Standard model, Higgs

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Standard model

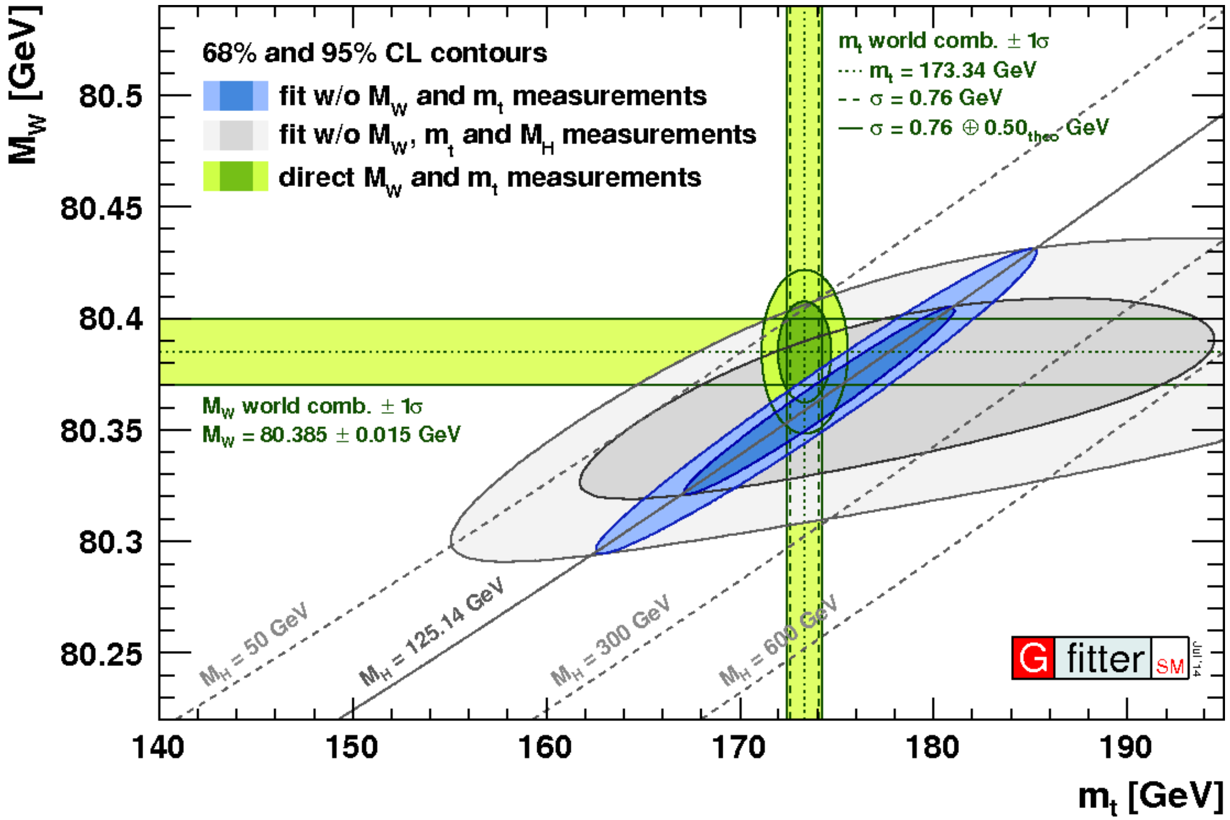
ATLAS: arxiv.1701.07240

W mass

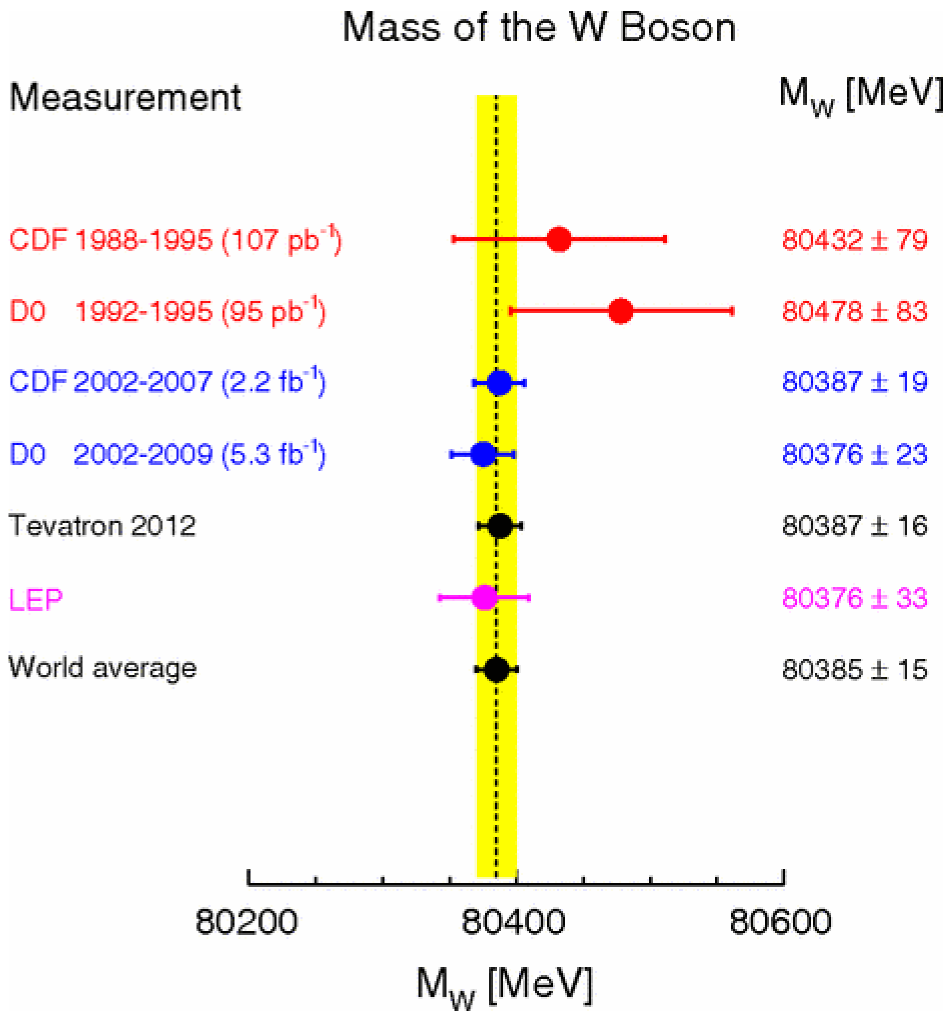
- 標準理論の内部整合性の検証
- 既に*W* mass測定精度がボトルネック

- LHCで？
  - Tevatronに比べてsea-クォークの重要度が増す
  - *s*-, *c*-quarkがproductionの25 %に寄与
  - challenging!!

arxiv.1407.3792



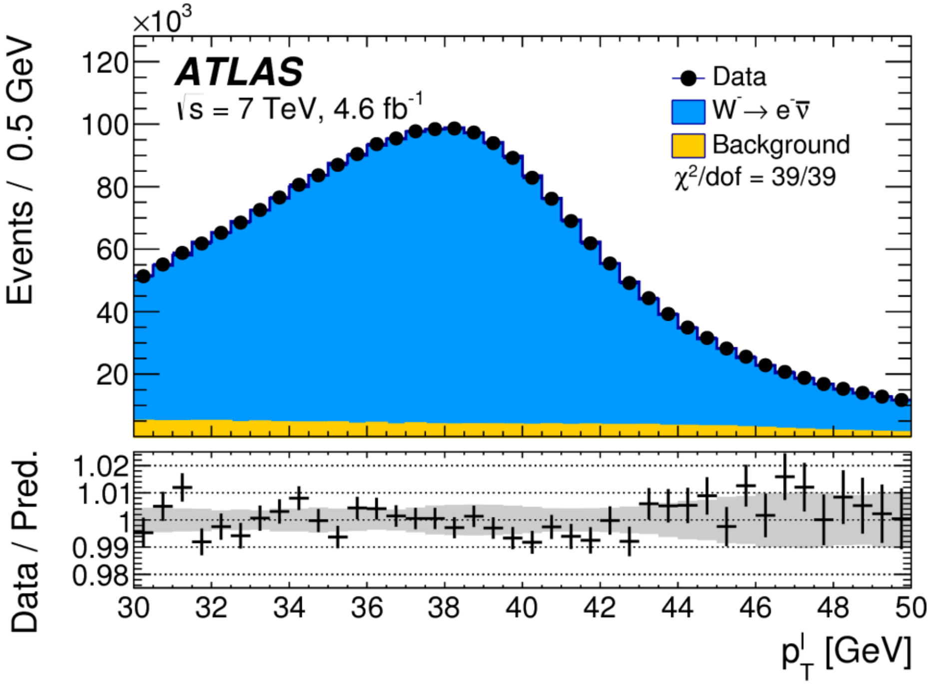
Phys. Rev. D 88 (2013) 052018



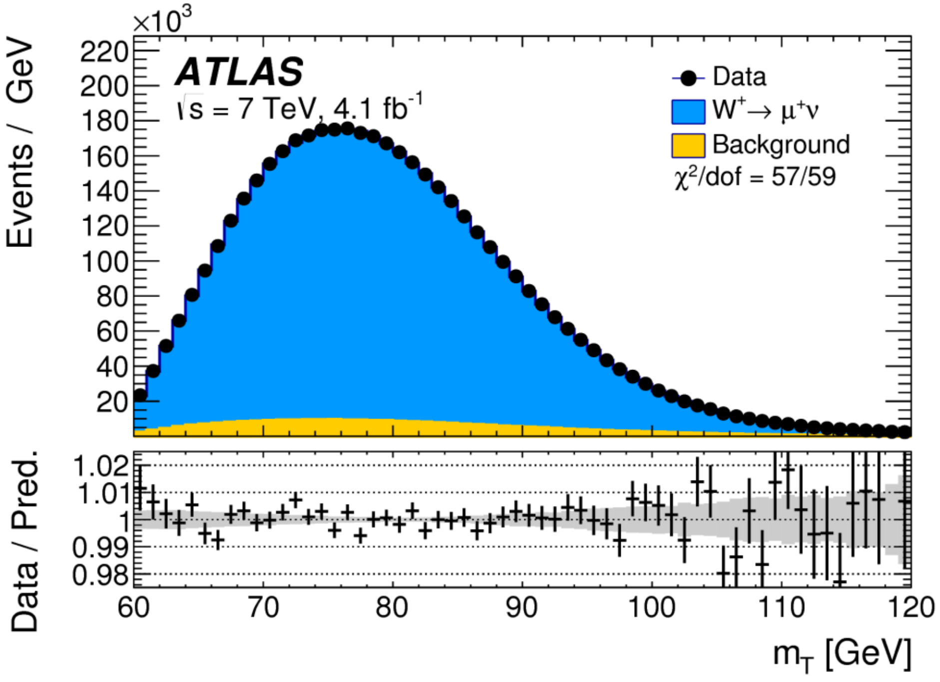
W mass

- 測定方法
  - $W\to\ell\nu$を使用
  - $p_{\mathrm{T}}^{\ell}, m_{\mathrm{T}}^{W}$のtemplateでfit
  - Powheg Pythia8
  - leptonのmomentumはZ massを使ってcalibration → 実質Z massとの比の測定？

p_{T}^{ℓ}: Wのrecoilによるuncertaintyに強い



m_{T}^{W} : modeling uncertaintyに強い



ATLAS: arxiv.1701.07240

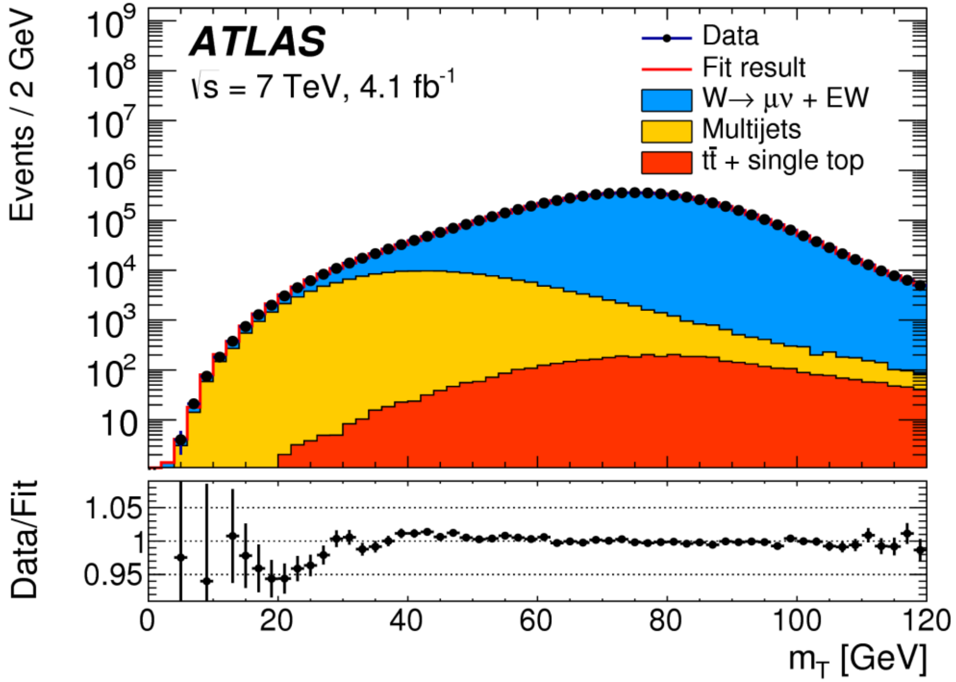
W mass

- 7 TeV 4.6 fb^{-1} (muon channelは4.1 fb^{-1}) を使用

- Event selection
  - recoil $u_{\mathrm{T}} < 30$ GeV
    - u_{T}: vector sum of the E_{T} of all calorimeter clusters
    - Wがboostしているときのmodel uncertaintyを減らす
  - MET > 30 GeV
  - transverse mass m_{T}^{W} > 60 GeV

  } QCD除去

- main BG: $Z \to \ell\ell$ (~5 %)
- QCD BGはtemplate methodで見積もり
  - MET, m_{T}^{W} の要求をlooseにした領域を使用
  - 数は少ないが系統誤差大



ATLAS: arxiv.1701.07240

W mass

$$m_W = 80370 \pm 7\,(\mathrm{stat.}) \pm 11\,(\mathrm{exp.\,syst.}) \pm 14\,(\mathrm{mod.\,syst.})\ \mathrm{MeV}$$
$$= 80370 \pm 19\,\mathrm{MeV}$$

lepton calibration uncertainty

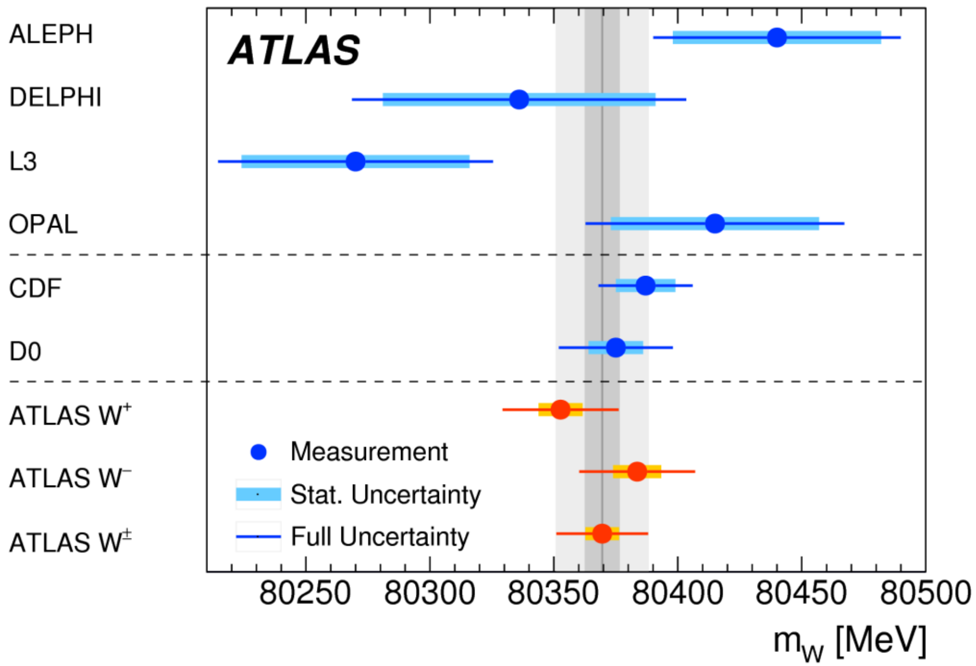
QCD BG

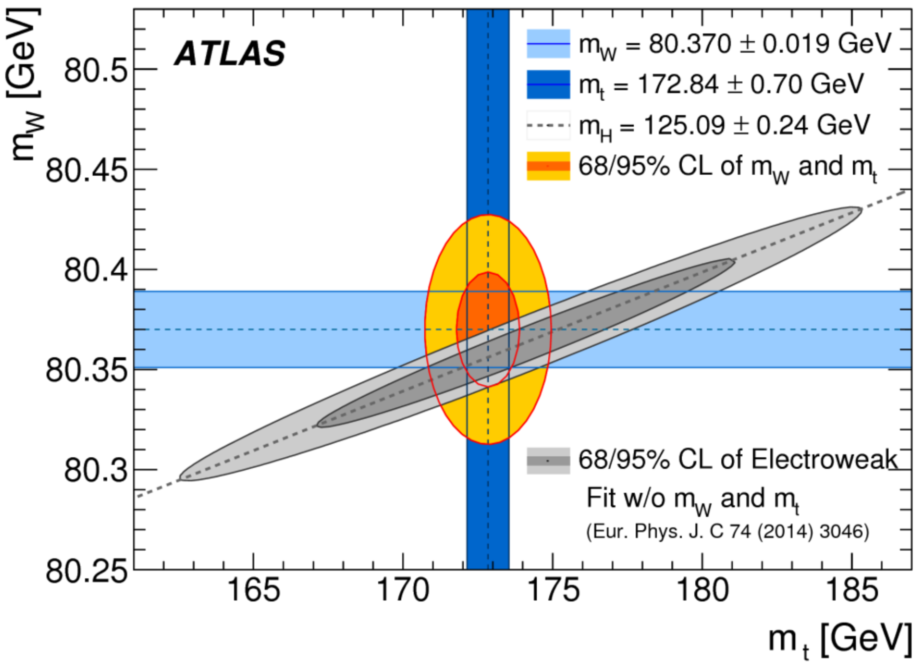
Fixed-order PDF uncertainty

- Tevatronと同程度の精度！

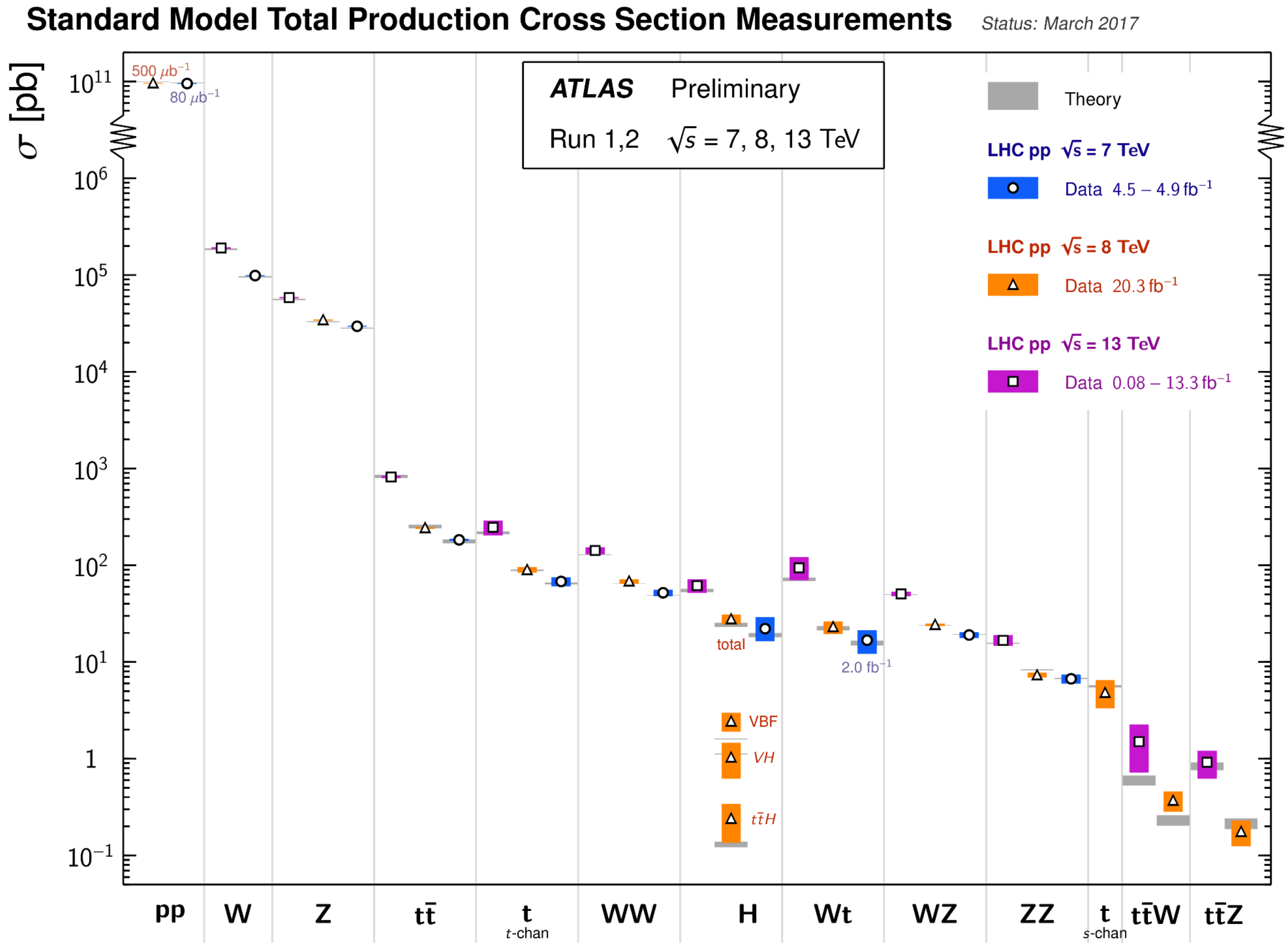
- topとHiggs massの測定結果を使うとW massの予測値は
- $m_W^{\mathrm{Fit}} = 80356 \pm 8\ \mathrm{MeV}$
- $(m_t = 172.84 \pm 0.70\ \mathrm{GeV}, m_H = 125.09 \pm 0.24\ \mathrm{GeV})$

- 標準理論は整合性が取れている…





Cross section measurement

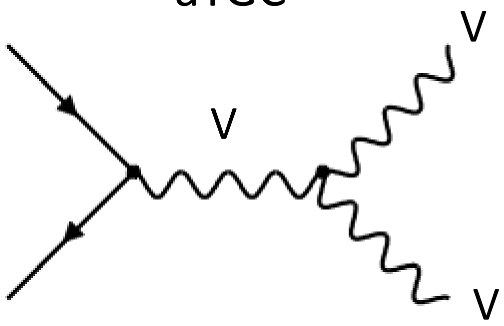


標準理論の威力…

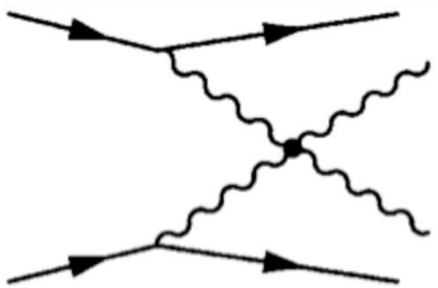
Multi-boson

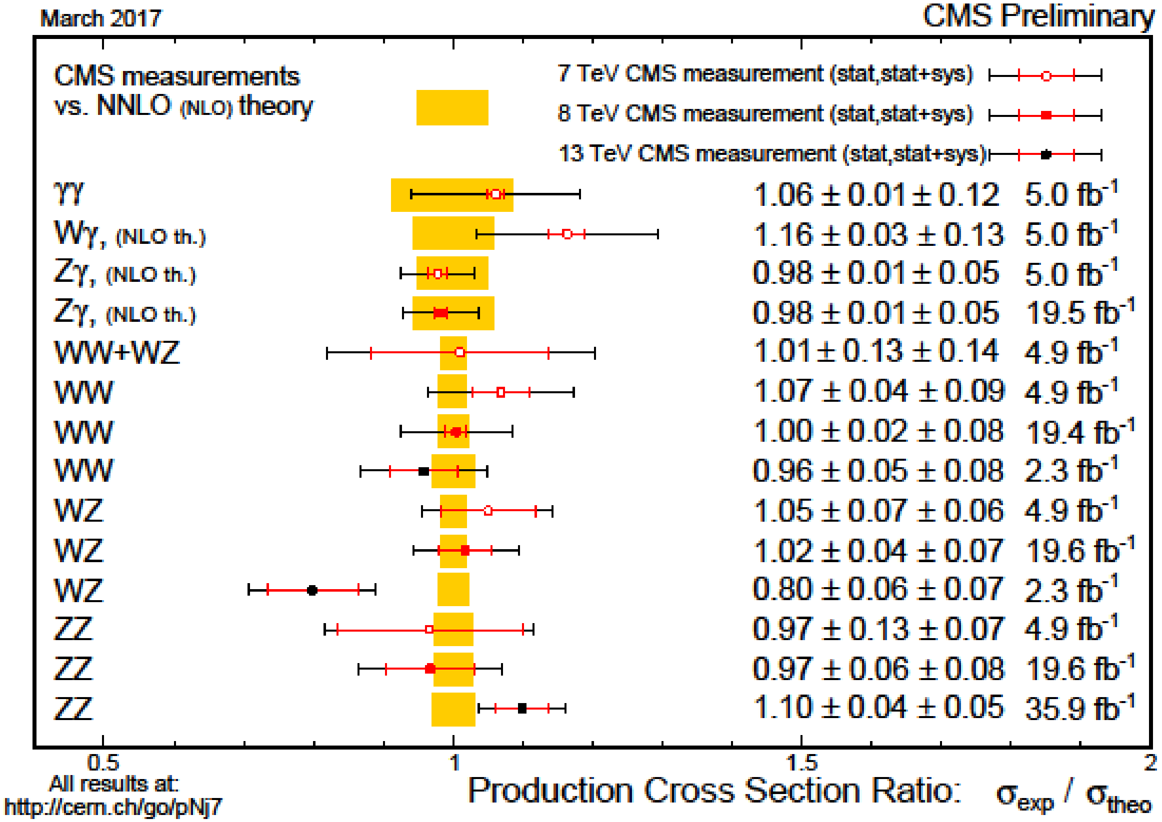
- anomalous Triple(Quartic) Gauge Couplings (aTGC, aQGC)
- Vector Boson Scattering (VBS)

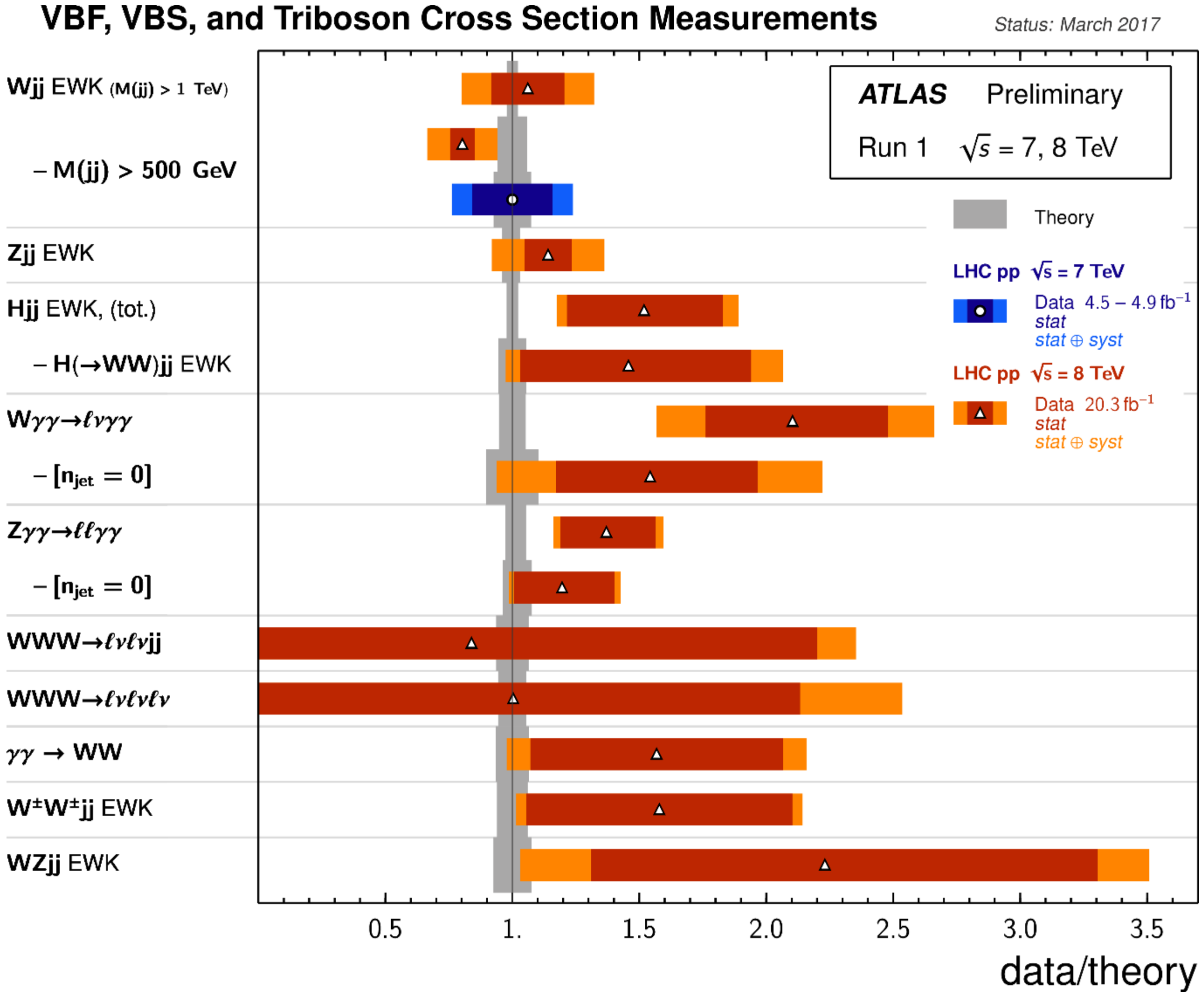
aTGC



VBS

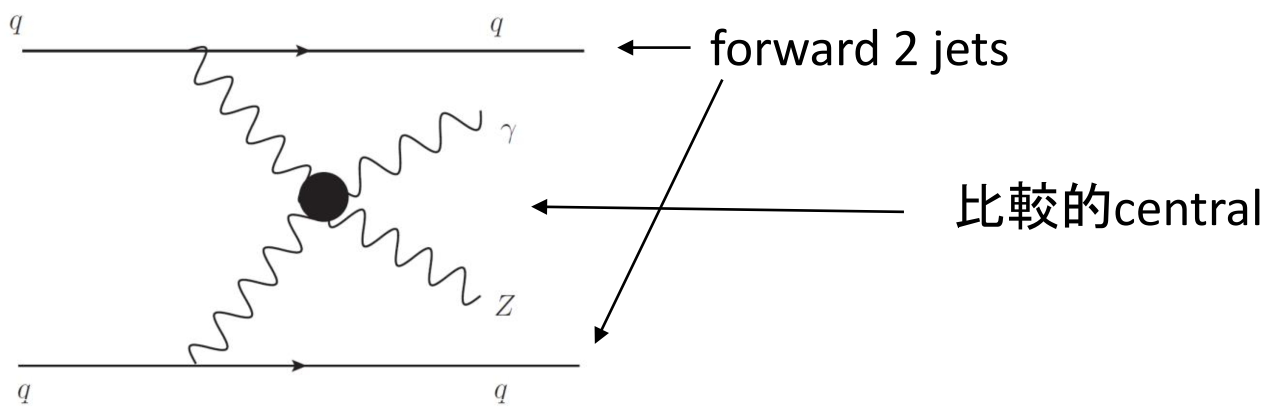


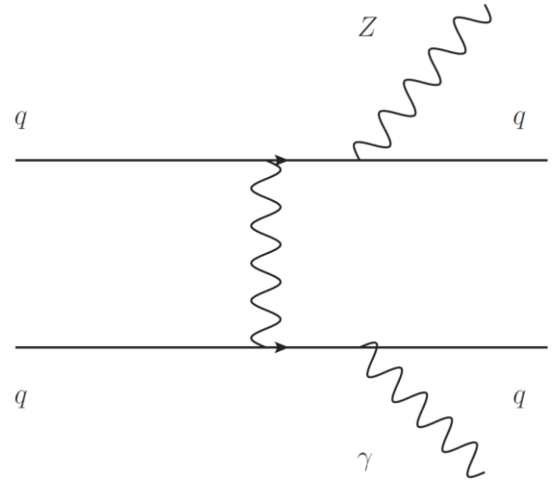




VBS $Z\gamma$ at 8 TeV

ATLAS: STDM-2015-21





等と強く干渉

- $Z \to \ell\ell$ channel
  - $m_{Z\gamma}$ > 182 GeV
  - m_{jj} > 500 GeV
  - centrality observable ζ
    - 2 forward jetsに対してどれだけcentralか

$$\zeta_{Z\gamma} \equiv \left| \frac{\eta_{Z\gamma} - \bar{\eta}_{jj}}{\Delta\eta_{jj}} \right|$$

$$\bar{\eta}_{jj} = \frac{\eta_{j1} + \eta_{j2}}{2}$$

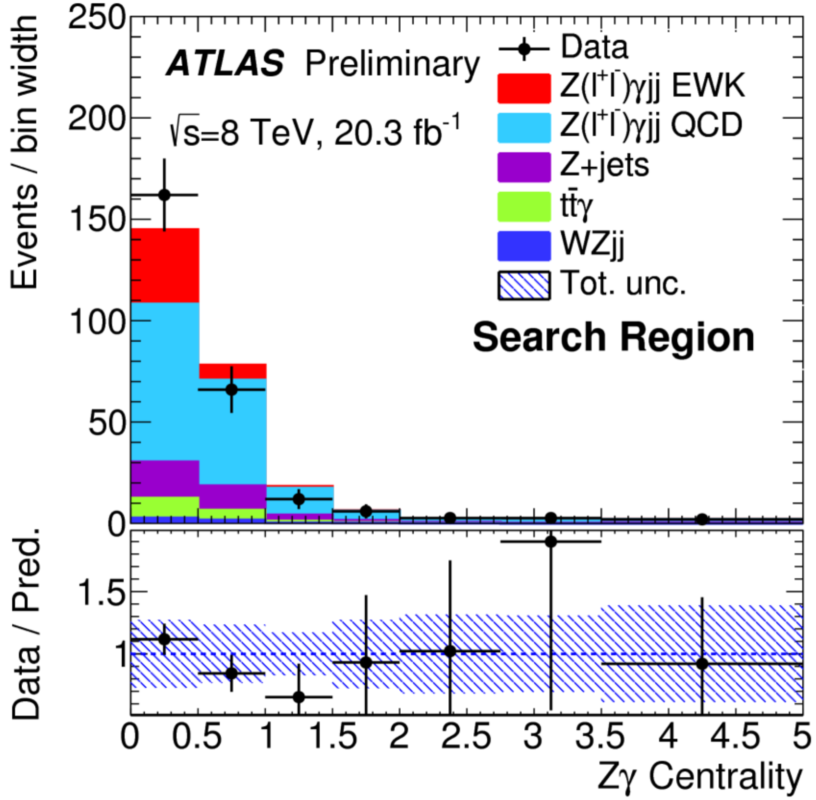
$$\Delta\eta_{jj} = \eta_{j1} - \eta_{j2}$$

- $Z \to \nu\nu$ channel
  - m_{jj} > 600 GeV
  - MET > 100 GeV
  - angular selection, $\nu\bar{\nu}\gamma jj$のp_T-balance, γ のcentralityを要求
  - E_T^{γ} > 150 GeV
  - aQGC用

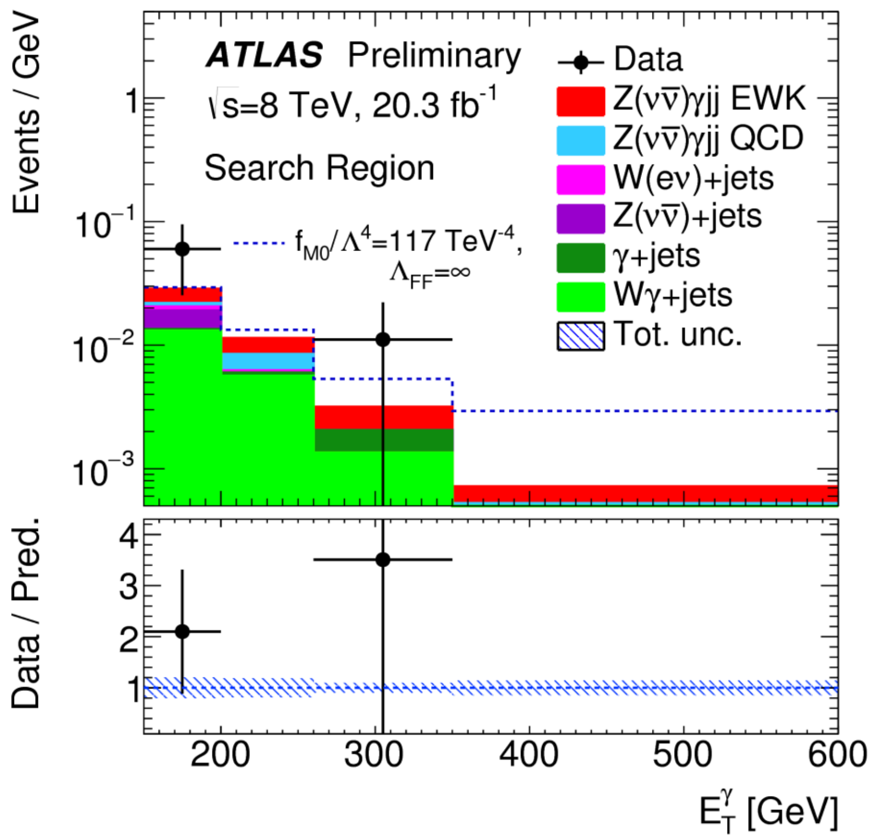
ATLAS: STDM-2015-21

VBS $Z\gamma$ at 8 TeV

$Z \to \ell\ell$ channel



$Z \to \nu\nu$ channel



- EWK課程での$Z\gamma jj$ cross section

$$\sigma_{Z\gamma jj}^{\text{EWK}} = 1.1 \pm 0.5\,(\text{stat.}) \pm 0.4\,(\text{syst.})\ \text{fb}$$
$$\sigma_{Z\gamma jj}^{\text{VBFNLO,EWK}} = 0.94 \pm 0.09\,(\text{theo.})\ \text{fb}$$

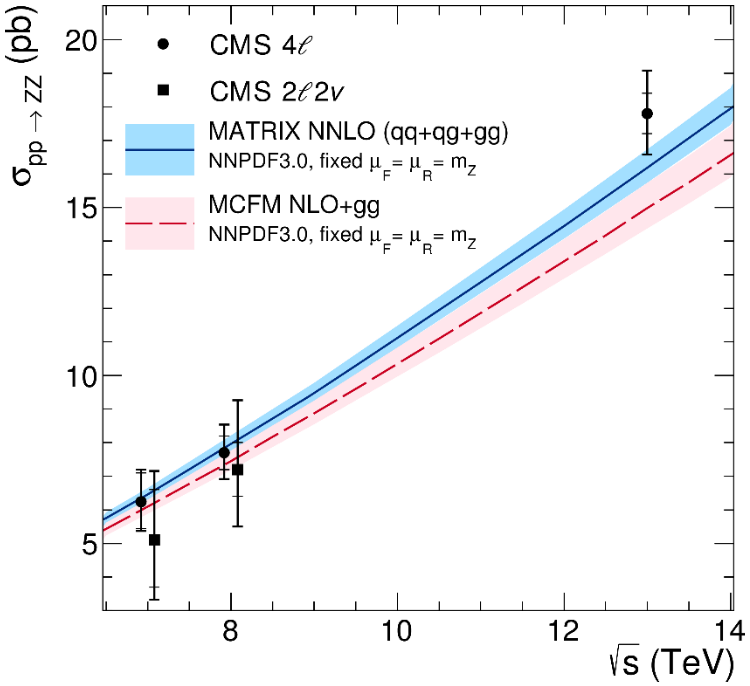
aQGC見えず

CMS: SMP-16-017

ZZ at 13 TeV

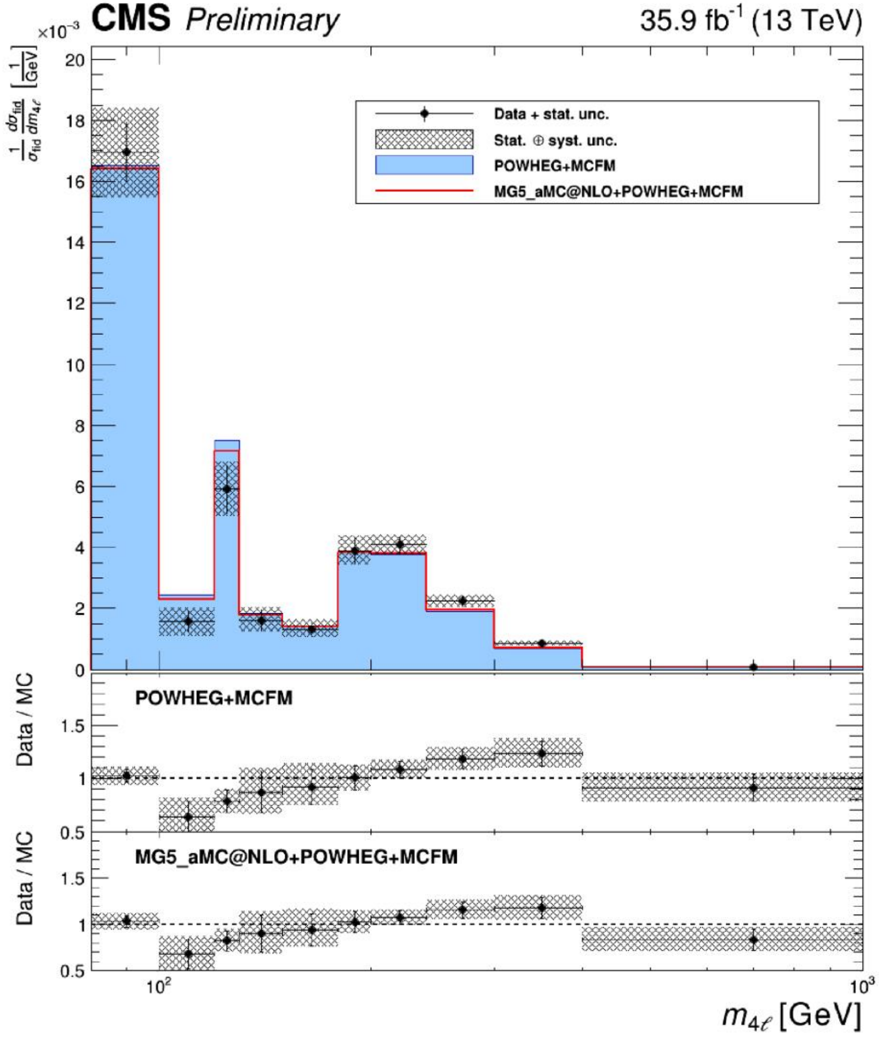
- ZZ → 4ℓ

total cross section

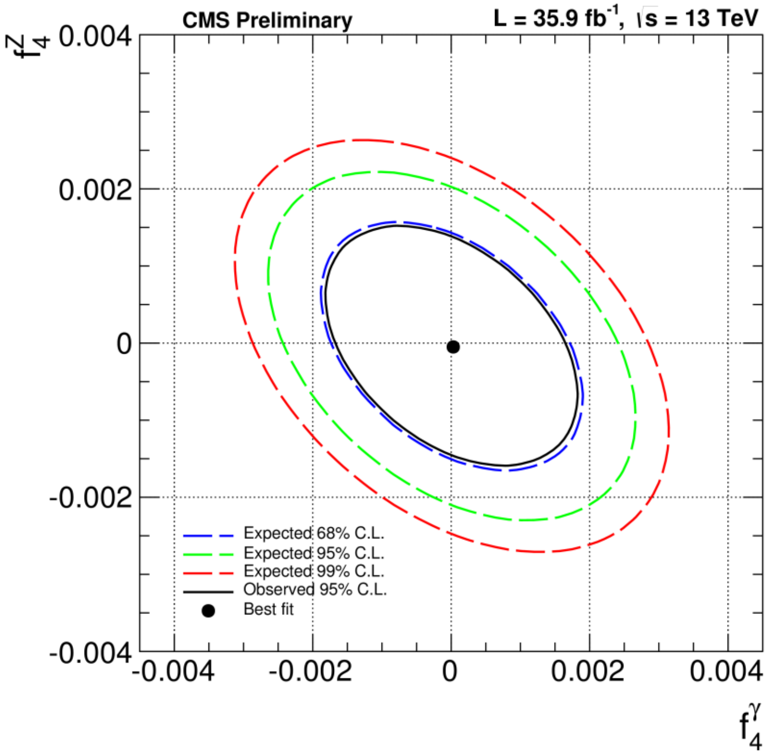


NNLOとよく一致

differential cross section



high m_{ZZ} eventからaTGCにlimit

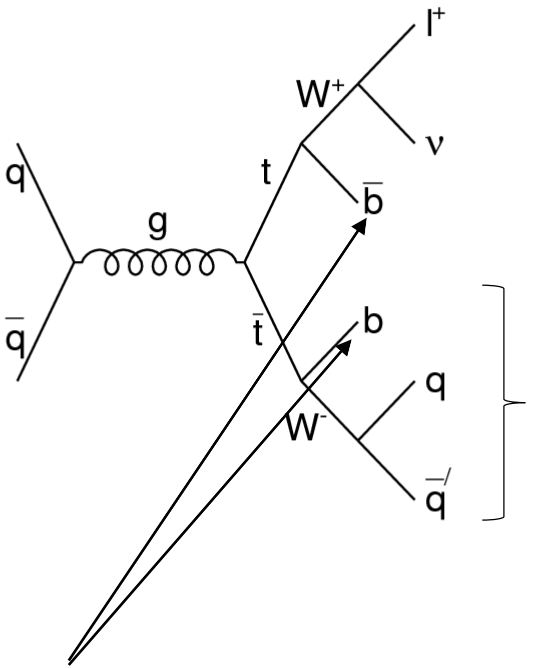


CMS: TOP-16-022

Top mass

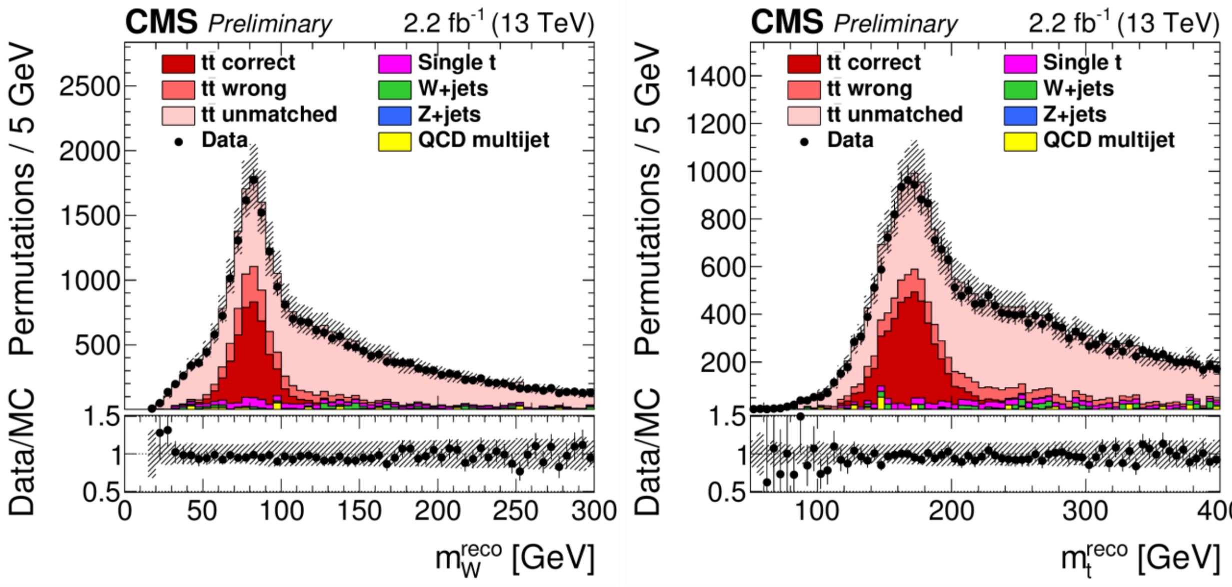
muon + 4 jets with CMS

- direct measurement (not pole mass)
- 2.2 fb^{-1} at 13 TeV



これらでmassを組む

b-jetの候補は2つあるので、どちらも試す
(どちらもhistogramにfillする)



correct: 正しいb-jetの組み合わせ
wrong: 誤った組み合わせ
unmatched: truth quarkとmatchしない

Top mass

CMS: TOP-16-022

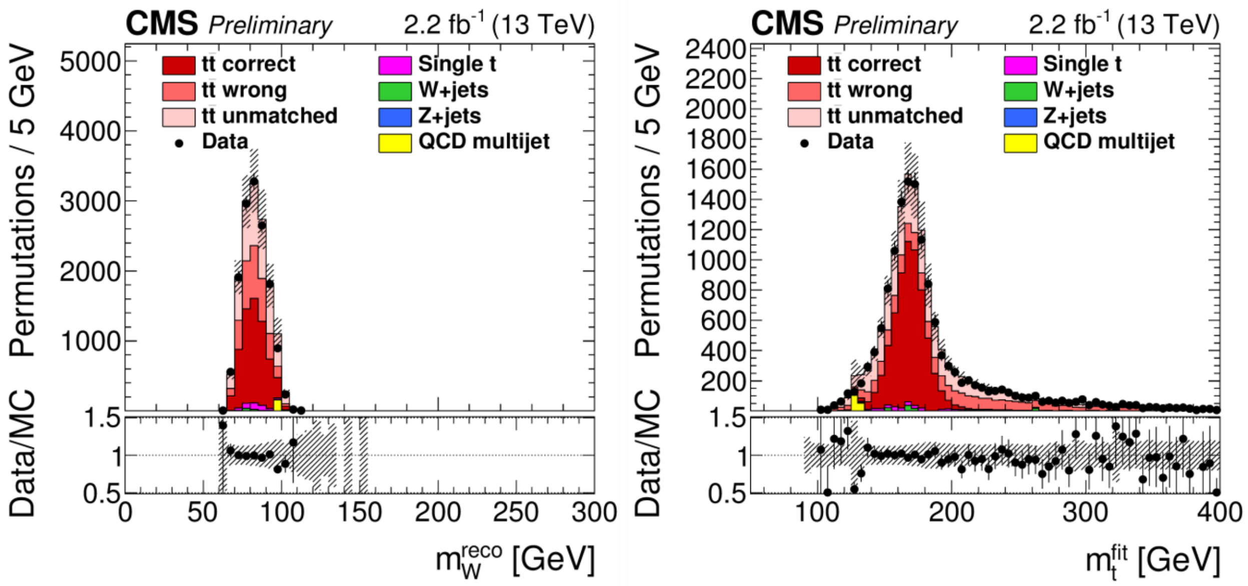
kinematic fit

- ttbarらしさをχ^2で計算
- inputは終状態粒子のmomentum (METを含む)
- ただし、momentumはuncertaintyの範囲内で動かせる
- Wのmass等の束縛条件を加えてfit

⇒

- χ^2でttbarとBGが分離
- 終状態粒子のmomentum resolution向上

- χ^2が小さいことを要求
- $-\frac{1}{2}\chi^2$を各イベント、b-jetの組み合わせに重みとしてかける



- 最終的にm_Wとm_tを同時にfitしてjet energy scaleとtop massを同時に決定

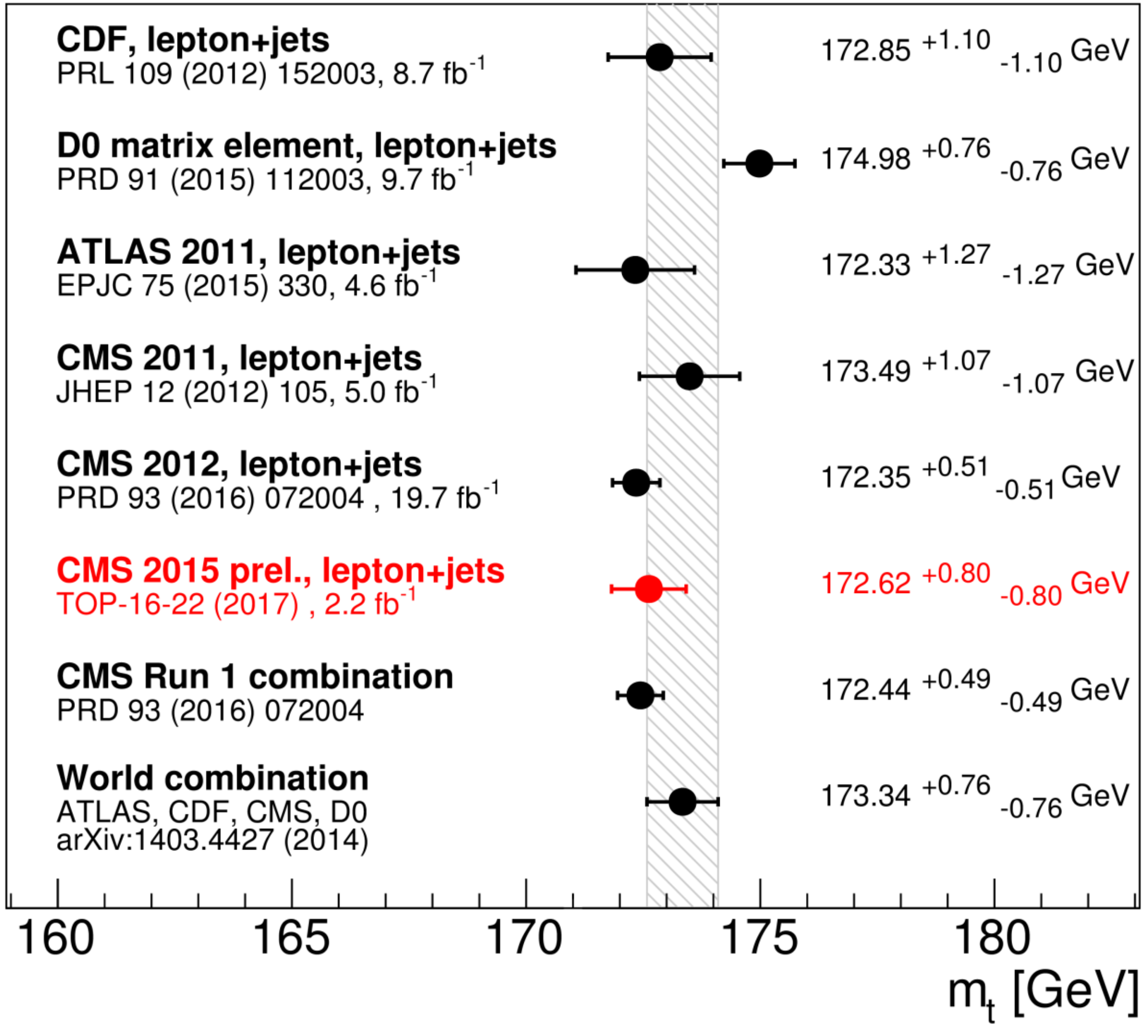
$$m_{top} = 172.62 \pm 0.38\,(\text{stat.}) \pm 0.70\,(\text{syst.})\ [\text{GeV}]$$

- b-jet energy scaleが系統誤差に効いている
- 最も感度の高い解析の一つ

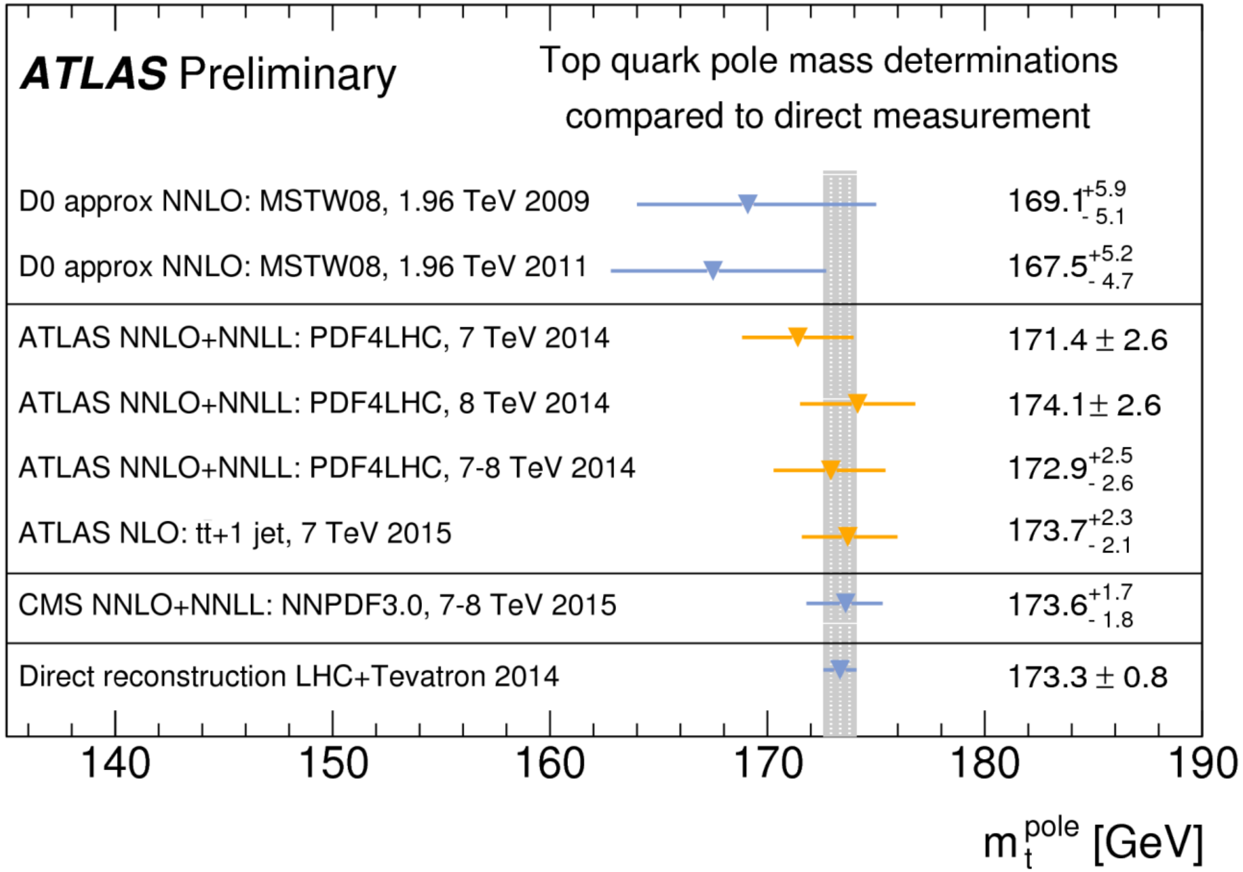
Top mass

CMS: TOP-16-022

direct top mass measurement



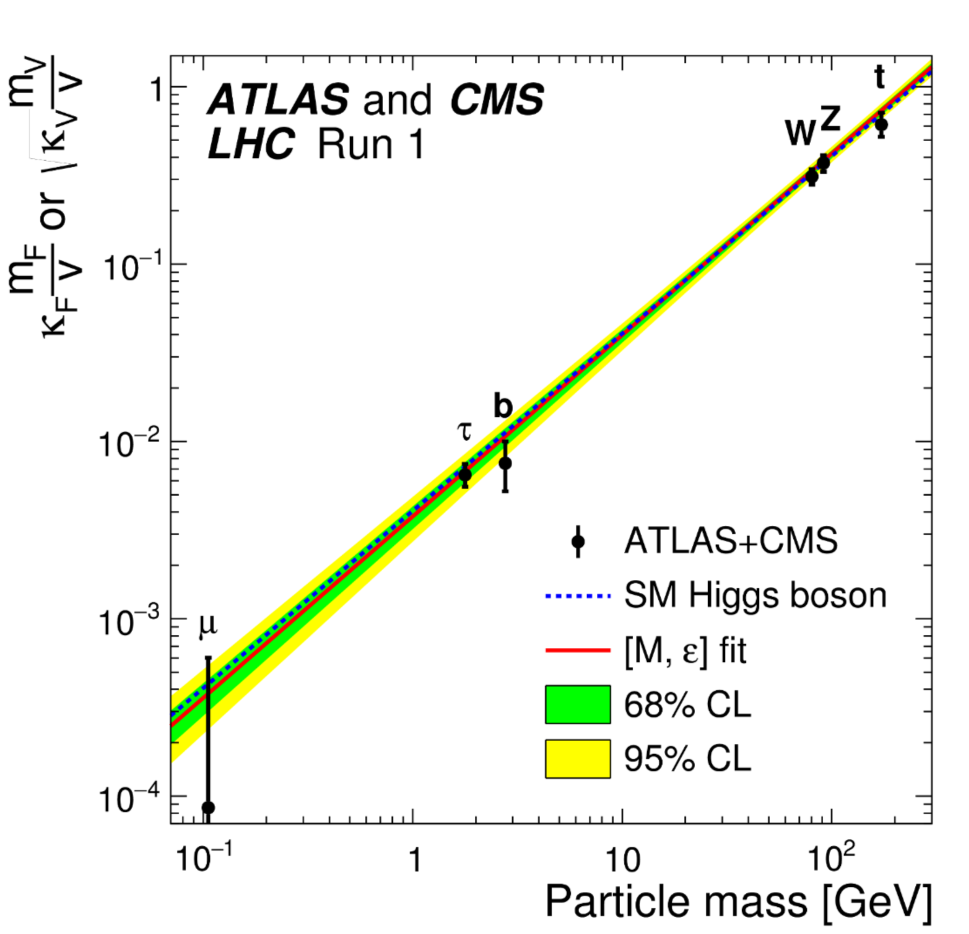
top quark pole mass measurement



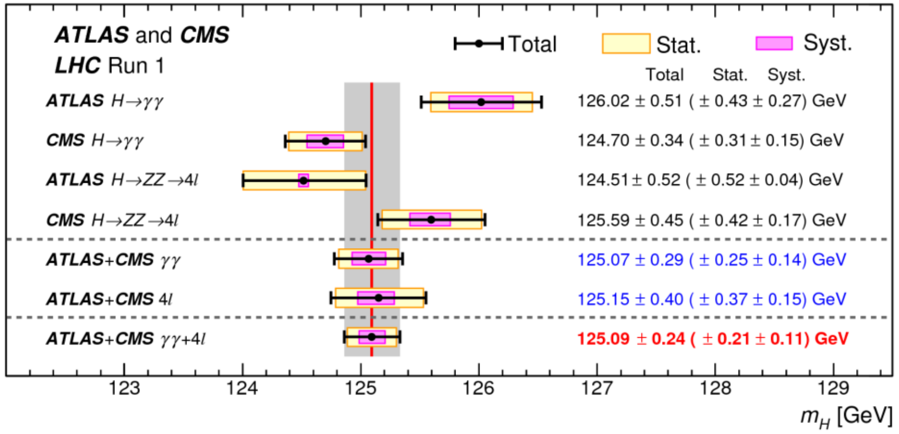
Higgs

これまでの状況: Run1

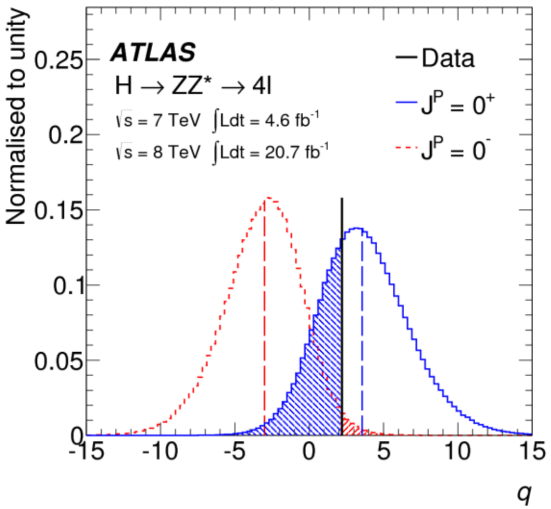
2012年 発見 → 性質測定



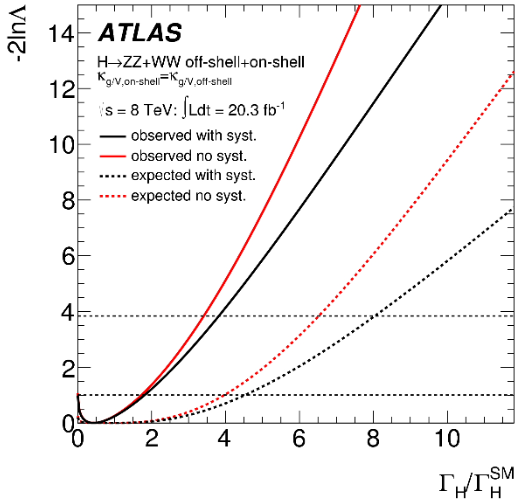
$\gamma\gamma$, ZZ, WW, ττ decayモードで発見



m_H = 125.09 ± 0.24 GeV



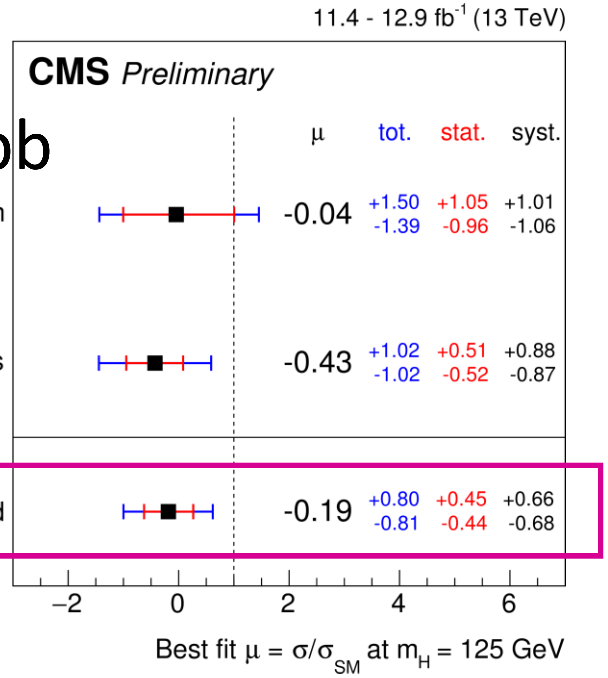
$J^{CP} = 0^{++}$



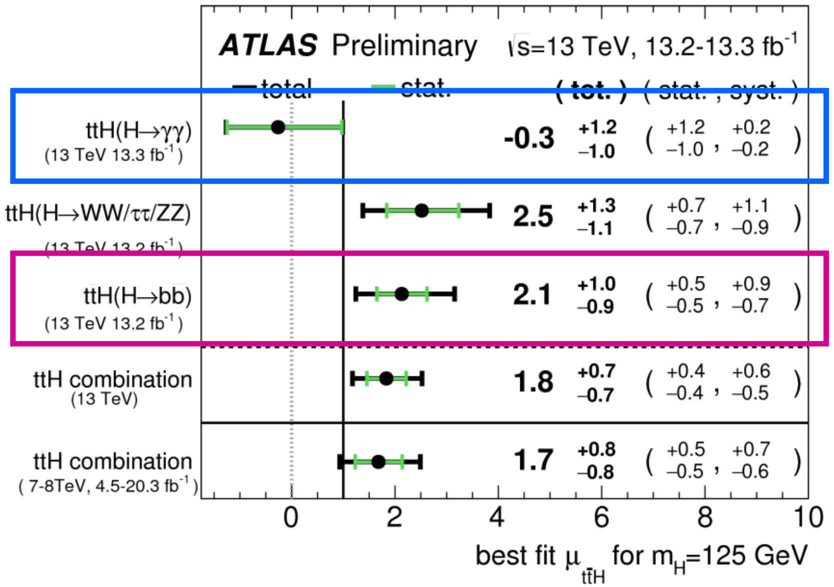
$\Gamma_H/\Gamma_H^{SM} < \sim4$

これまでの状況: Run2でのtop, bottom湯川

ttH bb

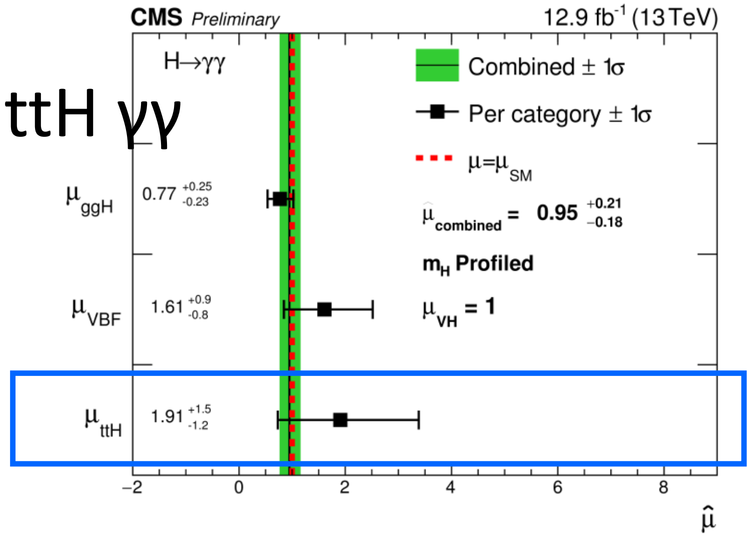


ttH comb.

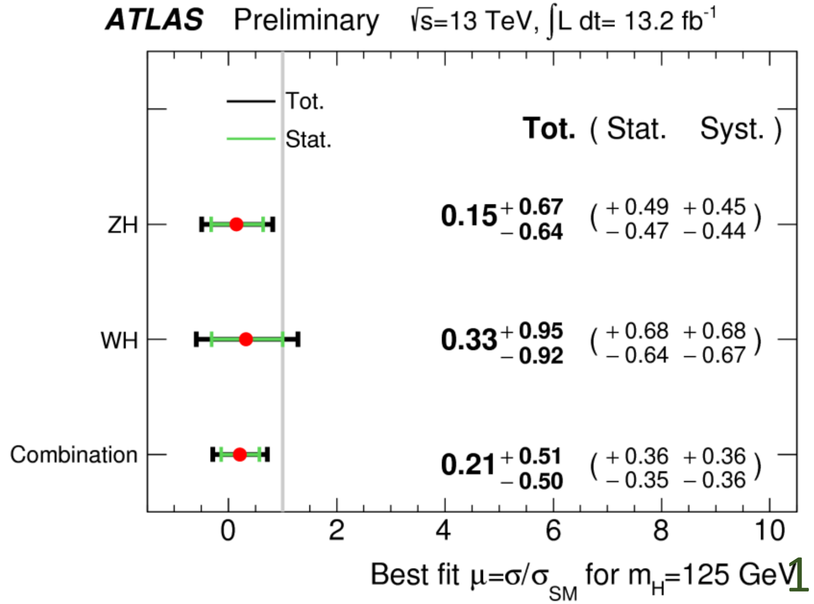


VH(bb) 探索
μ < 1に振れている
Run1と同じ傾向 (ATLAS)

ttH γγ



ttH探索
CMSとATLASで逆向きに振れている
combineすると ~1??

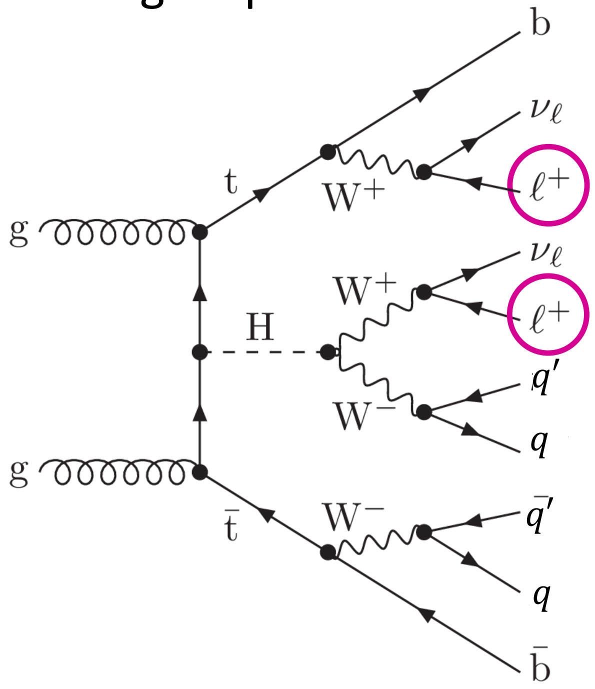


ttH, multi-lepton

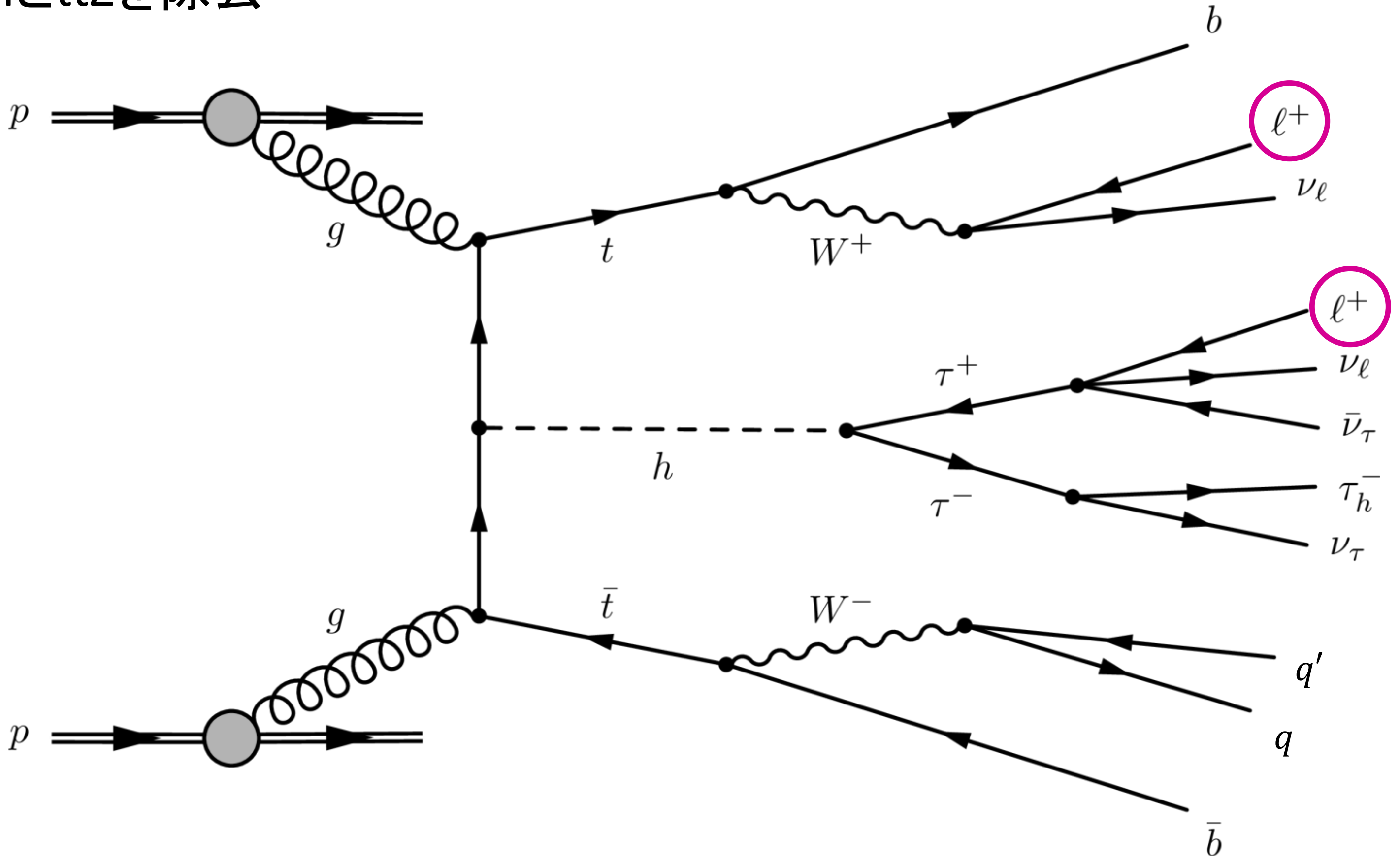
CMS: HIG-17-003
HIG-17-004

- targetは$h \rightarrow WW, ZZ, \tau\tau$
- 感度が高いのは
  - 2 same sign leptons: ≥4 jets, ≥1 b-tag
  - 2 same sign leptons + 1 τ_{had}: ≥3 jets, ≥1 b-tag
- same signを要求することでDrell-YanとttZを除去

2 same sign leptons



2 same sign leptons + 1 τ_{had}



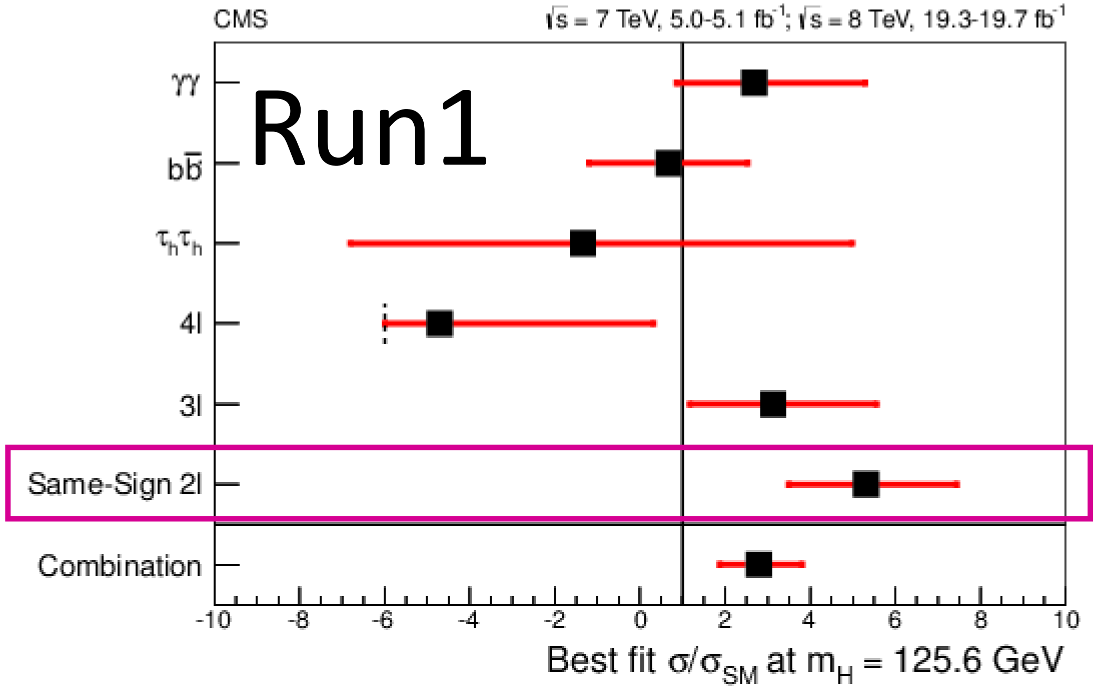
ttH, multi-lepton

CMS: HIG-17-003
HIG-17-004

2 same sign leptons

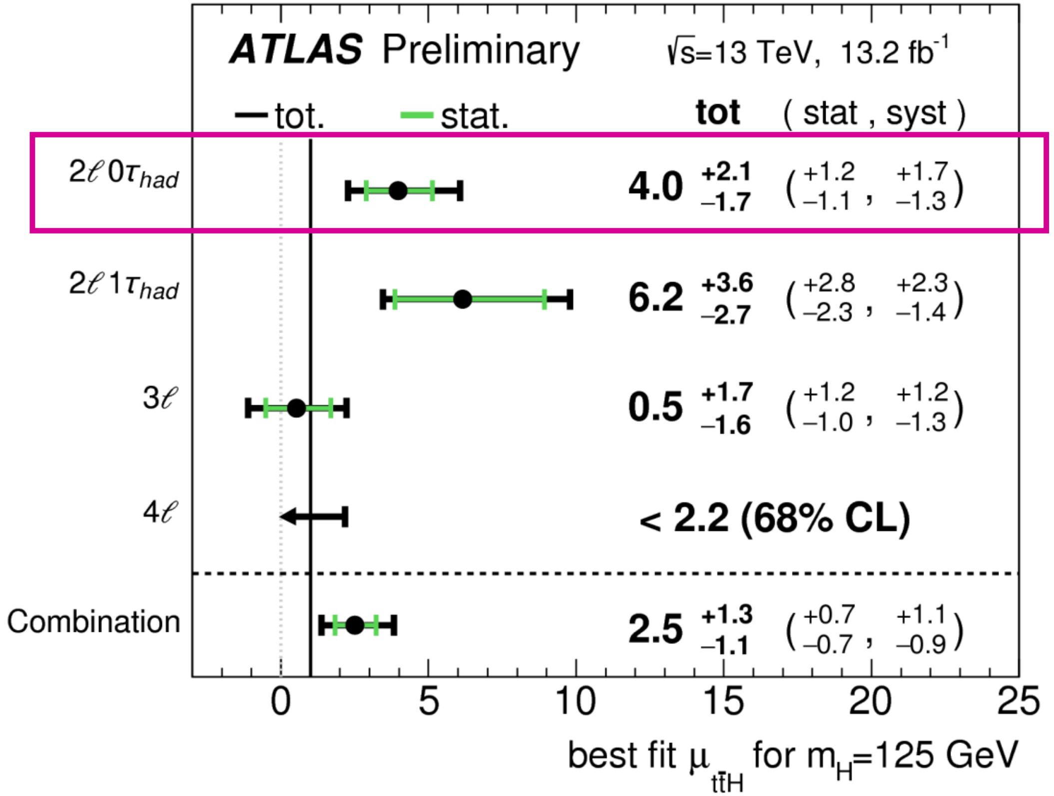
- Run1では大きなsignal strengthが
- ATLASでも大きい

arXiv:1408.1682



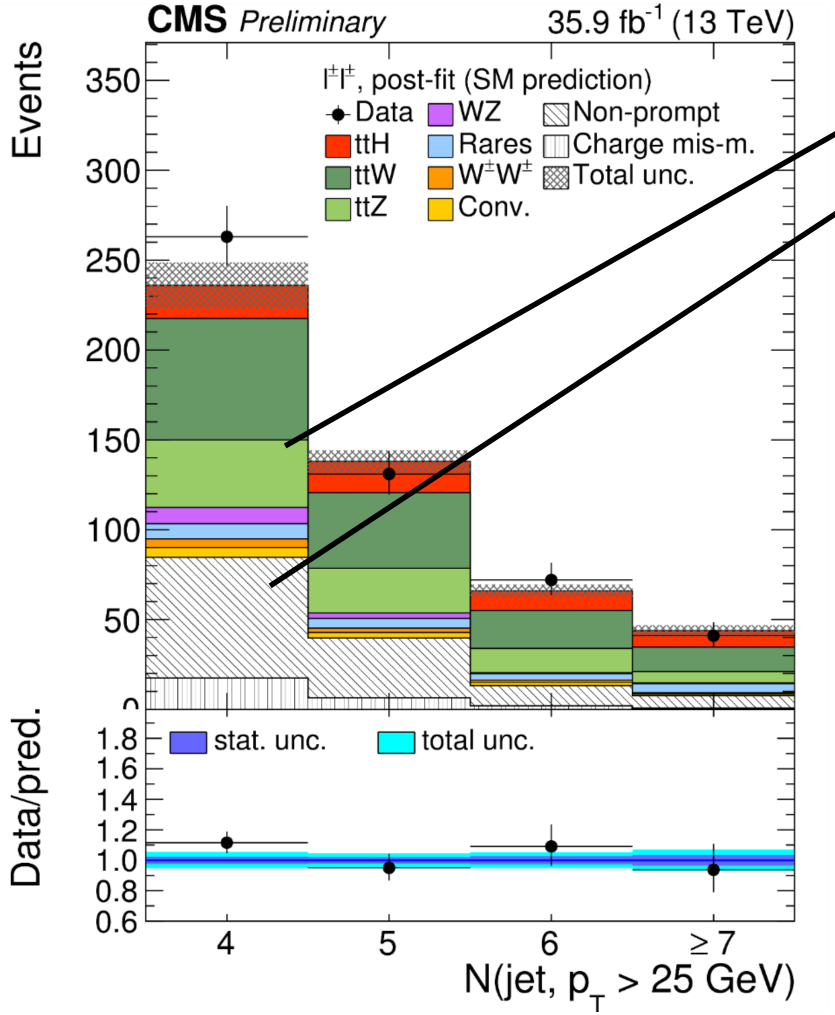
ATLAS ICHEP2016

ATLAS-CONF-2016-058



ttH, multi-lepton

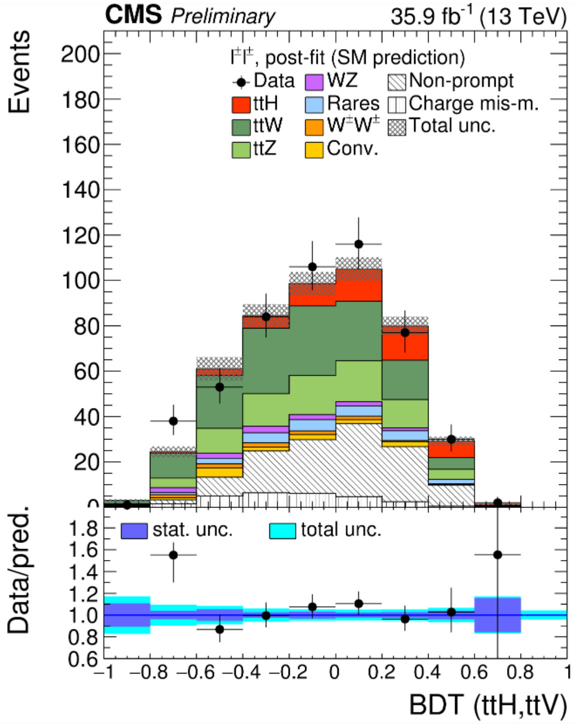
CMS: HIG-17-003
HIG-17-004



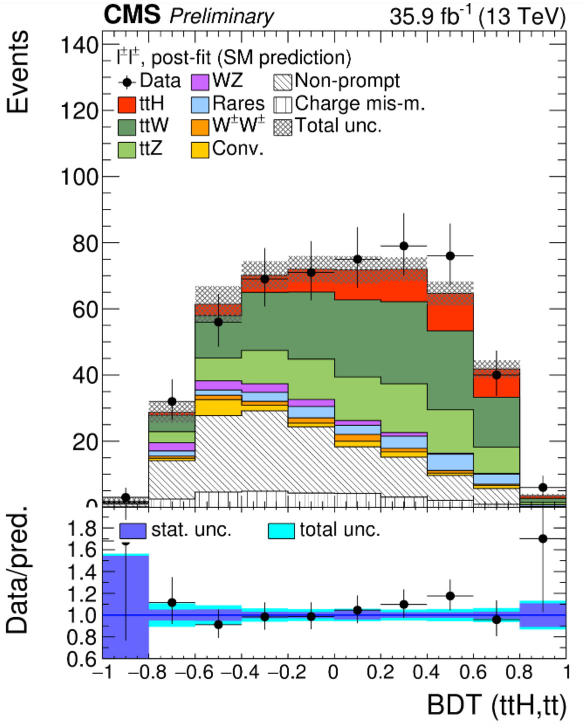
2 same sign leptons

- main BG
  - *tt* + *W*/*Z*/*γ**: irreducible, MCから見積もり
  - *tt* + jets: jetがleptonにfake, reducible, data-drivenで見積もり
- 効率の良いBG除去のため、2種のBDTを使用
  - top tagging等をinput

tt + *W*/*Z*/*γ**用BDT



tt + jets用BDT

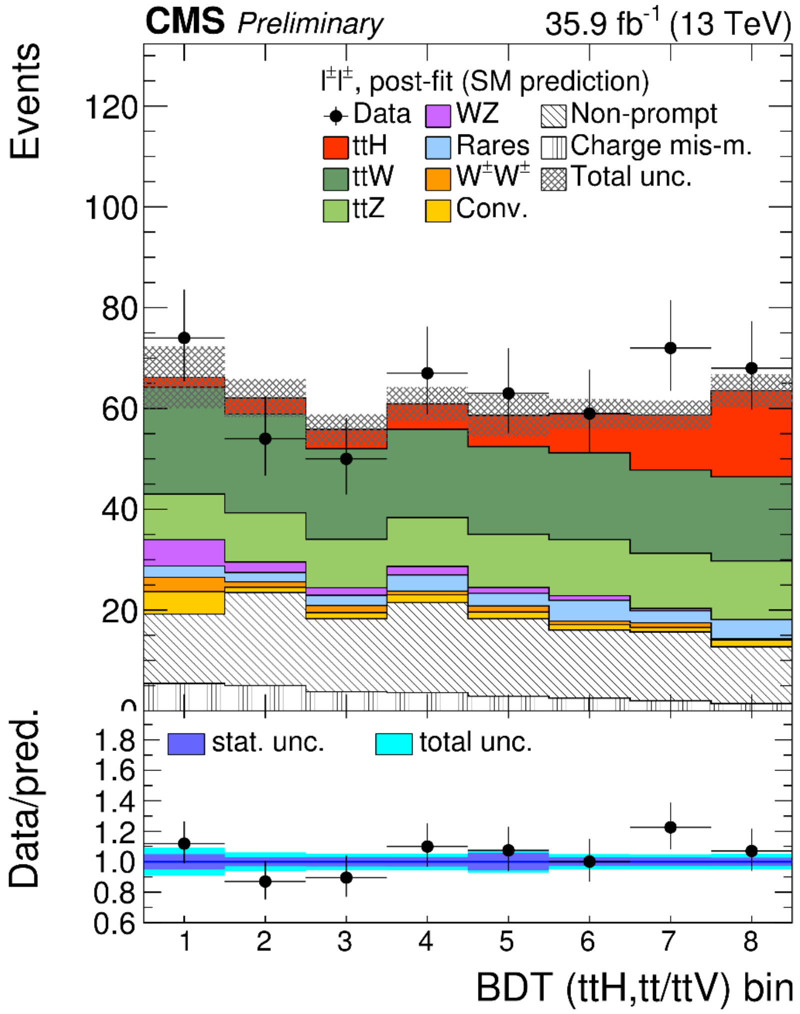


ttH, multi-lepton

CMS: HIG-17-003
HIG-17-004

2 same sign leptons

- 2D BDTを1Dに変換: final discriminant



hadronic tauを含まない終状態の結果

- discovery significance: 3.3σ (2.4σ) obs. (exp.)
- signal strength

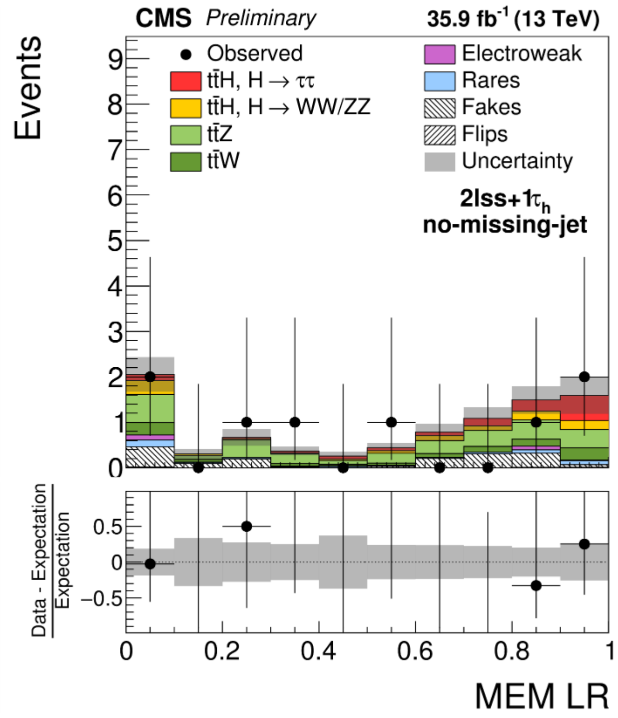
	obs.	exp.
2 same sign leptons	$1.7^{+0.6}_{-0.5}$	$1.0^{+0.5}_{-0.5}$
3 leptons	$1.0^{+0.8}_{-0.7}$	$1.0^{+0.8}_{-0.7}$
4 leptons	$0.9^{+2.3}_{-1.6}$	$1.0^{+2.4}_{-1.6}$
combined	$1.5^{+0.5}_{-0.5}$	$1.0^{+0.5}_{-0.4}$

ttH, multi-lepton

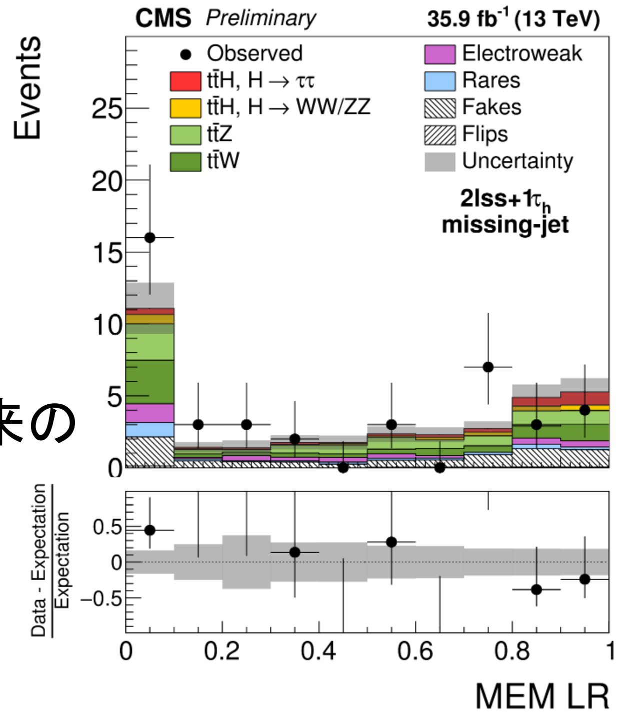
CMS: HIG-17-003
HIG-17-004

2 same sign leptons + 1 τ_{had}

- main BG
  - $tt + W/Z/\gamma^*$: irreducible, MCから見積もり
  - tt + jets: jetがτ_{had}にfake, reducible, data-drivenで見積もり (fake factor)
- matrix element method (MEM) でttVを分離
- MEMでlikelihood ratio (LR) を計算: final discriminant



no-missing-jet: ν以外の
全終状態粒子が再構成



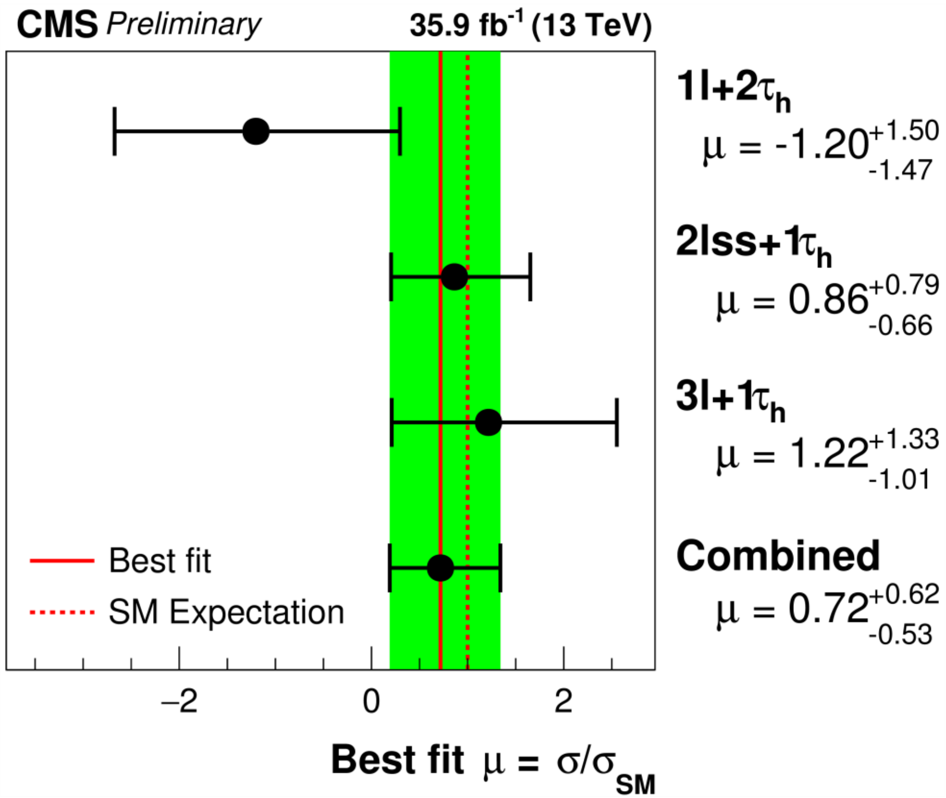
missing-jet: W由来の
jetがmissing

ttH, multi-lepton

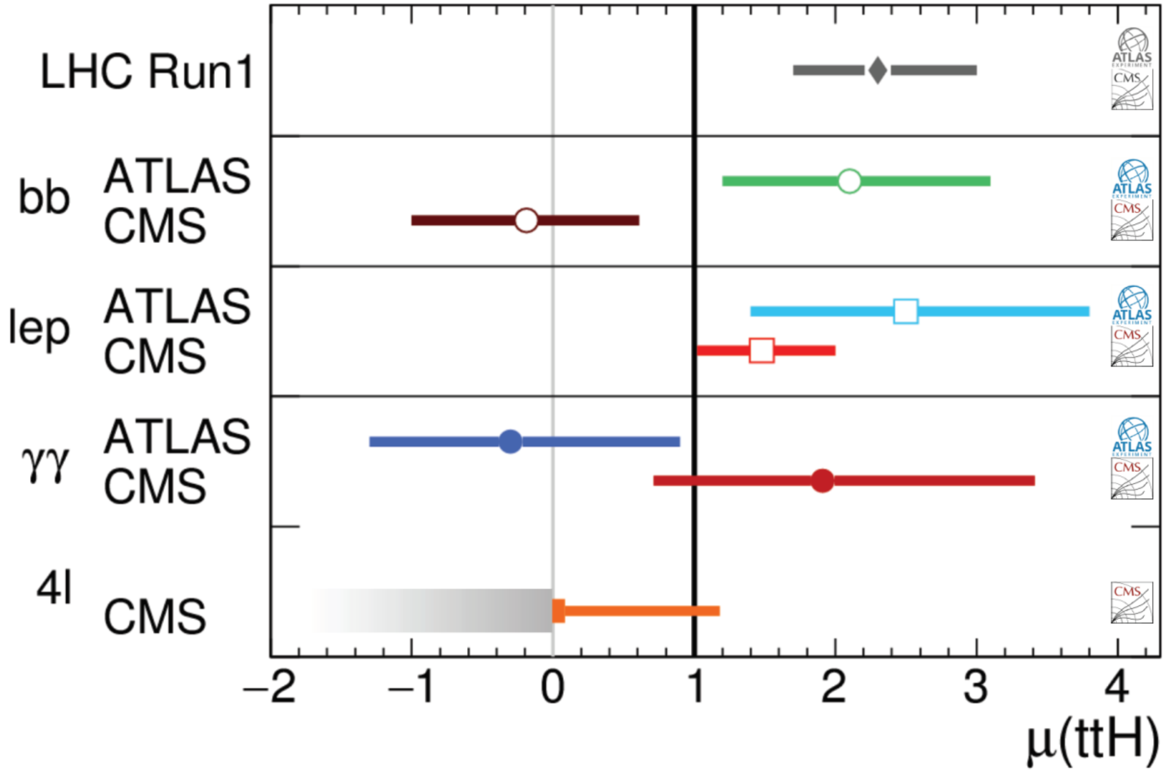
CMS: HIG-17-003
HIG-17-004

hadronic tauを含む終状態の結果

- discovery significance: 1.4 σ (1.8 σ) obs. (exp.)
- signal strength



- ttH summary



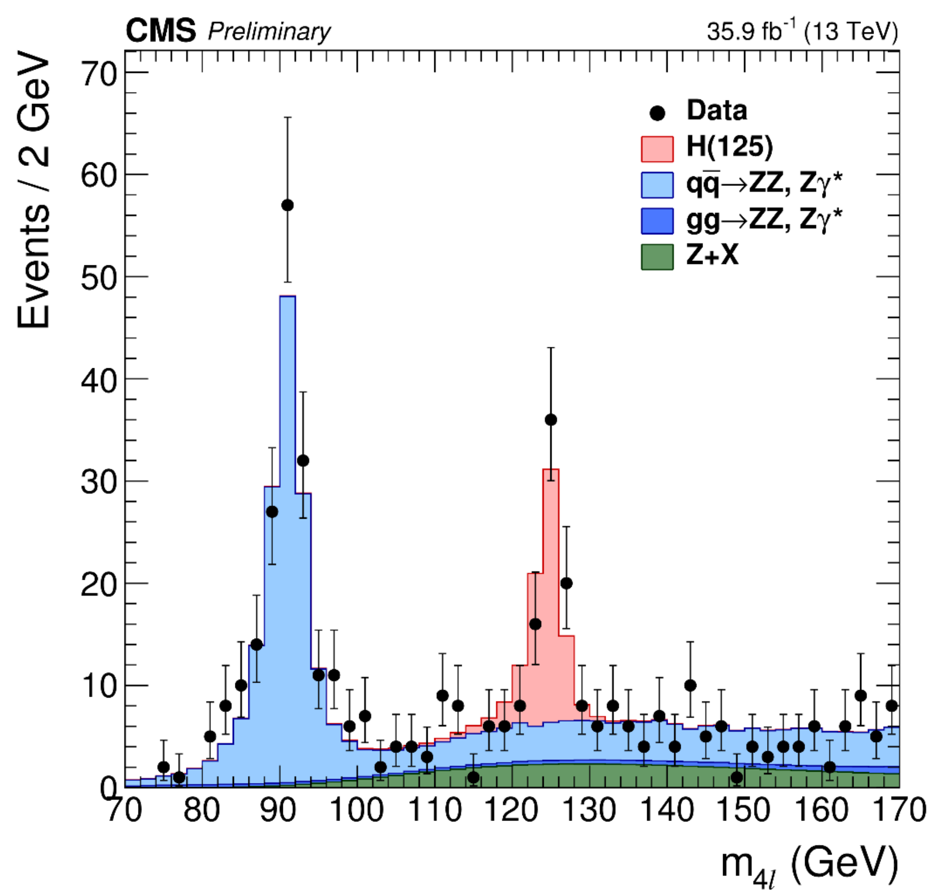
Run1で見られたexcessは今回の結果では見られなかった

CMS: HIG-16-041

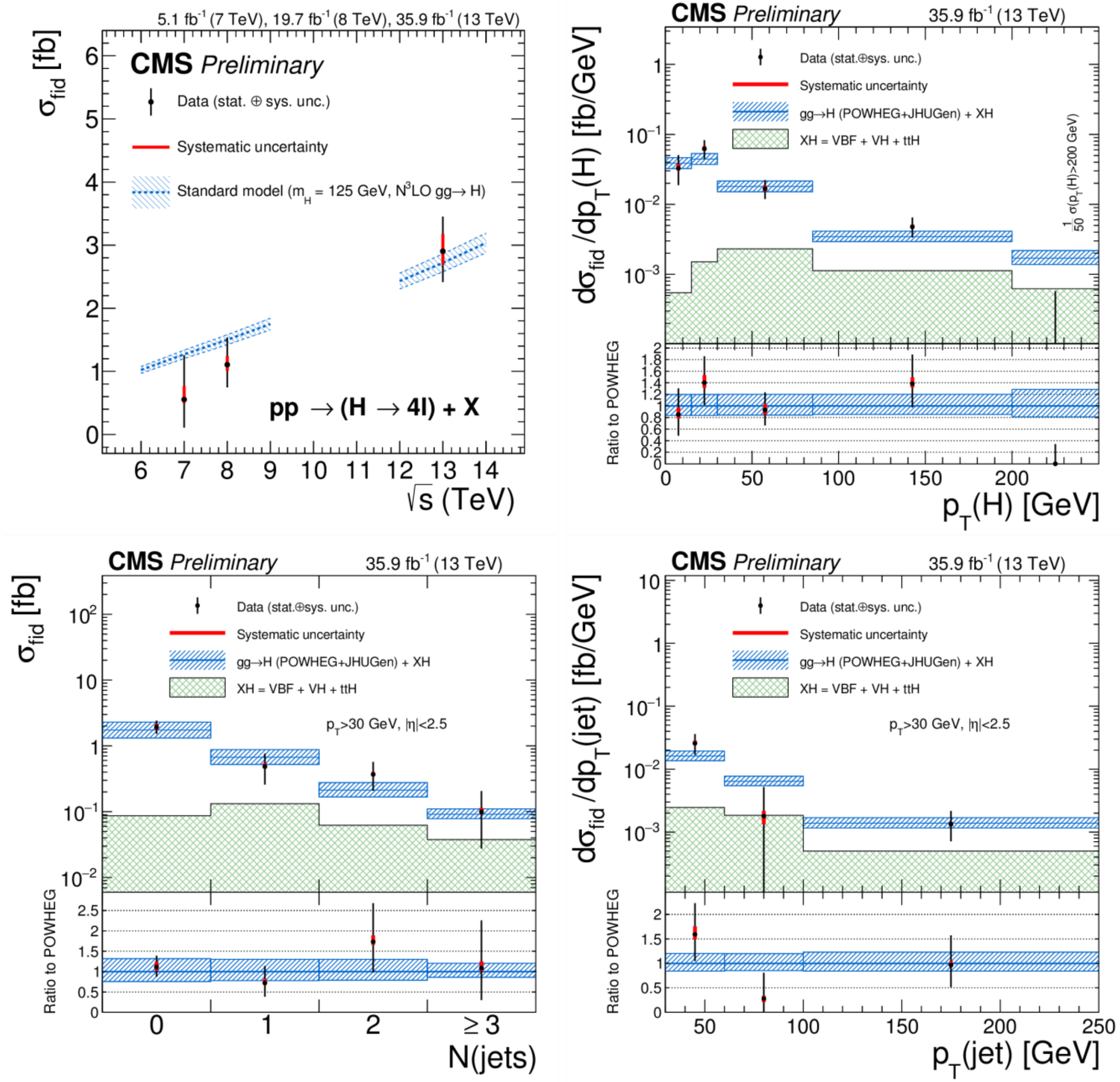
$h \to ZZ \to 4\ell$

differential cross section

クリーンなHiggs signal sampleを使って性質測定

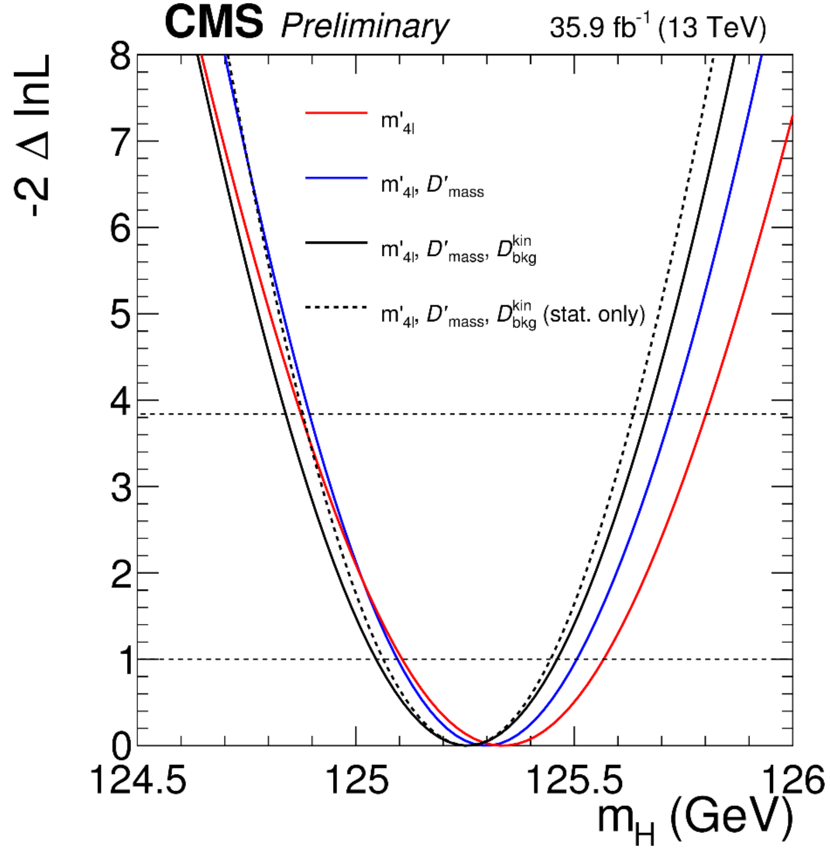


$$\mu = 1.05^{+0.15}_{-0.14}\,(\mathrm{stat.})^{+0.11}_{-0.09}\,(\mathrm{syst.})$$

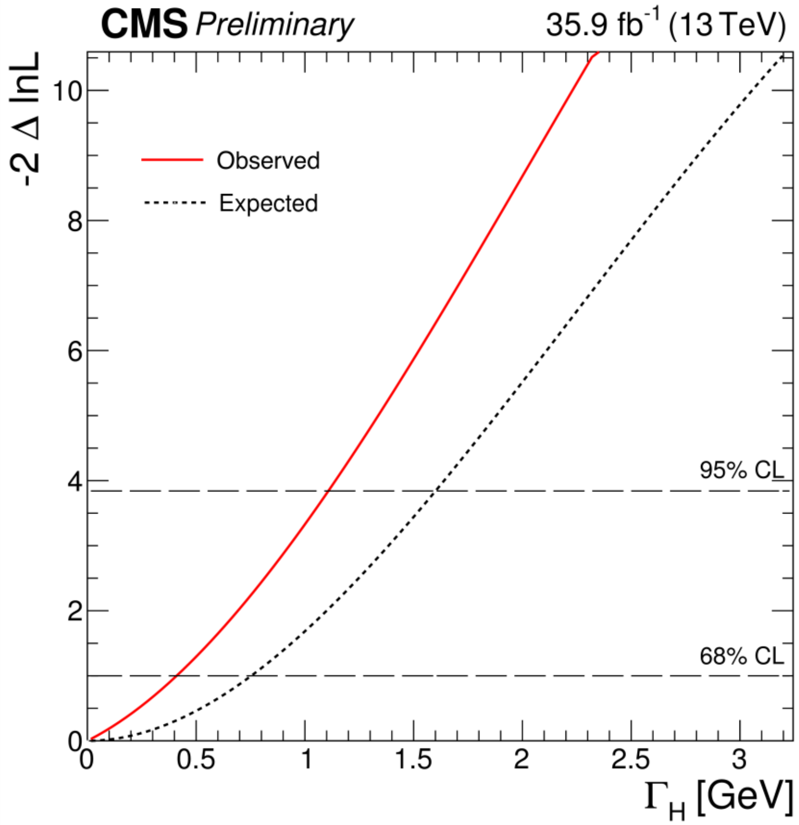


$h \to ZZ \to 4\ell$

mass測定



width測定



- event-by-eventのmass uncertainty
- matrix elementから計算された、signalらしさ

を考慮することで、精度を11 %向上

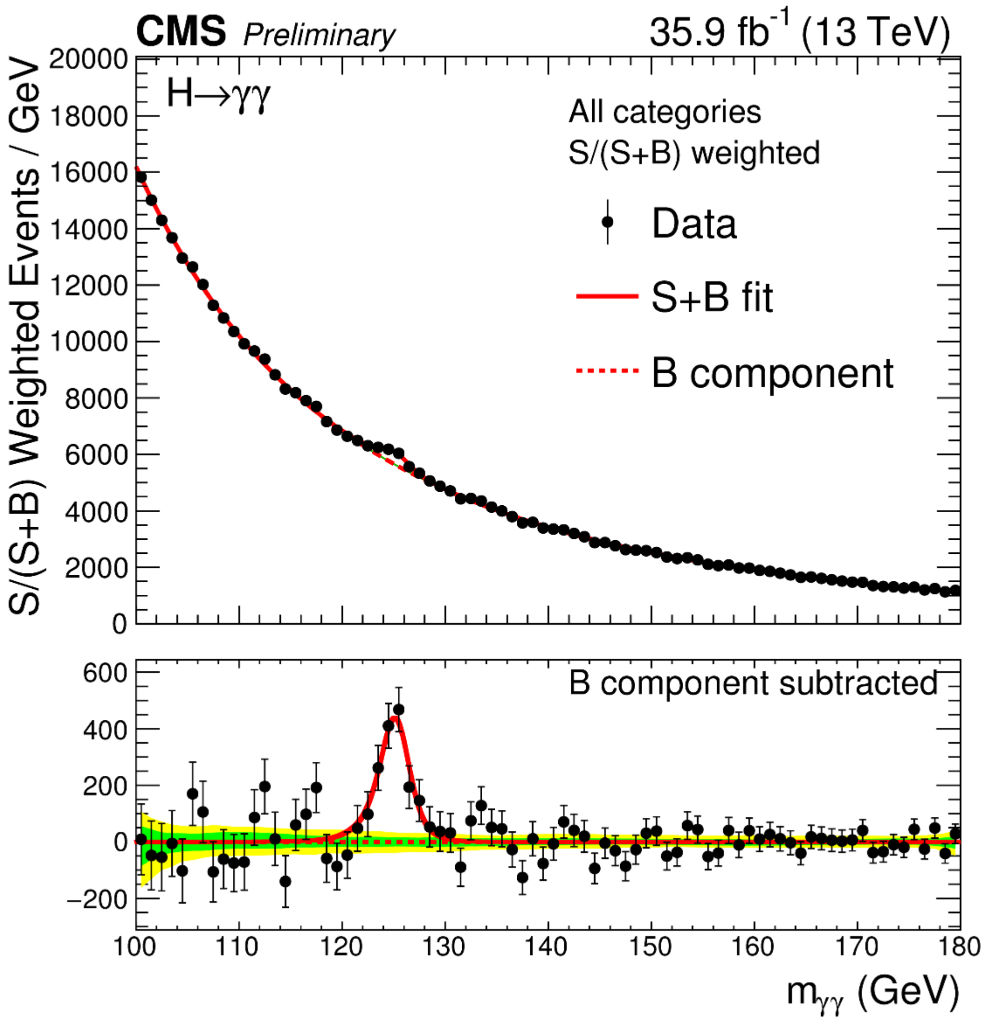
$$m_H = 125.26 \pm 0.20\,(\text{stat.}) \pm 0.08 \text{ GeV}$$

- Higgs peakで直接測定
- model independent

$$\Gamma_H = 0.00 \begin{array}{l} +0.41 \\ -0.00 \end{array} \text{GeV}$$

CMS: HIG-17-015

$h \to \gamma\gamma$

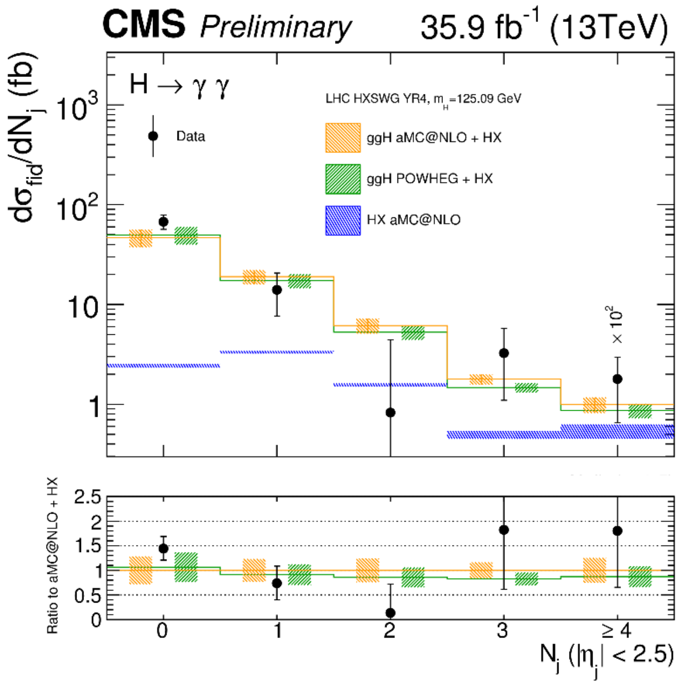


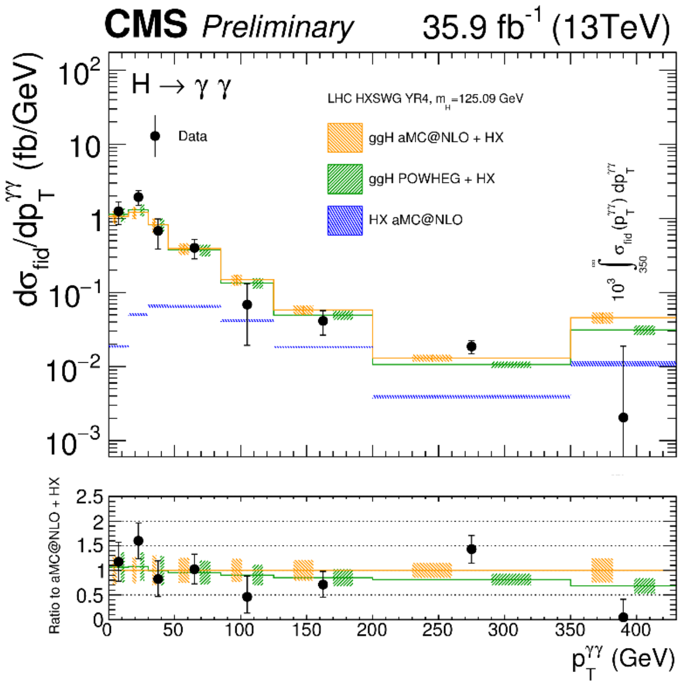
fiducial cross section

$$\sigma_{\text{fiducial}} = 84 \pm 11\,(\text{stat.}) \pm 7\,(\text{syst.})\text{ fb}$$

$$\sigma_{\text{fiducial}}^{\text{theory}} = 75 \pm 4\text{ fb}$$

differential cross section



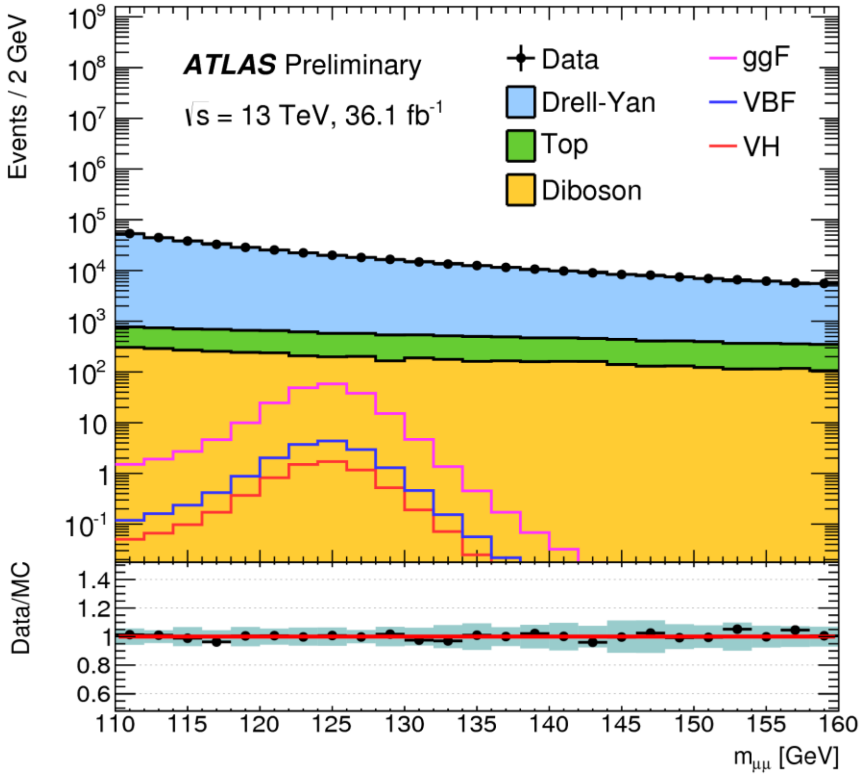


NLOとよく一致

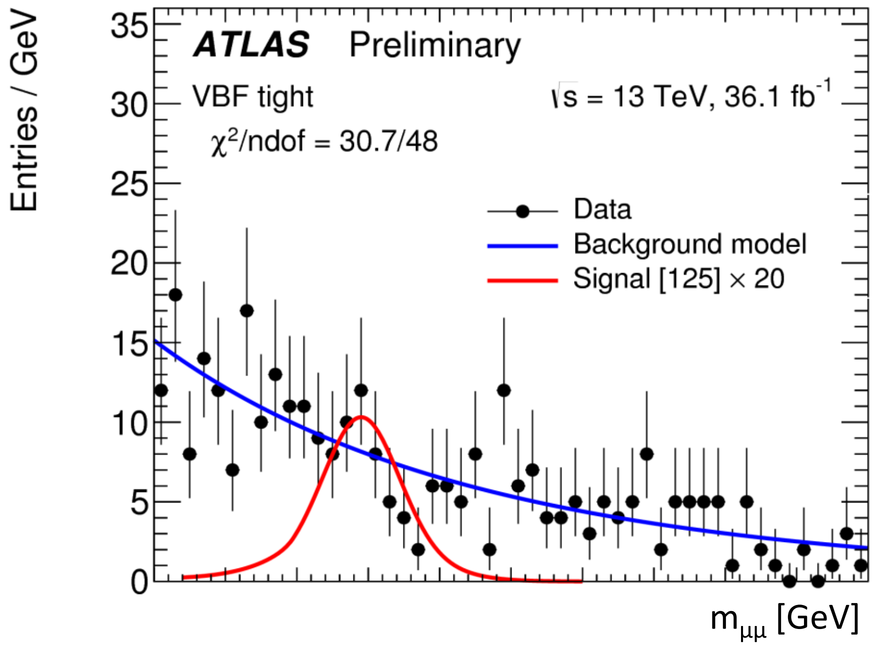
$h \to \mu\mu$

ATLAS: ATLAS-CONF-2017-014

- muonとの湯川結合探索
- BR ~2.18 x 10^{-4}
- $m_{\mu\mu}$を使って多量のDrell-Yan BG上にHiggs peakを探す
  - mass resolution < 2 GeV
- ggFとVBFをtargetに
  - ggF: Higgs p_Tでカテゴリー分け
  - VBF: BDTでカテゴリー分け



VBF categoryは感度高



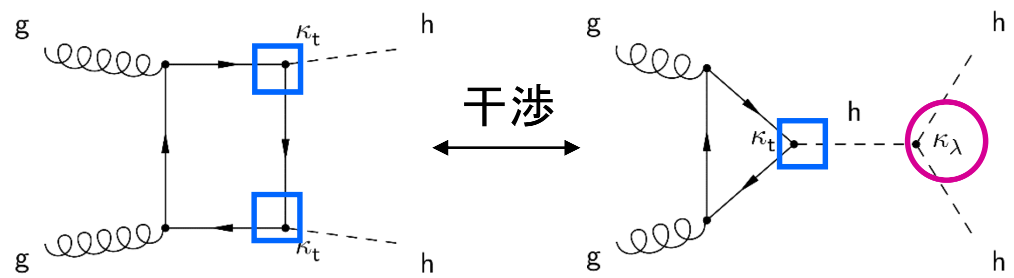
	95 % upper limit obs.	95 % upper limit exp.	signal strength
Run2	3.0	3.1	-0.1 ± 1.5
Run1+2 comb.	2.8	2.9	-0.1 ± 1.4

$hh \to bb\ell\nu\ell\nu$

CMS: HIG-17-006

self coupling!

- 標準理論でのdi-higgs cross section: $\sigma_{\mathrm{NNLO}}^{hh} = 33$ fb
  - 今の統計ではBSM search
- $bb\ell\nu\ell\nu$ channel: シグナル数大, 多量のttbar BG…
  - どう落とす？ → Deep Neural Network (DNN)



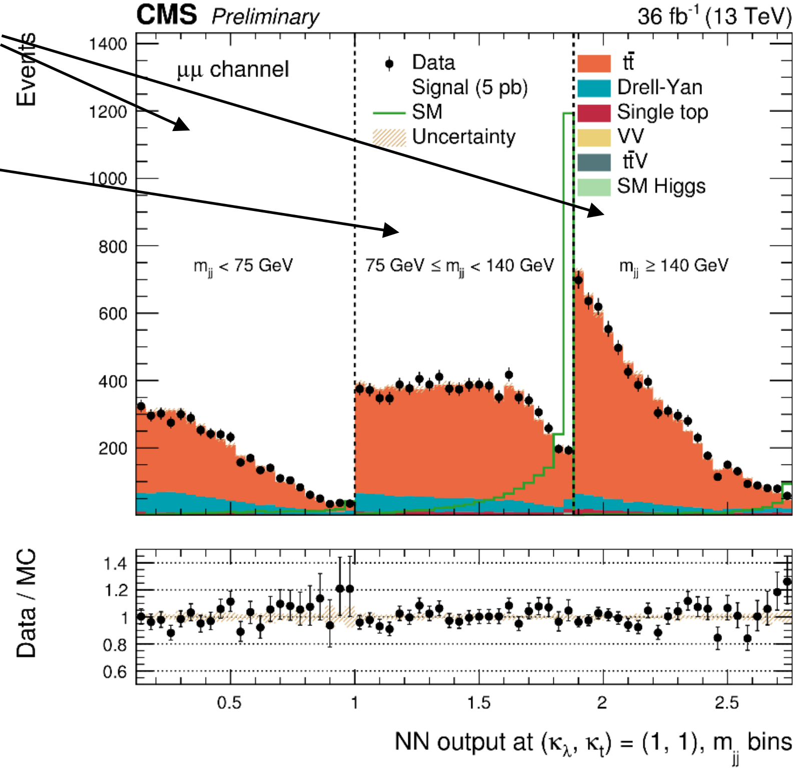
non-resonance 用DNN

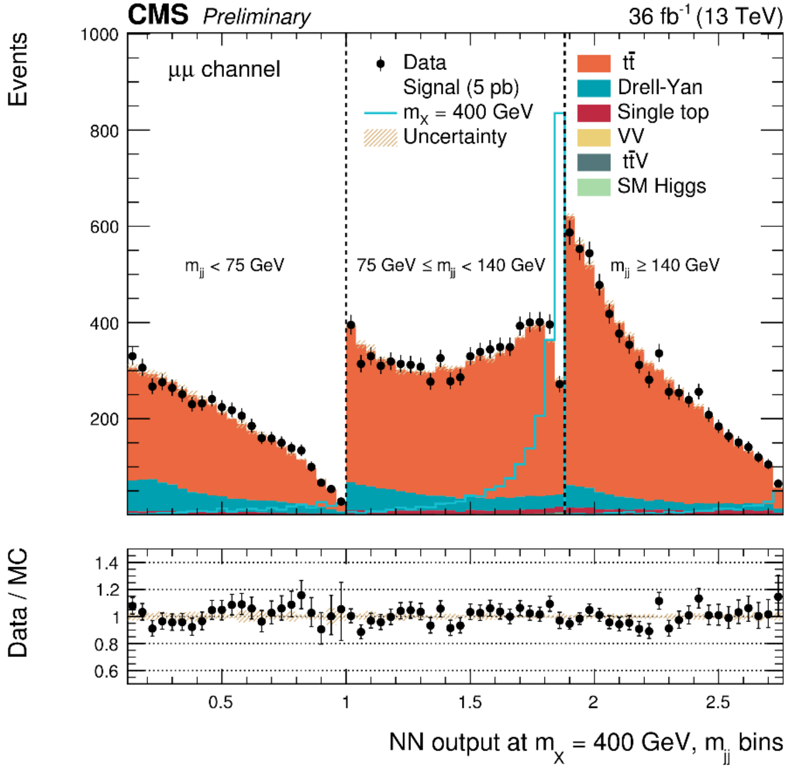
resonance (X → *hh*) 用DNN

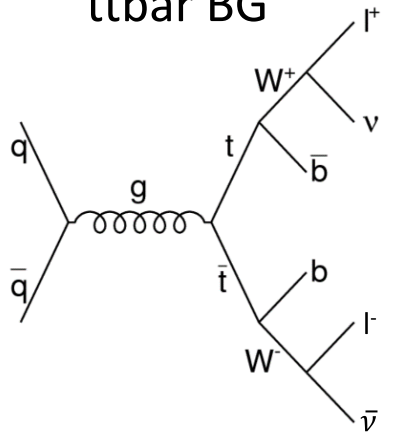
ttbar BG

m_{bb} side-band

$m_{bb} \sim m_H$



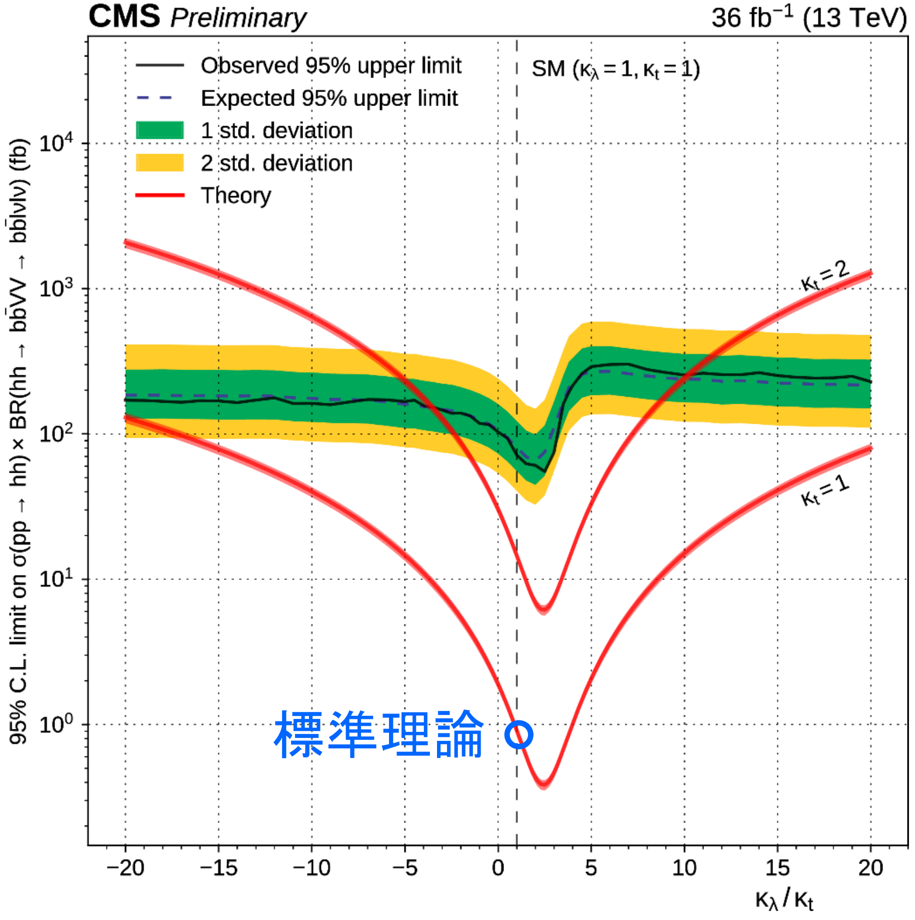




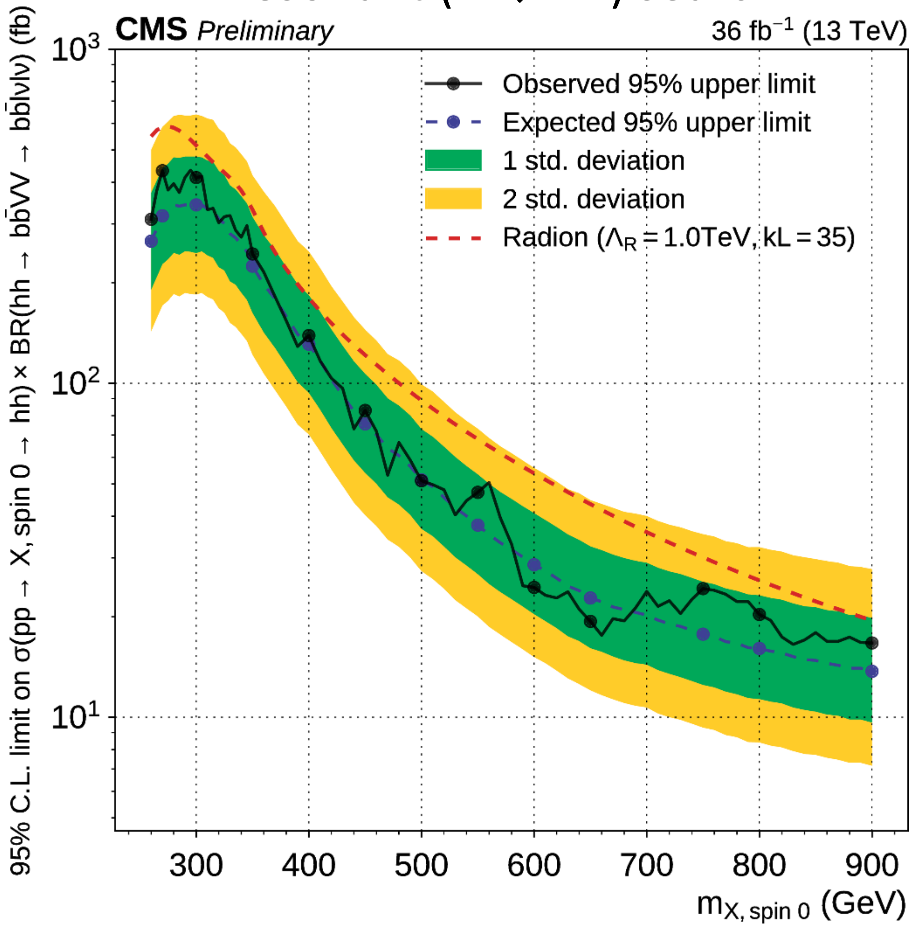
$hh \to bb\ell\nu\ell\nu$

CMS: HIG-17-006

non-resonant search



resonant (X → hh) search



標準理論に対して $\sigma_{hh}/\sigma_{\text{SM}} < 79$ (89) obs. (exp.)

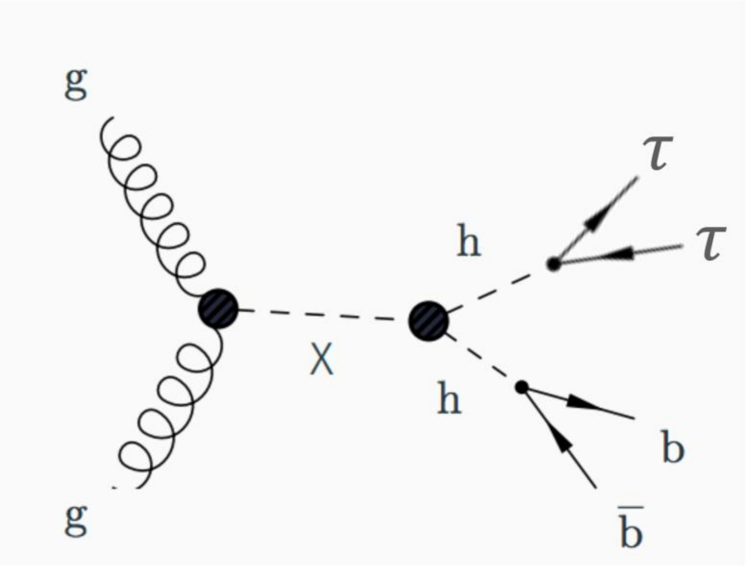
no excess

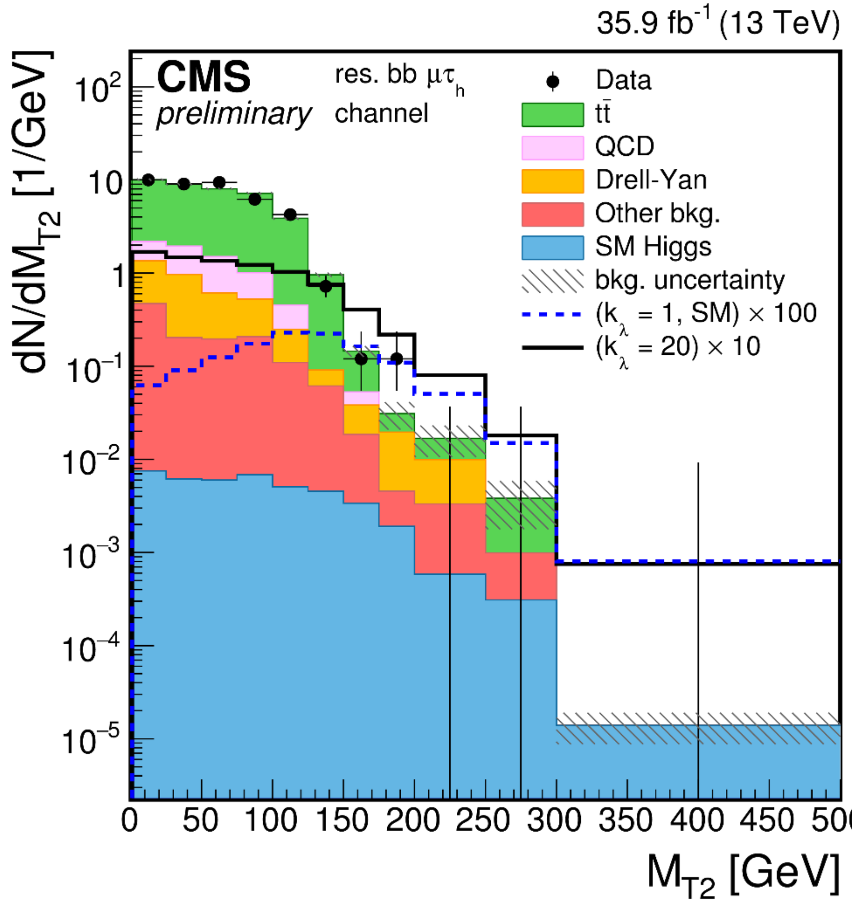
$hh \to bb\tau\tau$

- $bb\ell\nu\ell\nu$に比べてシグナル少、クリーン
- BDT cut → ttbar除去
- $m_{\tau\tau}$, m_{bb} cut
- non-resonant search
  - stransverse mass: $M_{T2} = \min_{p_T^{\tau}+p_T^{\tau'}=p_T^{\Sigma}} \{\max(m_T, m'_T)\}$

$p_T^{\tau} + p_T^{\tau'} = p_T^{\Sigma}$ のconstraintで τ momentumを振って最少を探す

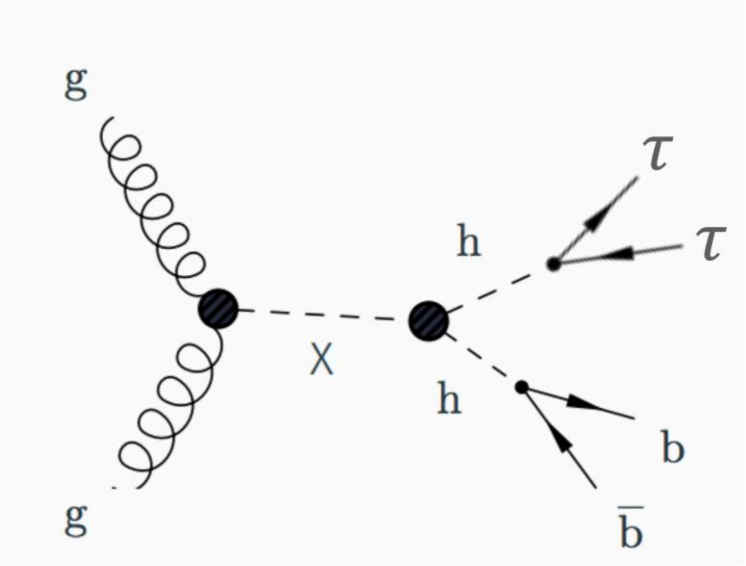
p_T^{τ}: neutrinoを考慮したτ momentum
m_T: τとbで組んだtransverse mass
$p_T^{\Sigma} = \mathrm{MET} + p_T^{\mathrm{vis}}(\tau) + p_T^{\mathrm{vis}}(\tau')$

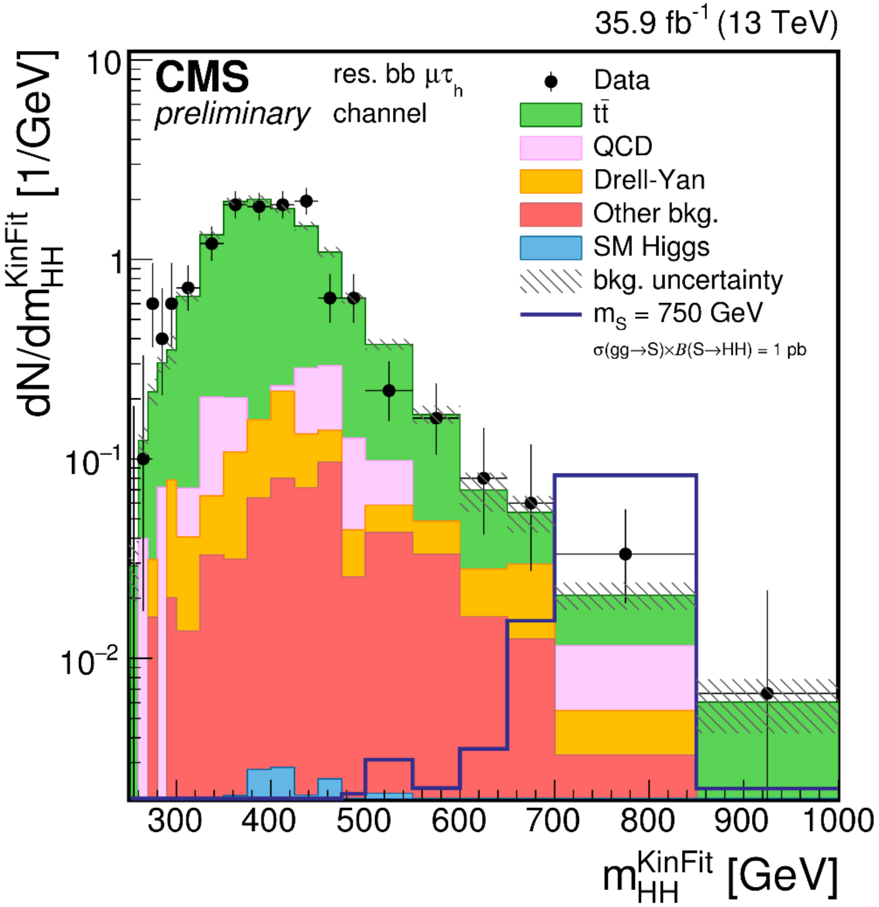




$hh \rightarrow bb\tau\tau$

- $bb\ell\nu\ell\nu$に比べてシグナル少、クリーン → ゴールデンチャンネル！
- BDT cut → ttbar除去
- $m_{\tau\tau}$, m_{bb} cut
- resonant search
  - m_{hh}^{KinFit}: kinematic fitでresolutionを向上させたm_{hh}

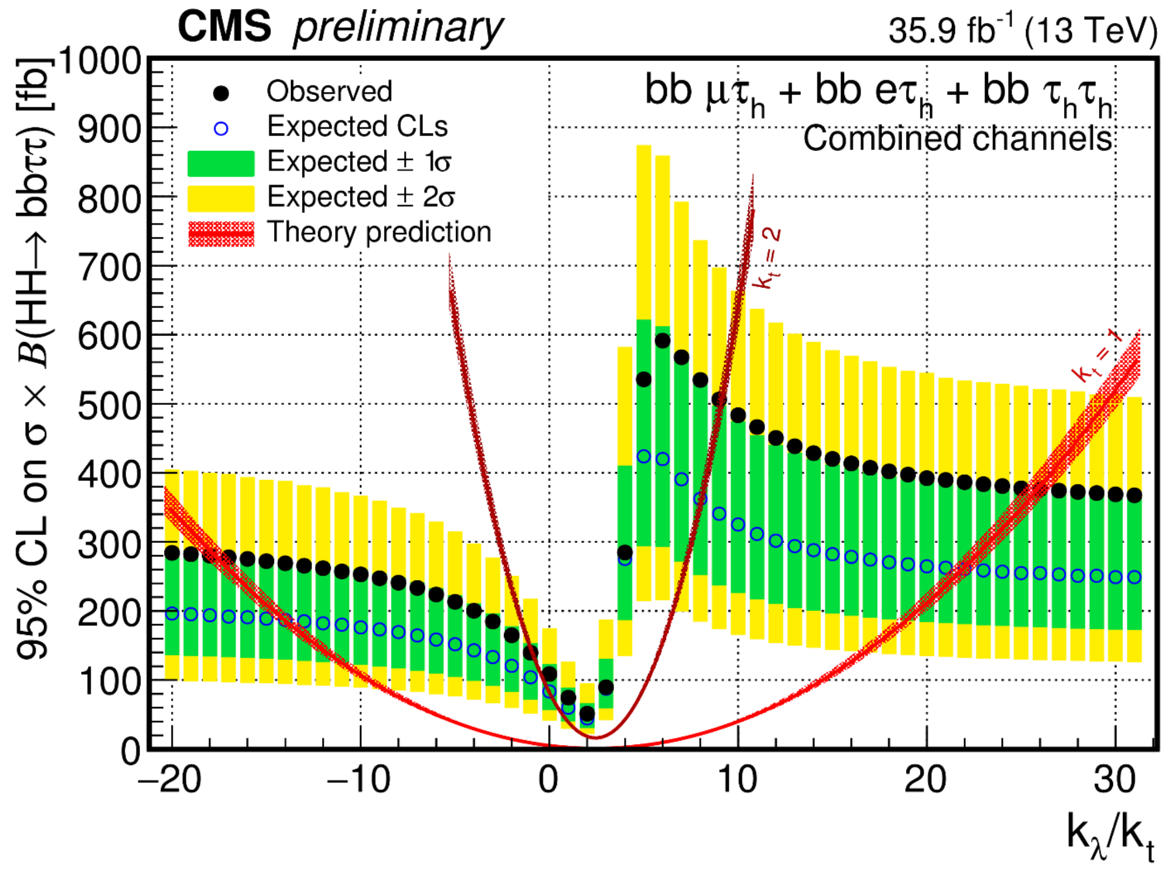




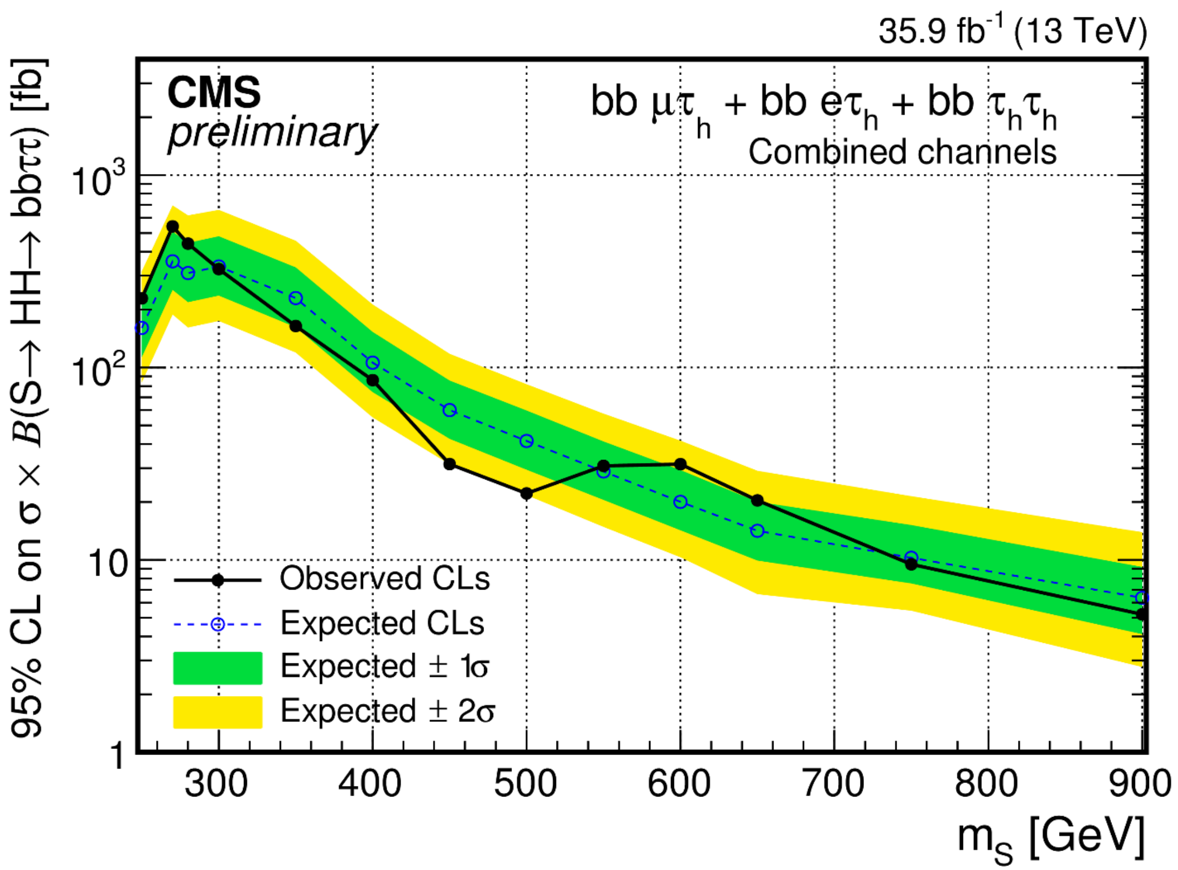
$hh \to bb\tau\tau$

CMS: HIG-17-002

non-resonant search



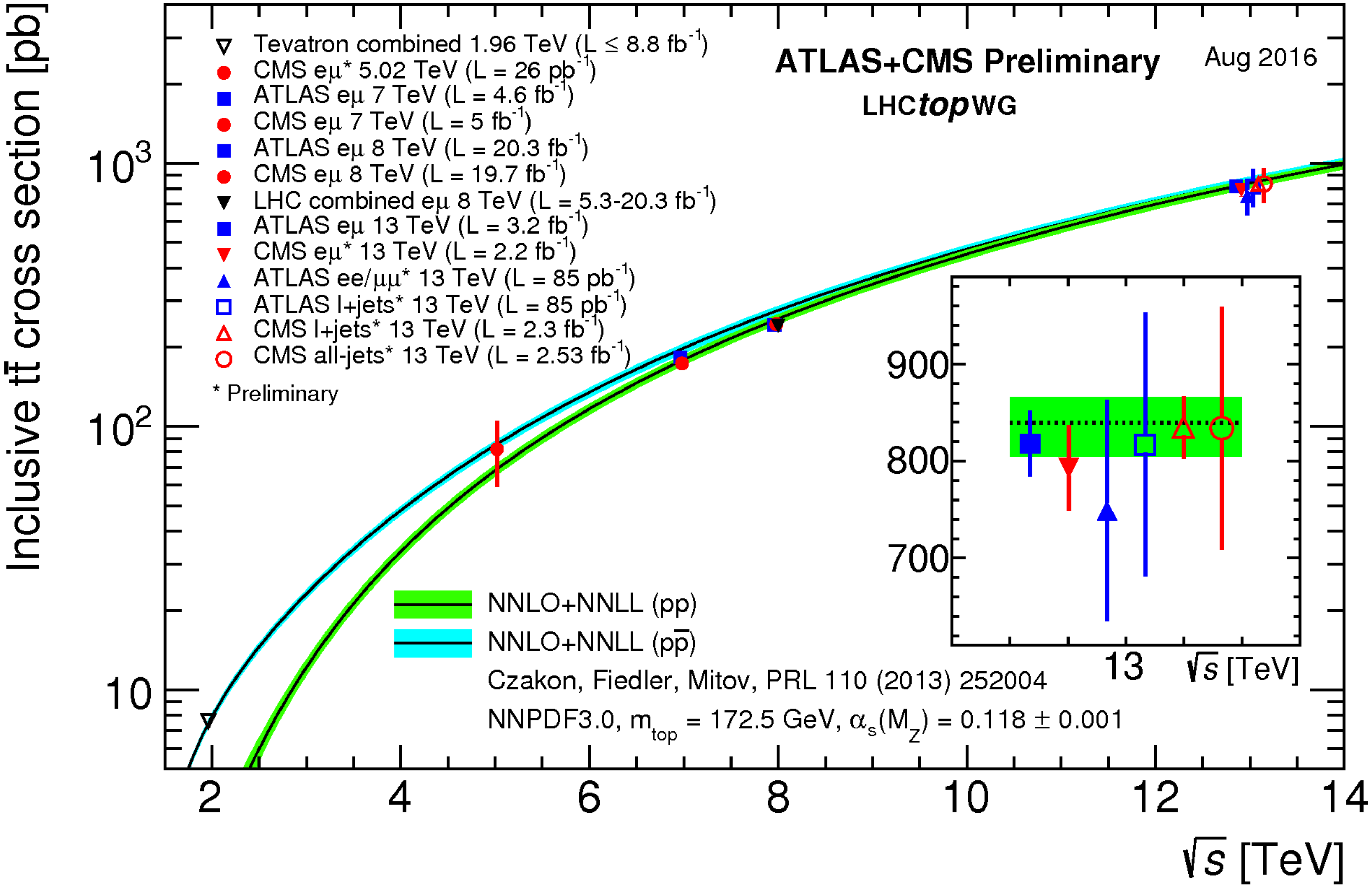
resonant (X → *hh*) search



標準理論に対して $\sigma_{hh}/\sigma_{\mathrm{SM}} < 28$ (25) obs. (exp.)

no excess

backup



Inclusive tt̄ cross section [pb]
Tevatron combined 1.96 TeV (L ≤ 8.8 fb-1)
CMS eμ* 5.02 TeV (L = 26 pb-1)
ATLAS eμ 7 TeV (L = 4.6 fb-1)
CMS eμ 7 TeV (L = 5 fb-1)
ATLAS eμ 8 TeV (L = 20.3 fb-1)
CMS eμ 8 TeV (L = 19.7 fb-1)
LHC combined eμ 8 TeV (L = 5.3-20.3 fb-1)
ATLAS eμ 13 TeV (L = 3.2 fb-1)
CMS eμ* 13 TeV (L = 2.2 fb-1)
ATLAS ee/μμ* 13 TeV (L = 85 pb-1)
ATLAS l+jets* 13 TeV (L = 85 pb-1)
CMS l+jets* 13 TeV (L = 2.3 fb-1)
CMS all-jets* 13 TeV (L = 2.53 fb-1)
* Preliminary
ATLAS+CMS Preliminary
Aug 2016
LHCtopWG
NNLO+NNLL (pp)
NNLO+NNLL (pp̄)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
NNPDF3.0, m_top = 172.5 GeV, α_s(M_Z) = 0.118 ± 0.001
√s [TeV]

Run1 LHC comb.	$2.3^{+1.2}_{-1.0}$	
	ATLAS Run2	CMS Run2
bb	$2.1^{+1.0}_{-0.9}$	$-0.2^{+0.8}_{-0.8}$
multi-lepton	$2.5^{+1.3}_{-1.1}$	$1.5^{+0.5}_{-0.5}$
ττ	-	$0.7^{+0.6}_{-0.5}$
γγ	$-0.3^{+1.2}_{-1.0}$	$1.9^{+1.5}_{-1.2}$
4ℓ	-	$0.0^{+1.2}_{-0.0}$
comb.	$1.8^{+1.2}_{-1.0}$	-