Search for heavy resonances decaying to ZZ or ZW and axion-like particles mediating non resonant ZZ or ZH production at sqrt(s) = 13 TeV

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Rogelio Reyes-Almanza, CINVESTAV.

Phenomenological Models

- Bosons like extension of the SM
  - Resonances, Non-resonances, Heavy narrow, or Light-mass and long-lived particles.

- Some resonant examples:
- Spin-1:
  - **Heavy Vector Triplet (HVT) model (W' Z')**. Two working points:
  - **Model A**: g_V = 1; weakly coupled scenario. BR to fermions and EWK bosons similar;
  - **Model B**: g_V = 3; strongly coupled scenario, typical of Composite Higgs Models; BR to EWK bosons dominant; sensitivity dominated by diboson analyses.

- Spin-2:
  - **KK-Graviton** from Bulk Warped Extra Dimension model; k_tilde = 0.5.
  - BR to top, Higgs and EWK bosons are dominant.

Dorigo T, Prog.Part.Nucl.Phys. 100 (2018) 211-261

Phenomenological Models: ALPs

- ALPs (Axion-like Particles) are well motivated theoretically as neutral pseudo-scalar Pseudo-Goldstone Bosons (PGB) of a new spontaneously broken global symmetry. Examples: axions, technipions.

- ALP interactions parameterized with a general Effective Field Theory Lagrangian, consistent with SM gauge symmetries and CP. Two implementations of EFTs: linear (related to weakly coupled new physics models, minimal) and chiral (related to strongly coupled new physics models, more parameters).

- ALP interactions are derivative: they grow with momentum; couplings are proportional to Wilson coefficient *c* and inversely proportional to new physics energy scale f_a. This is a real advantage for high-energy experiments.

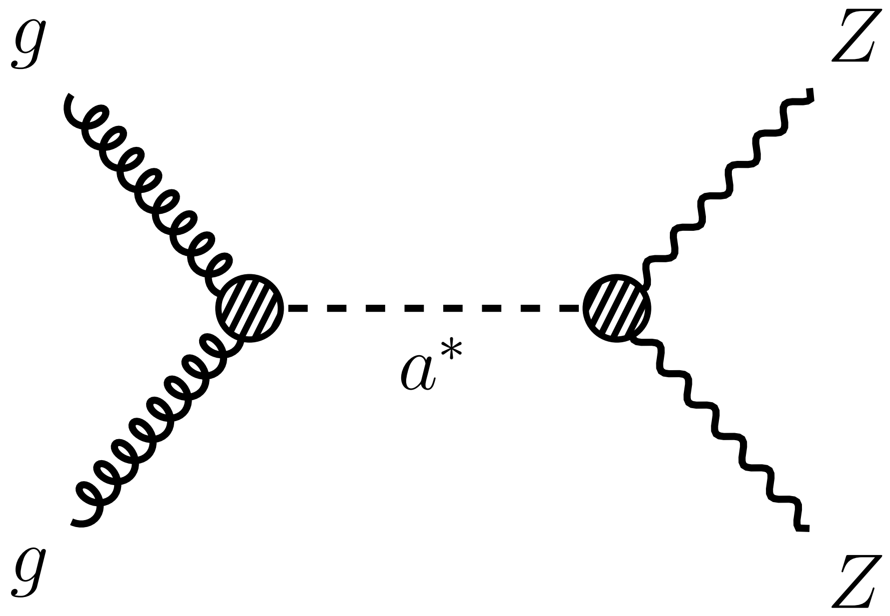
- Colliders allow searches in a wide range of ALP masses and couplings. We can explore ALP masses beyond astrophysical constraints, and even there, provide important crosschecks. At the LHC, natural sensitivity is to f_a scales in the TeV region.

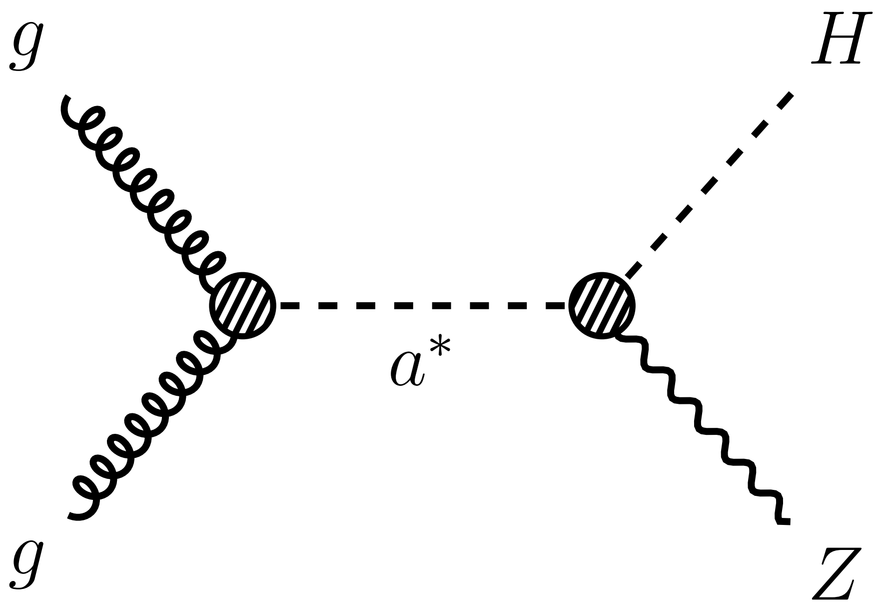
PRL 124 (2020) 051802, JHEP 06 (2022) 113

Phenomenological Models: GGF ALP-Mediated Processes

- Gluon-initiated ALP-mediated processes provide new possibilities to test the ALP universe beyond classical searches.

- These channels are sensitive to the product of the ALP coupling to gluons times the coupling to EWK dibosons.





Gavela, No, Sanz, Trocóniz; PRL 124 (2020) 051802

GGF ALP-Mediated Non-Resonant Diboson Production

- Off-shell ALP production. This is very promising because the cross-sections are large enough to constraint significantly the theoretical models using data.

- ALPs are s-channel mediators in $gg \rightarrow$ VV production with s-hat >> M_a^2. The size of s-hat is enhanced by the mass threshold of the on-shell diboson system in the final state; but most importantly by the hard pT-spectrum provided by the derivative couplings.

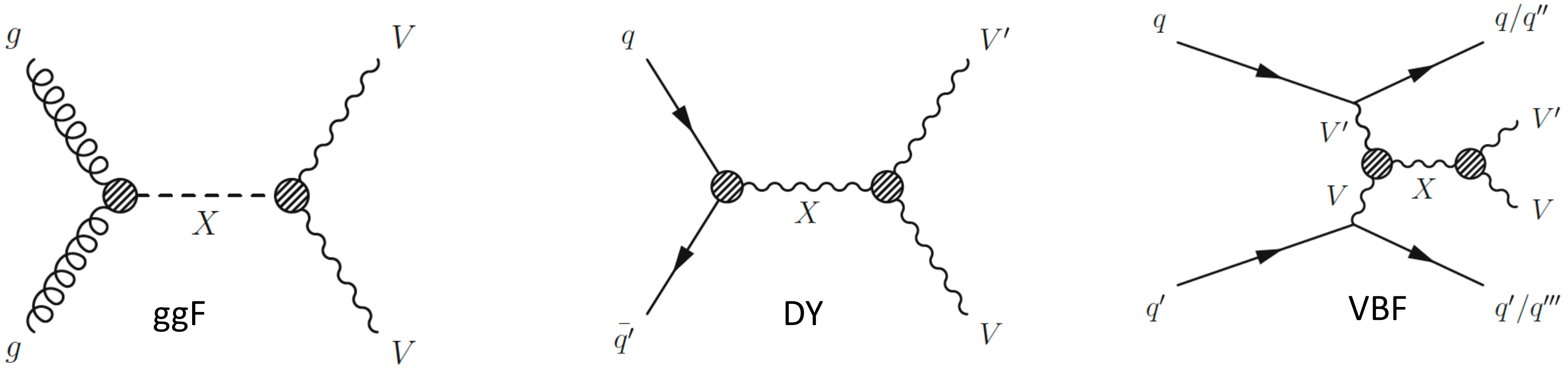
- The analysis uses the ZV, WW, ZH searches looking for high-pT / high-mass deviations in the tails of the transverse momentum / mass spectra with respect to SM expectations.

- For ALPs light enough the cross-sections, kinematical distributions, and expected limits are found independent of M_a, from the very-light limit up to masses of the order of 100 GeV.

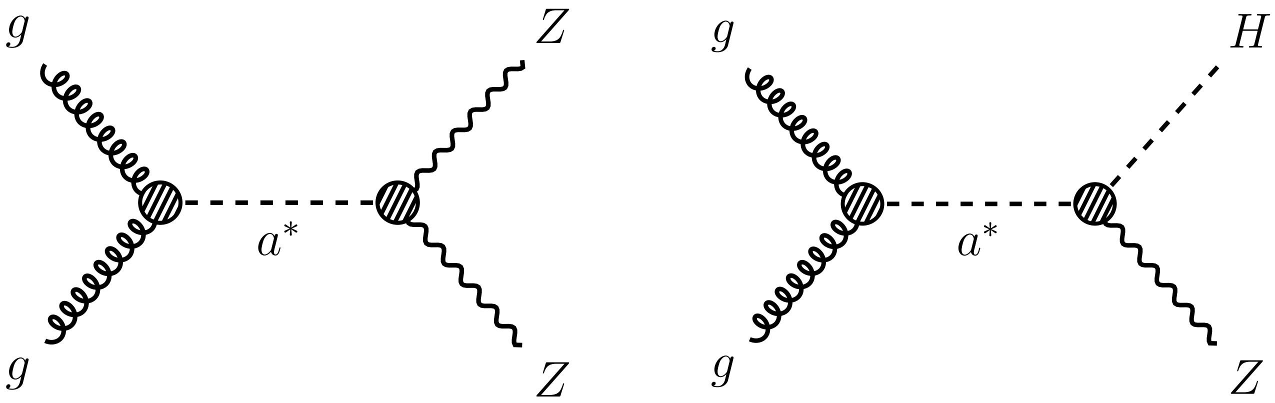
Gavela, No, Sanz, Trocóniz; PRL 124 (2020) 051802

Hadron Z / W / H: Resonances and Non-resonances

ATLAS, Eur. Phys. J. C 80 (2020) 1165



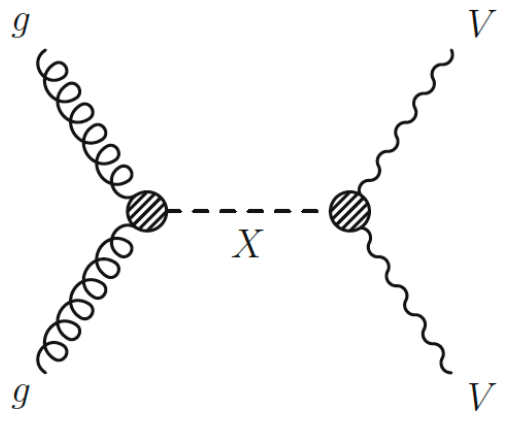
ALPS →

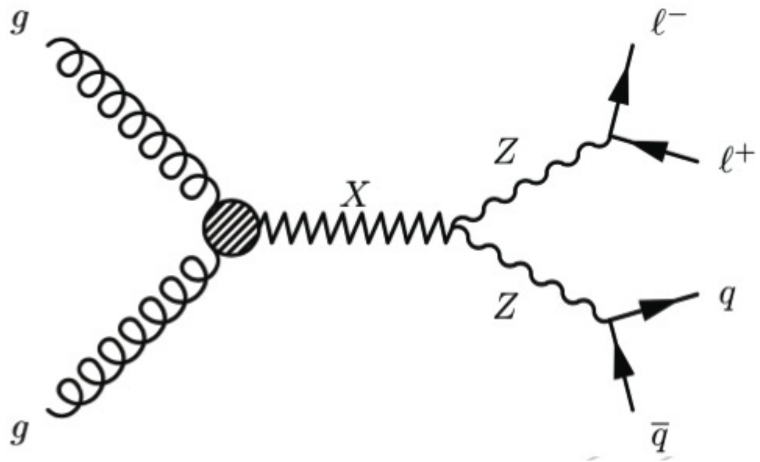


gluon-iniated ALP-mediated

CMS, JHEP 04 (2022) 087

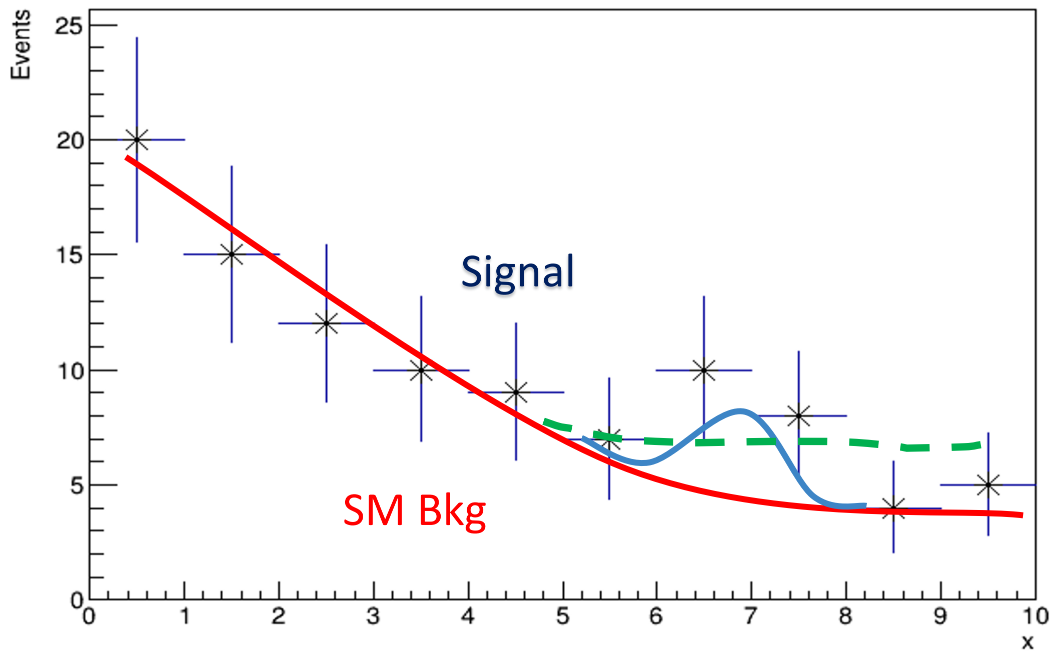
Hadron Z / W / H: Resonances and Non-resonaces





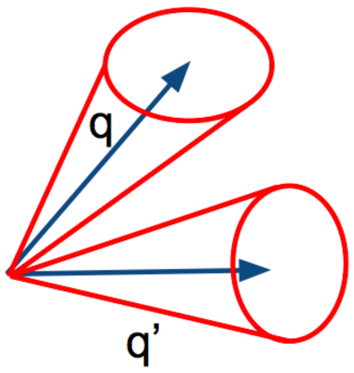
Pros: Large Branching Fractions
-Sensitive in 400-2000 GeV mass region

Cons: Large backgrounds from V+jets, QCD.
-Estimate via NLO QCD and/or sideband (SB) data.



Hadron Z / W / H: Heavy Resonance = Boosted Regime

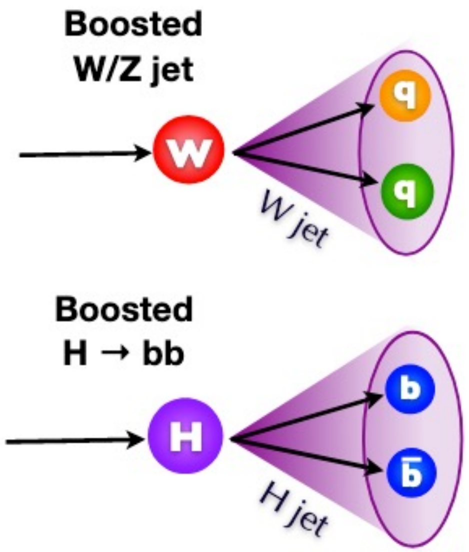
Resolved



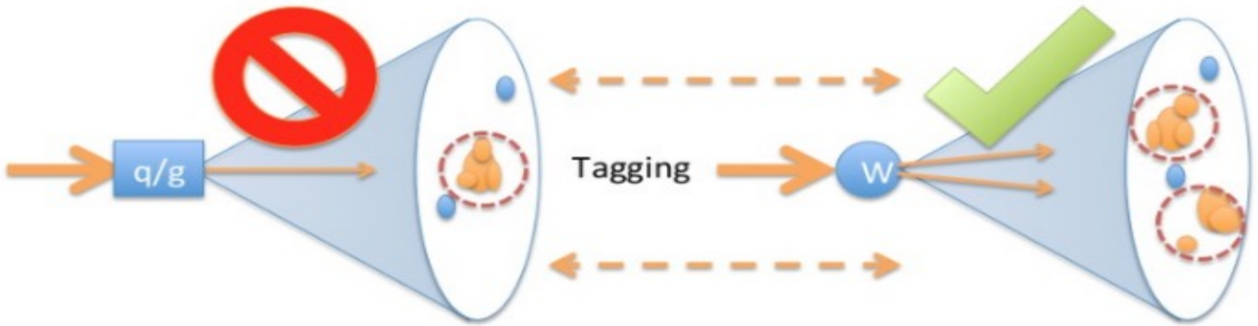
Standard Jets (AK4)

BOOST

pT > 2.5 Mass



Merged Jet (AK8)



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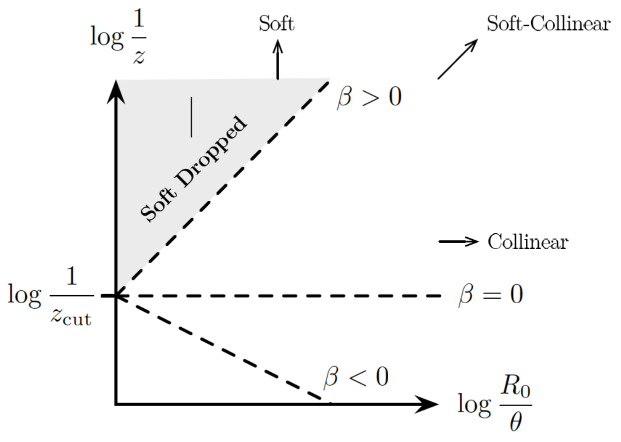
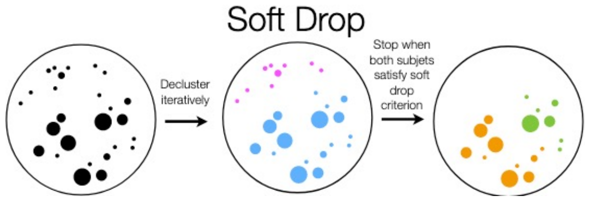
Z, W, H Jets vs QCD

- Standard discrimination against QCD in CMS uses:
  1. PU mitigation: **CHS**: Charged Hadron Subtraction, **PUPPI**: Pile Up Per Particle Identification.
  2. Jet Grooming: Recluster jet removing soft radiation and wide angle constituents (PU). Main observable is the groomed M(J); grooming pushes QCD to lower M(J) values and improves signal mass resolution. **The Soft Drop method**.
  3. Jet Substructure: **N-subjettiness** is a measure of how consistent a jet is with a hypothesized number of subjets.
  4. B-tagging in boosted topologies: DeepCSV: Combined Secondary Vertex on SD subjets; Double-B: Double b-tagging (mostly) dedicated to boosted H decays. DeepJet, DeepAK8 and etc.

Z, W, H Jets vs QCD: Soft Drop Grooming (SD)

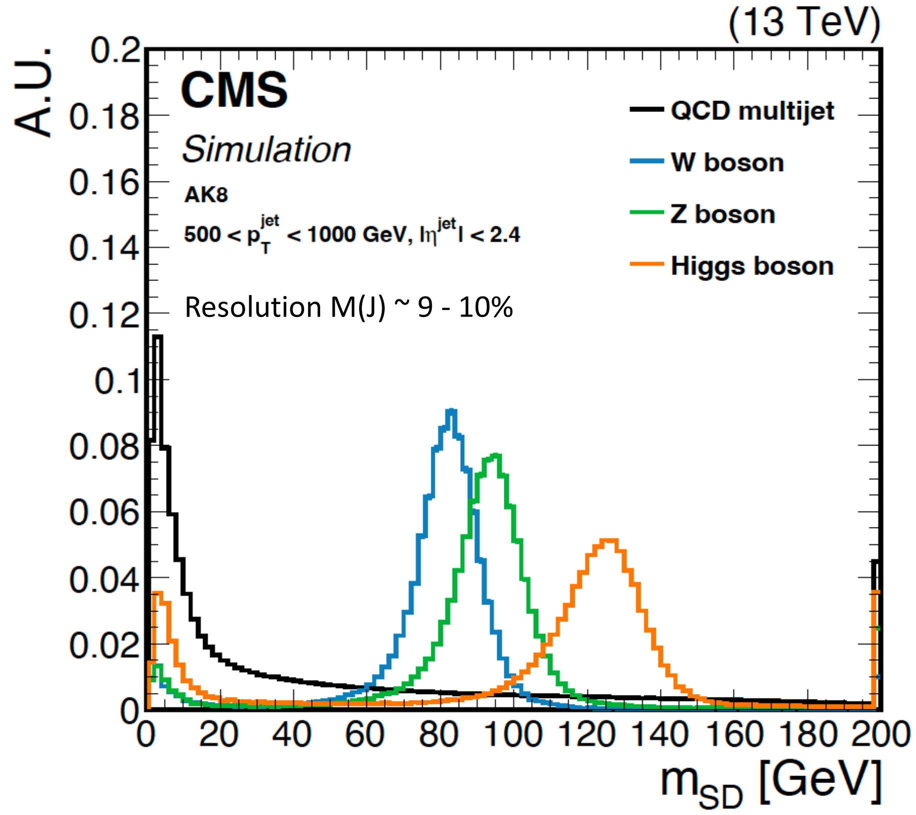
- After re-clustering CA into 2 subjets:
- If $\frac{\min(pT1, pT2)}{pT1+pT2} > z_{cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$, declare SD jet is defined.
- Else, drop softer subjet and iterate on harder one.
- For β = 0, soft radiation removed (A.K.A Modified mass drop tagger)





- Two subjets returned by the SD algorithm are used to calculate the SD jet mass

CMS Collaboration, JINST 15 (2020) P06005

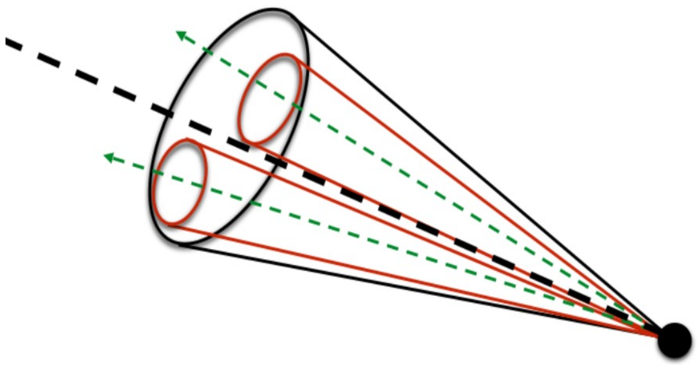


SB | Signal Region | SB

Z, W, H Jets vs QCD: N-subjettiness

We know how many final state objects to expect from Boson decays

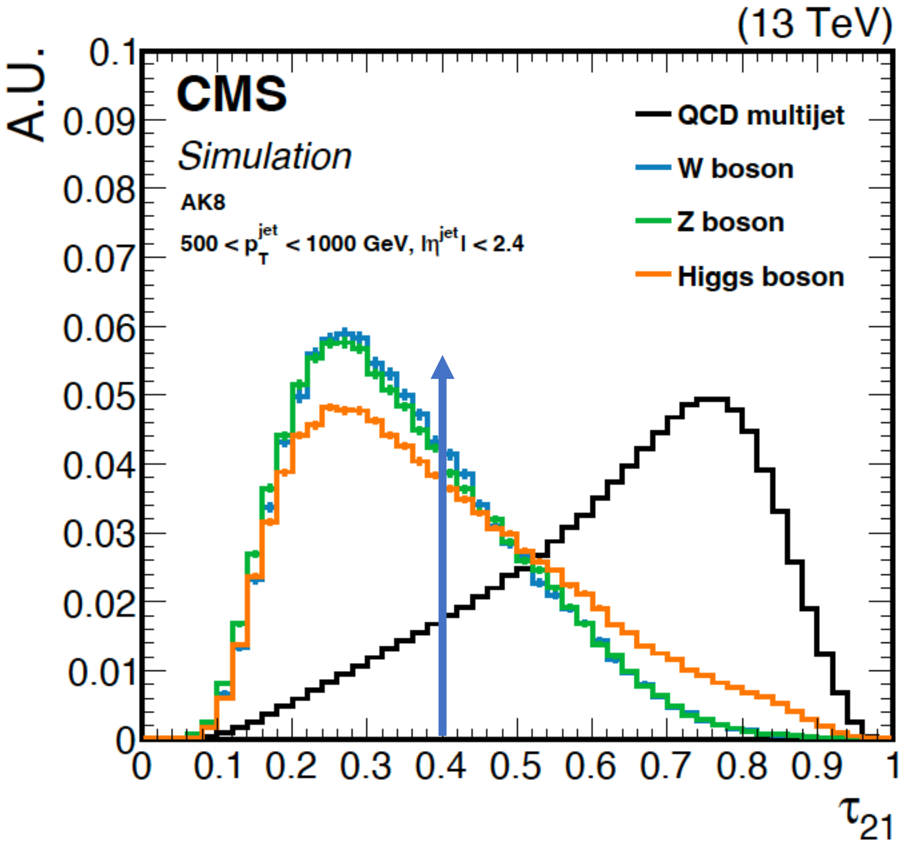
- ‣Can look inside the jet for the expected substructure
  - Top decays → 3 subjets
  - W/Z/H decays → 2 subjets



$$\tau_N = \frac{1}{\sum_i p_{T,i} \cdot R} \sum_i p_{T,i} \cdot \min(\Delta R_{1,i}, \Delta R_{2,i}, \ldots, \Delta R_{N,i})$$

- τN provides a measure of the number of subjets that can be found inside of the jet.
- Low τN→ consistent with N (or fewer) subjets

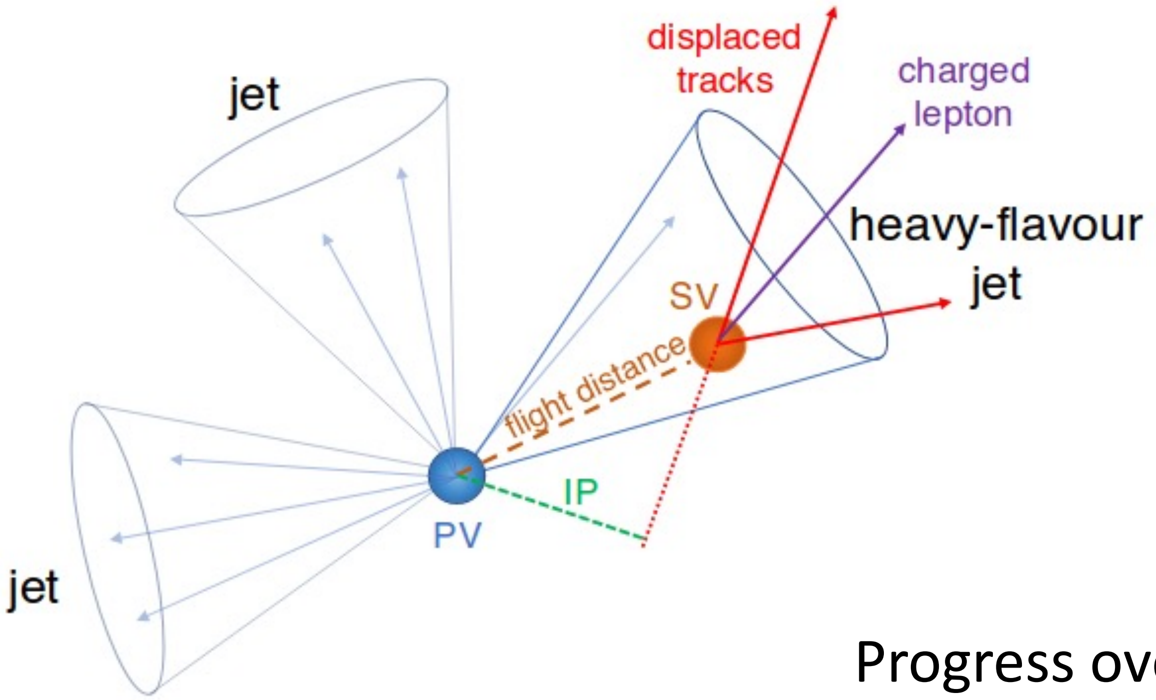
- τ21 = τ2 / τ1 is found a very powerful discriminant boosted decays
- Analysis uses HP cut τ21 < 0.4



CMS Collaboration, JINST 15 (2020) P06005

Z, W, H Jets vs QCD: B-tagging Subjets

CMS Collaboration, JINST 15 (2020) P06005

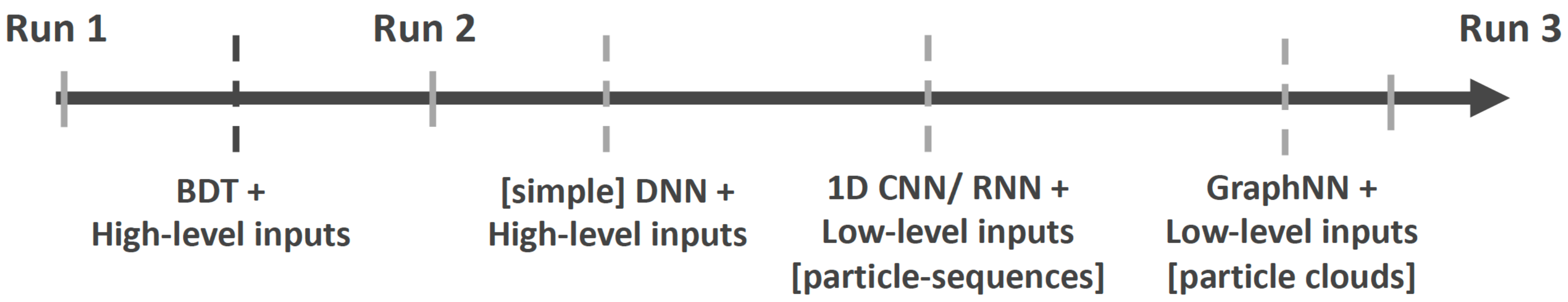


Key ingredients **for b/c vs. light** :

- ❑ Large lifetime & decay lengths
- ❑ Displaced vertices/tracks
- ❑ Large impact parameters
- ❑ Non-isolated leptons (soft)
- ❑ Harder fragmentation

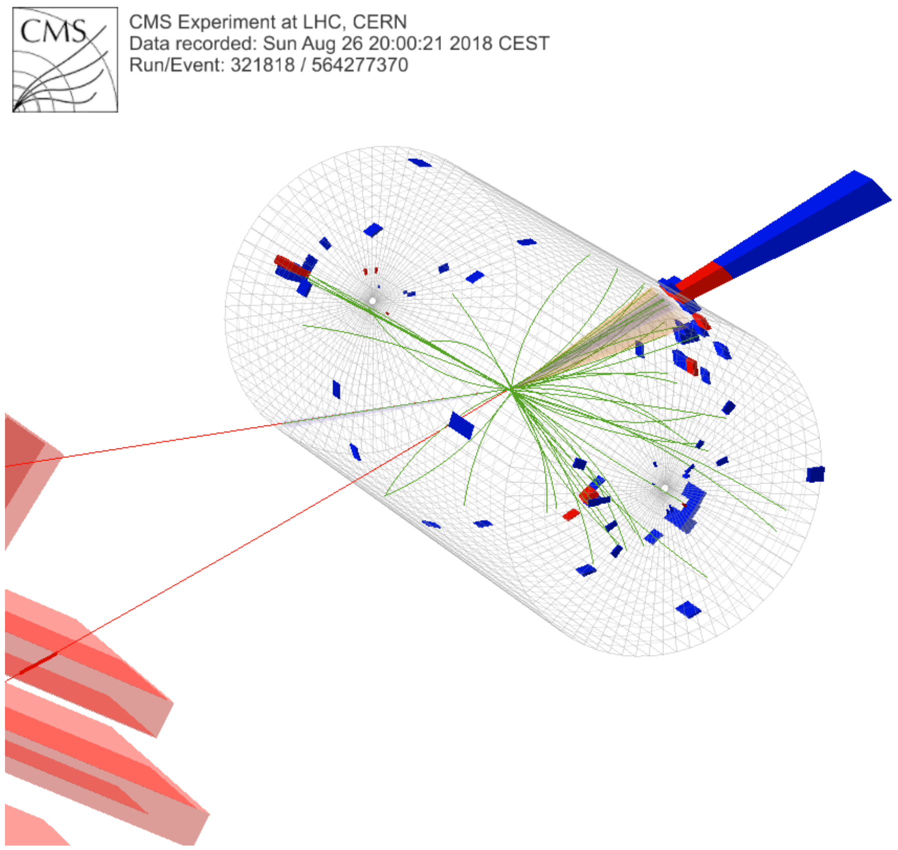
- ❑ Analysis uses DeepCSV technique
- ❑ **Tagged event: 1Loose + 1Medium**

Progress over years

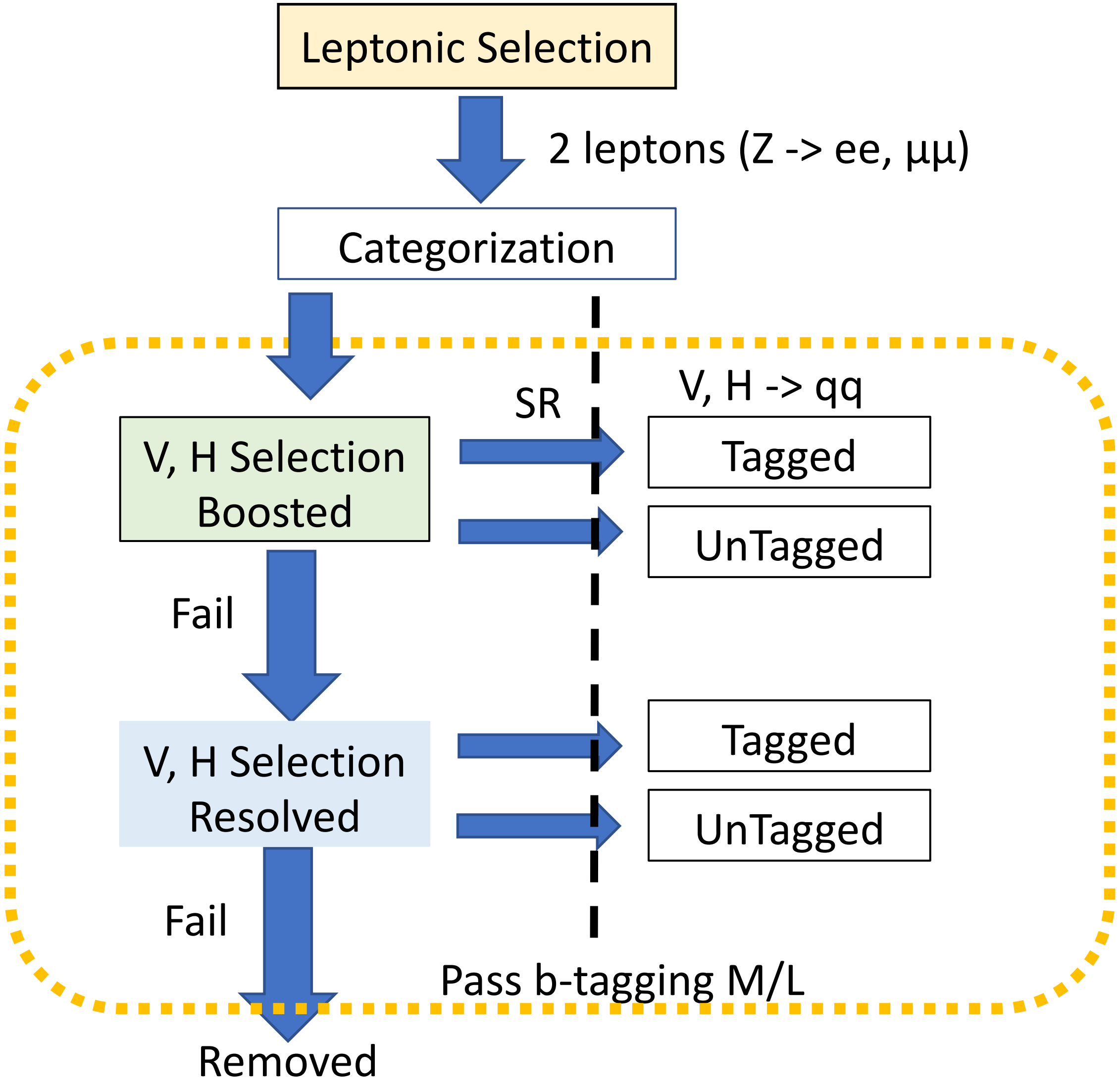


Selection events

Selection and Categorization Events



- Both Boosted and Resolved considered
- Background estimated using SB data-corrected
- NLO Z+jets MC prediction
- Categorization based on b-tagging



Results

SR1 ZZ/ZW: 2l2q Mass Distributions

- Fit m(ZV) distributions for electrons / muons, boosted / resolved, tagged / untagged categories in SR1 + SB.
- Z+jets normalizations float in the fit.
- Z+jets shape corrections float in the fit.

→ Signal (red line) normalized to 95% CL ALP linear ZZ cross-section limit for $f_a = 3$ TeV.

Boosted Untagged

(10948 ev.)

Boosted Tagged

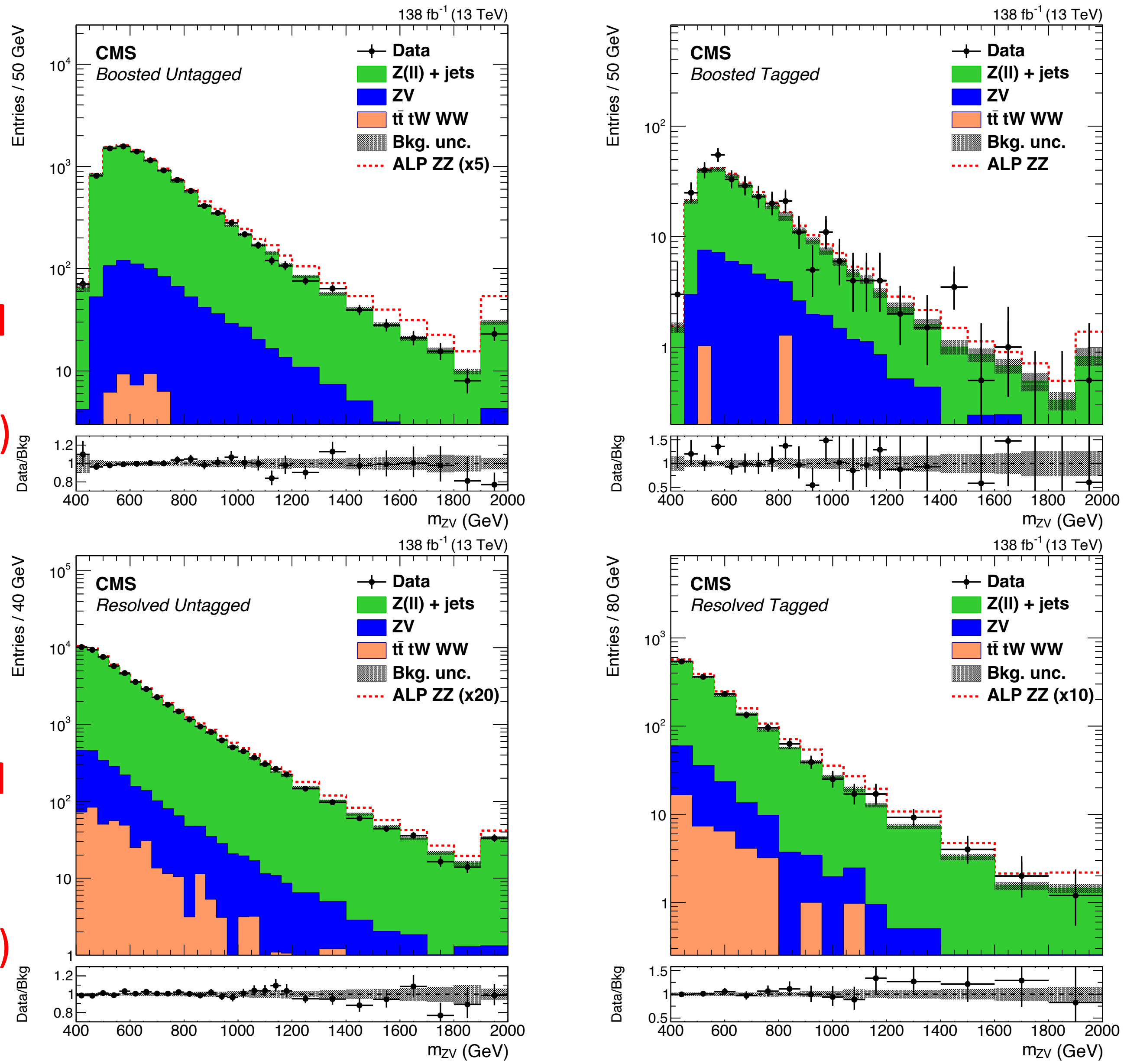
(312 ev.)

Resolved Tagged

(1566 ev.)

Resolved Untagged

(56324 ev.)



SR2 ZH: 2l2q Mass Distributions

- Fit m(ZH) distributions for electrons / muons, boosted / resolved, tagged / untagged categories in SR2 + SB.
- Z+jets normalizations float in the fit.
- Z+jets shape corrections floating in the fit.

→ Signal (red line) normalized to 95% CL ALP chiral ZH cross-section limit for $f_a = 3$ TeV.

Boosted Untagged

(4499 ev.)

Boosted Tagged

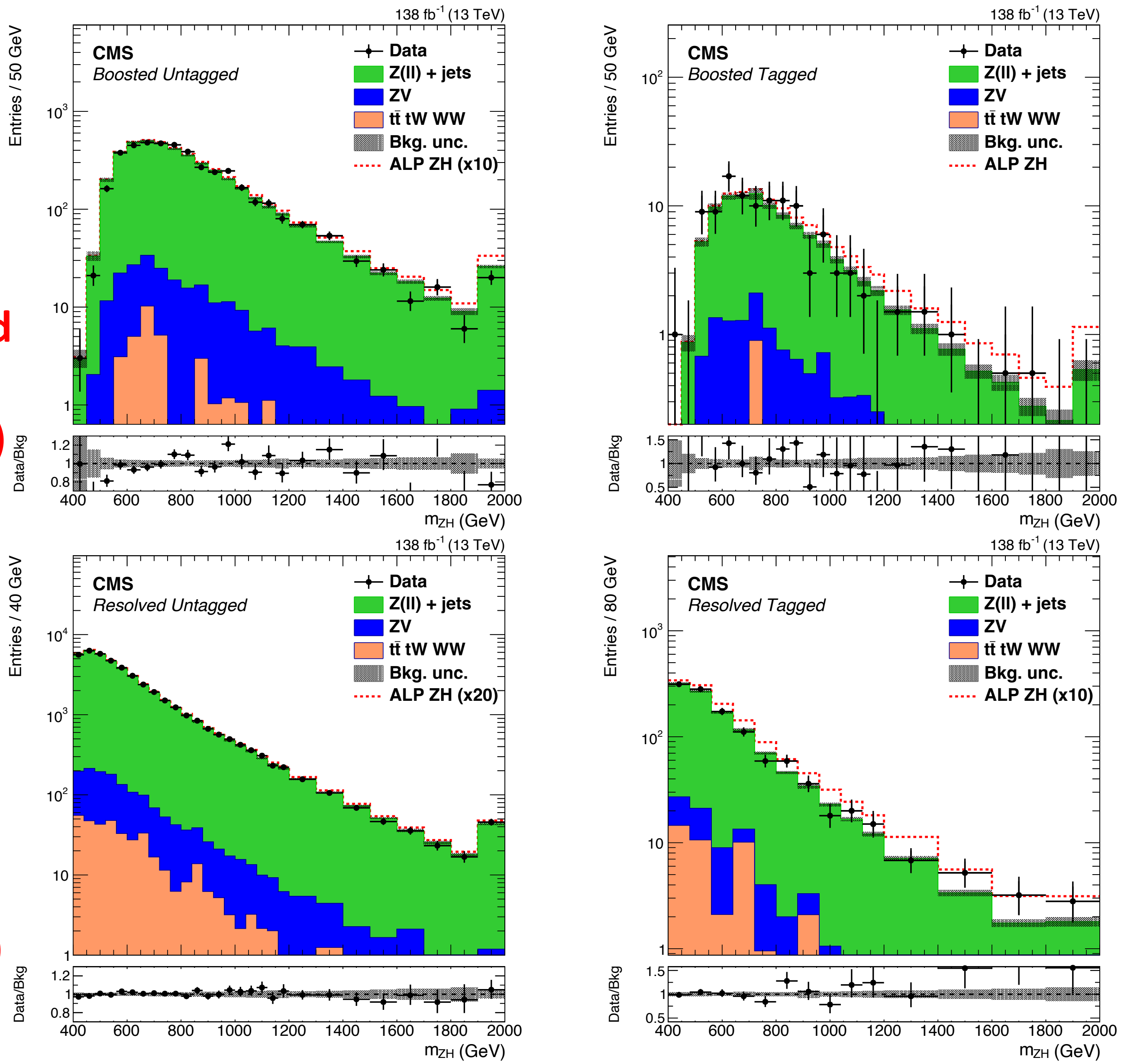
(117 ev.)

Resolved Untagged

(42662 ev.)

Resolved Tagged

(1130 ev.)

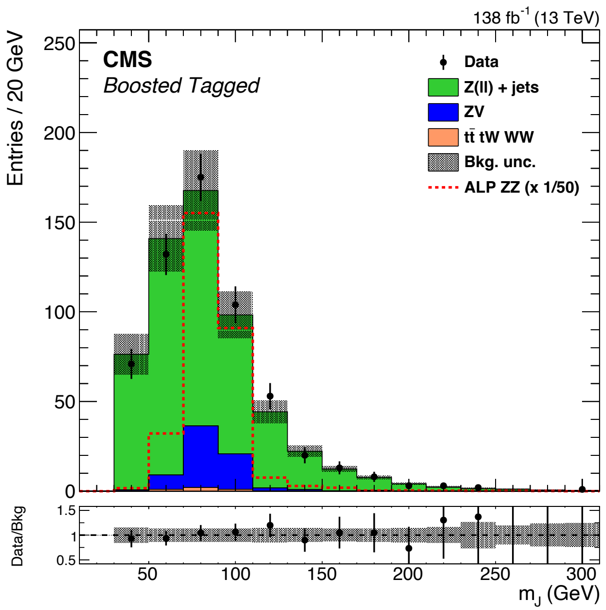


Boosted m(J) / Resolved m(jj) Distributions

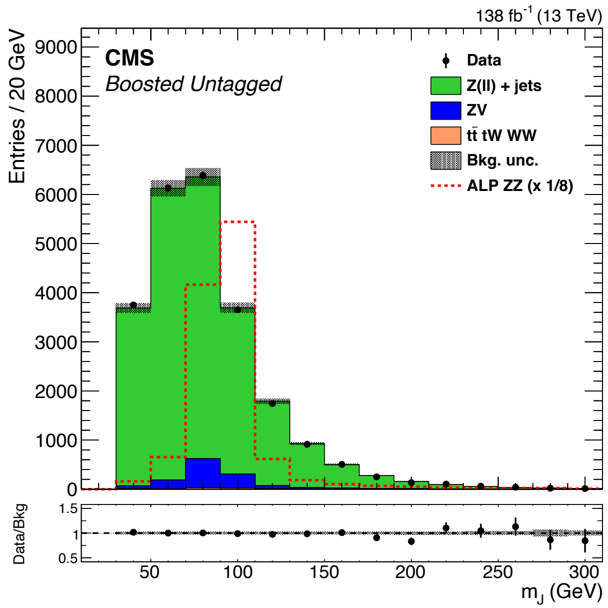
- Postfit background normalization.

→ Signal (red line) normalized to hypothetical ALP linear cross-section with 1TeV^{-1} couplings to gluons and ZZ, and f_a = 3 TeV.

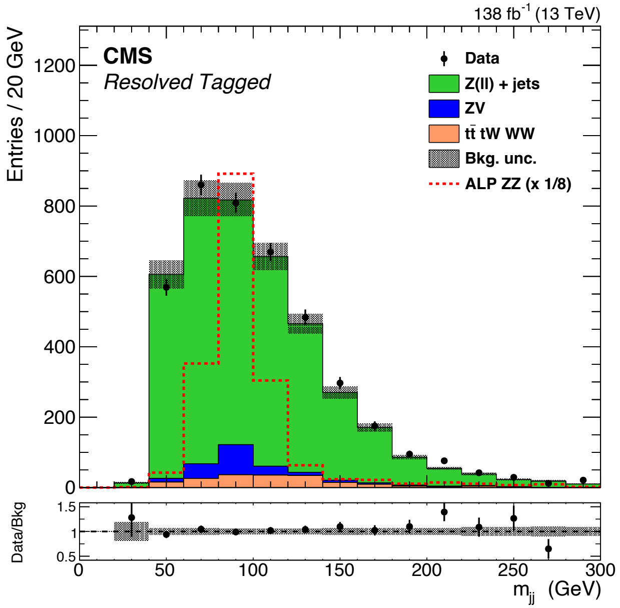
Boosted Tagged



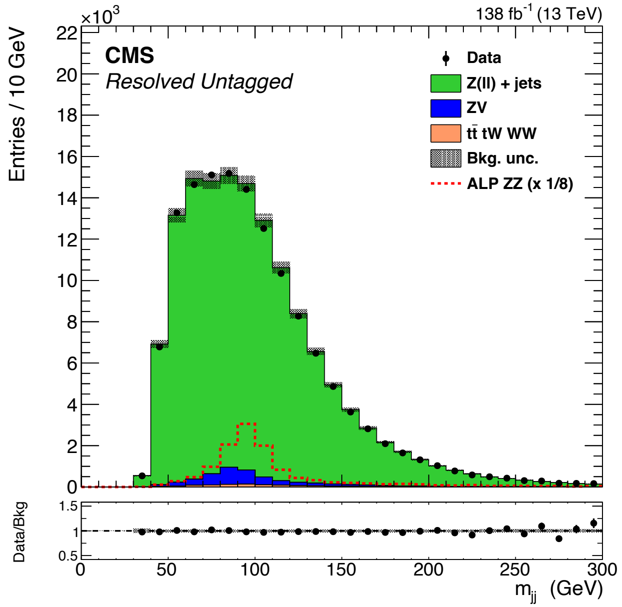
Boosted Untagged



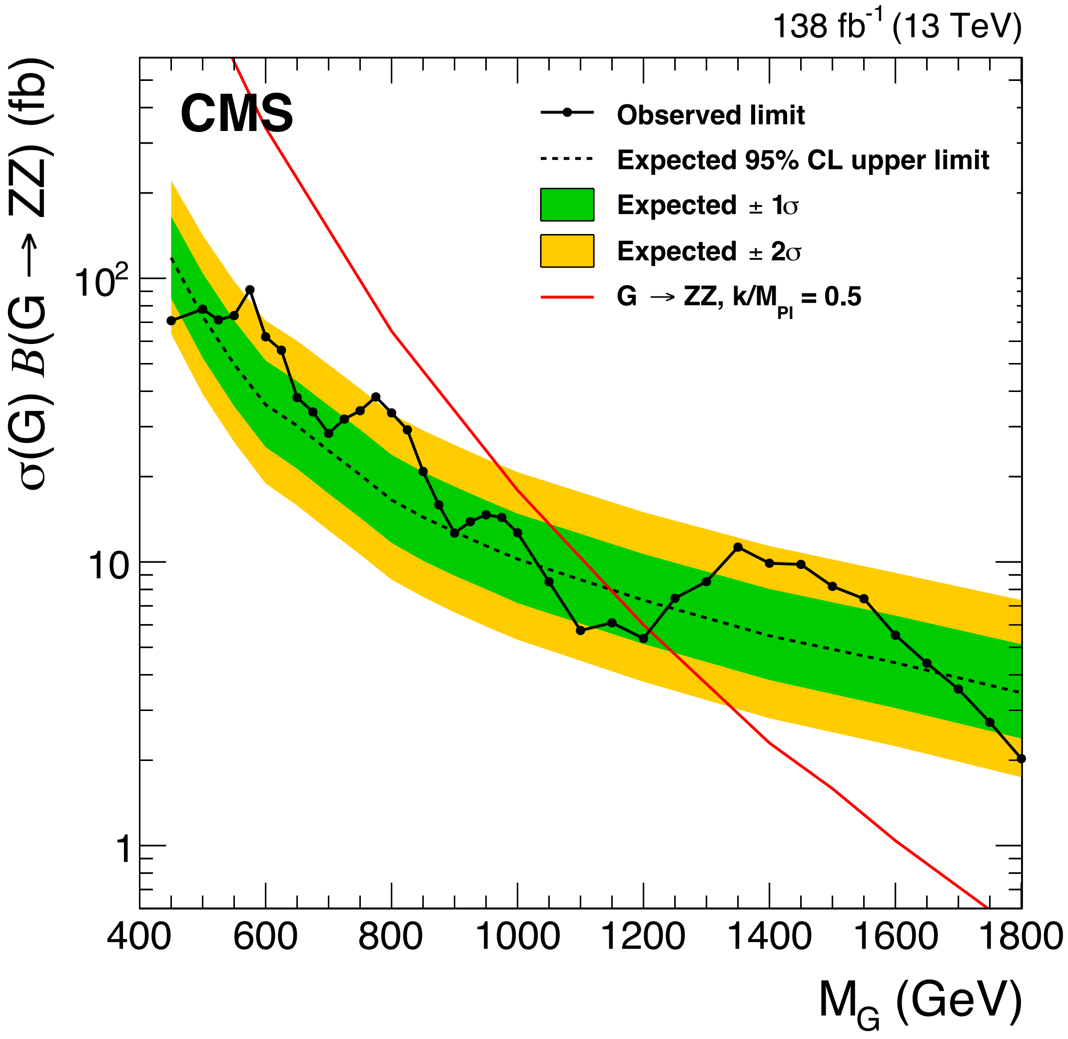
Resolved Tagged

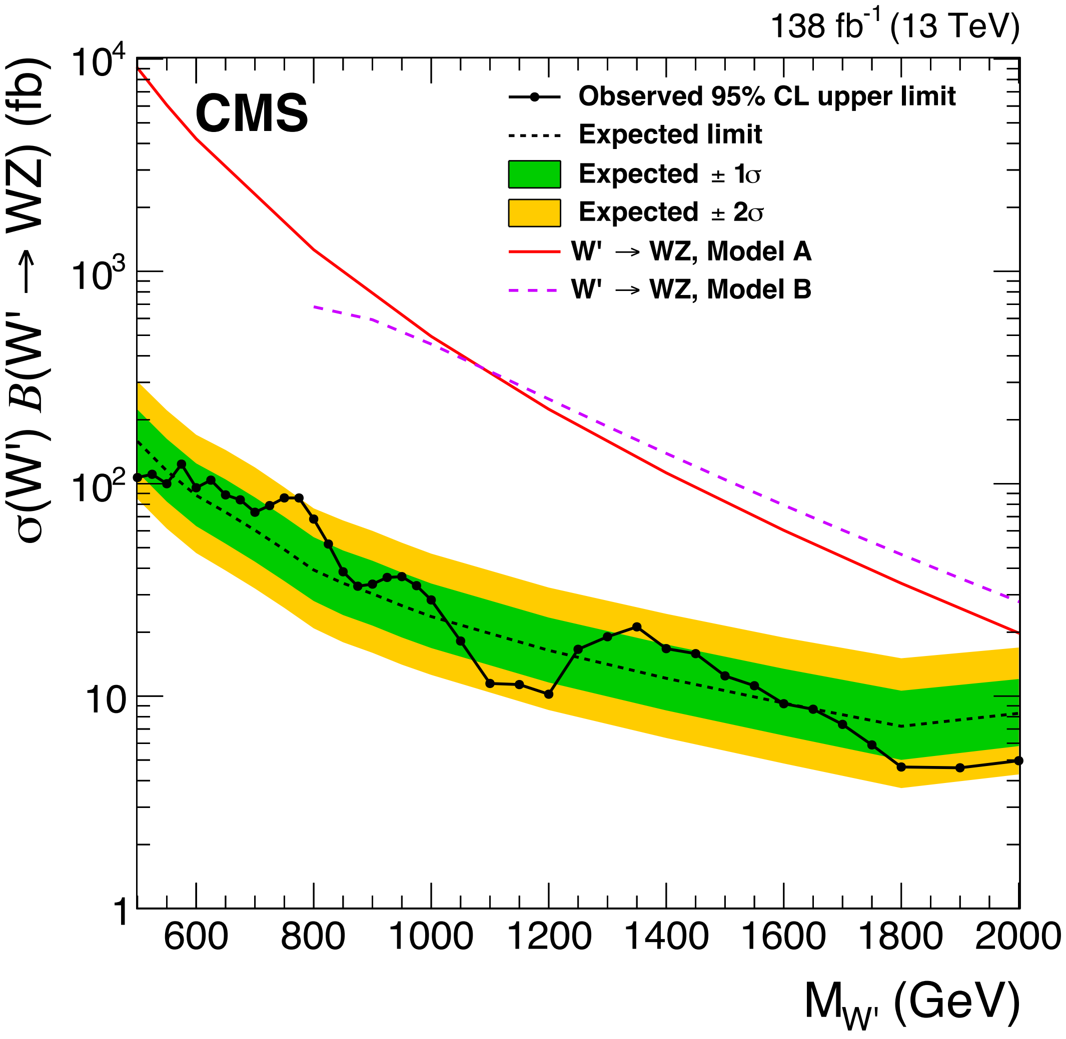


Resolved Untagged



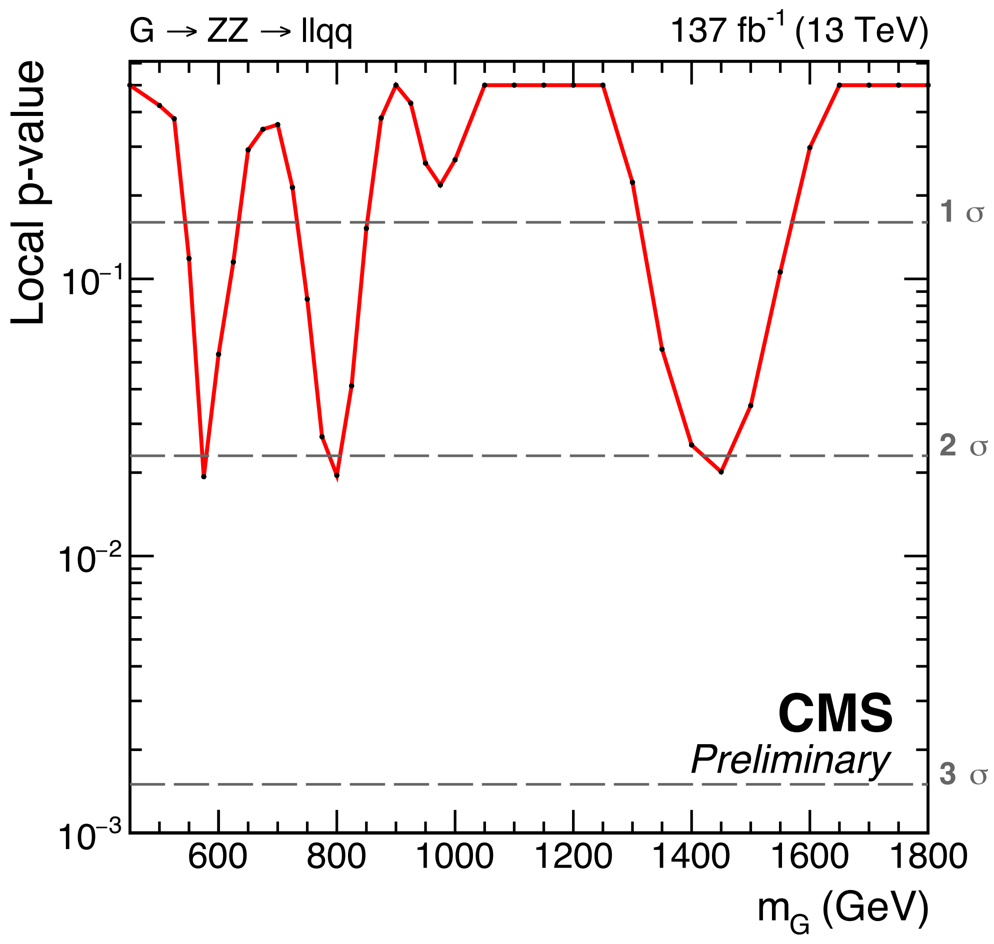
Observed and expected Limits: Bulk and W’



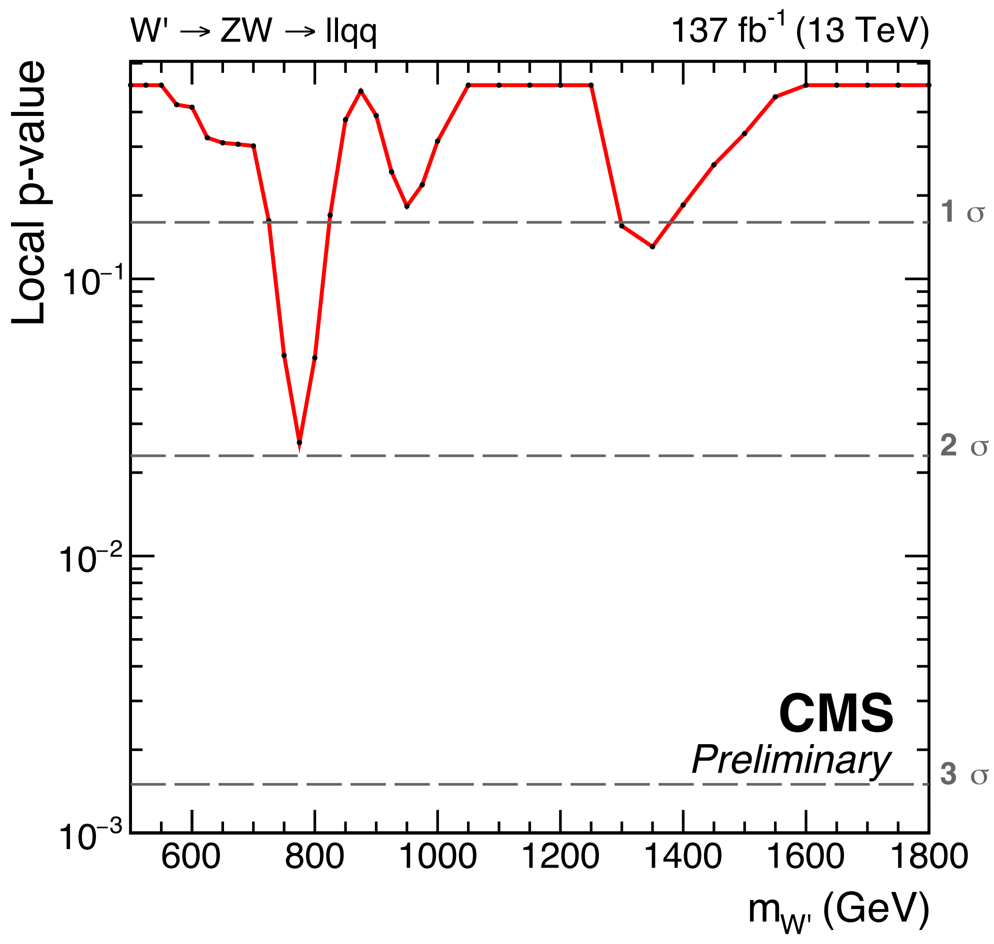


- These limits improve published results of 2016 in the 450-1800 GeV region by a factor of 2.5-3

Observed Local p-values: No significant excess

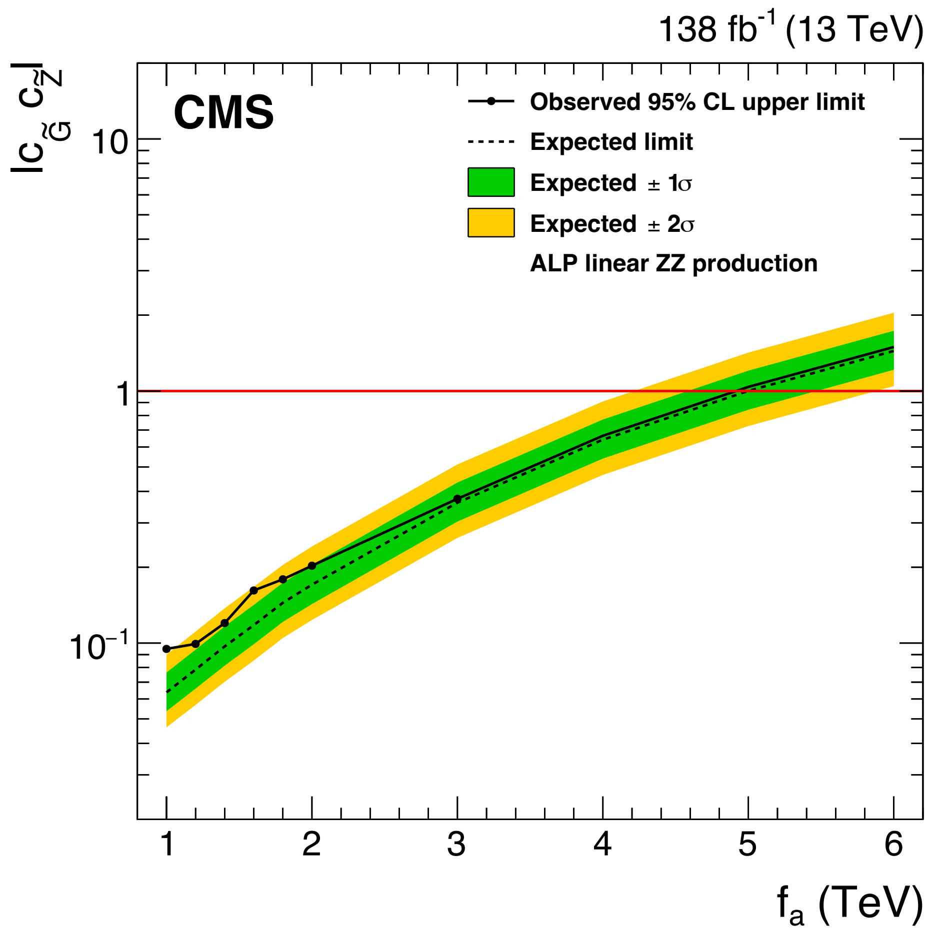


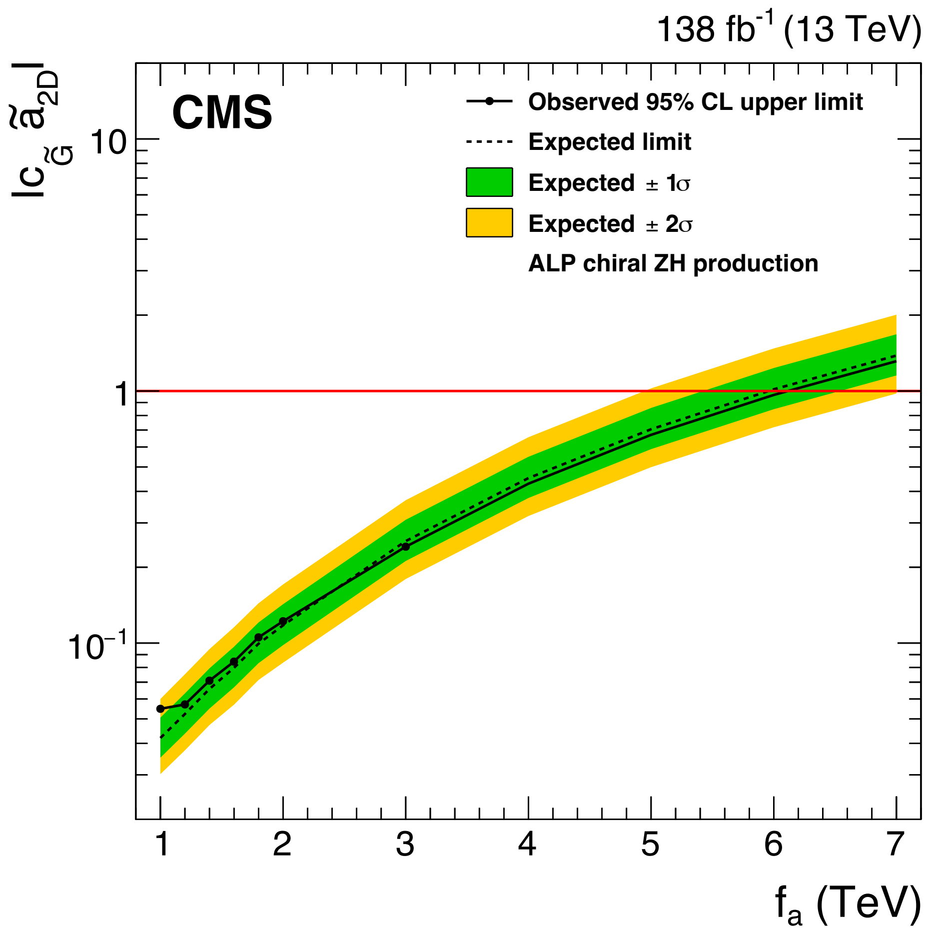
Bulk Graviton



HVT W’

Observed and Expected ALP Limits: ALP linear ZZ and chiral ZH





CMS, JHEP 04 (2022) 087

Observed and Expected ALP Limits

- Expected and observed 95% CLs upper limits on $\sigma(gg \to a^* \to$ ZZ/ZH) (fb) for f_a = 3 TeV.

Model	-2σ	-1σ	Expected Median	$+1\sigma$	$+2\sigma$	Observed
ALP linear ZZ	79	107	151	218	304	162
ALP chiral ZH	32	39	64	94	134	57

- For $f_a \geq 3$ TeV the observed (expected) 95% CL limits on:
    - ALP linear ZZ: $|c_G \cdot c_Z| / f_a^2 = 0.0415\ (0.0400)\ \mathrm{TeV}^{-2}$,
    - ALP chiral ZH: $|c_G \cdot \tilde{a}_{2D}| / f_a^2 = 0.0269\ (0.0281)\ \mathrm{TeV}^{-2}$.

CMS, JHEP 04 (2022) 087

Back up

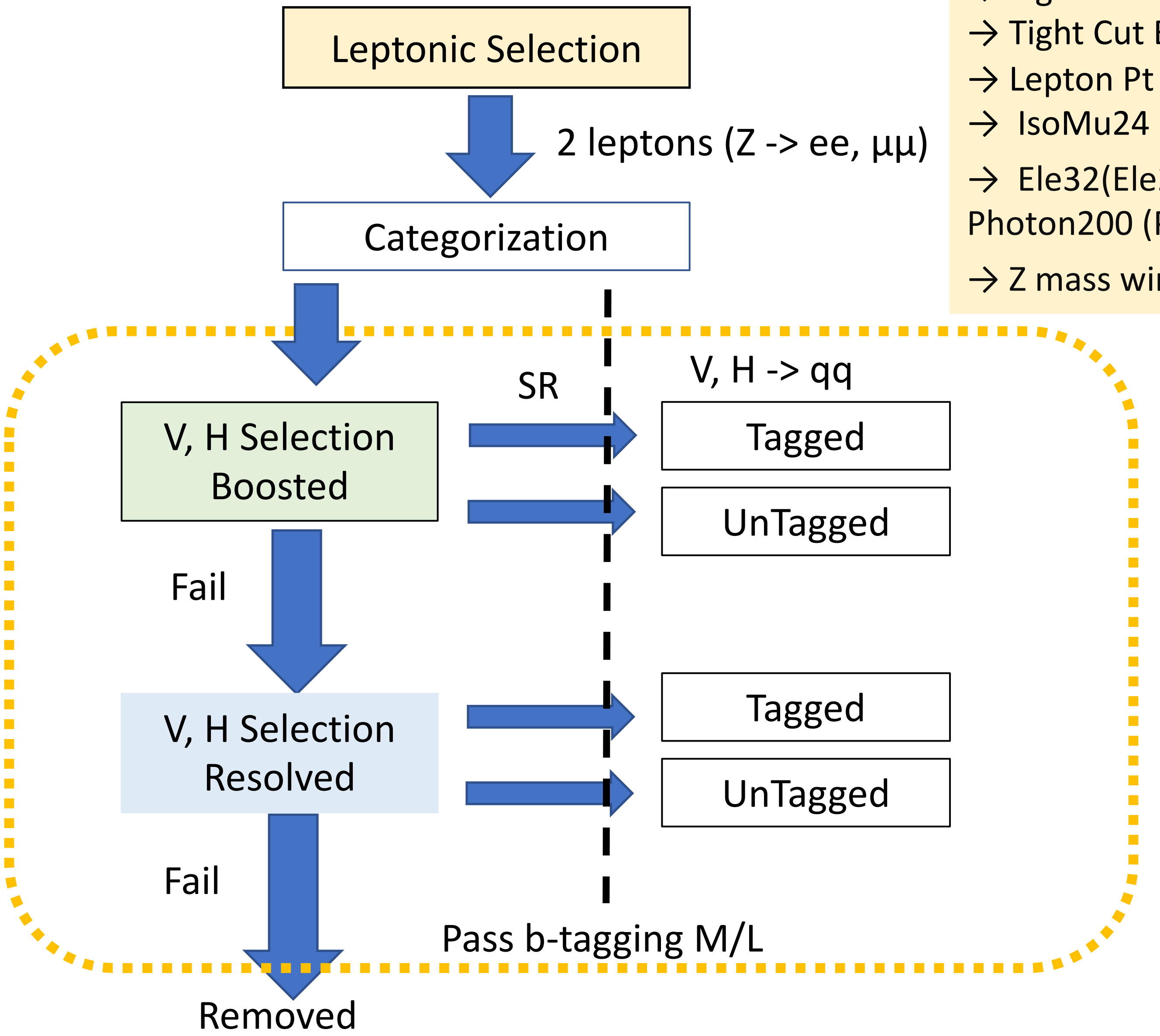
Event Selection and Categorization

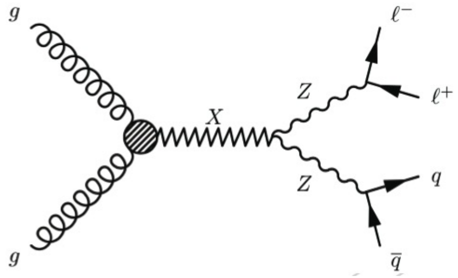
Leptonic Z

→ Tight Muon ID with Loose PF Iso
→ Tight Cut Based Electron ID
→ Lepton Pt > 40 GeV
→ IsoMu24 (IsoMu27)
→ Ele32(Ele27)_WPTight || Ele115 || Photon200 (Photon175)
→ Z mass window: 76 < M(ll) < 106 GeV

Boosted V/H

AK8 PF jet – Boosted V tagging with PUPPI softdrop mass and τ21 HP cut
→ V/H Pt > 200 GeV
→ Z(ll) Pt > 200 GeV
V SR1(m_J) : 65→105 GeV
H SR2 (m_J): 95→135 GeV
SB : 30→65 + 135→ 300 GeV
B-tagging: 1Loose 1Medium





Resolved V/H

2 AK4 PF jets - If no Boosted V candidate look for dijet
→ V/H Pt > 150 GeV
→ Z(ll) Pt > 150 GeV
→ DeltaR(jj) < 1.5
V SR1 (m_jj) : 65→110 GeV
H SR2 (m_jj) : 95→135 GeV
SB : 30→65 + 135→180 GeV
B-tagging: 1Loose 1Medium

Systematic Uncertainties: Normalization

	Boosted		Resolved	
Source	Background	Signal	Background	Signal
Integrated luminosity	1.8		1.8	
Electron trigger and ID	2.0		2.0	
Muon trigger and ID	1.5		1.5	
Electron energy scale	0.8	$<$0.1–0.2	0.9	$<$0.1
Muon momentum scale	0.5	$<$0.1–0.1	0.6	$<$0.1
Jet energy scale	1.0	$<$0.1–0.1	2.8	0.1–1.9
Jet energy resolution	0.3	$<$0.1–0.3	0.3	1.0
b tag SF untagged	0.1	1.0–7.4	0.1	0.7–2.2
b tag SF tagged	12	12	3.6	4
Mistag SF untagged	0.3	$<$0.1–0.2	0.2	0.1
Mistag SF tagged	3.5	0.1–0.3	3.8	0.4–1.0
SM ZV production	12	—	12	—
t + X normalization	4 (eμ)	—	4 (eμ)	—
V identification (τ_{21})	5 (ZV)	5	—	—
V identification (extrap.)	—	2.6–6.0	—	—
V mass scale	0.6 (ZV)	0.4–0.8	—	—
V mass resolution	5.0 (ZV)	5.0–6.0	—	—
Pileup	0.5	0.1–0.2	0.1	0.1–0.2
SR-to-SB norm. ratio	3 (DY)	—	5 (DY)	—
PDFs	—	1.5–1.6	—	0.3–1.1
QCD renorm./fact. scales	—	0.1–0.3	—	0.2–0.3

Z+jets Background Shape Systematic

- Corrections to the shape of the m(ZX) distributions of the Z+jets background are implemented multiplying the MC predictions in the SR and SB regions by a linear function.

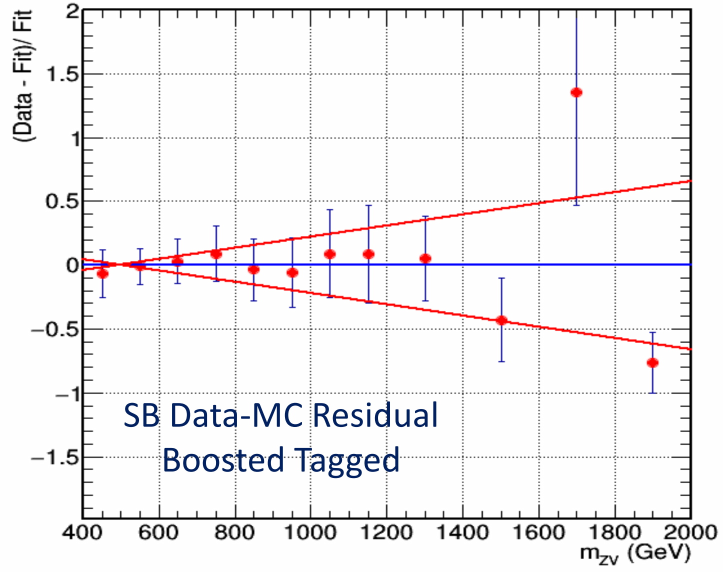
- One single parameter: slope (s) of the linear shape correction.

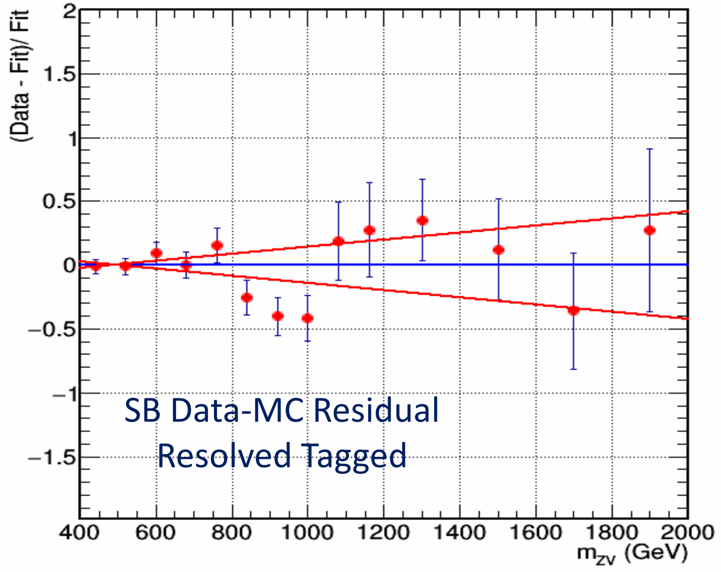
- The linear shape correction is conventionally defined as 1 for m(ZX) = 500 GeV. Other definitions are equivalent; the change is absorbed in a redefinition of the overall normalization.

- In the SB-only and SR + SB fits, the linear shape correction is allowed to float, constrained by the residual differences between data and simulation.

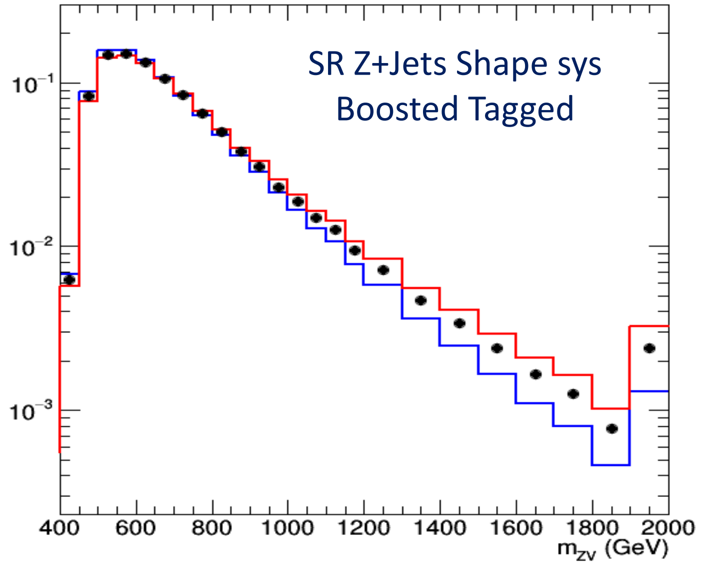
Z+jets Background Shape Systematic

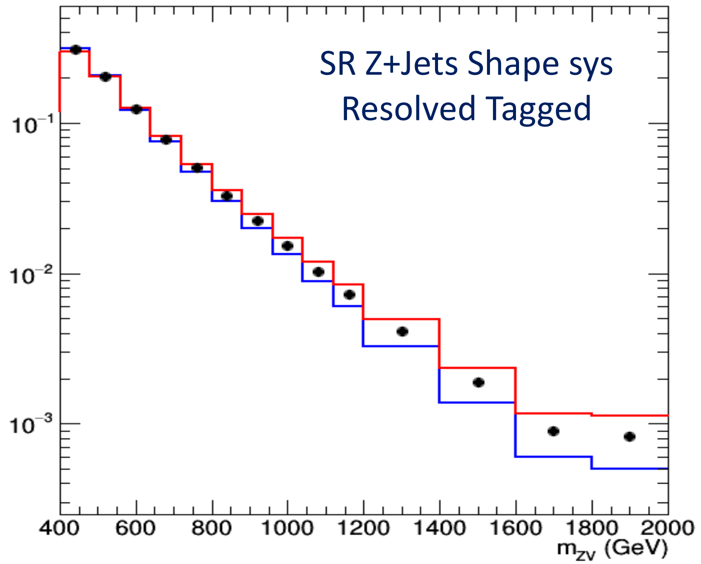
- Residuals data-MC from SB fit. Red lines correspond to 2σ of the error given by the fit.



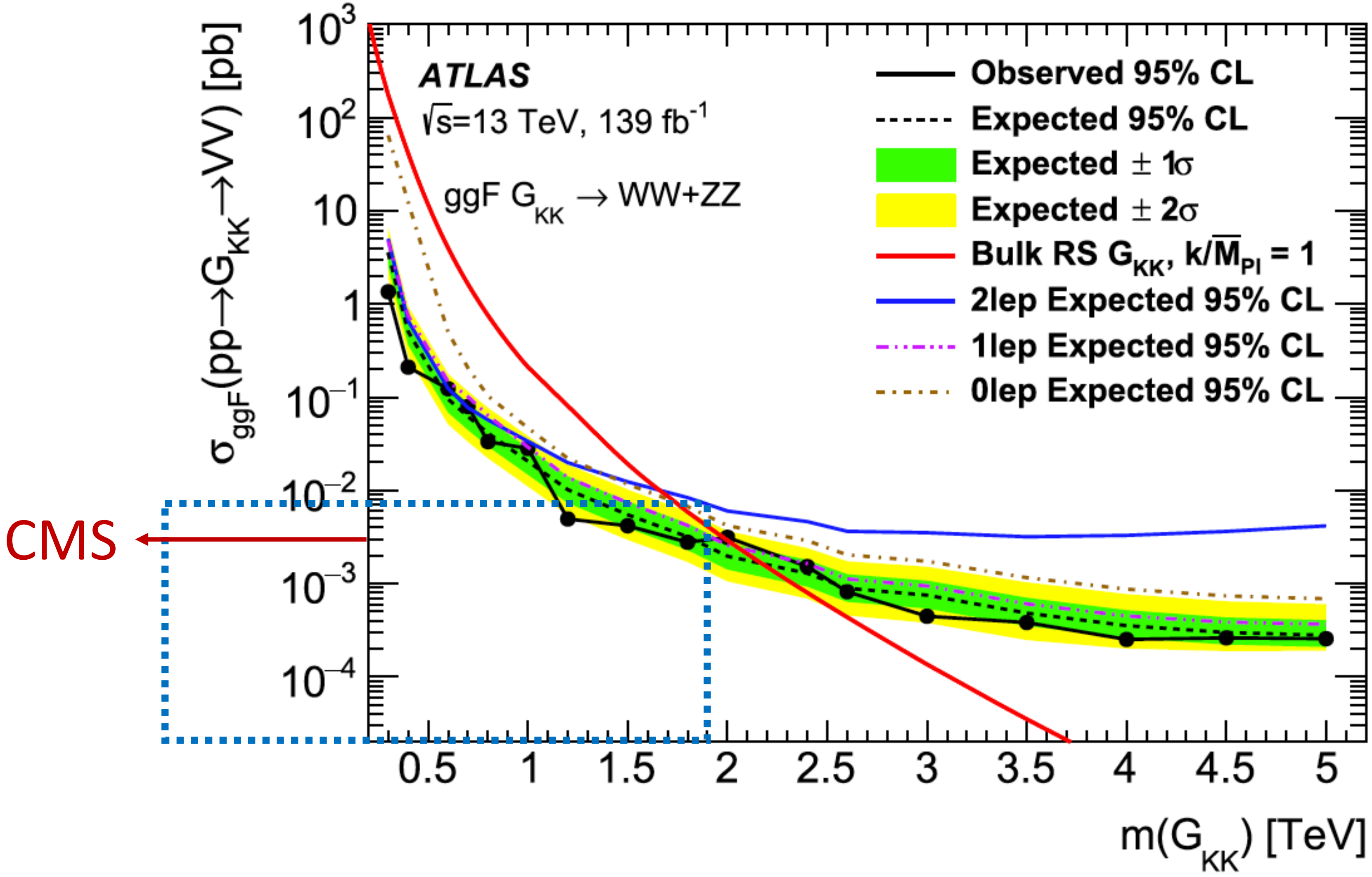


- SR: Z+jets standard (dots), Z+jets - 2σ (blue), Z+jets +2σ (red).





Expected Limits: Bulk Graviton



Expected Limits: Bulk Graviton