ATLAS実験の最近の物理結果から

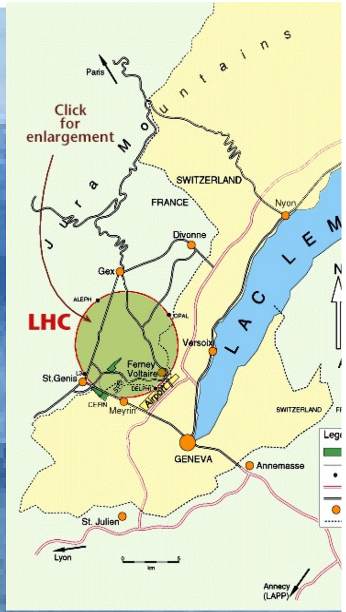
佐藤構二

宇宙史センター 構成員会議

2019年11月18日（月）

LHC実験

スイス･アルプス山脈



世界最高エネルギーでの加速器実験

$\sqrt{s}$ ≤14 TeVでの陽子･陽子衝突

2010年　LHC加速器稼動開始。

2011-12年　物理Run開始。Ecm=7 – 8 TeV, 25 fb^{-1}のデータ取得。

2012年　LHC加速器のATLAS/CMS両実験がヒッグス粒子を発見。

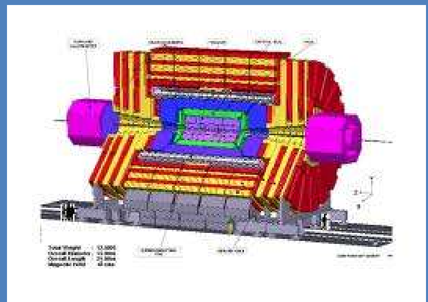
2015-18年　エネルギーをEcm=13 TeVに上げてRun 2実験。

2021-2023年　Run 3。Ecm=14 TeV，～300 fb^{-1}のデータセット。

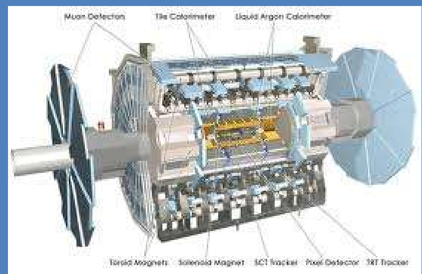
2026-203X年　HL-LHC実験。～3000 fb^{-1}の大データセット。

ジュネーブ市街

CMS実験



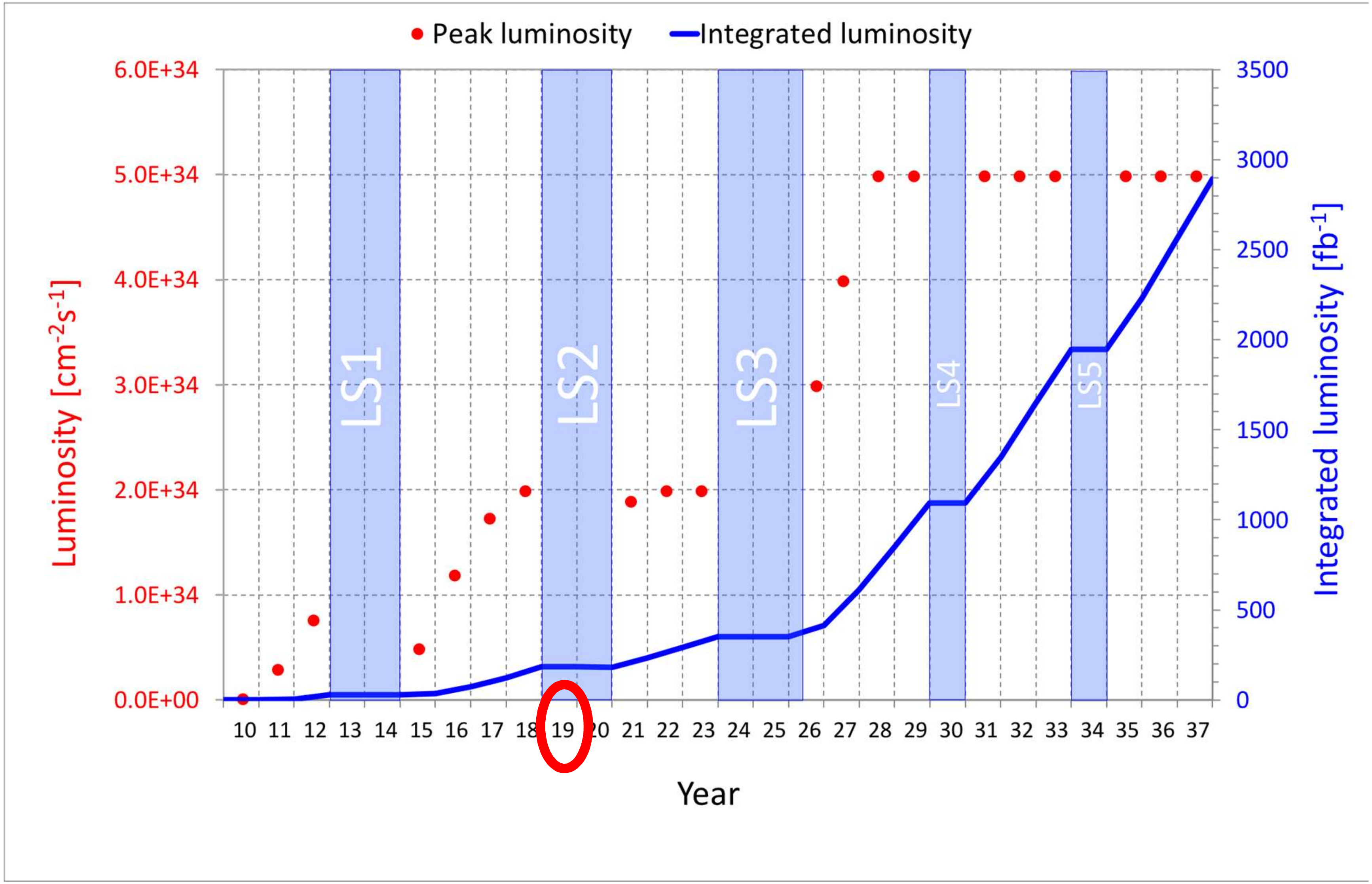
ATLAS実験



円周27km

陽子を最大7 TeVまで加速して正面衝突

LHCの長期将来計画



Peak luminosity
Integrated luminosity
6.0E+34
5.0E+34
4.0E+34
3.0E+34
2.0E+34
1.0E+34
0.0E+00
Luminosity [cm-2s-1]
3500
3000
2500
2000
1500
1000
500
0
Integrated luminosity [fb-1]
LS1
LS2
LS3
LS4
LS5
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
Year

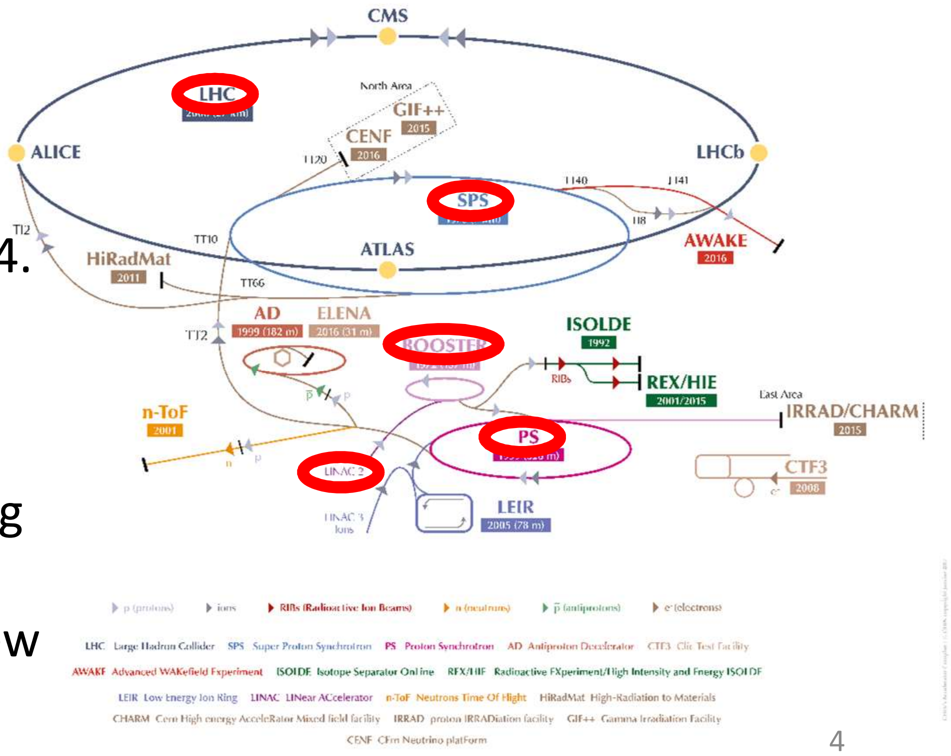
Accelerator LS2 Upgrades

- 2019-2020: Long Shutdown (LS2) preparing for Run 3 in 2021-2023.

Key Plans for LS2 Accelerator Upgrades

https://home.cern/news/news/accelerators/key-plans-next-two-years-lhc

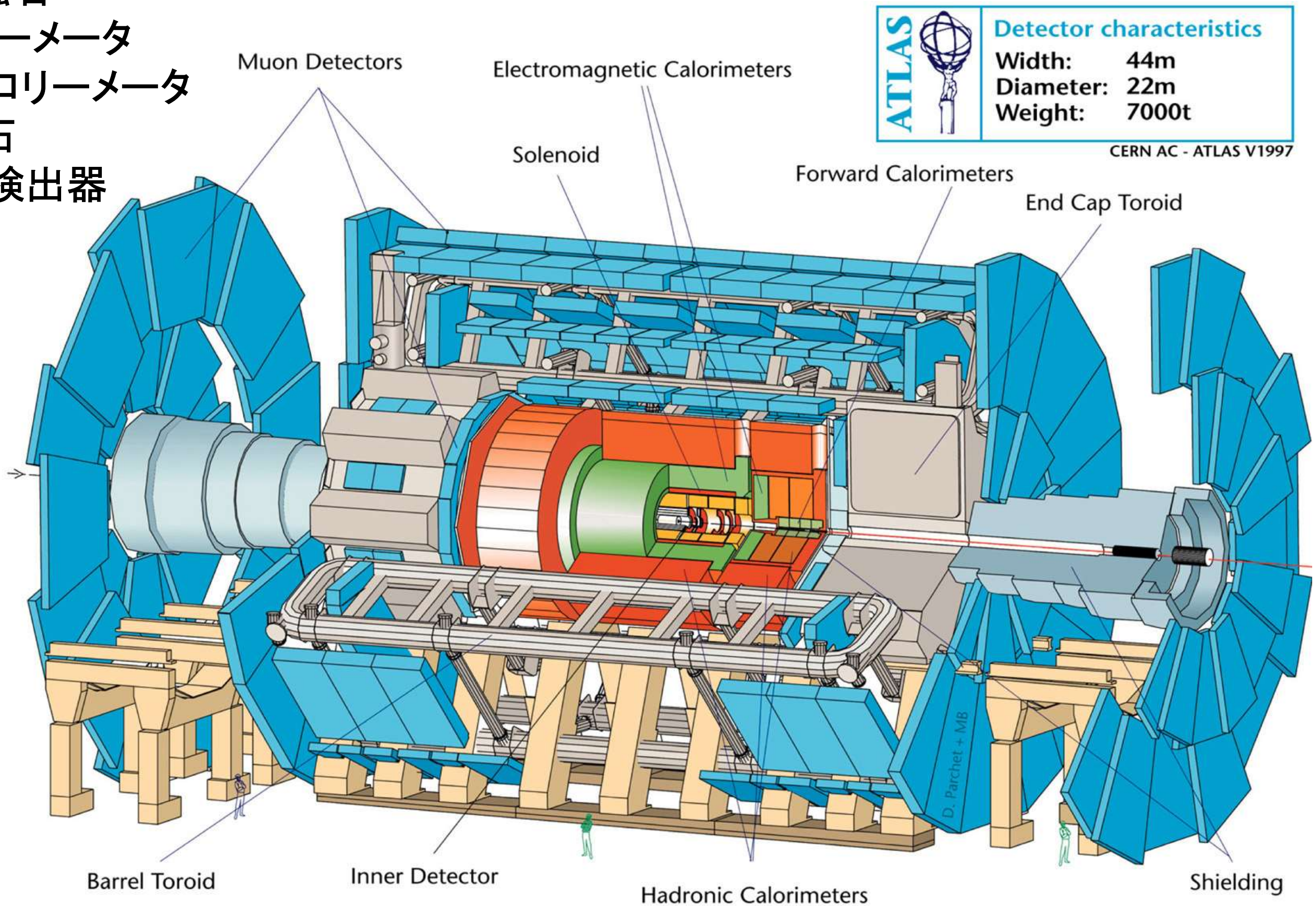
- Preparation for HL-LHC, as well as Run 3 and maintenance.
- More intense, concentrated beam, with new Linac accelerating H- instead of proton.
    - Replace Linac 2 with new Linac 4.
    - Upgrade Booster injection.
    - New RF system in SPS.
- Bring beam energy up to 7 TeV.
    - Consolidate the diodes providing current to dipole magnets
- ~20 magnet replacements, install new lifts, …



ATLAS検出器

- シリコン検出器
- 飛跡検出器
- ソレノイド磁石
- 電磁カロリーメータ
- ハドロンカロリーメータ
- トロイド磁石
- ミューオン検出器

総重量　**7,000 t**

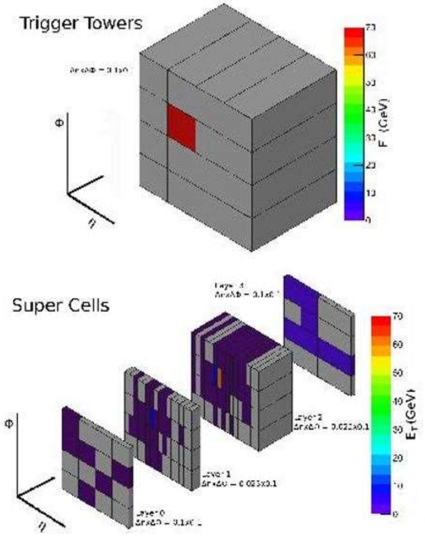


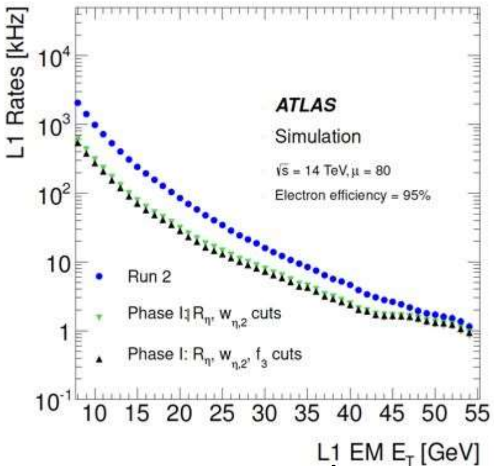
- 最高エネルギーでの、さまざまな素粒子反応の研究
  - ヒッグス粒子、標準理論、トップクォーク、Bメソン、超対称性、新物理探索、重イオン衝突…

ATLAS LS2 Upgrades

L1 Calo Trigger Upgrade

読み出しを細分化することで、他バンチのヒットの影響を減らす。





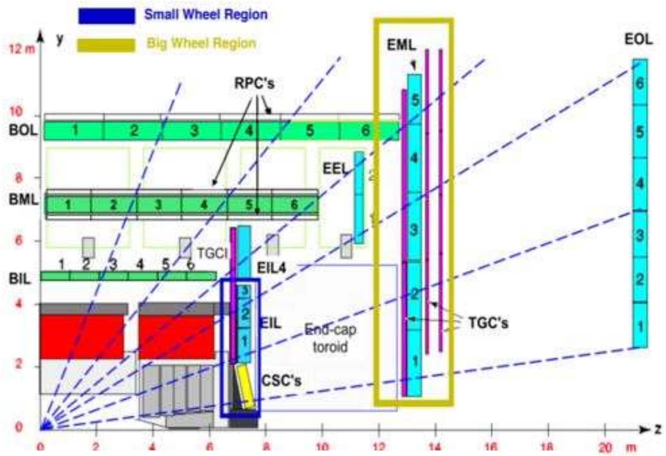
Improvement on Jet and MET triggers, too.

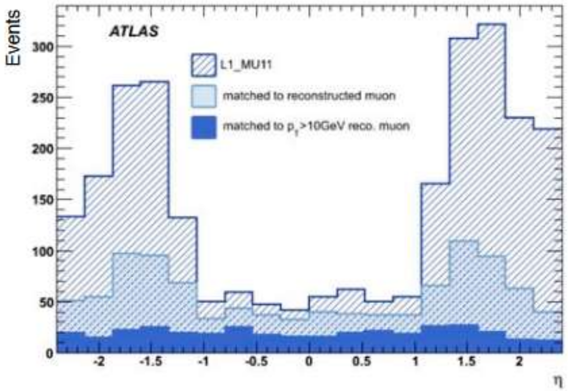
Nucl.Instrum.Meth. A824 (2016) 374-378

New Muon Small Wheel

For L1 Trigger

内層に新しいトリガーチェンバーを入れる。



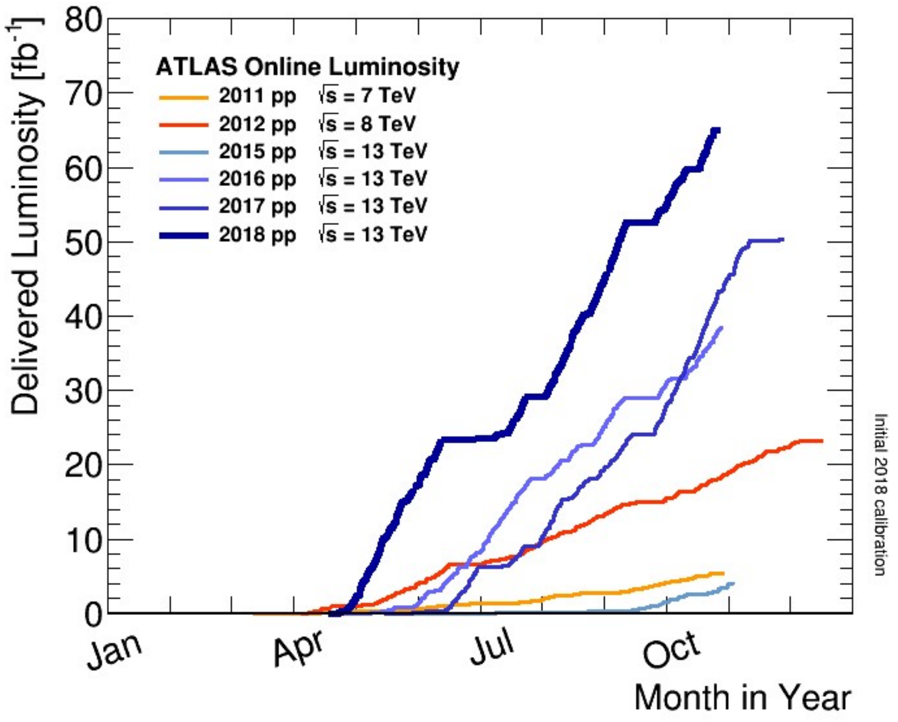


arXiv:1810.01394

FTK Upgrade – new track trigger in L2 trigger.

TDAQ Upgrade

Luminosities in Run 2

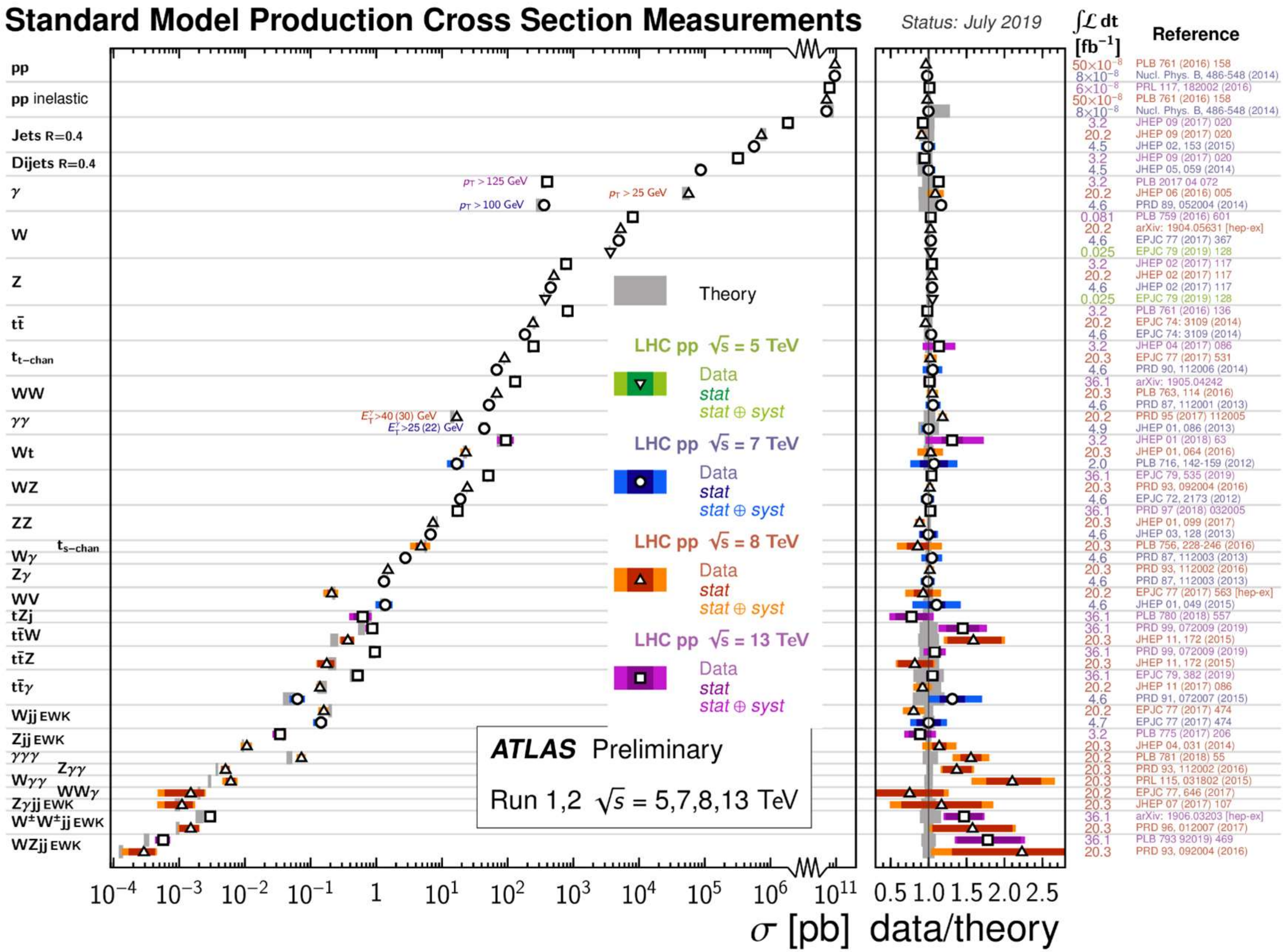


Run 1	E_{CM}(TeV)	integ lumi [fb-1]
2011	7	5
2012	8	21

$E_{CM} = 13$ (TeV)

Run 2	Peak lumi E34 $cm^{-2}s^{-1}$	Days pp physics	Recorded integ lumi [fb-1]	Good for Physics [fb-1] 累積
2015	0.5	56	3.9	3.2
2016	1.4	122	36.0	**36**
2017	1.9	150	46.9	**80**
2018	2.1	152	65.0	**139**

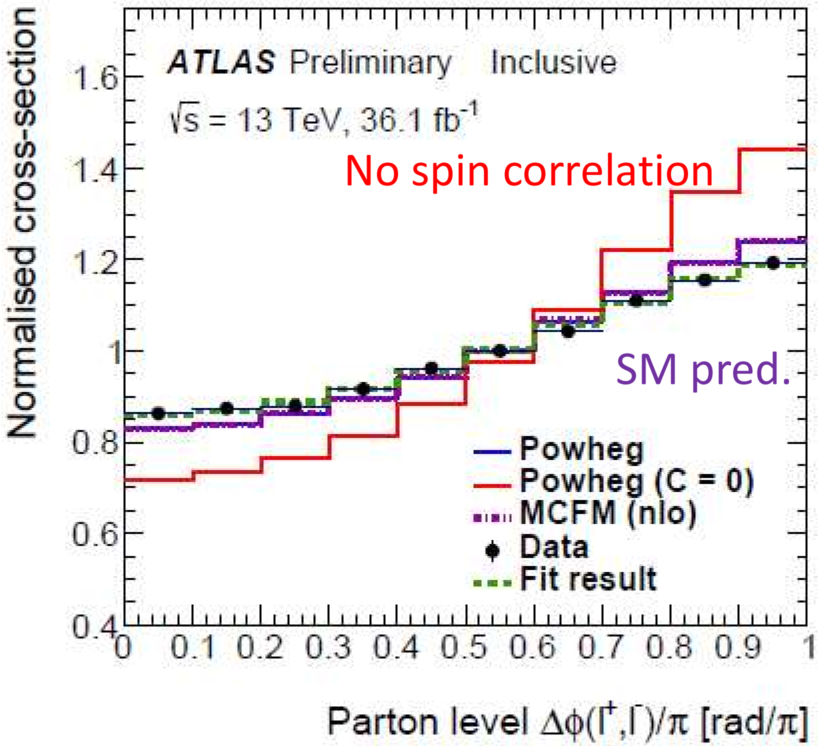
標準理論の大成功



15桁にわたって、理論＝実験がよく合っている。

Top Spin Correlation

2018年11月
宇宙市センター構成員会議



- $t\bar{t} \rightarrow (Wb)(Wb) \rightarrow (e\nu b)(\mu\nu b)$
- eとμの間の角度相関。
- SM(NLO QCD)の予言値よりも強い相関がみられた。
- テンプレート・フィット

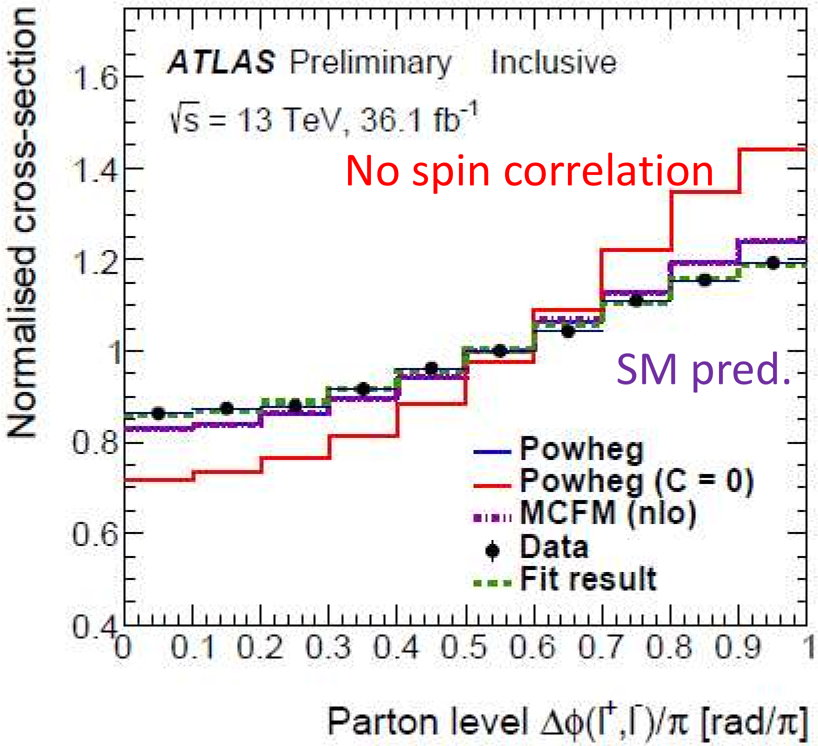
$$n_i = f_{SM} \cdot n_{spin} + (1 - f_{SM}) \cdot n_{nospin}$$

フィット結果：

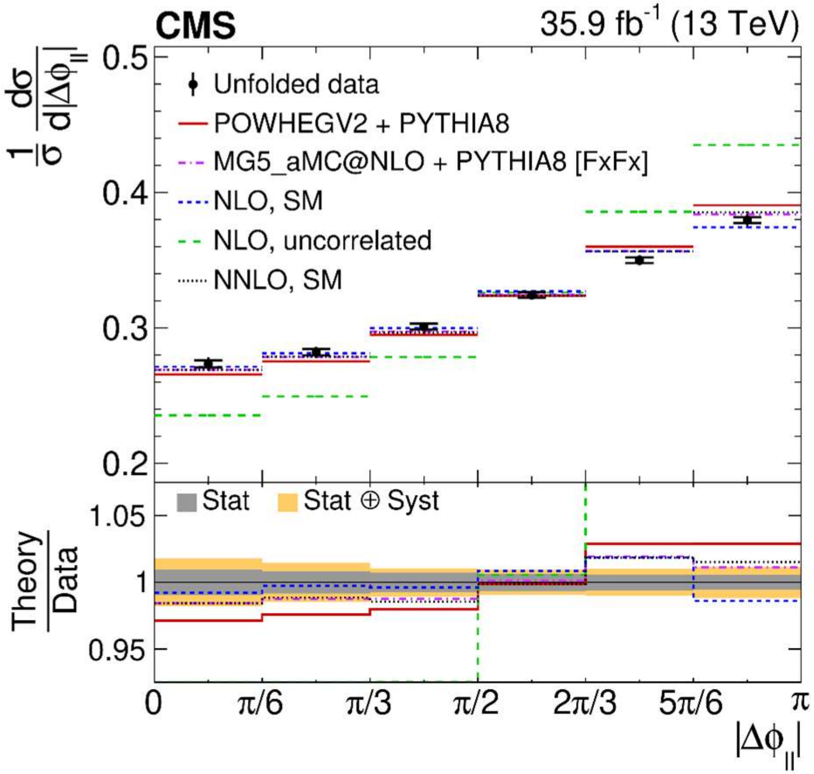
$$f_{SM} = 1.250 \pm 0.026 \pm 0.063$$

- SMからのずれ： 3.2σ (syst込み)

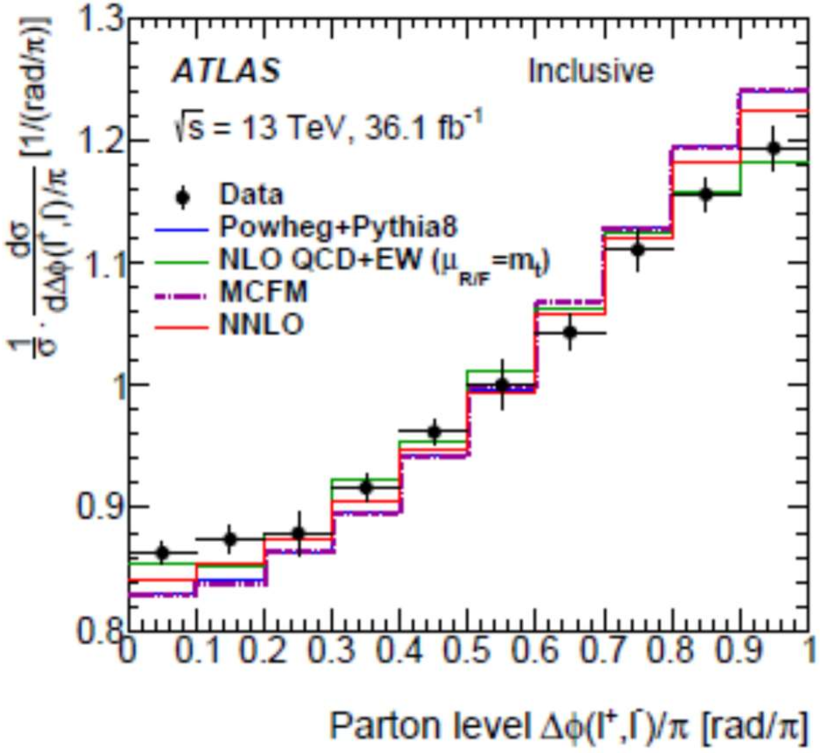
Top Spin Correlation CMSの分布

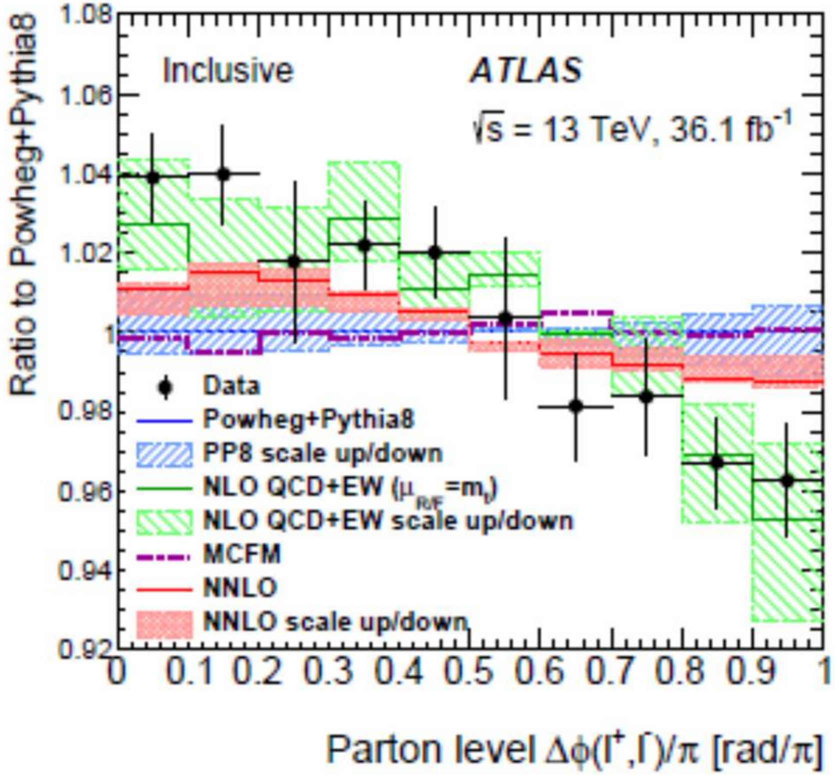


arXiv:1907.03729



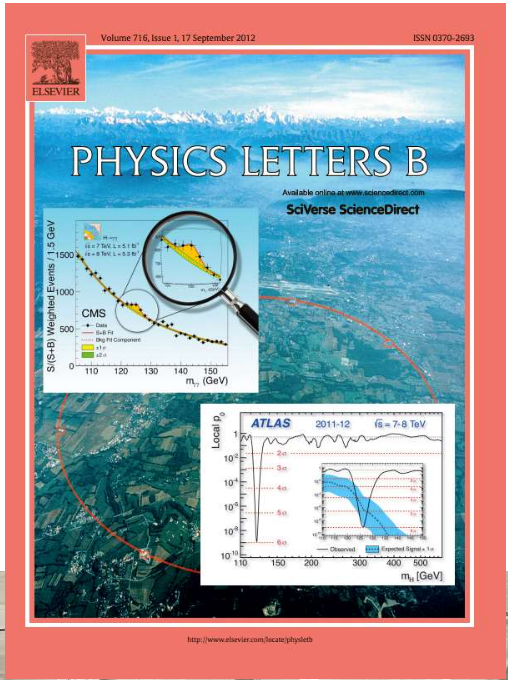
Top Spin Correlation　今年の夏のアップデート

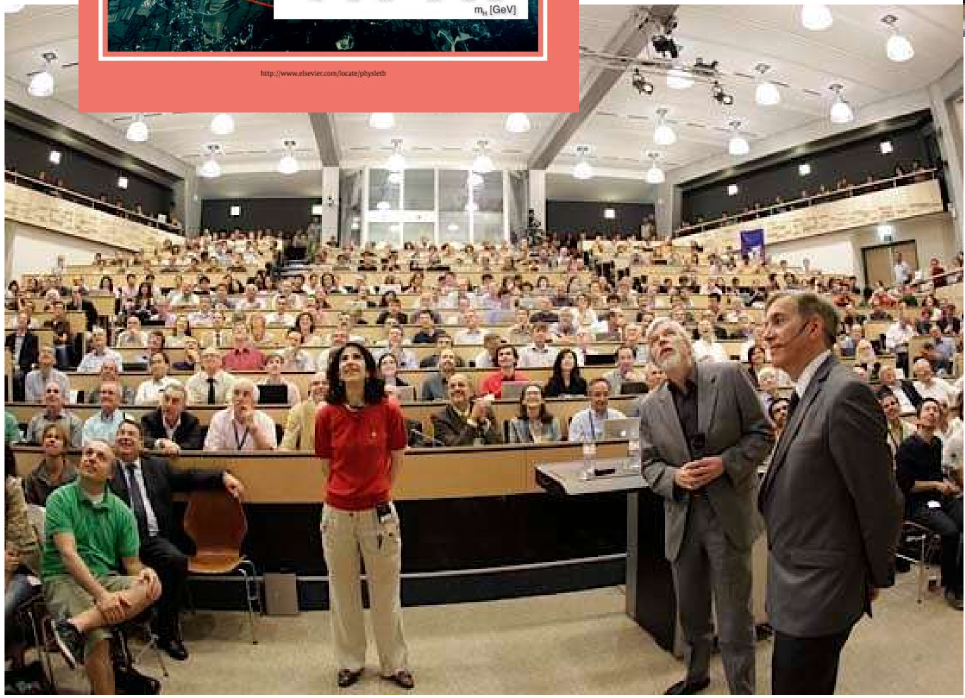




- NLO QCD+EWKはデータをよく再現する。
- 理論計算の精度が足りていないせいと結論できるか。

ヒッグス粒子発見の発表





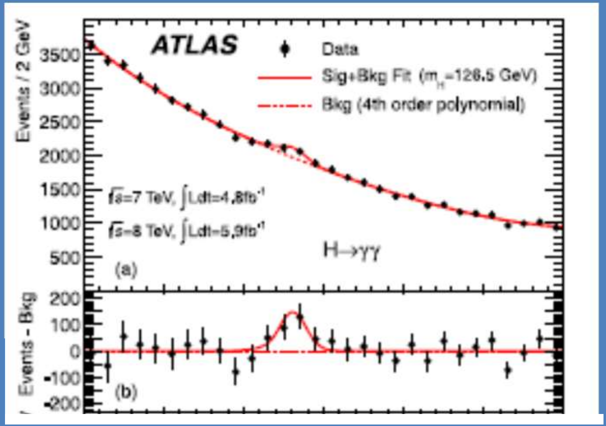
2012年7月4日　LHC加速器の
ATLAS/CMS両実験が発見を報告

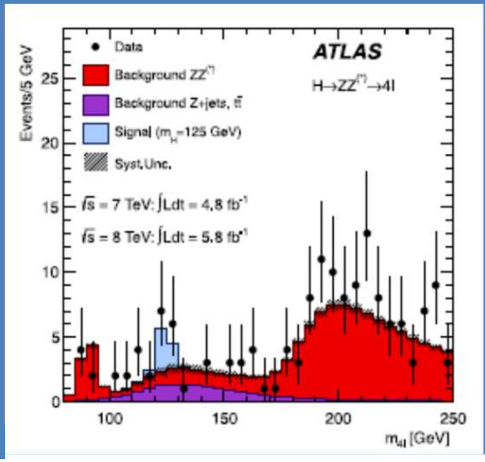
2013年　アングラール、ヒッグス
がノーベル物理学賞を受賞

ヒッグス発見チャンネルの現在

2012年夏、ヒッグス粒子発見時のデータ

[Phys. Lett. B 716 (2012) 1-29]

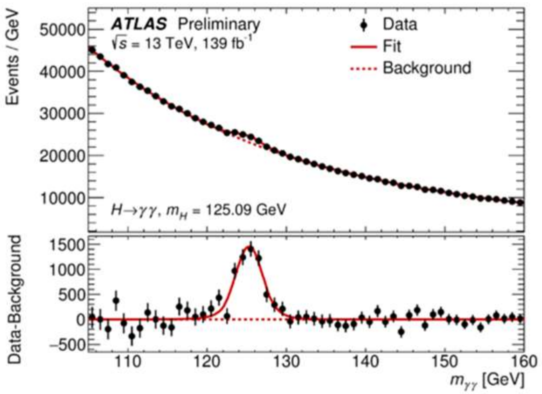




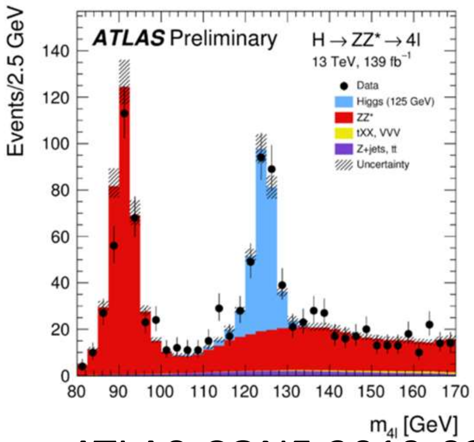
２チャンネル合わせて5.9σ.

$H \to \gamma\gamma$

$H \to ZZ^* \to 4\ell$



ATLAS-CONF-2019-032

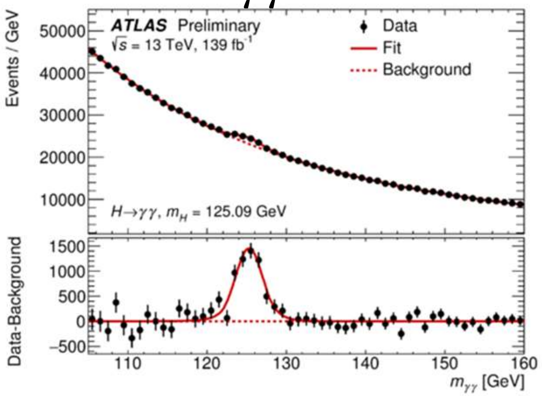


ATLAS-CONF-2019-025

現在では、$H \to \gamma\gamma, H \to ZZ^* \to 4\ell$チャンネルは大量の候補事象。

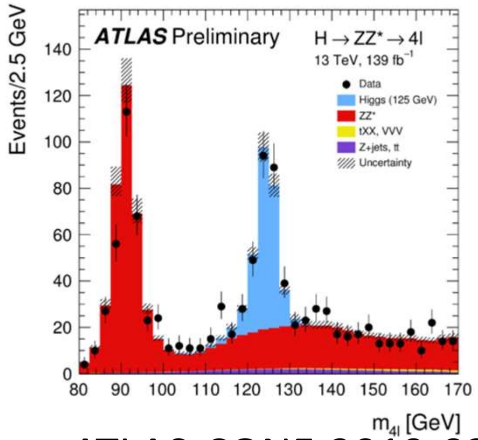
ヒッグス発見チャンネルの現在(2)

$H \to \gamma\gamma$



ATLAS-CONF-2019-032

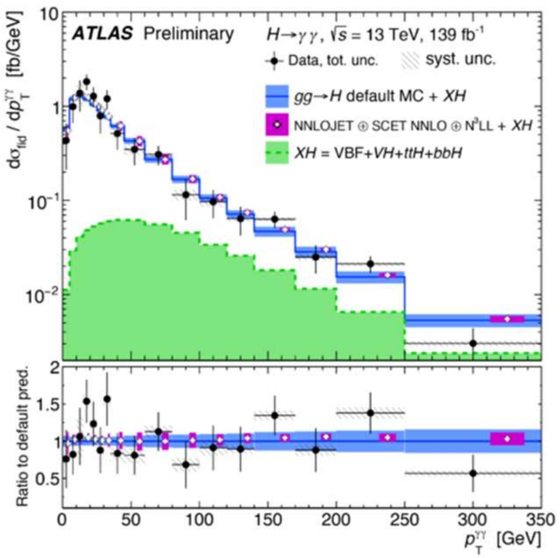
$H \to ZZ^* \to 4\ell$

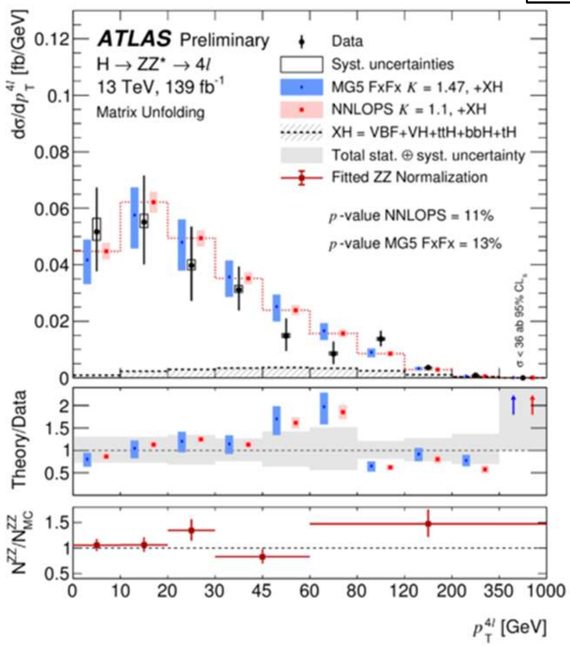


ATLAS-CONF-2019-025

現在では、$H \to \gamma\gamma, H \to ZZ^*$チャンネルは大量の候補事象。

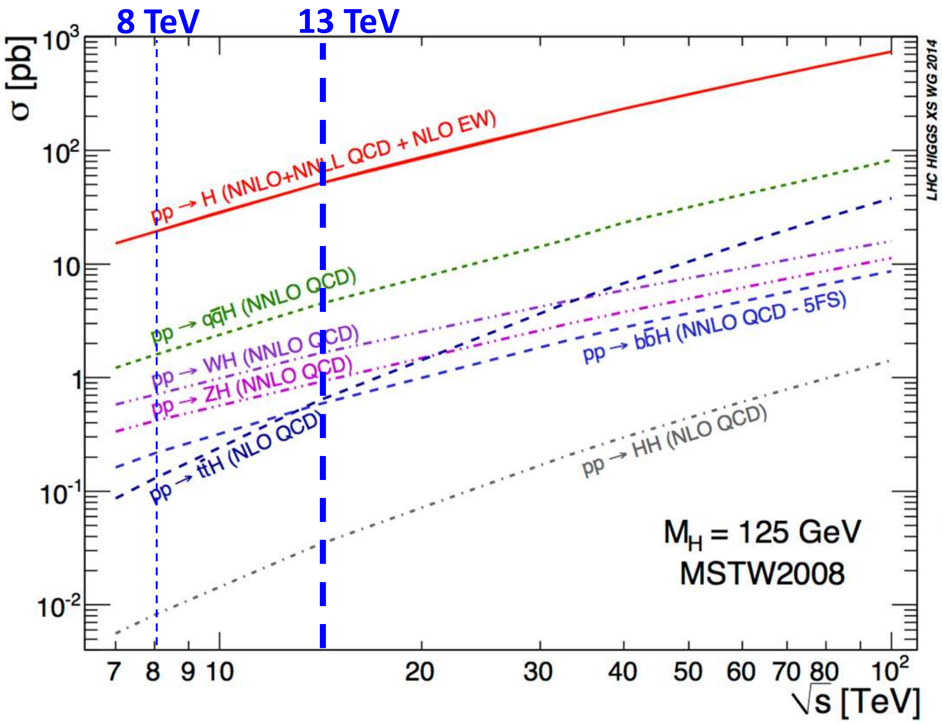
微分断面積を測定し、ヒッグス粒子事象の精査を続ける。





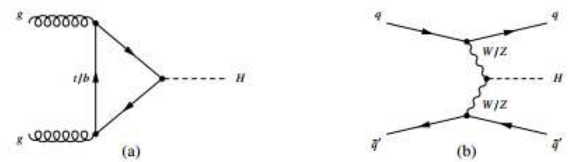
LHCでのヒッグス粒子の生成

- 生成断面積

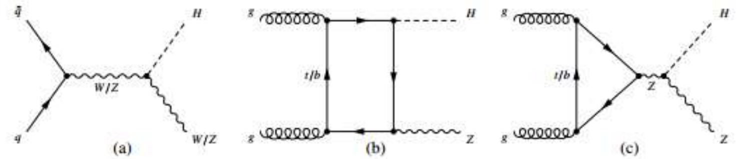


	σ(14TeV)/σ(8TeV)
gg→H	2.6 (M_X=M_H)
qq→qqH	2.6 (probes high M_X)
qq→VH	2.1 (M_X=M_V+M_H)
gg→ttH	4.7 (phase space+M_X)

$gg \to H$ $\qquad$ $qq \to qqH$



$qq \to VH$ ynman diagrams for Higgs boson production via the (a) ggF and (b) VBF production



$gg \to ttH$ ıman diagrams of Higgs boson production via the (a) $q\bar{q} \to VH$ and (b,c) $gg \to ZH$

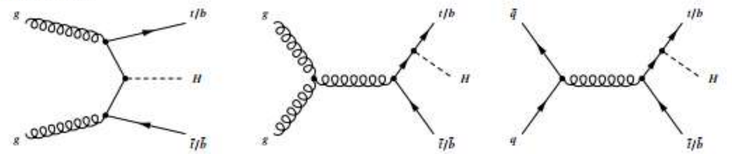


Figure 3: Leading-order Feynman diagrams of Higgs boson production via the $q\bar{q}/gg \to t\bar{t}H$ and $q\bar{q}/gg \to bbH$ processes.

$\sigma_{gg \to H}$

√s (TeV)	σ
13	48.61 pb
14	54.72 pb
27	146.65 pb

ヒッグス粒子の崩壊

$H \to WW/ZZ$　　$H \to fermion\ pair$

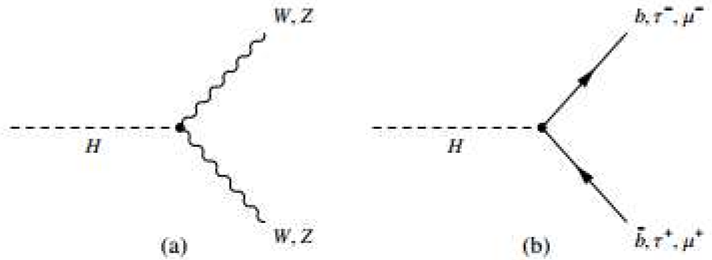


Figure 5: L $H \to \gamma\gamma$ ynman diagrams of Higgs boson decays (a) to W and Z bosons and (b) to fermions.

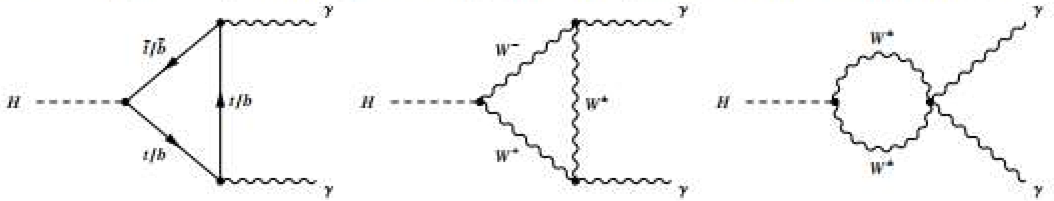


Figure 6: Leading-order Feynman diagrams of Higgs boson decays to a pair of photons.

さまざまな生成・崩壊モード
- さまざまな測定を行い、標準理論を検証できる。

重心エネルギー8 TeV⇒13 TeV
- 生成断面積は、**2-5**倍。
- Run2では、たくさん作って様々なチャンネルで精密測定する。

- 崩壊分岐比　(m_H= 125 GeV)

$H \to b\bar{b}$	$H \to \tau^+\tau^-$	$H \to \mu^+\mu^-$	$H \to c\bar{c}$
57.7%	6.32%	0.022%	2.91%

$H \to gg$	$H \to \gamma\gamma$	$H \to Z\gamma$	$H \to WW$	$H \to ZZ$	Γ_H [MeV]
8.6%	0.23%	0.15%	21.5%	2.64%	4.07

Run1での信号の有意度

3年ほど前のスライドから

ATLAS、CMS個別

Channel	References for individual publications		Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[51]	[52]	$1.15^{+0.27}_{-0.25}$ $\binom{+0.26}{-0.24}$	$1.12^{+0.25}_{-0.23}$ $\binom{+0.24}{-0.22}$	5.0 (4.6)	5.6 (5.1)
$H \to ZZ \to 4\ell$	[53]	[54]	$1.51^{+0.39}_{-0.34}$ $\binom{+0.33}{-0.27}$	$1.05^{+0.32}_{-0.27}$ $\binom{+0.31}{-0.26}$	6.6 (5.5)	7.0 (6.8)
$H \to WW$	[55, 56]	[57]	$1.23^{+0.23}_{-0.21}$ $\binom{+0.21}{-0.20}$	$0.91^{+0.24}_{-0.21}$ $\binom{+0.23}{-0.20}$	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	[58]	[59]	$1.41^{+0.40}_{-0.35}$ $\binom{+0.37}{-0.33}$	$0.89^{+0.31}_{-0.28}$ $\binom{+0.31}{-0.29}$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	[38]	[39]	$0.62^{+0.37}_{-0.36}$ $\binom{+0.39}{-0.37}$	$0.81^{+0.45}_{-0.42}$ $\binom{+0.45}{-0.43}$	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	[60]	[61]	-0.7 ± 3.6 (± 3.6)	0.8 ± 3.5 (± 3.5)		
ttH production	[28, 62, 63]	[65]	$1.9^{+0.8}_{-0.7}$ $\binom{+0.72}{-0.66}$	$2.9^{+1.0}_{-0.9}$ $\binom{+0.88}{-0.80}$	2.7 (1.6)	3.6 (1.3)

3σ：”兆候が見えた“
5σ：“発見した”

- メインの生成・崩壊過程の多くはRun 1で発見がすんだ。
- ttH生成、$H \to bb$はRun2で検証していく。
- LHC Run 2では、一個一個の過程の理解を確立し、精密測定に入っていく。

ATLAS＋CMS

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

ATLAS-CONF-2015-044

Run1での信号の有意度

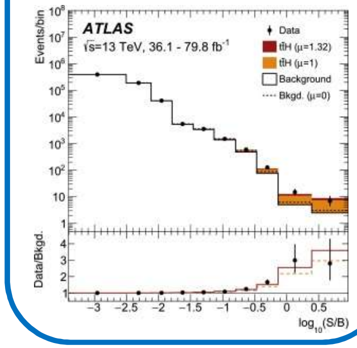
ATLAS、CMS個別

Channel	References for individual publications		Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[51]	[52]	$1.15^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$	$1.12^{+0.25}_{-0.23}$ $\left(^{+0.24}_{-0.22}\right)$	5.0 (4.6)	5.6 (5.1)
$H \to ZZ \to 4\ell$	[53]	[54]	$1.51^{+0.39}_{-0.34}$ $\left(^{+0.33}_{-0.27}\right)$	$1.05^{+0.32}_{-0.27}$ $\left(^{+0.31}_{-0.26}\right)$	6.6 (5.5)	7.0 (6.8)
$H \to WW$	[55, 56]	[57]	$1.23^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$	$0.91^{+0.24}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	[58]	[59]	$1.41^{+0.40}_{-0.35}$ $\left(^{+0.37}_{-0.33}\right)$	$0.89^{+0.31}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	[38]	[39]	$0.62^{+0.37}_{-0.36}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81^{+0.45}_{-0.42}$ $\left(^{+0.45}_{-0.43}\right)$	~~1.7~~ 5.3 (2.7)	2.0 (2.5)
$H \to \mu\mu$	[60]	[61]	-0.7 ± 3.6 (± 3.6)	0.8 ± 3.5 (± 3.5)		
ttH production	[28, 62, 63]	[65]	$1.9^{+0.8}_{-0.7}$ $\left(^{+0.72}_{-0.66}\right)$	$2.9^{+1.0}_{-0.9}$ $\left(^{+0.88}_{-0.80}\right)$	5.8 ~~2.7~~ (1.6)	3.6 (1.3)

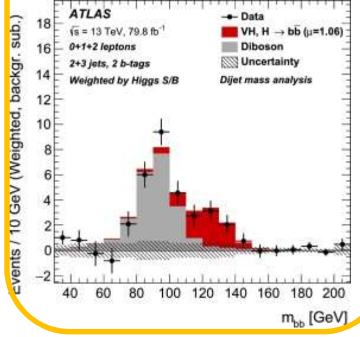
3σ：”兆候が見えた“
5σ：“発見した”

- ゲージボソンと第三世代との結合は確立できた。
- 第2世代との結合、見えるか？

ttH生成
5.8 σ Observation



***H* → *bb*崩壊**
5.3 σ Observation



ATLAS＋CMS

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

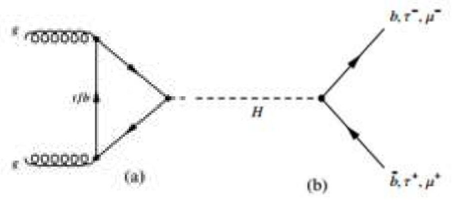
ATLAS-CONF-2015-044

ATLAS-CONF-2018-026

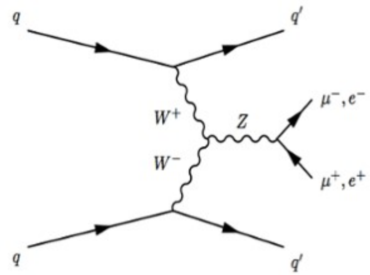
Search for $H \rightarrow \mu\mu$

- 第３世代(τ, b, t)との湯川カップリングは確認できた。
- 第2世代粒子との湯川カップリングの発見を目指す
  - VBFに特化した信号領域を定義して解析感度を向上
    - 前後方dijet, high m(jj)　＝＞　VBFチャンネル

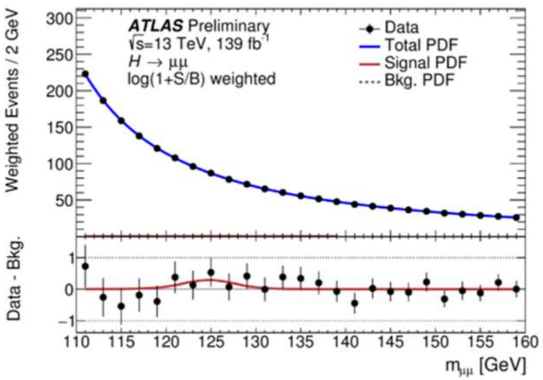
gg-fusion生成



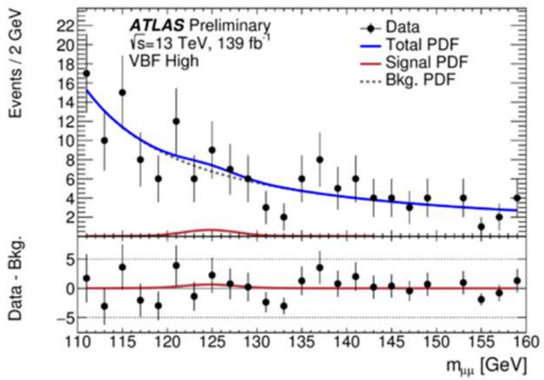
Vector Boson Fusion生成



all candidates(ggF+VBF)



VBF channel:



信号強度

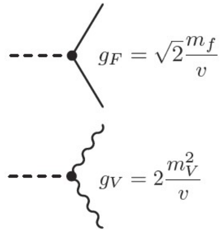
$$\mu = \frac{(\sigma_H \times Br_{H\rightarrow\mu\mu})^{meas}}{(\sigma_H \times Br_{H\rightarrow\mu\mu})^{pred}} = 0.5 \pm 0.7$$

信号強度のリミット:

$$\boldsymbol{\mu < 1.7\ (95\%\ CL)}$$

Higgs Coupling Measurement

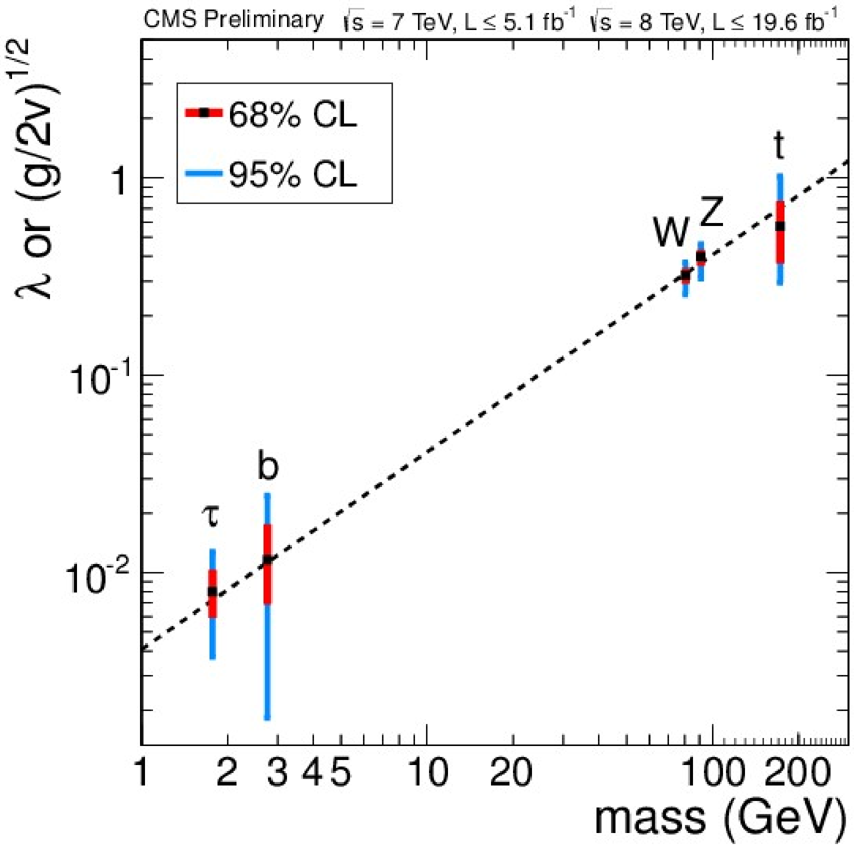
$$L_h = \frac{1}{2}(\partial^\mu h)(\partial_\mu h) + \frac{M_h^2}{2} h^2 - \frac{M_h^2}{2v} h^3 - \frac{M_h^2}{8v^2} h^4$$
$$+ \left(M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu \right) \left(1 + \frac{h}{v}\right)^2$$
$$- \sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right). \qquad (19)$$



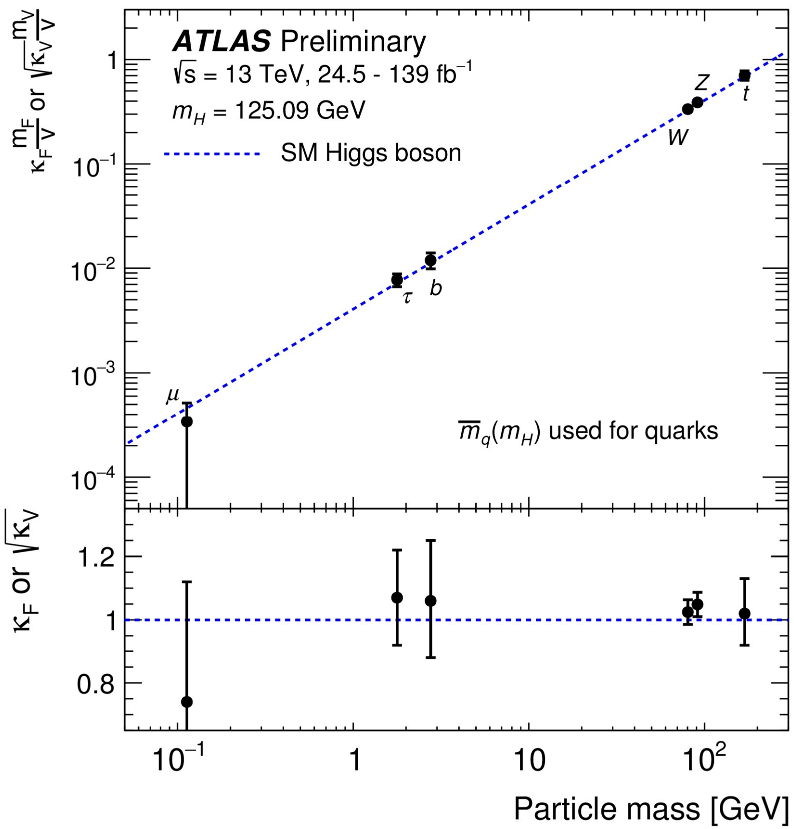
$$g_F^{meas} = \sqrt{2}\kappa_F \frac{m_f}{v}$$

$$g_V^{meas} = 2\kappa_V \frac{m_V^2}{v}$$

Run 1 full data (CMS)



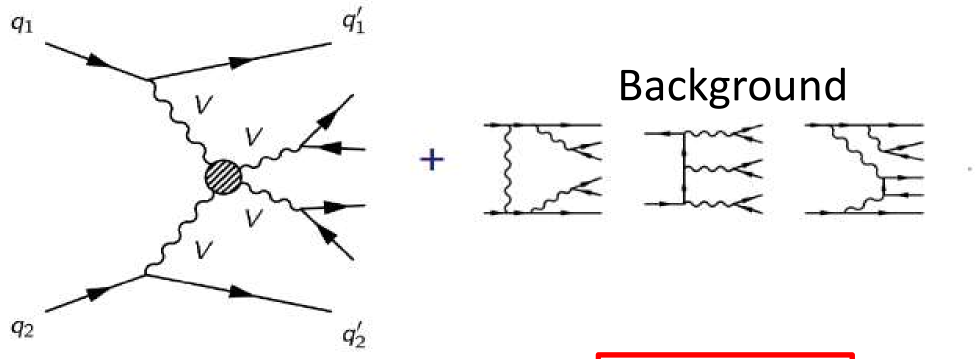
現在

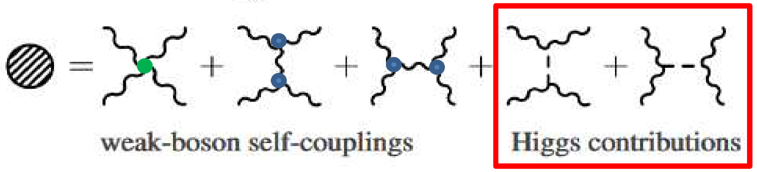


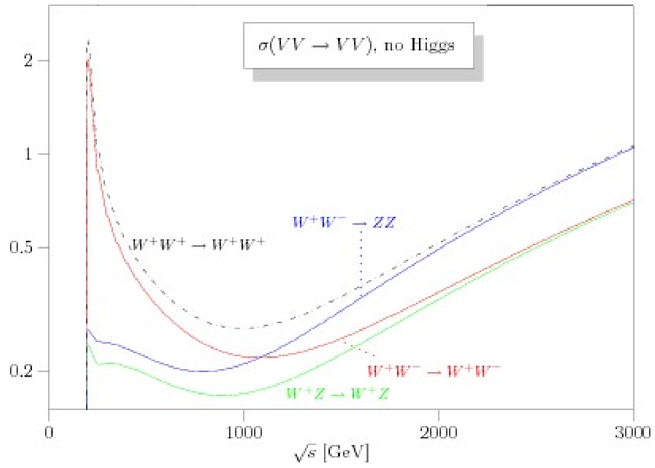
JHEP 0811 (2008)

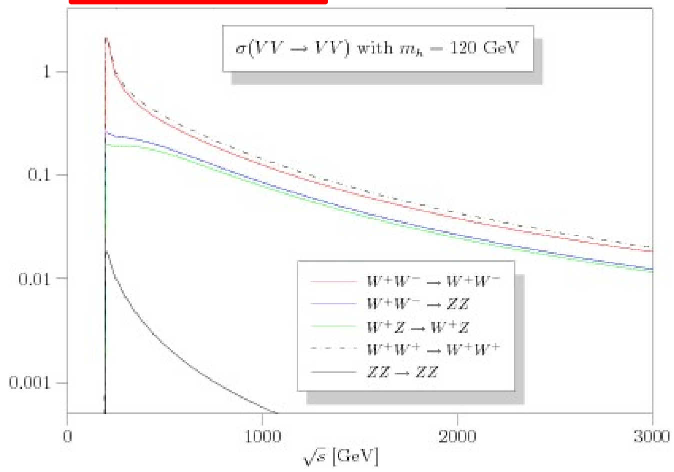
Vector Boson Scattering Processes

- Vector boson scattering involves
  - Triple and Quadratic Gauge Couplings
  - Higgs restores unitarity at high energies



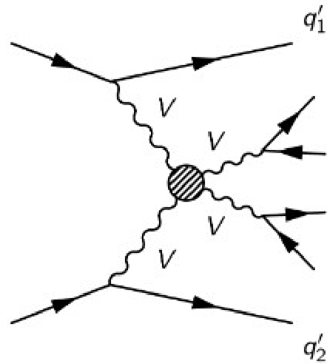






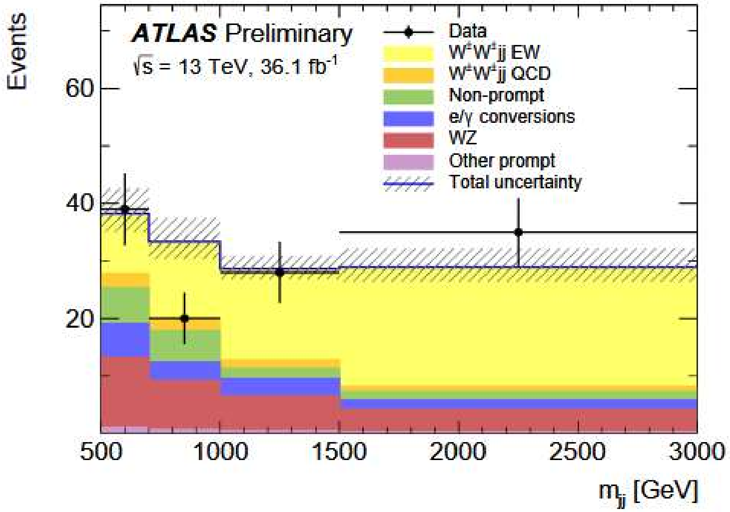
2018夏の結果

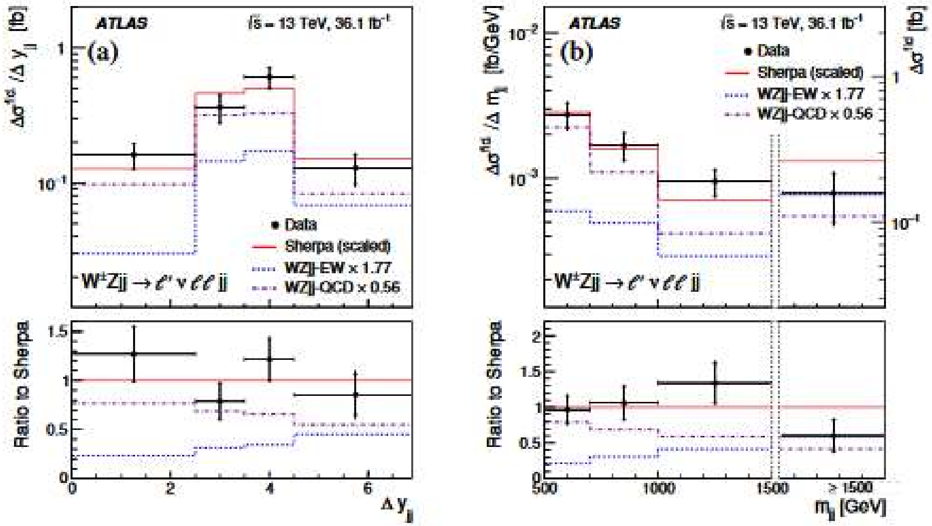
Vector Boson Scattering



- 前後方にdijet + vector bosonの崩壊

- $W^{\pm}W^{\pm}jj \rightarrow \ell^{\pm}\ell^{\pm} + MET + jj$
- $WZjj \rightarrow 3\ell + jj$





$\sigma^{EWK} = 2.91^{+0.51}_{-0.47}\,(\text{stat.}) \pm 0.27\,(\text{sys.})\ \text{fb}$

$\sigma_{WZjj\text{-EW}} = 0.57\ ^{+0.14}_{-0.13}\,(\text{stat.})\ ^{+0.05}_{-0.04}\,(\text{exp. syst.})\ ^{+0.05}_{-0.04}\,(\text{mod. syst.})\ ^{+0.01}_{-0.01}\,(\text{lumi.})\ \text{fb}.$

6.9σ observation
(expected 4.6σ)

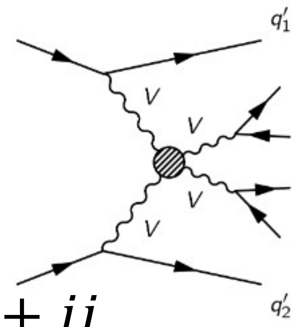
5.3σ observation
(expected 3.2σ)

ATLAS-CONF-2018-030

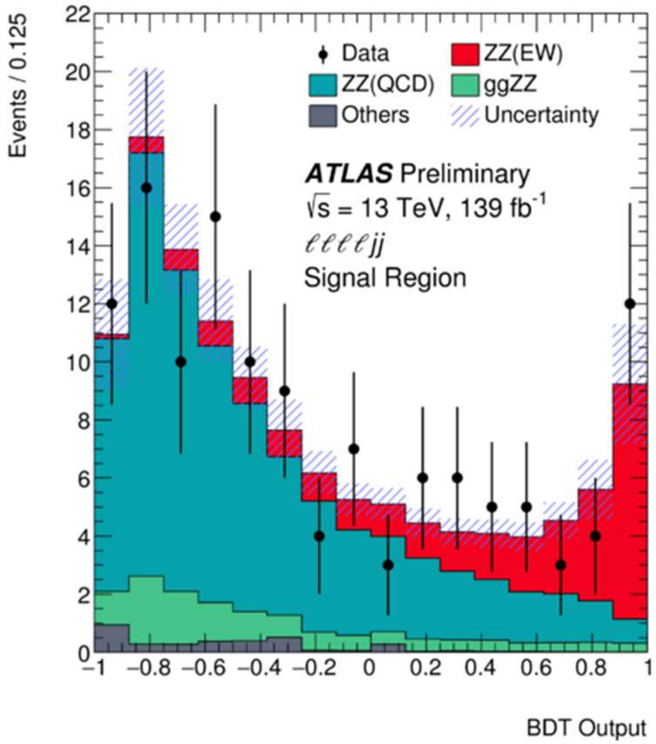
arXiv:1812.09740

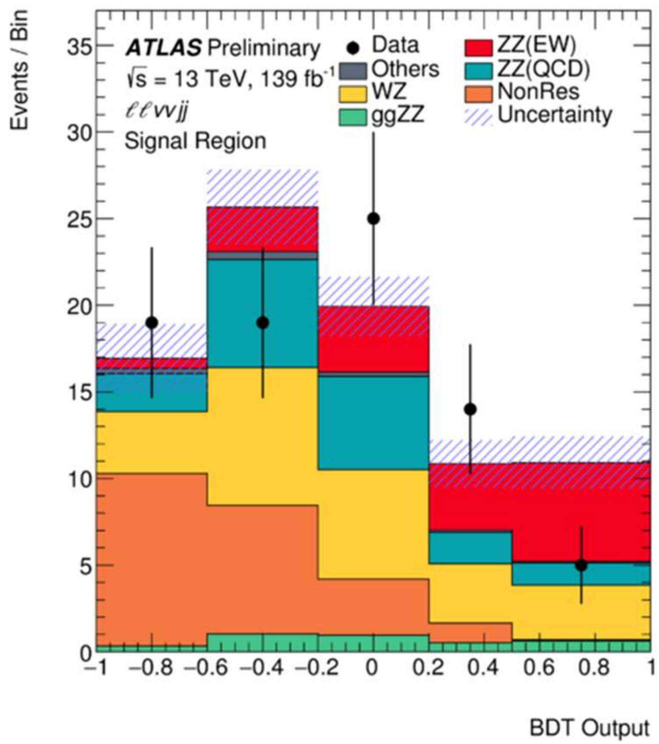
VBSは、ちょうどプロセスが発見に達したところ。
これから、ヒッグスとの干渉について、精密検証を行う。

Vector Boson Scattering (2)



- $VVjj \rightarrow ZZjj \rightarrow 4\ell + jj$
- $VVjj \rightarrow ZZjj \rightarrow \ell^+\ell^- + 2\nu + jj$





$\sigma^{EWK} = 0.82 \pm 0.21$ fb

5.5 σ observation (expected 4.3 σ)

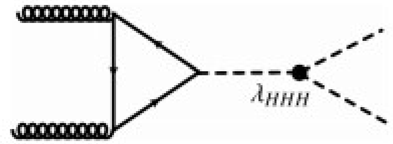
ATLAS-CONF-2019-033

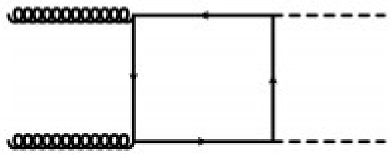
D2 若狭
$VVjj \rightarrow WVjj \rightarrow semileptonic$

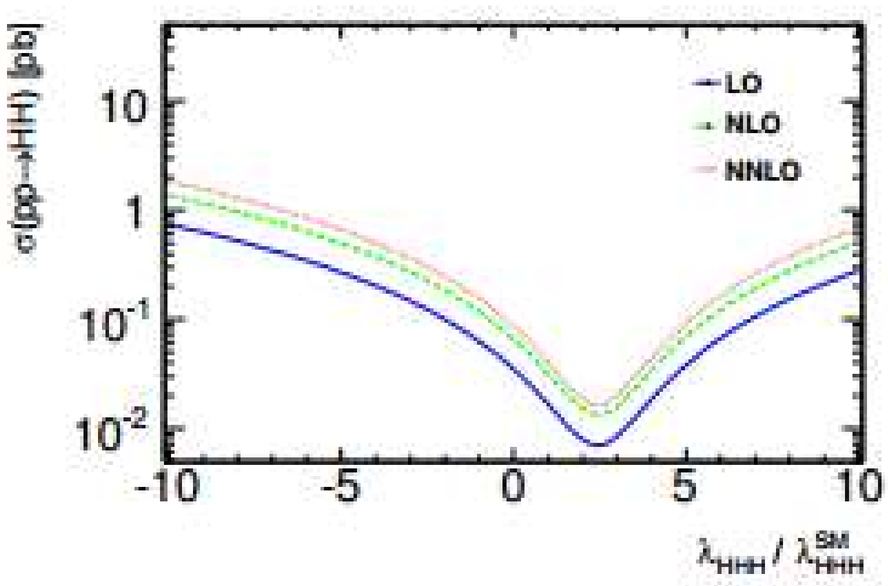
VBSは、WW,WZ,ZZの終状態が観測に達した。
これから、ヒッグスとの干渉について、精密検証を行う。

ヒッグス自己結合測定

- DiHiggs事象を探して解析する。
- DiHiggsは、2つのダイヤグラムの干渉が起こる。
- もし自己相互作用(λ_{HHH})がなければ、HH生成の断面積は2倍になる。







Expected event yields for $\frac{\lambda_{HHH}}{\lambda^{SM}} = 1$

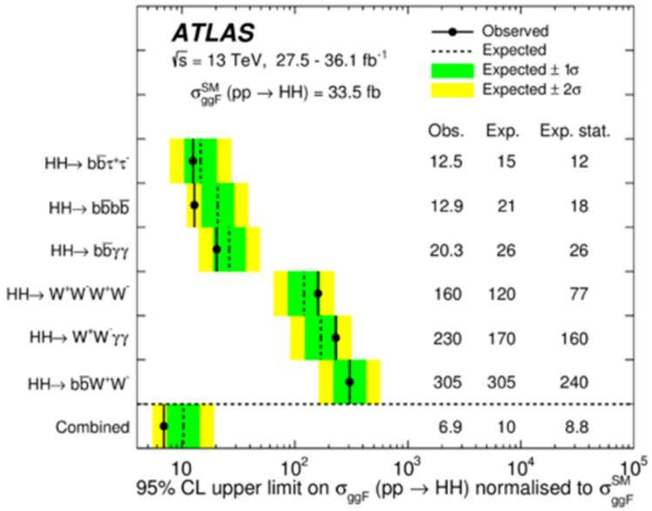
Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	40,000
$b\bar{b} + W^+W^-$	25%	31,000
$b\bar{b} + \tau^+\tau^-$	7.3%	8,900
$ZZ + b\bar{b}$	3.1%	3,800
$W^+W^- + \tau^+\tau^-$	2.7%	3,300
$ZZ + W^+W^-$	1.1%	1,300
$\gamma\gamma + b\bar{b}$	0.26%	320
$\gamma\gamma + \gamma\gamma$	0.0010%	1.2

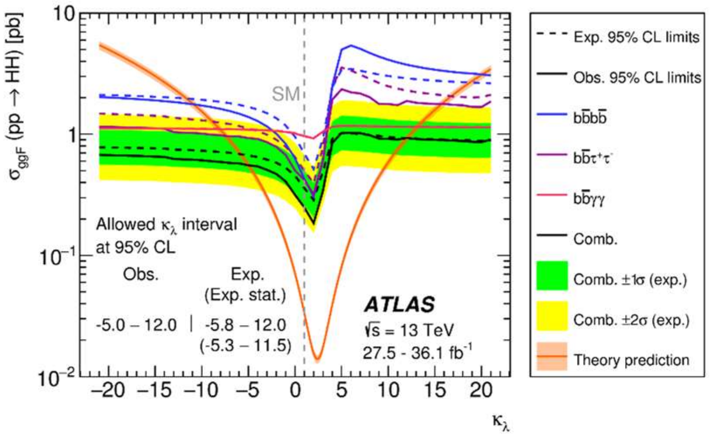
ATL-PHYS-PUB-2014-019

Run 2でのDihiggs探索結果

- まずはDihiggs事象を探している。

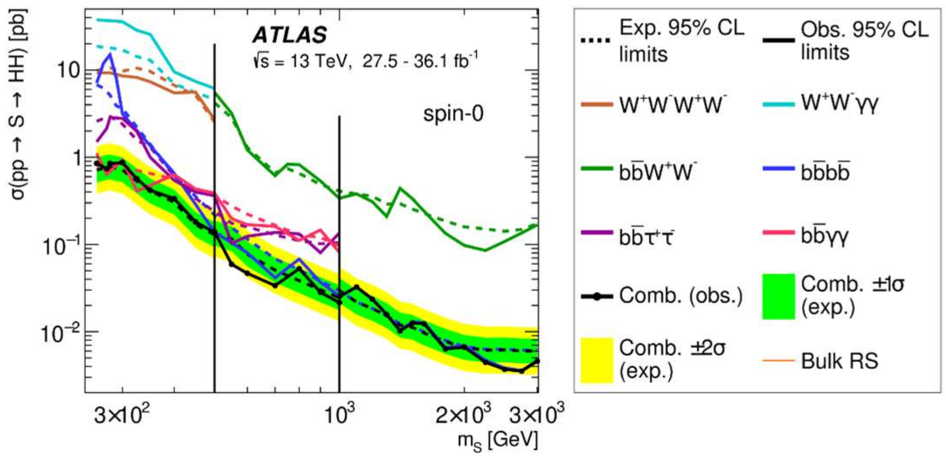
Dihiggs事象の生成断面積に対する上限　自己相互結合に対する制限





$-5.0 < \kappa_\lambda < 12.1\ at\ 95\%\ \mathrm{CL}.$

$\boldsymbol{S \to hh}$事象の探索として、同じデータを解釈することもできる:
(e.g. S=heavy Higgs)

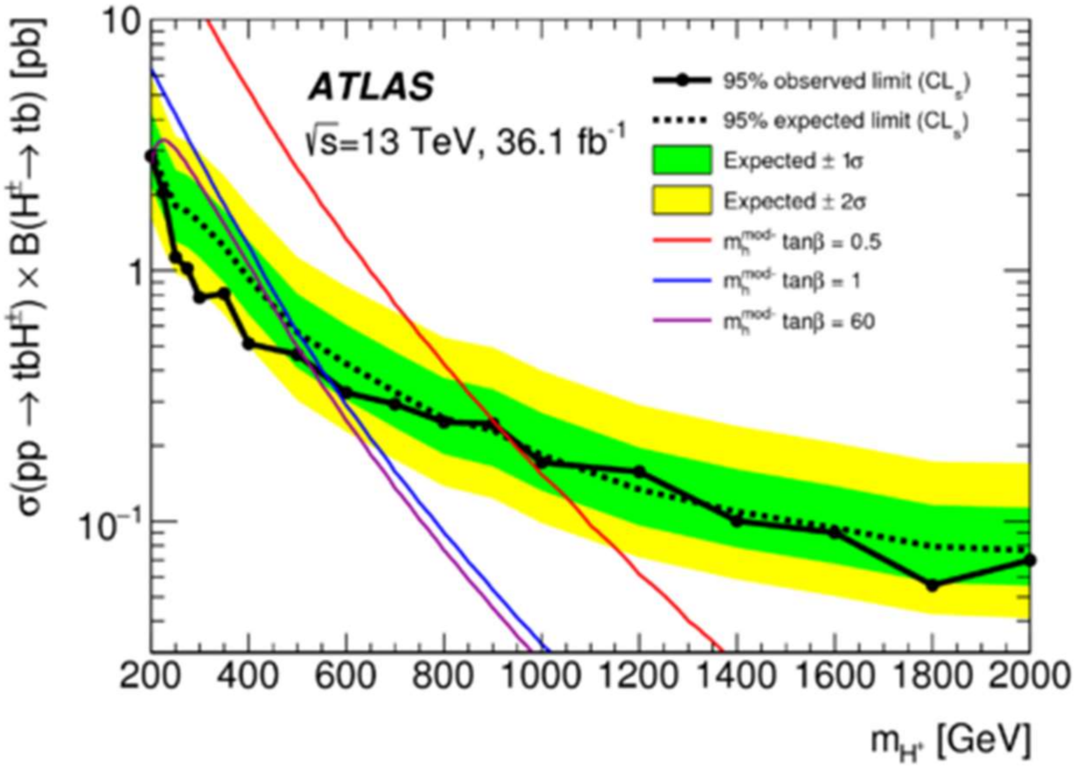


JHEP 11 (2018) 085

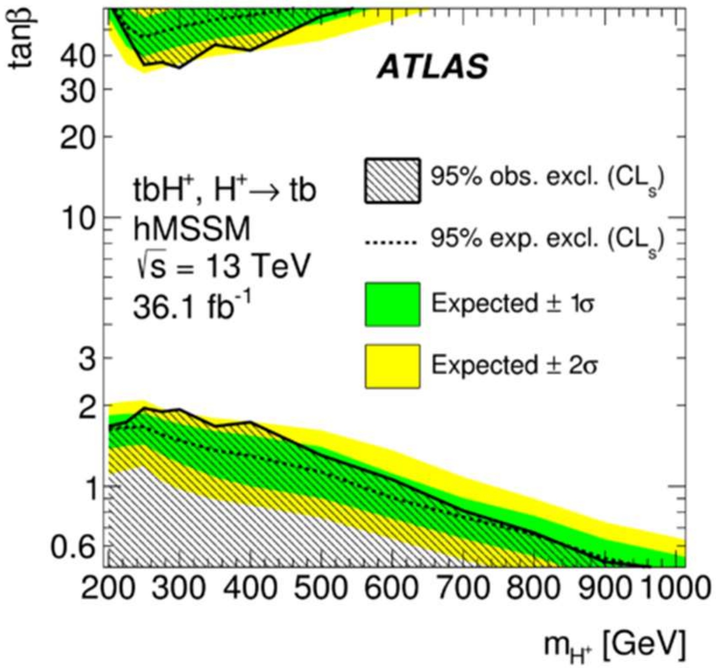
荷電ヒッグス粒子に対する制約

- 荷電ヒッグス粒子の信号は見つからず、
データはバックグラウンドとよく一致した。

生成断面積に対する制約



MSSM（hMSSMシナリオ）に対する制約

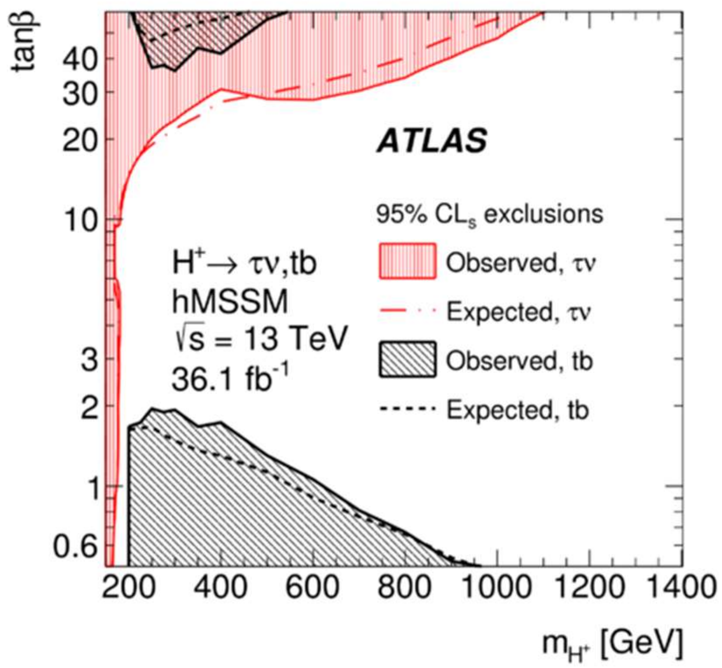


D1 山内

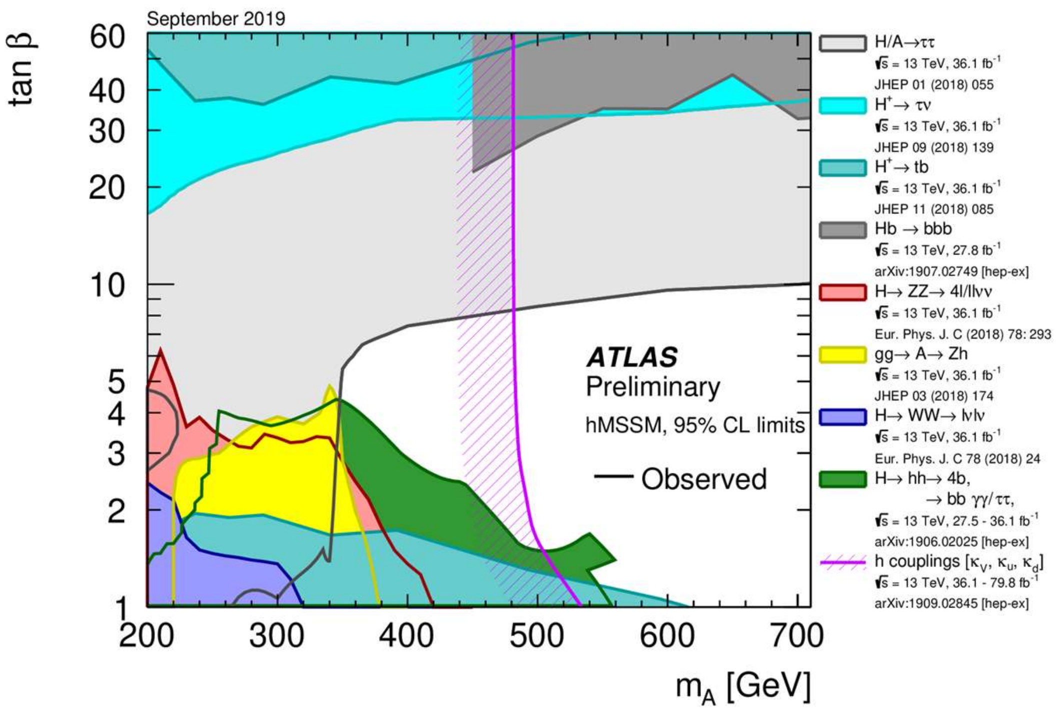
$H^+ \to \tau\nu$チャンネルとの比較

- $H^+ \to \tau\nu$チャンネルとは、感度のある領域が異なるため、MSSMの解析という意味でも相補的といえる。

JHEP 11 (2018) 085

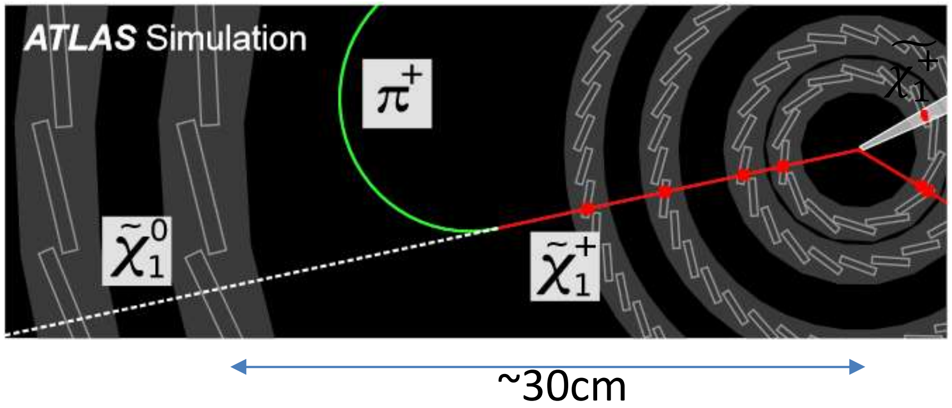


ATLASでのMSSMヒッグス探索のまとめ

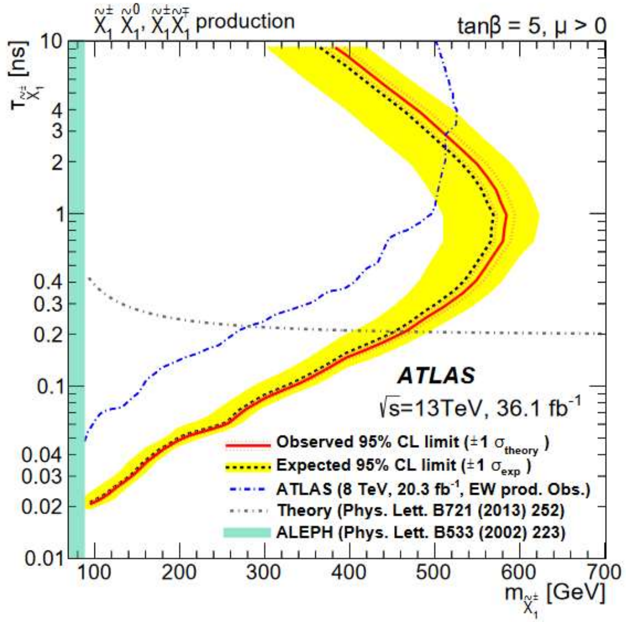


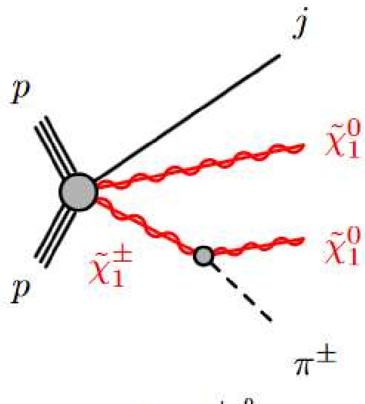
Long Lived Chargino

- WinoがLSPの場合に、$\widetilde{\chi_1^+}$, $\widetilde{\chi_1^0}$の質量が縮退する場合がある。
  - AMSBでは、この$\widetilde{\chi_1^0}$がDMになりうる。
- $\widetilde{\chi_0^+}$は長寿命→Long Lived Particle (**LLP**)になる。

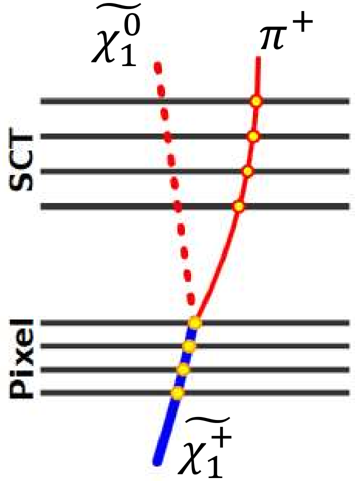


JHEP 06 (2018) 022





(a) $pp \to \tilde{\chi}_1^\pm \tilde{\chi}_1^0 j$



ATLAS Supersymmetry Searches

ATLAS SUSY Searches* - 95% CL Lower Limits

October 2019

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV

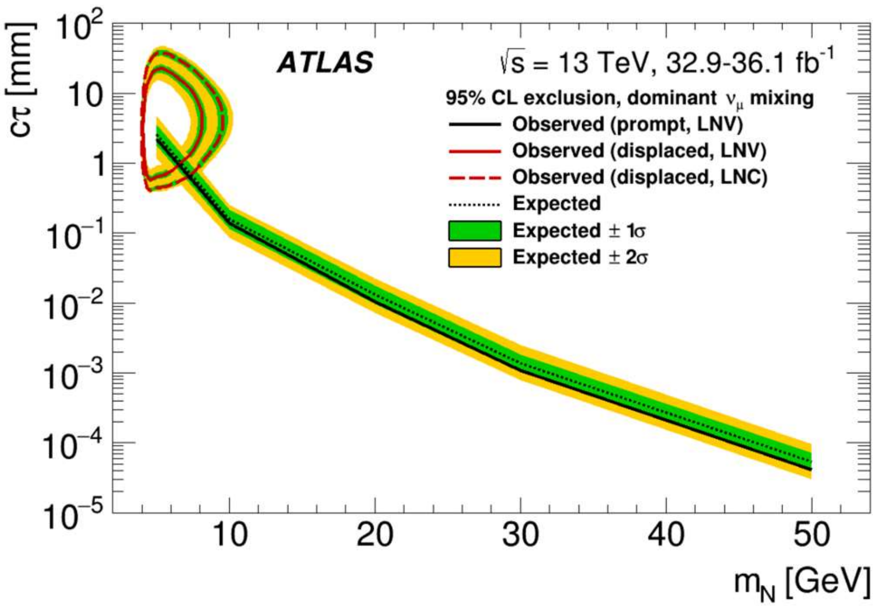
	Model	Signature			$\int \mathcal{L}\,dt$ [fb^{-1}]	Mass limit			Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{q}$ [10× Degen.]	1.9	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2019-040
		mono-jet	1-3 jets	E_T^{miss}	36.1	$\tilde{q}$ [1×, 8× Degen.]	0.43, 0.71	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{g}$	2.35	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2019-040
						$\tilde{g}$	Forbidden, 1.15-1.95	$m(\tilde{\chi}_1^0)$=1000 GeV	ATLAS-CONF-2019-040
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e,μ	4 jets		36.1	$\tilde{g}$	1.85	$m(\tilde{\chi}_1^0)$<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	E_T^{miss}	36.1	$\tilde{g}$	1.2	$m(\tilde{g})$-$m(\tilde{\chi}_1^0)$=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 e,μ	7-11 jets	E_T^{miss}	36.1	$\tilde{g}$	1.8	$m(\tilde{\chi}_1^0)$ <400 GeV	1708.02794
		SS e,μ	6 jets		139	$\tilde{g}$	1.15	$m(\tilde{g})$-$m(\tilde{\chi}_1^0)$=200 GeV	1909.08457
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	E_T^{miss}	79.8	$\tilde{g}$	2.25	$m(\tilde{\chi}_1^0)$<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$	1.25	$m(\tilde{g})$-$m(\tilde{\chi}_1^0)$=300 GeV	ATLAS-CONF-2019-015
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$	Forbidden, 0.9	$m(\tilde{\chi}_1^0)$=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$	Forbidden, 0.58-0.82	$m(\tilde{\chi}_1^0)$=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($t\tilde{\chi}_1^\pm$)=0.5	1708.09266
			Multiple		139	$\tilde{b}_1$	Forbidden, 0.74	$m(\tilde{\chi}_1^0)$=200 GeV, $m(\tilde{\chi}_1^\pm)$=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1	ATLAS-CONF-2019-015
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$	0 e,μ	6 b	E_T^{miss}	139	$\tilde{b}_1$	Forbidden, 0.23-1.35	$\Delta m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=130 GeV, $m(\tilde{\chi}_1^0)$=100 GeV	1908.03122
						$\tilde{b}_1$	0.23-0.48	$\Delta m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=130 GeV, $m(\tilde{\chi}_1^0)$=0 GeV	1908.03122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	E_T^{miss}	36.1	$\tilde{t}_1$	1.0	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	1 e,μ	3 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$	0.44-0.59	$m(\tilde{\chi}_1^0)$=400 GeV	ATLAS-CONF-2019-017
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1 τ + 1 e,μ,τ	2 jets/1 b	E_T^{miss}	36.1	$\tilde{t}_1$	1.16	$m(\tilde{\tau}_1)$=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}_1^0$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$	0.85	$m(\tilde{\chi}_1^0)$=0 GeV	1805.01649
						$\tilde{t}_1$	0.46	$m(\tilde{t}_1,\tilde{c})$-$m(\tilde{\chi}_1^0)$=50 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	36.1	$\tilde{t}_1$	0.43	$m(\tilde{t}_1,\tilde{c})$-$m(\tilde{\chi}_1^0)$=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1-2 e,μ	4 b	E_T^{miss}	36.1	$\tilde{t}_2$	0.32-0.88	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$= 180 GeV	1706.03986
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	E_T^{miss}	139	$\tilde{t}_2$	Forbidden, 0.86	$m(\tilde{\chi}_1^0)$=360 GeV, $m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$= 40 GeV	ATLAS-CONF-2019-016
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2-3 e,μ		E_T^{miss}	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.6	$m(\tilde{\chi}_1^0)$=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.205	$m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=5 GeV	ATLAS-CONF-2019-014
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW	2 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm$	0.42	$m(\tilde{\chi}_1^0)$=0	1908.08215
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	0-1 e,μ	2 b/2 γ	E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	Forbidden, 0.74	$m(\tilde{\chi}_1^0)$=70 GeV	ATLAS-CONF-2019-019, 1909.09226
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm$	1.0	$m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2019-008
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}_1^0$	2 τ		E_T^{miss}	139	$\tilde{\tau}$ [$\tilde{\tau}_L$, $\tilde{\tau}_{R,L}$]	0.16-0.3, 0.12-0.39	$m(\tilde{\chi}_1^0)$=0	ATLAS-CONF-2019-018
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0 jets	E_T^{miss}	139	$\tilde{\ell}$	0.7	$m(\tilde{\chi}_1^0)$=0	ATLAS-CONF-2019-008
		2 e,μ	≥ 1	E_T^{miss}	139	$\tilde{\ell}$	0.256	$m(\tilde{\ell})$-$m(\tilde{\chi}_1^0)$=10 GeV	ATLAS-CONF-2019-014
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq 3\,b$	E_T^{miss}	36.1	$\tilde{H}$	0.13-0.23, 0.29-0.88	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	E_T^{miss}	36.1	$\tilde{H}$	0.3	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	E_T^{miss}	36.1	$\tilde{\chi}_1^\pm$	0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^\pm$	0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$	2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		36.1	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns]	2.05, 2.4	$m(\tilde{\chi}_1^0)$=100 GeV	1710.04901,1808.04095
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$			3.2	$\tilde{\nu}_\tau$	1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0$, $\lambda_{12k}\neq 0$]	0.82, 1.33	$m(\tilde{\chi}_1^0)$=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$		4-5 large-R jets		36.1	$\tilde{g}$ [$m(\tilde{\chi}_1^0)$=200 GeV, 1100 GeV]	1.3, 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5]	1.05, 2.0	$m(\tilde{\chi}_1^0)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2]	0.55, 1.05	$m(\tilde{\chi}_1^0)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs]	0.42, 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$	0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0, 1.6	BR($\tilde{t}_1\to q\mu$)=100%, $\cos\theta_t$=1	ATLAS-CONF-2019-006

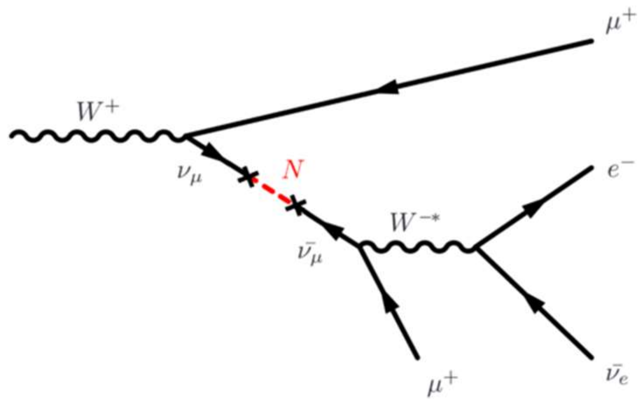
Mass scale [TeV] (axis: 10^{-1}, 1)

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Long Lived Heavy Neutral Lepton Search

- Search for right handed majorana neutrino (N or HNL)
  - Production and decay: function of m_N and coupling strength $|U|^2$
- A trigger muon w/ pT>28GeV (prompt)
- DV (Displaced Vertex) with two leptons
  - $4 < r_{DV} < 300$mm
  - m_{DV}>4GeV
- Background: hadron interaction w/ material, metastable b- and s-hadrons, accidental crossing particles, cosmic ray.



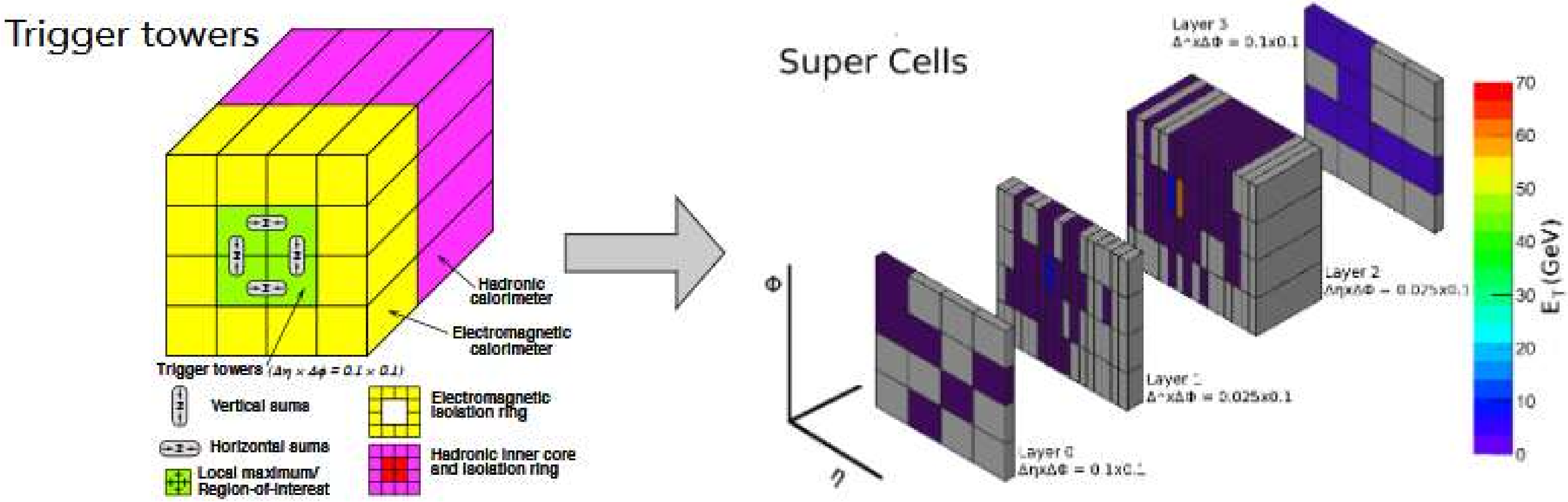


D1 和田

バックアップ

Super Cells

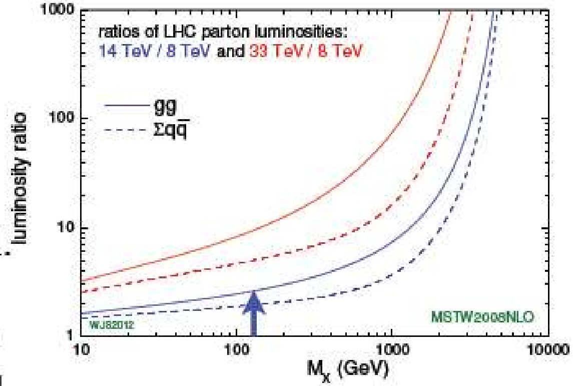
- Trigger tower ⟹ 10 Super Cells (SCs)



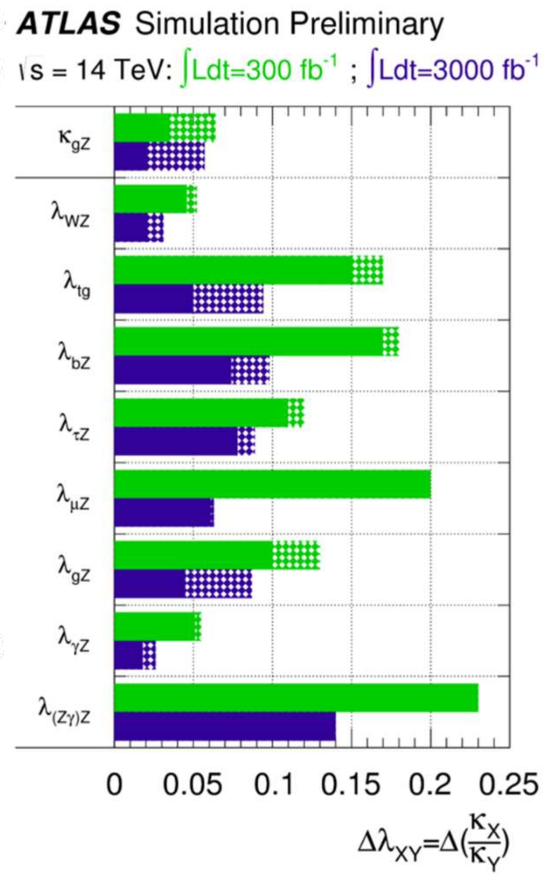
	Elementary Cell	Trigger Tower		Super Cell	
Layer (barrel)	$[\Delta\eta \times \Delta\varphi]$	$[n_\eta \times n_\varphi]$	$[\Delta\eta \times \Delta\varphi]$	$[n_\eta \times n_\varphi]$	$[\Delta\eta \times \Delta\varphi]$
Presampler (layer 0)	0.025 × 0.1	4 × 1	0.1 × 0.1	4 × 1	**0.1 × 0.1**
Front (layer 1)	0.003125 × 0.1	32 × 1		8 × 1	**0.025 × 0.1**
Middle (layer 2)	0.025 × 0.025	4 × 4		1 × 4	**0.025 × 0.1**
Back (layer 3)	0.05 × 0.025	2 × 4		2 × 4	**0.1 × 0.1**

High Luminosity LHC (HL-LHC)

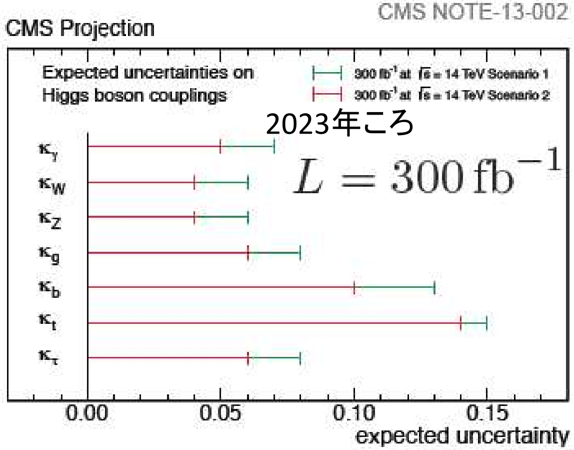
- ECFA HL-LHC with L=300 fb^{-1} (3 ab^{-1}) physics study.
- Higgs mass precision ΔM_H ~100 (50) MeV.
- Access to top-Yukawa coupling via ttH, and rare decay $H \rightarrow \mu\mu$.
- Coupling precision of 10 to 5% reachable (even few% in κ_γ/κ_Z).
- Detector performances (trigger, lepton-id, fake, τ/b-id) are crucial.
- Theory uncertainty dominates - challenge for theorists!

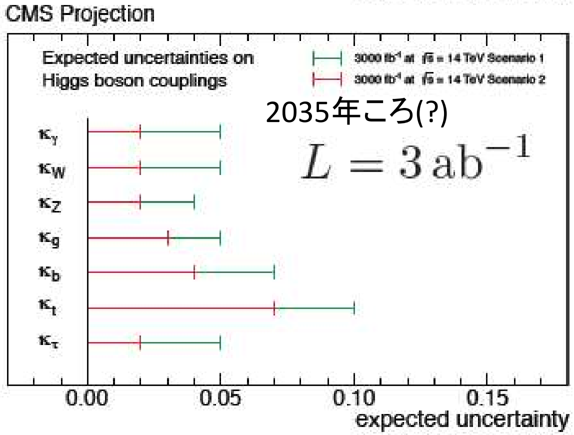


ATL-PHYS-PUB-2014-016



CMS NOTE-13-002





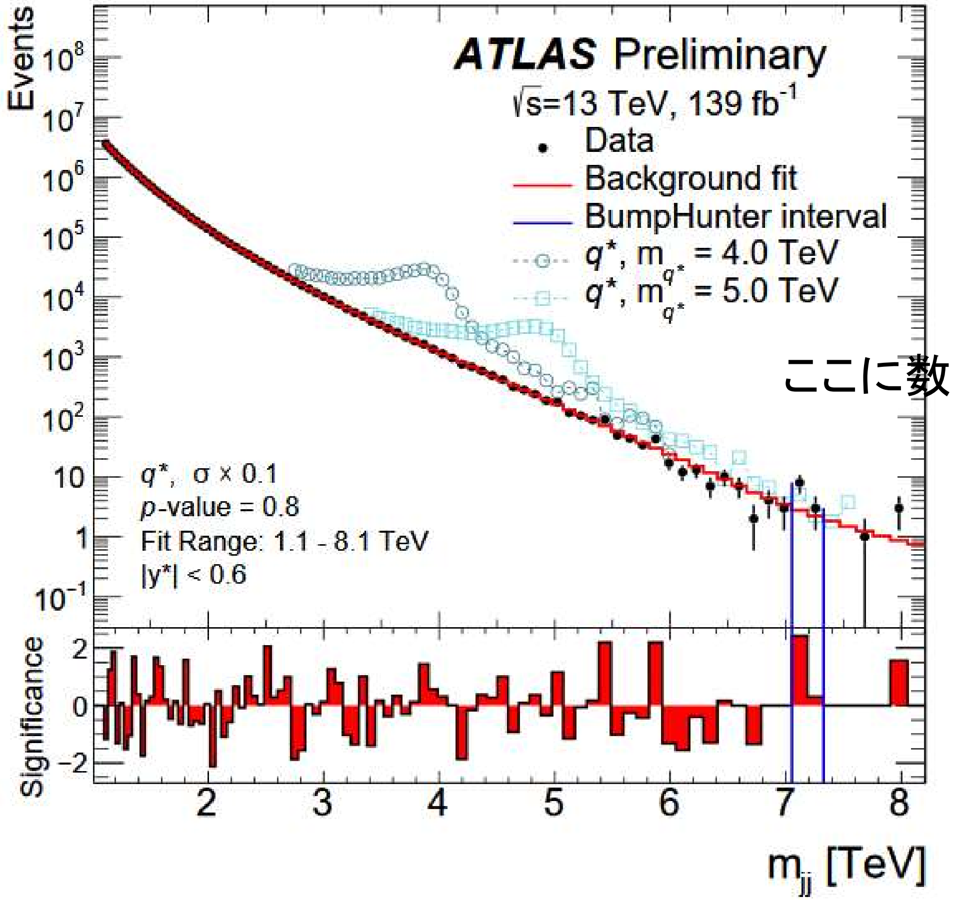
	σ(14TeV)/σ(8TeV)
gg→H	**2.6** (M_X=M_H)
qq→qqH	**2.6** (probes high M_X)
qq→VH	**2.1** (M_X=M_V+M_H)
gg→ttH	**4.7** (phase space+M_X)

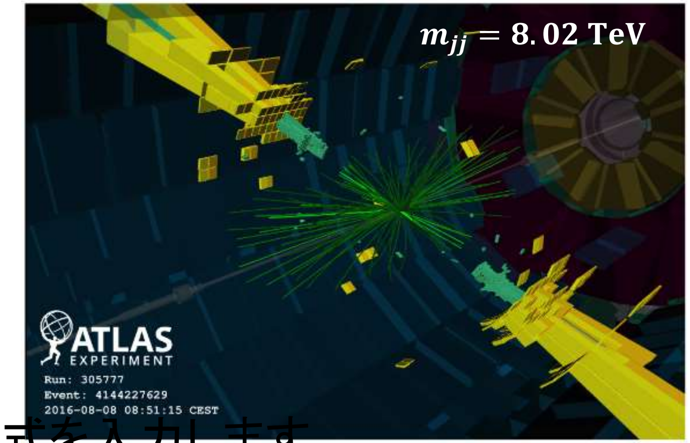
CMS
Scenario 1
 current systematic uncert.
Scenario 2
 theory uncert. ↘ 1/2
 other systematics ↘ 1/√L

ATLAS-CONF-2019-007

Full Run 2 Dijet Resonance Search

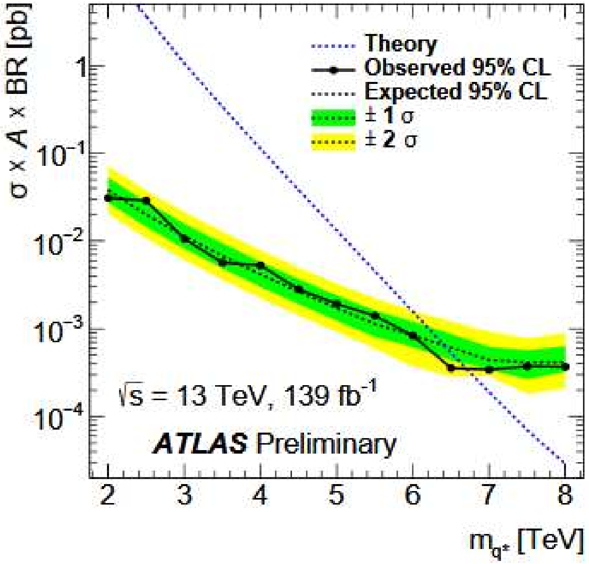
Dijet mass spectrum





ここに数式を入力します。

Limit on excited quark model

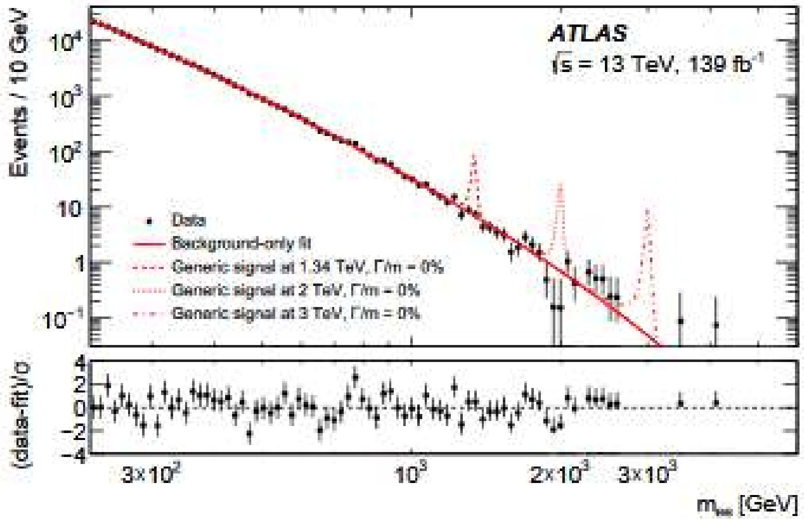


$m_{q^*} > 6.7\ \mathrm{TeV}$

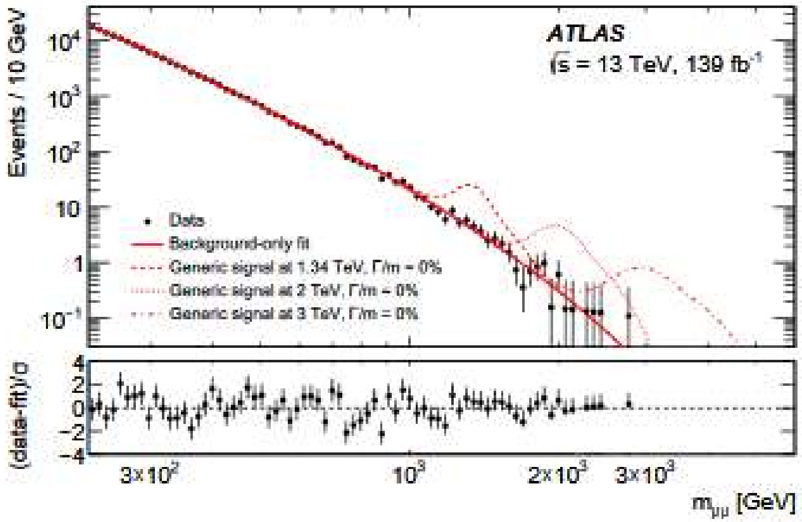
arXiv:1903.06248

Full Run 2 Dilepton Resonance Search

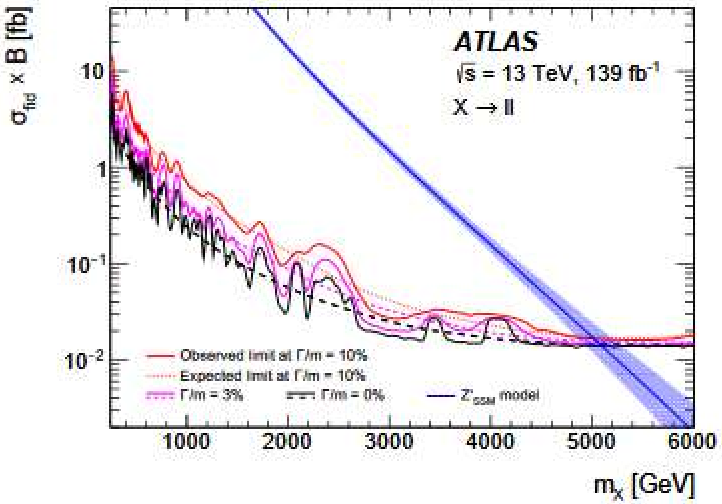
Dielectron invariant mass

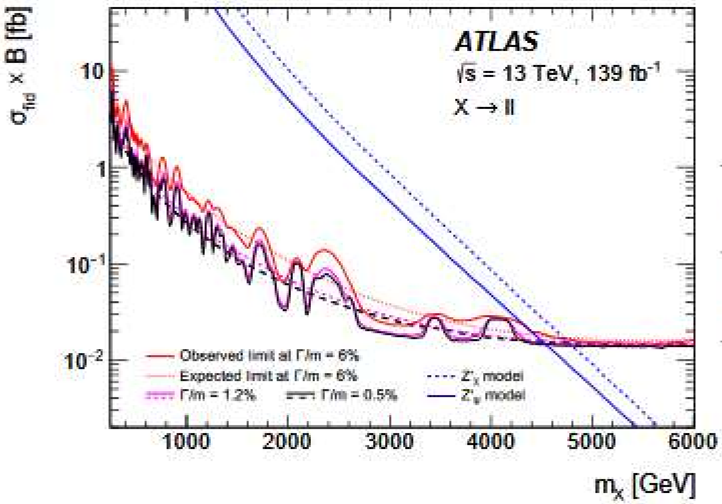


Dimuon invariant mass



No significant excess, set limit on production cross section of heavy particle.





Lower limit on Z' mass

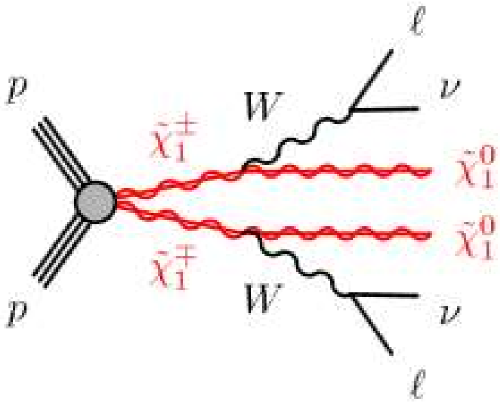
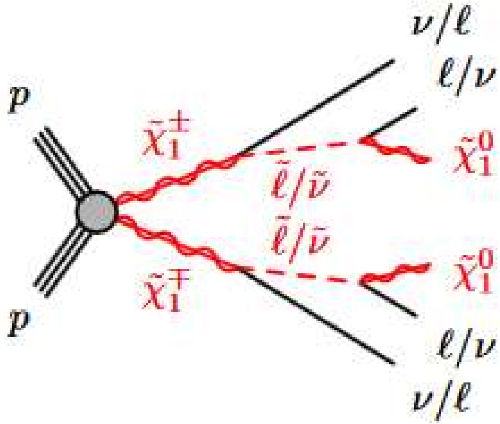
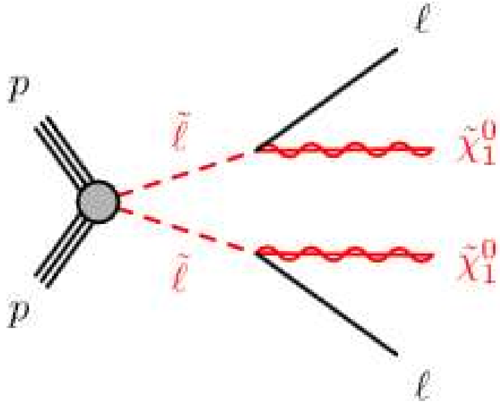
Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_ψ	4.1	4.3	4.0	4.0	4.5	4.5
Z'_χ	4.6	4.6	4.2	4.2	4.8	4.8
Z'_{SSM}	4.9	4.9	4.5	4.5	5.1	5.1

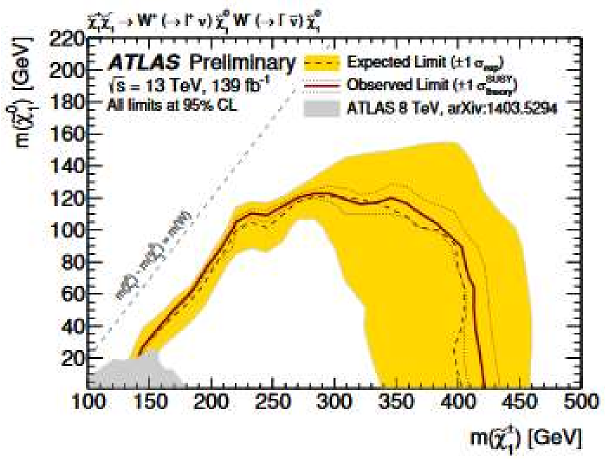
Full Run 2

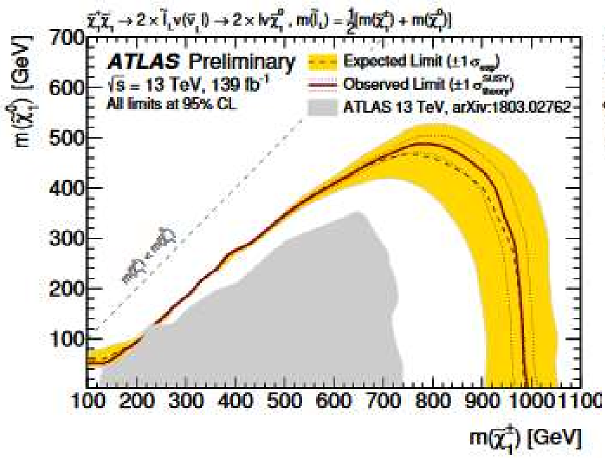
ATLAS-CONF-2019-008

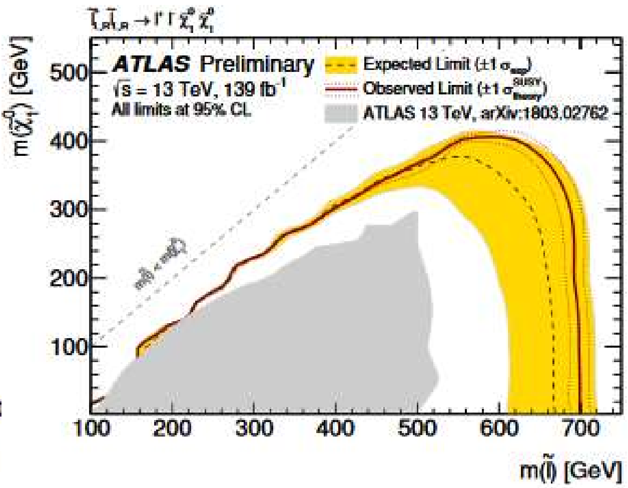
Chargino and Slepton Searches

- Final states: $2\ell + missing\ E_T$
- Use stransverse mass M_{T2}



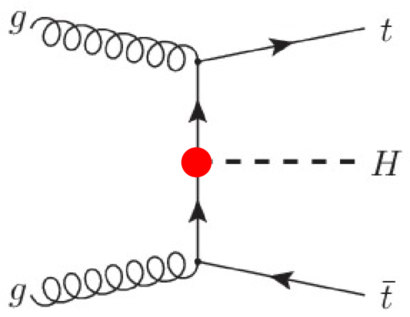




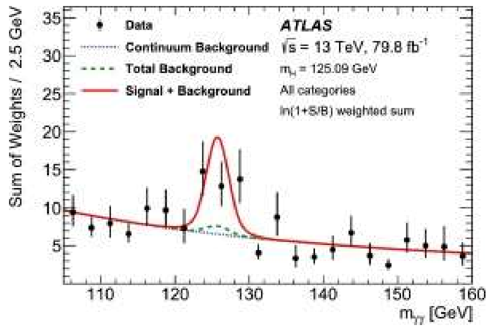
[Phys. Lett. B 784 (2018) 173](#)

Observation of ttH production

- Top quarkの湯川カップリングを直接測定
- Combination of analyses with decays:
  - $H \to \gamma\gamma \quad (79.8\ \mathrm{fb}^{-1})$
  - $H \to WW/ZZ \to leptons \quad (36.1\ \mathrm{fb}^{-1})$
  - $H \to \bar{b}b \quad (36.1\ \mathrm{fb}^{-1})$ ← 本多D論(2018)

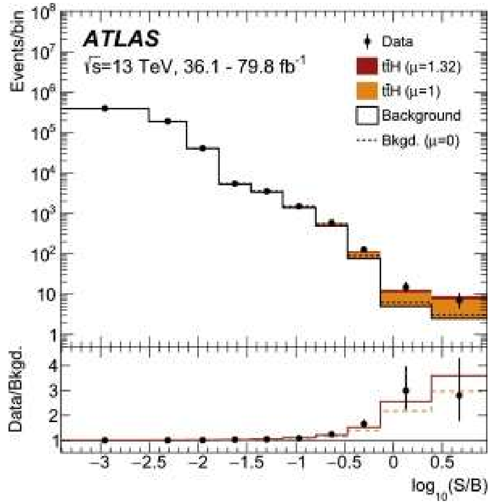


$H \to \gamma\gamma$イベント

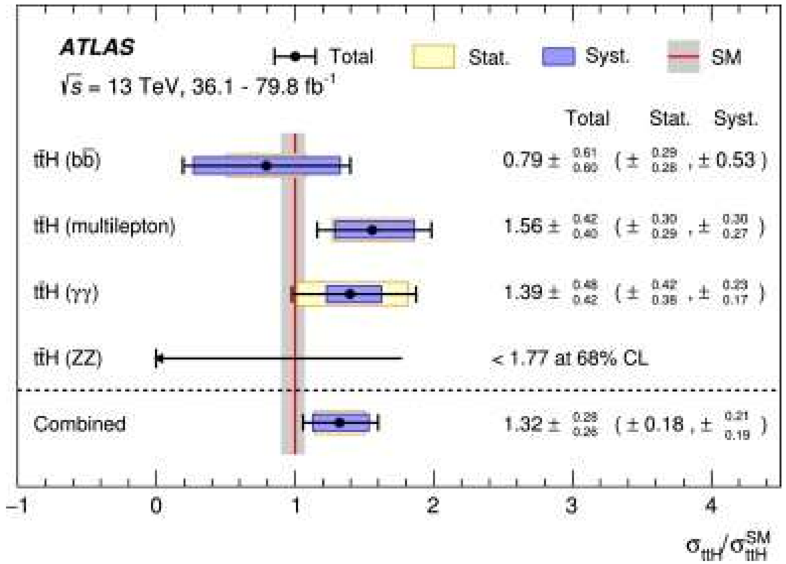


単独だと、3.7σ

Candidate eventのS/B分布



測定された信号強度

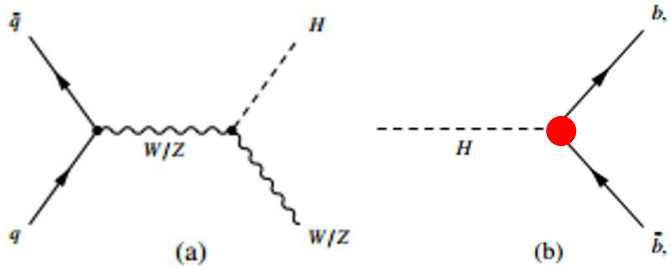


5.8 σ Observation
(expected sensitivity: 4.9 σ)

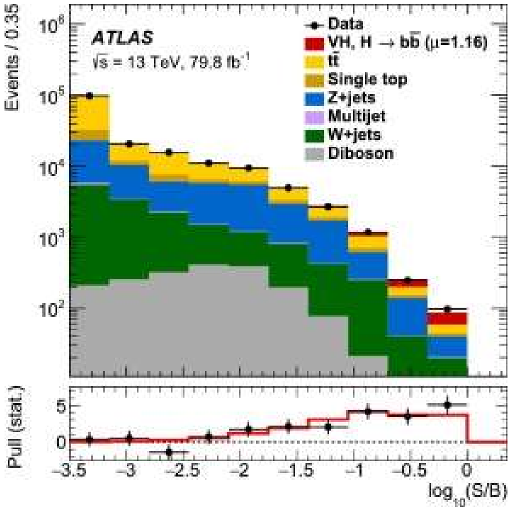
[Phys. Lett. B 786 (2018) 59]

Observation of $H \to b\bar{b}$

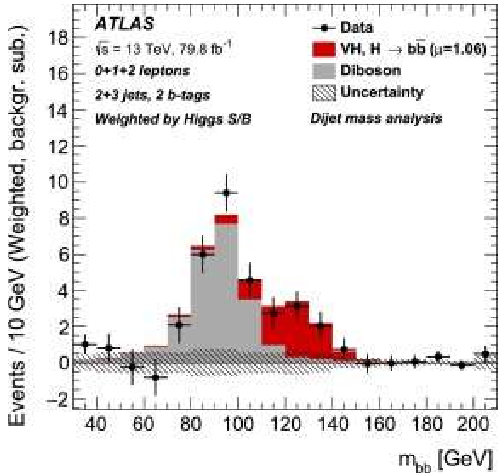
- bottom quarkの湯川カップリング
- Combination of processes:
  - $ZH \to (\nu\nu)(bb)$
  - $WH \to (\ell\nu)(bb)$
  - $ZH \to (\ell\ell)(bb)$



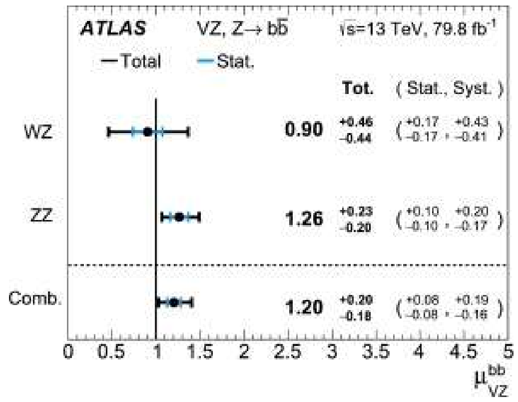
Candidate eventのS/B分布



m_{bb}分布



測定された信号強度



5.3 σ Observation
(expected sensitivity: 4.8 σ)

HNL production and decay

$$\sigma(pp \to W) \cdot \mathcal{B}(W \to \ell N) = \sigma(pp \to W) \cdot \mathcal{B}(W \to \ell \nu) \cdot |U|^2 \left(1 - \frac{m_N^2}{m_W^2}\right)^2 \left(1 + \frac{m_N^2}{2m_W^2}\right). \qquad (1)$$

2.2 HNL decay

For this search, partial widths are calculated for all HNL decay channels including leptons and quarks. The calculations consider charged- and neutral-current-mediated interactions as well as QCD loop corrections, which are all described in Ref. [26]. The HNL lifetime τ_N has a strong dependence on the coupling strength $|U|^2$ and also the mass m_N due to phase-space effects. For a given $|U|^2$ and m_N, the total width $\Gamma = \sum_i \Gamma_i \left(m_N, |U|^2\right)$ is computed, and the mean lifetime is obtained as $\tau_N = \hbar/\Gamma$. In the relevant range $4.5 \leq m_N \leq 50$ GeV, the result agrees within 2% with the following parameterisations given in Ref. [27]: $\tau_{N_\mu} = (4.49 \cdot 10^{-12}\ \mathrm{s})|U|^{-2}(m_N/1\ \mathrm{GeV})^{-5.19}$ and $\tau_{N_e} = (4.15 \cdot 10^{-12}\ \mathrm{s})|U|^{-2}(m_N/1\ \mathrm{GeV})^{-5.17}$ for dominant mixing to ν_μ and ν_e, respectively. These relationships, however, assume no LNV decays. If LNV is allowed, twice as many decay channels are allowed, and τ_N is reduced by a factor of 2. More elaborate models do not necessarily allow for LNV [23] and thus may or may not contain this factor of 2. To account for this model dependence, both interpretations are considered in the case of the displaced signature, which is not limited to LNV processes.