Higgs, SMの最新結果

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ATLAS EXPERIMENT

ICEPP The University of Tokyo

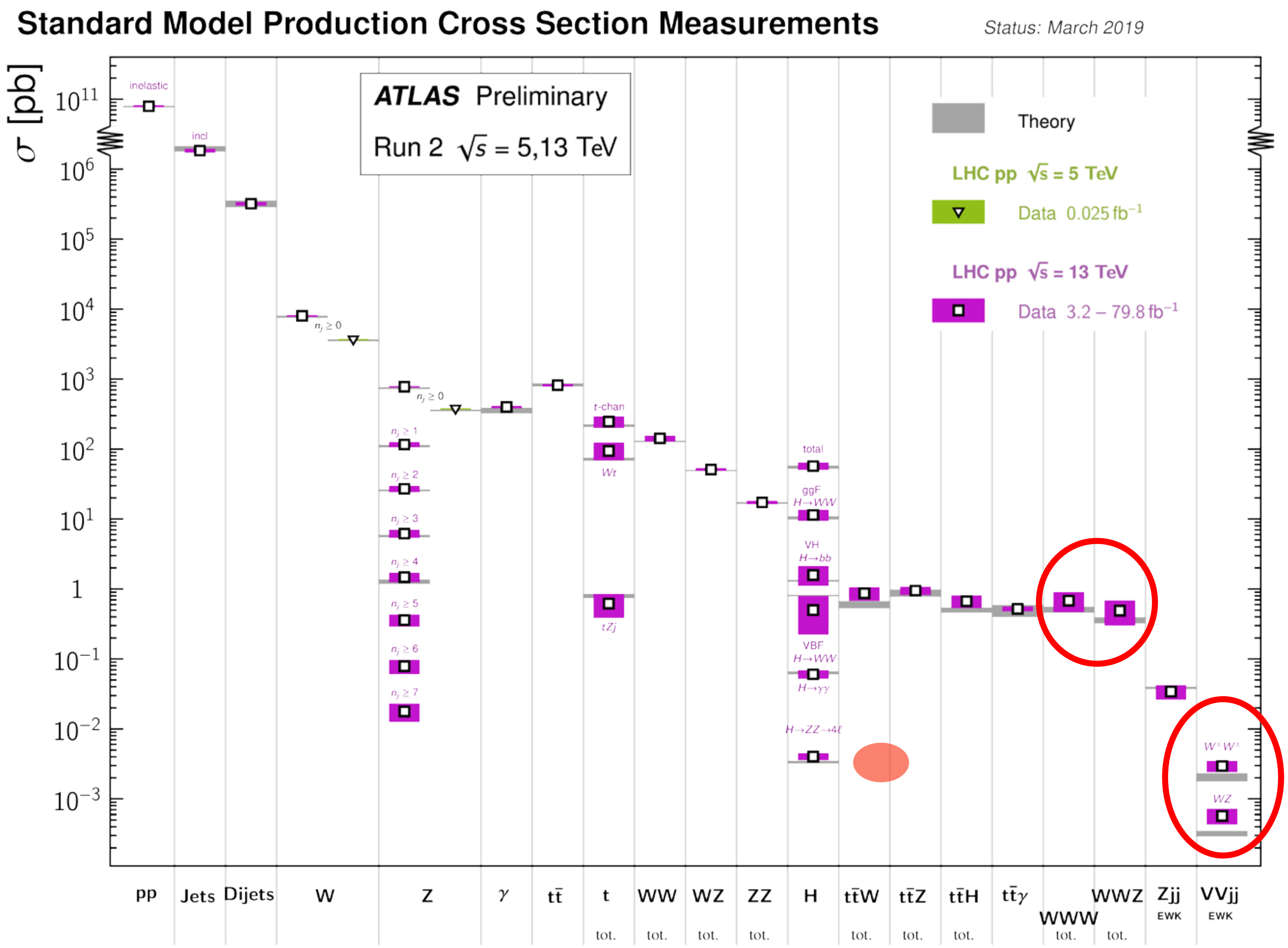
新テラスケール研究会　2019 June 8th

今日のトピック

- 興味深いStandard Model プロセス
  - マルチ-X
  - Top
- Higgs

SMプロセス　生成断面積

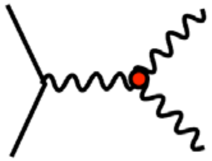
New for Moriond2019

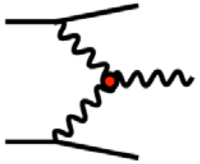


- Multi-boson
- Four tops?

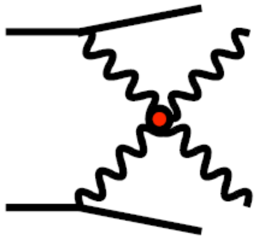
Rare Multi-boson production

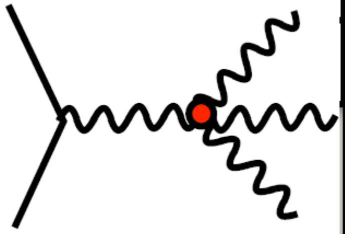
- Diboson and Vector Boson Fusion have Triple Gauge Coupling(TGC)





Now we can access Quartic Gauge Coupling(QGC)





Multiboson final states	CMS data analyzed (multi-lep)	ATLAS data analyzed (multi-lep)	CMS data analyzed (semi-lep)	ATLAS data analyzed (semi-lep)
VBS WW	36 fb^{-1}	36 fb^{-1}	36 fb^{-1}	36 fb^{-1}
VBS WZ	36 fb^{-1}	36 fb^{-1}	36 fb^{-1}	36 fb^{-1}
VBS ZZ	36 fb^{-1}	-	36 fb^{-1}	36 fb^{-1}
WWW	36 fb^{-1}	80 fb^{-1}	-	-
WWZ	-	80 fb^{-1}	-	-
WZZ	-	80 fb^{-1}	-	-
ZZZ	-	-	-	-

$l^{\pm}l^{\pm}\nu\nu$+jj

	Signif.	fiducial cross section
CMS	$5.5\sigma_{obs}$ $(5.7\sigma)_{exp}$	$3.83 \pm 0.66 \pm 0.35$ fb (stat) (syst)
ATLAS	$6.9\sigma_{obs}$ $(4.6\sigma)_{exp}$	$2.91^{+0.51}_{-0.47} \pm 0.27$ fb. (stat) (syst)

$l\nu ll$ + jj

	Signif.	fiducial cross section
CMS	$2.2\sigma_{obs}$ $(2.5\sigma)_{exp}$	Expected from MG5: $3.18\ ^{+0.57}_{-0.52}\ ^{+0.43}_{-0.36}$ fb (stat) (syst)
ATLAS	$5.3\sigma_{obs}$ $(3.2\sigma)_{exp}$	$0.57\ ^{+0.14}_{-0.13}\ ^{+0.07}_{-0.06}$ fb (stat) (syst)

Expected from Sherpa

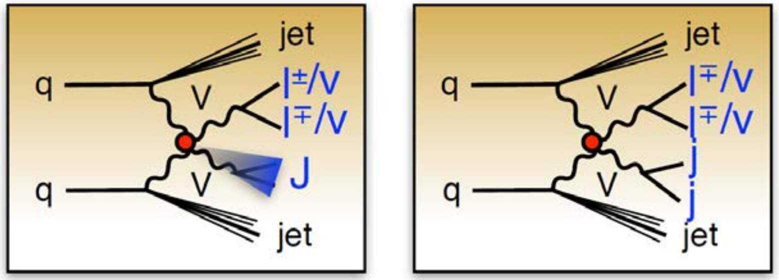
$llll$ + jj

	Signif.	fiducial cross section
CMS	2.7σ (1.6σ)	$0.40\ ^{+0.21}_{-0.16}\ ^{+0.13}_{-0.09}$ fb

P. Chang氏 LHCP2019でのスライドより

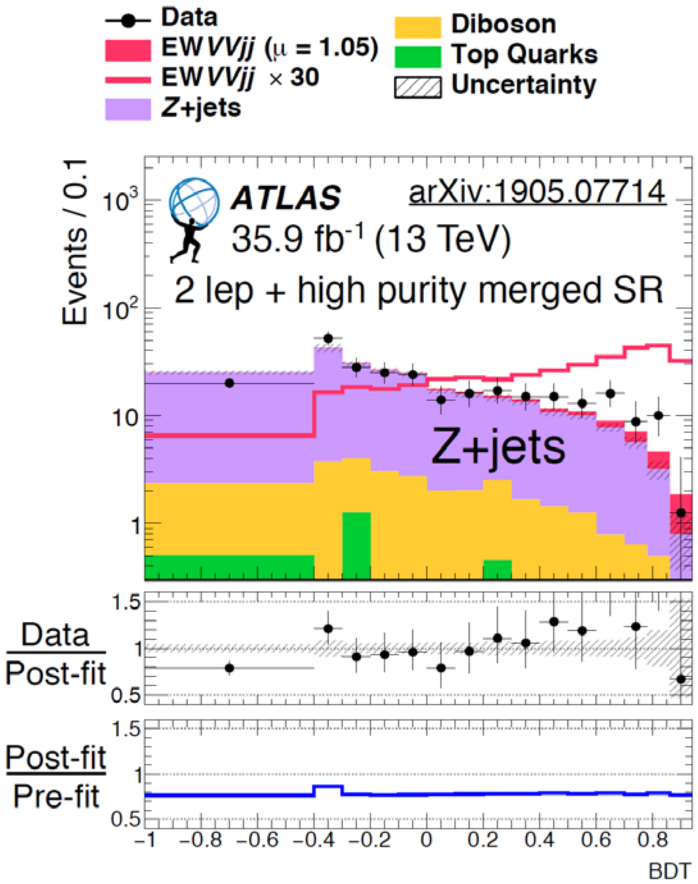
VBS semi-leptonic channel

New for Moriond2019



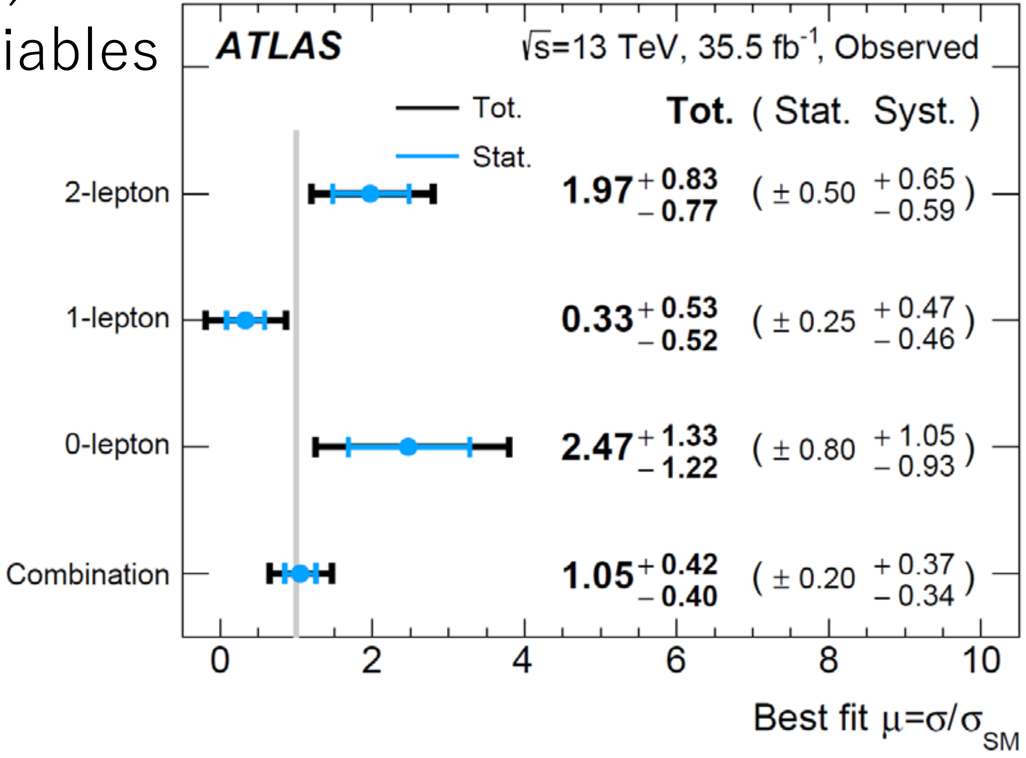
- V: W or Z
  - 0, 1, 2 lepton channel
- J: Large-R jet (R=1.0)
  - Use substructure variables to tag W or Z.

1905.07714



Multivariate Technique

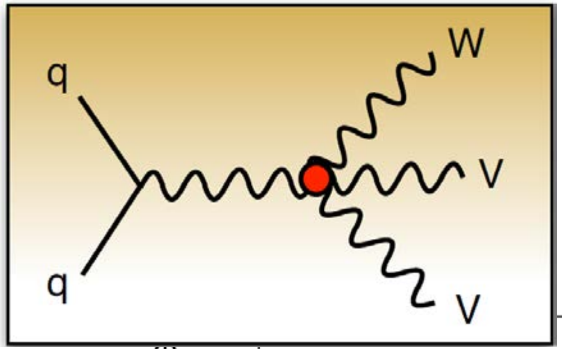
- Forward jets rapidity diff.
- leptonic boson
- Mass
- Quark-Gluon separation (Ntrk of Jets)



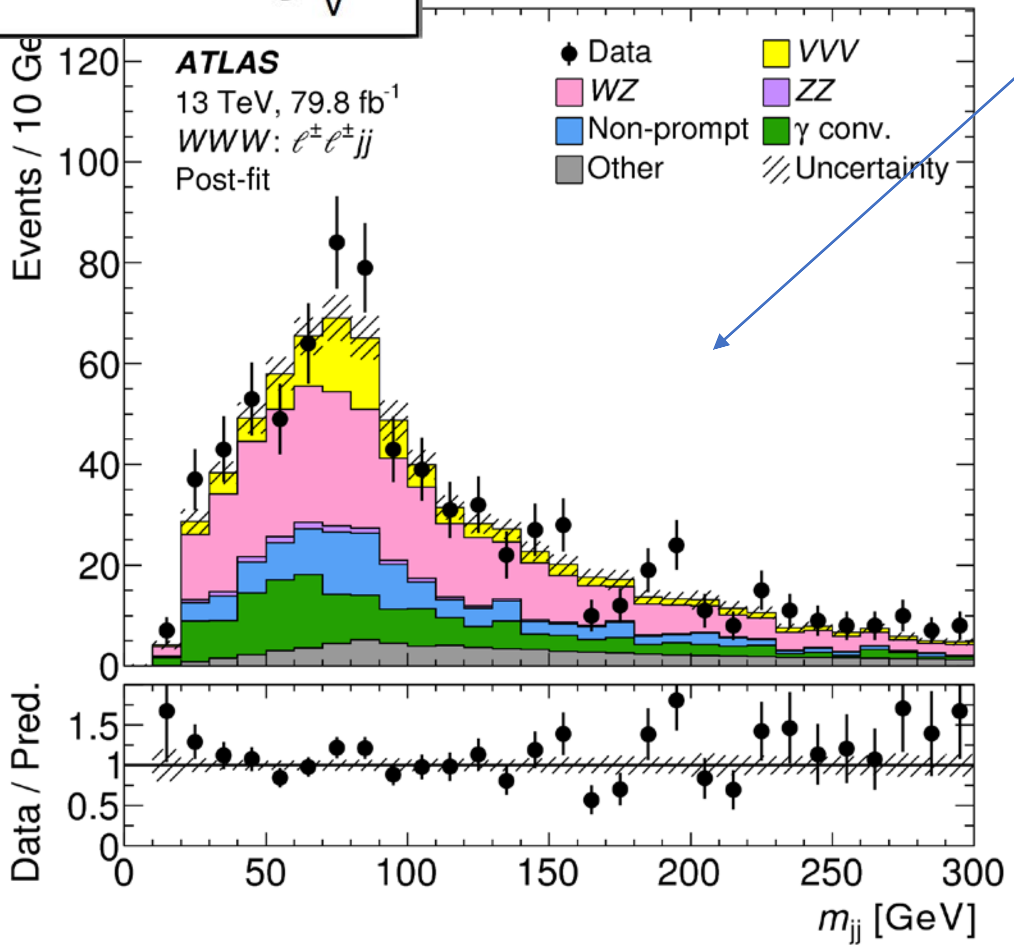
	Signif.	fiducial cross section
	$2.7\sigma_{obs}$ (2.5σ)$_{exp}$	$45.1 \pm 8.6\ ^{+15.9}_{-14.6}$ fb (stat) (syst)

Multi-boson production

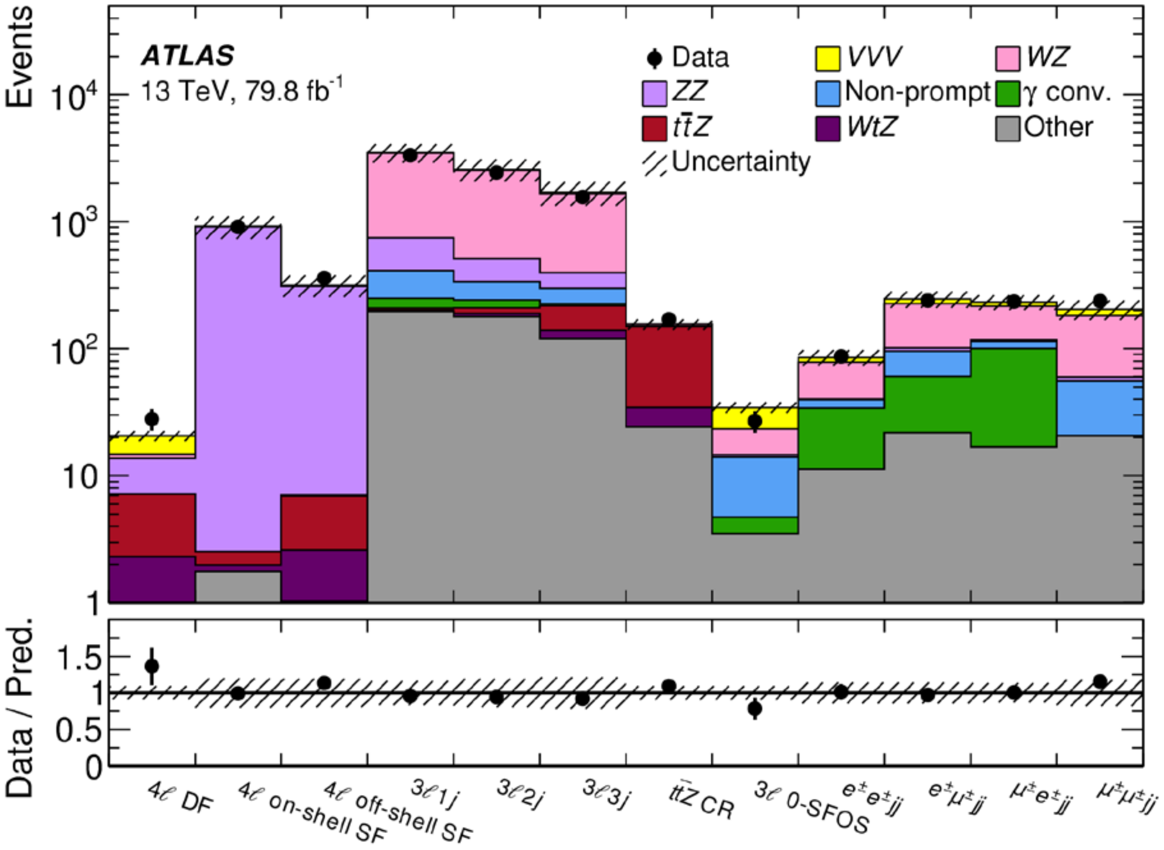
New for Moriond2019



- Three on-shell W or Z.
  - 2 or 3 or 4 leptons
  - Most sensitive one is same sign dilepton + jj



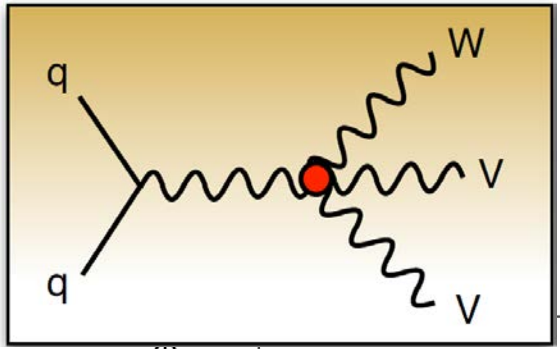
[1903.10415](https://arxiv.org/abs/1903.10415)



Multi-boson production

New for Moriond2019

1903.10415



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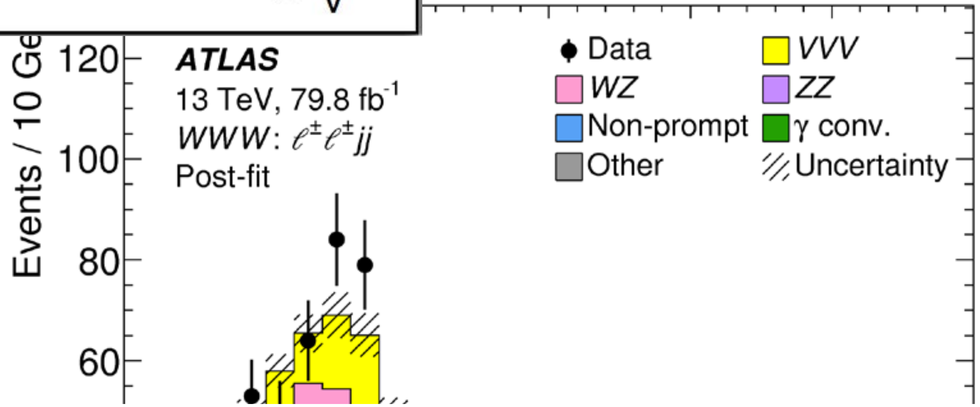
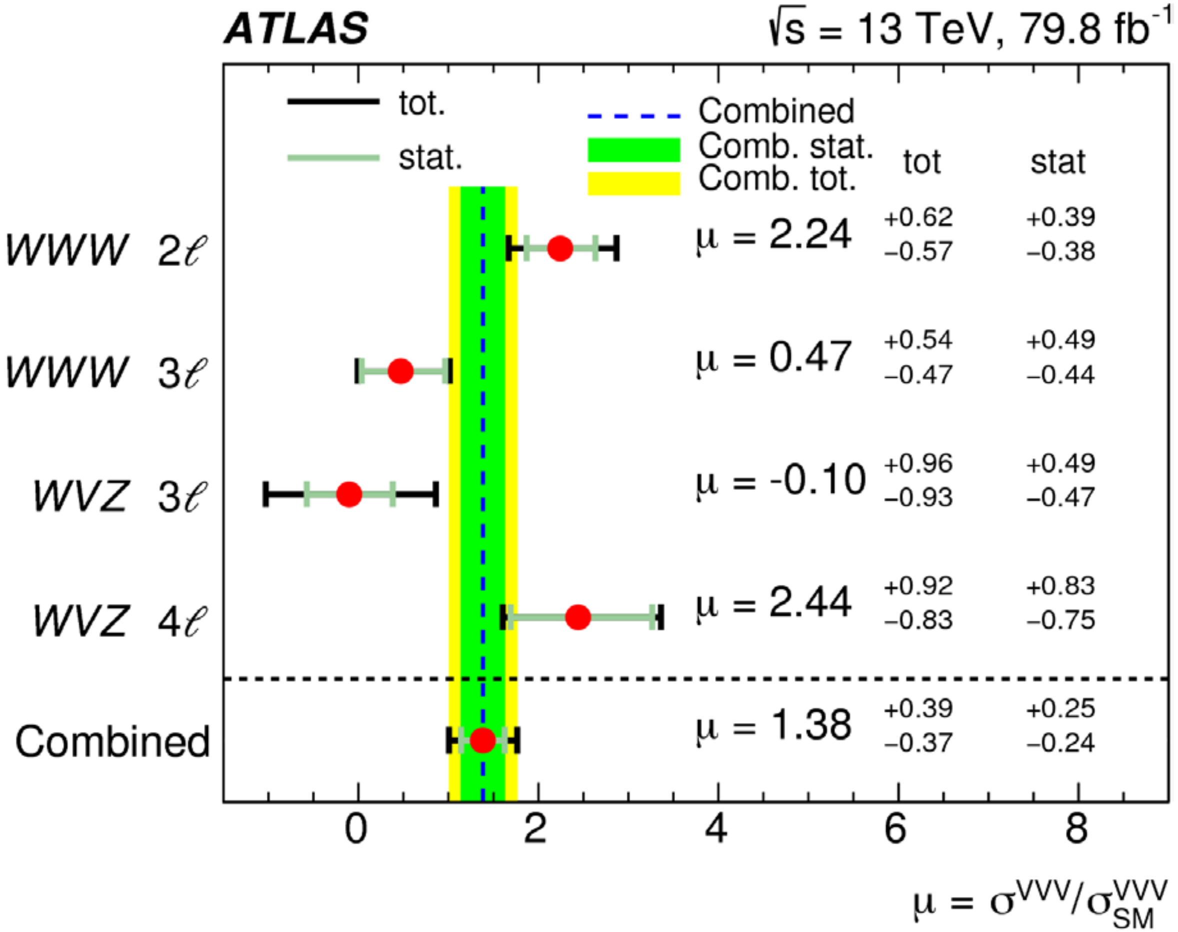


	Signif.	Signal strength
	$4.0\sigma_{obs}$ $(3.1\sigma)_{exp}$	$1.38^{+0.39}_{-0.37}$



First evidence for production of three massive vector boson

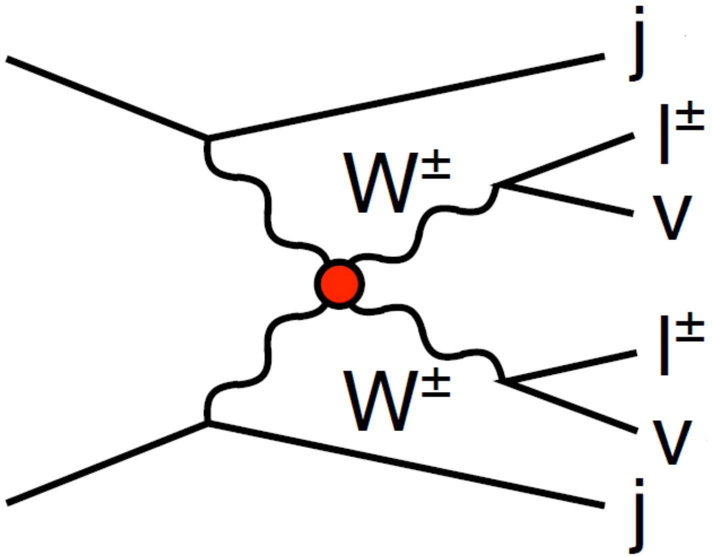
Longitudinal VBS

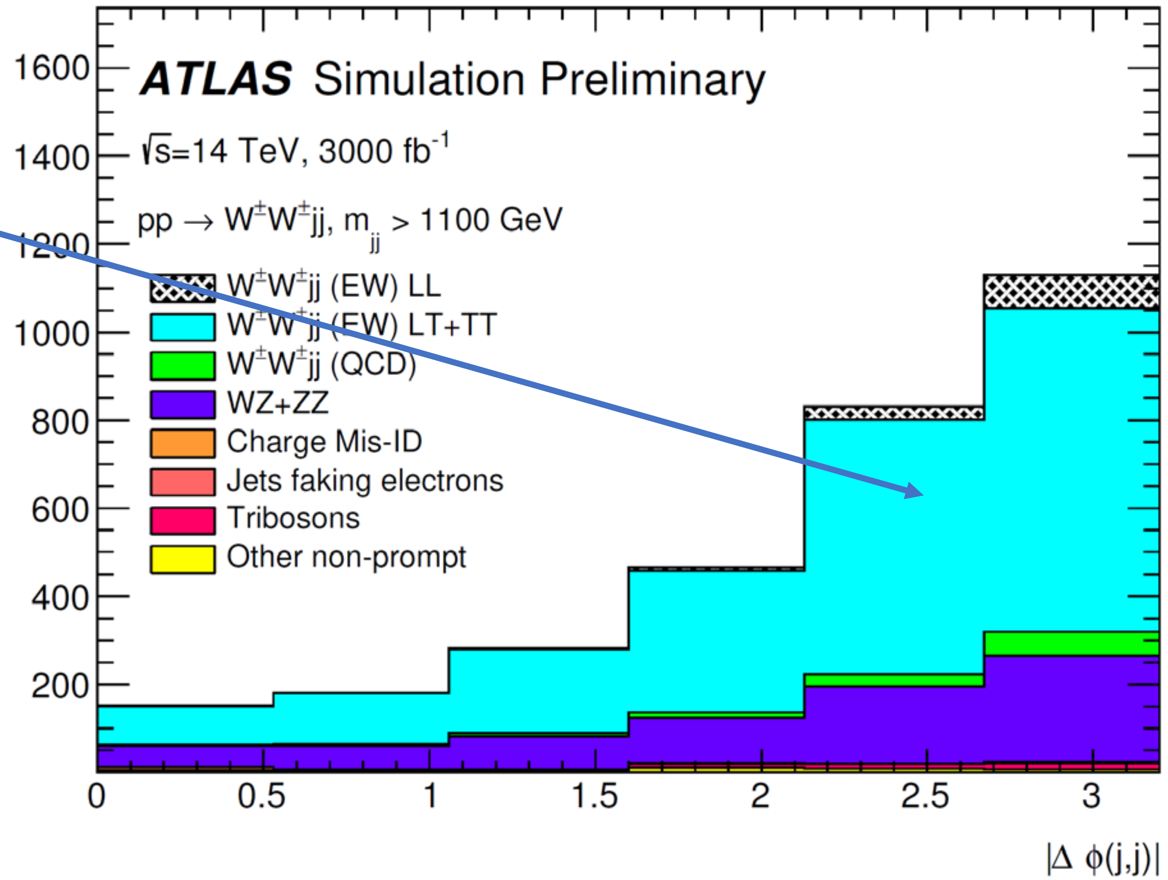
ATL-PHYS-PUB-2018-052

- Higgs機構のテストには

$$W_L^{\pm} W_L^{\pm} \rightarrow W_L^{\pm} W_L^{\pm}$$

を見たい。





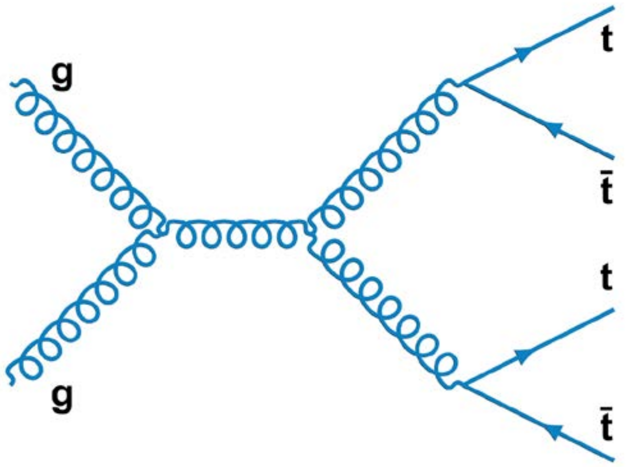
CMSとCombineすれば、HL-LHCの3000 fb^{-1}で3 σに到達するか。
更なる改善を目指して。。。

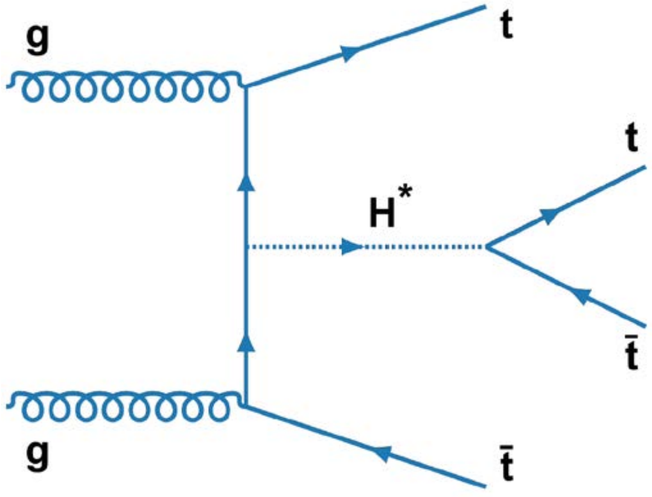
Four Tops

PhysRevD.99.052009

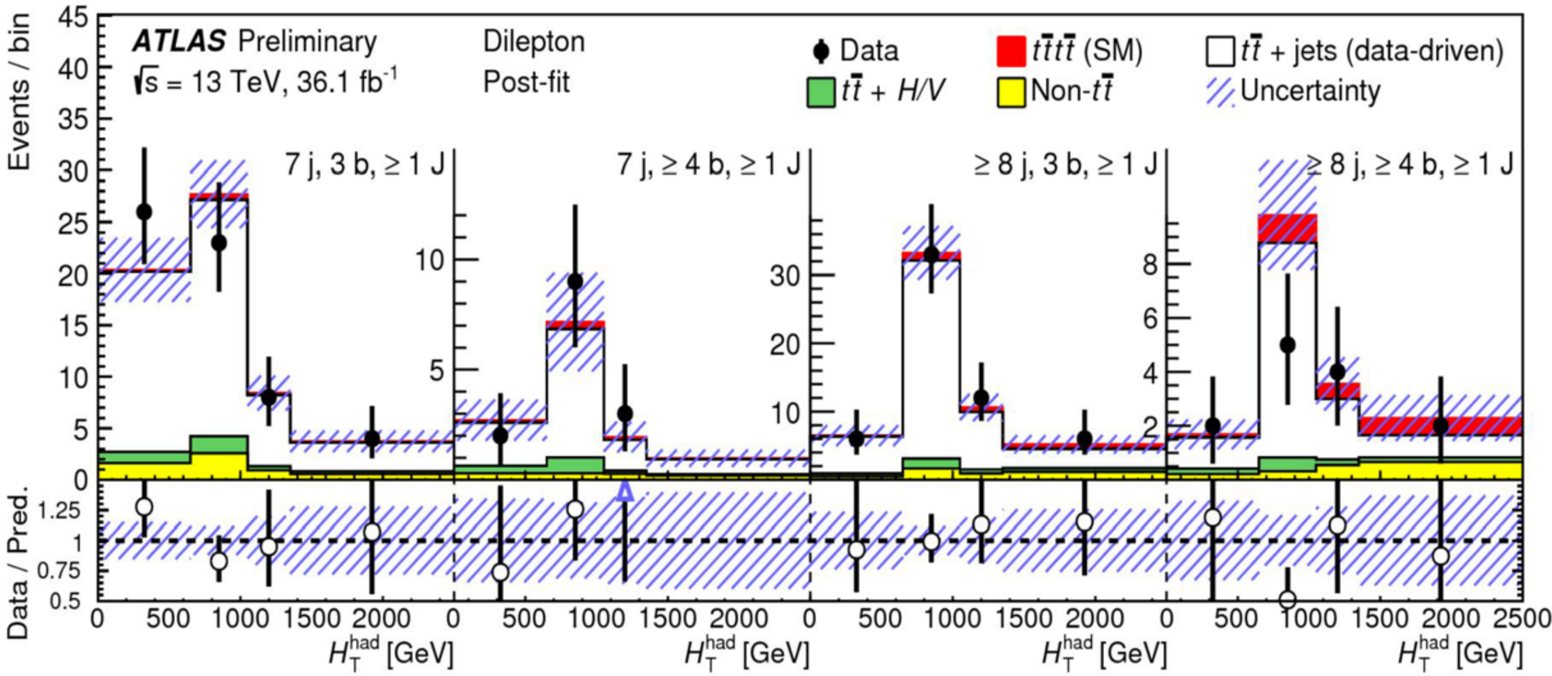
$t\bar{t}t\bar{t}$

New for LHCP2019





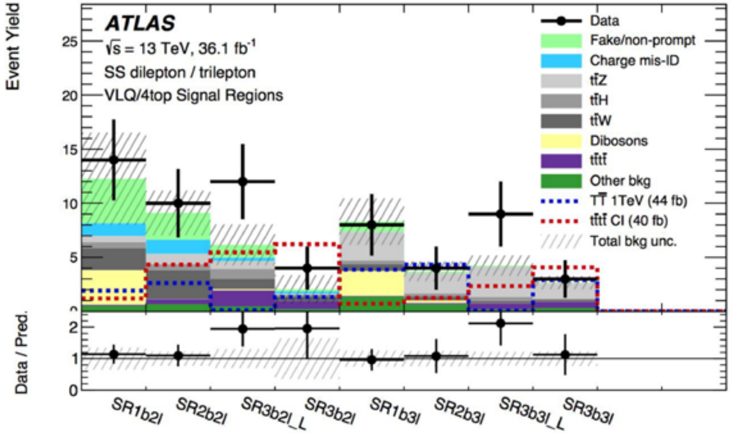
- Expected total cross section
  - 9.2 fb @ LO
    - ~ 100 events per year
- Analysis
  - Lepton+jets or OS dilepton
  - Same Sign dilepton or multi-lepton

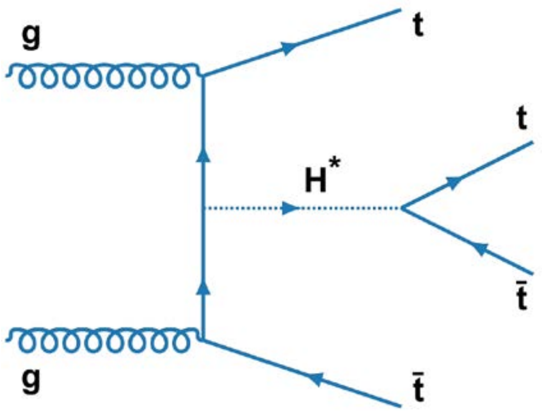


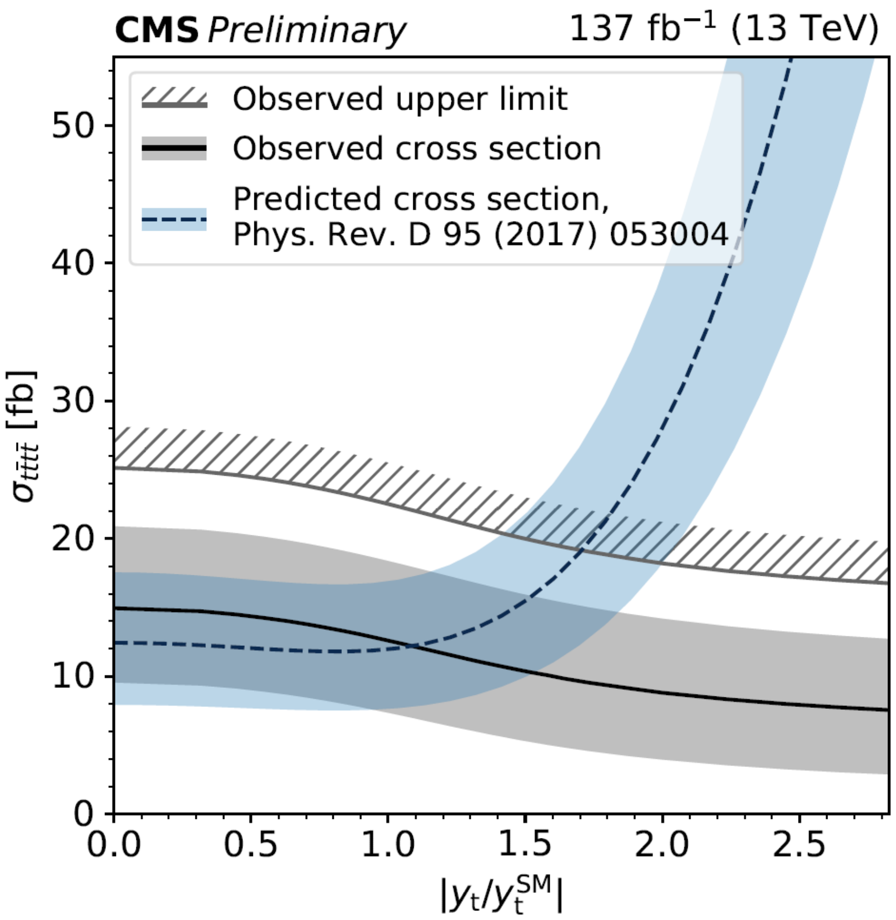
Four Tops

PhysRevD.99.052009

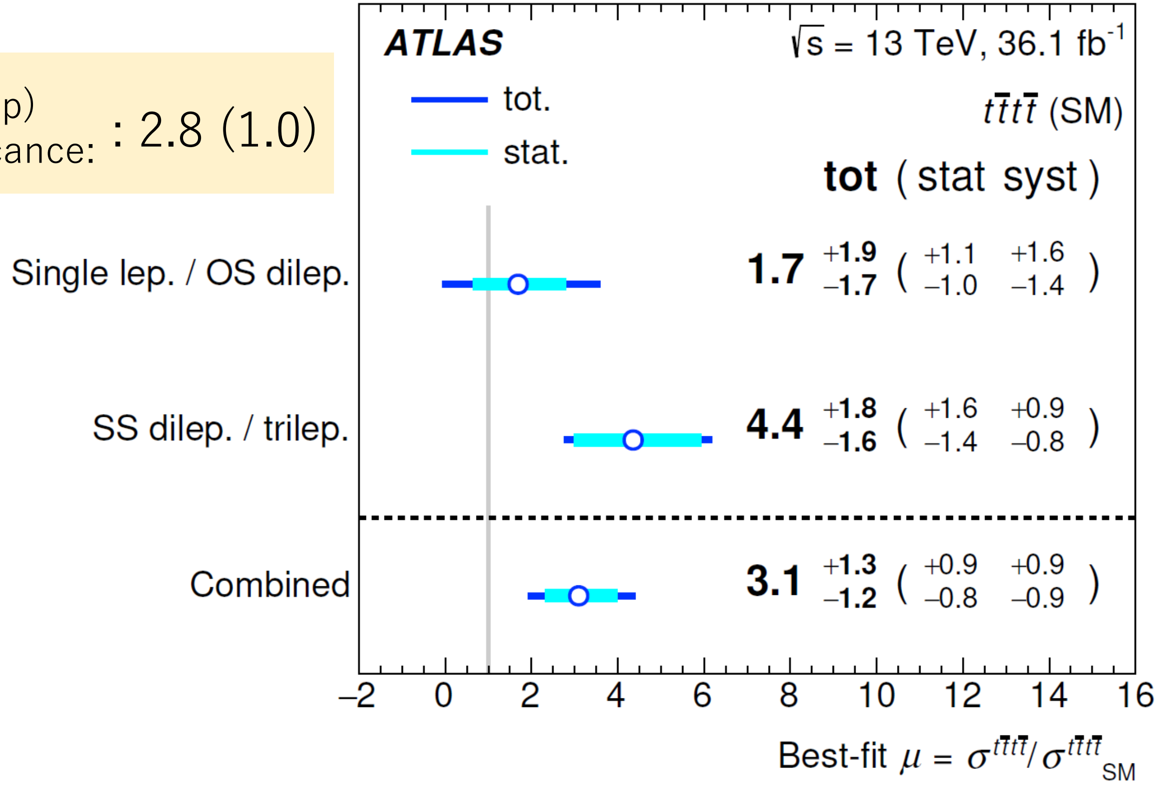
New for Moriond2019





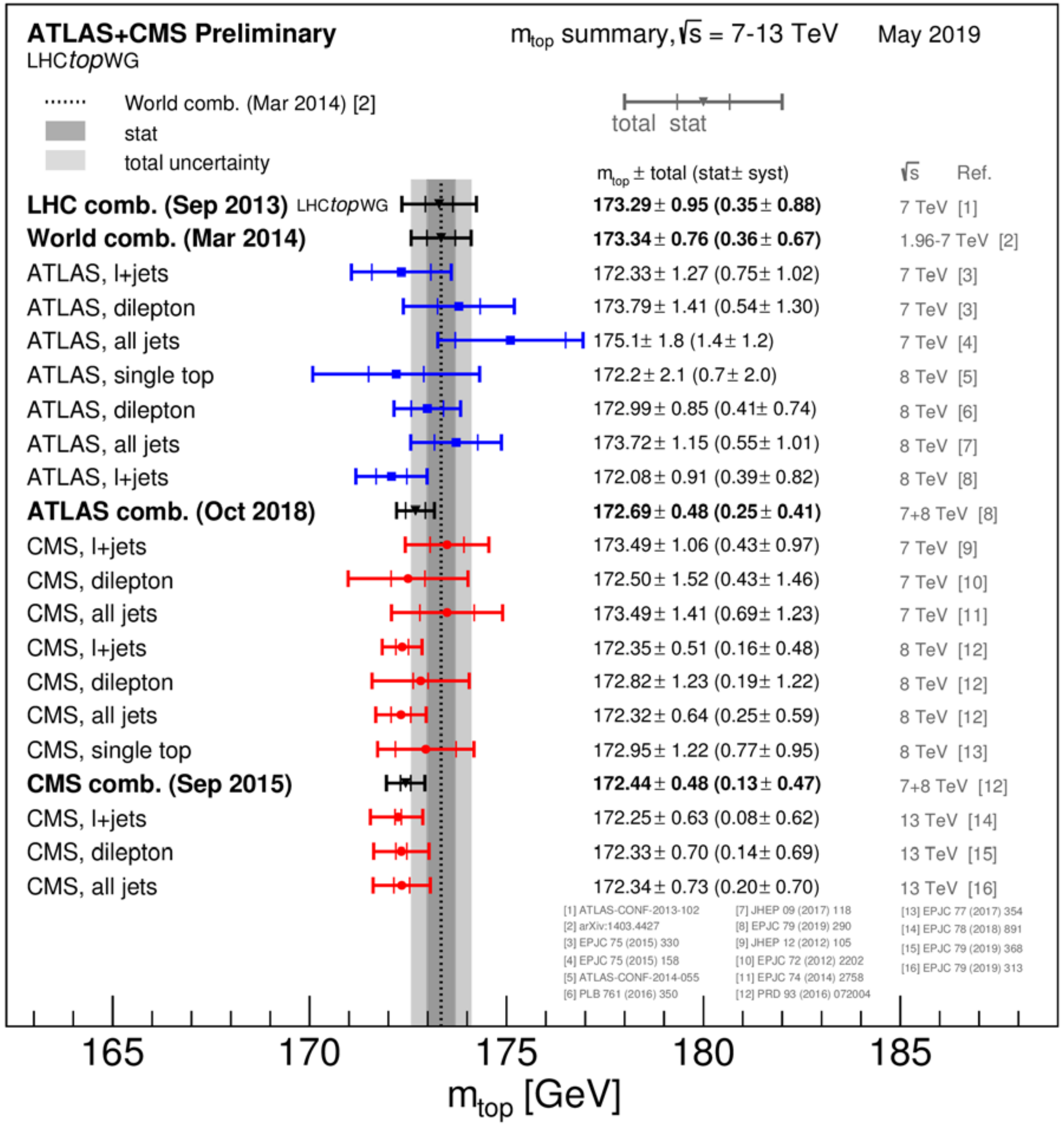


Obs (exp) significance: 2.8 (1.0)



- top湯川結合に感度！
  新しいアプローチ

Top quark mass

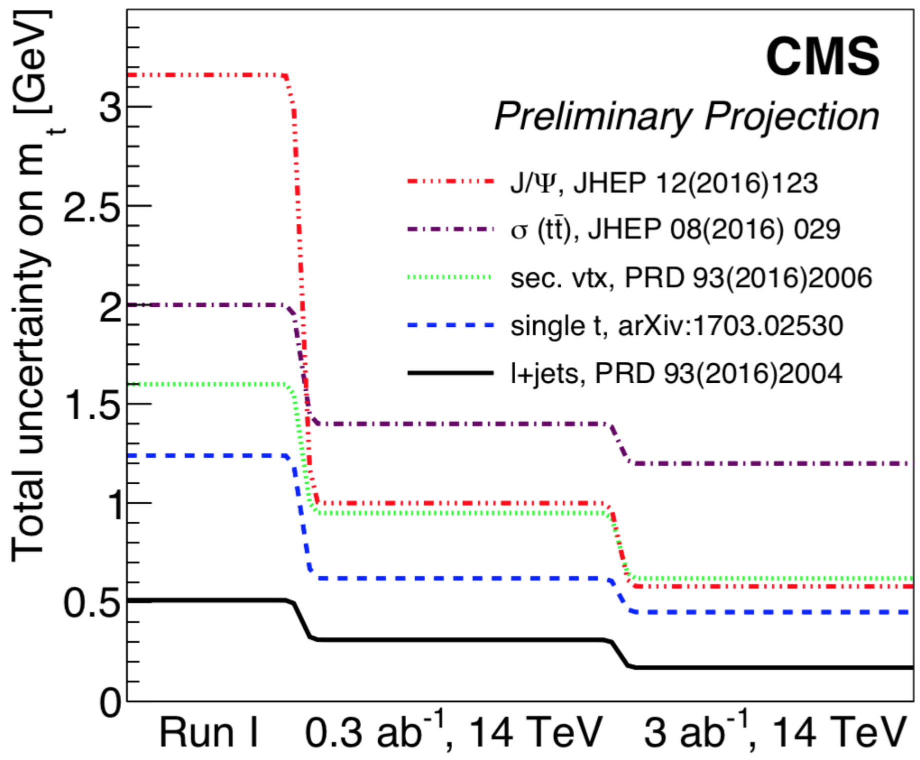


ATLAS: $m_{top} = 172.44 \pm 0.48$ GeV

CMS : $m_{top} = 172.69 \pm 0.48$ GeV

MC mass precision : 0.28 %

どこまでいけるか？



Top quark mass

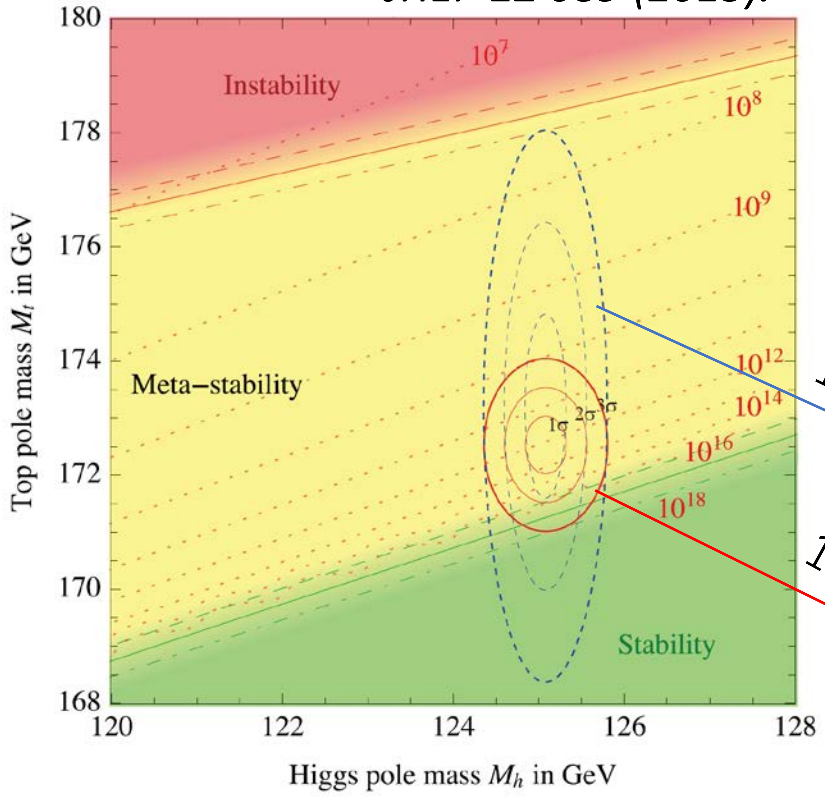
- Top の質量と真空の安定性
  - Meta stabilityなのか？
  - MC massとPole massの違いも

ATLAS: $m_{top} = 172.44 \pm 0.48$ GeV

CMS : $m_{top} = 172.69 \pm 0.48$ GeV

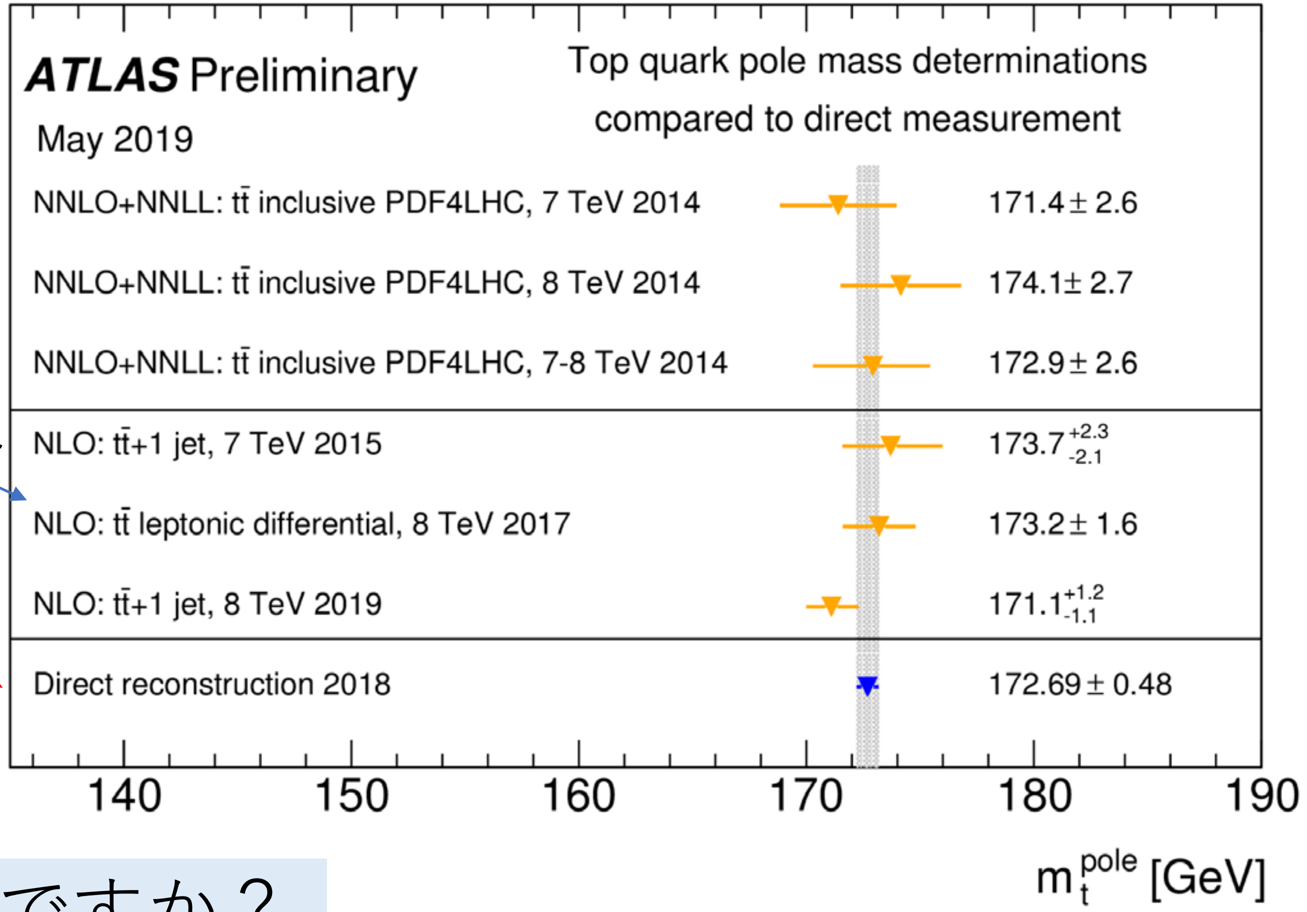
MC mass precision : 0.28 %

JHEP ***12*** *089 (2013).*



1,2,3 σ

1,2,3 σ

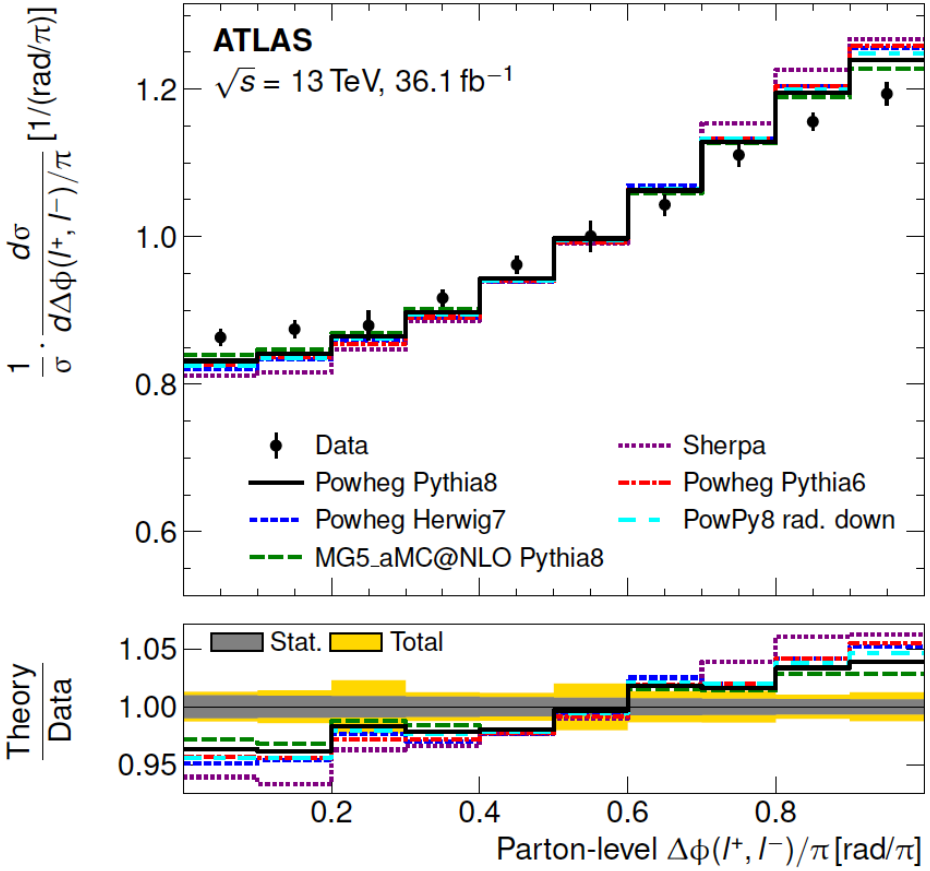


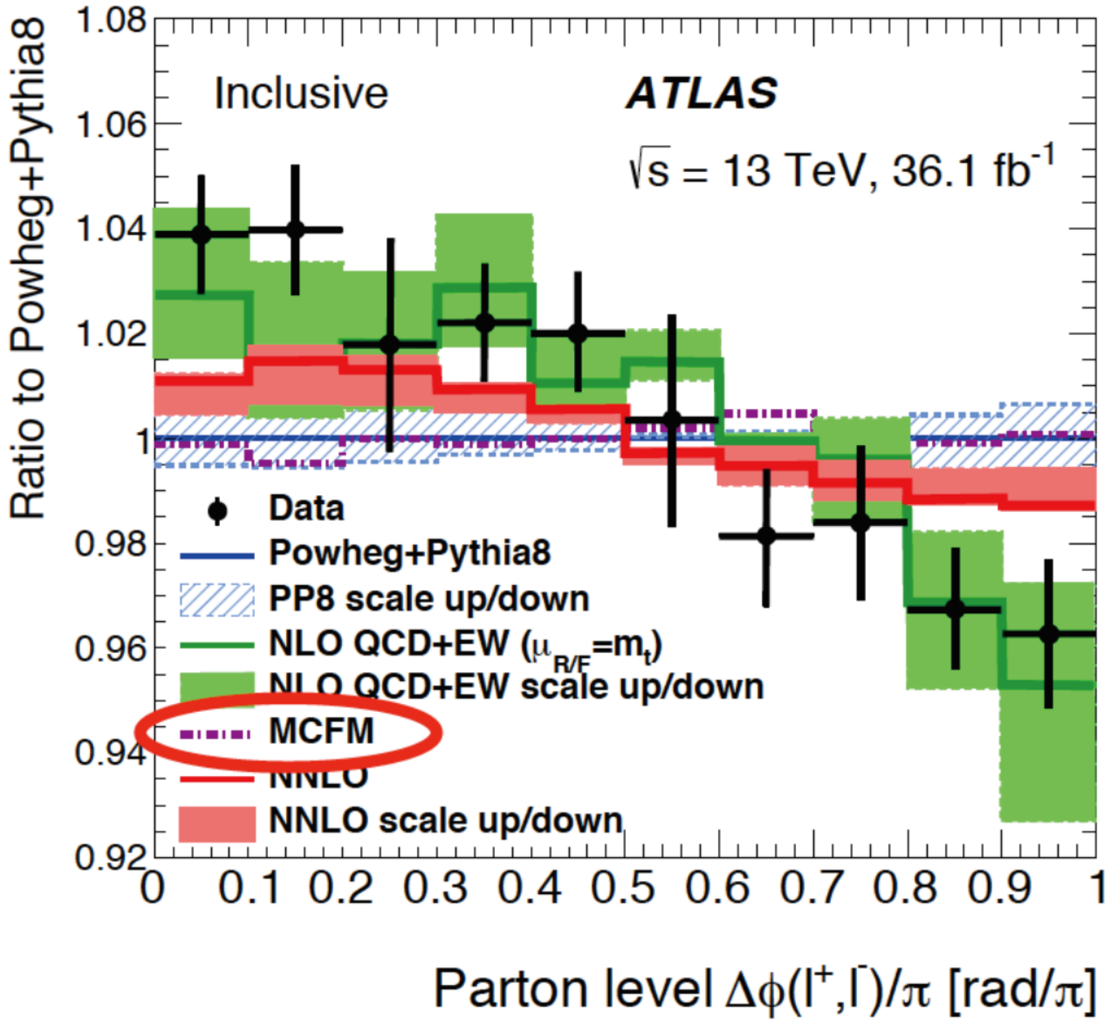
理論の方へ：解決策はないですか？

去年話題のTop Spin Correlation

- Had 3 σ level discrepancy on $\Delta\phi_{//}$
  - In di-lepton channel

$$f_{SM} = 1.25 \pm 0.02 \pm 0.06 \pm 0.04$$





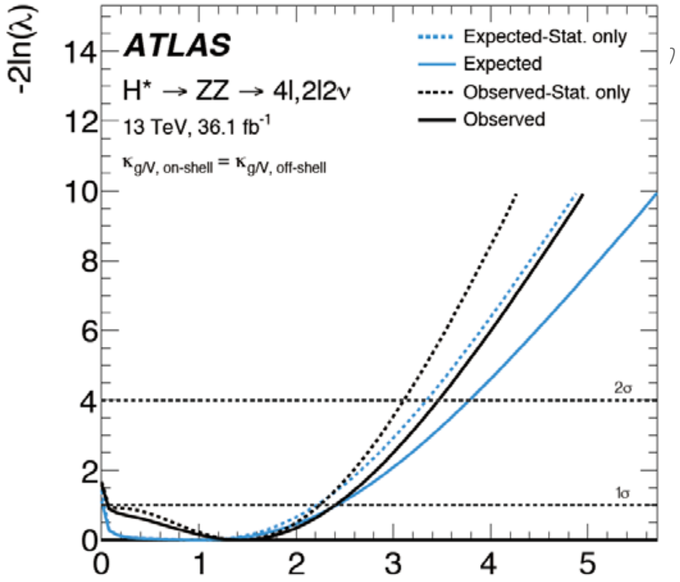
NLO QCD+EWはデータを再現。
計算精度が足りていないためと結論できるか。

Higgsの結果

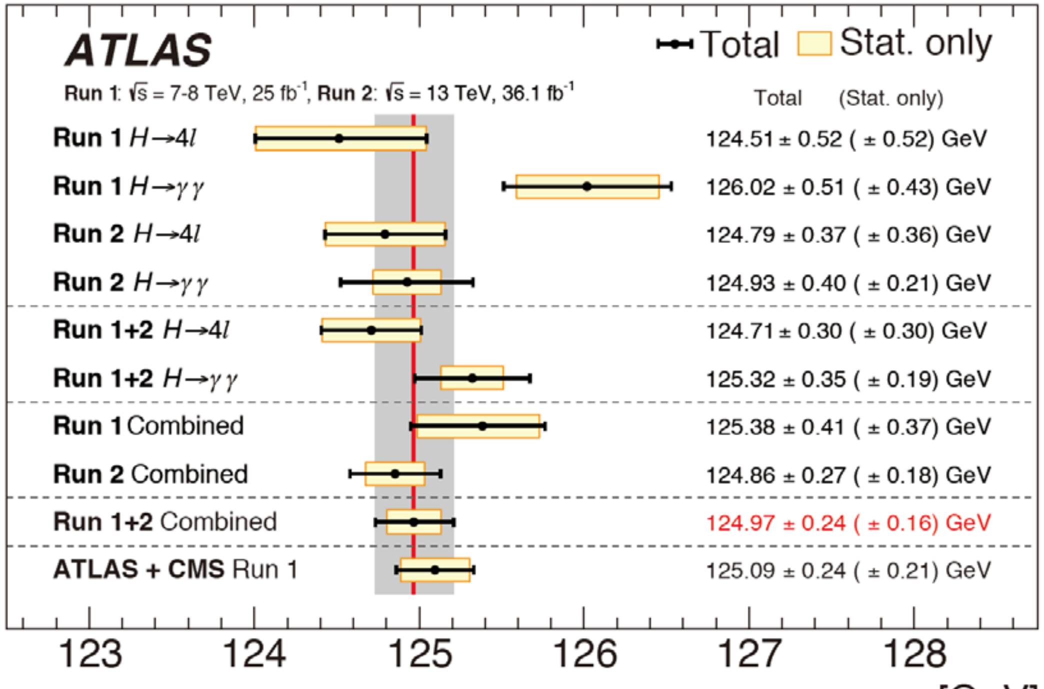
- プロパティ
- 生成・崩壊
- 新物理探索のアプローチ

Higgs Properties

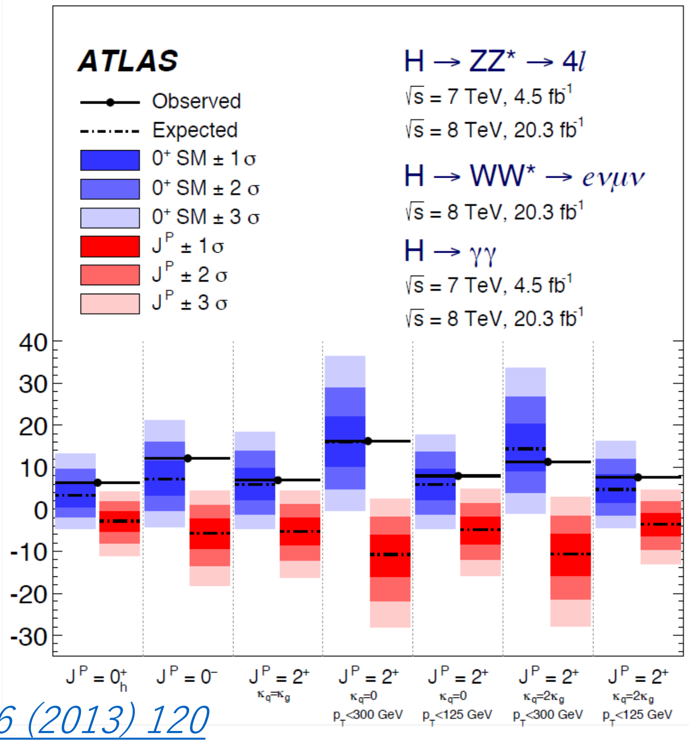
- 質量： 124.97 ± 0.24 GeV
- Width: < 14.4 MeV (Expected 4.2 MeV)
  - Indirect: 15.2 MeV
- Spin-parity: $J^{PC} = 0^{++}$



Phys. Lett. B 786 (2018) 223



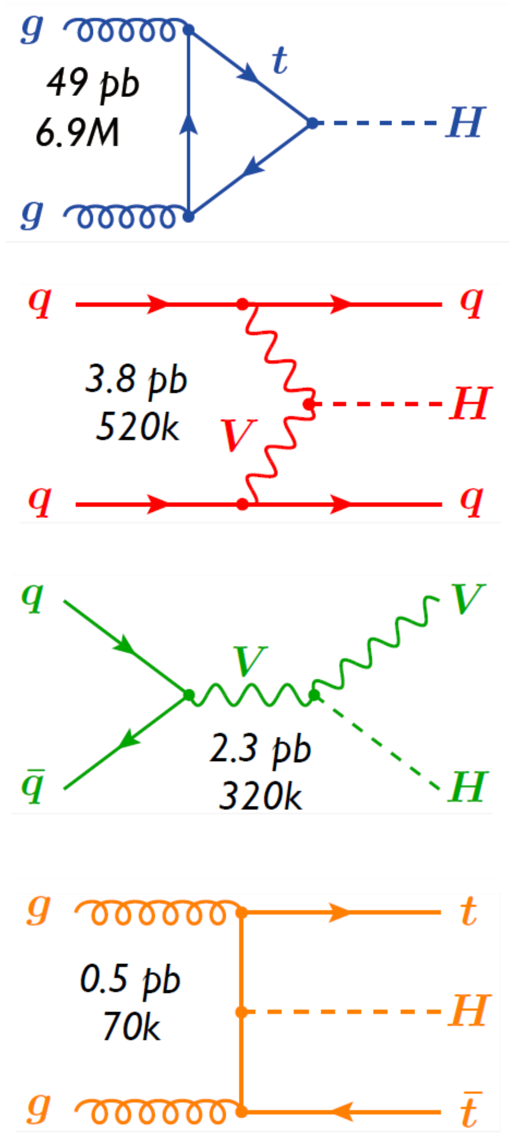
Phys. Lett. B 784 (2018) 345



Phys. Lett. B 726 (2013) 120

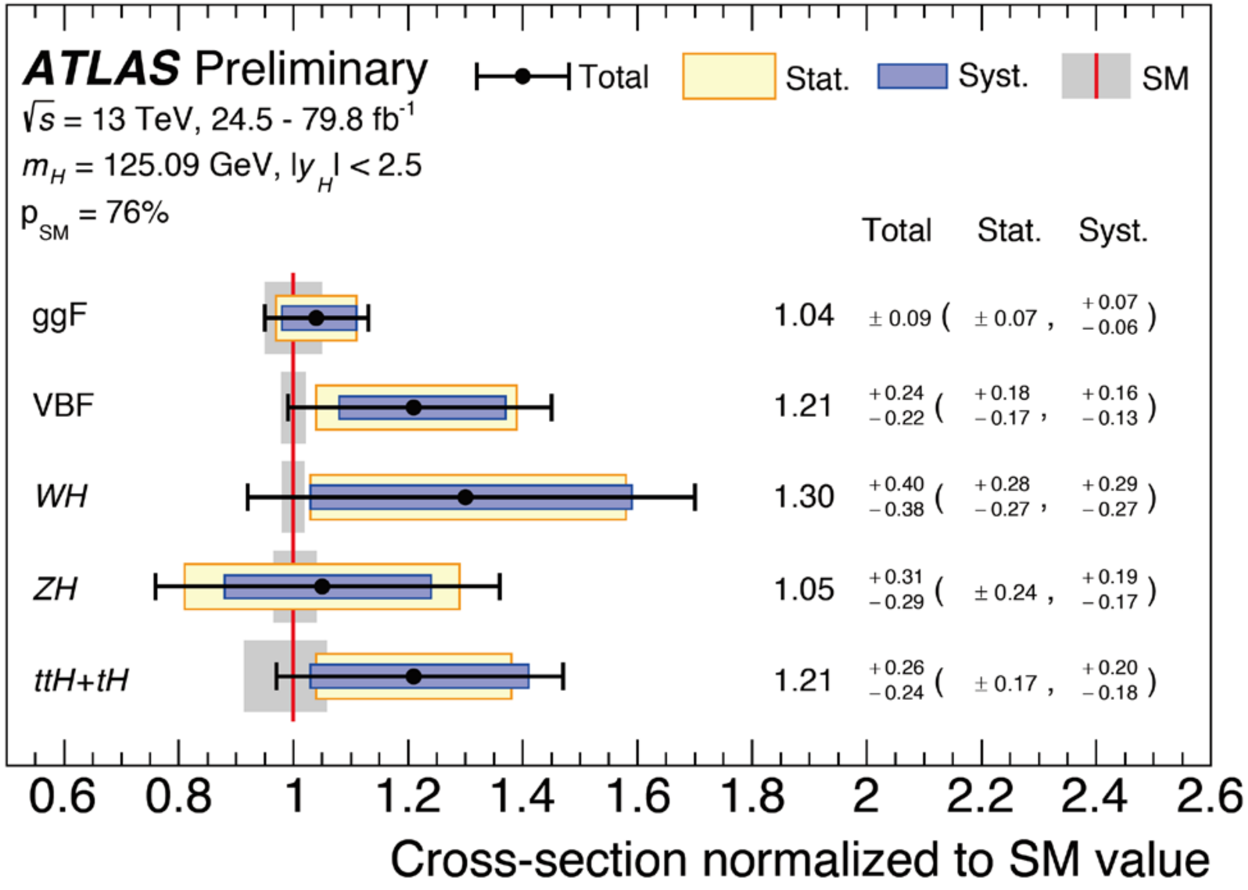
Production processes and Decays

Xsec@13 TeV,
# of event in Run2



- Latest result from Moriond2019

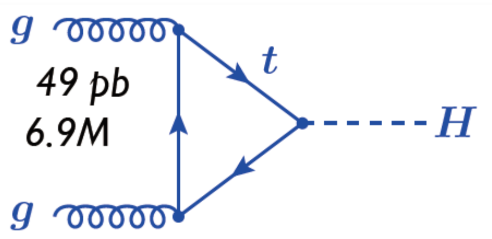
$$\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05(\text{stat.})^{+0.05}_{-0.04}(\text{exp.})^{+0.05}_{-0.04}(\text{sig. th.})^{+0.03}_{-0.03}(\text{bkg. th.})$$

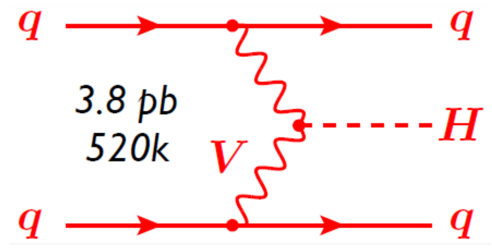


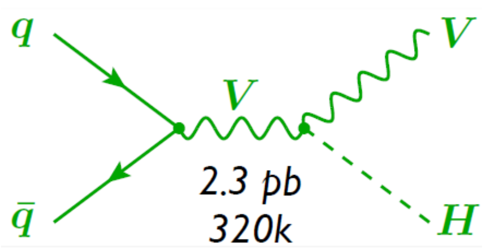
10％の精度に到達！

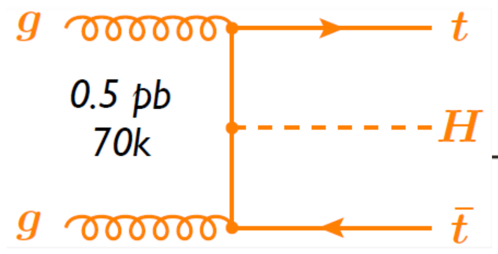
Production processes and Decays

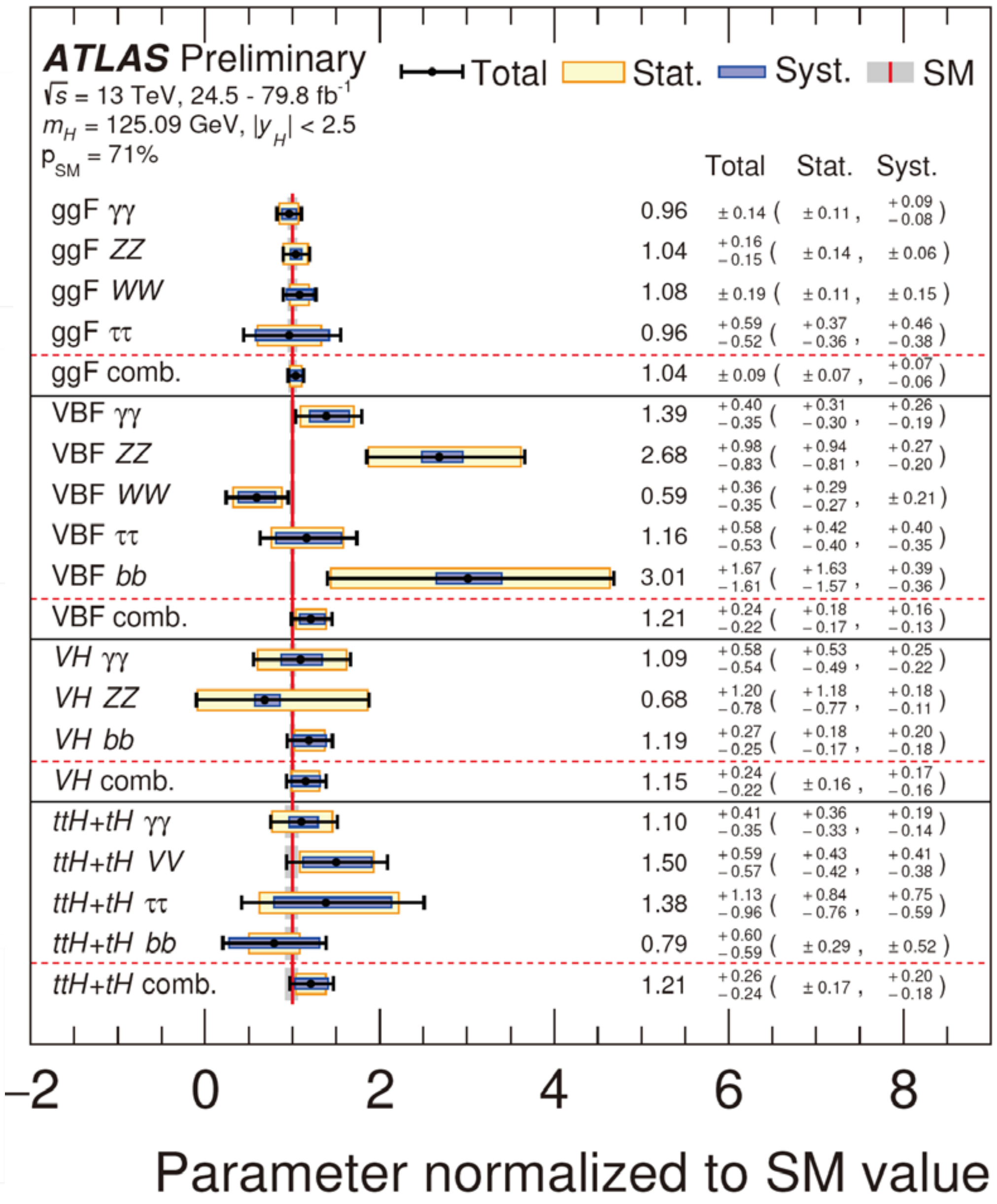
New @ LHCP2019











Production processes and Decays

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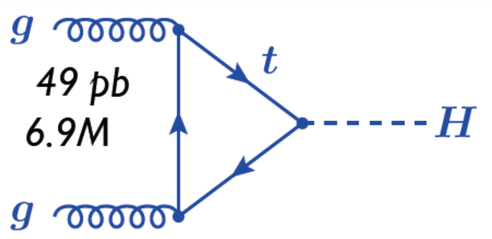
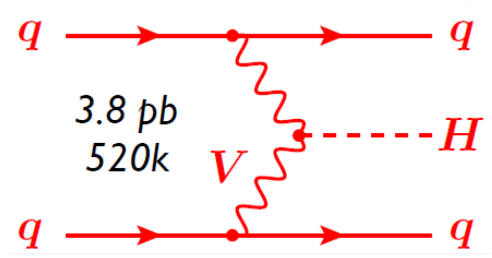
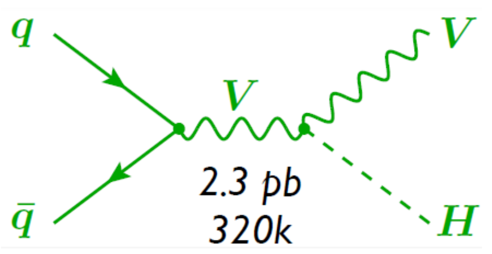
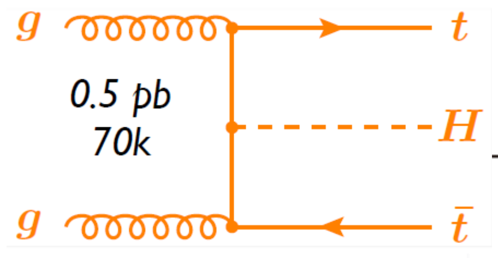
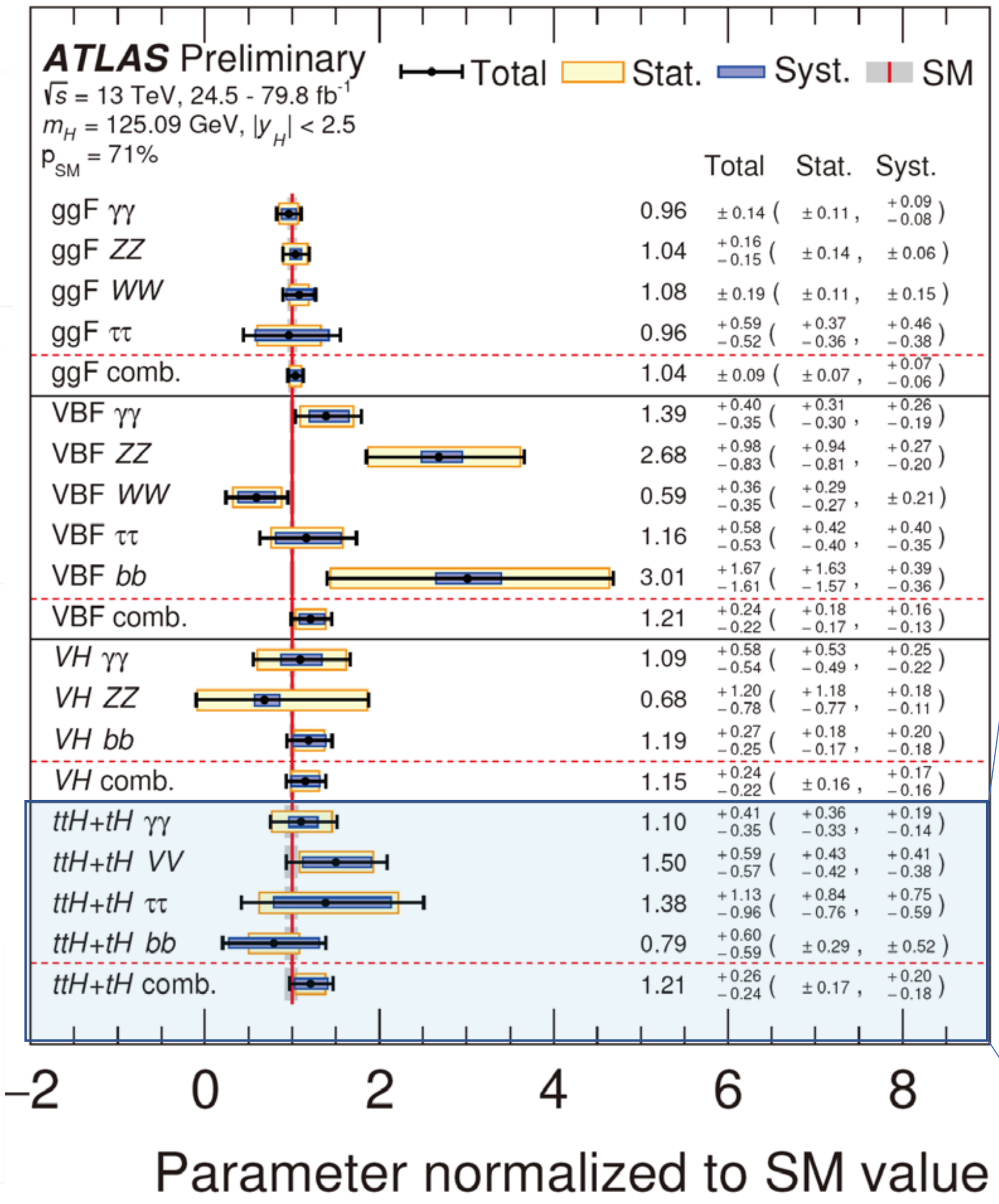




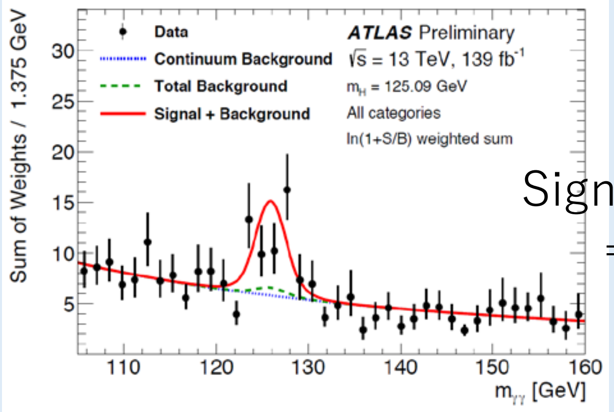






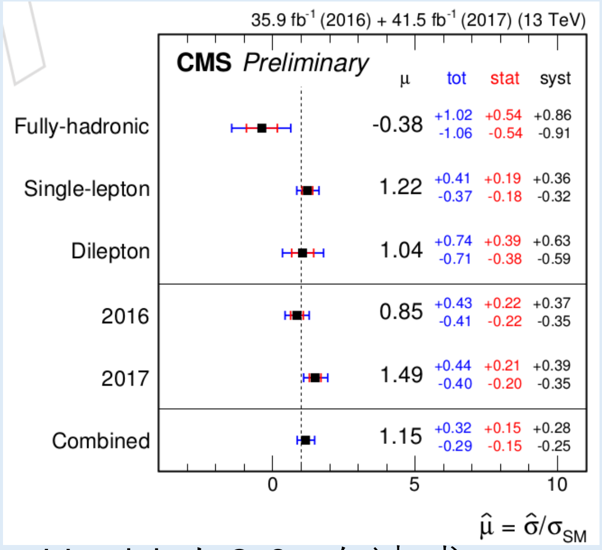
ttHは6.3σで 既にObserved（2018）

New: Full data analysis on H→γγ



Significance =4.9 σ

New: H→bb解析 from CMS



H→bbも3.9σを達成

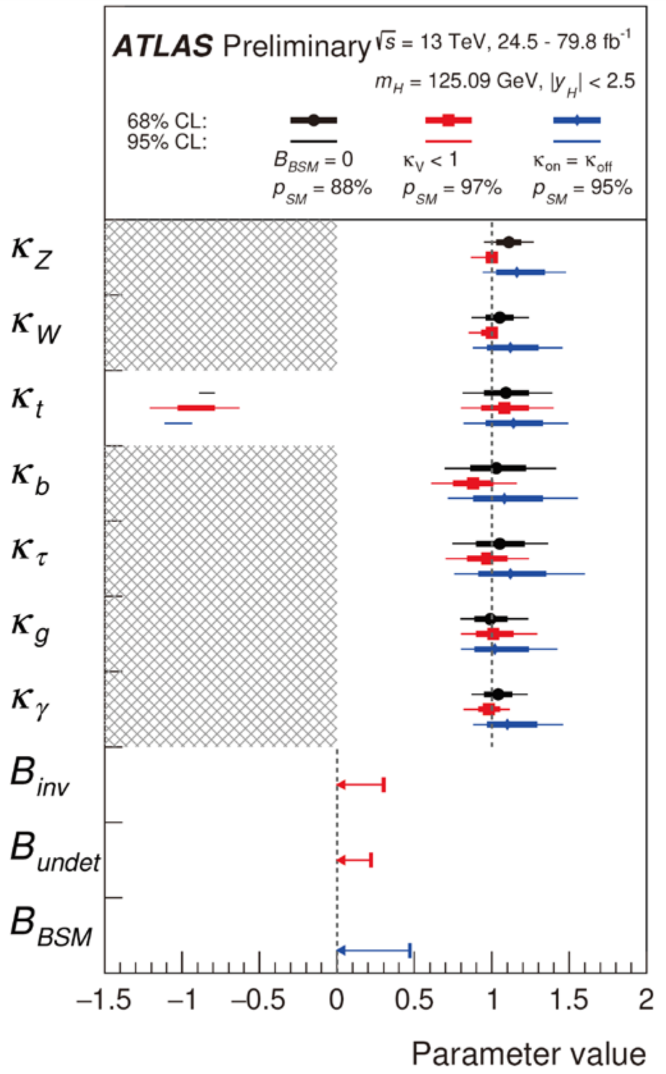
（系統誤差は大丈夫？）

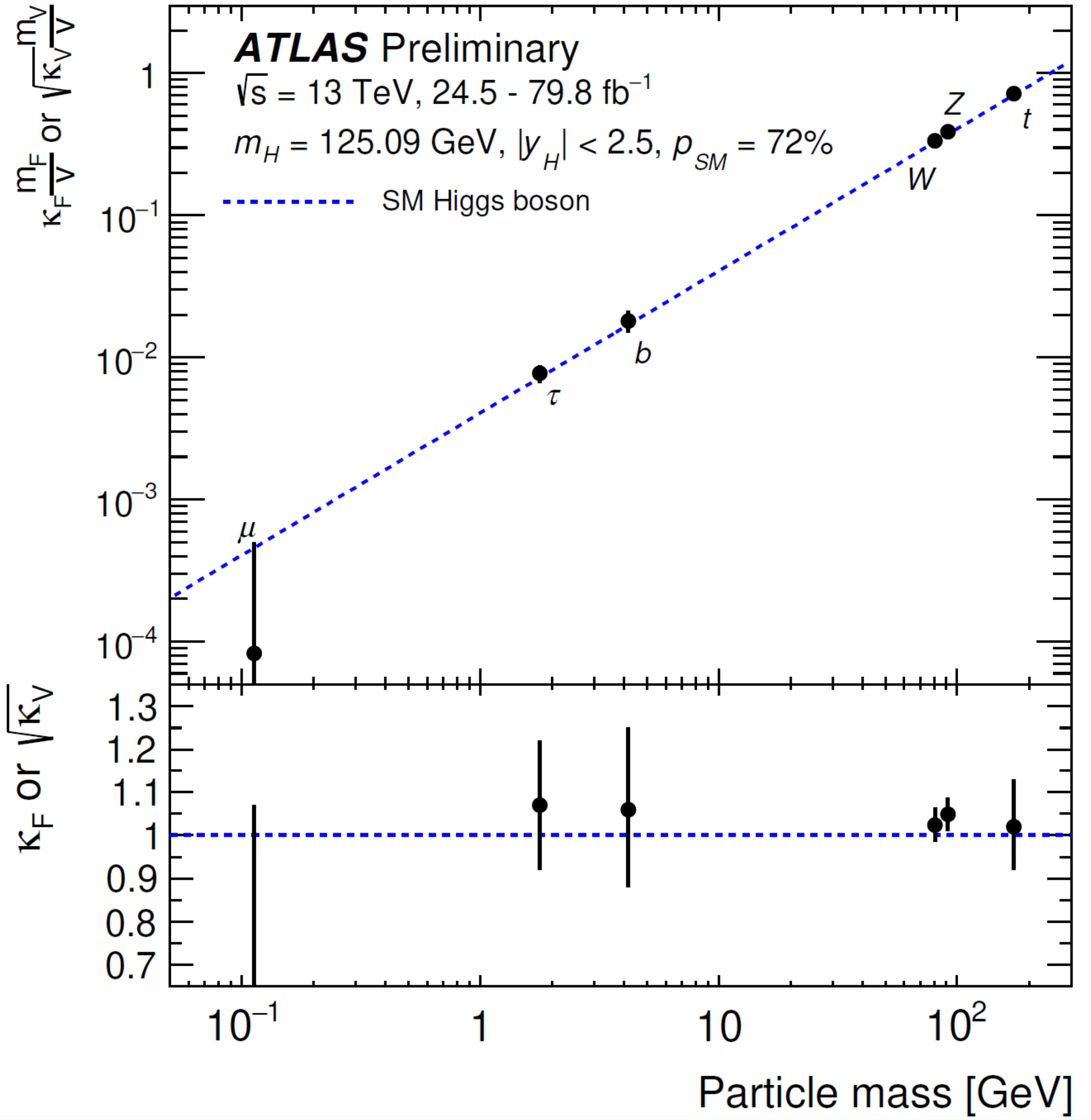
Higgs結合定数と質量

New @ Moriond2019

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\rm SM}}$$

$$\kappa_j^2 = \frac{\Gamma^j}{\Gamma^j_{\rm SM}}$$





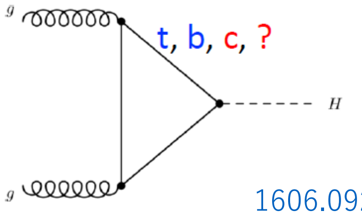
- 新粒子が無いとして解釈

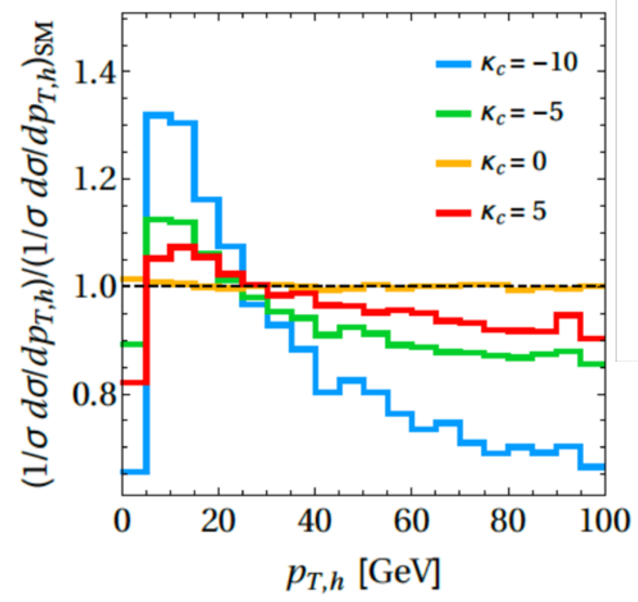
Higgsの精密測定

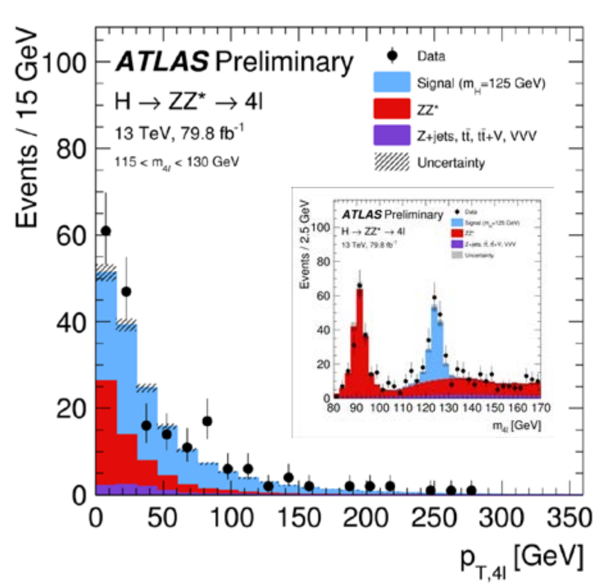
- 恩恵は？
- 新物理探索のアプローチ

Higgsの精密測定の恩恵

- 精密測定と言えばDifferential distribution（微分断面積）
  - 例えば、Higgs ｐT
    - 直接測定が難しい、Charm quarkとの湯川結合に感度が！



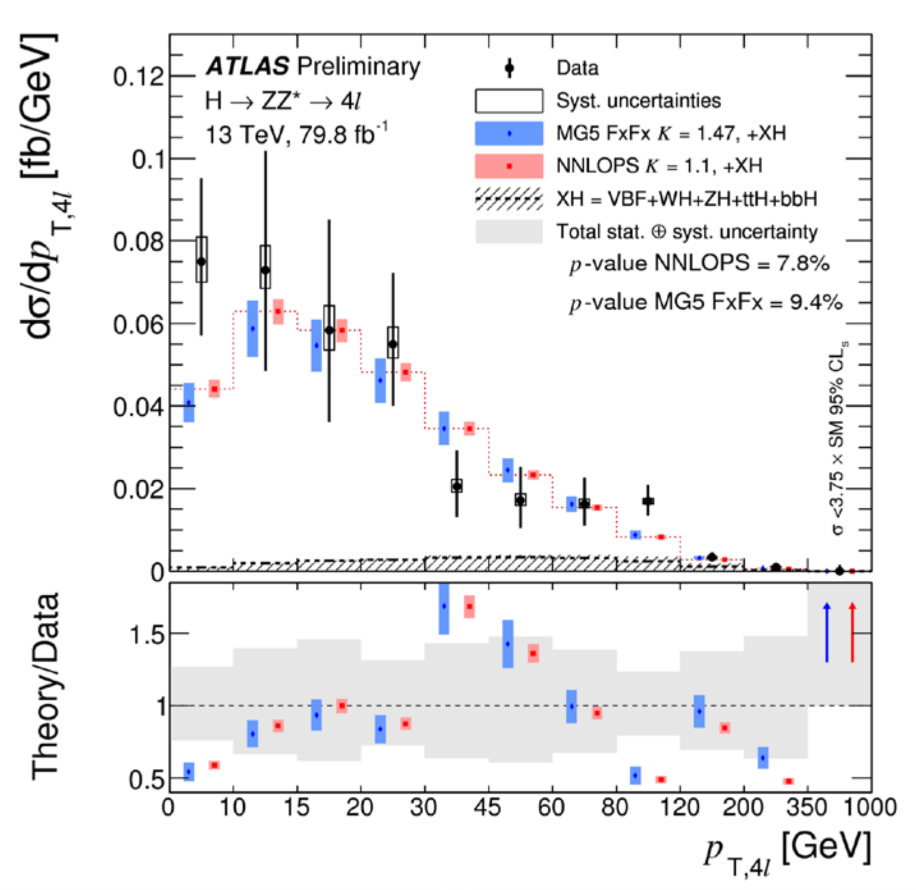




$$\frac{d\sigma_i}{dx} = \frac{N_i^{sig}}{c_i \, \Delta x_i \, \mathcal{L}_{int}}$$

各Binにおいて
- 背景事象引く
- Acceptance
を補正(相関も考慮)

ATLAS-CONF-2018-028



比較！

Higgsの精密測定の恩恵

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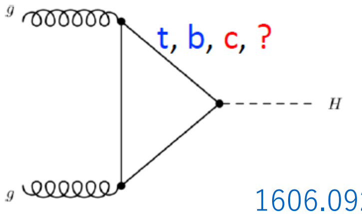

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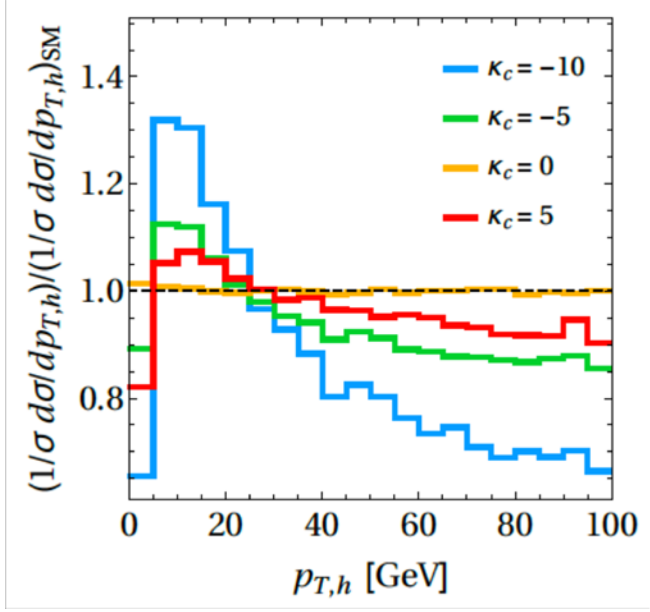
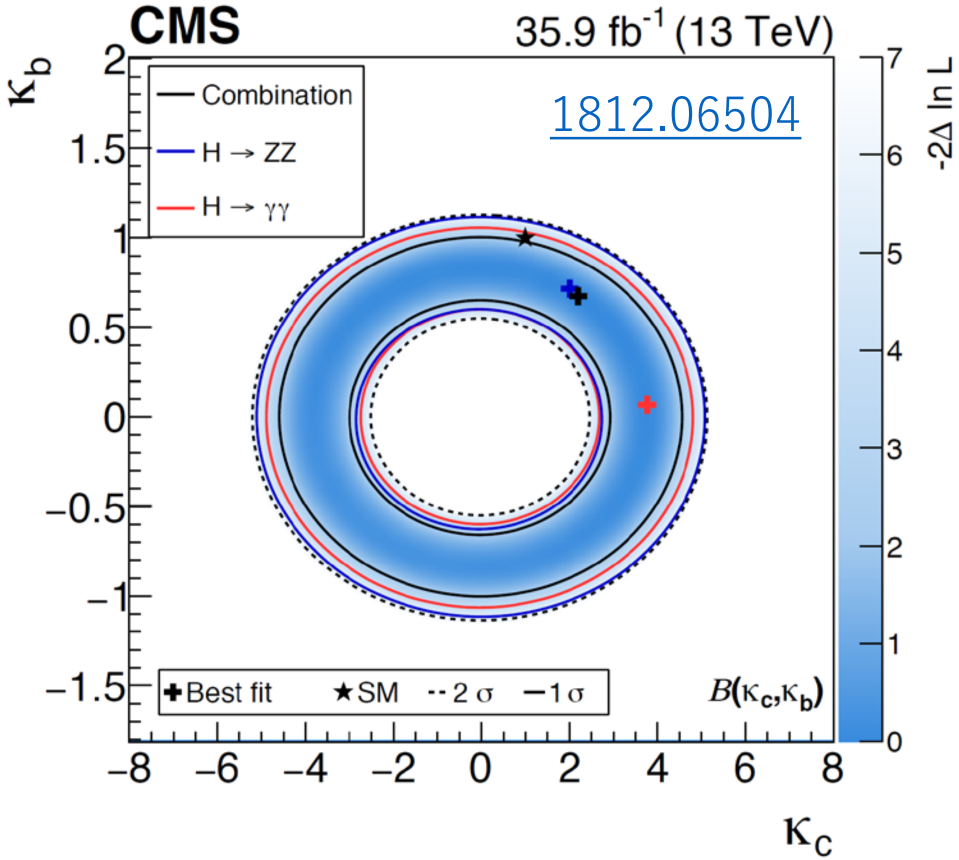




1812.06504

仮定：崩壊分岐比がCouplingに依存

$$-1.1 < \kappa_b < 1.1$$
$$-4.9 < \kappa_c < 4.8$$ (95%CL)

(現在のZH→llcc解析は10 程度)

仮定無し、Shapeだけの時は

$$-8.5 < \kappa_b < 18$$
$$-33 < \kappa_c < 38$$

Higgsの精密測定による新物理探索

- 精密測定と言えばDifferential distribution（微分断面積）
  - Multi-dimensionalで測定するのが理想
  - 標準理論の予想と合っているか？
  - Excessがあった場合、どんなモデルと合うか、検証したい！

    → Effective Field Theory.
- Simplified Template Cross Section (STXS)
  - 解析ごとに違った前提を取ると、Combineが困難！
  - 約束を決め、共有！

Higgsの精密測定による新物理探索

[Handbook of LHC Higgs Xsecs]

- Effective Field Theoryにより
  - どのような相互作用が強く（弱く）出ているかを探る。

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

レプトン数を破る

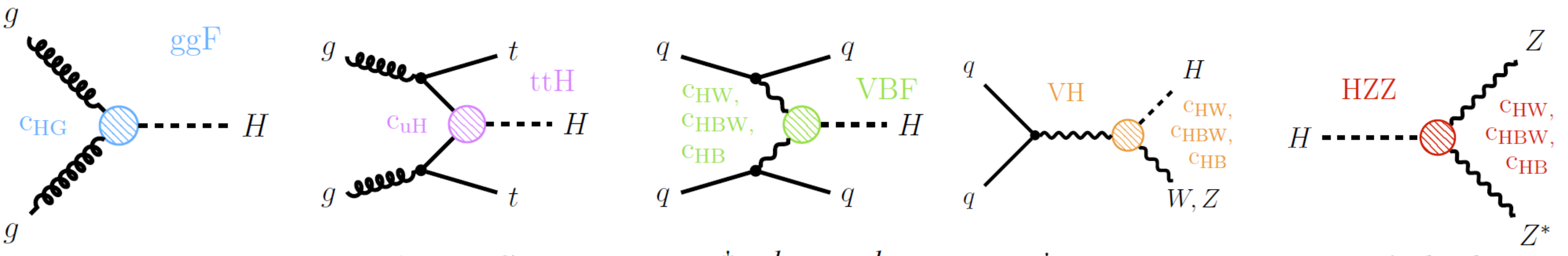
B-L数を破る

Dimension 6だけでも2499個の係数。
いろいろな仮定の上、減らす。

52個のCP-even
17個のCP-odd

LOでHiggsに関係する
19個の項に注目

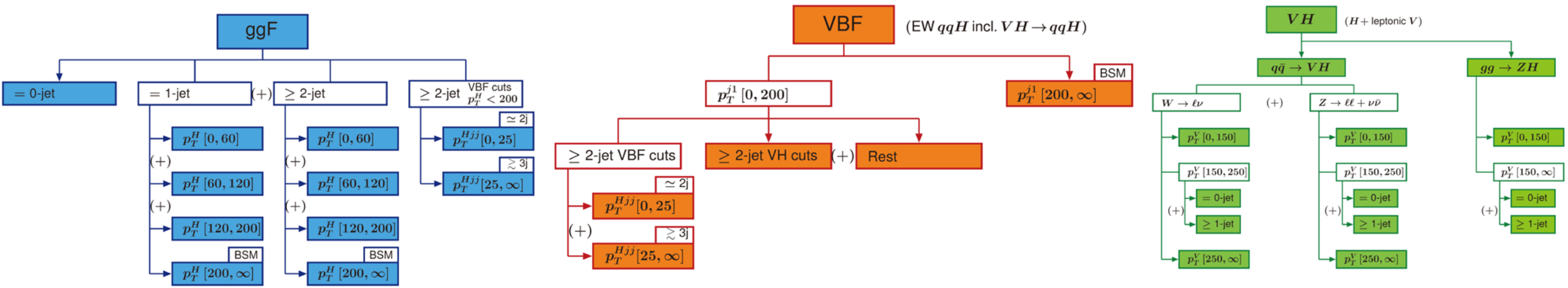
Wilson係数の例：



$HH^\dagger G^A_{\mu\nu}G^{\mu\nu A}$ $\quad$ $HH^\dagger \bar{q}_p u_r \tilde{H}$ $\quad$ $HH^\dagger W^l_{\mu\nu}W^{\mu\nu l}$ $\quad$ $HH^\dagger B_{\mu\nu}B^{\mu\nu}$ $\quad$ $HH^\dagger \tau^l W^l_{\mu\nu}B^{\mu\nu}$

Simplified Template Cross Section

- STXSの目標：標準理論を超える物理を明らかに
  Effective Field Theoryでアプローチ
  - 理論不定性を最小限に抑えつつ、測定感度を最大に
  - モデルの判別が出来るように
  - 多くの解析をCombineする
    最終的にはATLAS＋CMS
- STXSの手法：カテゴリ分け
  各カテゴリでMVA解析などを行える。

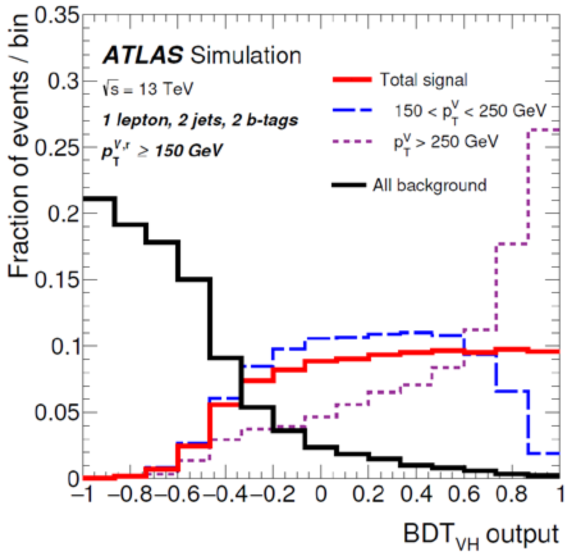


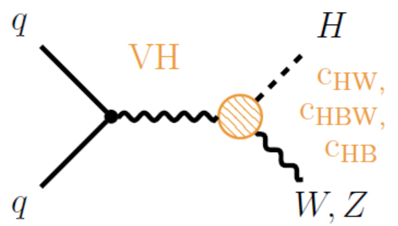
H→bb

New @ Moriond2019

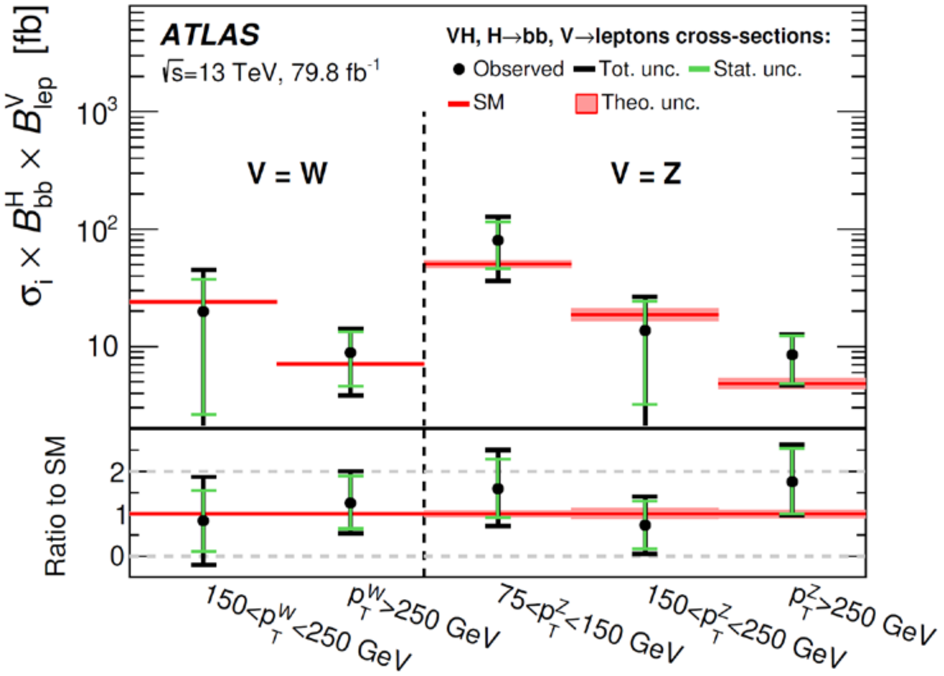
JHEP05(2019)141

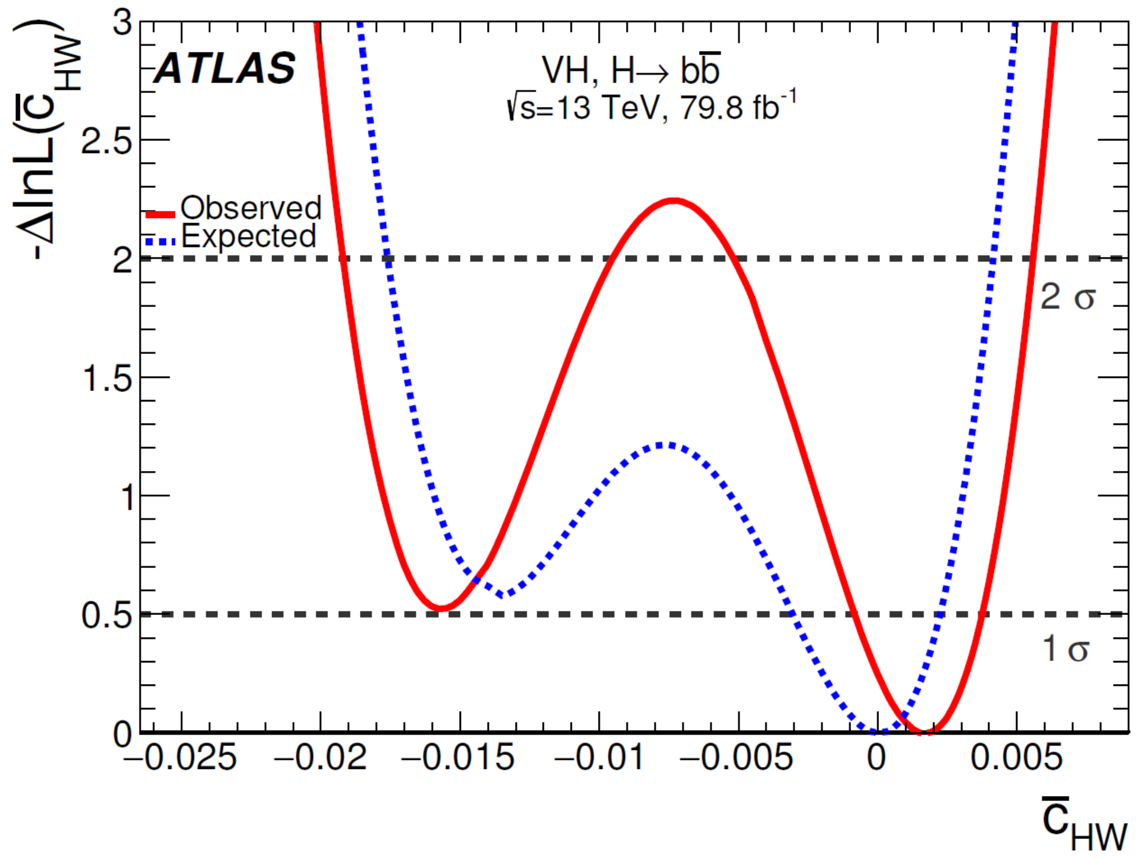
- Hbb observationからの更新
  - VpT>250 GeVカテゴリを新設
  - STXSを適用！
- Wilson 係数へのLimitを導出





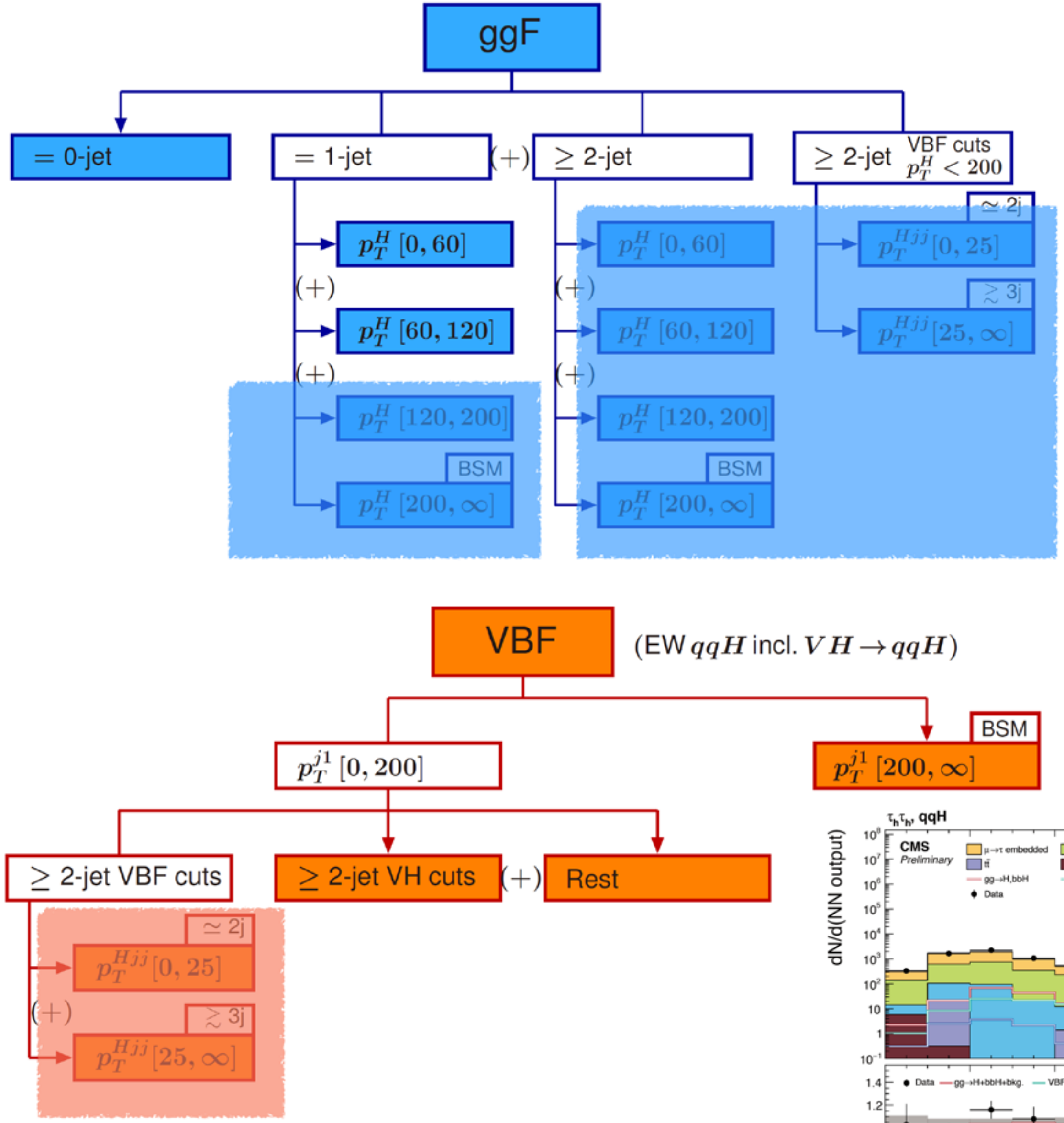
$$HH^{\dagger}B_{\mu\nu}B^{\mu\nu}$$

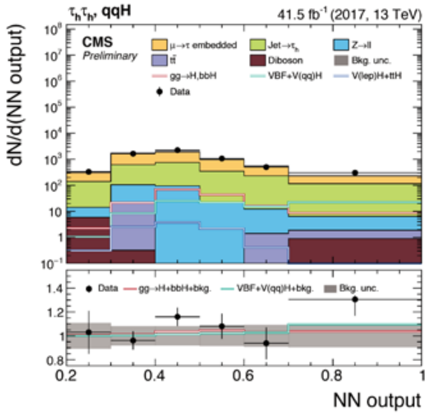


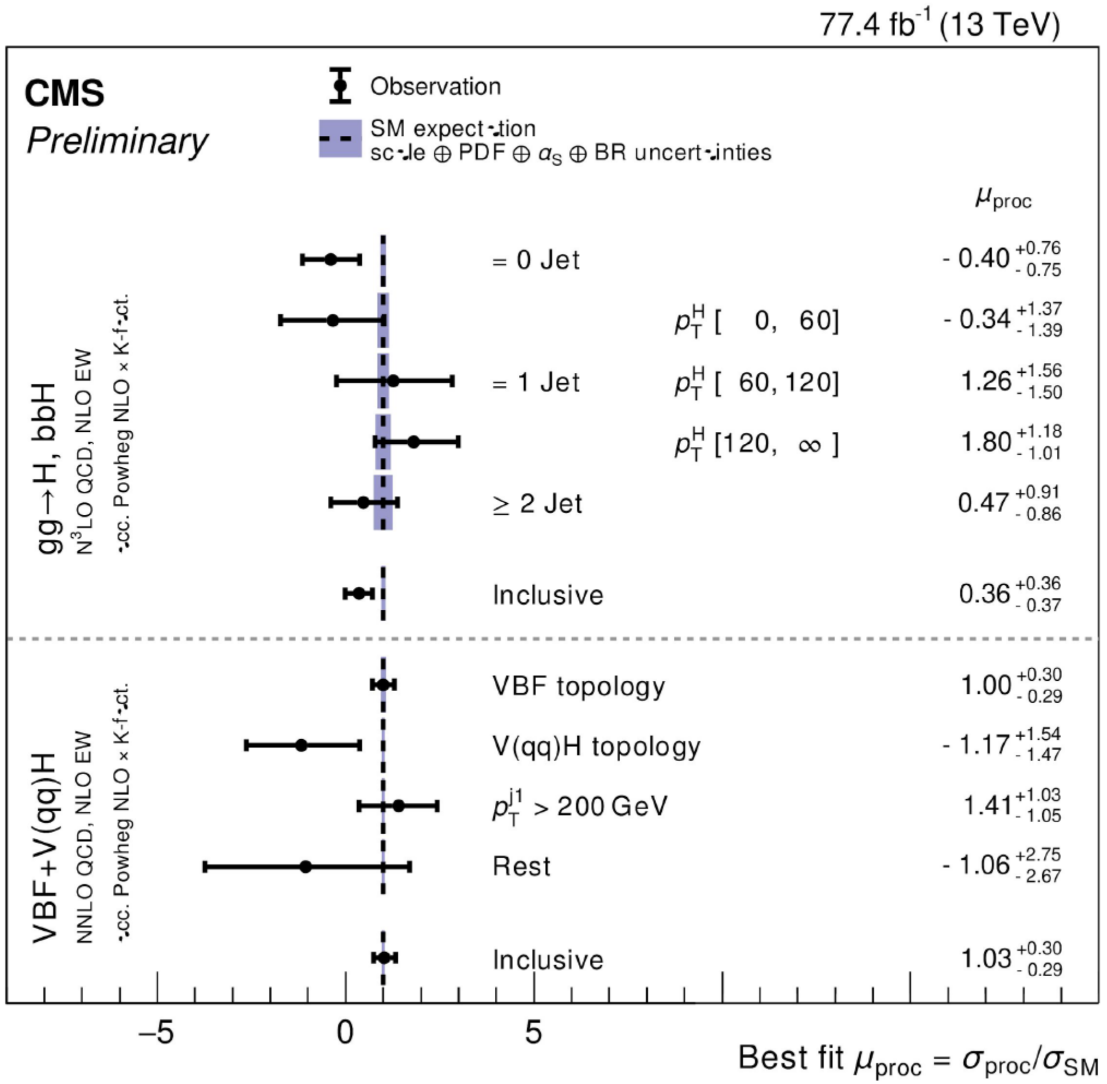


H→ττ

New @ LHCP2019







- CMSはStage-1で結果

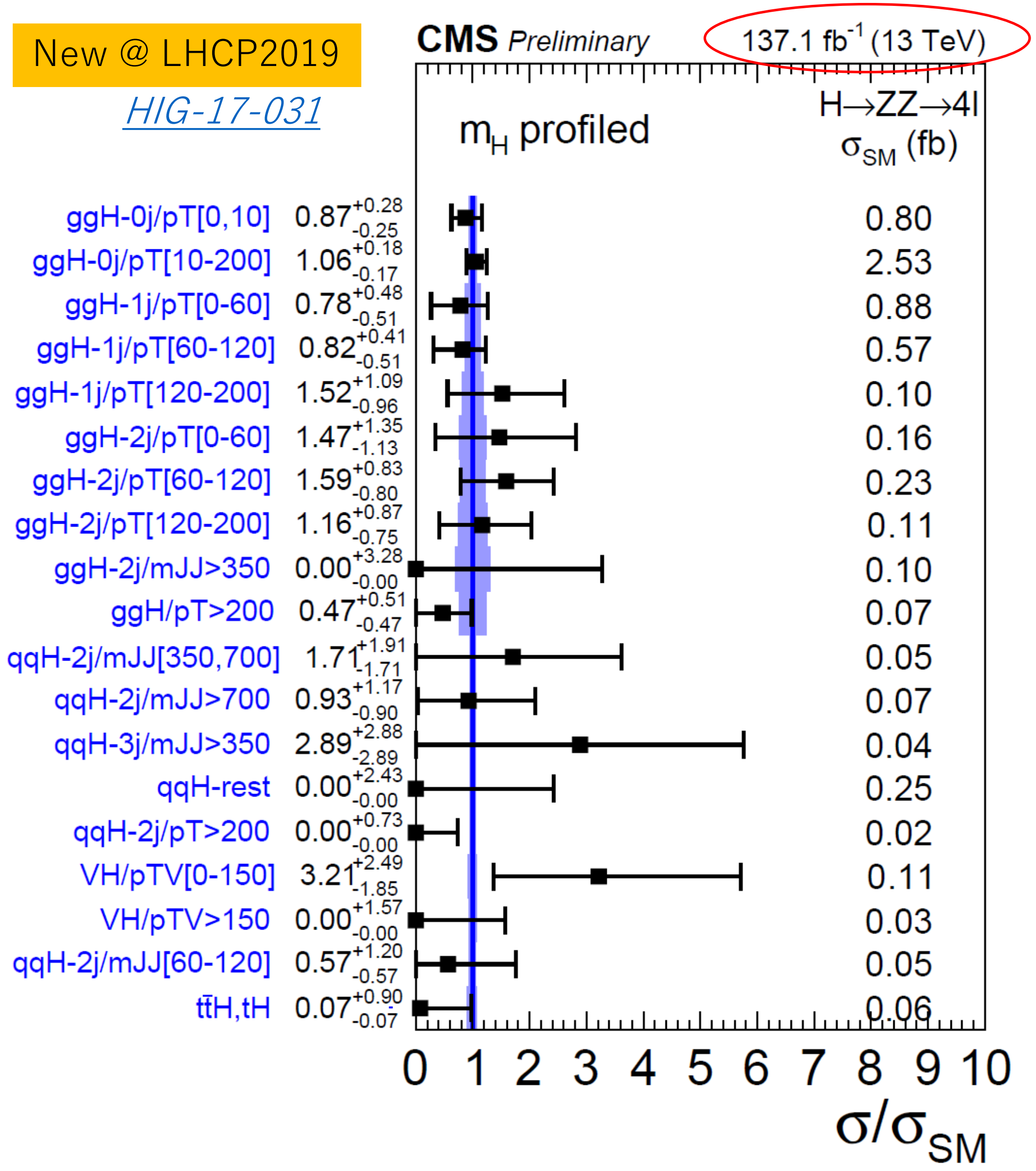
Stage-1: finer binning.

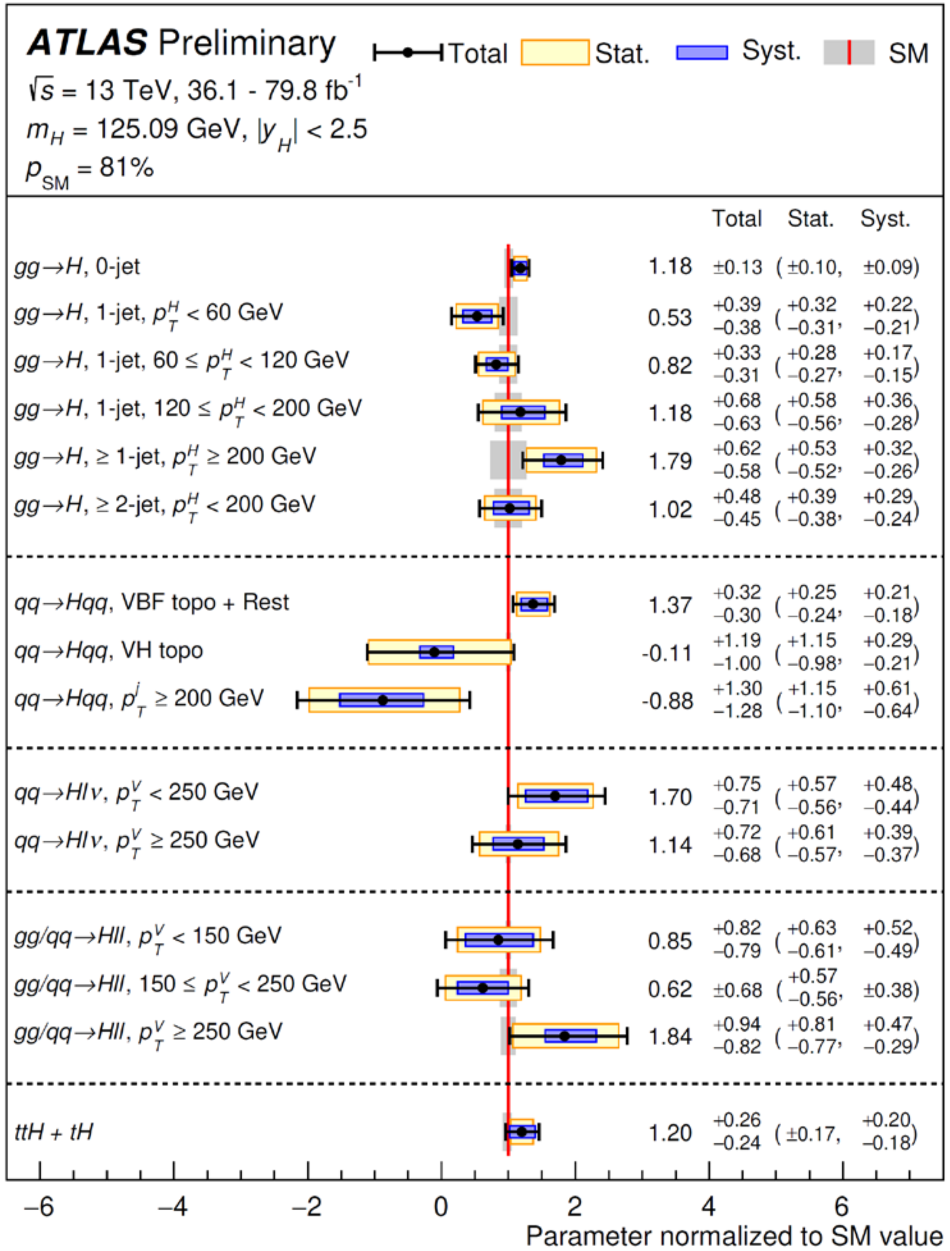
New @ Moriond2019

ATLAS-CONF-2019-005

New @ LHCP2019

HIG-17-031





Combination

- H→γγ
- H→ZZ
- H→WW
- H→ττ
- H→bb
- H→μμ
- ttH

Higgs自己結合定数へ

New @ Moriond2019

ATL-PHYS-PUB-2019-009

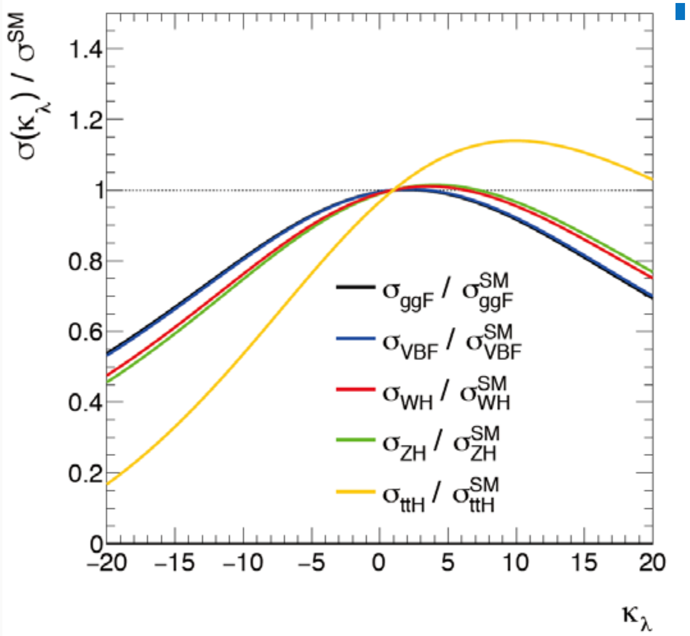
$$V(H) = \frac{1}{2}m_H^2 + \underline{\lambda_3 \nu H^3} + \frac{1}{4}\lambda_4 H^3 + O(H^5)$$

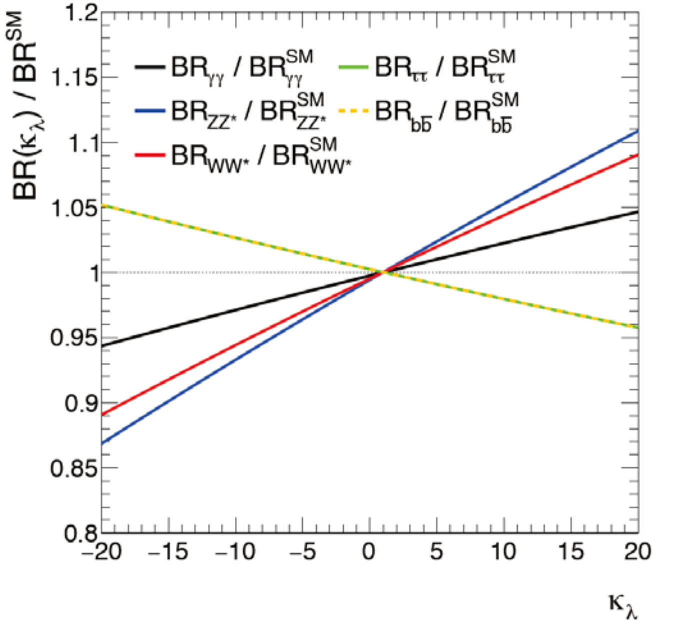
$$\lambda_3 = \underline{\kappa_\lambda}\lambda_3^{SM}$$

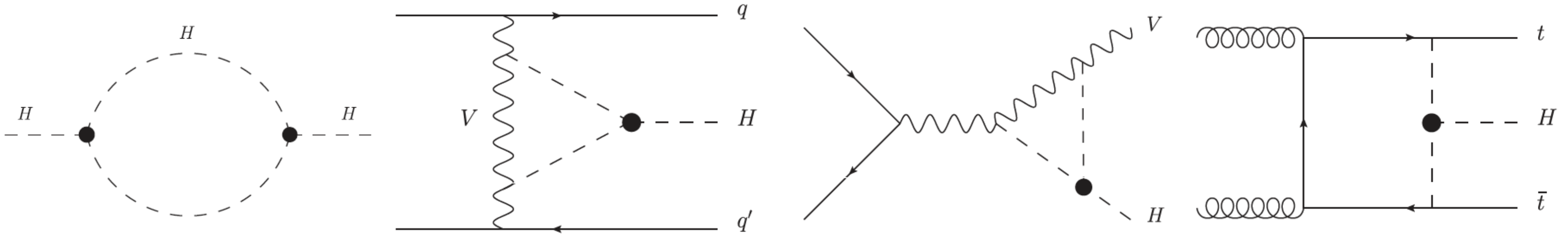
$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{\text{BSM}}}{\sigma^{\text{SM}}} = \frac{1}{1-(\kappa_\lambda^2 - 1)\delta Z_H}\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{\text{EW}}^i}\right]$$

$$\mu_f(\kappa_\lambda, \kappa_f) = \frac{\text{BR}_f^{\text{BSM}}}{\text{BR}_f^{SM}} = \frac{\kappa_f^2 + (\kappa_\lambda - 1)C_1^f}{\sum_j \text{BR}_j^{\text{SM}}\left[\kappa_j^2 + (\kappa_\lambda - 1)C_1^j\right]}$$

decay mode	$H \to \gamma\gamma$	$H \to WW^*$	$H \to ZZ^*$	$H \to b\bar{b}$	$H \to \tau\tau$
$C_1^f \times 100$	0.49	0.73	0.82	0	0
κ_f^2	$1.59\kappa_V^2 + 0.07\kappa_F^2 - 0.67\kappa_V\kappa_F$	κ_V^2	κ_V^2	κ_F^2	κ_F^2







Higgs自己結合定数へ

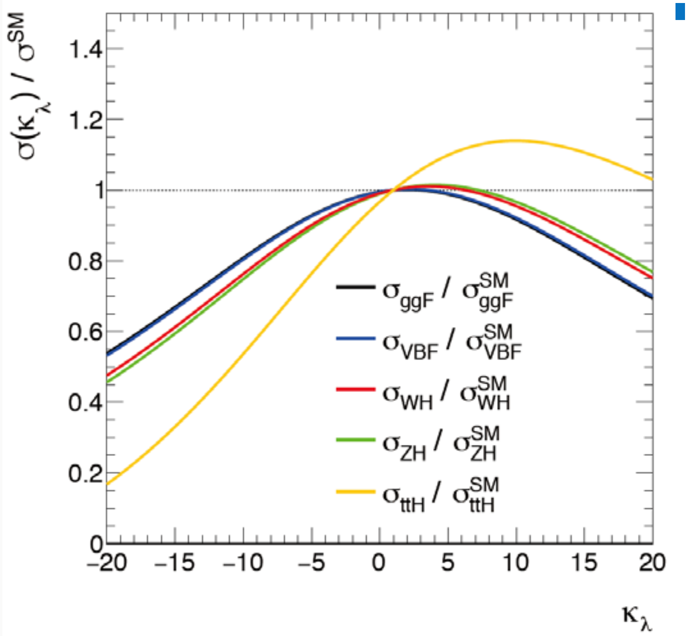
New @ Moriond2019

ATL-PHYS-PUB-2019-009

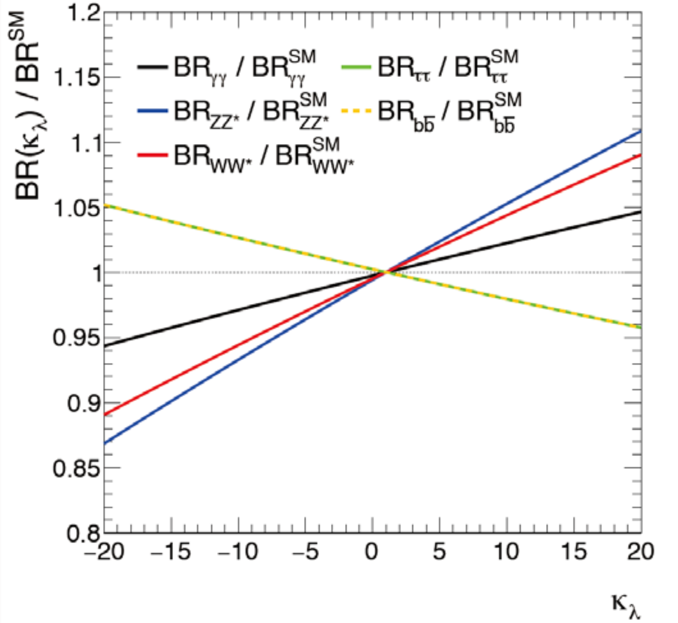
$$V(H) = \frac{1}{2}m_H^2 + \underline{\lambda_3 \nu H^3} + \frac{1}{4}\lambda_4 H^3 + O(H^5)$$

$$\lambda_3 = \underline{\kappa_\lambda}\lambda_3^{SM}$$

$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{\rm BSM}}{\sigma^{\rm SM}} = \frac{1}{1-(\kappa_\lambda^2 - 1)\delta Z_H}\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{\rm EW}^i}\right]$$



$$\mu_f(\kappa_\lambda, \kappa_f) = \frac{{\rm BR}_f^{\rm BSM}}{{\rm BR}_f^{SM}} = \frac{\kappa_f^2 + (\kappa_\lambda - 1)C_1^f}{\sum_j {\rm BR}_j^{\rm SM}\left[\kappa_j^2 + (\kappa_\lambda - 1)C_1^j\right]}$$



decay mode	$H \to \gamma\gamma$	$H \to WW^*$	$H \to ZZ^*$	$H \to b\bar{b}$	$H \to \tau\tau$
$C_1^f \times 100$	0.49	0.73	0.82	0	0
κ_f^2	$1.59\kappa_V^2 + 0.07\kappa_F^2 - 0.67\kappa_V\kappa_F$	κ_V^2	κ_V^2	κ_F^2	κ_F^2

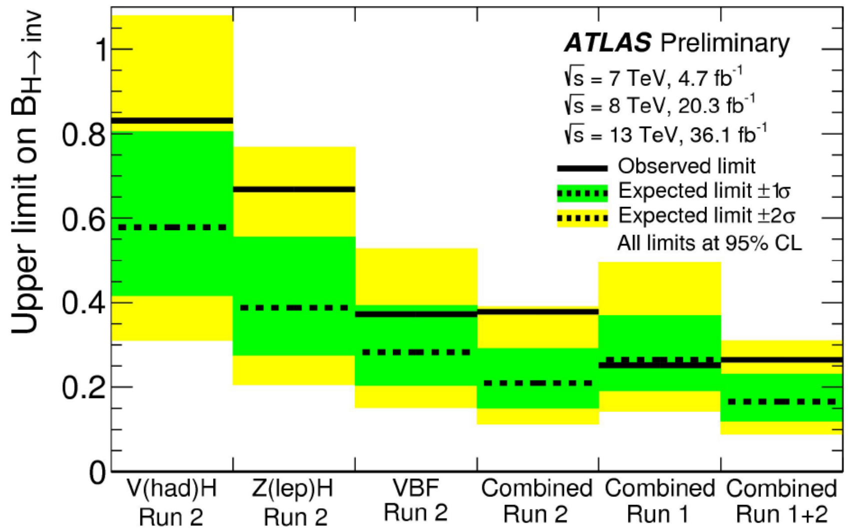
$$\kappa_\lambda = 4.0^{+3.7}_{-3.6}({\rm stat.})^{+1.6}_{-1.5}({\rm exp.})^{+1.3}_{-0.9}({\rm sig.th})^{+0.8}_{-0.9}({\rm bkg.th})$$

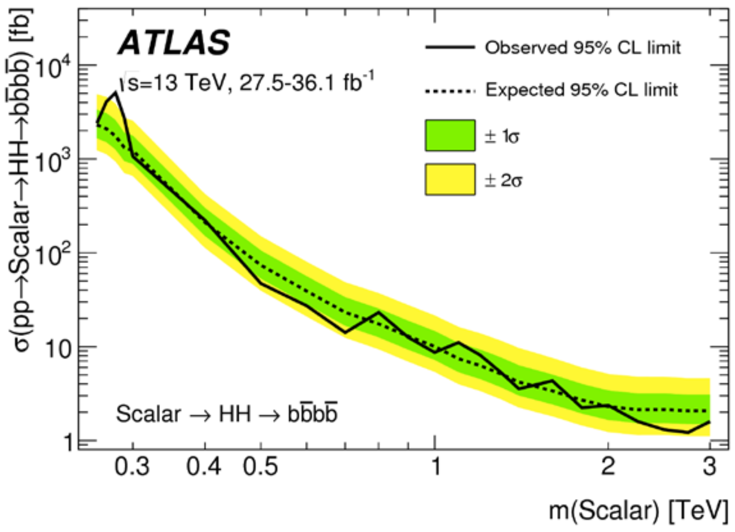
$$-3.2 < \kappa_\lambda < 11.9 \quad \text{@ 95\% CL}$$

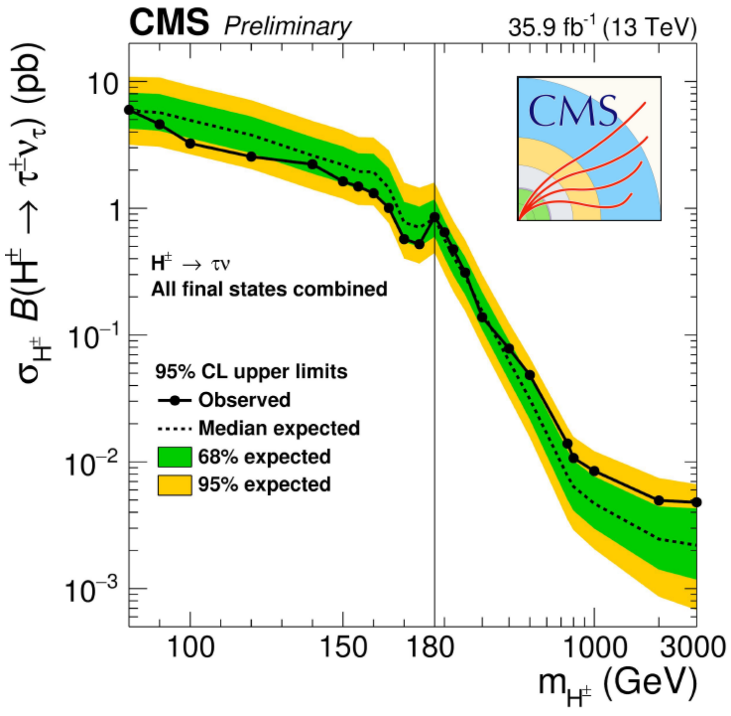
BSM Higgs?

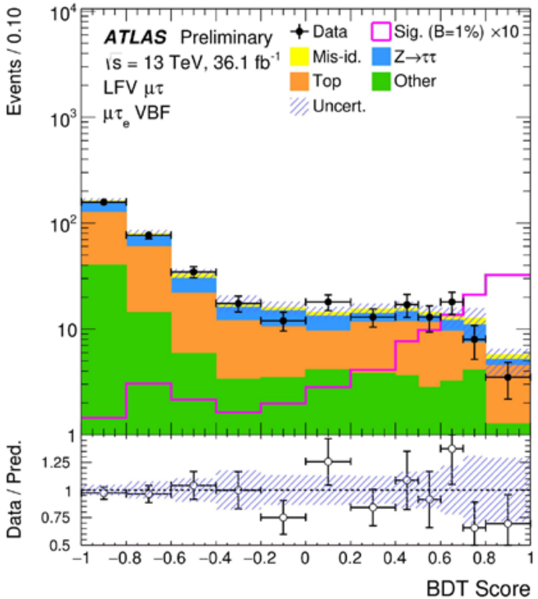
- Many analyses are on going.
- New result coming soon!

Br(H→inv)<0.26









Observed Upper limit
Br(H→μτ)<0.28%
Br(H→eτ)<0.61%
@95% CL

まとめ

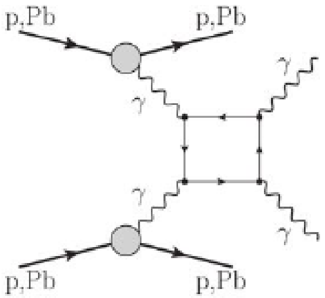
- Standard model
  - Jets, V+jetsも重要。詳細解析が進行中
  - Rare processが面白い。
    - 理論の方へ：他にありませんか？
  - Topの質量、スピンなどの解析も進んでいる。
- Higgs
  - 主要なプロセス、主要崩壊モードは確立
    次は第2世代: H→cc, μμ
  - 精密測定に向け、
    - 微分断面積の測定
    - STXS解析　　　　を精力的に進めている。
  - BSM Higgsも進んでいます。
    - もう少しお待ちください。
    - Run3は低い方も行けるか。。

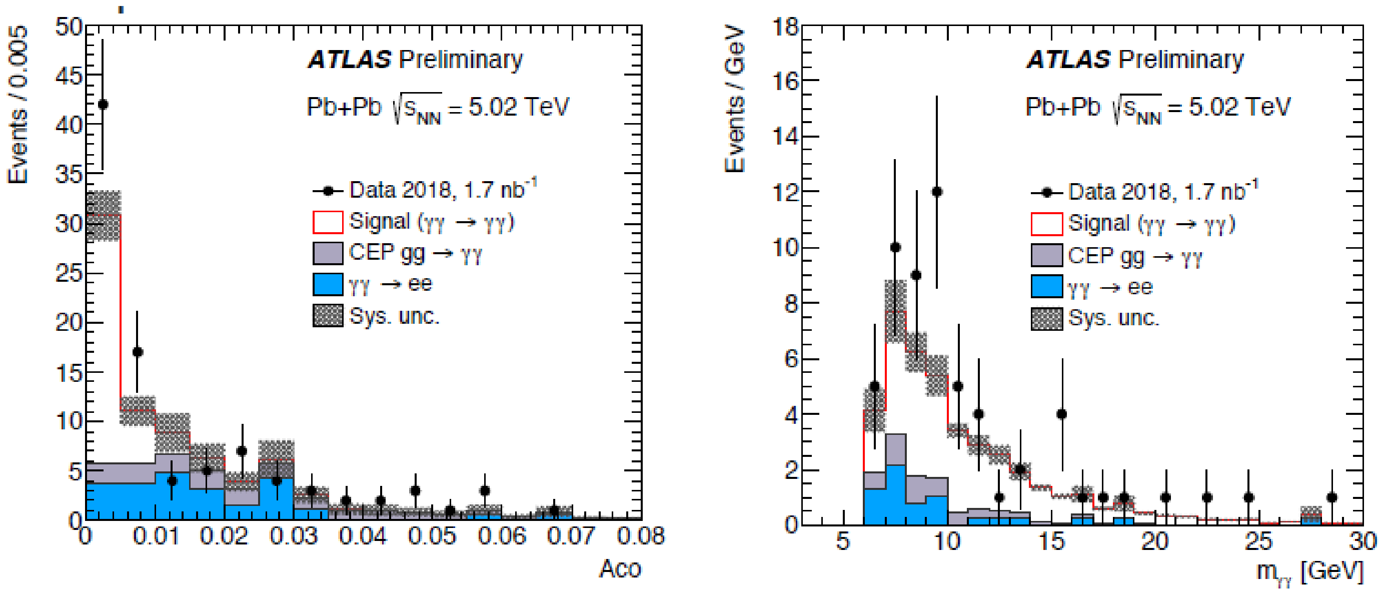
Extra materials

Light-by-Light

Observation of Light-by-Light Scattering

- Forbidden process at tree level enhanced in Pb-Pb collisions
  - Cross section proportional to Z^4
  - Another probe of anomalous gauge couplings and BSM contributions
  - Evidence had been reported already
- First observation by ATLAS in collisions recorded in Nov 2018
  - better trigger and enhanced identification of photons





σ_{ATLAS} = 78 ±13 (stat) ±8 (sys) nb

SM predictions: 49 ±5 nb

Top mass definition

Top mass definitions

LHCP2019 A. Viciniのスライド

Renormalisation → pole mass definition — the renormalised mass is the pole of the propagator

→ MSbar mass definition — only $1/\epsilon + \gamma_E - \ln 4\pi$ are subtracted with the mass ct

The infrared sensitivity of the quarks makes the very concept of mass problematic

→ contribution of infrared renormalons

→ given a final state, defined an observable, which part of QCD radiation has to be associated with the top field? or:
how does the sensitivity to mtop of a given observable change with radiation?

→ the description of QCD radiation entails a certain modelling, making mtop model dependent

$$m_t^{MC} = m_t^{pole} + \Delta_m^{pert} + \Delta_m^{non\ pert} + \Delta_m^{MC}$$

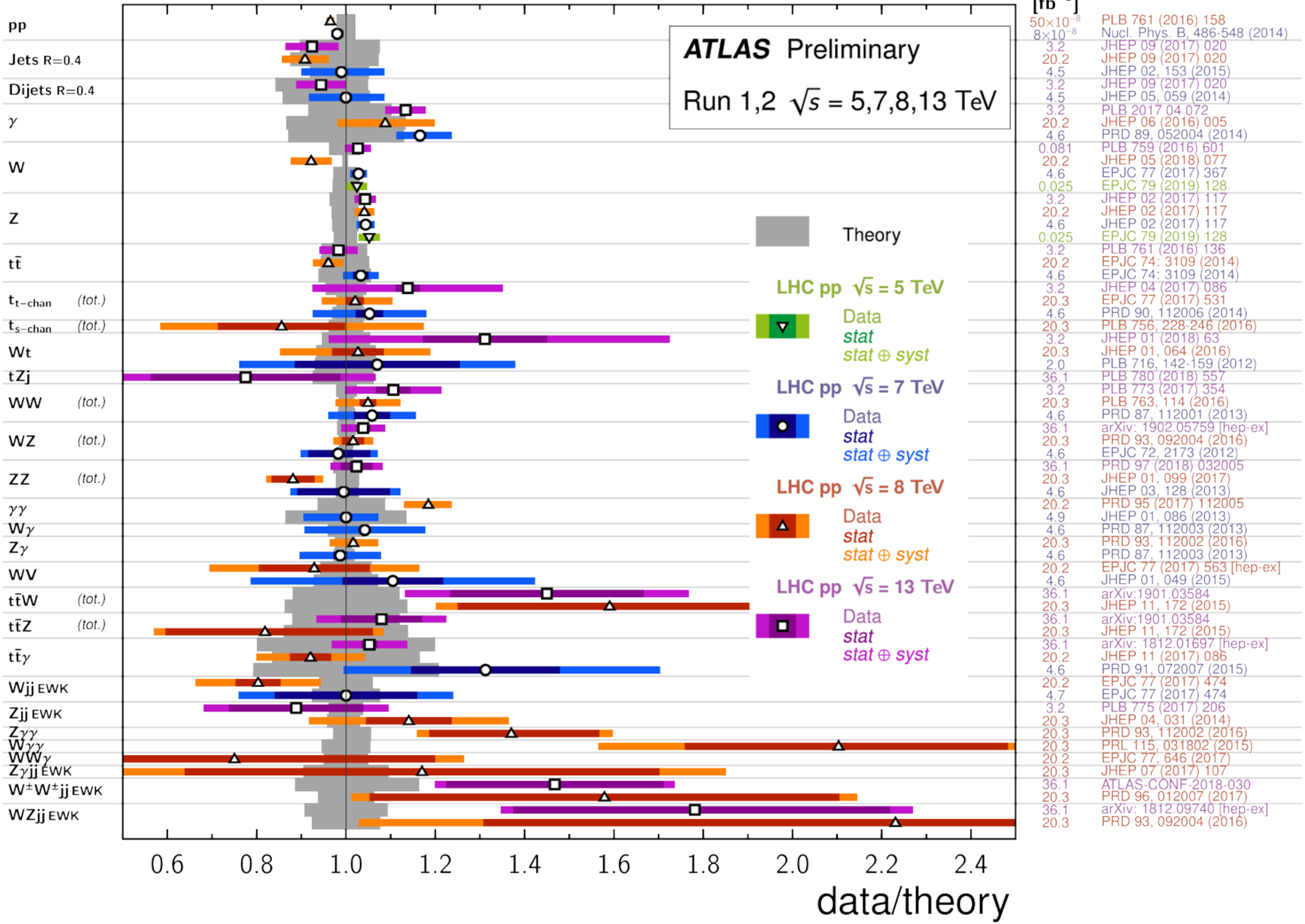
The notion of MC mass assigns a status of mass, a primitive concept,
to the non universal, process and observable dependent corrections of (non-)perturbative modelling,
whereas all these effects
modify the accuracy of the description of the chosen observable and bias the result of the fit
but do not affect the template fit logic, where it is the Lagrangian parameter to be varied in the fit

in the MW case QCD corrections modify in completely different ways MT and ptlep and in turn MW

Standard Model Production Cross Section Measurements

Status: March 2019

$\int \mathcal{L}\,dt$ [fb^{-1}] Reference

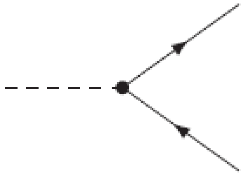


- Extracting Higgs coupling from σxBr requires assumptions at LHC

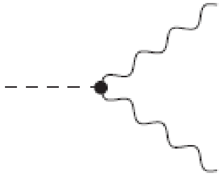
$$\sigma \cdot B\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

- Total width is not measurable, we assume
  - Total width controlled by H→bb
  - H→cc is 5% unmeasured contribution
    - Scale with bb
    - bb/cc scale with ττ
  - No new invisible modes
- In measurement, introduce scaling parameter, κ_X^2, which scales cross section and decay width to probe them.

$$g_{Hff} = \frac{\sqrt{2}m_f}{\upsilon}$$

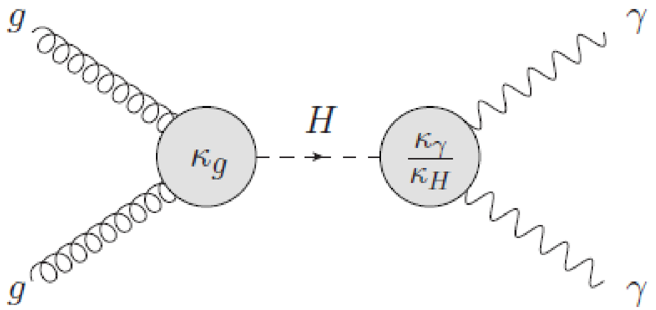


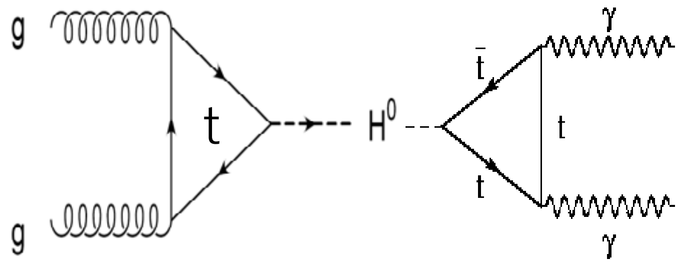
$$g_{HVV} = \frac{2m_V^2}{\upsilon}$$



$$g_{Hff} = \kappa_f \cdot \frac{\sqrt{2}m_f}{\upsilon}$$

$$g_{HVV} = \kappa_V \cdot \frac{2m_V^2}{\upsilon}$$





- ggH: κ_g, Hγγ: κ_γ/κ_H

$$(\sigma\cdot BR)(gg\to H\to\gamma\gamma)=\left[\sigma(gg\to H)\cdot BR(H\to\gamma\gamma)\right]_{SM}\times\boxed{\frac{\kappa_g^2\cdot\kappa_\gamma^2}{\kappa_H^2}}$$

κ_H^2 : the scale factor to the total Higgs decay width

→ This allows to probe BSM in the loop

$$\kappa_H^2=\sum\kappa_x^2\cdot\frac{BR_{SM}(H\to xx)}{1-BR_{BSM}}$$

- Decompose Loops (if necessary)

ggH:

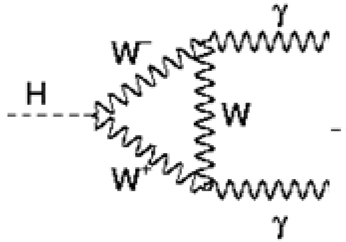
$$\sigma_{SM}=\sigma_{tt}+\sigma_{bb}+\sigma_{tb}$$

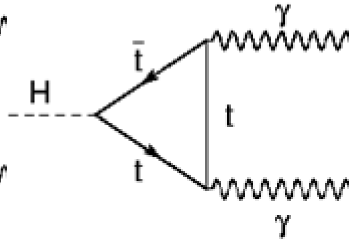
$$=\kappa_t^2\sigma_{tt}+\kappa_b^2\sigma_{bb}+\kappa_t\kappa_b\sigma_{tb}$$

$$\kappa_g^2=\frac{\sigma}{\sigma_{SM}}=\frac{\kappa_t^2\sigma_{tt}+\kappa_b^2\sigma_{bb}+\kappa_t\kappa_b\sigma_{tb}}{\sigma_{tt}+\sigma_{bb}+\sigma_{tb}}$$

$$\approx 1.058\kappa_t^2+0.007\kappa_b^2-0.065\kappa_t\kappa_b\ ^*$$

Hγγ:





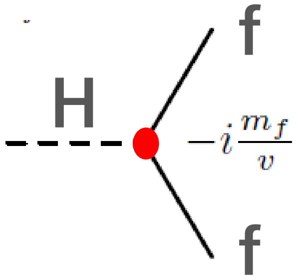
$$\kappa_\gamma^2=\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}}=\frac{\kappa_t^2\Gamma_{\gamma\gamma}^{tt}+\kappa_W^2\Gamma_{\gamma\gamma}^{WW}+\kappa_t\kappa_W\Gamma_{\gamma\gamma}^{tW}}{\Gamma_{\gamma\gamma}^{tt}+\Gamma_{\gamma\gamma}^{WW}+\Gamma_{\gamma\gamma}^{tW}}$$

(M_H=125.5 GeV) $\approx 0.07\kappa_t^2+1.59\kappa_W^2-0.66\kappa_t\kappa_W\ ^*$

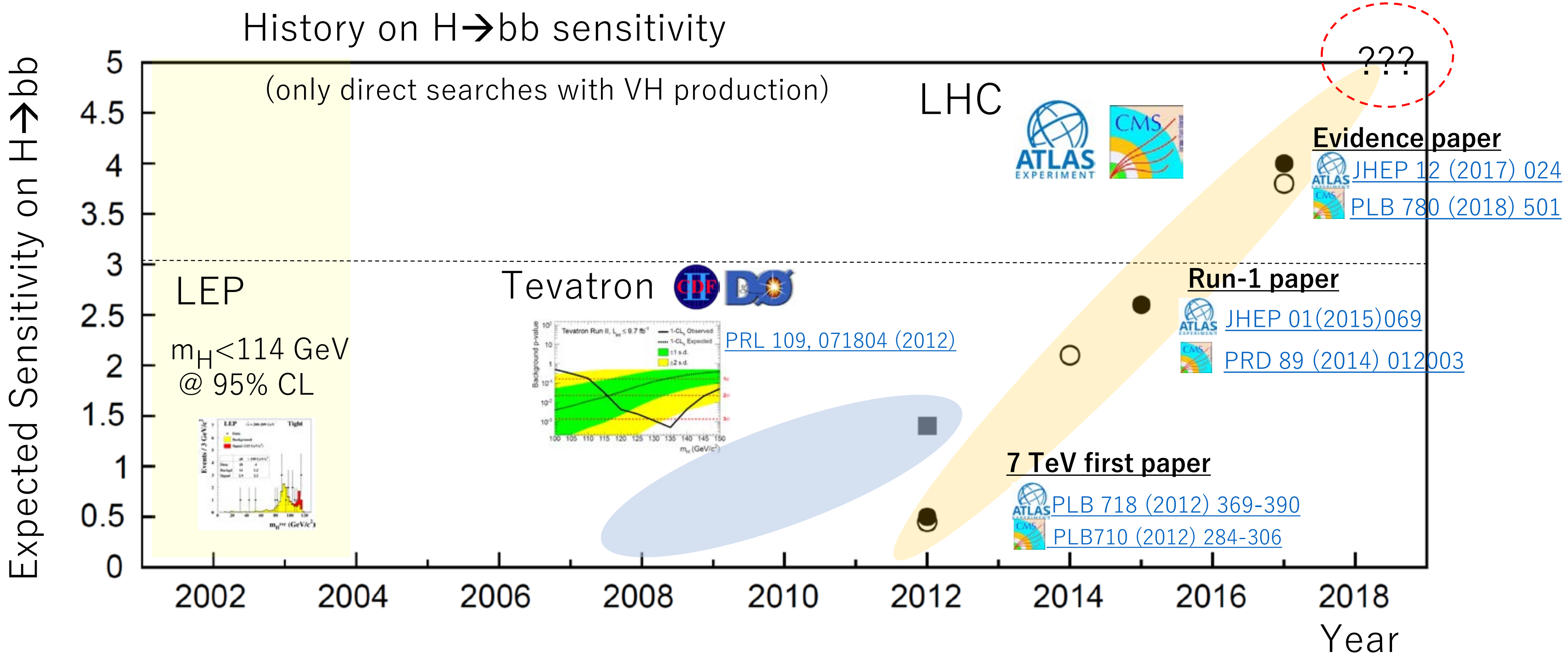
Road to discovery of H→bb

- Higgs mechanism: EWSB and Yukawa coupling.
- H→bb was one of key channels for Higgs search.
- Started in LEP era, developed in Tevatron, then LHC.

$$\frac{g_f}{\sqrt{2}} = \frac{m_f}{v}$$



History on H→bb sensitivity



H→fermion BR at m_H = 125 GeV

Decay	Br
bb	58 %
ττ	6.3 %
cc	2.9 %
μμ	0.022 %