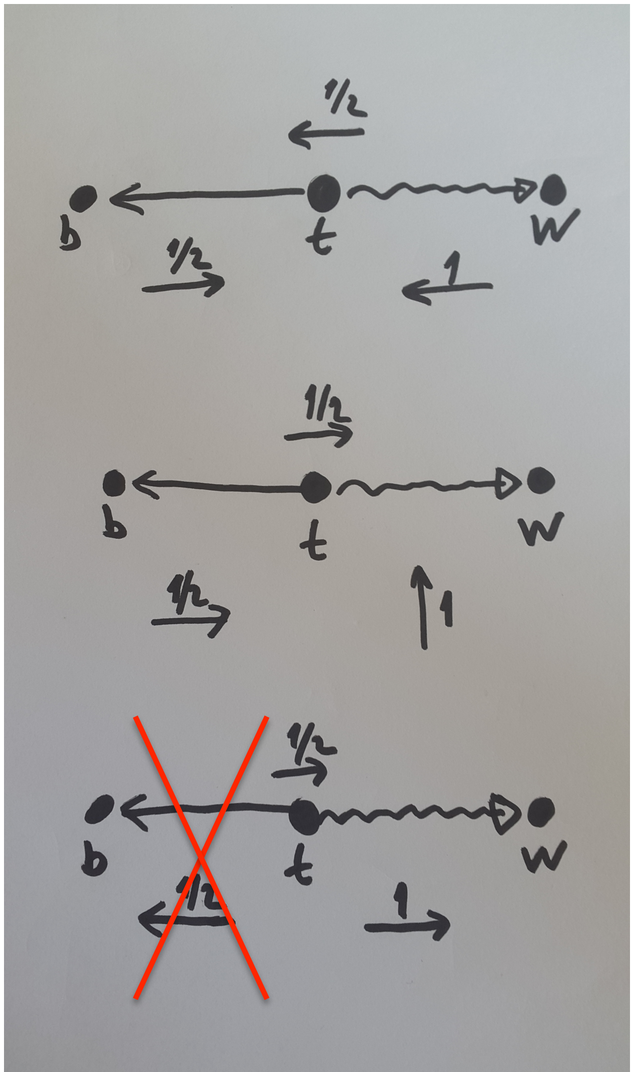
longitudinal
(zero helicity)

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
Left-handed
(negative helicity)

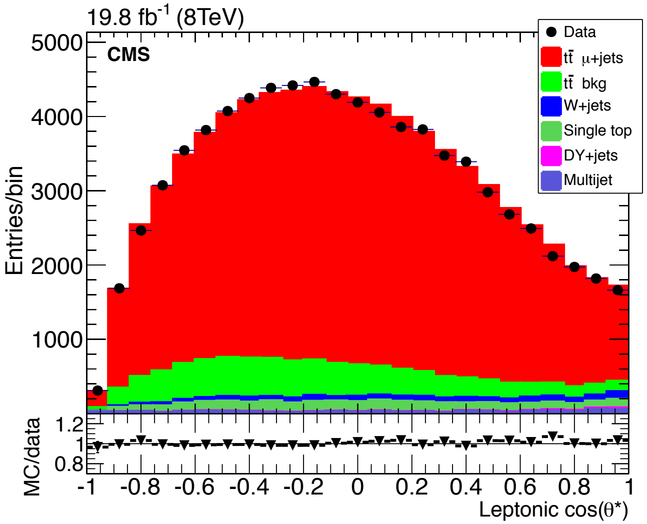
F_0~0.7
longitudinal
(zero helicity)

F_R~0
Right-handed
(positive helicity)

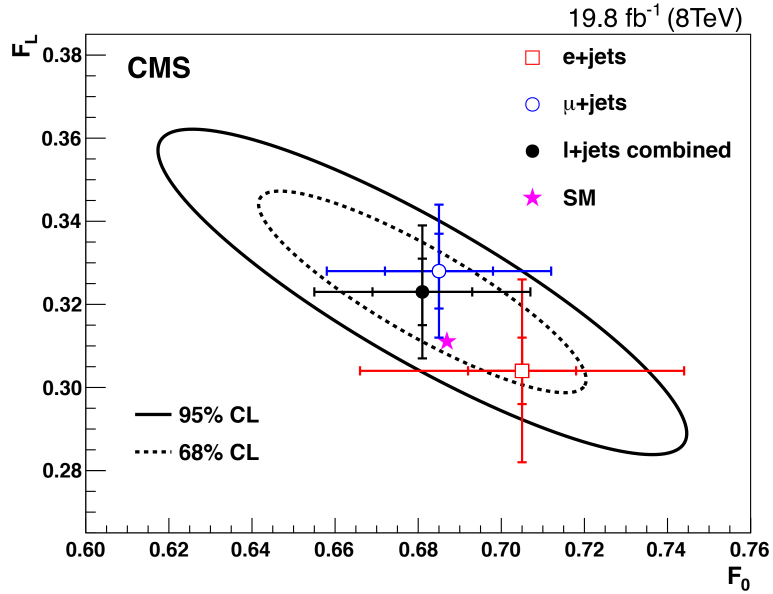
Top quark prefers to couple more to longitudinally polarized W bosons.

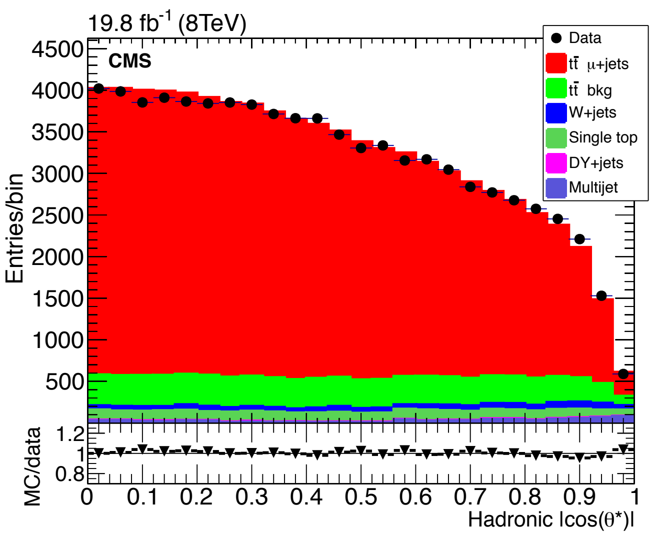
Higher orders (at NNLO QCD) with $m_b \neq 0$ modify the helicity fractions by ~2%.

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.

Most precise measurement of helicity fractions to date.

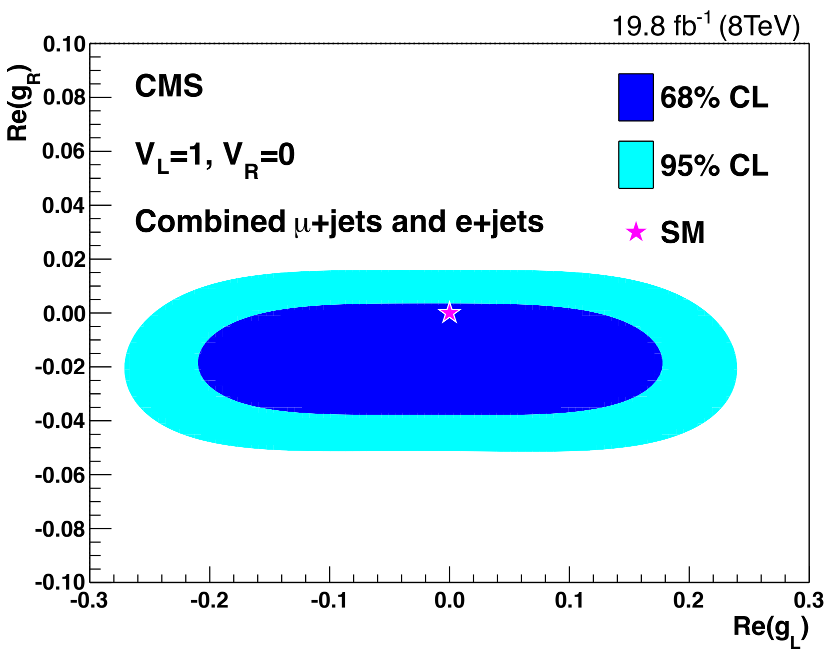
CMS-PAPER-TOP-13-008, submitted to PLB

W Boson Polarization

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

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

$$SM: \; V_L = V_{tb} \approx 1$$
$$V_R = g_L = g_R = 0$$



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

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

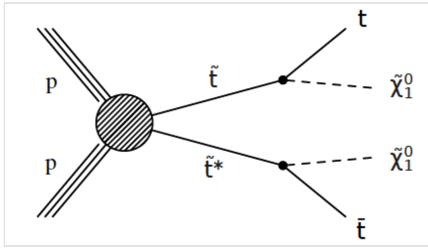
- Inclusive ttbar cross section already at NNLO precision.
- Single top t-channel precisely established.
- In both cases starting to probe differential spectra to understand new MCs
- Establish couplings to all bosons in Run II.
- Direct or indirect indications of new physics?

QUESTIONS

BONUS

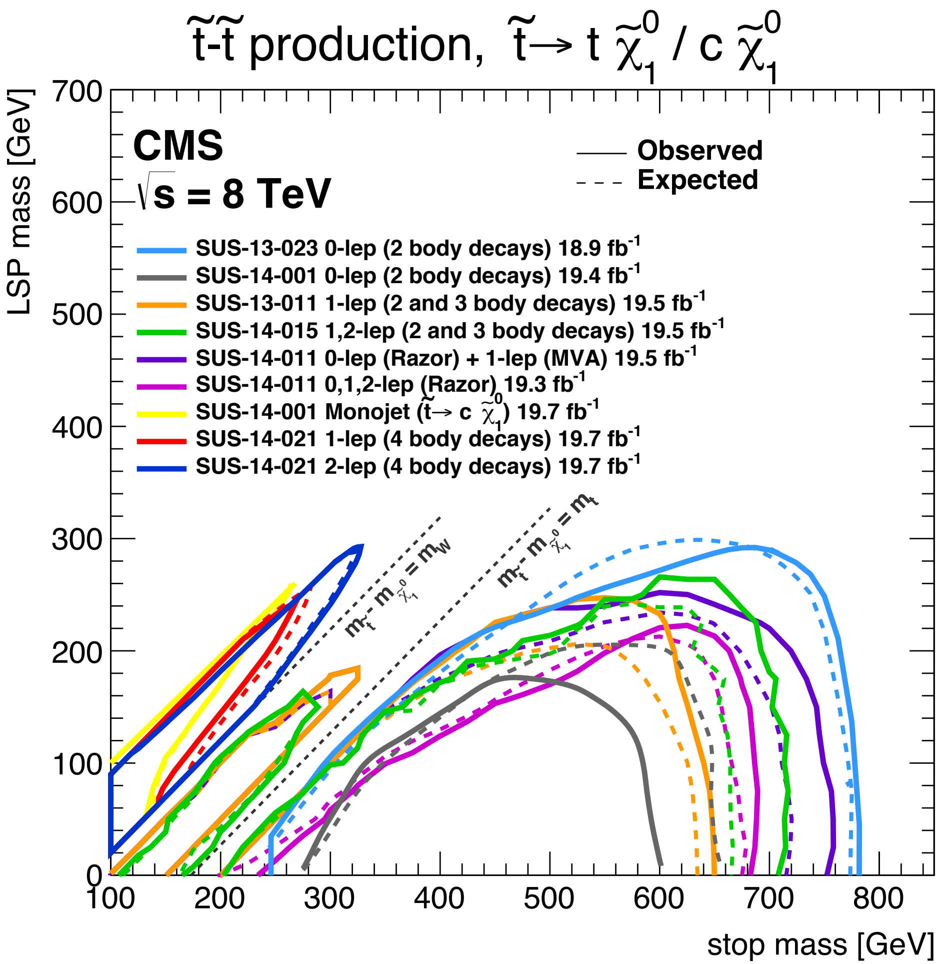
Top Square Pair Production

arXiv:1603.02303



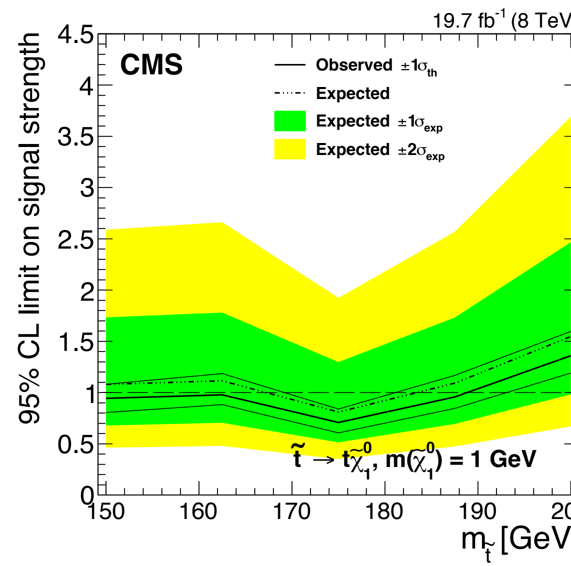
$$m(\tilde{t}) \approx m(\tilde{\chi}_1^0) + m_t \rightarrow \sigma_{t\bar{t}}$$ (and ttbar spin correlations)

more sensitive than standard SUSY searches for low $m(\tilde{\chi}_1^0)$ and $m(\tilde{t}) \approx m_t$



Simplified model with two parameters:

$$m(\tilde{t}), m(\tilde{\chi}_1^0)$$



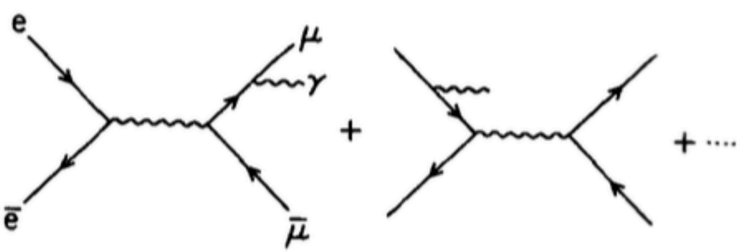
$$m(\tilde{t}; \tilde{\chi}_1^0 = 1\ GeV) > 189\ GeV$$

$$m(\tilde{t}; \tilde{\chi}_1^0) \notin 185 - 189\ GeV$$

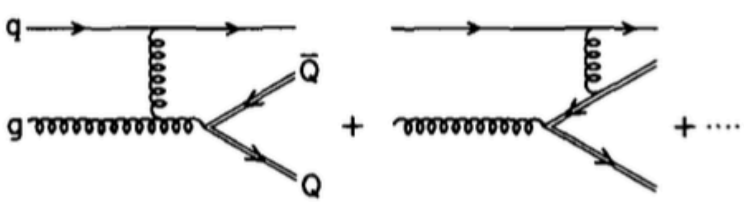
Asymmetry from Interference - $t\bar{t}$

- First calculation of asymmetry by Halzen et al. 1987 (PLB 195, 74) for m_t = 45 GeV!
- Making analogy to QED.
- But considered only real gluon emission.

$$q\bar{q} \to Q\bar{Q}g$$

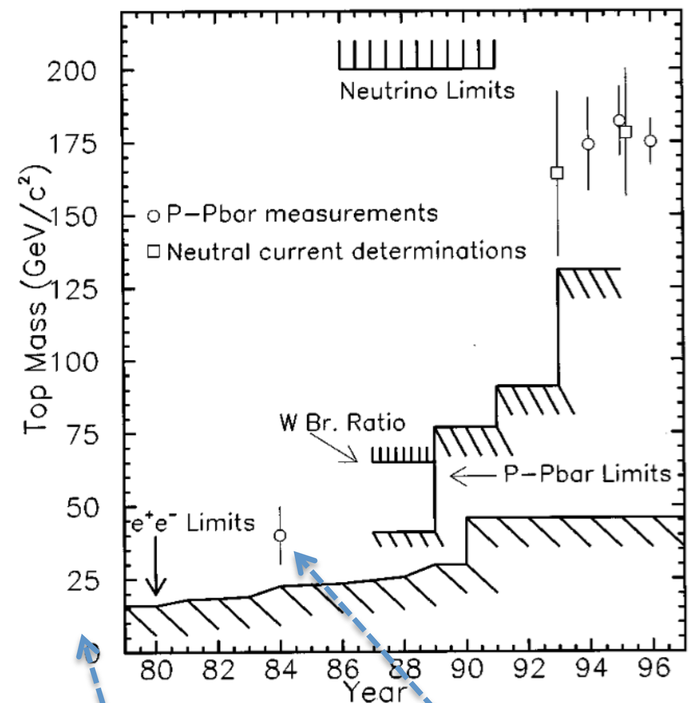


(a)



(b)

$$qg \to Q\bar{Q}q$$

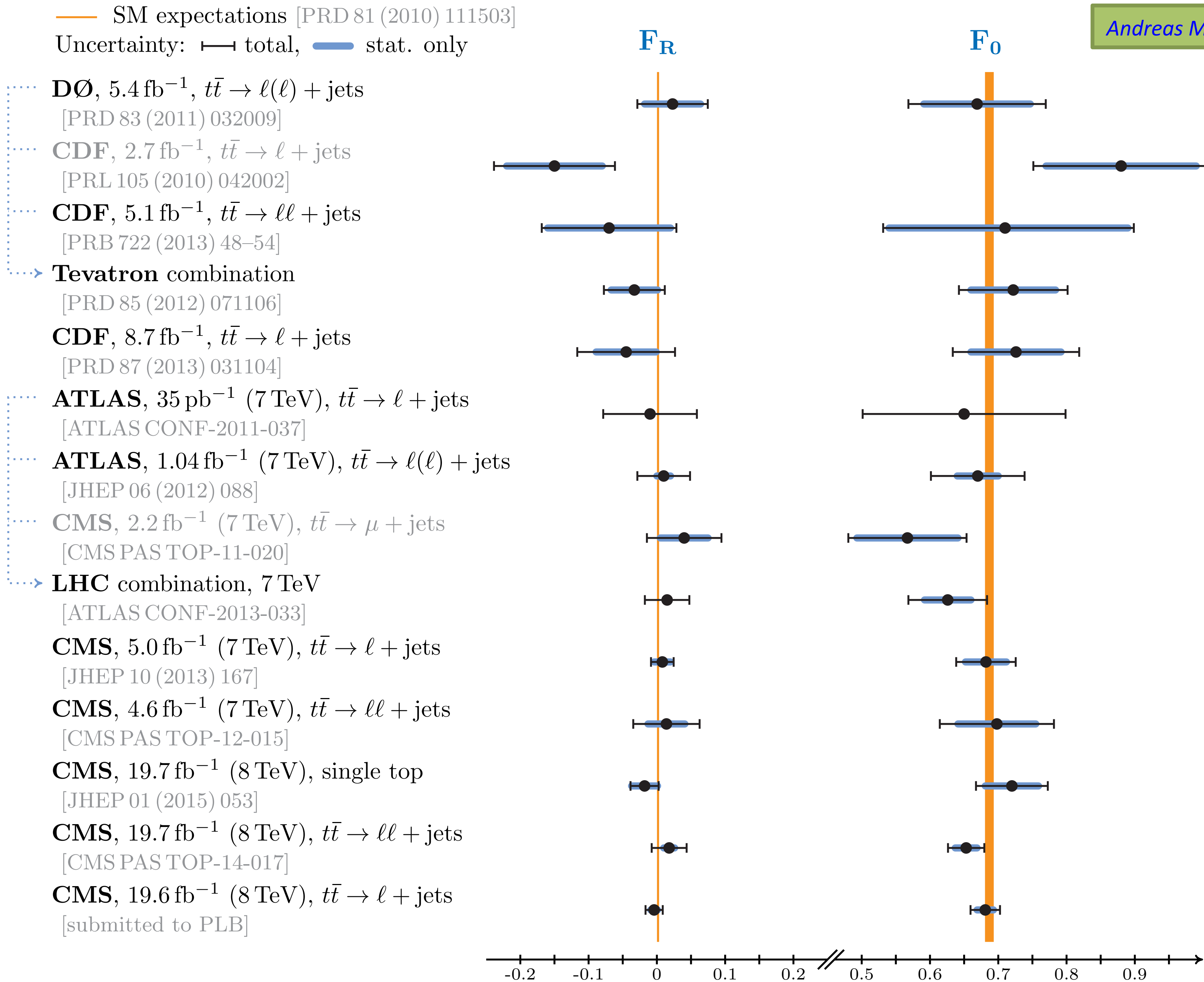


Campagnari & Franklin
Rev. Mod. Phys. 69, 137 (1997)

Example predictions of m_t:
→ **5-65 GeV**
(J. Ellis, et. al. NPB 131 (1977) 285)
→ **16-19 GeV**
(T. Yanagida, PRD 20 (1979) 2986)
→ **~148 GeV**
(H. Terazawa, PRD 22 (1980) 2921)

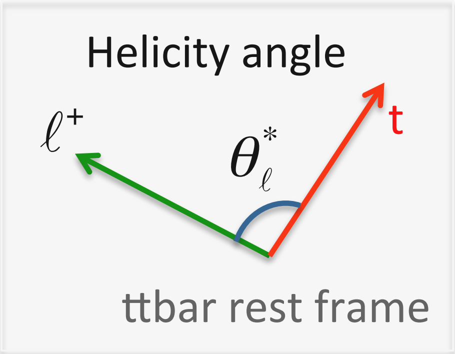
1984 UA1 measurement
m_t = 40+/-10 GeV.

Andreas Meyer



Top Quark Polarization in ttbar Dilepton Channel

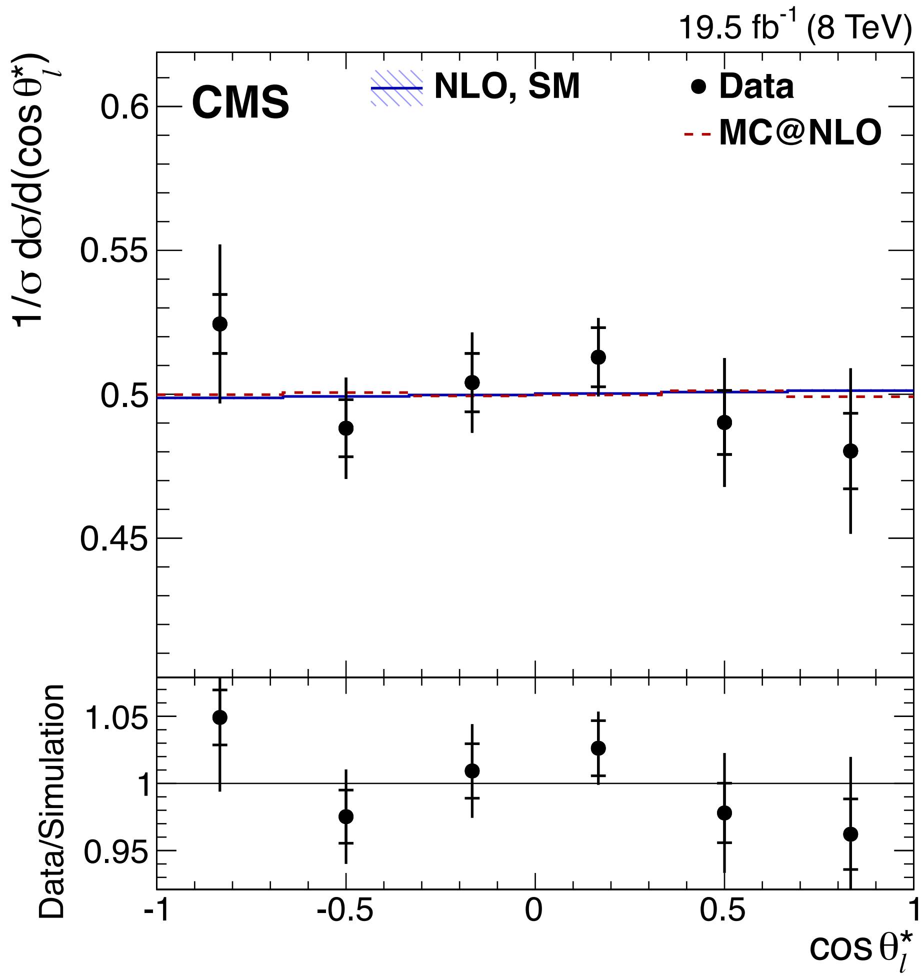
PRD 93 (2016) 052007



$$\frac{1}{2}P^{\pm} = A_{P^{\pm}} = \frac{N\left(\cos\theta^*_{\ell^\pm} > 0\right) - N\left(\cos\theta^*_{\ell^\pm} < 0\right)}{N\left(\cos\theta^*_{\ell^\pm} > 0\right) + N\left(\cos\theta^*_{\ell^\pm} < 0\right)}$$

$$P^{SM\,(CP-conserving)} = \left(A_{P+} + A_{P-}\right) = -0.022 \pm 0.058$$

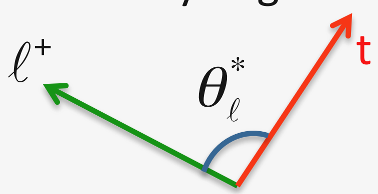
$$P^{CP-violating} = \left(A_{P+} - A_{P-}\right) = 0.000 \pm 0.016$$



Top Quark Spin Correlation in Dilepton Channel

PRD 93 (2016) 052007

Helicity angle



ttbar rest frame

$$\frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{\sigma}{4}\left(1+\alpha_+ P_+ \cos\theta_+ + \alpha_- P_- \cos\theta_- + A\alpha_+\alpha_- \cos\theta_+ \cos\theta_-\right)$$

$$A_{c_1c_2} = \frac{N(c_1c_2>0)-N(c_1c_2<0)}{N(c_1c_2>0)+N(c_1c_2<0)}$$

$$c_1 = \cos\theta^*_{\ell^+}$$

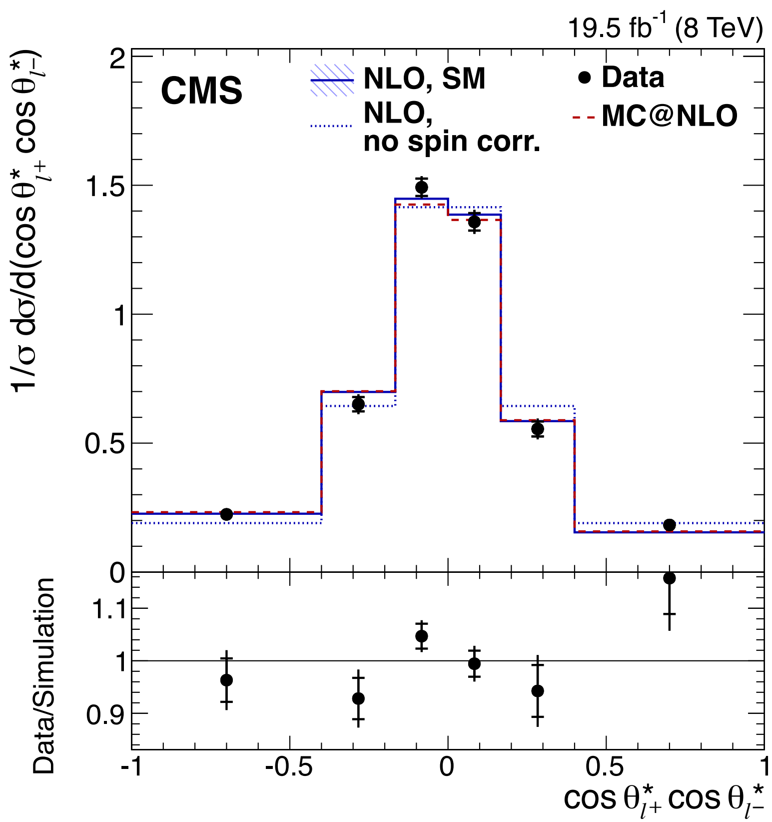
$$c_2 = \cos\theta^*_{\ell^-}$$

$$C_{hel} = -4A_{c_1c_2}$$

(spin correlation coefficient)

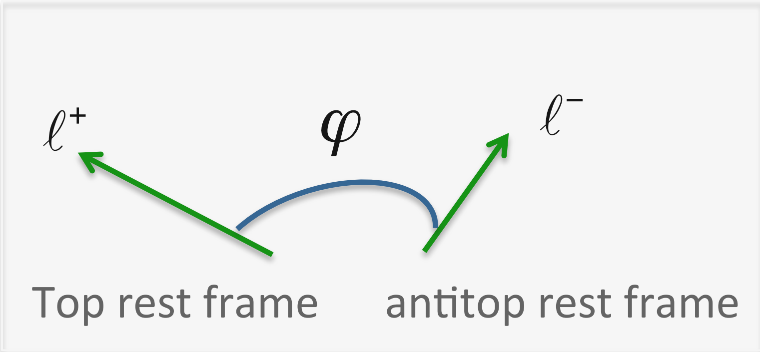
$$f^{SM}_{c1c2} = 0.87 \pm 0.27$$

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



Top Quark Spin Correlation in Dilepton Channel

PRD 93 (2016) 052007

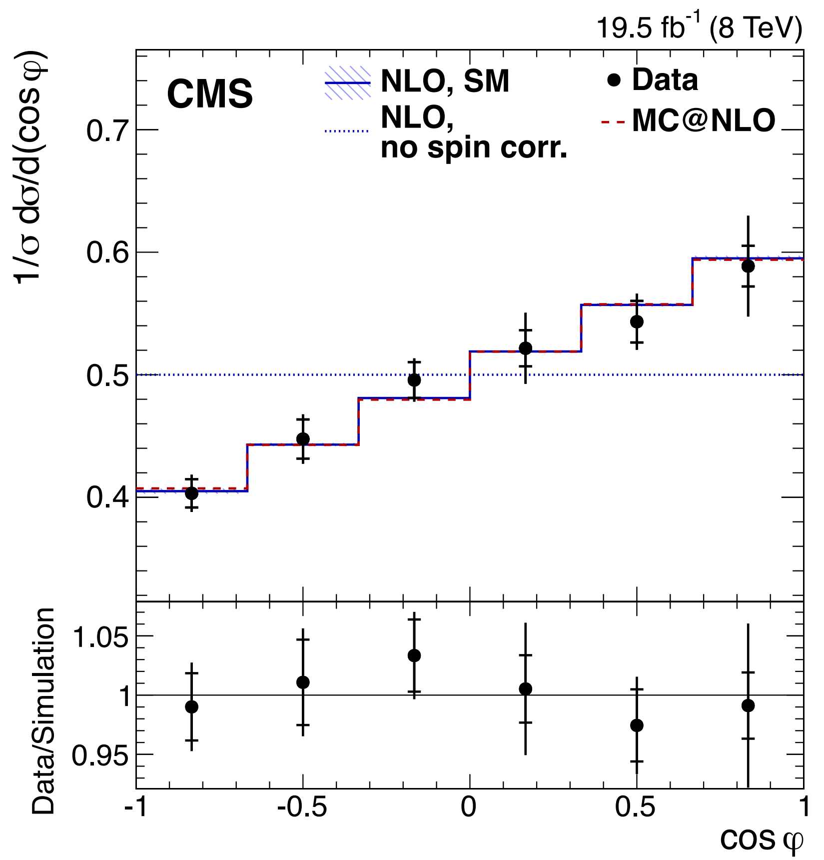


$$A_{\cos\varphi} = \frac{N(\cos\varphi > 0) - N(\cos\varphi < 0)}{N(\cos\varphi > 0) + N(\cos\varphi < 0)}$$

$D = -2A_{\cos\varphi}$ (spin correlation coefficient)

$$f_{\cos\varphi}^{SM} = 0.90 \pm 0.15$$

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



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 ($M > m_t$) :

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

Chromo magnetic dipole moment
CP conserving

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

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

Chromo electric dipole moment
CP violating

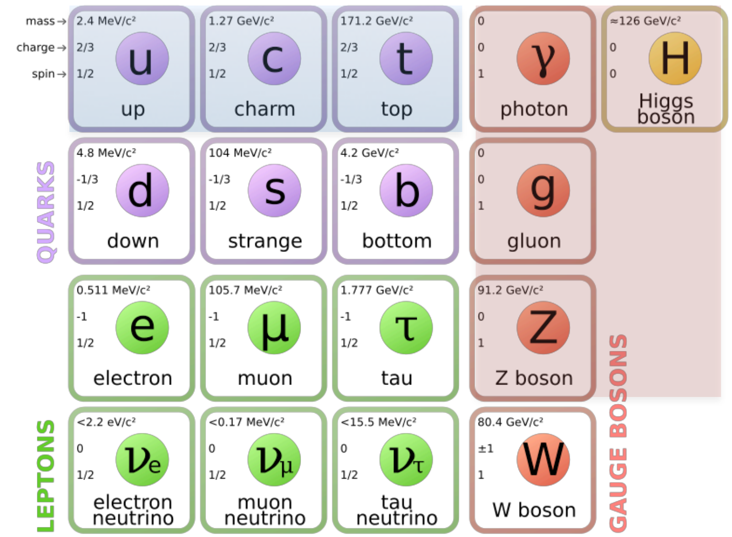
$$P^{CP-violating} = \mathrm{Im}\left(\hat{d}_t\right) P_{NP}^{CP-violating}$$

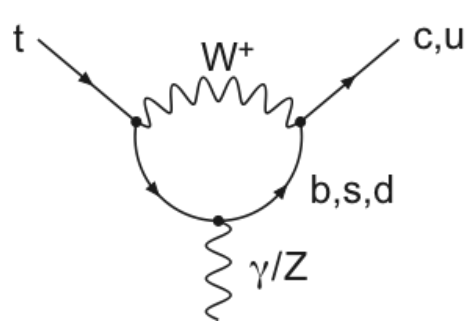
$$-0.068 < \mathrm{Im}\left(\hat{d}_t\right) < 0.067 \ \ @95\% \ C.L$$

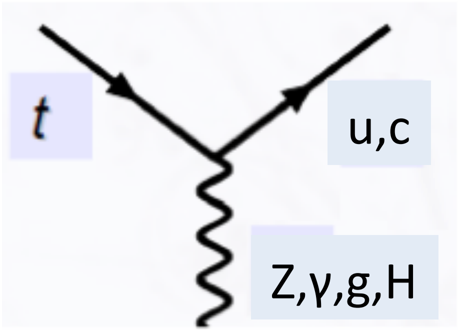
Bernreuther & Si,
PLB 725 (2013) 115
PLB 744 (2015) 413

Flavor Changing Neutral Currents

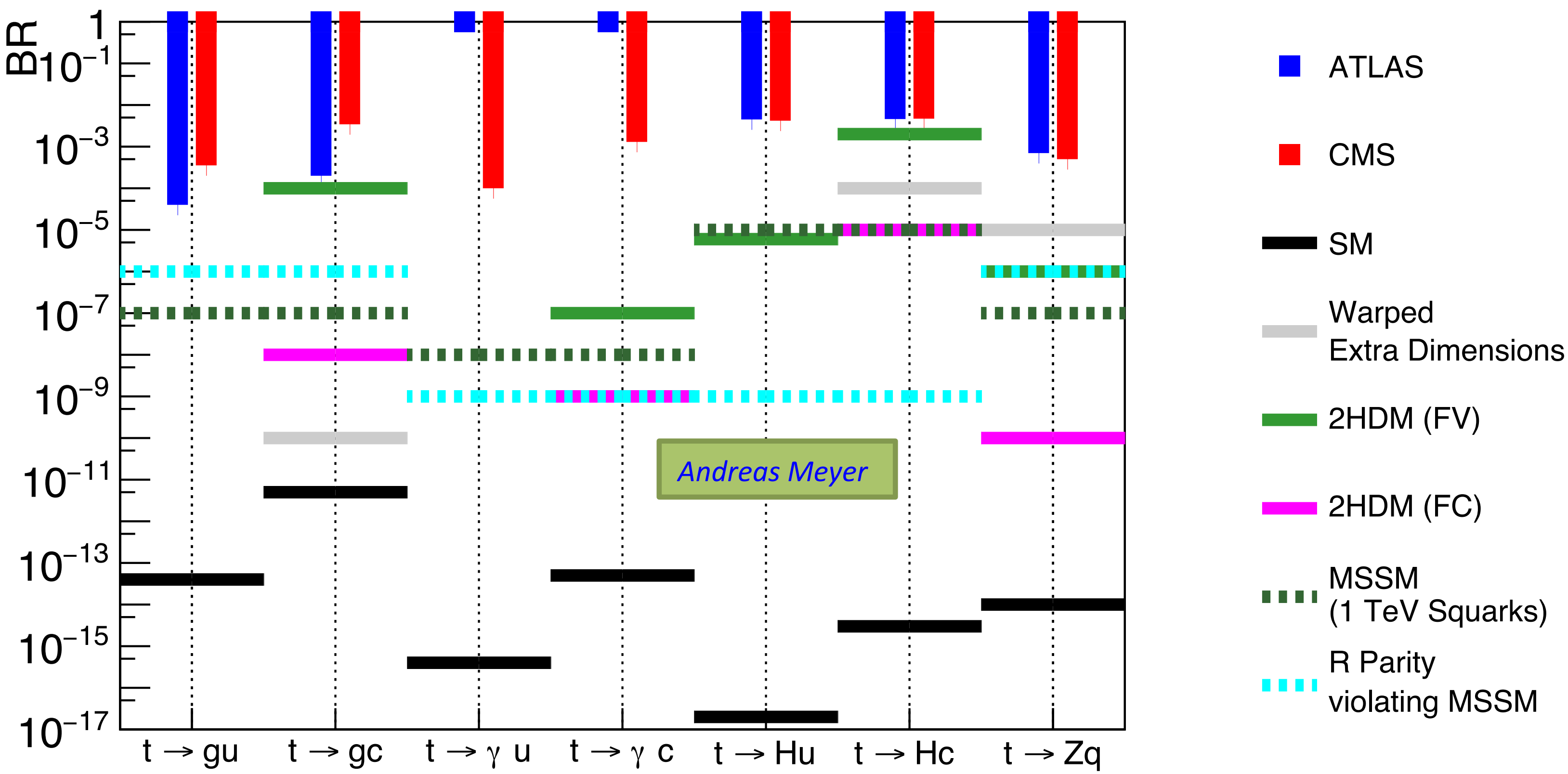
- SM: Forbidden at tree level
- Suppressed at higher orders due to GIM mechanism.
- Occurs only at the level of loop corrections with $\mathcal{B}(t\rightarrow Xq)\sim10^{-15}\text{-}10^{-10}\%$
- BSM $\mathcal{B}(t\rightarrow Xq)\sim10^{-7}\text{-}10^{-1}\%$
- Measurements$\sim10^{-2}\text{-}1\%$







FCNC vs Data in Some Particular Models



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