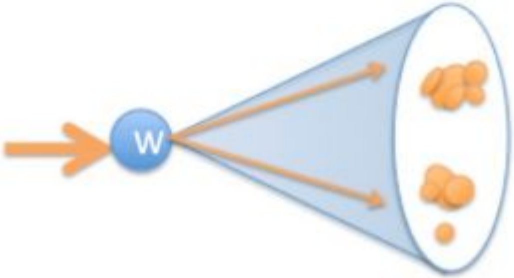
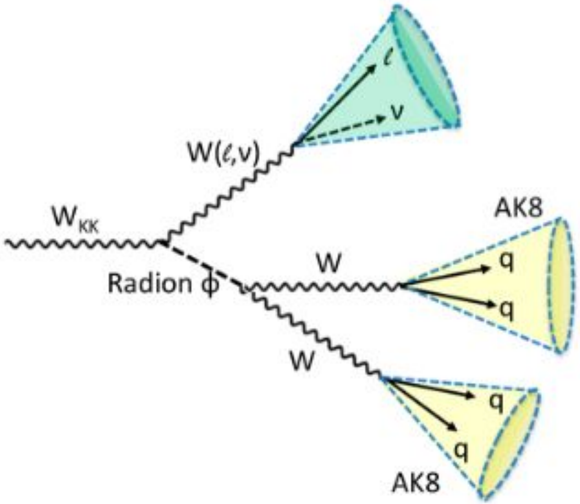
Boosted Multi-bosons

May 19th, 2019





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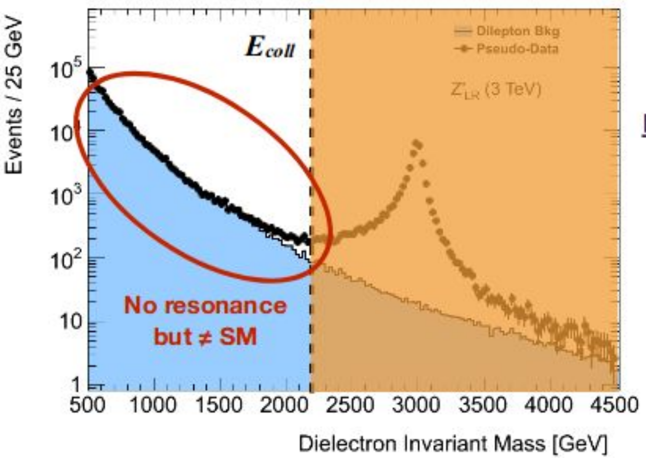
Shu Li, TDLI/SJTU
Yusheng Wu, USTC

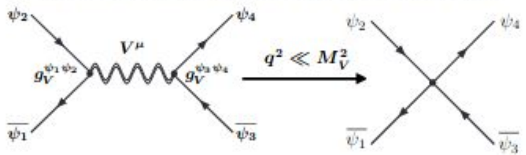
23rd Mini-workshop on the frontier of LHC

Direct and Indirect searches



If $E_{coll} < M_{Z'}$ one can still test *virtual effects* of NP looking for "deformations" in SM measurements

For $E_{coll} \ll M_{Z'}$ these low-energy effects can be well described by effective interactions



In general, the whole set of such possible deformations can be studied with minimal reference to the nature of the UV theory

Details in previous discussion led by Shu Li

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{Z'} + \mathcal{L}_{{\rm SM}-Z'} \xrightarrow{q^2 \ll M_V^2} \mathcal{L}_{\rm Eff}$$

Multi-boson: **Dim-6 aTGC, Dim-8 aQGC, EWDim6, Warsaw Basis (SMEFT)**
Di-boson, tri-boson resonances; VBS, VBF

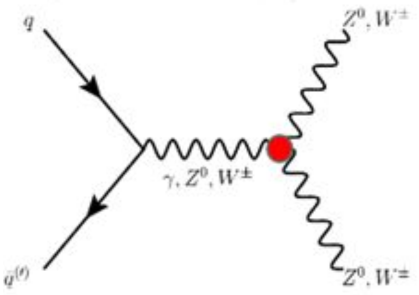
$$\mathcal{O}_{WWW} = Tr[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}]$$
$$\mathcal{O}_W = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_B = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)$$

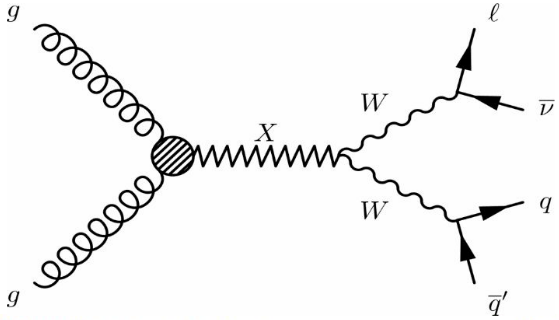
Dim 6 | Dim 8

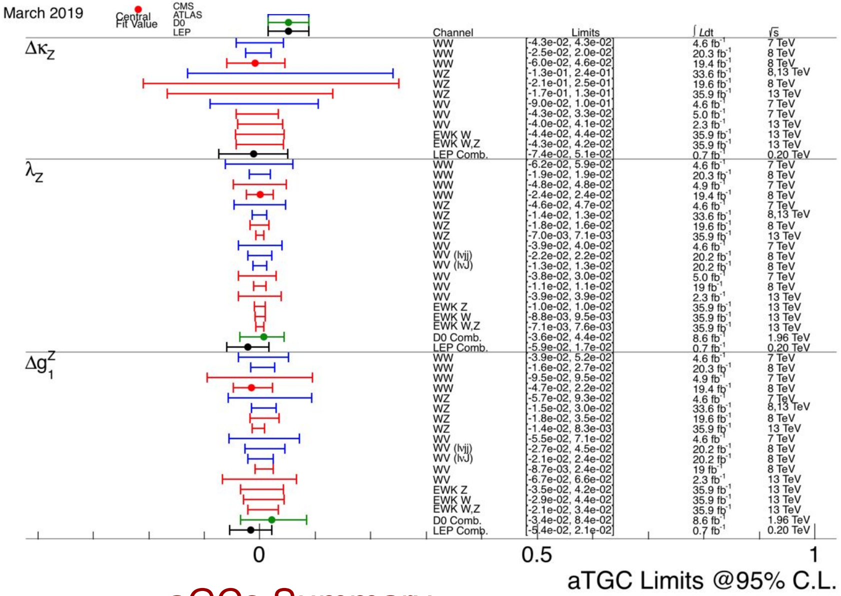
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{i=WWW,W,B,\Phi W,\Phi B} \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_{j=1,2} \frac{f_{S,j}}{\Lambda^4}\mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4}\mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4}\mathcal{O}_{M,j}$$

Pure Higgs field | Pure Field-strength tensor | Mixed Higgs-field-strength

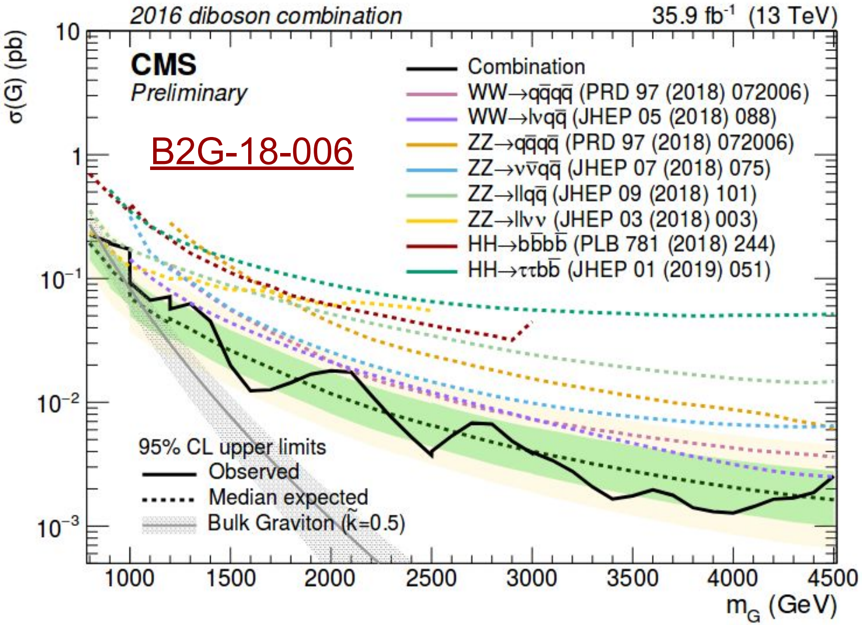
aGCs vs VV searches







aGCs Summary



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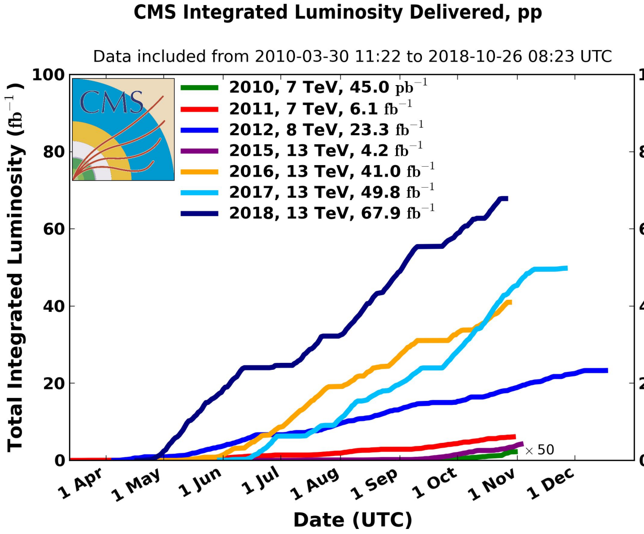
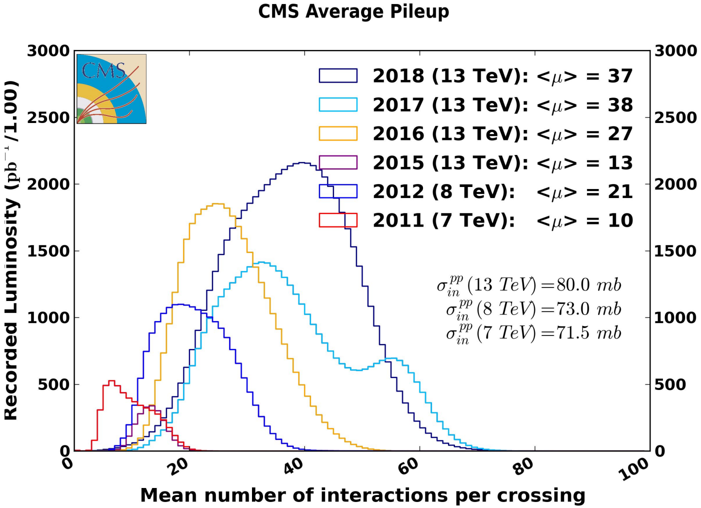
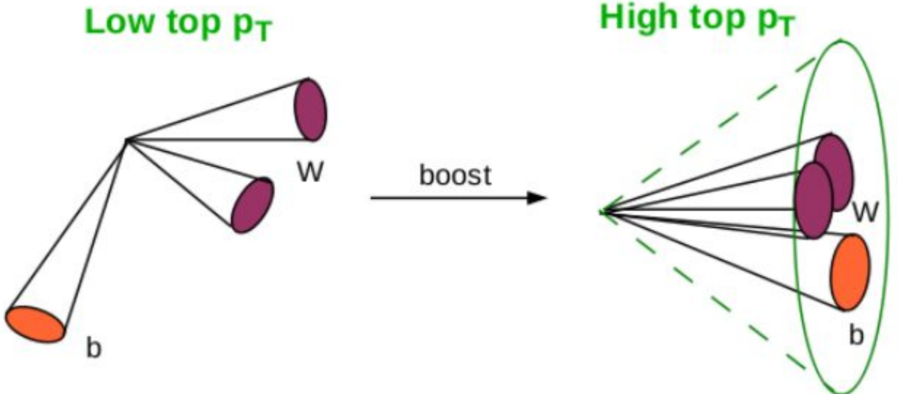
Citius, Altius, Fortius





$$\Delta R_{ij} \sim \frac{m}{p_T} \frac{1}{\sqrt{z(1-z)}} \sim \frac{2m}{p_T}$$

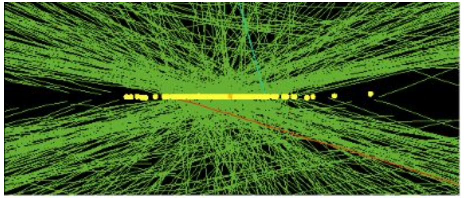


Novel Reco.
or
Deeper Digging

see e.g. 1302.0260

Pileup Mitigation

PUPPI (PileUp Per Particle Id): based on PF paradigma general framework that determines, per particle, weight for how likely a particle is from PU

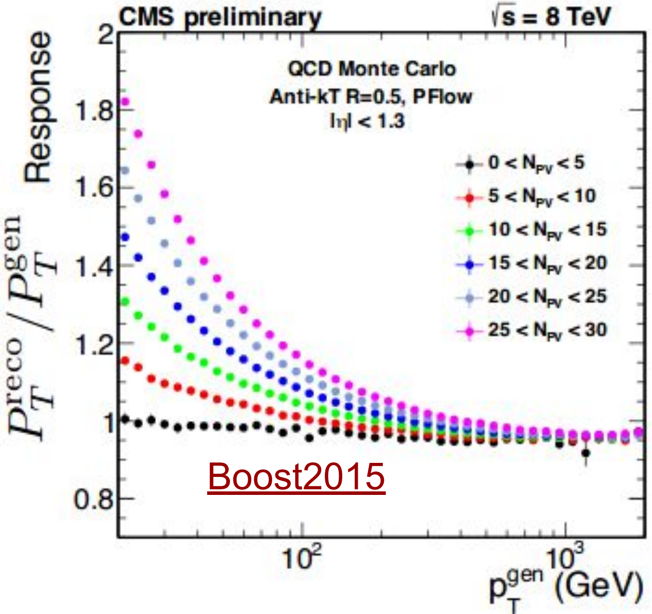


$$\alpha_i = \log \sum_{\substack{j \in Ch,PV \\ j \neq i}} \left(\frac{p_{T,j}}{\Delta R_{ij}}\right)^2 \Theta(R_0 - \Delta R_{ij})$$

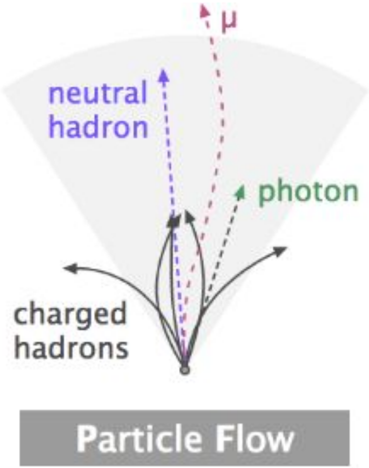
evaluated for each particle i, looking at all the charged particle j from PV within R0

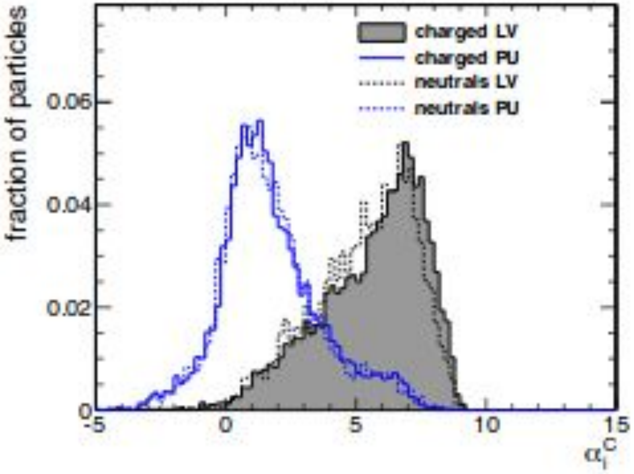
$$\alpha_i = \log \sum_{j \neq i} \frac{p_{T,j}}{\Delta R_{ij}} \Theta(R_0 - \Delta R_{ij})$$

Forward region use all pf-Inputs since no tracking vertex constraint



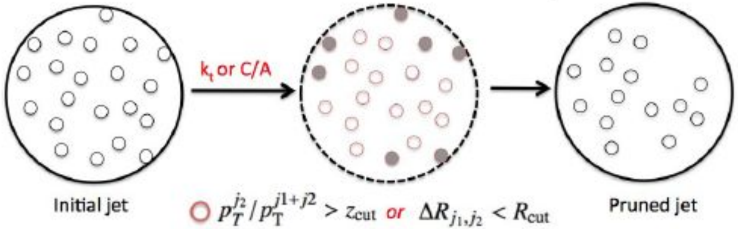
Boost2015





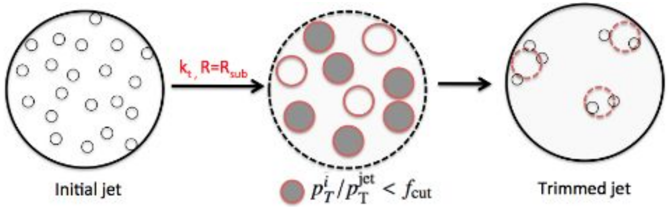
Boosted Technique: grooming

- **"Pruning"** http://arxiv.org/abs/0912.0033 (S. Ellis, C. Vermilion, J. Walsh)
  - Recombine jet constituents with C/A or kt while vetoing wide angle (R_{cut}) and softer (z_{cut}) constituents. Does not recreate subjets but prunes at each point in jet reconstruction

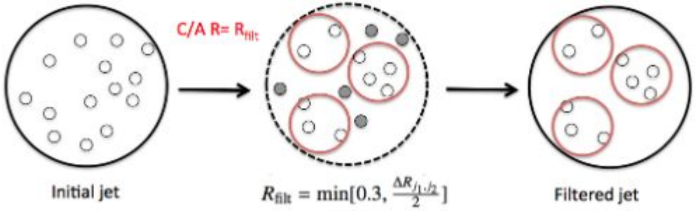


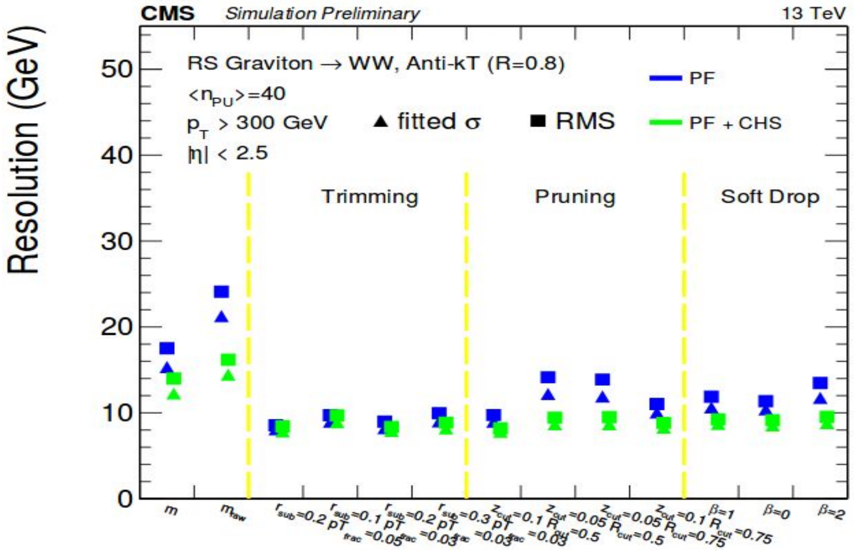
Tuned parameters: R_{cut} and z_{cut}

- Trimming



- Filtering





Boosted Technique: softdrop

– Undo last stage of C/A clustering, label subjets j1,j2

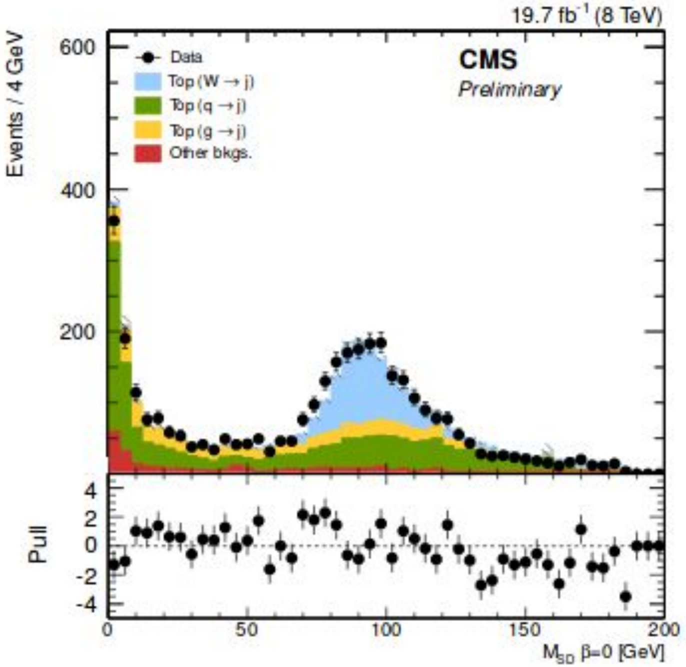
– If :

$$\frac{min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

then j is soft dropped
else redefine j to be the harder, and iterate

– Recovers (modified) mass drop BDRS tagger for beta=0

- This case always removes soft radiation entirely (hence the name)

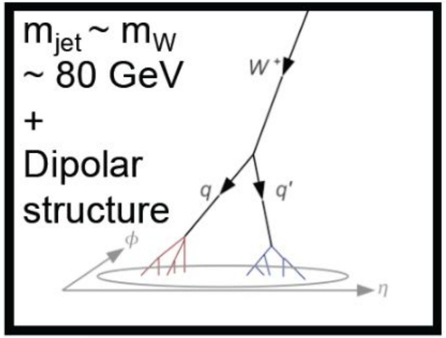


CMS: R0=0.8; beta=0; zcut=0.1

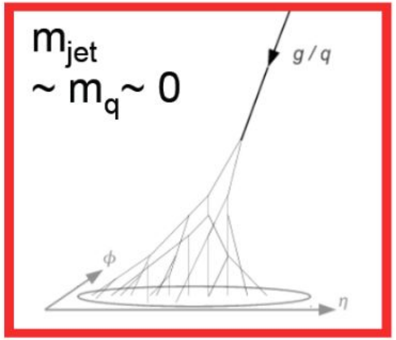
CMS PAS-JME-14-002

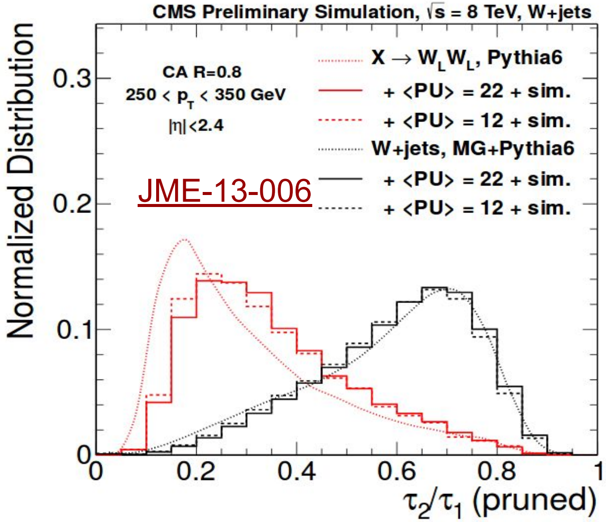
Boosted Technique: tagging

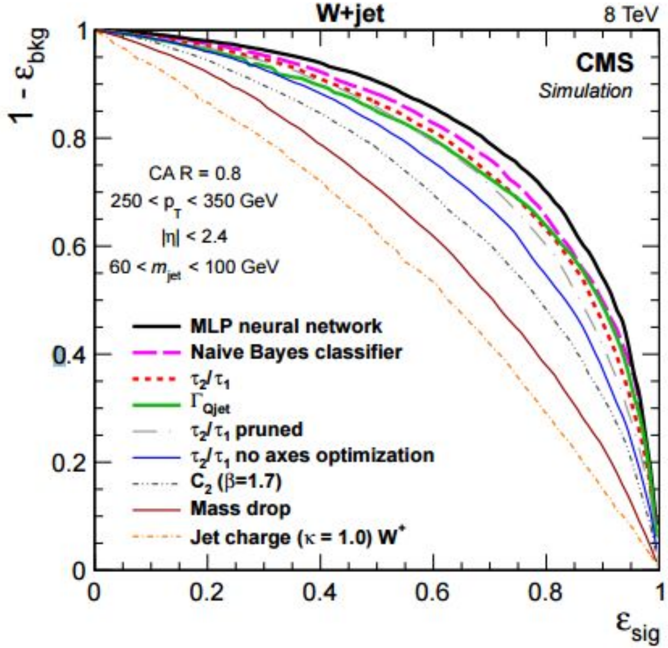
SIGNAL



BACKGROUND







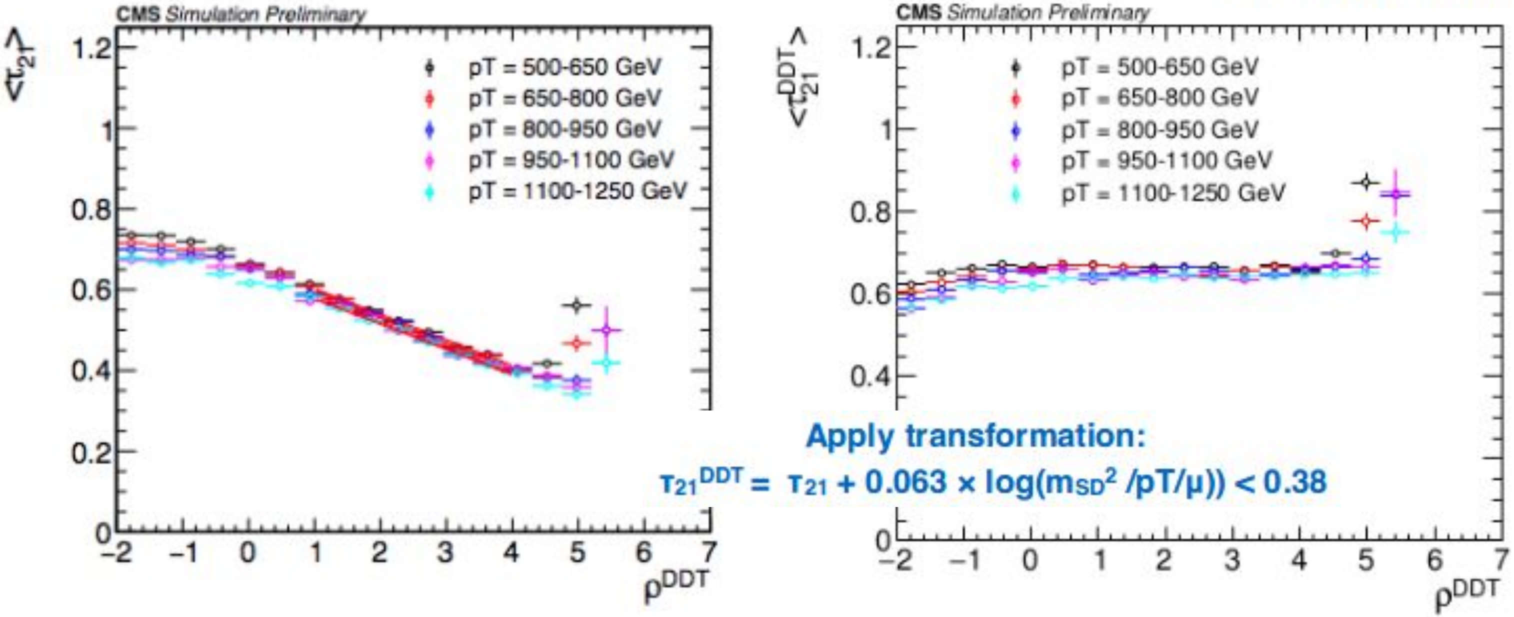
N-subjettiness: How likely is a Jet to have "N" subjets

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min\left\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\right\}$$

Boosted Technique: mass decorrelation

- Explore τ_2/τ_1 kinematic dependence
- Use QCD scaling variable $\rho^{DDT} = \log(m_{SD}^2/pT/\mu)$ to get rid of kinematic correlation:

CMS-EXO-16-030



Apply transformation:

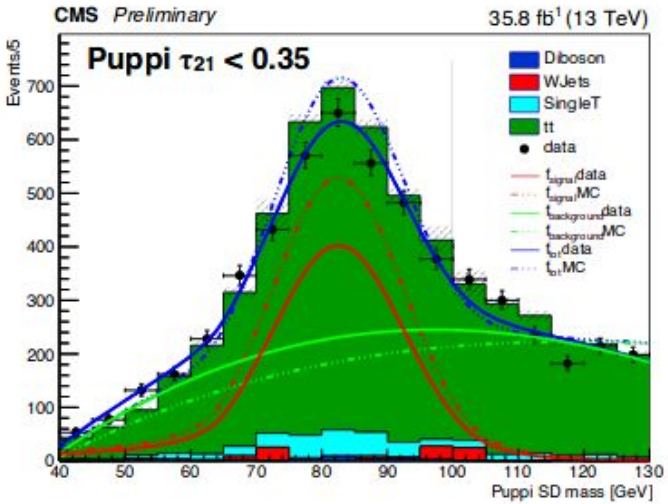
$$\tau_{21}^{DDT} = \tau_{21} + 0.063 \times \log(m_{SD}^2/pT/\mu)) < 0.38$$

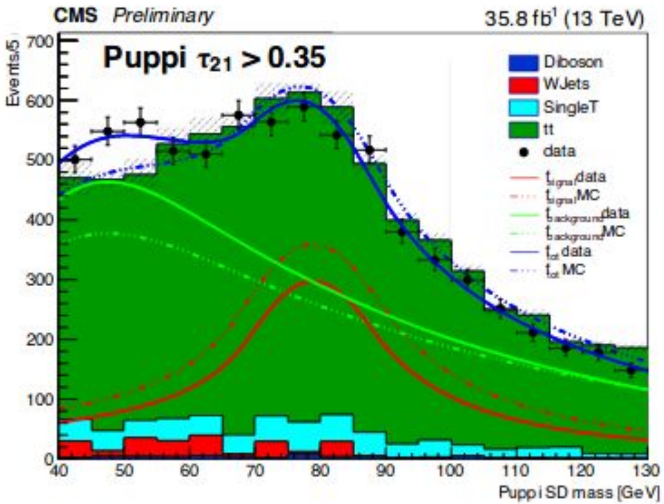
Designing De-correlated Taggers (DDT)

Boosted Technique: Calibration

Extract scale factor, mass scale, and resolution from fit in TTbar Control Region

Fit distributions (Puppi 0.35)

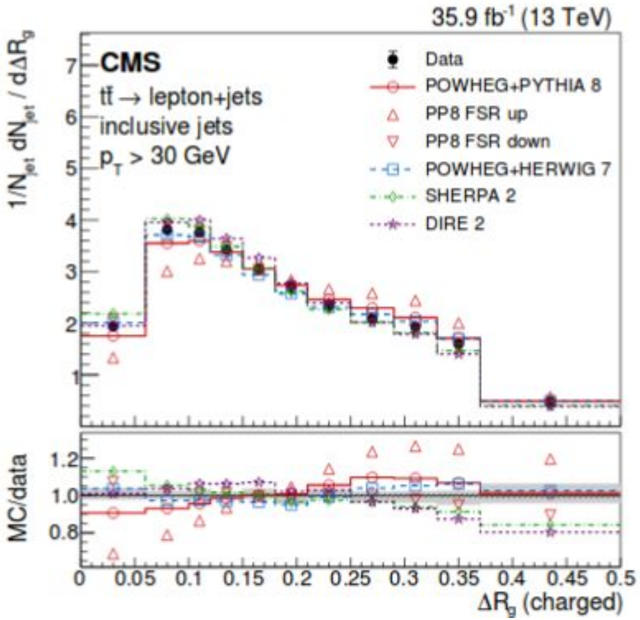




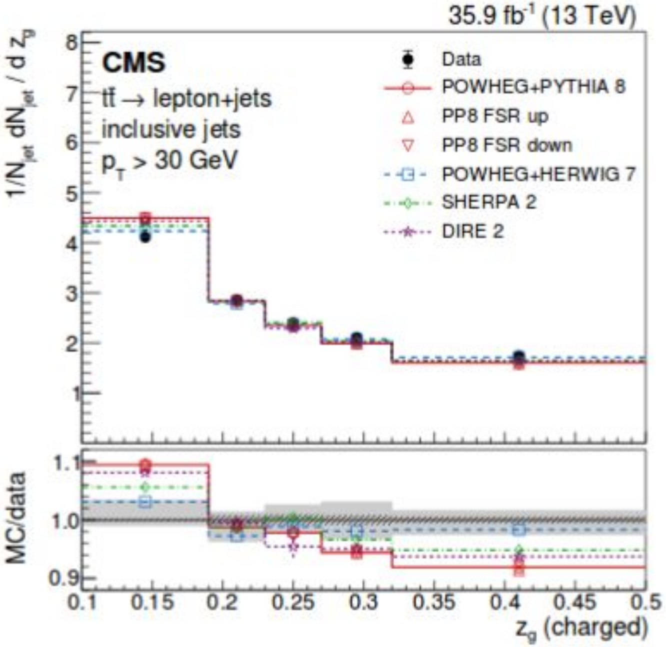
Puppi τ_{21} WP = 0.35	
ε	0.99 ± 0.05 (stat) ± 0.03 (syst) ± 0.04 (syst)
μ	0.999 ± 0.009 (stat) ± 0.03 (syst) ± 0.02 (syst)
σ	1.06 ± 0.03 (stat) ± 0.09 (syst) ± 0.08 (syst)

Boosted Technique: Validation

jet substructure observables in $t\bar{t}$ events

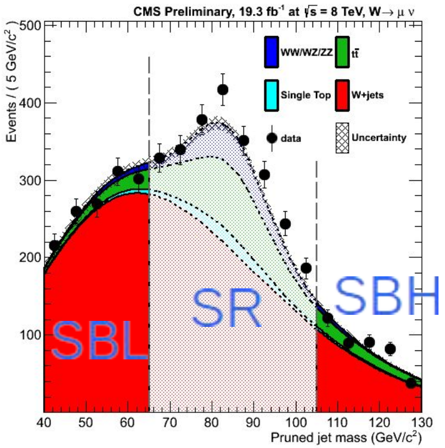


angle between the groomed subjets, unfolded to particle level



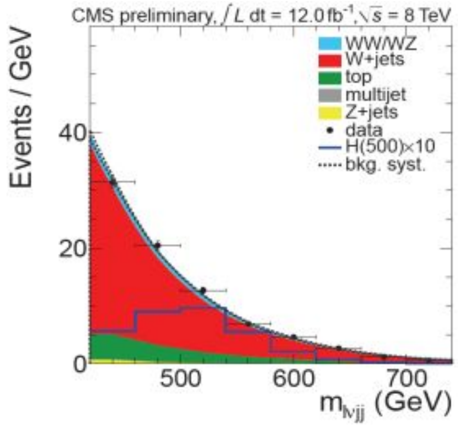
groomed momentum fraction PT_{j2}/PT_{j0}

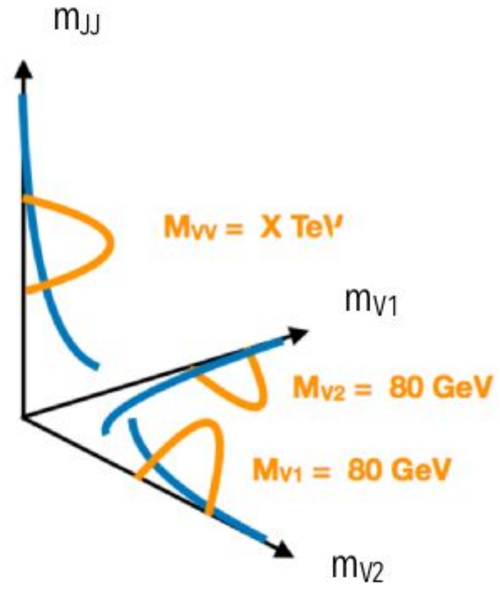
Background Estimations: alpha and 2/3D



$$\alpha_{\mathrm{MC}}(m_{l\nu j}) = \frac{F_{\mathrm{MC,SR}}(m_{l\nu j})}{F_{\mathrm{MC,SB}}(m_{l\nu j})}$$

$$F_{\mathrm{data,SR}}(m_{l\nu j}) = \alpha_{\mathrm{MC}}(m_{l\nu j}) \times F_{\mathrm{data,SB}}(m_{l\nu j})$$





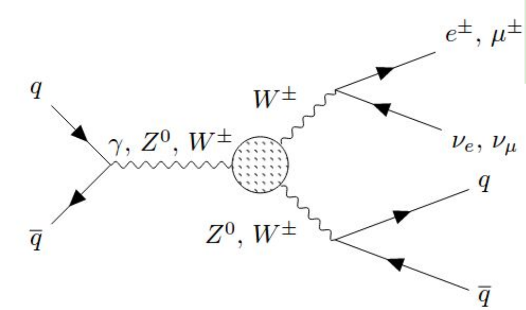
- Each event contributing to a 1D/2D gaussian kernel defined by detector scale and res.

Forward folding kernel approach to ensure smooth QCD templates

- 3D templates derived from MC
- Particle-level evts smeared using detector resolution
- same procedure for resonant bkg. (W/Z)

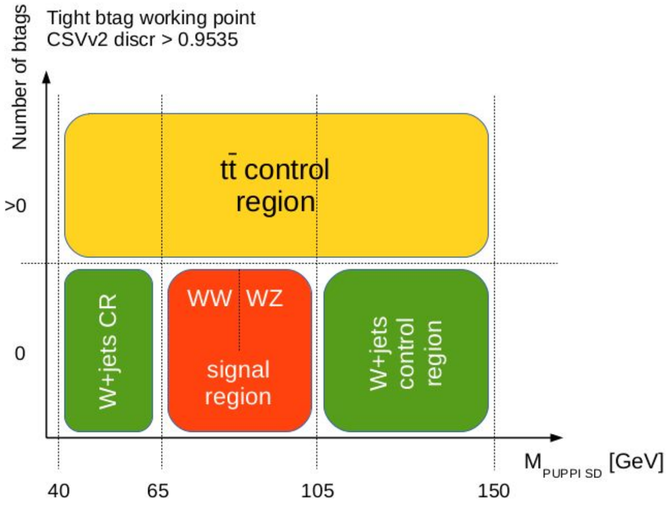
$$P(m_{jj}, m_{jet1}, m_{jet2}) = P_{VV}(m_{jj}) \times P_{cond,1}(m_{jet1}|m_{jj}) \times P_{cond,2}(m_{jet2}|m_{jj})$$

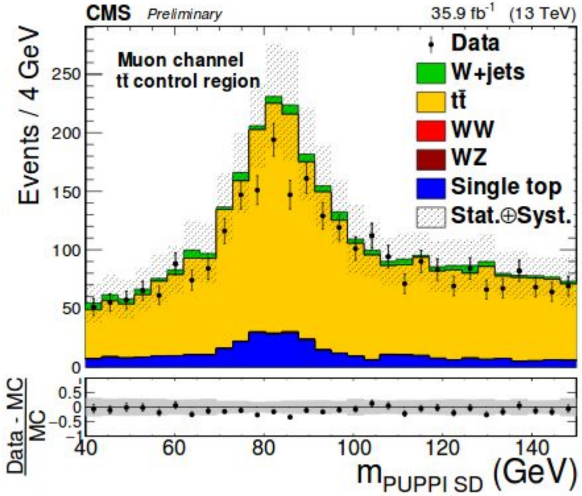
WV@13TeV: aTGC



Hadronic W/Z candidate: leading AK8 jet with p T > 200 GeV
Invariant mass of the diboson system (M WZ) > 900 GeV
Puppi Softdrop mass: 65-105 GeV and N-subjettiness < 0.6

- WW sensitive region: [65,85]GeV
- WZ sensitive region: [85,105]GeV
- Sideband: [40, 65] ∪ [105, 150]GeV

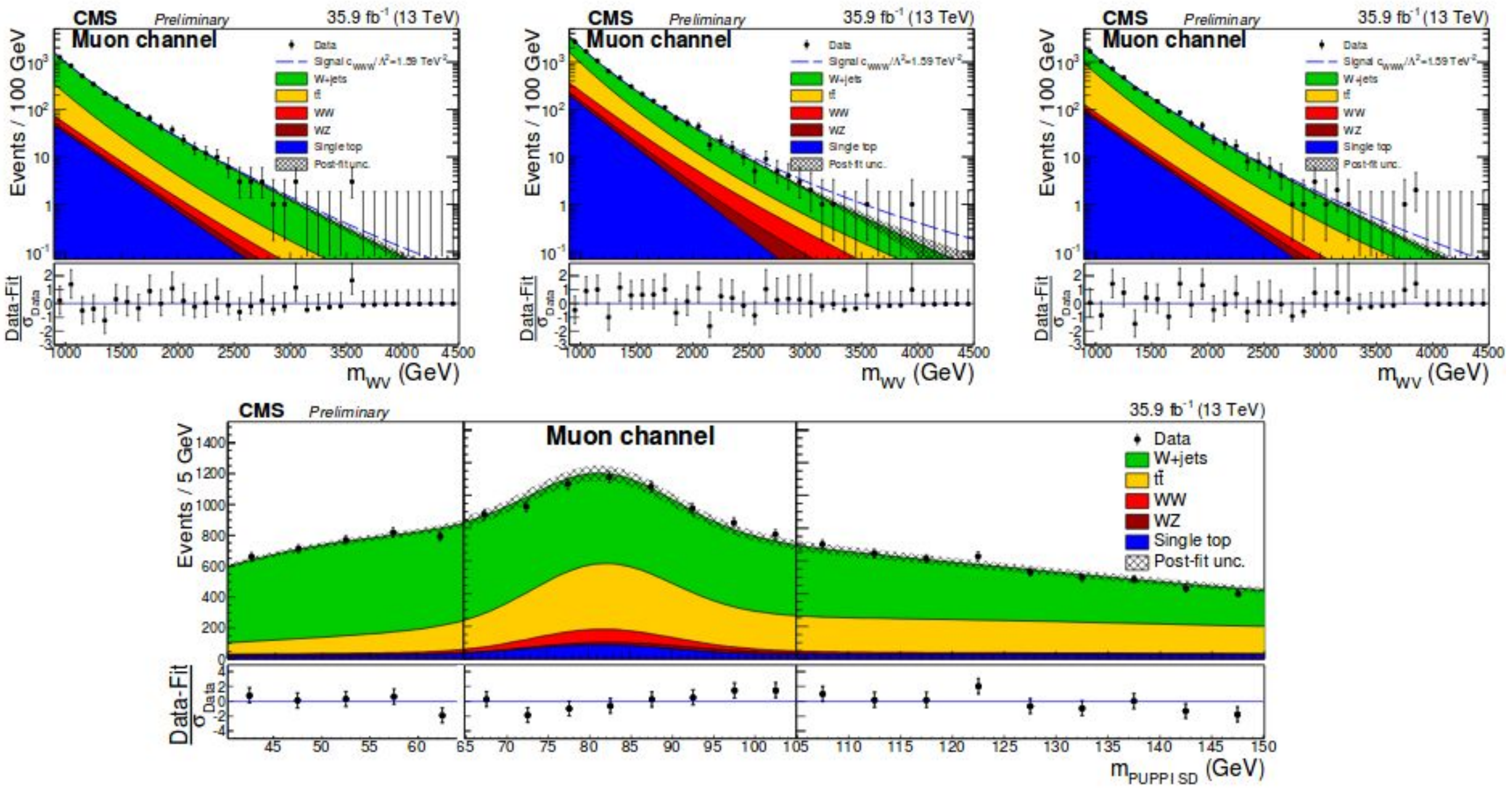




$$F^{\rm SR}_{\rm bkg}(m_{\rm WV}) = F^{\rm SB,\,data}_{\rm W+jets}\,\alpha^{\rm MC}(m_{\rm WV}) + F^{\rm SR,\,MC}_{\rm t\bar{t}} + F^{\rm SR,\,MC}_{\rm Single\ top} + F^{\rm SR,\,MC}_{\rm Diboson}$$

$$= F^{\rm SB,\,data}_{\rm W+jets}\frac{F^{\rm SR,\,MC}_{\rm W+jets}}{F^{\rm SB,\,MC}_{\rm W+jets}} + F^{\rm SR,\,MC}_{\rm t\bar{t}} + F^{\rm SR,\,MC}_{\rm Single\ top} + F^{\rm SR,\,MC}_{\rm Diboson},$$

WV@13TeV: aTGC



Post-fit mWV (upper) and PUPPI SD (lower) mass distributions.
The lower sideband, signal, and upper sideband regions are shown on the left, middle, and right.

WV@13TeV: aTGC

The signal modelling function consists of terms corresponding to different contributions:

$$F_{WV} = N_{SM}(e^{a_0 x} + e^{a_{corr} x})$$ SM contribution

$$+ \sum_i (N_{c_i,1}.c_i^2.e^{a_{i,1}x}.\frac{1+Erf((x-a_{0,i})/a_{w,i})}{2}$$ pure aTGC term

$$+ N_{c_i,2}.c_i.e^{a_{i,2}x})$$ SM-aTGC interference

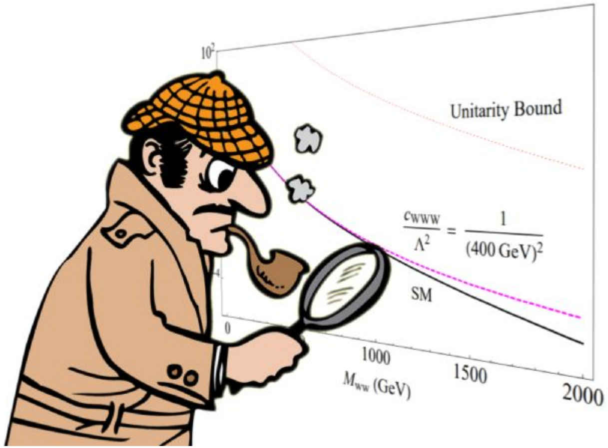
$$+ \sum_{i \neq j}^{i<j} (N_{c_i,c_j}.c_i.c_j.e^{a_{ij}x})$$ aTGC-aTGC interference

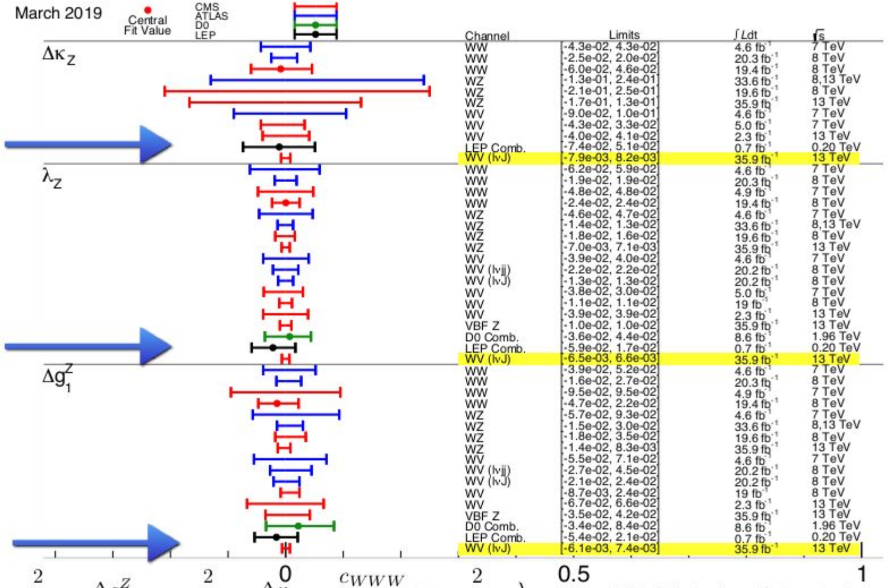
W+jets normalization floating freely in the fit.
Dominant unc from V-tagging, PDF/Scales

	Electron channel			Muon channel		
	Pre-fit	Post-fit	Scale factor	Pre-fit	Post-fit	Scale-factor
W+jets	2421	3036 ± 123	1.25 ± 0.05	4319	4667 ± 182	1.08 ± 0.04
$t\bar{t}$	1491 ± 324	1127 ± 119	0.76 ± 0.08	2632 ± 570	1978 ± 202	0.75 ± 0.08
Single top quark	271 ± 39	242 ± 26	0.89 ± 0.10	509 ± 69	449 ± 43	0.88 ± 0.08
Diboson	314 ± 314	267 ± 102	0.85 ± 0.32	552 ± 552	465 ± 162	0.84 ± 0.29
Total expected	4497	4672 ± 201	1.04 ± 0.04	8012	7559 ± 319	0.94 ± 0.04
Data		4691			7568	

WV@13TeV: aTGC

Parametrization	aTGC	Expected limit	Observed limit	Run I limit
EFT	c_{WWW}/Λ^2 (TeV^{-2})	[-1.44, 1.47]	[-1.58, 1.59]	[-2.7, 2.7]
	c_W/Λ^2 (TeV^{-2})	[-2.45, 2.08]	[-2.00, 2.65]	[-2.0, 5.7]
	c_B/Λ^2 (TeV^{-2})	[-8.38, 8.06]	[-8.78, 8.54]	[-14, 17]
LEP	λ_Z	[-0.0060, 0.0061]	[-0.0065, 0.0066]	[-0.011, 0.011]
	Δg_1^Z	[-0.0070, 0.0061]	[-0.0061, 0.0074]	[-0.009, 0.024]
	$\Delta\kappa_Z$	[-0.0074, 0.0078]	[-0.0079, 0.0082]	[-0.018, 0.013]



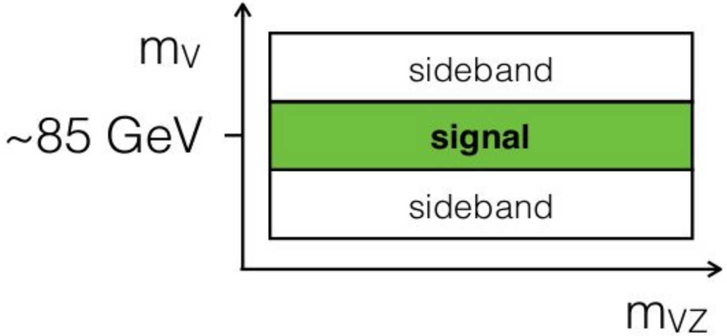


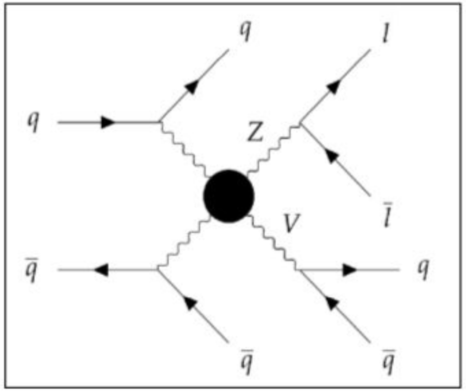
$$\frac{C_B}{\Lambda^2} = \frac{2}{\tan^2\theta_W M_Z^2}\Delta g_1^Z - \frac{2}{\sin^2\theta_W M_Z^2}\Delta\kappa_Z \qquad \frac{c_{WWW}}{\Lambda^2} = \frac{2}{3g^2 m_W^2}\lambda_Z$$

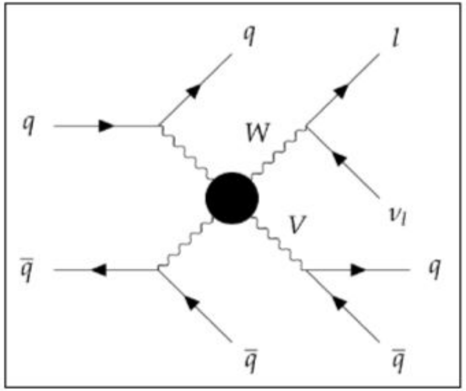
VBS WV@13TeV: aQGC

- **WV** with $W \to \ell\nu$ and $V \to J$
- **ZV** with $Z \to \ell\ell$ and $V \to J$
- **boosted V reconstruction**
- **tight VBS selections:**
  - $m_{jj} > 800$ GeV, $\Delta\eta_{jj} > 4.0$
  - centrality requirements
- very large **QCD bkg** ($\mathcal{O}(\alpha^4\alpha_S^2)$ and $\mathcal{O}(\alpha^2\alpha_S^4)$)
  - global fit of m_{VV} distribution
  - reducible bkg measured in m_V sidebands

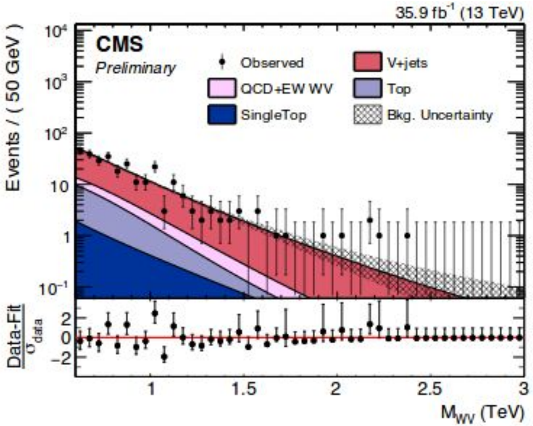
Puppi AK8 Jet
tau21<0.55,
PT>200 GeV

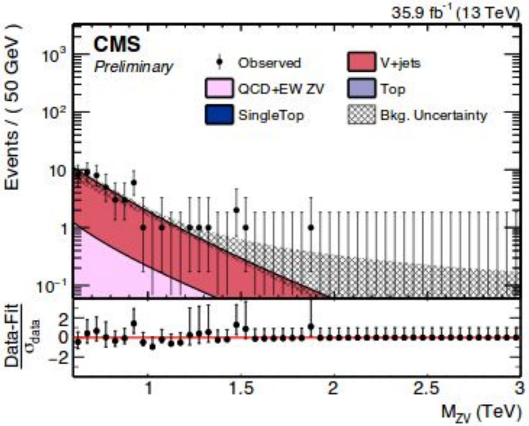






VBS WV@13TeV: aQGC

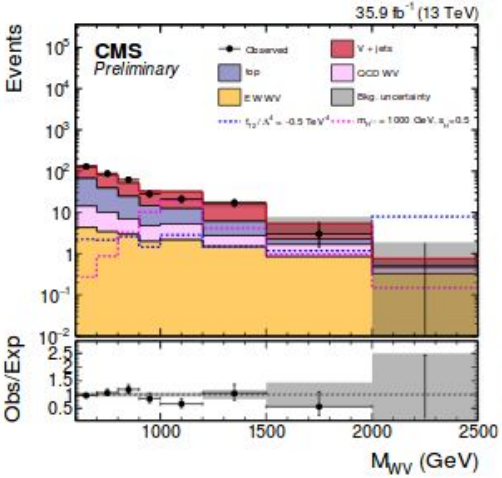


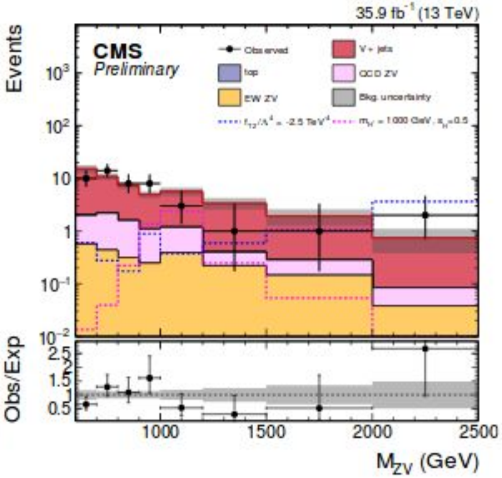


Sideband Region

40GeV<mv<65GeV

105GeV<mv<150GeV

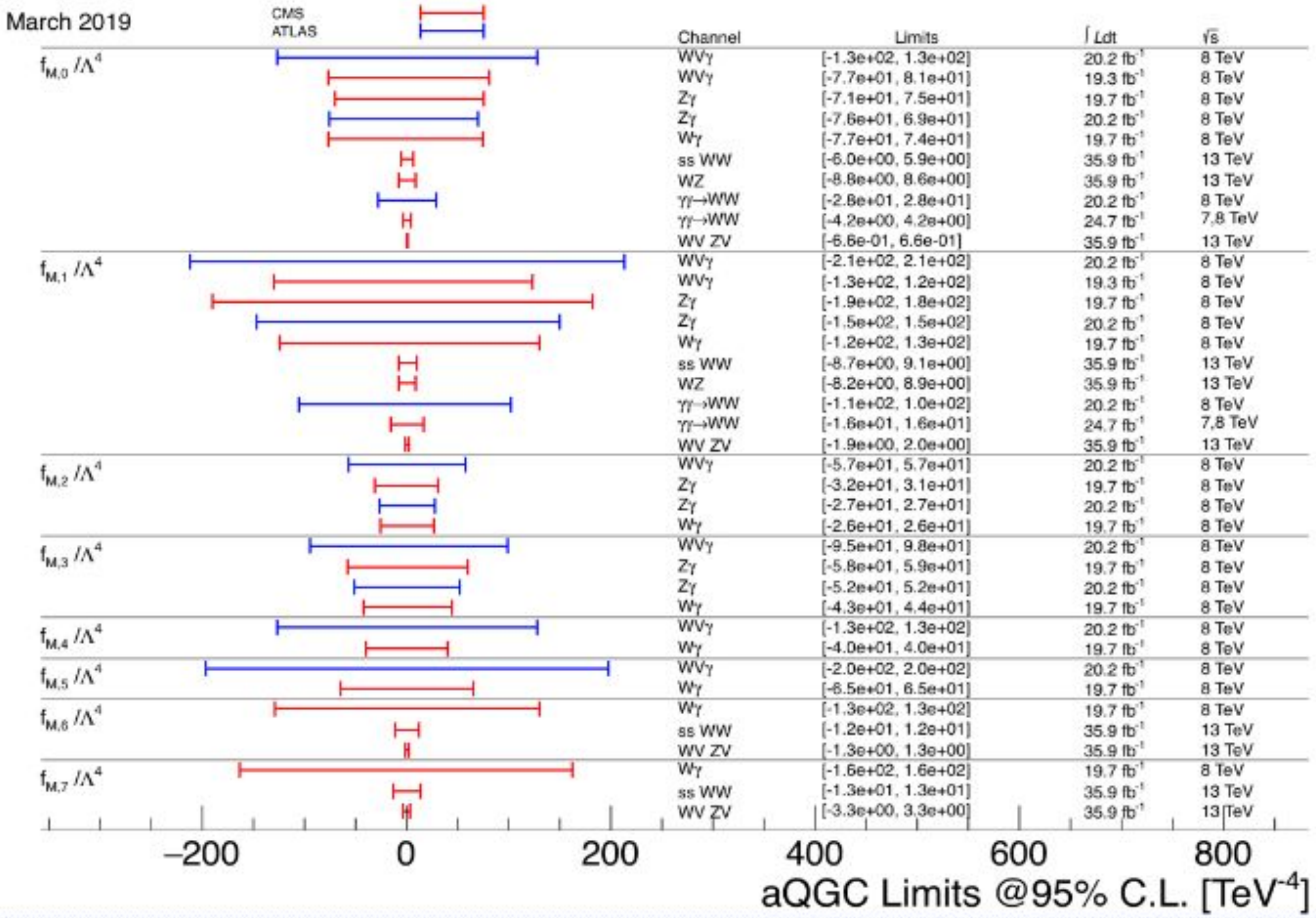




Signal Region

Final state	WV	ZV
Data	347	47
V+jets	187 ± 21	41.2 ± 6.1
top	120 ± 18	0.16 ± 0.04
SM QCD VV	28 ± 10	6.4 ± 2.2
SM EW VV	17 ± 2	2.4 ± 0.4
Total bkg.	352 ± 21	50.1 ± 5.9
$f_{T2}/\Lambda^4 = -0.5, -2.5$ TeV^{-4}	22 ± 1	7.6 ± 0.6
$m_{H_5} = 500$ GeV, $s_H = 0.5$	40 ± 1	4.3 ± 0.1

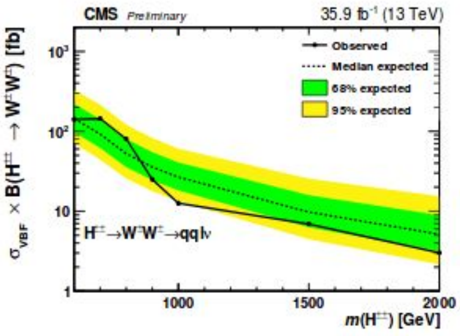
VBS WV@13TeV: aQGC



Most Stringent limits.

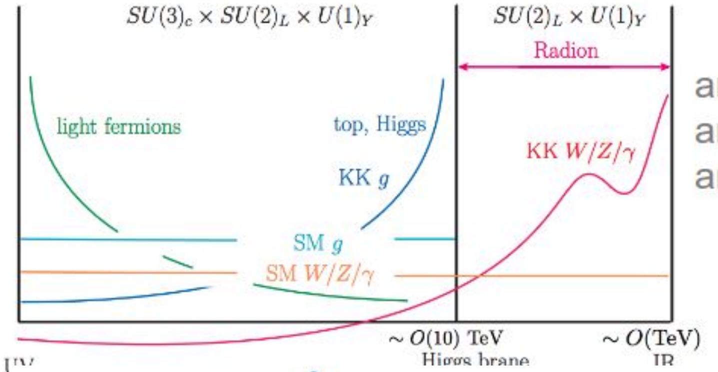
More can be found from [the twiki]

Limits also set on (d-)charged Higgs



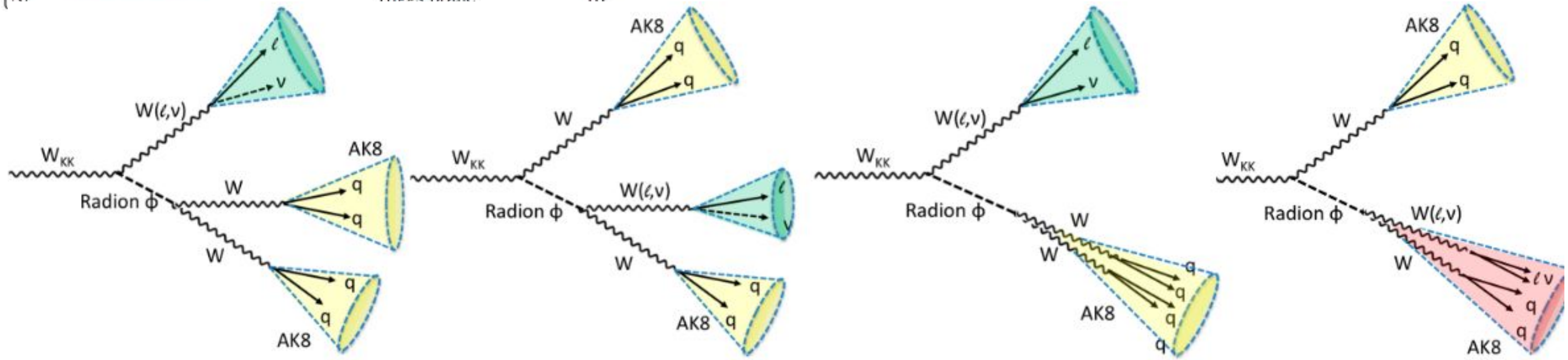
WWW: SM and BSM

Recent updates on SM measurement from both ATLAS (3.3sigma, 79.8fb-1) and CMS (0.6sigma, 35.9fb-1)
Direct search for WWW resonance on going, inspired by the model



arXiv:1608.00526
arXiv:1612.00047
arXiv:1711.09920

Ongoing works.
To appear soon!

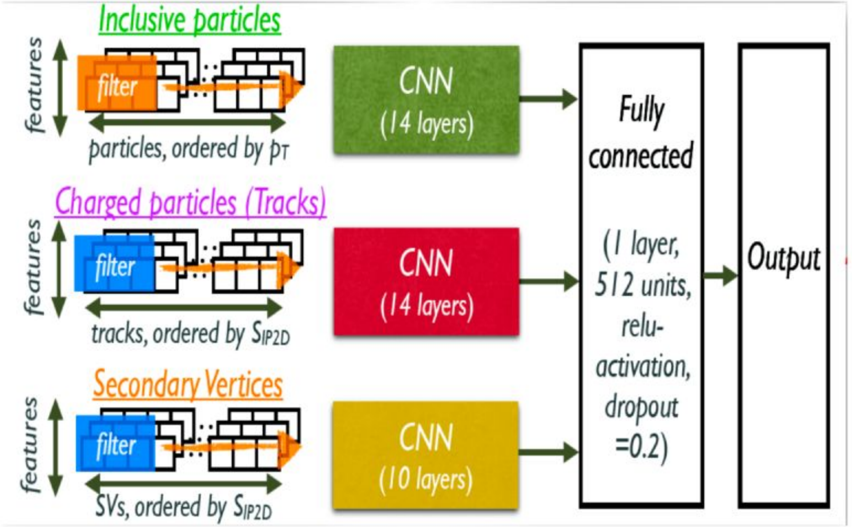


Future: Deep AK8

DeepAK8

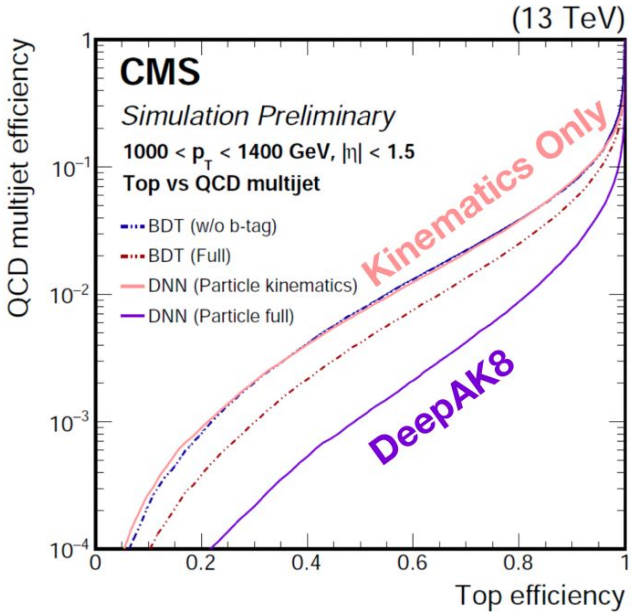
CMS-DP-2017-049
10.1007/JHEP10(2017)005

- Deep AK8 takes advantage of this additional information
  - Includes particle and detector-level quantities (tracking, vertex formation)
  - Individual jet constituents as inputs
- Uses convolutional NNs to take advantage of nearby correlations

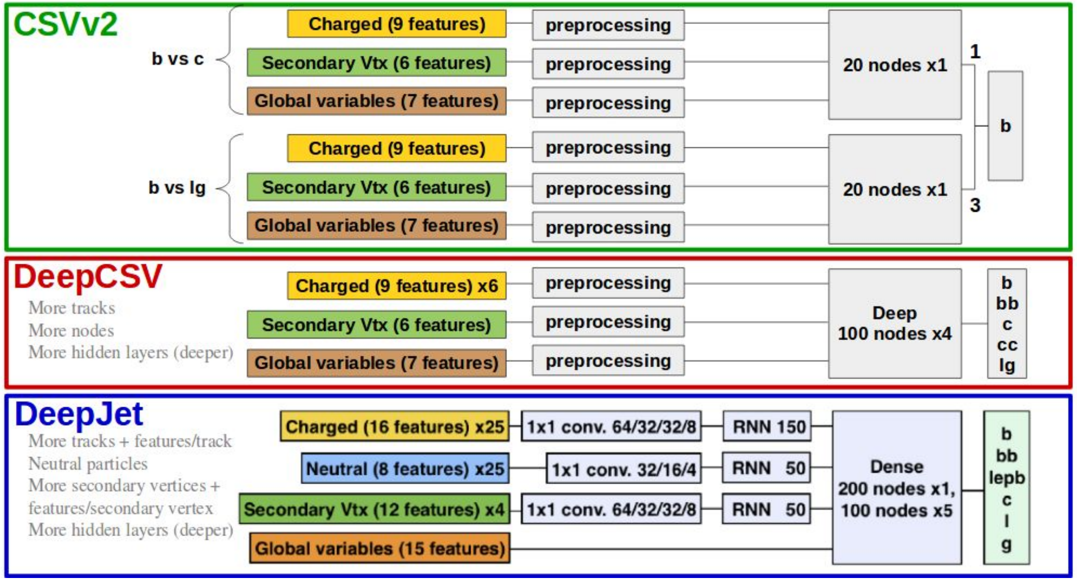


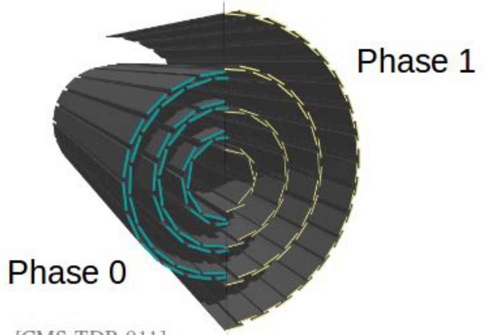
Many output categories!

Category	Label
Higgs	H (bb)
	H (cc)
	H (VV*→qqqq)
Top	top (bcq)
	top (bqq)
	top (bc)
	top (bq)
W	W (cq)
	W (qq)
Z	Z (bb)
	Z (cc)
	Z (qq)
QCD	QCD (bb)
	QCD (cc)
	QCD (b)
	QCD (c)
	QCD (others)

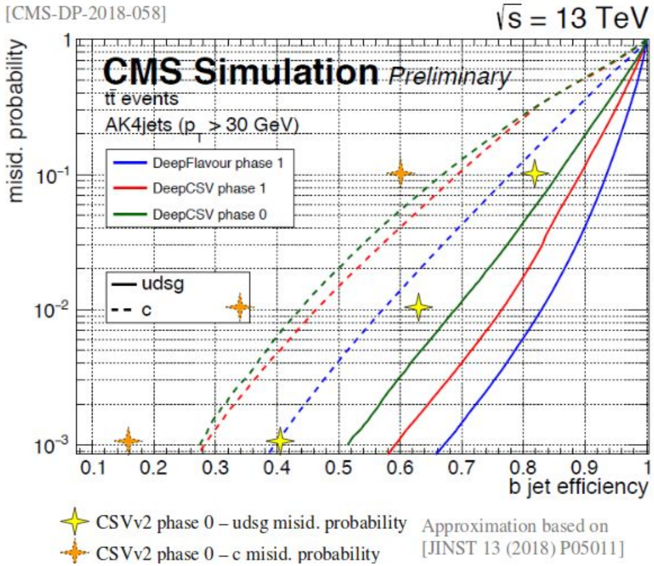


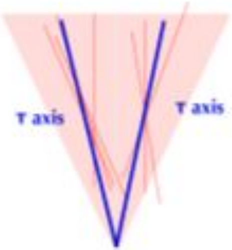
Future: Deep Flavor





[CMS-TDR-011]

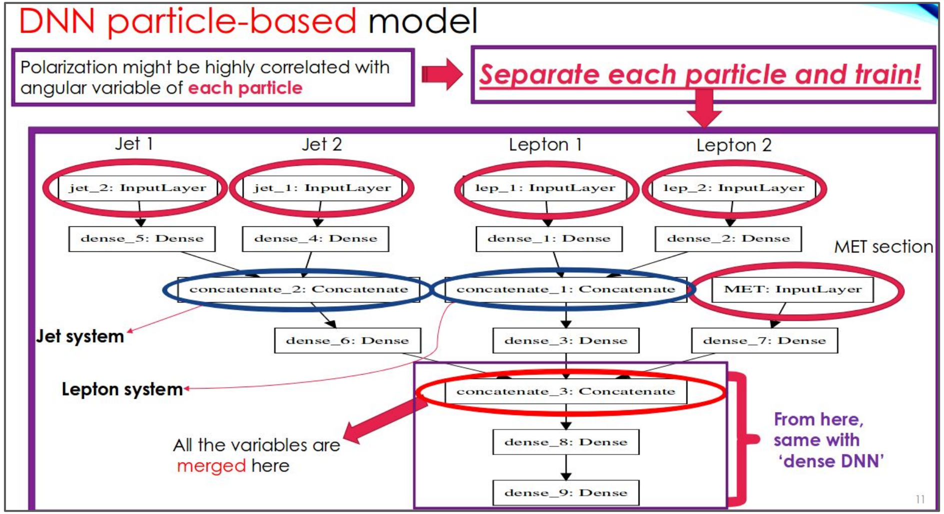


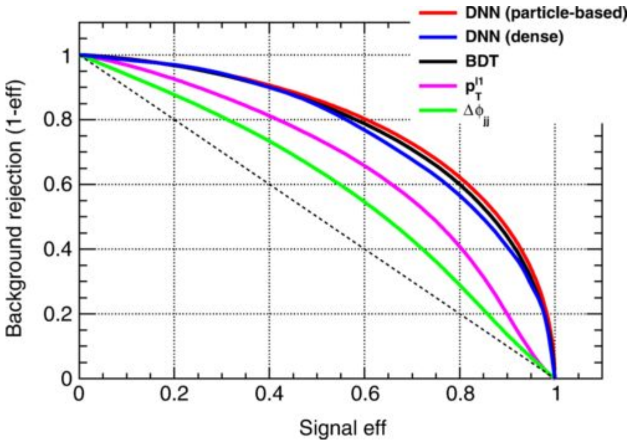


Decidated DNN tagger for boosted H/Z→bb and H/Z→cc

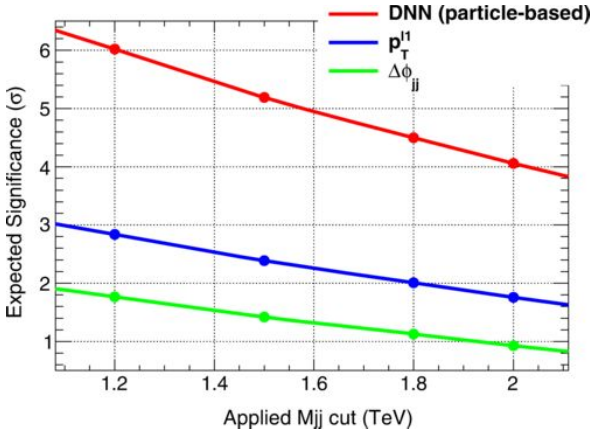
Future: Deep Learning on $W_L W_L$ scattering

More details can be found from talk by Junho Lee (PKU)





4-5 sigma possible at HL-LHC, CMS only

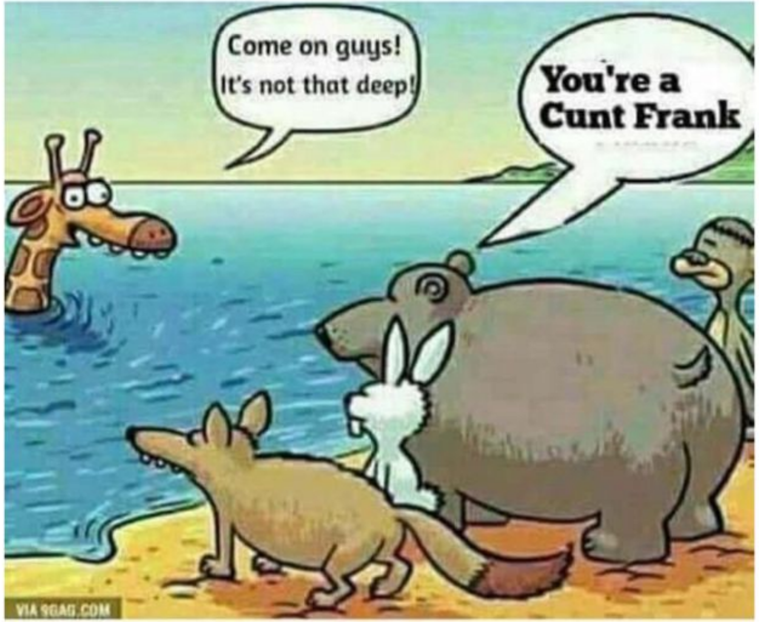


WW scattering: Phys. Rev. D 99, 033004 (2019)

ZZ scattering and aQGC: to appear soon

Summary

Over the last year(s) many developments happened:
deep → deeper → deepest



Petra Van Mulders

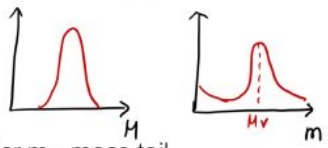
Indirect and Direct searches: rich results ahead, new idea welcome!

Backup

Background estimation

Signal peaks in both m_{WV} and m_{jet}

Signal



$$P_{sig}\left(m_{WV},m_{jet}\middle|\theta(M_X)\right) = P_{WV}(m_{WV}|\theta_1(M_X))\times P_j(m_{jet}|\theta_2(M_X))$$

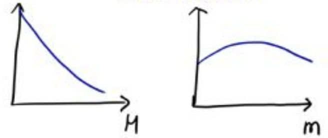
- Fit both dimensions

double crystal-ball functions, for LP additional exponential is used for m_{jet} mass tail

- Interpolate using polynomials as a function of the resonance mass hypothesis (M_X)

Non-resonant background: W+jets

Non-resonant



Conditional probability of m_{WV} as function of m_{jet}:

$$P_{W+jets}\left(m_{WV},m_{jet}\right) = P_{WV}(m_{WV}|m_{jet},\theta_1)\times P_j(m_{jet}|\theta_2)$$

- P_{WV} templates created using kernel method starting from particle level, clustering as for reconstructed jets
- Determine scale and resolution as function of true jet p_T (encode uncertainties by varying those)
- Populate templates as sums of 2D gaussian templates in bins of m_{jet}
- Smoothen mWV from 2.5 TeV as function of mWV fitting exponential from 2 TeV to avoid empty bins

Backup

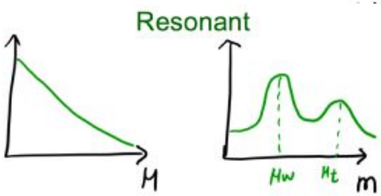
Background estimation

Resonant background: W+V

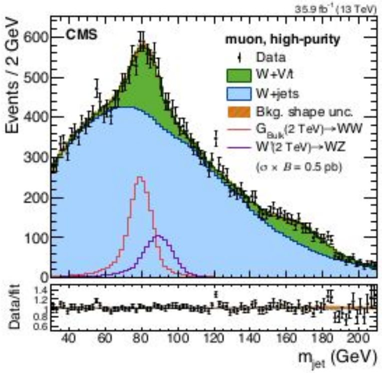
Conditional probability of m_{WV} as function of m_{jet}:

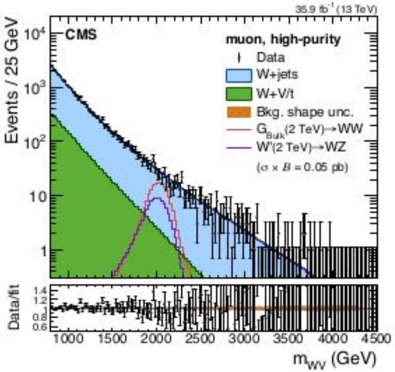
$$P_{W+V}(m_{WV}, m_{jet}|\theta) = P_{WV}(m_{WV}|\theta_1) \times P_j(m_{jet}|\theta_2(m_{WV}))$$

- P_{WV} templates created using kernel method as for W+jets (1D)
- Smoothen m_{WV} from 1.2 TeV as function of m_{WV} fitting exponential
- m_{jet} template described by W and top mass peaks



HP muon





arXiv:1802.09407

Backup

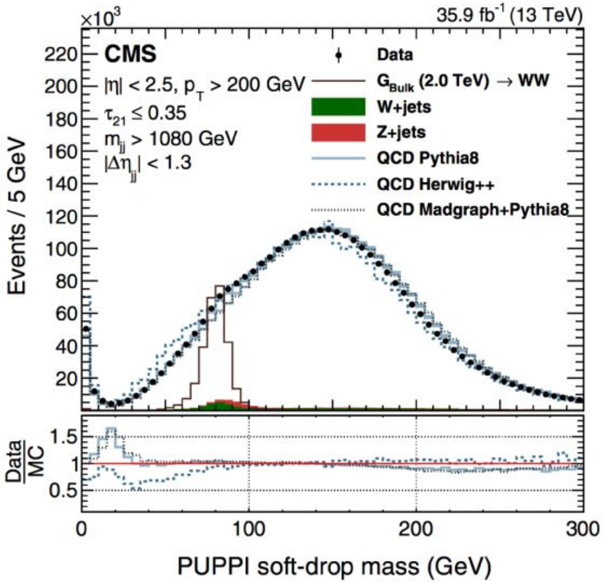
Mass Decorrelation

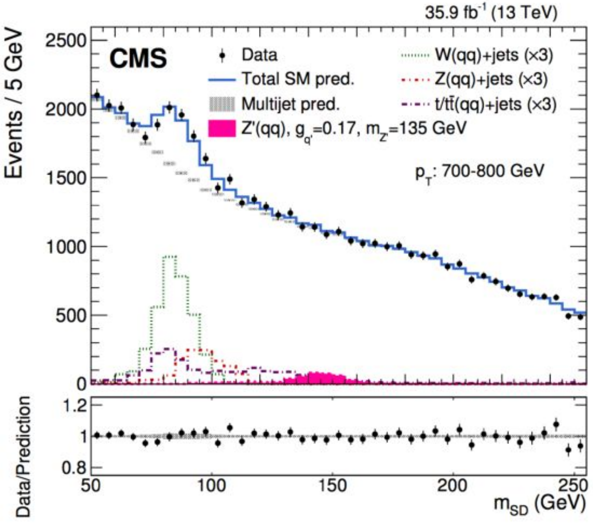
CMS-B2G-17-001
CMS-EXO-17-001

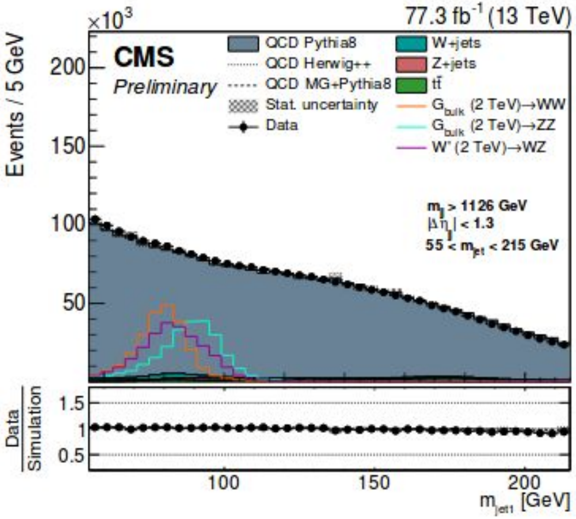
- In some cases, the new taggers have inconvenient behavior for practical use
  - Tagger outputs can sculpt background distributions
    - Do not want to look for peaks on top of peaks

B2G-18-002

- Aim to make NN outputs mass-independent through **decorrelation procedures**





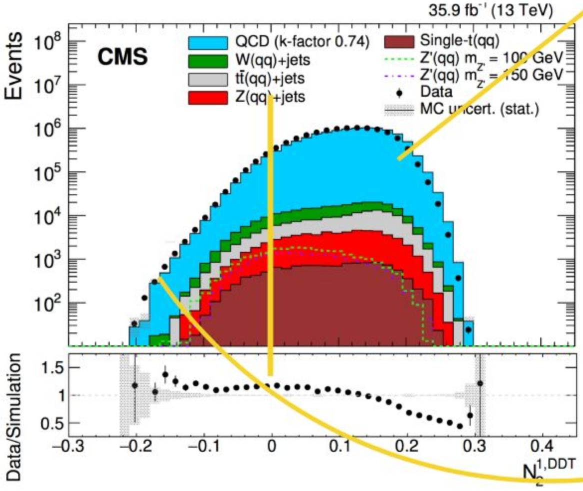


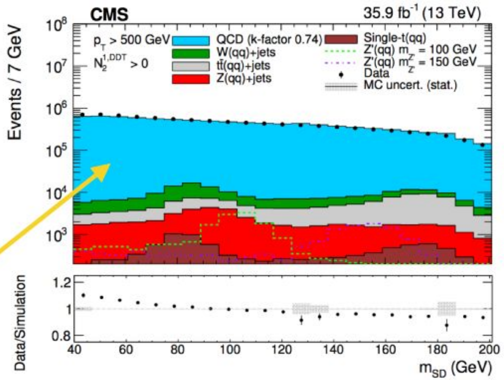
Backup

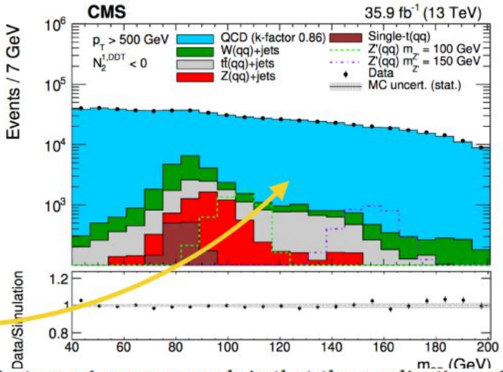
DDT Procedure

Dolen, Harris, Marzani, Rappoccio, Tran, JHEP05(2016)156

- Can apply a transformation of the variable to result in a mass-independent shape
  - Resulting mass distributions show smoothly-falling behavior







CMS-EXO-17-001
10.1007/JHEP01(2018)097

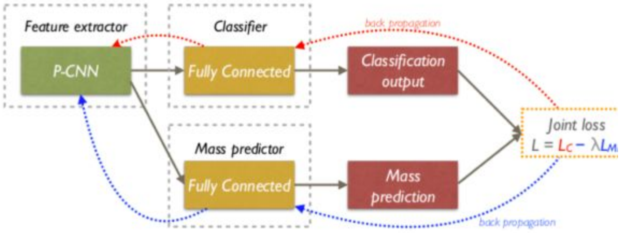
The key feature of our approach is that the application of the substructure requirement preserves the shape of the soft-drop jet mass distribution. Improving on the decorrelation procedure proposed in Ref. [62], we apply a DDT (designed decorrelated tagger) transformation of N_2^1 to $N_2^{1,\mathrm{DDT}}$. It is defined as $N_2^{1,\mathrm{DDT}}(\rho, p_\mathrm{T}) \equiv N_2^1(\rho, p_\mathrm{T}) - X_{(5\%)}(\rho, p_\mathrm{T})$, where $X_{(5\%)}$ is derived from the simulated N_2^1 distribution and illustrated in Fig. 2. We require events to pass

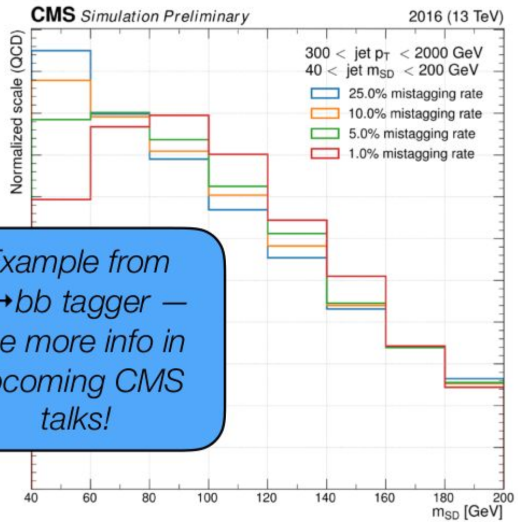
Backup

Adversarial Training

CMS-DP-2018-046

- Version of DeepAK8 applies an adversarial network to penalize the machine for accurately predicting the jet mass
  - Slight loss in performance





Example from H→bb tagger — see more info in upcoming CMS talks!