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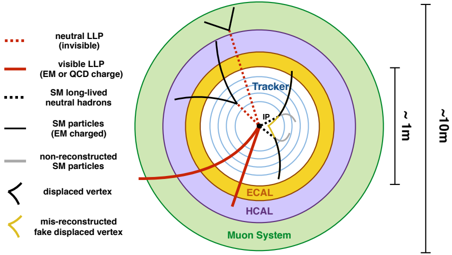
Search for long lived particles decaying in b-quarks in CMS calorimeters

$H \to \pi_v \pi_v \to b\bar{b}b\bar{b}$



D-CMS Workshop, 11–13 September 2019

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Motivation and experimental signatures

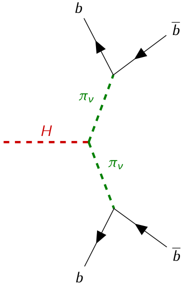
Csaki et al., (Searching for Displaced Higgs Decays)

Twin Higgs & long lived particles

- Solution for **hierarchy problem** of Higgs mass
- **Twin Higgs** models: dark QCD sector mixing with SM via Higgs boson
- Higgs can decay into couple of scalars π_v, which decay into SM particles (mixing with the Higgs) $\rightarrow b\bar{b}$ decays dominant ($c\bar{c}, \tau\tau$)

Long lived phenomenology

- π_v particles travel in CMS before decaying into $b\bar{b} \rightarrow$ displacement
- ➠ We consider SM VBF Higgs production (benefit from larger cross-section)
- ➠ $H \rightarrow \pi_v\pi_v \rightarrow b\bar{b}b\bar{b}$ can manifest into different experimental signatures depending on $c\tau$ and m_{π_v}:
  - very short lifetimes ($c\tau < 1$ mm) $\rightarrow$ b-quark like signature
  - decay in tracker (1 mm $< c\tau <$ 1 m) $\rightarrow$ displaced vertices
  - decay in calorimeters (1 m $< c\tau <$ 2 m) $\rightarrow$ **trackless jets**
  - decay in muon chambers (up to $c\tau \sim$ 10 m) $\rightarrow$ **no activity in inner detector (E_T^{miss})**



Samples and datasets

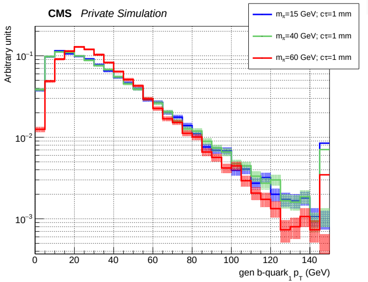
2016 menu

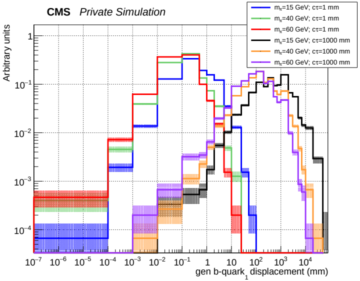
MC samples

- Private production[1] of VBF $H \to \pi\pi \to bbbb$ samples ($15 < m_\pi < 60$ GeV; $0 < c\tau < 10$ m)
  `VBFH_HToSSTobbbb_MH-125_MS-*_ctauS-*`
  `TuneCUETP8M1_13TeV-powheg-pythia8`
- Inclusive background considered (QCD, $t\bar{t}$, single-t, W+jets, DY+jets, diboson)
- 2016 `MiniAODv2 Moriond17` campaign

Data

- `DisplacedJet` dataset
- `MET` dataset
- `SingleMuon` (trigger studies)

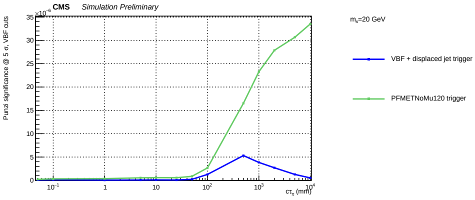




[1] We produced also gluon fusion samples; ZH/WH centrally produced

Trigger approaches

2016 menu



1. VBF + displaced jet trigger

HLT_VBF_DisplacedJet40_VTightID_Hadronic

- VBF pair jets ($|\Delta\eta_{jj}| > 3$, $m_{jj} > 400$ GeV)
- Additional displaced jet ($p_T > 40$ GeV with large hadronic deposits)

pro Using jet neutral components: good signal/background discrimination

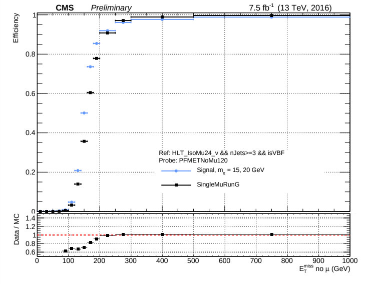
con Trigger available only in 2016 data

con Data-MC turn-on curves in strong disagreement (online-offline discrepancies)

2. E_T^{miss} trigger

HLT_PFMETNoMu120_PFMHTNoMu120_IDTight

pro Data-MC turn-on curves in agreement



pro Good signal efficiency for long lifetimes ($c_\tau \sim 1$m)

pro Trigger available in full Run2

con Events with large displacement (hence large E_T^{miss}) suffer reconstruction → few jets surviving

Physics objects

VBF jets

- AK4 CHS jets, JEC and JER applied
- $p_T > 20$ GeV, $|\eta| < 5.2$, Tight ID

DisplacedJet: $m_{jj} > 400$ GeV, $|\Delta\eta_{jj}| > 3.$ → mirroring trigger

E_T^{miss}: $m_{jj} > 250$ GeV, $|\Delta\eta_{jj}| > 2.5$ → improving signal acceptance

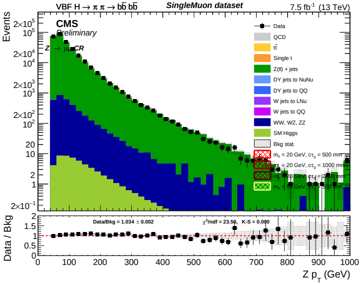
Barrel jets

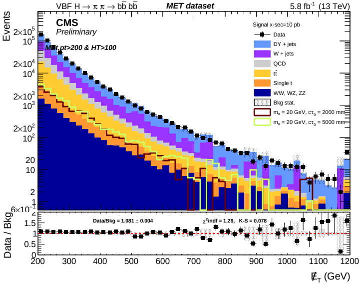
- AK4 CHS jets, JEC and JER applied
- $|\eta| < 2.4$, no ID, $p_T > 15$ GeV → next slides

E_T^{miss}, ℓ, γ

- $H_T = \sum_i p_{T,i}^{\text{jets}}$; with jets $|\eta| < 3$, $p_T > 30$ GeV, tight ID
- E_T^{miss} filters applied

E_T^{miss} veto on: veto ID e $p_T > 10$ GeV; loose ID μ $p_T > 10$ GeV; veto ID γ $p_T > 15$ GeV; loose DeltaBetalso ID τ $p_T > 18$ GeV





1. DisplacedJet trigger analysis (I)

Discriminating variables

Selections

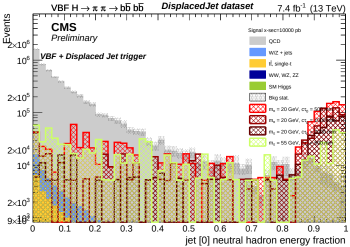
- VBF + displaced jet trigger
- VBF condition offline $m_{jj} > 400$ GeV, $|\Delta\eta_{jj}| > 3$.
- $H_T > 100$ GeV

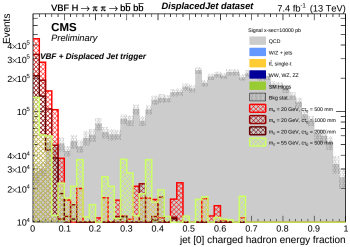
Displaced jet features

- few track PF constituents → enhancement of neutral components
- larger neutral hadron energy fraction $\frac{\sum_i^n E_i}{\text{raw } E_j}$, where n = number of neutral hadron jet constituents
- nHadEFrac: good S/B discriminating variable

!!! We are left with 0 background!

➠ MC samples can't give reliable predictions of sensitivity, alternative estimation...



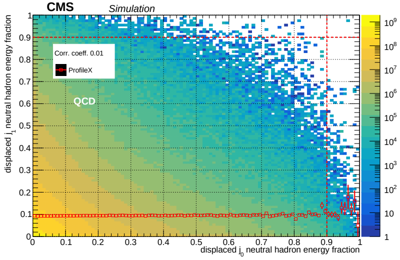


1. DisplacedJet trigger analysis (II)

Background predictions & exclusion limits

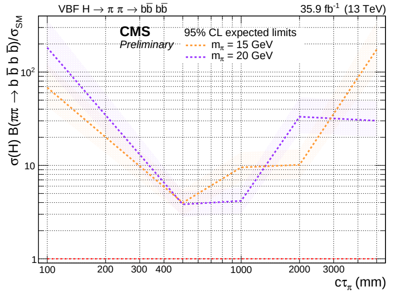
ABCD method

- Looking at nHadEFrac of j_0 and j_1
- Perfomed correlation check (not correlated)
- Closure checked on MC samples with looser requirements (DiJet trigger)
- Closure achieved within 20% uncertainty
- $n_D = n_A \times n_C / n_B$



Exclusion limit

- Exclusion limits calculated with ABCD method
- SR: nHadEFrac $j_0 > 0.9$ & $j_1 > 0.9$
- Uncertainties included: event yield and luminosity
- Best sensitivity: c_τ range 500–1000 mm



2. E_T^{miss} trigger analysis (I)

Signal reconstruction

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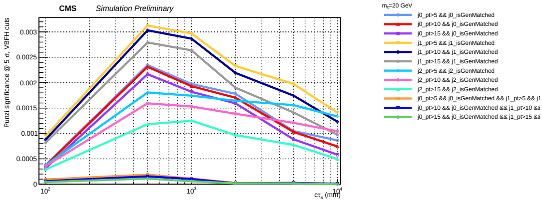
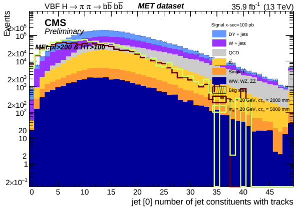
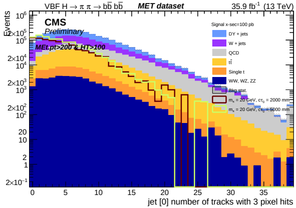
Jet reclustering at lower p_T

- With approach 1. setup, few jets survive
- By applying displacement → significance loss
- ➠ Recluster PF CHS jets with lower p_T (5 GeV; cut 10 GeV in MINIAOD)
- Signal different from background:
  - Small n. of track constituents
  - Few tracks with 3 pixel hits
- !!! JEC calculated for $p_T > 10$ GeV





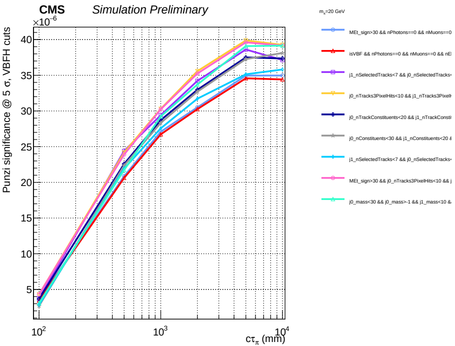


2. E_T^{miss} trigger analysis (II)

Selections & exclusion limits

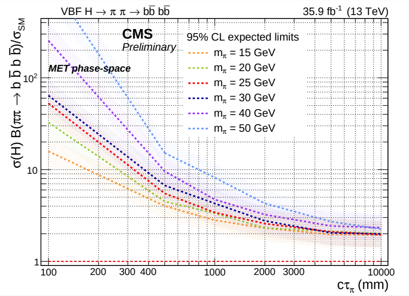
Selections

- E_T^{miss} trigger
- VBF condition offline $m_{jj} > 250$ GeV, $|\Delta\eta_{jj}| > 2.5$
- $H_T > 100$ GeV, E_T^{miss} significance > 30
- Veto μ, e, γ, τ



Exclusion limits

- Exclusion limits calculated from MC
- SR: n. tracks with 3 pixel hits $j_0 < 10$ & $j_1 < 3$
- Uncertainties included: event yield and luminosity
- Best sensitivity: $c_\tau \sim 10$ m



Outlook: machine learning

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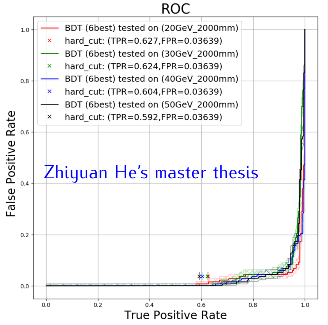
CMS

BDT approach for VBF + displaced jet

- Aim: building a displaced jet tagger for VBF + displaced jet phase-space
- Training samples: signal vs QCD
- First studies: using jet high level variables for training a boosted decision tree
- BDT outperforms a simple cut based approach



Alternative approaches for VBF + displaced jet

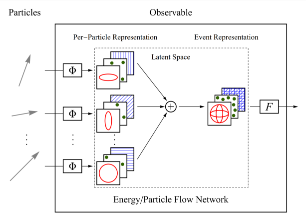
- Architectures (LoLa) using 4-momenta of jet constituents not working better

! Lack of statistics (both S and B) → overfitting

!! Large QCD weights: problematic convergence

Outlook for E_T^{miss} phase-space

- Difficult jet reconstruction → per-event classification algorithm
- Deep sets approach



Conclusions

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- A search for exotic Higgs decays into a pair of long lived particles, decaying in b-quarks, has been presented
- Focus on VBF Higgs production, but planning to extend to ggH and ZH/WH
- Calorimeter lifetimes have not been explored in CMS so far
- When $c_\tau \sim 1$ m, signal reconstruction is challenging $\rightarrow$ E_T^{miss} as a signature
- b-quark displaced jets are soft and with few charged components $\rightarrow$ discrimination power
- Improving VBF jet pair tagging is a key point
- Reclustering of PF CHS jets at lower p_T increases chances of catching signal
- First exclusion limits: $2\times$ SM cross-section
- Planning to explore machine learning tools to improve sensitivity

Thanks for your attention!

Backup slides

Additional Higgs production mechanisms (I)

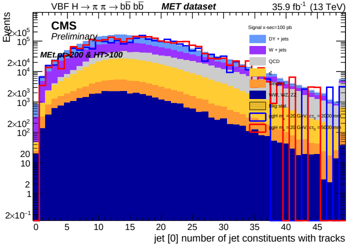
Gluon fusion

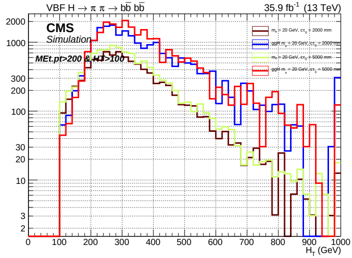
pro Benefit from larger cross-section

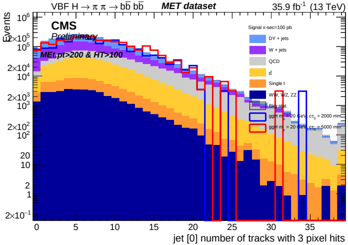
- E_T^{miss} trigger quite efficient
- Expected larger event yield w.r.t. VBF

con Signal and background look the same

- Disentangle ISR jets from signal?







Additional Higgs production mechanisms (II)

ZH, WH associated production

pro Leptons → high trigger efficiency, additional handles on Z and W

con Extremely smaller cross-section

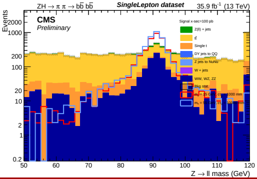
- For calo-lifetimes: E_T^{miss} requirement
- Displaced jet candidates look similar to VBF phase-space

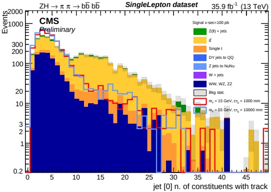
First look at $ZH \to \ell\ell H$

$Z \to \mu\mu$ `IsoMu24` trigger, 2 tight μ

$Z \to ee$ `Ele27WPTight` trigger, 2 tight e

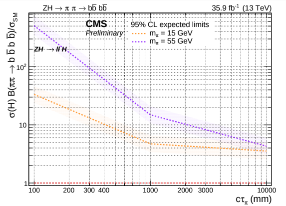
- $p_{T,Z}$ >50, 80 < m_Z < 110 GeV, E_T^{miss}significance > 30, E_T^{miss} >100





Exclusion limits

- SR: n. track constituents in jets $j_0 < 10$ & $j_1 < 10$
- Despite larger reconstruction efficiency, exclusion limits combining $Z \to (\mu\mu, ee)$: worse than VBF



VBF + DisplacedJet trigger

VBF + DisplacedJet trigger

ABCD method studies

Signal region:

- `HLT_VBF_DisplacedJet40_VTightID_Hadronic`
- $H_T > 100$ GeV
- VBF tagged AK4 PF CHS jets:
  - Loose ID, $\eta_{j_0} \cdot \eta_{j_1} < 0$; $\Delta\eta_{jj} > 3$, $m_{jj} > 400$ GeV
- Additional 2 AK4 PF CHS (displaced candidates): No ID, $p_T > 40$ GeV; $|\eta| < 2.4$
- Displaced jets should have large nHadEFrac
- j0 and j1 nHadEFrac are uncorrelated (tested in p_T and η ranges)
- Issue: we are left with 0 MC background!

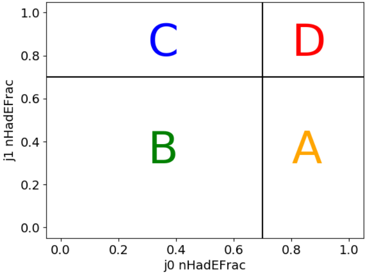


Figure: ABCD regions. D is the SR.

- We defined some control regions with larger statistics (by using different triggers) to check the ABCD closure
- In regions where we have enough stat, ABCD underestimates up to 15%: we introduce a 20% uncertainty on event yield

DiPFJetAve80 control region

1. select events with 2 jets, DiPFJetAve80 fired
2. span over different SR (considering different ranges of nHadEFrac)
3. calculate SR yield with ABCD and compare to truth (per bin!)
4. percentage discrepancy (per bin!), that is, $(n_{ABCD} - n_{true})/n_{true} \times 100$ (left plot)

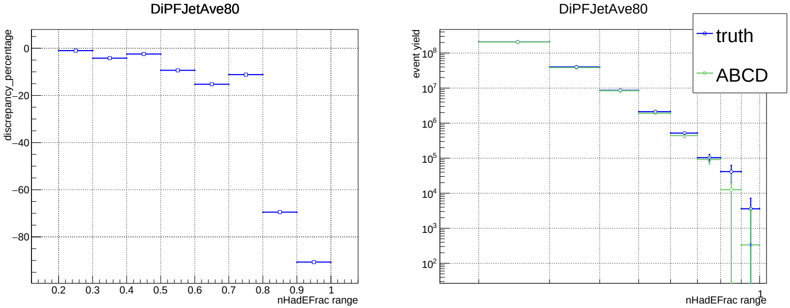
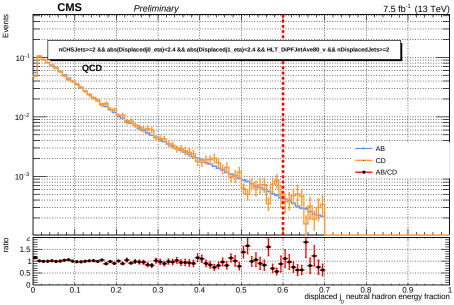
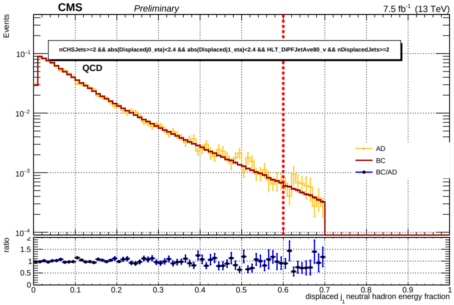


Figure: Left: ABCD discrepancy (percentage). Right: per-bin event yield (truth, ABCD).

DiPFJetAve80 control region: an example

- Trying ABCD in SR [0.6,0.7]
- Having a look at marginal distributions
- nQCD_ABCD MC: 4.41e+05 +- 3.95e+03; nQCD_D MC: 5.20e+05 +- 5.55e+04
- deviation: -7.93e+04; -15.3%
- excess of events in regions including D, in the tails → justify the 15% underestimation





L1 seed control region

1. select events with 2 jets, L1_TripleJet fired
2. span over different SR (considering different ranges of nHadEFrac)
3. calculate SR yield with ABCD and compare to truth (per bin!)
4. percentage discrepancy (per bin!), that is, $(n_{ABCD} - n_{true})/n_{true} \times 100$ (left plot)
5. starting to have low stat issues, but when stat is enough → up to 20% discrepancy

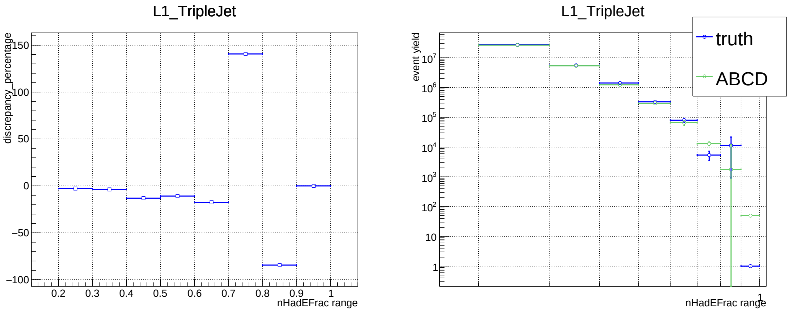


Figure: Left: ABCD discrepancy (percentage). Right: per-bin event yield (truth, ABCD).

MET trigger

VBF recipes: wrap up

- How often are VBF jet candidates gen matched to VBF/displaced gen level partons?
- How "clean" are VBF recipes? How much signal do they kill?

cut	0 VBF gen match	1 VBF gen match	2 VBF 2 gen match	0 displaced gen match	1 displaced gen match
$m_{jj} > 400, \Delta\eta_{jj} > 3.0, p_T > 20$	0.9%	4.5%	7%	12%	0.10%
$m_{jj} > 400, \Delta\eta_{jj} > 2.5, p_T > 20$	0.9%	4.5%	7%	12%	0.12%
$m_{jj} > 400, \Delta\eta_{jj} > 2.5, p_T > 30$	0.2%	2%	8%	10%	0.14%
$m_{jj} > 300, \Delta\eta_{jj} > 2.5, p_T > 20$	1.0%	5%	7%	13%	0.16%
$m_{jj} > 300, \Delta\eta_{jj} > 2.5, p_T > 30$	0.2%	2%	8.5%	11%	0.18%
$m_{jj} > 250, \Delta\eta_{jj} > 2.5, p_T > 20$	1.0%	5%	7.5%	13%	0.17%
$m_{jj} > 250, \Delta\eta_{jj} > 2.5, p_T > 30$	0.3%	2%	8.5%	11%	0.19%

- Better displaced jet rejection: VBF selections with $p_T > 20$
- Better VBF jet identification: VBF selections with $p_T > 30$
- Better signal survival (previous plot): VBF selections with $p_T > 20$
- The best on signal: $m_{jj} > 250, \Delta\eta_{jj} > 2.5, p_T > 20$, to be checked on background!