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

XVIII Mexican Workshop on Particles and Fields

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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.

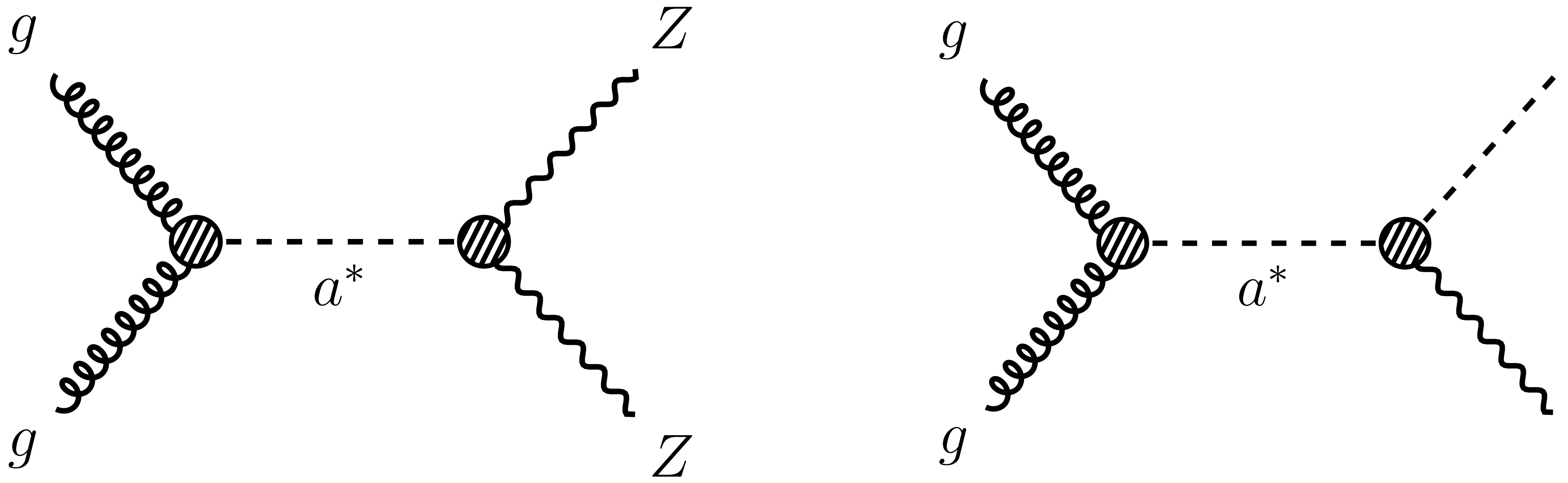
- Colliders allow searches in a wide range of ALP masses and couplings. We can explore ALP masses beyond astrophysical constraints, and even there, provide important crosschecks. At the LHC, natural sensitivity is to f_a scales in the TeV region.

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.

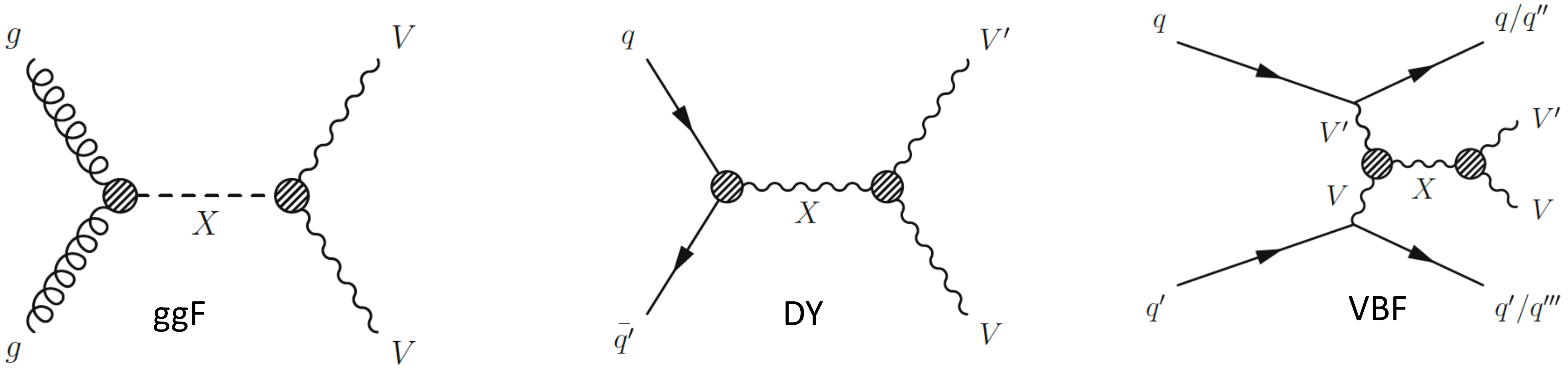
- The analysis uses the ZV, WW, ZH searches looking for high-pT / high-mass deviations in the tails of the transverse momentum / mass spectra with respect to SM expectations.

- 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.

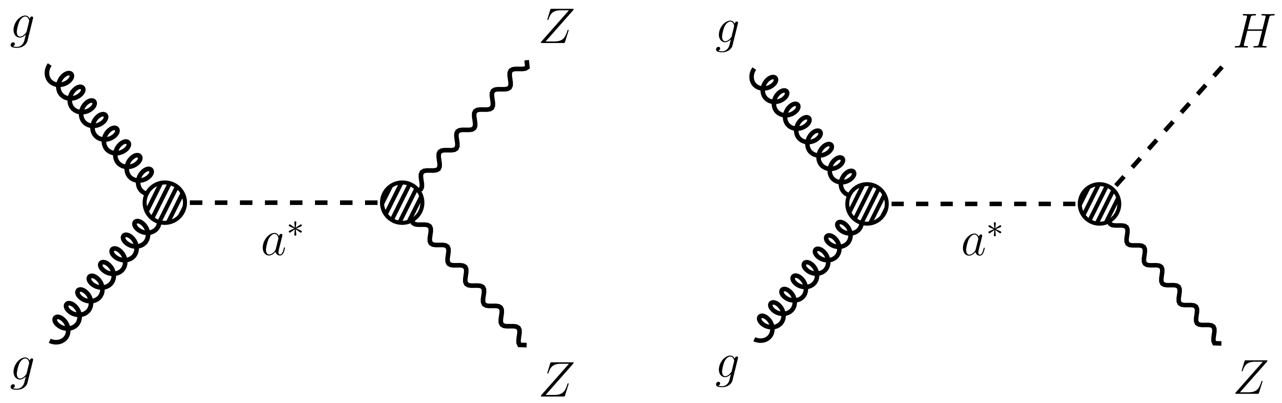
Gavela, No, Sanz, Trocóniz; PRL 124 (2020) 051802

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

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



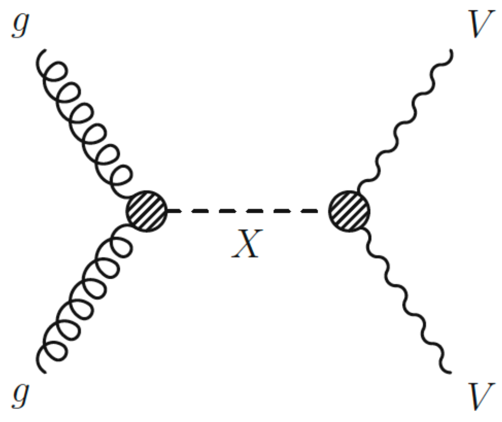
ALPS →

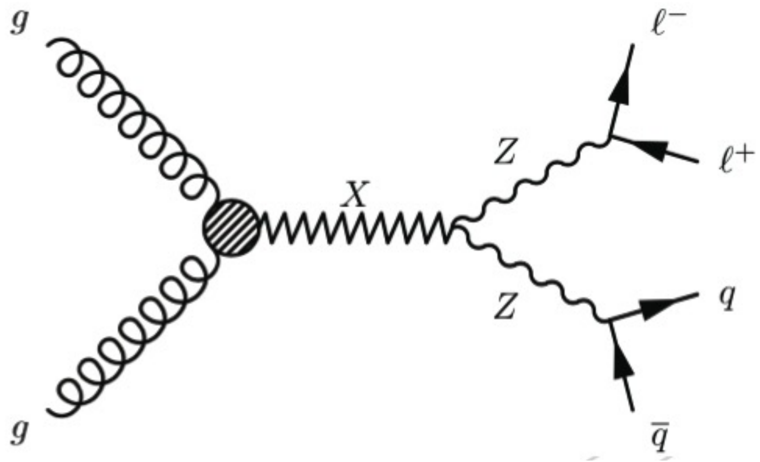


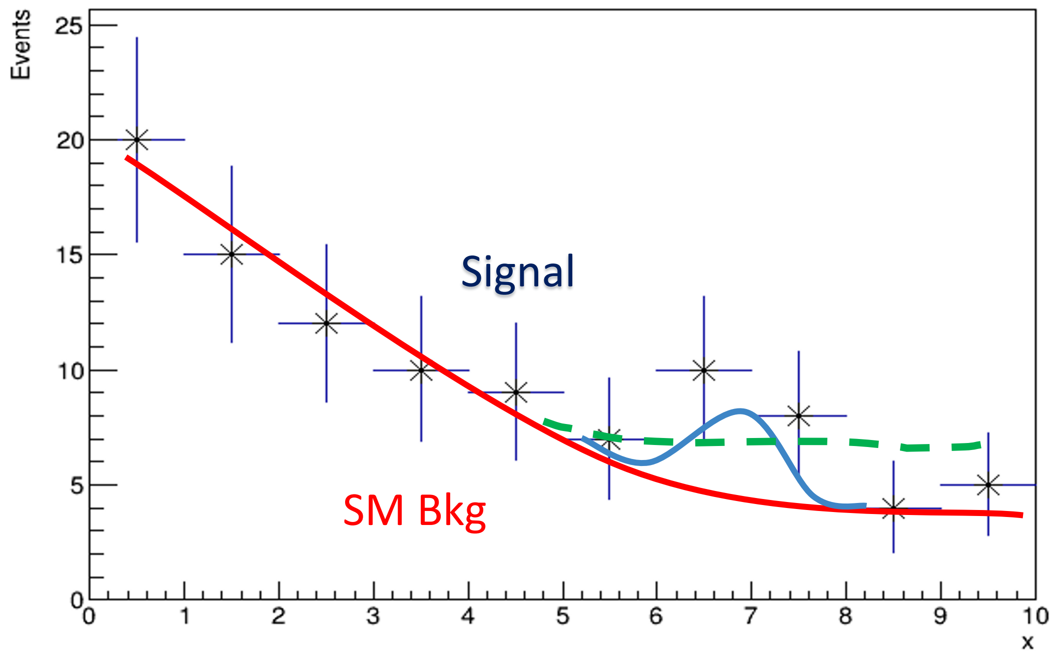
gluon-iniated ALP-mediated

CMS, JHEP 04 (2022) 087

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





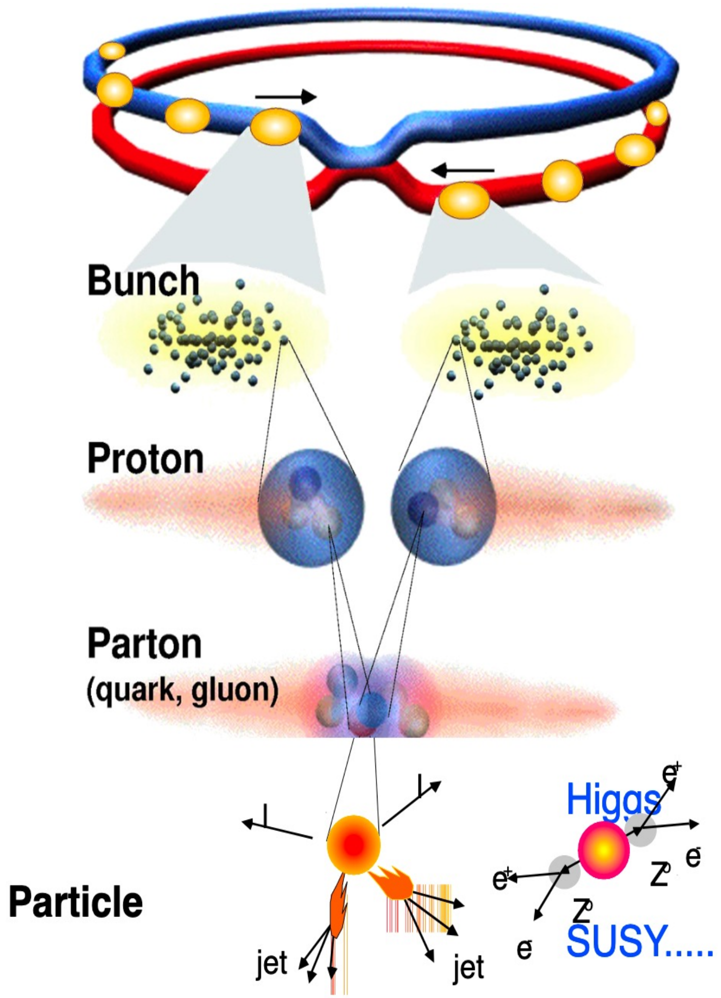


Pros: Large Branching Fractions
-Sensitive in 400-2000 GeV mass region

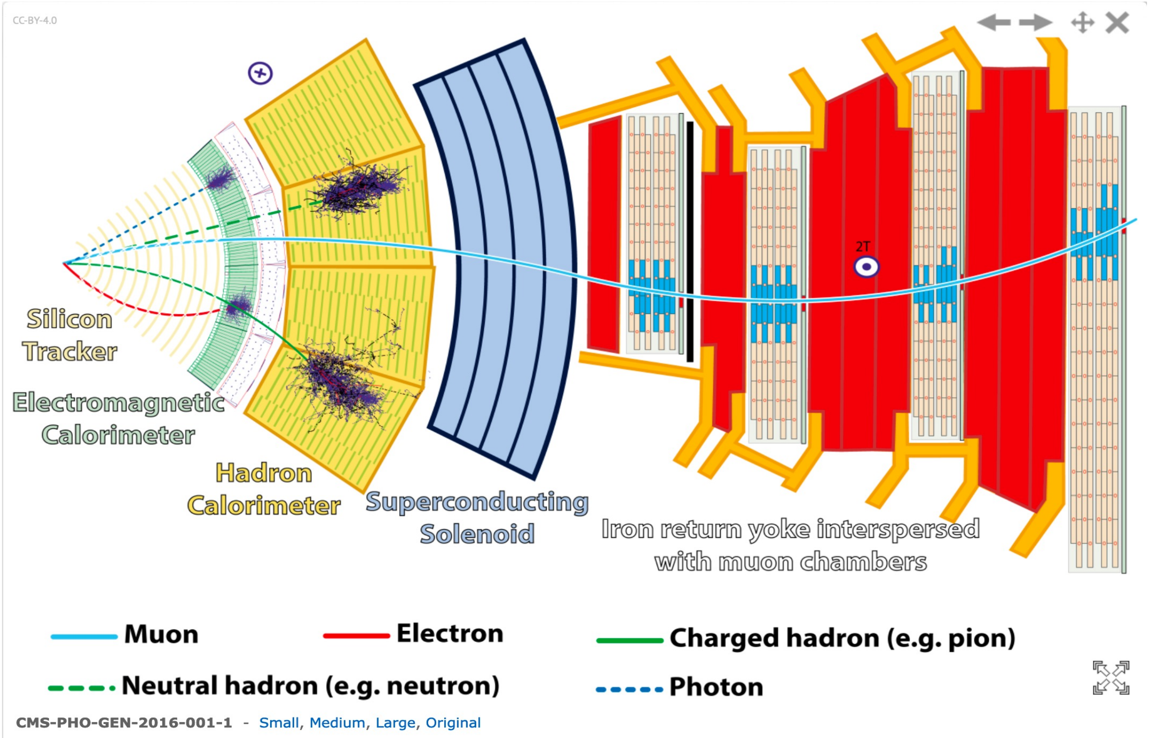
Cons: Large backgrounds from QCD V+jets.
-Estimate via NLO QCD and/or sideband (SB) data.

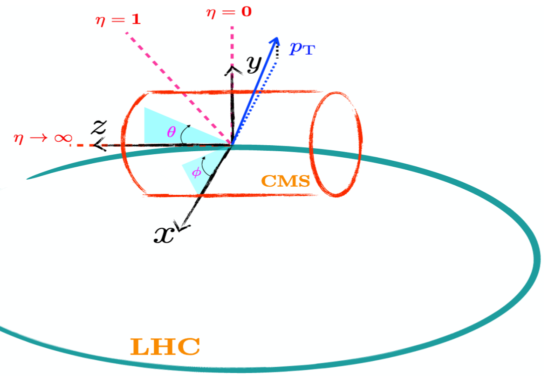
Experiment and Reconstruction

Experiment: CMS at LHC



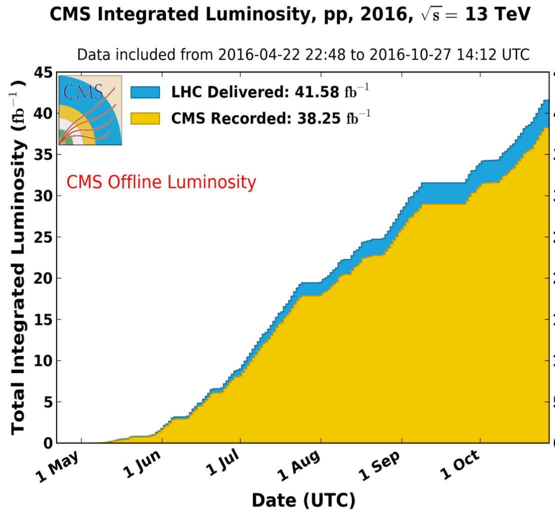
LHC

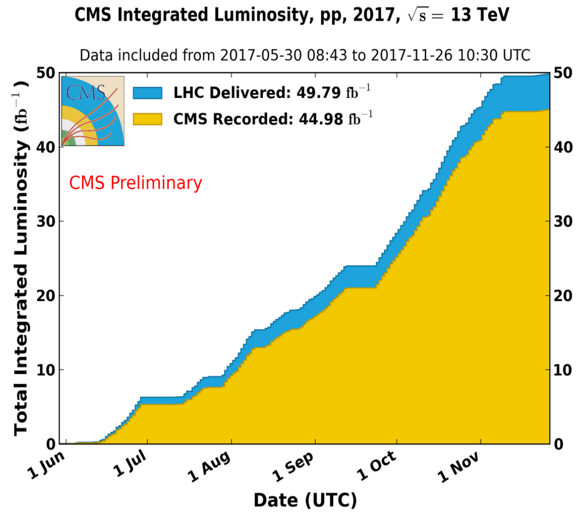


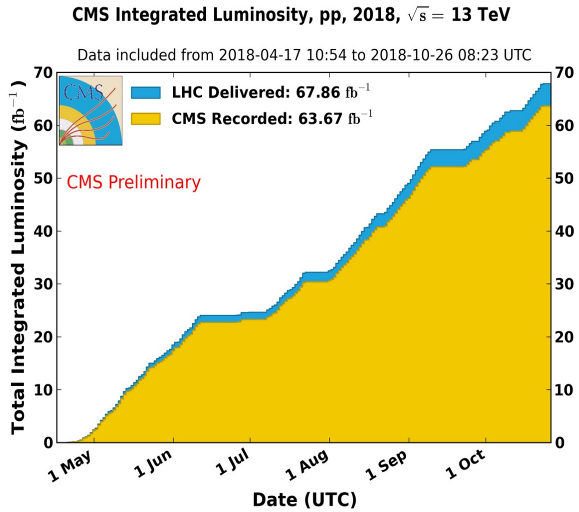


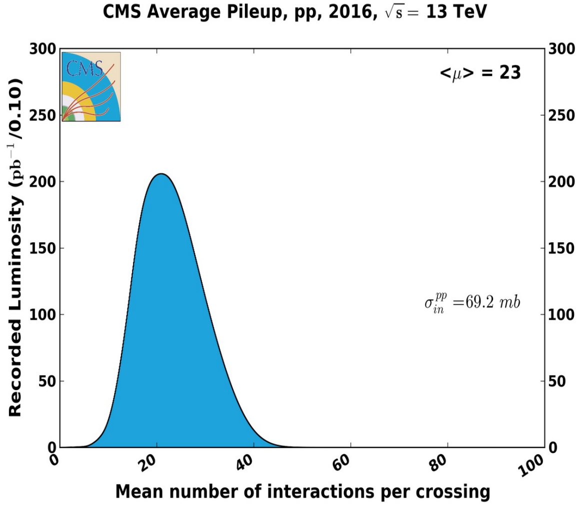
Experiment: CMS at LHC

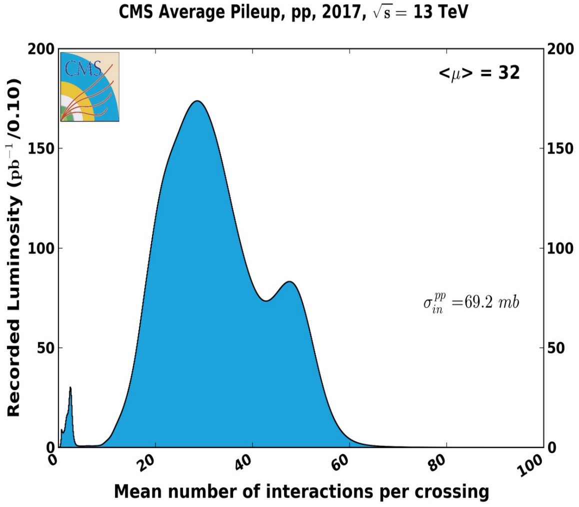
2016 **2017** **2018**

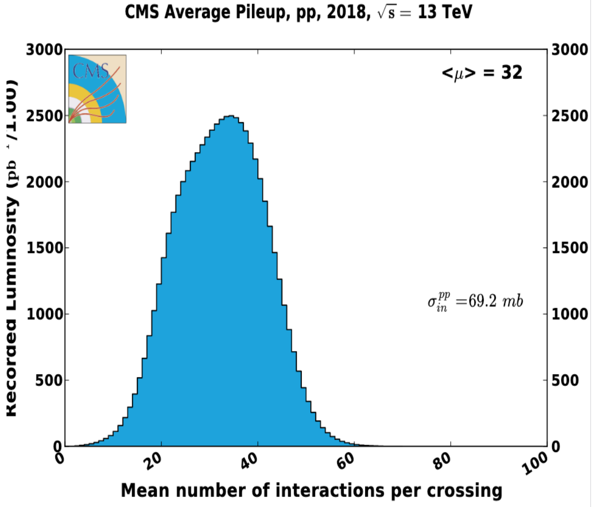








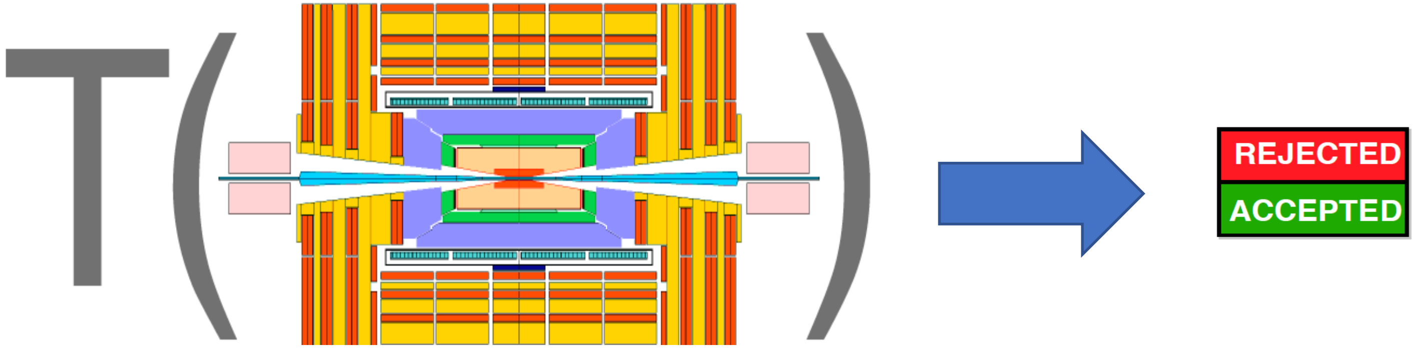




Experiment: CMS triggering

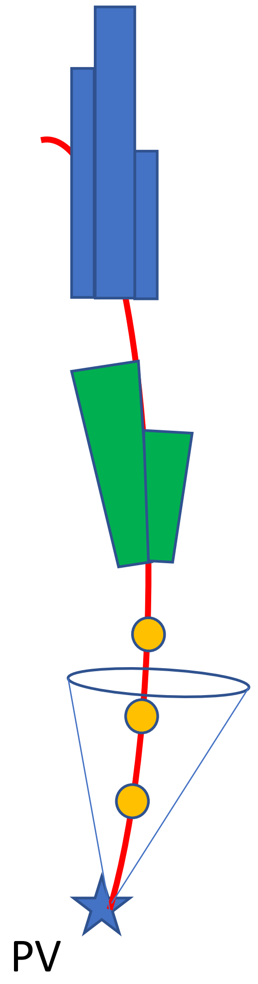
- Required:
  - Look at (almost) all bunch crossings,
  - Select most interesting ones.
  - Collect all detector information and store/sort it for off-line analysis.

Trigger is a function of



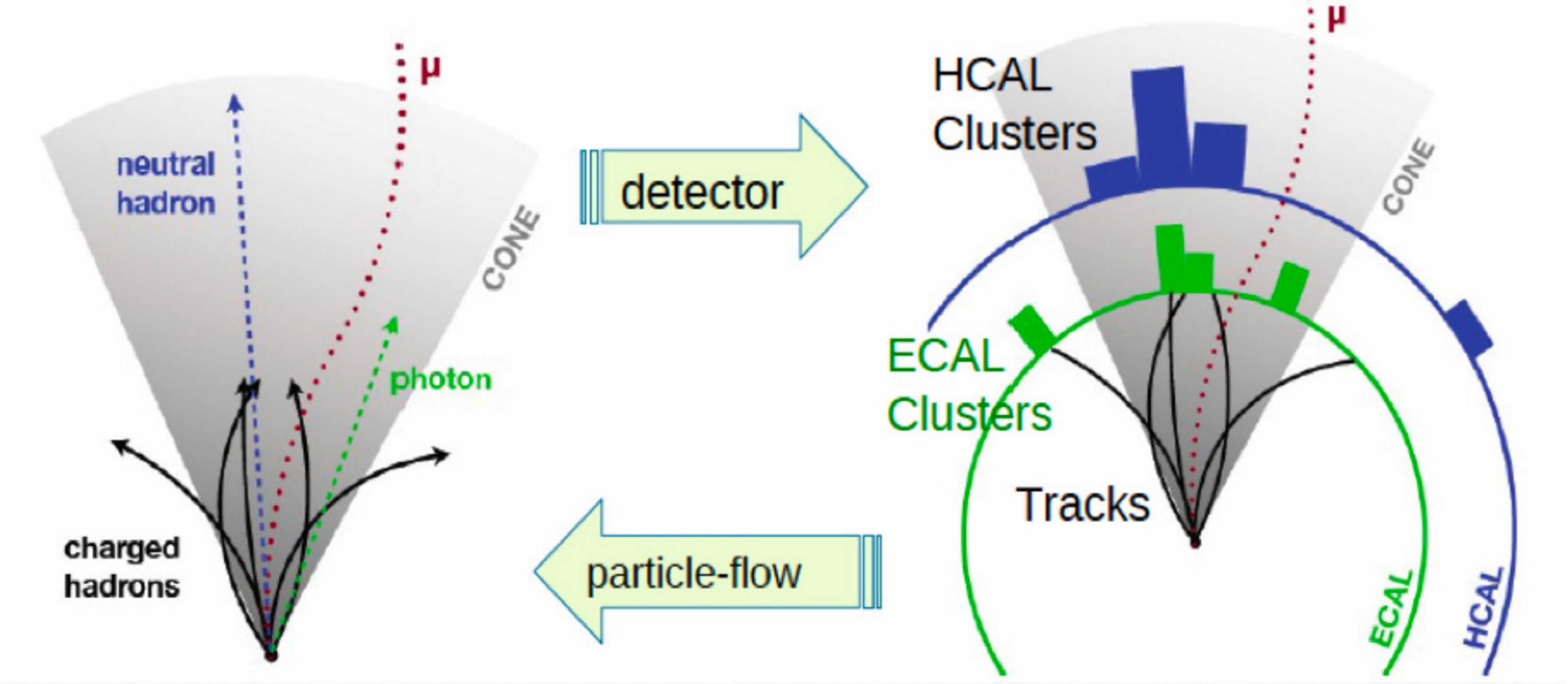
Experiment: CMS triggering

- Two levels;
  - L1; recognize parameters as charge, time, patterns, etc.
  - HLT; algorithms to filter L1 objects, and build complete events.
- Trigger menus; sum of all object definitions and algorithms to take a decision and build an event.
  - Adjust thresholds to be sensitive to electroweak or new physics.
  - “Single muon trigger”
  - “Single electron trigger”



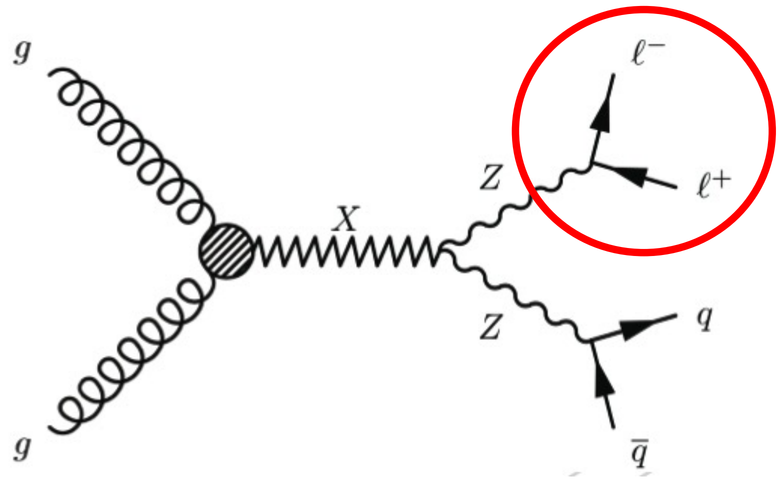
Reconstruction : CMS Particle Flow

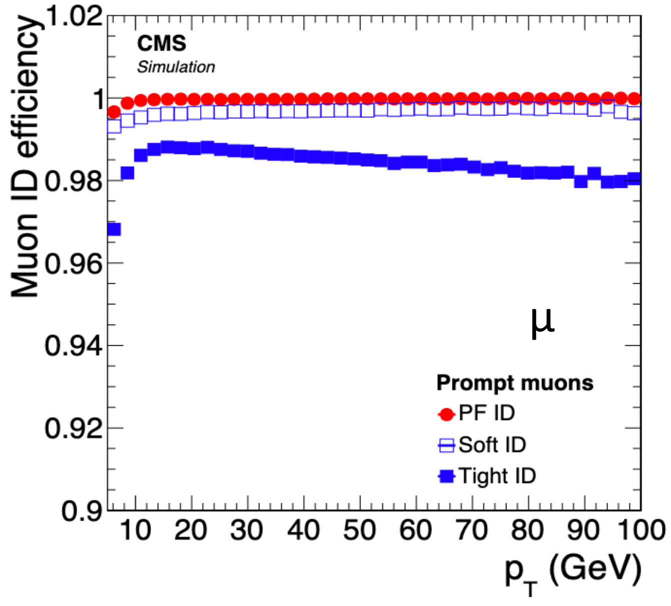
- Principle: Combine information from all detectors. Trading information from low- to high-resolution detectors
- Deal types of particles

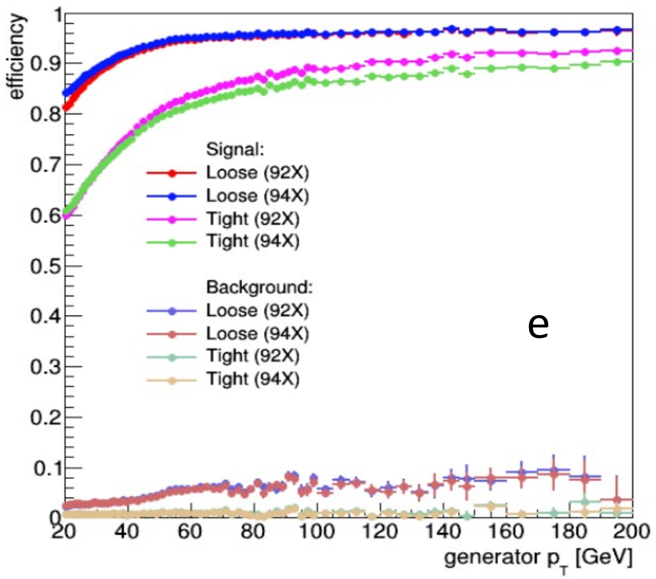


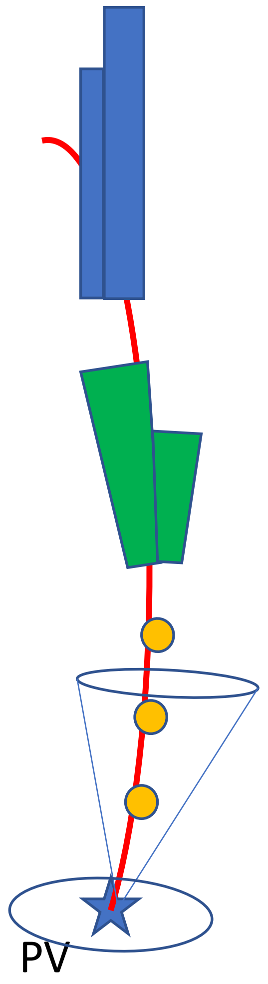
DOI:[10.1088/1748-0221/12/10/P10003](10.1088/1748-0221/12/10/P10003)

Reconstruction: Leptonic

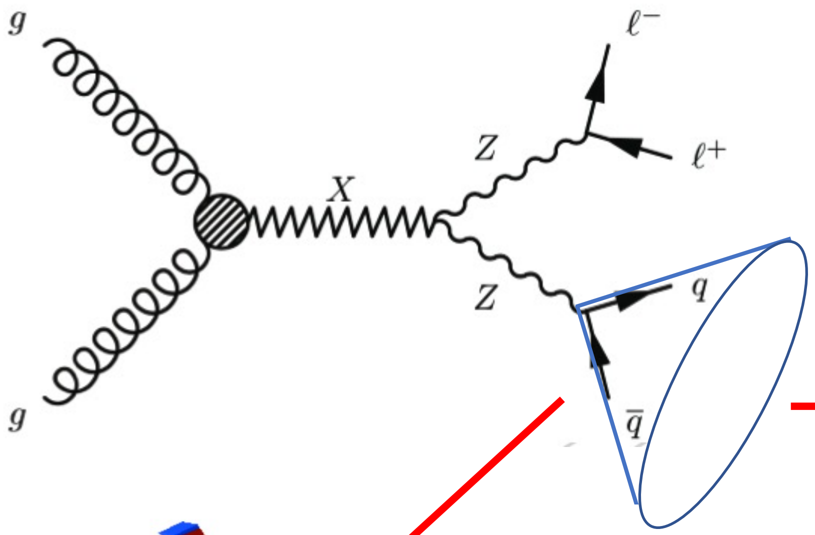


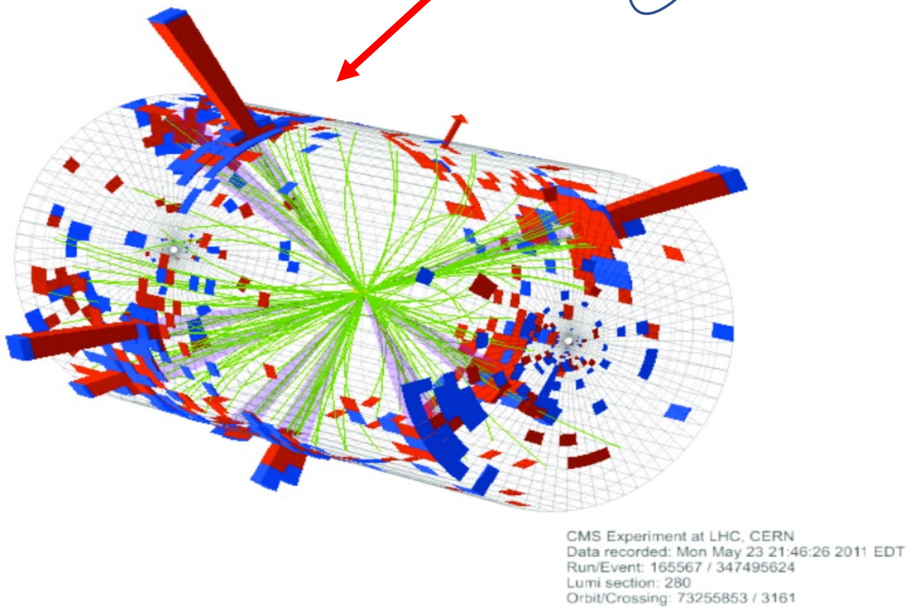




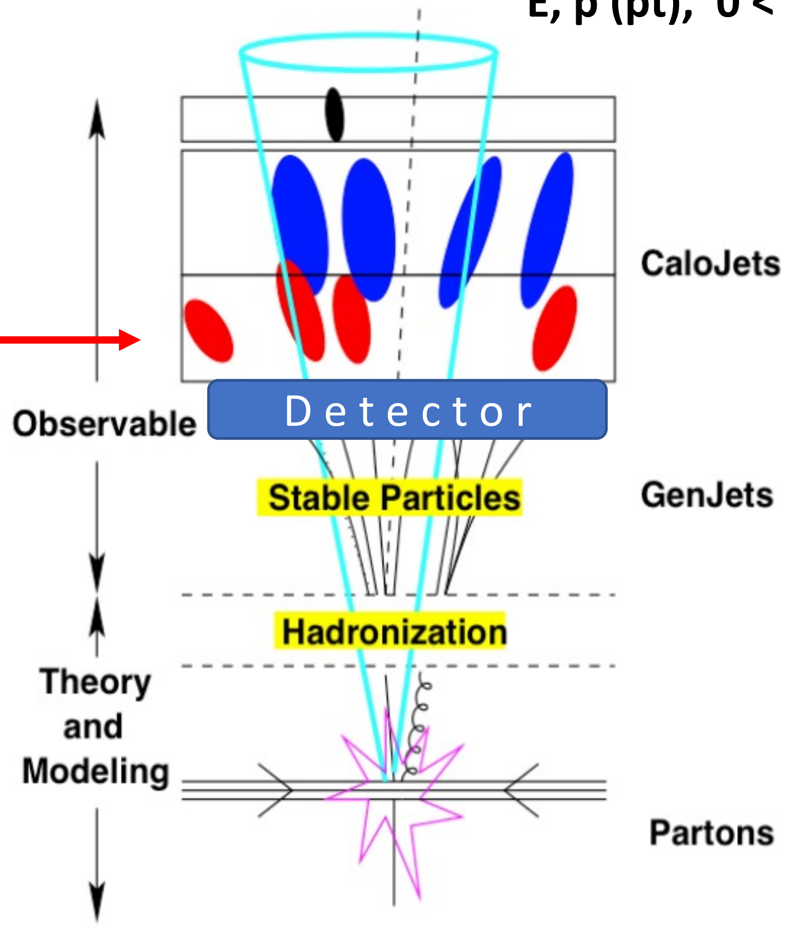


Reconstruction: Hadronic (Jets)



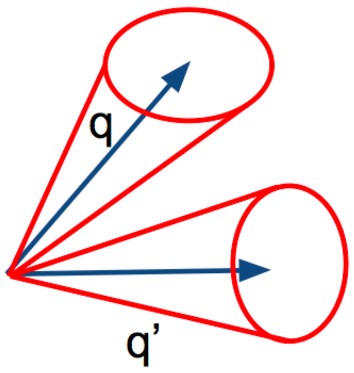


AK algorithm
E, p (pt), 0 < R ≤ 1, 4, 8, ...



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

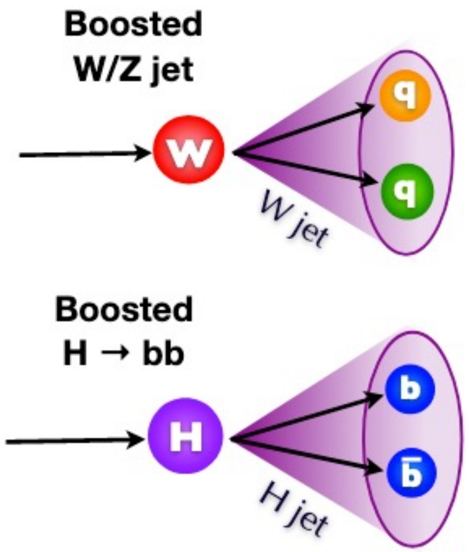
Resolved



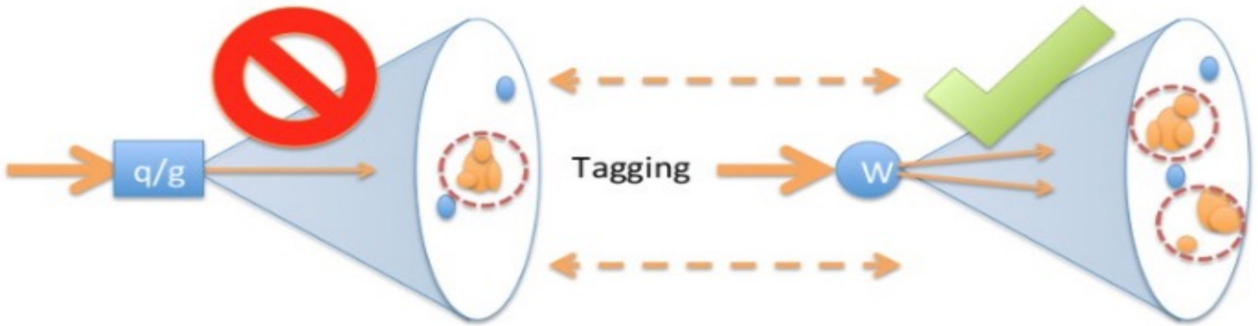
Standard
Jets (AK4)

BOOST

pT > 2.5 Mass



Merged Jet
(AK8)



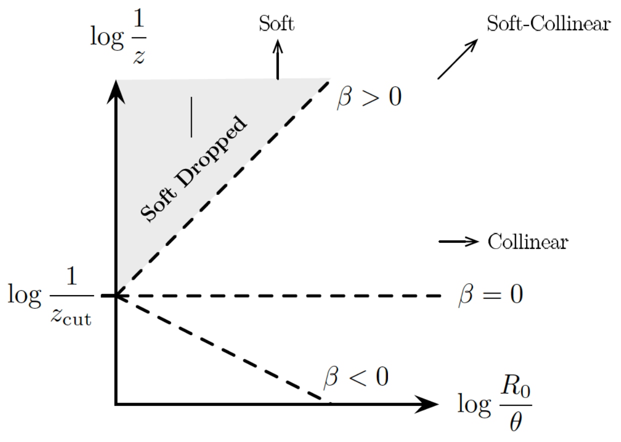
?

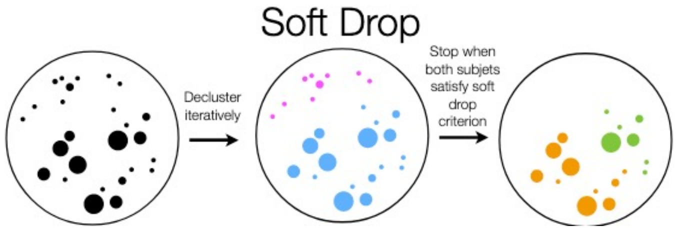
Z, W, H Jets vs QCD

- 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)

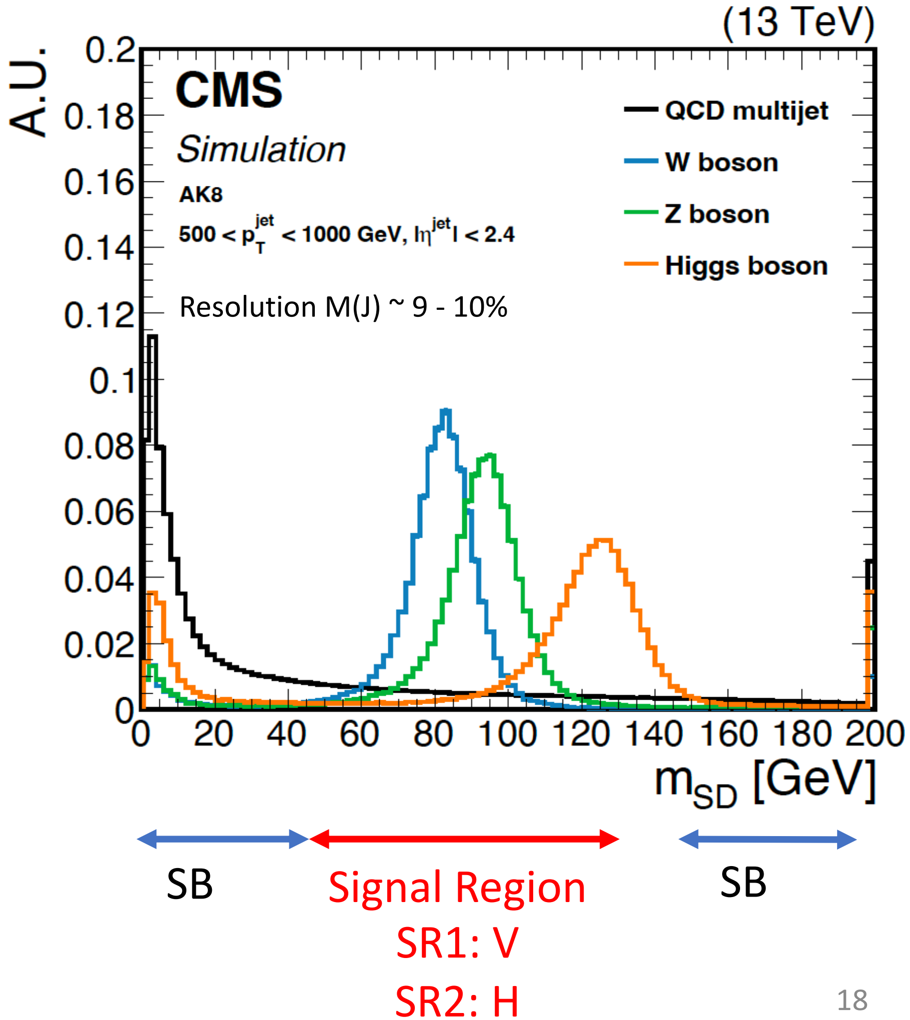
- After re-clustering CA into 2 subjets:
- If $\frac{\min(pT1,pT2)}{pT1+pT2} > z_{cut}\left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$, declare SD jet is defined.
- Else, drop softer subjet and iterate on harder one.
- For β = 0, soft radiation removed (A.K.A Modified mass drop tagger)





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

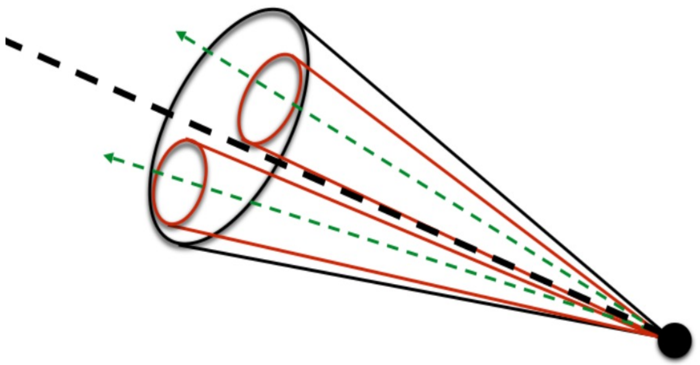
CMS Collaboration, JINST 15 (2020) P06005



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

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

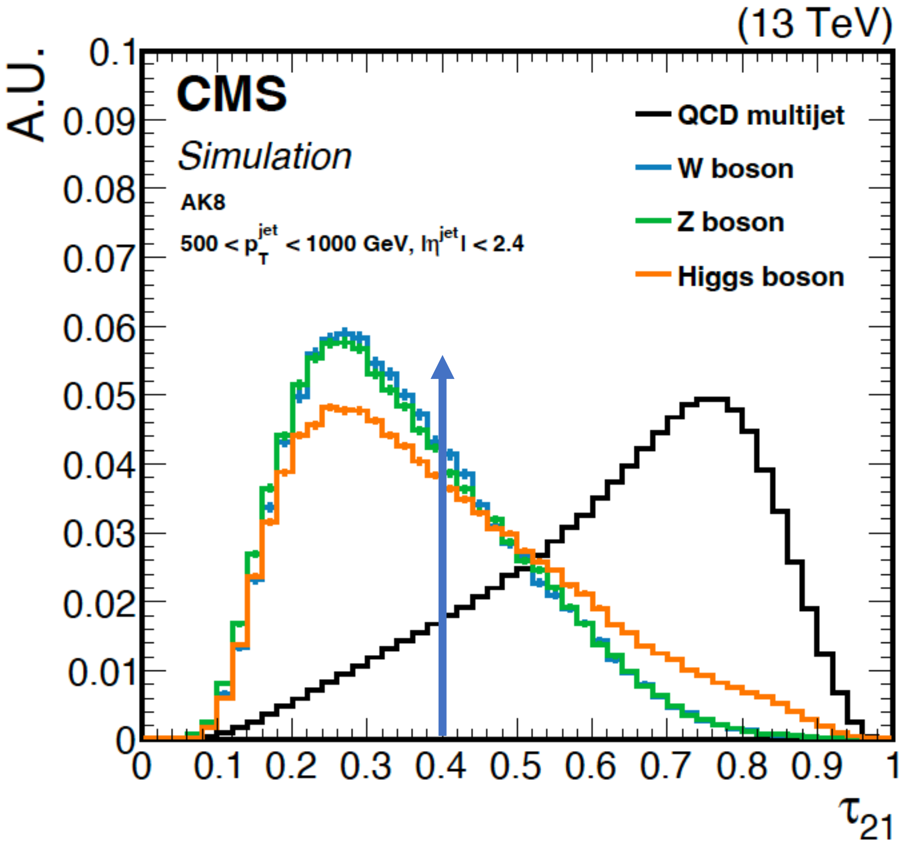
- ‣Can look inside the jet for the expected substructure
  - Top decays → 3 subjets
  - W/Z/H decays → 2 subjets



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

- 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

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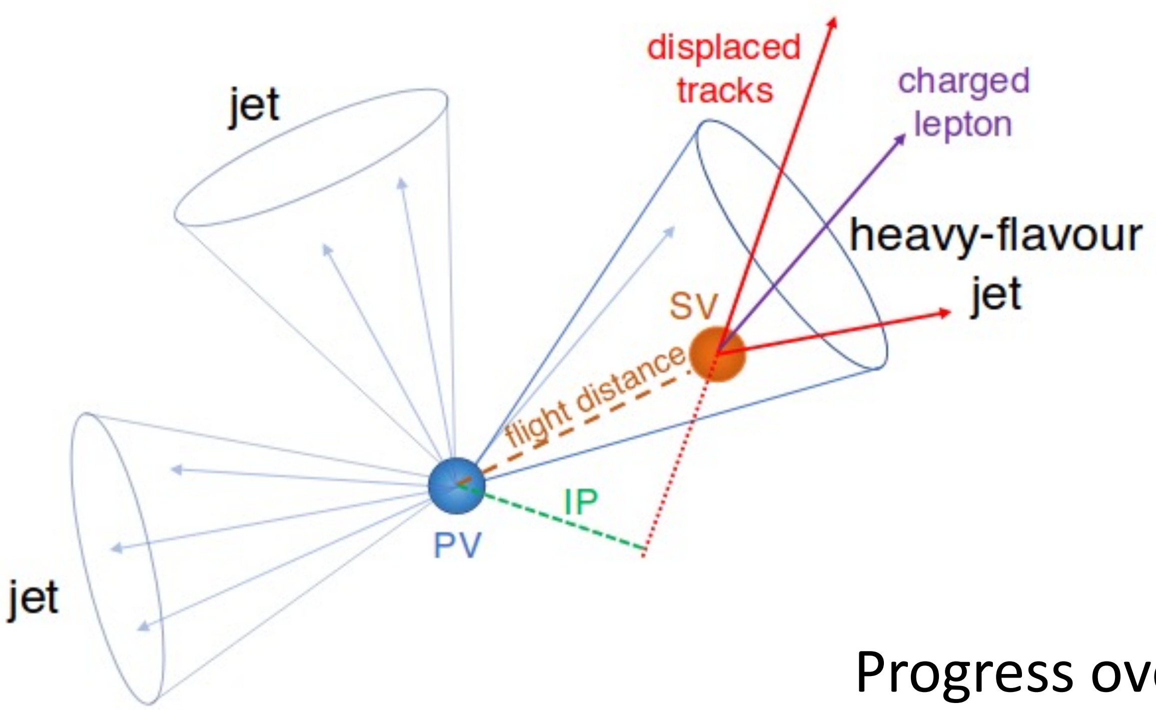
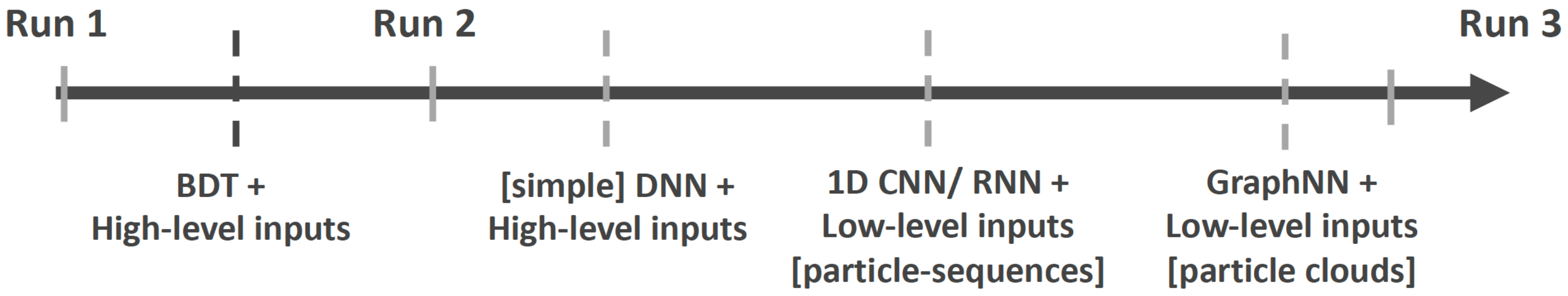


Key ingredients **for b/c vs. light** :
- ❑ Large lifetime & decay lengths
- ❑ Displaced vertices/tracks
- ❑ Large impact parameters
- ❑ Non-isolated leptons (soft)
- ❑ Harder fragmentation

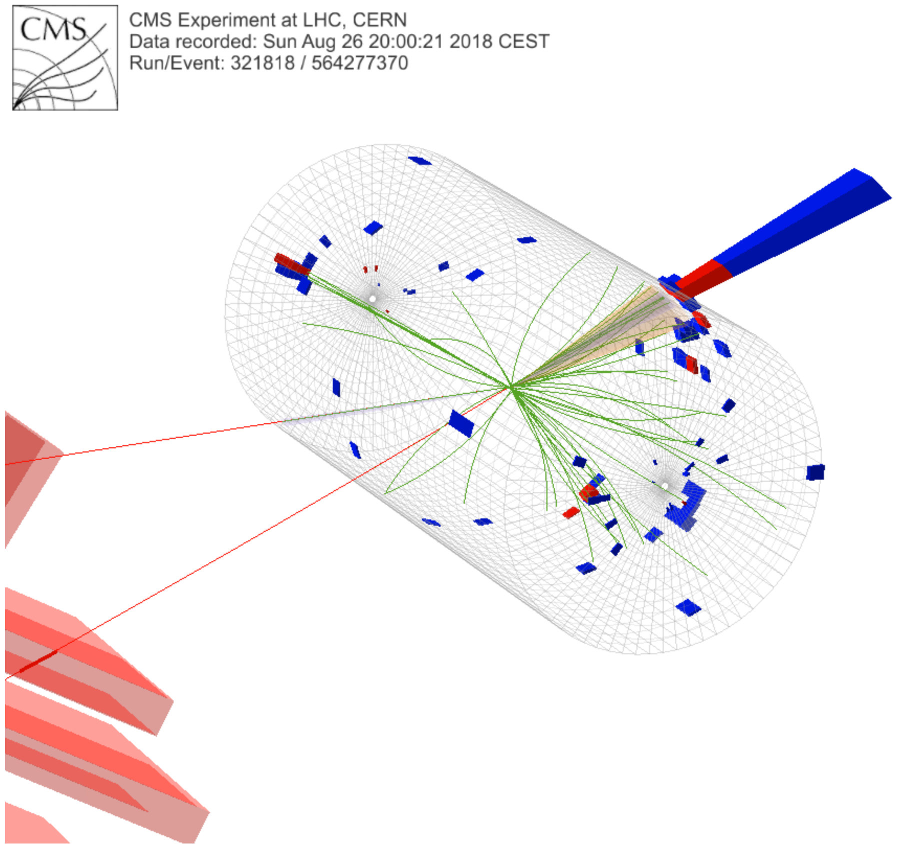
- ❑ Analysis uses DeepCSV technique
- ❑ **Tagged event: 1Loose + 1Medium**

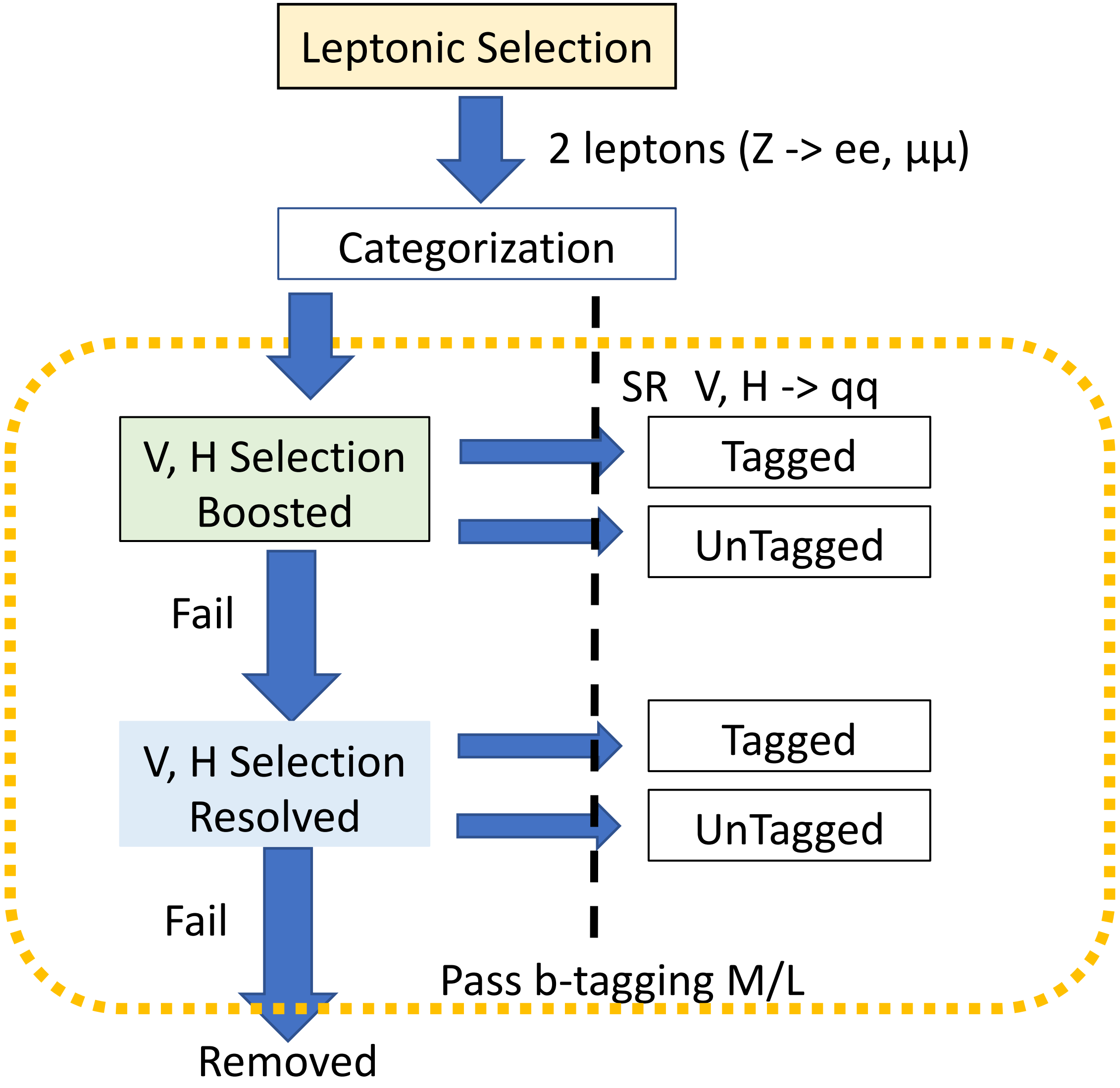
Progress over years



Selection events

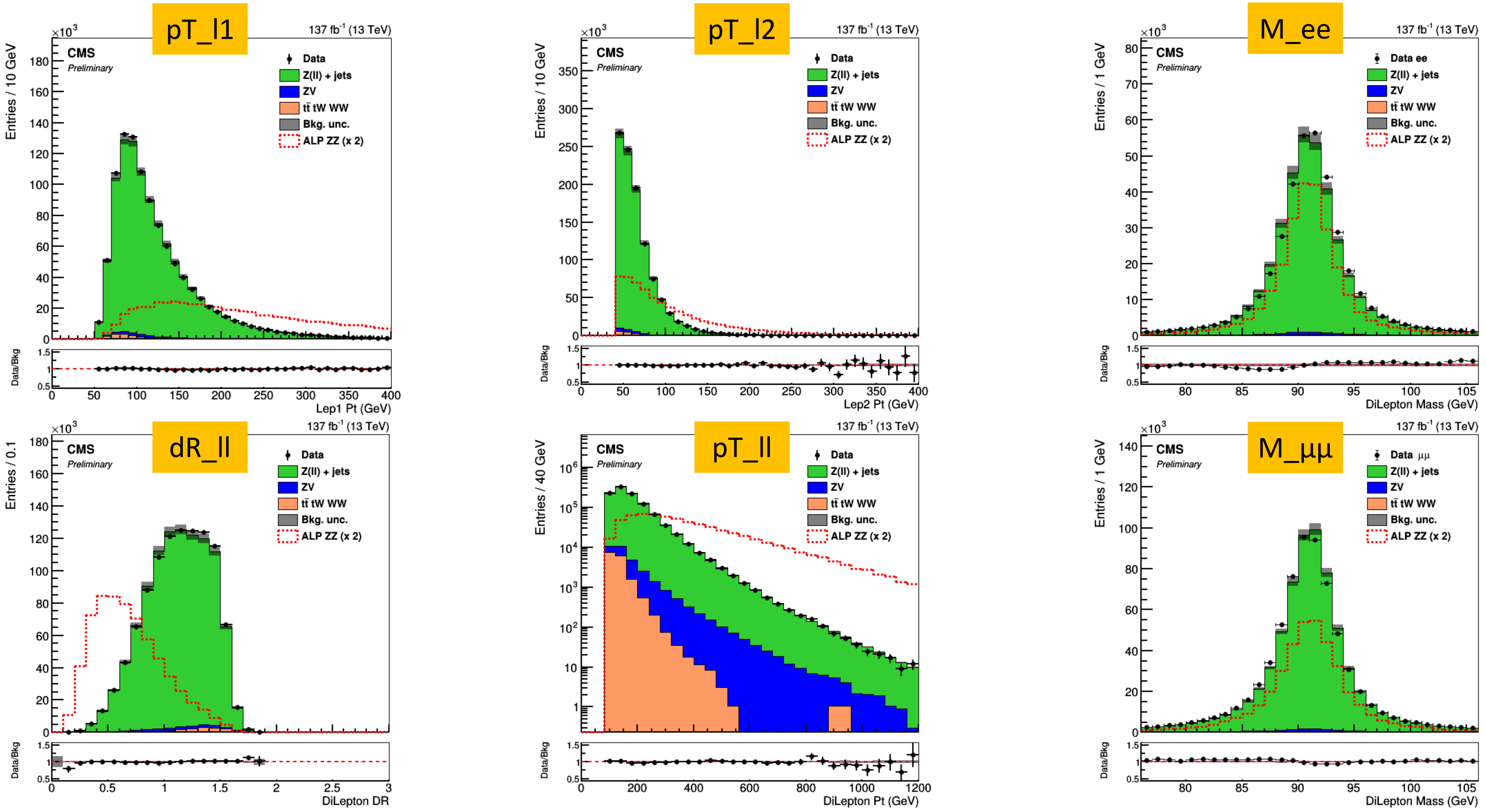
Selection and Categorization Events





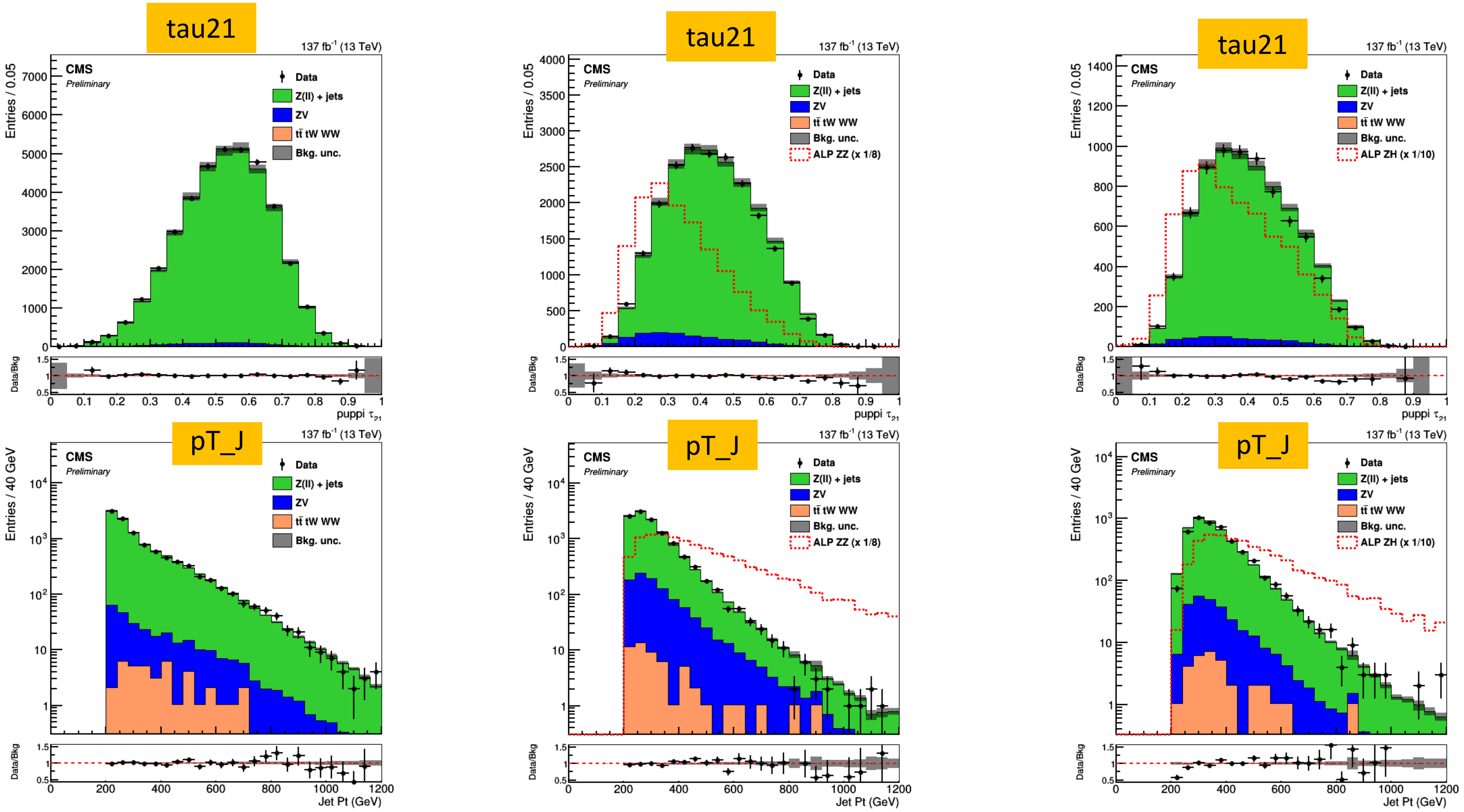
- Both Boosted and Resolved considered
- Background estimated using SB data and corrected NLO Z+jets MC prediction
- Categorization based on b-tagging

Basic Selection: Leptonic Z



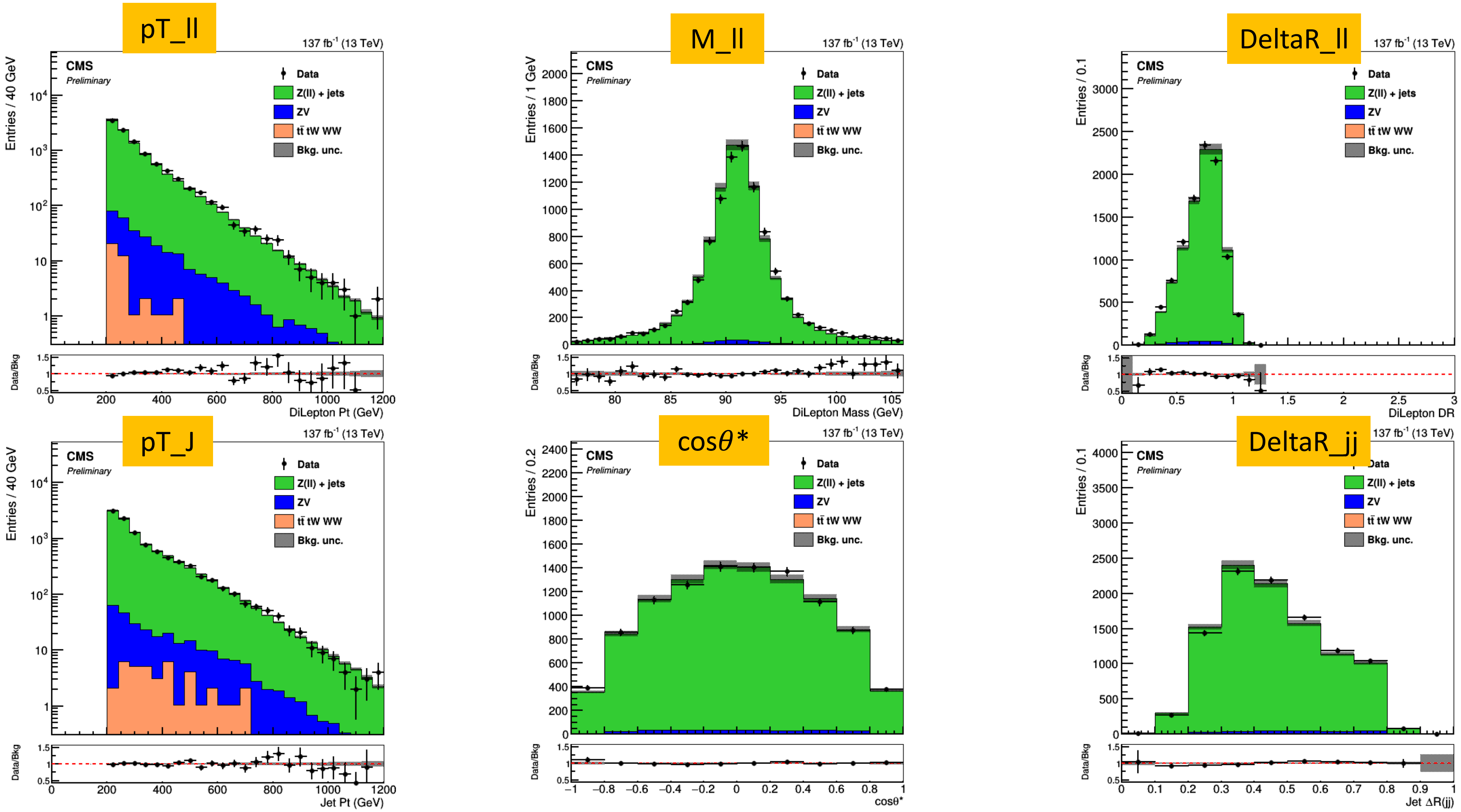
Z+jets background distribution normalized to data (2%)

Boosted Selection: AK8 Jets (SB/SR1/SR2)



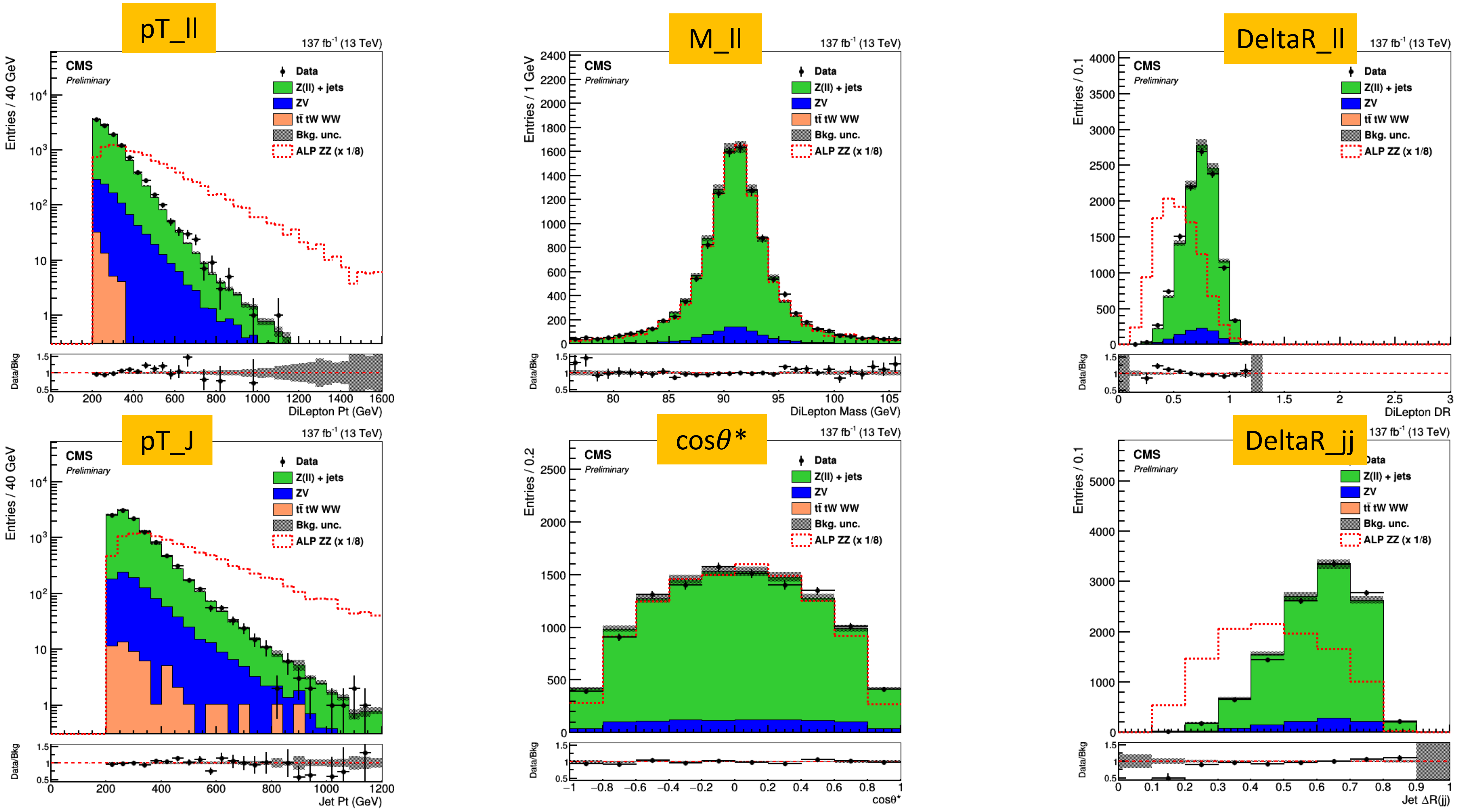
Postfit normalization of Z+jets from SB/SR1/SR2 background only fits to m(ZV/ZH).

Boosted Selection: SB region



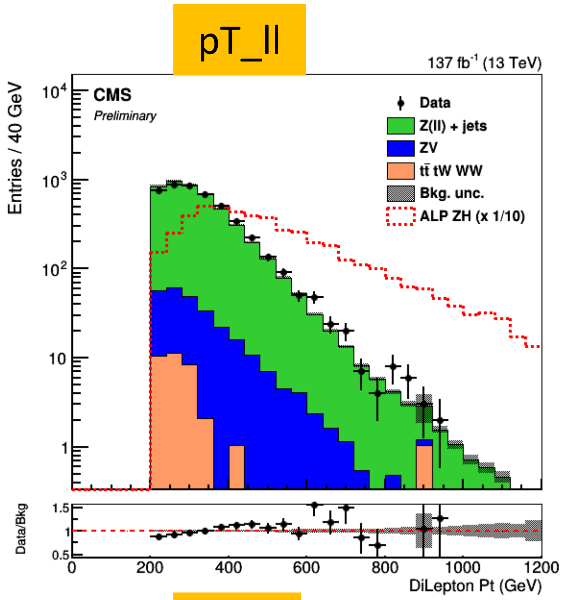
Postfit normalization of Z+jets from sideband region background only fit to m(ZV).

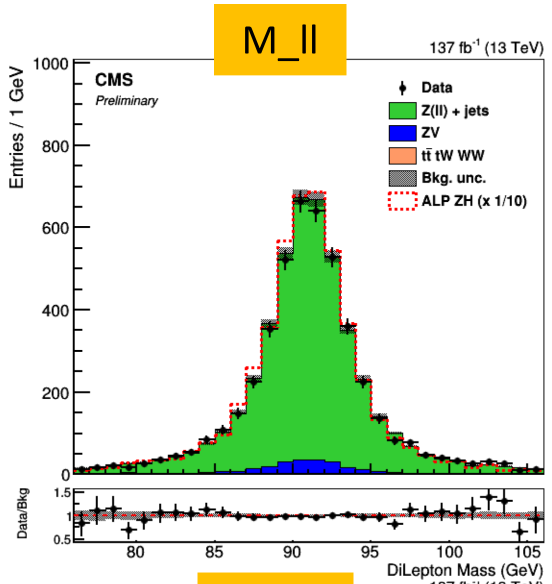
Boosted Selection: SR1 (V) region

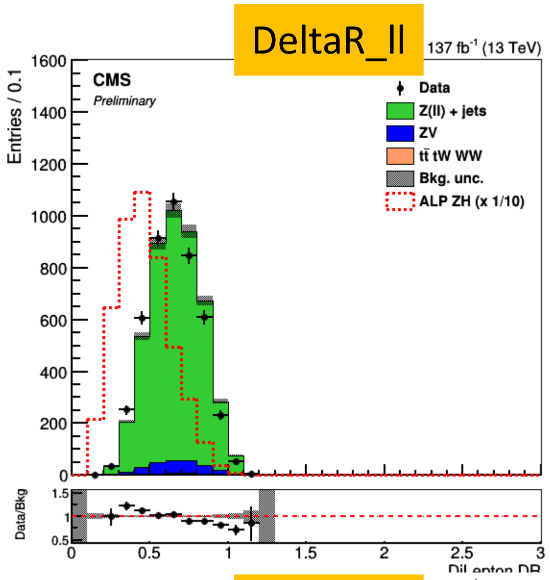


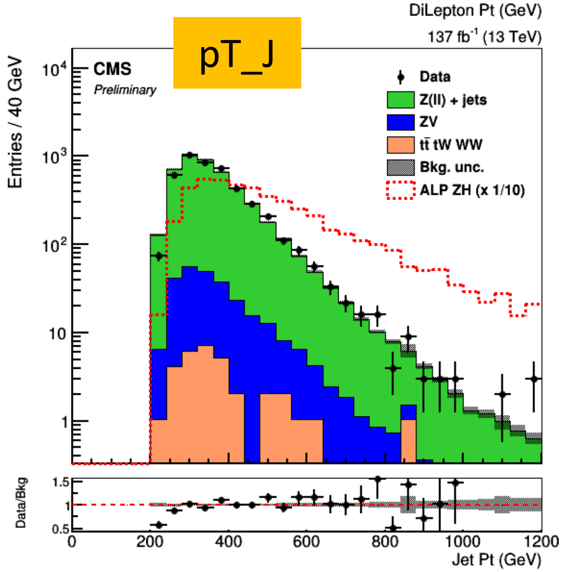
Postfit normalization of Z+jets from signal region background only fit to m(ZV).

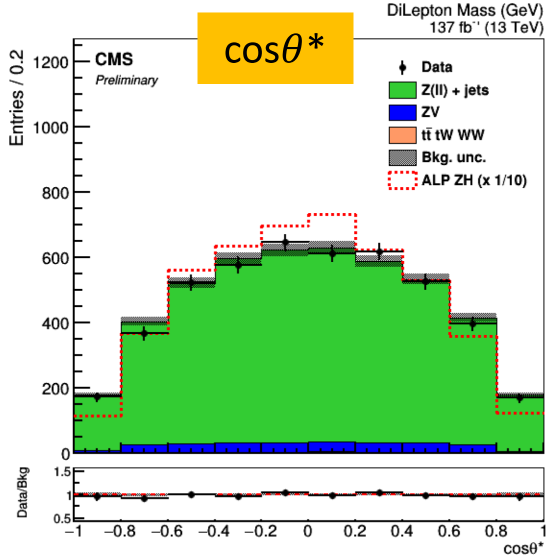
Boosted Selection: SR2 (H) region

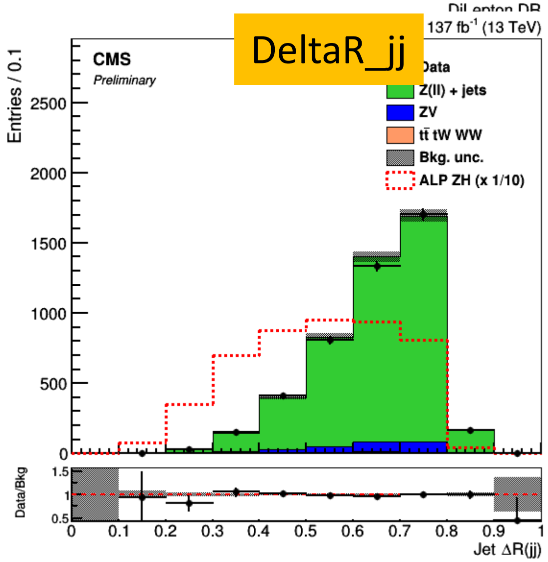






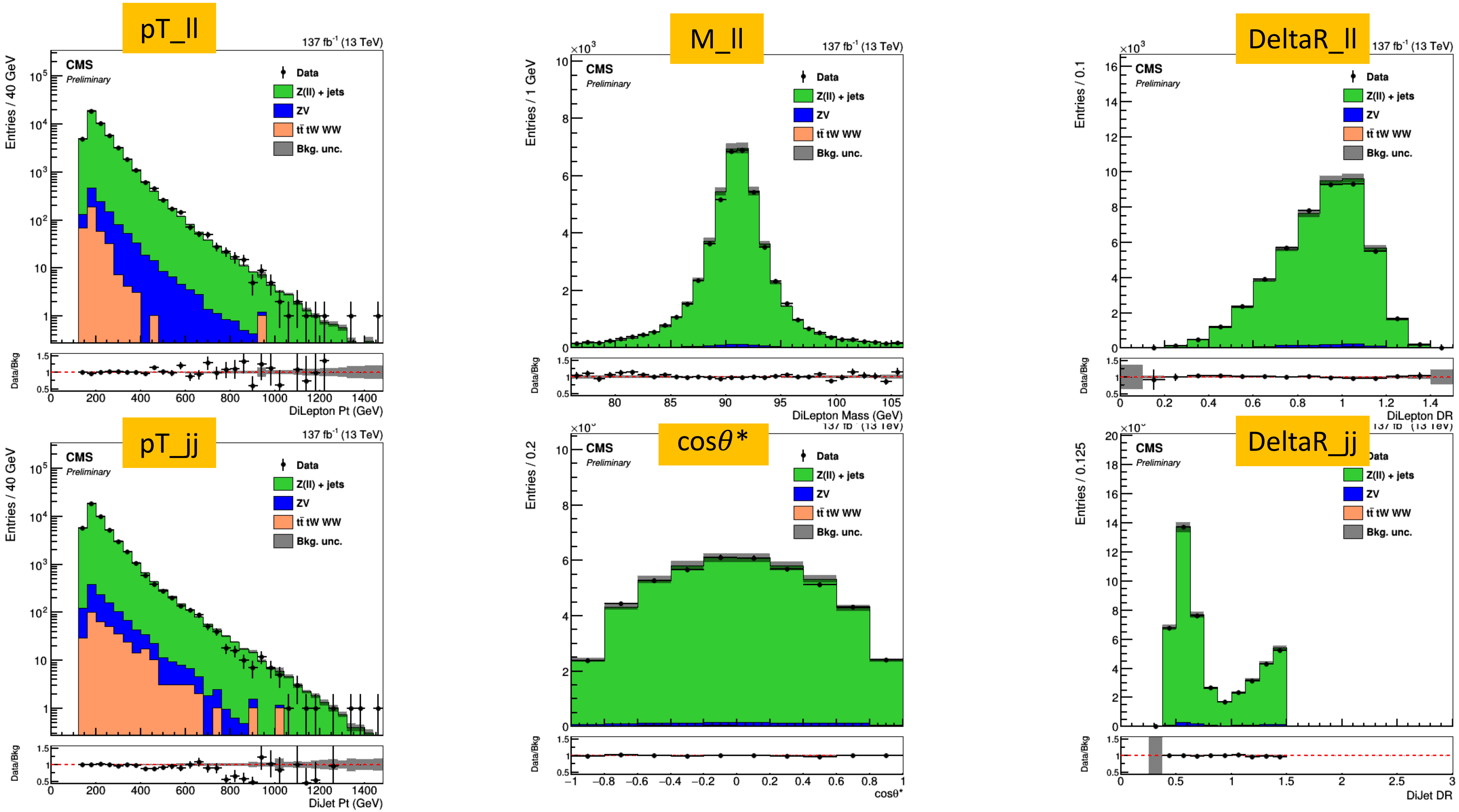






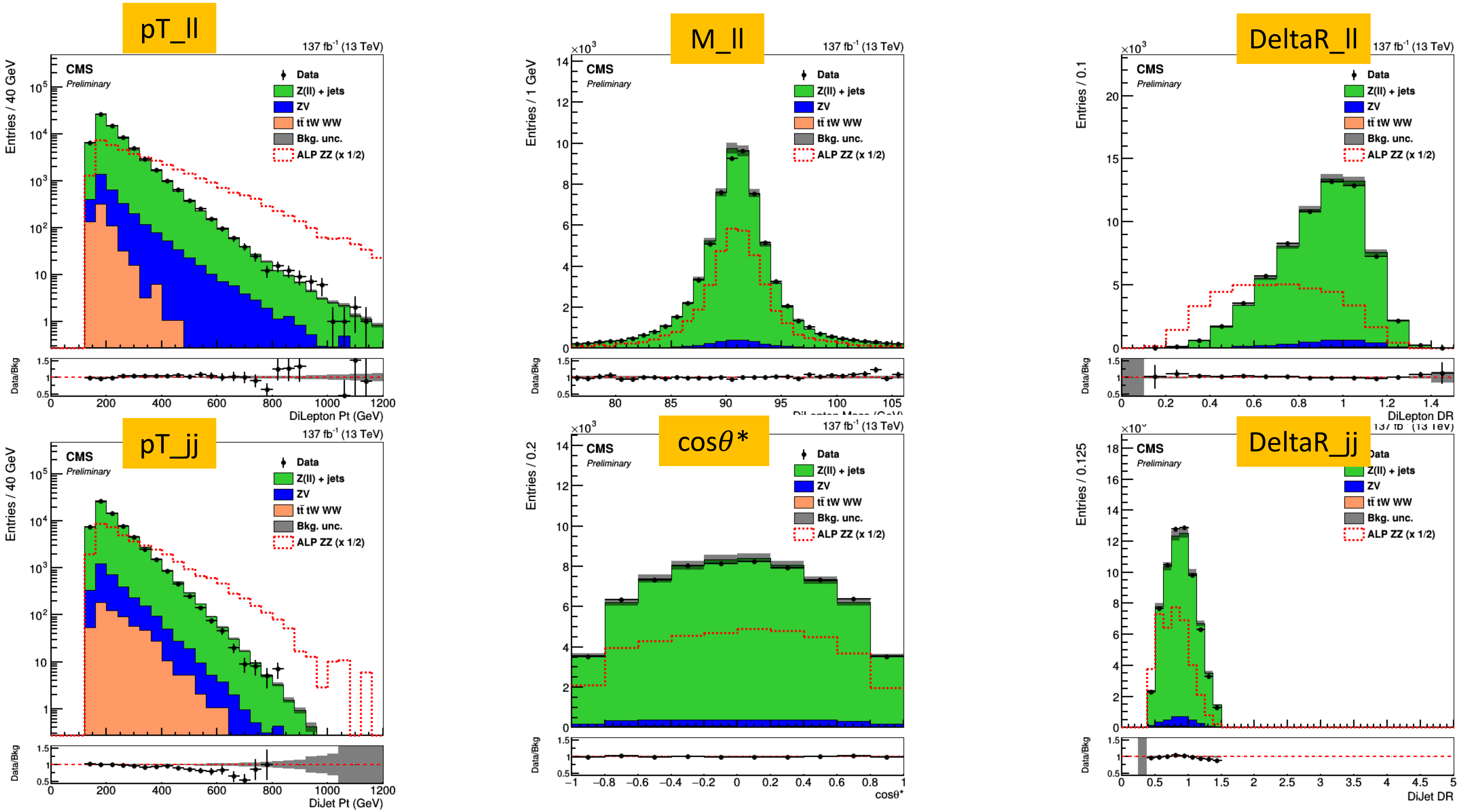
Postfit normalization of Z+jets from signal region background only fit to m(ZH).

Resolved Selection: SB region



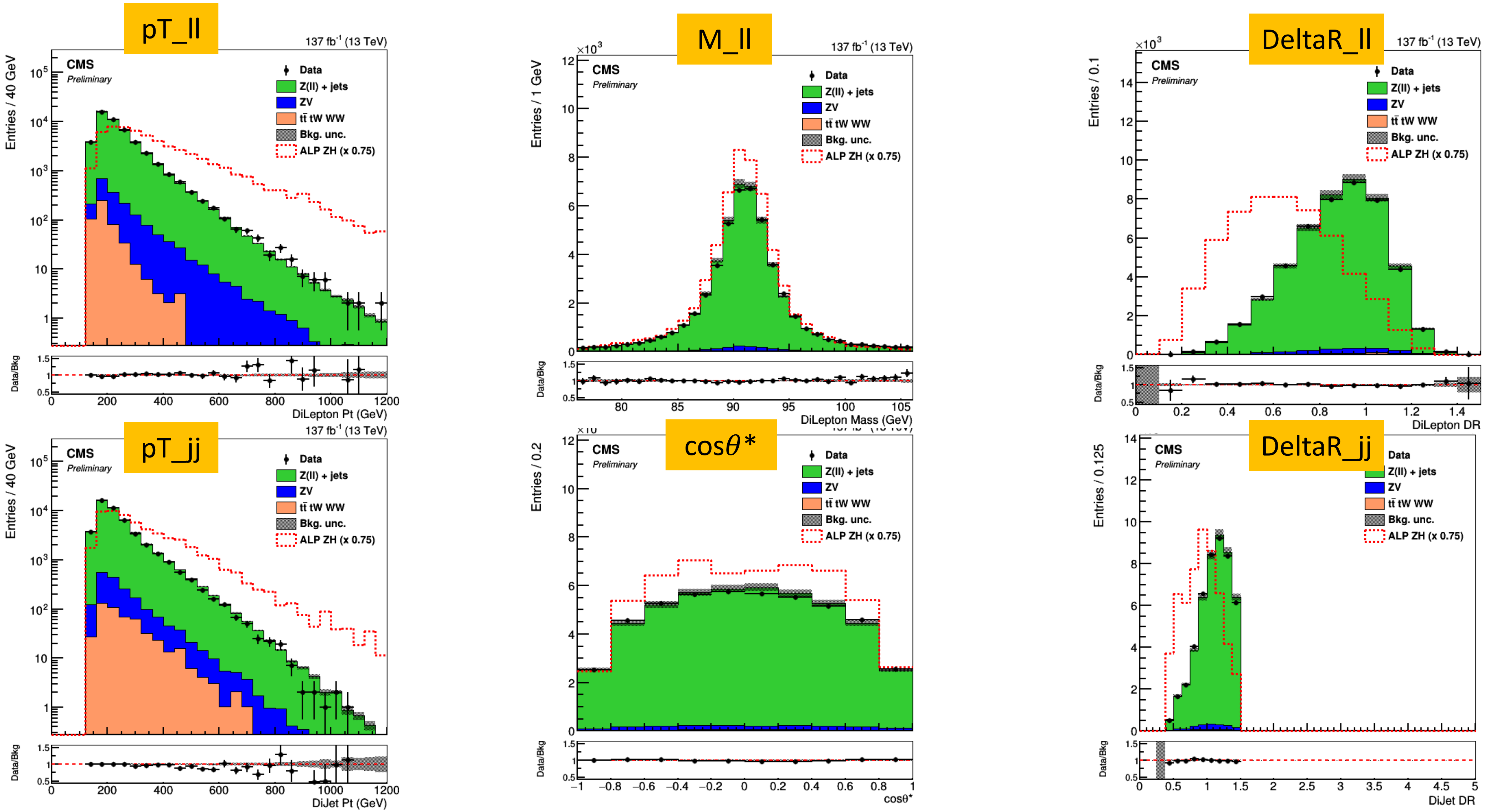
Postfit normalization of Z+jets from sideband region background only fit to m(ZV).

Resolved Selection: SR1 (V) region



Postfit normalization of Z+jets from signal region background only fit to m(ZV).

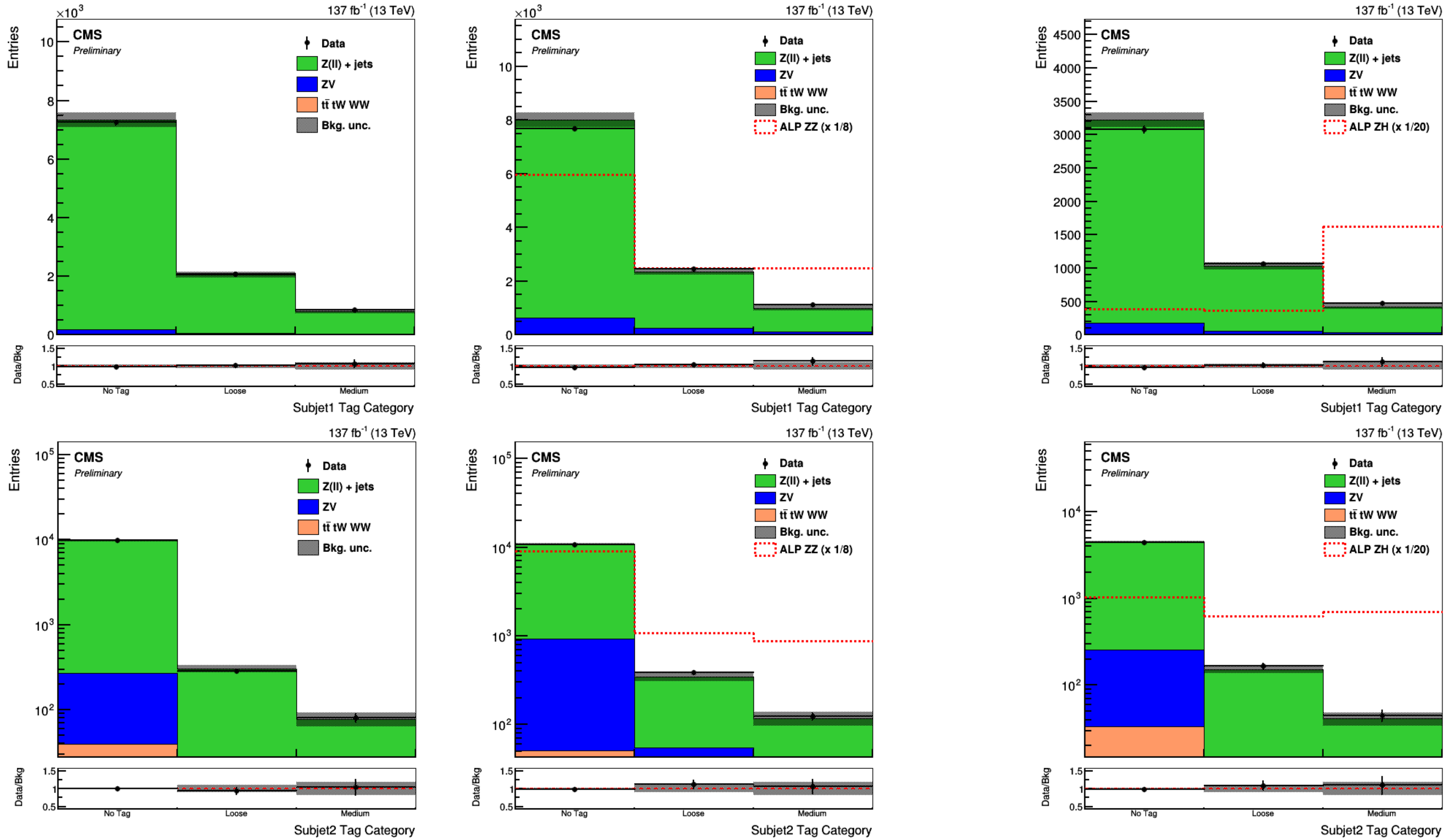
Resolved Selection: SR2 (H) region



Postfit normalization of Z+jets from signal region background only fit to m(ZH).

B-tagging: Boosted Selection SB/SR1/SR2

Double-tagged events:
1 Medium and
1 Loose
DeepCSV tags.



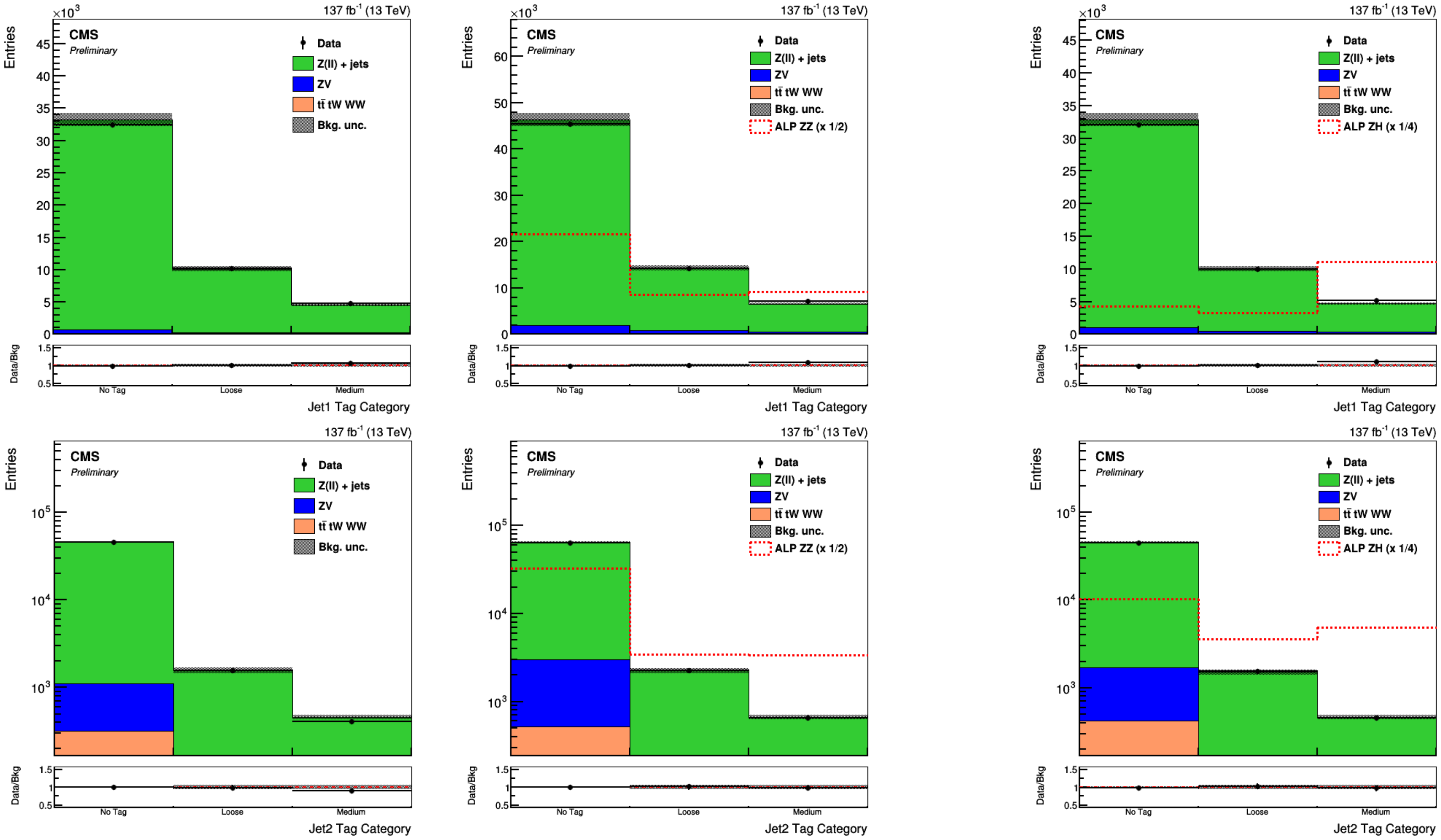
Most b-like subjet

Less b-like subjet

Postfit normalization of Z+jets from SB/SR1/SR2 background only fits to m(ZV/ZH).

B-tagging: Resolved Selection SB/SR1/SR2

Double-tagged events:
1 Medium and
1 Loose
DeepCSV tags.



Most b-like jet

Less b-like jet

Postfit normalization of Z+jets from SB/SR1/SR2 background only fit to m(ZV/ZH).

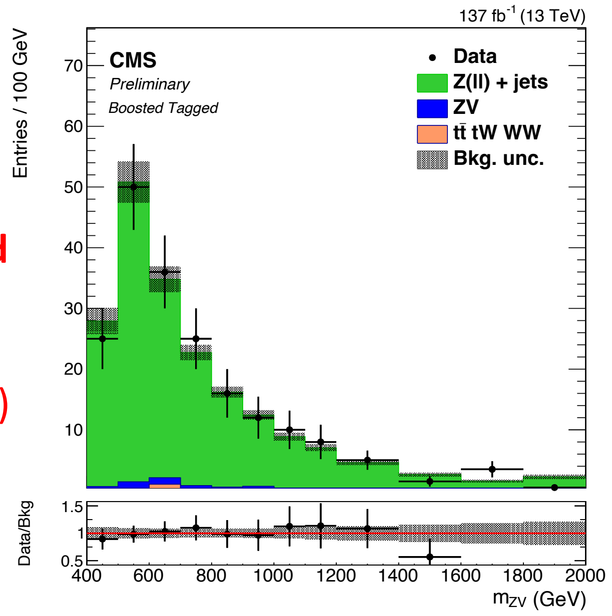
Fit to the SB 2l2q Mass Distributions

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

→ Postfit norm. and shape in good agreement to prefit prediction.

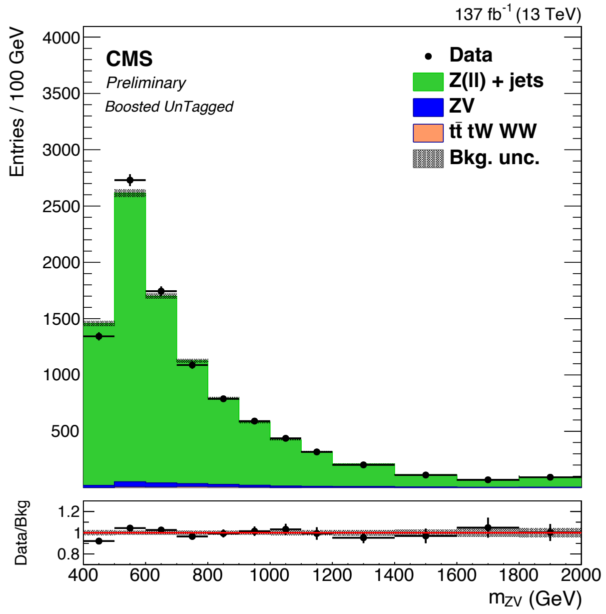
Boosted Tagged

(203 ev.)



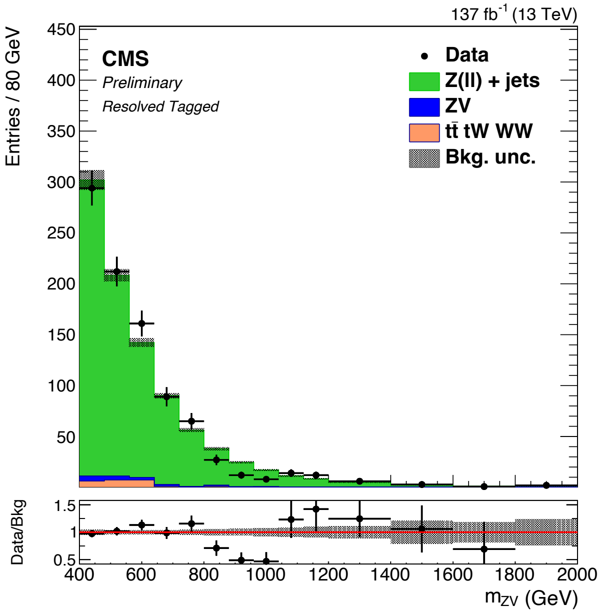
Boosted Untagged

(9980 ev.)



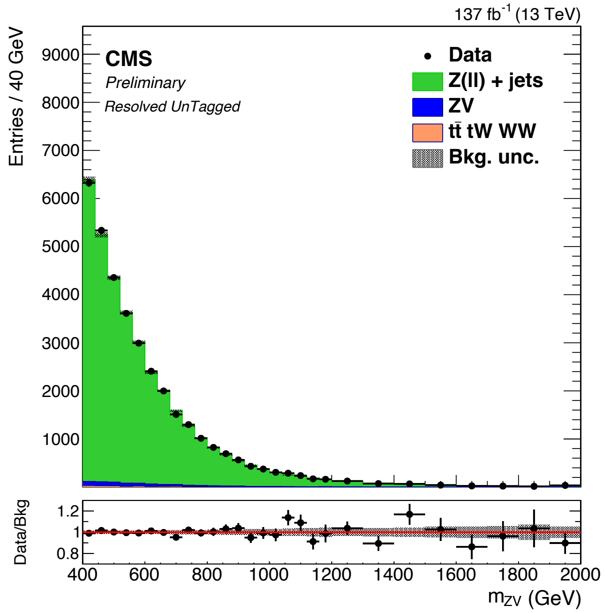
Resolved Tagged

(923 ev.)



Resolved Untagged

(35867 ev.)



Subdominant Backgrounds

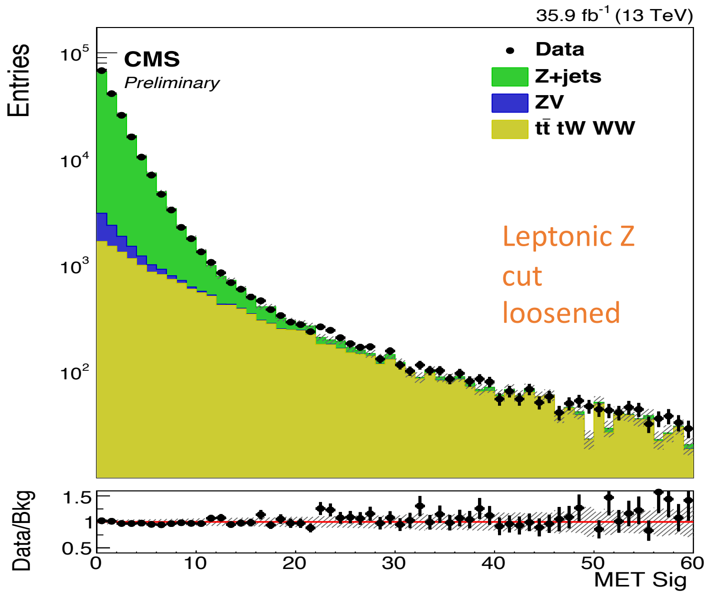
t+X background

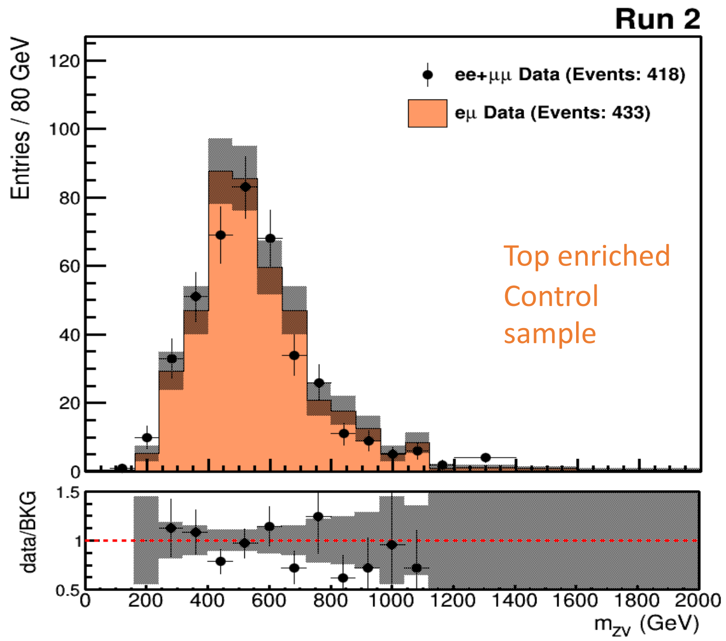
- Lepton flavor symmetric backgrounds determined from *eμ* data ($t\bar{t}$, tW, WW, Z to $\tau\tau$, fakes).
- Leptonic Z cut loosened (m(ll) > 50 GeV) to enhance background.
- Tested in a top quark-enriched control region: MET significance > 6, Im(ll) – m(Z)I > 10 GeV, 1M DeepCSV tag.

→ Agreement within *eμ* vs. (ee + *μμ*): 4%.

SM ZV background

- Small: taken from simulation.
- Size: 3 - 20%.

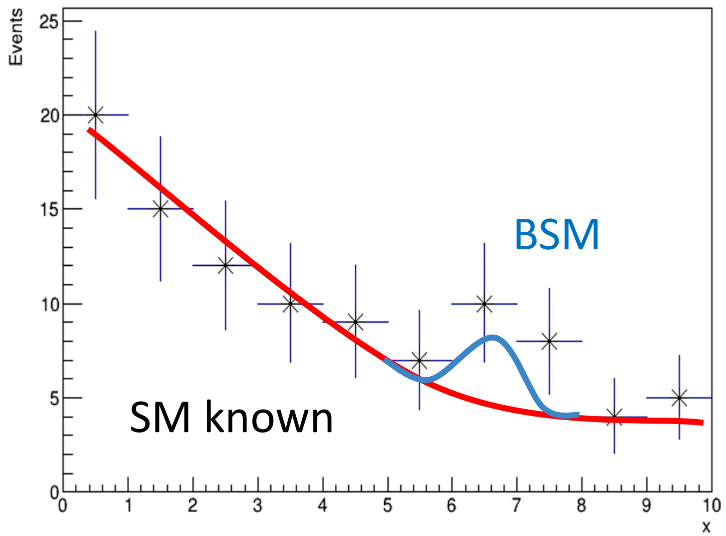




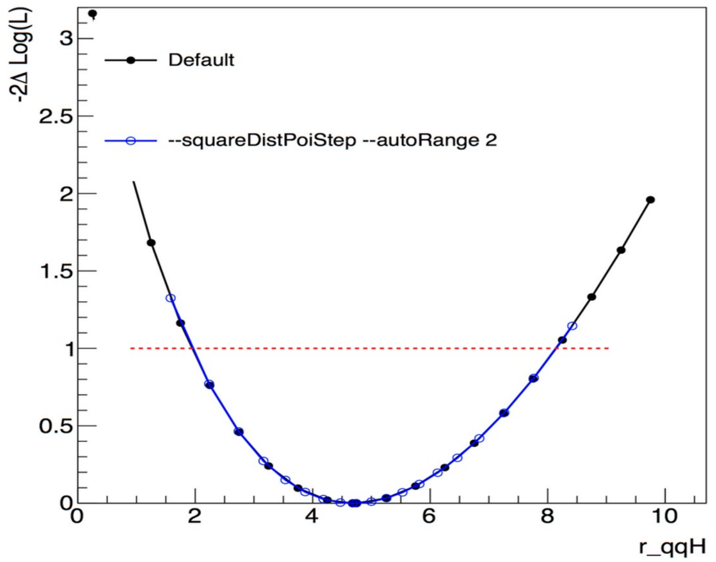
Fit to Data

Fit to 2l2q Invariant Mass

$$p(d \mid f) = \frac{f^{d} e^{-f}}{d!} \quad \xrightarrow{\text{N-bins}} \quad L = \prod_{i=1}^{N} \frac{f_i^{d_i} e^{-f_i}}{d_i!}$$



- **Counting experiment**
  - d are the data measured; Signal (S) + Background (B),
  - f (r, θ); the model prediction, SM; POI -> r = S strength; θ nuisance params.
- **Syst. Unc. split into two types** - normalization and shape-based,
  - Normalization unc. uniformly affects yields in all bins (ex. luminosity)
  - Shape-based has non-uniform effect on bin yields (ex. p_T dependent).
- **Binned-Shape analysis,**
  - ee/mm *x* boosted/resolved *x* tagged/untagged
  - Norm and Shape are floating free



Fitting Procedure

- Maximum-likelihood fit to m(ZV/ZH) distributions for electrons / muons, boosted / resolved, tagged / untagged categories in SR + SB simultaneously.
- The background-only hypothesis is tested against the combined signal + background hypothesis.
- Systematic and MC statistical uncertainties included as nuisance parameters in the fit.
- Z+jets normalizations and shape corrections float in the fit, independently for the boosted / resolved and tagged / untagged categories.
- Overflow bin includes events with m(ZV/ZH) up to 3000 GeV.
- In the ALP fits, for given value of the f_a scale, events with m(ZZ/ZH) > f_a are excluded from the fit.

Results

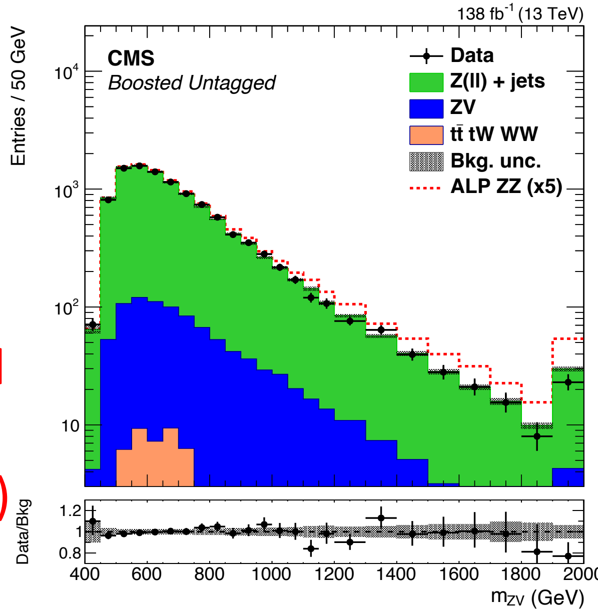
SR1 ZZ/ZW: 2l2q Mass Distributions

- 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.

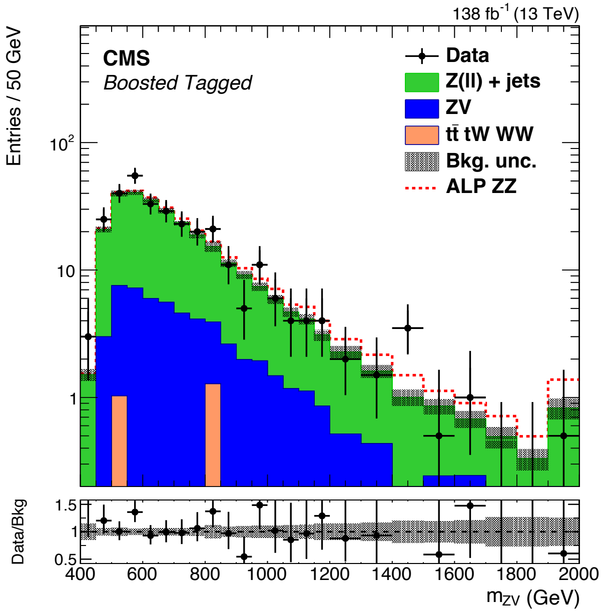
Boosted Untagged

(10948 ev.)



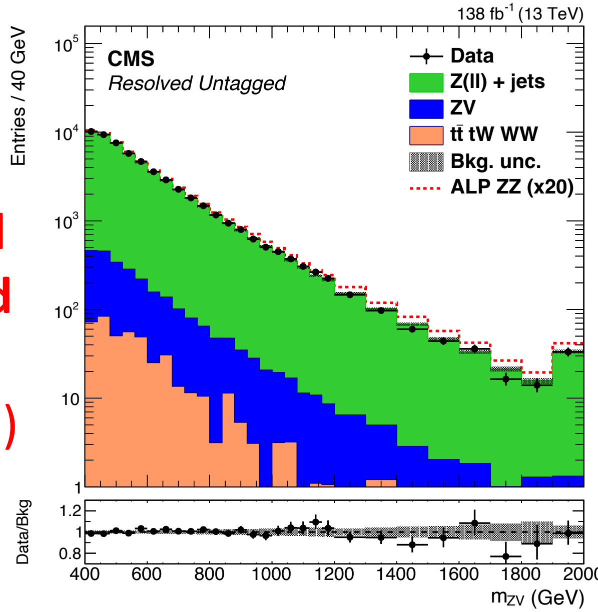
Boosted Tagged

(312 ev.)



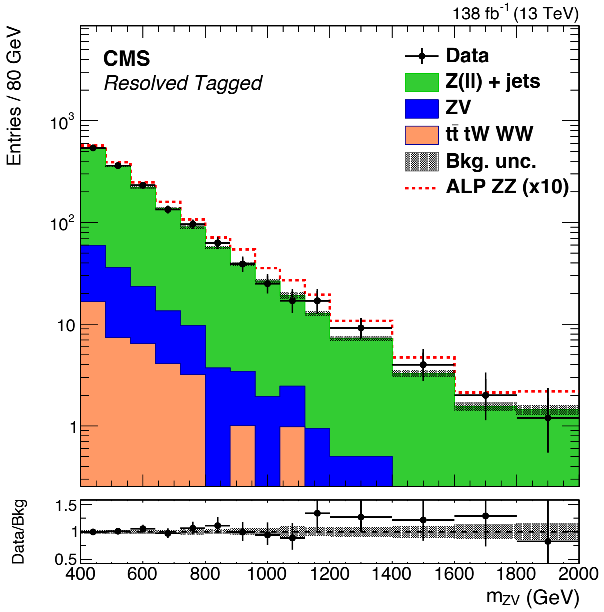
Resolved Untagged

(56324 ev.)



Resolved Tagged

(1566 ev.)



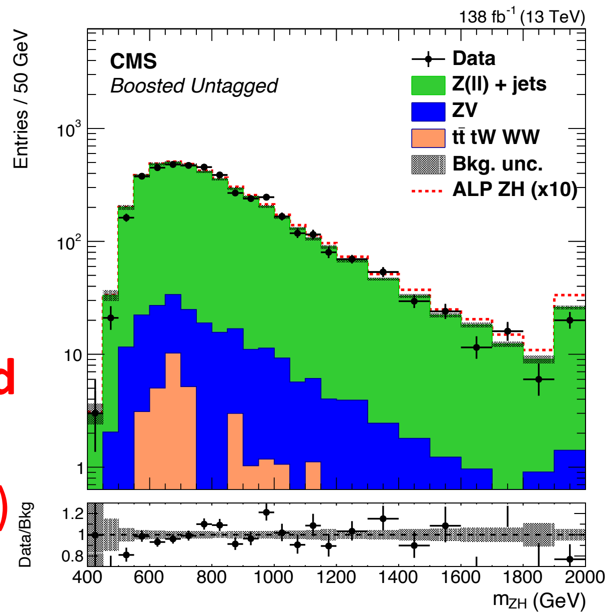
SR2 ZH: 2l2q Mass Distributions

- 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.

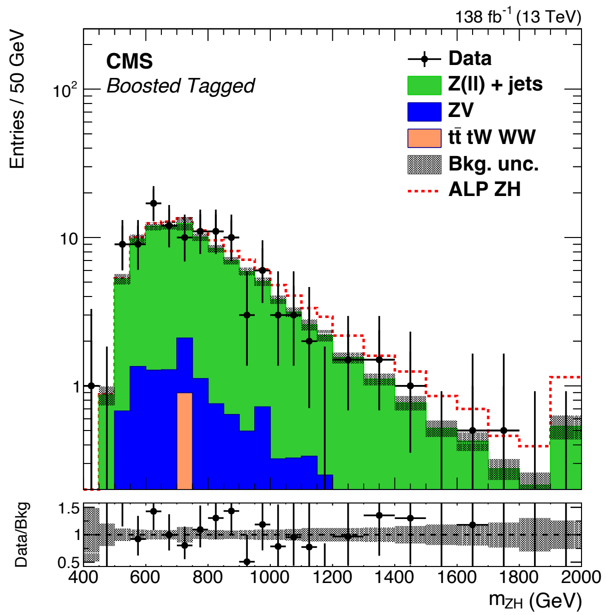
Boosted Untagged

(4499 ev.)



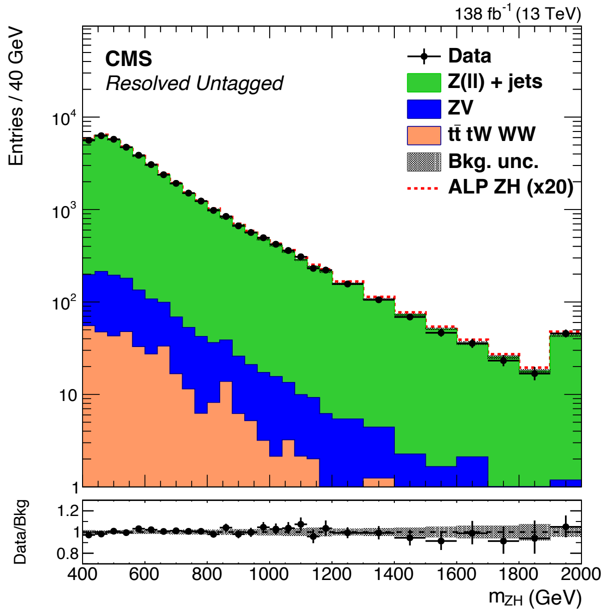
Boosted Tagged

(117 ev.)



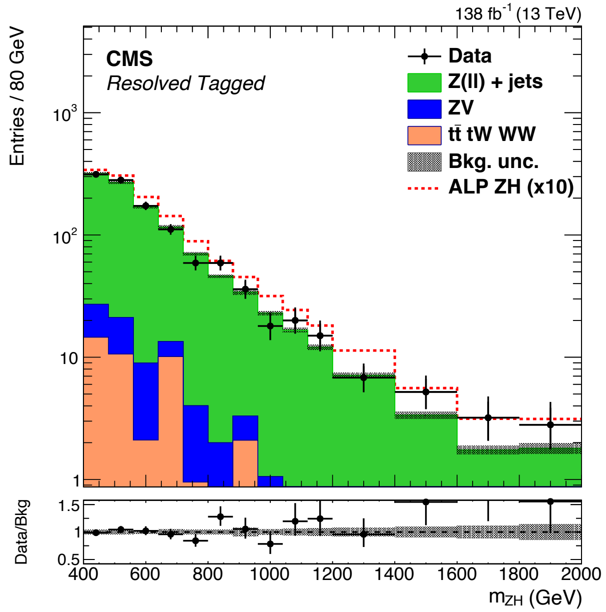
Resolved Untagged

(42662 ev.)



Resolved Tagged

(1130 ev.)



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

- Postfit background normalization.

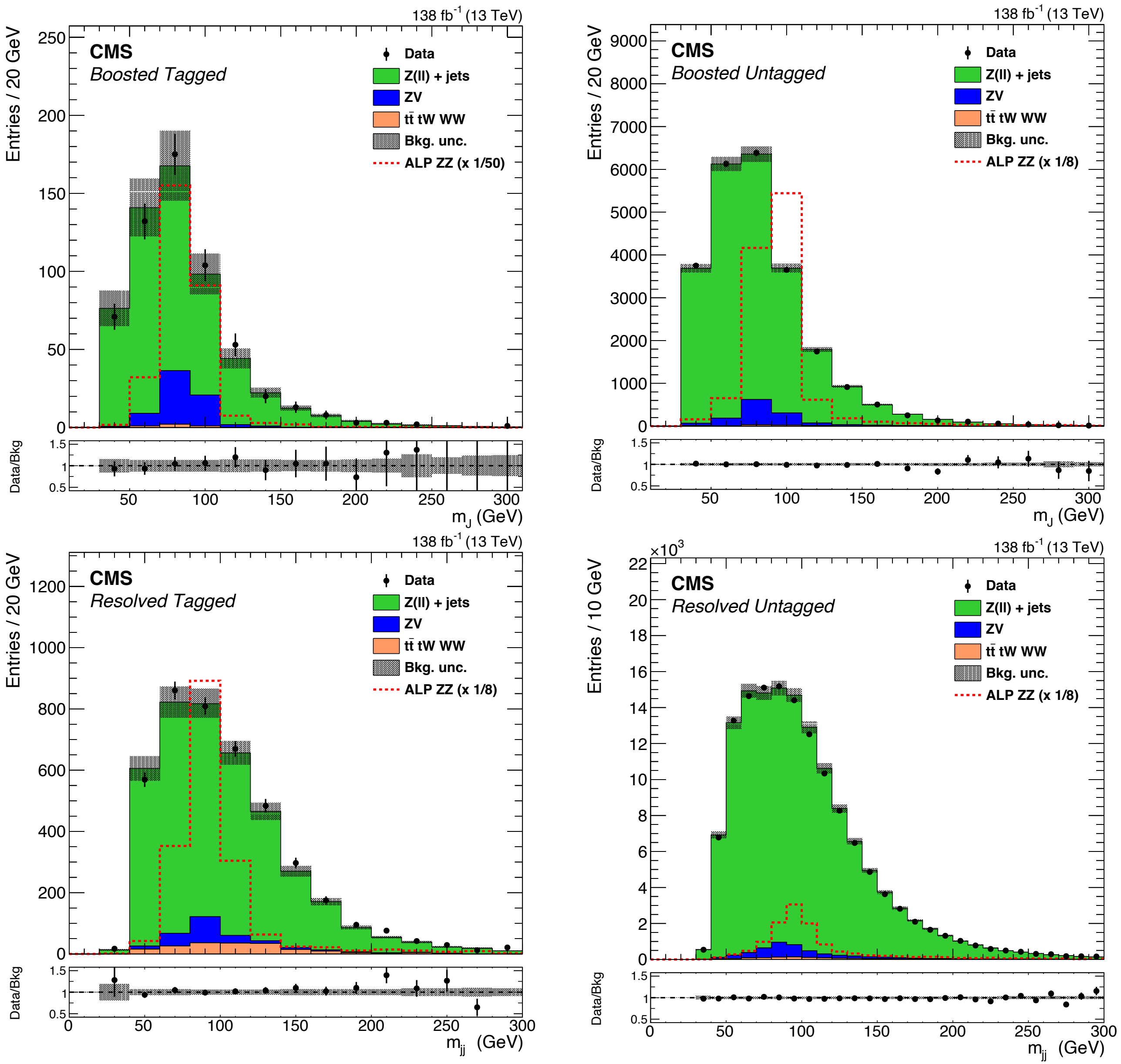
→ Signal (red line) normalized to hypothetical ALP linear cross-section with 1TeV^{-1} couplings to gluons and ZZ, and f_a = 3 TeV.

Boosted Tagged

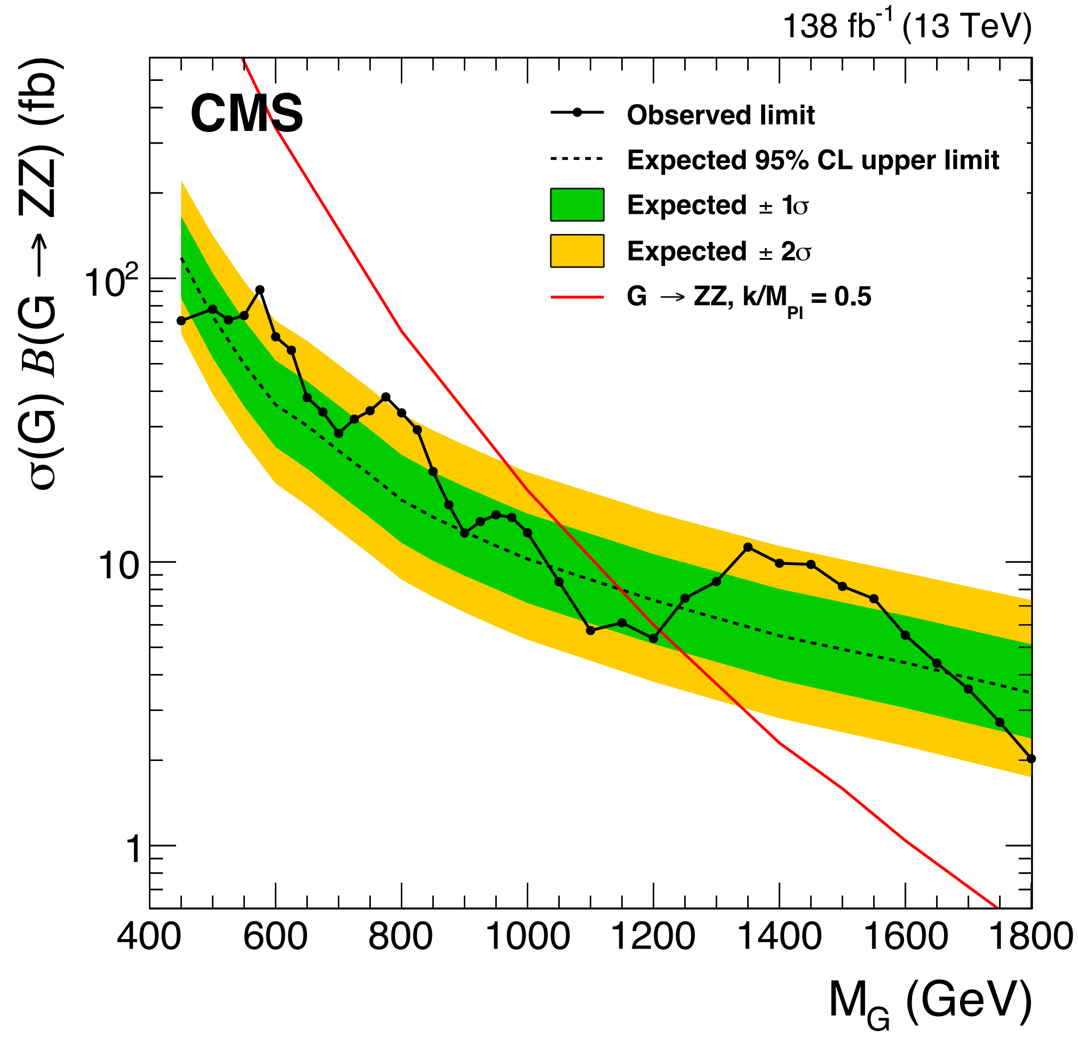
Boosted Untagged

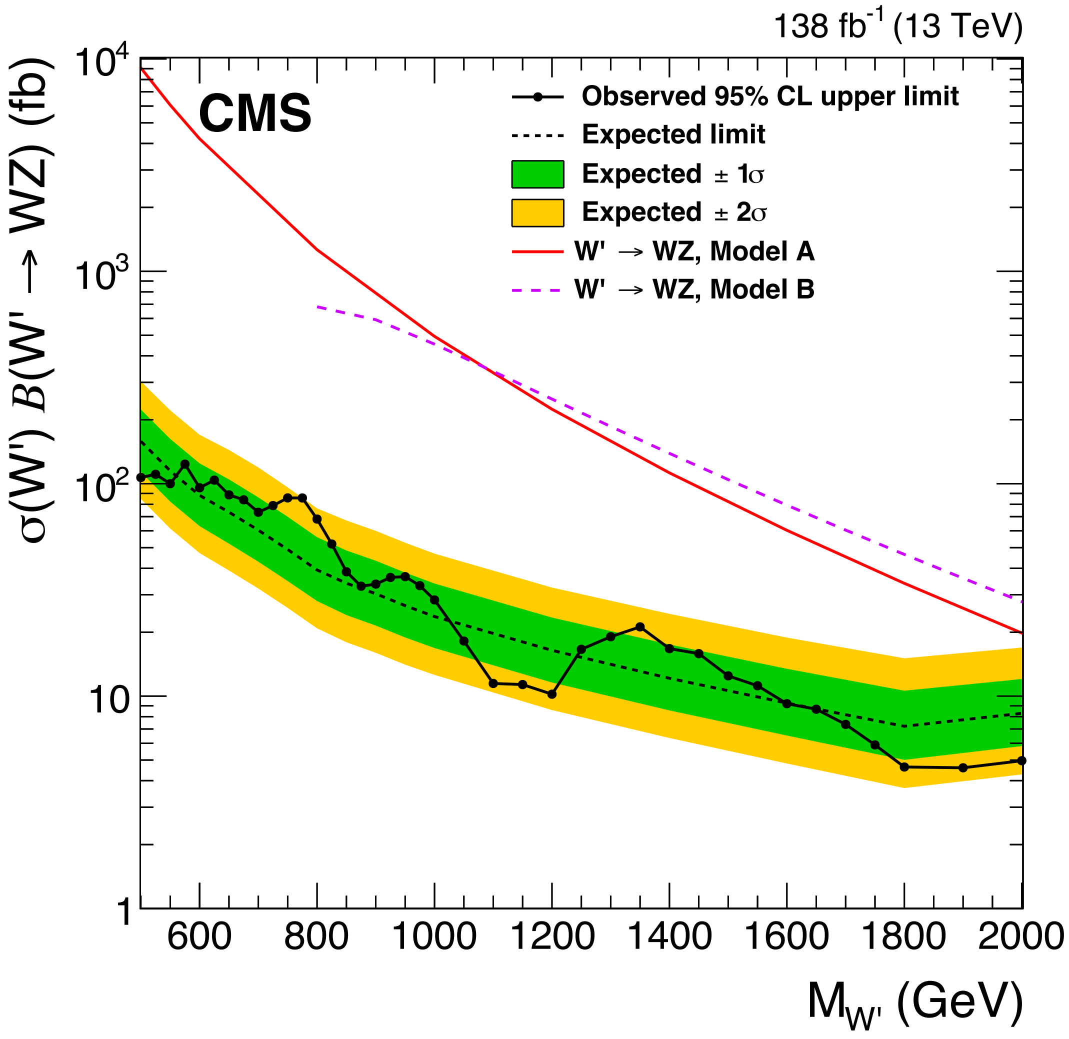
Resolved Tagged

Resolved Untagged



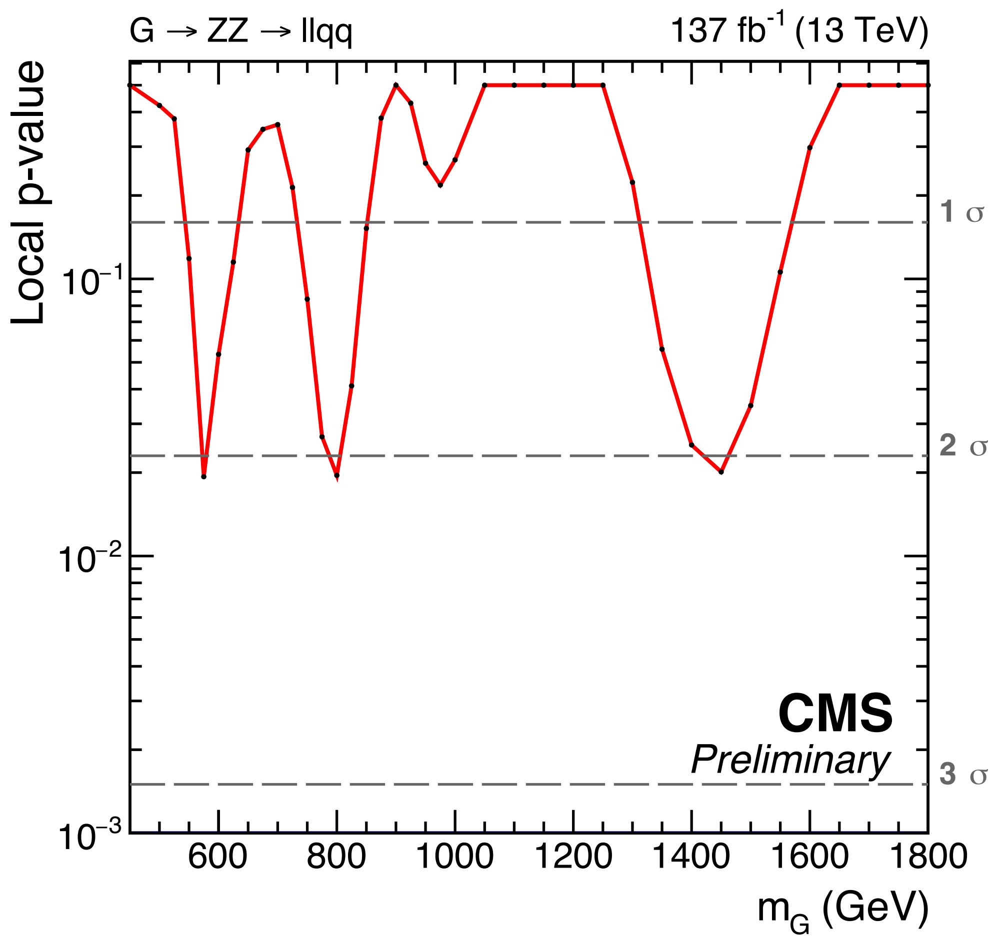
Observed and expected Limits: Bulk and W’



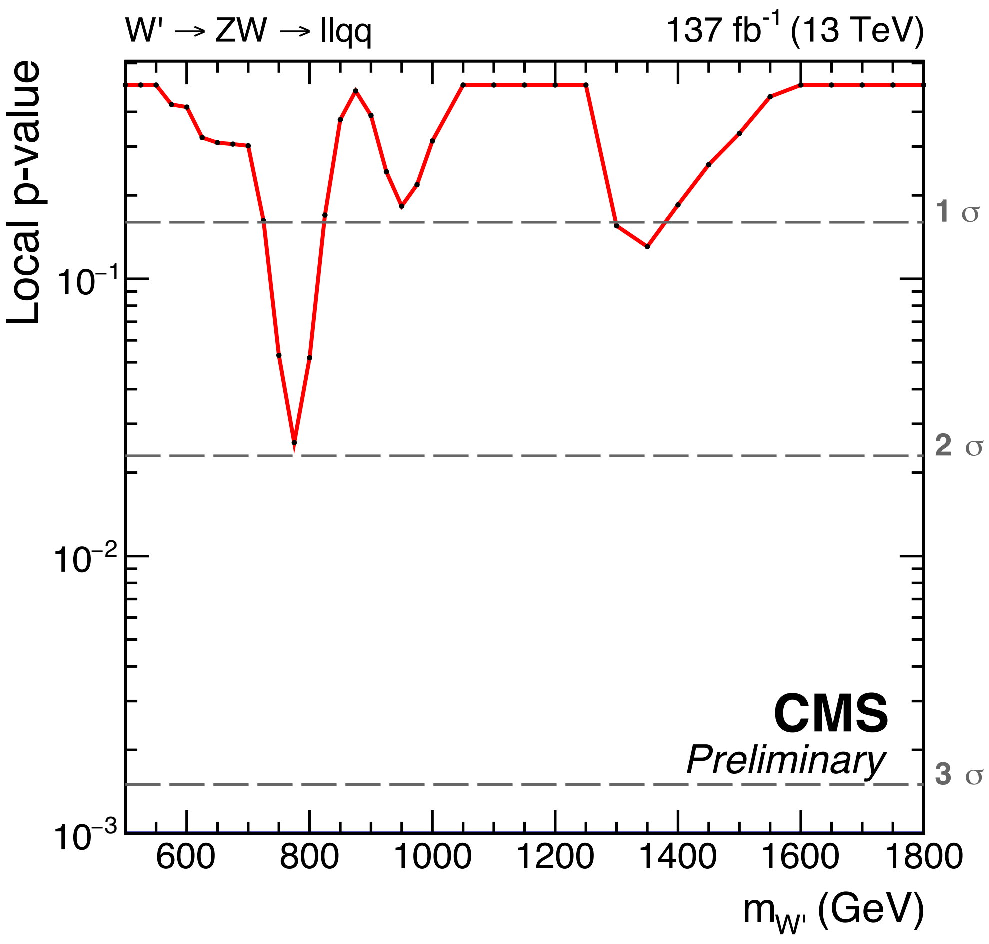


- These limits improve published results of 2016 in the 450-1800 GeV region by a factor of 2.5-3

Observed Local p-values: No significant excess

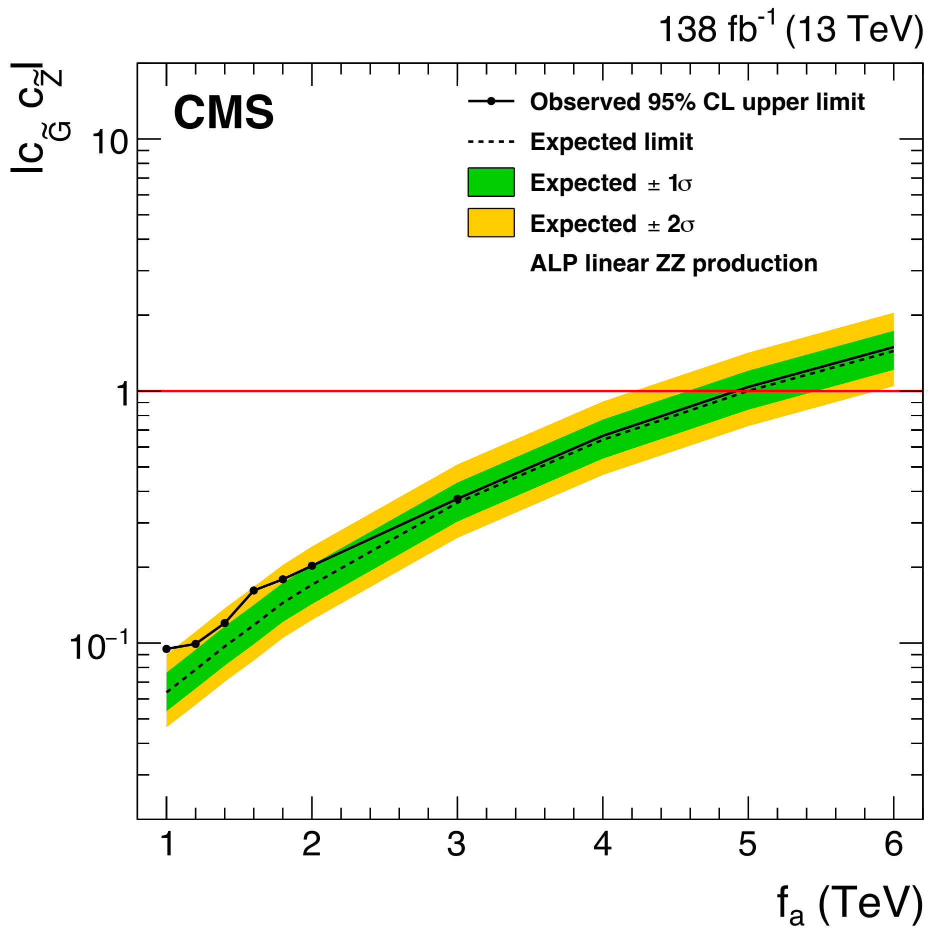


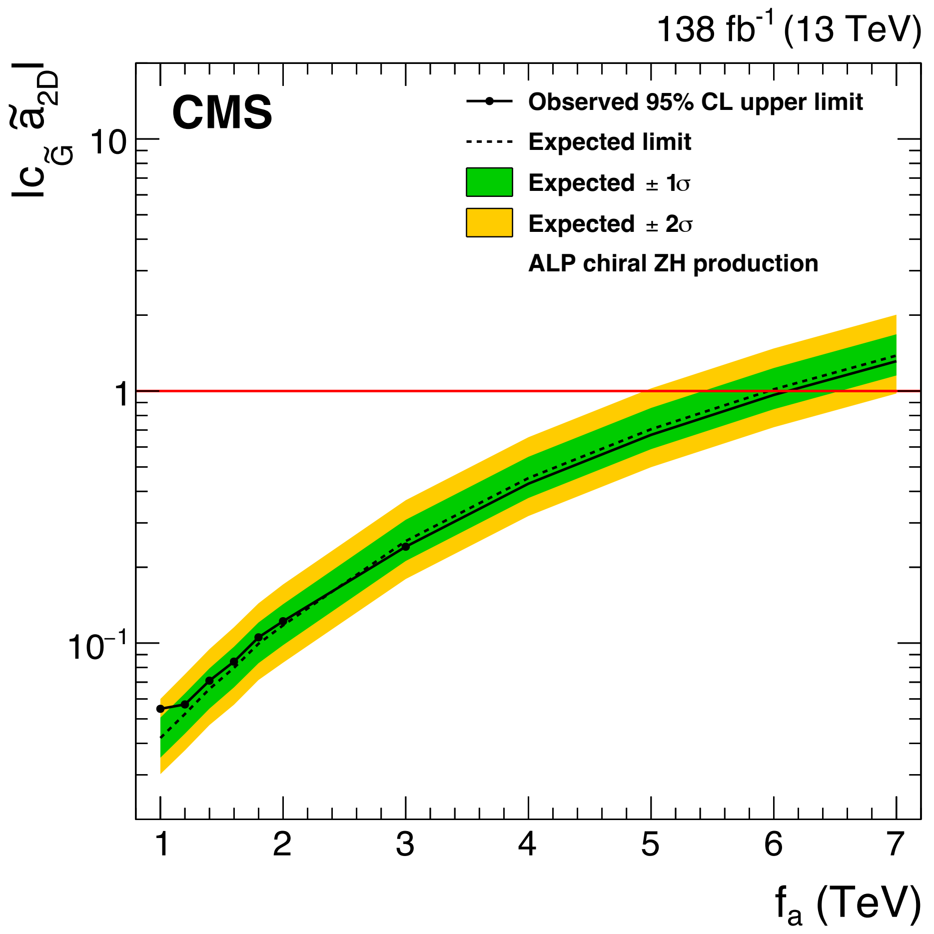
Bulk Graviton



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			Expected			Observed
	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	
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: $|c_G \cdot c_Z| / f_a^2 = 0.0415\ (0.0400)\ \text{TeV}^{-2}$,
  - ALP chiral ZH: $|c_G \cdot \tilde{a}_{2D}| / f_a^2 = 0.0269\ (0.0281)\ \text{TeV}^{-2}$.

CMS, JHEP 04 (2022) 087

Back up

Event Selection and Categorization: Summary

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

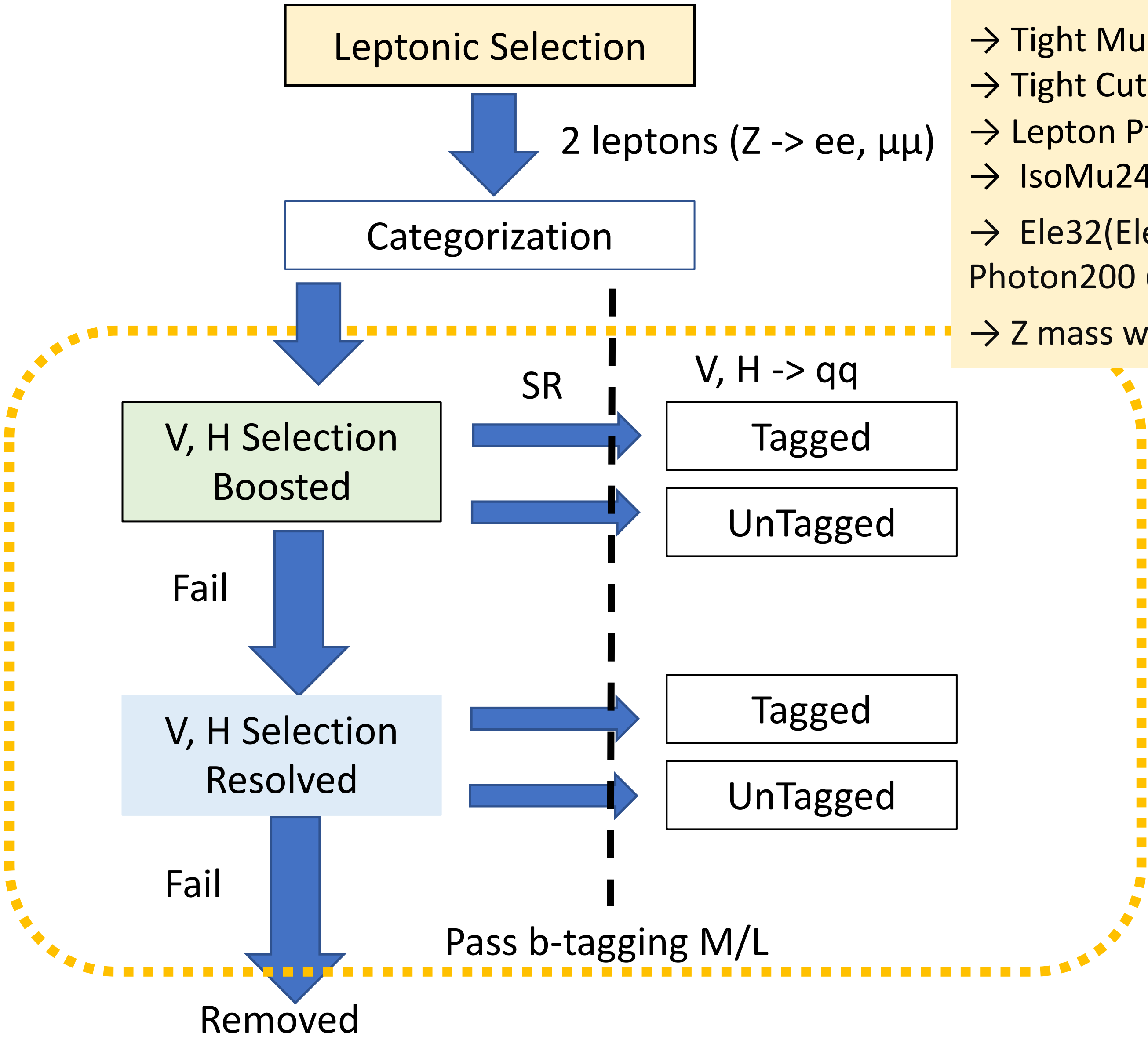
→ DeltaR(jj) < 1.5

V SR1 (m_jj) : 65→110 GeV

H SR2 (m_jj) : 95→135 GeV

SB : 30→65 + 135→180 GeV

B-tagging: 1Loose 1Medium



Leptonic Z

→ Tight Muon ID with Loose PF Iso

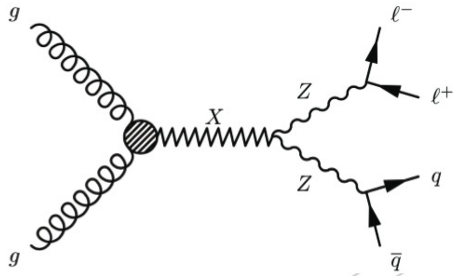
→ Tight Cut Based Electron ID

→ Lepton Pt > 40 GeV

→ IsoMu24 (IsoMu27)

→ Ele32(Ele27)_WPTight || Ele115 || Photon200 (Photon175)

→ Z mass window: 76 < M(ll) < 106 GeV



Systematic Uncertainties Of 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.

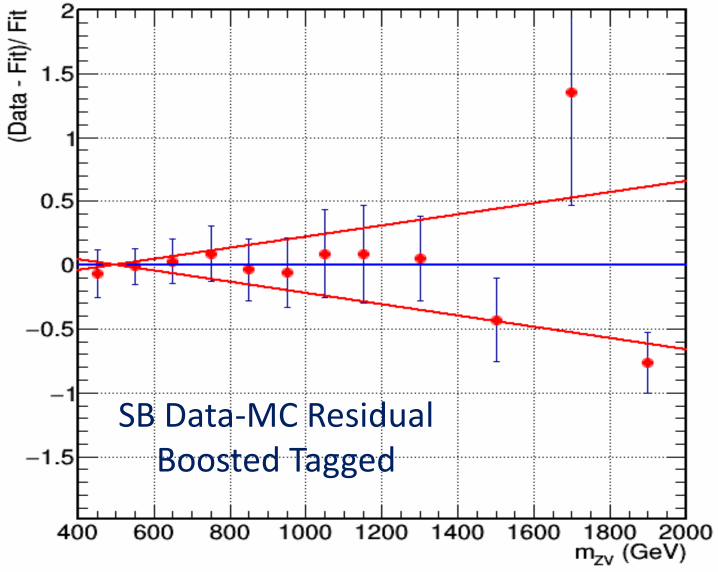
- One single parameter: slope (s) of the linear shape correction.

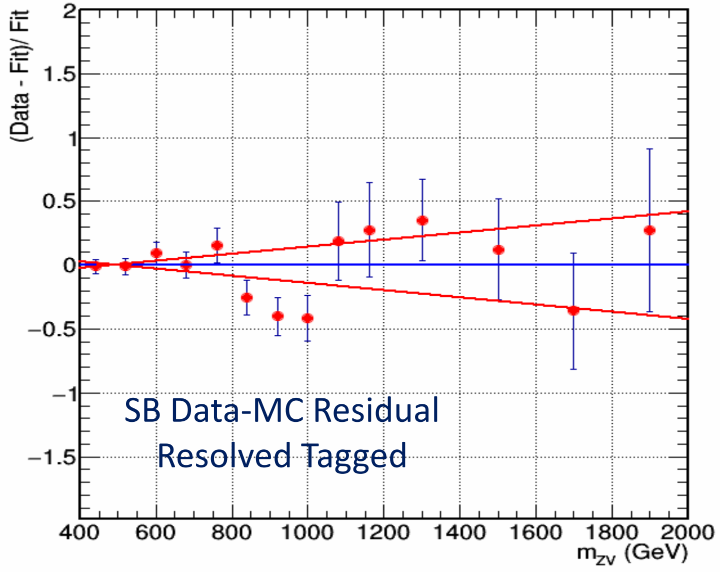
- The linear shape correction is conventionally defined as 1 for m(ZX) = 500 GeV. Other definitions are equivalent; the change is absorbed in a redefinition of the overall normalization.

- 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.

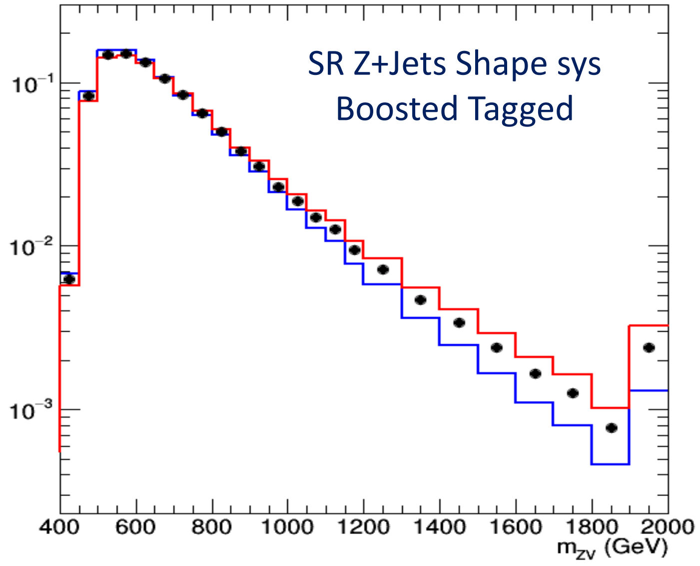
Z+jets Background Shape Systematic

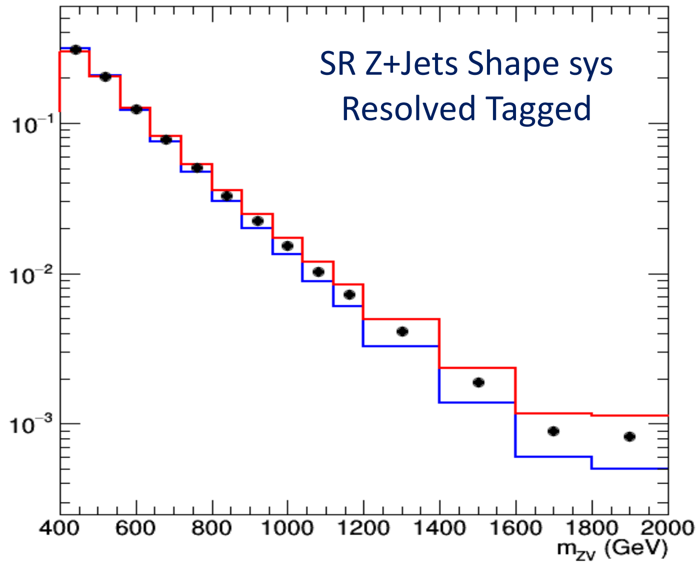
- Residuals data-MC from SB fit. Red lines correspond to 2σ of the error given by the fit.



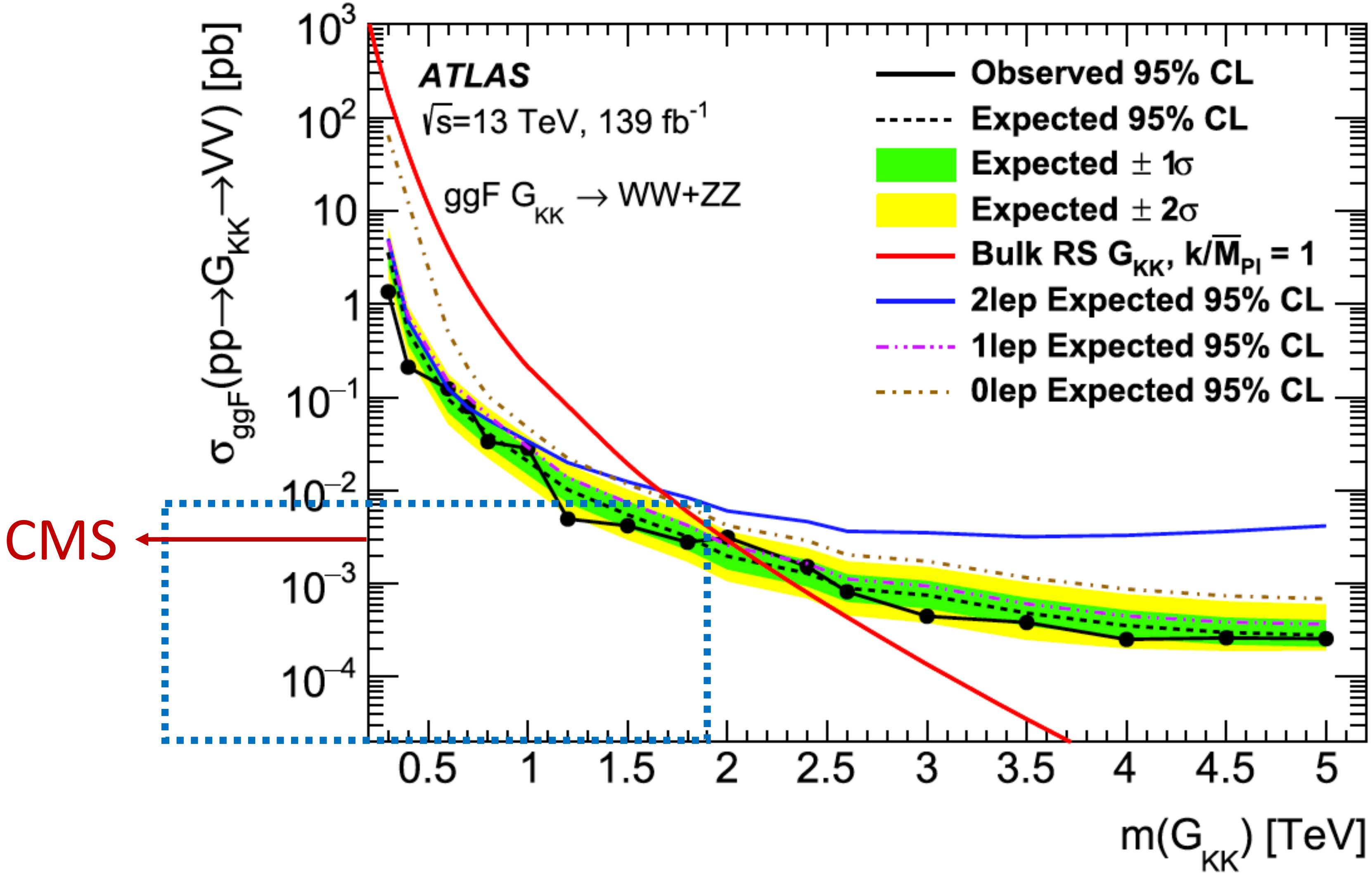


- SR: Z+jets standard (dots), Z+jets - 2σ (blue), Z+jets $+2\sigma$ (red).





Expected Limits: Bulk Graviton



Expected Limits: Bulk Graviton