LHC ATLAS 実験

佐藤構二
宇宙史センター 構成員会議
2019年6月3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} \leq$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。

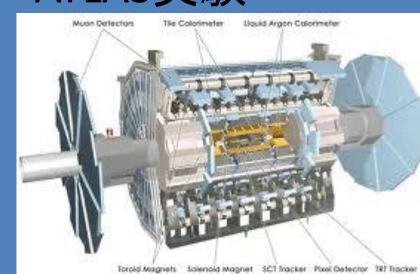
2021-2023年　Run 3。Ecm=13-14 TeV , ～300 fb^{-1}のデータセット

ジュネーブ市街

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

CMS実験

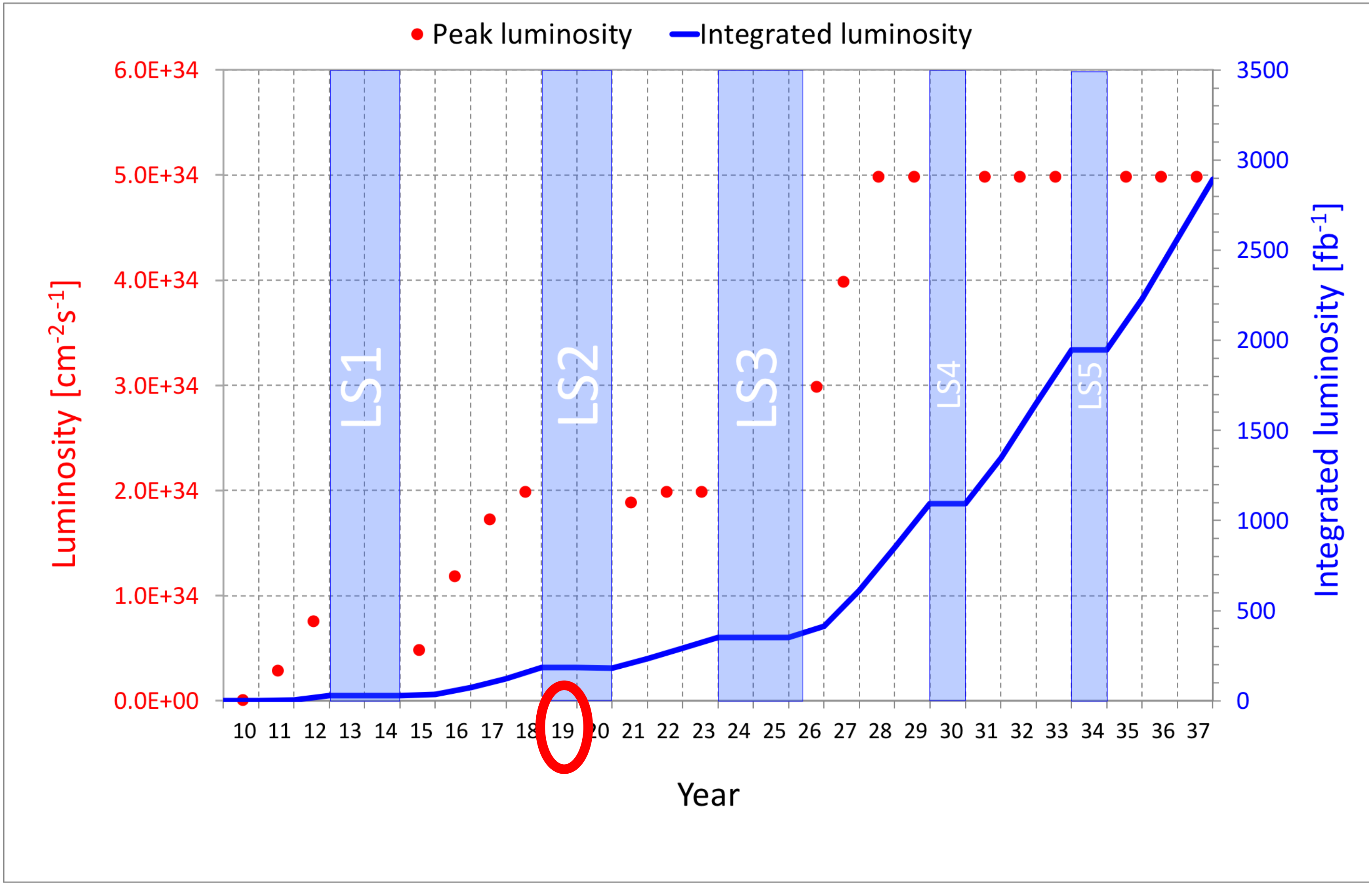
ATLAS実験



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

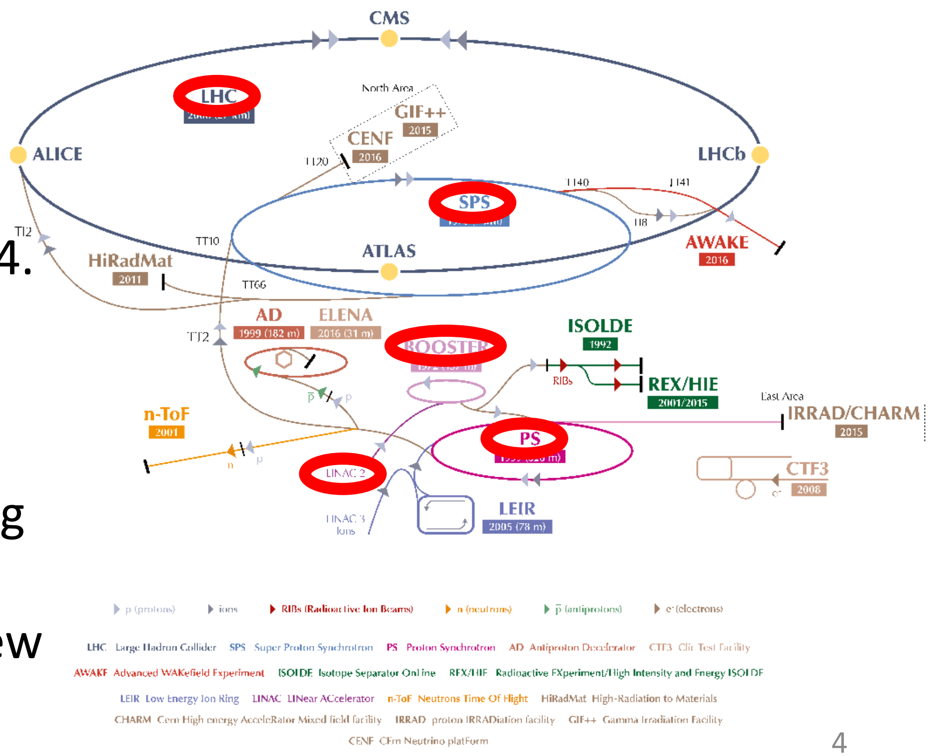
Accelerator LS2 Upgrades

- 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

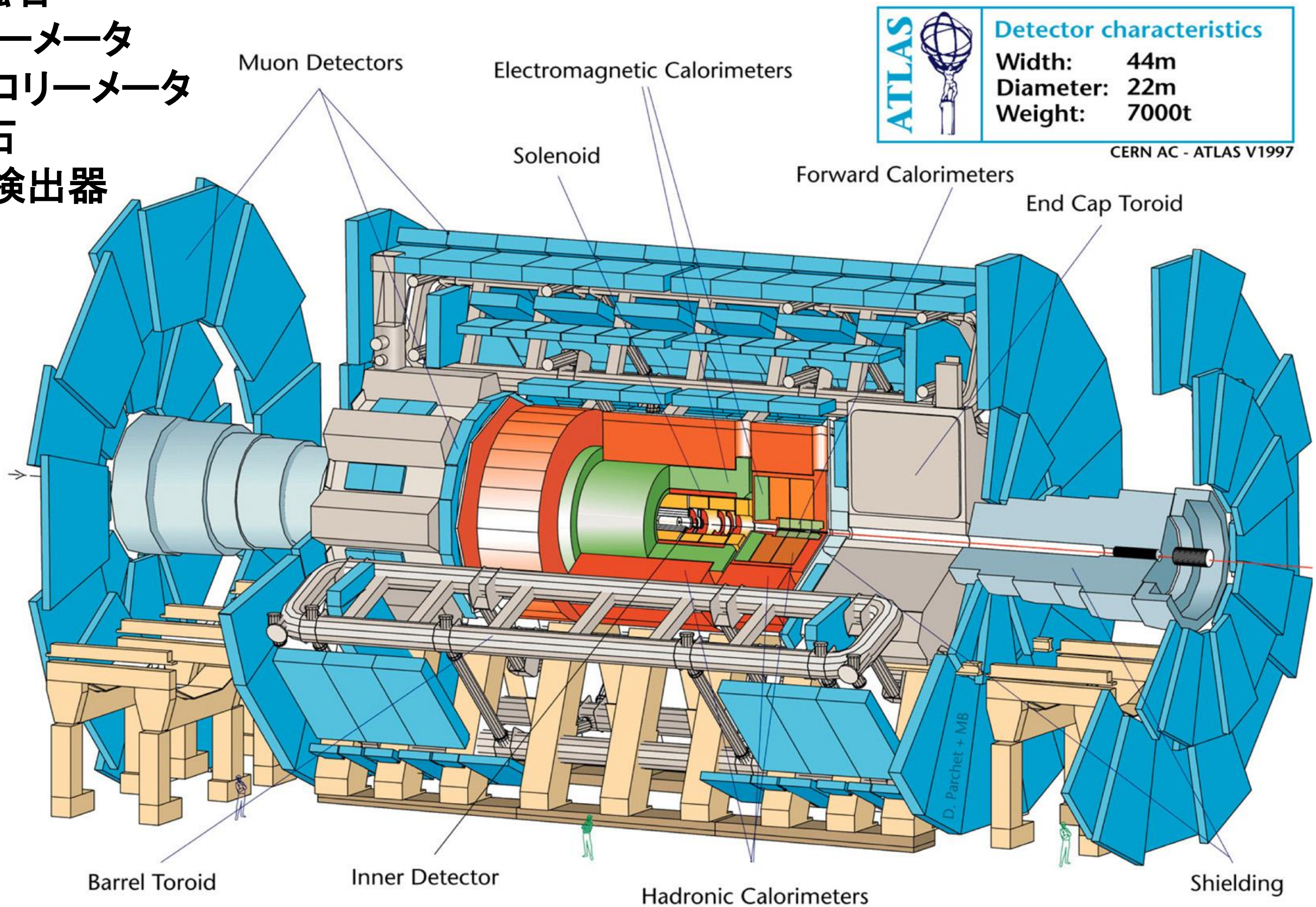
- Preparation for HL-LHC, as well as Run 3 and maintenance.
- More intense, concentrated beam, with new Linac accelerating H- instead of proton.
    - Replace Linac 2 with new Linac 4.
    - Upgrade Booster injection.
    - New RF system in SPS.
- Bring beam energy up to 7 TeV.
    - Consolidate the 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

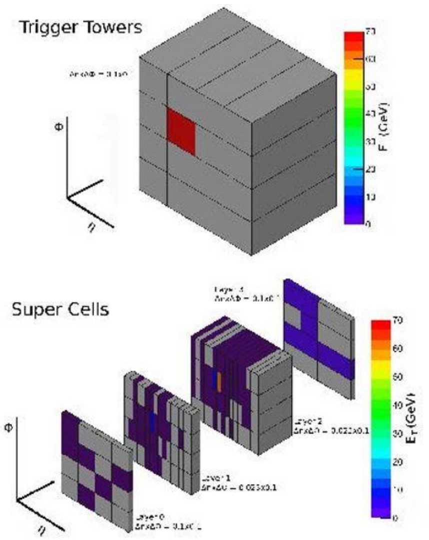
総重量　7,000 t

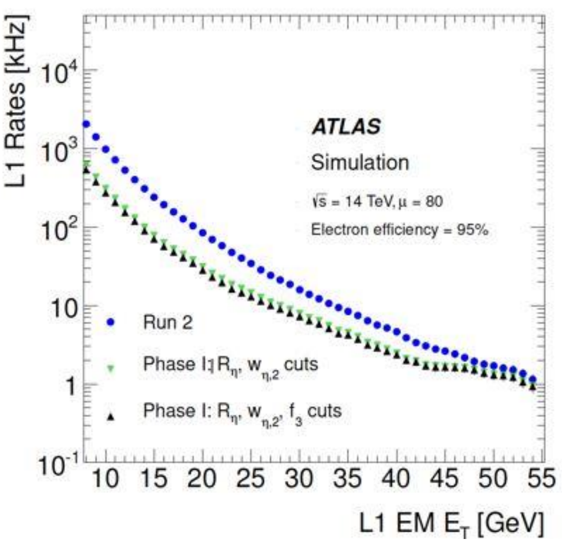


- 最高エネルギーでの、さまざまな素粒子反応の研究
  - ヒッグス粒子、標準理論、トップクォーク、Bメソン、超対称性、新物理探索、重イオン衝突...

ATLAS LS2 Upgrades

L1 Calo Trigger Upgrade

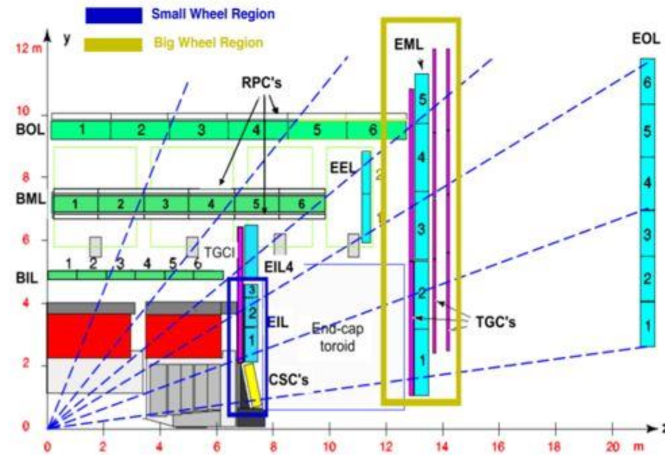


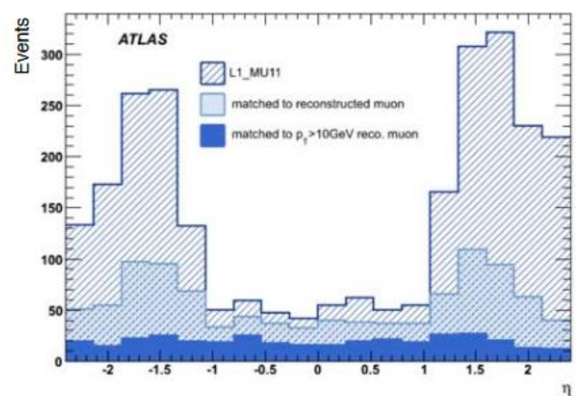


Improvement on Jet and MET triggers, too.

Nucl.Instrum.Meth. 825 (2016) 374-378

New Muon Small Wheel
For L1 Trigger

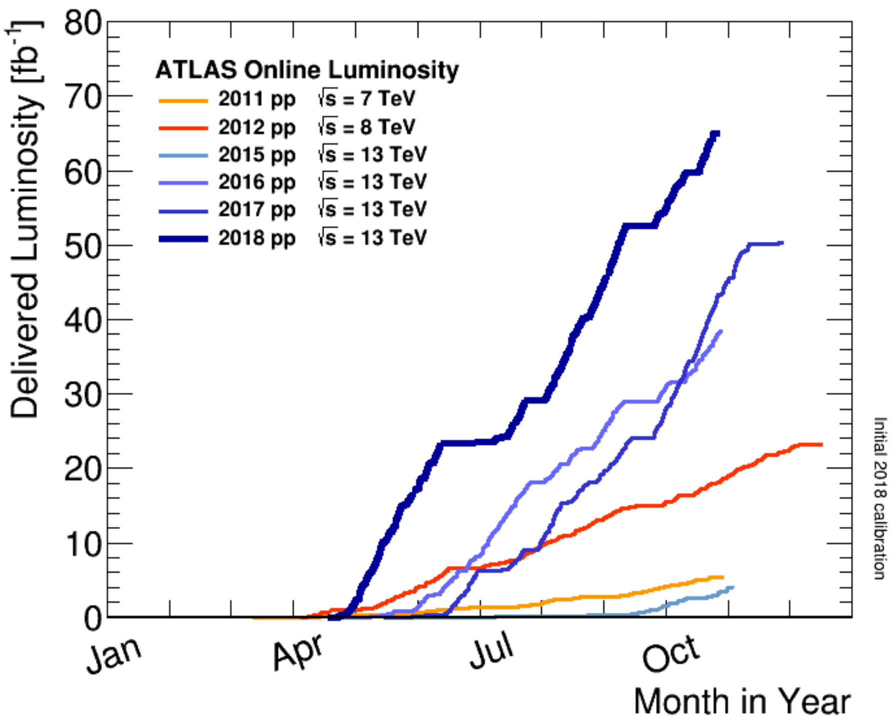




arXiv:1810.01394v

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

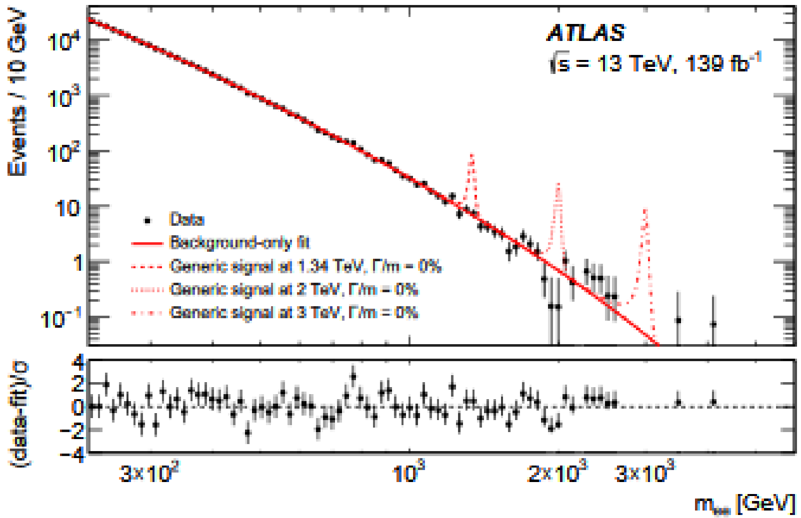
$E_{CM} = 13$ (TeV)

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**

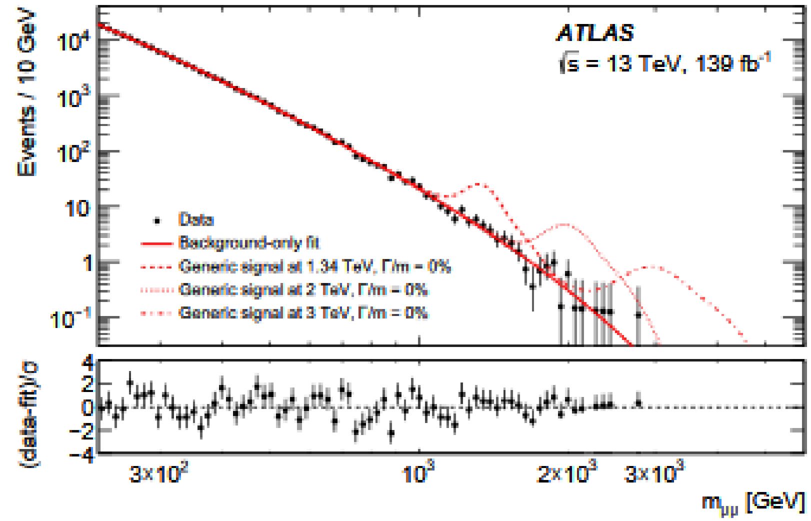
arXiv:1903.06248

Full Run 2 Dilepton Resonance Search

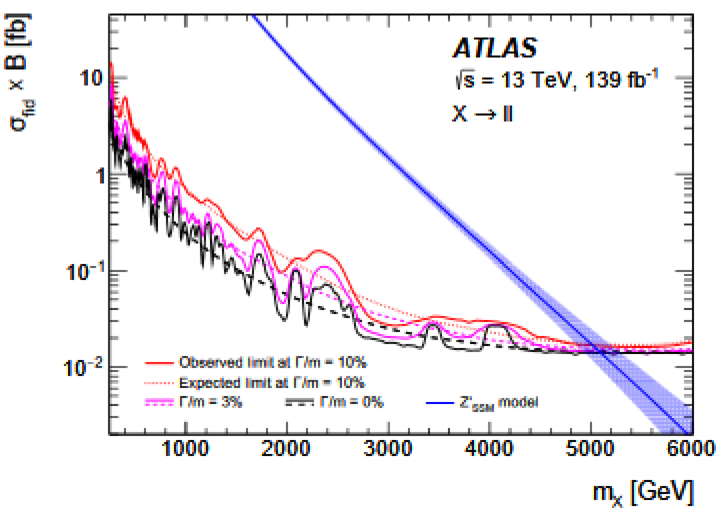
Dielectron invariant mass

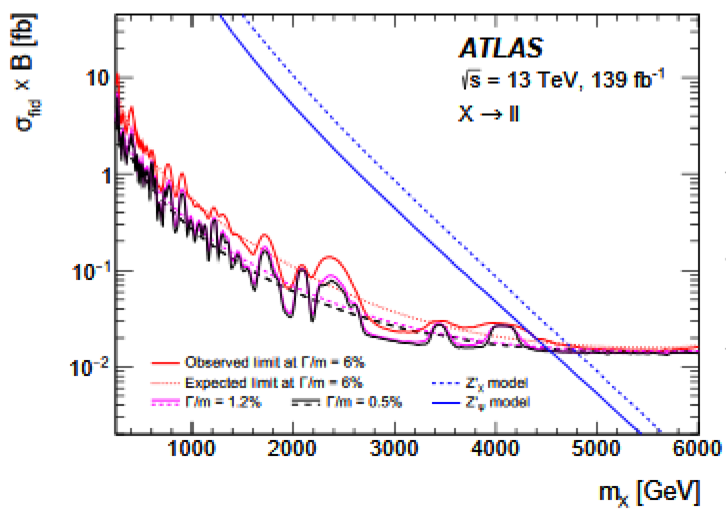


Dimuon invariant mass



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



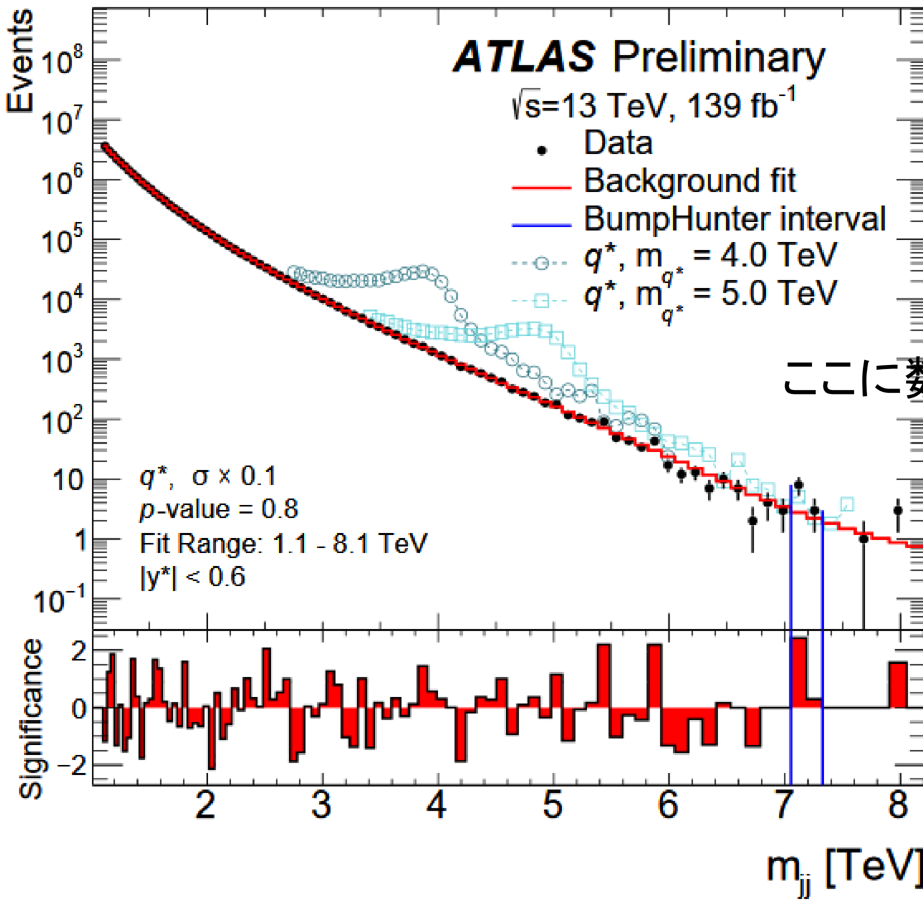


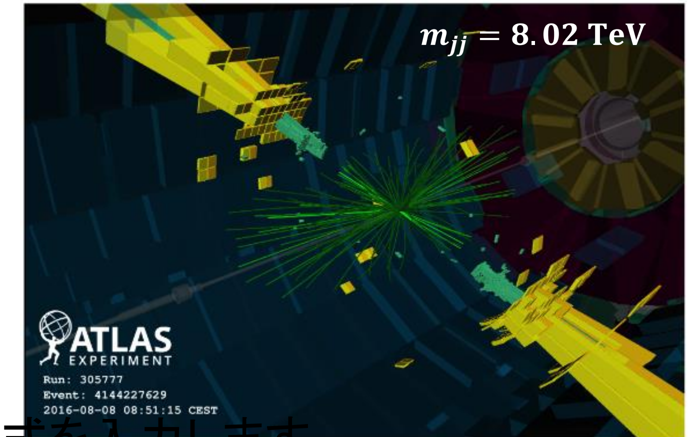
Lower limit on Z' mass

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 Dijet Resonance Search

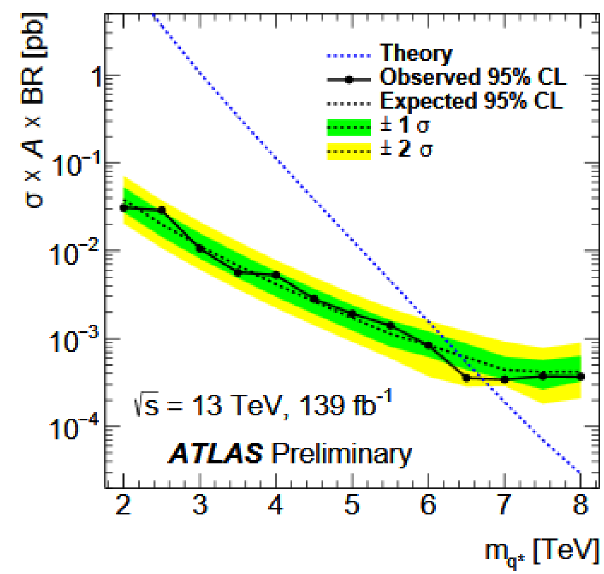
Dijet mass spectrum





ここに数式を入力します。

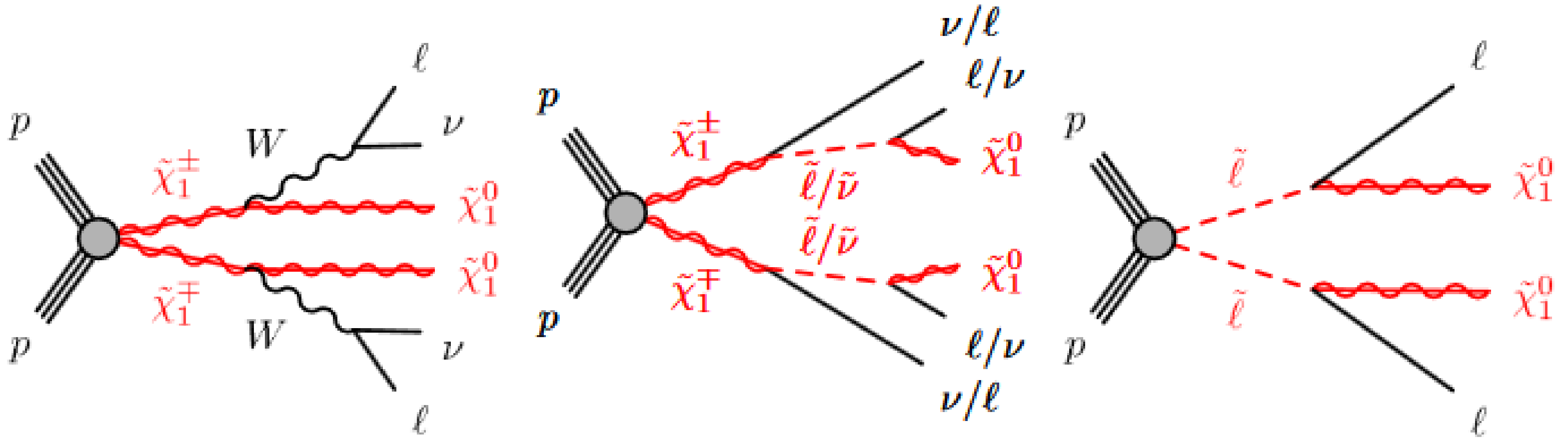
Limit on excited quark model

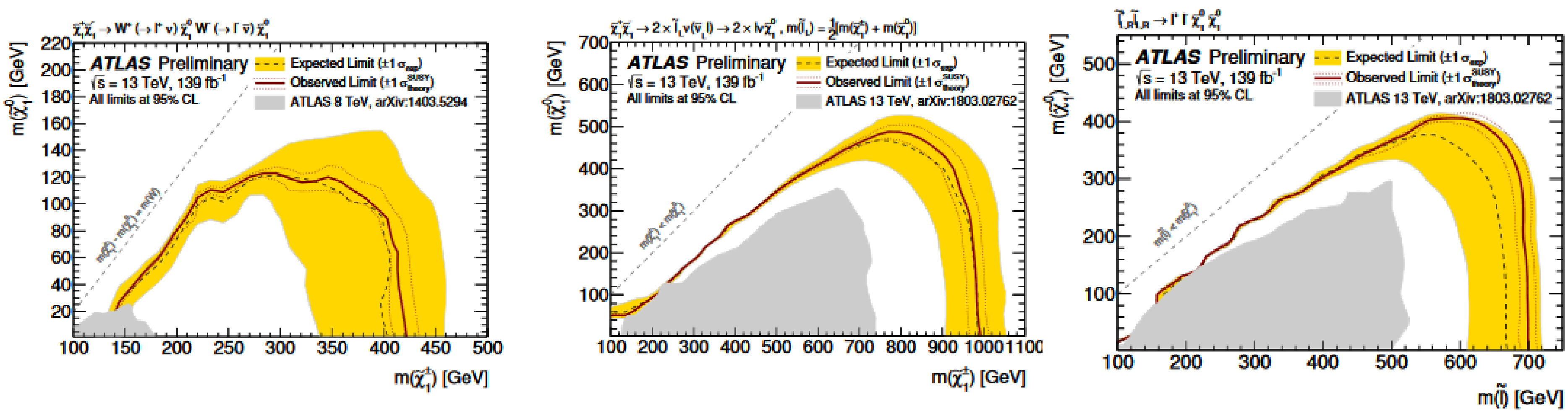


$m_{q^*} > 6.7$ TeV

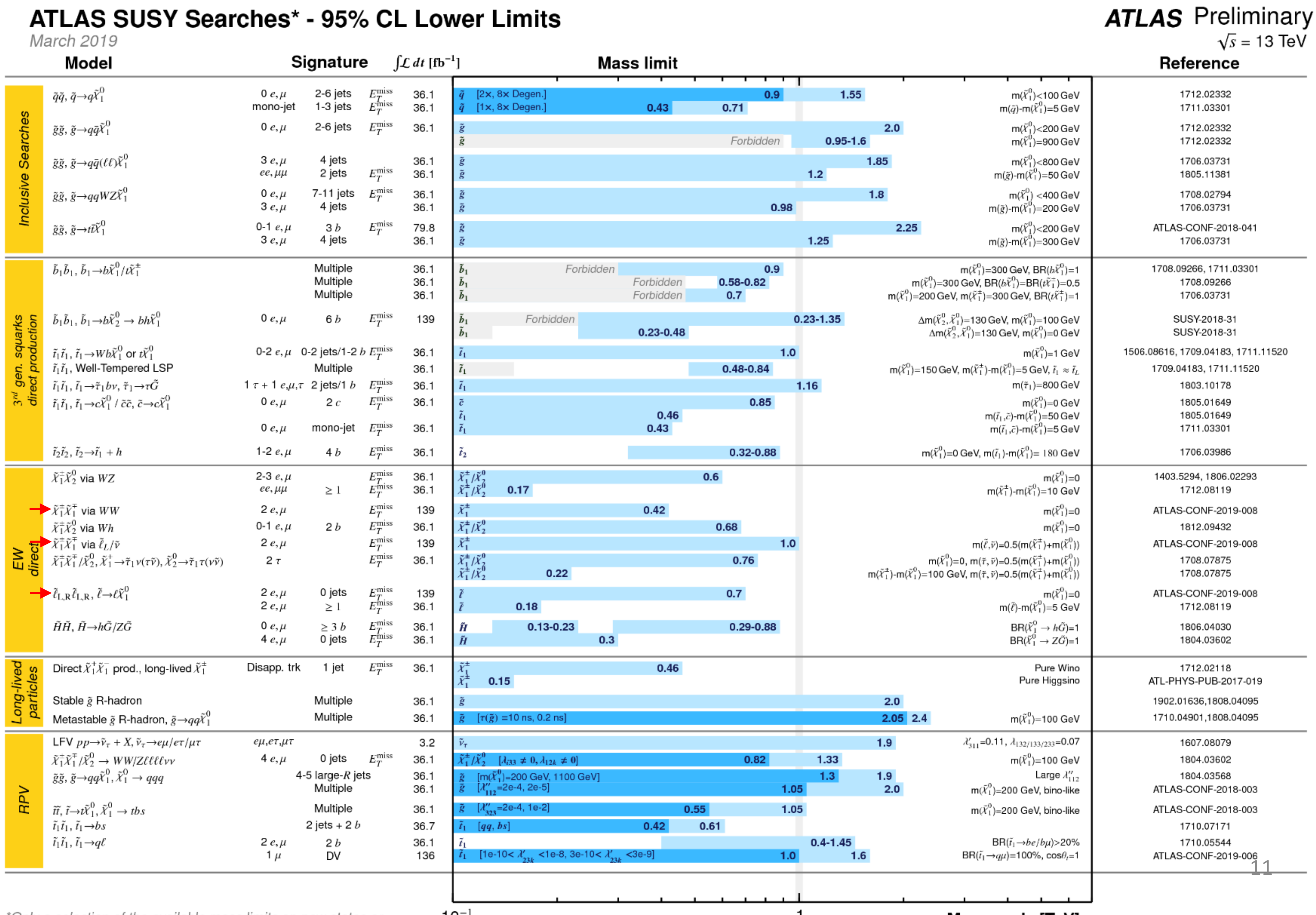
Full Run 2
Chargino and Slepton Searches

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

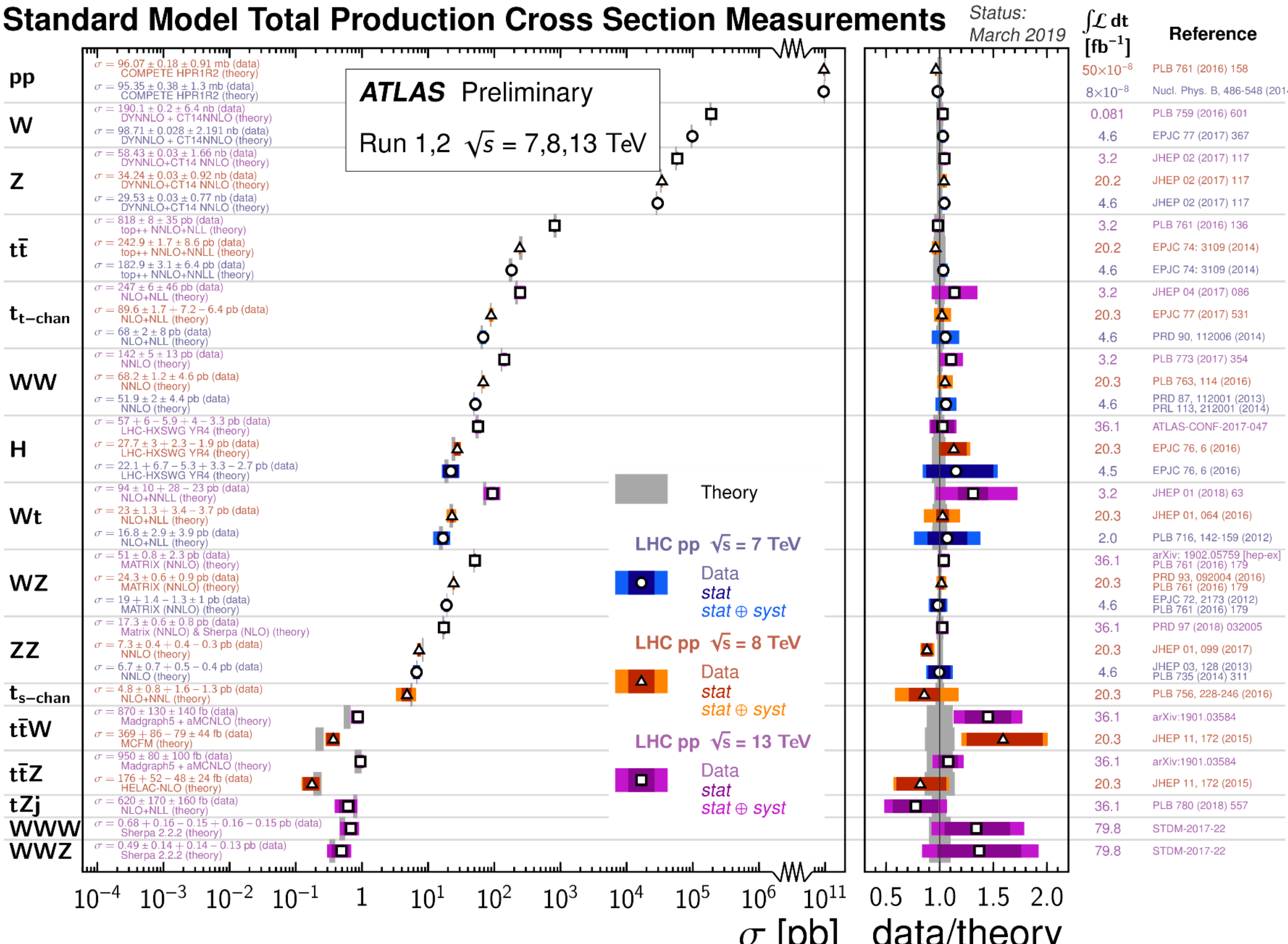




Supersymmetry Searches

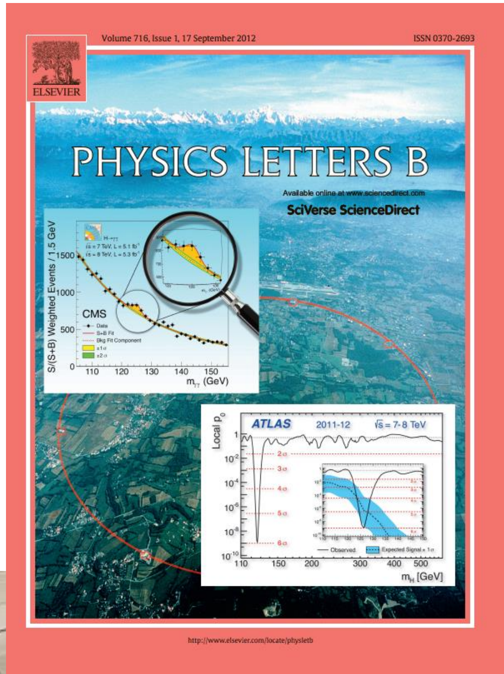


標準理論の大成功



15桁にわたって、理論＝実験がよく合っている。

ヒッグス粒子発見の発表



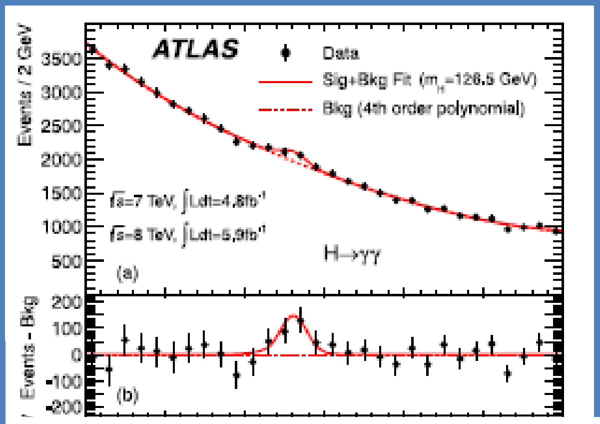
2012年7月4日　LHC加速器のATLAS/CMS両実験が発見を報告

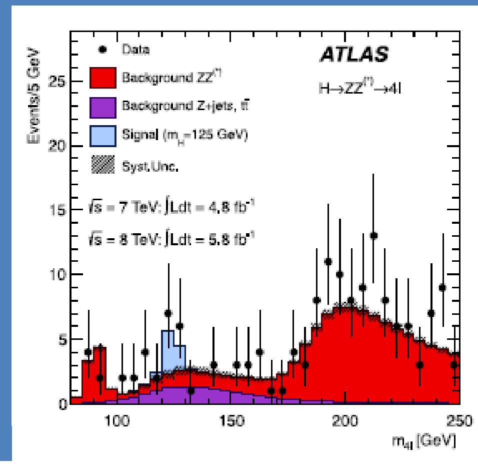
2013年　アングラール、ヒッグスがノーベル物理学賞を受賞

全Run 1データでのアップデート

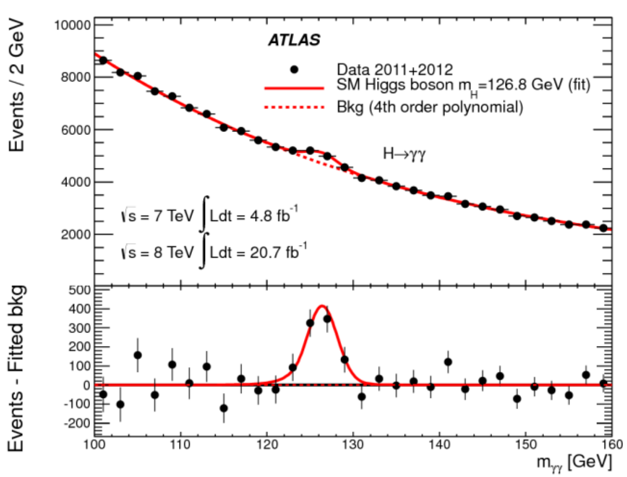
2012年夏の結果

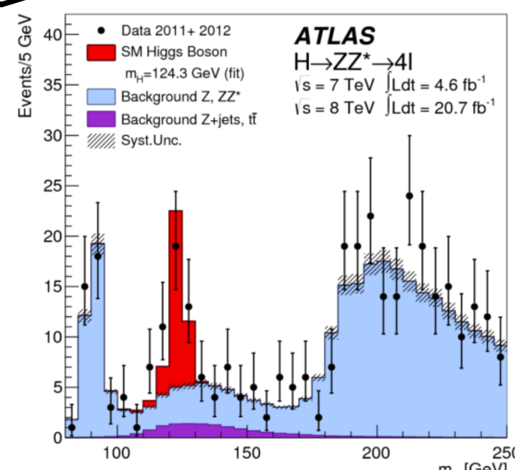
[Phys. Lett. B 716 (2012) 1-29]





2チャンネル合わせて5.9σ.





データが増えたため、ヒッグス粒子のピークがよりハッキリ見える（Run１終わりですでに）
→これからは、ヒッグス粒子の精密測定の時代

[Phys. Lett. B 726 (2013), pp. 88-119]

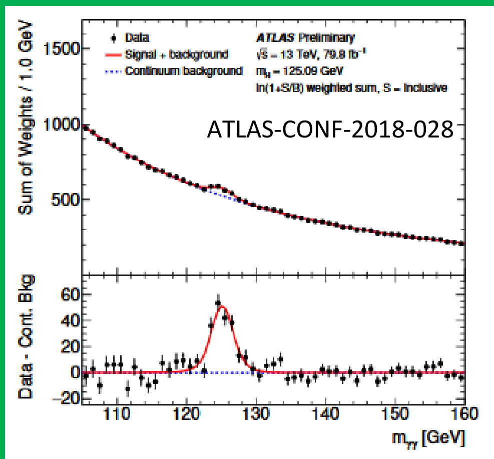
2013年夏の結果

Signal significance:
Observed: 7.4 σ
Expected: 4.3 σ

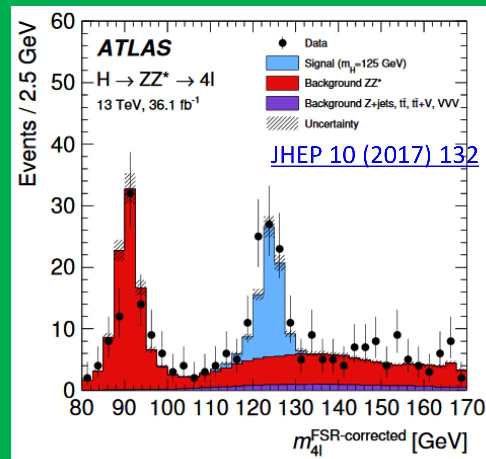
Significance:
Observed: 6.6σ
Expected: 4.4σ

Higgs Peaks - Run 1 vs Run 2

2018年夏(13 TeV, 80 fb-1)



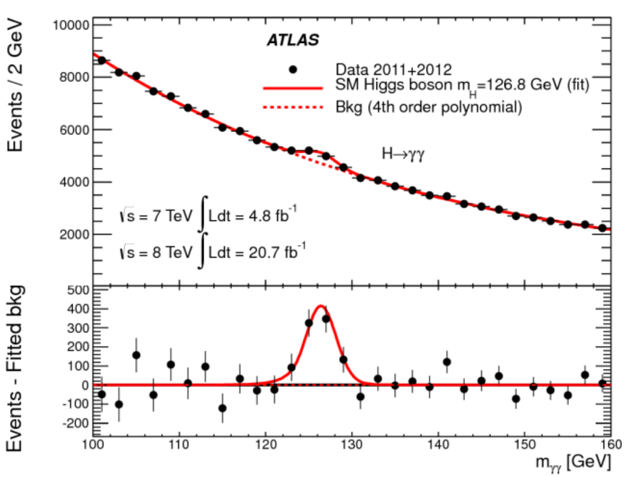
2017年夏(13 TeV, 36 fb-1)



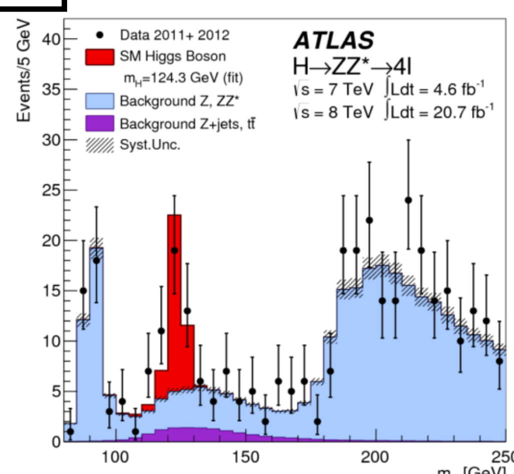
Run 2はさらに多くのヒッグス粒子を観測した。

↓

精密測定



Signal significance:
Observed: 7.4 σ
Expected: 4.3 σ



Significance:
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Expected: 4.4σ

データが増えたため、ヒッグス粒子のピークがよりハッキリ見える(Run1終わりですでに)
→これからは、ヒッグス粒子の精密測定の時代

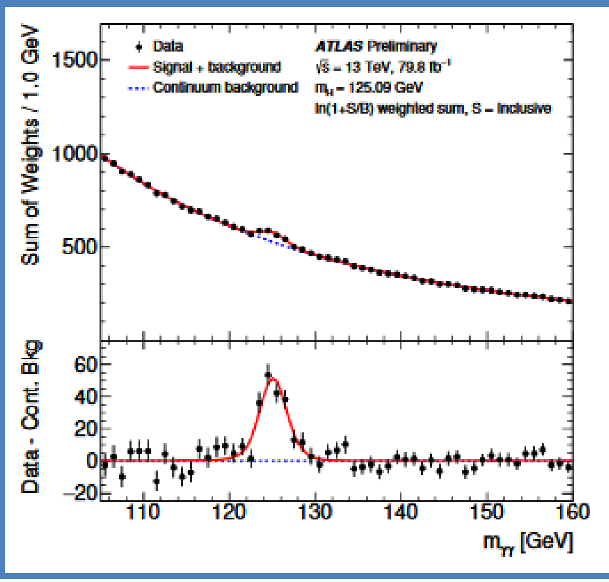
Phys. Lett. B 726 (2013), pp. 88-119

2013年夏の結果

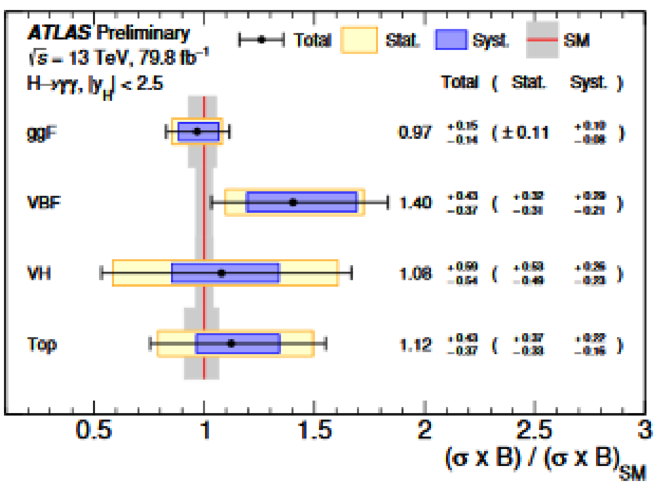
$H \to \gamma\gamma$、生成過程ごとの解析

ATLAS-CONF-2018-028

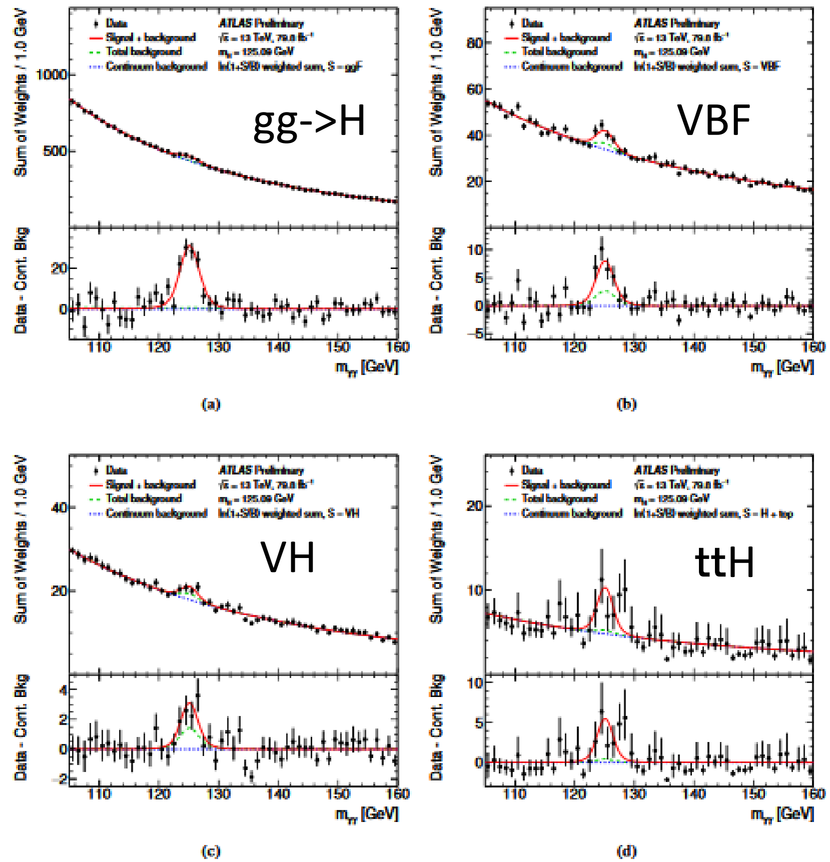
全$H \to \gamma\gamma$候補事象



$\sigma_{\text{fid}} = 60.4 \pm 6.1\,(\text{stat.}) \pm 6.0\,(\text{exp.}) \pm 0.3\,(\text{theo.})$ fb,



キネマティックスによって、生成過程ごとのサブチャンネルを解析する。

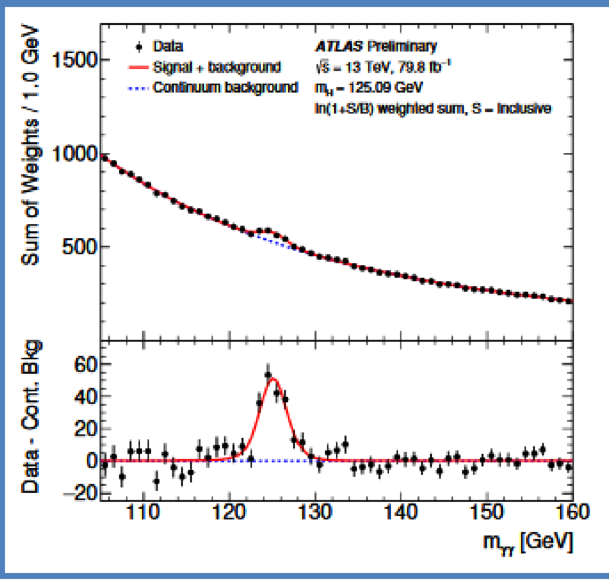


Process ($\|y_H\| < 2.5$)	Result [fb]	Total	Stat.	Exp.	Theo.	SM prediction [fb]
ggF	98	$^{+15}_{-14}$	± 11	$^{+9}_{-8}$	$^{+4}_{-3}$	$102\ ^{+5}_{-7}$
VBF	11.2	$^{+3.4}_{-3.0}$	$^{+2.6}_{-2.4}$	$^{+1.3}_{-1.2}$	$^{+1.9}_{-1.1}$	8.0 ± 0.2
VH	4.9	$^{+2.7}_{-2.5}$	$^{+2.4}_{-2.2}$	$^{+1.0}_{-0.9}$	$^{+0.6}_{-0.5}$	4.5 ± 0.2
Top	1.5	$^{+0.6}_{-0.5}$	$^{+0.5}_{-0.4}$	± 0.2	$^{+0.2}_{-0.1}$	1.3 ± 0.1

$H \to \gamma\gamma$、生成過程ごとの解析

ATLAS-CONF-2018-028

全$H \to \gamma\gamma$候補事象



$\sigma_{\text{fid}} = 60.4 \pm\ 6.1\ (\text{stat.}) \pm\ 6.0\ (\text{exp.}) \pm\ 0.3\ (\text{theo}$

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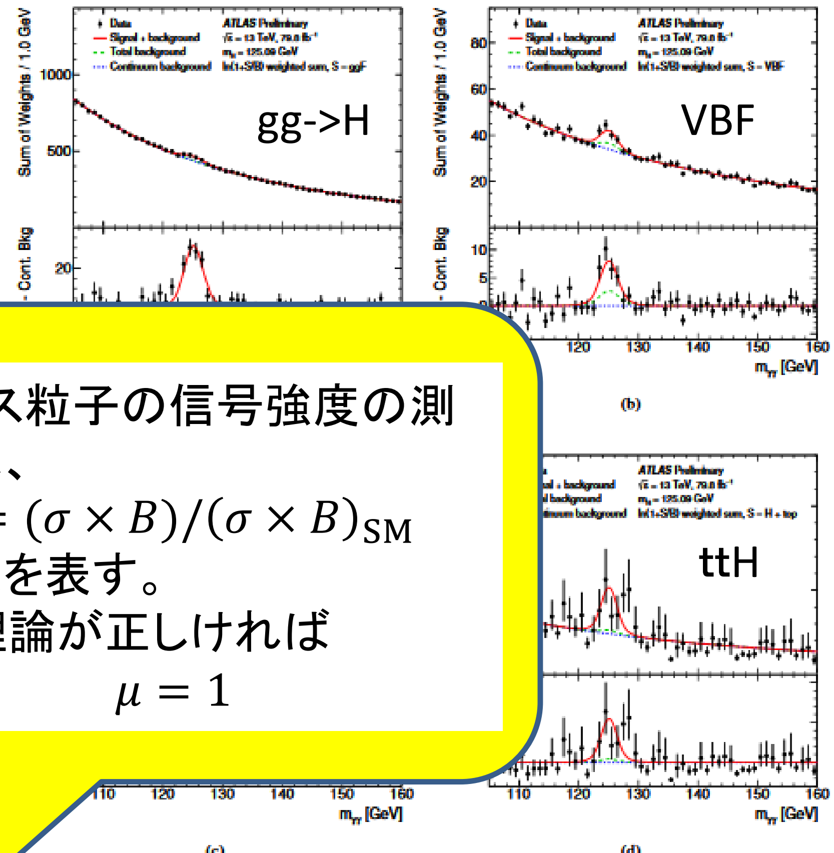
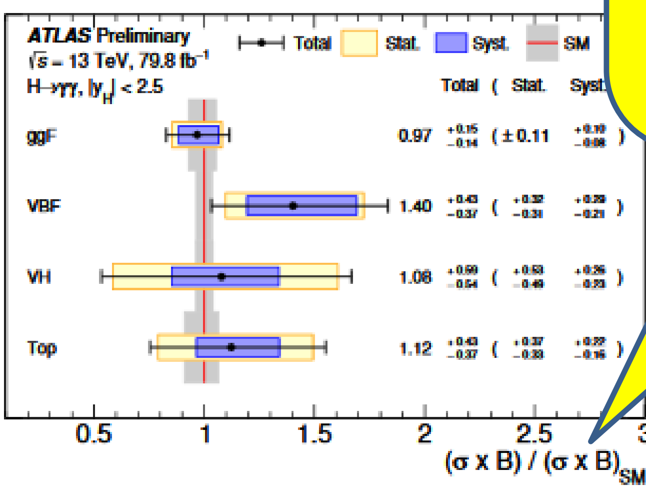


ヒッグス粒子の信号強度の測定では、

$$\mu = (\sigma \times B)/(\sigma \times B)_{\text{SM}}$$

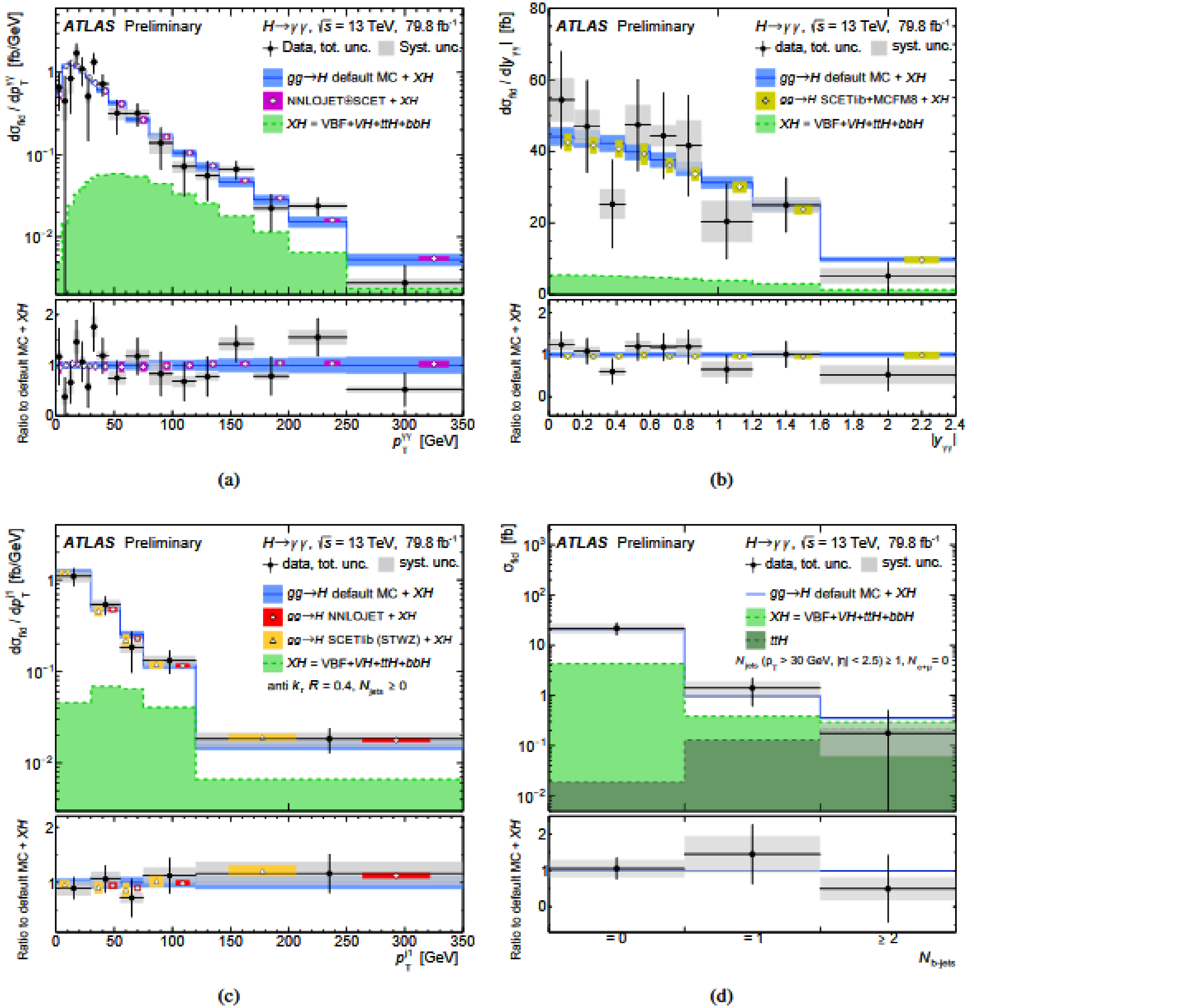
で結果を表す。
標準理論が正しければ

$$\mu = 1$$



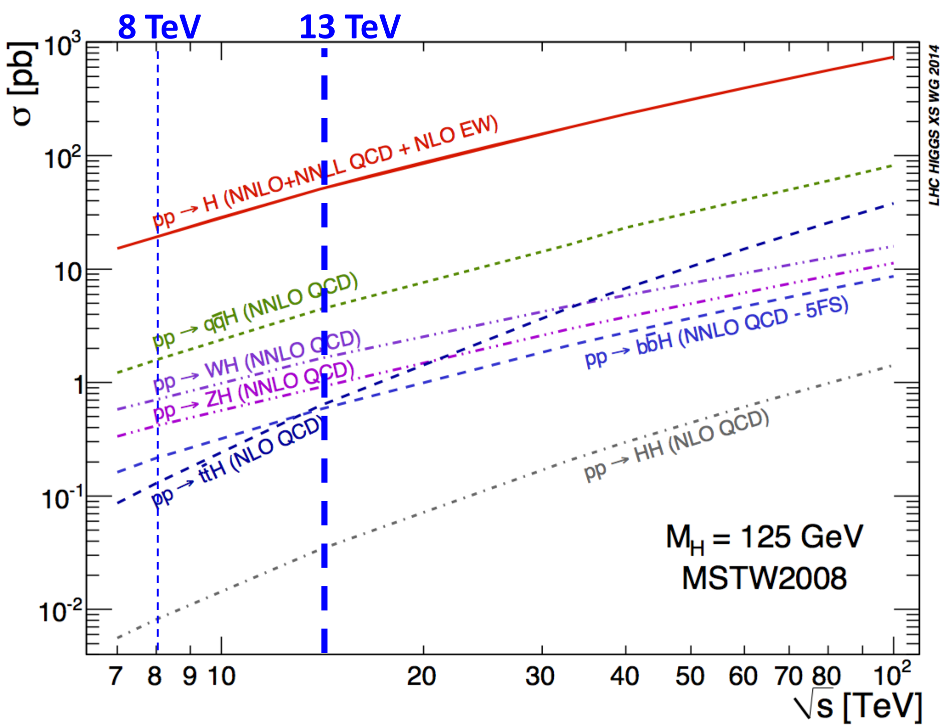
Process ($\lvert y_H \rvert < 2.5$)	Result [fb]	Uncertainty [fb] Total	Stat.	Exp.	Theo.	SM prediction [fb]
ggF	98	$^{+15}_{-14}$	± 11	$^{+9}_{-8}$	$^{+4}_{-3}$	$102\ ^{+5}_{-7}$
VBF	11.2	$^{+3.4}_{-3.0}$	$^{+2.6}_{-2.4}$	$^{+1.3}_{-1.2}$	$^{+1.9}_{-1.1}$	8.0 ± 0.2
VH	4.9	$^{+2.7}_{-2.5}$	$^{+2.4}_{-2.2}$	$^{+1.0}_{-0.9}$	$^{+0.6}_{-0.5}$	4.5 ± 0.2
Top	1.5	$^{+0.6}_{-0.5}$	$^{+0.5}_{-0.4}$	± 0.2	$^{+0.2}_{-0.1}$	1.3 ± 0.1

$H \to \gamma\gamma$、微分断面積 ATLAS-CONF-2018-028



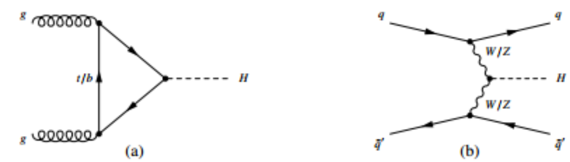
ヒッグス粒子の性質(標準理論の計算)

- 生成断面積



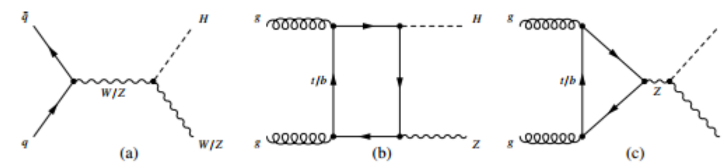
	σ(14TeV)/σ(8TeV)
gg→H	2.6 (M_X=M_H)
qq→qqH	2.6 (probes high M_X)
qq→VH	2.1 (M_X=M_V+M_H)
gg→ttH	4.7 (phase space+M_X)

$gg \to H$ $\quad$ $qq \to qqH$



ynman diagrams for Higgs boson production via the (a) ggF and (b) VBF production

$qq \to VH$



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

$gg \to ttH$

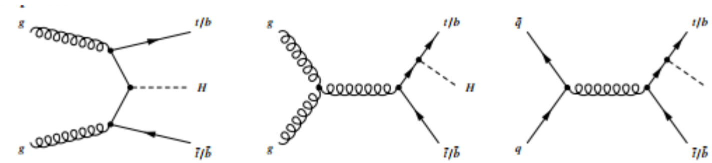


Figure 3: Leading-order Feynman diagrams of Higgs boson production via the $q\bar{q}/gg \to t\bar{t}H$ and $q\bar{q}/gg \to bbH$ processes.

ヒッグス粒子の性質(標準理論の計算)

$H \to WW/ZZ$ $\quad$ $H \to fermion\ pair$

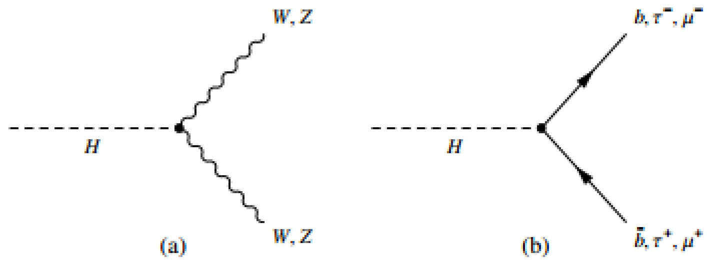


Figure 5: L[$H \to \gamma\gamma$]ynman diagrams of Higgs boson decays (a) to W and Z bosons and (b) to fermions.

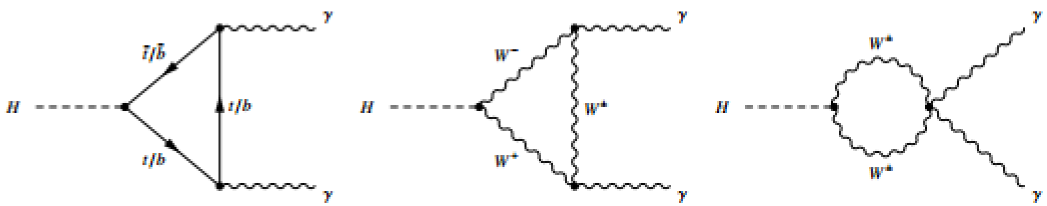


Figure 6: Leading-order Feynman diagrams of Higgs boson decays to a pair of photons.

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 $(m_H = 125\ \mathrm{GeV})$

$H \to b\bar{b}$	$H \to \tau^+\tau^-$	$H \to \mu^+\mu^-$	$H \to c\bar{c}$
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

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 (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]	$1.9^{+0.8}_{-0.7}$ $\left(^{+0.72}_{-0.66}\right)$	$2.9^{+1.0}_{-0.9}$ $\left(^{+0.88}_{-0.80}\right)$	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

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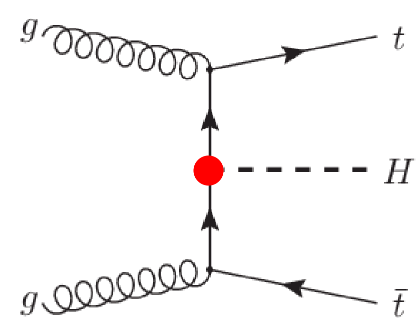
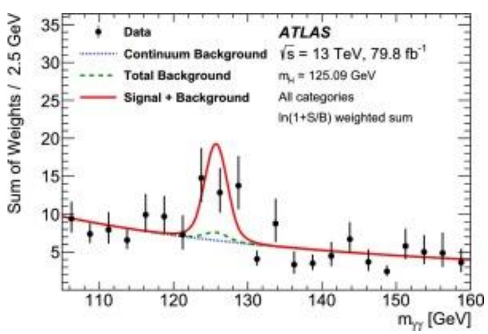
Observation of ttH production

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

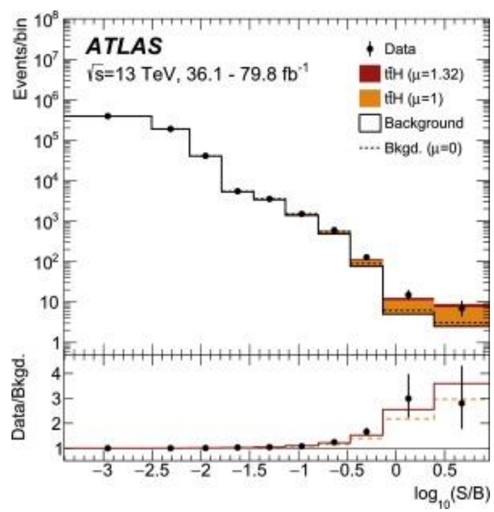


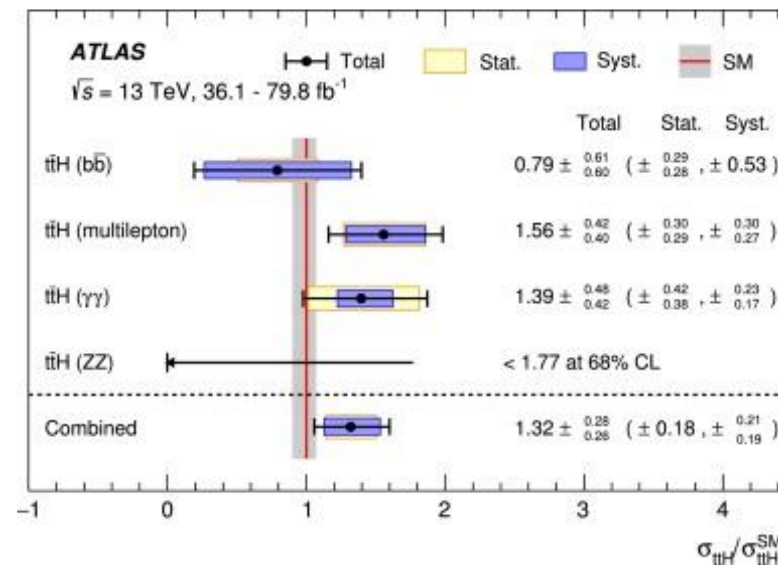
Candidate eventのS/B分布　**測定された信号強度**

$H \to \gamma\gamma$イベント



単独だと、3.7σ



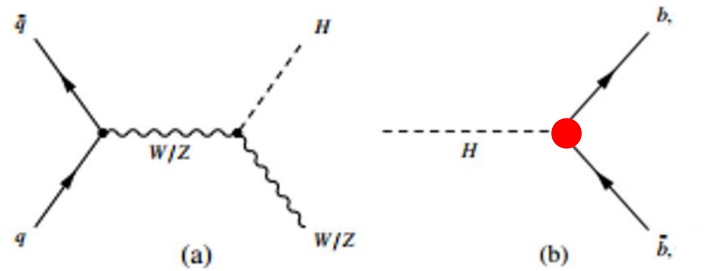


5.8 σ Observation
(expected sensitivity: 4.9 σ)

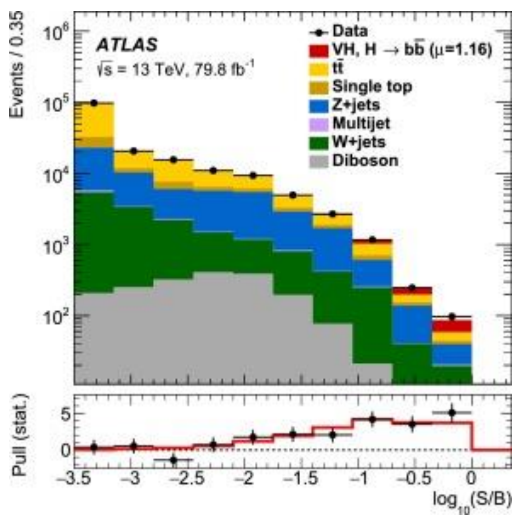
Phys. Lett. B 786 (2018) 59

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

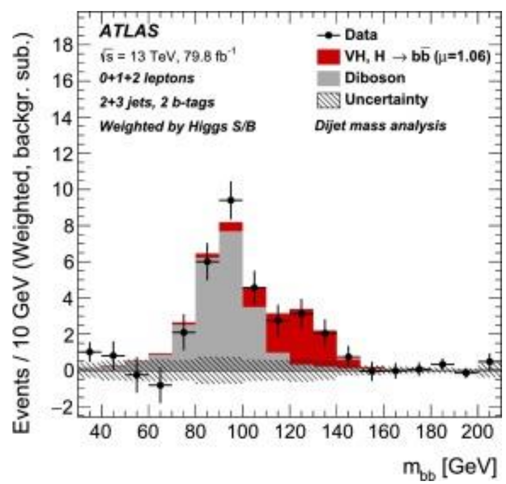
- bottom quarkの湯川カップリング
- Combination of processes:
  - $ZH \to (\nu\nu)(bb)$
  - $WH \to (\ell\nu)(bb)$
  - $ZH \to (\ell\ell)(bb)$



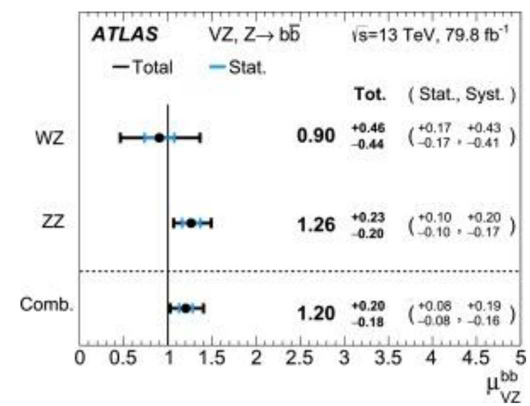
Candidate eventのS/B分布



m_{bb}分布



測定された信号強度



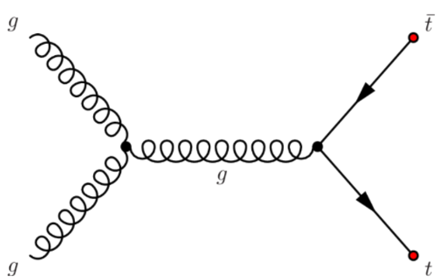
5.3 σ Observation
(expected sensitivity: 4.8 σ)

ATLAS-CONF-2018-026

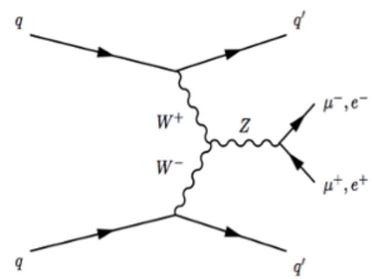
Search for $H \to \mu\mu$

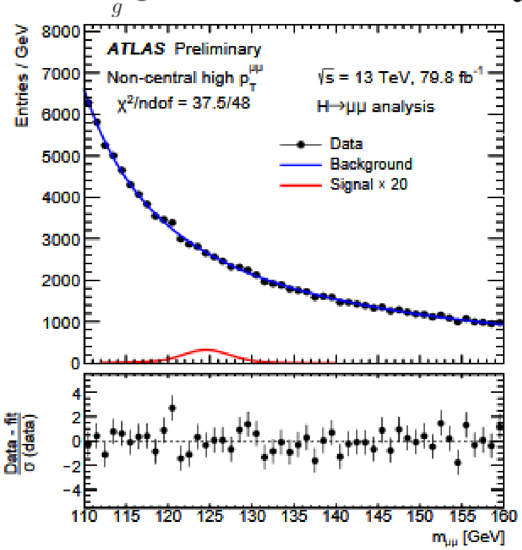
- 第3世代(τ, b, t)との湯川カップリングは確認できた。
- 第2世代粒子との湯川カップリングの発見を目指す
  - – VBFに特化した信号領域を定義して解析感度を向上
    - 前後方dijet, high m(jj)

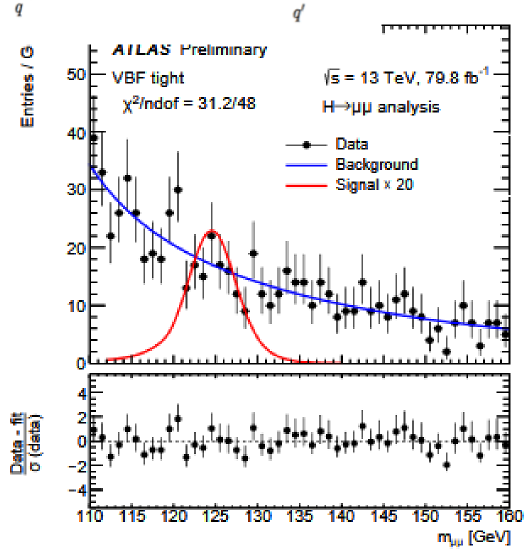
gg-fusion生成



Vector Boson Fusion生成







信号強度

$$\mu = 0.1^{+1.0}_{-1.1}$$

信号強度のリミット:

$$\boldsymbol{\mu < 2.1\ (95\%\ CL)}$$

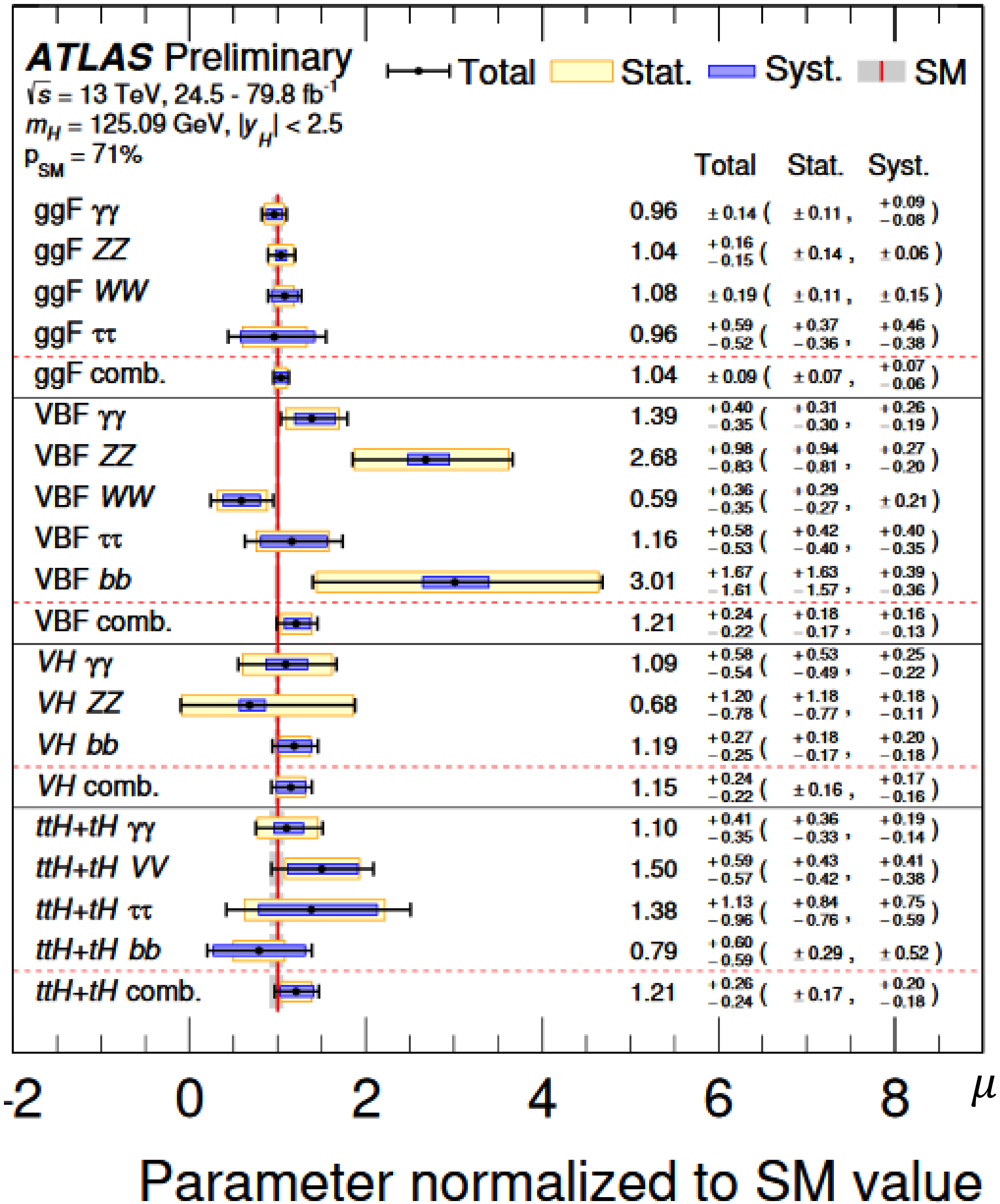
Combined Higgs Boson Coupling Measurement

ATLAS-CONF-2019-005

Analysis	Integrated luminosity (fb^{-1})
$H \to \gamma\gamma$ (including $t\bar{t}H$, $H \to \gamma\gamma$)	79.8
$H \to ZZ^* \to 4\ell$ (including $t\bar{t}H$, $H \to ZZ^* \to 4\ell$)	79.8
$H \to WW^* \to e\nu\mu\nu$	36.1
$H \to \tau\tau$	36.1
VH, $H \to b\bar{b}$	79.8
VBF, $H \to b\bar{b}$	24.5 – 30.6
$H \to \mu\mu$	79.8
$t\bar{t}H$, $H \to b\bar{b}$ and $t\bar{t}H$ multilepton	36.1
$H \to$ invisible	36.1
Off-shell $H \to ZZ^* \to 4\ell$ and $H \to ZZ^* \to 2\ell 2\nu$	36.1

Coambined Higgs Boson Coupling Measurement

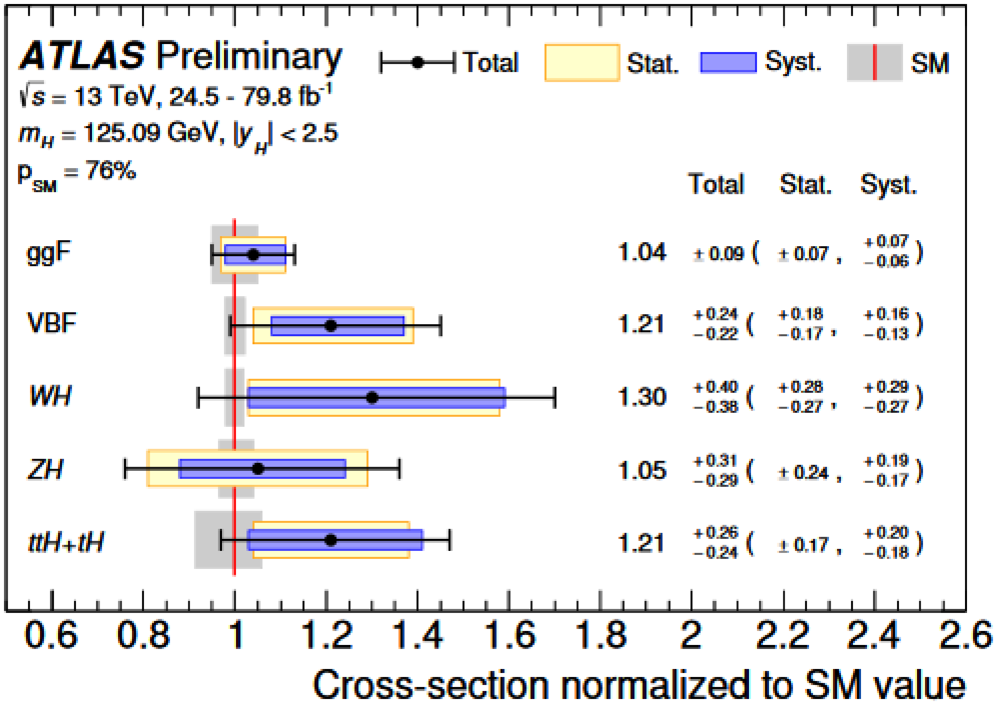
ATLAS-CONF-2019-005



$$\mu = (\sigma \times B)/(\sigma \times B)_{\mathrm{SM}}$$

Coambined Higgs Boson Coupling Measurement

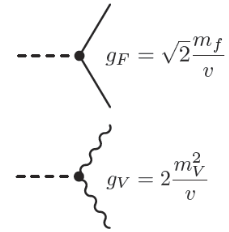
ATLAS-CONF-2019-005



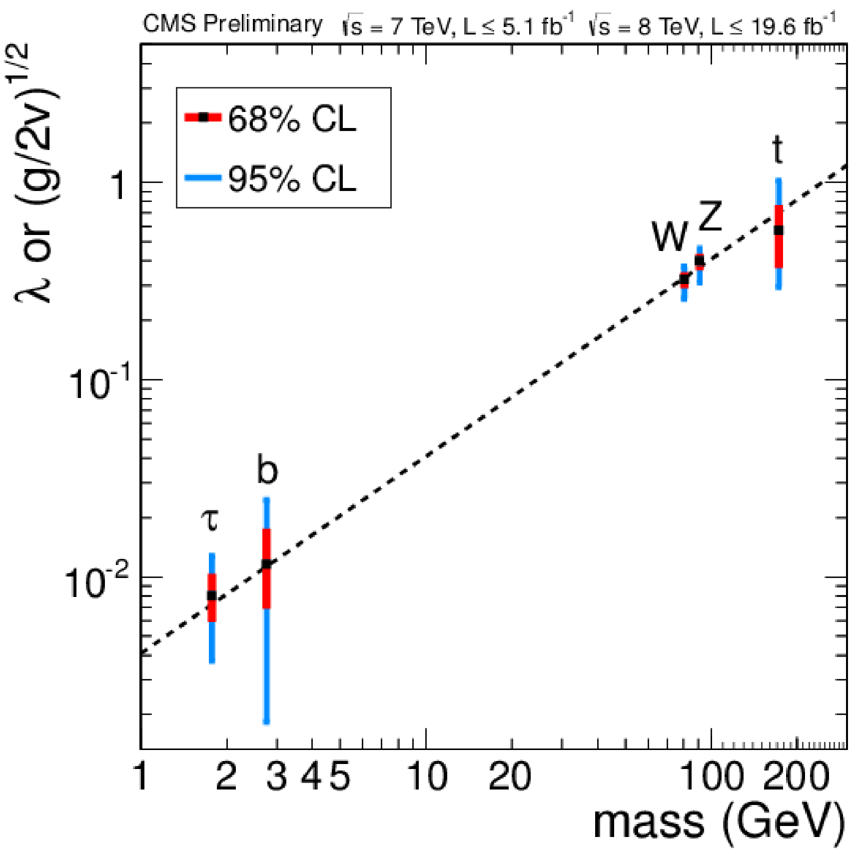
Process ($\|y_H\| < 2.5$)	Value [pb]	Uncertainty [pb] Total	Stat.	Exp.	Sig. th.	Bkg. th.	SM pred. [pb]	Significance obs. (exp.)	
ggF	46.5	±4.0	±3.1	±2.2	±0.9	±1.3	44.7 ± 2.2	-	
VBF	4.25	$^{+0.84}_{-0.77}$	$^{+0.63}_{-0.60}$	$^{+0.35}_{-0.32}$	$^{+0.42}_{-0.32}$	$^{+0.14}_{-0.11}$	3.515 ± 0.075	6.5 (5.3)	
WH	1.57	$^{+0.48}_{-0.46}$	$^{+0.34}_{-0.33}$	$^{+0.25}_{-0.24}$	$^{+0.11}_{-0.07}$	±0.20	1.204 ± 0.024	3.5 (2.7)	5.3 (4.7)
ZH	0.84	$^{+0.25}_{-0.23}$	±0.19	±0.09	$^{+0.07}_{-0.04}$	±0.10	$0.797^{+0.033}_{-0.026}$	3.6 (3.6)	
$t\bar{t}H+tH$	0.71	$^{+0.15}_{-0.14}$	±0.10	±0.07	$^{+0.05}_{-0.04}$	$^{+0.08}_{-0.07}$	$0.586^{+0.034}_{-0.049}$	5.8 (5.4)	

Higgs Coupling Measurement

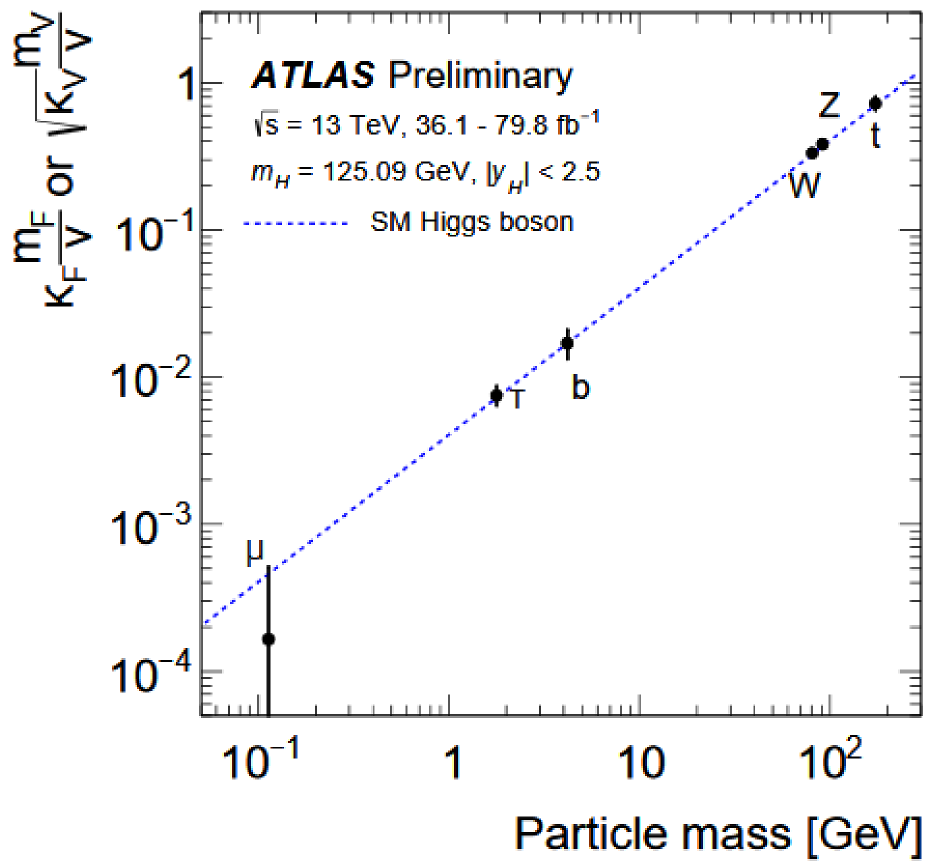
$$L_{\rm h} = \frac{1}{2}(\partial^{\mu}h)(\partial_{\mu}h) + \frac{M_{\rm h}^2}{2}h^2 - \frac{M_{\rm h}^2}{2v}h^3 - \frac{M_{\rm h}^2}{8v^2}h^4 + \left(M_{\rm W}^2 W_{\mu}^{+}W^{-\mu} + \frac{1}{2}M_{\rm Z}^2 Z_{\mu}Z^{\mu}\right)\left(1+\frac{h}{v}\right)^2 - \sum_f m_f \bar{f} f\left(1+\frac{h}{v}\right). \quad (19)$$



Run 1 full data (CMS)



2019年春、Run 2 data半分くらい

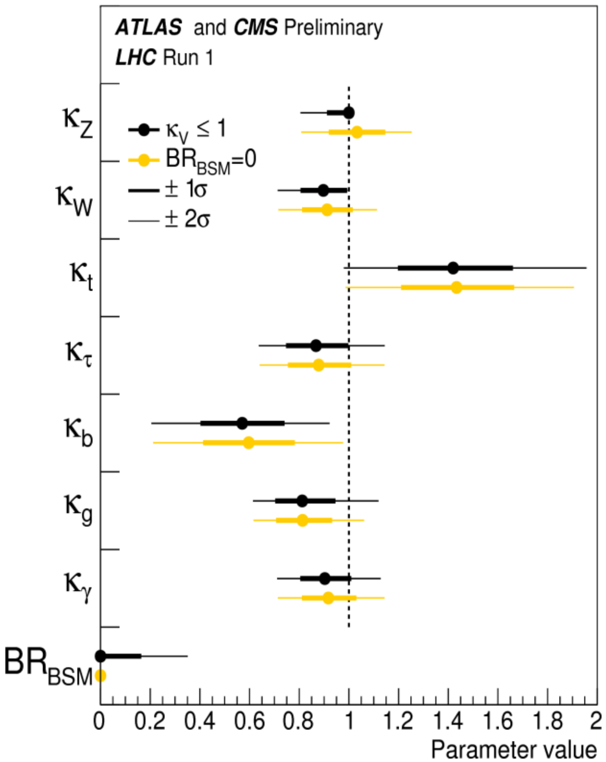


ATLAS-CONF-2019-005

ヒッグス結合、Run 1結果との比較

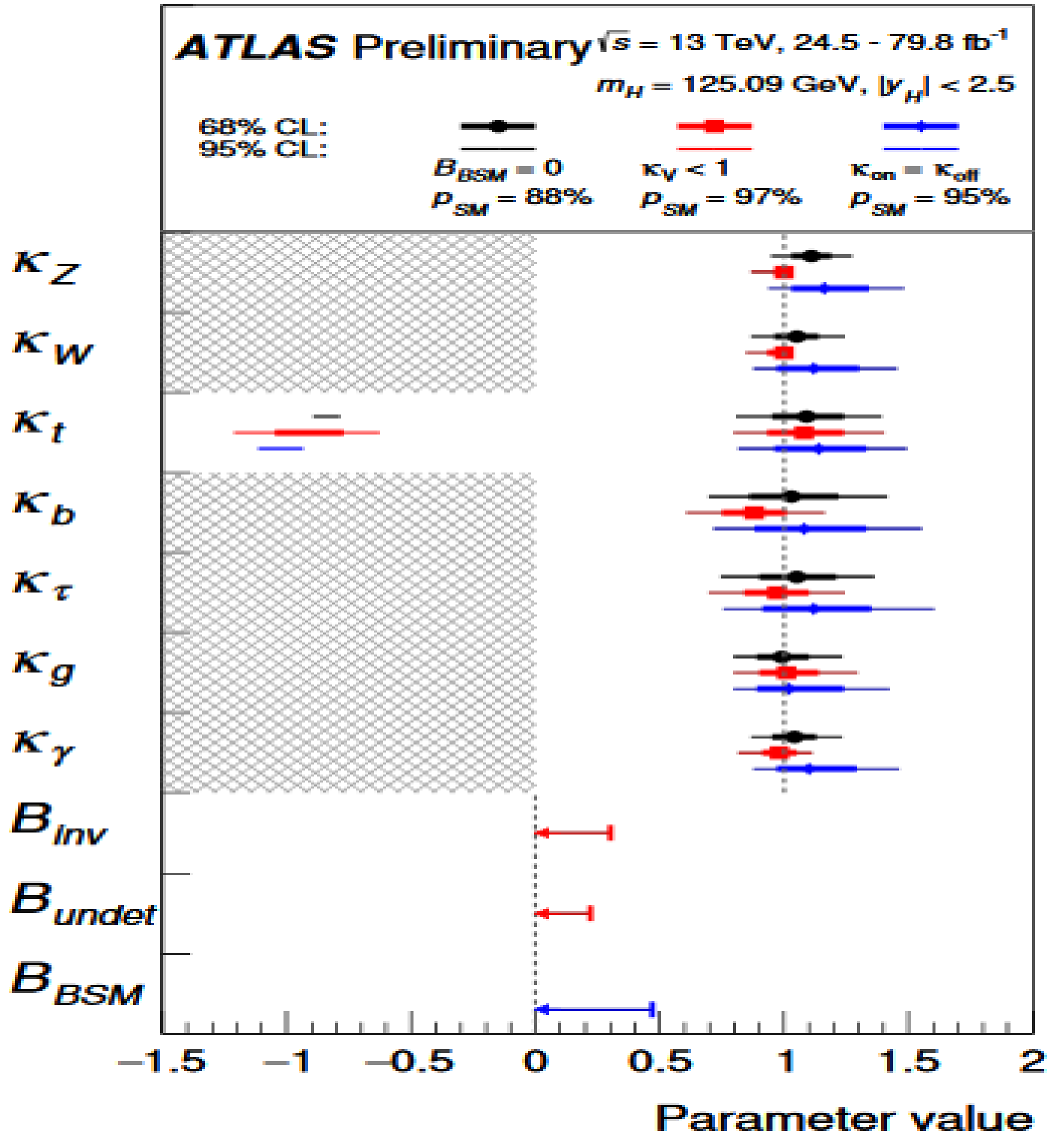
ヒッグス結合の測定も、
$\kappa = g/g_{SM}$
で表す場合が多い。

Run 1フル・データ



ATLAS-CONF-2015-044

2019年春

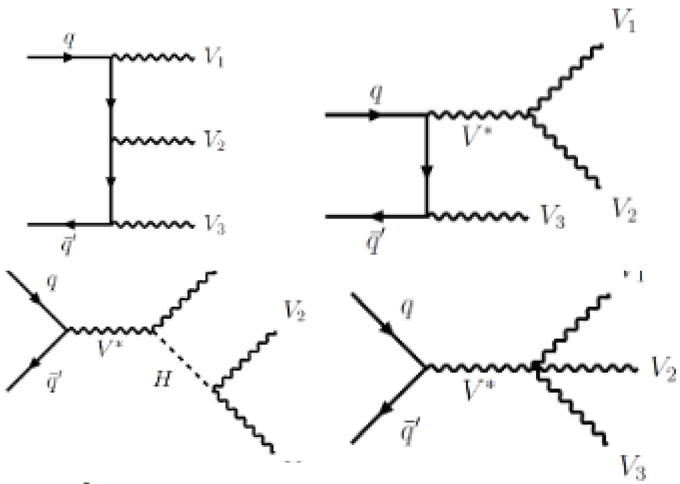


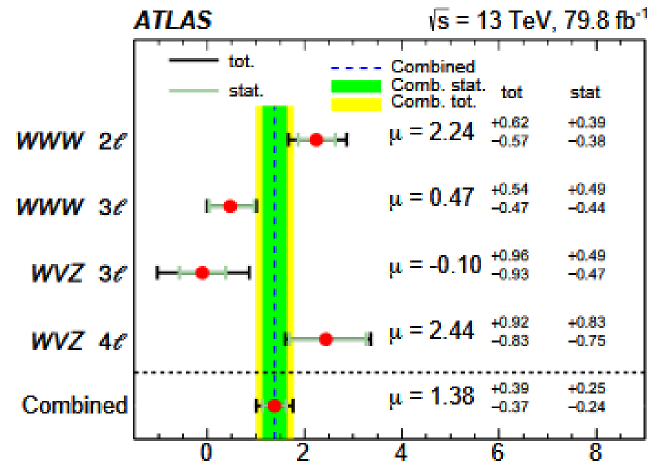
arXiv:1903.10415

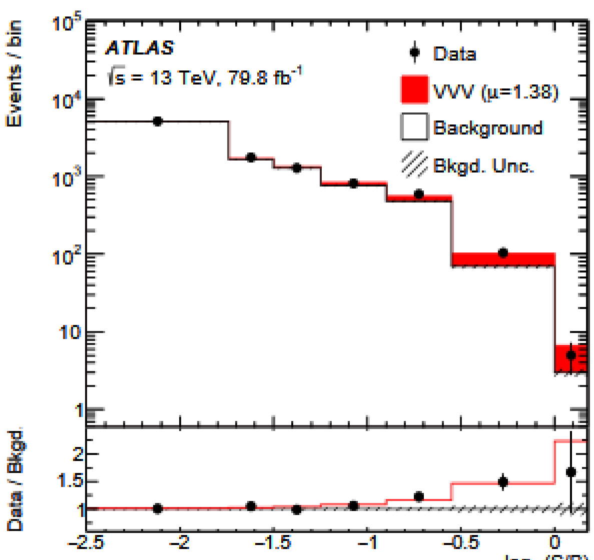
Heavy Triple Gauge Boson Production

- Test of non-Aberian gauge structure.
- SM predicts small cross sections:

$$\sigma_{WWW} = 0.50 \text{ pb}, \sigma_{WWZ} = 0.29 \text{ pb}.$$



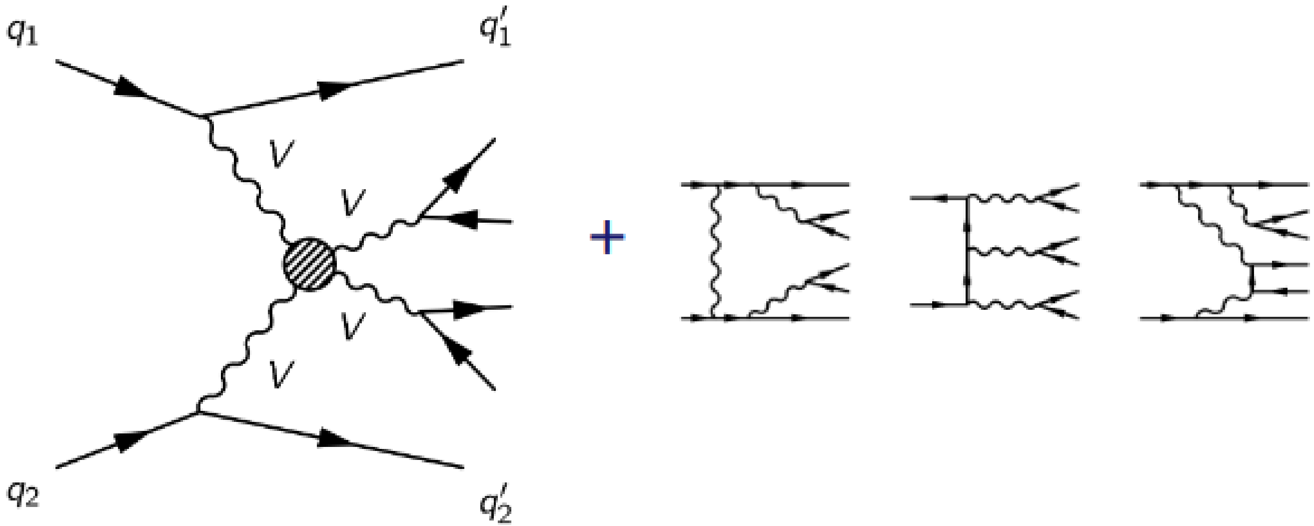


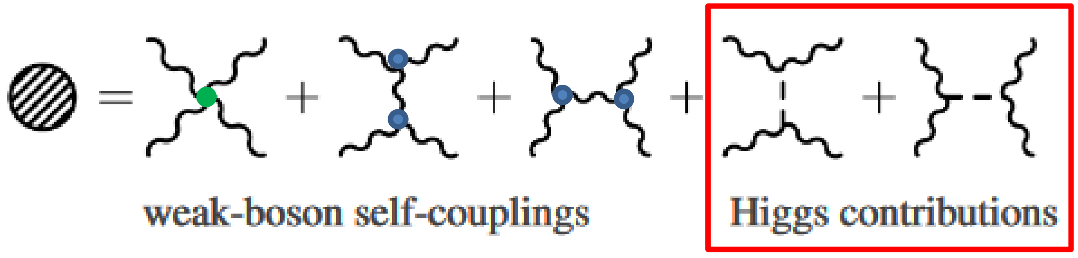


Decay channel	Significance	
	Observed	Expected
WWW combined	3.3σ	2.4σ
$WWW \to \ell\nu\ell\nu qq$	4.3σ	1.7σ
$WWW \to \ell\nu\ell\nu\ell\nu$	1.0σ	2.0σ
WVZ combined	2.9σ	2.0σ
$WVZ \to \ell\nu qq\ell\ell$	–	1.0σ
$WVZ \to \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$	3.5σ	1.8σ
VVV combined	4.0σ	3.1σ

Vector Boson Scattering Processes

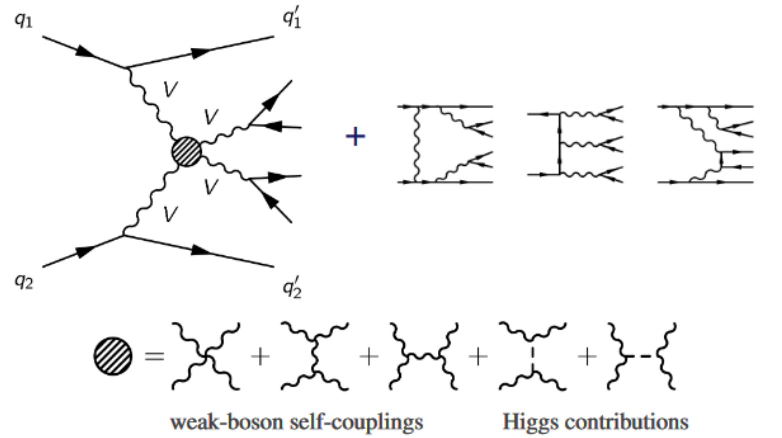
- Vector boson scattering involves
  - Triple and Quadratic Gauge Couplings
  - Higgs restores unitarity at high energies

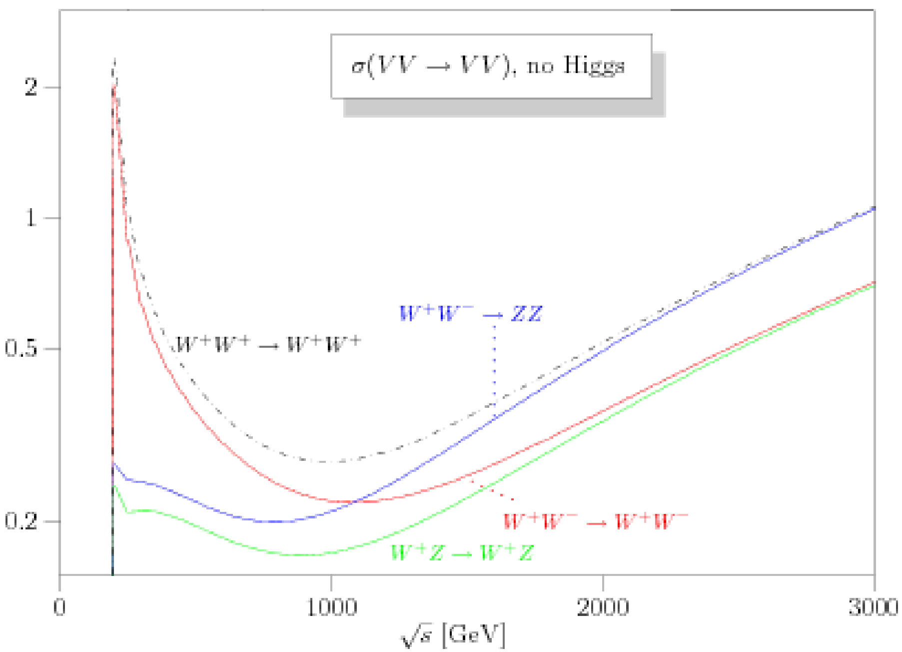


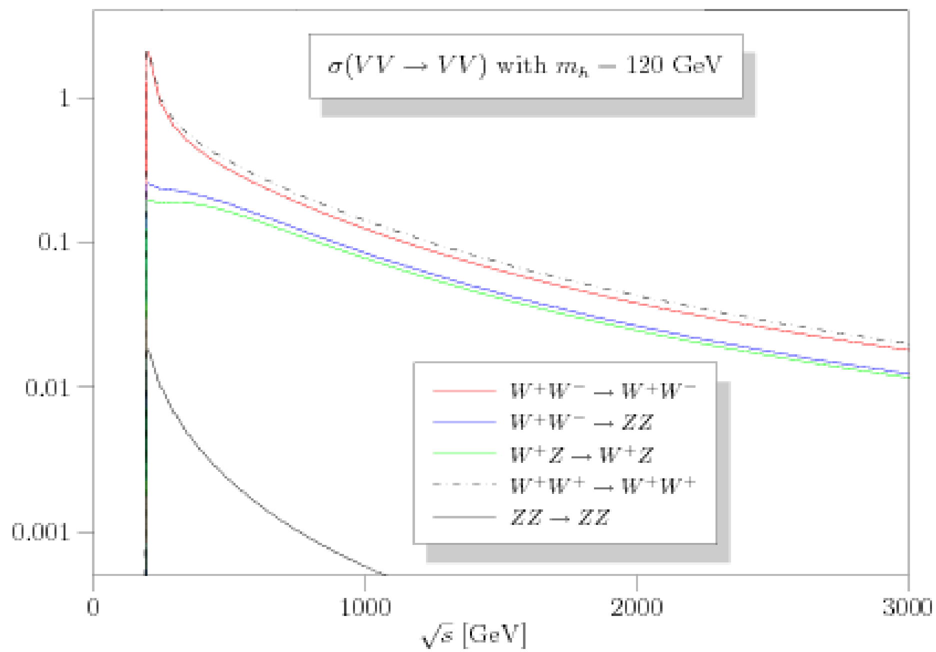


JHEP 0811 (2008)

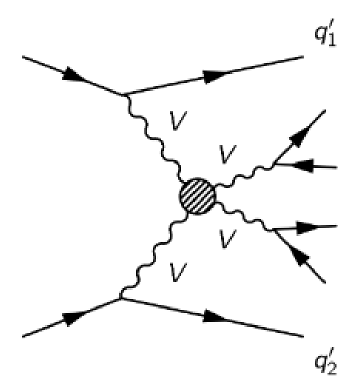
Vector Boson Scattering Processes





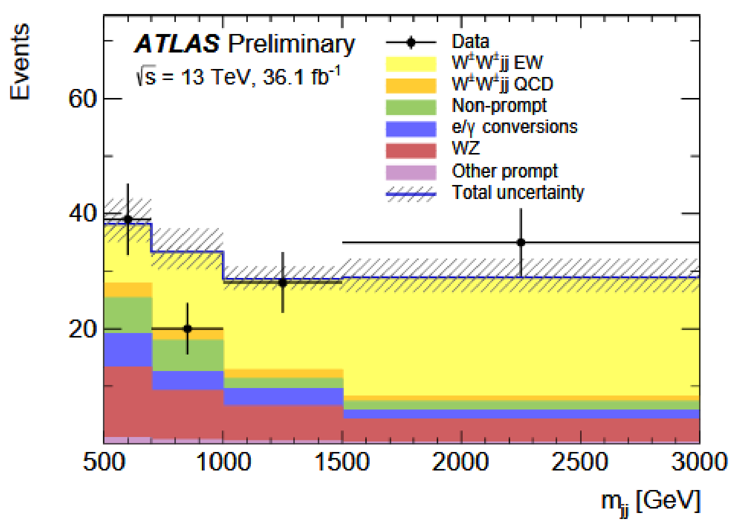


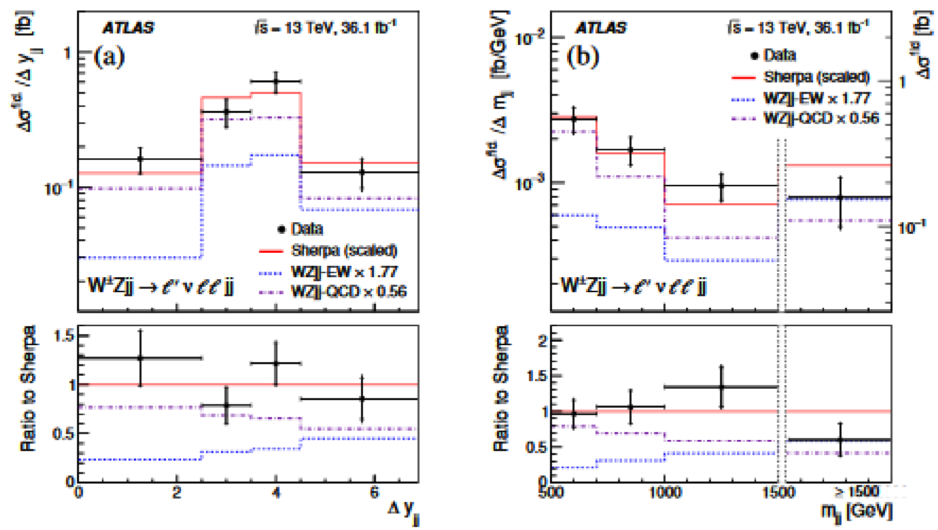
Vector Boson Scattering



- 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)

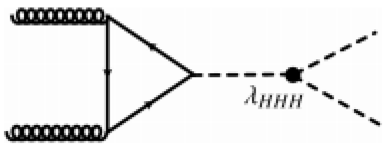
ATLAS-CONF-2018-030

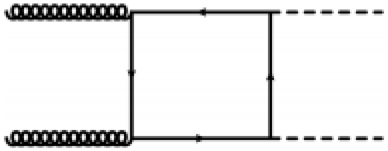
arXiv:1812.09740

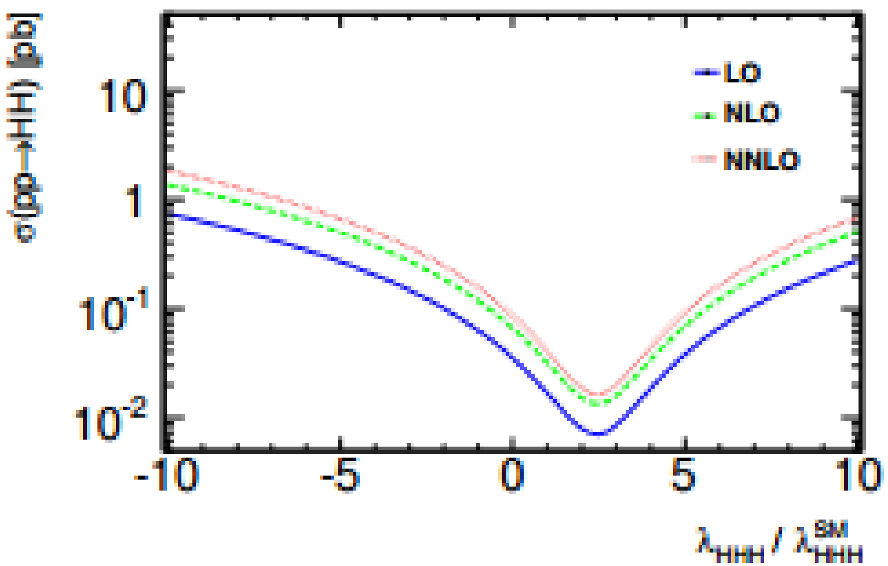
VBSは、ちょうどプロセスが発見に達したところ。
これから、ヒッグスとの干渉について、精密検証を行う。

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 $\frac{\lambda_{HHH}}{\lambda^{SM}} = 1$

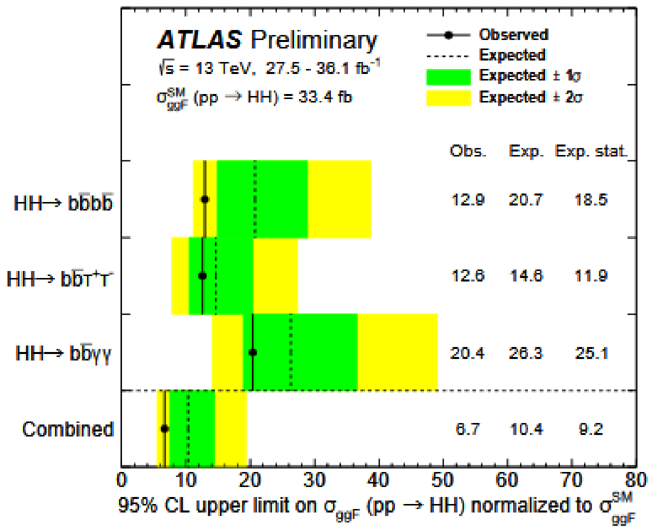
Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	40,000
$b\bar{b} + W^+W^-$	25%	31,000
$b\bar{b} + \tau^+\tau^-$	7.3%	8,900
$ZZ + b\bar{b}$	3.1%	3,800
$W^+W^- + \tau^+\tau^-$	2.7%	3,300
$ZZ + W^+W^-$	1.1%	1,300
$\gamma\gamma + b\bar{b}$	0.26%	320
$\gamma\gamma + \gamma\gamma$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

ATL-PHYS-PUB-2014-019

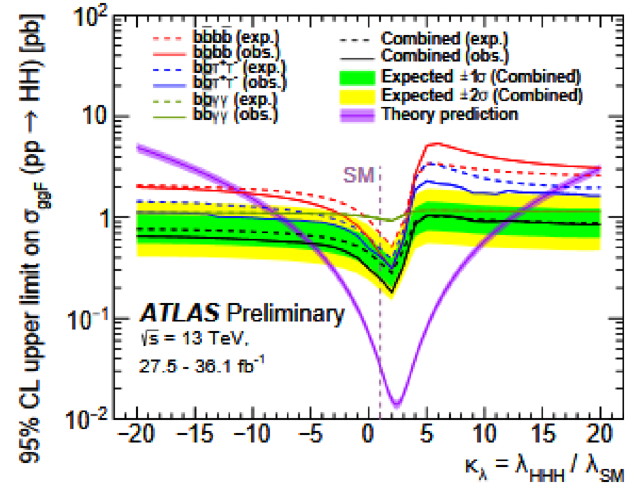
Run 2でのDihiggs探索結果

- 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



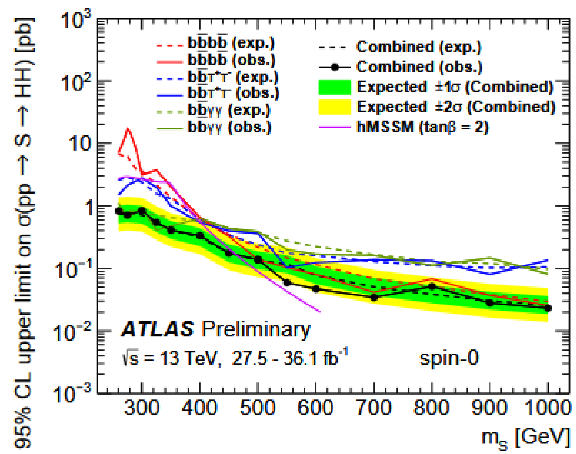
自己相互結合に対する制限



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

***$S \to hh$*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)

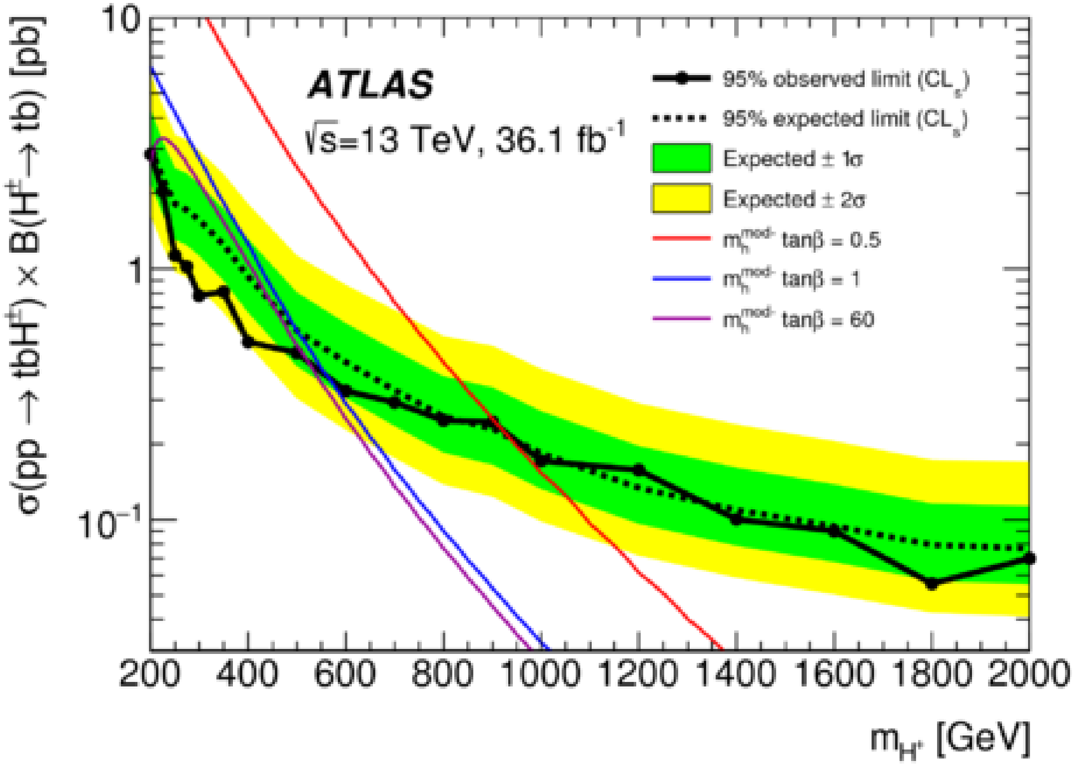


JHEP 11 (2018) 085

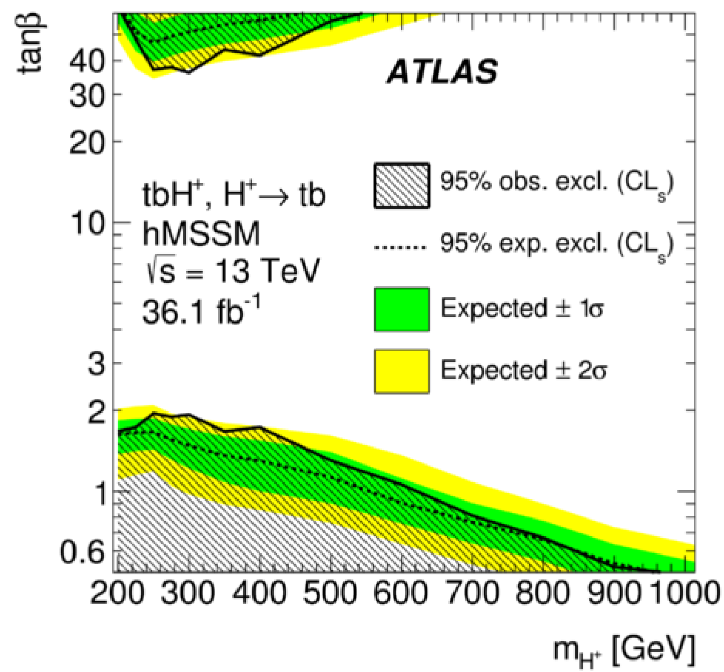
荷電ヒッグス粒子に対する制約

- 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



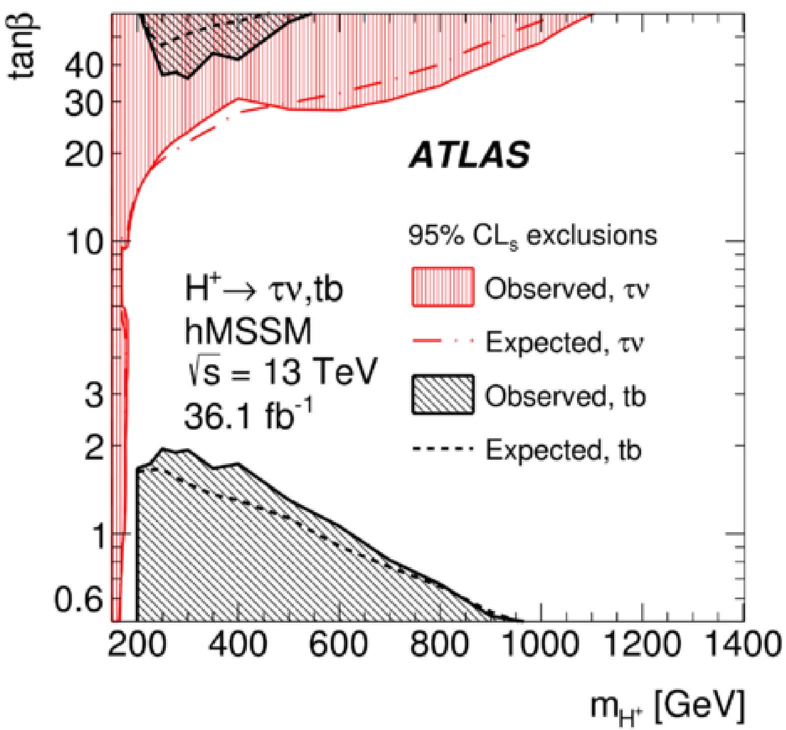
MSSM（hMSSMシナリオ）に対する制約

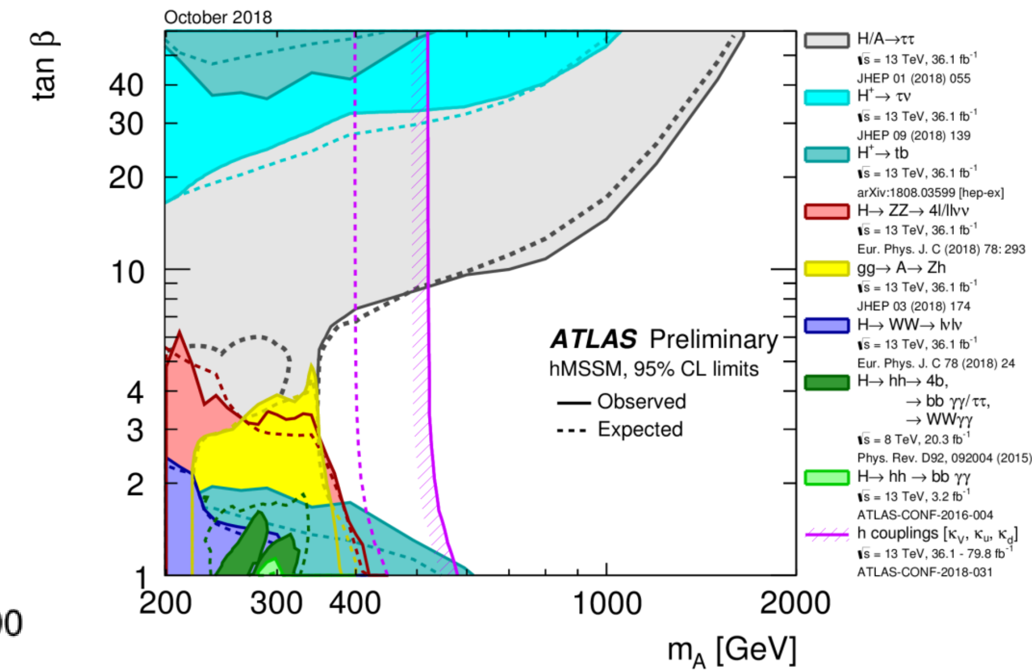


$H^+ \to \tau\nu$チャンネルとの比較

- $H^+ \to \tau\nu$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]

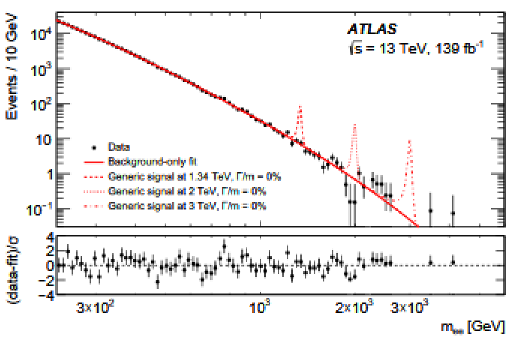




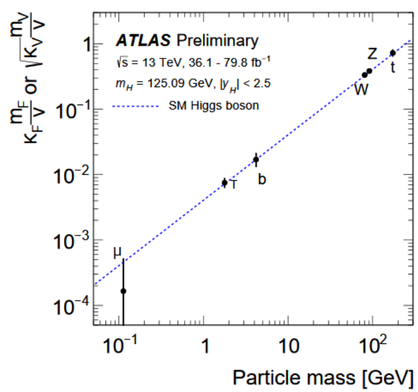
結論

- LHCは2015～2018年のRun 2を終えた。
  - 2019－2020はアップグレードのシャットダウン。
- シャットダウン中はフルRun 2の139 fb^{-1}データセットを解析する。(すでにいくつかの解析が出ている)
  - これまで公表されてきた物理結果は、36 fb^{-1}(2015+2016)、80 fb^{-1}(2015-2017)を使ってきた。
- Run 2のデータで、標準理論を厳しく検証、新物理を探索し続ける。

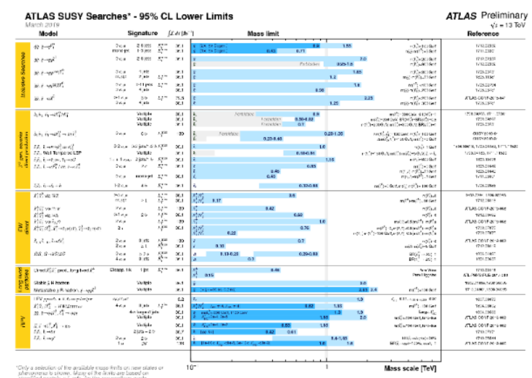
Dielectron mass spectrum (139 fb^{-1})



Updated Higgs coupling measurements

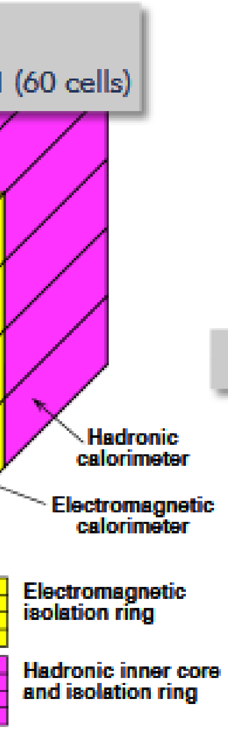


SUSY Searches in many different event topologies

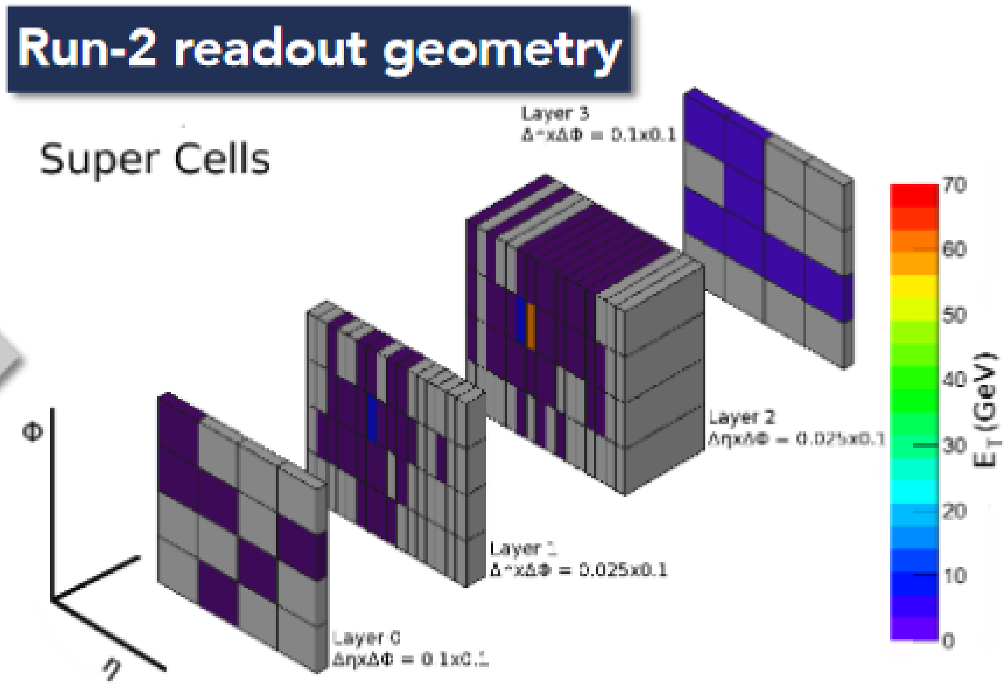


バックアップ

LAr trigger readout: Super Cells



(box: minimal readout element)



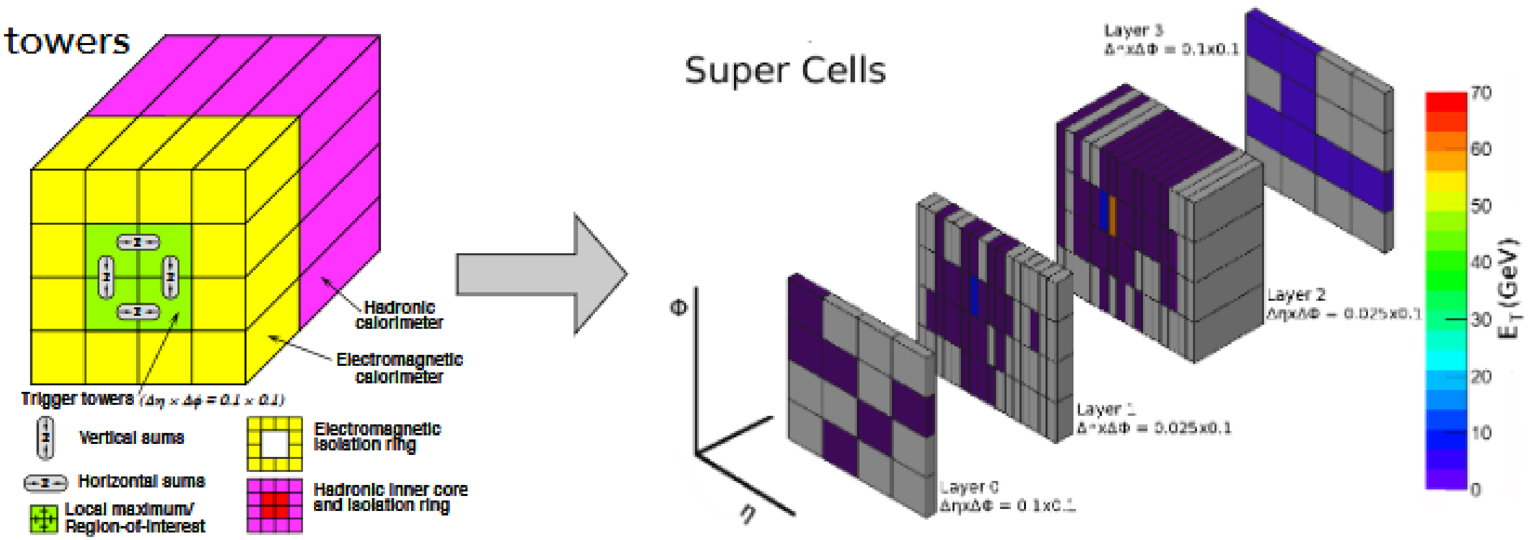
ity: trigger tower ⟹ 10 Super Cells (SCs)

cells in each layer

Super Cells

- Trigger tower $\Longrightarrow$ <u>10 Super Cells (SCs)</u>

Trigger towers



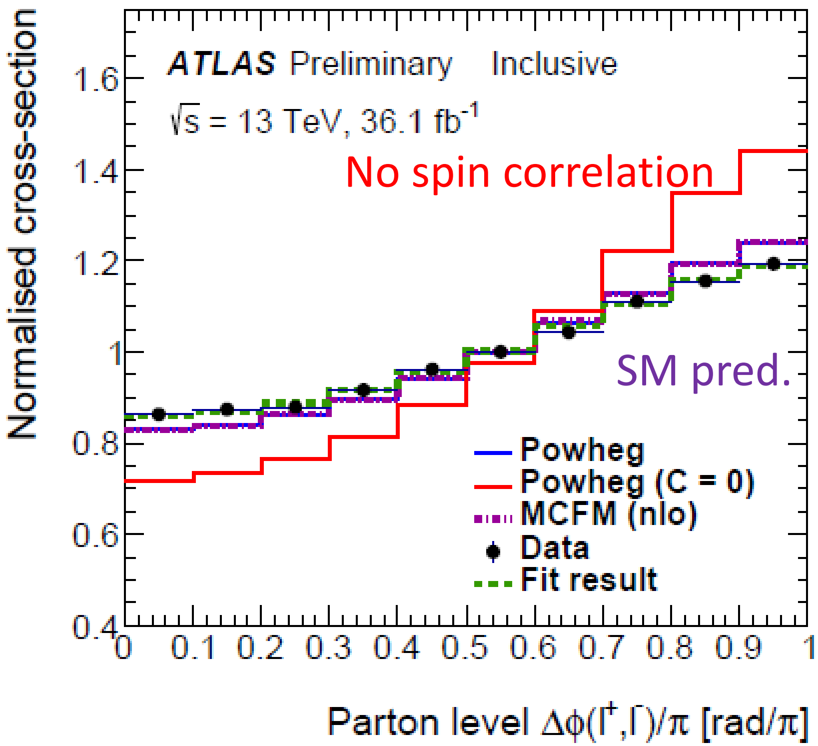
	Elementary Cell	Trigger Tower		Super Cell	
Layer (barrel)	[Δη × Δφ]	[$n_\eta \times n_\varphi$]	[Δη × Δφ]	[$n_\eta \times n_\varphi$]	[Δη × Δφ]
Presampler (layer 0)	0.025 × 0.1	4 × 1	0.1 × 0.1	4 × 1	**0.1 × 0.1**
Front (layer 1)	0.003125 × 0.1	32 × 1		8 × 1	**0.025 × 0.1**
Middle (layer 2)	0.025 × 0.025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

$H \rightarrow \gamma\gamma$ Event Categories

ATLAS-CONF-2018-028

Category label	Selection
ttH lep BDT1	$N_{\text{lep}} \geq 1,\ N_{b-\text{jet}} \geq 1,\ \text{BDT}_{\text{ttHlep}} > 0.987$
ttH lep BDT2	$N_{\text{lep}} \geq 1,\ N_{b-\text{jet}} \geq 1,\ 0.942 < \text{BDT}_{\text{ttHlep}} < 0.987$
ttH lep BDT3	$N_{\text{lep}} \geq 1,\ N_{b-\text{jet}} \geq 1,\ 0.705 < \text{BDT}_{\text{ttHlep}} < 0.942$
ttH had BDT1	$N_{\text{lep}} = 0,\ N_{\text{jets}} \geq 3,\ N_{b-\text{jet}} \geq 1,\ \text{BDT}_{\text{ttHhad}} > 0.996$
ttH had BDT2	$N_{\text{lep}} = 0,\ N_{\text{jets}} \geq 3,\ N_{b-\text{jet}} \geq 1,\ 0.991 < \text{BDT}_{\text{ttHhad}} < 0.996$
ttH had BDT3	$N_{\text{lep}} = 0,\ N_{\text{jets}} \geq 3,\ N_{b-\text{jet}} \geq 1,\ 0.971 < \text{BDT}_{\text{ttHhad}} < 0.991$
ttH had BDT4	$N_{\text{lep}} = 0,\ N_{\text{jets}} \geq 3,\ N_{b-\text{jet}} \geq 1,\ 0.911 < \text{BDT}_{\text{ttHhad}} < 0.971$
VH dilep	$N_{\text{lep}} \geq 2,\ 70\,\text{GeV} \leq m_{\ell\ell} \leq 110\,\text{GeV}$
VH lep High	$N_{\text{lep}} = 1,\ \lvert m_{e\gamma} - 89\,\text{GeV}\rvert > 5\,\text{GeV},\ p_{\text{T}}^{\ell+E_{\text{T}}^{\text{miss}}} > 150\,\text{GeV}$
VH lep Low	$N_{\text{lep}} = 1,\ \lvert m_{e\gamma} - 89\,\text{GeV}\rvert > 5\,\text{GeV},\ p_{\text{T}}^{\ell+E_{\text{T}}^{\text{miss}}} < 150\,\text{GeV},\ E_{\text{T}}^{\text{miss}}$ significance > 1
VH MET High	$150\,\text{GeV} < E_{\text{T}}^{\text{miss}} < 250\,\text{GeV},\ E_{\text{T}}^{\text{miss}}$ significance > 9 or $E_{\text{T}}^{\text{miss}} > 250\,\text{GeV}$
VH MET Low	$80\,\text{GeV} < E_{\text{T}}^{\text{miss}} < 150\,\text{GeV},\ E_{\text{T}}^{\text{miss}}$ significance > 8
qqH BSM	$N_{\text{jets}} \geq 2,\ p_{\text{T,j1}} > 200\,\text{GeV}$
VH had BDT tight	$60\,\text{GeV} < m_{\text{jj}} < 120\,\text{GeV},\ \text{BDT}_{\text{VH}} > 0.78$
VH had BDT loose	$60\,\text{GeV} < m_{\text{jj}} < 120\,\text{GeV},\ 0.35 < \text{BDT}_{\text{VH}} < 0.78$
VBF high-p_{T}^{Hjj} BDT tight	$\lvert\Delta\eta_{jj}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\text{j1}} + \eta_{\text{j2}})\rvert < 5,\ p_{\text{T}}^{Hjj} > 25\,\text{GeV},\ \text{BDT}_{\text{VBF}}^{\text{high}} > 0.47$
VBF high-p_{T}^{Hjj} BDT loose	$\lvert\Delta\eta_{jj}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\text{j1}} + \eta_{\text{j2}})\rvert < 5,\ p_{\text{T}}^{Hjj} > 25\,\text{GeV},\ -0.32 < \text{BDT}_{\text{VBF}}^{\text{high}} < 0.47$
VBF low-p_{T}^{Hjj} BDT tight	$\lvert\Delta\eta_{jj}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\text{j1}} + \eta_{\text{j2}})\rvert < 5,\ p_{\text{T}}^{Hjj} < 25\,\text{GeV},\ \text{BDT}_{\text{VBF}}^{\text{low}} > 0.87$
VBF low-p_{T}^{Hjj} BDT loose	$\lvert\Delta\eta_{jj}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\text{j1}} + \eta_{\text{j2}})\rvert < 5,\ p_{\text{T}}^{Hjj} < 25\,\text{GeV},\ 0.26 < \text{BDT}_{\text{VBF}}^{\text{low}} < 0.87$
ggF 2J BSM	$N_{\text{jets}} \geq 2,\ p_{\text{T}}^{\gamma\gamma} \geq 200\,\text{GeV}$
ggF 2J High	$N_{\text{jets}} \geq 2,\ p_{\text{T}}^{\gamma\gamma} \in [120, 200]\,\text{GeV}$
ggF 2J Med	$N_{\text{jets}} \geq 2,\ p_{\text{T}}^{\gamma\gamma} \in [60, 120]\,\text{GeV}$
ggF 2J Low	$N_{\text{jets}} \geq 2,\ p_{\text{T}}^{\gamma\gamma} \in [0, 60]\,\text{GeV}$
ggF 1J BSM	$N_{\text{jets}} = 1,\ p_{\text{T}}^{\gamma\gamma} \geq 200\,\text{GeV}$
ggF 1J High	$N_{\text{jets}} = 1,\ p_{\text{T}}^{\gamma\gamma} \in [120, 200]\,\text{GeV}$
ggF 1J Med	$N_{\text{jets}} = 1,\ p_{\text{T}}^{\gamma\gamma} \in [60, 120]\,\text{GeV}$
ggF 1J Low	$N_{\text{jets}} = 1,\ p_{\text{T}}^{\gamma\gamma} \in [0, 60]\,\text{GeV}$
ggF 0J Fwd	$N_{\text{jets}} = 0$, one photon with $\lvert\eta\rvert > 0.95$
ggF 0J Cen	$N_{\text{jets}} = 0$, two photons with $\lvert\eta\rvert \leq 0.95$

Top Spin Correlation



- $t\bar{t} \rightarrow (Wb)(Wb) \rightarrow (e\nu b)(\mu\nu b)$
- 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)

Overview of VBS measurements @ the LHC

TECHNISCHE UNIVERSITÄT DRESDEN

Recent update:

Channel	Final state	Observed (expected) significance	Recent measurements	Experimental Challenges
VBS $W^{\pm}W^{\pm}$	$l^{\pm}l^{\pm}\nu\nu$ jj	5.5 (5.7) σ NEW	CMS @13 TeV ATLAS @13 TeV	"golden channel": first observation of VBS in this channel, very good EW/QCD ratio, mostly experimental backgrounds
VBS $W^{\pm}Z$	$lll\nu$ jj	1.9 (1.0) σ NEW	CMS @13 TeV ATLAS @13 TeV	similar cross section as ssWW, but larger QCD backgrounds, reasonable reconstruction of final state (m_T^{WZ})
VBS ZZ	llll jj	2.7 (1.6) σ	CMS @13 TeV	very clean channel, reconstruction of final state, low background but small cross section
VBS $W^{\pm}V$	$l^{\pm}\nu jj$ jj	only BSM interpretation @8 TeV		large backgrounds, but promising when looking for BSM effects in boosted topology
VBS $\gamma\gamma \rightarrow W^+W^-$	$ll\nu\nu$ jj	3.4 (2.8) σ	ATLAS & CMS @8 TeV	huge backgrounds (dileptonic ttbar), no sensitivity to BSM EWSB
VBS Wγ/Zγ	$l\nu\gamma$ jj / $ll\nu\gamma$ jj	2.7 (1.5) σ / 3.0 (2.1) σ	CMS @8 TeV	higher statistics due to photon, but no sensitivity to BSM EWSB

Today's focus:

- Measurement in fully leptonic final states in VBS $W^{\pm}W^{\pm}$jj and $W^{\pm}$Zjj with the ATLAS detector @13 TeV

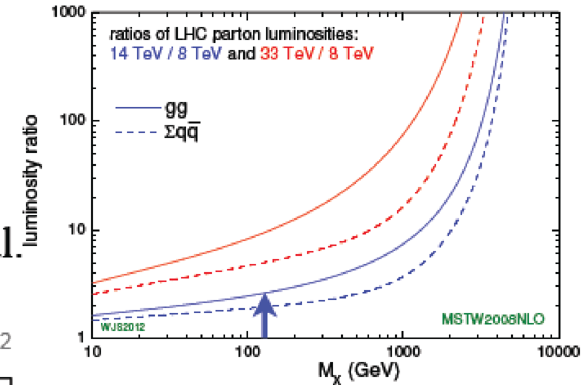
Stefanie Todt at Corfu2018

VBSは、ちょうどプロセスが発見に達したところ。

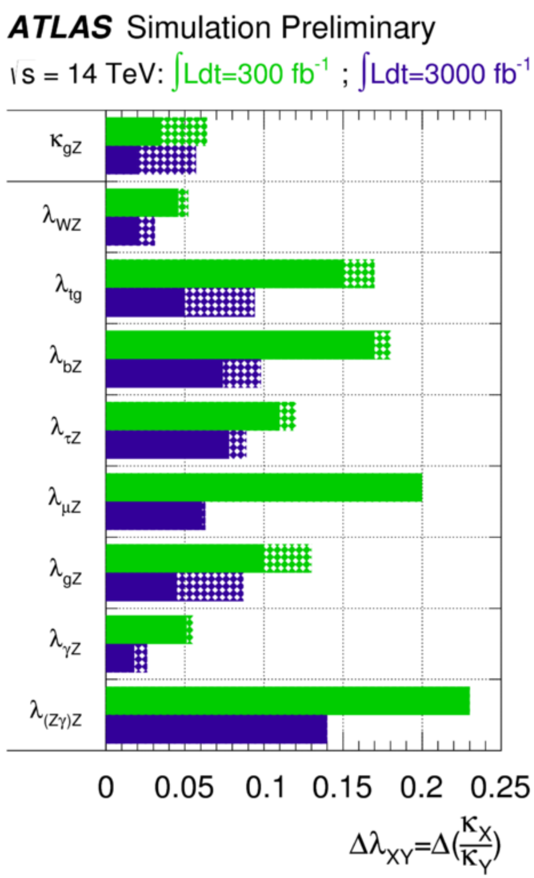
これから、ヒッグスとの干渉について、精密検証を行う。

High Luminosity LHC (HL-LHC)

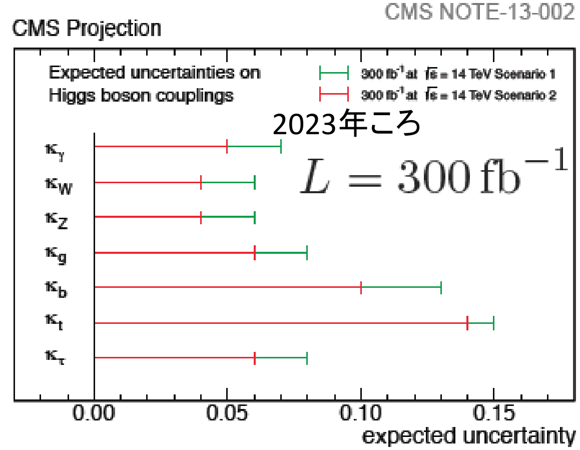
- ECFA HL-LHC with L=300 fb^{-1} (3 ab^{-1}) physics study.
- Higgs mass precision ΔM_H ~100 (50) MeV.
- Access to top-Yukawa coupling via ttH, and rare decay $H \rightarrow \mu\mu$.
- Coupling precision of 10 to 5% reachable (even few% in κ_γ/κ_Z).
- Detector performances (trigger, lepton-id, fake,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

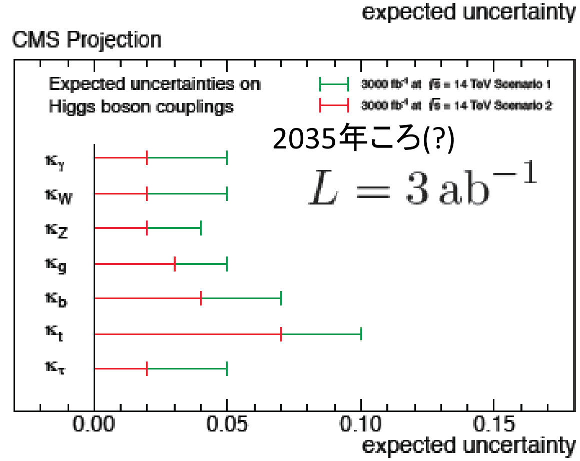


ATL-PHYS-PUB-2014-016



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