Invisible Higgs Decays

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for the CMS Collaboration
Higgs Coupling 2016
Nov. 10th, 2016

Outline

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- Motivation for Invisible Higgs Search
- Comparison of direct search channels
- Review of latest results
    - qqH (VBF) overview
    - Z(ll)H(inv.) in detail
    - gH (mono-Jet) overview
    - Combination
- Outlook for Invisible Higgs

Higgs Couplings: Still room for BSM

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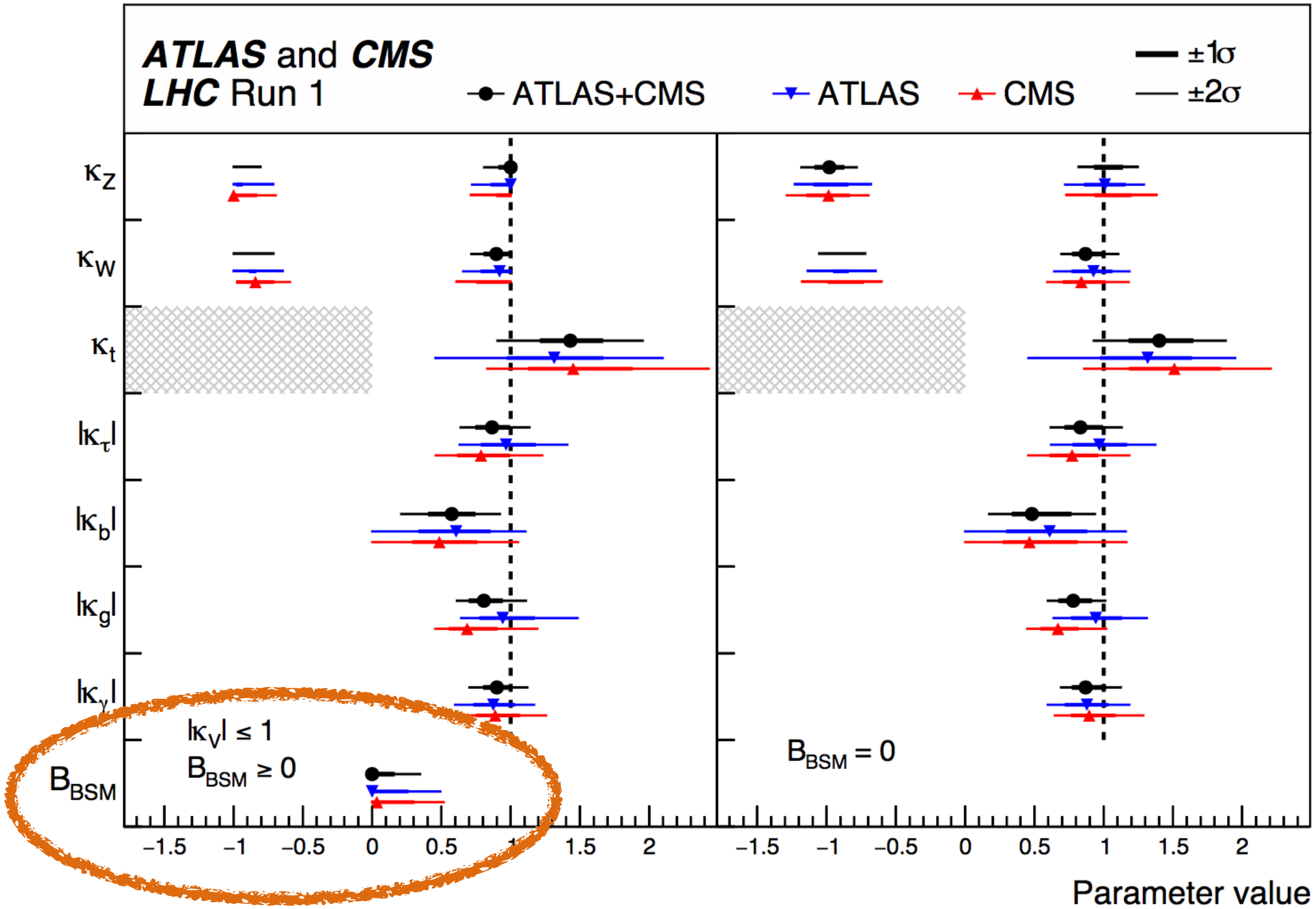
- Conference namesake!
- Direct measurement → better constraints



arXiv:1606.02266

The Higgs as a Dark Matter Portal

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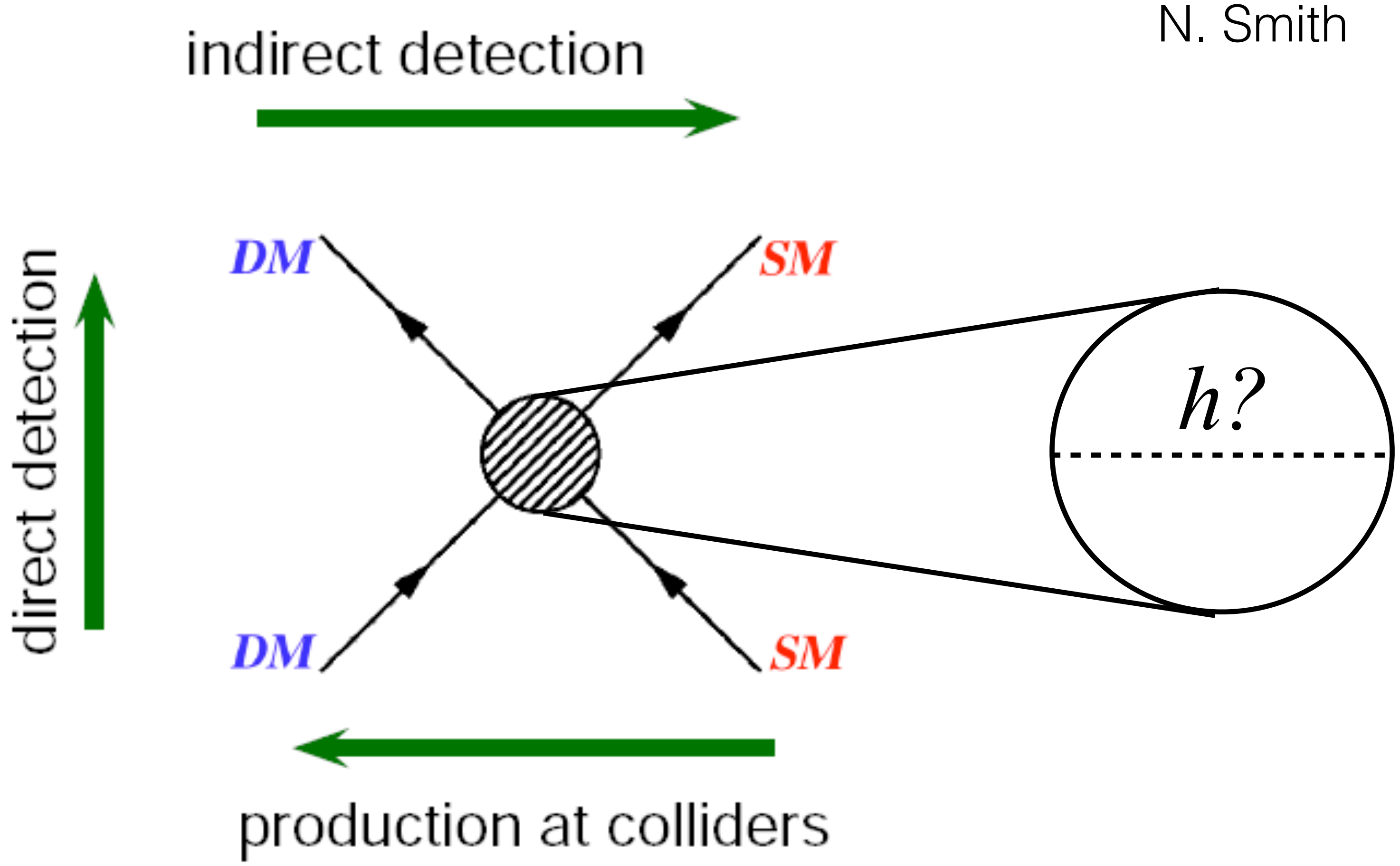
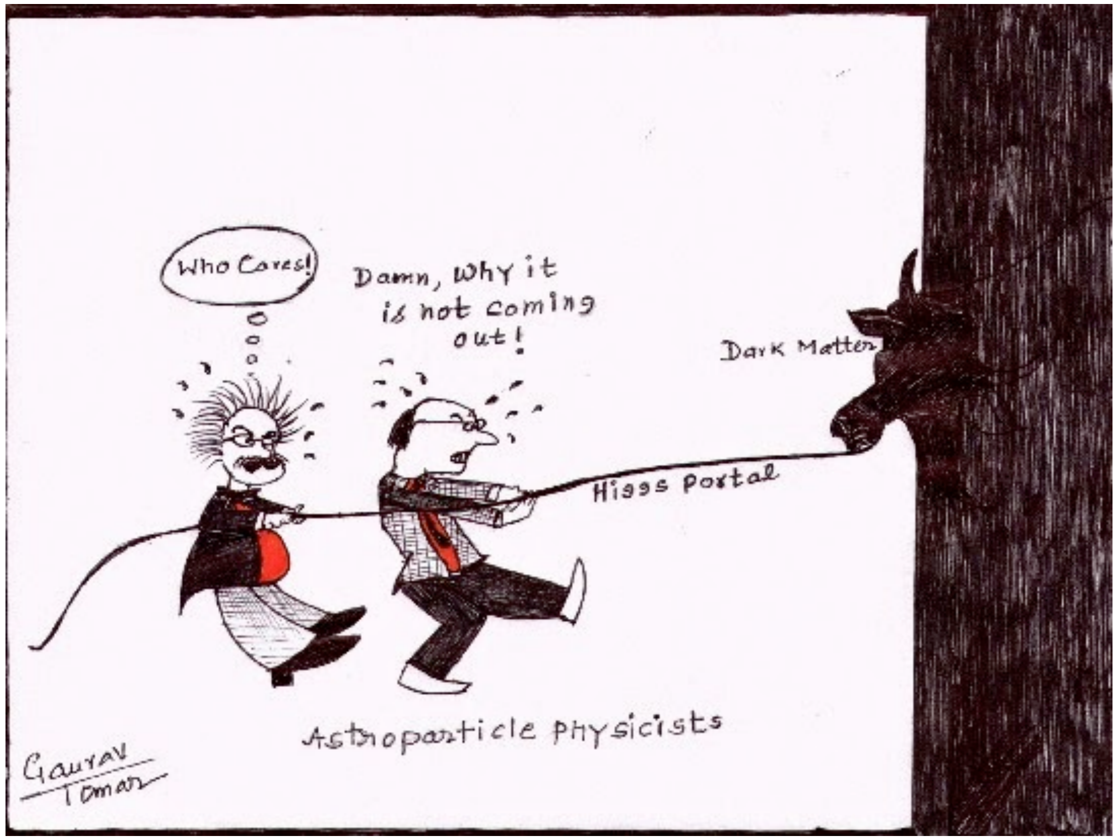
Does the Higgs connect the Standard Model to dark matter?

- DM mass < Higgs / 2
- Complementary to direct detection



$$\boxed{\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2},$$

$$\boxed{\Delta\mathcal{L}_f = -\frac{1}{2}m_f \bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda} H^\dagger H \bar{\chi}\chi}$$



http://rejuvenatte.blogspot.com

Seeing Invisible Higgs Decays

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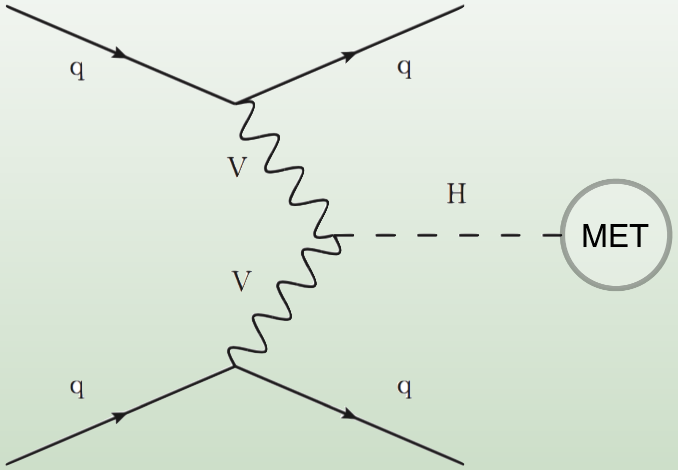
Invisible Higgs decay → missing energy (MET)

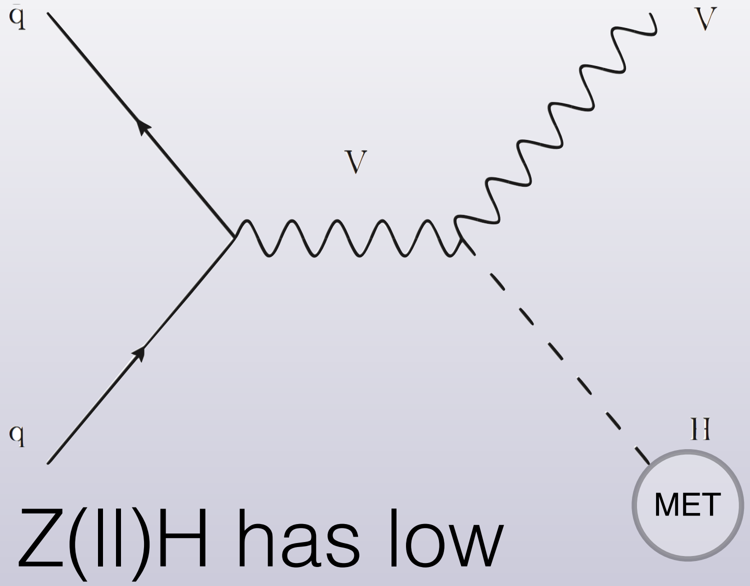
Tag SM Higgs production mode with recoil topology

qqH



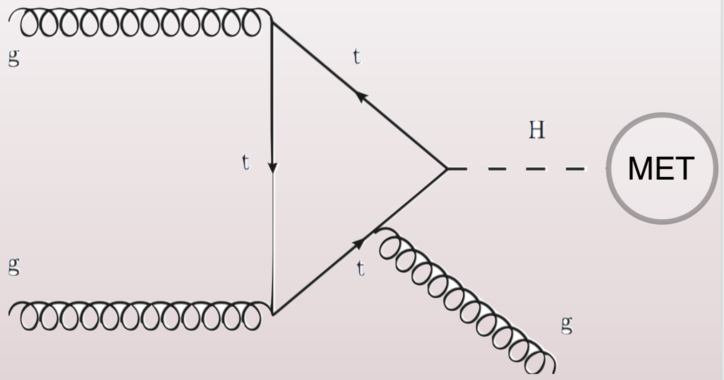
- Most sensitive
- VBF signature: two well-separated jets
- Dedicated Trigger

VH



- Z(ll)H has low background
- V(qq)H uses jet substructure techniques

gH



- Mono-Jet reinterpretation
- Large backgrounds

Latest Results

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Papers & Conference Notes in 2016 with Higgs Invisible limits

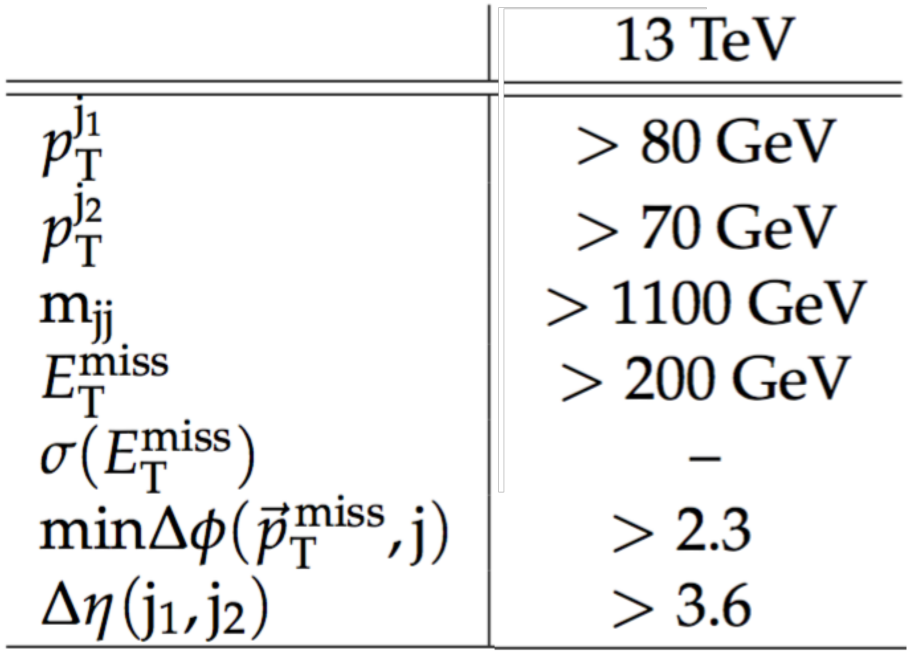
- arXiv:1610.09218
  - Combination of 7,8,13TeV results in all production modes
  - Includes Moriond '16 results: HIG-16-008, HIG-16-009, EXO-16-013
- CMS-PAS-EXO-16-037
  - ICHEP '16 Mono-(Jet/V)
- CMS-PAS-EXO-16-038
  - ICHEP '16 Z(ll)H(inv.)

Table of Observed (Expected) Limits on $\sigma \times B(H \rightarrow \text{inv.})/\sigma(SM)$

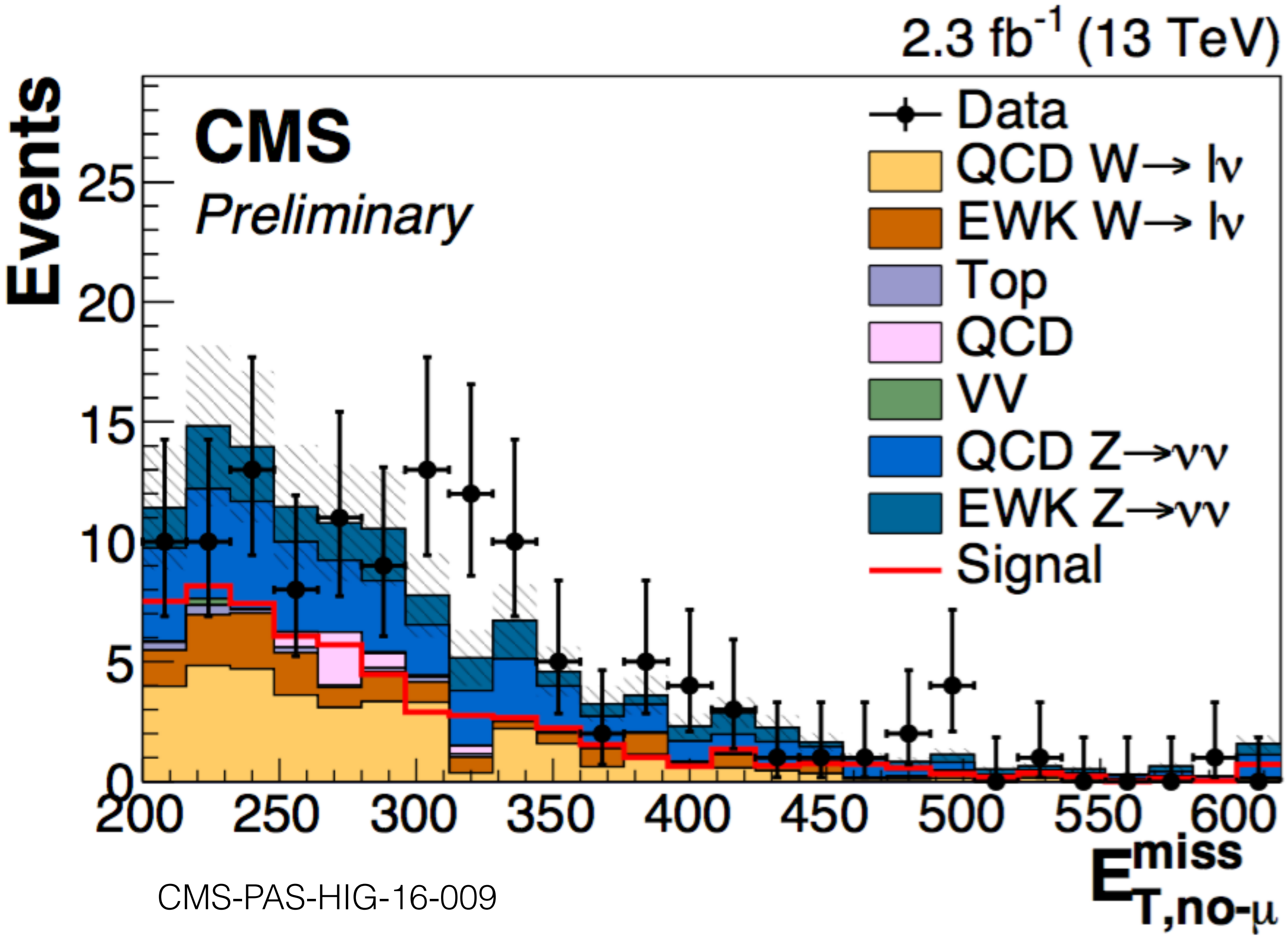
	qqH (VBF)	**Z(ll)H**	**V(qq)H**	**gH**
CMS-PAS-HIG-16-009	0.69 (0.62)			
arXiv:1610.09218	0.24 (0.23) Combined			
CMS-PAS-EXO-16-037			1.17 (0.72)	0.48 (0.85)
CMS-PAS-EXO-16-038		0.86 (0.70)		

qqH - Overview

- Select VBF topology, reject extra leptons
- Offline selection driven by trigger thresholds:
  - MET > 140 GeV
  - Δη(jj) > 3.5
  - M(jj) > 600 GeV



	13 TeV
$p_T^{j_1}$	> 80 GeV
$p_T^{j_2}$	> 70 GeV
m_{jj}	> 1100 GeV
E_T^{miss}	> 200 GeV
$\sigma(E_T^{miss})$	–
$\min\Delta\phi(\vec{p}_T^{miss},j)$	> 2.3
$\Delta\eta(j_1,j_2)$	> 3.6



CMS-PAS-HIG-16-009

qqH - Limits

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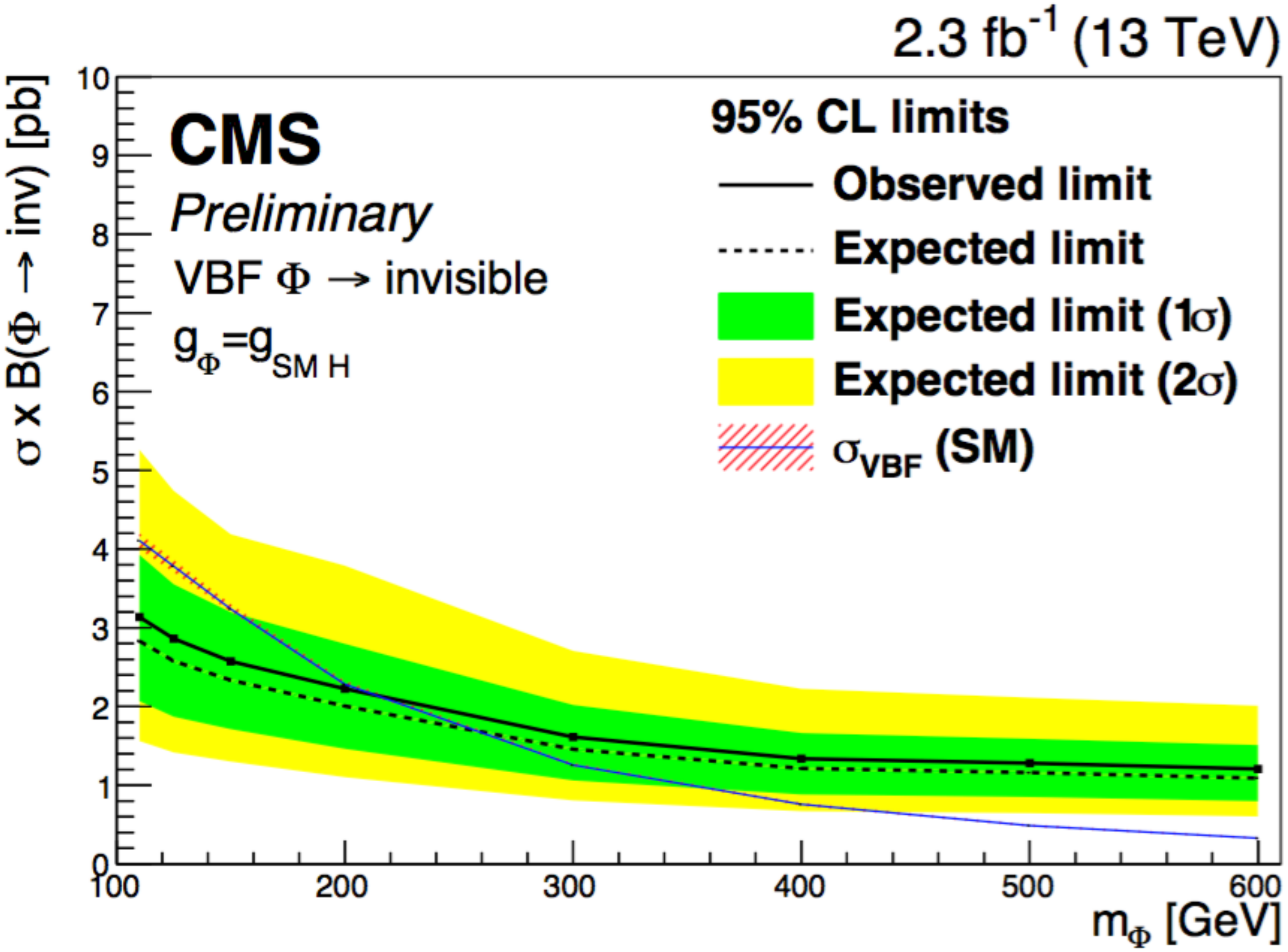
- W to Z fiducial cross section ratio is dominant uncertainty
  - Need better EWK production predictions
- Limits scanned by mass of scalar boson
  - Couplings to vector bosons = Higgs coupling for given mass

Systematic uncertainty	Impact
Common	
W to Z ratio in QCD produced V+jets	13%
W to Z ratio in EW produced V+jets	6.3%
Jet energy scale+resolution	6.0%
QCD multijet normalisation	4.3%
PU mis-modelling	4.2%
Lepton efficiencies	2.5%
Luminosity	2.2%
Signal specific	
ggH acceptance	3.8%
QCD scale + PDF (qqH)	1.8%
QCD scale + PDF (ggH)	$< 0.2\%$
Total statistical only	$-27/+28\%$
Total uncertainty	$-33/+32\%$



CMS-PAS-HIG-16-009

Z(ll)H - Selection

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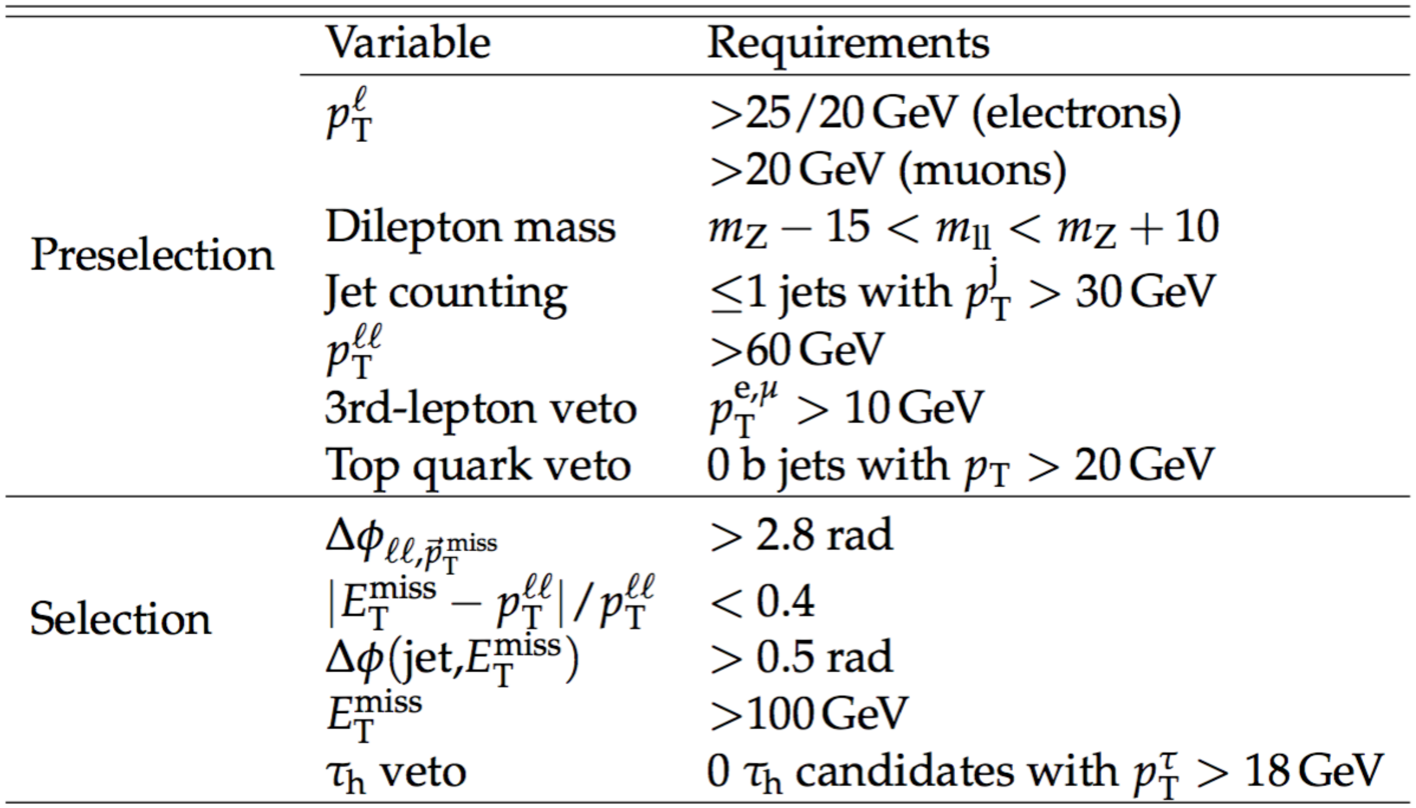
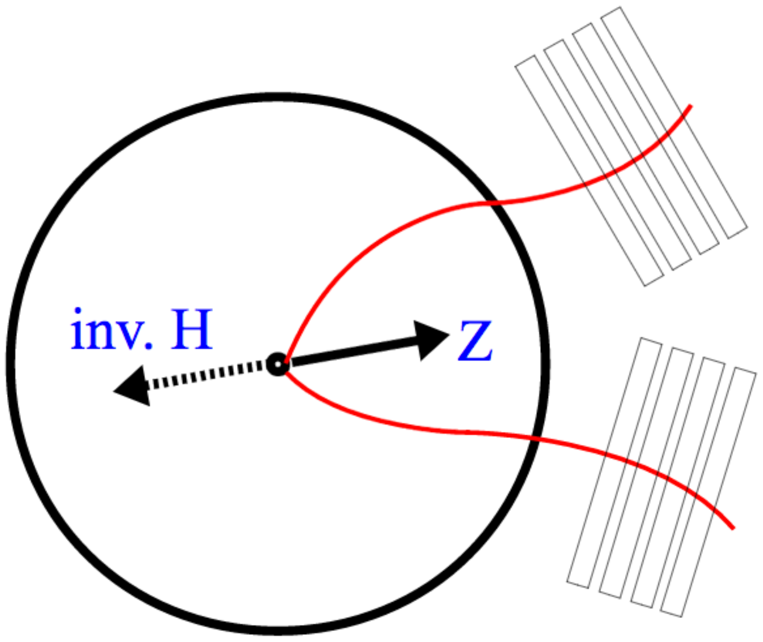
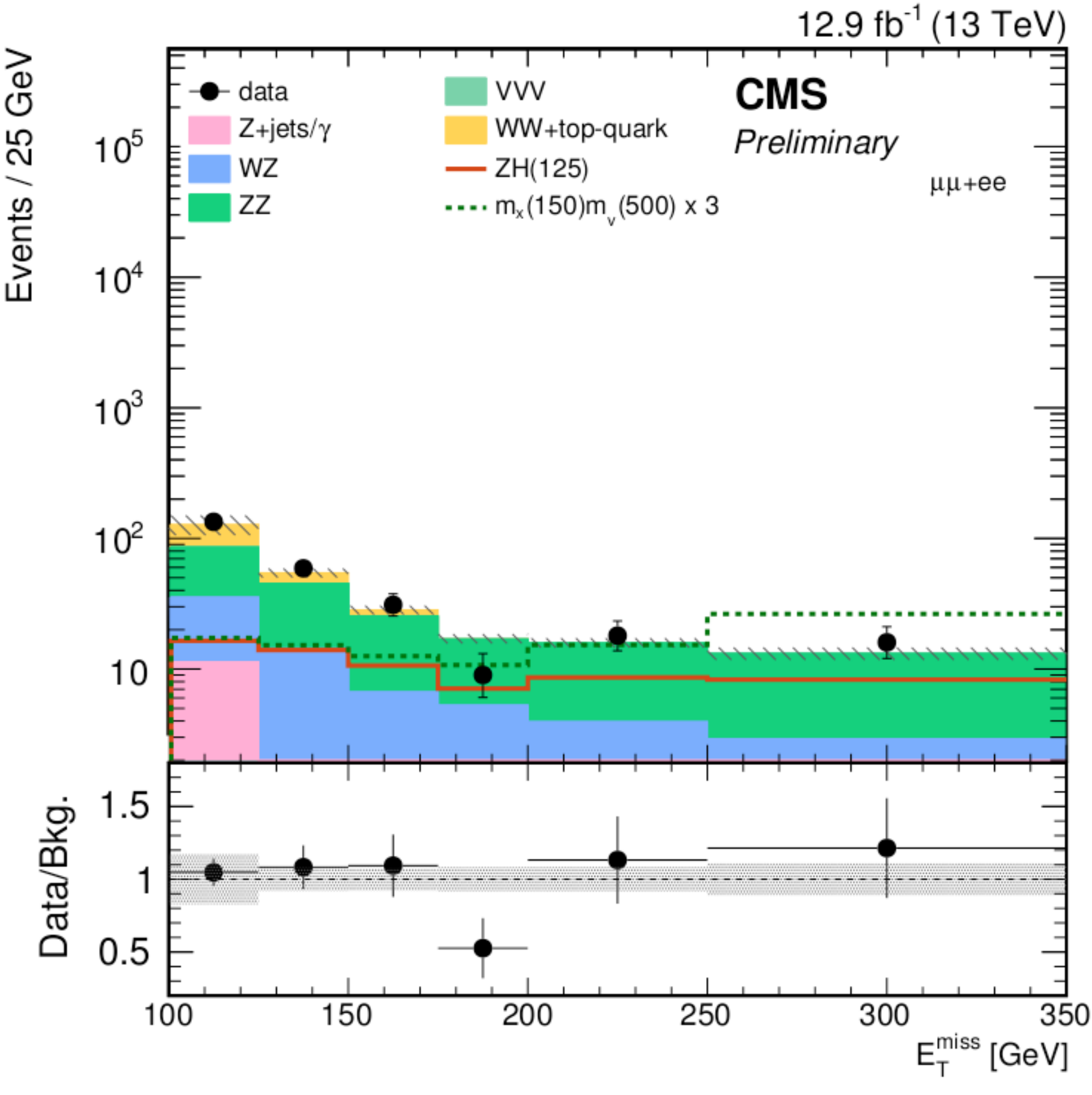
- Select good Z bosons + back-to-back topology with MET



	Variable	Requirements
Preselection	p_T^ℓ	>25/20 GeV (electrons) >20 GeV (muons)
	Dilepton mass	$m_Z - 15 < m_{ll} < m_Z + 10$
	Jet counting	$\leq$1 jets with $p_T^j > 30$ GeV
	$p_T^{\ell\ell}$	>60 GeV
	3rd-lepton veto	$p_T^{e,\mu} > 10$ GeV
	Top quark veto	0 b jets with $p_T > 20$ GeV
Selection	$\Delta\phi_{\ell\ell,\vec{p}_T^{miss}}$	> 2.8 rad
	$\lvert E_T^{miss} - p_T^{\ell\ell}\rvert / p_T^{\ell\ell}$	< 0.4
	$\Delta\phi(\text{jet},E_T^{miss})$	> 0.5 rad
	E_T^{miss}	>100 GeV
	τ_h veto	0 τ_h candidates with $p_T^\tau > 18$ GeV





CMS-PAS-EXO-16-038

Z(ll)H - Backgrounds I

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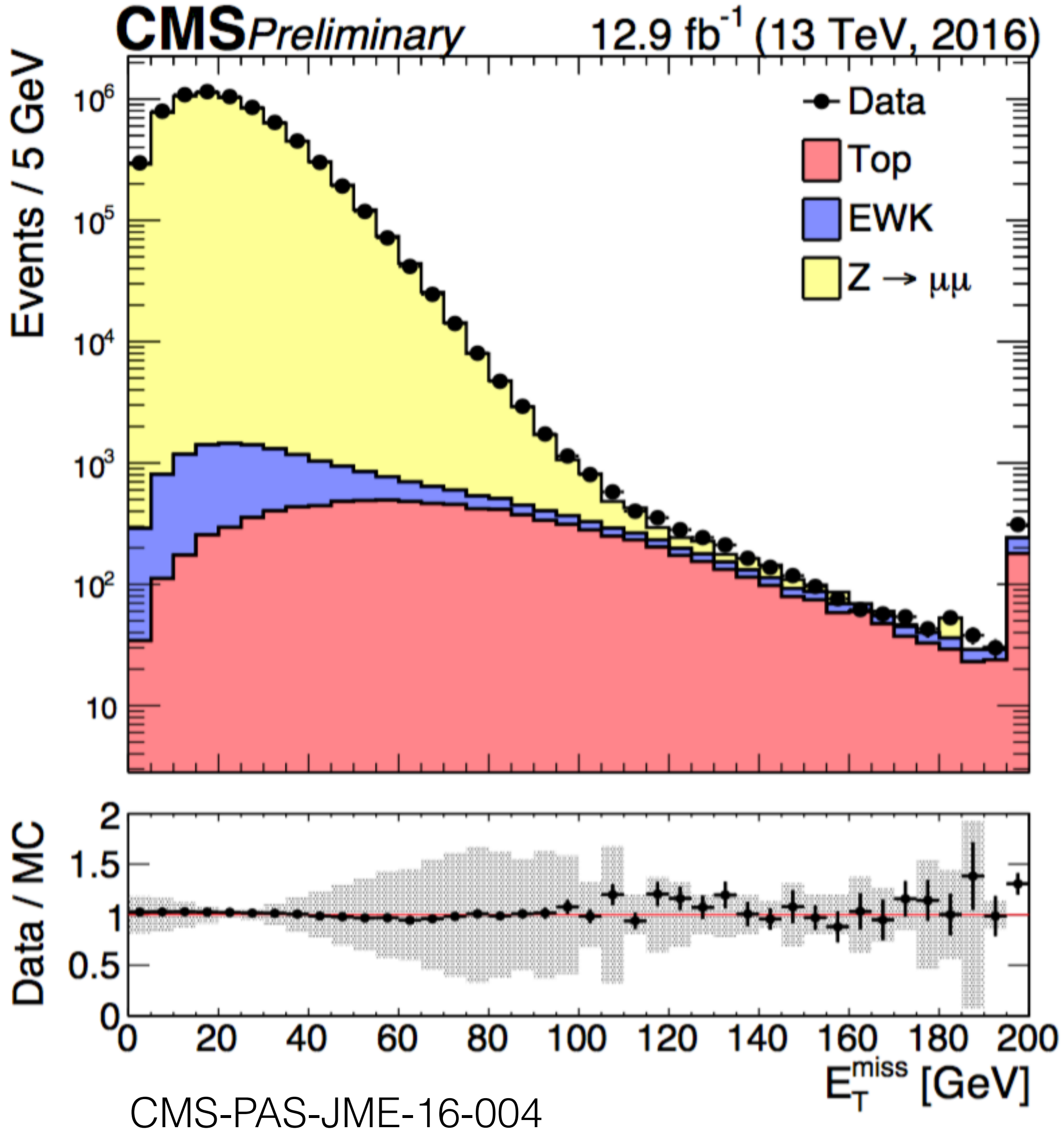
Nonresonant Backgrounds (Top, WW, etc.)

- Data-driven using eμ final state
  - Uses flavor universality

$$N^{peak}_{bkg,ee} = \kappa_{ee} \cdot N^{peak}_{e\mu}, \qquad \kappa_{ee} = \frac{1}{2}\sqrt{\frac{N^{peak}_{sign,ee}}{N^{peak}_{sign,\mu\mu}}}$$

DY+Jets

- Drell-Yan σ + MET resolution = long tail
  - Increasing with pileup
- Data-driven using γ+Jets control region



CMS-PAS-JME-16-004

Z(ll)H - Backgrounds II

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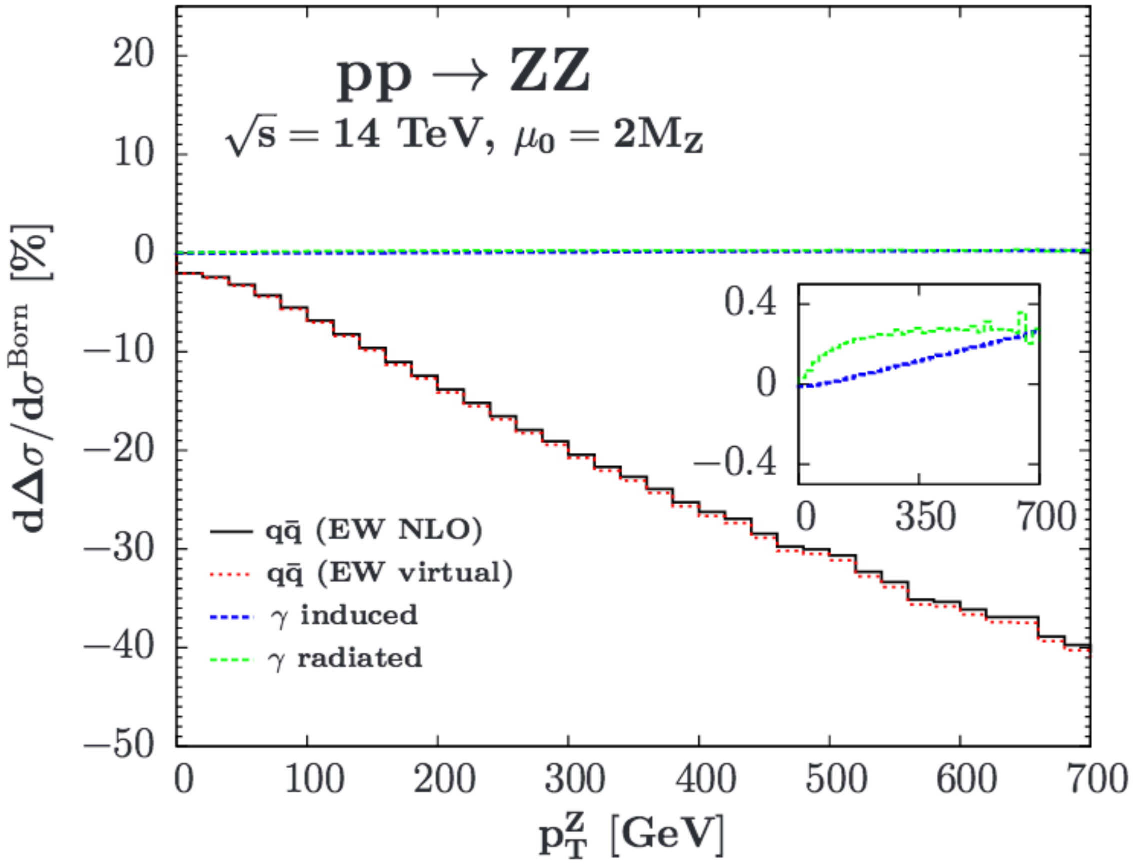
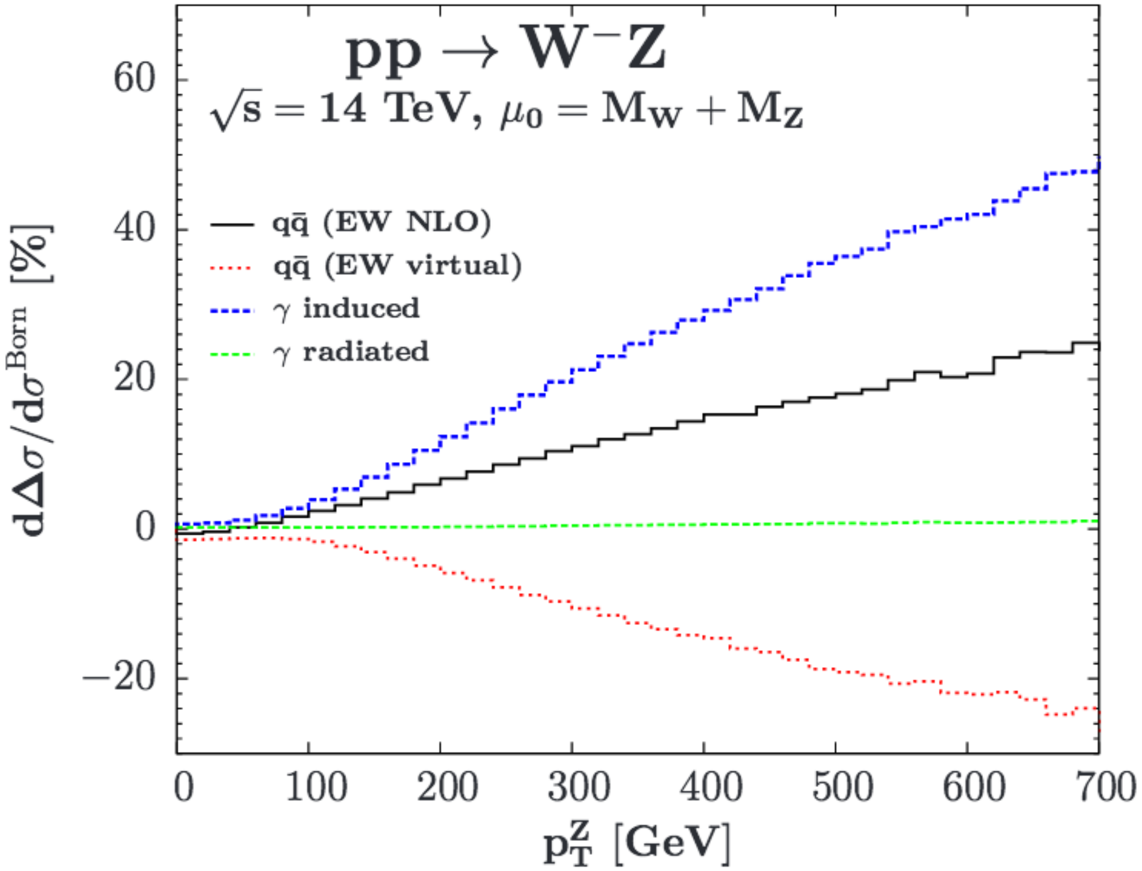
- NLO EWK corrections applied to ZZ->2l2v sample
  - Changes this dominant background yield up to -10%
- Corrections for WZ are not applied (small net contribution)





arXiv:1305.5402 (T.Kasprzik *et al.*)
arXiv:1307.4331 (J.Baglio *et al.*)
arXiv:1401.3964 (S.Gieseke *et al.*)

Z(ll)H - Limits

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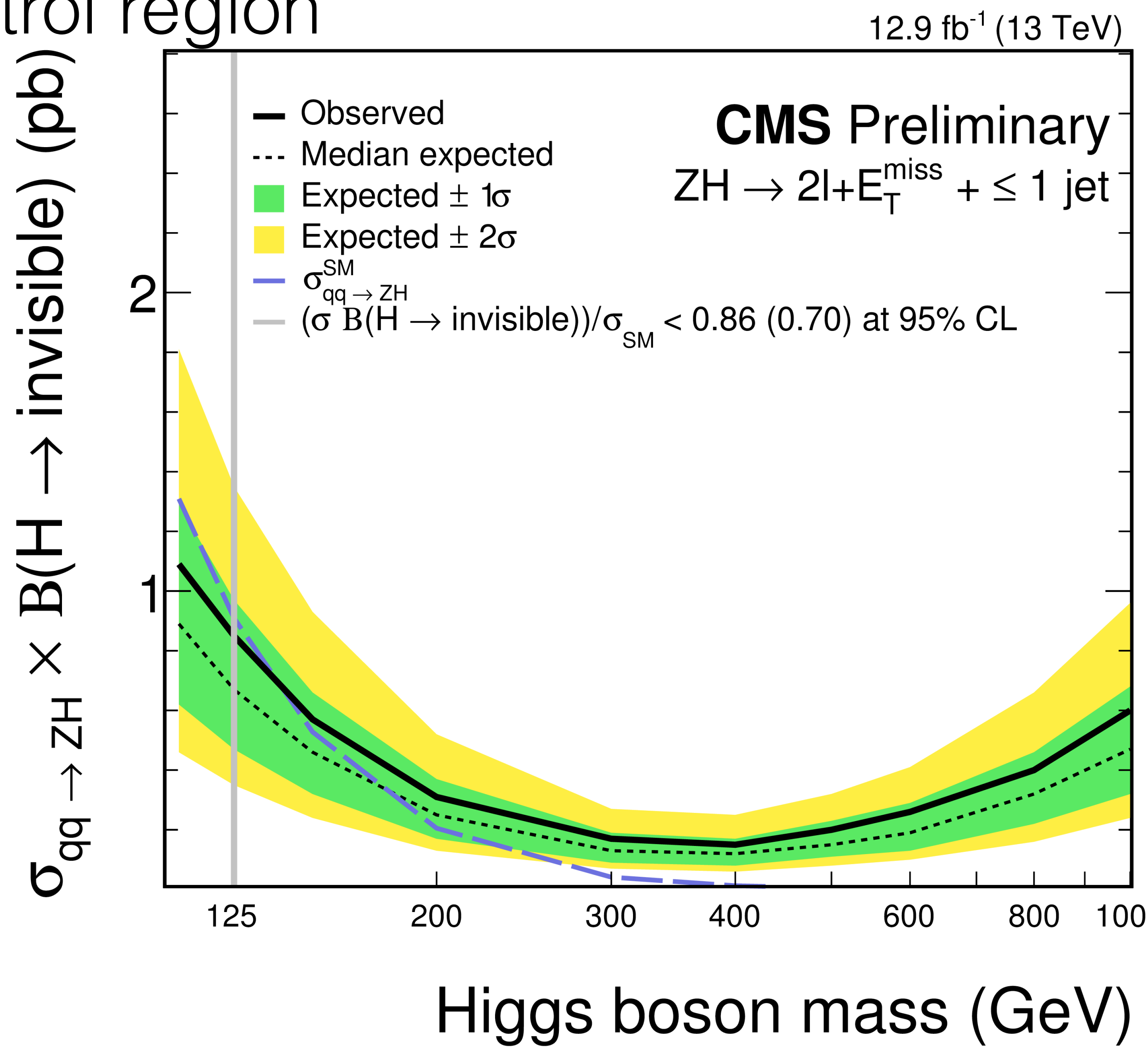
- Scan limits over Higgs masses
- SM Higgs limit includes ggH contribution
- Diboson cross section is dominant uncertainty
    - Higher-order MC would help
    - Future: sufficient luminosity for control region

Systematic uncertainty	Impact
Common	
ZZ background theory	16%
luminosity	8.4%
b jet tag efficiency	6.2%
Electron efficiency	6.2%
Muon efficiency	6.2%
Electron energy scale	3.2%
Muon momentum scale	3.2%
Jet energy scale	2.2%
Diboson normalisation	5.3%
$e\mu$ region extrapolation	4.0%
$Z(l^+l^-)$normalisation	4.8%
Signal specific	
QCD scale + PDF (qqZH)	7.4%
QCD scale + PDF (ggZH)	4.0%
Total statistical only	$-50/+56\%$
Total uncertainty	$-55/+62\%$



CMS-PAS-EXO-16-038

V(qq)H - Overview

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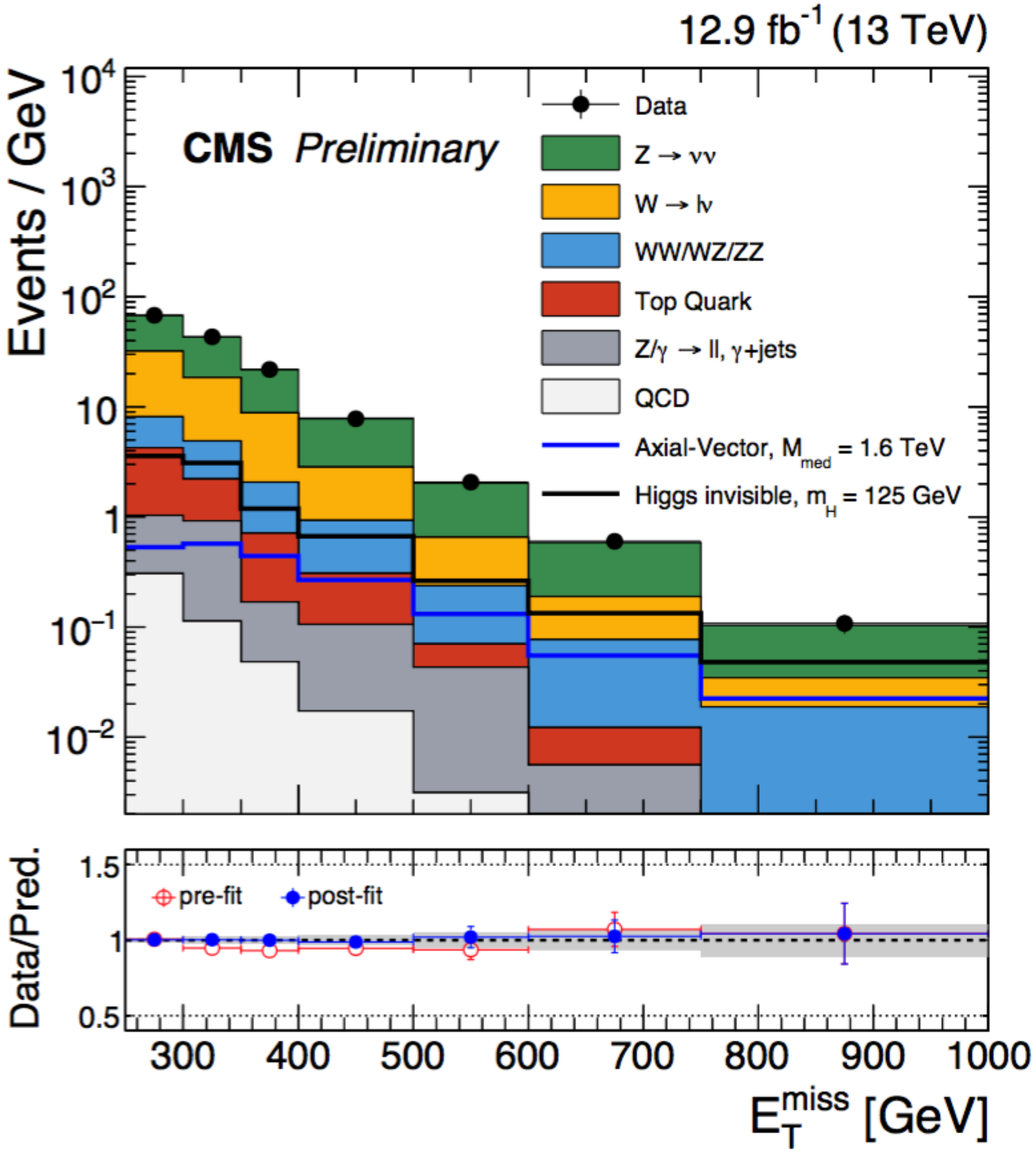
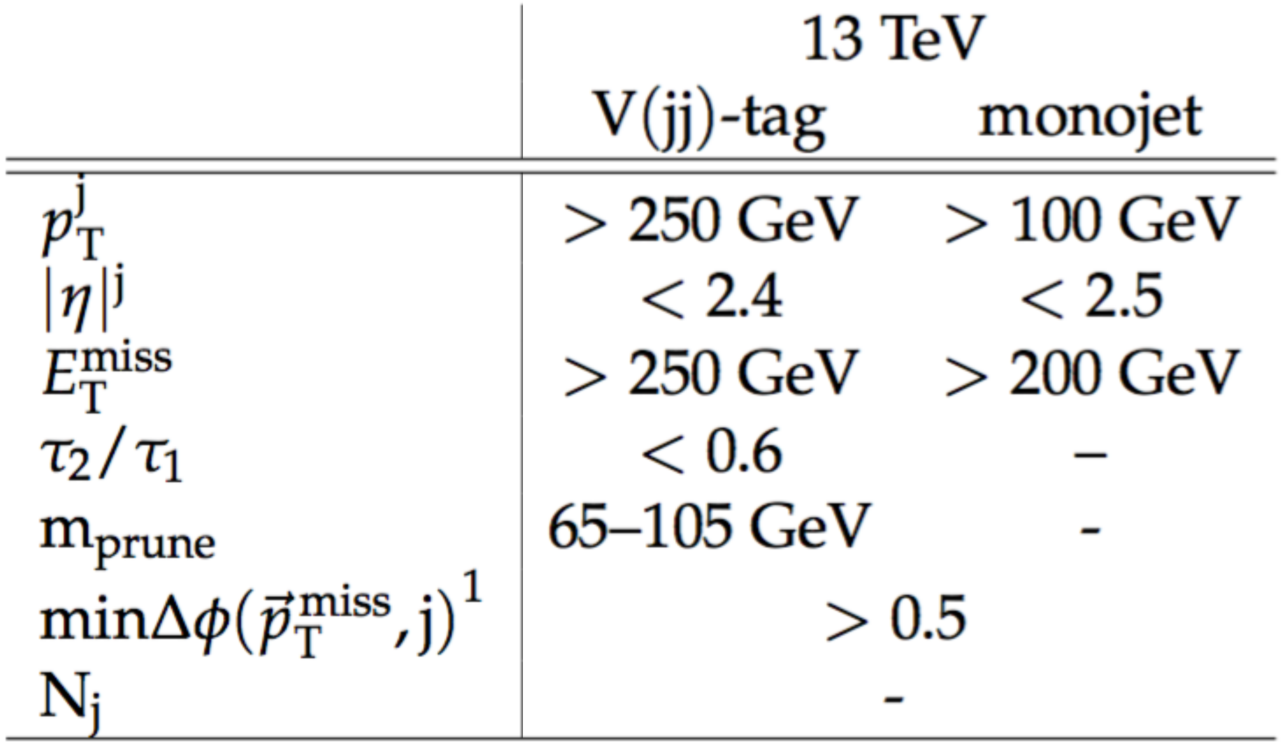
- Triggered by soup of MET and MHT
  - 95% Efficient >200GeV
- Jet quality requirements
- Veto events with any
  - Leptons (eμτ)
  - Photons
  - B jets
- AK8 jets with subjet cuts to tag V



CMS-PAS-EXO-16-037



	13 TeV	
	V(jj)-tag	monojet
p_T^j	> 250 GeV	> 100 GeV
$\lvert\eta\rvert^j$	< 2.4	< 2.5
E_T^{miss}	> 250 GeV	> 200 GeV
τ_2/τ_1	< 0.6	–
m_{prune}	65–105 GeV	-
$\min\Delta\phi(\vec{p}_T^{miss}, j)^1$	> 0.5	
N_j	-	

gH - Overview

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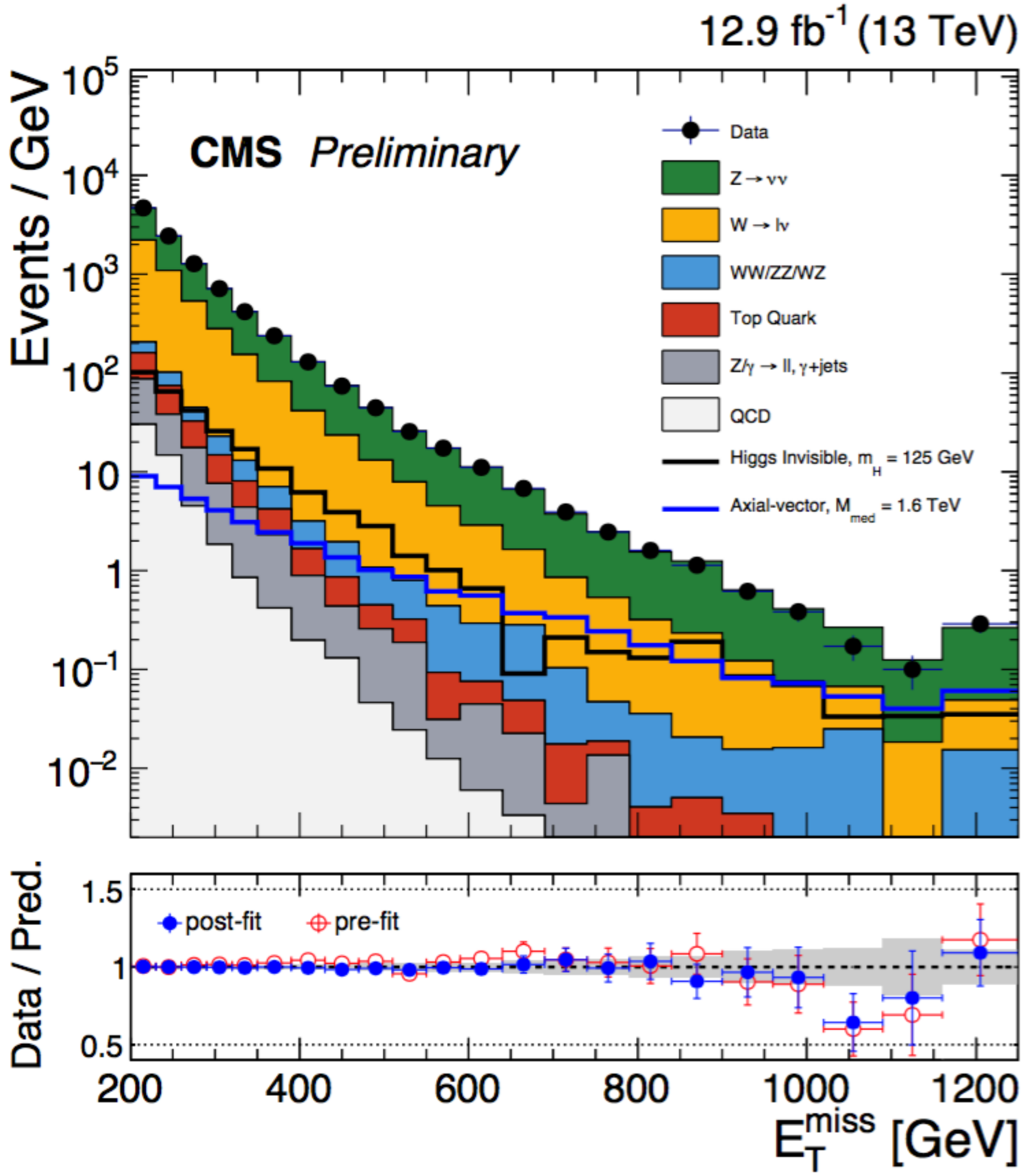
- Events with high quality AK4 jets
- Veto events with any
  - Leptons (eμτ)
  - Photons
  - B jets
- Includes events failing V-tagging

	13 TeV	
	V(jj)-tag	monojet
p_T^j	> 250 GeV	> 100 GeV
$\lvert\eta\rvert^j$	< 2.4	< 2.5
E_T^{miss}	> 250 GeV	> 200 GeV
τ_2/τ_1	< 0.6	–
m_{prune}	65–105 GeV	-
$\min\Delta\phi(\vec{p}_T^{miss}, j)^1$	> 0.5	
N_j	-	



CMS-PAS-EXO-16-037

Z(qq)H & gH - Limits

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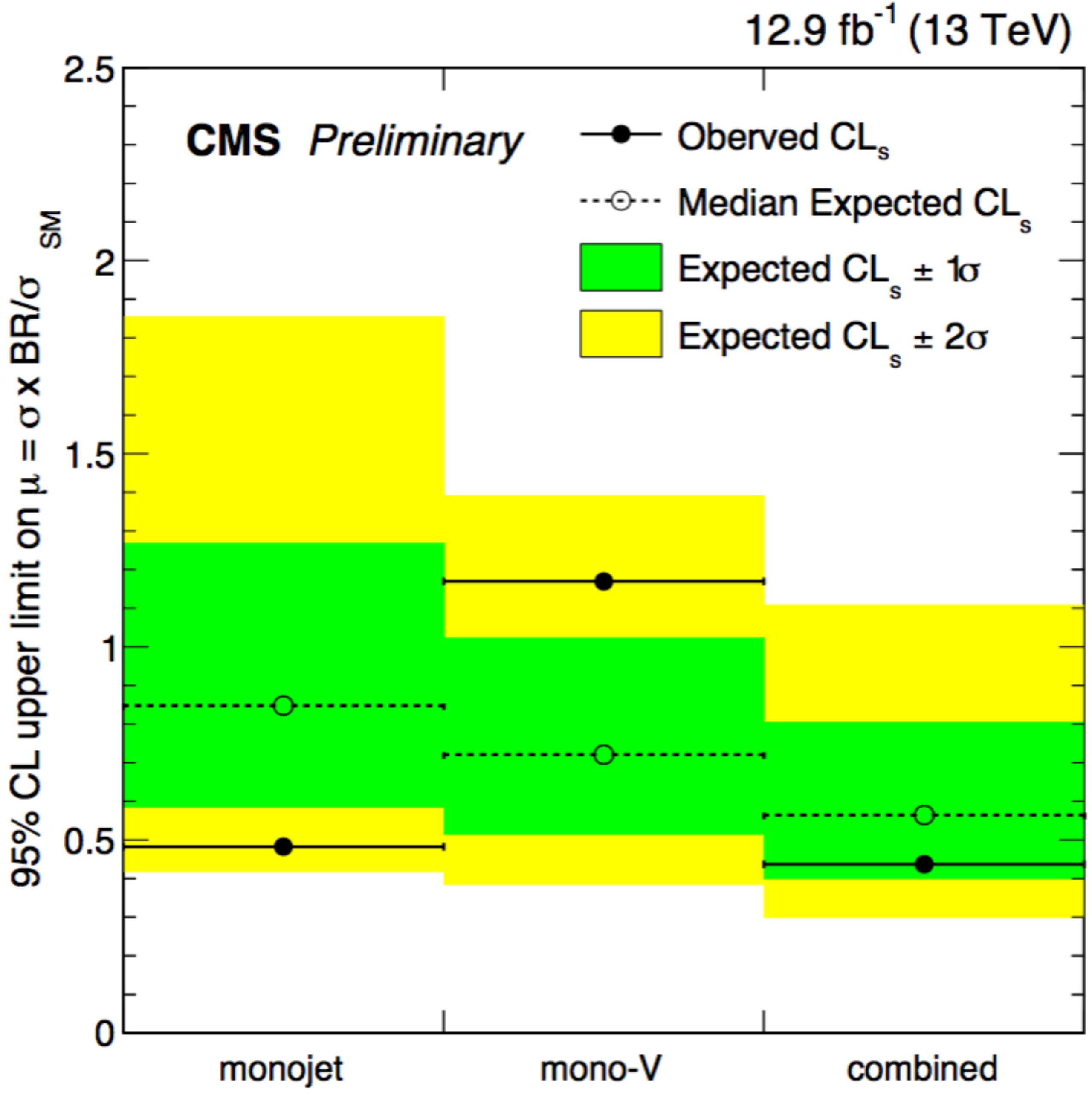
- Transfer factors are dominant uncertainty
    - Need better EWK production theory
- 5 Control region simultaneous fit
    - 2 W(lν)+Jets (e, μ)
    - 3 Z(νν)+Jets (ee, μμ, γ)

Systematic uncertainty	Impact
Common	
γ+jets/Z($\nu\nu$)+jets ratio theory	32%
W($l\nu$)+jets/Z($\nu\nu$)+jets ratio theory	21%
Jet energy scale+resolution	12%
V-tagging efficiency	12%
Lepton veto efficiency	13%
Electron efficiency	13%
Muon efficiency	8.6%
b jet tag efficiency	5.7%
Photon efficiency	3.1%
E_T^{miss} scale	4.6%
Top quark background normalisation	6.0%
Diboson background normalisation	$< 1\%$
Luminosity	$< 1\%$
Signal specific	
ggH p_T-spectrum	12%
QCD scale + PDF (ggH)	3.0%
QCD scale + PDF (VH)	1.4%
Total statistical only	$-46/+50\%$
Total uncertainty	$-69/+74\%$



CMS-PAS-EXO-16-037

The Combination

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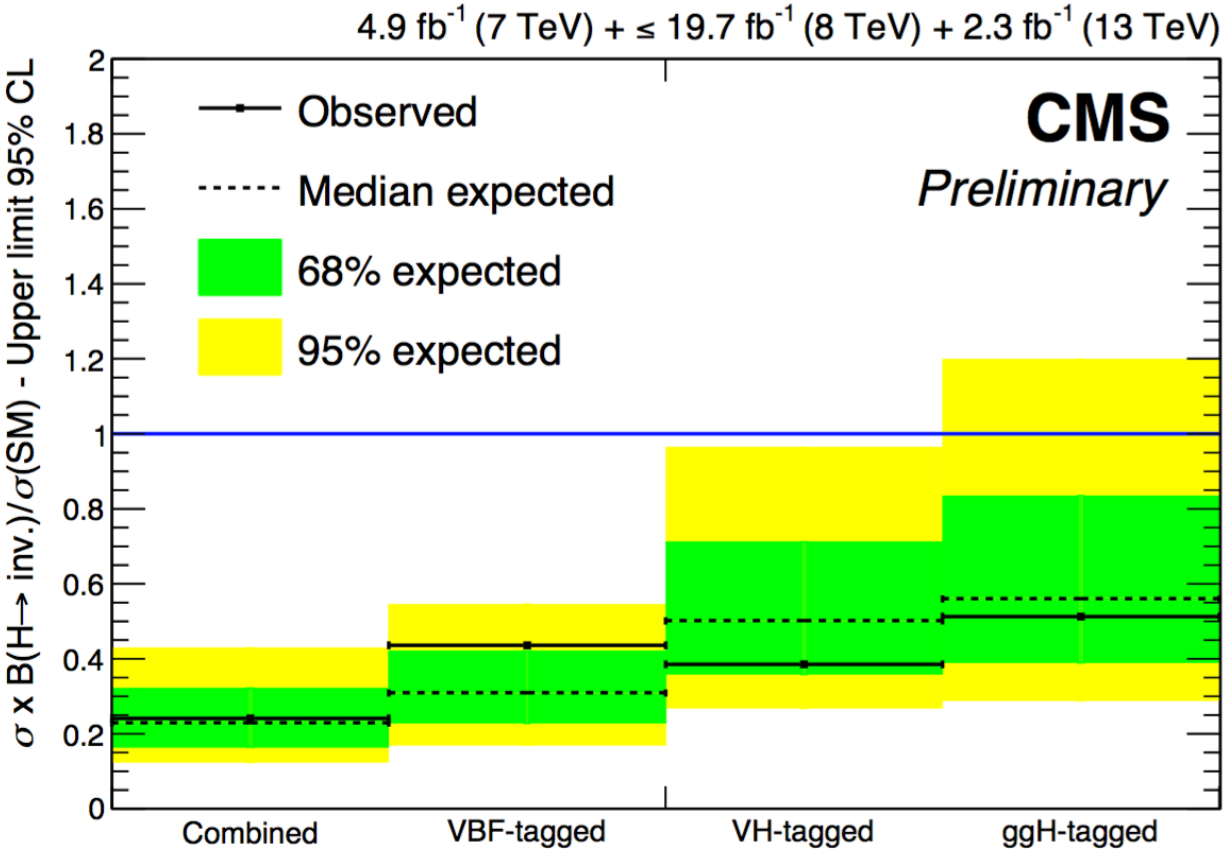
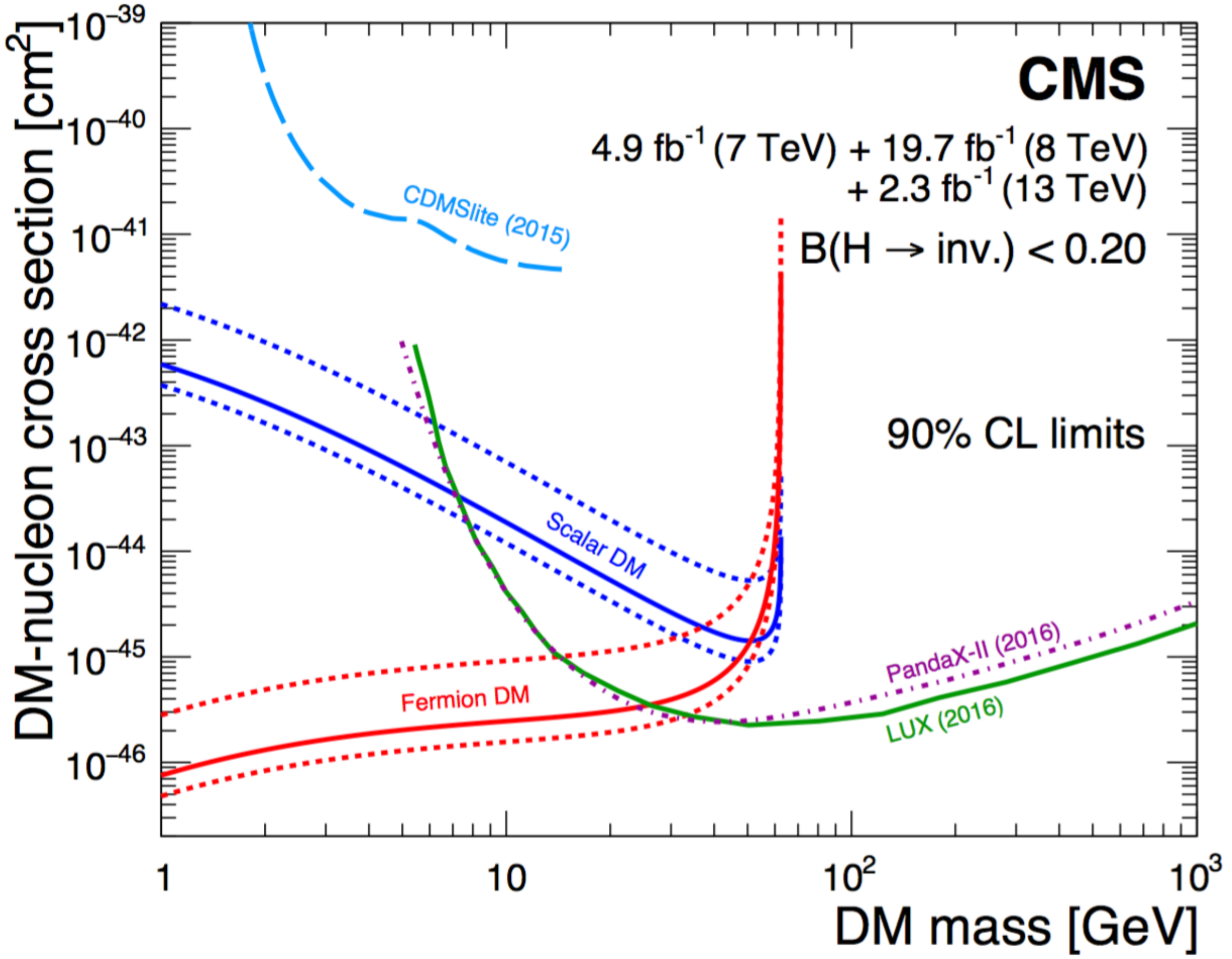


- Leverage statistical power
- No excess → set upper limits

- Translation to dark matter direct detection limits
- Complementary phase space



CMS-PAS-HIG-16-016

Outlook

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Will CMS see Higgs Invisible Signal?

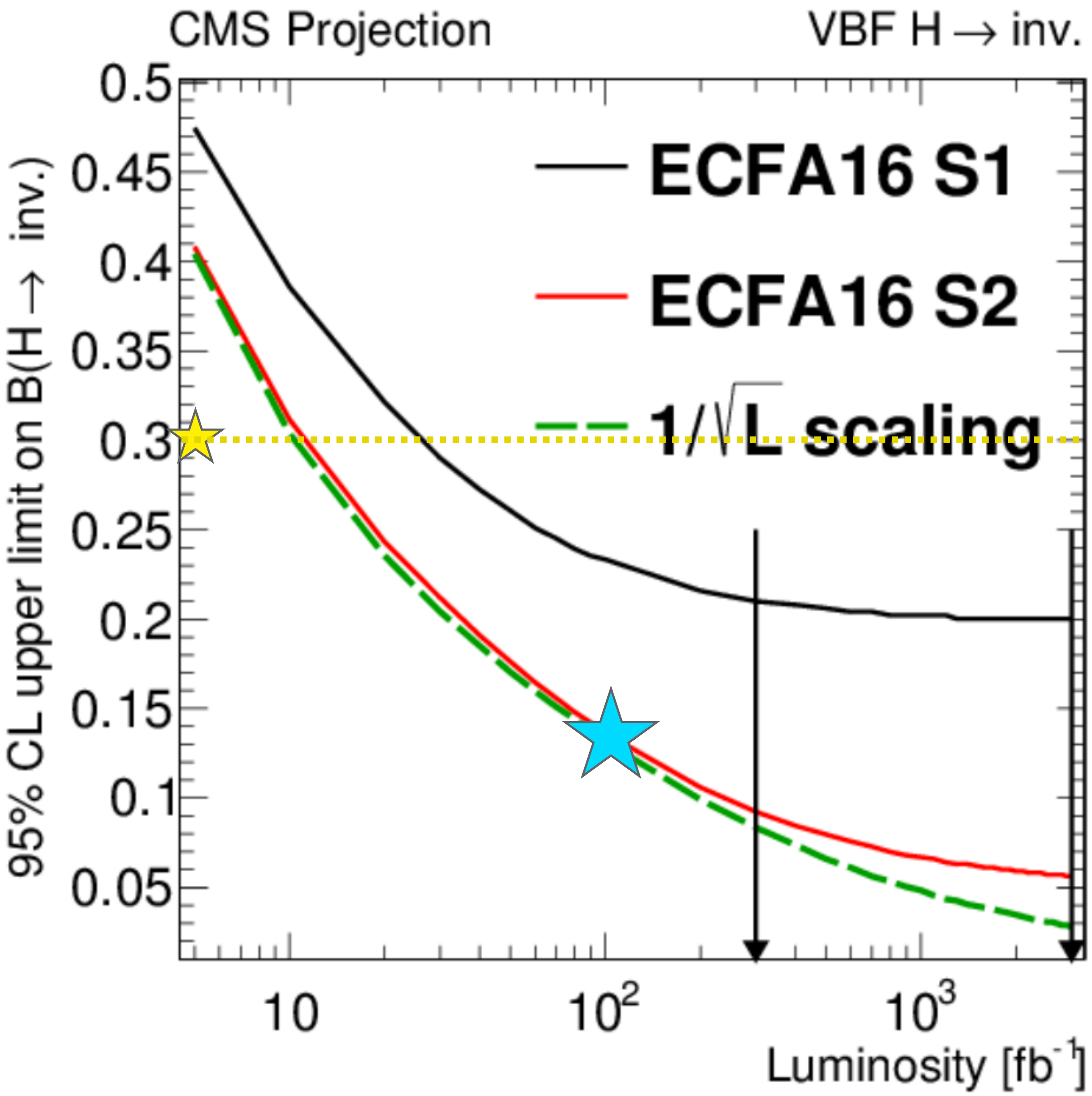
- SM predicts BR(H→inv.) = 0.001
  - H→ZZ*→4ν
- BSM could be around the corner

Future Collider Workshop study:

- Extrapolate result under different assumptions about uncertainties

★ arXiv:1610.09218

★ Projected limit by 2018



CMS-DP-2016-064

Backup

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Systematics Extrapolation

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Extrapolation strategy for ECFA16 projections

Public results are extrapolated to larger data sets 300 and 3000 fb^{-1}. In order to summarize the future physics potential of the CMS detector at the HL-LHC, extrapolations are presented under different uncertainty scenarios:

S1 All systematic uncertainties are kept constant with integrated luminosity. The performance of the CMS detector is assumed to be unchanged with respect to the reference analysis.

S1+ All systematic uncertainties are kept constant with integrated luminosity. The effects of higher pileup conditions and detector upgrades on the future performance of CMS are taken into account.

S2 Theoretical uncertainties scaled down by a factor 1/2, while experimental systematic uncertainties are scaled down by the square root of the integrated luminosity until they reach a defined lower limit based on estimates of the achievable accuracy with the upgraded detector. The performance of the CMS detector is assumed to be unchanged with respect to the reference analysis.

S2+ Theoretical uncertainties scaled down by a factor 1/2, while experimental systematic uncertainties are scaled down by the square root of the integrated luminosity until they reach a defined lower limit based on estimates of the achievable accuracy with the upgraded detector. The effects of higher pileup conditions and detector upgrades on the future performance of CMS are taken into account.

Theoretical uncertainties follow the prescriptions of the LHC Yellow Report 4 (in preparation).