LHC diboson status

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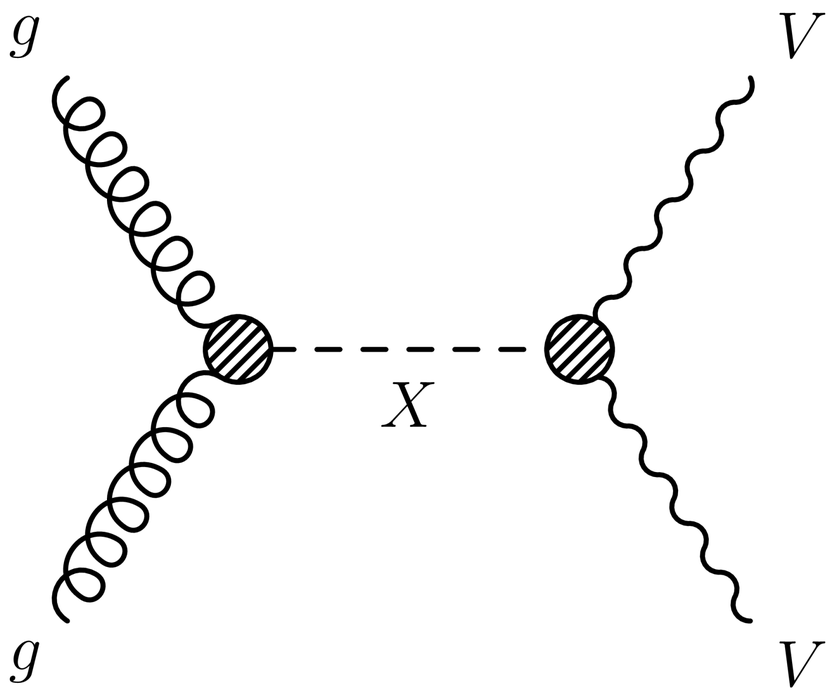
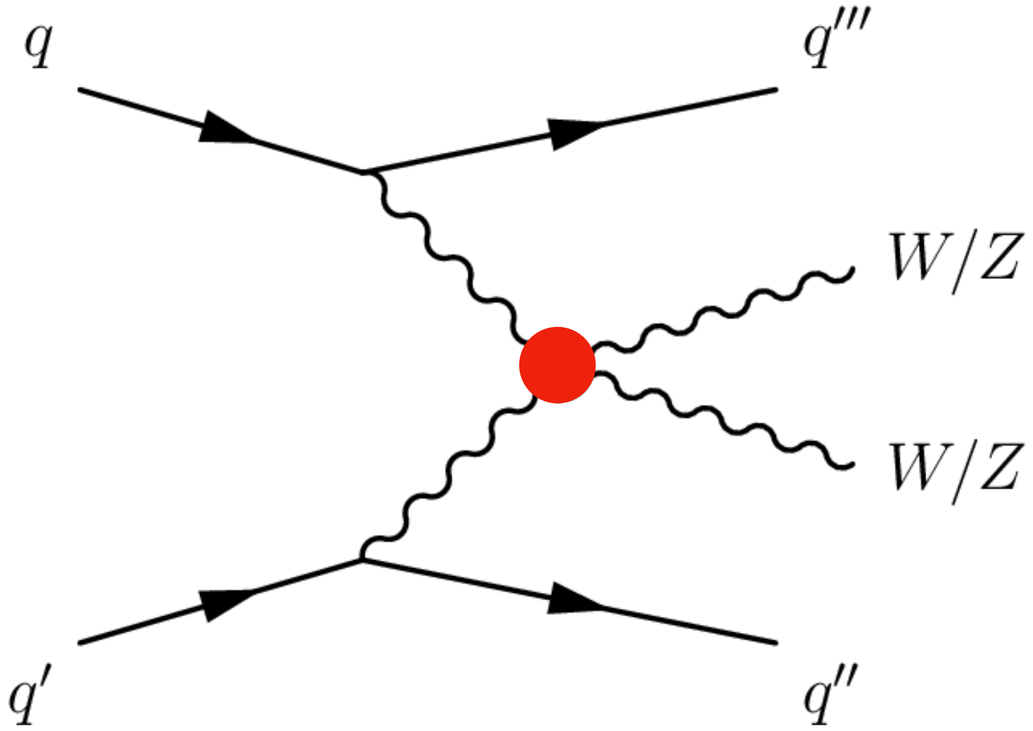
12/8/2020@テラスケール研究会

LHCにおけるdiboson processes



- 新物理直接探索（共鳴探索）

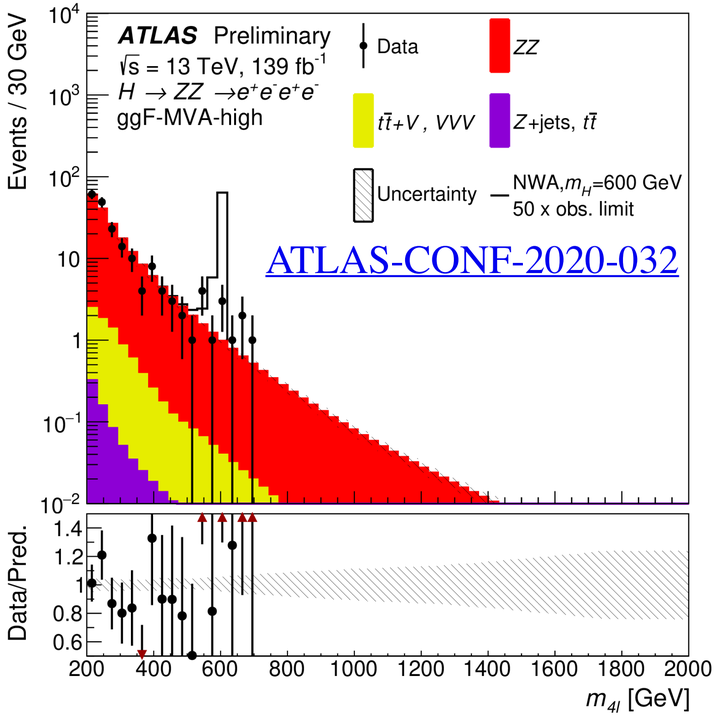


- SM検証 (EWSB)、散乱断面積測定
- より高いエネルギースケールの新物理に対するEFTによる検証 (aQGC/aTGC)

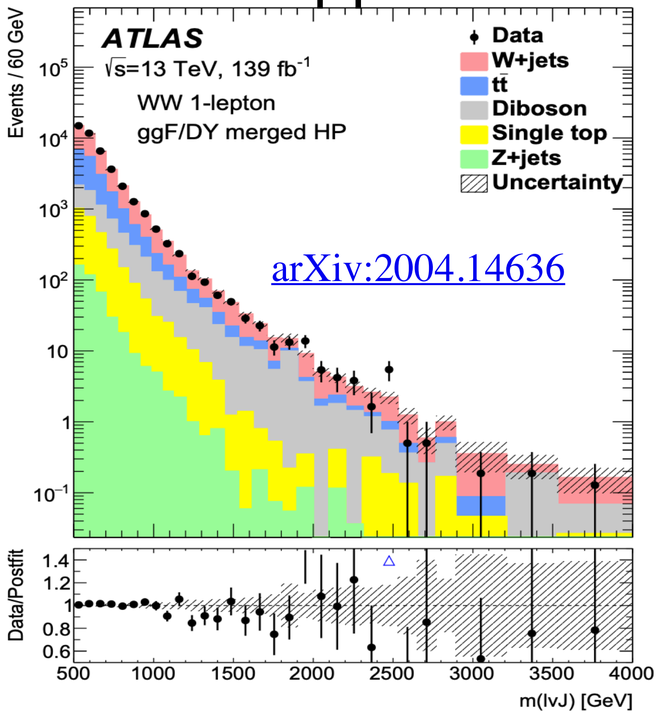
共鳴探索、最新結果@ICHEP

- 広い質量レンジで模型に依らず探す（2HDM <~500GeV／KK Graviton O(TeV)）

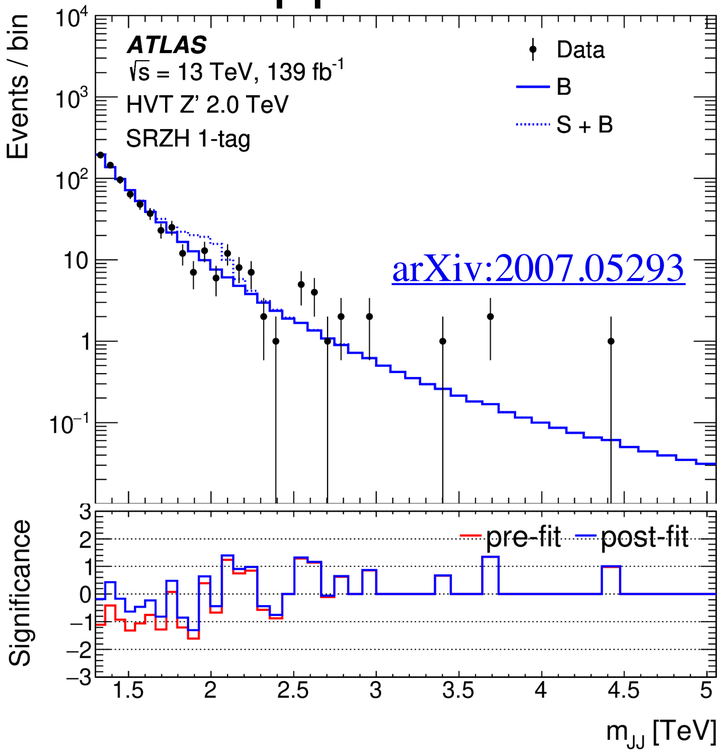
ZZ→4L



WV→lvqq

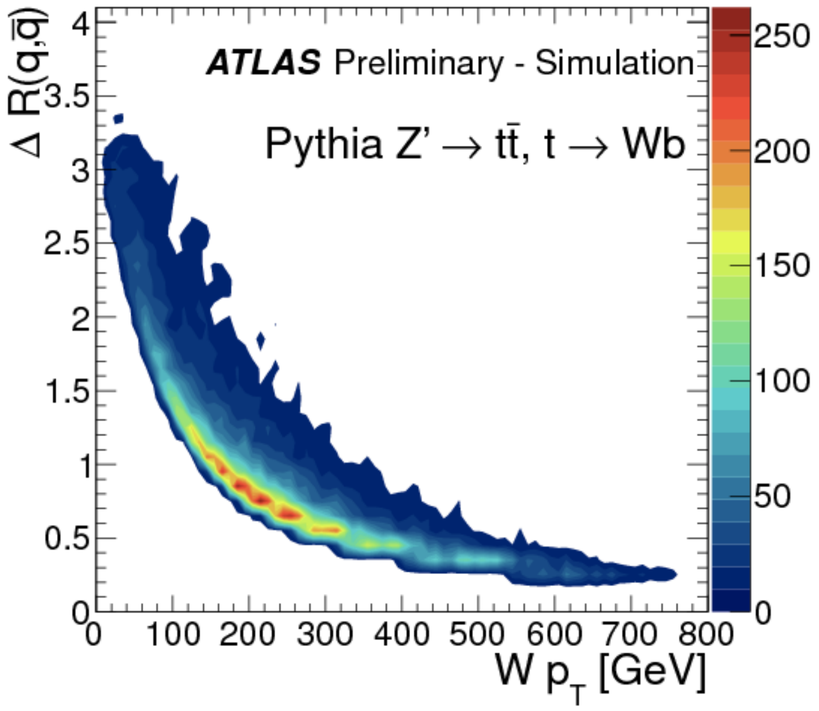


Vh→qqbb

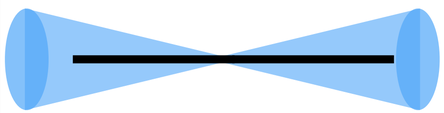


HVT W'/Z' model B(large $g_{V'VV}$のベンチマーク)<~4TeV、Bulk RS G<~2TeVまで棄却

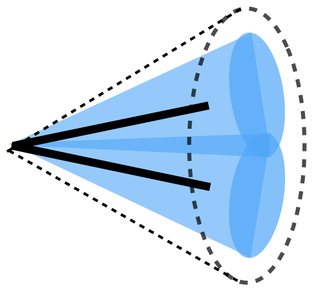
Boosted W/Z/h→qq reconstruction



ボソンの静止系

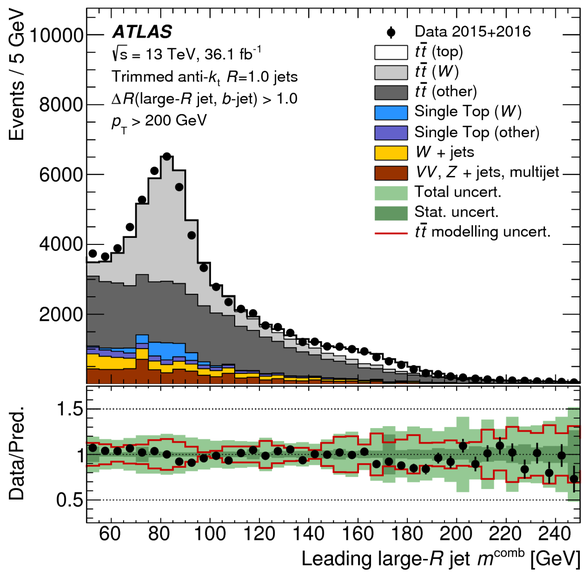


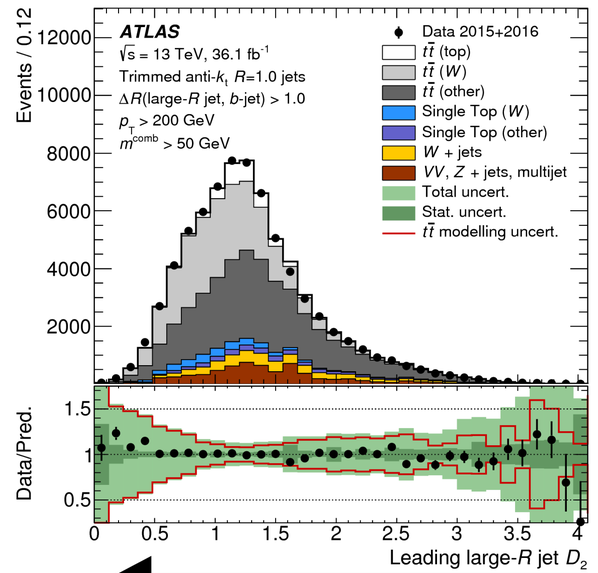
Boosted frame



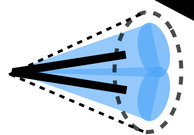
- High-mass diboson共鳴探索はhigh-p_T
  ハドロンジェット改良のベンチマークとしても大事
- Large-Rジェットを用いたboosted W/Z/hボソン再構成は
  HL-LHCや将来実験において重要度を増す

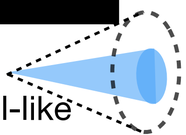
EPJC75(2019)375





2-prong-like

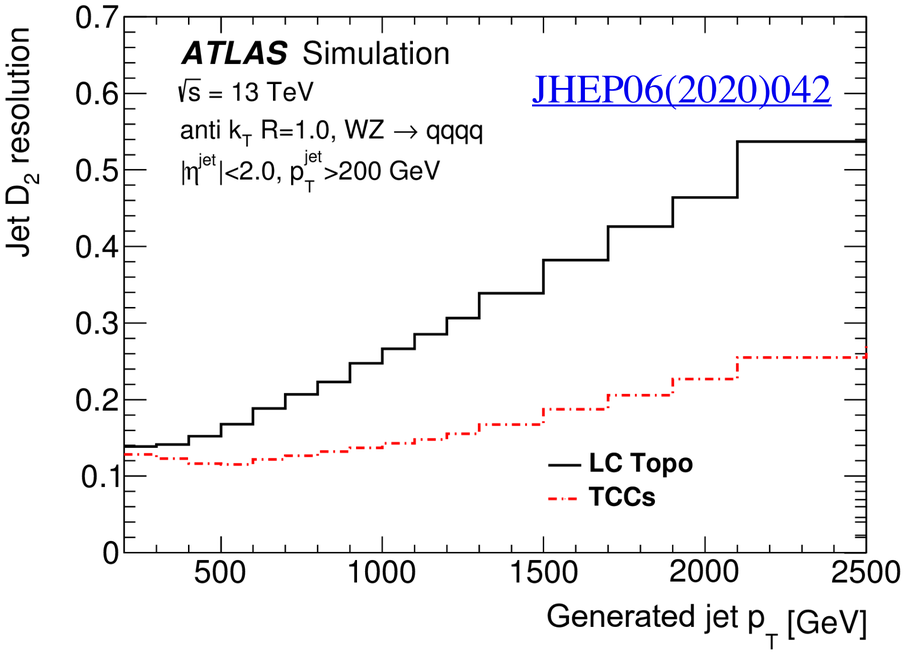


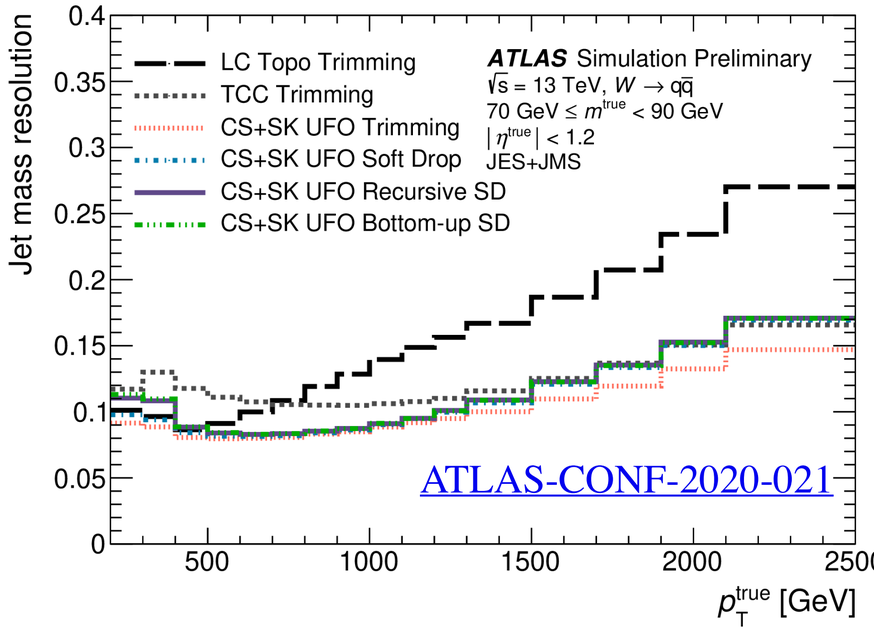


Background: pencil-like

Jet再構成の改良

- **LCTopo** (現行): カロリメータクラスターからジェットを再構成
- **Particle-flow (PFlow)**
  - 荷電粒子は飛跡で、中性粒子はカロリメータで4-vectorを測る
  - トラッカーのresolutionからhigh-p_Tで性能悪化
- **Track-Calo cluster (TCC)**
  - 荷電粒子の角度は飛跡で、エネルギーはカロリメータで測る
  - High-p_TでD_2 resolutionが劇的に向上
    Low-p_Tではmass resolutionが悪化
- **Unified-flow object (UFO)**
  - High-p_TではTCCを、low-p_TではPFlowを使う
  - 全p_T領域でベストなパフォーマンス
    → Run-3におけるATLAS標準アルゴリズムになる予定





Jet再構成の改良

- W-taggingの観点で性能評価 (mass+D_2 cut 2D scan)

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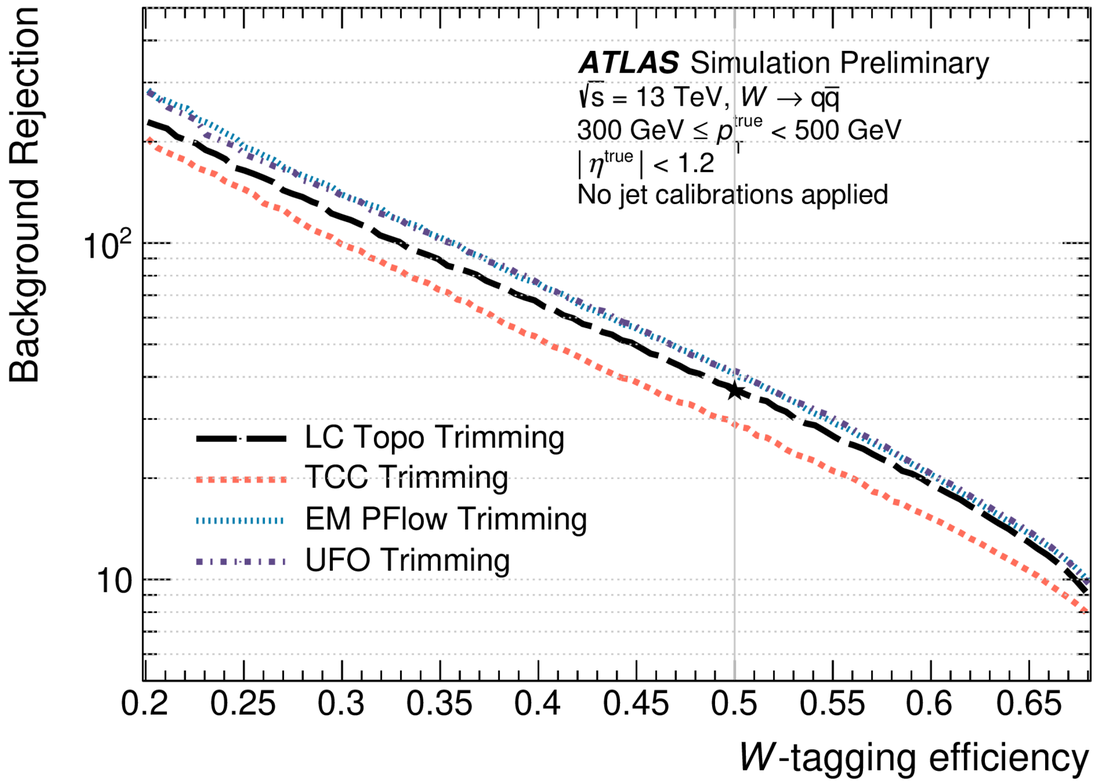
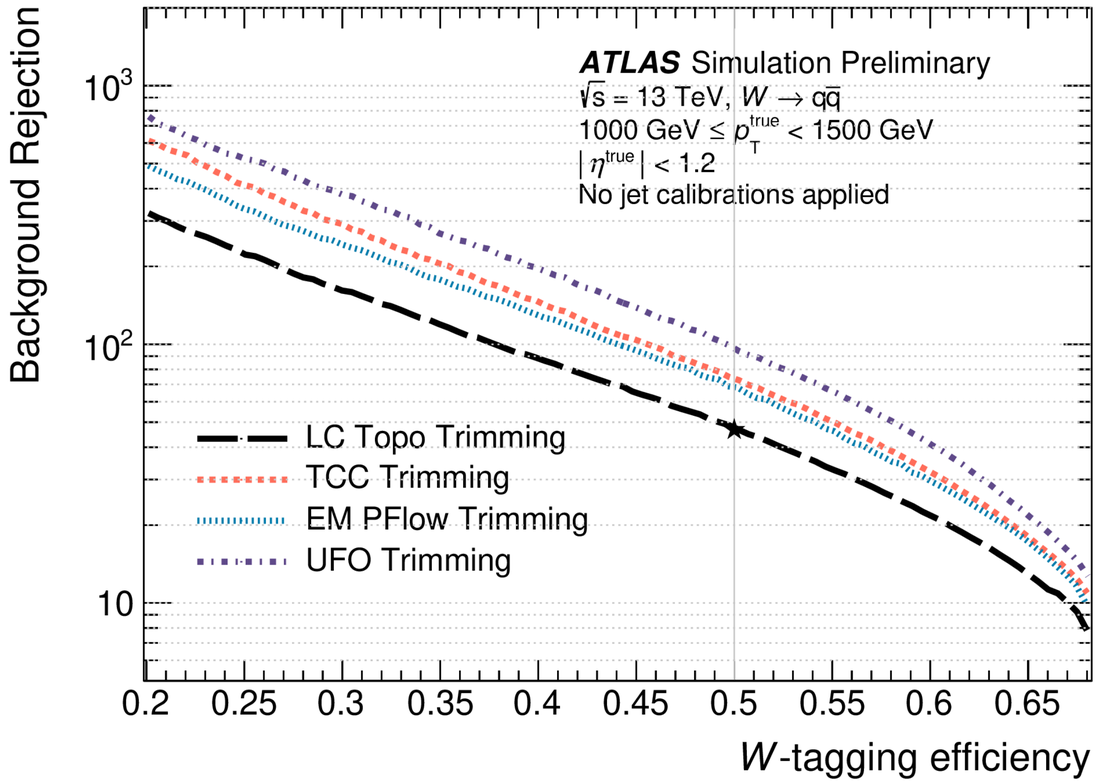


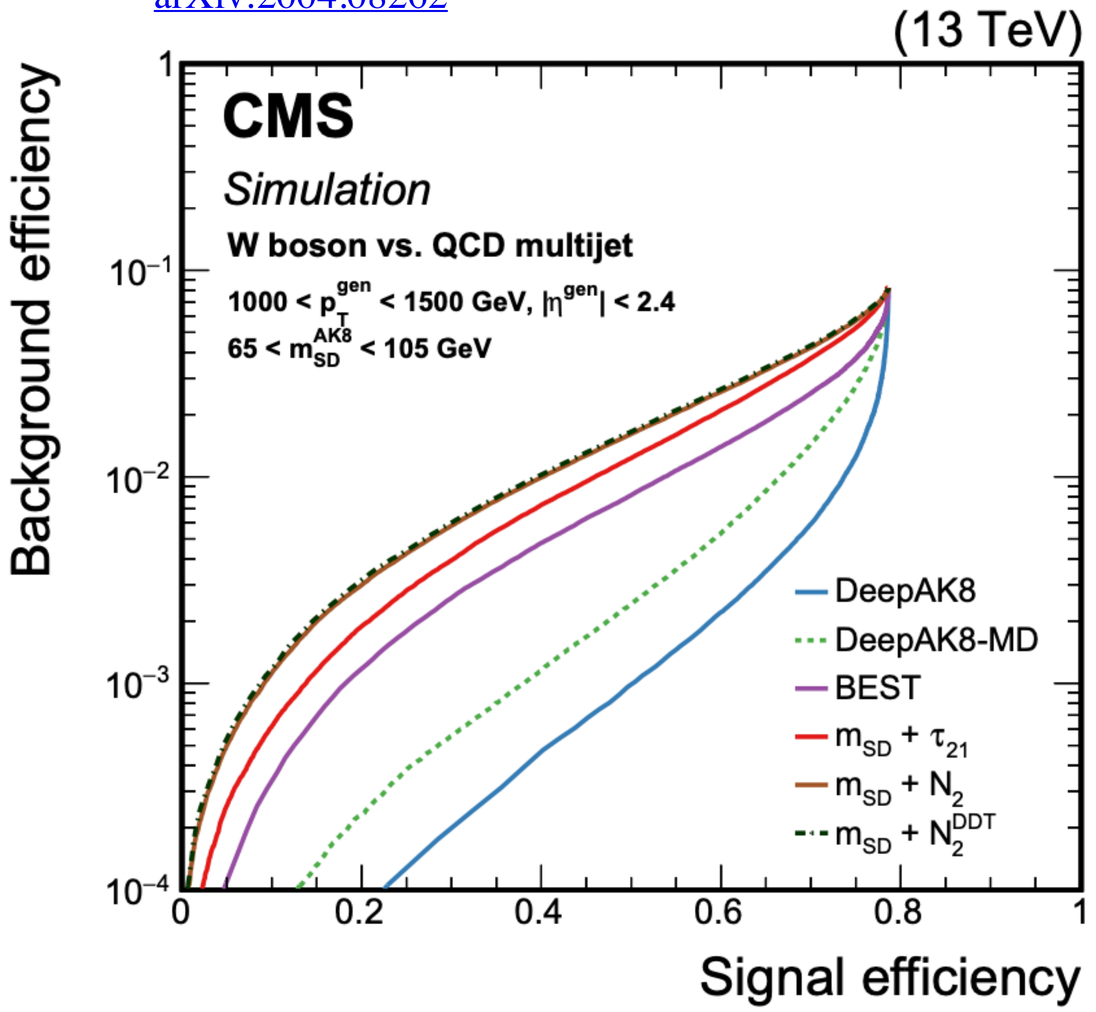


Low-p_T: UFO~PFlow >> TCC

High-p_T: UFO>TCC>PFlow

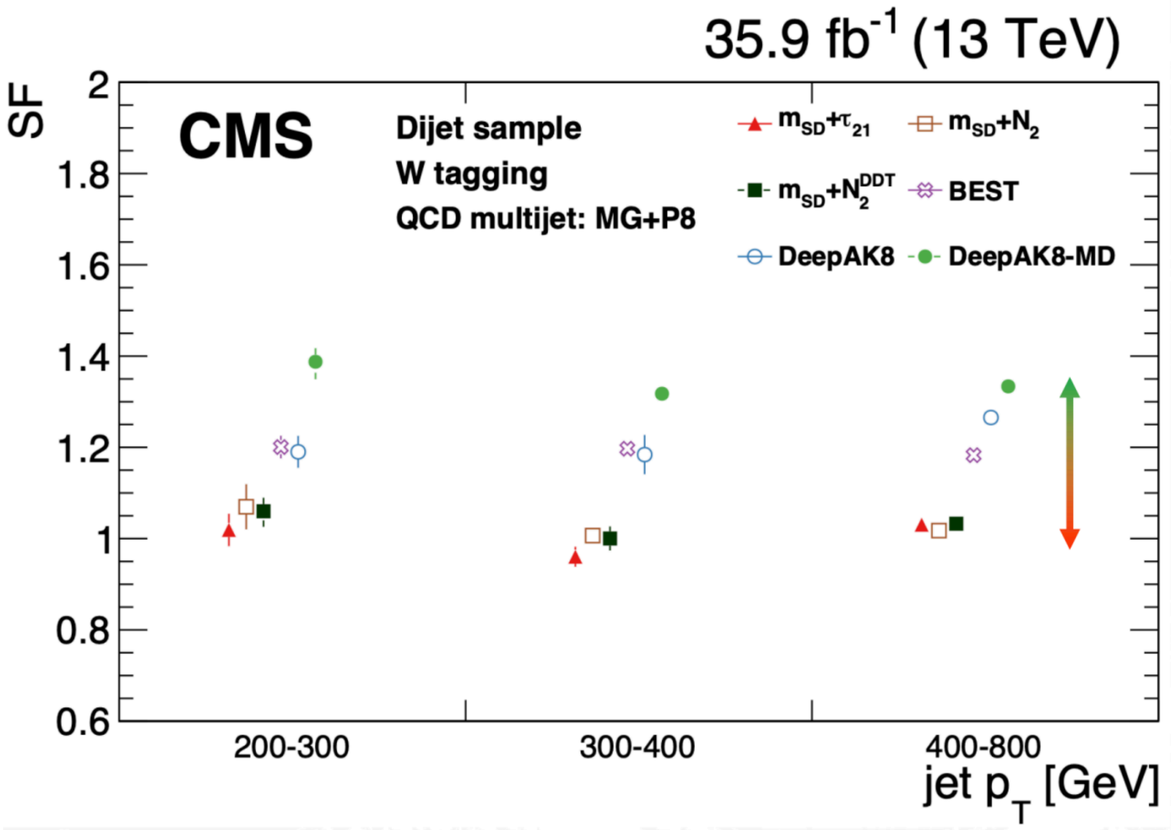
ML-based taggers (CMS)

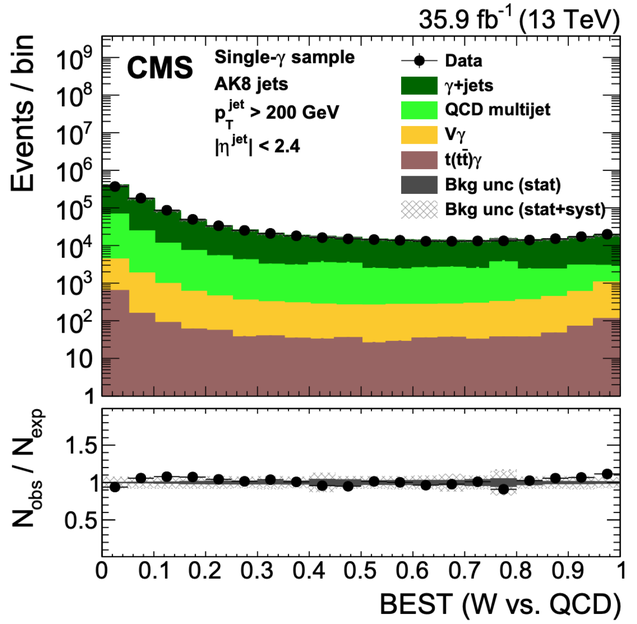
arXiv:2004.08262

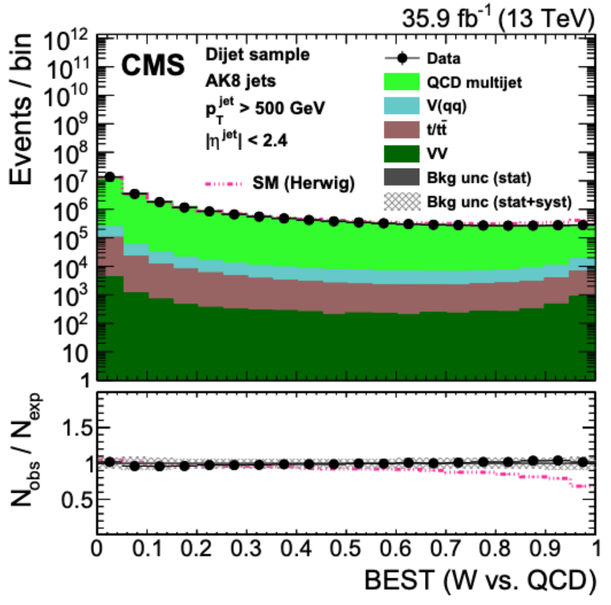


- W-/Z-/Higgs-/t-taggingのmulti-classタガー
- **BEST:**
  - Jet mass, τ_{21}などsubstructure variablesをインプット
  - Fully-connected network
  - ATLASの似たようなタガーとほぼ同じ性能
- **DeepAK8:**
  - p-flow objects (up-to 100本/jet, p_T-ordered)をインプット
  - それぞれのparticleが4-momentum, track qualityなどの42変数を持つ
  - 1D CNNで処理

ML-based taggers (CMS)

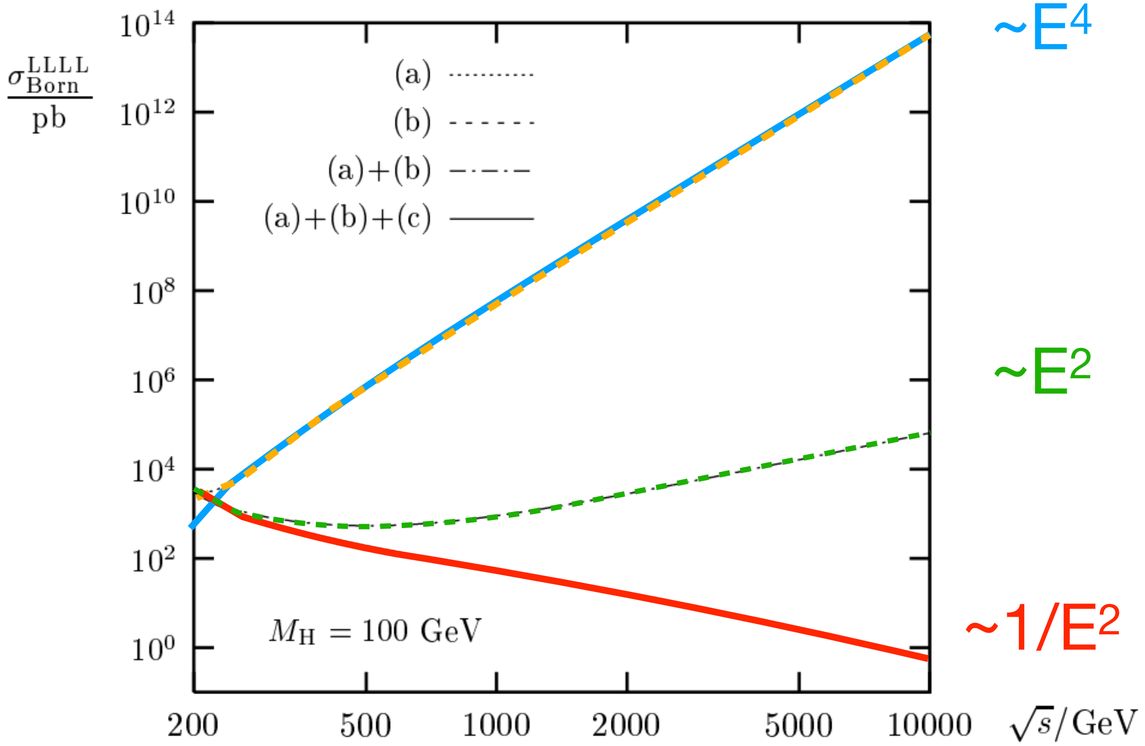






- タガーが複雑になるほどdata/MC合わない
- Substructure variablesのmeasurement重要に

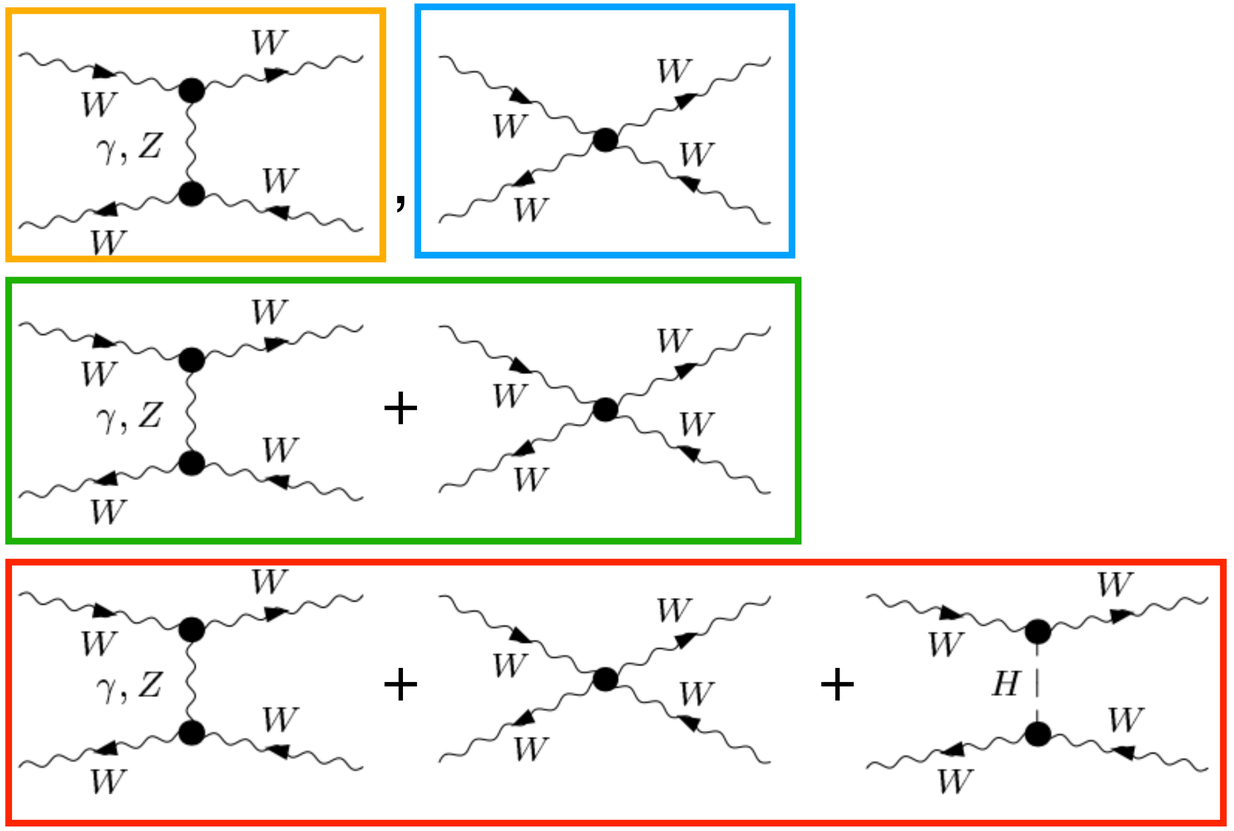
$W_L W_L$ scattering



~E⁴

~E²

~1/E²



E² term $-\frac{g^2}{4M_W^2}u$ $+\frac{g^2}{4M_W^2}u$

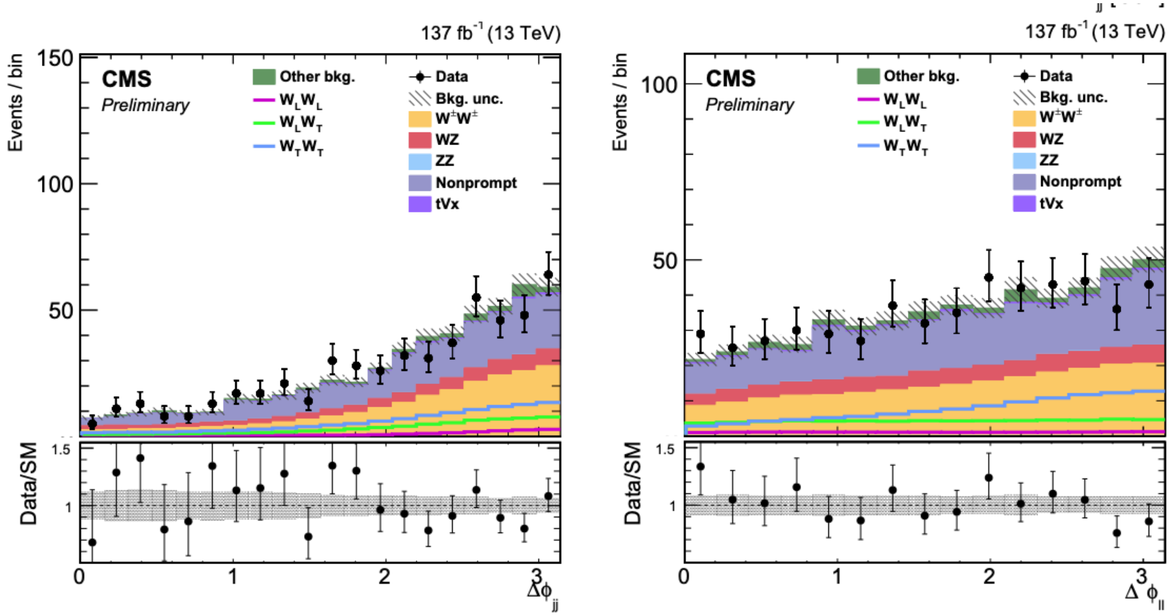
In the SM, completely canceled out

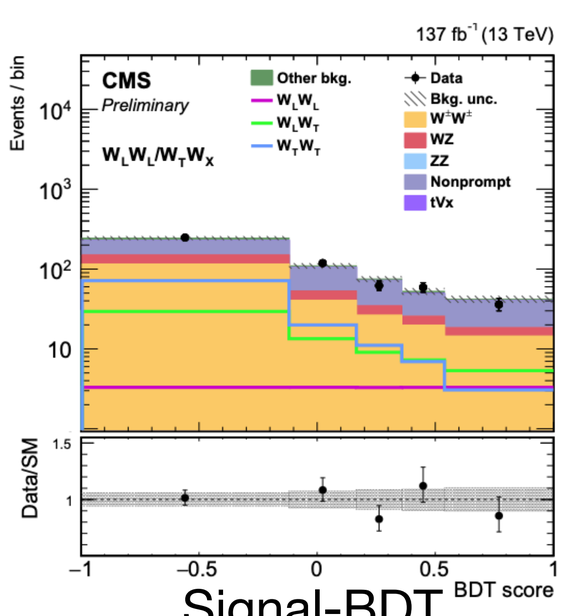
https://arxiv.org/abs/hep-ph/9711302

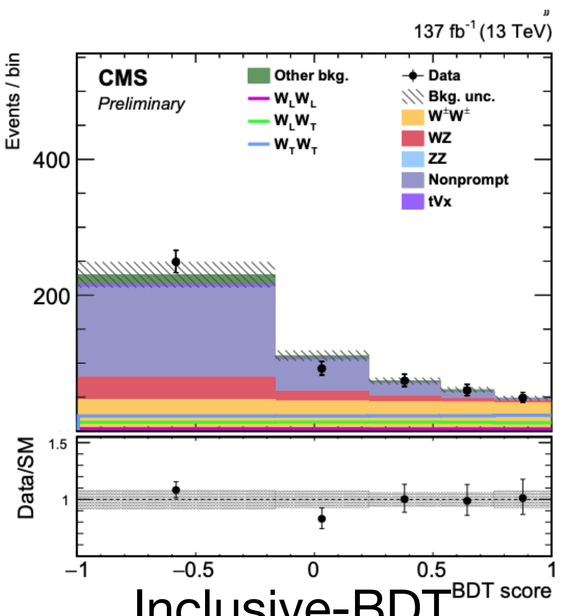
Same-sign W±W± → l±νl±ν

CMS-PAS-SMP-20-006

- W_LW_L / W_TW_L / W_TW_T の信号を生成（MadGraph LO). WW静止系とinitial parton静止系で定義した2セットの信号を検証
- Signal-BDT (2-jetの角度相関、2-leptonの角度相関、dilepton/dijetの運動量バランスなど)、
  Inclusive-BDT (信号/バックグラウンド分離、主にm_{jj}など)の2次元likelihood fitで信号を抽出







Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^\pm W_L^\pm$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W_X^\pm W_T^\pm$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W_L^\pm W_X^\pm$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W_T^\pm W_T^\pm$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

- まだまだですが (2-3σ expected@3ab^{-1})、
  今後色々なチャンネルを足していける

New physics modeling (aQGC)

- In the effective field theory, dimension-8 operators are added to the SM Lagrangian (dim-6 is covered by the other measurements)

$$\left|A_{\mathrm{SM}}+\sum_i \frac{f_i}{\Lambda^4}A_i\right|^2 = |A_{\mathrm{SM}}|^2 + \sum_i 2\frac{f_i}{\Lambda^4}Re(A_i^* A_{\mathrm{SM}}) + \sum_i \frac{f_i^2}{\Lambda^8}|A_i|^2 + \sum_{i\neq j} 2\frac{f_i f_j}{\Lambda^8}Re(A_i^* A_j)$$

EFT-SM interference | EFT term | EFT cross term

- Limits on cut-off scale and coupling coefficient are obtained by each process

	WWWW	WWZZ	ZZZZ	WWZA	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$f_{S0/1}/\Lambda^4$	✔	✔	✔						
$f_{M0/1/6/7}/\Lambda^4$	✔	✔	✔	✔	✔	✔	✔		
$f_{M2/3/4/5}/\Lambda^4$		✔	✔	✔	✔	✔	✔		
$f_{T0/1/2}/\Lambda^4$	✔	✔	✔	✔	✔	✔	✔	✔	✔
$f_{T5/6/7}/\Lambda^4$		✔	✔	✔	✔	✔	✔	✔	✔
$f_{T8/9}/\Lambda^4$			✔			✔	✔	✔	✔

aQGC couplings

https://arxiv.org/abs/hep-ph/0606118v2

$$\mathcal{L}_{S,0} = \frac{f_0}{\Lambda^4}\left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] ,$$

$$\mathcal{L}_{S,1} = \frac{f_1}{\Lambda^4}\left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right] .$$

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$

$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$

$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$

$$\mathcal{L}_{T,3} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\hat{W}^{\nu\alpha}\right] \times B_{\beta\nu}$$

$$\mathcal{L}_{T,4} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\alpha\mu}\hat{W}^{\beta\nu}\right] \times B_{\beta\nu}$$

$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$

$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$

$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

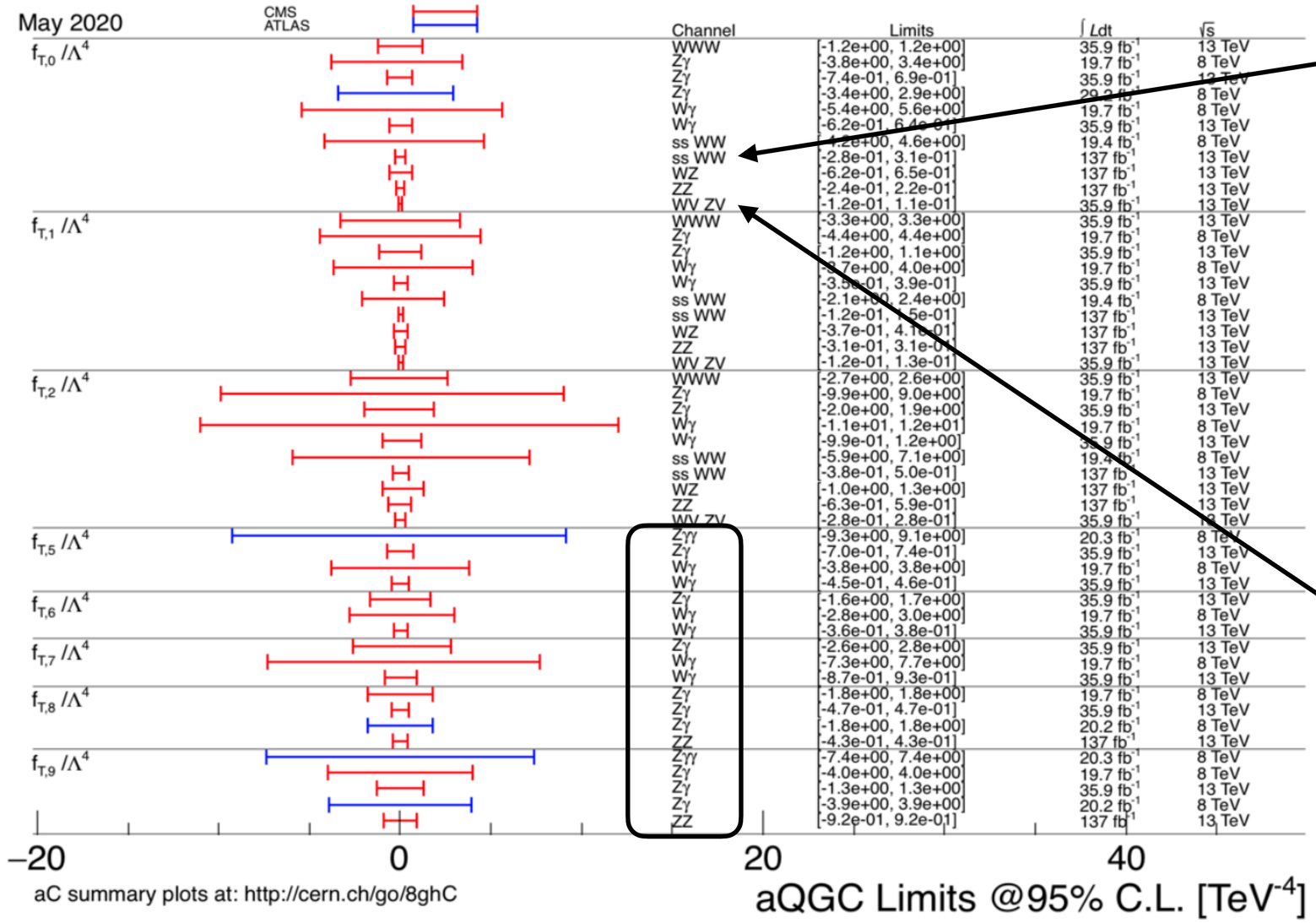
$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu}$$

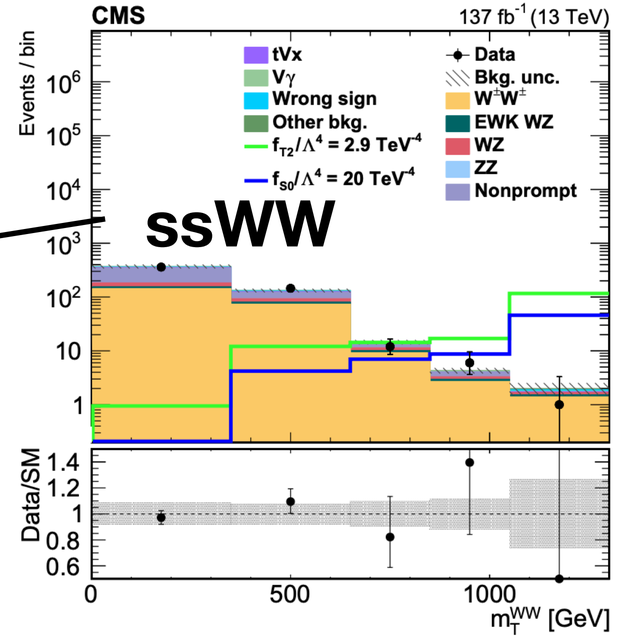
$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}D^\nu\Phi\right] \times B^{\beta\mu}$$

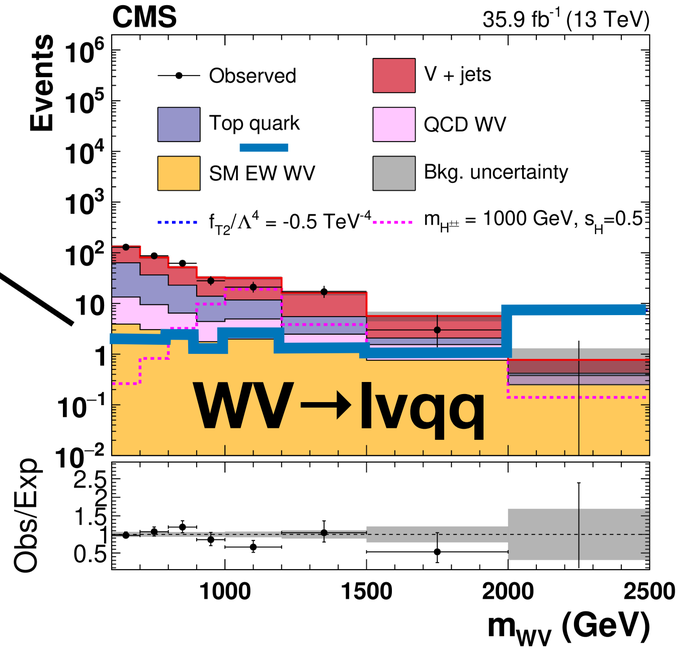
$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu}D^\mu\Phi\right]$$

$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu}D^\nu\Phi\right]$$

Limits on aQGC (tensor-type)



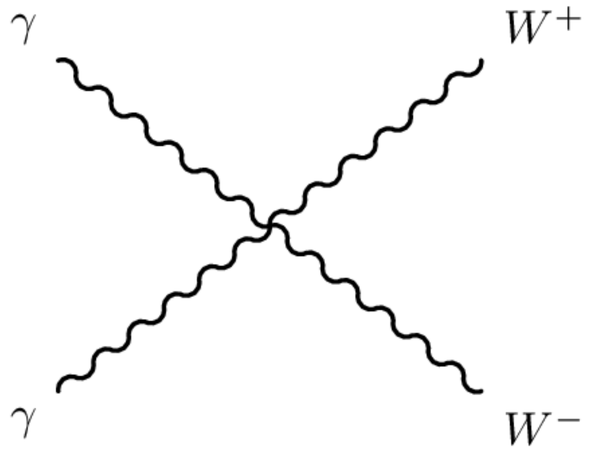




https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

γγ→WW scattering

- 2レプトン(eμ)のvertexに他のtrackが付随していないことを要求
- SR+CR同時フィットで信号を抽出



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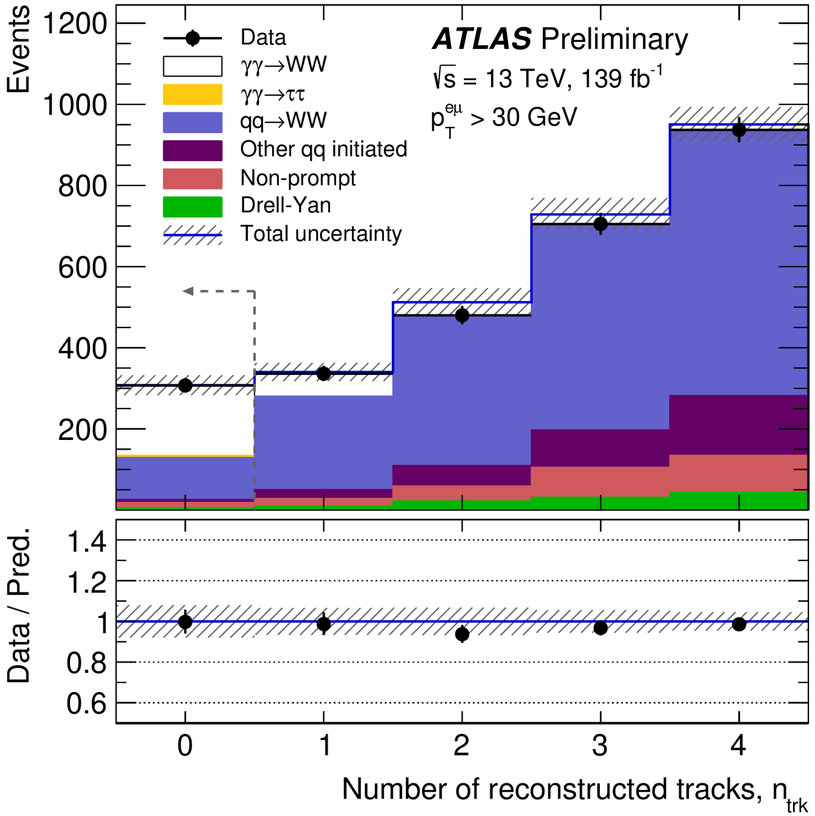
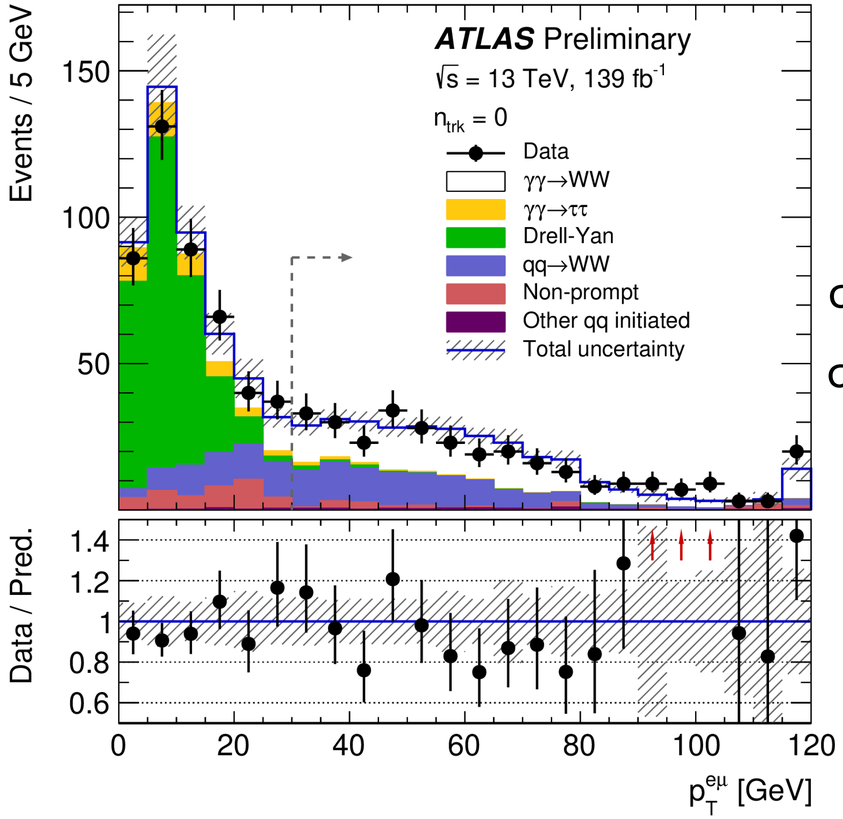




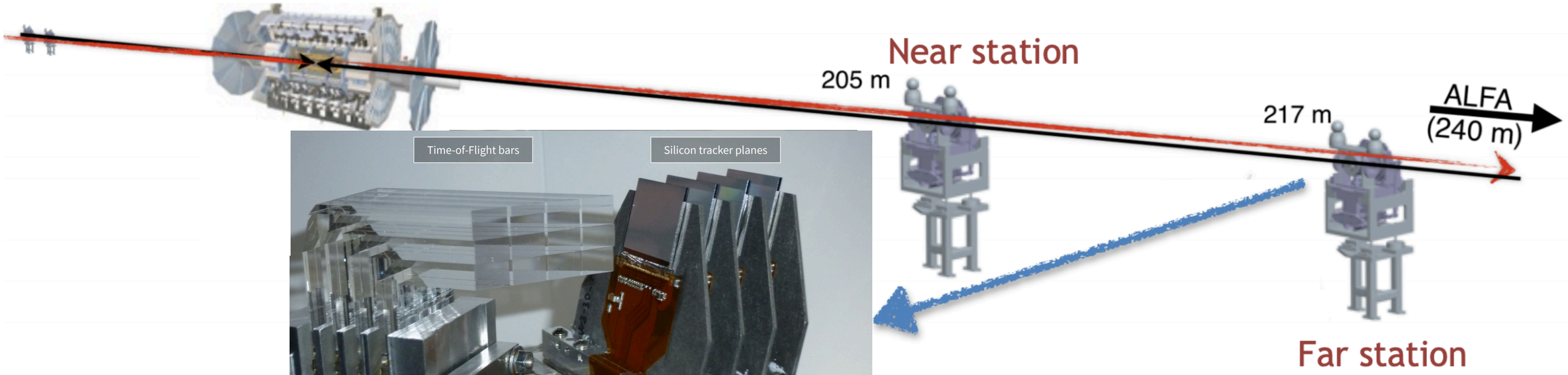
σ(γγ→WW)=3.13±0.31(stat)±0.28(syst) fb

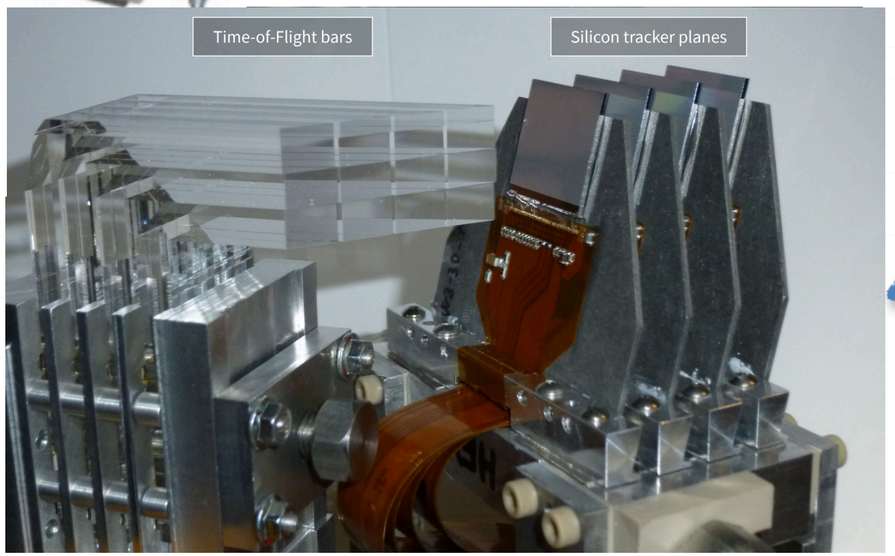
σ(Herwig7 LO)=2.34±0.27 fb

8.4σ measurement of γγ→WW process (6.7σ expected)

AFP (ATLAS forward proton) detector

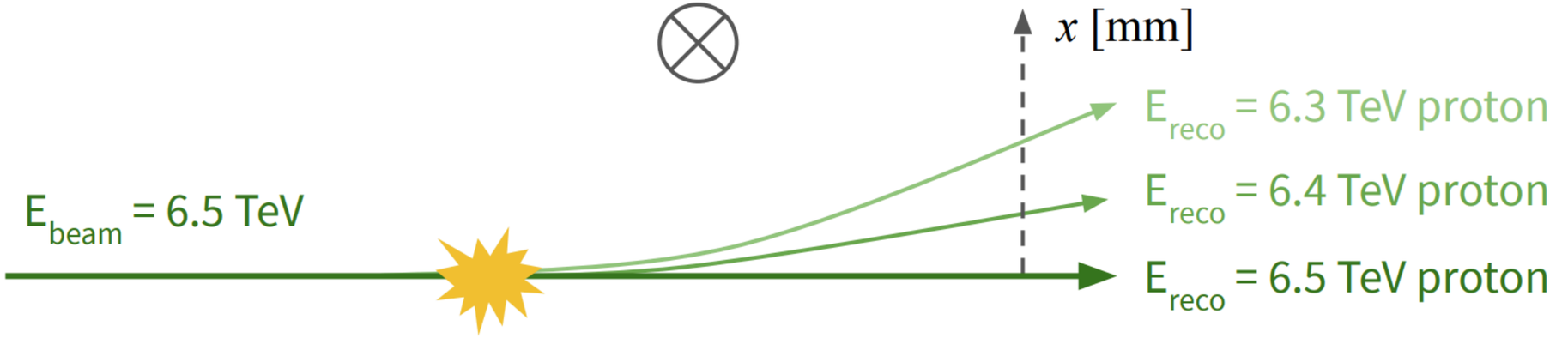
- Near station: シリコントラッカー、track efficiency~100%
- Far station: シリコントラッカー(＋ToF from run3)、~96%
- Forward proton要求でバックグラウンドを大幅に抑制
- ToFはA/C sideのタイミング差からvertex positionの測定に用いる。タイミング分解能O(10)ps目指す





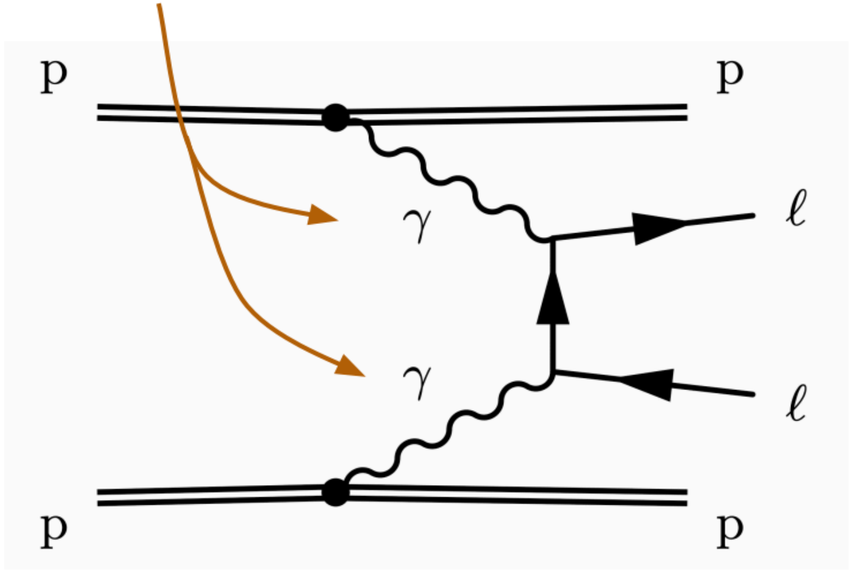
B field from
LHC dipoles

1) Measure *spatial* coordinate



$$\xi_{\mathrm{AFP}}^{\mathrm{A,C}} = 1 - E_{\mathrm{reconstructed}} / E_{\mathrm{beam}}$$

2) Infer *energy* lost by proton



3) Know initial photon energy

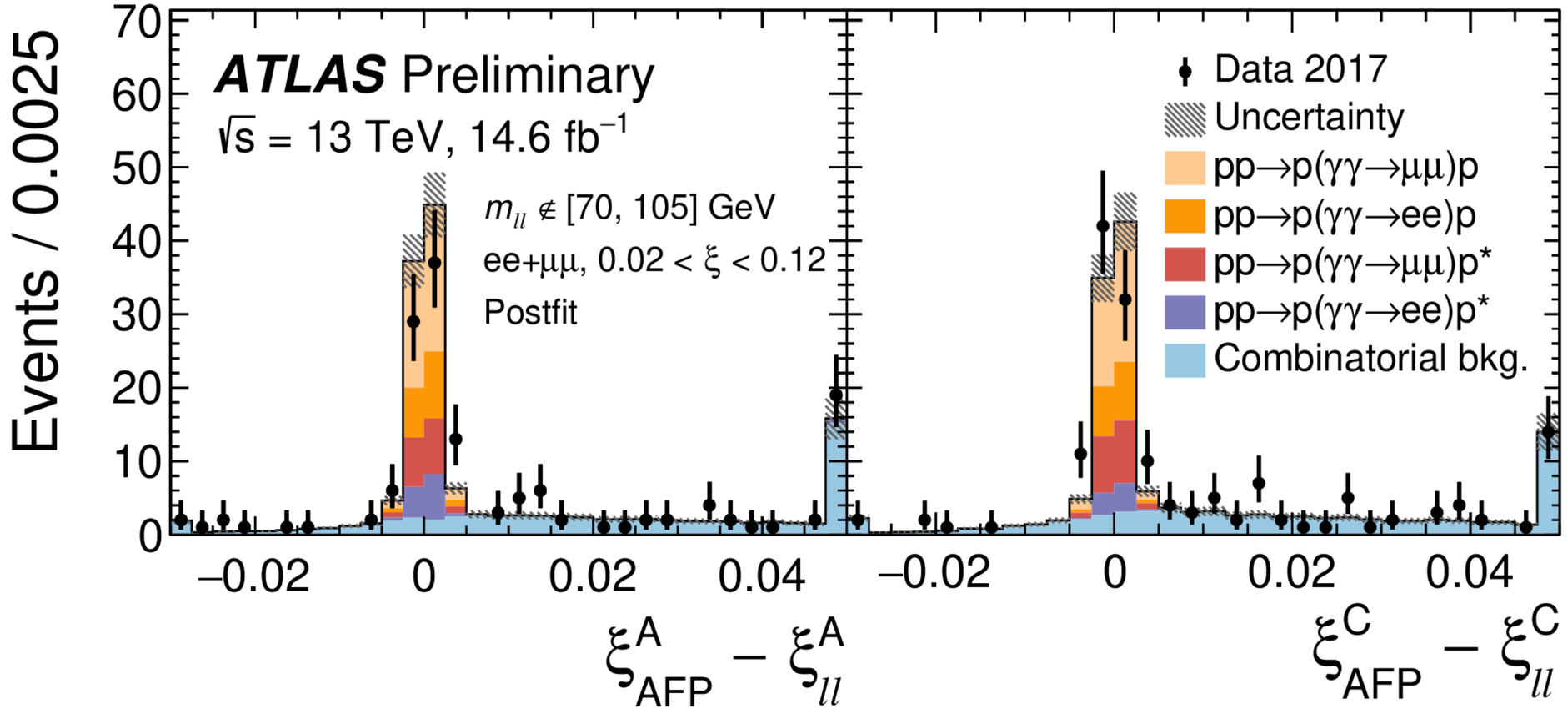
Novelty: reconstruct γγ system
without central ATLAS detectors

AFP alignment

- $\xi^{\pm}_{\ell\ell} = (m_{\ell\ell}/\sqrt{s})e^{\pm y_{\ell\ell}}$でアライメント、差でカットするとpileupも落ちてほぼbkg freeに

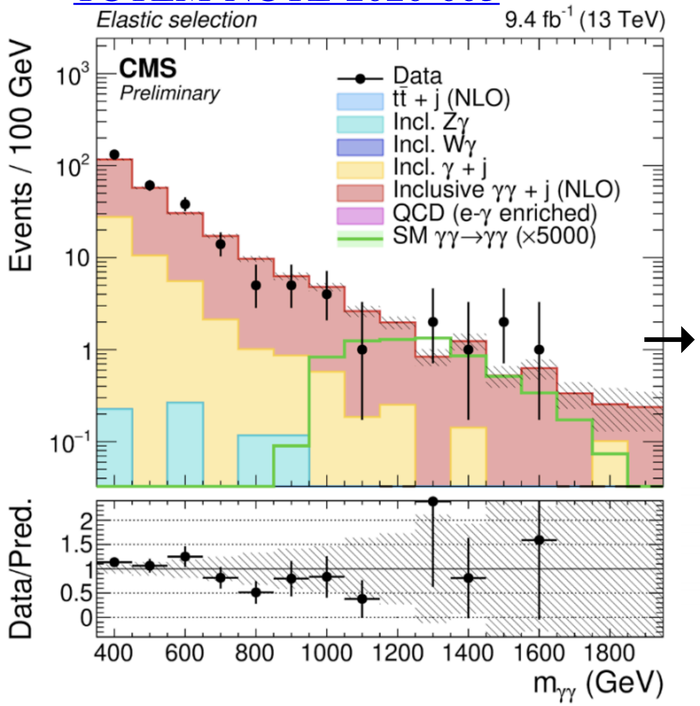
- pp→p(γγ→X)p(*)を精度良く測定可能

ATLAS-CONF-2020-041



Prospects with forward proton tagging

TOTEM-NOTE-2020-003



→ forward proton 要求で0 events

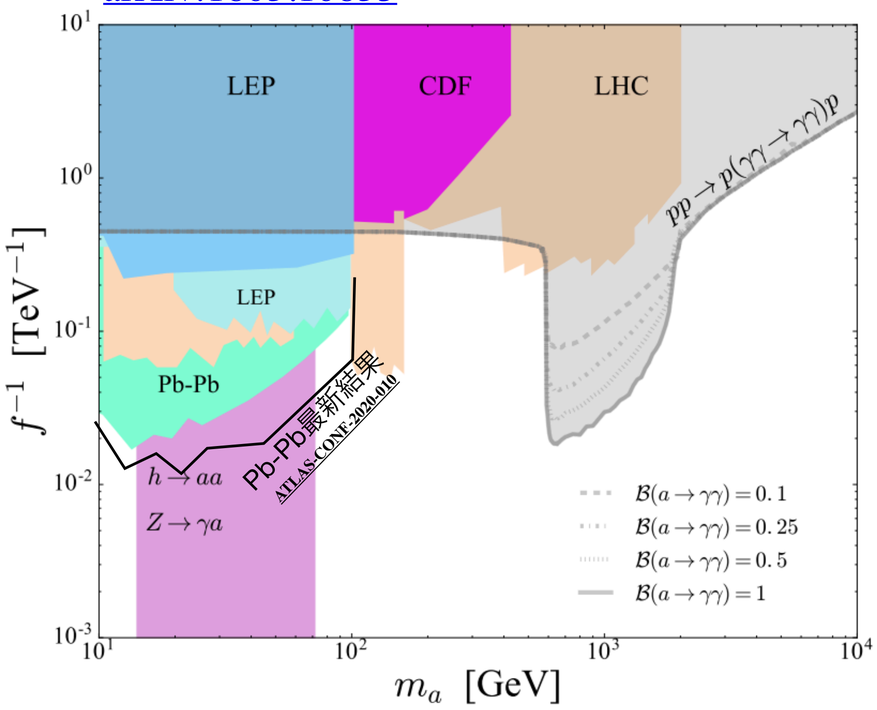
$$|\zeta_1| < 3.7 \times 10^{-13}\ \text{GeV}^{-4}$$
$$|\zeta_2| < 7.7 \times 10^{-13}\ \text{GeV}^{-4}$$

γγ→γγ scattering

- aQGC T7/8 coupling coefficientsへの感度は、10fb^{-1}データでfull run-2 (ZZ→4L)jj measurementとほぼ同じくらい

$$L_8^{\gamma\gamma\gamma\gamma} = \zeta_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2 F_{\mu\nu}F^{\mu\rho}F_{\rho\sigma}F^{\sigma\nu} \quad \text{with} \quad \zeta_{1,2} = a_{1,2}^{\gamma\gamma}/\Lambda^4$$

arXiv:1803.10835



- Diphoton共鳴探索 (300fb^{-1})
- AFP要求でALP-photon couplingが一桁下げられる

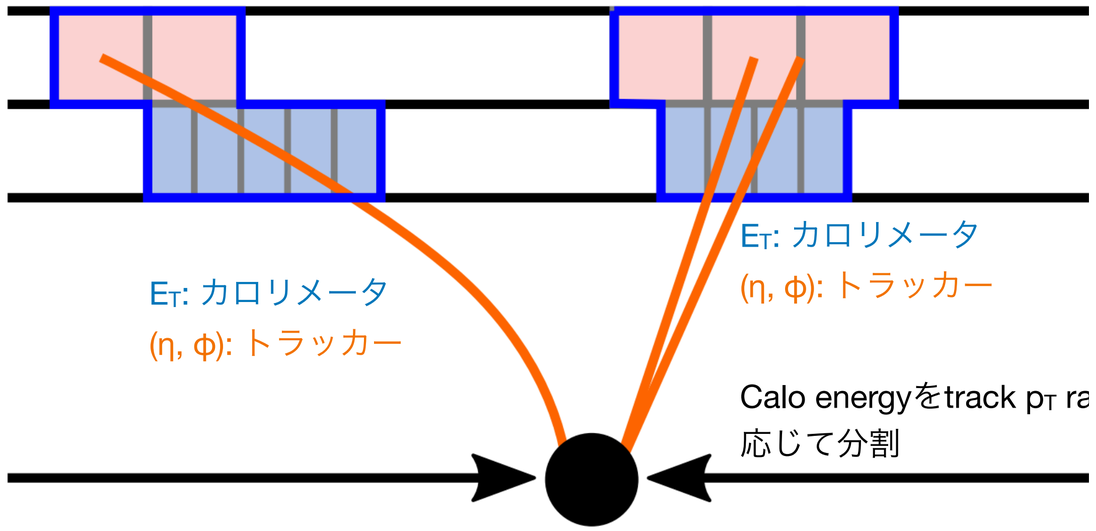
LHC Diboson status

- **Diboson共鳴探索**
  - 多くのチャンネルでfull run-2 dataを用いた結果が報告された
  - 200GeV-5TeVのレンジでデータはSMに合っている
  - **Boosted boson tagging**テクニックさらに改良される予定
    - Energy clusteringからbottom-upに変える and/or ML tagger
- **SM VV+jj測定**
  - いくつかのチャンネルでfull run-2 dataを用いた結果が報告された
  - **W_LW_L散乱**測定を初めて試みた
  - EFTを用いた**新物理への制限**が更新された
- **γγ interaction測定**
  - 新しい**forward proton検出器**でほぼバックグラウンドfreeな解析が可能に
  - Run-2 pp衝突データを用いた初結果が報告された。Run-3から本格稼働します

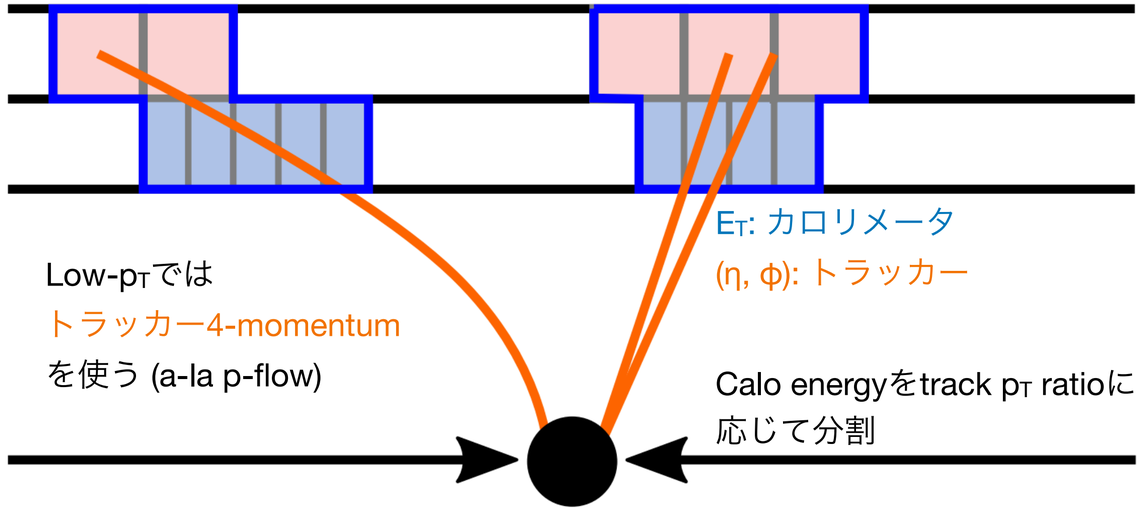
予備資料

Jet再構成の改良

Track Calo Cluster (TCC)

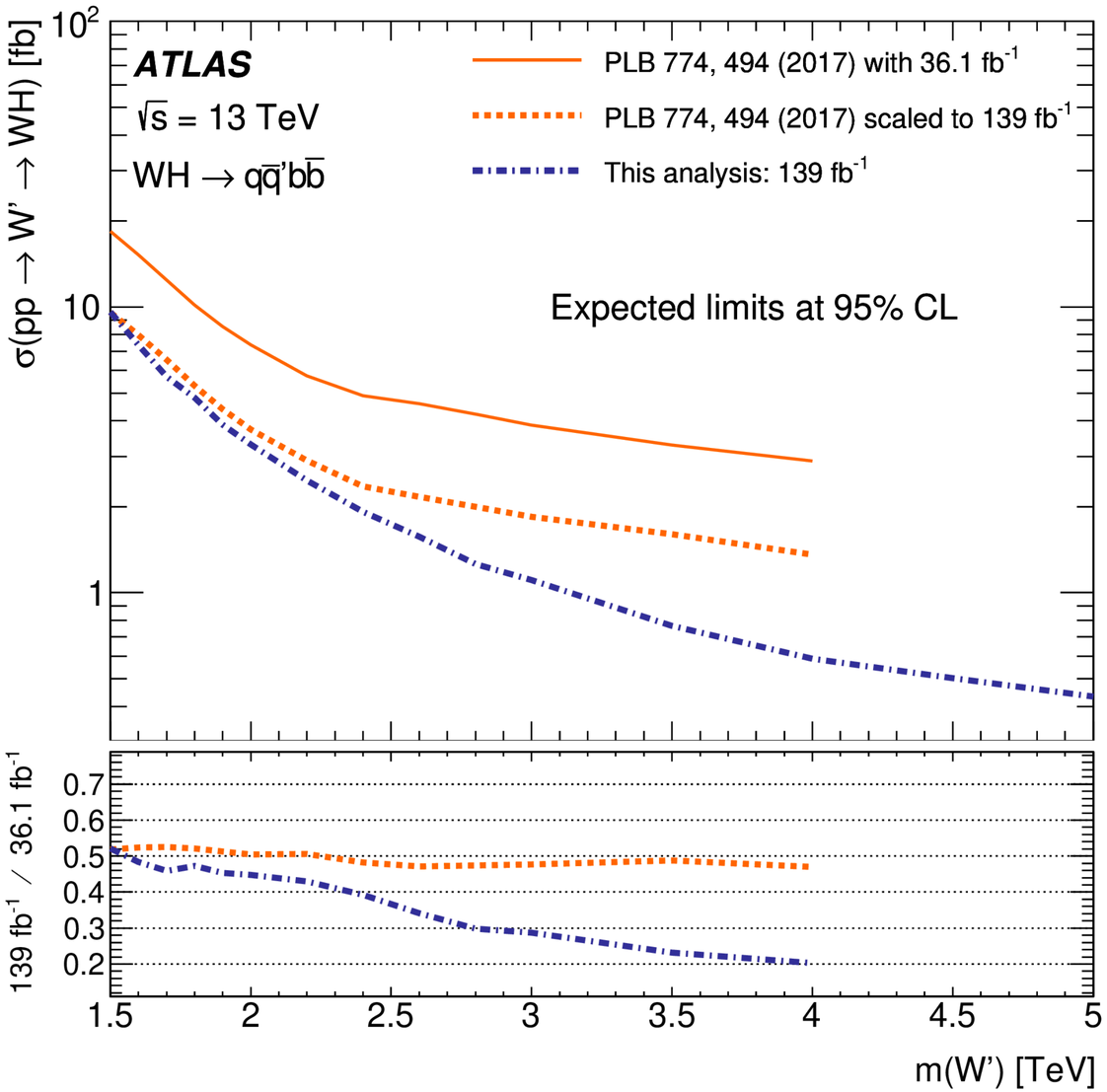


UFO



- トラッカーのほうが角度分解能が良い
- カロリメータ → High-energyにいくほど高分解能 ($\sigma \propto 1/\sqrt{E}$)
- トラッカー → Low-p_Tで高運動量分解能 ($\sigma \propto p_T$)
- それぞれ得意な部分を組み合わせる

TCC + VR jet b-tagging effect for qqbb resonance search



Zh resonance

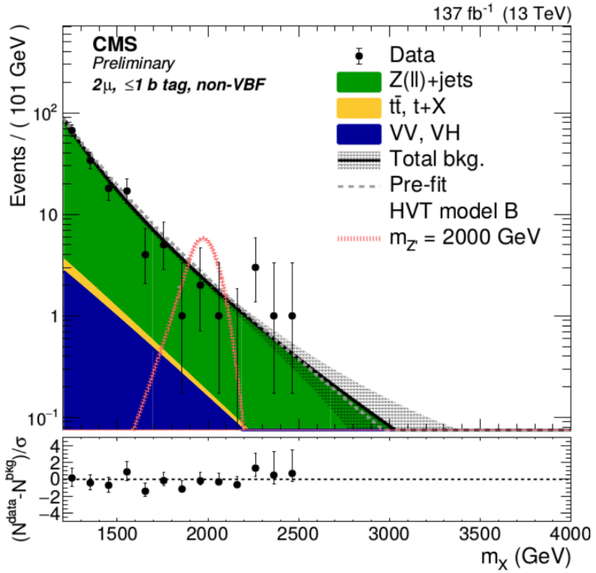
- Boosted H→bb + 0L/2L
- Large-R jet近傍に

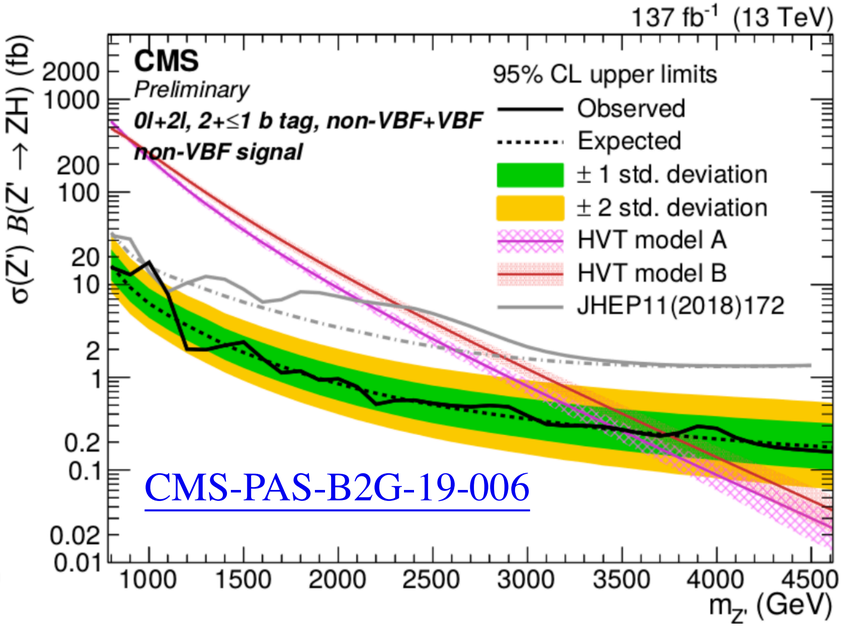
  (1) #b-jets=2
  (2) #b-jets<=1
  の2カテゴリー

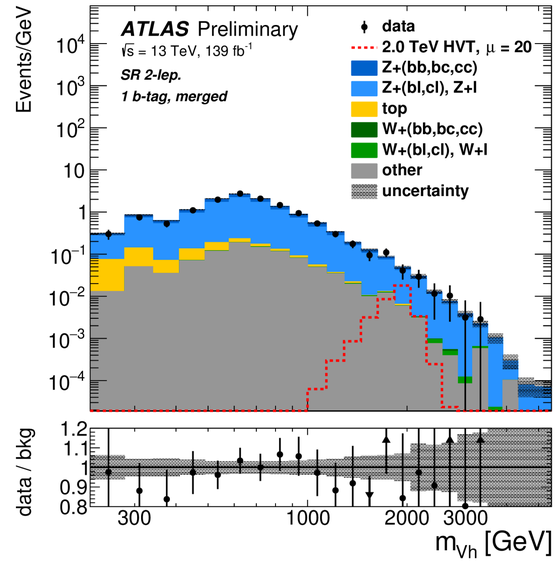
- ATLAS/CMSでほぼ同じような解析
- Z'→Zh, A→Zhで解釈

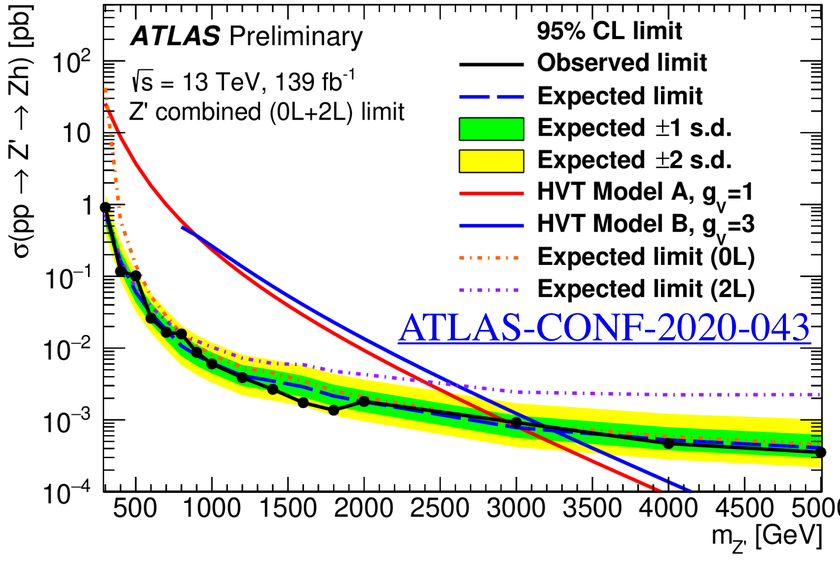
[メモ]
ATLASのほうが2-3倍悪い.
ほぼ同じ解析に見えるが、なんで？

BR(Z→ll/vv)~0.3を
CMSかけ忘れてたりして

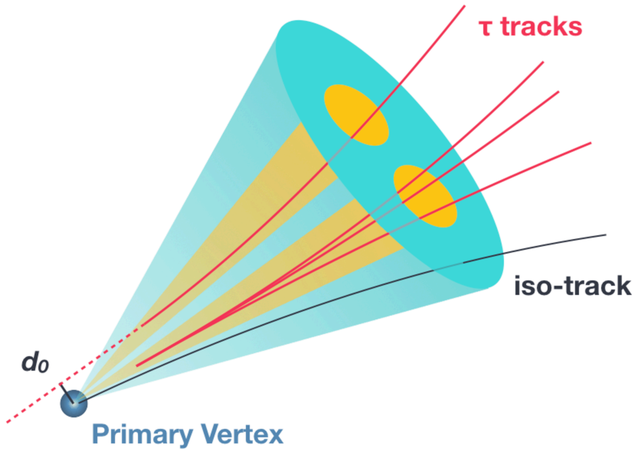


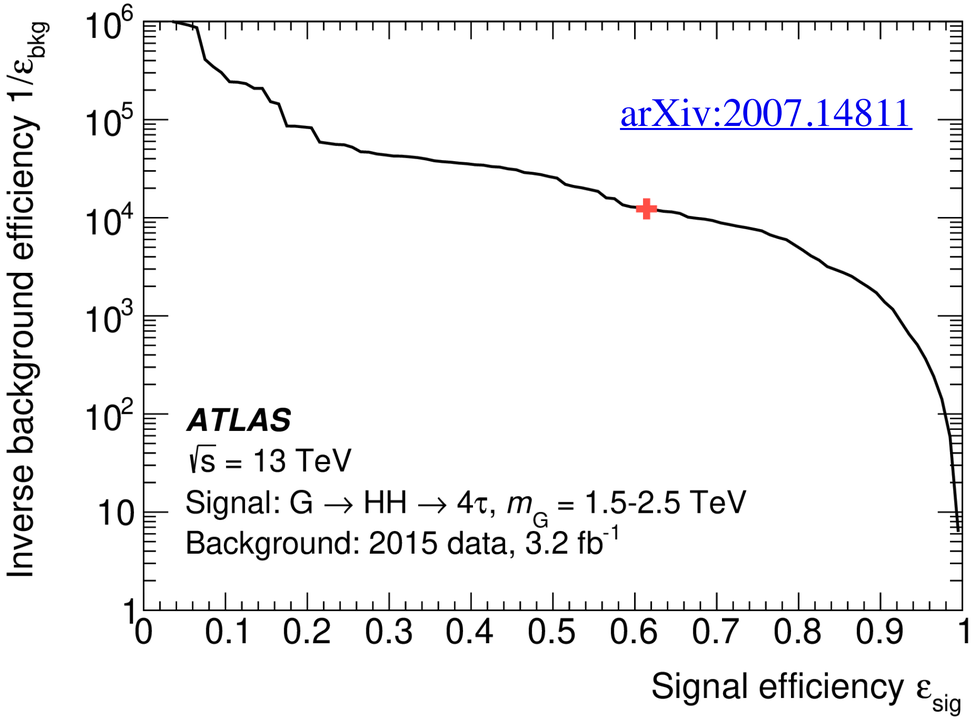






Boosted di-τ for di-Higgs→ττbb search



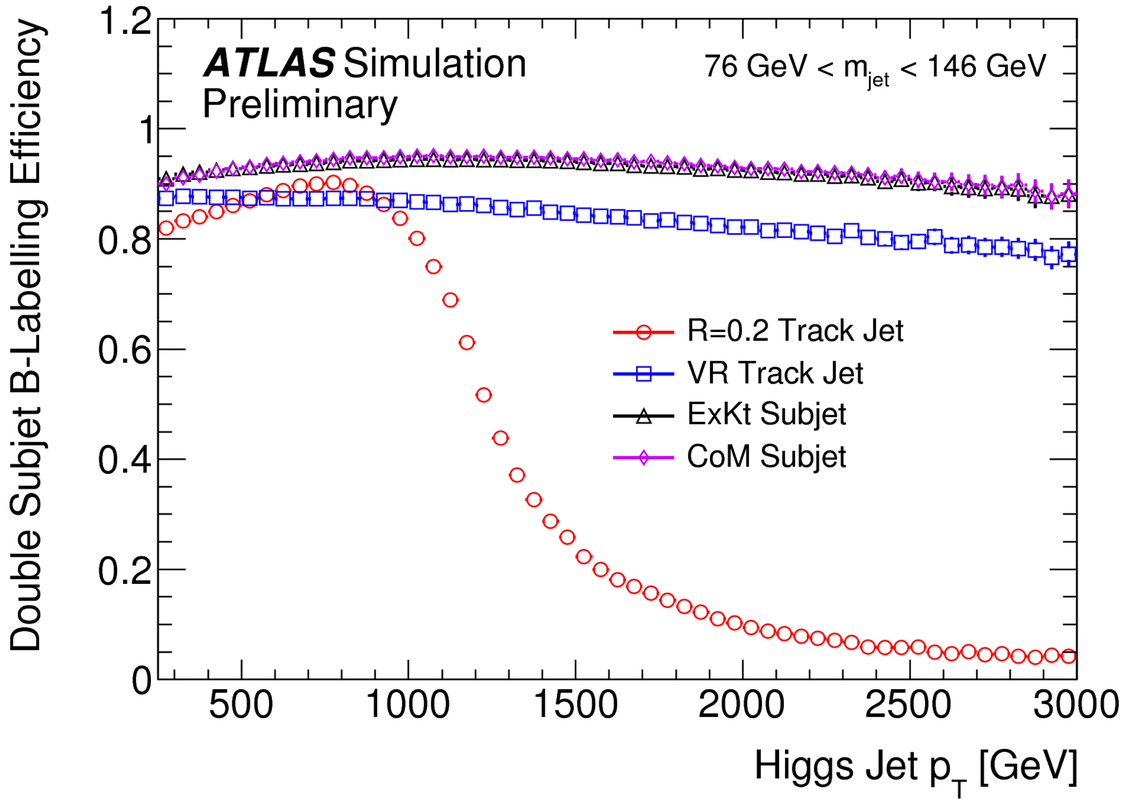


- Leading 2 subjetsとそれらに付随したトラックを使う
  → BDTで処理
- Boosted di-τ 信号 v.s. QCDジェットの分類器
- トレーニングでは#tracks情報はleading subjetのみ使用
  → 解析の段階でそれぞれのsubjetsで=1 or 3を要求

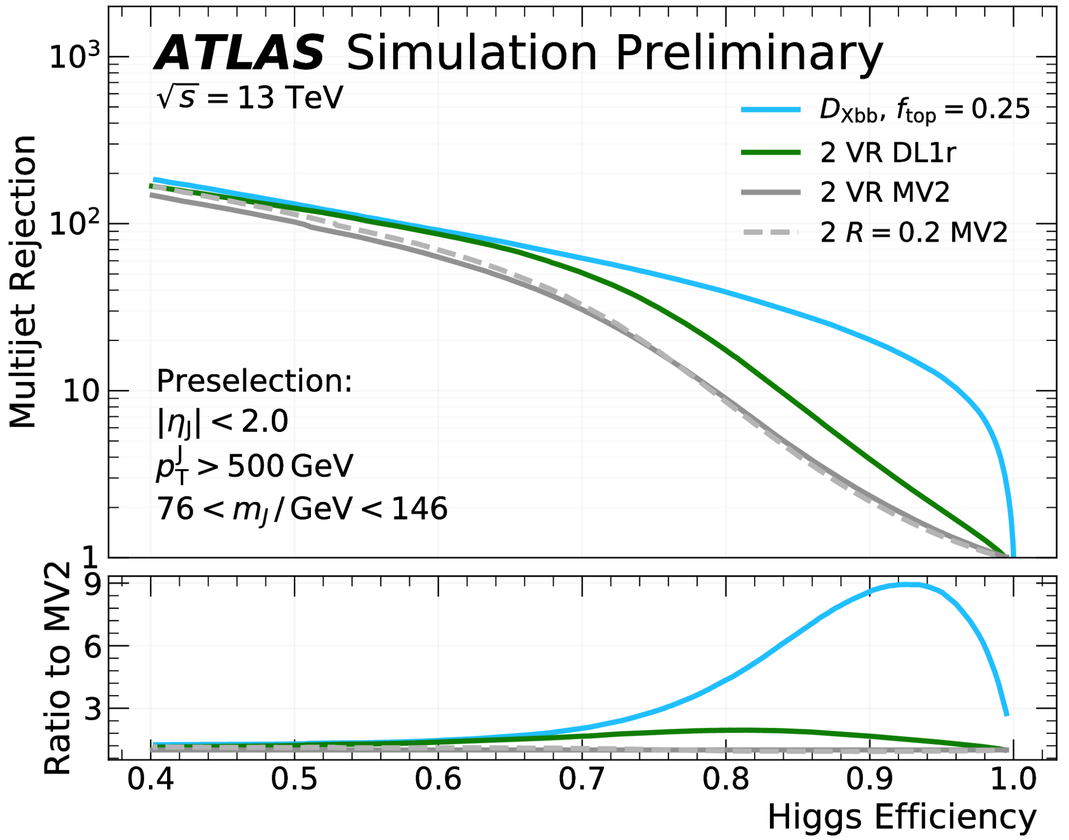
60% efficiency wp
p_T依存性、pileup依存性、小さい

Boosted H→bb tagging

ATL-PHYS-PUB-2017-010



ATL-PHYS-PUB-2020-019



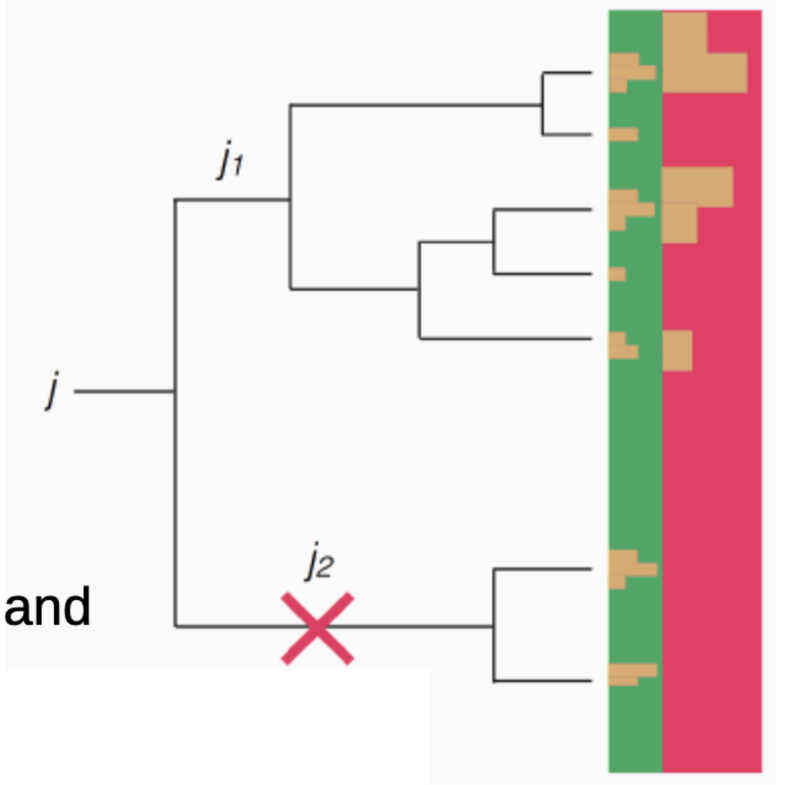
Multii-class tagger

H/t/bkg likelihoodsの比でカット

The Soft-Drop algorithm clusters jet constituents with Cambridge-Aachen, and retraces the clustering history from the last branching. For each branch, it checks that

$$\frac{min(p_{T,j1}, p_{T,j2})}{(p_{T,j1} + p_{T,j2})} > z_{cut}(\frac{\Delta R_{j1,j2}}{R})^{\beta}$$

If it is satisfied, the algorithm stops.
If not, the soft branch j2 is removed, and the algorithm is applied recursively on j1.

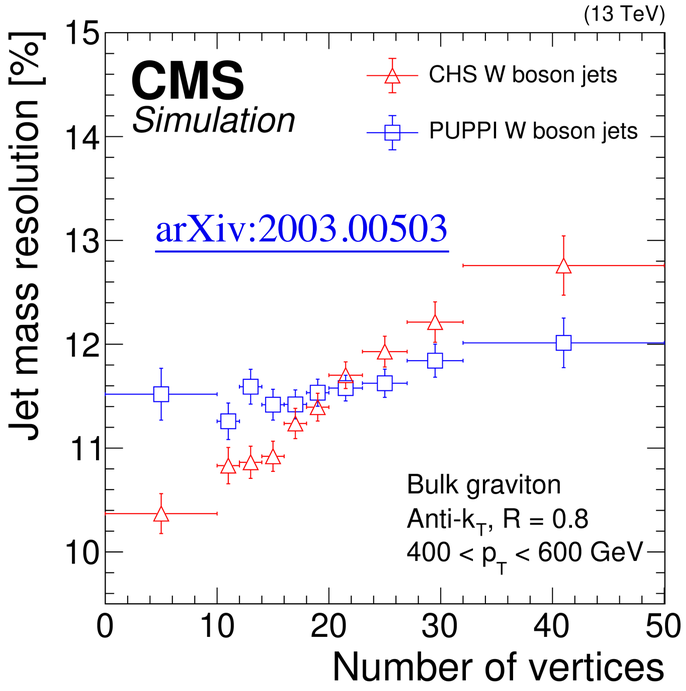


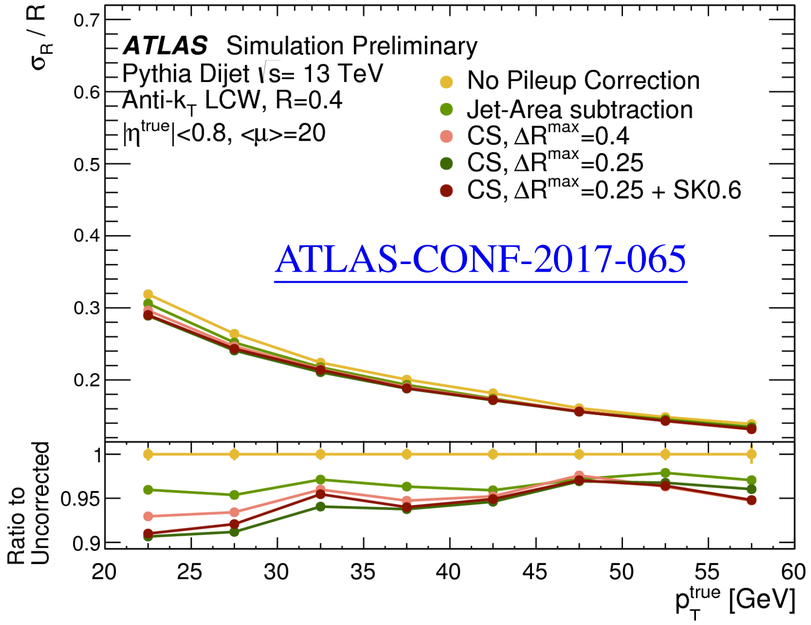
This procedure removes soft radiation, according to the scale z_{cut}, and large-angle emission, according to the parameter β (chosen)

- 現行のtrimmingと比べて、理論比較しやすい
- Soft-drop parametersのdifferential measurement: PRD101(2020)052007
- Lund plane measurement: PRL124(2020)222002

Constitute-level pileup subtraction

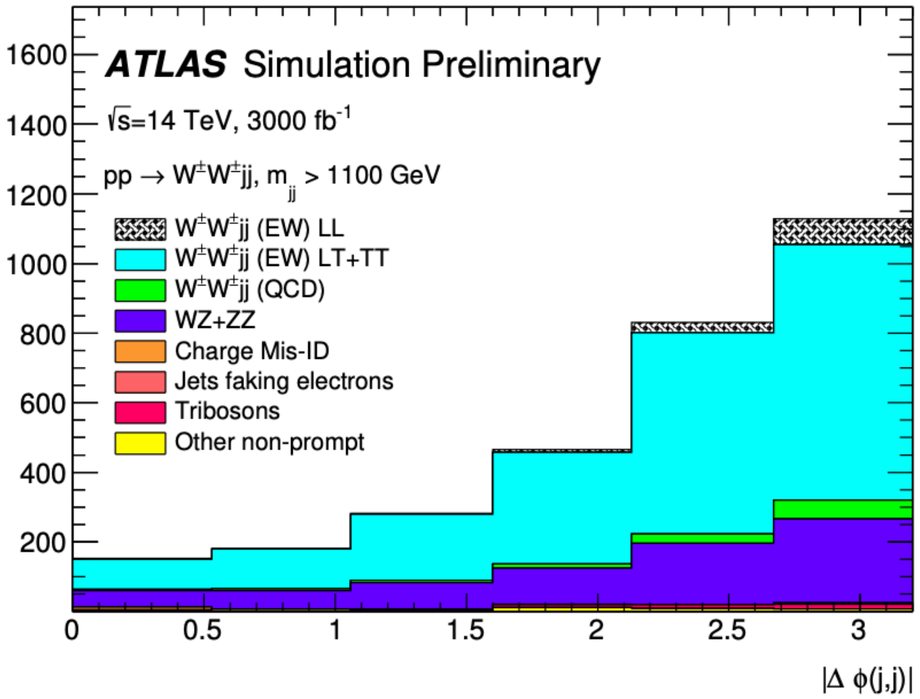
- CMS: PUPPI
  - Pileup粒子のlikelihoodを荷電粒子から導出
    →中性粒子にapply
- ATLAS
  - Constituent Subtraction (CS): Constituent-level でarea subtraction (pileup density ρをevent-by-eventに測定)
  - Soft-killer (SK): ρ=0になるようにpT cut
  - この2つは併用できる（CS+SK）

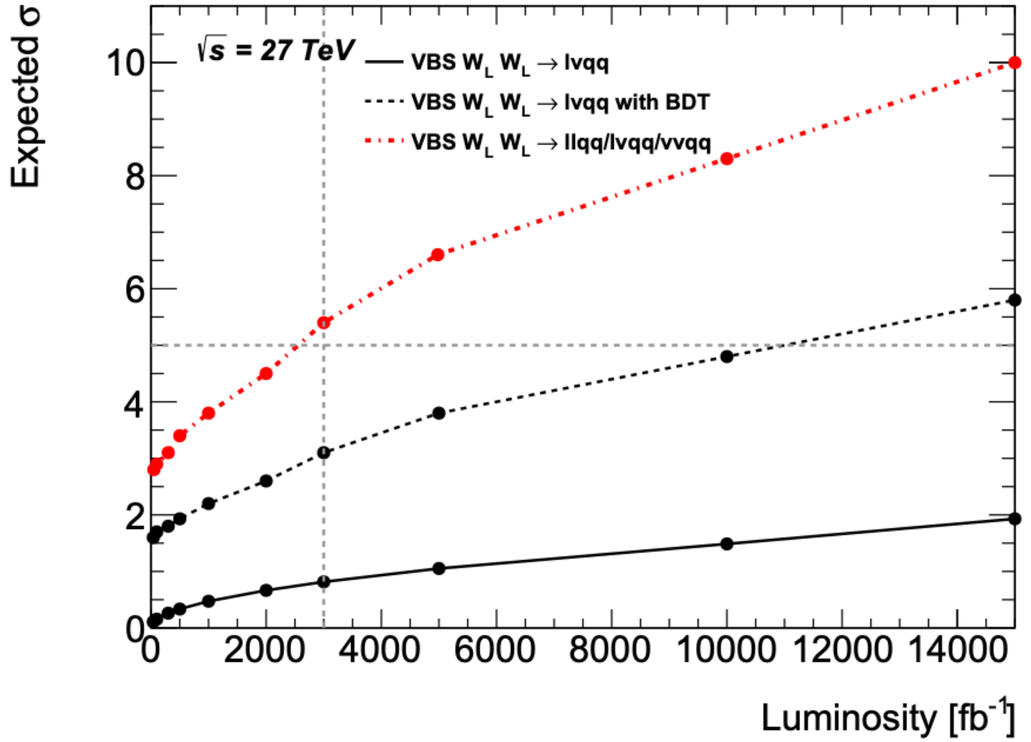




VBS measurement at HL/HE-LHC

https://arxiv.org/pdf/1902.04070.pdf





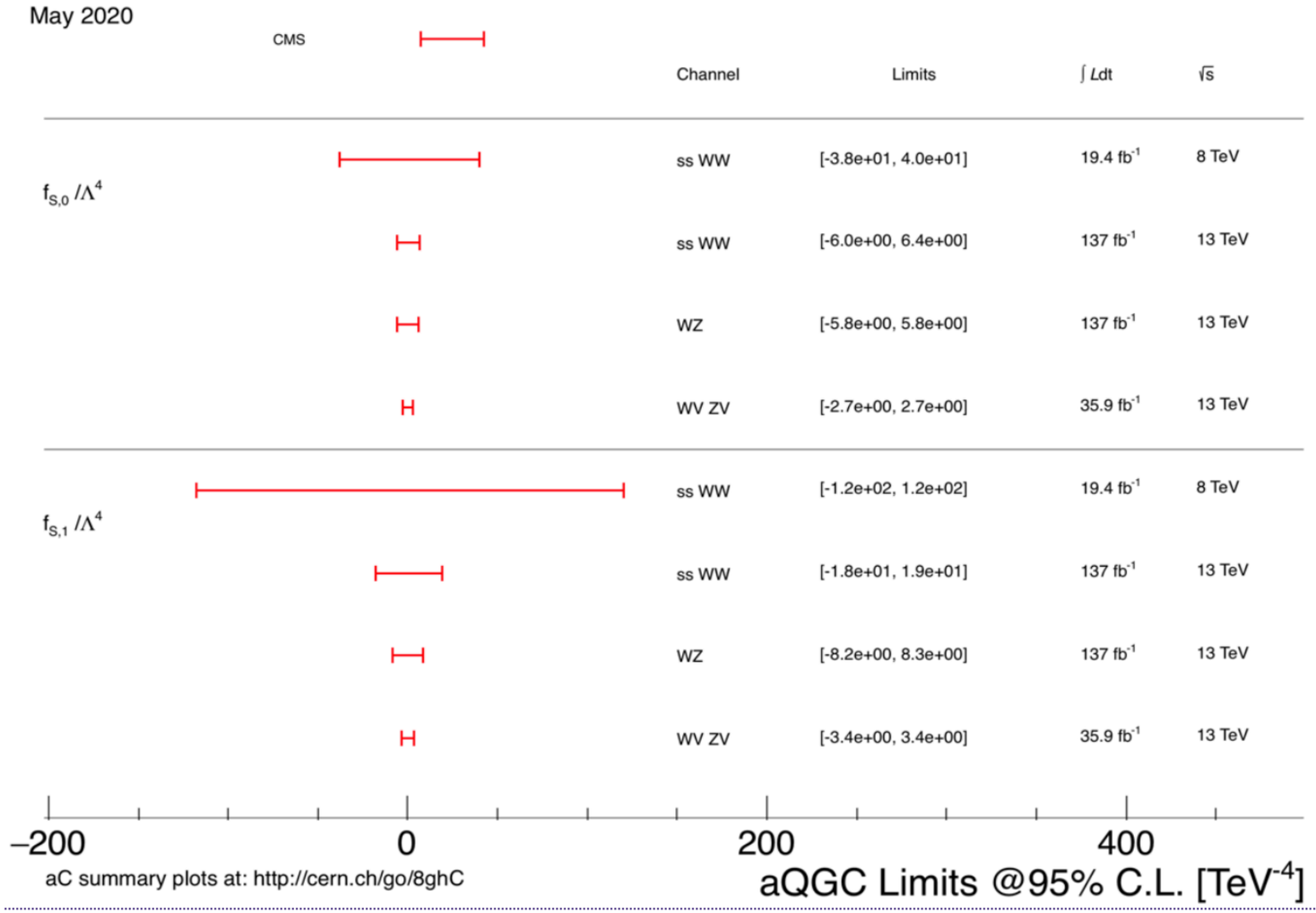
ssW$_L$W$_L$ 2-3σ予想

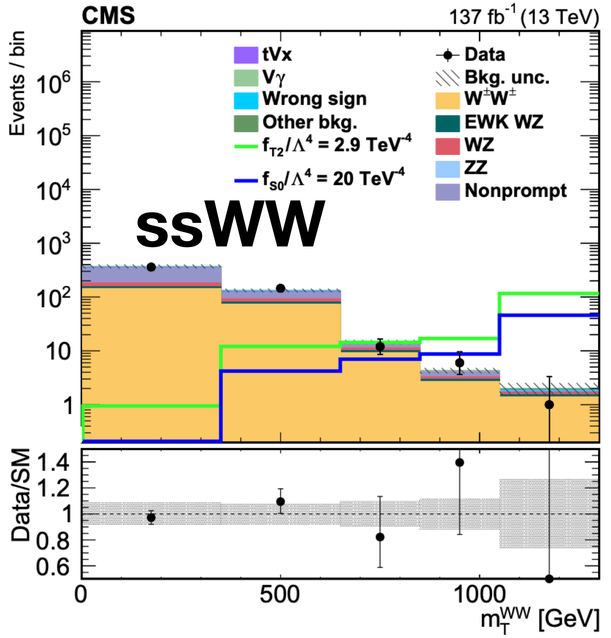
W$_L$Z$_L$ 1.5-2.5σ予想

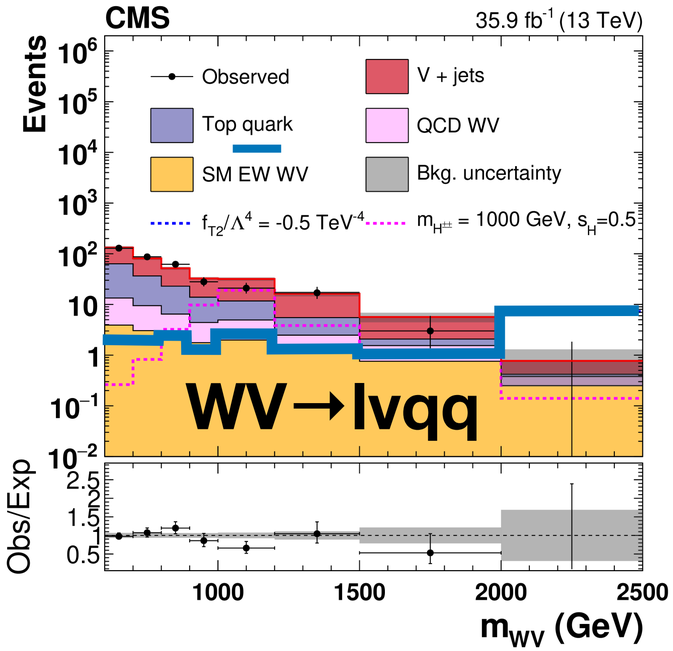
Z$_L$Z$_L$ ~1.5σ予想

Semi-leptonic channels,
HE-LHCで3-5σ予想

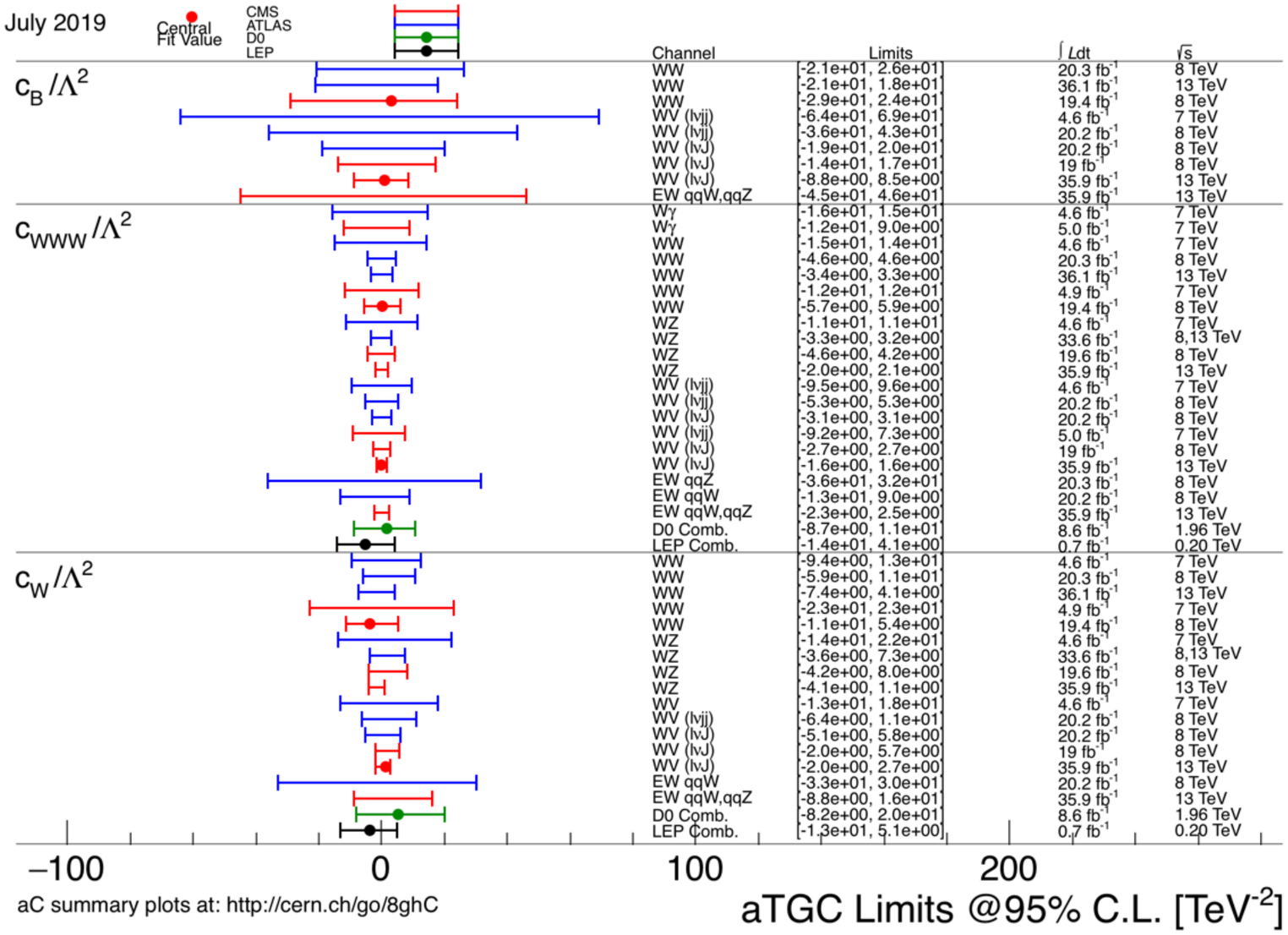
Limits on aQGC (scalar type)



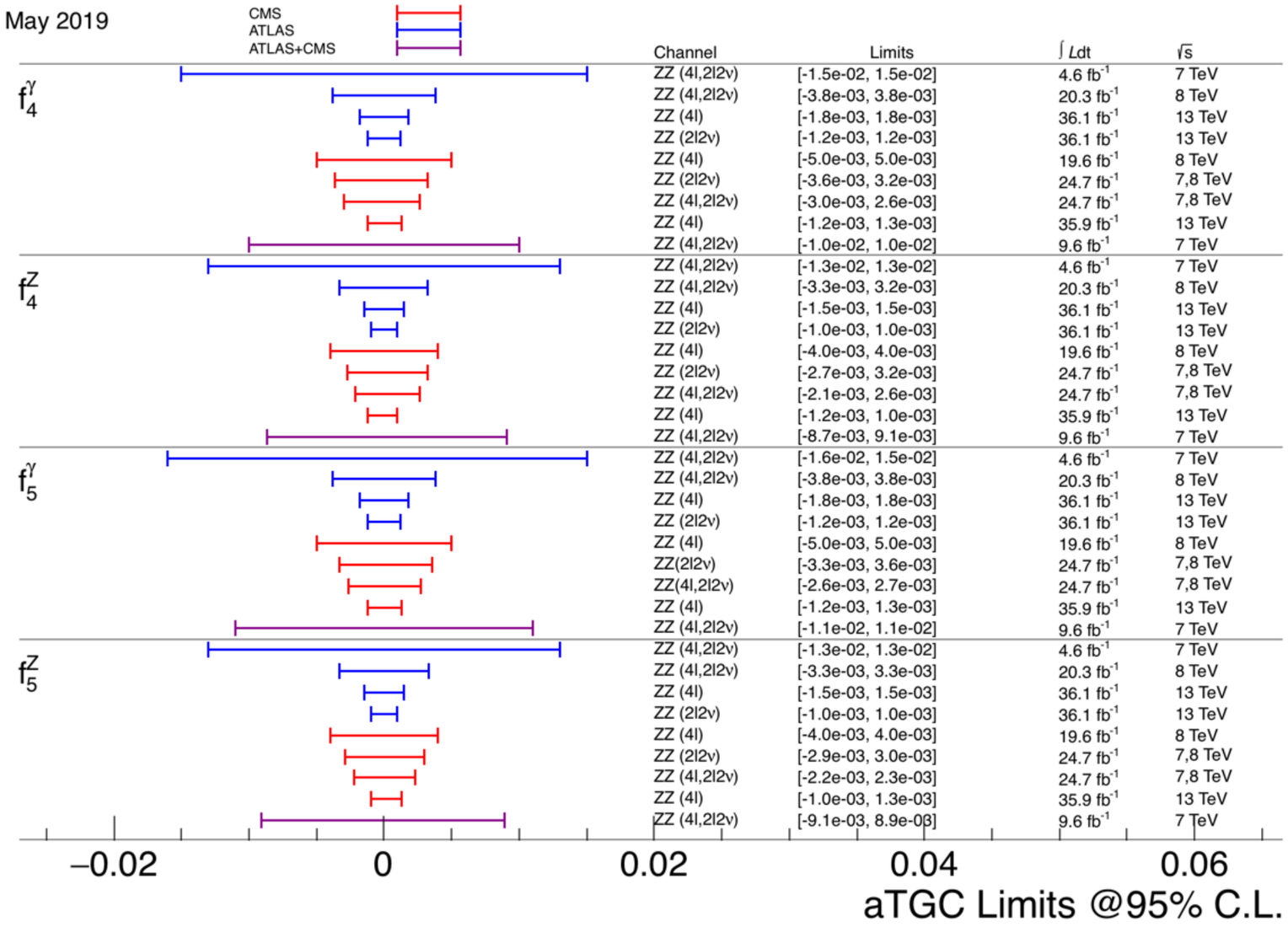




Limits on aTGC (WWW)



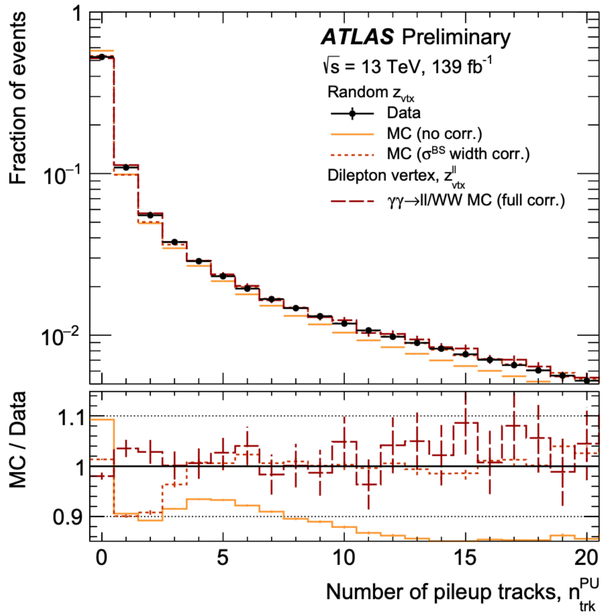
Limits on aTGC (ZZγ)

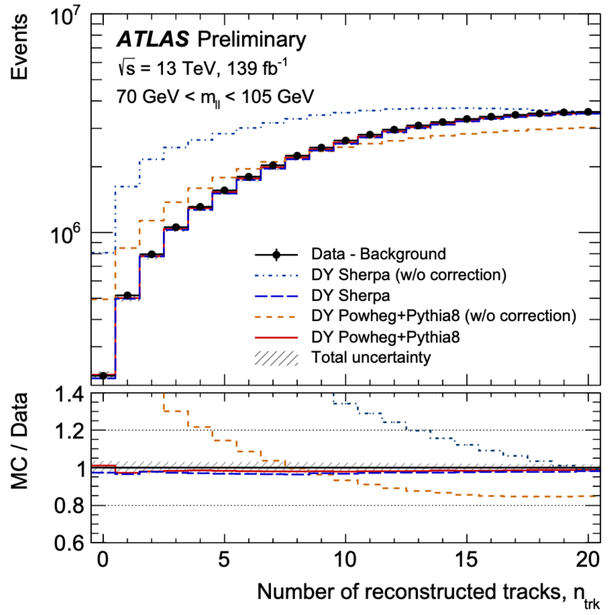
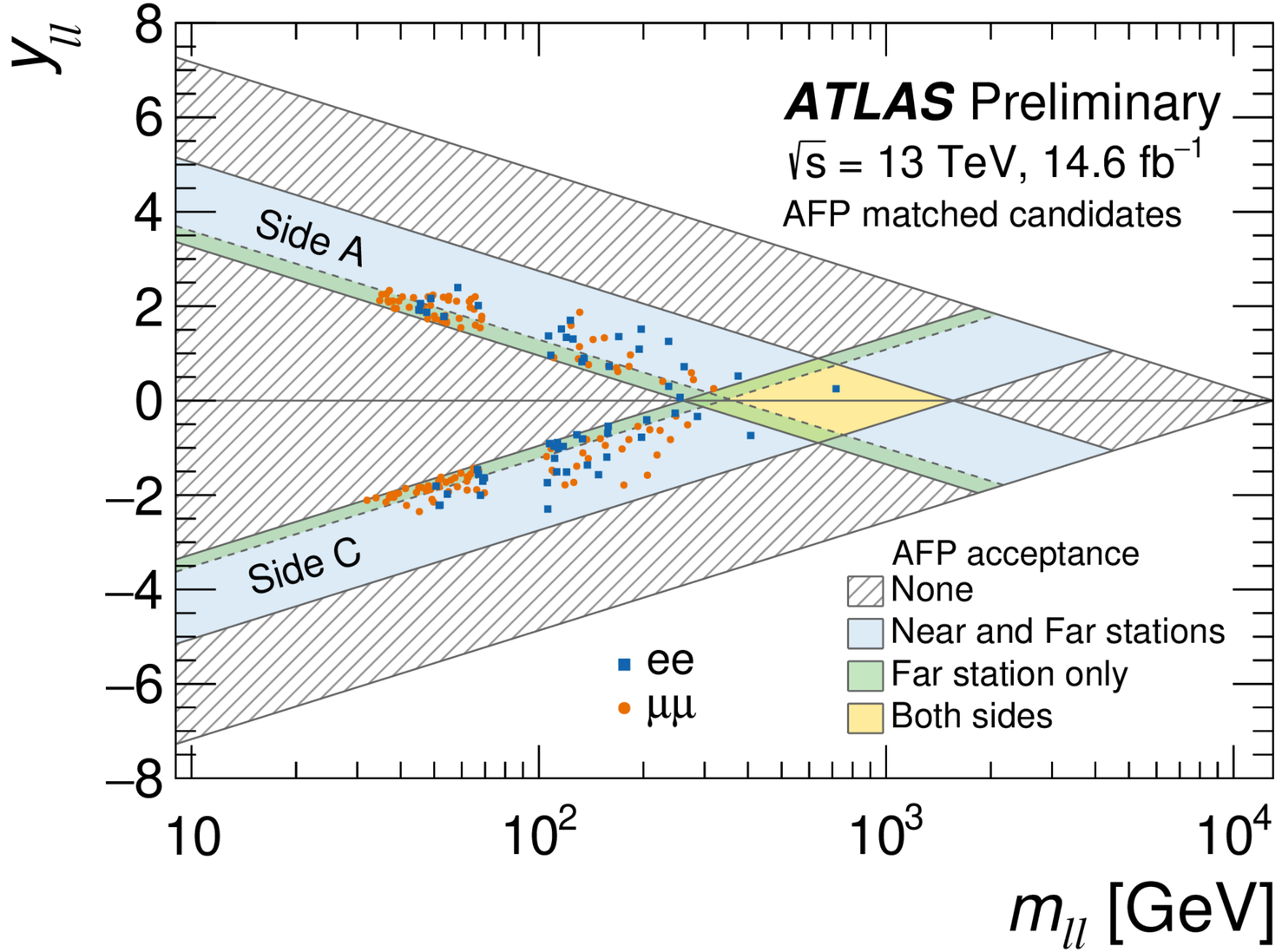


Channel	Limits	∫ Ldt	√s
ZZ (4l,2l2ν)	[-1.5e-02, 1.5e-02]	4.6 fb^{-1}	7 TeV
ZZ (4l,2l2ν)	[-3.8e-03, 3.8e-03]	20.3 fb^{-1}	8 TeV
ZZ (4l)	[-1.8e-03, 1.8e-03]	36.1 fb^{-1}	13 TeV
ZZ (2l2ν)	[-1.2e-03, 1.2e-03]	36.1 fb^{-1}	13 TeV
ZZ (4l)	[-5.0e-03, 5.0e-03]	19.6 fb^{-1}	8 TeV
ZZ (2l2ν)	[-3.6e-03, 3.2e-03]	24.7 fb^{-1}	7,8 TeV
ZZ (4l,2l2ν)	[-3.0e-03, 2.6e-03]	24.7 fb^{-1}	7,8 TeV
ZZ (4l)	[-1.2e-03, 1.3e-03]	35.9 fb^{-1}	13 TeV
ZZ (4l,2l2ν)	[-1.0e-02, 1.0e-02]	9.6 fb^{-1}	7 TeV
ZZ (4l,2l2ν)	[-1.3e-02, 1.3e-02]	4.6 fb^{-1}	7 TeV
ZZ (4l,2l2ν)	[-3.3e-03, 3.2e-03]	20.3 fb^{-1}	8 TeV
ZZ (4l)	[-1.5e-03, 1.5e-03]	36.1 fb^{-1}	13 TeV
ZZ (2l2ν)	[-1.0e-03, 1.0e-03]	36.1 fb^{-1}	13 TeV
ZZ (4l)	[-4.0e-03, 4.0e-03]	19.6 fb^{-1}	8 TeV
ZZ (2l2ν)	[-2.7e-03, 3.2e-03]	24.7 fb^{-1}	7,8 TeV
ZZ (4l,2l2ν)	[-2.1e-03, 2.6e-03]	24.7 fb^{-1}	7,8 TeV
ZZ (4l)	[-1.2e-03, 1.0e-03]	35.9 fb^{-1}	13 TeV
ZZ (4l,2l2ν)	[-8.7e-03, 9.1e-03]	9.6 fb^{-1}	7 TeV
ZZ (4l,2l2ν)	[-1.6e-02, 1.5e-02]	4.6 fb^{-1}	7 TeV
ZZ (4l,2l2ν)	[-3.8e-03, 3.8e-03]	20.3 fb^{-1}	8 TeV
ZZ (4l)	[-1.8e-03, 1.8e-03]	36.1 fb^{-1}	13 TeV
ZZ (2l2ν)	[-1.2e-03, 1.2e-03]	36.1 fb^{-1}	13 TeV
ZZ (4l)	[-5.0e-03, 5.0e-03]	19.6 fb^{-1}	8 TeV
ZZ(2l2ν)	[-3.3e-03, 3.6e-03]	24.7 fb^{-1}	7,8 TeV
ZZ(4l,2l2ν)	[-2.6e-03, 2.7e-03]	24.7 fb^{-1}	7,8 TeV
ZZ (4l)	[-1.2e-03, 1.3e-03]	35.9 fb^{-1}	13 TeV
ZZ (4l,2l2ν)	[-1.1e-02, 1.1e-02]	9.6 fb^{-1}	7 TeV
ZZ (4l,2l2ν)	[-1.3e-02, 1.3e-02]	4.6 fb^{-1}	7 TeV
ZZ (4l,2l2ν)	[-3.3e-03, 3.3e-03]	20.3 fb^{-1}	8 TeV
ZZ (4l)	[-1.5e-03, 1.5e-03]	36.1 fb^{-1}	13 TeV
ZZ (2l2ν)	[-1.0e-03, 1.0e-03]	36.1 fb^{-1}	13 TeV
ZZ (4l)	[-4.0e-03, 4.0e-03]	19.6 fb^{-1}	8 TeV
ZZ (2l2ν)	[-2.9e-03, 3.0e-03]	24.7 fb^{-1}	7,8 TeV
ZZ (4l,2l2ν)	[-2.2e-03, 2.3e-03]	24.7 fb^{-1}	7,8 TeV
ZZ (4l)	[-1.0e-03, 1.3e-03]	35.9 fb^{-1}	13 TeV
ZZ (4l,2l2ν)	[-9.1e-03, 8.9e-03]	9.6 fb^{-1}	7 TeV

γγ→WW: background見積もり

- 2leptonで測定したz_{vtx}の周辺±1mmにtrackがassociateしていないことを要求
- Pileup補正：
  - z方向のbeam densityが大事。Beam-spot widthを考慮したpileup reweighting
  - Control sample dataで、ランダムなz positionにたまたまmatchするtrack数を見積もって、pileupトラックがたまたま同じvertexに来てしまうprobabilityを見積もる
- Underlying分布補正:
  - Z→ll vertexにassociateしたcharged particle multiplicityをdataに合わせる





AFP acceptance