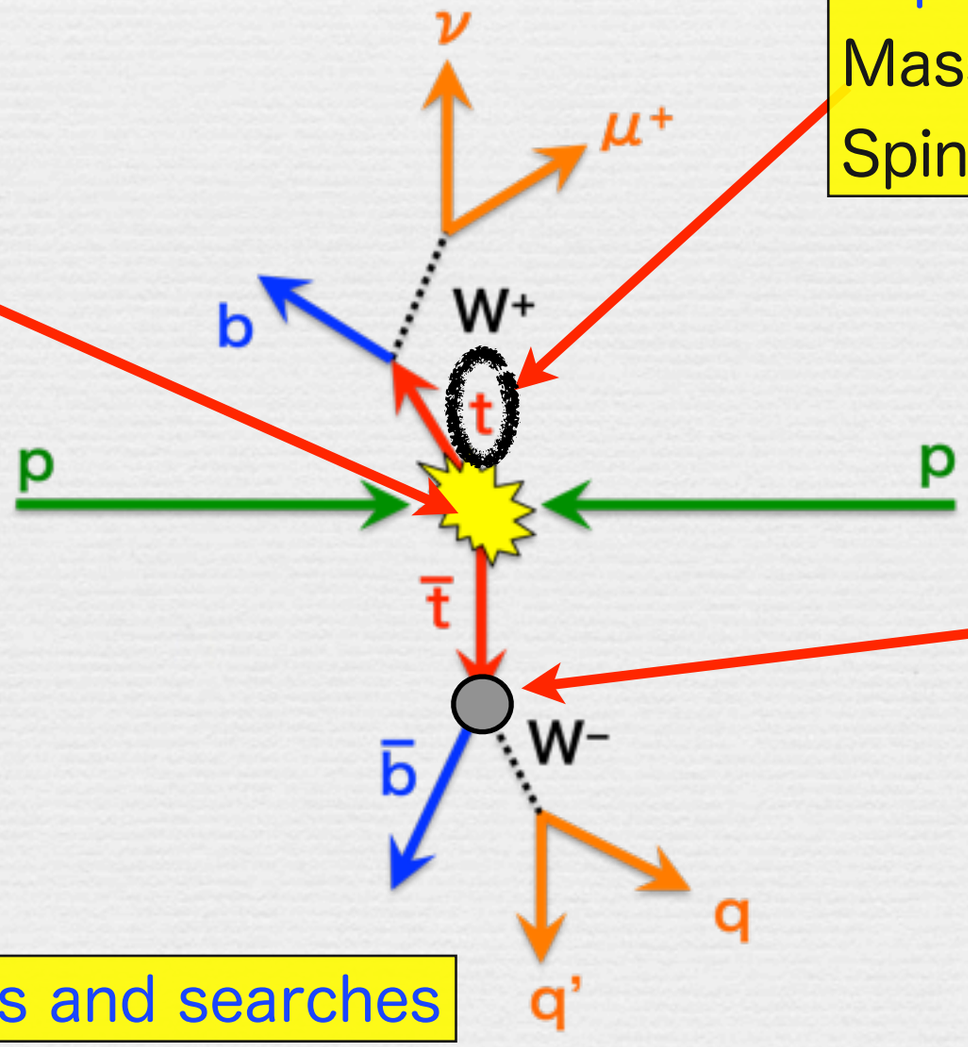
Top
Summary & Perspective

戸本 誠
名古屋大学

Top quark physics

- Heaviest particle in SM
  湯川結合～1, EWSBで特別な役割？, 新物理に感度？
- Short lifetime ~10^{-25}s, ハドロン化前に崩壊
  bare quarkの性質がわかる
- 生成や崩壊から豊富な物理

Top production
test QCD, test EW
Charge asymmetry
anomalous coupling
tt+X production
Resonance Production
top from new particle



Top properties
Mass, Width, Spin, Charge
Spin correlation, polarization

Top decay
test EW
W helicity
Wtb coupling
anomalous coupling
CP violation
FCNC
New particle from top

Major background for Higgs and searches

SM Top quark production @ LHC

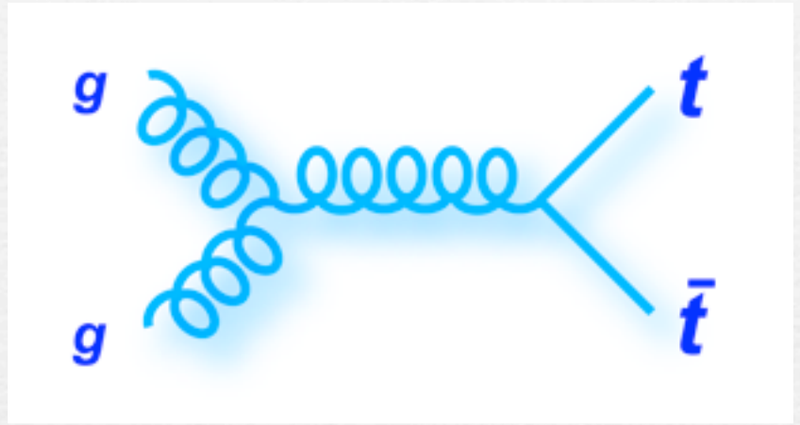
○ Top quark pair production via QCD

PRL 110 252004 (2013), arXiv:1303.6254

$$\sigma_{t\bar{t}} = 177.3^{+10.1}_{-10.8}\ \mathrm{pb} \quad \text{(7TeV)}$$

$$\sigma_{t\bar{t}} = 252.9^{+13.3}_{-14.5}\ \mathrm{pb} \quad \text{(8TeV)}$$

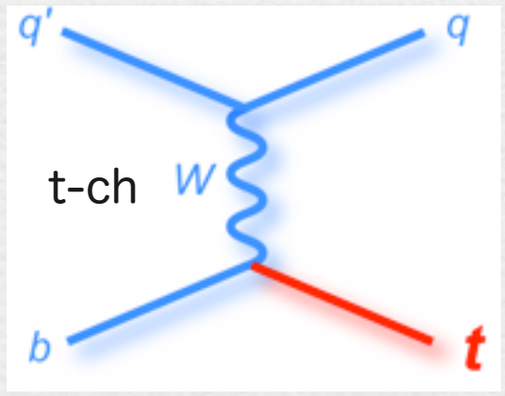
@NNLO+NNLL (m_t=172.5GeV) top++ 2.0

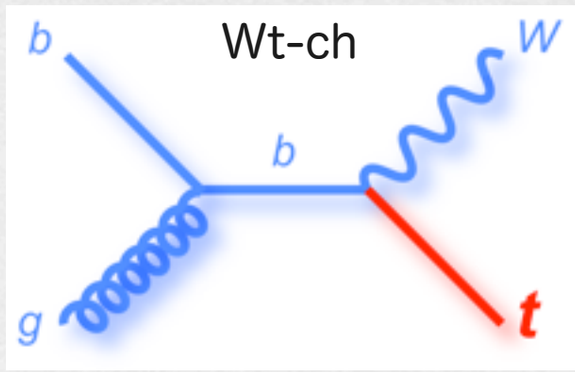


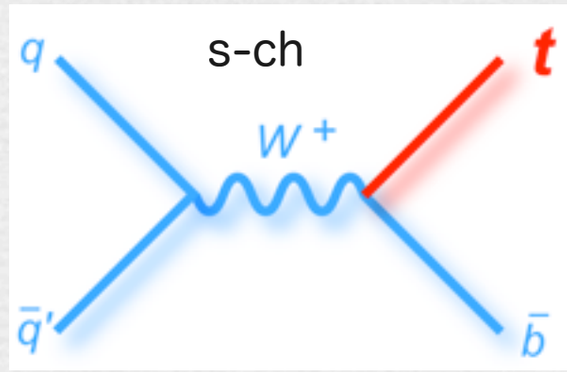
→ ~6.4M top quark pairs in LHC Run 1

○ Single top production via EW

Phys. Rev. D 83 (2011) 091503, arXiv:1103.2792 [hep-ph].
Phys. Rev. D 82 (2010) 054018, arXiv:1005.4451 [hep-ph].
Phys. Rev. D 81 (2010) 054028, arXiv:1001.5034 [hep-ph].







$$\sigma(\sqrt{s} = 7\mathrm{TeV}) = 64.6 \pm 2.4\ \mathrm{pb} \quad 15.7 \pm 1.1\ \mathrm{pb} \quad 4.6 \pm 0.2\ \mathrm{pb}$$

$$\sigma(\sqrt{s} = 8\mathrm{TeV}) = 87.8 \pm 3.4\ \mathrm{pb} \quad 22.4 \pm 1.5\ \mathrm{pb} \quad 5.6 \pm 0.2\ \mathrm{pb}$$

@NLO+NNLL (m_t=172.5GeV)

→ ~3M single tops in LHC Run 1

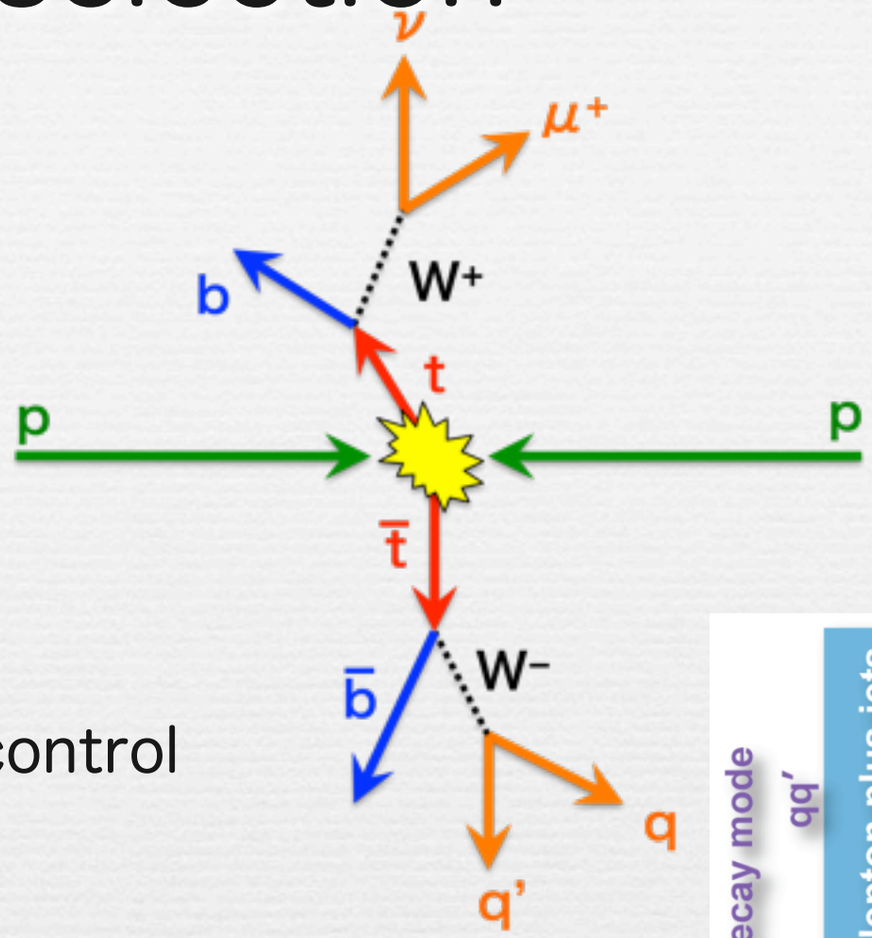
Event selection

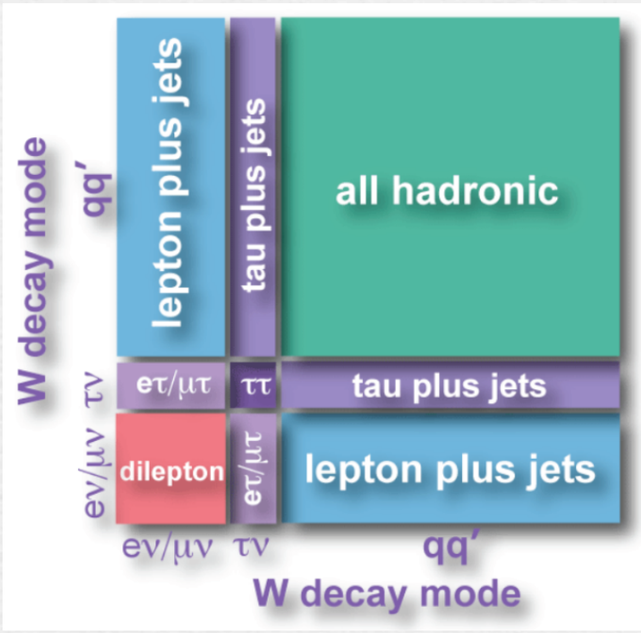
Top quark pair production

○ dilepton (11%)
- 2 isolated leptons
- Z mass veto (for ee, $\mu\mu$)
- ≧2 jets, at least one jet b-tagged

○ single lepton (43%)
- 1 isolated lepton
- E_T^{miss}, M_T(W)でmulti-jet, W+jetsをcontrol
- ≧4 jets, at least one jet b-tagged

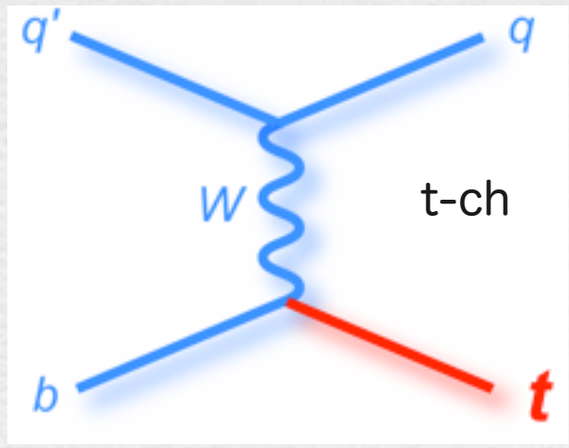
○ all-jets (46%)
- No isolated lepton
- ≧6 jets, 2 jets b-tagged
- Small E_T^{miss} significance, centrality





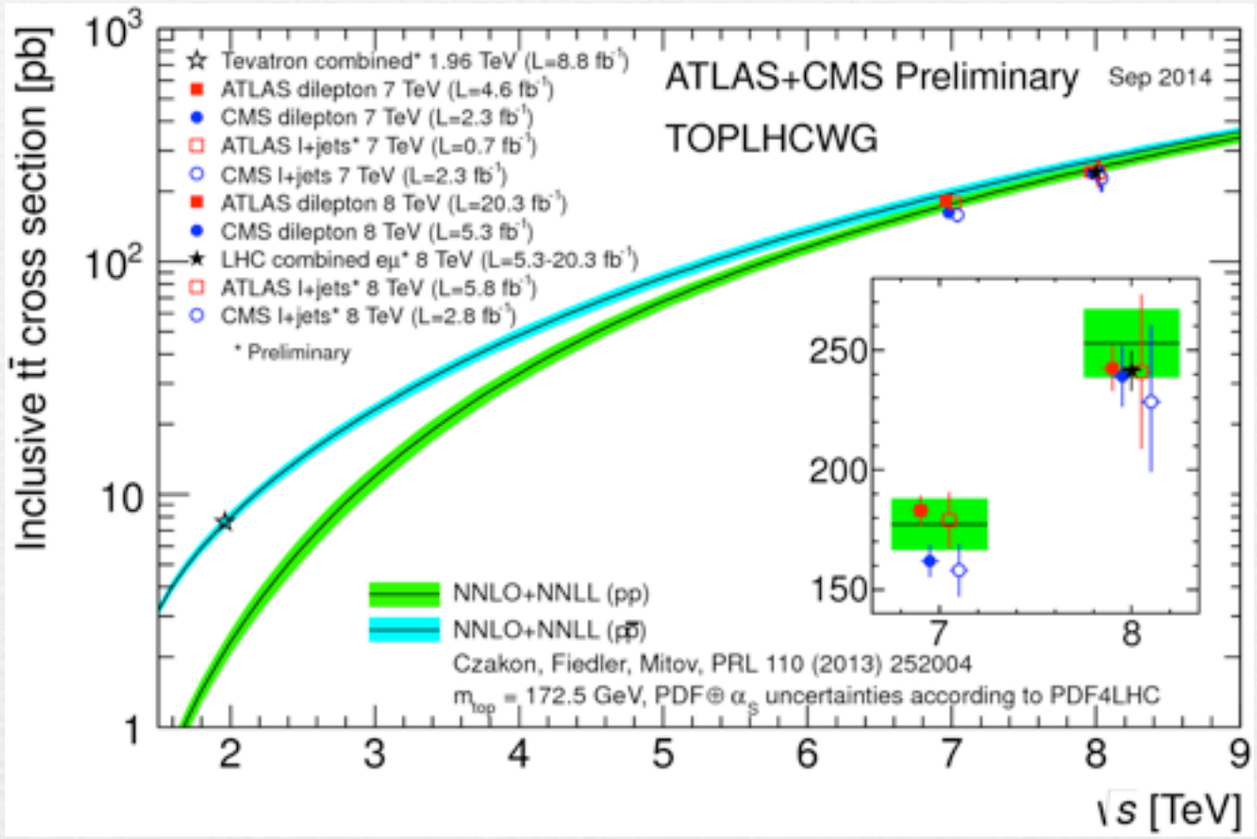
Single top production

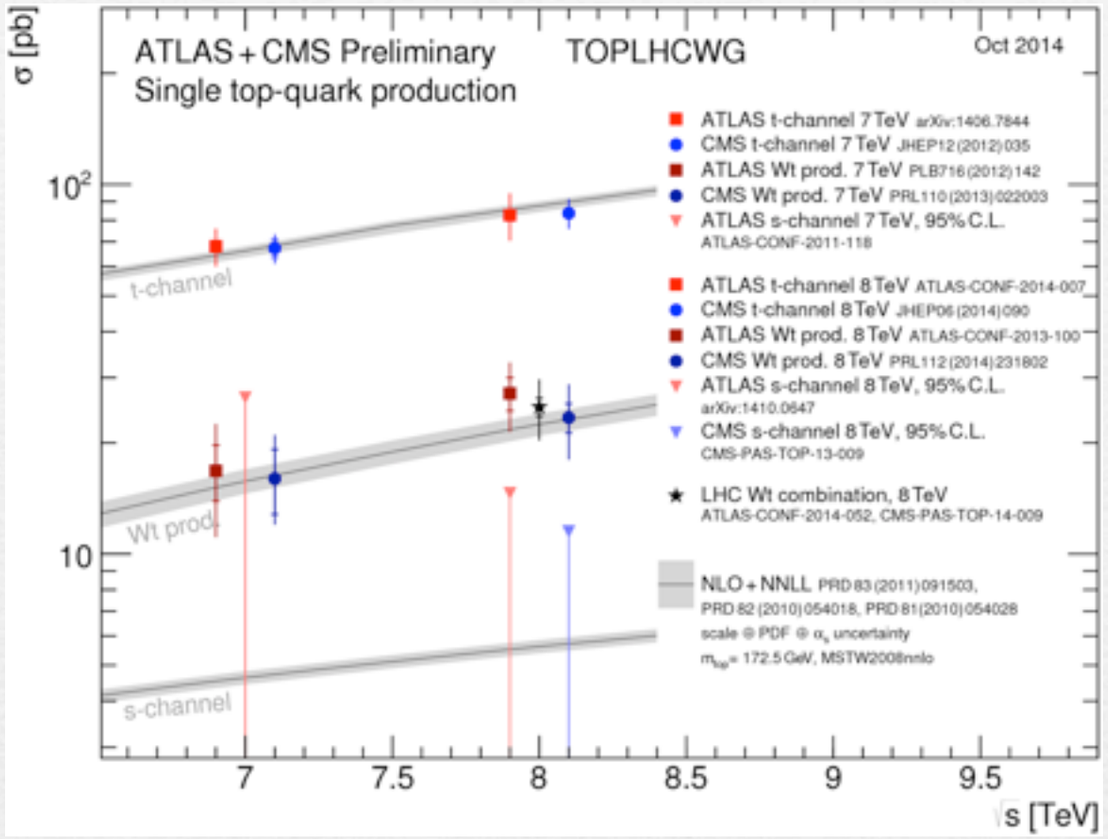
- 1 isolated lepton
- 2 jets, one is forward, the other is b-tagged
- large E_T^{miss}



b-tag: typically ε =70%,
rejection factor=130 (light quark), 5 (c-quark)

Inclusive cross-section measurement





$$\sigma_{t\bar{t}}(\sqrt{s} = 8\mathrm{TeV}) = 241.5 \pm 1.4 \pm 5.7 \pm 6.2\ \mathrm{pb} \rightarrow 3.5\%\ !!$$

Top physicsは摂動QCDやEWの精密検証へと移行

- Differential cross-section
- Top quark properties (Mass, charge, spin, helicity...)
- topの生成と崩壊に現れる新粒子探索

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

CMS : https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

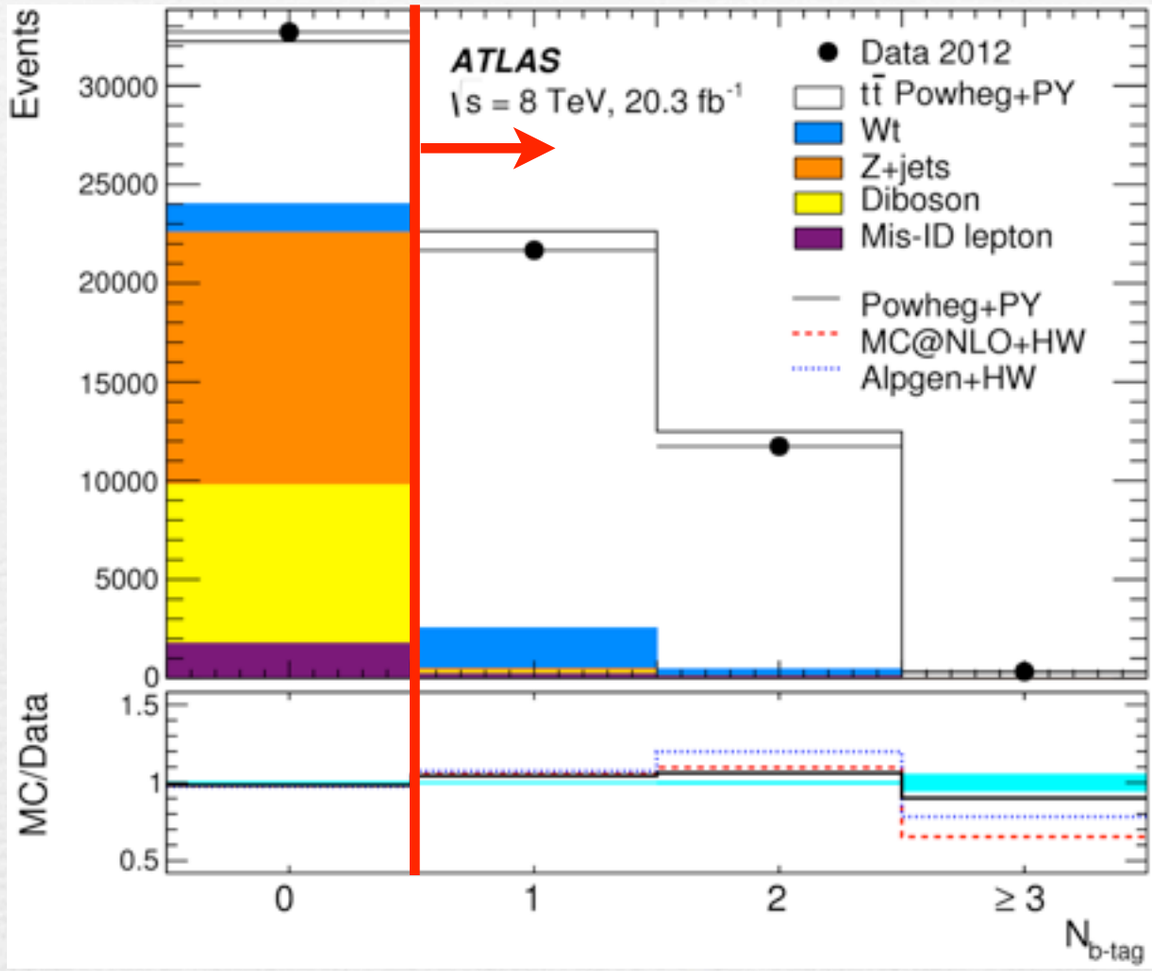
最高精度の断面積測定

Eur.Phys.J. C74 (2014) 3109, arXiv:1406.5375

○ 事象選別

opposite sign e+μ

≧1 b-tagged jet



○ 測定手法

σ ttとb-tag rateの同時測定

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

$$N_2 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} C_b {\epsilon_b}^2 + N_2^{\mathrm{bkg}}$$

C_b:tagging correlation coefficient

L: luminosity

○ 結果

$$\sigma_{t\bar{t}}(\sqrt{s} = 7\mathrm{TeV}) = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3\ \mathrm{pb}$$

$$\sigma_{t\bar{t}}(\sqrt{s} = 8\mathrm{TeV}) = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2\ \mathrm{pb}$$

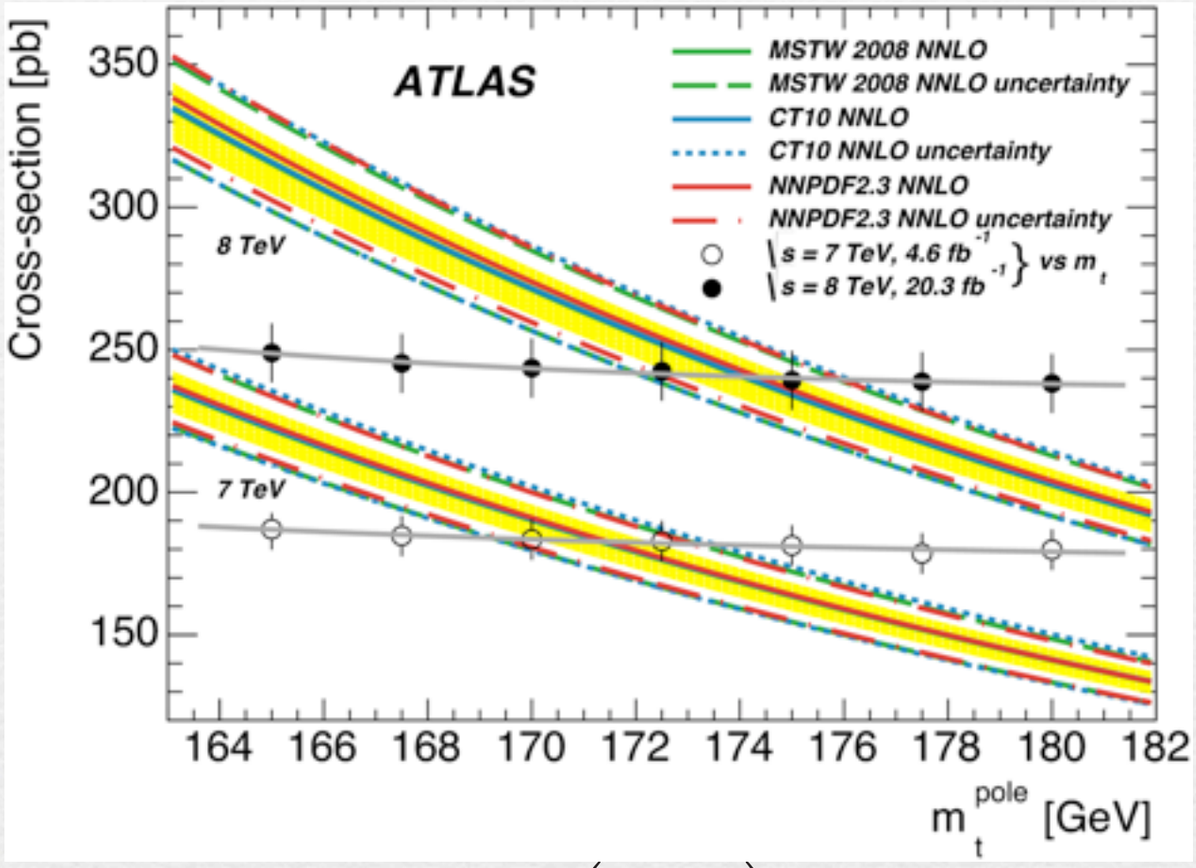
(stat) (syst) (lumi) (E_{beam})

単独実験で最も感度の良い実験 (4.3%)

断面積の精密測定から様々な測定へ

Eur.Phys.J. C74 (2014) 3109, arXiv:1406.5375

○ pole mass 測定



$$\sigma_{t\bar{t}}^{\mathrm{theo}}(m_t^{\mathrm{pole}}) = \sigma(m_t^{\mathrm{ref}}) \left(\frac{m_t^{\mathrm{ref}}}{m_t^{\mathrm{pole}}} \right) (1 + a_1 x + a_2 x^2)$$

$$x = (m_t^{\mathrm{pole}} - m_t^{\mathrm{ref}})/m_t^{\mathrm{ref}} \quad m_t^{\mathrm{ref}} = 172.5 \text{ GeV}$$

$$m_t^{\mathrm{pole}} = 171.4 \pm 2.6 \text{ GeV} \quad \text{(7TeV)}$$

$$m_t^{\mathrm{pole}} = 174.1 \pm 2.6 \text{ GeV} \quad \text{(8TeV)}$$

$$m_t^{\mathrm{pole}} = 172.9^{+2.6}_{-2.6} \text{ GeV} \quad \text{(combine)}$$

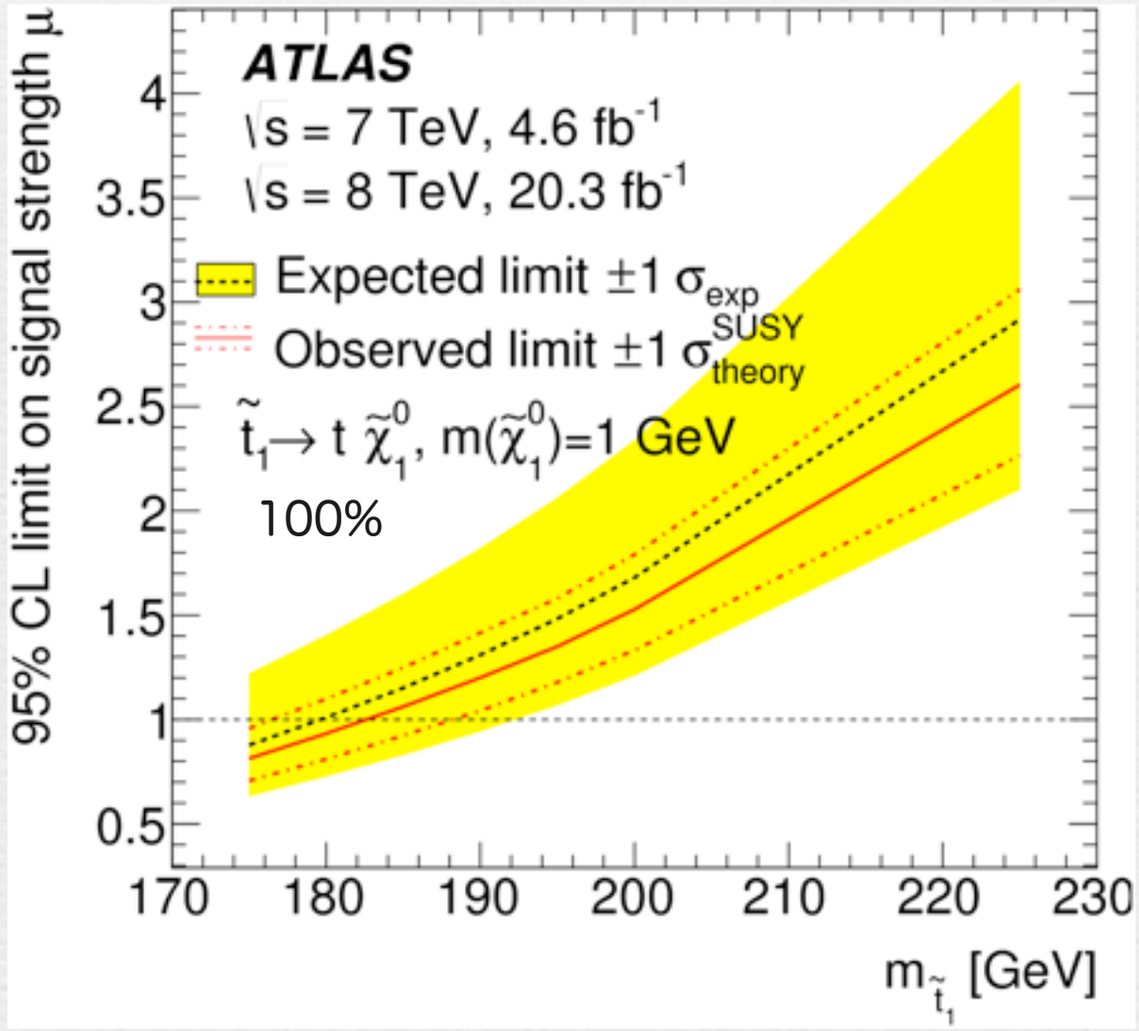
○ stop 探索

$$pp \to \tilde{t}_1 \bar{\tilde{t}}_1 \to t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$$

$$(m_{\tilde{t}_1} > m_t + m_{\tilde{\chi}_1^0})$$

$$\sigma_{\tilde{t}_1\tilde{t}_1} = 40 \text{ pb} \sim 20 \text{ pb}$$

$$(m_{\tilde{t}} = 175 \text{ GeV} \to 200 \text{ GeV})$$



$m_t < m_{\tilde{t}} < 177\mathrm{GeV}$ excluded (95%CL)

Differential cross-section

○ Njet, p_T(top), p_T(ttbar), m(ttbar), y(ttbar)...の依存性

reconstructed object → parton levelにunfoldして実験と理論を比較

摂動QCD計算のtestとして重要

○ New approach : pseudo-top quark ATLAS-CONF-2014-059

- reconstructed object → particle levelにunfoldして実験と理論を比較
- reconstructed → parton-levelへの大きな外挿を避け、model依存による不定性を軽減
- single lepton analysis @ √s=7TeV

leptonic top

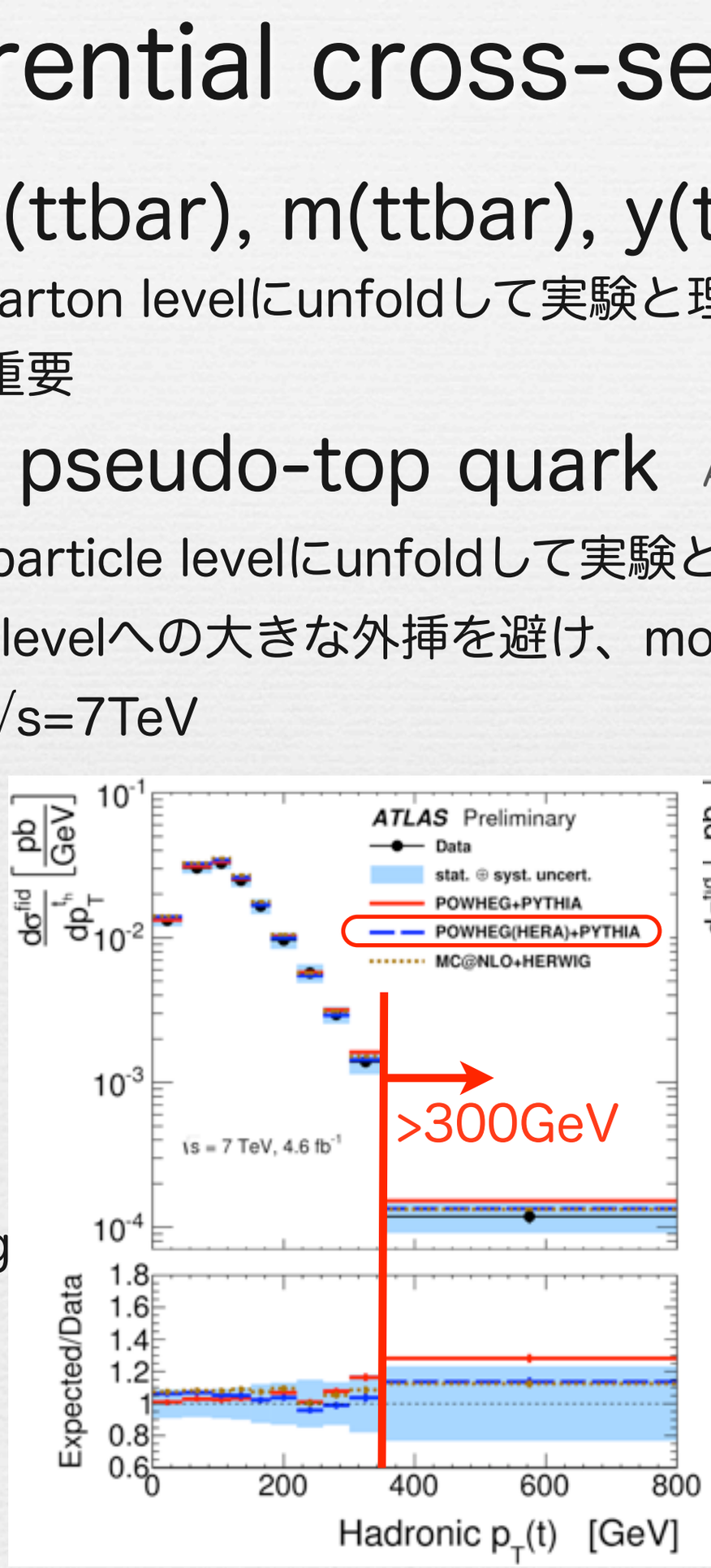
b-jet, lepton, E_T^{miss}

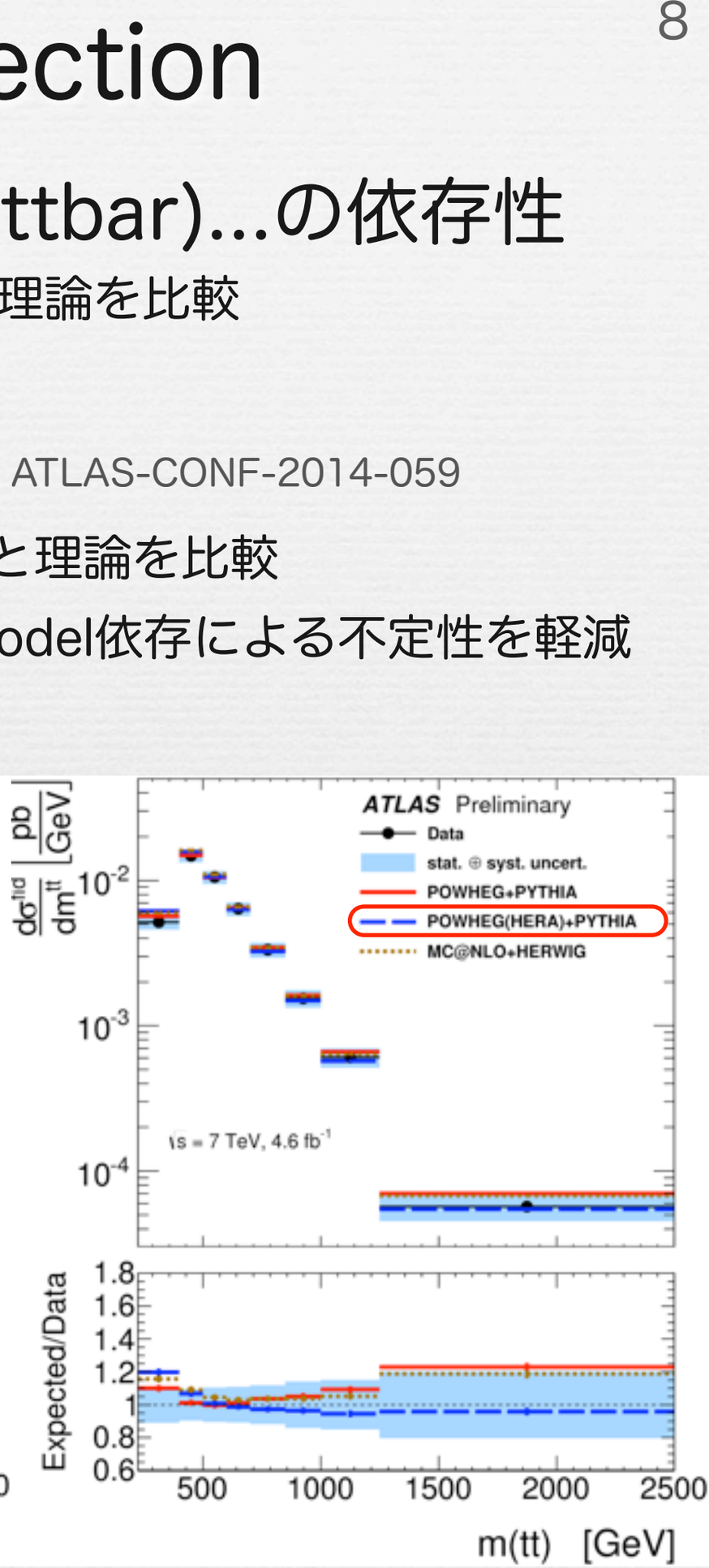
(p_z^{ν} from W constraint)

hadronic top

b-jet, 2 highest pT jets

iterative Bayesian unfolding to particle level





Differential cross-section with boosted top

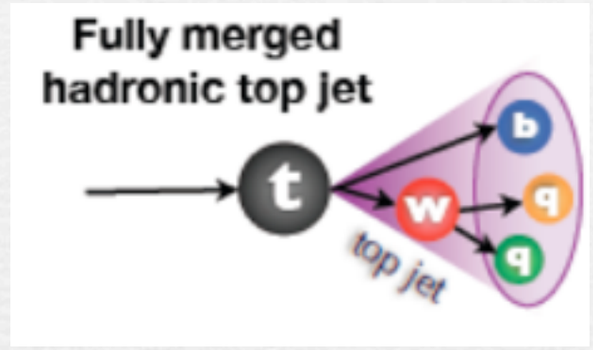
ATLAS-CONF-2014-057

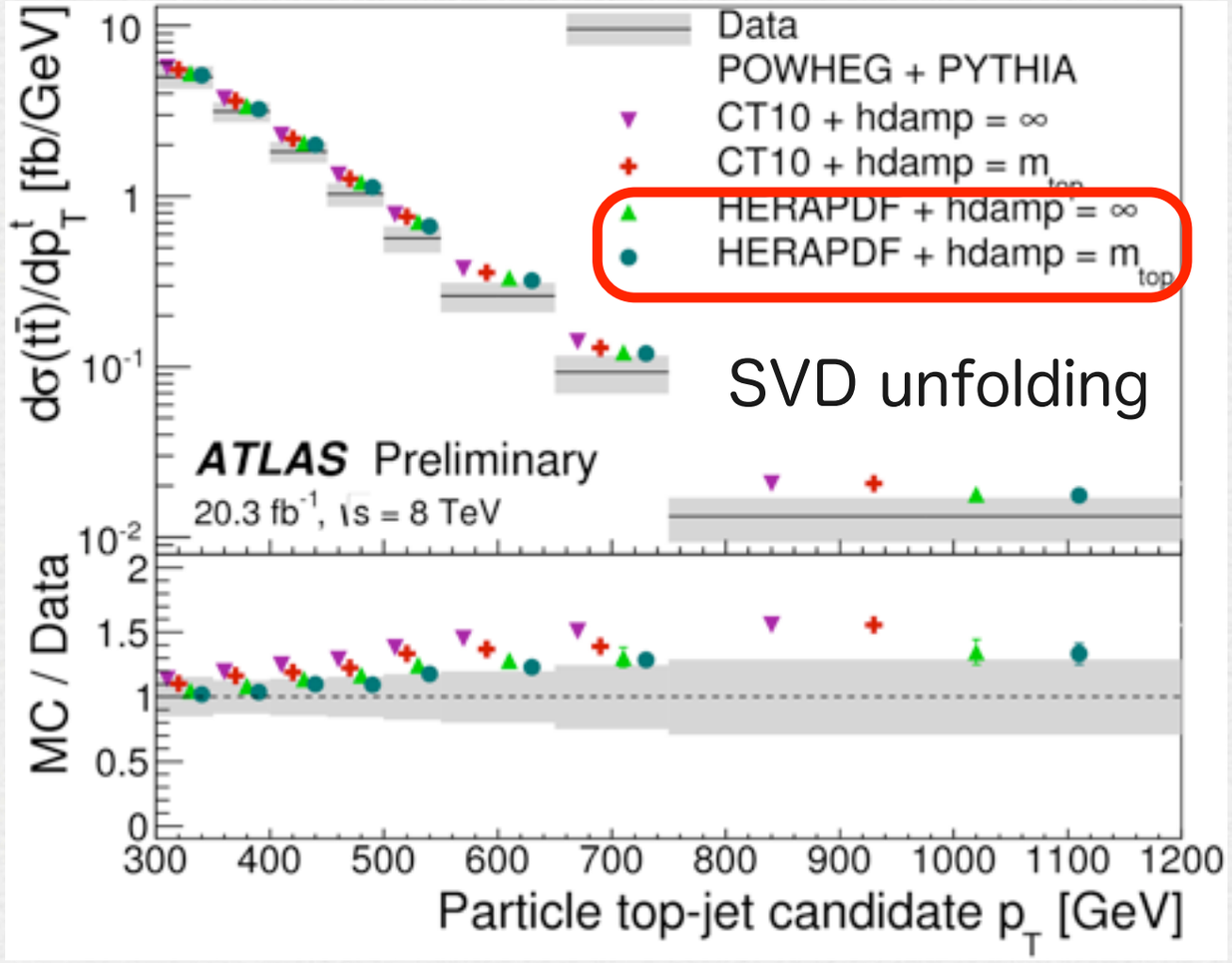
- ○ hadronic topのpT(p_T>300GeV)の関数で断面積測定
- ○ Boosted top の事象選別によりhigh pTまで感度

hadronic top : anti-kt jet with R=1.0, jet mass>100GeV

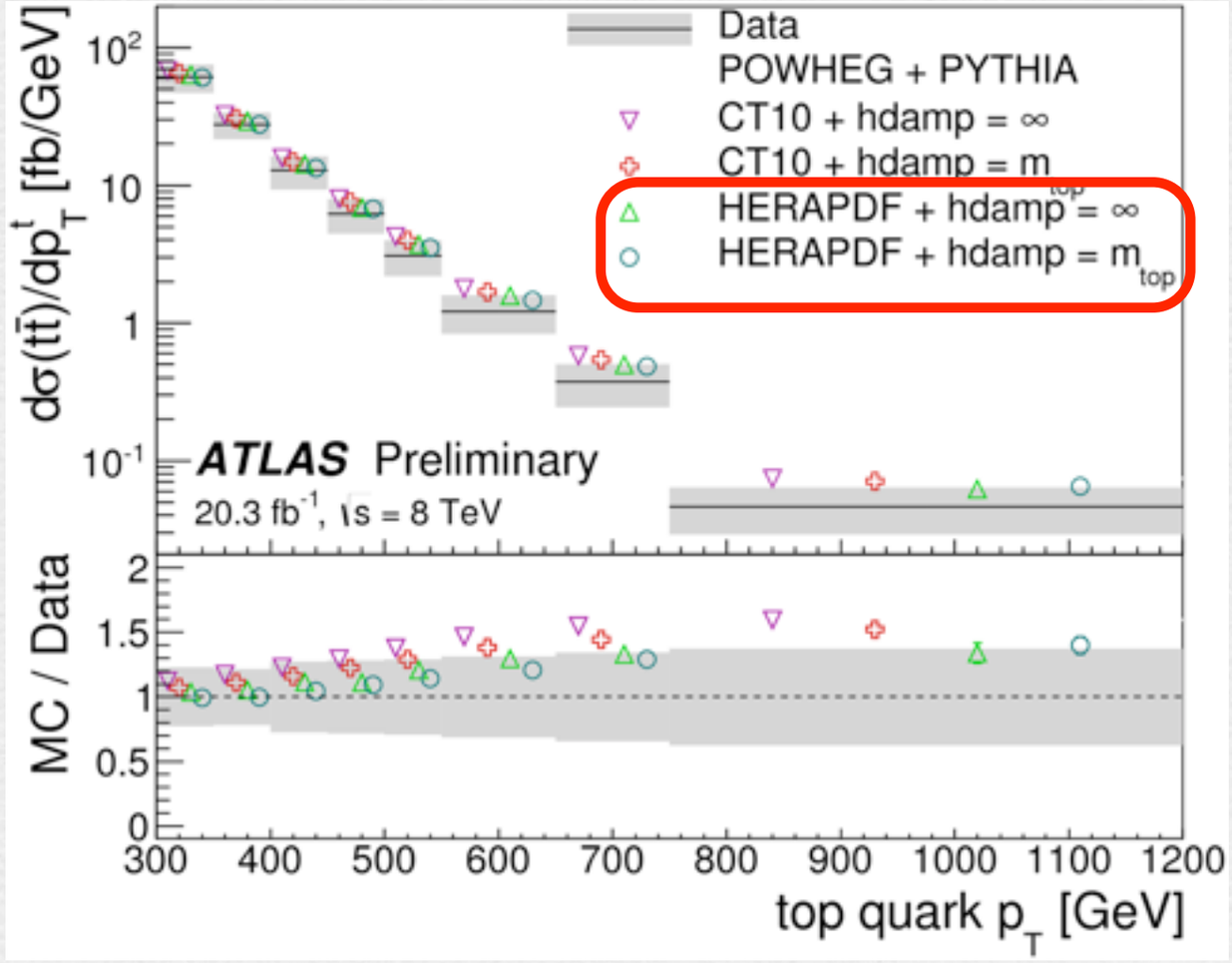
leptonic top : b-jet, 1 isolated lepton, large E_T^{miss}

parton levelにunfold





SVD unfolding



Top mass : Standard method

ATLAS-CONF-2014-046
ATLAS-CONF-2013-077
ATLAS-CONF-2012-082
etc.

○ Template methods

Kinematic likelihood fitでttbar事象を再構成

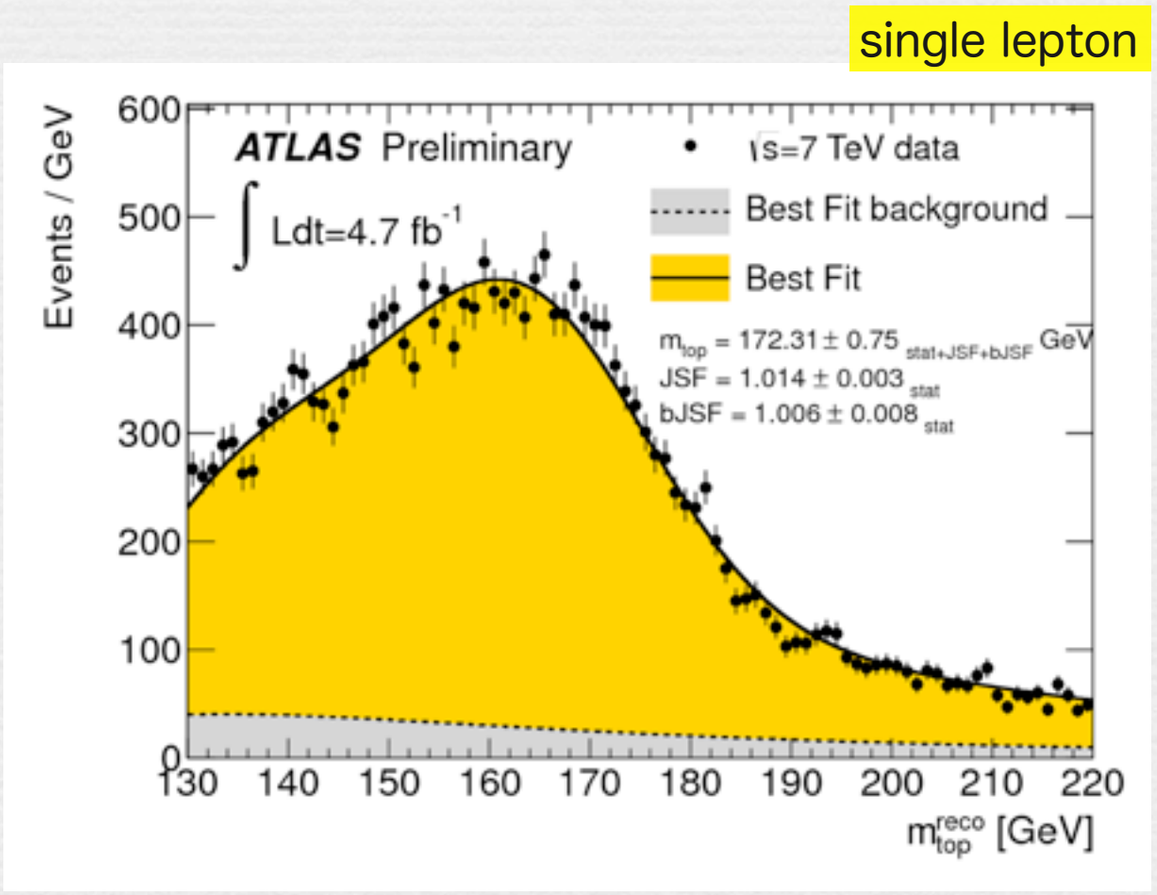
dilepton : 2 leptons, 2 b-jets→m_{lb}

single lepton : lepton, E_T^{miss}, 2 b-jets, 2 light-jets→m_{top}^{reco}

m_{top}^{reco}, m_W^{reco}, m_{lb}分布からmt, JSF, bJSFを同時決定

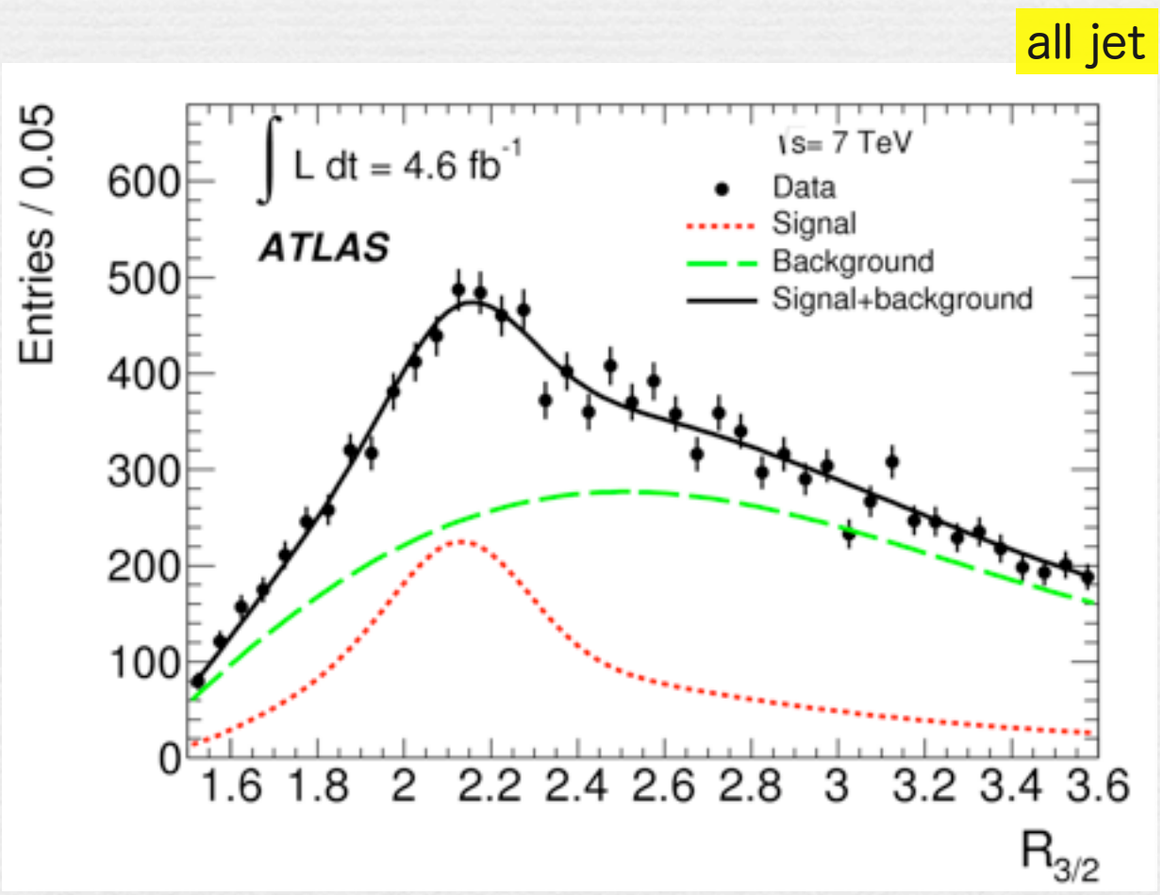
all jets : 2 b-jets, 4 light-jets→m_{jjj}/m_{jj}

single lepton



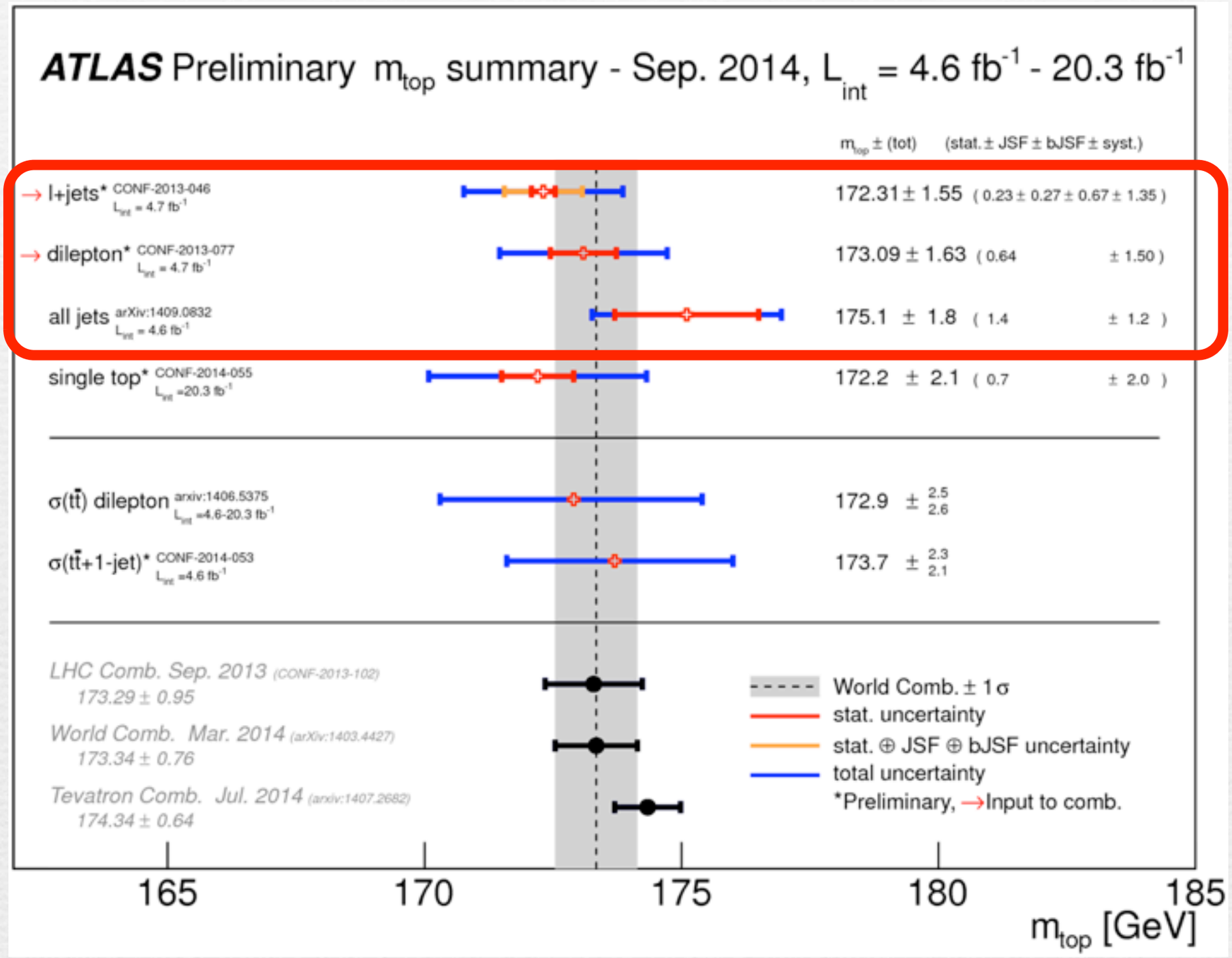
$m_t = 172.31 \pm 1.55$ GeV

all jet



$m_t = 175.1 \pm 1.8$ GeV

Standard Methodによる質量測定のまとめ



$$m_t = 173.29 \pm 0.95 \text{ GeV}$$ (LHC Comb.) 0.5%

ATLAS-CONF-2013-102

$$m_t = 173.34 \pm 0.76 \text{ GeV}$$ (World Comb.) 0.4%

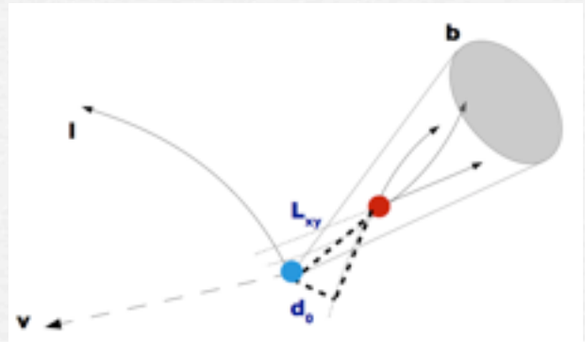
arXiv:14034427

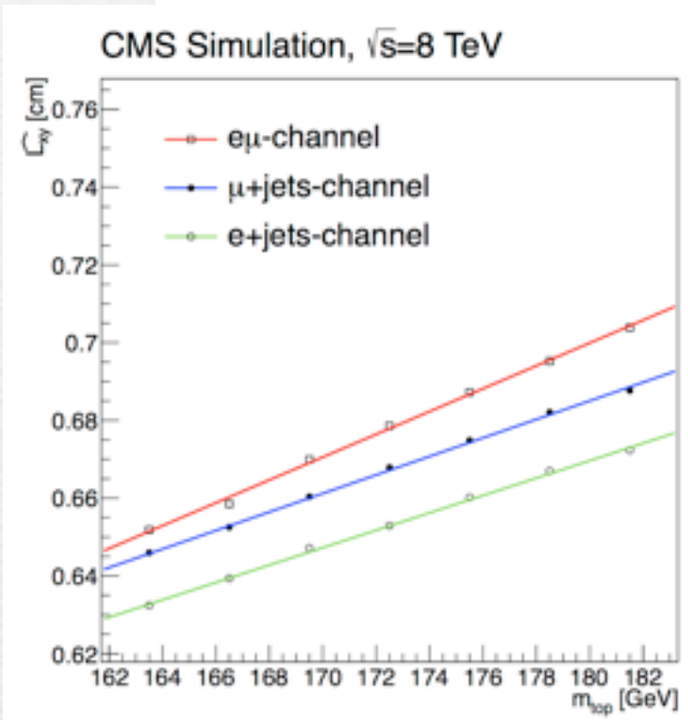
Top mass : Other methods

○ B-hadron Lifetime CMS-PAS-TOP-12-030

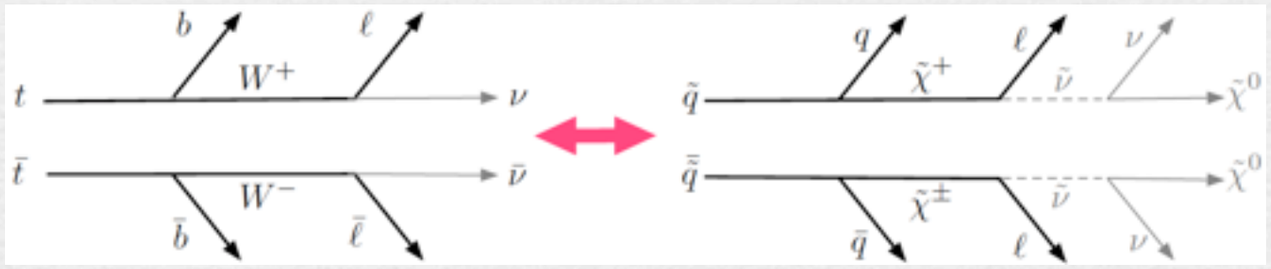
$$L_{xy} = \gamma_b \beta_B \tau_B \simeq 0.4 \cdot \frac{m_t}{m_B} \beta_B \tau_B \quad < L_{xy} > \sim 7 \text{ mm}$$

$$m_t = 173.5 \pm 1.5_{\text{stat}} \pm 1.3_{\text{syst}} \pm 2.6_{p_T(t)} \text{ GeV}$$





○ Kinematic Endpoint Eur.Phys.J.C(2013)73:2494

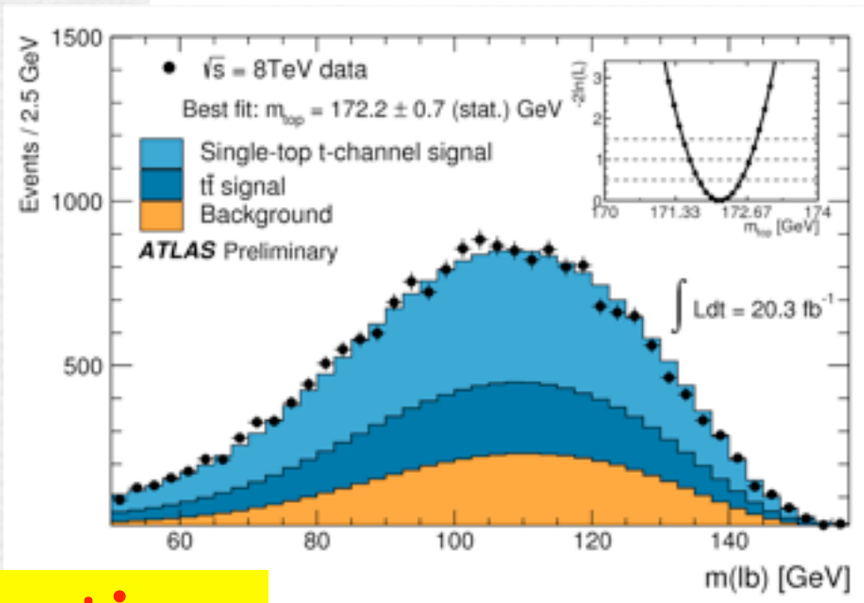


$$m_t = 173.9 \pm 0.9(\text{stat})^{+1.7}_{-2.1}(\text{syst}) \text{ GeV}$$

○ t-channel single top ATLAS-CONF-2014-055

Template fit of lepton-b-jet mass

$$m_t = 172.2 \pm 0.7(\text{stat}) \pm 2.0(\text{syst}) \text{ GeV}$$



→ Standard methodと異なるSystematics

Top mass : pole mass with ttbar+1 jet

ATLAS-CONF-2014-053

○ Differential cross sectionによる間接的なpole mass測定

Eur. Phys. J C73 (2013) 2438, arXiv:1303.6415 [hep-ph]にて紹介

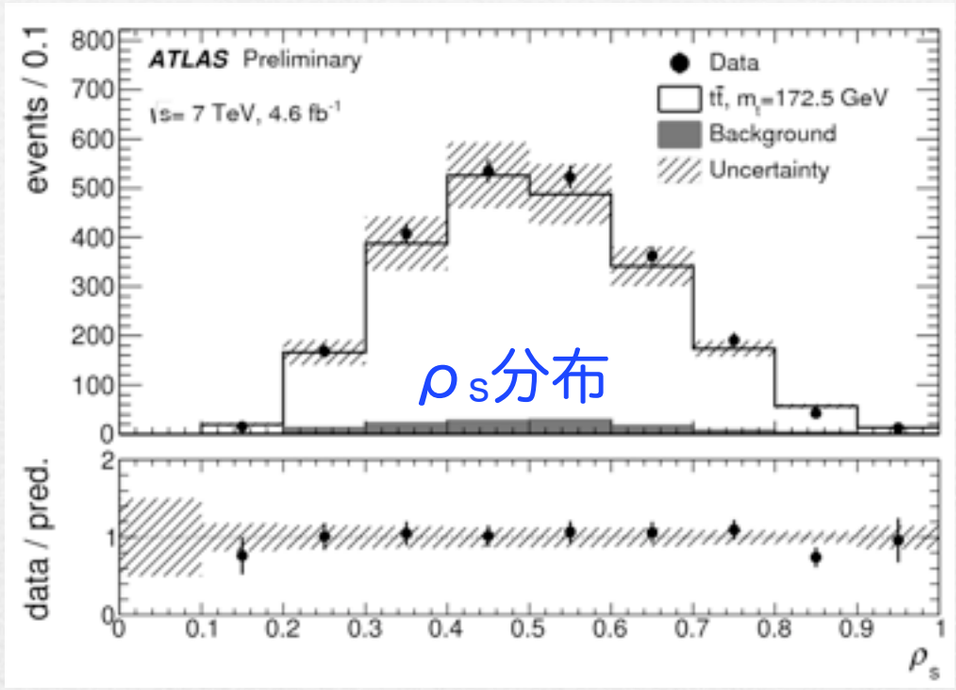
$$\mathcal{R}(m_t^{pole}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\mathrm{jet}}} \frac{d\sigma_{t\bar{t}+1\mathrm{jet}}}{d\rho_s}(m_t^{pole}, \rho_s)$$

$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}} \qquad m_0 = 170\ \mathrm{GeV}\ (\mathrm{m_t位の任意量})$$

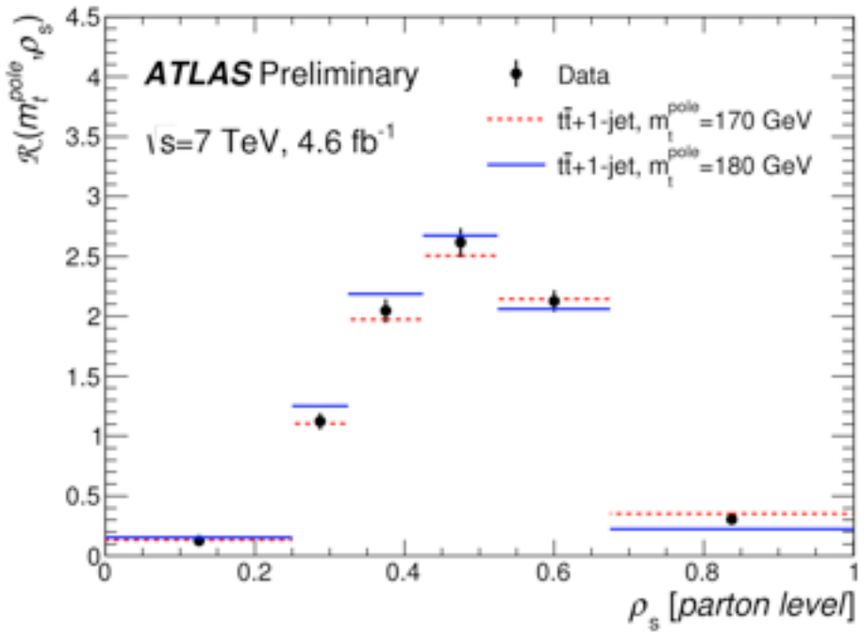
○ single lepton終状態による解析

- lepton, E_T^{miss}からleptonic topのWを再構成
- WのKinematics条件からhadronic top の2jetを選択
- $m_t^{\mathrm{lep}} - m_t^{\mathrm{had}}$ が最小となるb-jetとWの組を決定
- ttbar以外のjetは、pT>50GeVのleading jet
- ρ_s分布をunfoldしてχ^2 fitで質量を決定

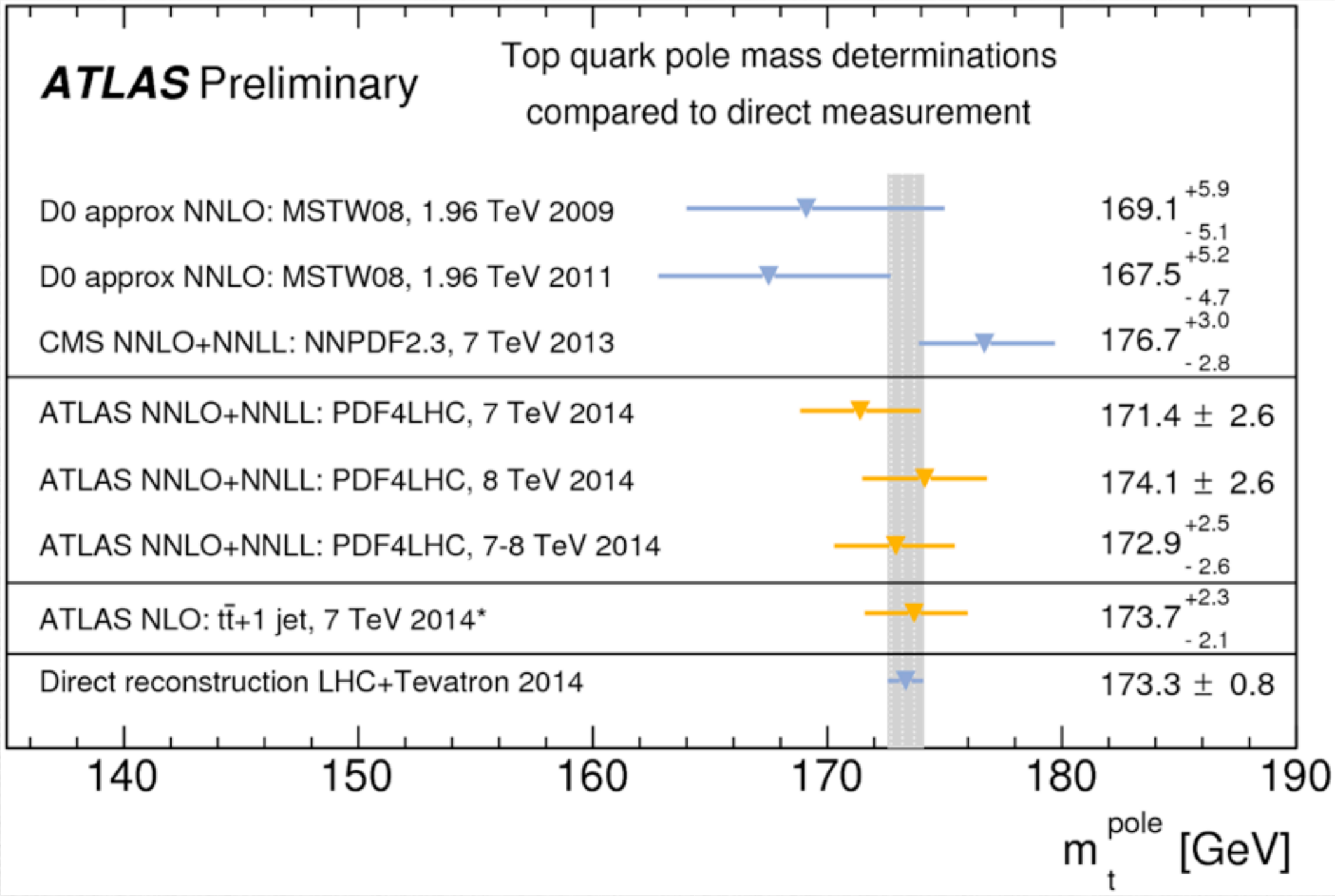
$$m_t^{\mathrm{pole}} = 173.7 \pm 1.5(\mathrm{stat.}) \pm 1.4(\mathrm{syst.})\ ^{+1.0}_{-0.5}(\mathrm{theo.})\ \mathrm{GeV}$$



↓ unfoldしてR(mt, ρ)に



Top mass : pole mass測定のまとめ



Top quark properties

○ Top quark charge JHEP11(2013)031

$$q_t = 0.64 \pm 0.02 \pm 0.08$$

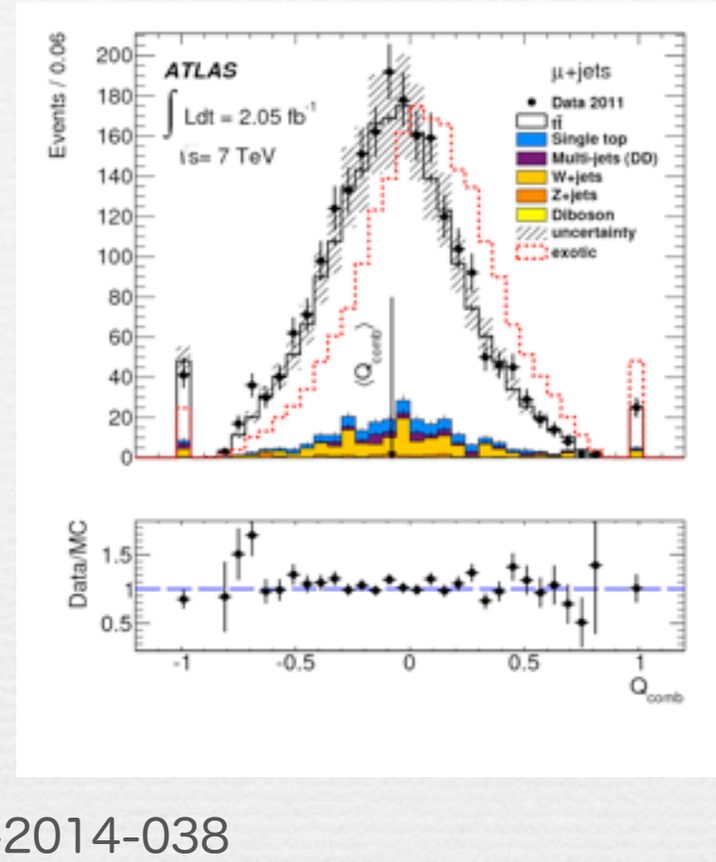
○ W polarization in top quark decay

JHEP06(2012)088 JHEP10(2013)167 arXiv:1410.1154

○ CP violation in single top

ATLAS-CONF-2013-032

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



○ Top polarization Phys. Rev. Lett 111, 232002 (2013)

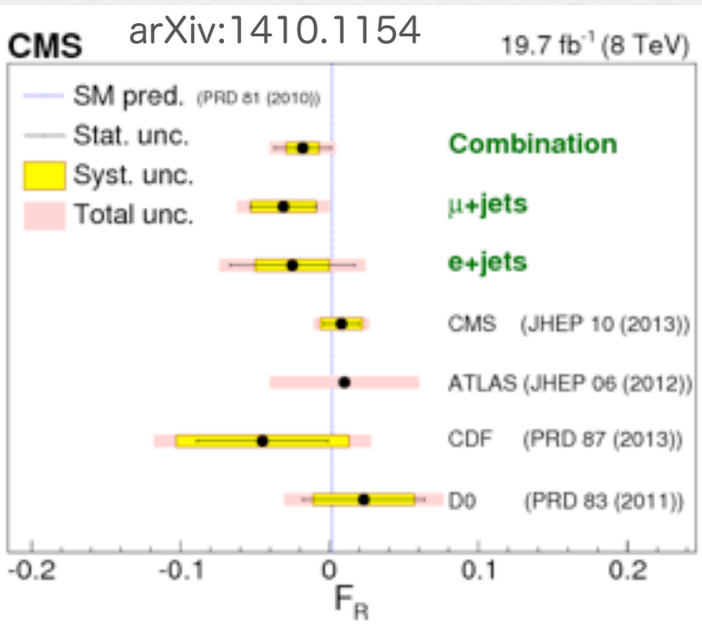
○ Evidence for associated production with W/Z ATLAS-CONF-2014-038

○ FCNC searches

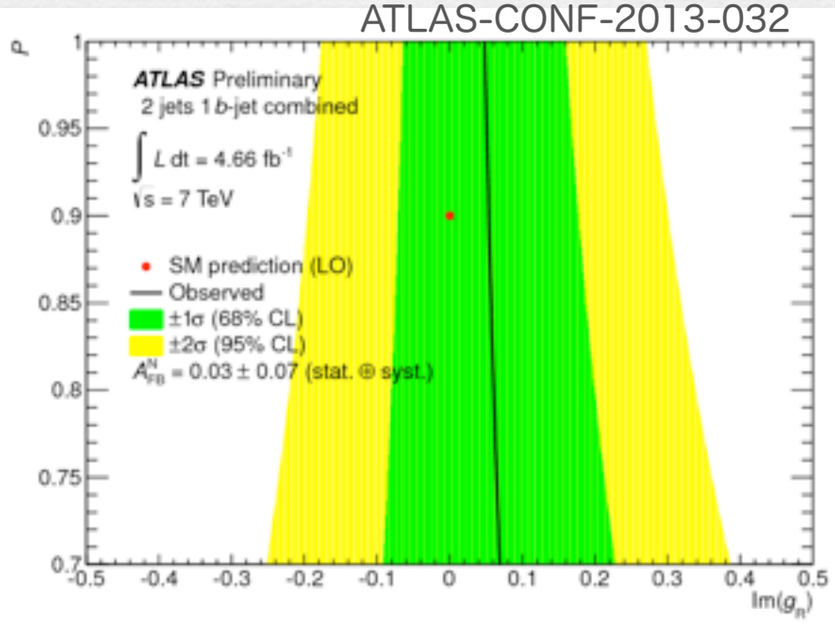
JHEP1209(2012)139 ATLAS-CONF-2013-063 CMS-PAS-TOP-14-003 PRL 112 (2014) 171802

$$\mathcal{B}(t \to Zq) < 0.05\% \quad \mathcal{B}(t \to u\gamma) < 0.0161\% \quad \mathcal{B}(t \to ug) < 0.0031\%$$

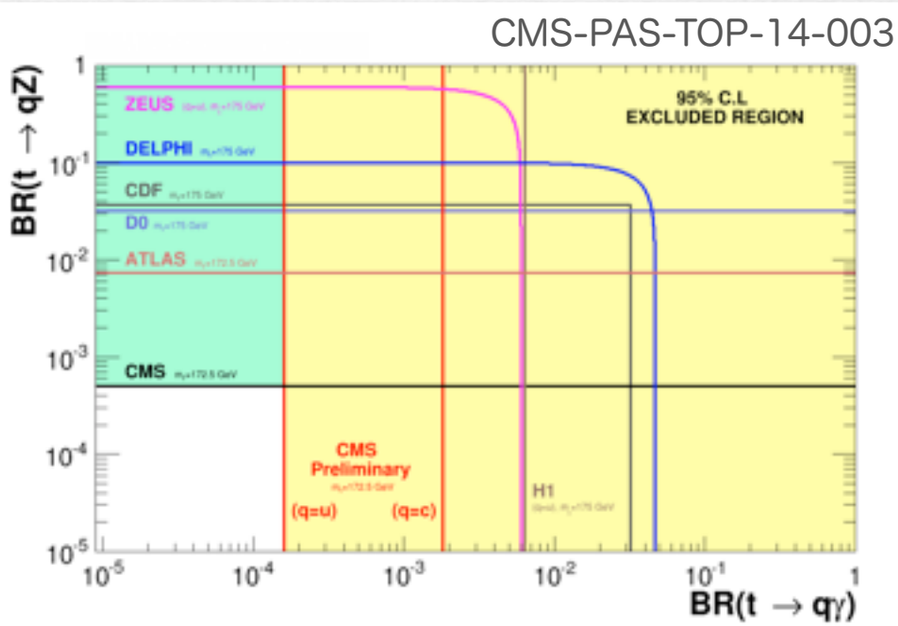
arXiv:1410.1154



ATLAS-CONF-2013-032



CMS-PAS-TOP-14-003



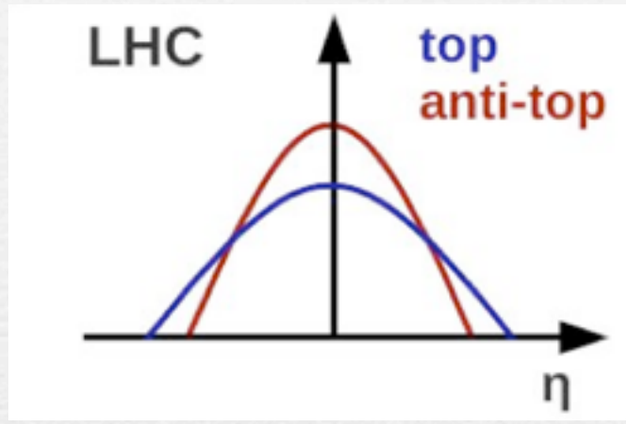
Top charge asymmetry

○ Charge asymmetry using √s=7TeV data

Charge asymmetry from |Δy| spectrum in single lepton events

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

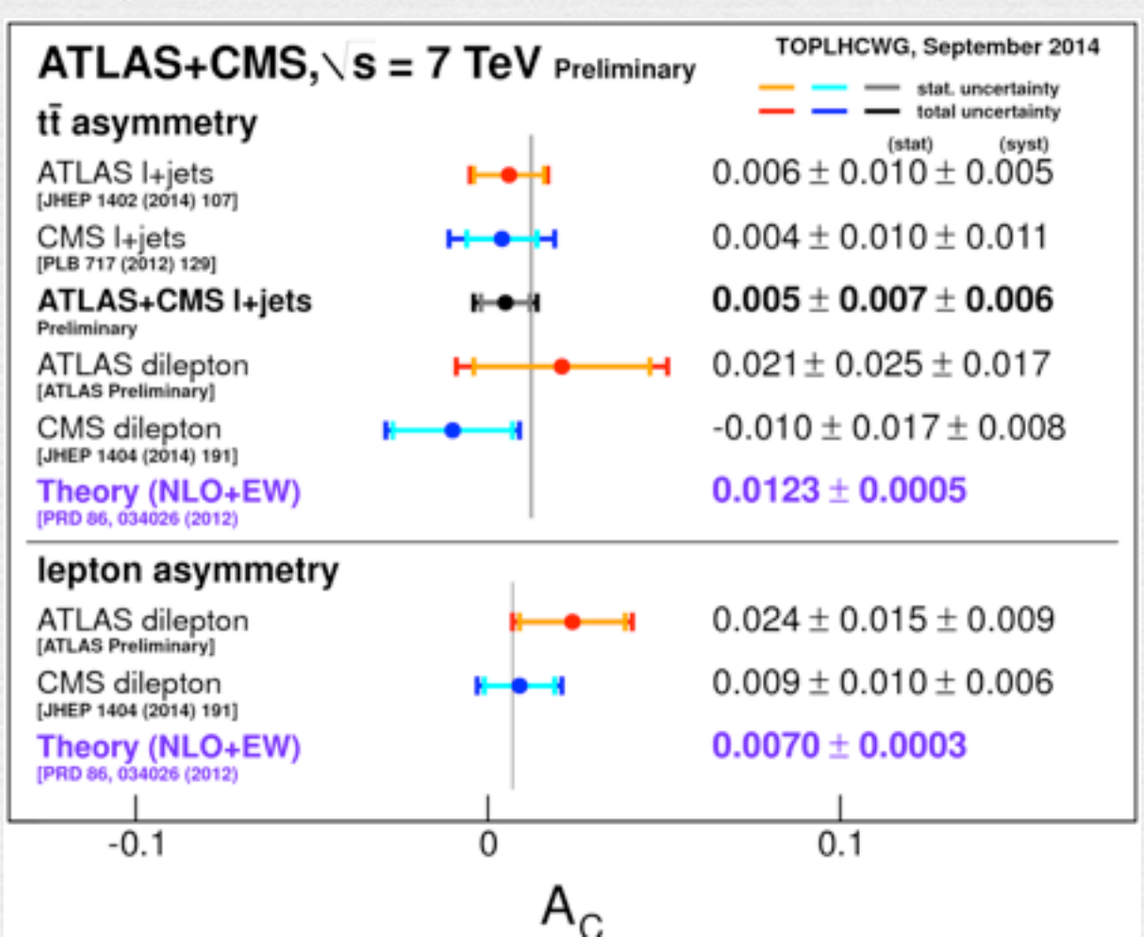
$$A_C^{\mathrm{SM}} = 0.006 \pm 0.010 \pm 0.005 \qquad A_C^{\mathrm{SM}} = 0.0123 \pm 0.0005$$

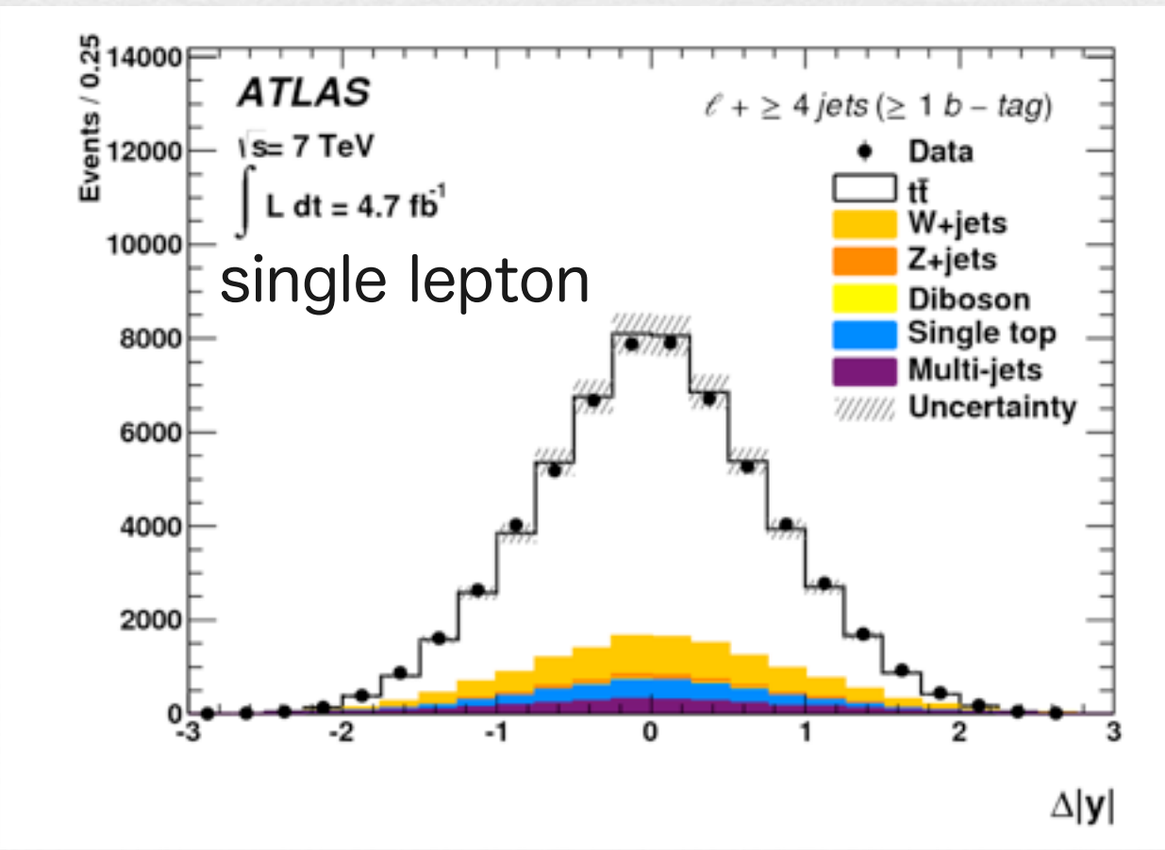


lepton-based charge asymmetry in dilepton events

$$A_C^{\ell\ell} = \frac{N(\Delta|\eta| > 0) - N(\Delta|\eta| < 0)}{N(\Delta|\eta| > 0) + N(\Delta|\eta| < 0)} \qquad \Delta|\eta| = |\eta_{\ell^+}| - |\eta_{\ell^-}|$$

$$A_C^{\ell\ell} = 0.024 \pm 0.015 \pm 0.009 \qquad A_C^{\ell\ell} = 0.0070 \pm 0.0003 \ \text{(SM)}$$





Top spin correlation in dilepton channel

Double differential distribution

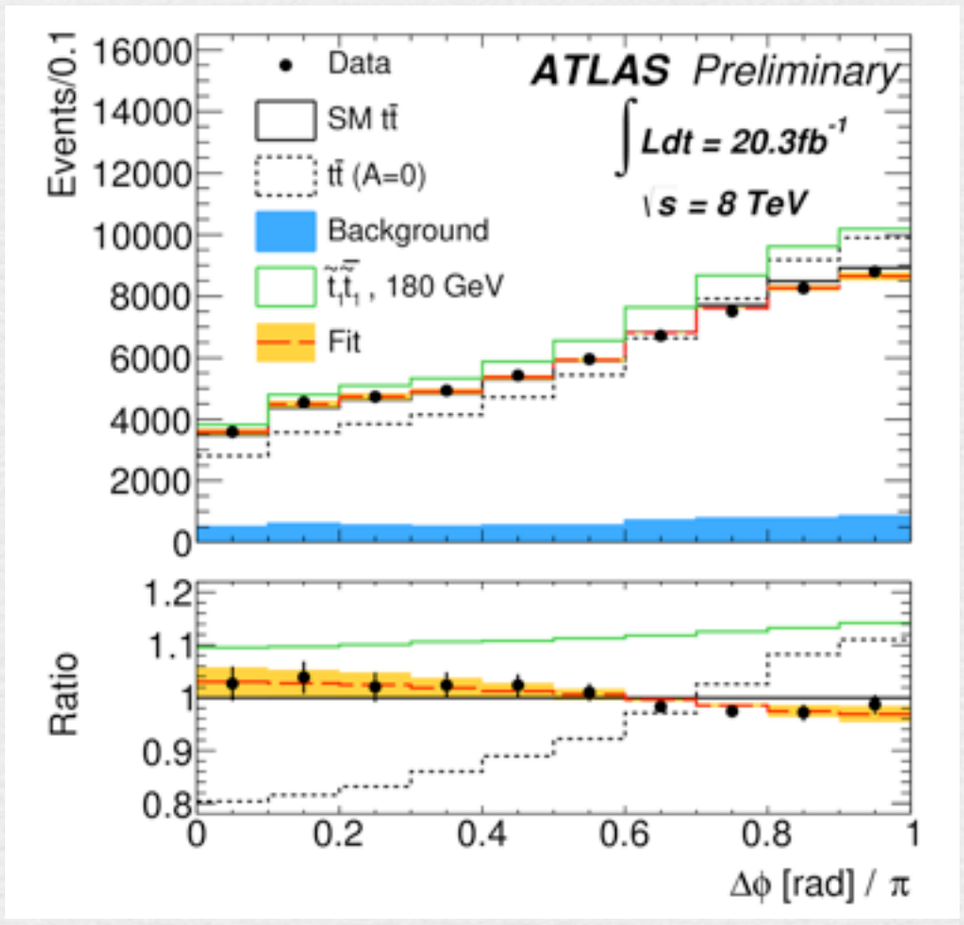
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1+\alpha_1 P_1\cos\theta_1 + \alpha_2 P_2\cos\theta_2 - C\cos\theta_1\cos\theta_2)$$

$\theta_1(\theta_2)$:t(tbar)から崩壊した粒子の角度分布

SM：unpolarized $\rightarrow \alpha P\cos\theta$ はnegligible

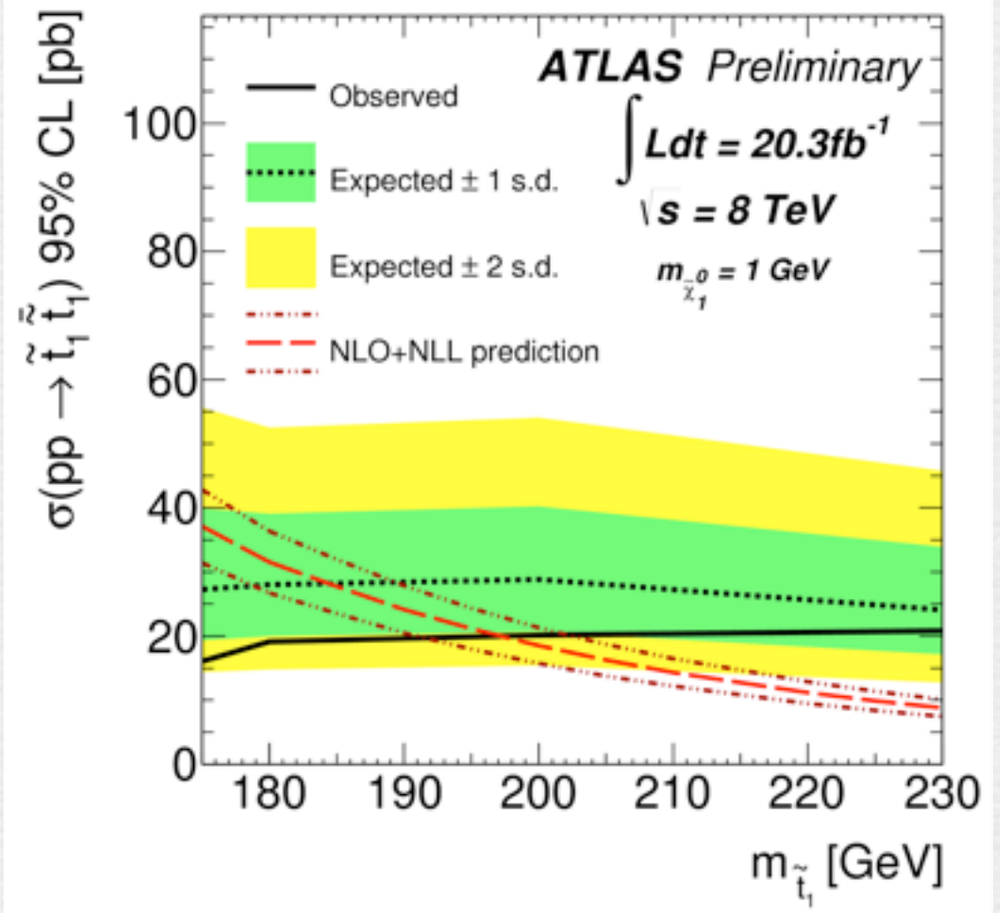
tのスピンはtbarのスピンと相関$\rightarrow \Delta\phi_{ll}$で測定する

$f_{SM}\times \mathrm{MC}^{SM}_{t\bar{t}} + (1.-f_{SM})\times \mathrm{MC}^{\mathrm{uncorr}}_{t\bar{t}}$ でfit



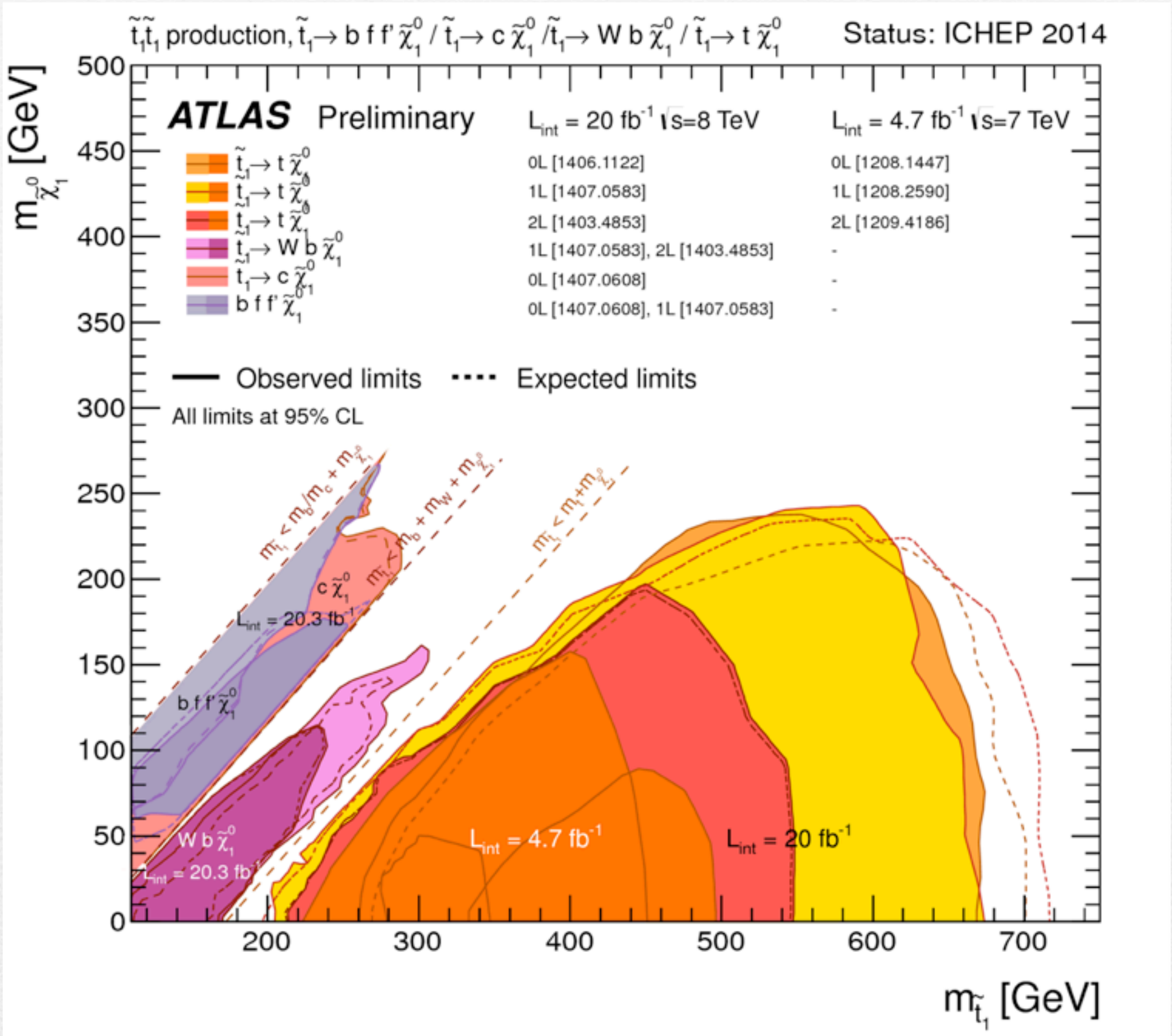
$f_{SM} = 1.20 \pm 0.05(\mathrm{stat.}) \pm 0.13(\mathrm{syst.})$

$pp \rightarrow \tilde{t_1}\bar{\tilde{t_1}} \rightarrow t\bar{t}\tilde{\chi}^0_1\tilde{\chi}^0_1 \ \ (m_{\tilde{t}_1} > m_t + m_{\tilde{\chi}^0_1})$



$m_t < m_{\tilde{t}} < 191\mathrm{GeV}$ excluded (95%CL)

stop exclusion from top quark physics



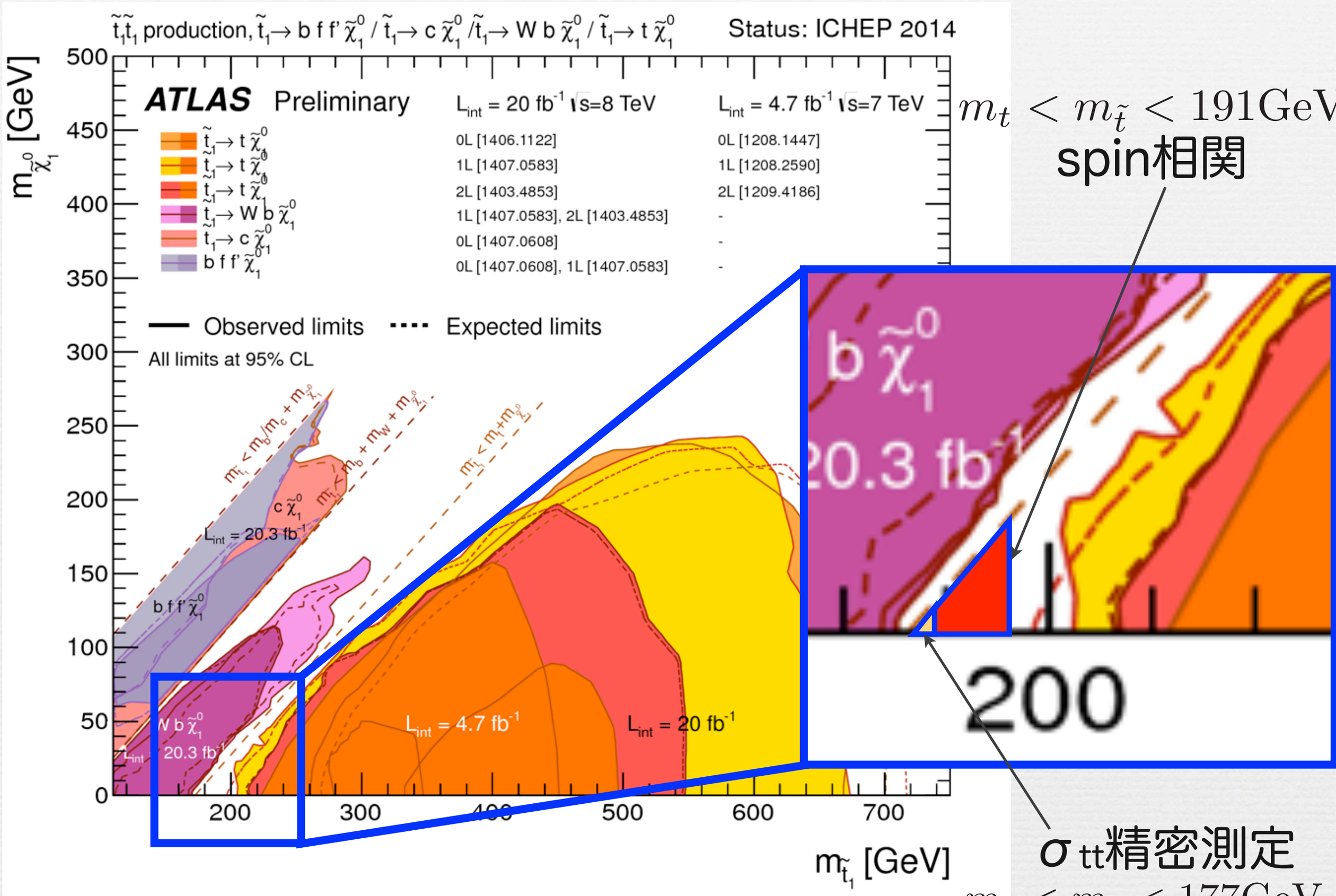
stop exclusion from top quark physics

$m_t < m_{\tilde{t}} < 191\mathrm{GeV}$

spin相関

$m_t < m_{\tilde{t}} < 177\mathrm{GeV}$

σ tt精密測定



Run2とそれ以降に向けて： perspective

○ √s=13~14TeVのbenefit

$\sigma_{t\bar{t}} = 831.8^{+40.2}_{-45.6}$ pb (13TeV)　　$\sigma_{t\bar{t}} = 984.5^{+47.4}_{-53.9}$ pb (14TeV)

Differential, 各種property精密、新物理探索へ

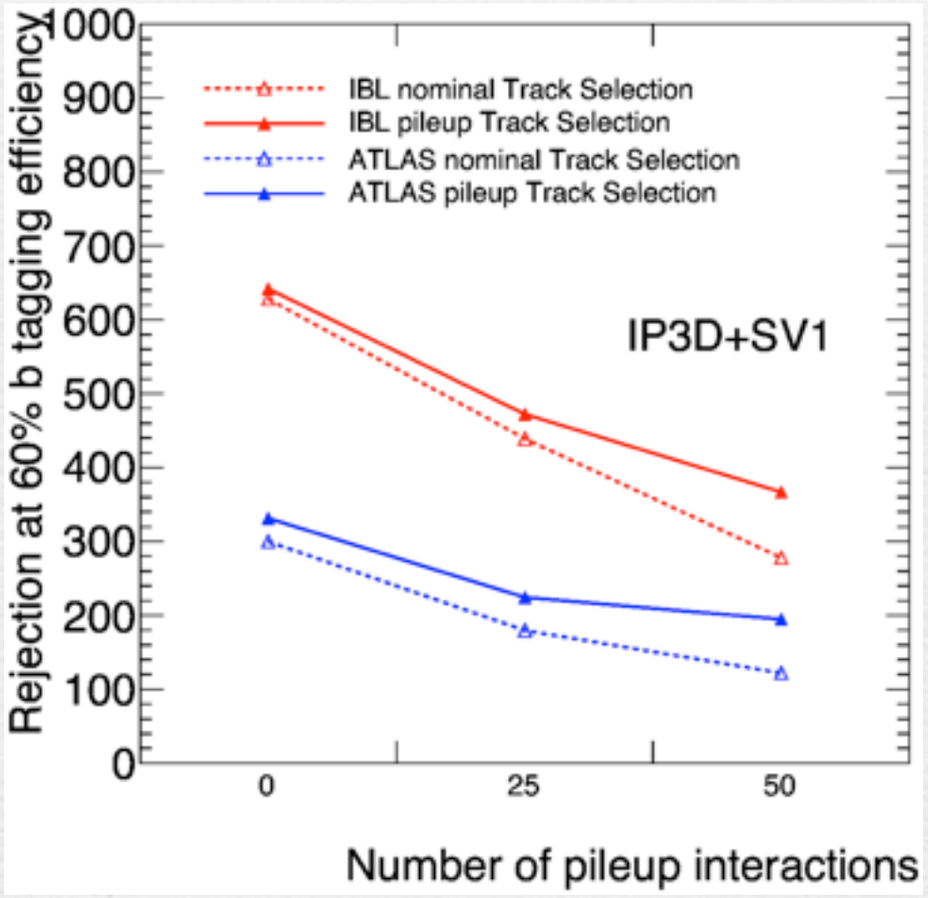
→ Boosted topの再構成

○ Pileupが厳しくなる

→ 様々なalgorithmが開発されている

○ IBLが稼働

→ 厳しいpileup下でb-tag向上



○ Triggerが厳しくなる：Tighter condition (同じpT閾値)？

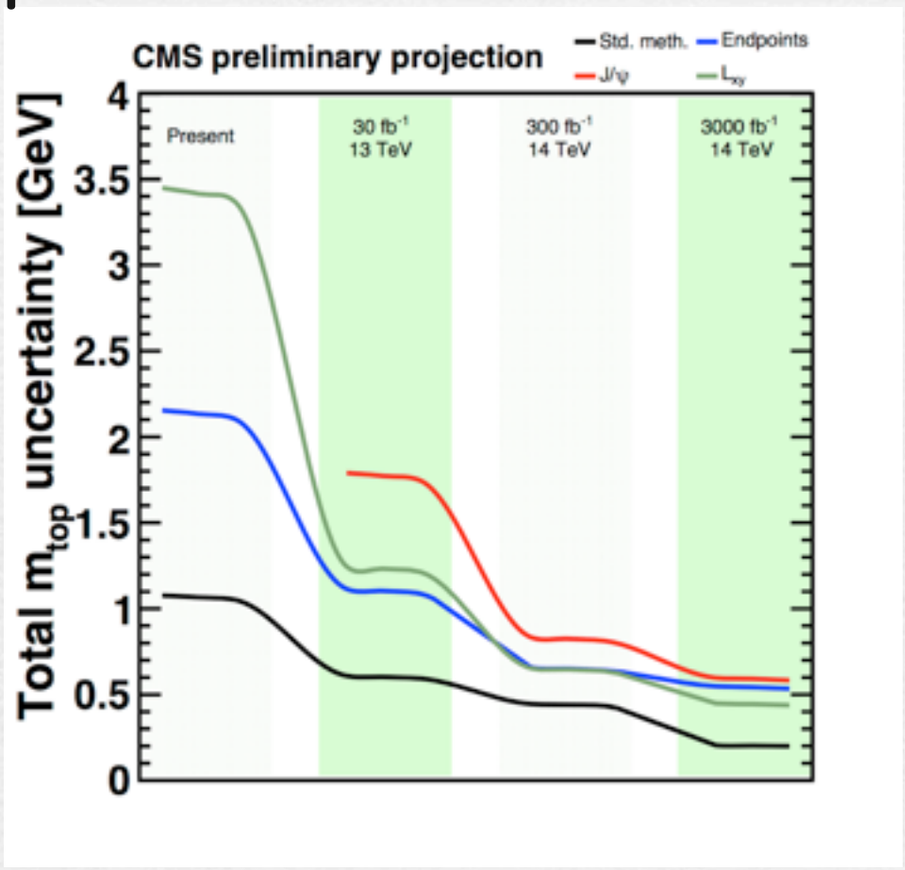
→ Run3以降のTrigger upgradeに期待

Run2とそれ以降に向けて： perspective

○ Cross-section

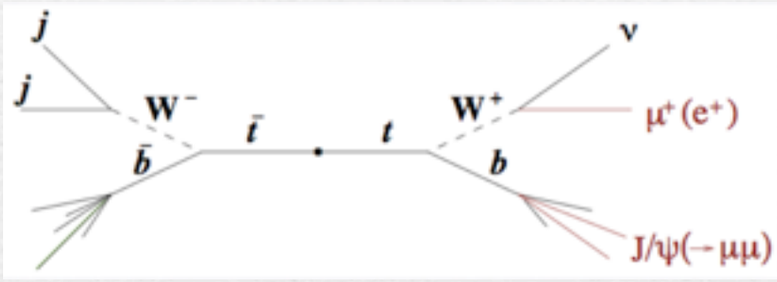
√s=13,14TeVの新しい点、Differential cross-section、light stop search

○ Top mass CMS-PAS-FTR-13-017



様々な手法で質量測定

Standard, Endpoint, L_{xy}, J/ψ method, ...

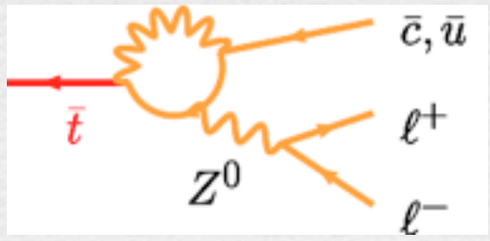


ATLASとCMSの良い解析手法を採用

Full NLO tools

○ 新物理 (FCNC) CMS-PAS-FTR-13-016

$\mathcal{B}(t \to Zq)$	19.5 fb^{-1} @ 8 TeV	300 fb^{-1} @ 14 TeV	3000 fb^{-1} @ 14 TeV
Exp. bkg. yield	3.2	26.8	268
Expected limit	$< 0.10\%$	$< 0.027\%$	$< 0.010\%$
1 σ range	$0.06 - 0.13\%$	$0.018 - 0.038\%$	$0.007 - 0.014\%$
2 σ range	$0.05 - 0.20\%$	$0.013 - 0.051\%$	$0.005 - 0.020\%$



SM:10^{-12}~10^{-17}

BSM: <10^{-4}

まとめ

○ LHCは世界唯一のTop factory実験

- Inclusive σ_{tt} は3.5%の精度→ $d\sigma_{tt}/dX$による精密測定へ
- 質量精度は1GeV以下, 0.5%に
- Charge, Spin, W helicity, FCNCなどの測定

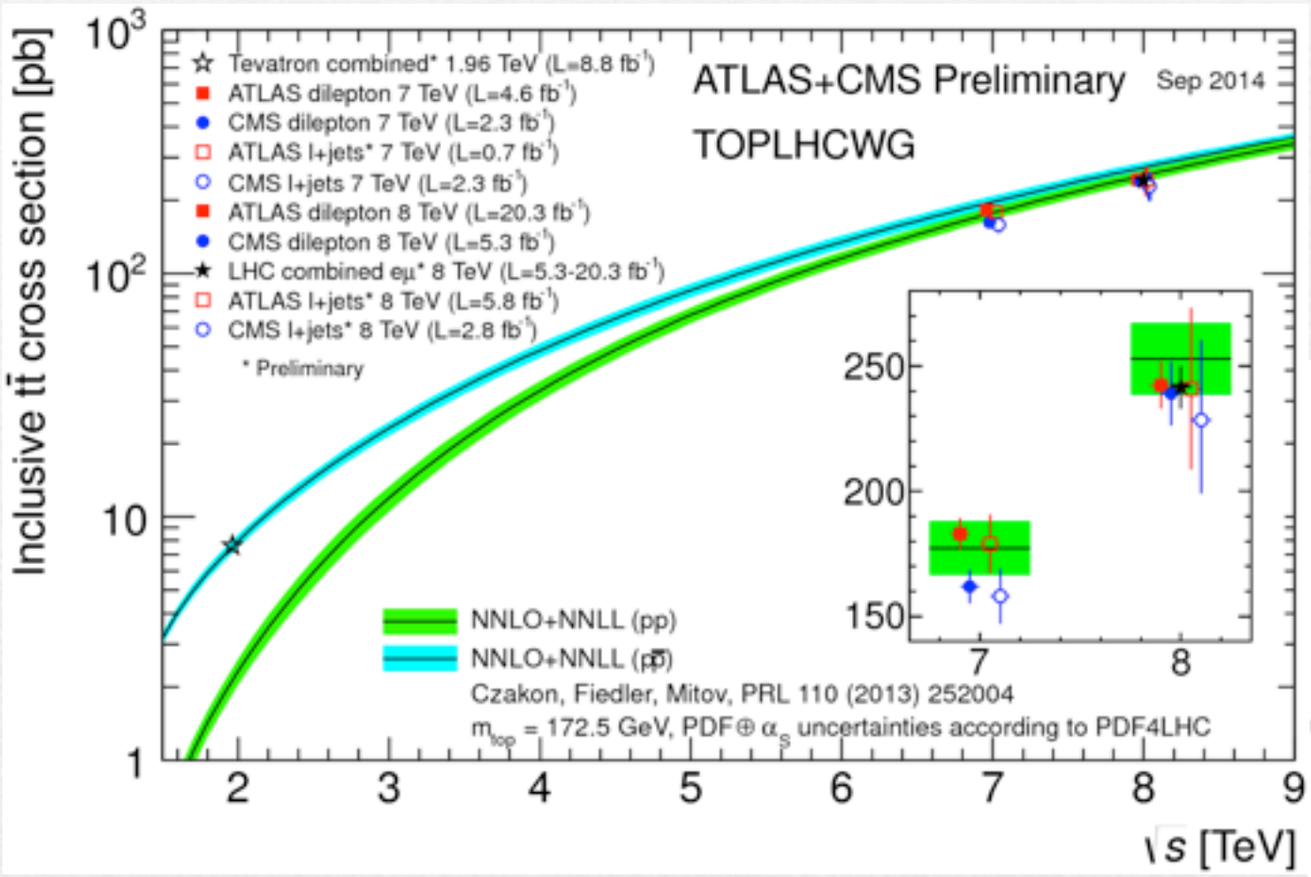
→ pQCDの検証, 新物理探索への本格的な貢献が始まった！

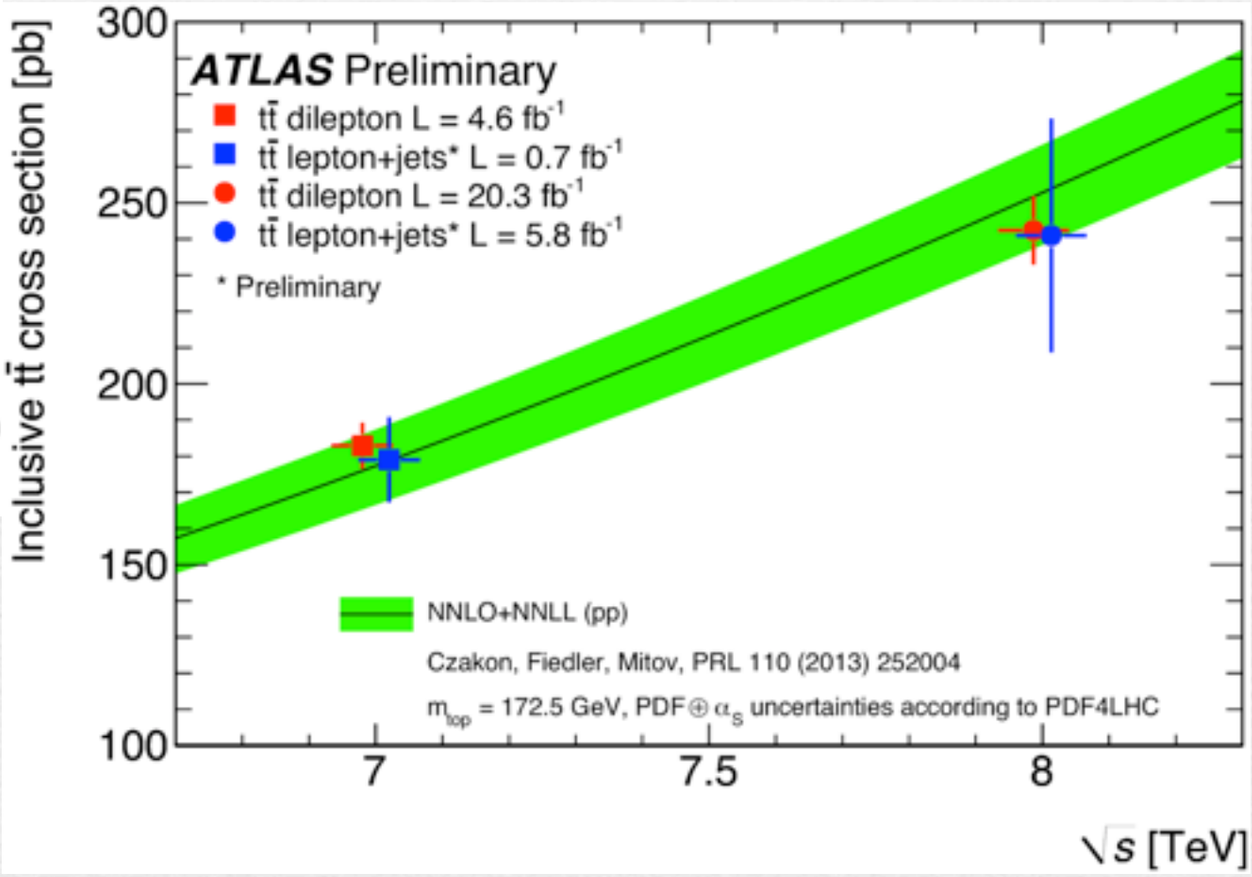
○ $\sqrt{s}$=8 TeVの結果がまだまだ沢山出る予定

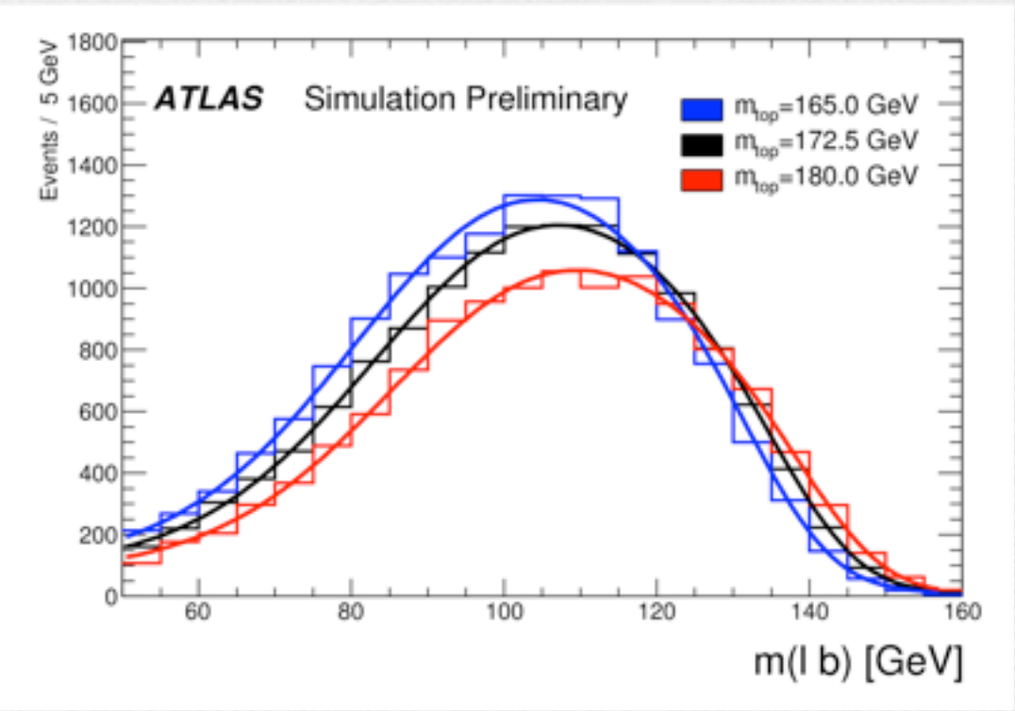
○ Run 2によるより高統計なtop quark物理に期待

backup

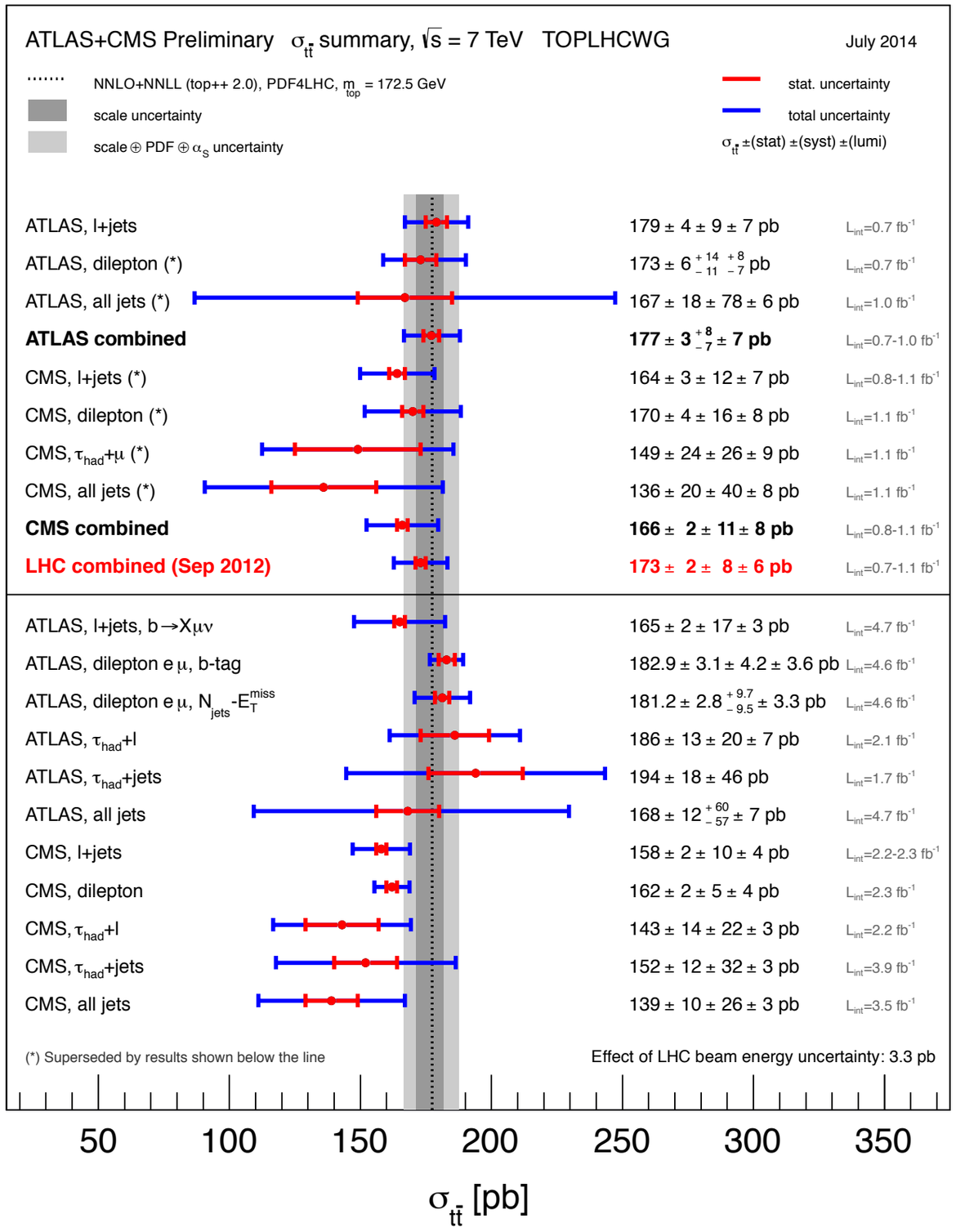
σ_{ttbar} summary

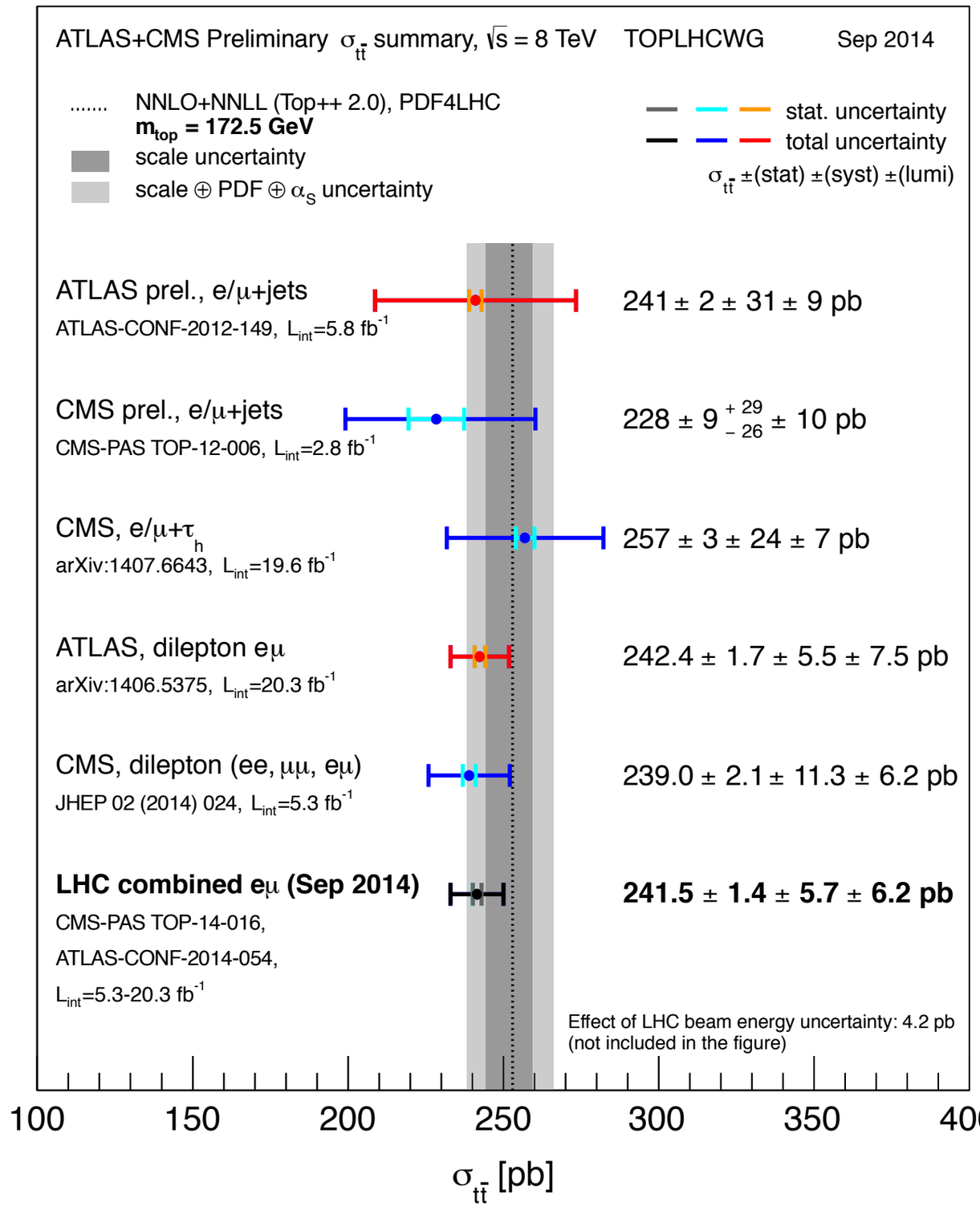




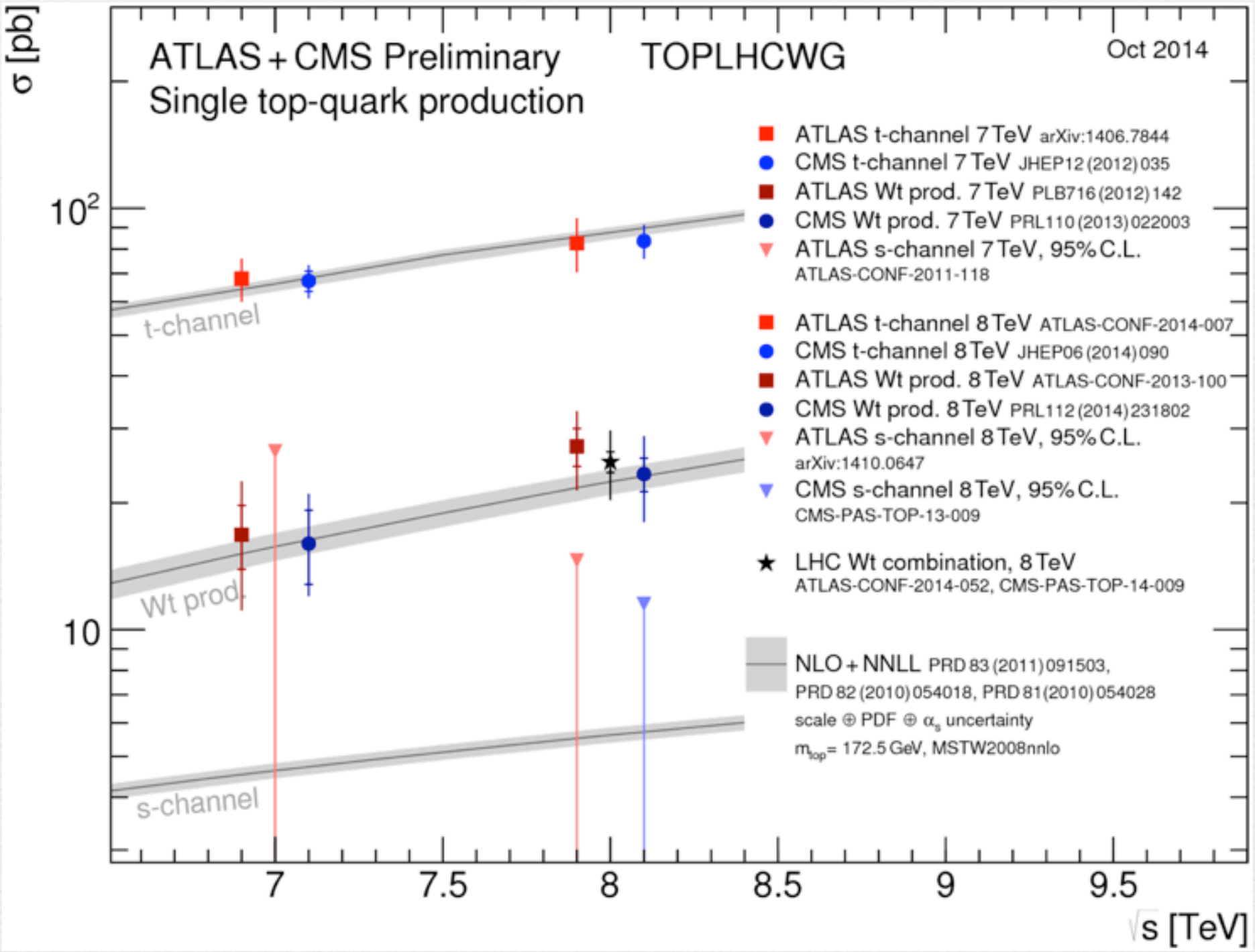


$\sigma_{t\bar{t}}$ summary

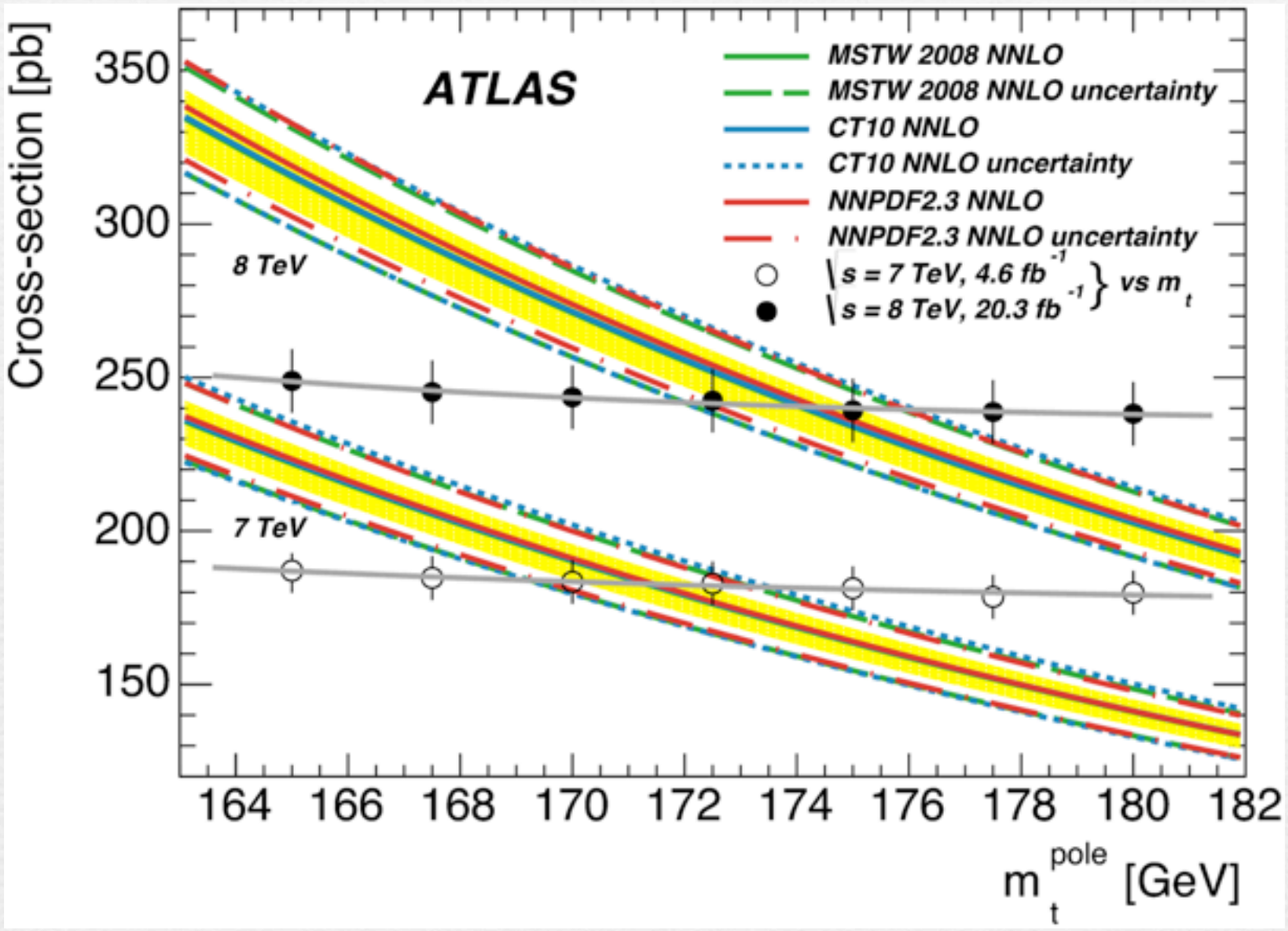




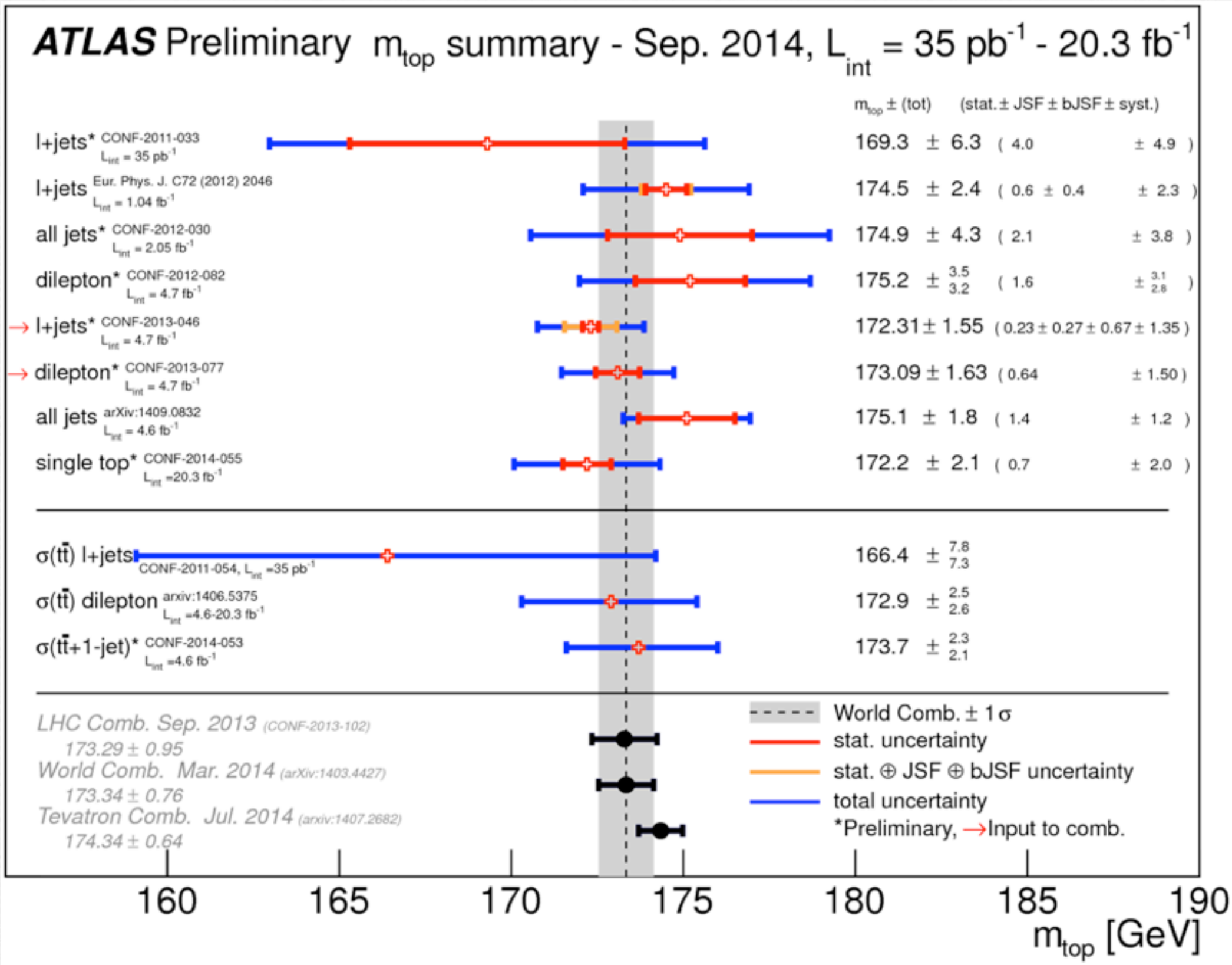
Single top-quark production summary



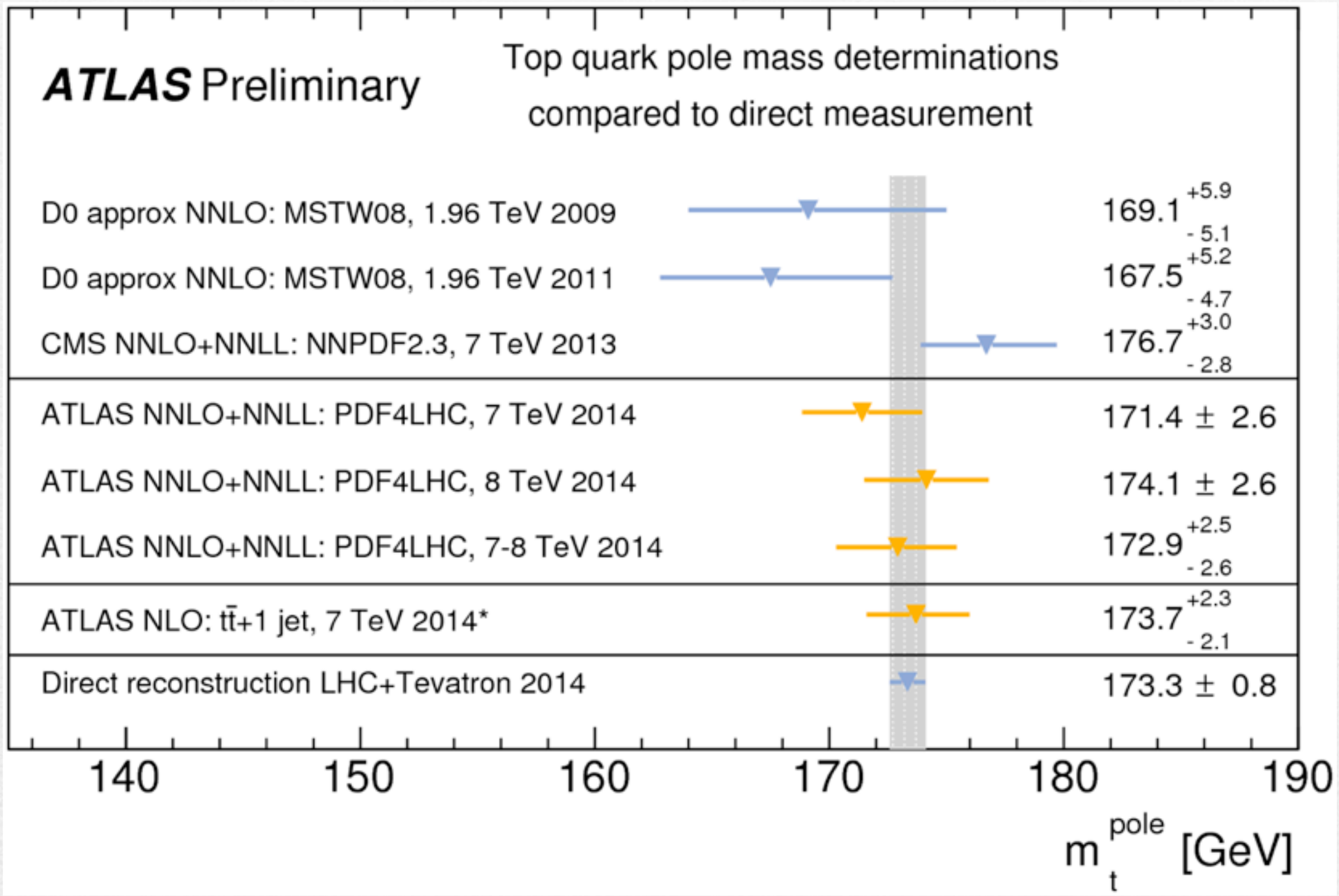
m_t^{pole} from σ_{ttbar} measuremant

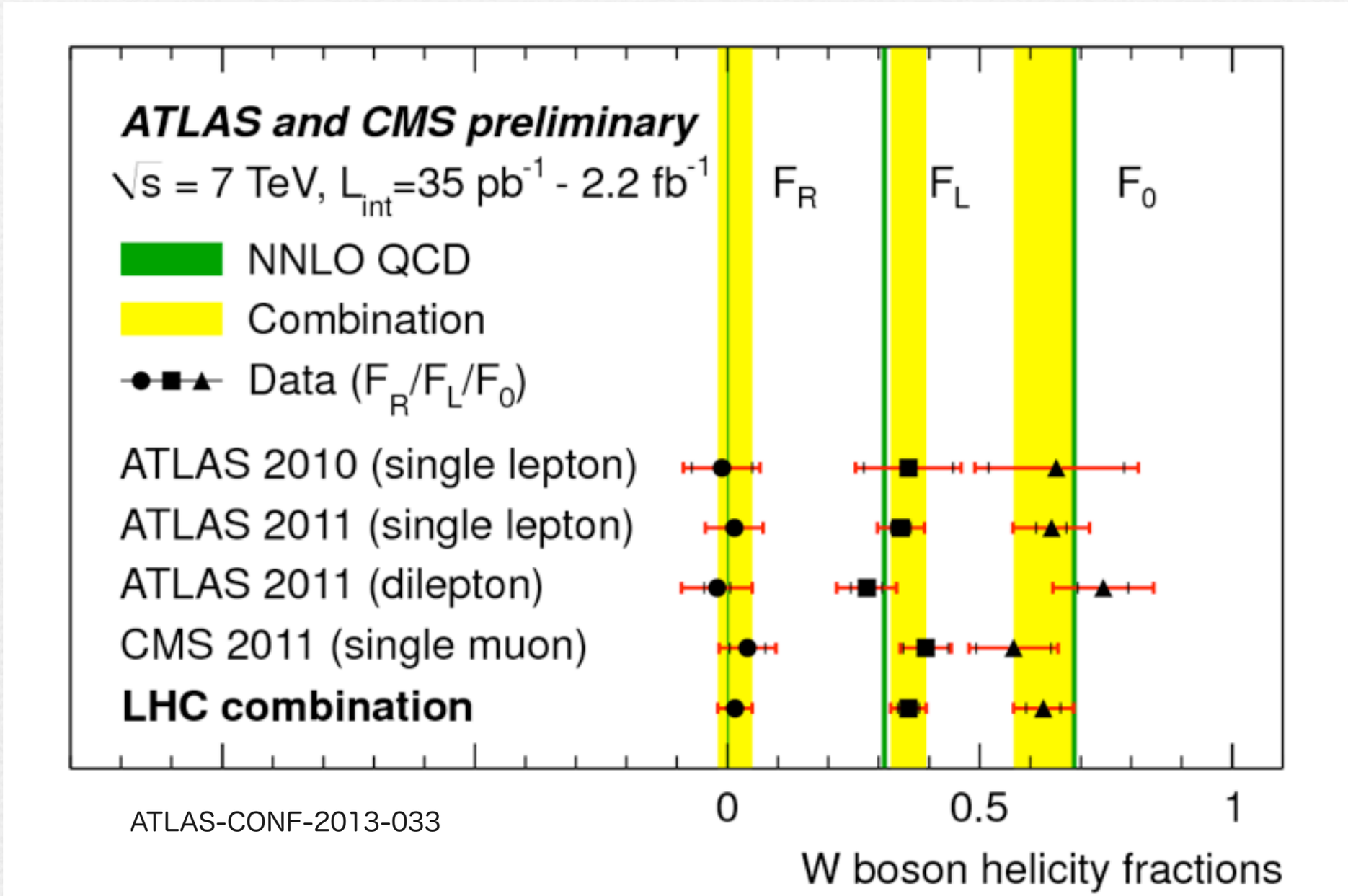


Top quark mass summary



Top quark pole mass





ATLAS-CONF-2013-033