

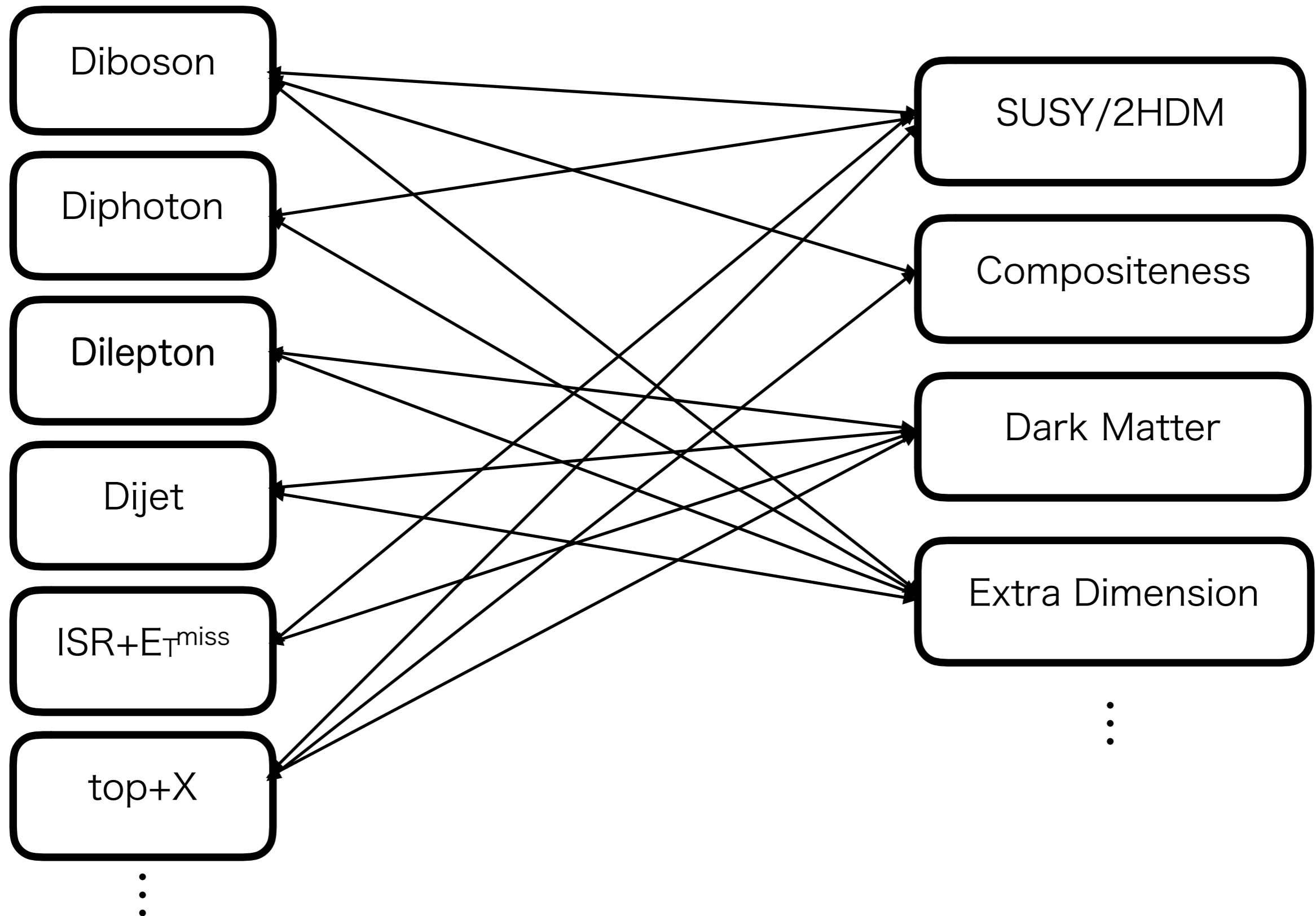
Exoticsまとめ

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東京大学素粒子物理国際研究センター

25/12/2017@新テラスケール研究会

Exotics探索

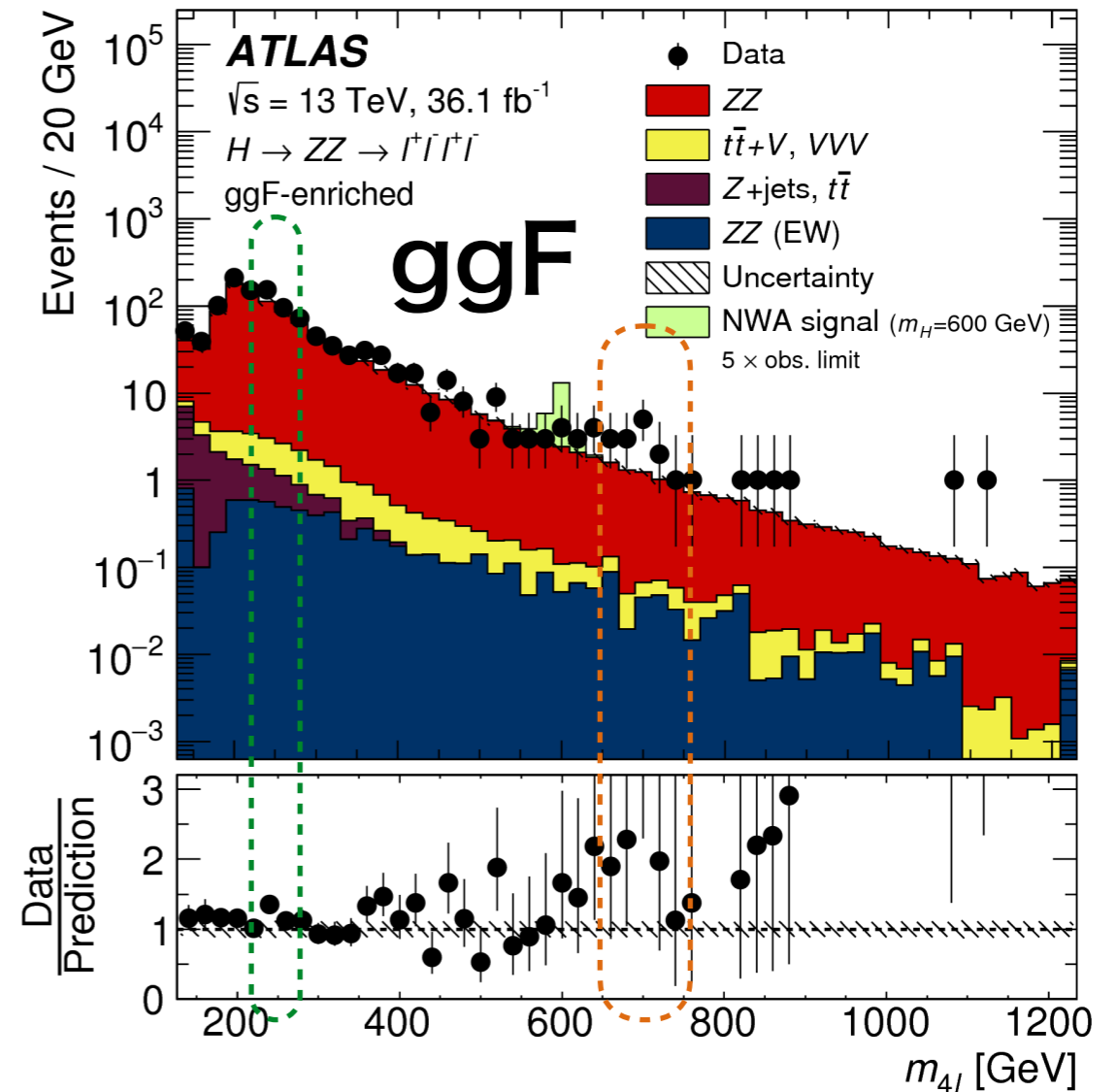
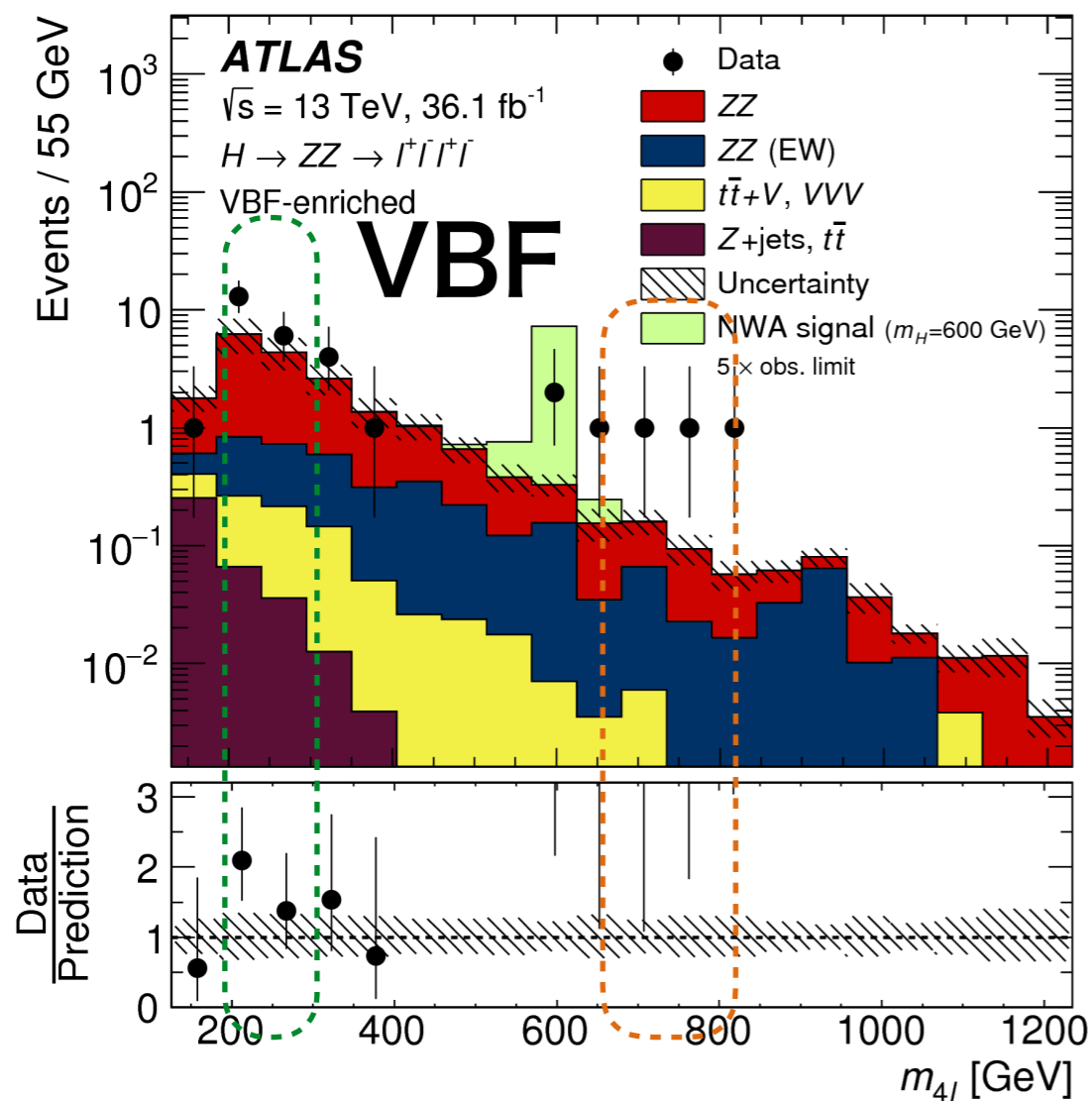


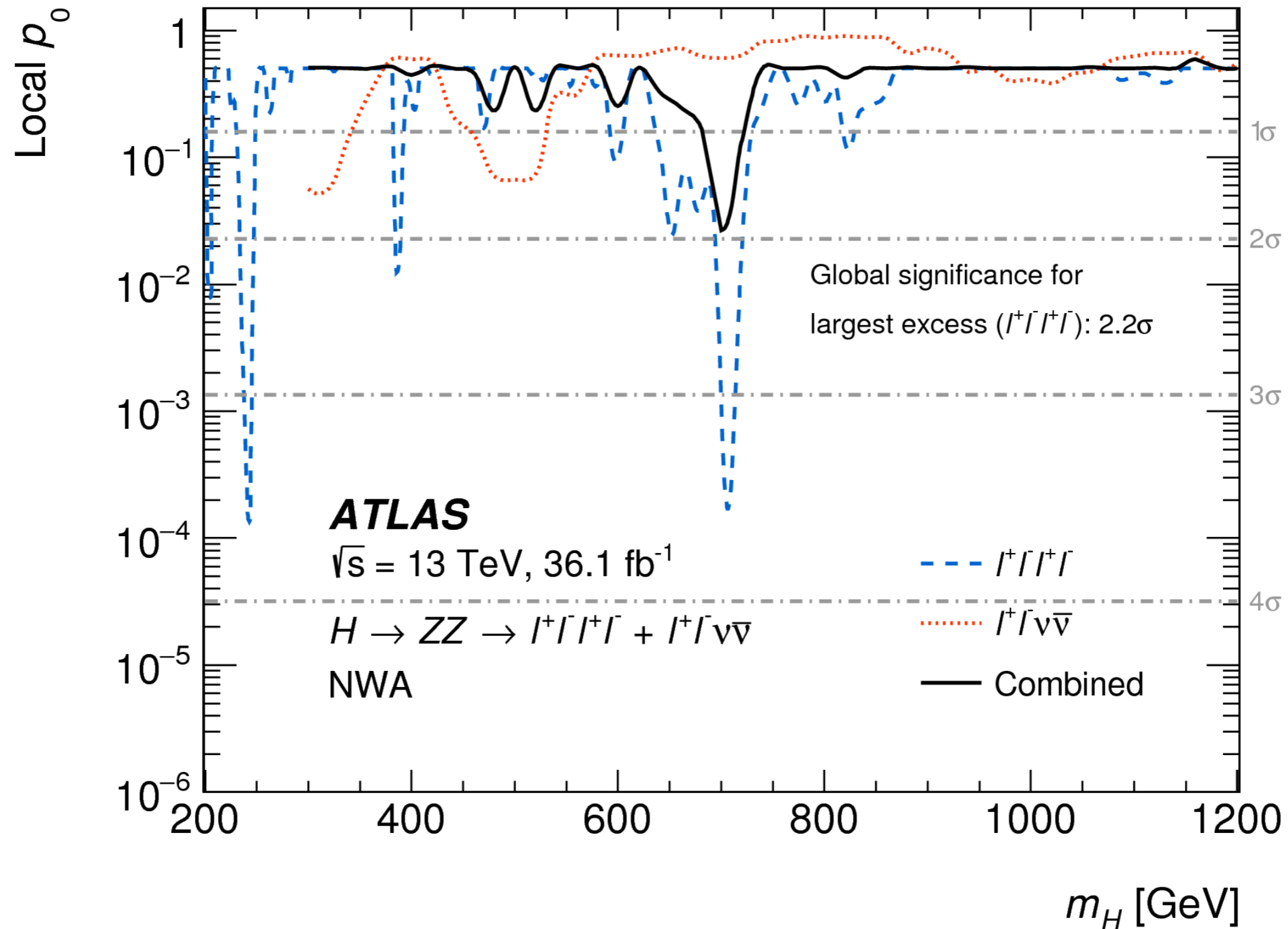
Introduction

- 前回の研究会以降の最新結果 (ATLAS/CMS Run-2 13TeV L=36 fb⁻¹)を報告します
 - VV/Vh/V γ 共鳴探索
 - 関連して、A \rightarrow Zh, H \rightarrow ZZ, A/H \rightarrow $\tau\tau$ 探索の2HDM解釈
 - 関連してbbA/H \rightarrow invisible (+dark matter interpretation)
 - 関連してmono-jet + MET, dijet (dark matter探索)
- LHCb & B-factoryで話題となったlepton flavor universalityの破れに関連し、Z'やleptoquark探索の最新情報については次の高橋さんのトークがカバーします

ZZ → 4-lepton

- 2つの $Z \rightarrow e^+e^-/\mu^+\mu^-$ 候補を探して不変質量を組むシンプルな解析
- 崩壊分岐比は小さいが背景事象が極めて少なく、断面積の大きい低質量領域で感度が高い
- Local 3.6σ excess @ $m \sim 240\text{GeV}$ & $m \sim 700\text{GeV}$

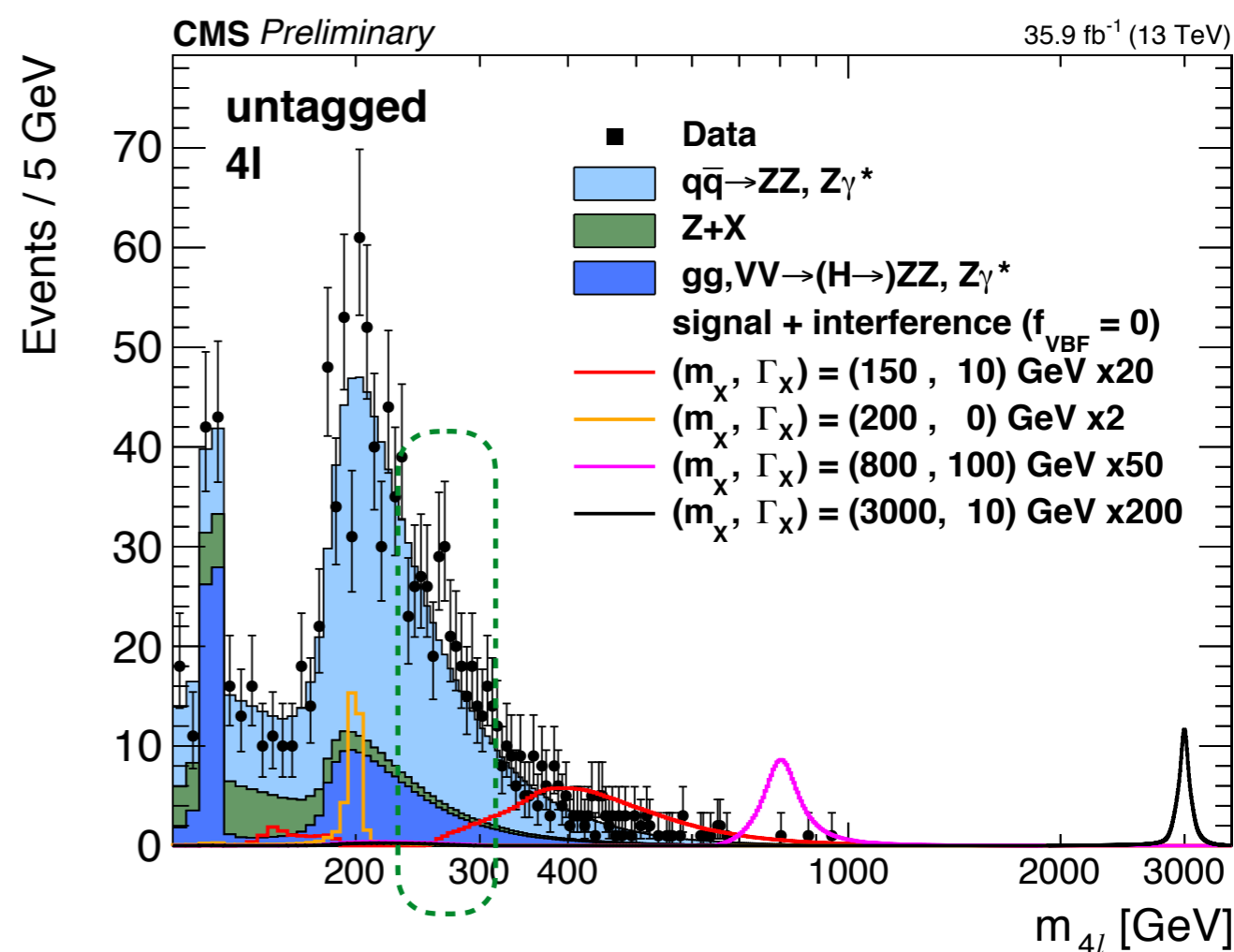
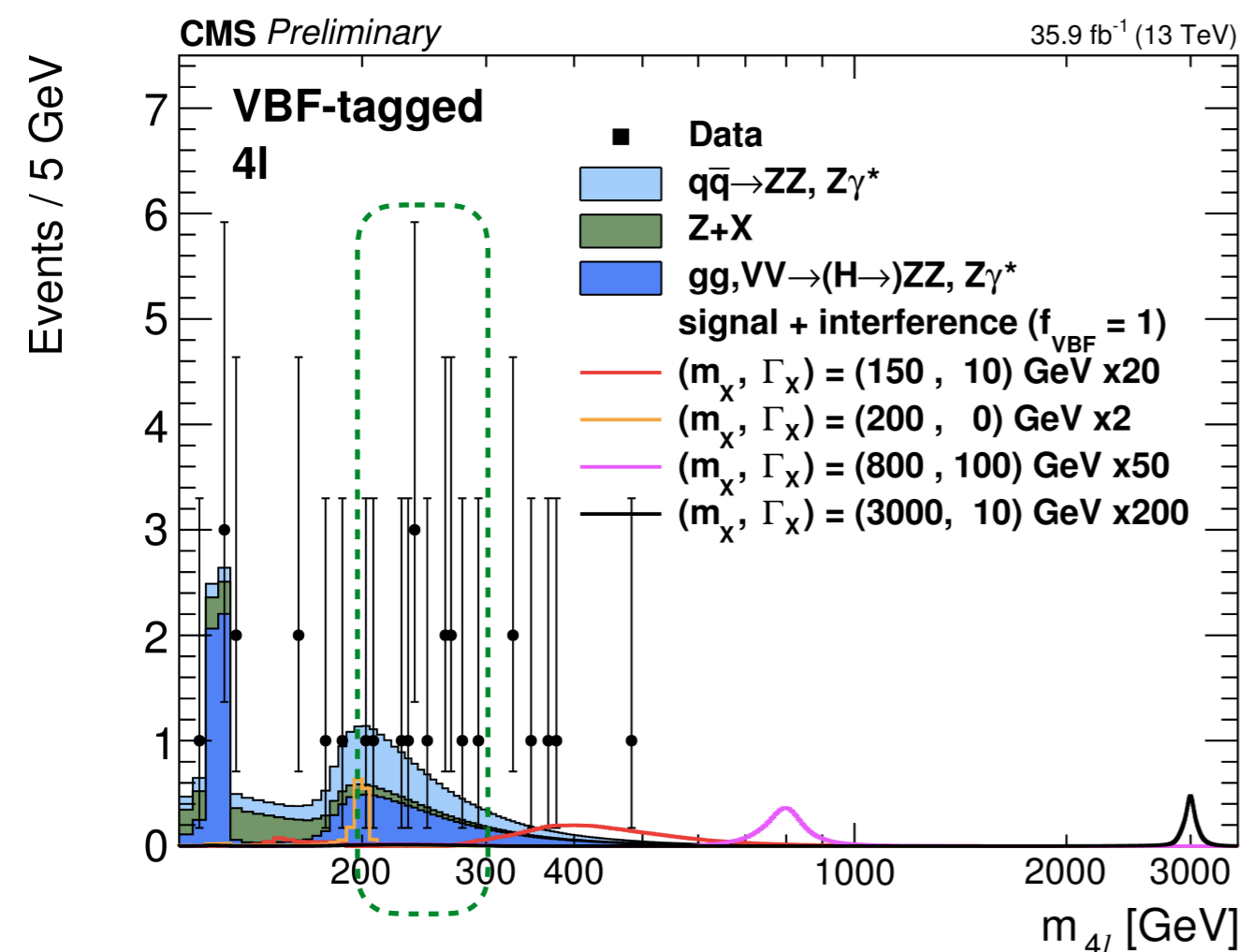




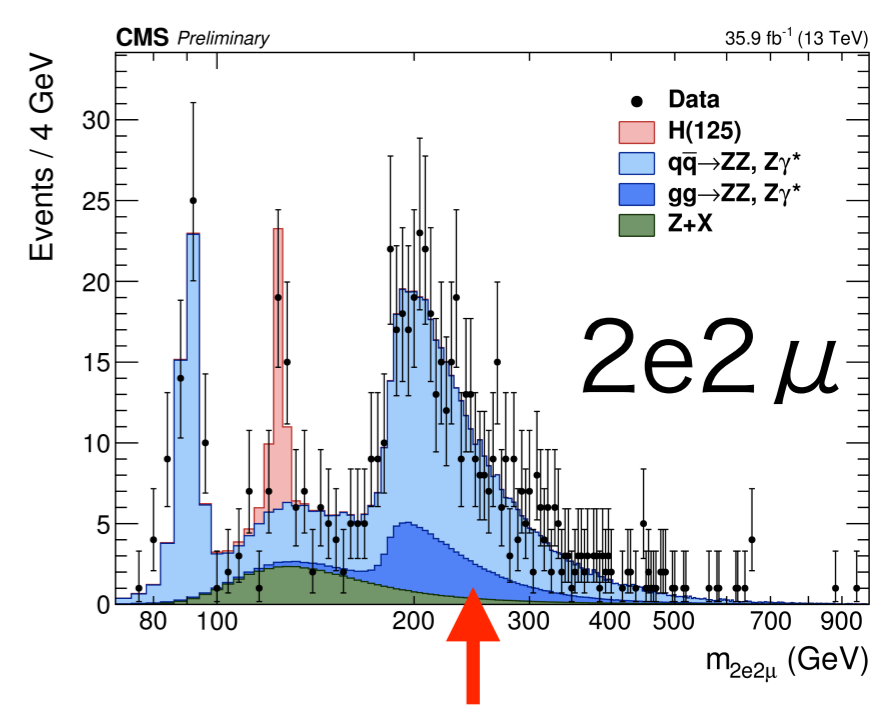
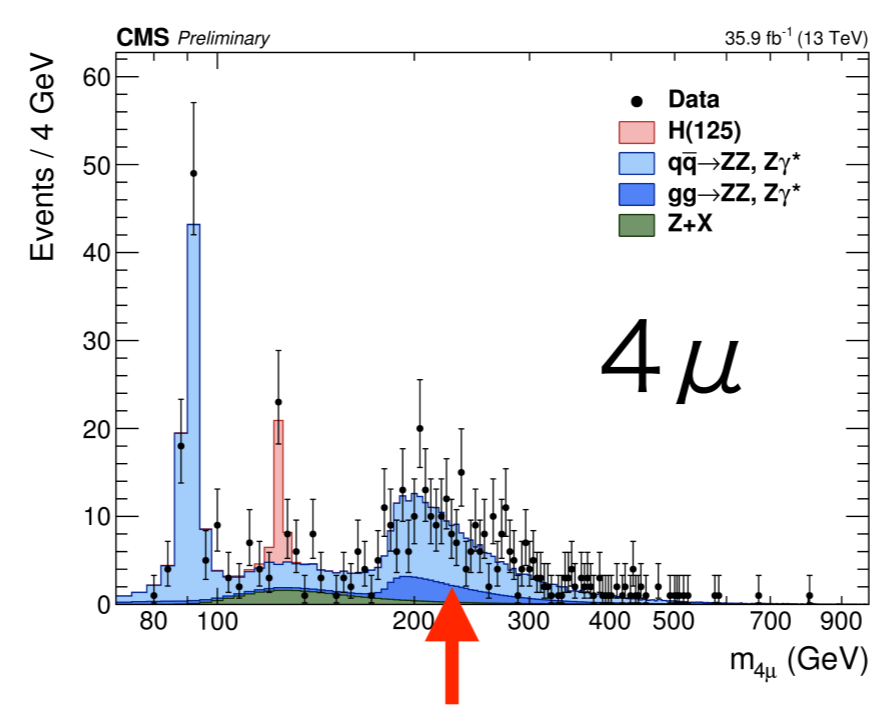
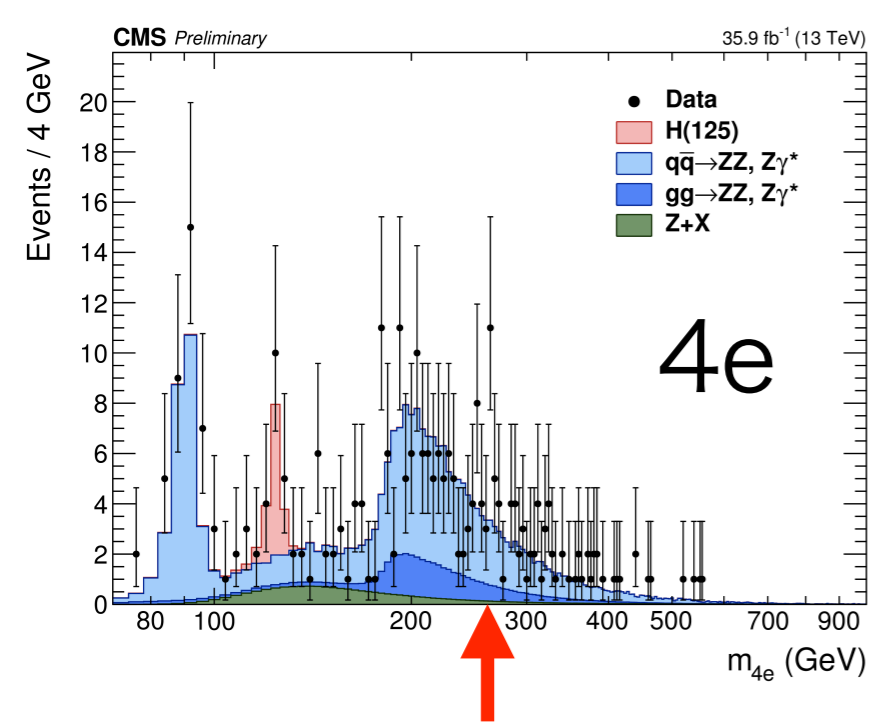
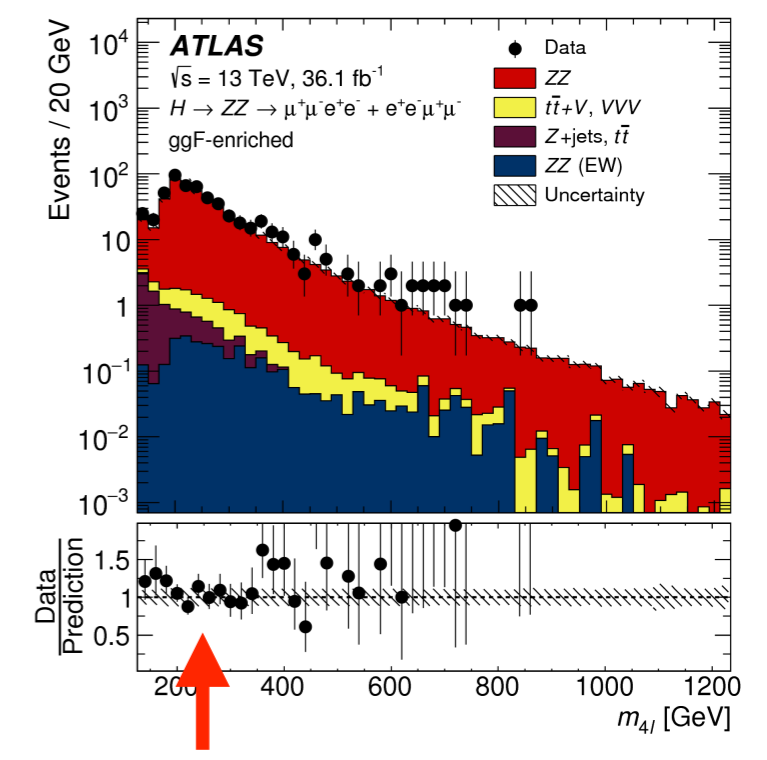
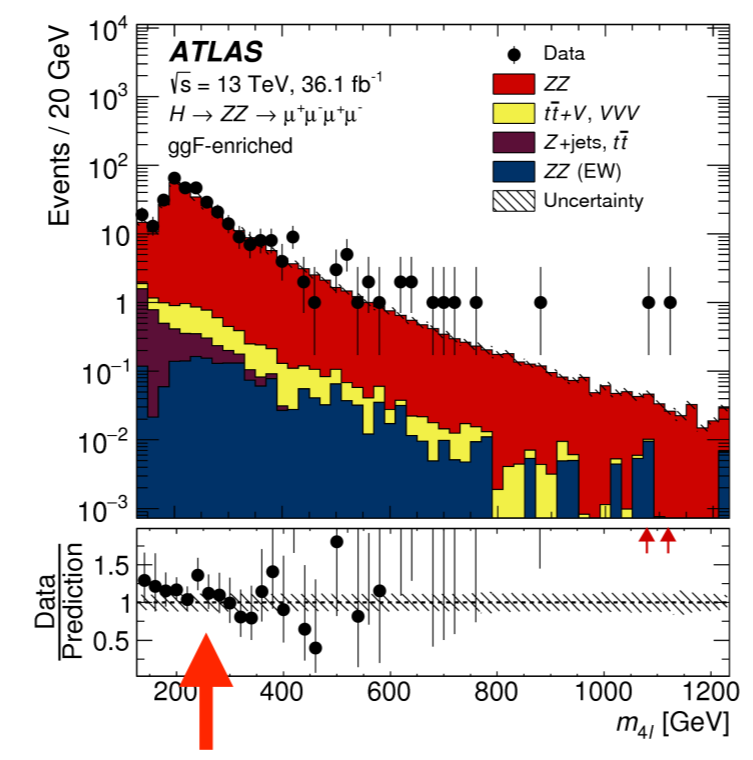
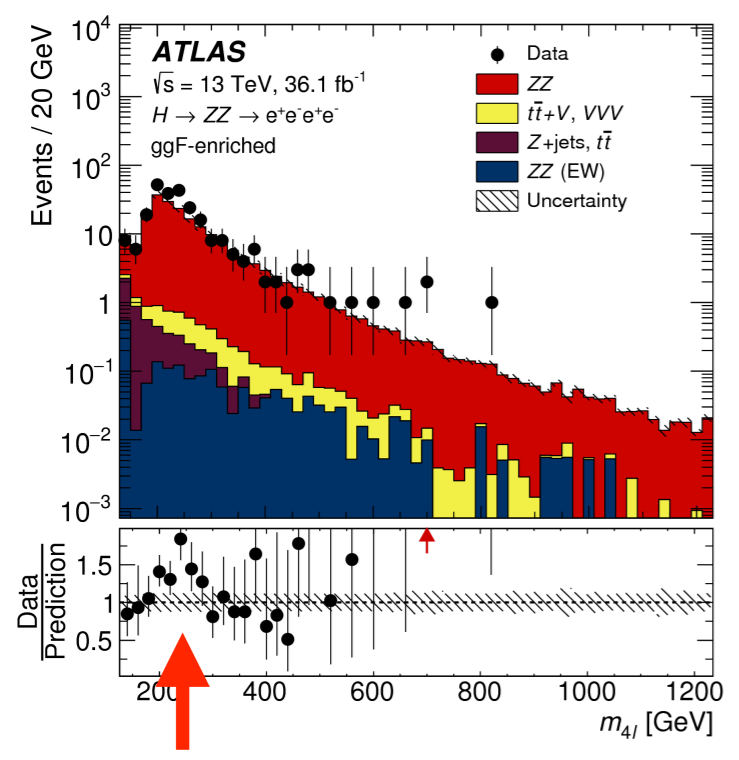
- 700GeVは $ll\nu\nu$ では見えていない。
- 240GeVはMET cut ($>120\text{GeV}$)のせいで $ll\nu\nu$ は感度無し

CMS 4-lepton (+ llvv + llqq)

- 4-leptonとllqqでは角度情報から計算したMatrix Element Likelihoodを用いる
- ~250GeVに~1σ (.....まあ。) のexcess、700GeVは何も無し

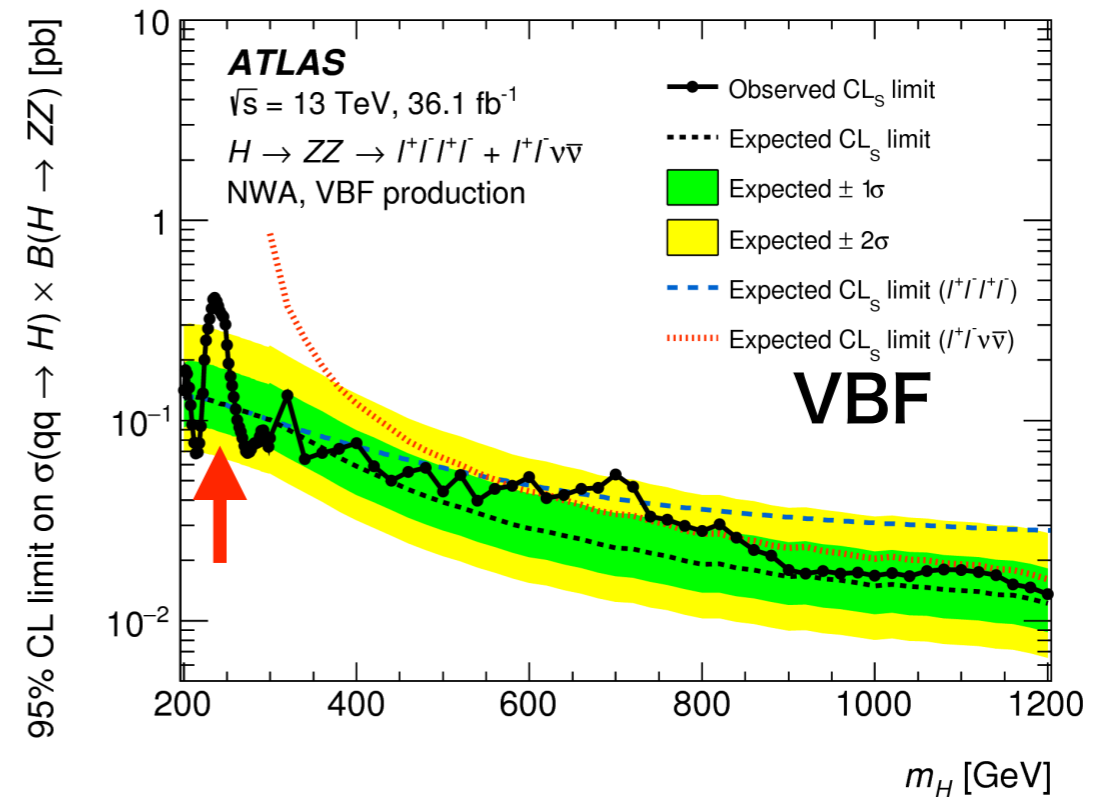
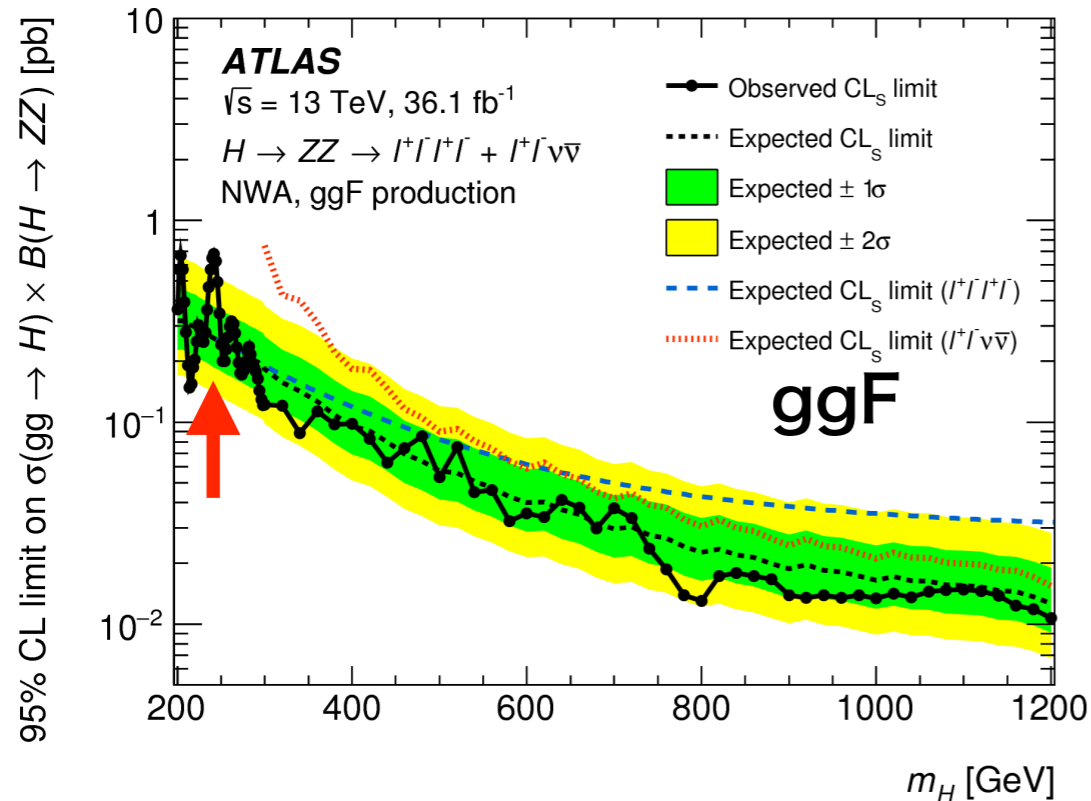
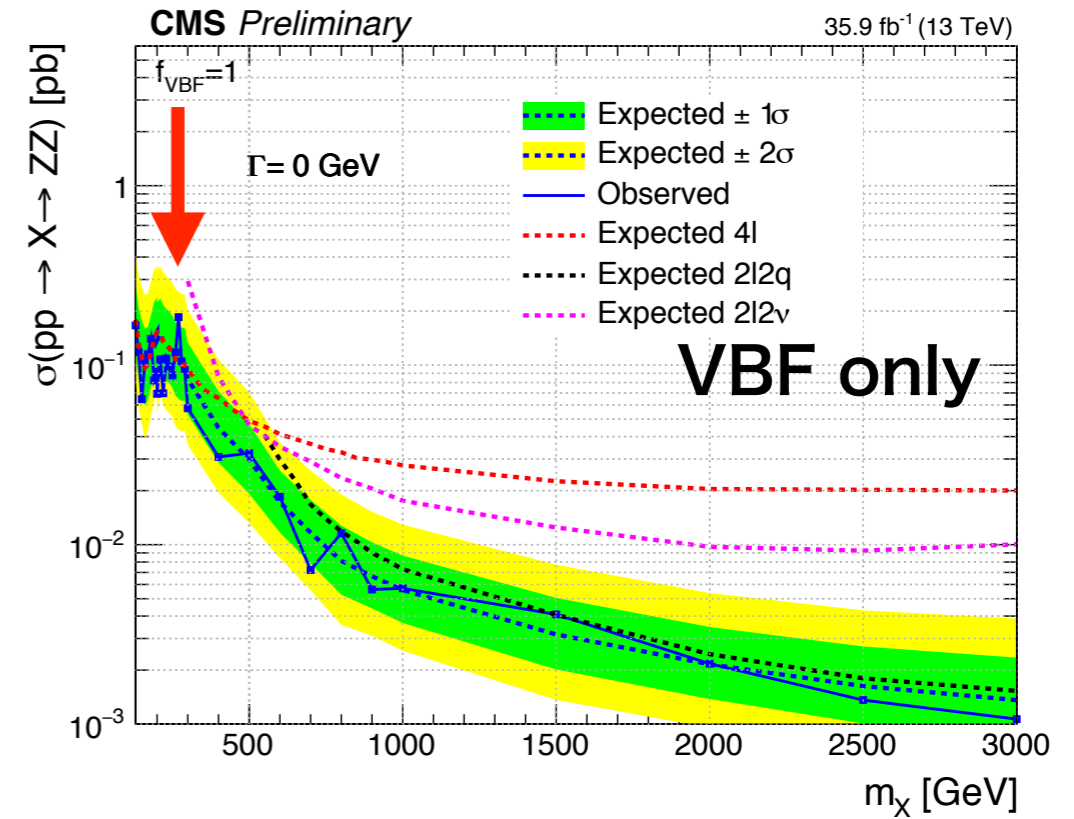
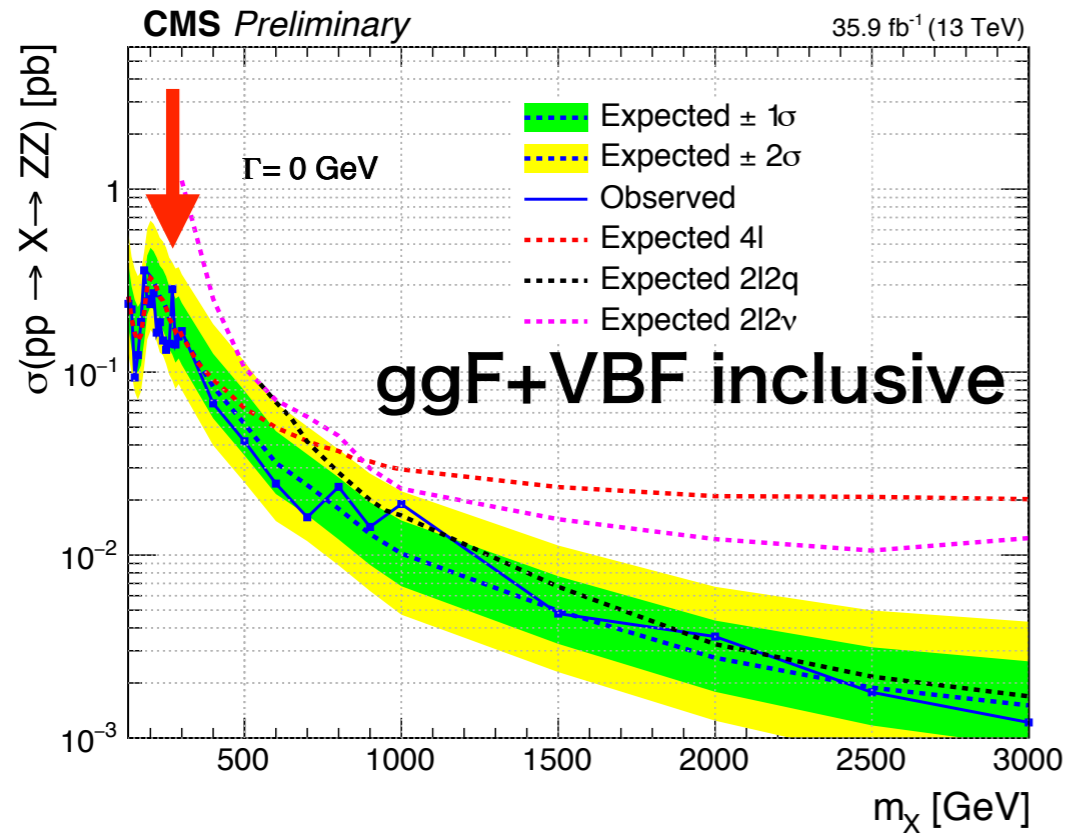


4-lepton mass: 各チャンネル



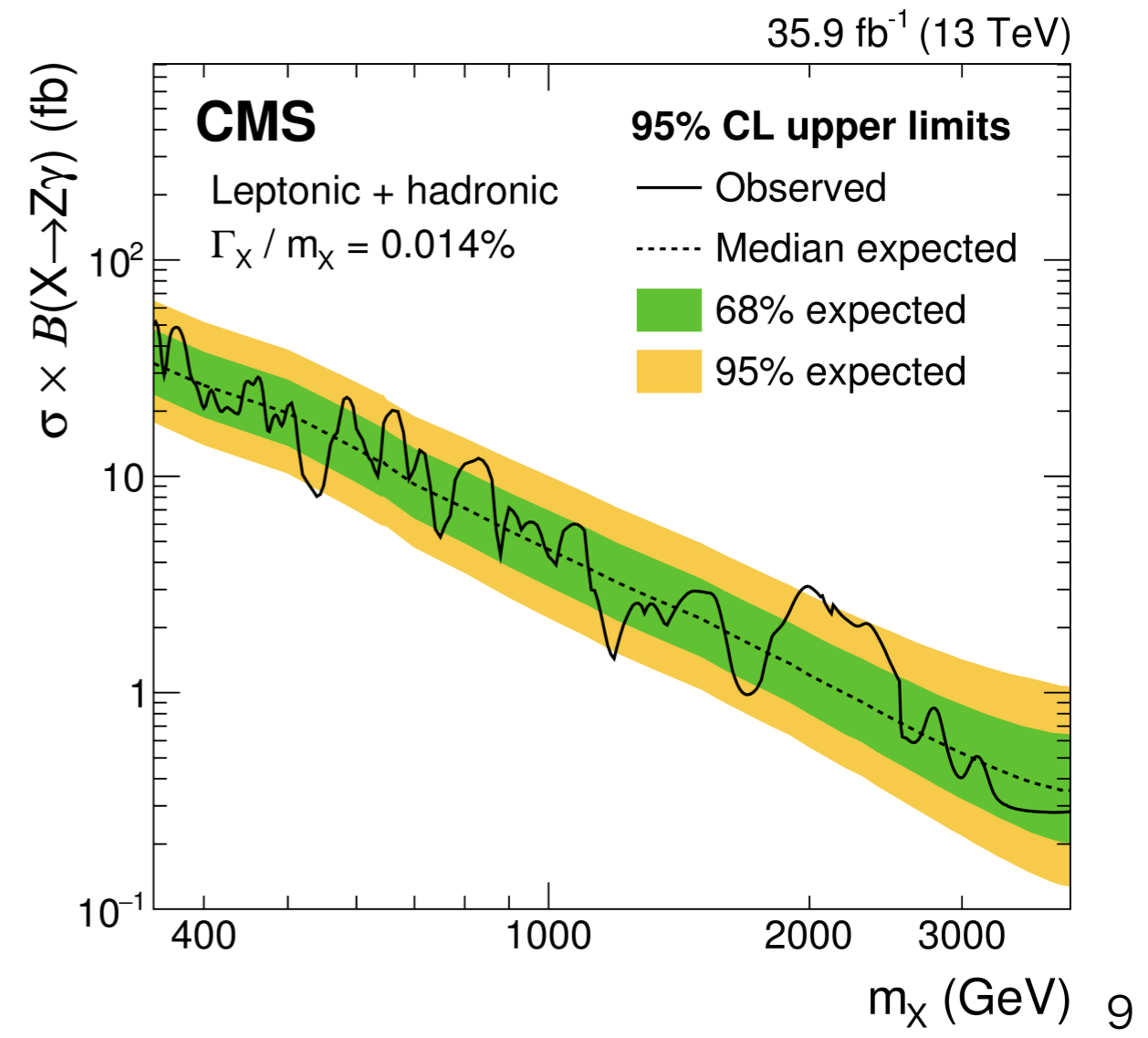
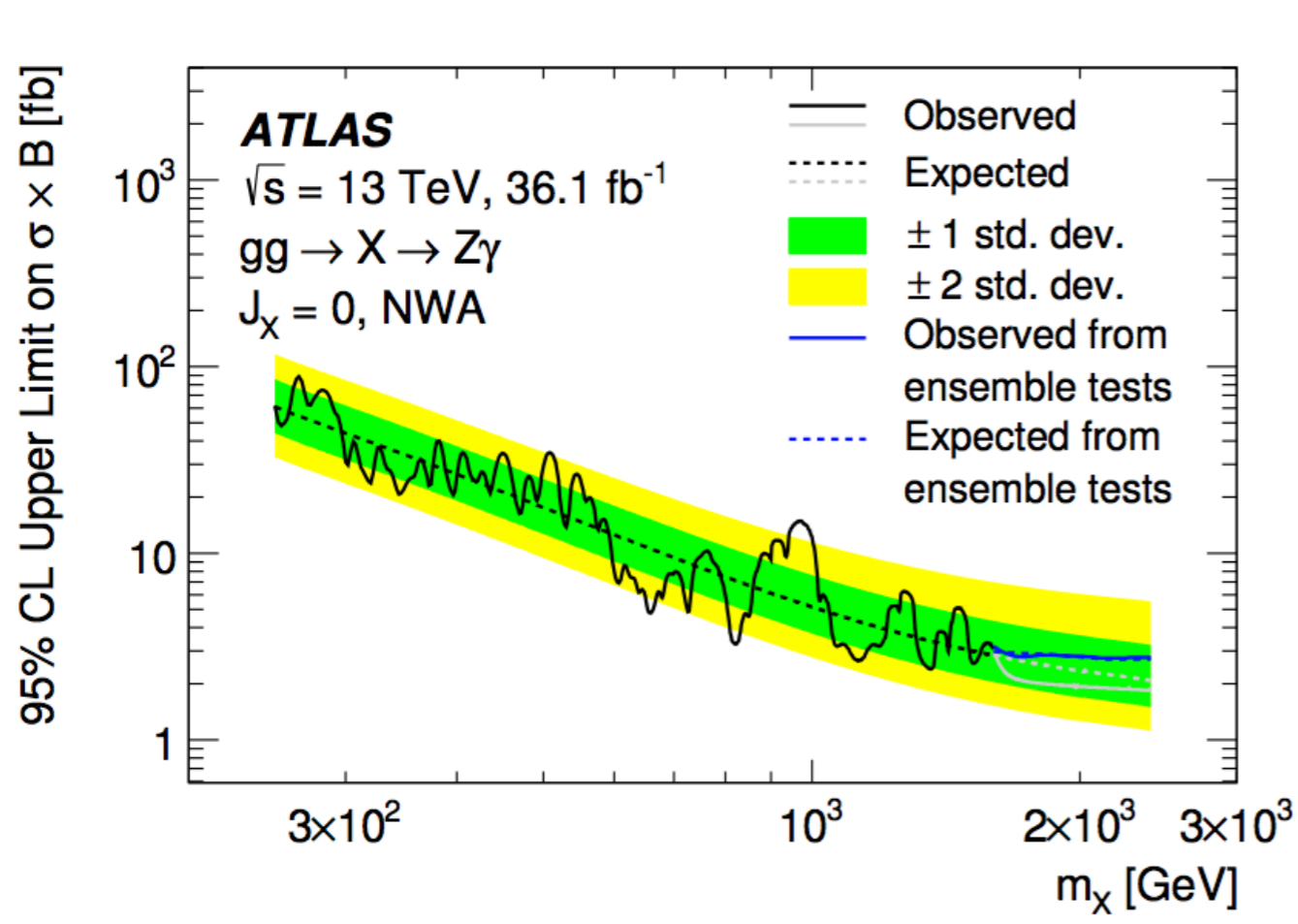
• Electron channelに多い印象

Upper limit on $\sigma(pp \rightarrow X \rightarrow ZV)$ lower mass

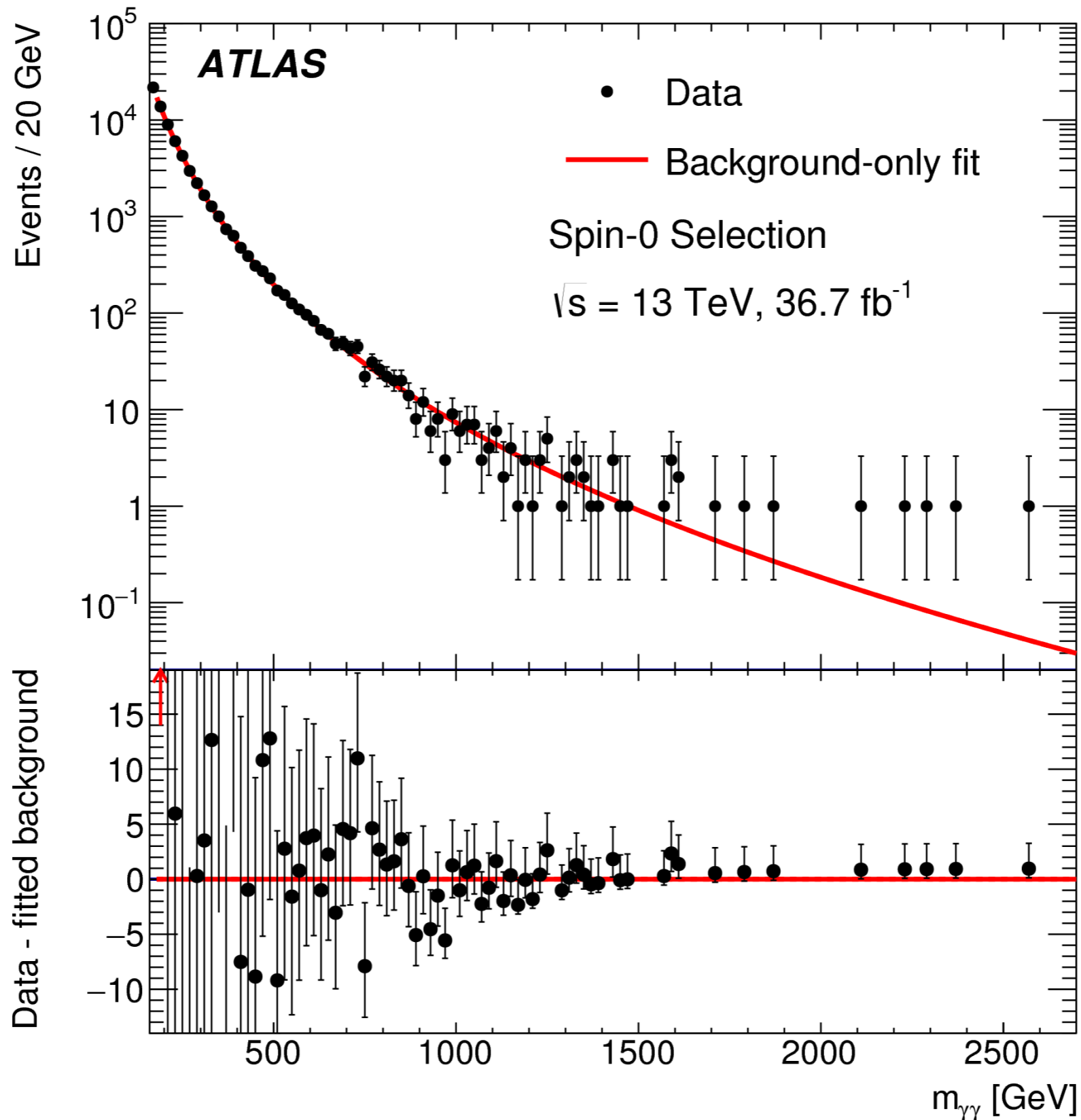


Zγ resonance

- CMS: combination of llγ and qqγ channels。250GeVはギリギリ感度が無い ($p_T(e) > 60\text{GeV}$, $p_T(\mu) > 50\text{GeV}$ でトリガー)
- ATLASはeeγ+μμγのみ。lepton trigger $p_T > 26\text{GeV}$ と取れているので、250GeVから見れている

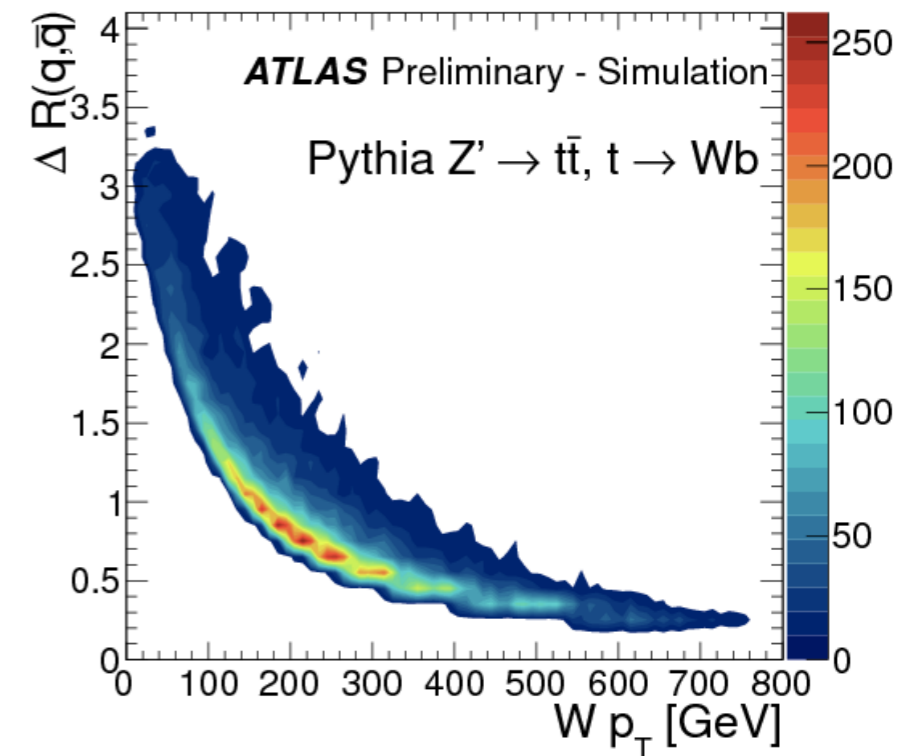


ちなみにdiphoton

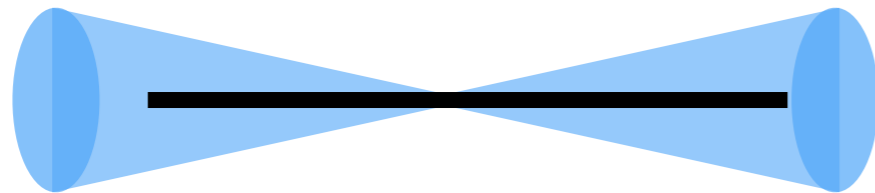


Boosted $W/Z/h \rightarrow qq$ の再構成

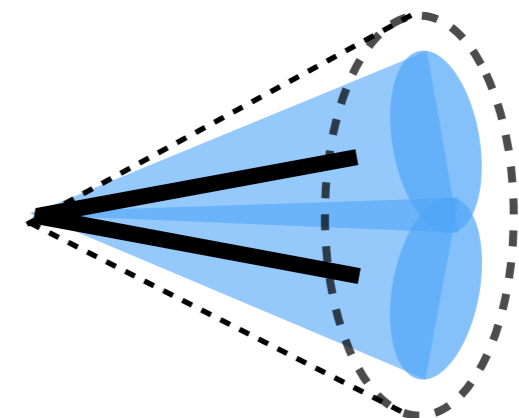
- 質量が高い信号 (生成断面積: 小) に迫る \rightarrow ボソンのハドロン崩壊モードを用いる
e.g. $BR(ZZ \rightarrow qqqq) \sim 50\%$ v.s. $BR(ZZ \rightarrow 4\text{lepton}) \sim 4\%$
- ボソンの崩壊で生じるクォーク間の距離: $\Delta R(q, q) \sim 2M/p_T$
 - $p_T = 300 \text{ GeV}$ の W ボソン: $\Delta R(q, q) \sim 0.5$
 \rightarrow 通常のジェットアルゴリズム (anti-kT cone parameter $R = 0.4$) では分離できない
 - 1本のジェット (**large-R jet**, $R = 1.0$) として再構成
 - パイルアップからの寄与はうまく取り除く



ボソンの静止系



Boosted frame



Large-R jet: ATLAS v.s. CMS

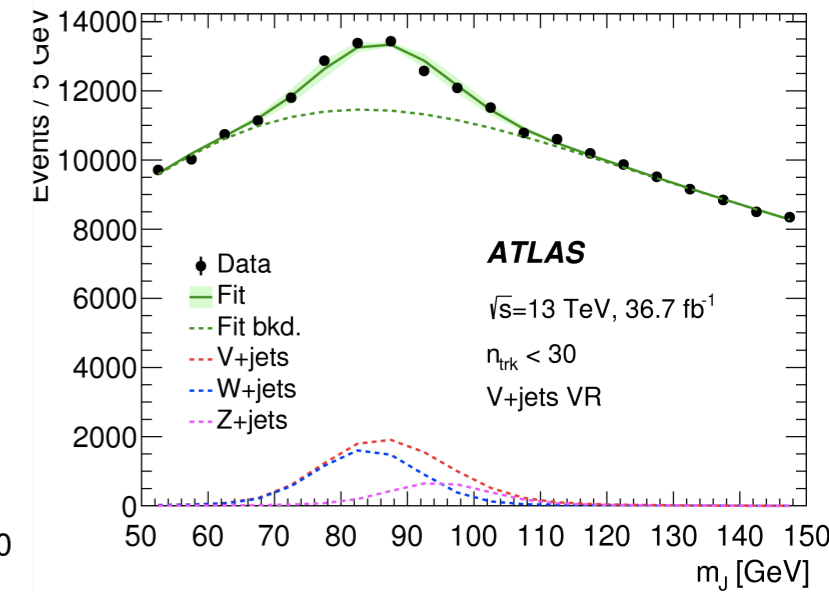
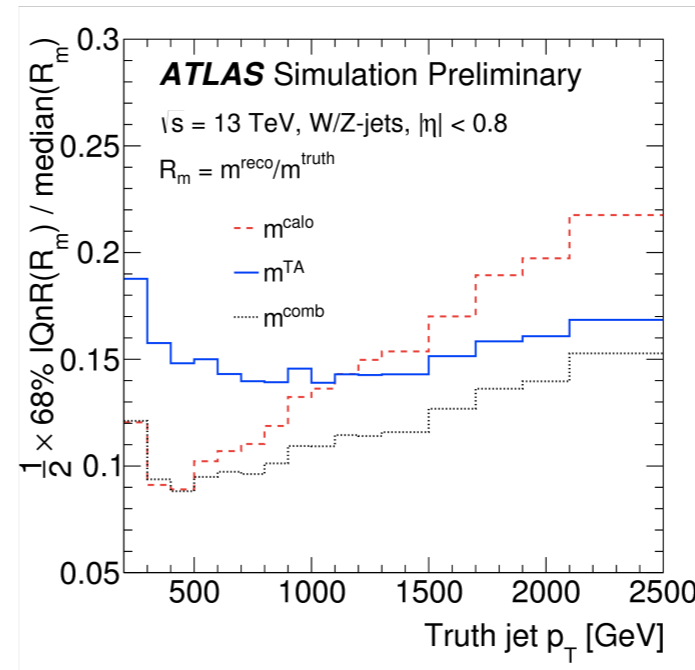
- Anti-kT **R=1.0** based on **topo-clusters**

- **Trimming**: $p_T(j)/p_T(J) < 0.05$ の subjet は落とす

- Combined **track-assisted** + calo mass

$$m_{J,TA} = m_{J,trk} \times p_{T,calo}/p_{T,trk}$$

- Energy correlation function (**D₂**)

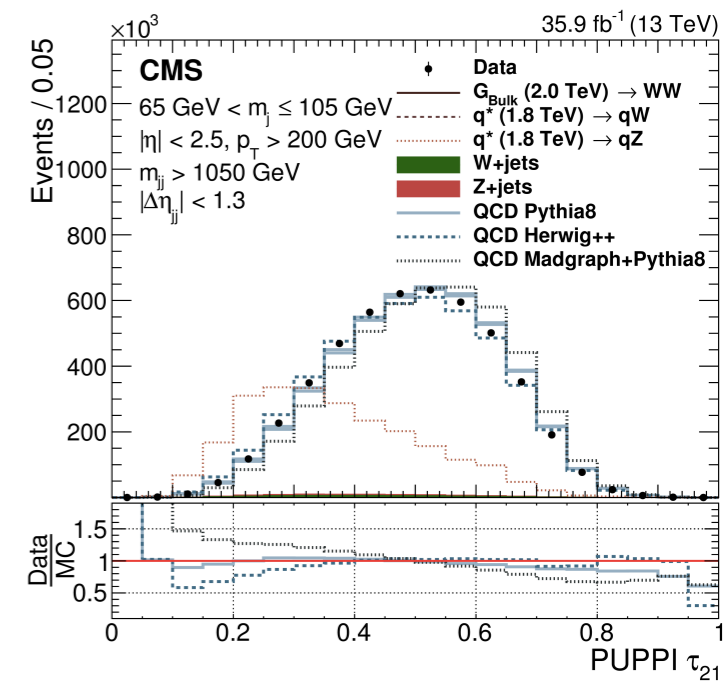
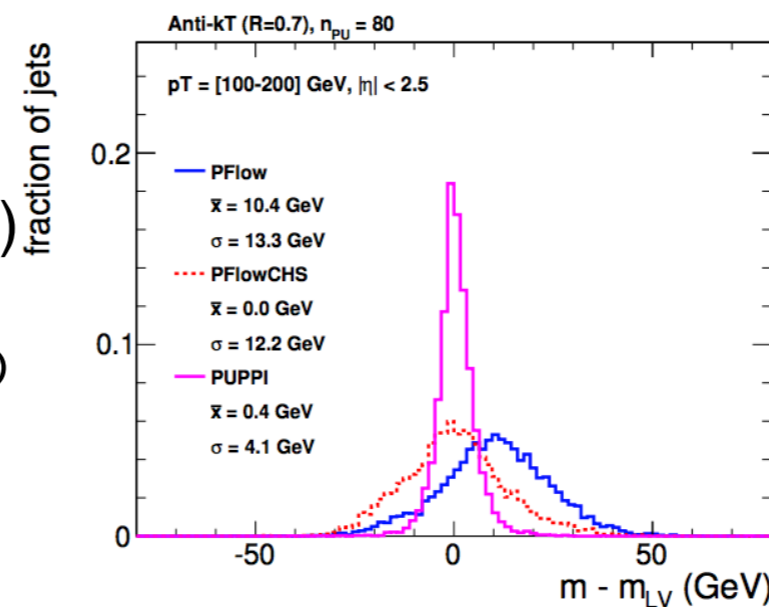


- Anti-kT **R=0.8** based on **particle-flow**

- **PUPPI** (pileup per particle identification)

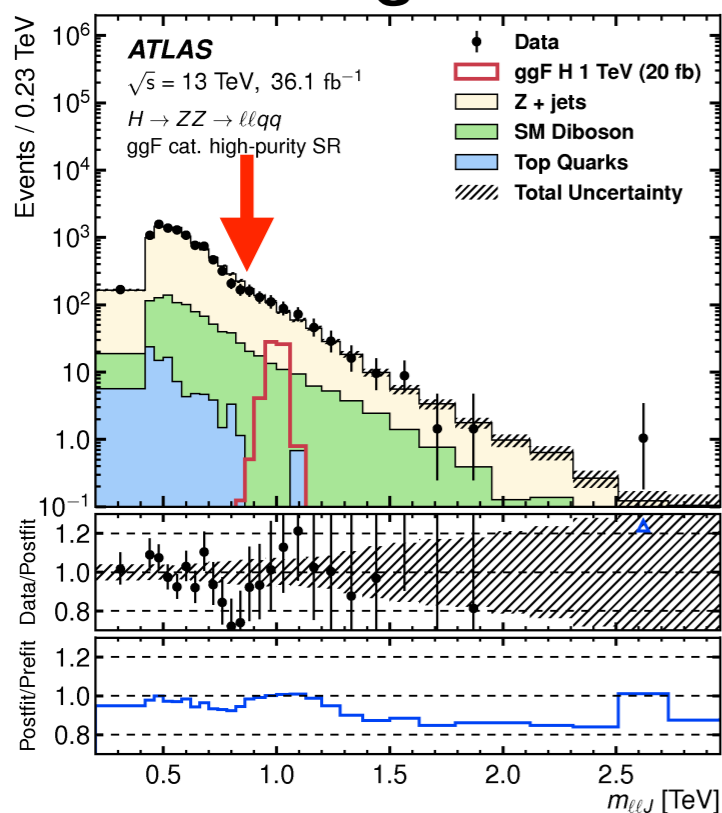
- **Soft drop**: C/A algorithm で組んだ2つの sub-jet の p_T がバランスすることを要求

- N-subjettiness ratio (**τ_{21}**)

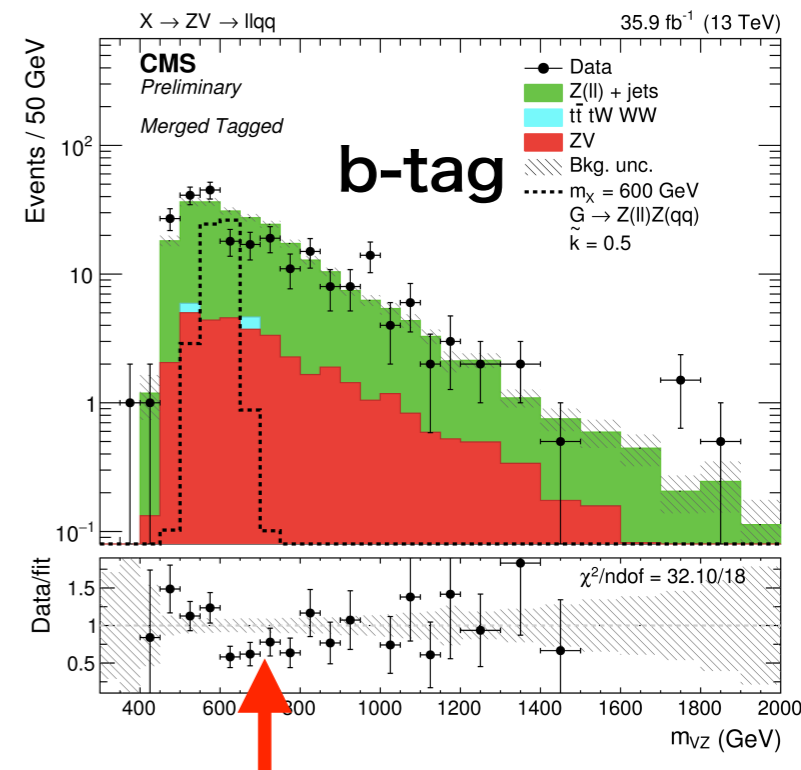
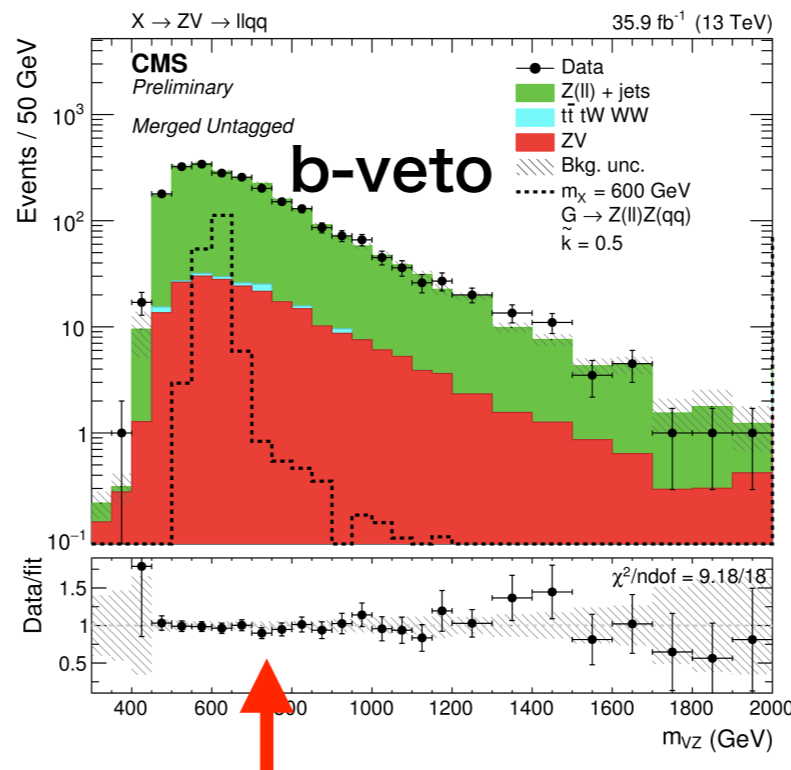


ZZ/ZW → llqq

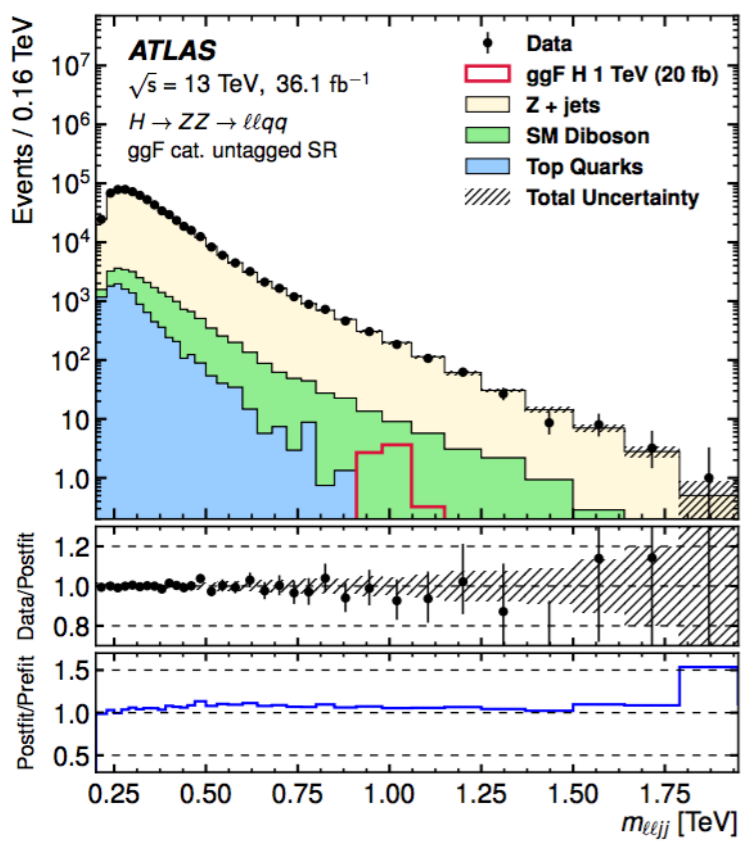
ATLAS high-mass



CMS intermediate-mass

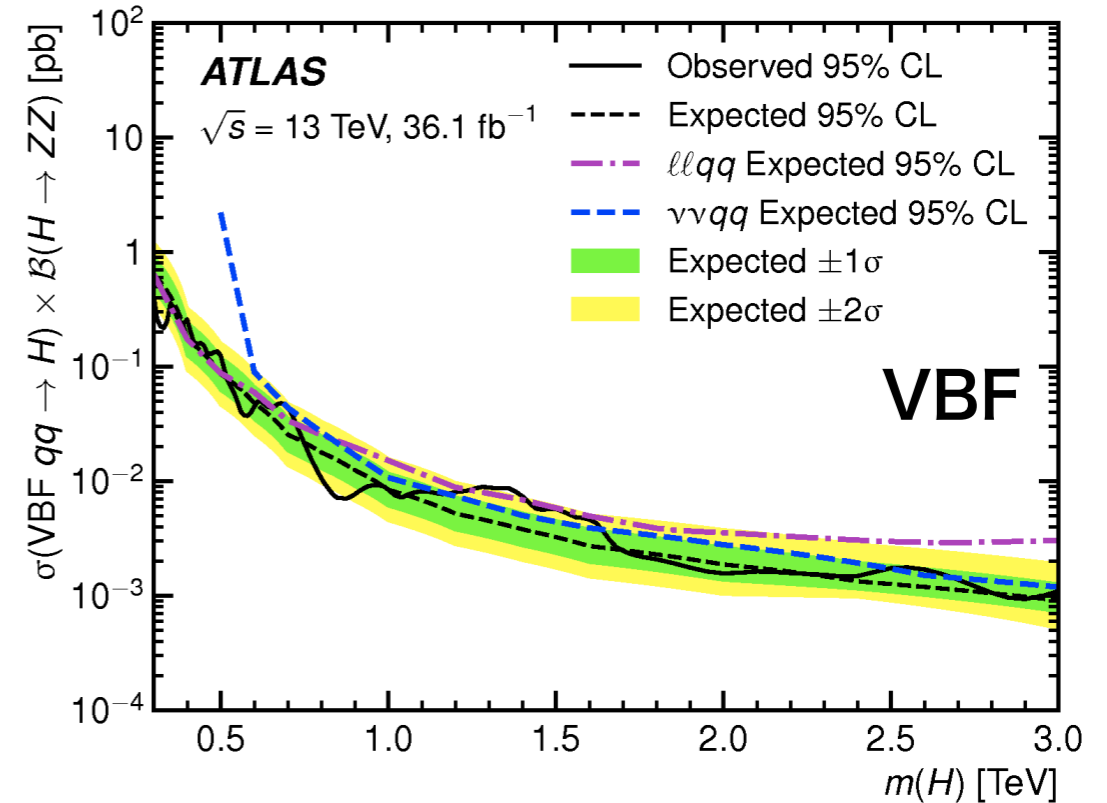
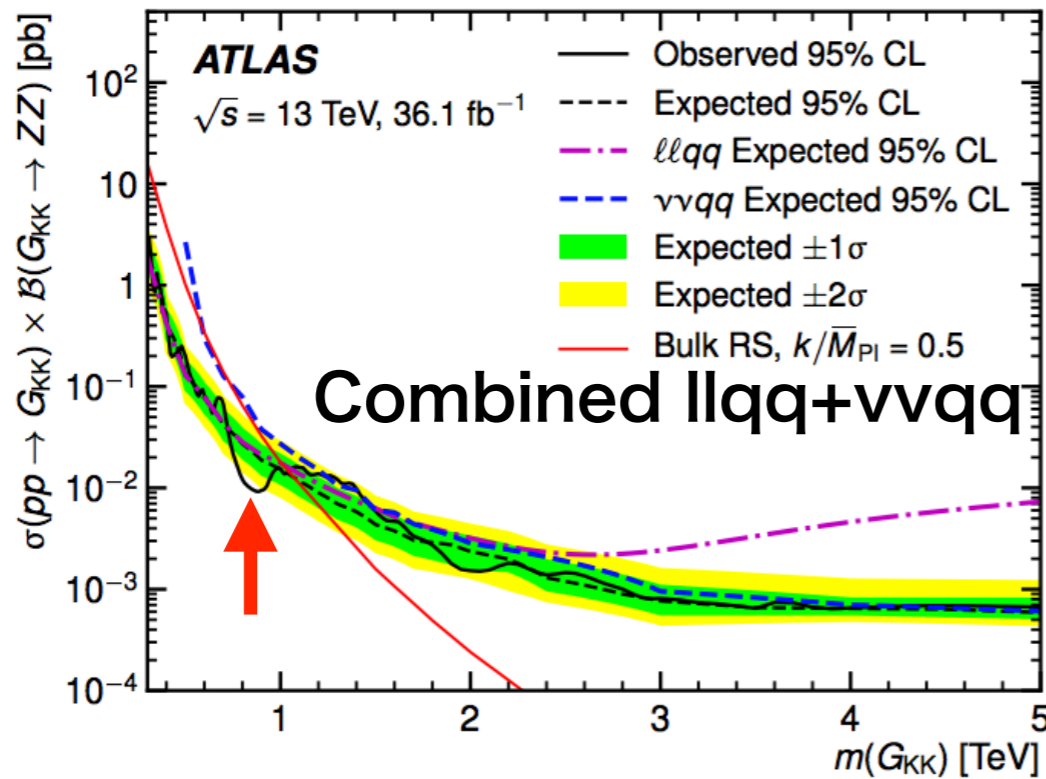
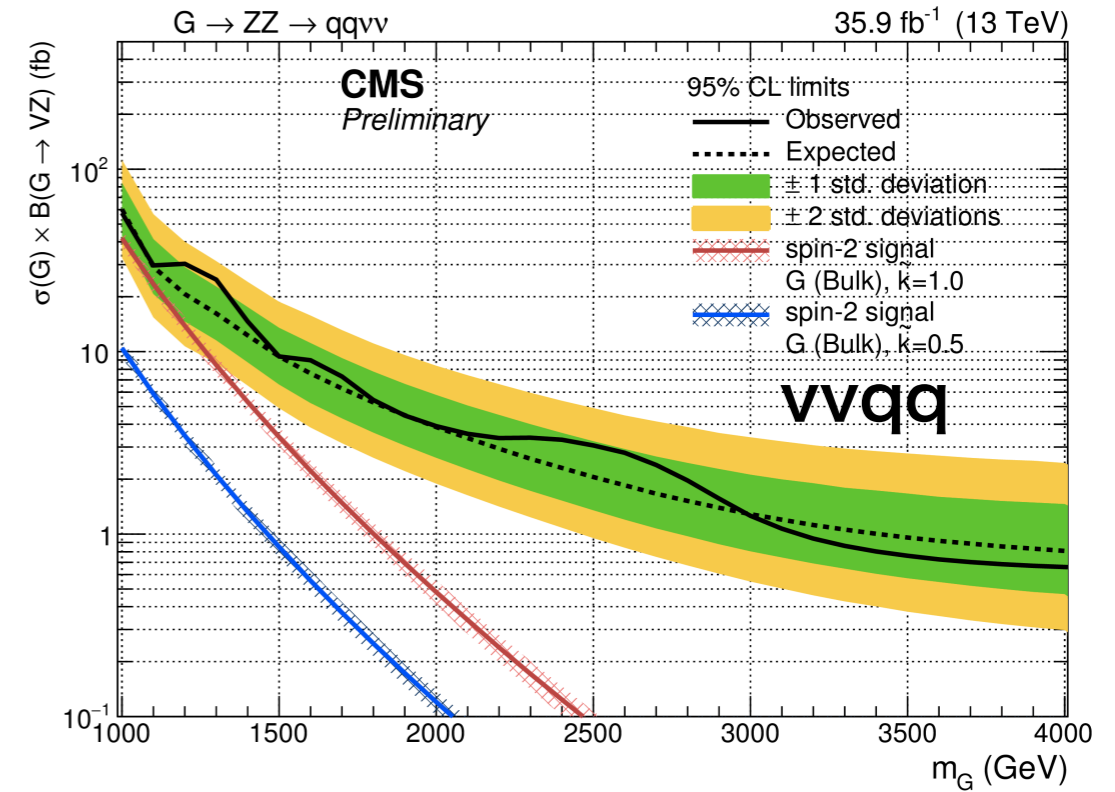
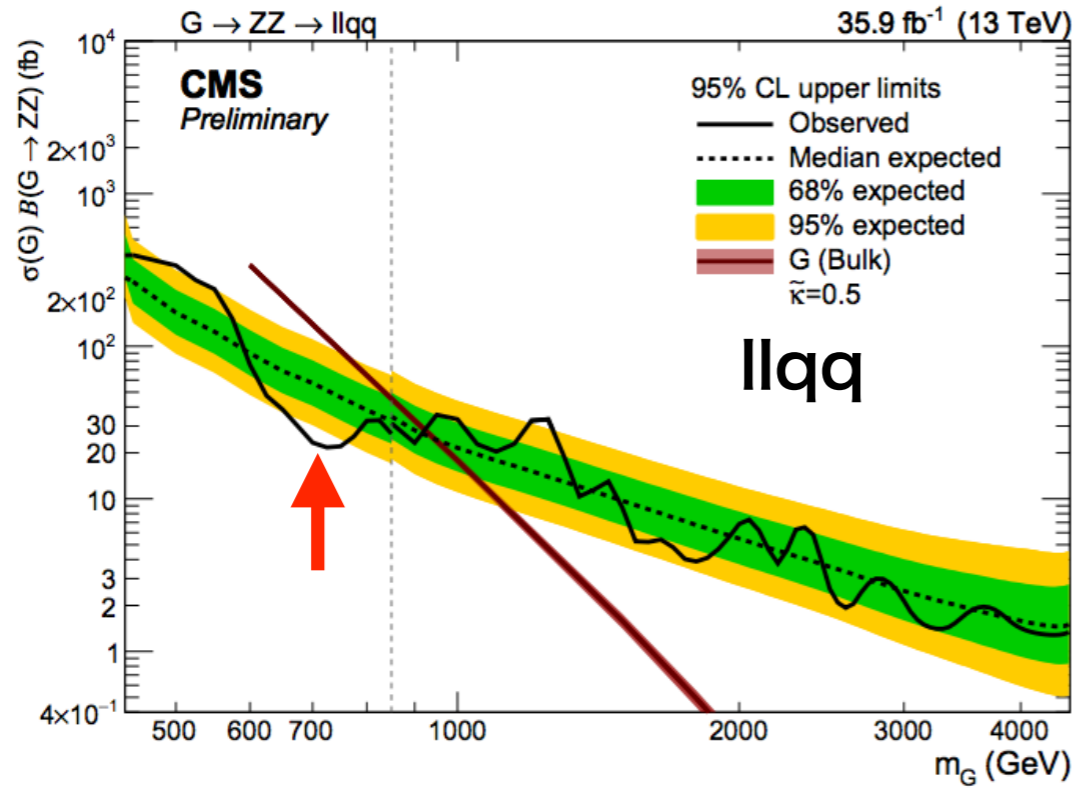


ATLAS low-mass

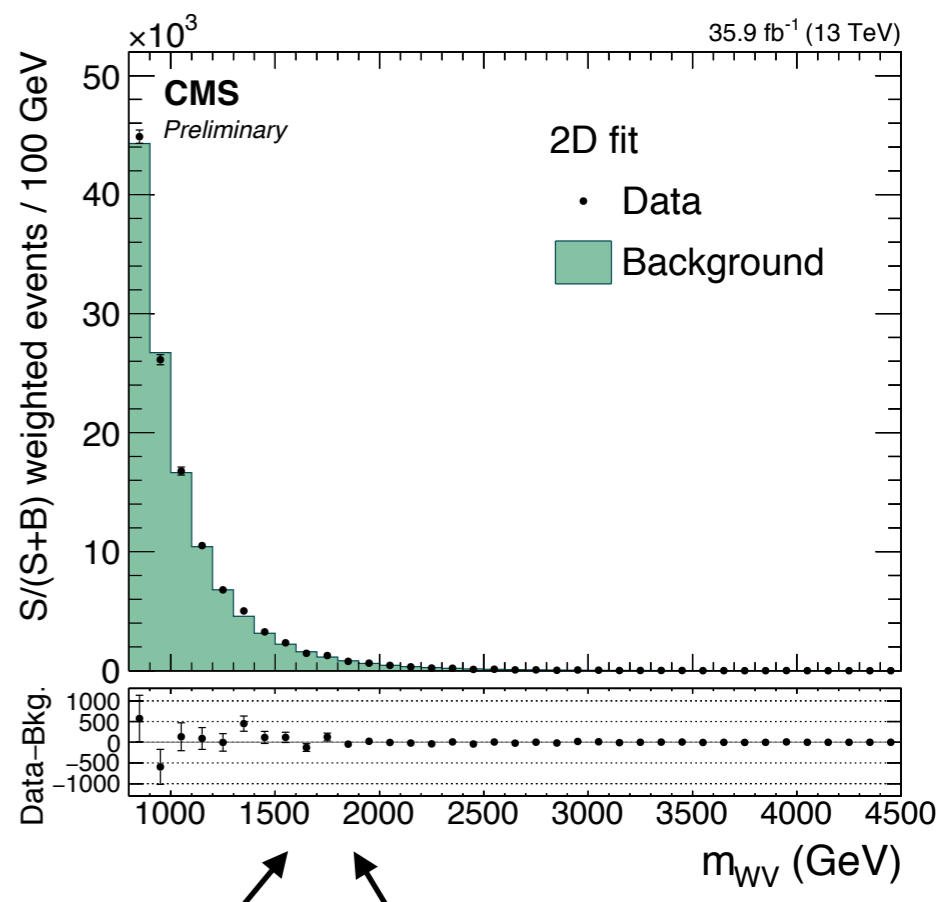
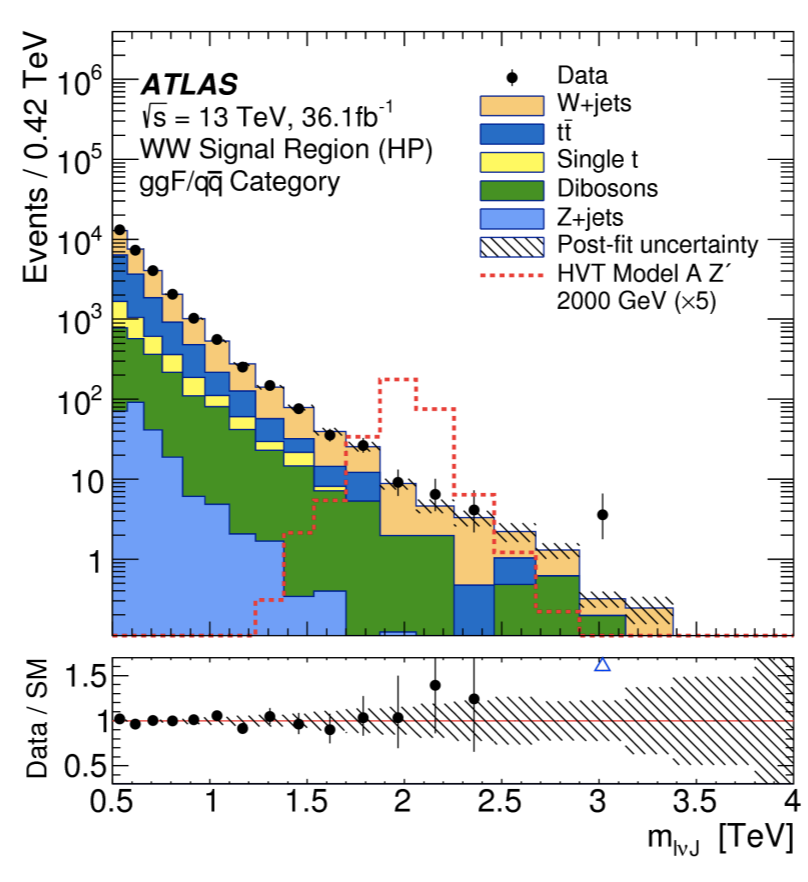
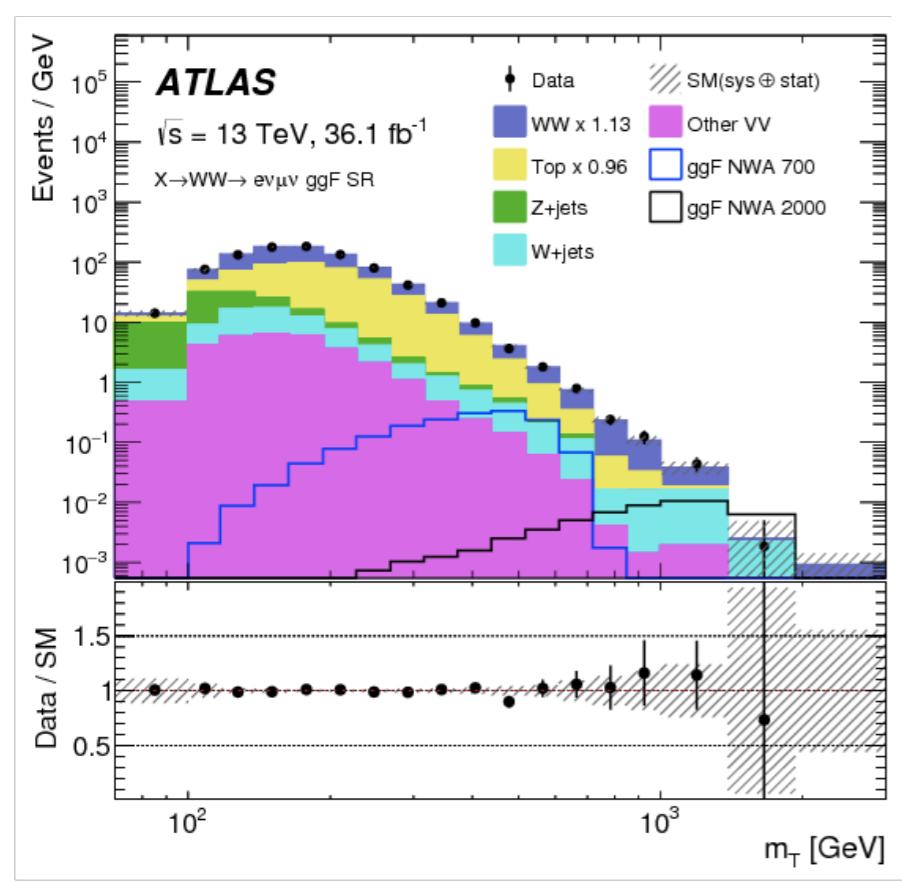


- 240GeVはギリギリ感度が無い
- 700GeV: deficit? $\sim 3\sigma$
ATLAS/CMS同じ場所に同じくらい
- Background prediction
 - ATLAS&CMS lower mass region: MC (ATLAS Sherpa, CMS MadGraph)

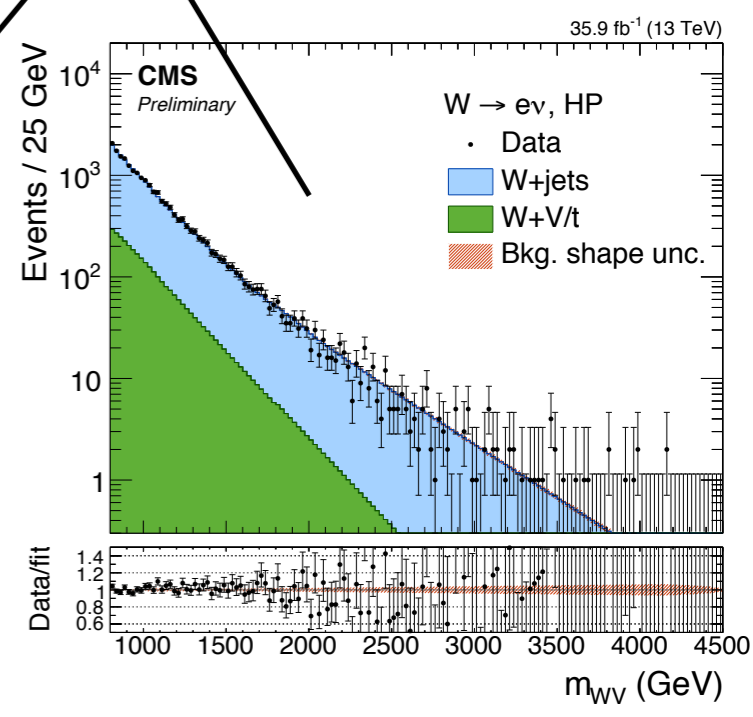
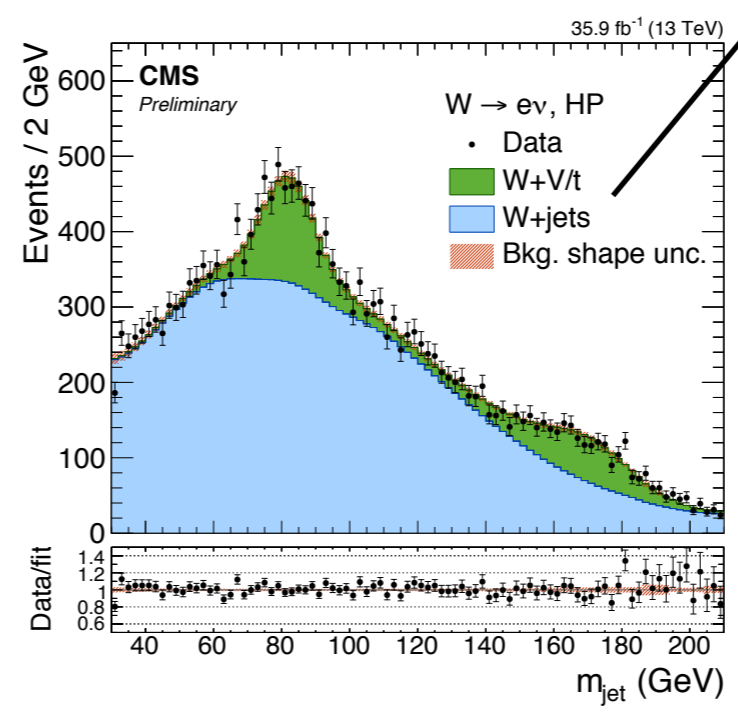
Upper limit on $\sigma(pp \rightarrow X \rightarrow ZV)$ higher mass



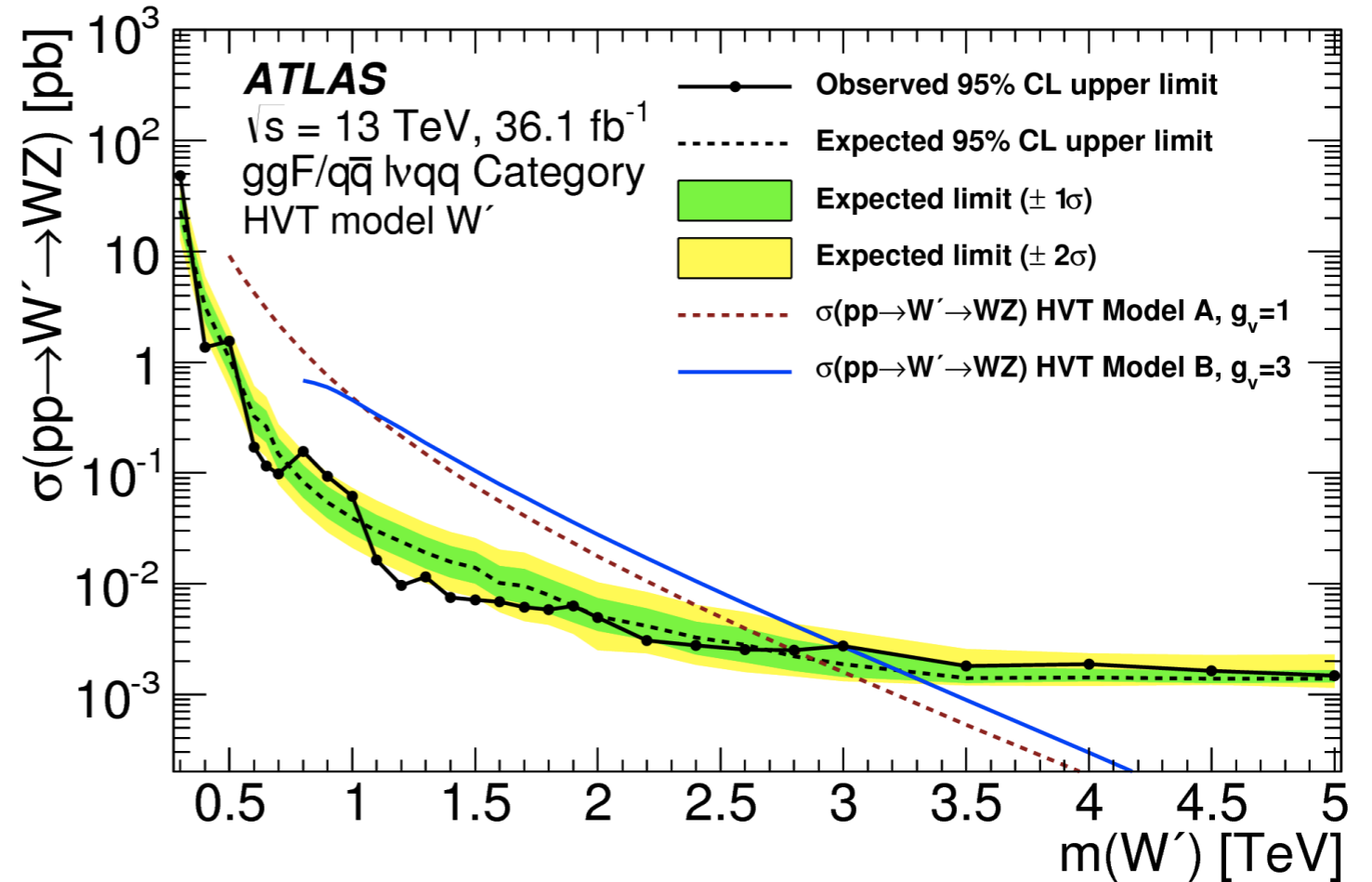
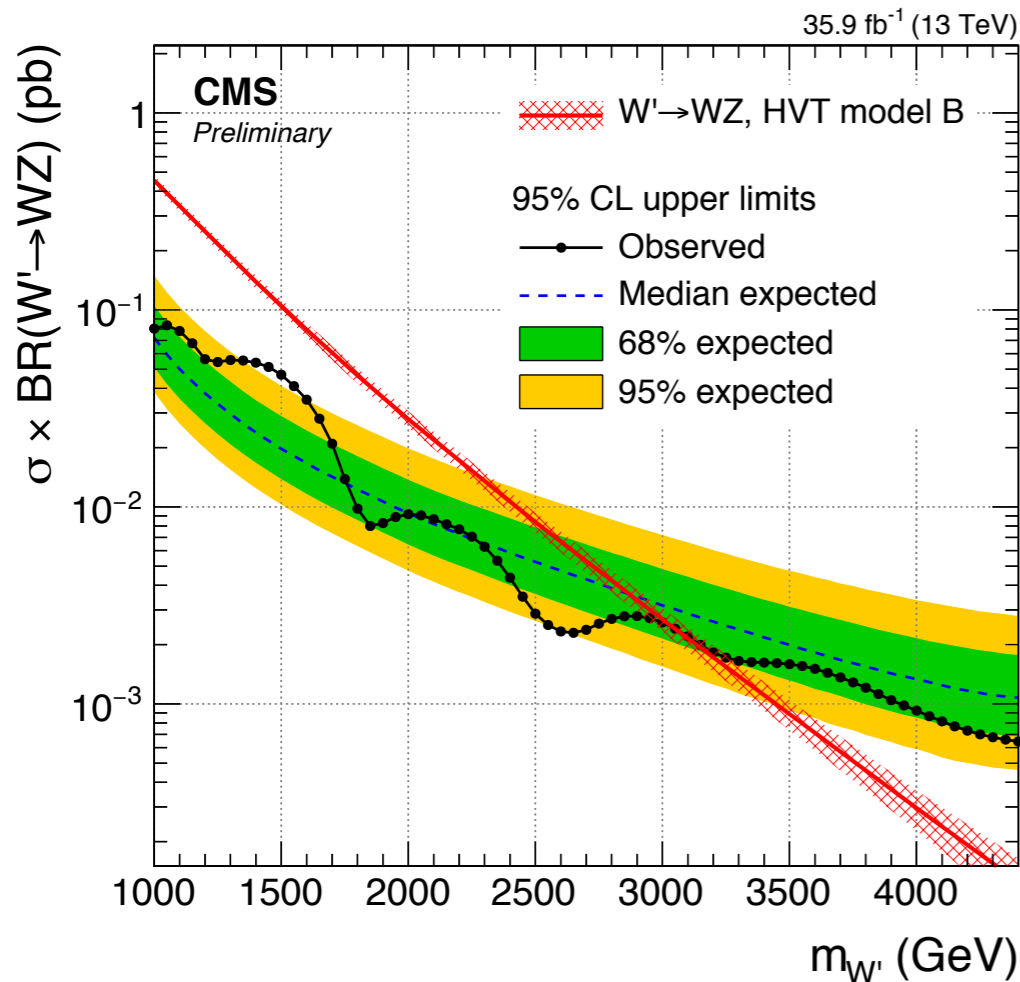
WW → eνμν, WW → lvqq



- 非常に良く合っている
- CMSは $m(J)$ と $m(WV)$ の2次元 likelihoodで信号を抽出
- 右上図は $S/(S+B)$ でweightをか
けた $m(WV)$ 分布

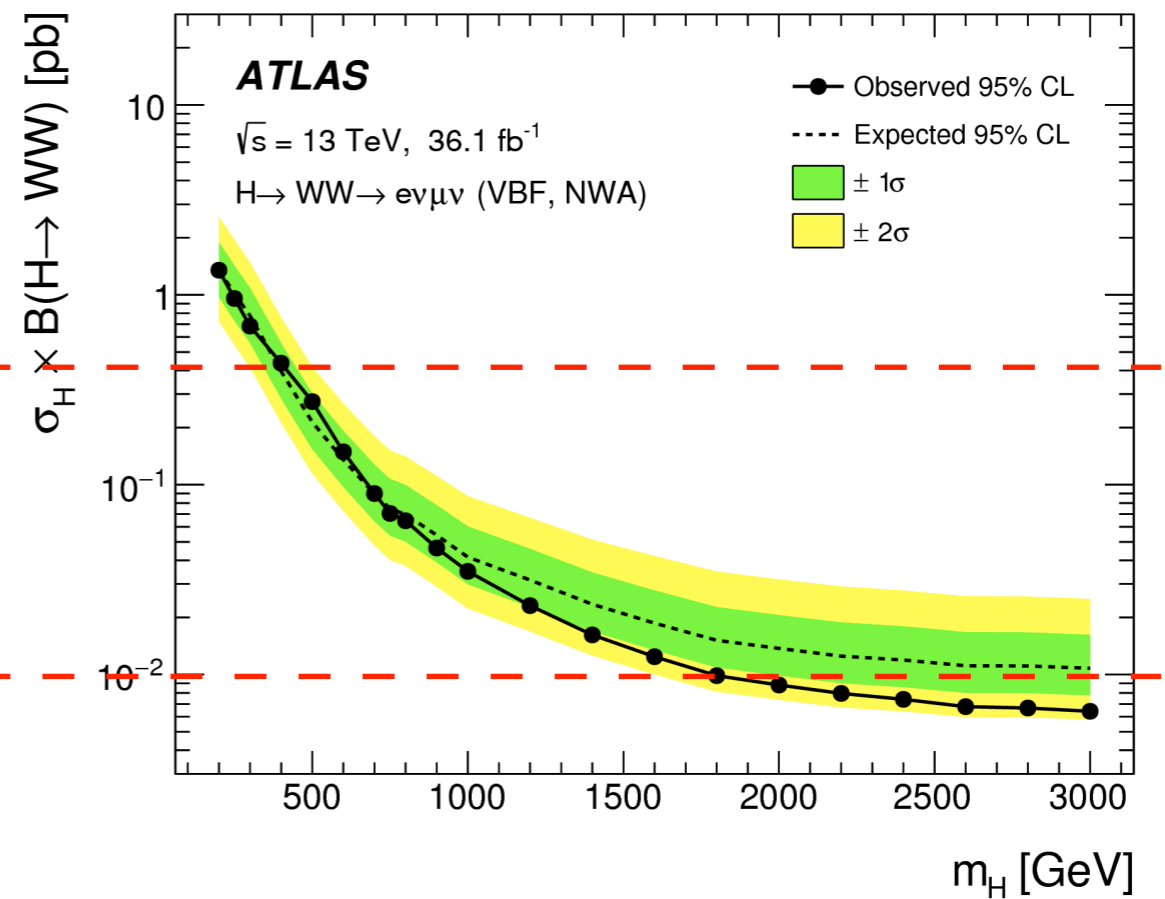
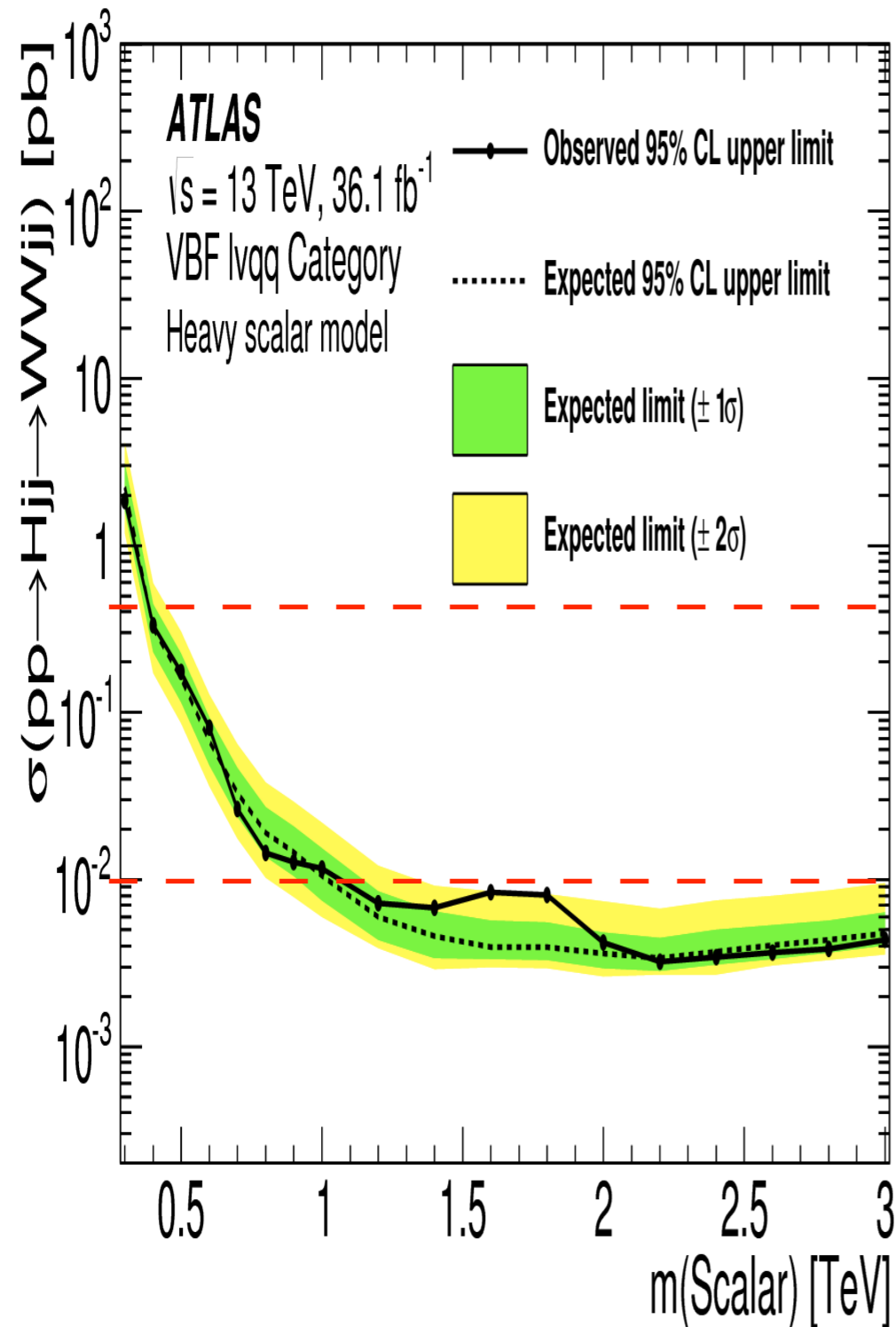


Upper limit on $\sigma(pp \rightarrow X \rightarrow WV)$ ggF/qq topologies

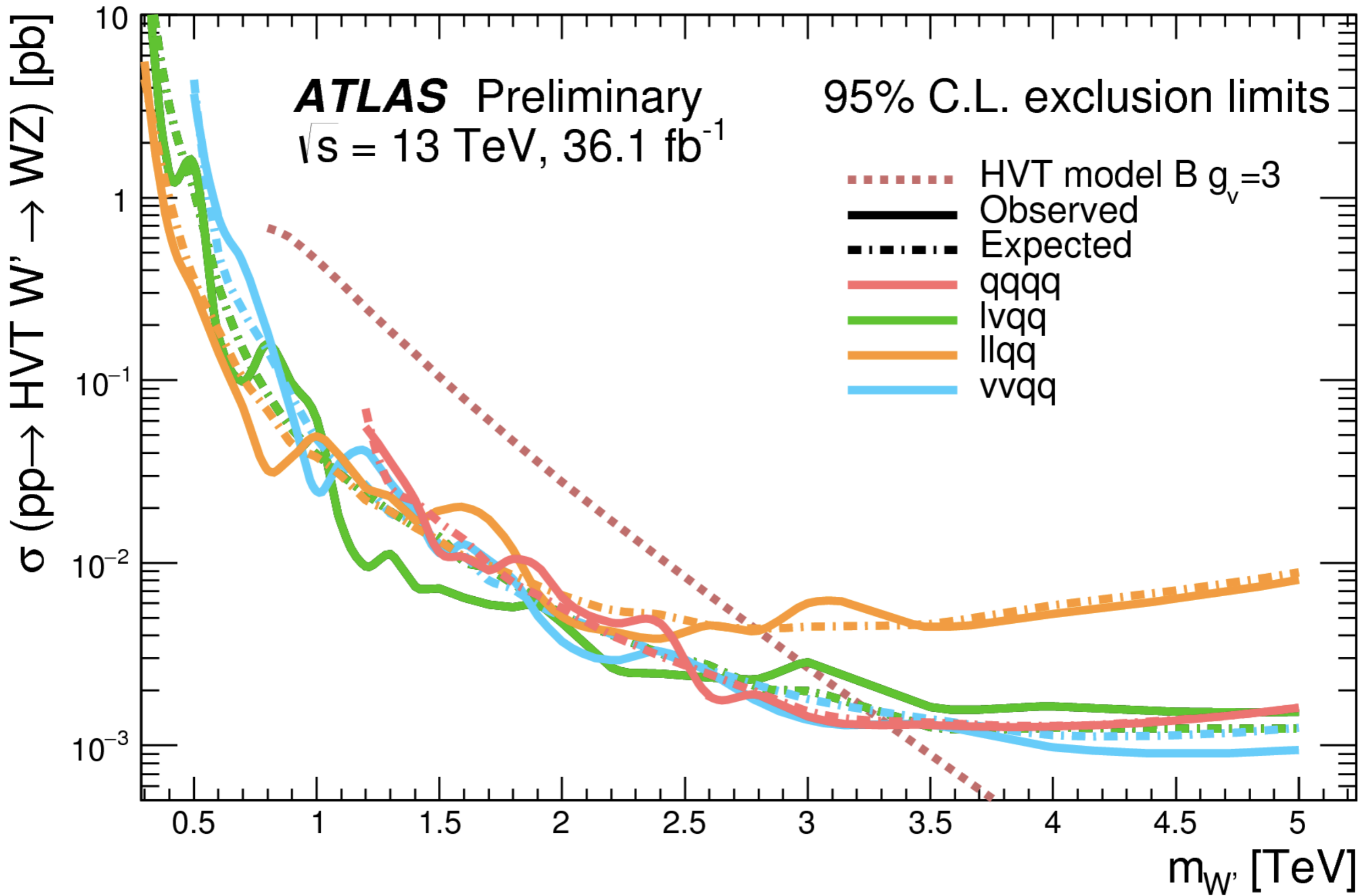


- ATLASのほうがややmodel-dependentなcut ($p_T(V)/m(VV) > 0.4$)を入れているぶん少し良いが、だいたい同じくらいの感度

Upper limit on $\sigma(pp \rightarrow X \rightarrow WW)$ VBF

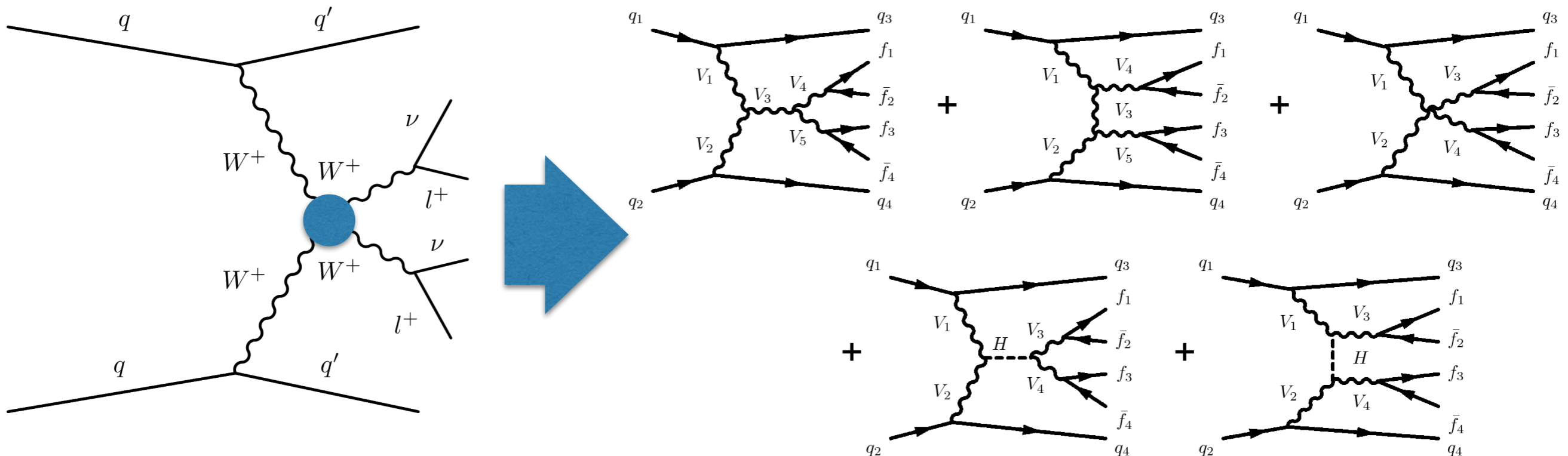


- $lvqq$ が強いが、 $m < 400 \text{ GeV}$ では $e\nu\mu\nu$ のほうが良い



Vector boson scattering

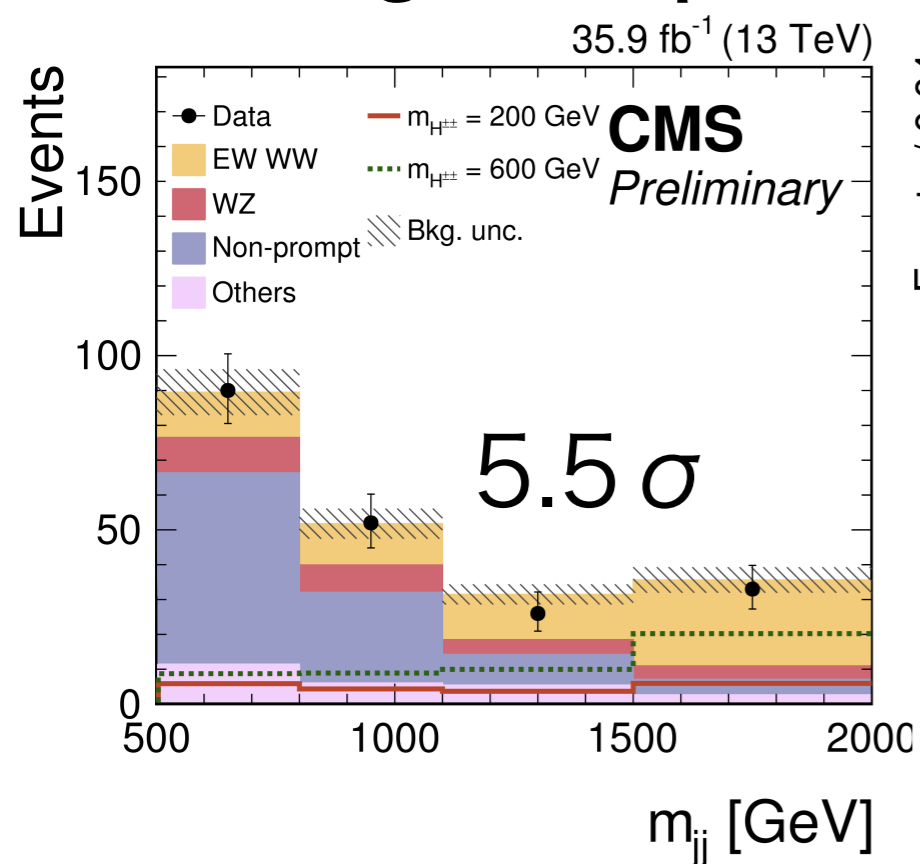
- Electroweak production of vector boson pair: ヒッグス機構の検証(ユニタリティの破れ)
- EFTでanomalous quartic gauge coupling (aQGC)に制限
- Effective c.m.s. energy (m_{VV}) の関数で見たい
- VBF Diboson共鳴探索とほぼ同じ解析だが、b.g.をさらに抑えるため $W^{\pm}W^{\pm}$ (same sign di-lepton)や4-lepton終状態を用いる
- 前後方のジェット2本を要求する \rightarrow high- $m(jj)$ & large $\Delta\eta(jj)$ に信号が見える



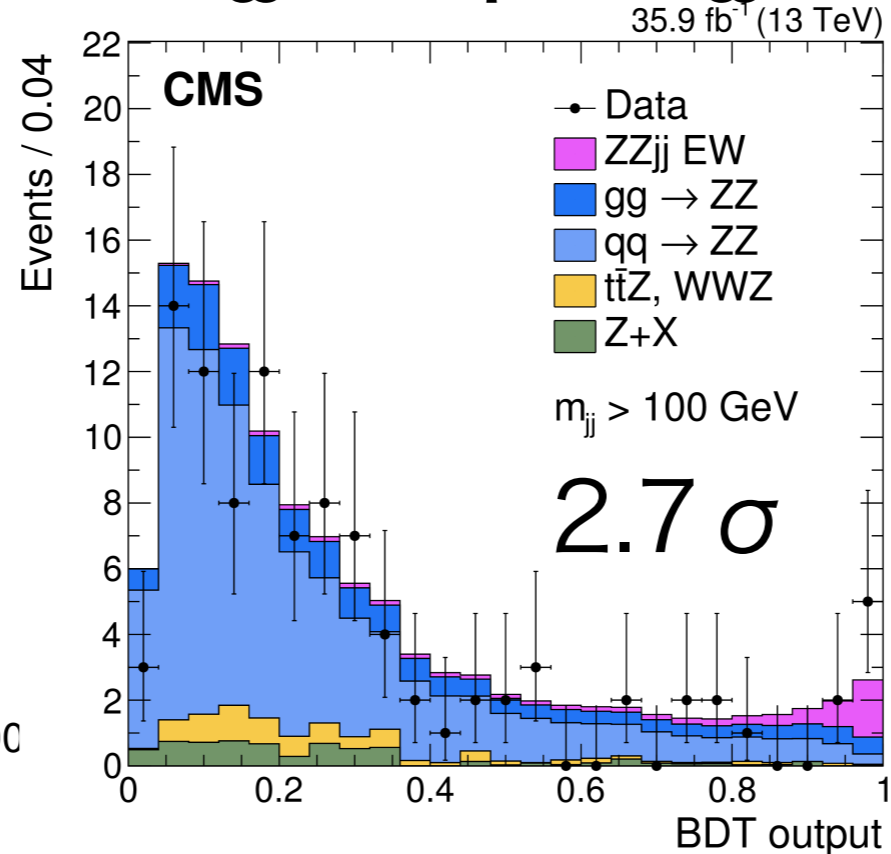
EW VBS cross section 測定結果

- Same-sign di-lepton:
 - ATLAS 8TeV 3.6σ (2.5σ expected)
 - CMS 13TeV 5.5σ (5.7σ expected), 8TeV 2.0σ (3.5σ expected)
- $ZZ \rightarrow 4\text{-lepton}$: CMS 13TeV 4-lepton 2.7σ (1.7σ expected)
- $WV \rightarrow l\nu qq$: 8TeV only. Branching fractionの分high-massまでprobe可

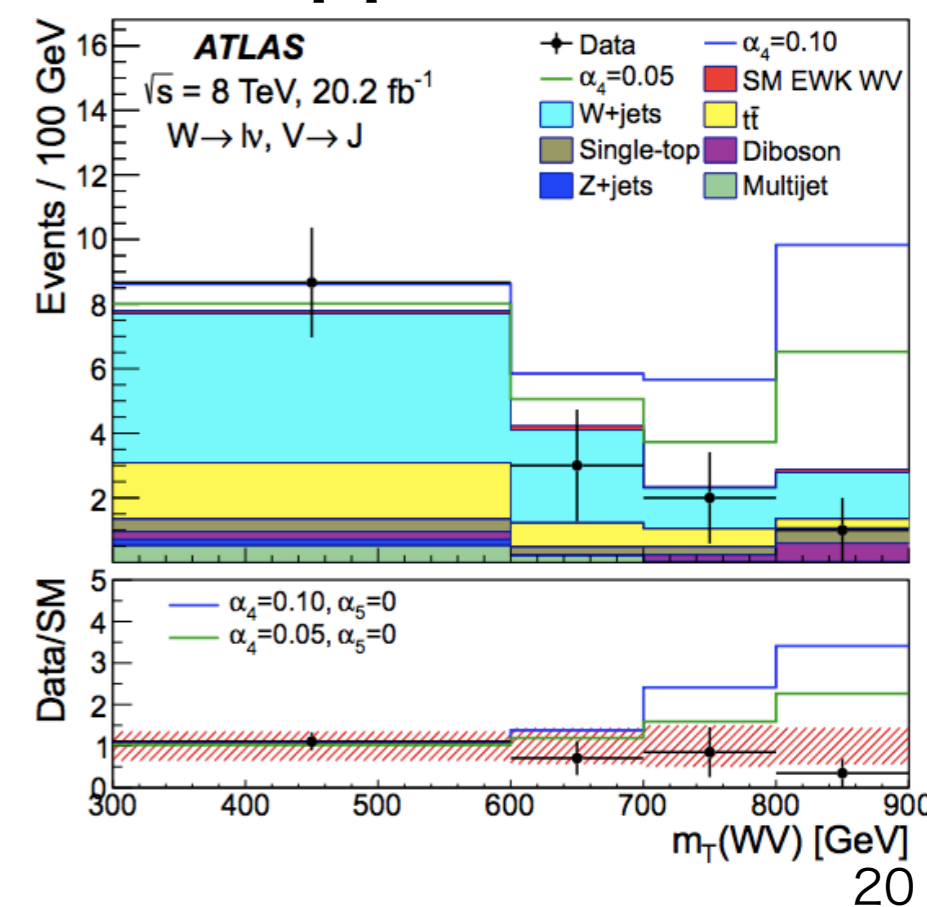
same-sign di-lepton



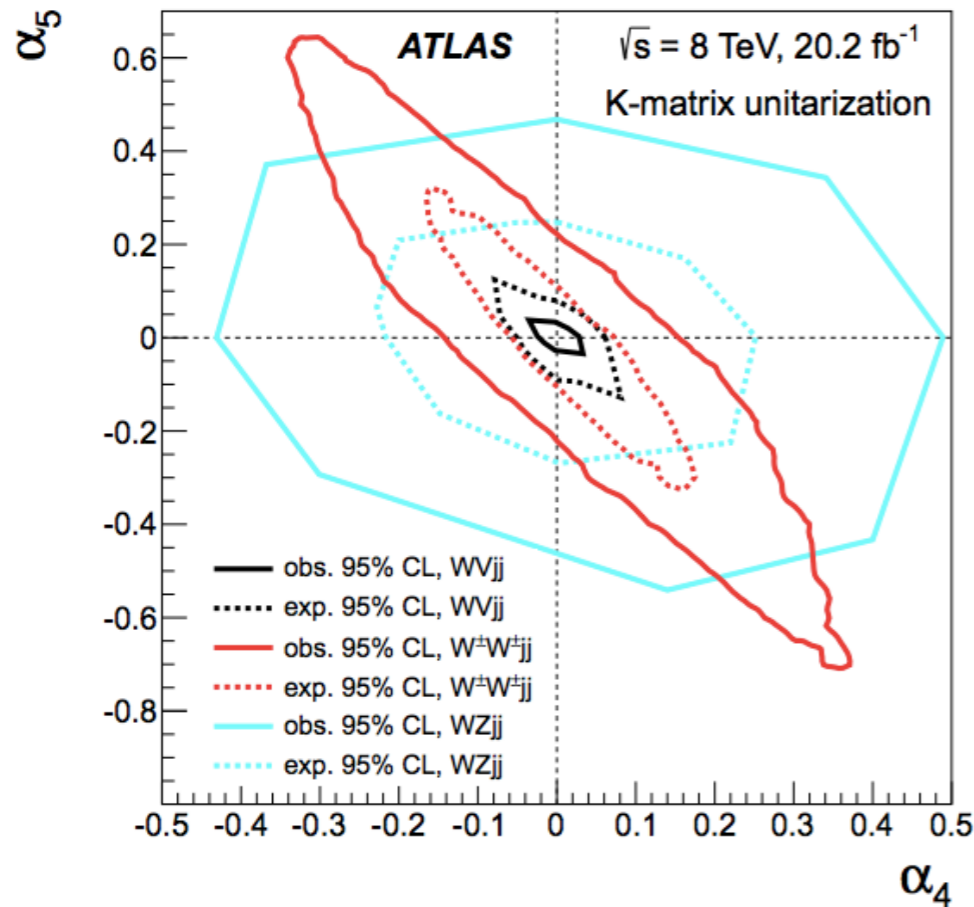
$ZZjj \rightarrow 4\text{lepton} + jj$



$l\nu qq$



aQGCに対する制限



- ATLAS 8TeV: $O(p^4)$ 項をSMに加え制限を設けた

$$\alpha_4 \mathcal{L}_4 = \alpha_4 \text{tr}[\mathbf{V}_\mu \mathbf{V}_\nu] \text{tr}[\mathbf{V}^\mu \mathbf{V}^\nu],$$

$$\alpha_5 \mathcal{L}_5 = \alpha_5 \text{tr}[\mathbf{V}_\mu \mathbf{V}^\mu] \text{tr}[\mathbf{V}_\nu \mathbf{V}^\nu],$$

- High-massで感度があるためlvqqからの制限が強い
- CMS & ATLAS 13TeV: dimension-8 operatorのco-efficient (Eboli model [link])に対して制限

- scalar型(S)、tensor型(T)、混合型(M)で18個の dimension-8演算子 e.g.

$$\mathcal{O}_{S,0} = [(D_\mu \Phi)^\dagger D_\nu \Phi] \times [(D^\mu \Phi)^\dagger D^\nu \Phi],$$

$$\mathcal{O}_{S,1} = [(D_\mu \Phi)^\dagger D^\mu \Phi] \times [(D_\nu \Phi)^\dagger D^\nu \Phi],$$

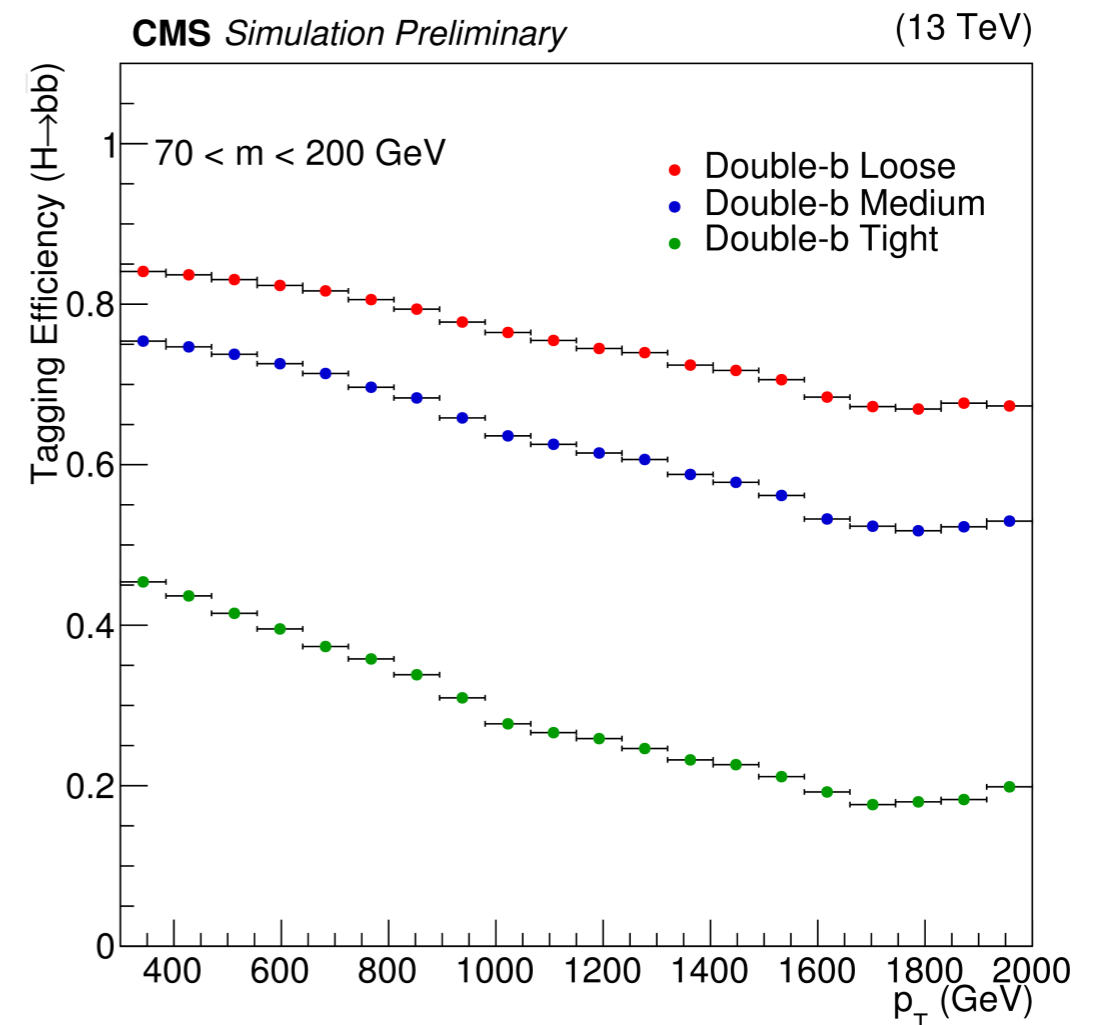
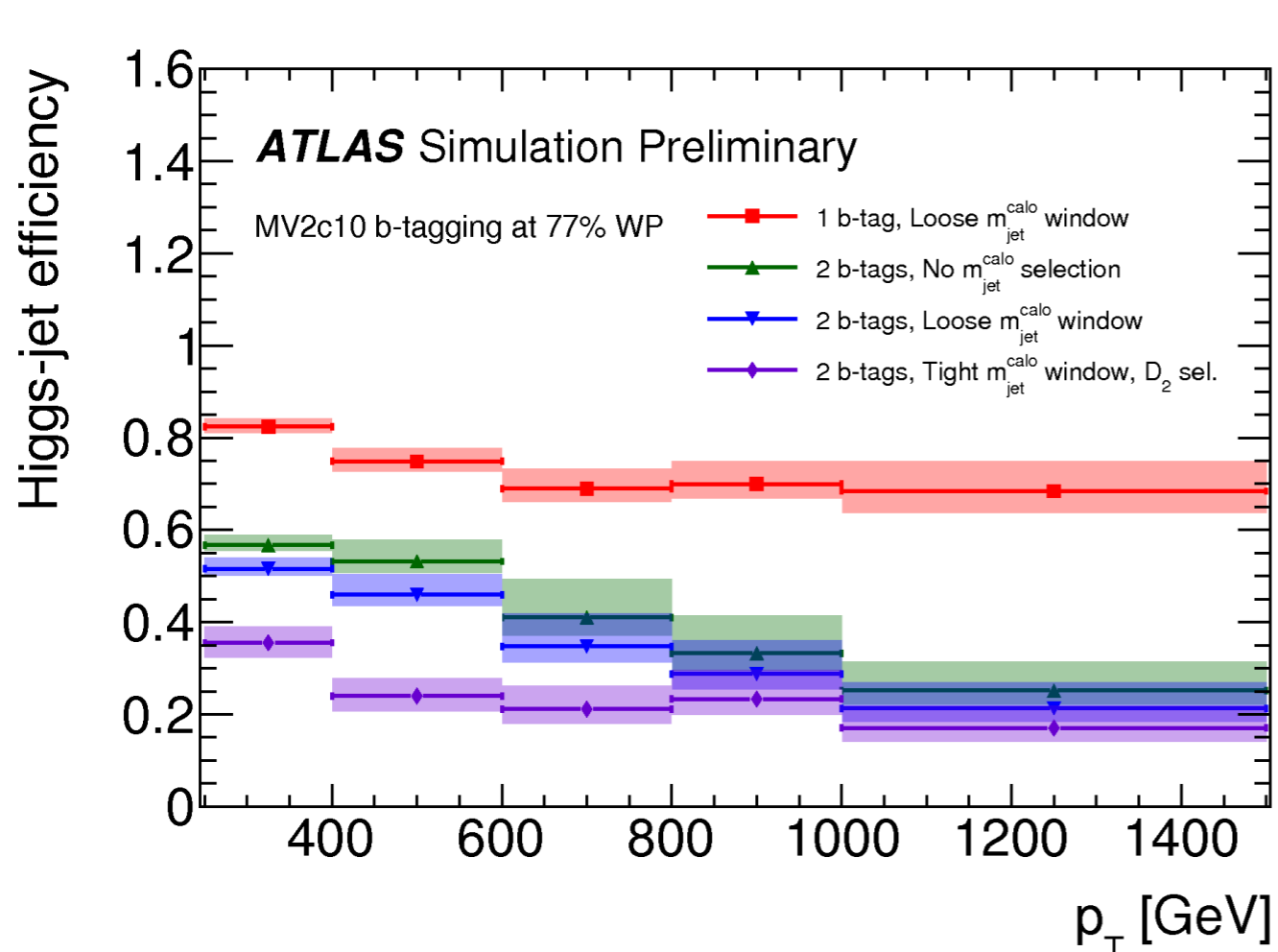
$$\mathcal{O}_{S,2} = [(D_\mu \Phi)^\dagger D_\nu \Phi] \times [(D^\nu \Phi)^\dagger D^\mu \Phi],$$

- ssWWは8TeV→13TeVで5倍の感度増
- CouplingによってZZ→4leptonやγγ→WWが良い感度を持つ
全チャンネルでの測定が大事

	Observed limits (TeV ⁻⁴)	Expected limits (TeV ⁻⁴)	Previously observed limits (TeV ⁻⁴)
f_{S0}/Λ^4	[-7.7, 7.7]	[-7.0, 7.2]	[-38, 40], [11]
f_{S1}/Λ^4	[-21.6, 21.8]	[-19.9, 20.2]	[-118, 120], [11]
f_{M0}/Λ^4	[-6.0, 5.9]	[-5.6, 5.5]	[-4.6, 4.6], [36]
f_{M1}/Λ^4	[-8.7, 9.1]	[-7.9, 8.5]	[-17, 17], [36]
f_{M6}/Λ^4	[-11.9, 11.8]	[-11.1, 11.0]	[-65, 63], [11]
f_{M7}/Λ^4	[-13.3, 12.9]	[-12.4, 11.8]	[-70, 66], [11]
f_{T0}/Λ^4	[-0.62, 0.65]	[-0.58, 0.61]	[-0.46, 0.44], [37]
f_{T1}/Λ^4	[-0.28, 0.31]	[-0.26, 0.29]	[-0.61, 0.61], [37]
f_{T2}/Λ^4	[-0.89, 1.02]	[-0.80, 0.95]	[-1.2, 1.2], [37]

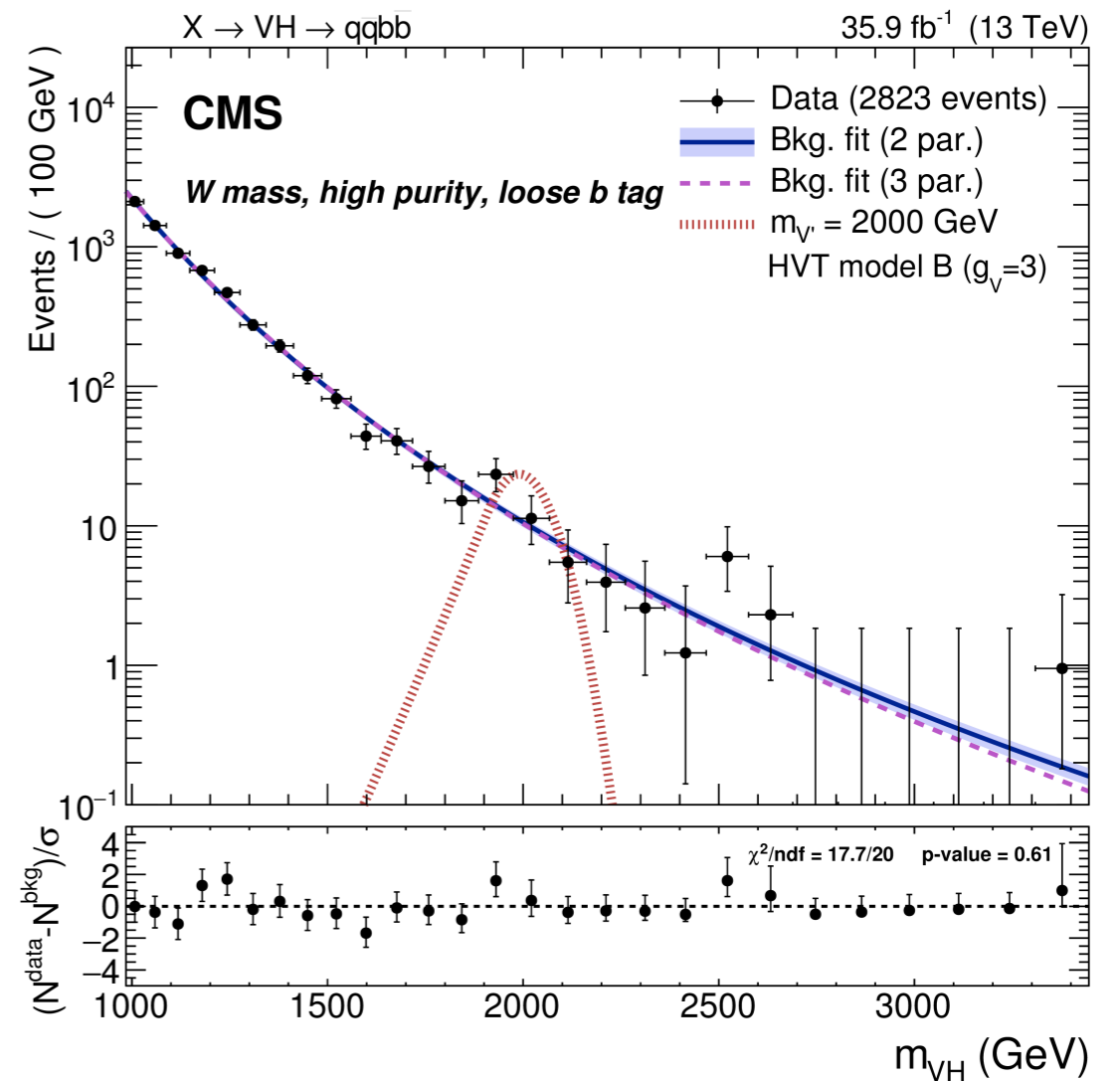
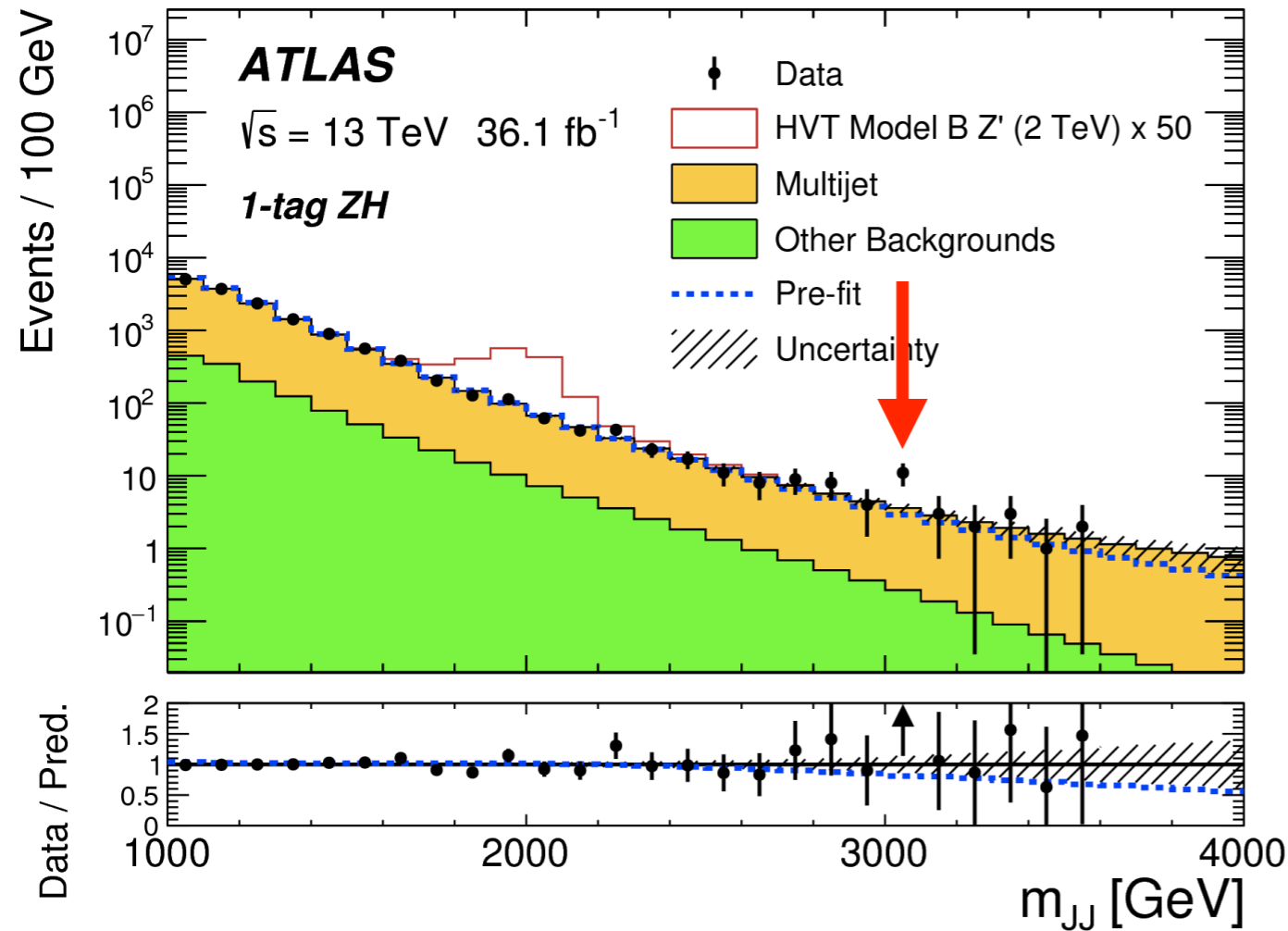
Boosted Higgs tagging

- $m(h)$ によるカットに加え、Large-R jetにb-jetが付随することを要求
- ATLASはsub-jetがb-tagされる本数（1本 or 2本）でカテゴリ分け
- CMSはMVA-baseのdouble b-taggingを用いている。ATLASも開発を進めている



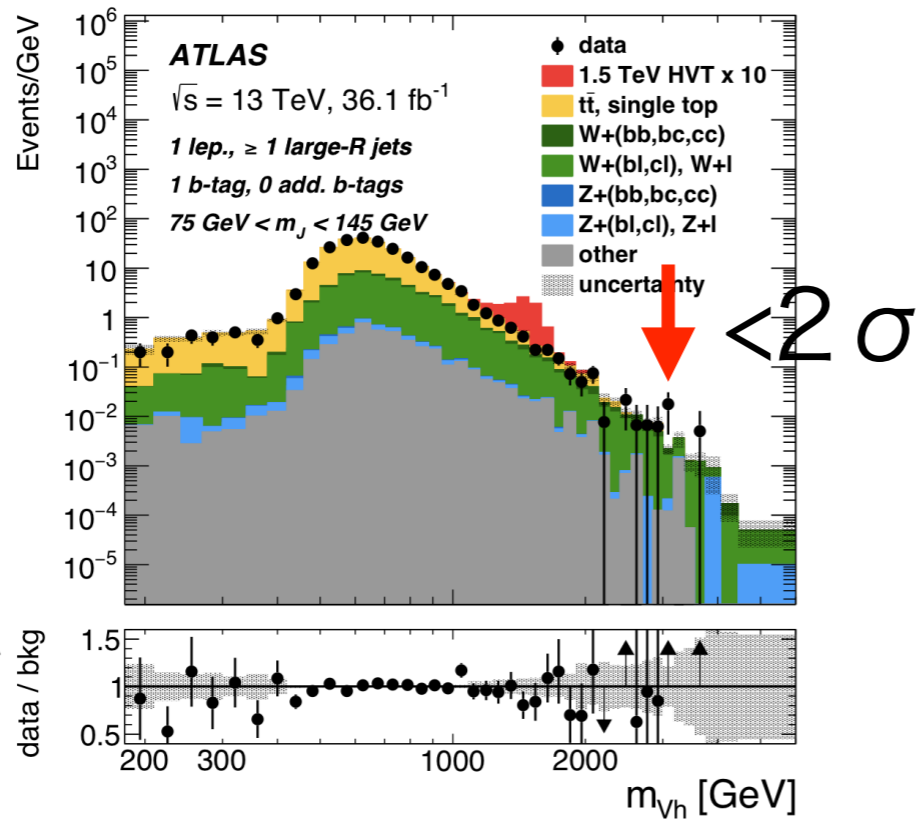
Vh共鳴探索

- ヒッグスタグしたlarge-R jetを用いたqqbbモードでの探索で、 $m=3\text{TeV}$ に $\sim 3\sigma$ のexcess
- CMSでは見られない (代わりに 2.5TeV にexcess)
- Semi-leptonic channelでも確認を行った

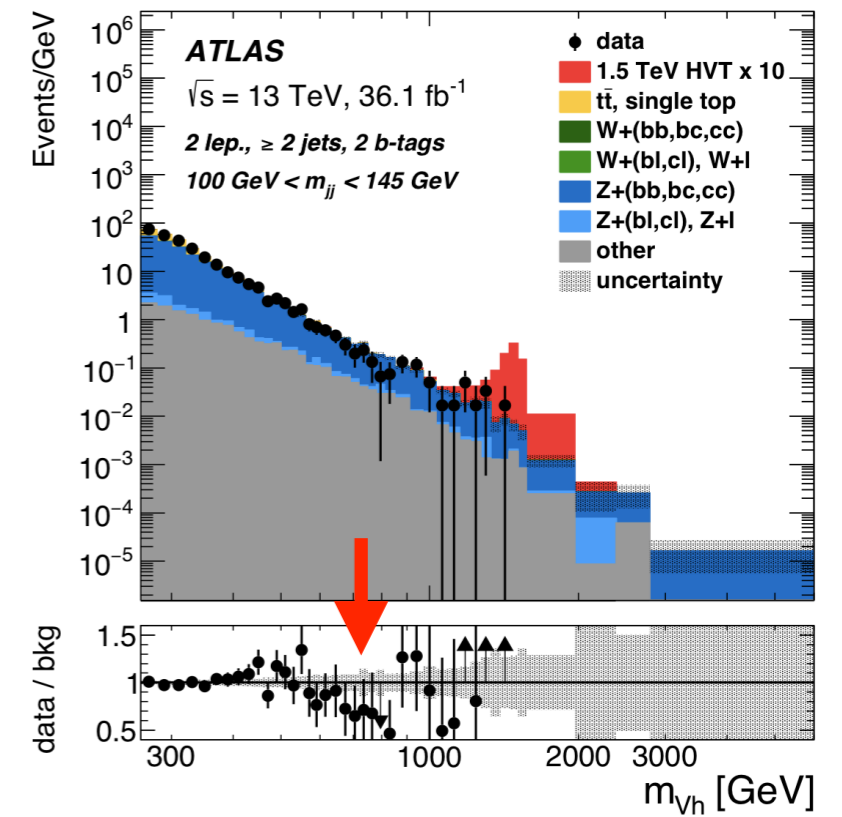


Vh semi-leptonic

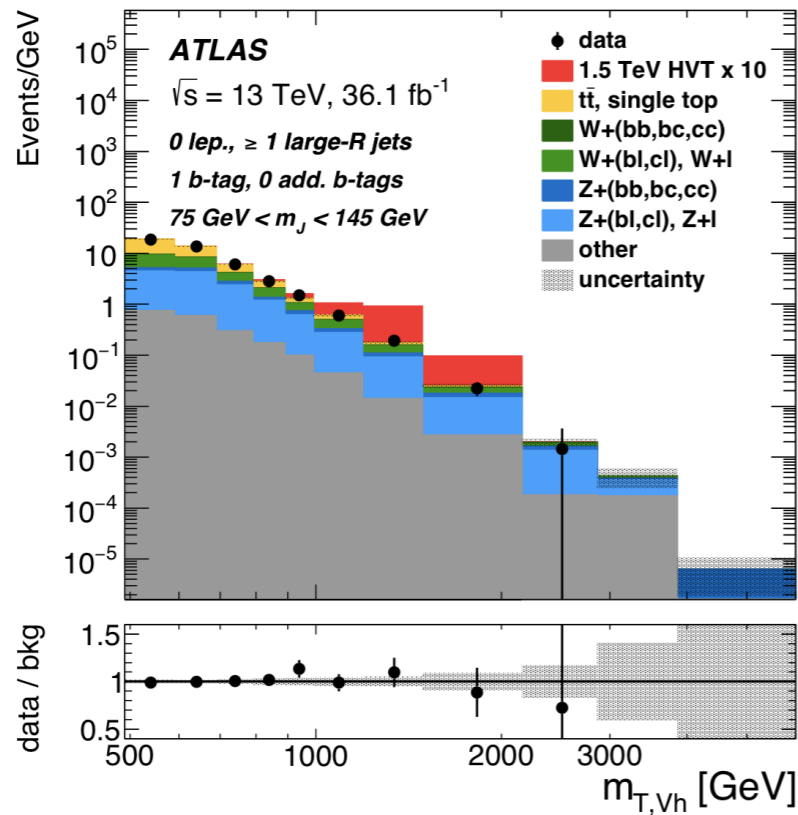
High-mass
WH (1-lep)



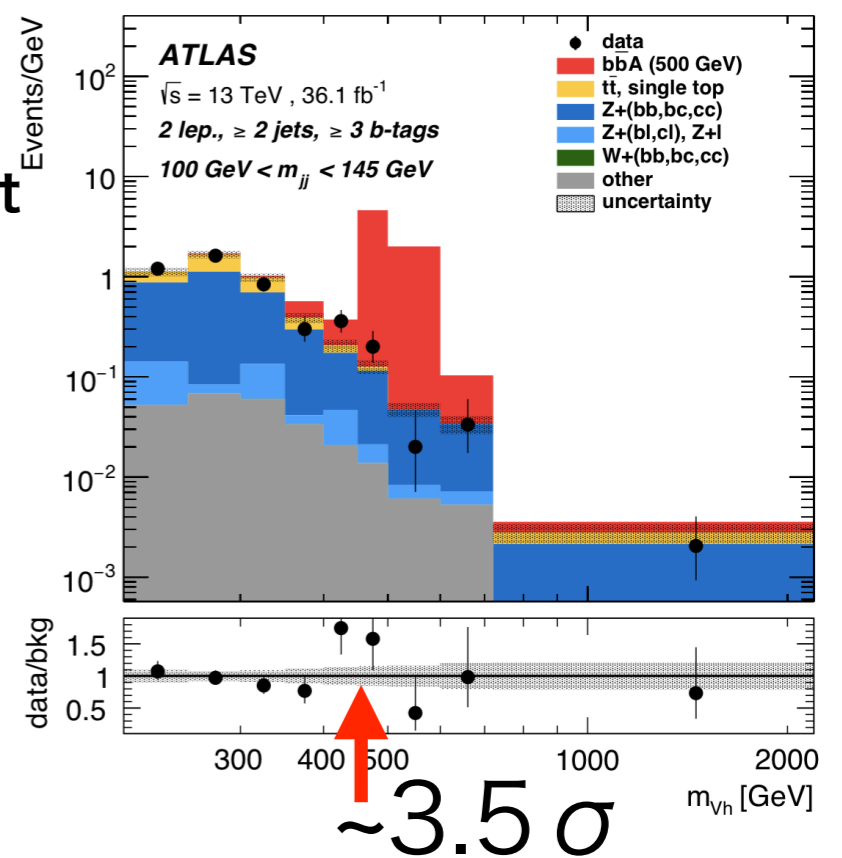
Low-mass
ZH (2-lep)

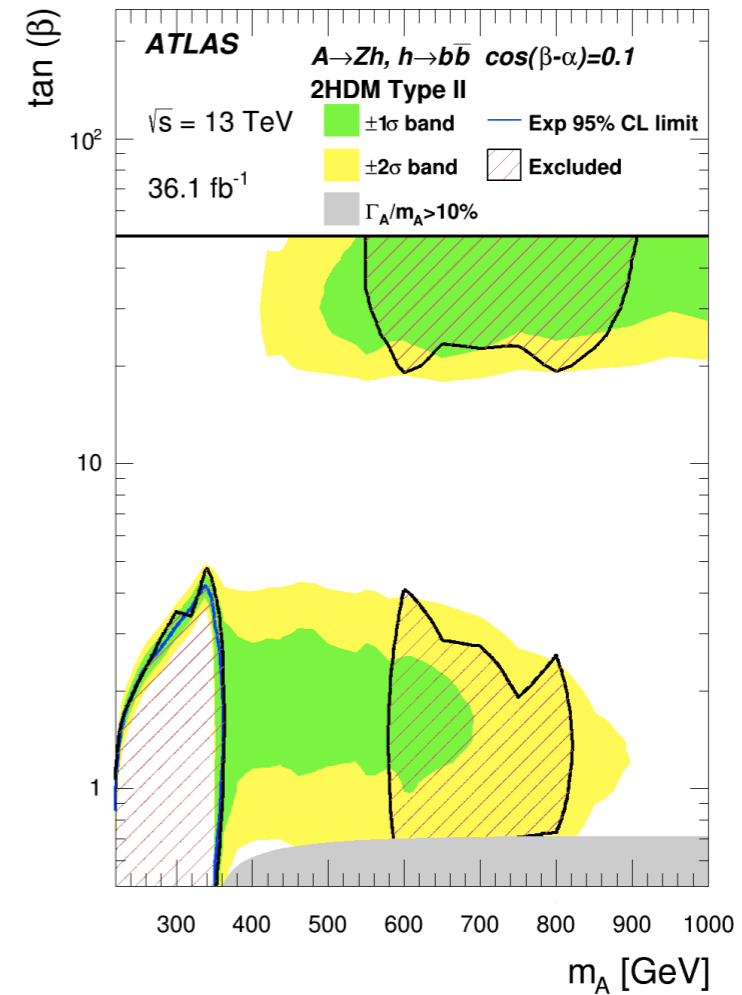
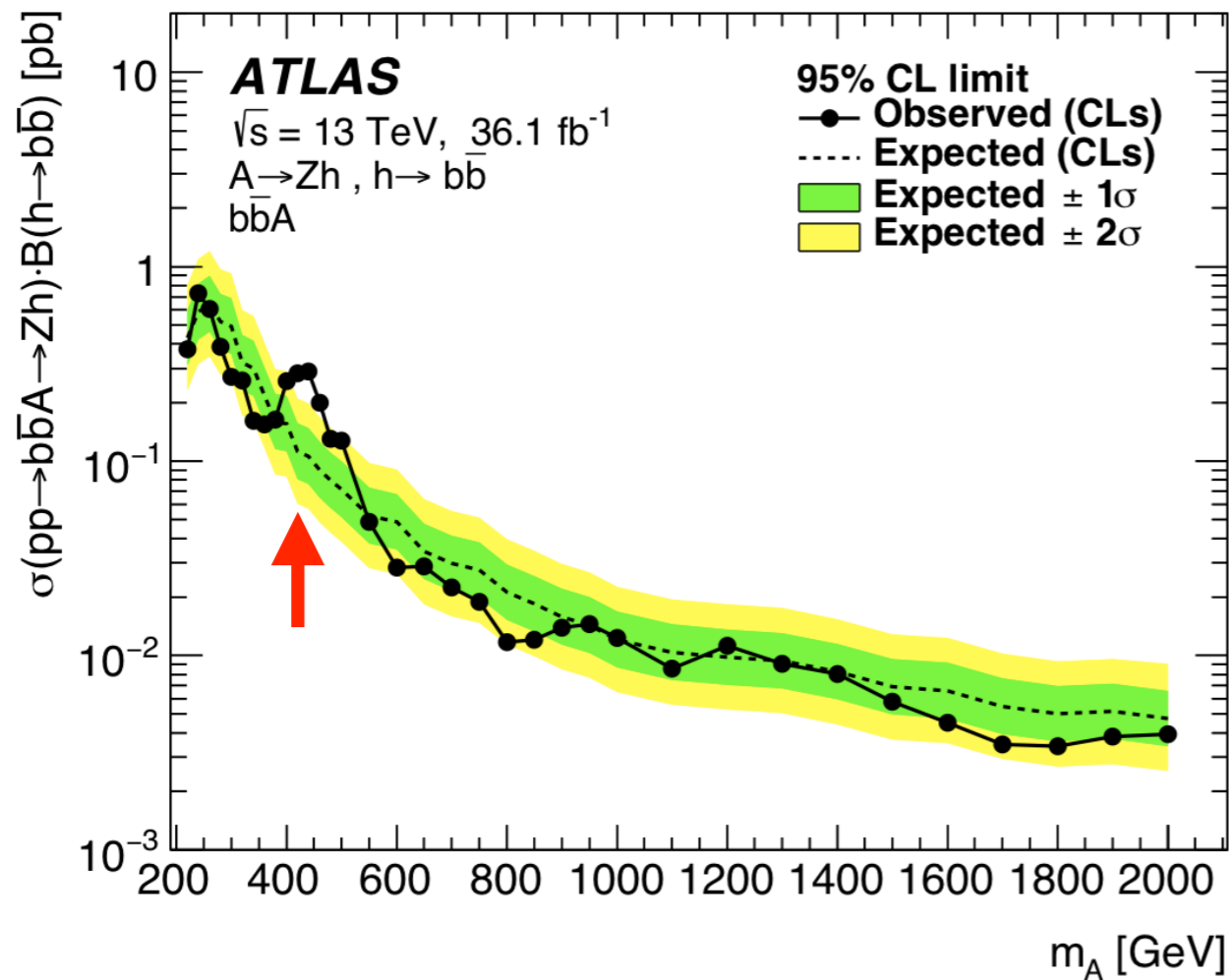
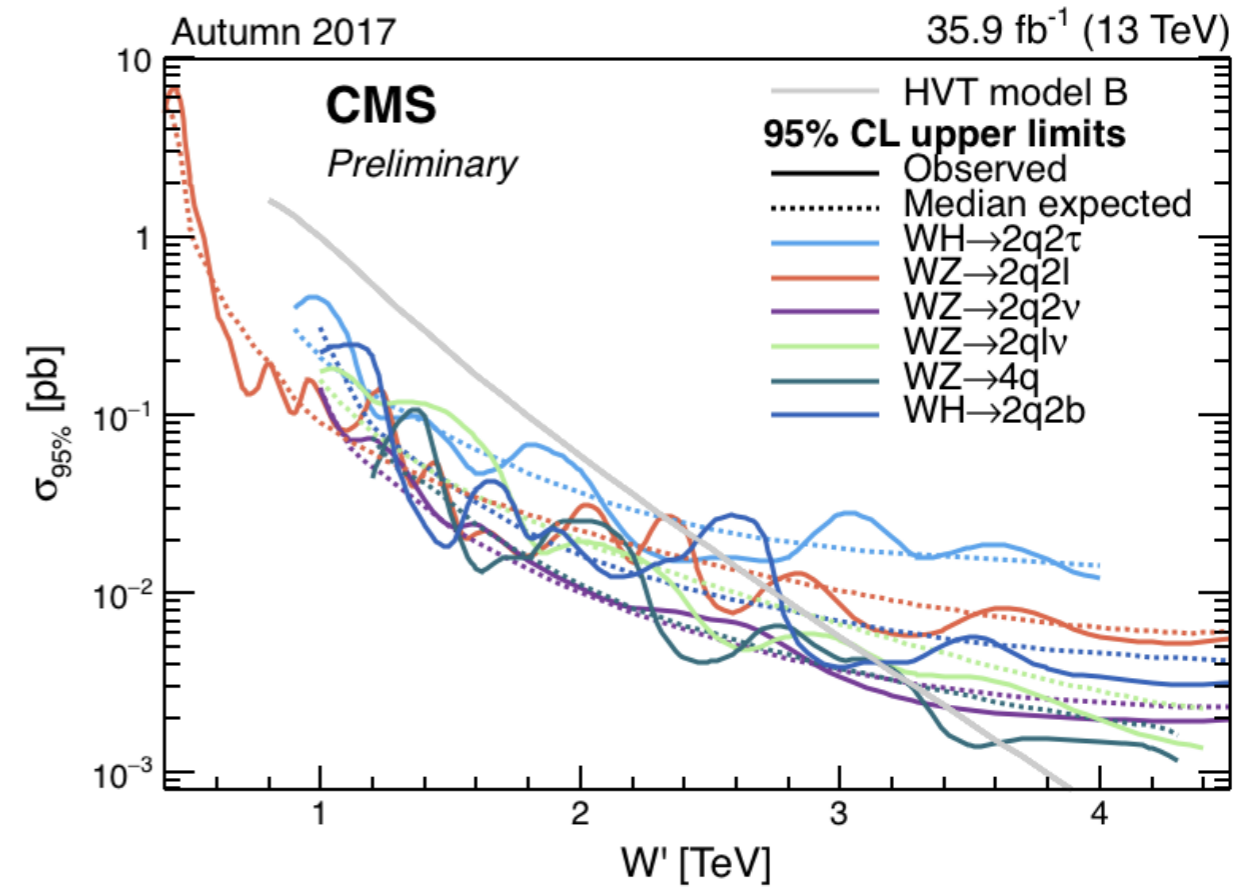
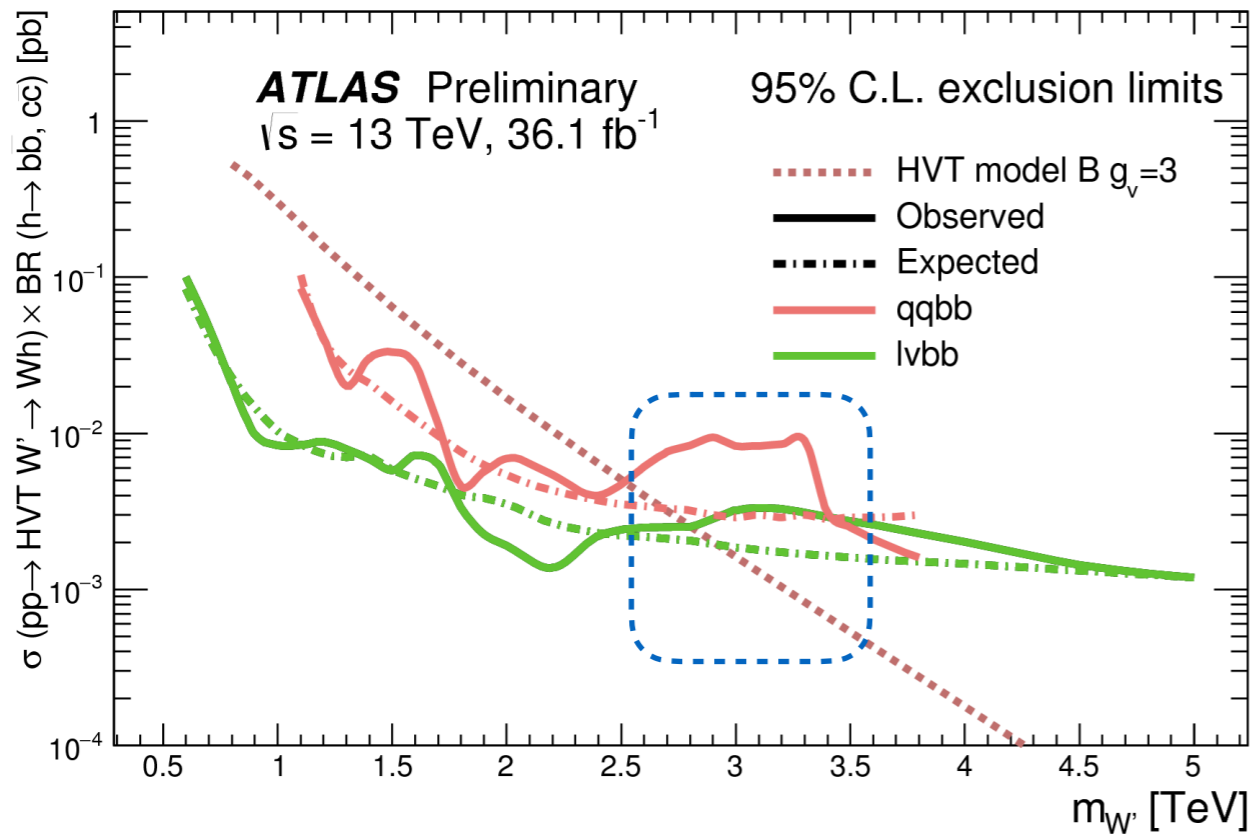


High-mass
ZH (0-lep)

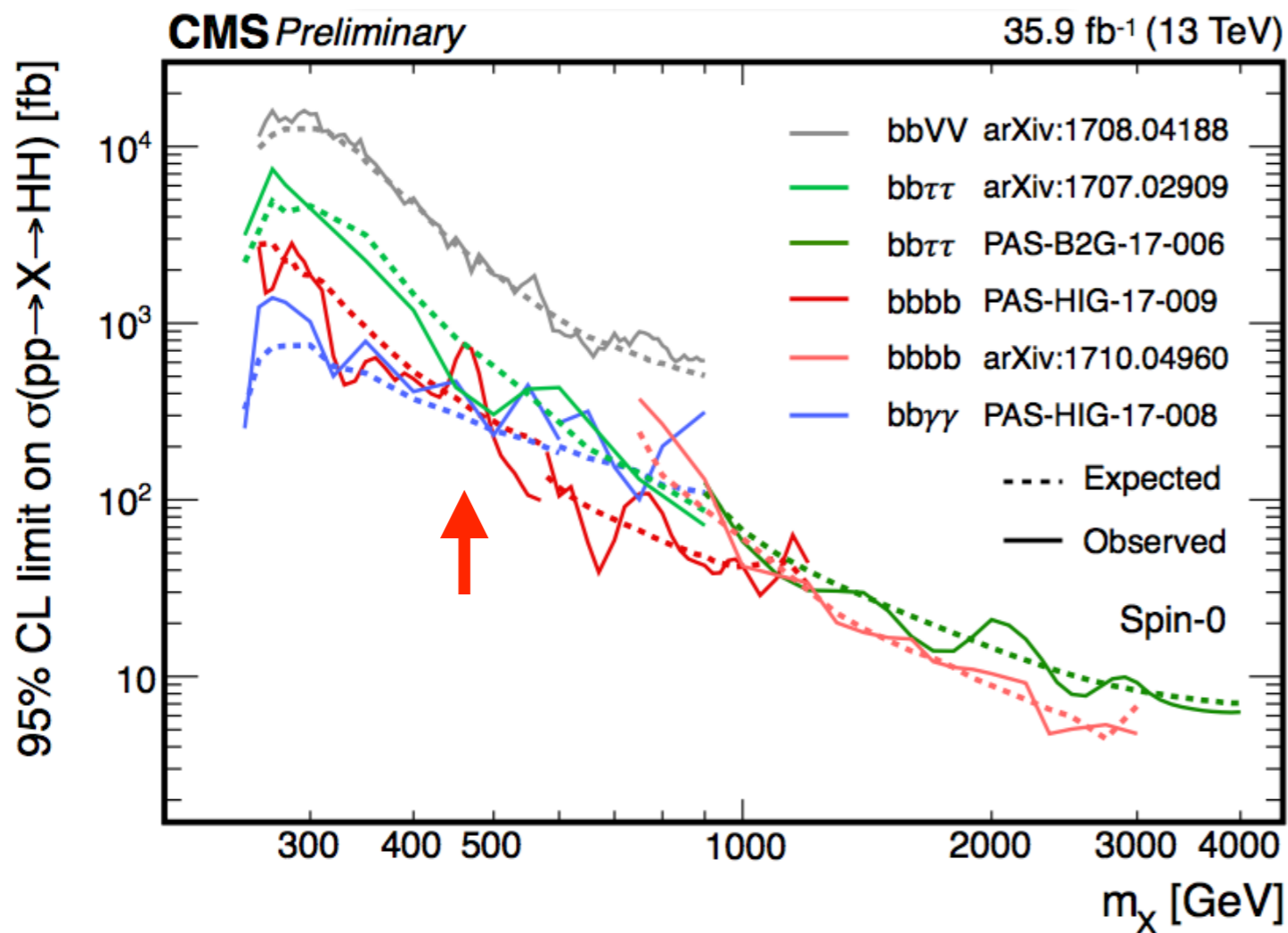


Low-mass
ZH (2-lep)
+ additional b-jet
bb(A \rightarrow Zh)

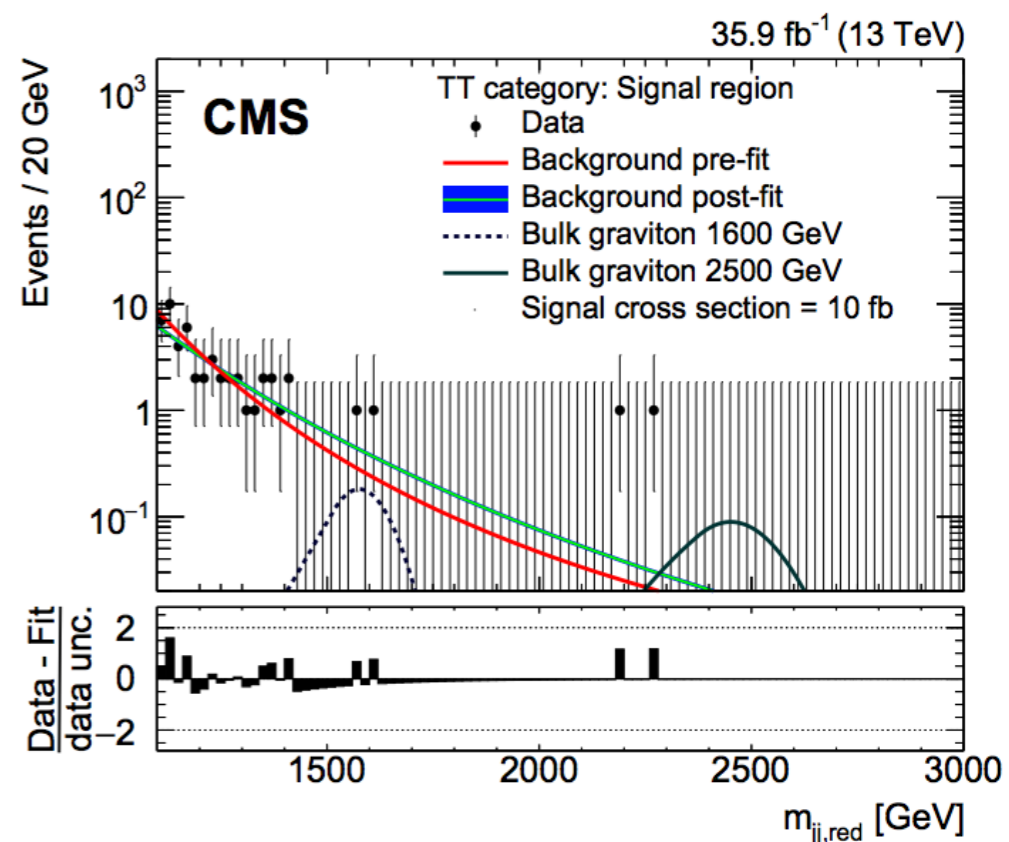
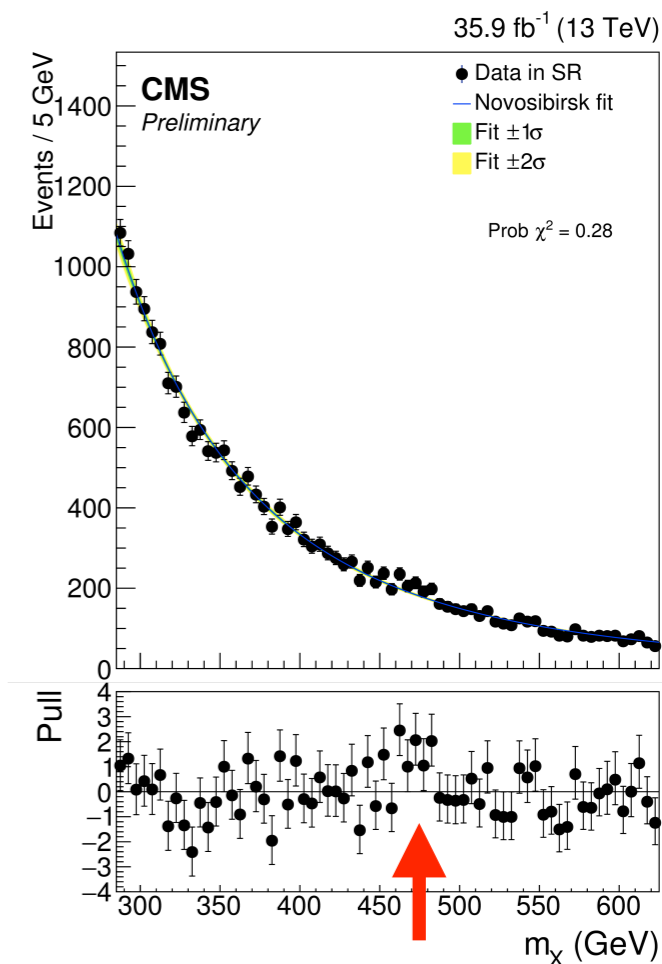




Di-higgs



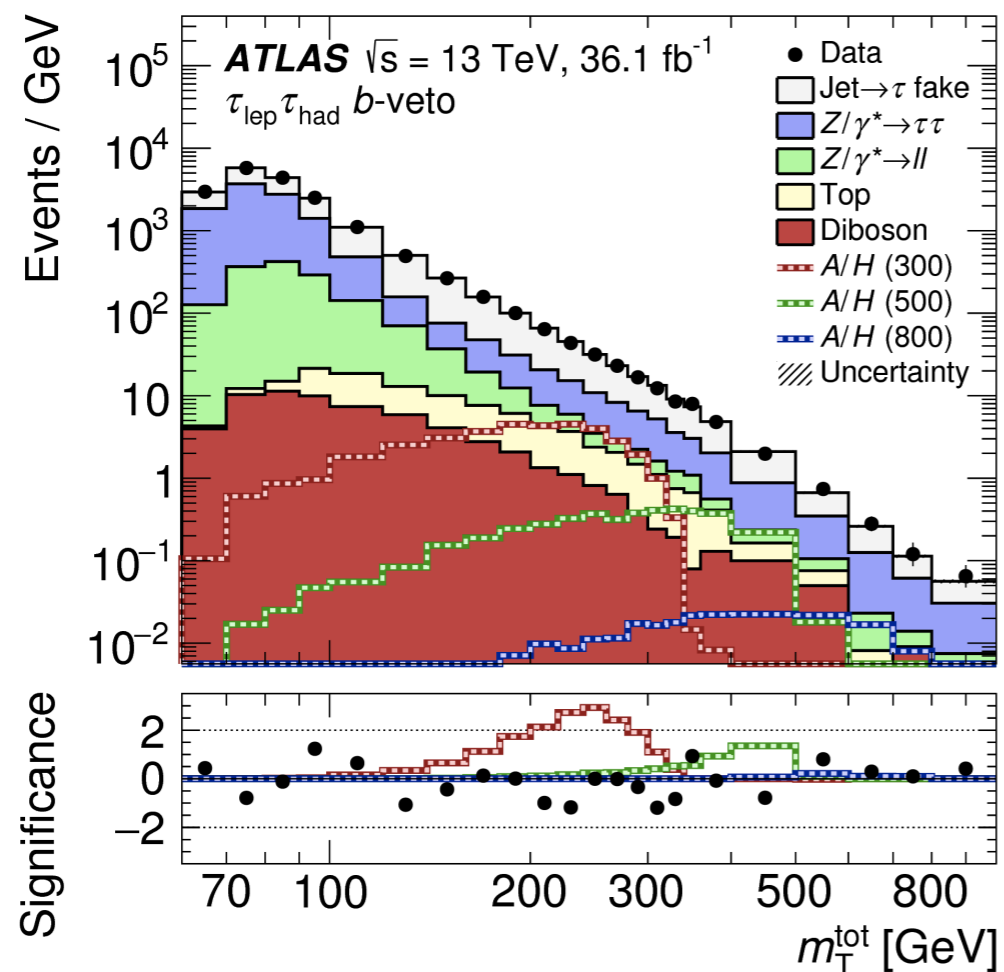
- Low-mass: 4つのb-jetsで質量を再構成
 - ~450GeVに $>2\sigma$ のexcess
 - ATLAS $A \rightarrow Zh$ とだいたい同じmass。しかしbb $\gamma\gamma$, bb $\tau\tau$ では見えていない
- High-mass: 2つのlarge-R jets w/double b-tagging



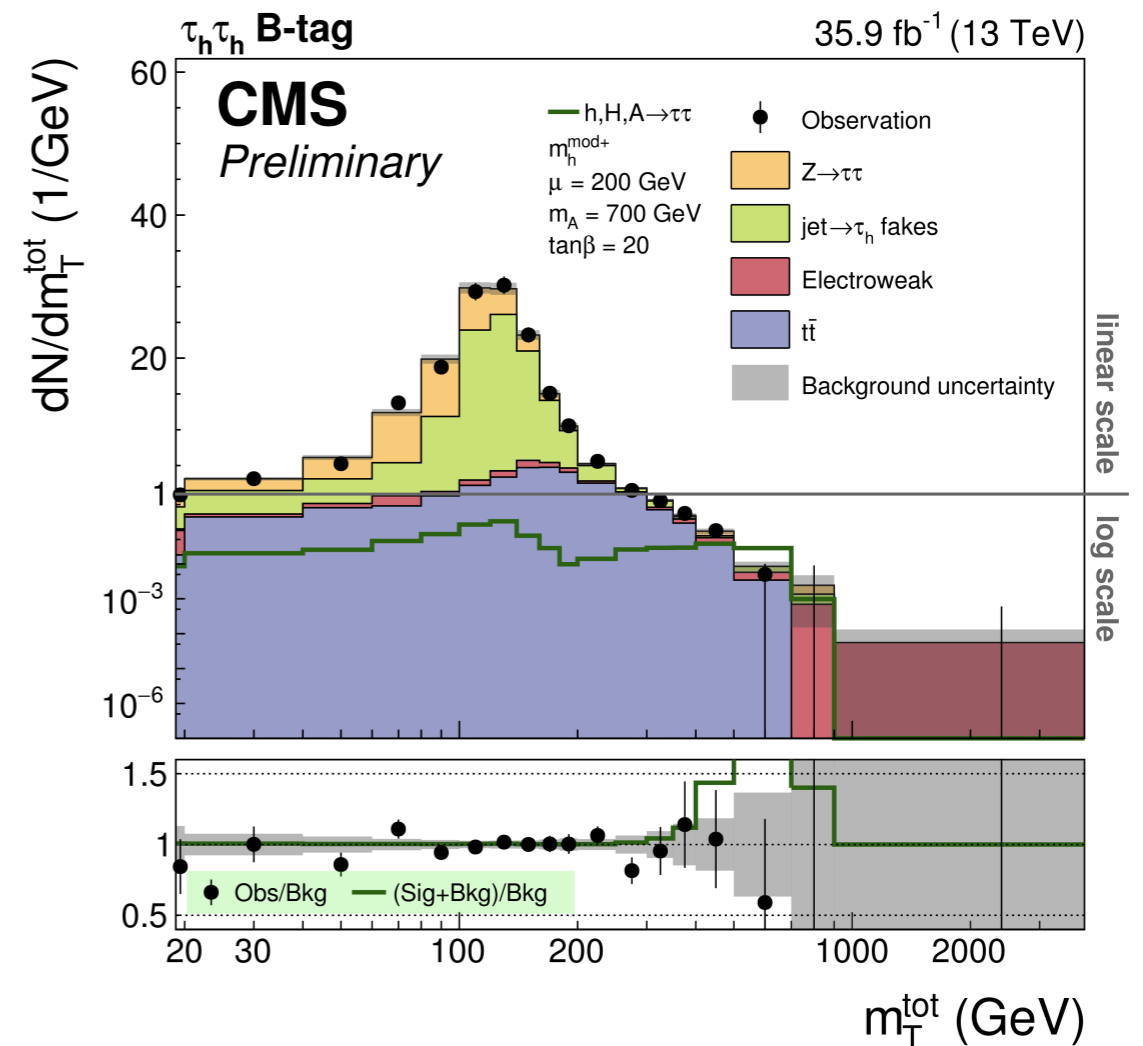
A/H \rightarrow $\tau\tau$

- τ のleptonic (e/ μ), hadronic decayを用いる
- bbA productionを考慮して、b-tag categoryを導入
- 有意な信号は観測されなかった

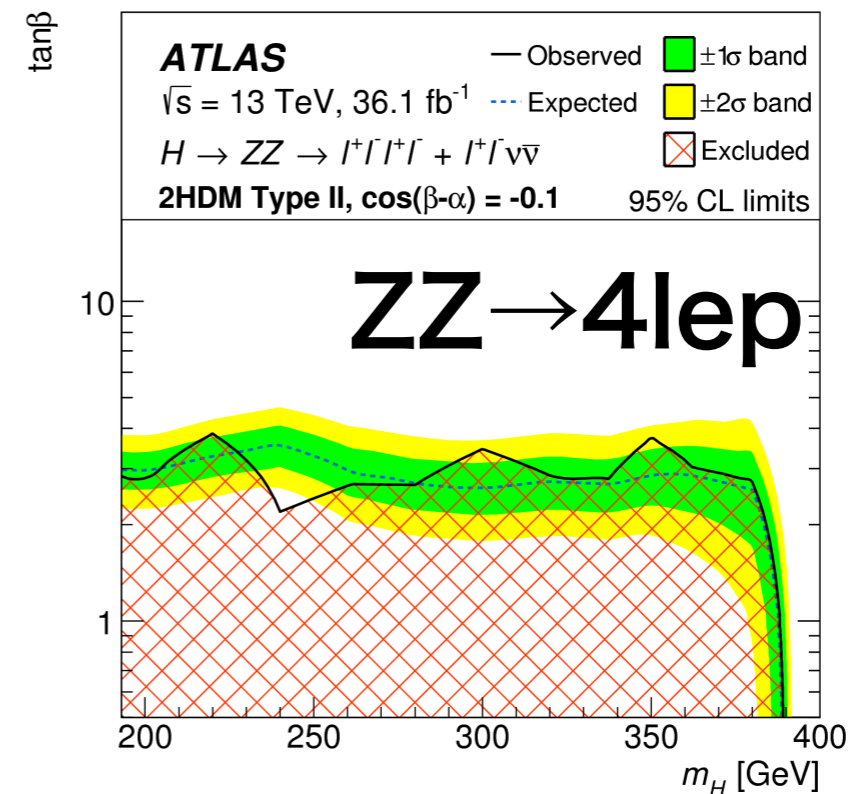
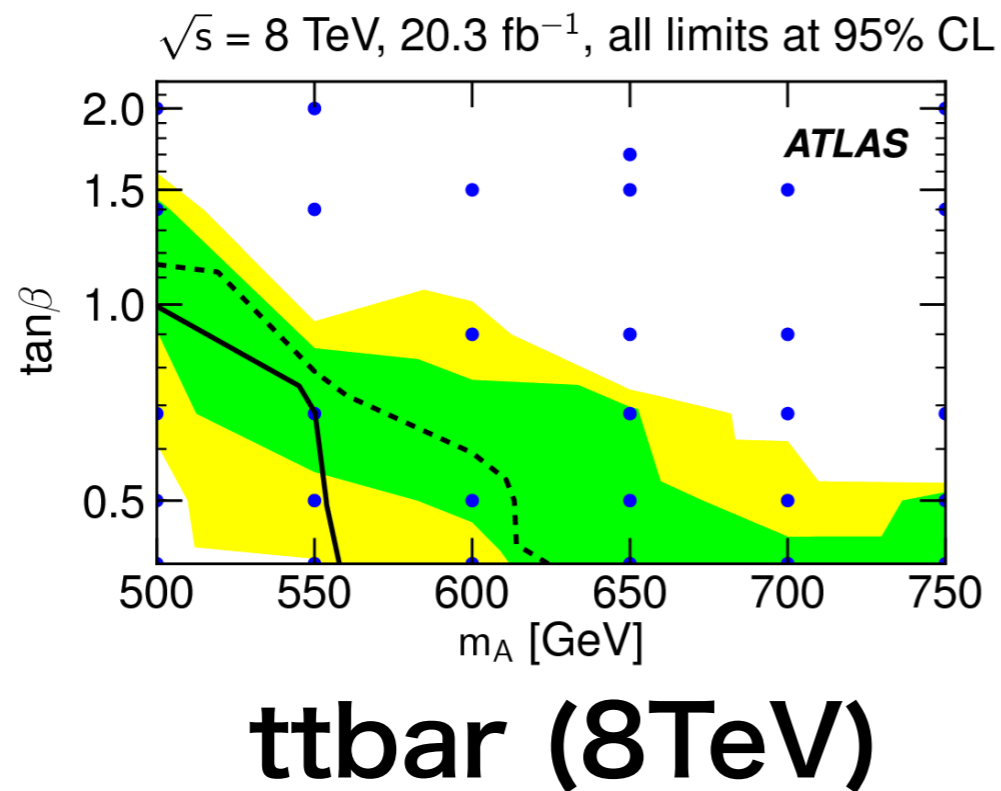
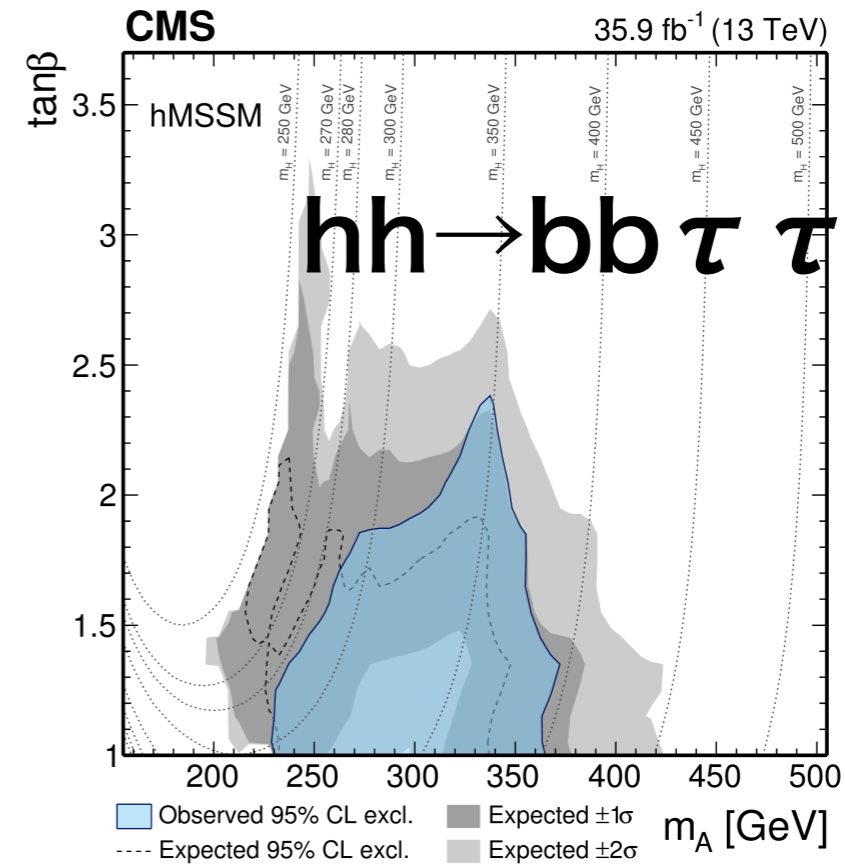
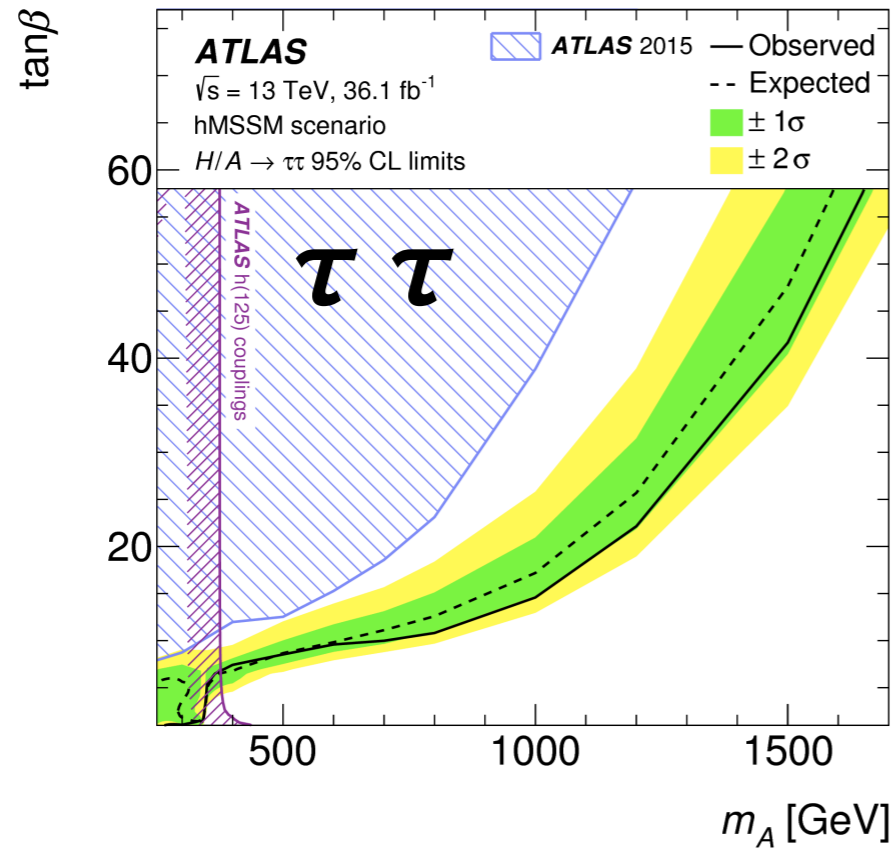
b-veto



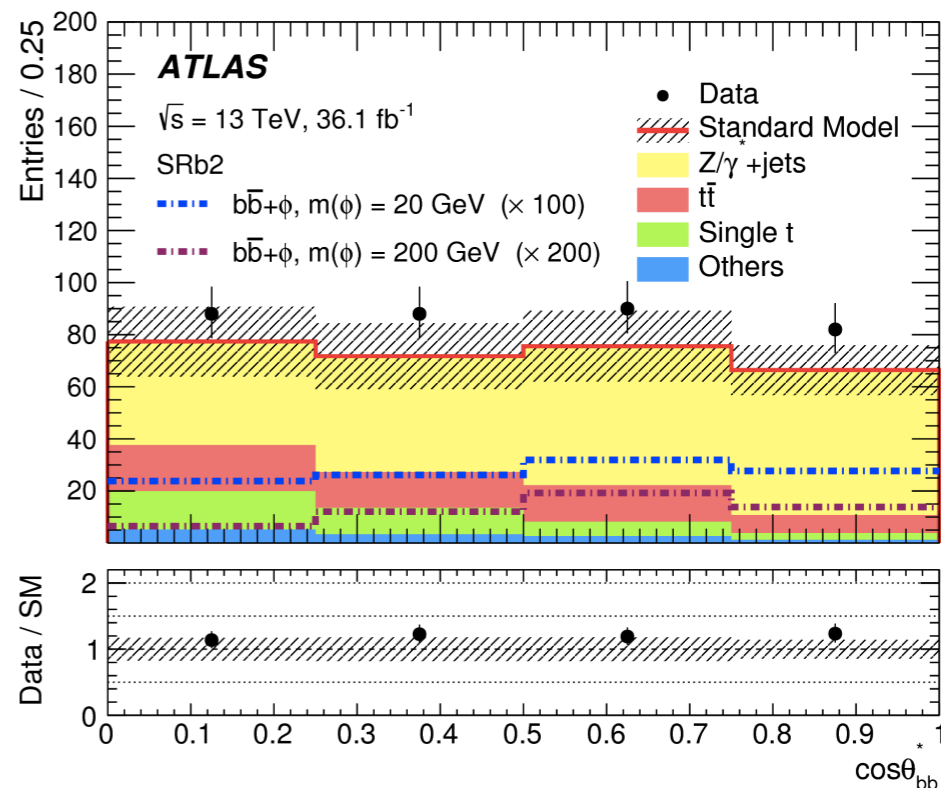
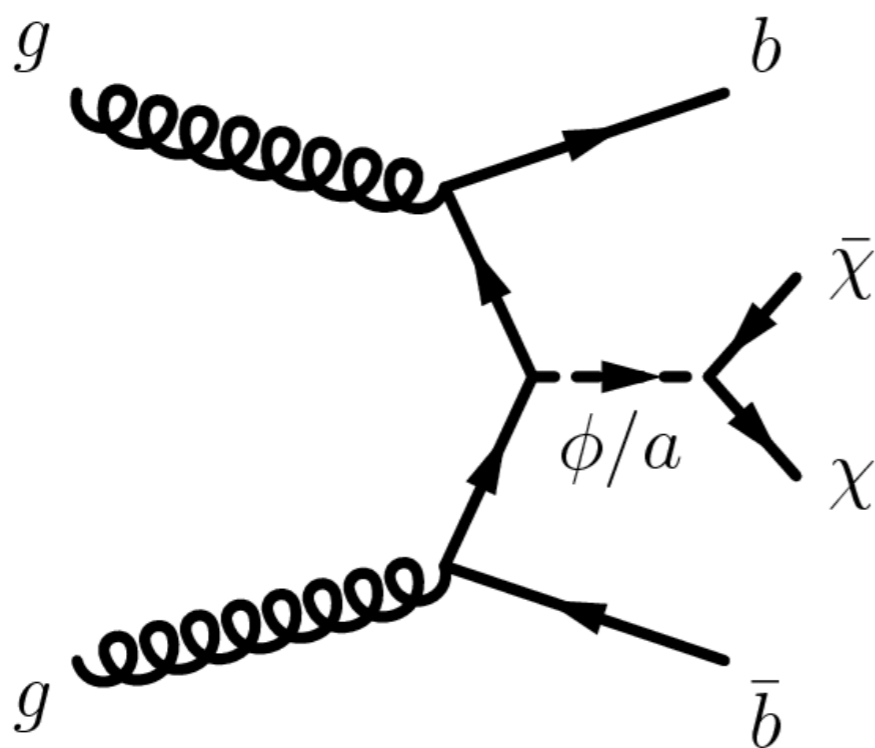
b-tag



2HDMに対する制限

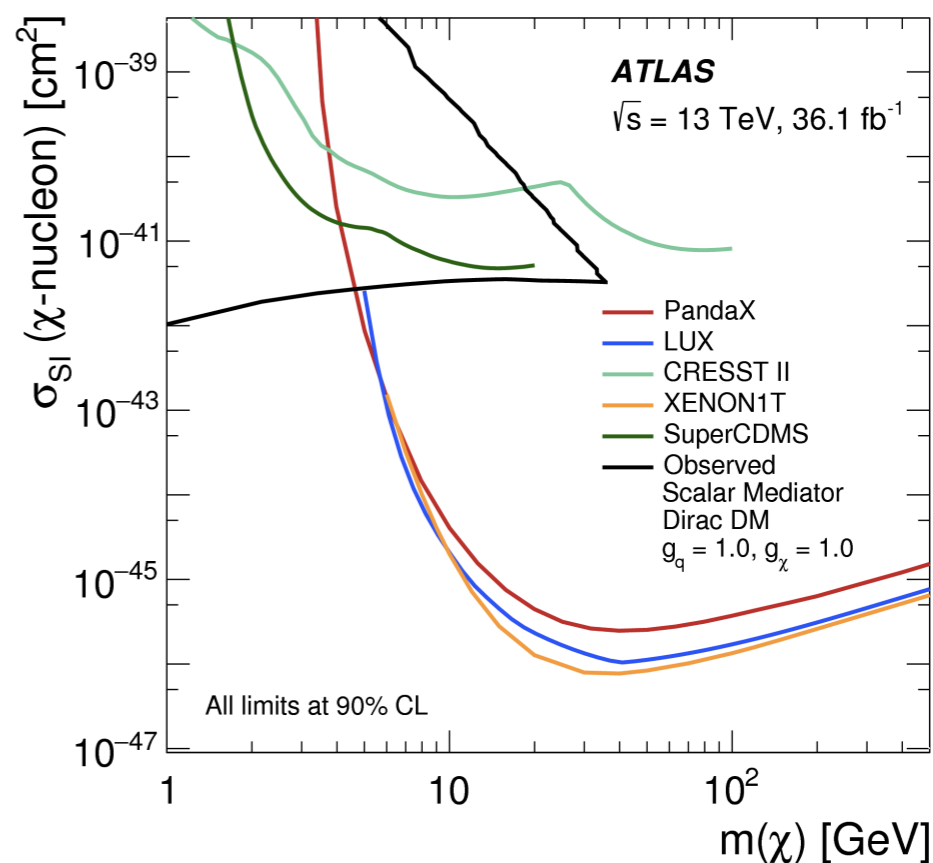


Invisible Higgs associated with b-quarks



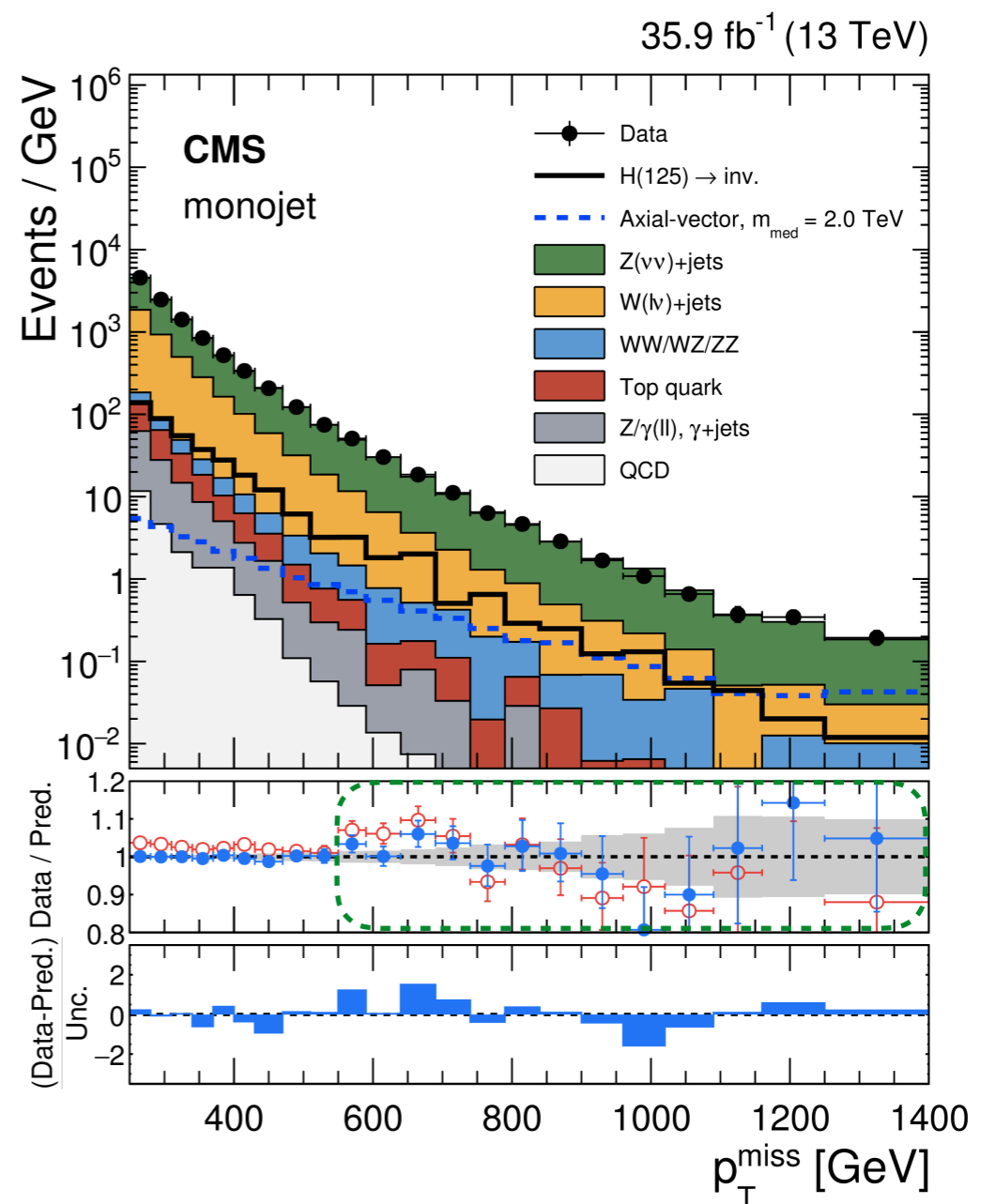
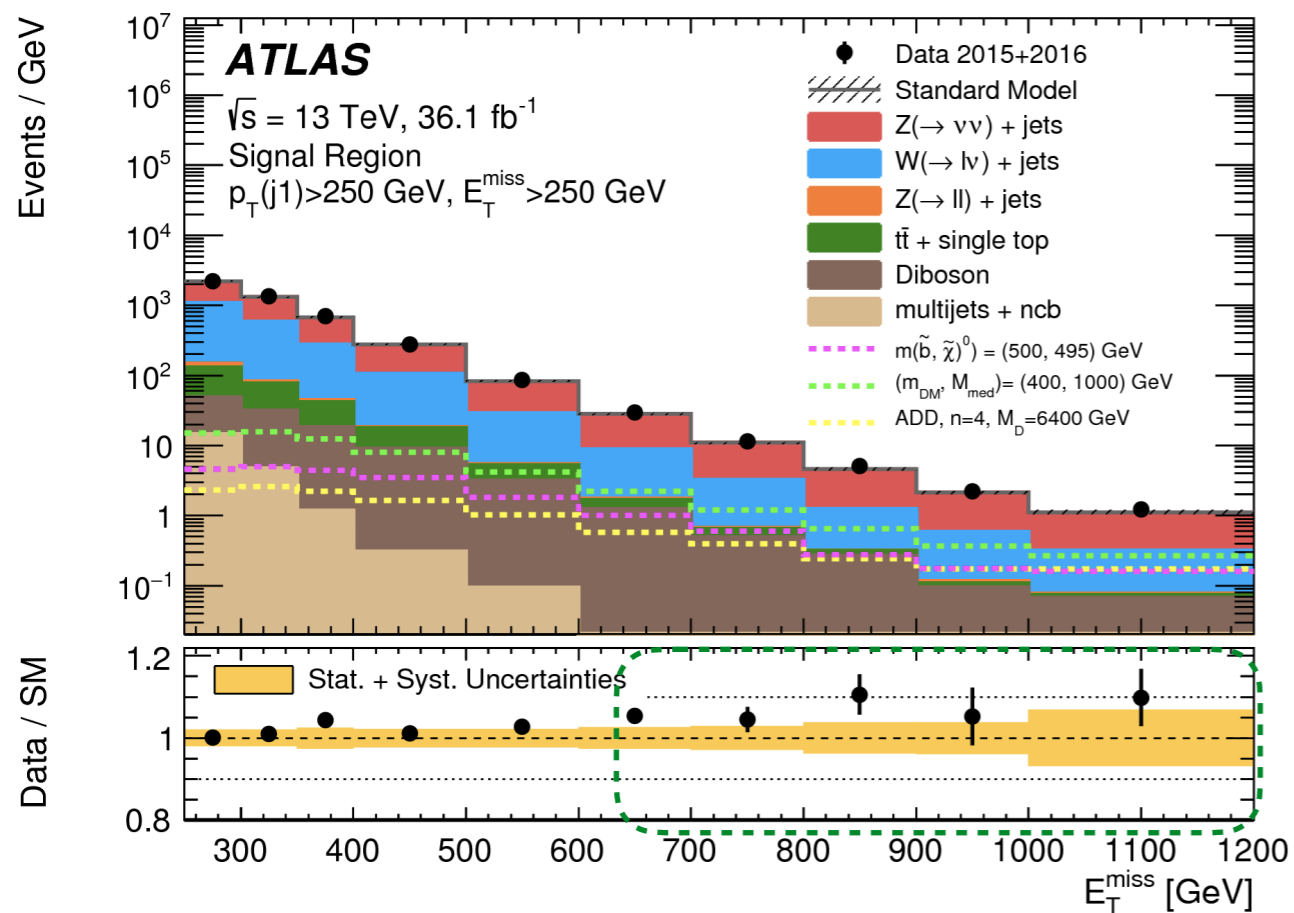
bbが前後方にいると $\cos \theta_{bb} \sim 1$ になる

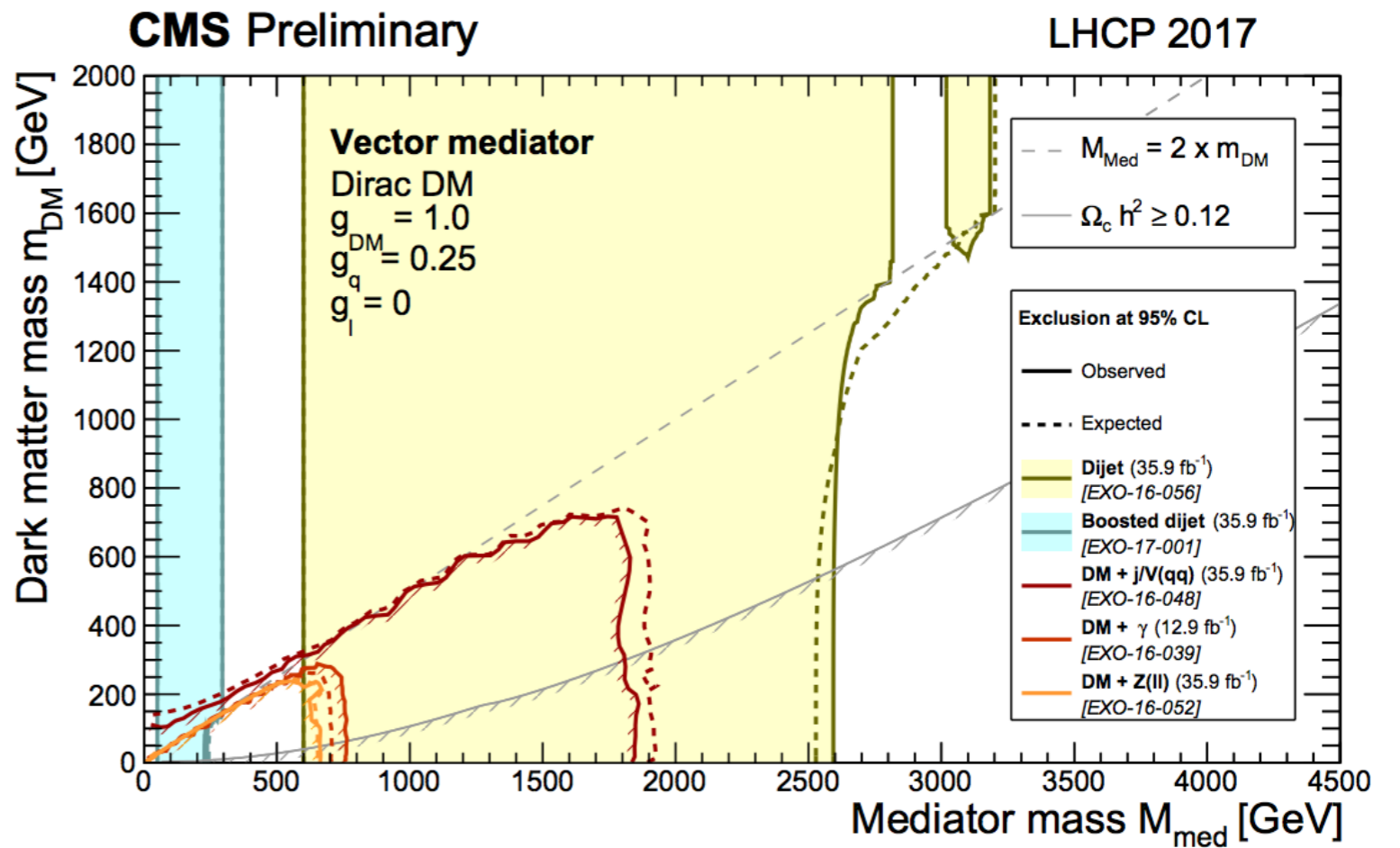
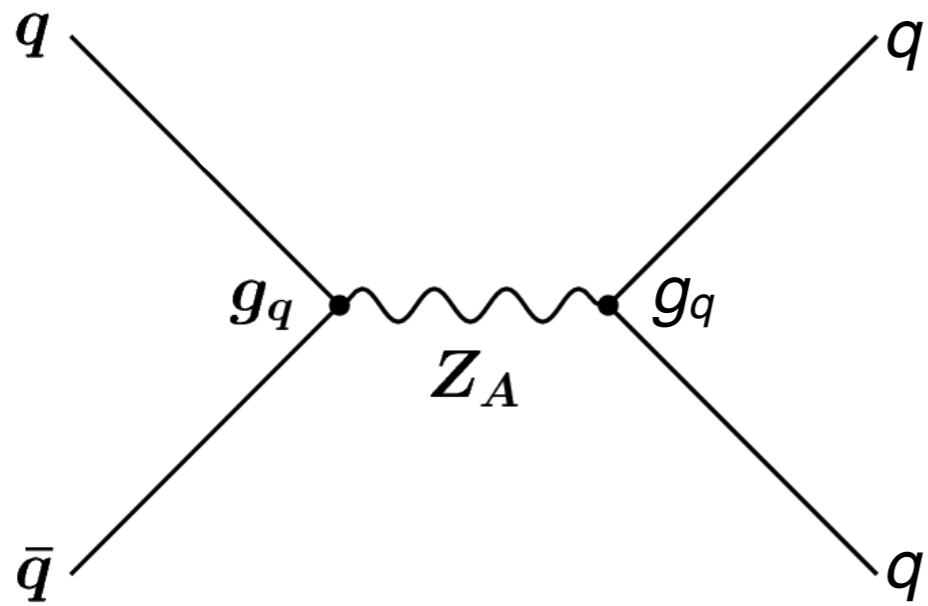
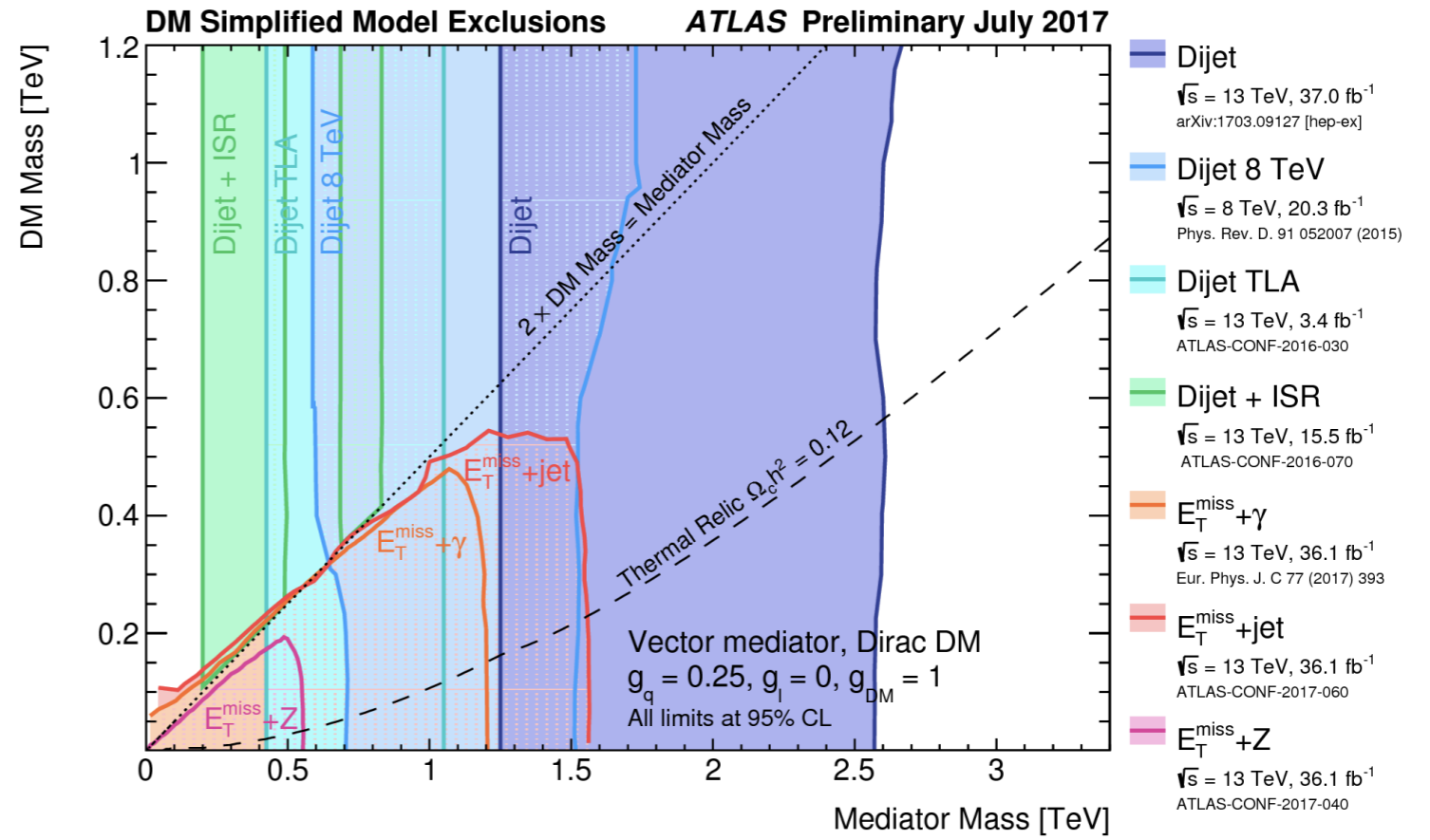
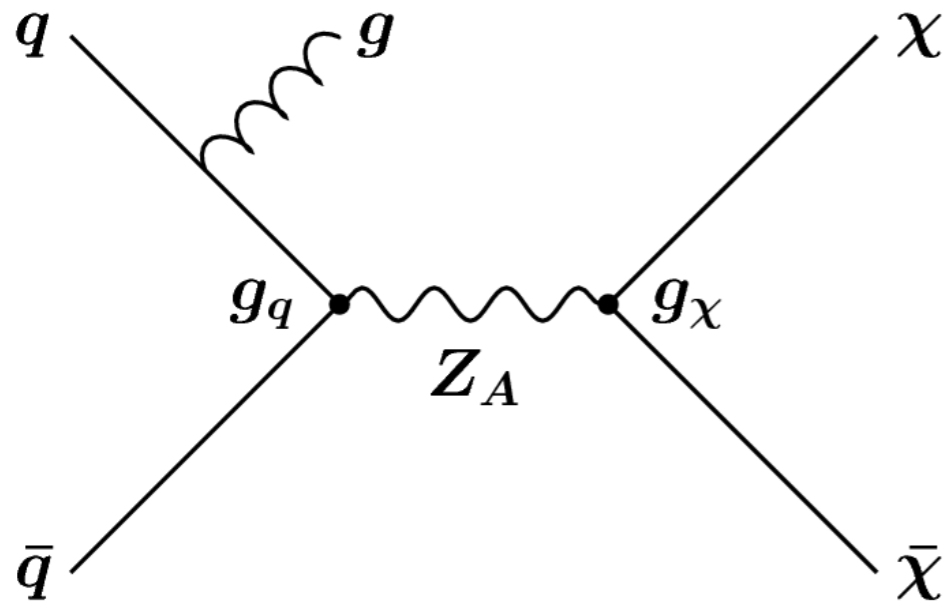
- $\sim 1\sigma$ の超過 (まあ、よく合っている)
- Invisible HiggsはZH (2-lepton) channelでも標準模型と非常によく合っている
- $ttH \rightarrow$ invisibleはstop searchのre-interpretationで見ている。やはり $\sim 1\sigma$ くらいのexcessはあるものの、SMに合っている



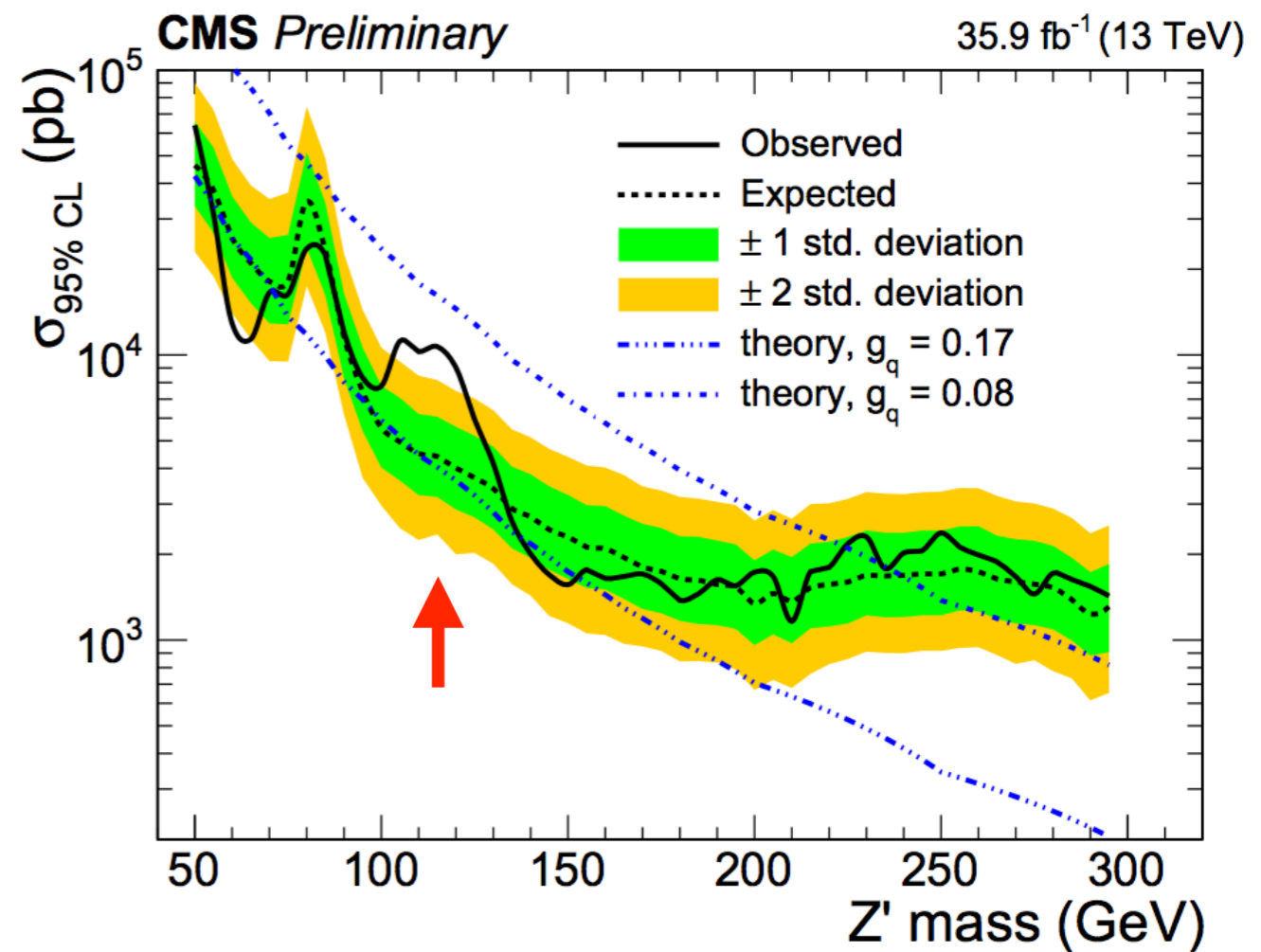
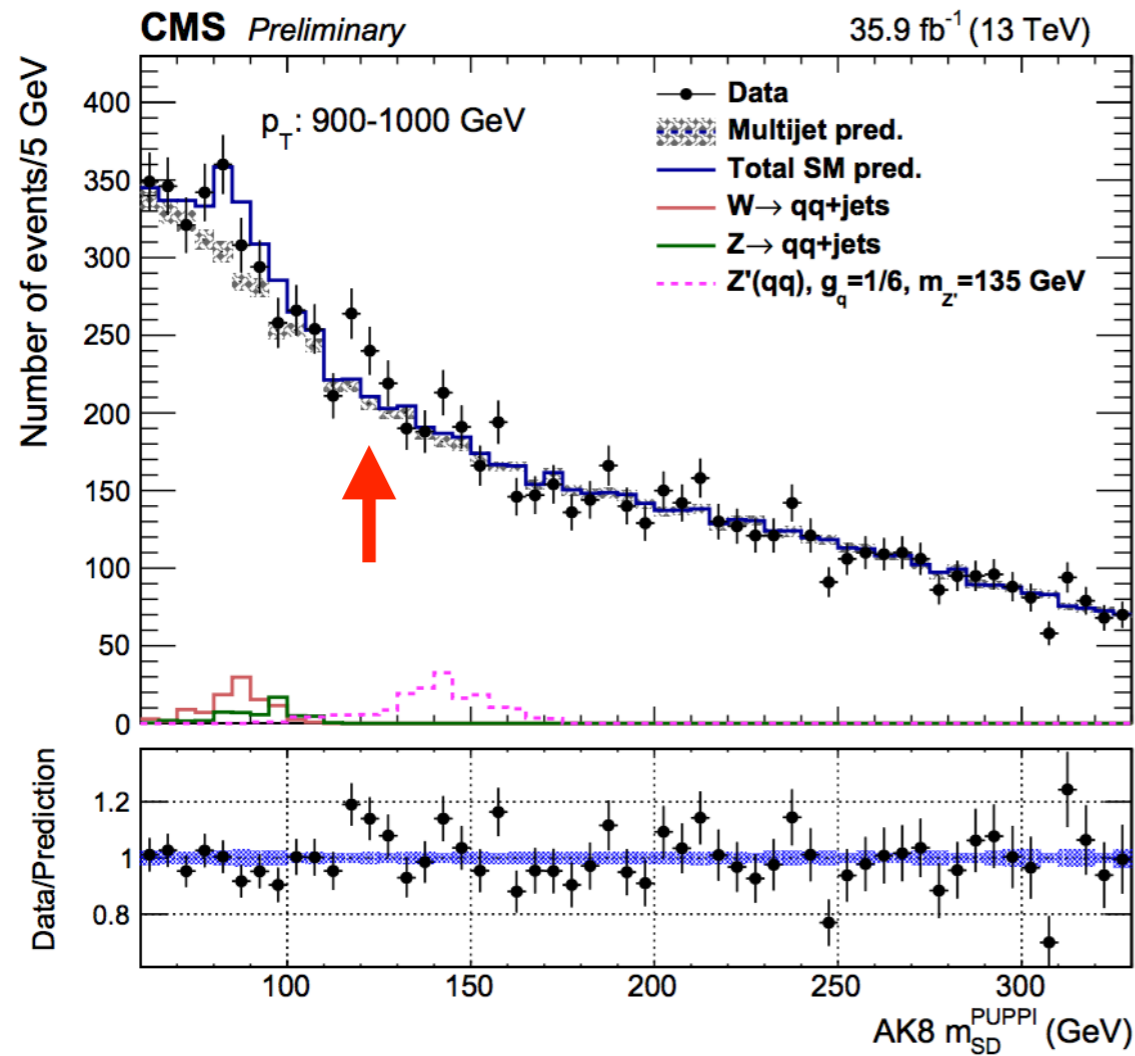
jet + missing 解析

- ではもっともシンプルなmono-jet解析はどうか？
- ATLAS $>1\sigma$, CMS $\sim 1\sigma$ のexcess。今後も要注目

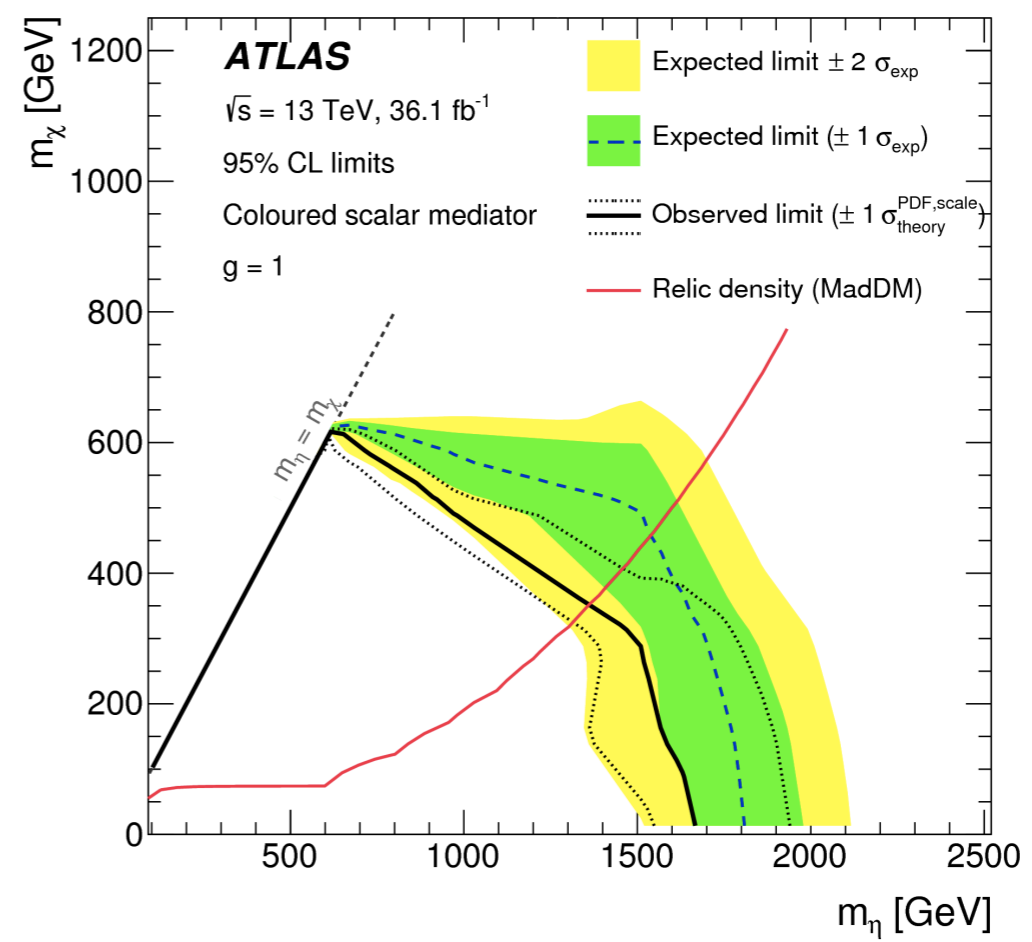
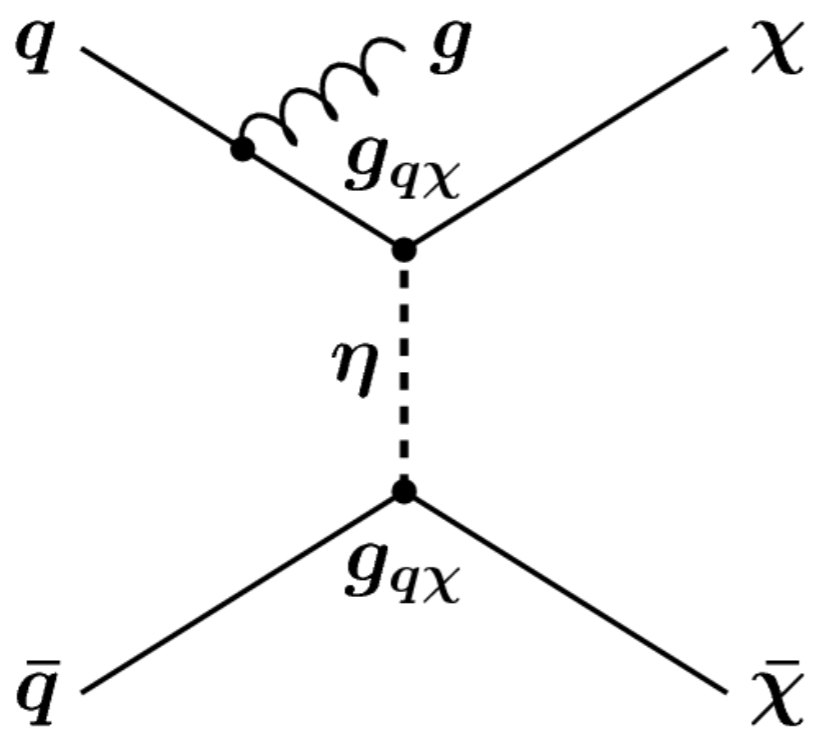
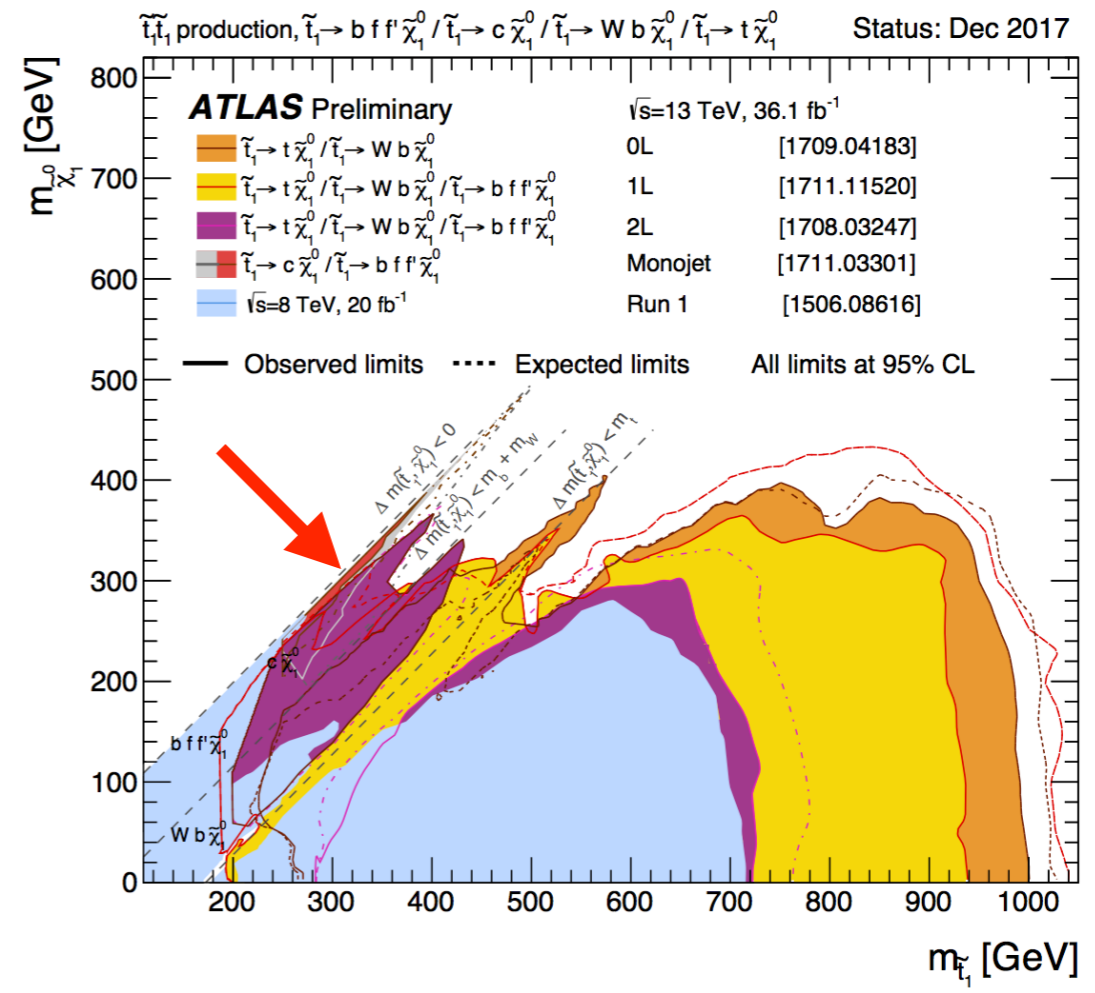
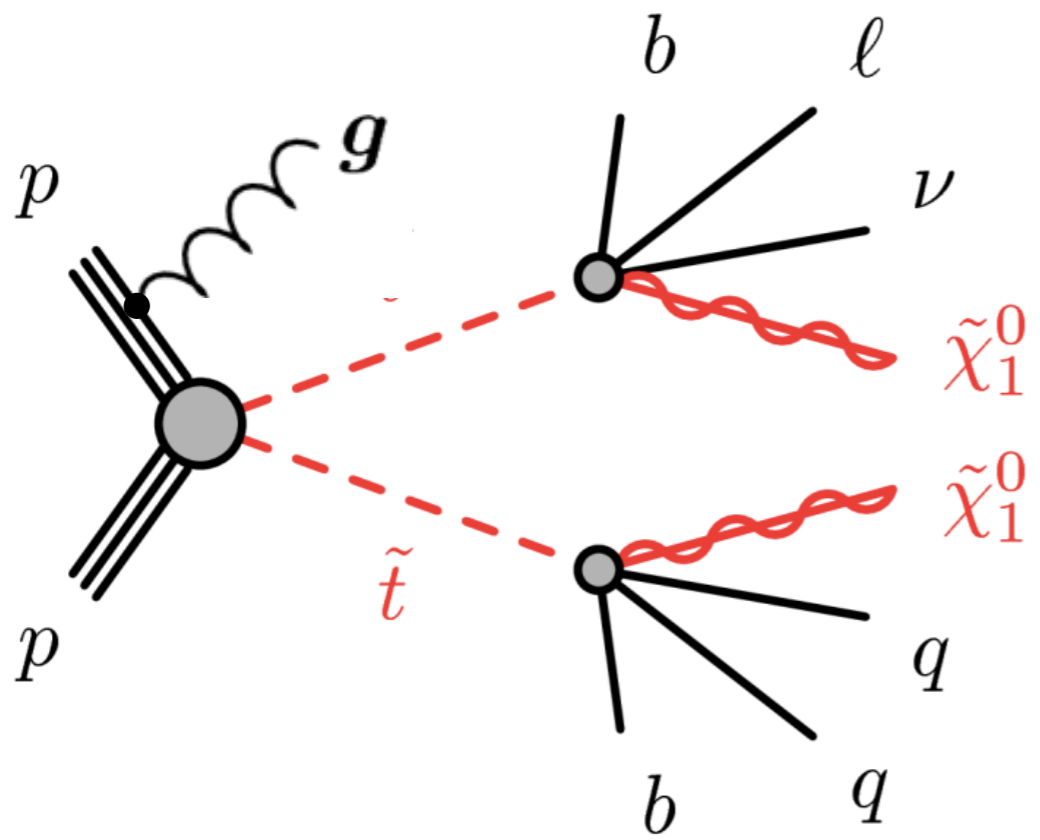




ISR + boosted $Z' \rightarrow qq$



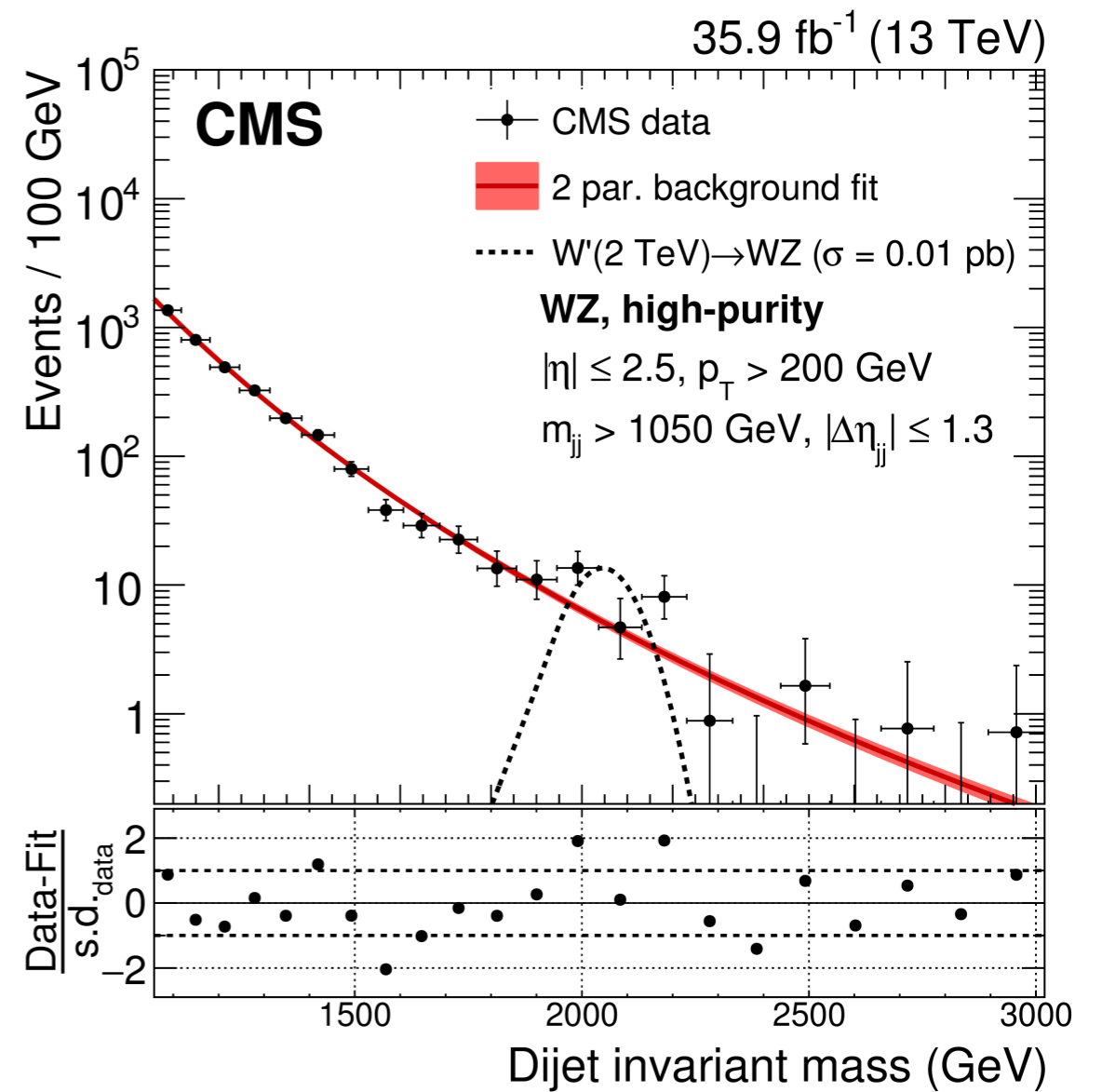
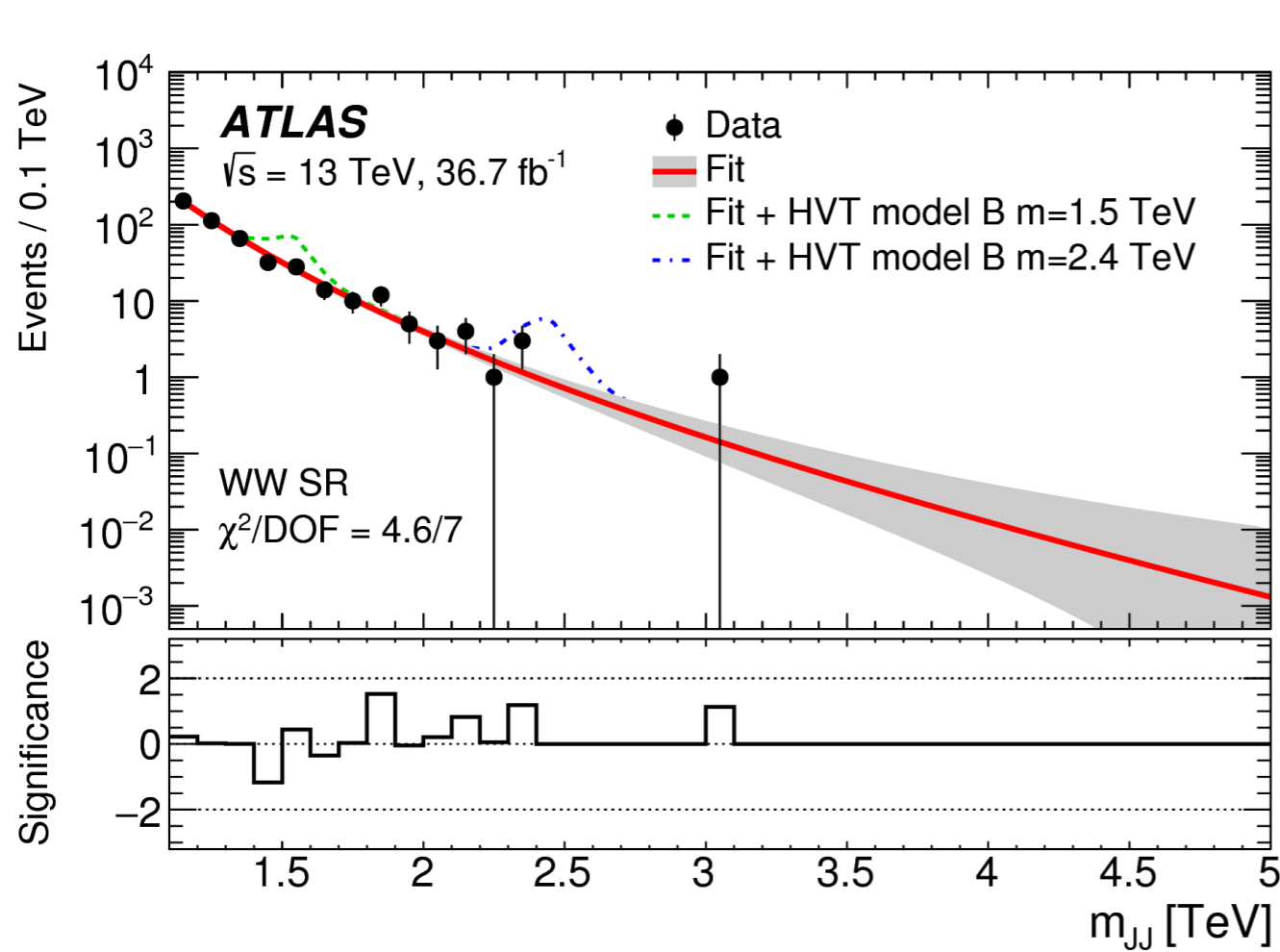
- $p_T > 500$ GeVを要求することで $m > 50$ GeV から見れる
- 115 GeV に $\sim 3\sigma$ excess
- ATLAS はまだ見ていない



Summary

	ATLAS	CMS	Comment
ZZ→4lepton ~250GeV	local ~3.5σ	local ~1σ	ggFとVBF-enriched SRの両方で見えている (ATLAS and CMS)。4-electron channelに多め
	~700GeV local ~3.5σ	No excess	他のチャンネル(llvv, llqq, vvqq)でも見えていない
ZZ→llqq ~700GeV	Deficit ~3σ	Deficit ~3σ	主なb.g. : Z+jets。ATLAS Sherpa v.s. CMS MadGraph
Vh→qqbb ~3TeV	local ~3σ	No excess	Wh→lvbbで<2σ。Zh→llbb/vvbbでは見えていない CMSのVH semi-leptonicはもうすぐ出る(らしい)
	A→Zh ~450GeV local ~3.5σ	まだ出てない	特にbbAで強く出ている。CMS HH→4b ~450GeVに~2σ。 bbγγ, bbττでは確認できない。ATLAS HHはもうすぐ出ます。 ttbarももうすぐ。A→ττでtanβ>~8は棄却されている。
SM EW VBS	8TeV only	Same-sign di-lepton 5σ measurement	ようやくSMに感度が出てきた。 今後はdifferentialを測定していき、ヒッグス機構を検証すると共に aQGCなどhigh-mass scaleの新物理の検証
mono-jet DM search	~1σ	~1σ	1σですが……ATLAS/CMSで同じ方向にズれている さらにデータを足して検証していく
	No excess	~3σ@>4.5TeV Angular analysis	N/A
Dijet	まだ出てない	~3σ@115GeV ISR+Boosted Z'→qq	DM mediator mass ~50GeVから~300GeVまでカバー

Diboson full-hadronic



EFT VBS

- SMに以下の項を加える
- Dimension-6演算子はtriple gauge couplingからの制限が強い (LEP) のでdimension-8を考える
- 右に列挙する18組の8次元演算子

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \sum_i \frac{f_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

scalar,

$$\begin{aligned} \mathcal{O}_{S,0} &= [(D_\mu \Phi)^\dagger D_\nu \Phi] \times [(D^\mu \Phi)^\dagger D^\nu \Phi], \\ \mathcal{O}_{S,1} &= [(D_\mu \Phi)^\dagger D^\mu \Phi] \times [(D_\nu \Phi)^\dagger D^\nu \Phi], \\ \mathcal{O}_{S,2} &= [(D_\mu \Phi)^\dagger D_\nu \Phi] \times [(D^\nu \Phi)^\dagger D^\mu \Phi], \end{aligned}$$

only field-strength tensors, called tensor,

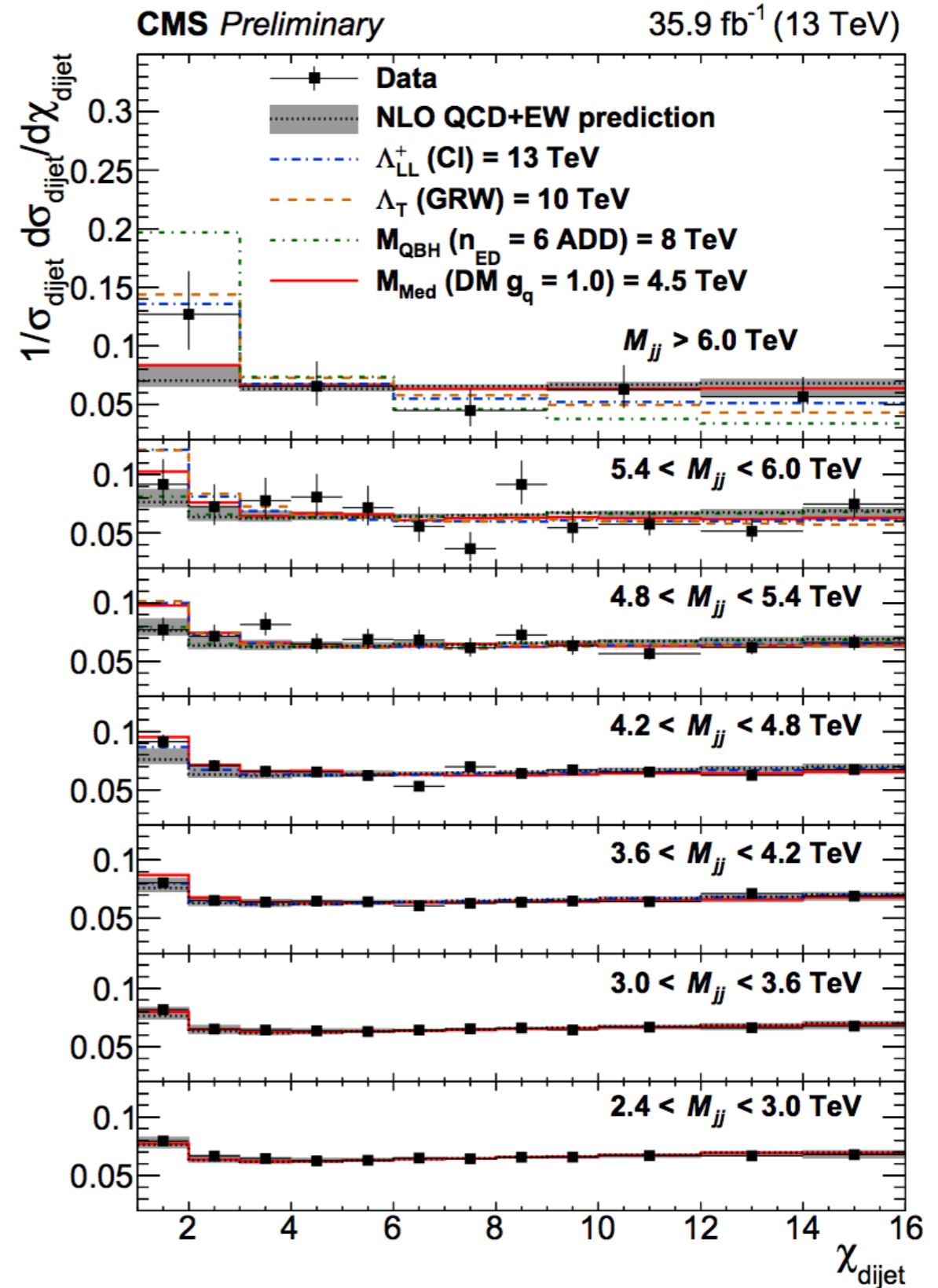
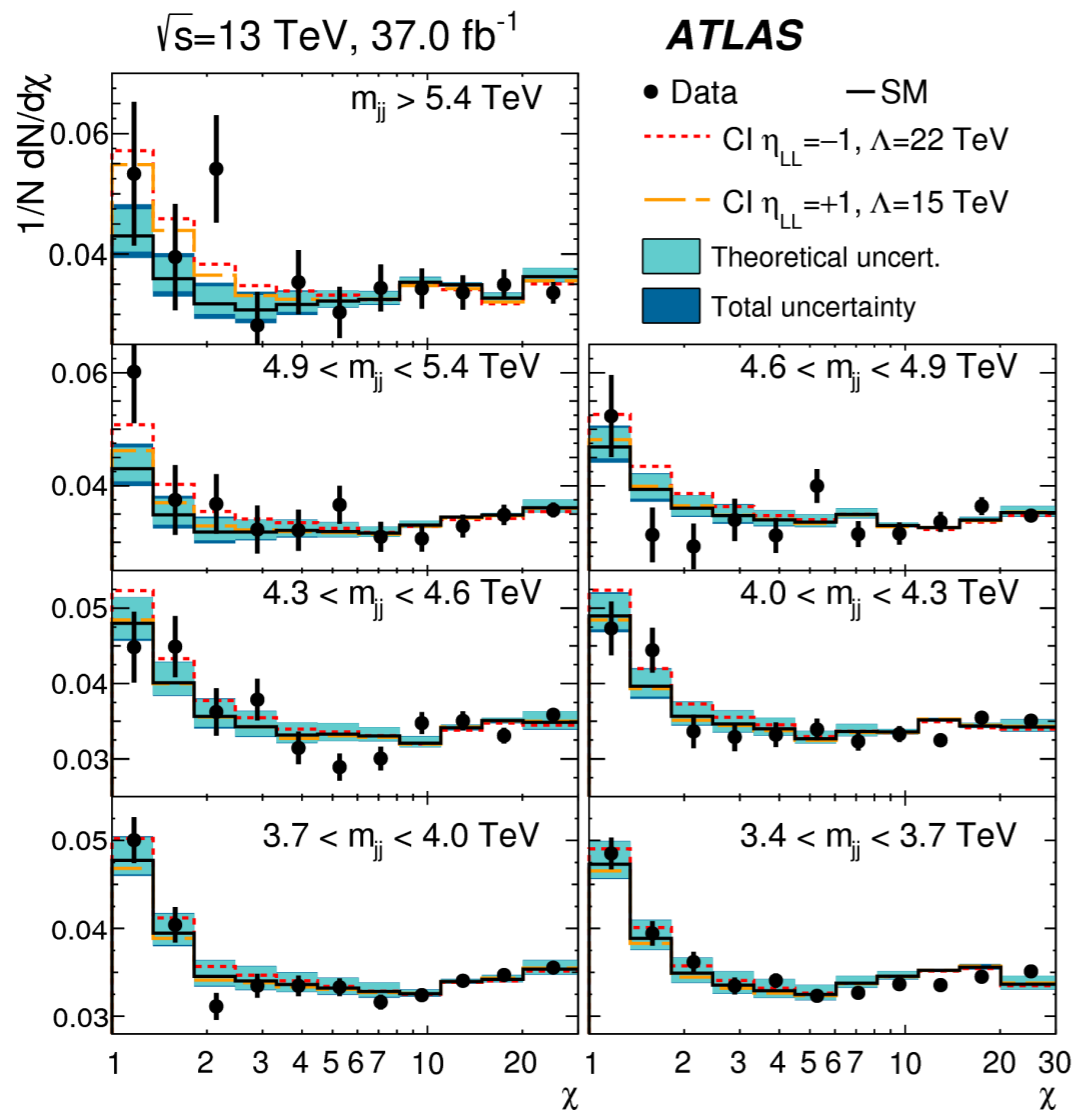
$$\begin{aligned} \mathcal{O}_{T,0} &= \text{Tr} [\widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu}] \times \text{Tr} [\widehat{W}_{\alpha\beta} \widehat{W}^{\alpha\beta}], \\ \mathcal{O}_{T,1} &= \text{Tr} [\widehat{W}_{\alpha\nu} \widehat{W}^{\mu\beta}] \times \text{Tr} [\widehat{W}_{\mu\beta} \widehat{W}^{\alpha\nu}], \\ \mathcal{O}_{T,2} &= \text{Tr} [\widehat{W}_{\alpha\mu} \widehat{W}^{\mu\beta}] \times \text{Tr} [\widehat{W}_{\beta\nu} \widehat{W}^{\nu\alpha}], \\ \mathcal{O}_{T,5} &= \text{Tr} [\widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu}] \times \widehat{B}_{\alpha\beta} \widehat{B}^{\alpha\beta}, \\ \mathcal{O}_{T,6} &= \text{Tr} [\widehat{W}_{\alpha\nu} \widehat{W}^{\mu\beta}] \times \widehat{B}_{\mu\beta} \widehat{B}^{\alpha\nu}, \\ \mathcal{O}_{T,7} &= \text{Tr} [\widehat{W}_{\alpha\mu} \widehat{W}^{\mu\beta}] \times \widehat{B}_{\beta\nu} \widehat{B}^{\nu\alpha}, \\ \mathcal{O}_{T,8} &= \widehat{B}_{\mu\nu} \widehat{B}^{\mu\nu} \widehat{B}_{\alpha\beta} \widehat{B}^{\alpha\beta}, \\ \mathcal{O}_{T,9} &= \widehat{B}_{\alpha\mu} \widehat{B}^{\mu\beta} \widehat{B}_{\beta\nu} \widehat{B}^{\nu\alpha}, \end{aligned}$$

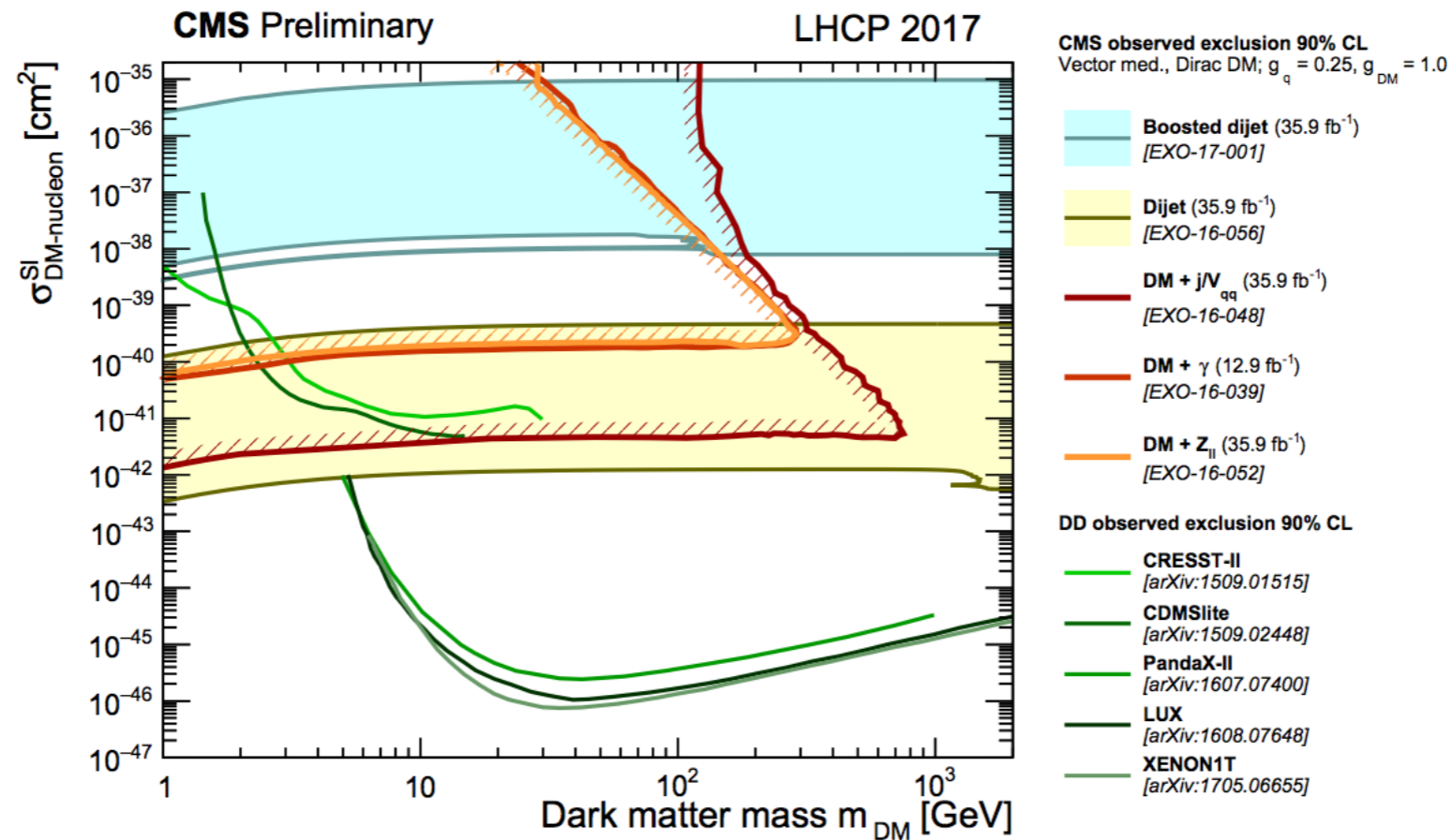
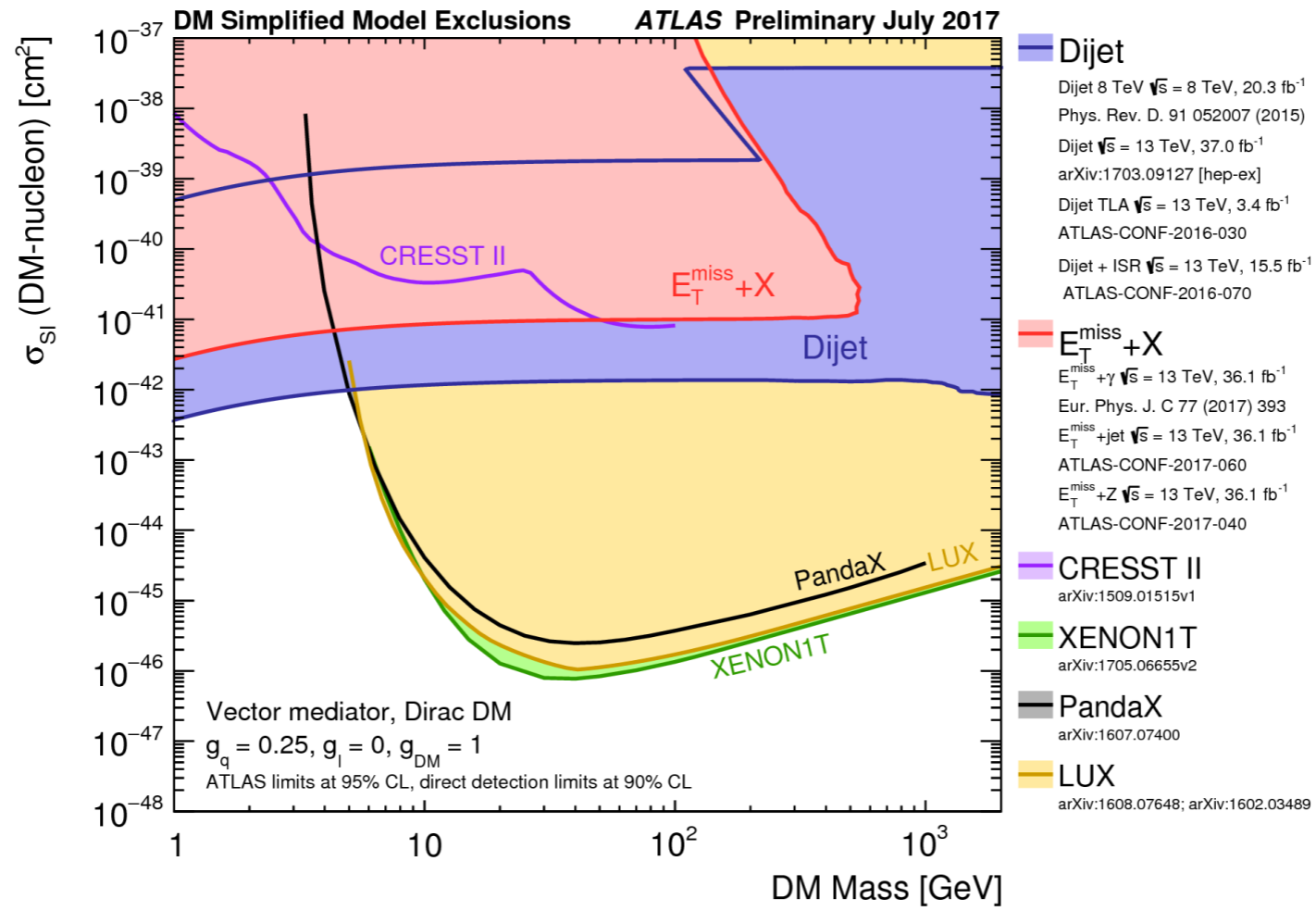
or two of them each, called mixed,

$$\begin{aligned} \mathcal{O}_{M,0} &= \text{Tr} [\widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu}] \times [(D_\beta \Phi)^\dagger D^\beta \Phi], \\ \mathcal{O}_{M,1} &= \text{Tr} [\widehat{W}_{\mu\nu} \widehat{W}^{\nu\beta}] \times [(D_\beta \Phi)^\dagger D^\mu \Phi], \\ \mathcal{O}_{M,2} &= [\widehat{B}_{\mu\nu} \widehat{B}^{\mu\nu}] \times [(D_\beta \Phi)^\dagger D^\beta \Phi], \\ \mathcal{O}_{M,3} &= [\widehat{B}_{\mu\nu} \widehat{B}^{\nu\beta}] \times [(D_\beta \Phi)^\dagger D^\mu \Phi], \\ \mathcal{O}_{M,4} &= [(D_\mu \Phi)^\dagger \widehat{W}_{\beta\nu} D^\mu \Phi] \times \widehat{B}^{\beta\nu}, \\ \mathcal{O}_{M,5} &= [(D_\mu \Phi)^\dagger \widehat{W}_{\beta\nu} D^\nu \Phi] \times \widehat{B}^{\beta\mu}, \\ \mathcal{O}_{M,7} &= [(D_\mu \Phi)^\dagger \widehat{W}_{\beta\nu} \widehat{W}^{\beta\mu} D^\nu \Phi]. \end{aligned}$$

Dijet angular analysis

$$\chi = e^{2|y^*|} \sim \frac{1 + \cos \theta^*}{1 - \cos \theta^*}$$





印象はcouplingによって大きく変わる

