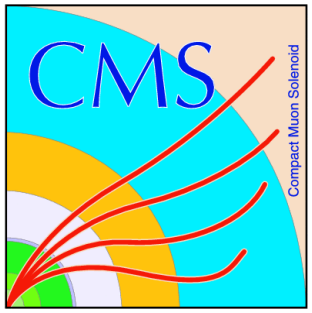
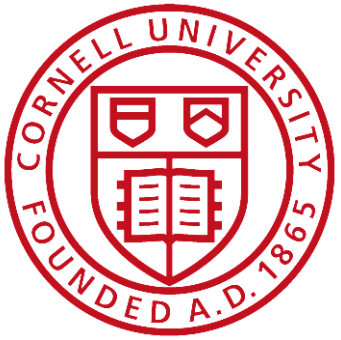


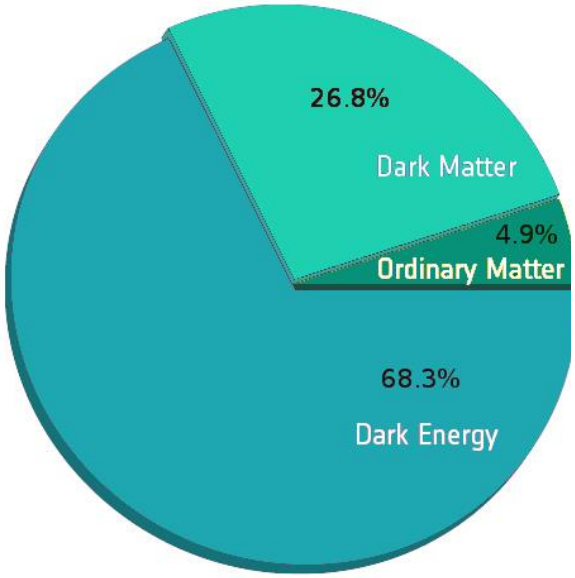


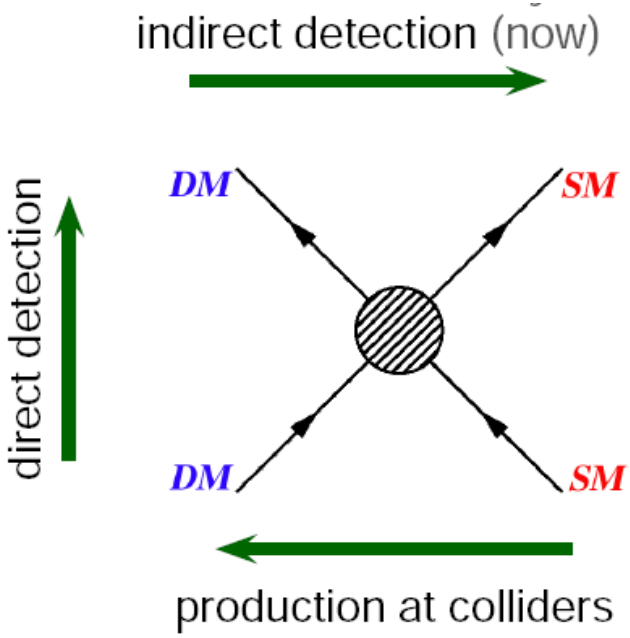
VBF-Dark Matter Search for CMS PhaseII Upgrade: Status and Plans

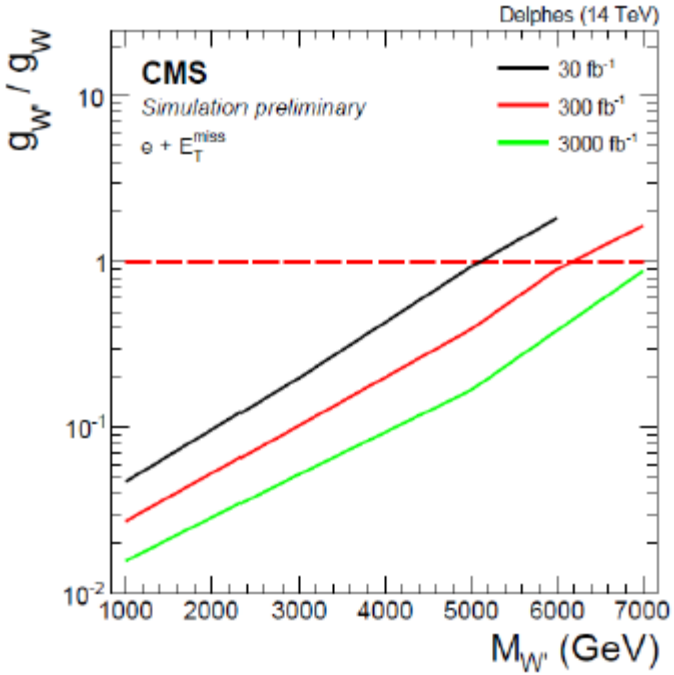
Yangyang Cheng, Bjoern Penning
Matteo Cremonesi , *Bo Jayatilaka*

ECFA Prep Meeting
09/15/2016

The Signal: Motivation



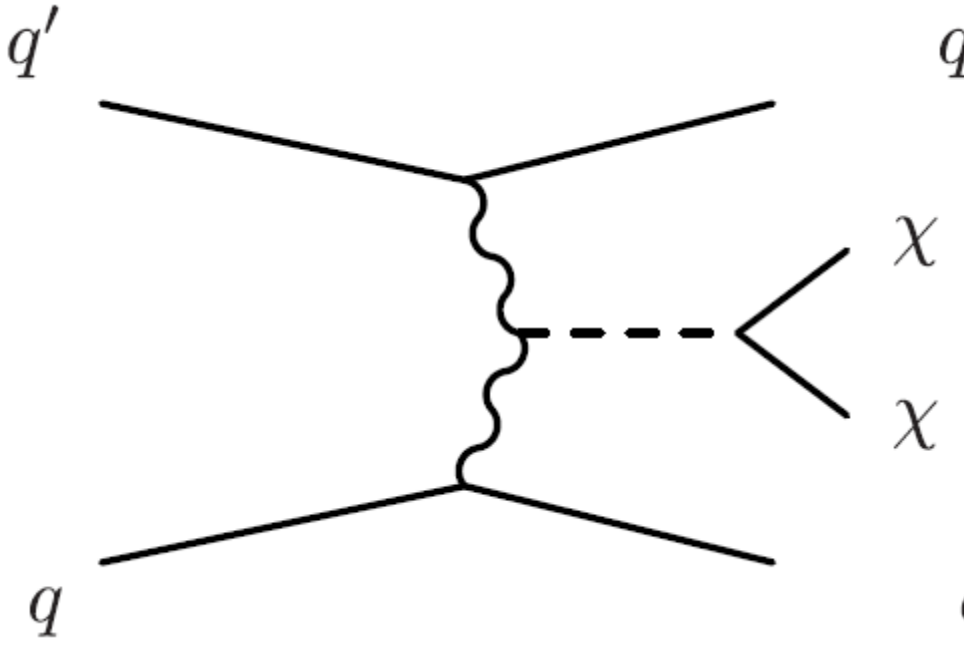




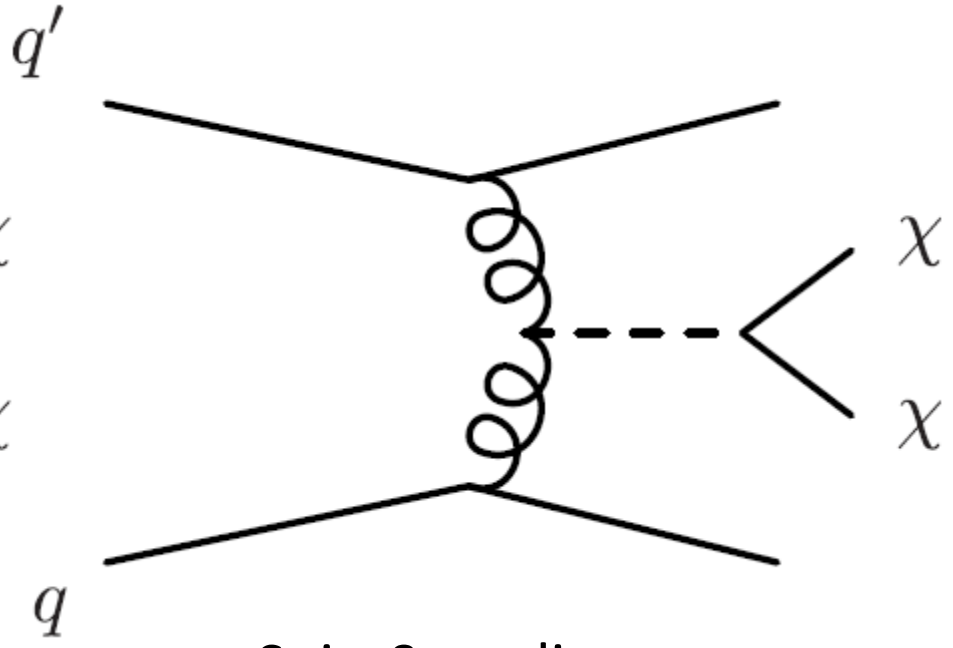
Dark Matter from VBF production with forward tagging jets (**arXiv: 1603.07739**)

- **New** class(es) of models with **distinct** topology:
  - simplified (spin-0 mediator) / **EFT models**
- Distinct from "conventional" MET+X signature (require high MET)
  - explore **different phase space** (different triggers; signal region selections…)
- **Forward jets** direct benefit from Phase2 upgrade
  - extended |eta| coverage in tracker & calo.

The Signal: Simplified Models



SM Higgs-portal

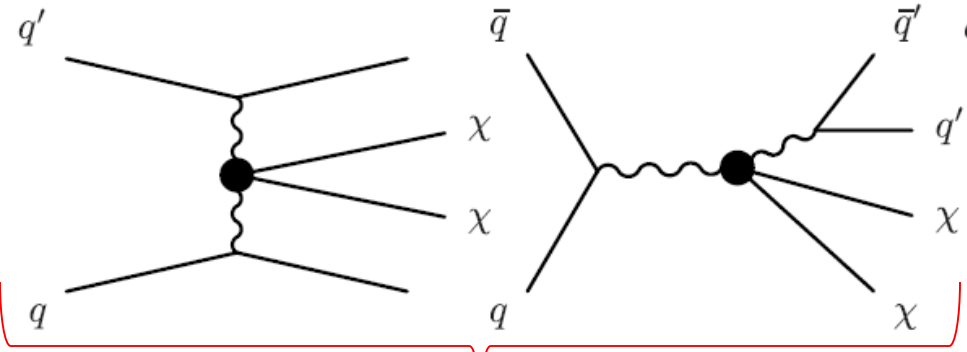


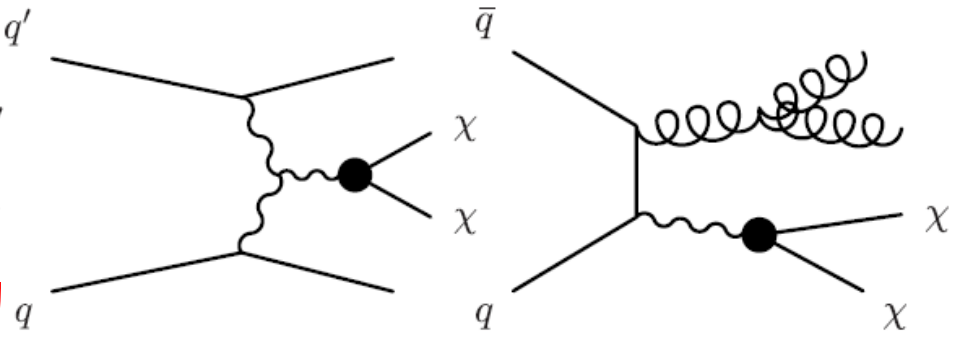
Spin-0 mediator,
incl. H, A, …

The Signal: EFT Models

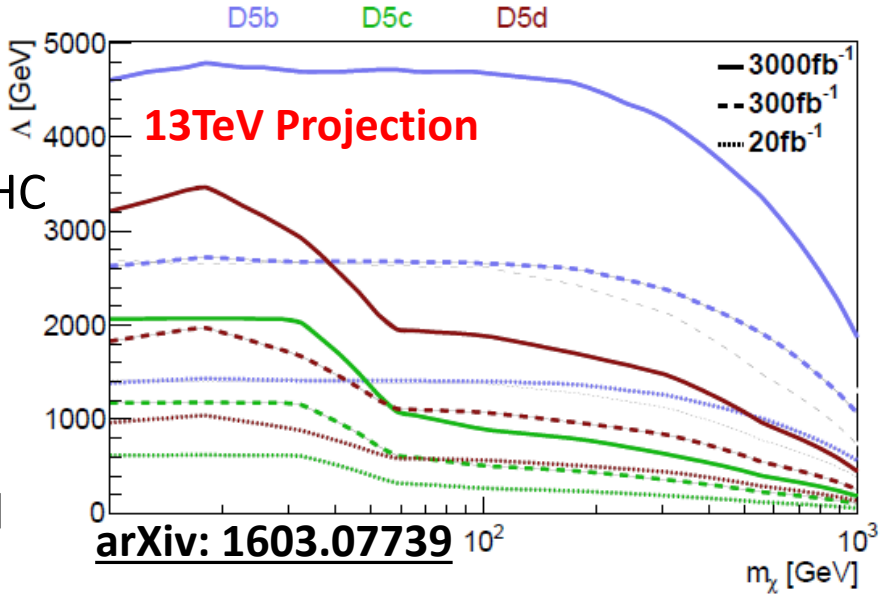
Sample Diagrams for EFT Models

D5, D6, D7 Operators



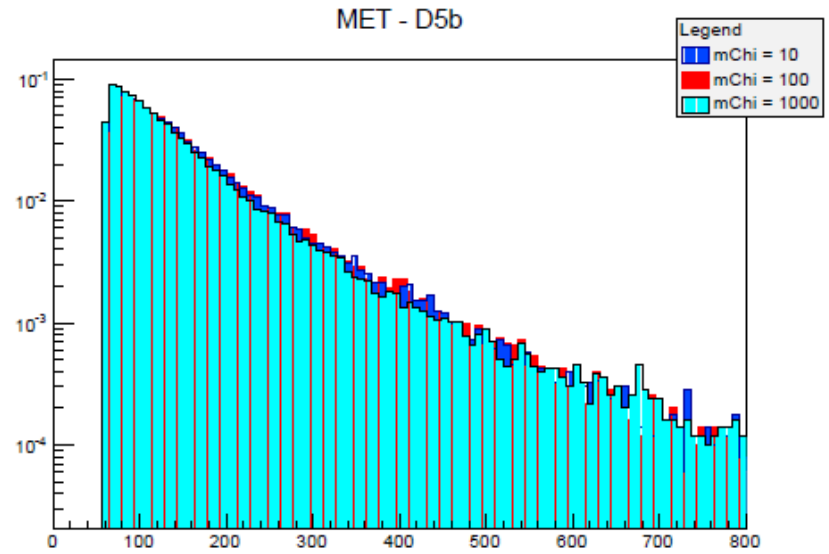


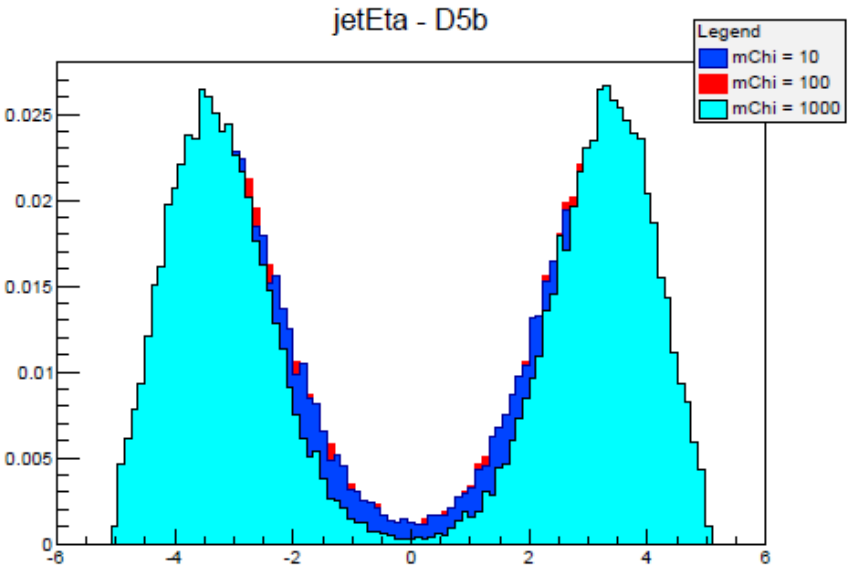
$$\mathcal{L}_{\mathrm{D5b}} \supseteq \frac{1}{\Lambda}\left[\bar{\chi}\gamma^5\chi\right]\left[\frac{Z_\mu Z^\mu}{2} + W_\mu^+ W^{-\mu}\right]$$



- Expect significant sensitivity increase @ HL-LHC
- Expect stronger limits than DD or other channels (e.g. Z→inv) for some operators/ regions of phase space
- **EFT models ~same final state as spin-0/BSM Higgs models: projection can be reinterpreted w/ simplified models**

The Signal: Cross-Section & Kinematics





M_DM (GeV)	Xsec (pb)
10	0.012
65	0.012
100	0.012
300	0.0094
500	0.0067
1000	0.0023

Values presented for D5b*

- λ=10TeV, xsec scales by 1/ λ^2
- Mg5+Delphes3.3.3pre16 (+Pythia8)
  - same as background (next page)
- Jet matching up to 3 jets is performed; matching eff. ~ 50%
- Explore other EFT's w/ larger xsec

Simulation Strategy

Detector Simulation

- Dedicated Delphes package:
  - Delphes3.3.3pre16 (+Pythia8)
- Simulation of **latest available CMS PhaseII detector design**
  - many improvements to TP
  - tracker extension to $|\eta|=4$
- **Both 0PU & 200PU** conditions
- Physics objects for this analysis:
  - Jets
    - **PUPPI**; recommended
    - AK4 for comparison
    - pT>30GeV, $|\eta|<4.7$, dR=0.4
  - E_t^{miss}
  - Lepton (veto)

SM Background

- Snowmass strategy:
  - arXiv:1308.1636
- Produced at LO
  - xsec scaled by K-factor
- Main bkgd for this analysis
  - V+jets (predominant)
  - Top (ttbar + single top)
  - Diboson
  - VBF Vjj
  - QCD (negligible; not simulated)

Signal Region: Selection

Based on CMS 8TeV VBF H(→inv) (arXiv: 1603.07739)

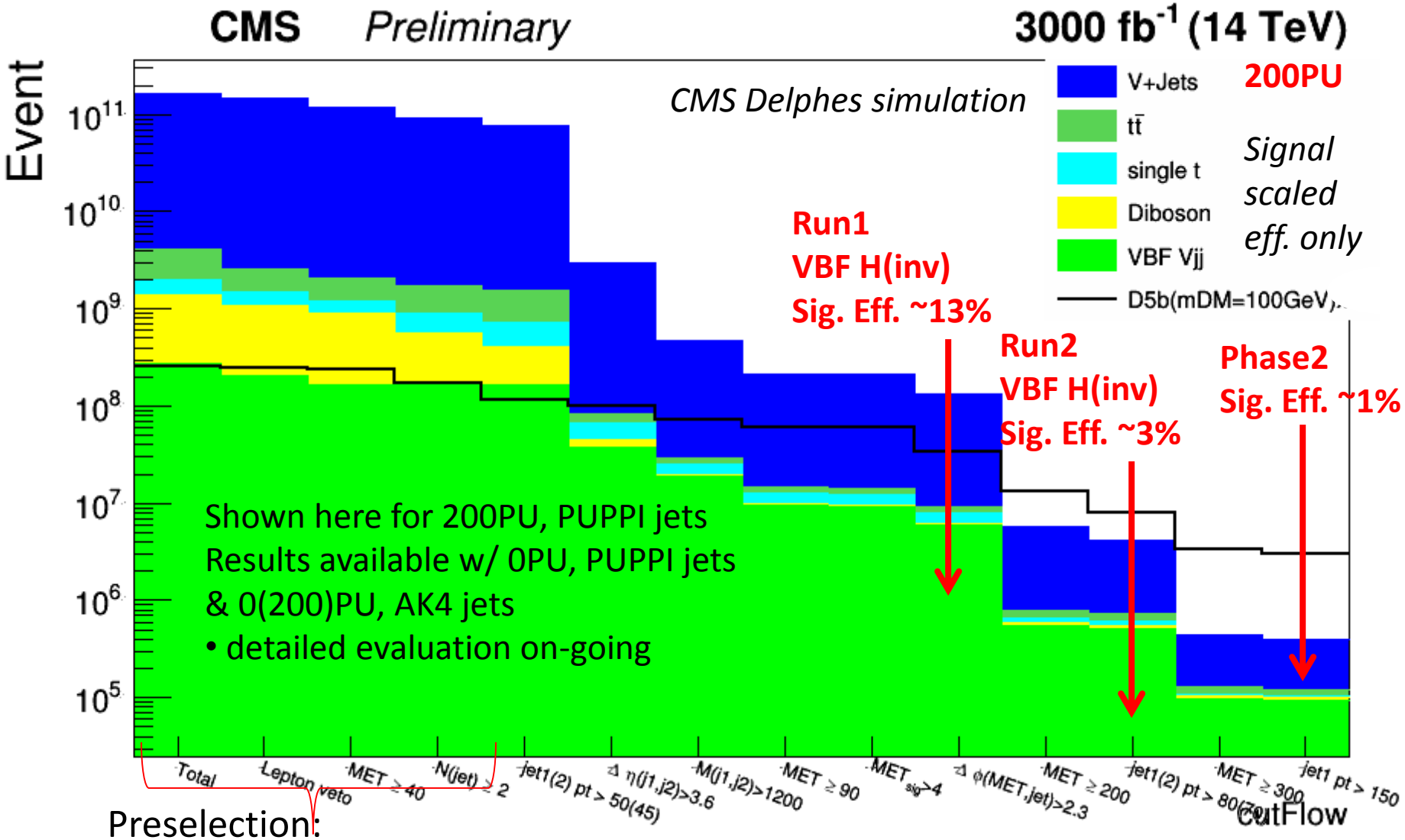
- similar to CMS 13TeV VBF H(→inv)
- raised E_t^{miss} & jet pT thresholds for Phase2 to improve sensitivity

Electron veto	$p_T > 10, \|\eta\| < 2.4$
Muon veto	$p_T > 10, \|\eta\| < 2.1$
Jet selection	$N_{jets} \geq 2$
	$p_T^{j1(j2)} > 150\ (70)$ GeV
	$\|\eta_{j1,2}\| < 4.7$
	$\eta_{j1} \cdot \eta_{j2} < 0$
	$\Delta\eta_{jj} > 3.6$
Dijet mass	$M_{jj} > 1200$ GeV
E_T^{miss}	> 300 GeV
E_T^{sig}	> 4 GeV$^{1/2}$
$\Delta\phi(E_T^{miss}, j)$	> 2.3

VBF H(inv) Run1:
j1(2)pT > 50 (45) GeV
VBF H(inv) Run2:
j1(2)pT> 80 (70) GeV

VBF H(inv) Run1:
E_t^{miss} > 90 GeV
VBF H(inv) Run2:
E_t^{miss} > 200 GeV

Signal Region: Cutflow

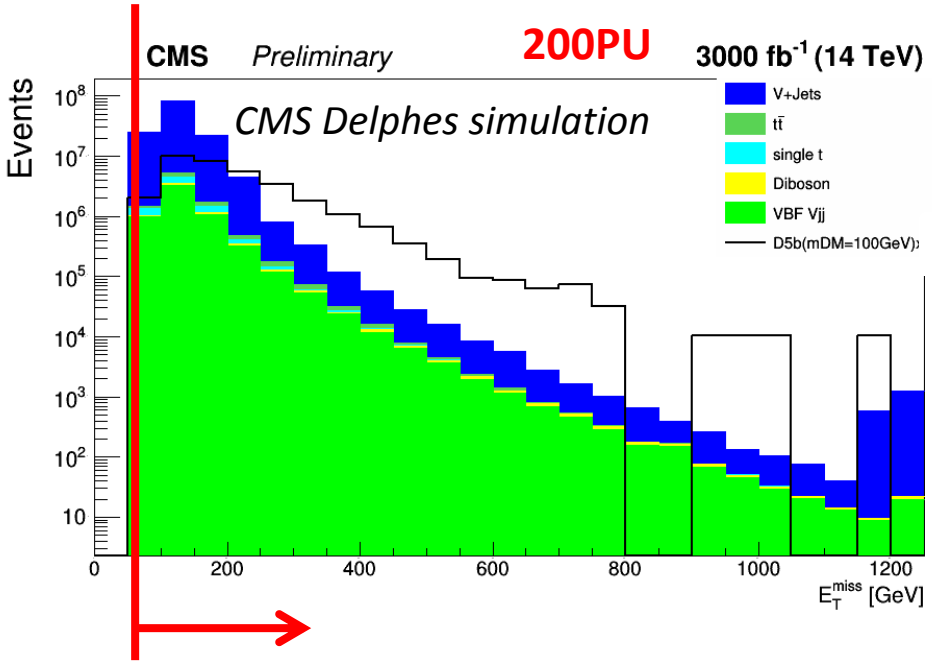


Preselection:

mimic trigger(s) used in Run1 VBF H(inv) (trigger eff. ~89%)

Kinematics: Missing ET

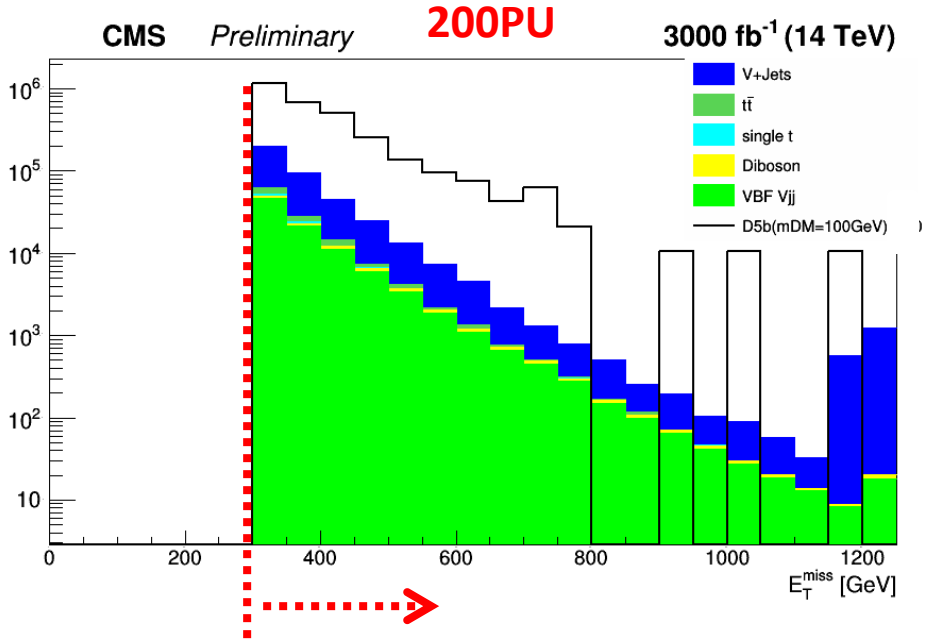
Run1 Selection



MET>90GeV

Signal Selection

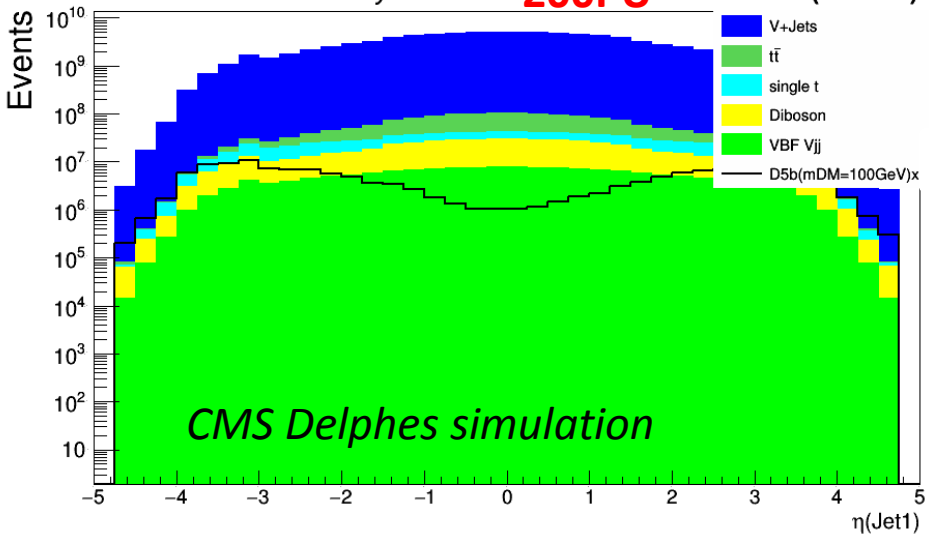
Signal scaled shape only



MET>300GeV

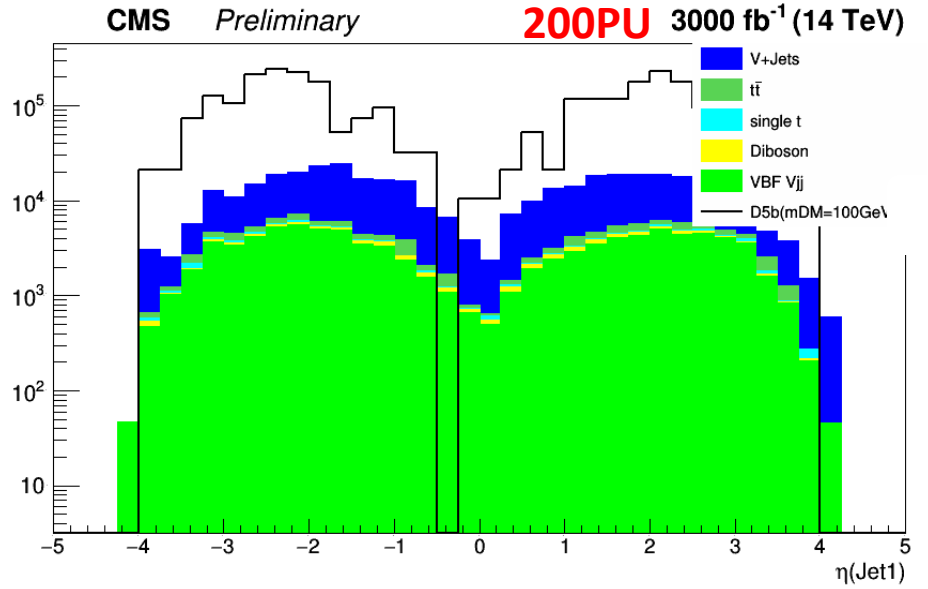
Kinematics: Leading Jet η

Preselection



Signal Selection

Signal scaled shape only



Systematics

CMS Run1 VBF H(→inv) (8TeV, 19.2fb-1)

Source	Total background	Signal
~~Control region data stat.~~	~~9.3~~	-
MC stat.	5.4	3.8
Jet energy scale	4.6	11
~~$W \to \tau\nu$ control region extrapolation~~	~~4.3~~	-
~~QCD normalisation~~	~~3.2~~	-
Jet energy resolution	3.0	1.8
Lepton ID efficiency	2.4	-
Unclustered energy scale	1.9	1.6
Pileup weight	1.1	1.5
~~Top MC scale factor unc.~~	~~0.25~~	-
Luminosity	0.02	2.6
QCD scale, PDF and cross section uncertainties	0.01	5.2

Strategy for this analysis:

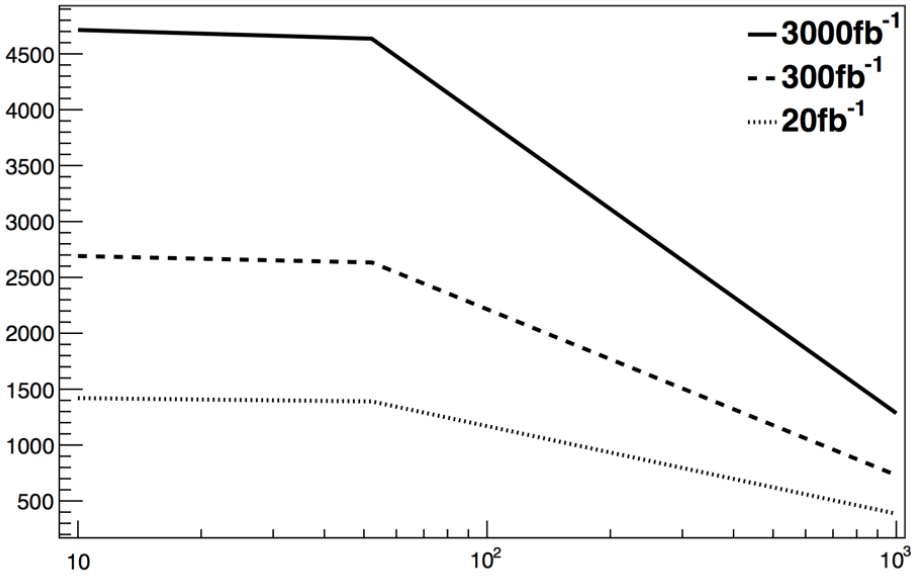
- **Scenario1 (no improvement):**
  - adopt Run1 systematics figures; scale by luminosity; assume no improvement to theory
- **Scenario2 (best knowledge):**
  - use numbers for current Ph2 simulation when available; apply factor of 2(3) to theory sys.
- **Scenario3 (optimal case; *optional*):** use a very small number (1%?) to evaluate extreme case

Limit Setting

- For ECFA, select one EFT model (D5b for now; options available)
- Calculate 95% CL lower limit on λ vs mDM
  - 10, 65, 100, 300, 500, 1000GeV
- Provide three limit plots:

(in *descending* order of priority)

  - 14TeV, 3000fb-1, Systematics Scenario2; **0PU & 200PU**
  - 14 TeV, 3000fb-1, 200PU; **Systematics Scenario 1, 2, (&3)**
  - 14 TeV, 200PU, Systematics Scenario2; **20, 300, &3000 fb-1**



This is a dummy plot to test tools.

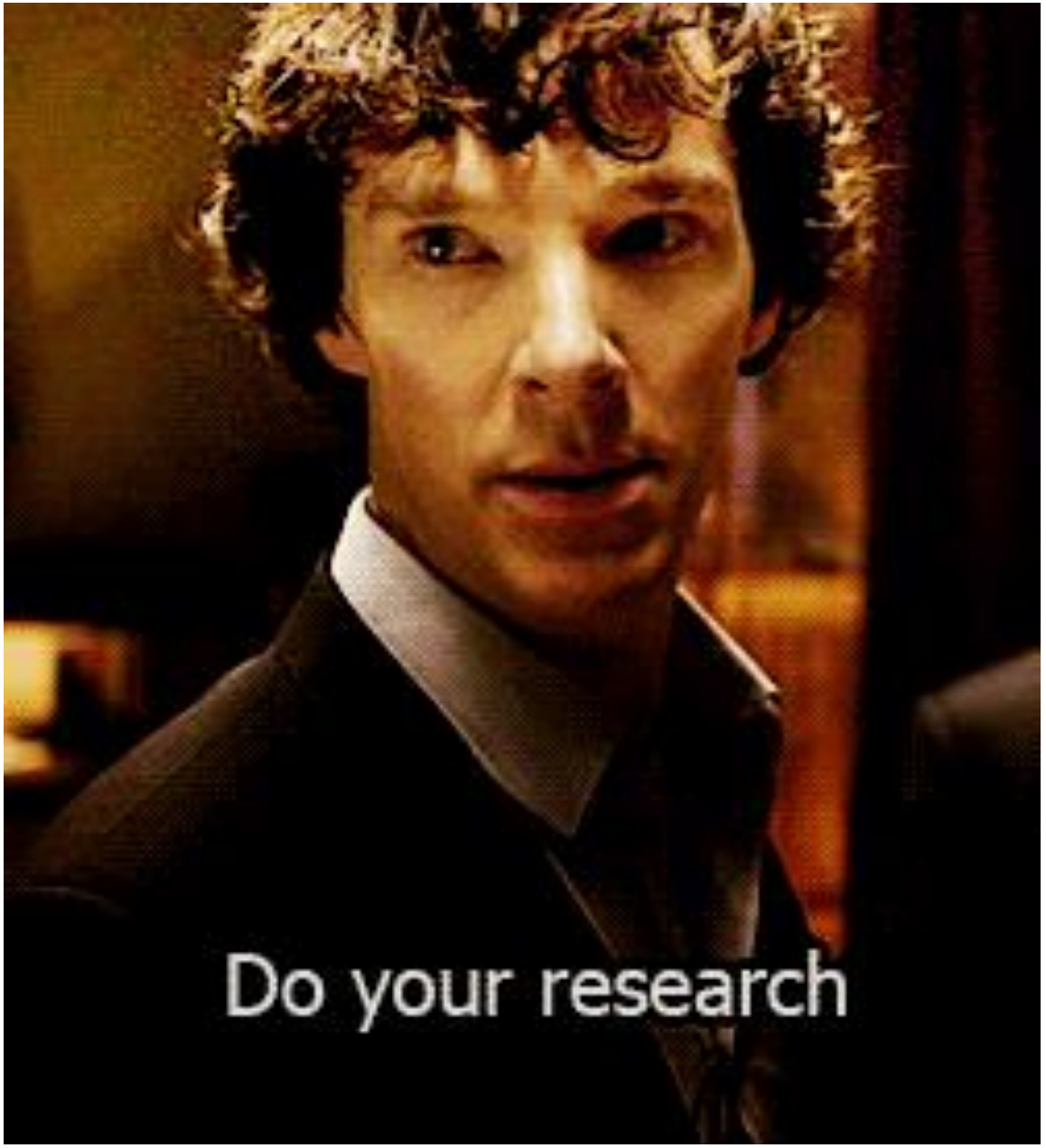
This is a NEW search
- No existing results from data analysis
- Phase2 simulation w/ different detector design/performance/PU conditions

Conclusions and Next Steps

- Presented status and plans on ECFA timeline for a **NEW SEARCH** for dark matter@HL-LHC
  - Distinct signature probes phase space not covered by mono-jet / VBF H(inv)
  - VBF production: take advantage of **forward extension** in CMS Ph2
- Signal selection optimized for Phase2 conditions
- Background analyzed for Phase2 CMS Delphes simulation, both 0PU&200PU
  - valuable information of PU effect in forward region & impact on jet/ E_t^{miss}
- Different systematics scenarios for sensitivity projection
- Limit setting tools developed
- Documentation in progress: almost complete; final results TBA
- In touch with theorists to verify model usage & xsec: expect results soon
- VBF jets + E_t^{miss} final state can be interpreted in other EFT/simplified models
  - **explore discovery potential in the forward region for HL-LHC!**

THANK YOU!

#MovePhysics Forward



VBF-DM Signal Kinematics

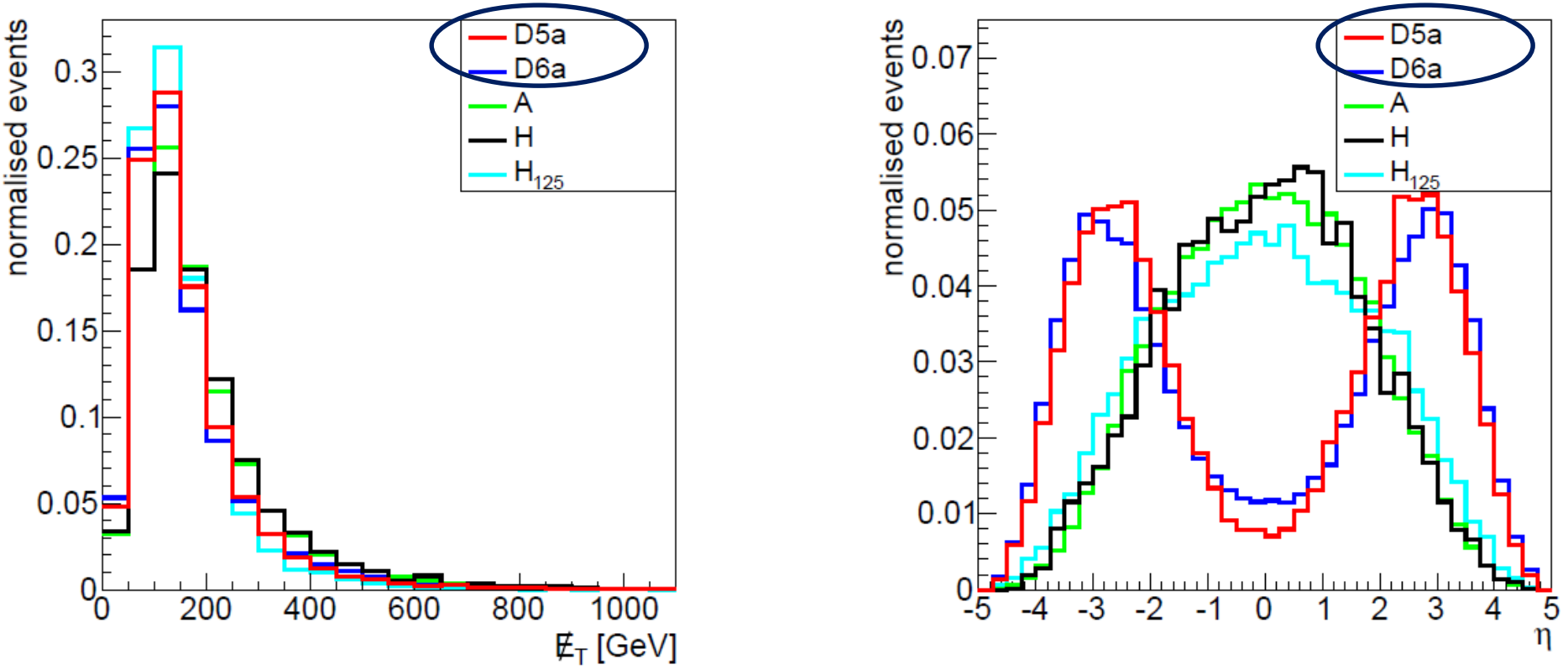


FIG. 4: Normalised differential distributions of $\not{E}_{\mathrm{T}}$ (left) and leading jet η (right) at the LHC Run-II for representative EFTs, as well as the H_{125} and spin-0 simplified models. The EFT distributions are made assuming $m_\chi = 100$ GeV. The H_{125} distribution assumes $m_\chi = 56.2$ GeV. The scalar, H, and pseudoscalar, A, distributions assume $m_\chi = 100$ GeV and $m_{H(A/2)} = 316.2$ GeV.

The Background in Run1 VBF H(inv)

CMS PAS HIG-14-038

Process	Event yields
$Z \to \nu\nu$	$158.1 \pm 37.3 \pm 21.2$
$W \to \mu\nu$	$102.5 \pm 6.2 \pm 11.7$
$W \to e\nu$	$57.9 \pm 7.4 \pm 7.7$
$W \to \tau\nu$	$94.6 \pm 13.1 \pm 23.8$
top	5.5 ± 1.8
VV	3.9 ± 0.7
QCD multijet	17 ± 14
Total Background	$439.4 \pm 40.7 \pm 43.5$
Signal(VBF)	273.1 ± 31.2
Signal(ggH)	23.1 ± 15.9
Observed data	508

V+jets ~
95% of bkgd

arXiv: 1603.07739
did NOT re-do background analysis: scaled from CMS VBF H(→inv) 8TeV results

The Background: Samples

Dataset Name	Main Processes	Final States	Order
Dominant Backgrounds			
B-4p, Bj-4p[a]	vector boson + jets	$V + nJ$	$\mathcal{O}(\alpha_s^n \alpha_w)$
BB-4p	divector + jets	$VV + nJ$	$\mathcal{O}(\alpha_s^n \alpha_w^2)$
TT-4p	top pair + jets	$TT + nJ$	$\mathcal{O}(\alpha_s^{2+n})$
TB-4p	top pair off-shell $T^* \to Wj$ + jets	$TV + nJ$	$\mathcal{O}(\alpha_s^{n+1} \alpha_w)$
TJ-4p	single top (s and t-channel) + jets	$T + nJ$	$\mathcal{O}(\alpha_s^{n-1} \alpha_w^2)$
LL-4p	off-shell $V^* \to LL$ + jets	$LL + nJ$ $[m_{ll} > 20$ GeV$]$	$\mathcal{O}(\alpha_s^n \alpha_w^2)$
Subdominant Backgrounds			
TTB-4p	top pair + boson	$(TTV + nJ), (TTH + nJ)$	$\mathcal{O}(\alpha_s^{2+n} \alpha_w)$
BLL-4p	off-shell divector $V^* \to LL$ + jets	$VLL + nJ$ $[m_{ll} > 20$ GeV$]$	$\mathcal{O}(\alpha_s^n \alpha_w^3)$
BBB-4p	tri-vector + jets, Higgs associated + jets	$(VVV + nJ), (VH + nj)$	$\mathcal{O}(\alpha_s^n \alpha_w^3)$
H-4p	gluon fusion + jets	$H + nJ$	$\mathcal{O}(\alpha_s^n \alpha_h)$
BJJ-vbf-4p	vector boson fusion + jets	$(V + nJ), (H + nJ)$ $[n \geq 2]$	$\mathcal{O}(\alpha_s^{n-2} \alpha_w^3)$

Signal Region: Event Yield

14TeV, 200PU

Selection	Total	RunI VBF H(→inv)	RunII VBF H(→inv)	PhaseII VBF DM
V+jets	1.79951878144e+11	146081728.0	4552046.0	418312.9
$t\bar{t}$	3176197376.0	1731667.1	179118.0	26040.2
Single top	553264832.0	1595614.4	59304.5	3733.2
Diboson	984915648.0	295907.3	24888.6	5700.6
V+jj	243396416.0	5255162.5	456112.2	83193.8
Tot.Bkgd.	1.84909652416e+11	154960079.344	5271469.40625	536980.693115
Signal				

14TeV, 0PU

Selection	Total	RunI VBF H(→inv)	RunII VBF H(→inv)	PhaseII VBF DM
V+jets	1.79950927872e+11	4058455.0	470410.3	106460.3
$t\bar{t}$	3176197376.0	260519.6	43319.6	8217.6
Single top	553267648.0	89351.9	5431.0	686.6
Diboson	984916736.0	28167.7	5562.0	1659.5
V+jj	243396416.0	637751.1	99376.0	25365.4
Tot.Bkgd.	1.84908706048e+11	5074245.26758	624099.001465	142389.287903
Signal				

Signal yield TBA: in discussion with theorists to check usage & cross-section.