Search for invisible decays of the 125 GeV Higgs boson using the CMS detector

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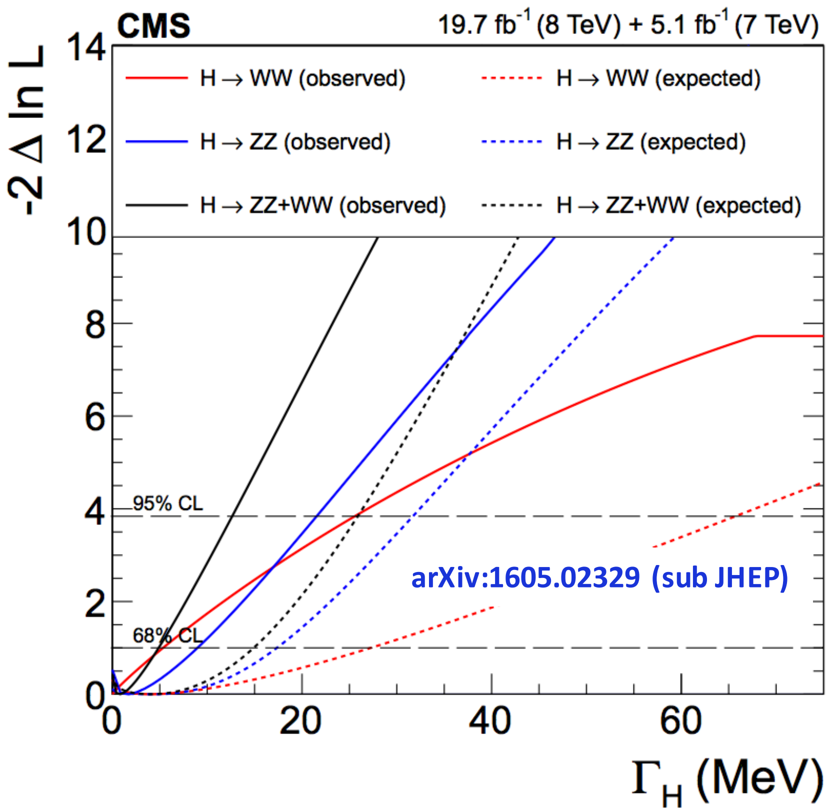
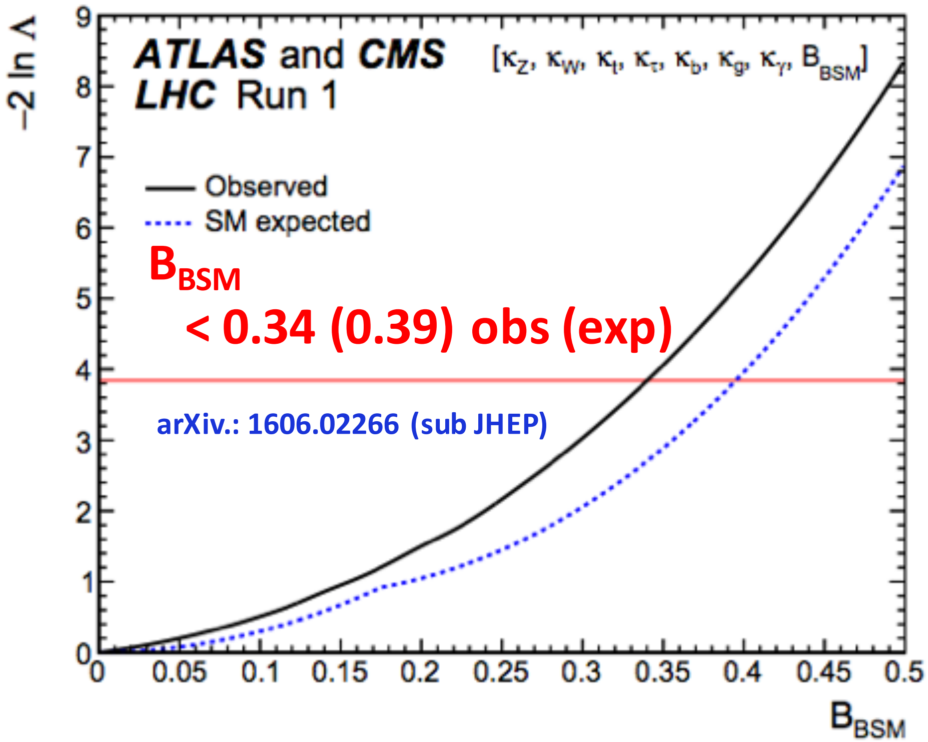
Nicholas Wardle - CERN
On behalf of the CMS collaboration

Introduction

Several BSM models predict additional contributions to Higgs boson width

Indirect constraints from
off-shell <-> on-shell combination…





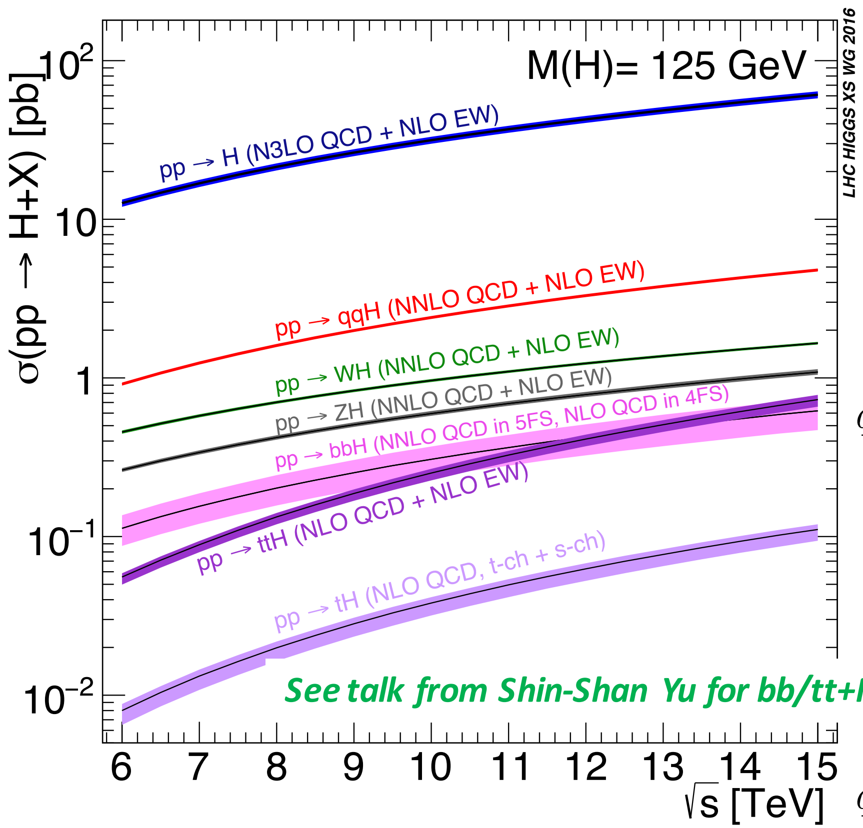
… and constraints on additional decay modes from Run-1 combined LHC couplings measurements (combined analysis of visible decay modes)

Invisible decay channels

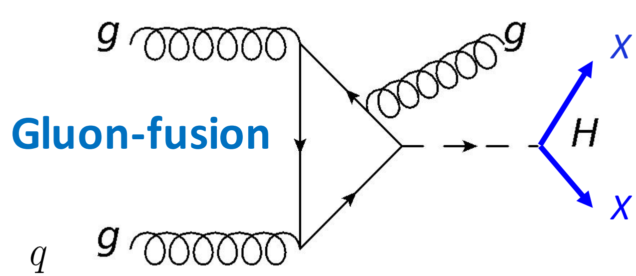
In SM, B(H->Inv) ~ 1.2x10^{-3} (H->4ν)

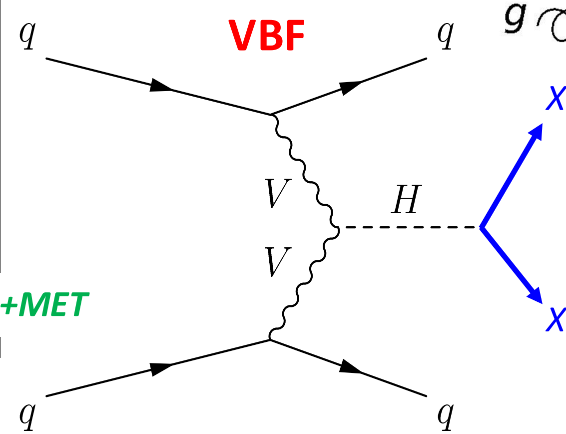
-> Invisible Higgs boson decays will be a hint of new physics

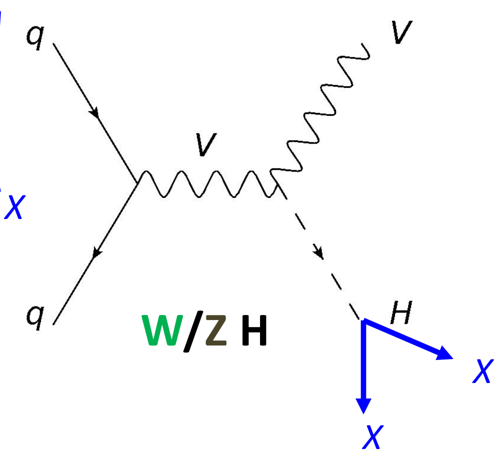
Search for invisible Higgs boson decays in several production modes, with different cross-sections and S/B ratios



See talk from Shin-Shan Yu for bb/tt+MET







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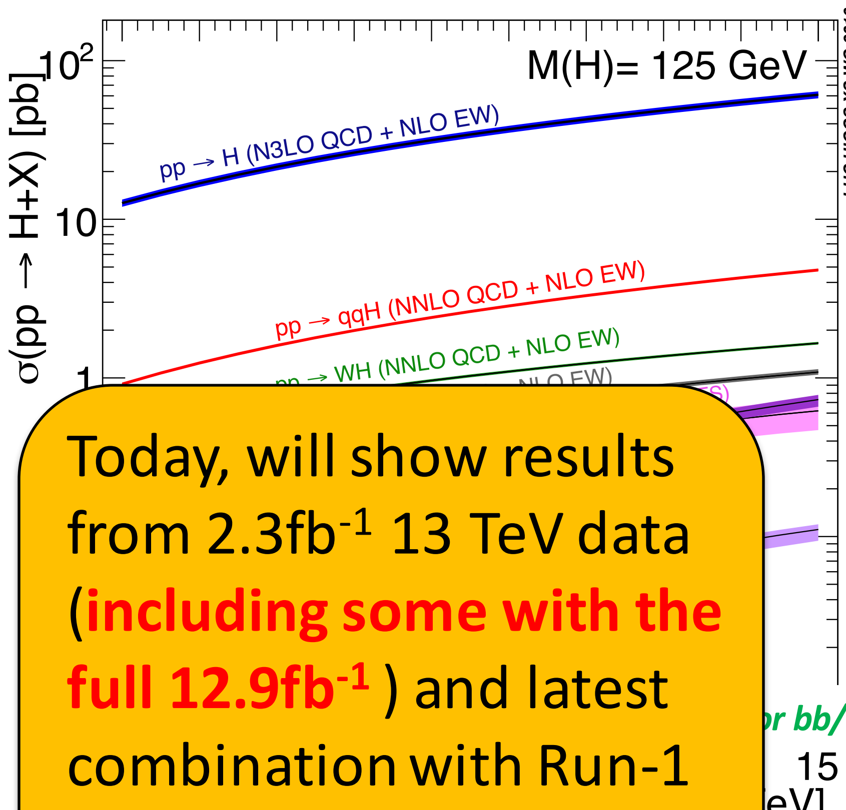
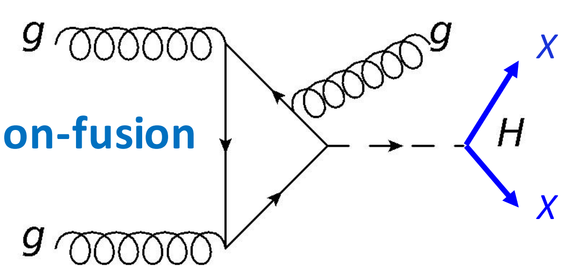
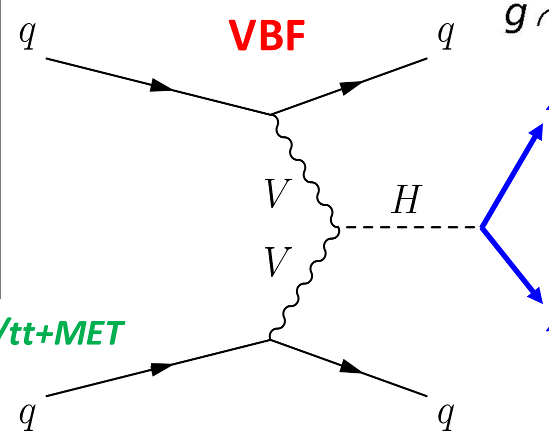
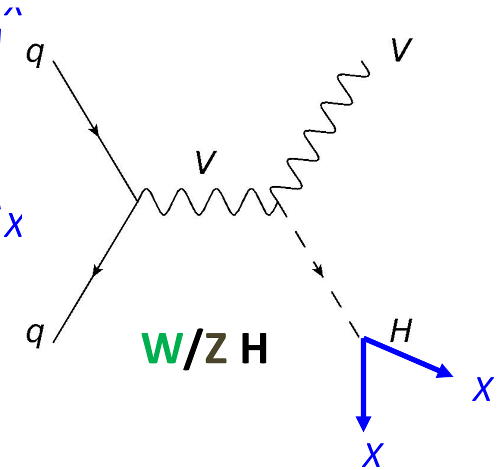


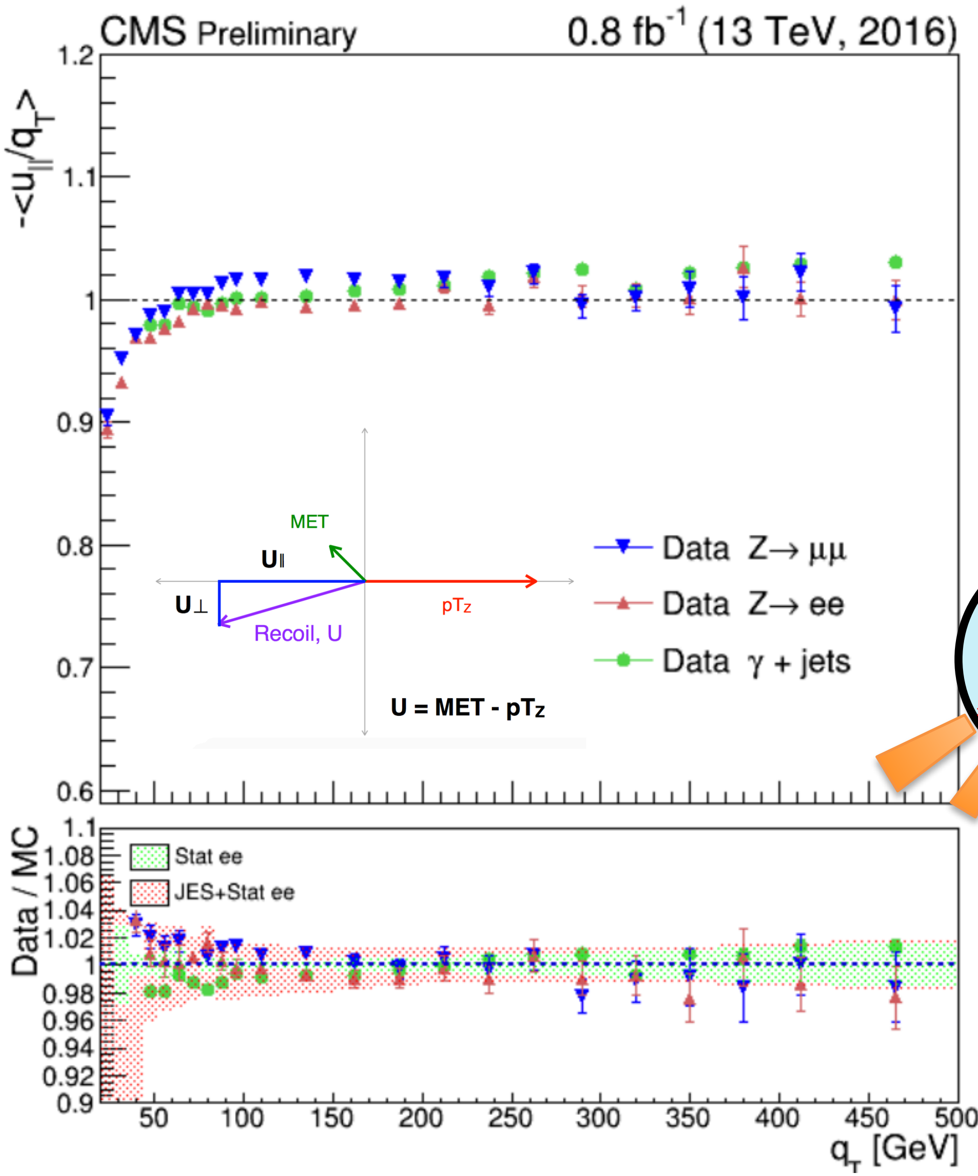
Today, will show results from 2.3fb^{-1} 13 TeV data (**including some with the full 12.9fb^{-1}**) and latest combination with Run-1 searches





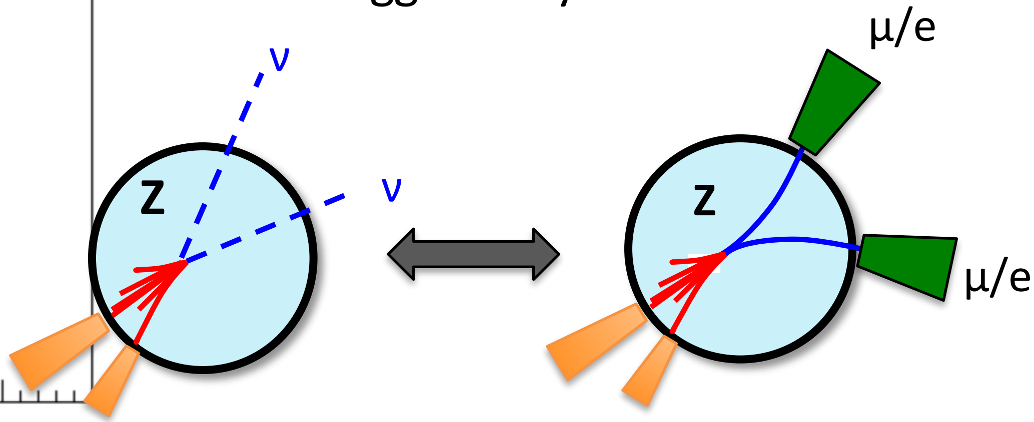


Missing Energy at CMS



Common signature is visible system recoiling against large **missing energy**

Well modelled missing energy response and resolution is key to invisible Higgs decay searches



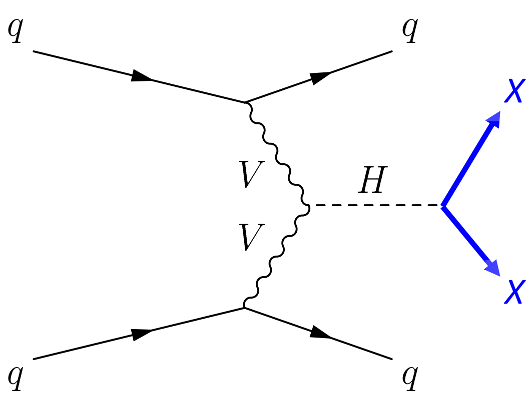
Recoil (U) used as proxy for missing energy in Z->ll + jets, W->lν +jets, and γ+jets events for modelling E_T^{miss} tails from SM backgrounds

Vector-boson Fusion

Look for two jets with VBF topology:

Dedicated VBF trigger selects events with two jets with

- high rapidity gap
- large dijet mass



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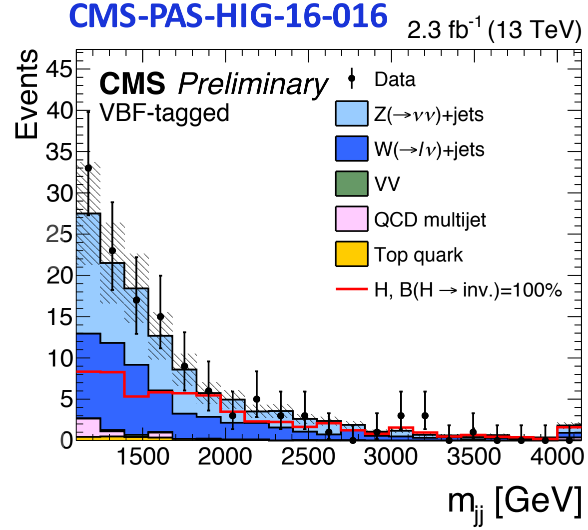
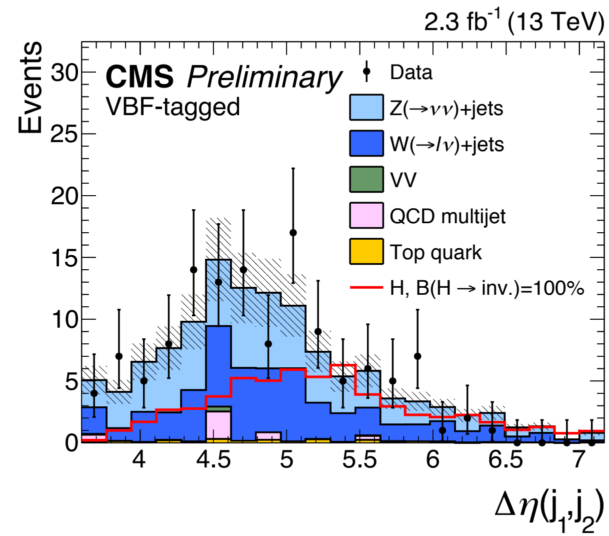




Offline selection driven by requirement to remain efficient wrt trigger

- $p_T^{j1,j2}$ > 80, 70 GeV
- m_{jj} > 1100 GeV
- E_T^{miss} > 200 GeV
- $\Delta\phi(j,E_T^{miss})$ > 2.3 rad
- $\Delta\eta(j,j)$ > 3.6

} *Optimized for H(125)*

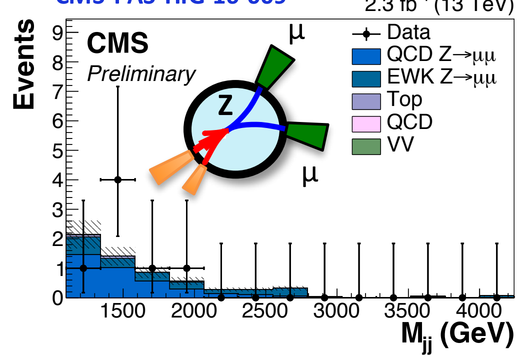
Upgrade in hardware trigger for 2016 data-taking will allow reduction of these thresholds ***(see talk by A. Tapper)***

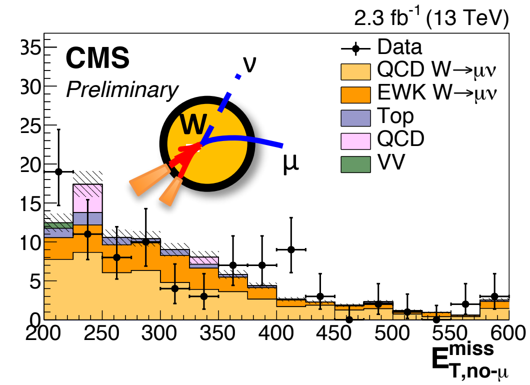
Vector-boson Fusion

Dominant backgrounds due to **SM W/Z+jets** -> Use lepton control regions in data to normalize

- Assume common scale-factor between W/Z processes
- **30%** systematic on ratio to account for HO corrections

CMS-PAS-HIG-16-009





Process		Signal region	Control regions: single e	single μ	single τ	$\mu^+\mu^-$	QCD
$Z(\mu^+\mu^-)$+jets	QCD	–	–	–	–	4.2 ± 1.1	–
	EW	–	–	–	–	2.0 ± 0.7	–
$Z(\nu\nu)$+jets	QCD	47 ± 12	–	–	–	–	–
	EW	21 ± 7	–	–	–	–	–
$W(\mu\nu)$+jets	QCD	13 ± 2	–	53 ± 5	0.40 ± 0.19	–	45 ± 5
	EW	4.3 ± 0.8	–	27 ± 3	–	–	6.0 ± 0.9
$W(e\nu)$+jets	QCD	9.3 ± 1.5	17 ± 3	–	0.2 ± 2.2	–	39 ± 4
	EW	5.4 ± 1.1	7.8 ± 1.3	–	0.2 ± 0.13	–	6.1 ± 1.0
$W(\tau\nu)$+jets	QCD	13 ± 2	0.06 ± 0.06	–	12 ± 2	–	74 ± 9
	EW	5.5 ± 1.2	–	–	5.1 ± 1.2	–	24 ± 3
Top quark		2.3 ± 0.4	1.5 ± 0.3	6.8 ± 0.9	7.1 ± 1.0	0.22 ± 0.06	82 ± 11
QCD multijet		3 ± 23	–	5 ± 3	0.4 ± 0.3	–	1200 ± 170
Dibosons		0.7 ± 0.3	0.4 ± 0.4	0.8 ± 0.4	–	0.02 ± 0.02	1.8 ± 0.7
Total bkg.		125 ± 28	27 ± 3	91 ± 8	25 ± 4	6.4 ± 1.4	1500 ± 170
Data		126	29	89	24	7	1461
Signal	qqH	53.6 ± 4.9					
$m_H = 125$ GeV	ggH	5.4 ± 3.6					

Vector-boson Fusion

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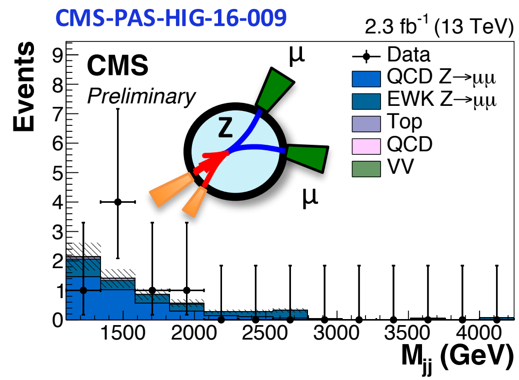

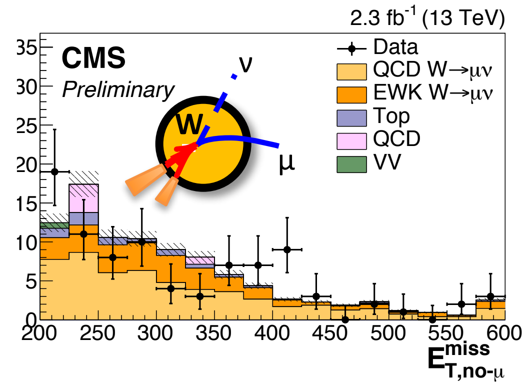

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$m_H = 125$ GeV	ggH	5.4 ± 3.6					

Simple counting experiment to extract potential signal

Backgrounds constrained ***in-situ*** via simultaneous fit across **signal and control regions**

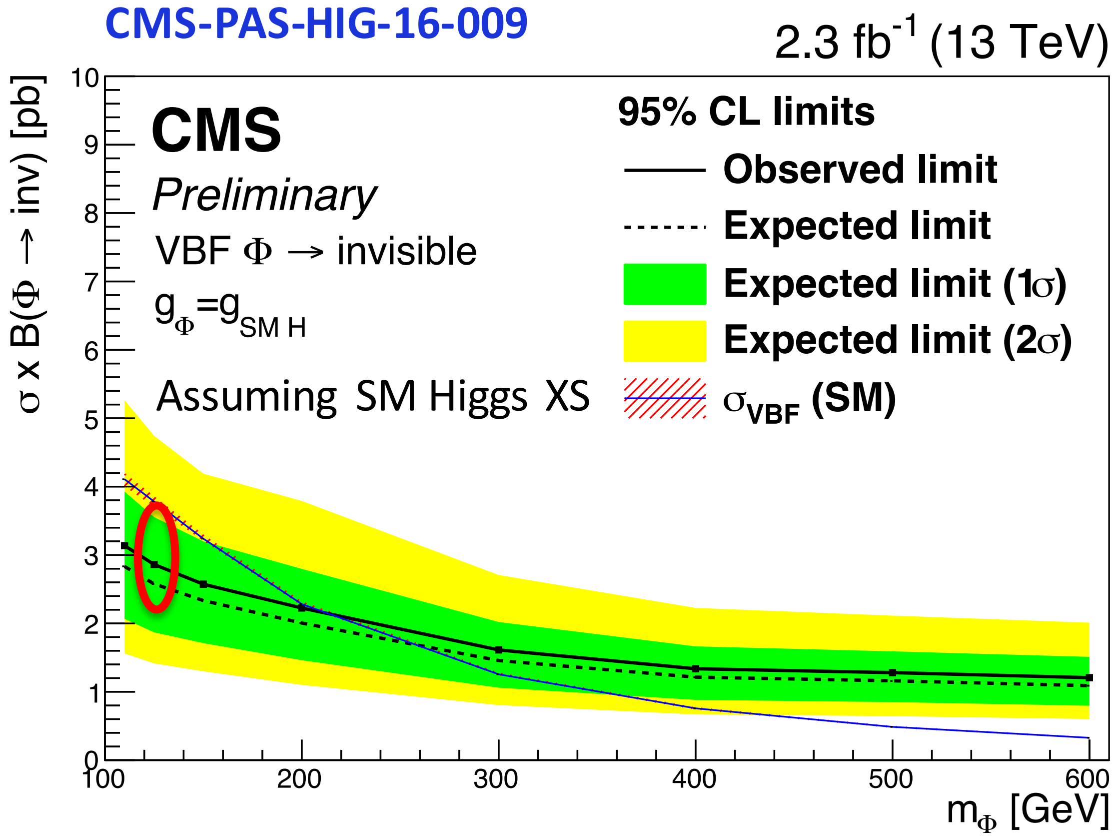
Vector-boson Fusion

Limits on **σxBR** of a scalar decaying invisibly as a function of hypothesised mass

-> Compare to "Higgs-like" scalar via VBF production

See talk from Bjoern Penning

CMS-PAS-HIG-16-009



B(H->inv) < 69% (62%) obs (exp) @ 125 GeV

Vector-boson Fusion

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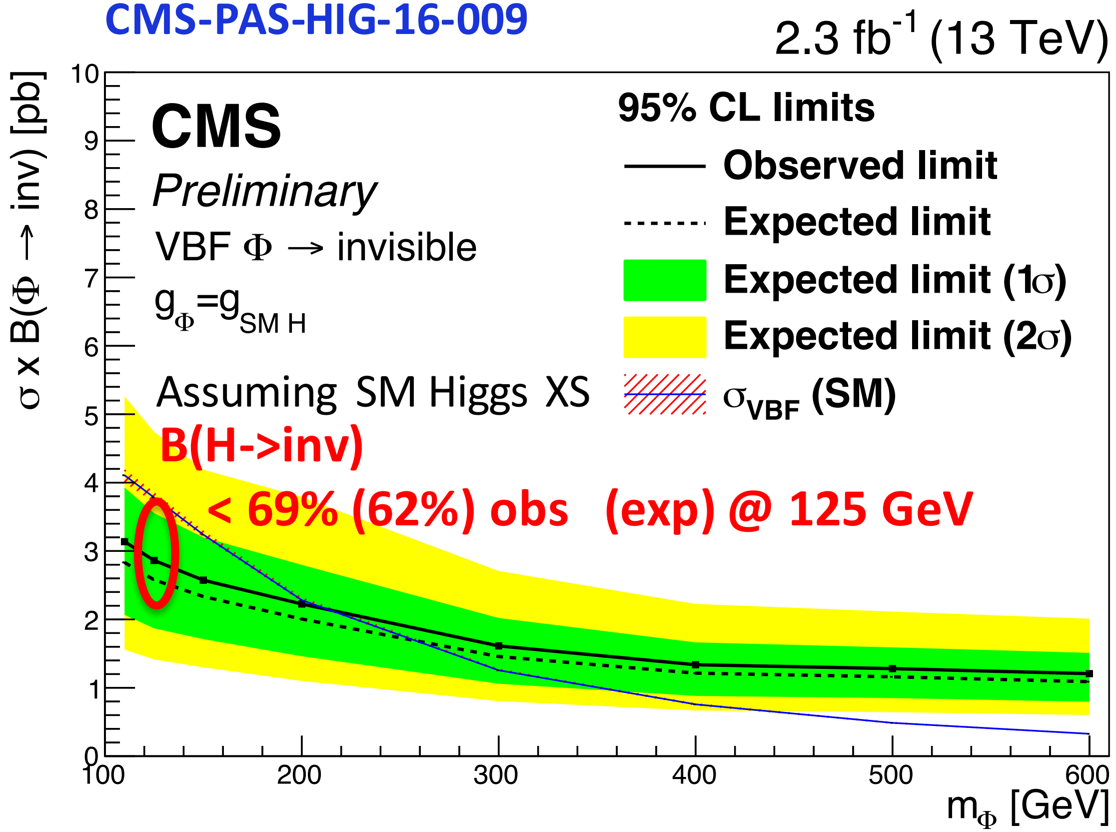


Largest systematic due to **W/Z ratio,** however sensitivity is **statistics limited**

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	$-33/+32\%$

Z(ll) H

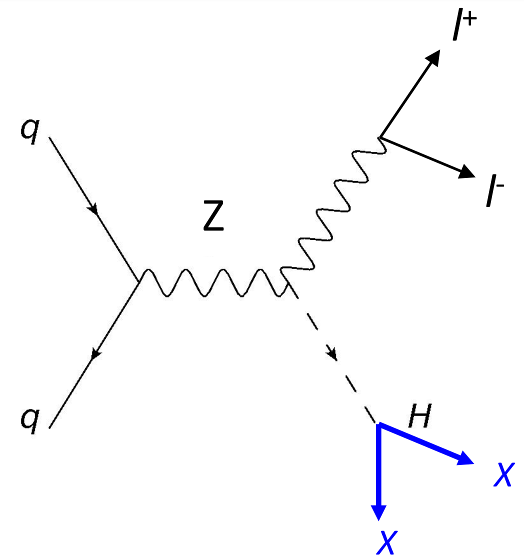
Leptonic Z decay offers clean final state

look for E_T^{miss} + 2 well isolated opposite sign, e/μ

-> p_T^l>20 GeV, 76 < mll < 106 GeV

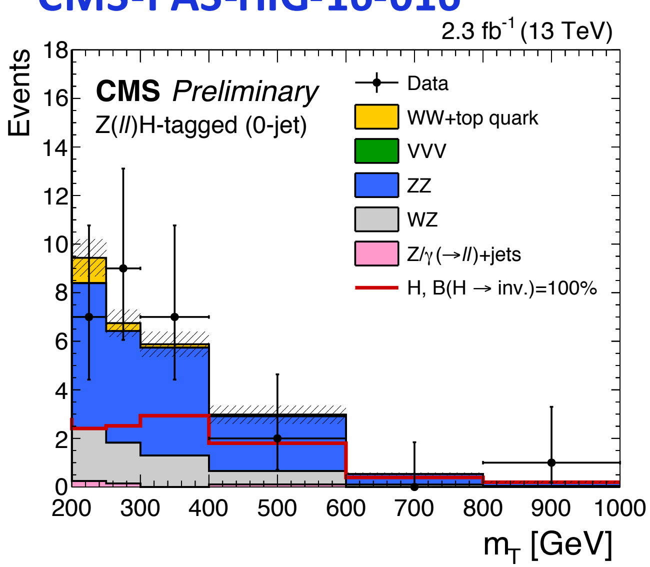
-> $\Delta\phi(Z, E_T^{miss}) > 2.8$

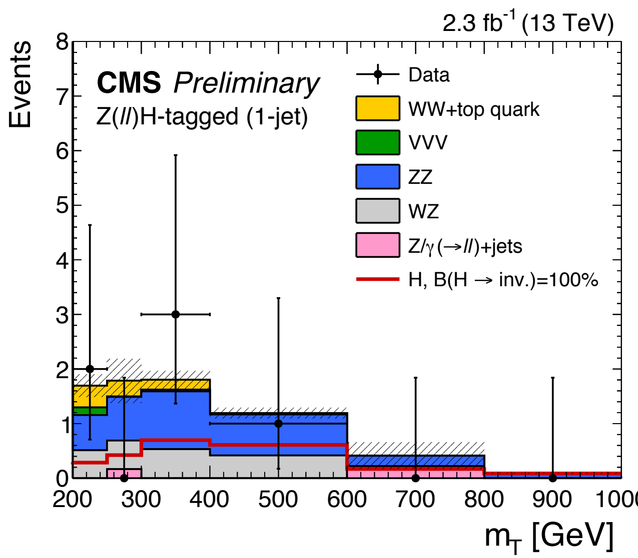
-> $\Delta\phi(j, E_T^{miss}) > 0.5$ - kills Z+jets background



Fit transverse mass (**m_T**) distributions in electron/muon channels, separated into 0 and 1 jet categories

CMS-PAS-HIG-16-016

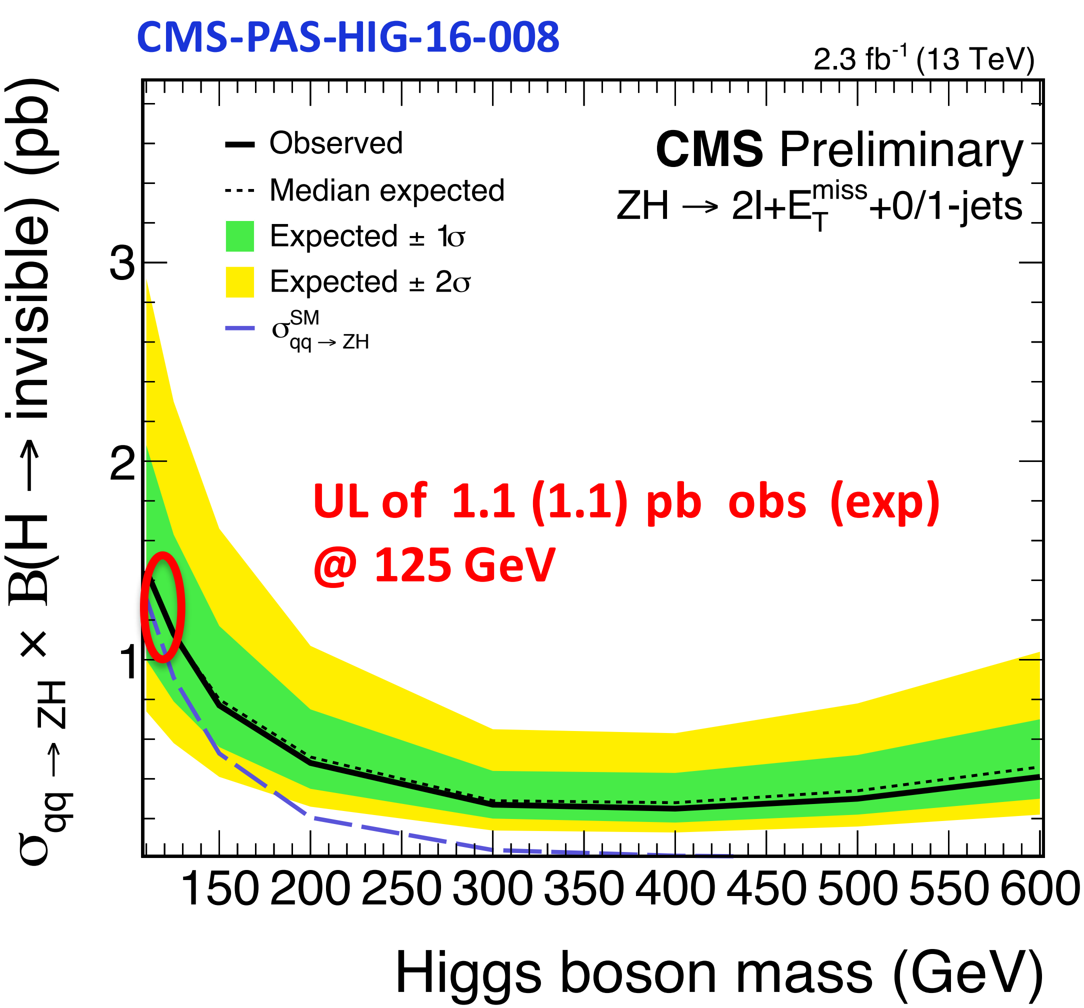




Backgrounds dominated by **diboson processes**

ZZ(2l2v) (70%)
WZ(lvll) (25%)
-> Estimated from simulation @NLO

Z(ll) H



Systematic uncertainty dominated by **theory in ZZ** backgrounds

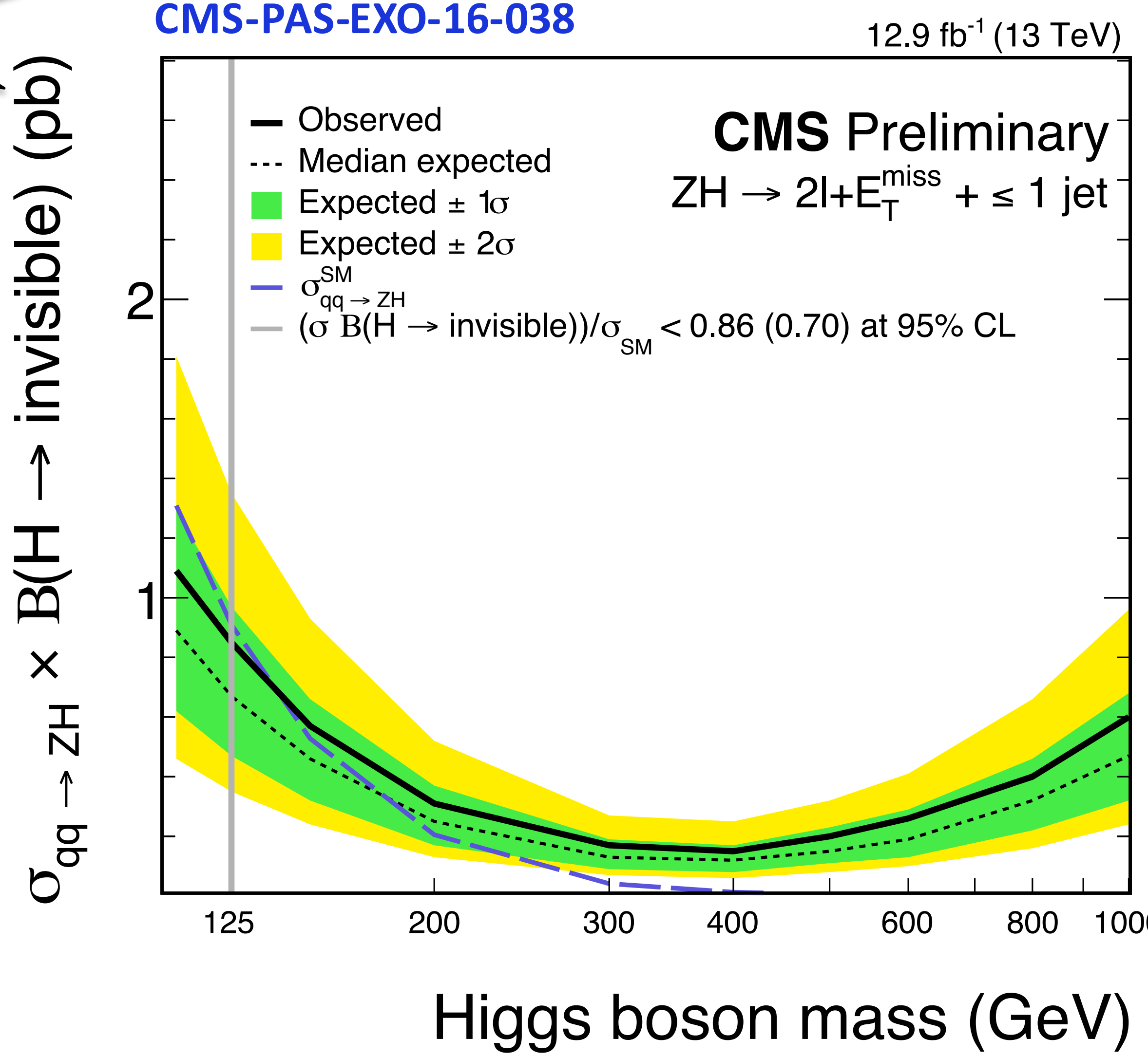
Sensitivity statistics limited

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	$-55/+62\%$

Z(ll) H

NEW with 12.9 fb^{-1}

CMS-PAS-EXO-16-038



Assuming SM x-section

B(H->inv)

< 86% (70%)

obs (exp)

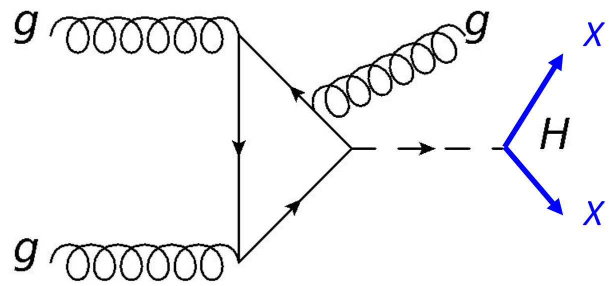
See talk from Shin-Shan Yu

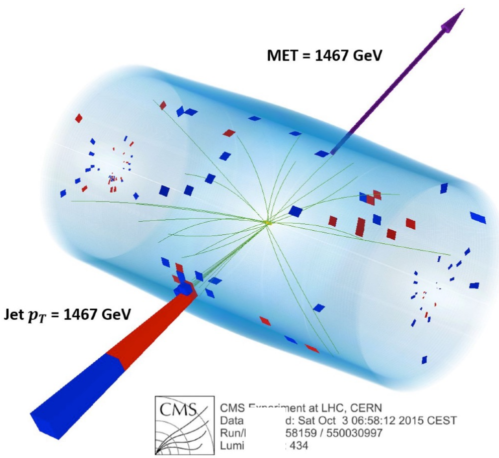
Gluon-fusion

Gluon-fusion production tagged via ISR jet(s)

Look for high p_T, central jet(s) + large missing energy

- $p_T^{\ j} > 100$ GeV
- $|\eta| < 2.5$
- $E_T^{miss} > 200$ GeV

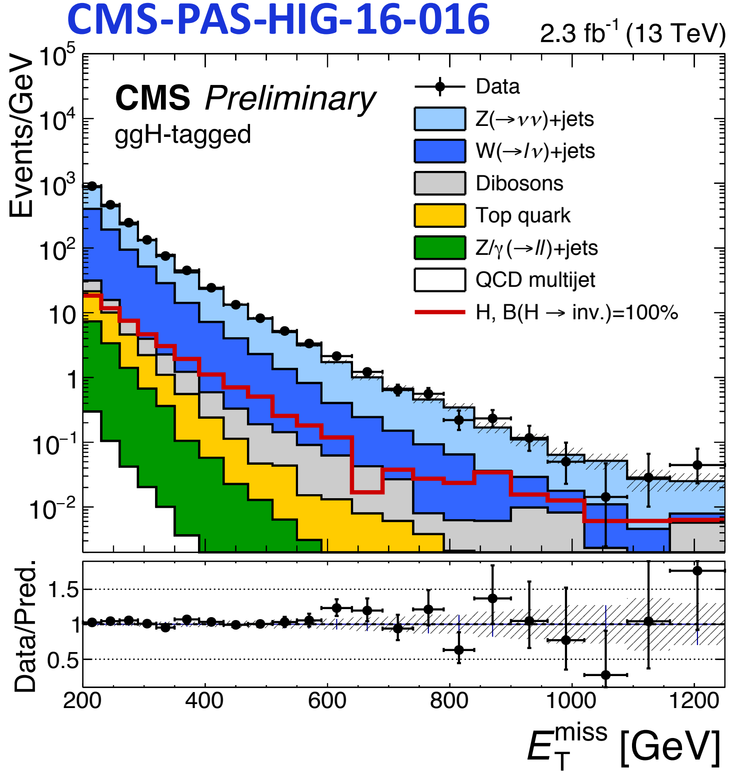




Analysis also used for generic DM searches

See talk from Shin-Shan Yu

CMS-PAS-HIG-16-016



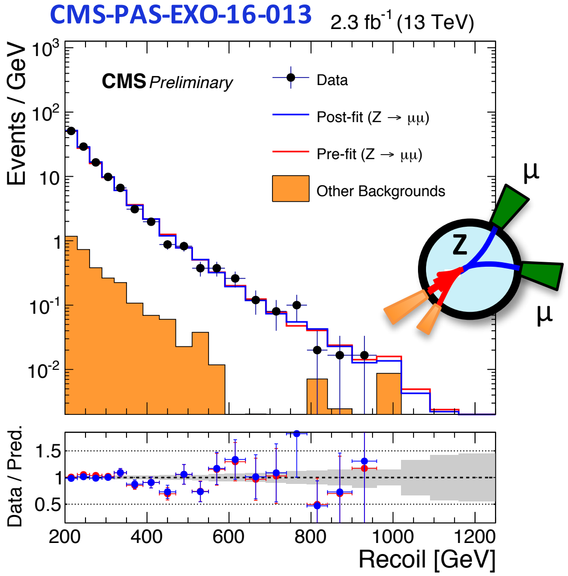
Signal extraction from fit to E_T^{miss} spectrum (sizeable theory systematics on ggH p_T spectrum)

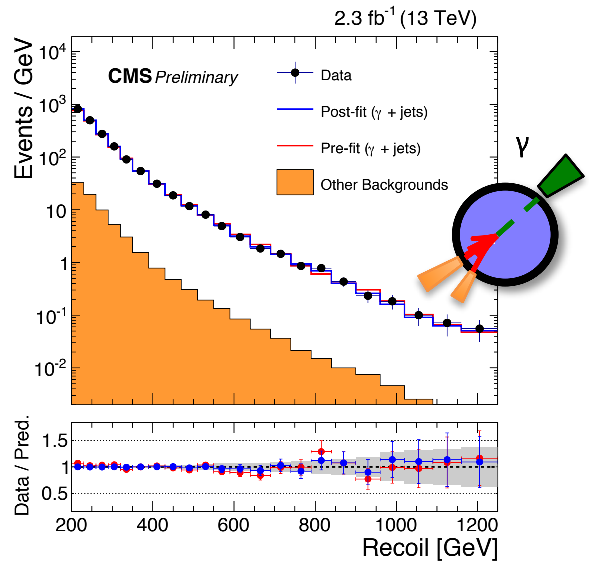
Dominant backgrounds from **W/Z**+jets

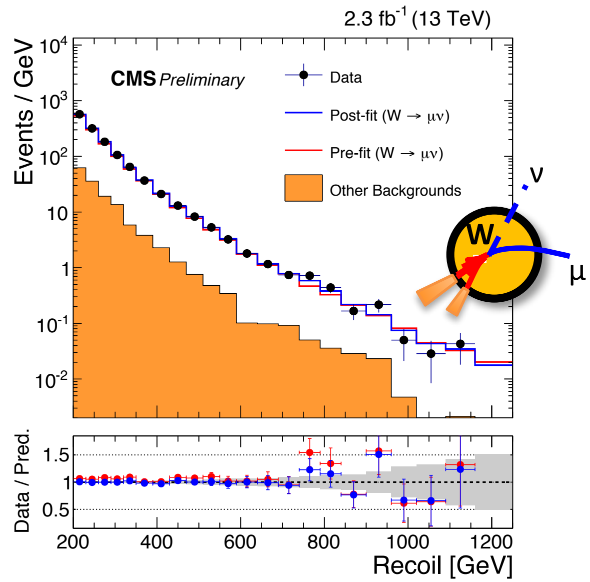
-> Constrain shape and normalization with lepton and photon control regions

Gluon-fusion

CMS-PAS-EXO-16-013







"Recoil" in control regions defined as

$$|\vec{E}_T^{miss} + \sum \vec{\mathrm{p}}_T^{ll/\gamma}|$$

For each bin of E_T^{miss} equivalent recoil bin in Z->μμ/ee, γ+jets and W->eν/μν translated to signal region via transfer factors.

Simultaneous fit across all regions allowing for sys.

- lepton/photon efficiency/purity
- W/Z and γ/Z ratios theory

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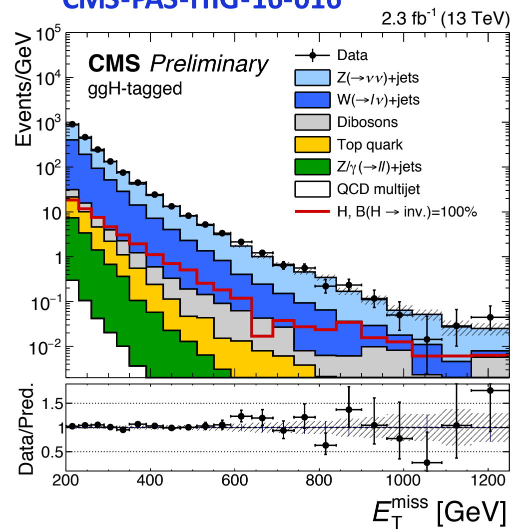
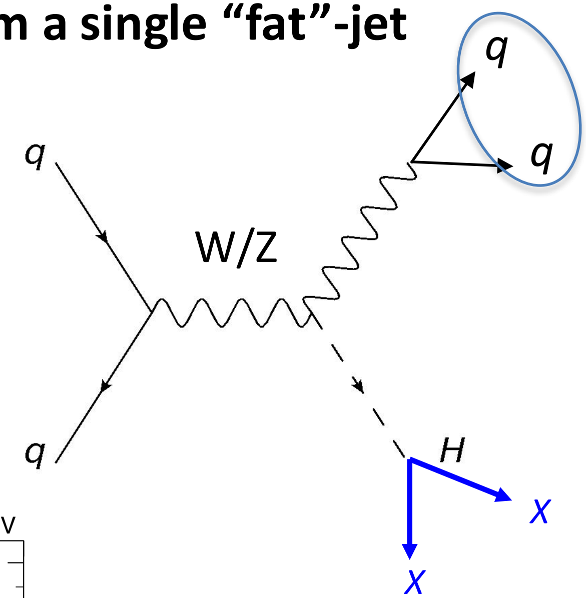


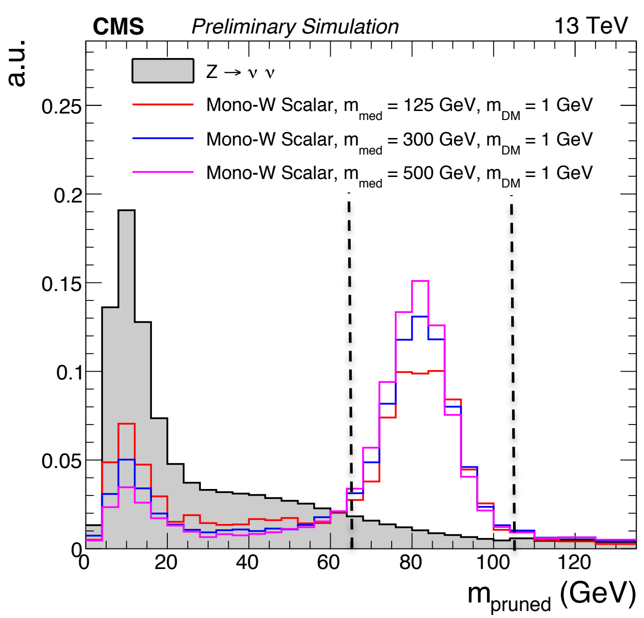
V(jj) H

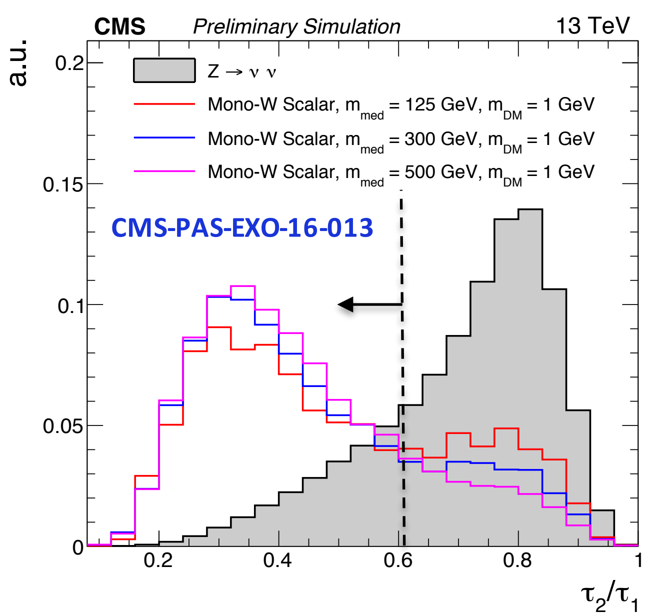
Boosted (high p_T) vector bosons decaying to jets will form a single "fat"-jet



Use jet substructure techniques to identify hadronically decaying V-bosons:

- Look for high-p_T "fat" jet with $\mathbf{m_J}$ close to m_W or m_Z
  - $65 < m_J < 105$ GeV
- N-subjettiness ($\boldsymbol{\tau_N}$) (likelihood for N-daughter hypotheses)
  - $\tau_2/\tau_1 < 0.6$





Additionally require

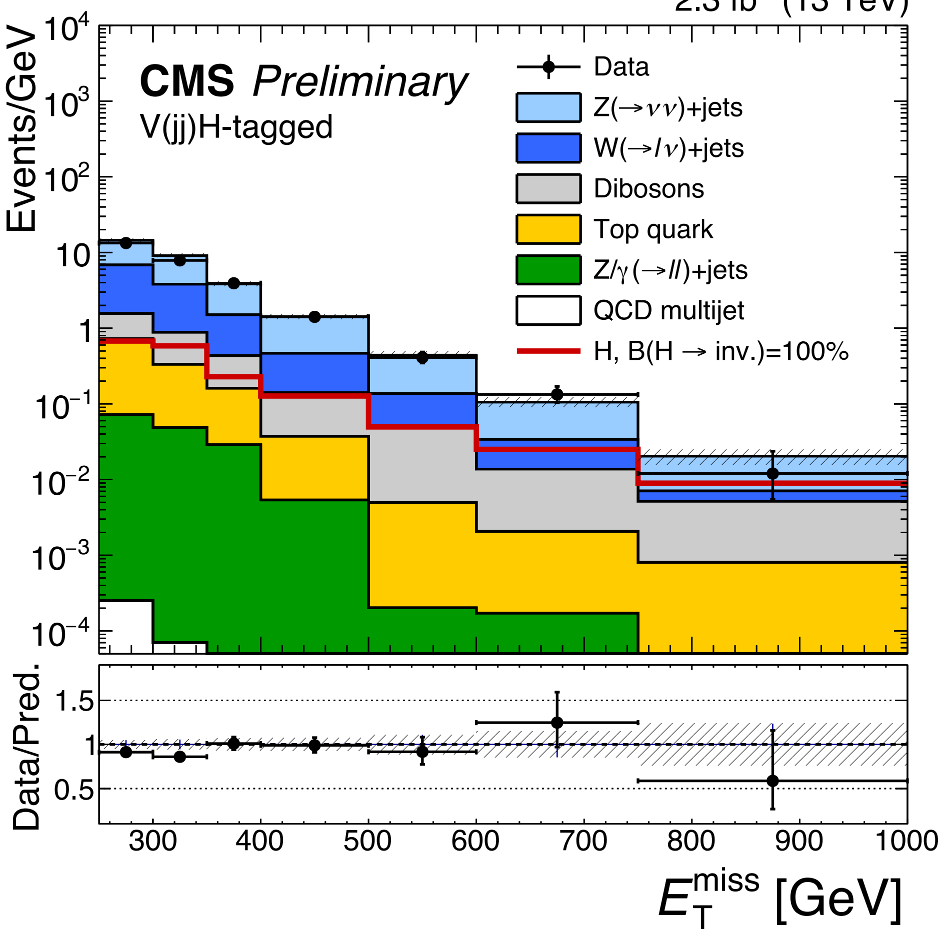
- $p_T^{\ J} > 250$ GeV
- **$E_T^{miss} > 250$ GeV**
- $\Delta\phi(J, E_T^{miss}) > 0.5$ rad

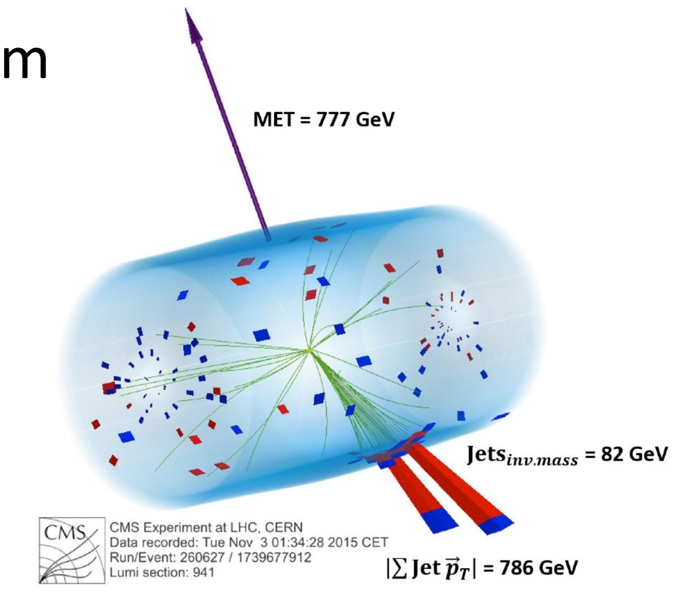
Events selected in this analysis are removed from gluon-fusion tag

V(jj) H

Signal extracted from fit to E_T^{miss} spectrum

CMS-PAS-HIG-16-016





Dominant backgrounds from SM V+jets

-> Use leptonic W/Z and γ + jets events in data to constrain backgrounds

-> Independent scale factors per bin

-> Systematics due to γ/Z and W/Z HO electroweak and QCD effects as in ggH

Gluon-fusion and V(jj)H

Upper limits on **σxBR/σ$_{SM}$** for Higgs decaying invisibly @ 125 GeV

Limits with 2.3fb^{-1}	Expected	Observed
ggH - tag	1.11	1.46
V(jj) H -tag	1.43	1.04
Comb.	0.84	**0.85**

Assume SM values for ratios of production cross-sections → Comb.

V(jj) H -tag

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%

ggH - tag

Systematic uncertainty	Impact
Common	
Muon efficiency	24%
Electron efficiency	22%
Lepton veto efficiency	16%
b jet tag efficiency	3.2%
W($l\nu$)+jets/Z($\nu\nu$)+jets ratio theory	16%
γ+jets/Z($\nu\nu$)+jets ratio theory	5.8%
Jet energy scale+resolution	10%
E_T^{miss} scale	1.8%
Luminosity	3.0%
Diboson background normalisation	2.7%
Top quark background normalisation	< 1%
Signal specific	
ggH p_T-spectrum	15%
QCD scale + PDF (ggH)	5.8%
Total statistical only	−22/ + 25%
Total uncertainty	−55/ + 62%

Systematic uncertainty dominated by W/Z and γ/Z theory systematics, JES and lepton ID

-> All related to transfer from CR to SR to constrain W/Z+jets backgrounds

Gluon-fusion and V(jj)H

Upper limits on **σxBR/σ_{SM}** for Higgs decaying invisibly @ 125 GeV

NEW with 12.9 fb^{-1}

CMS-PAS-EXO-16-037

	Expected	Observed
ggH - tag	0.85	0.48
V(jj) H -tag	0.72	1.17
Comb.	0.56	**0.44**

See talk from Shin-Shan Yu

Combination
Run-1 + 2015 data

Combination

NEW

Combination of H->invisible searches performed using **Run-1** dataset and **2.3 fb^{-1} of 13 TeV** (2015) data

Analysis Tag		$\int \mathcal{L}$ (fb^{-1}) 7 TeV	8 TeV	13 TeV	Expected Signal Composition (%) 7 or 8 TeV	13 TeV
qqH-tagged	VBF	–	19.2 [16]	2.3	7.8 (ggH), 92.2 (qqH)	9.1 (ggH), 90.9 (qqH)
VH-tagged	$Z(l^+l^-)$	4.9 [16]	19.7 [16]	2.3	100 (ZH)	100 (ZH)
	$Z(b\bar{b})$ *	–	18.9 [16]	–	100 (ZH)	100 (ZH)
	V(jj)-tagged	–	19.7 [56]	2.3	25.1 (ggH), 5.1 (qqH), 23.0 (ZH), 46.8 (WH)	38.7 (ggH), 7.1 (qqH), 21.3 (ZH), 32.9 (WH)
ggH-tagged	monojet	–	19.7 [56]	2.3	70.4 (ggH), 20.4 (qqH), 3.5 (ZH), 5.7 (WH)	69.4 (ggH), 21.9 (qqH), 4.2 (ZH), 4.6 (WH)

CMS-PAS-HIG-16-016

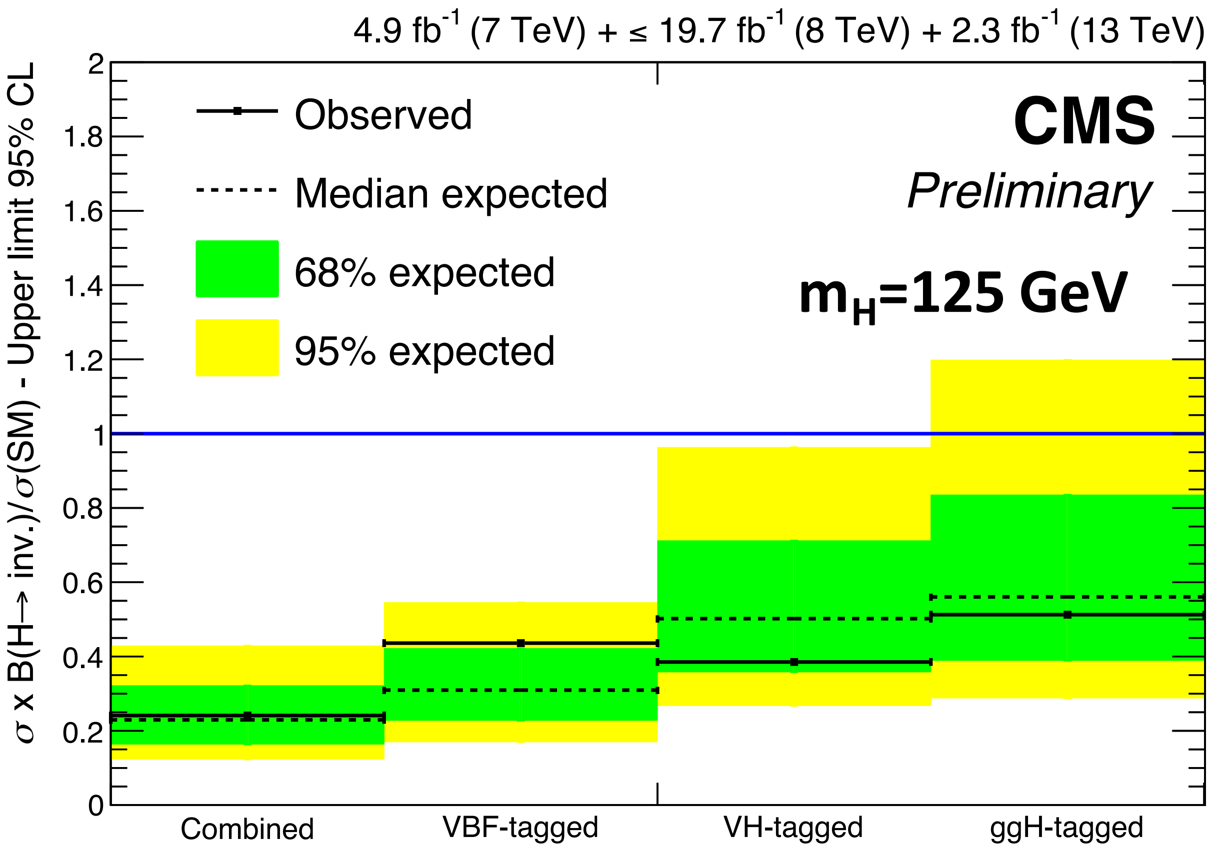
- Latest SM x-sections + uncertainties from LHC-HXSWG used as theory inputs
  -> Including N3LO ggH x-section (*Phys. Lett. B* **737** (2014))
- Explicit event selection vetos allow for combination of searches
  -> VBF tagged events removed from ggH/V(jj)H-tagged searches)

[16] *Eur. Phys. J. C* **74** (2014)
[56] arXiv:1607.05764 (sub JHEP)

*Also include 8TeV Z(bb) channel (not discussed today)

Combination

95% CL Upper limits on **σxBR** relative to SM production



VH includes Z(ll), Z(bb) and V(jj)H channels

Expected sensitivity dominated by vector-boson fusion channel

σxB(H->inv) < 24% observed (23% expected)

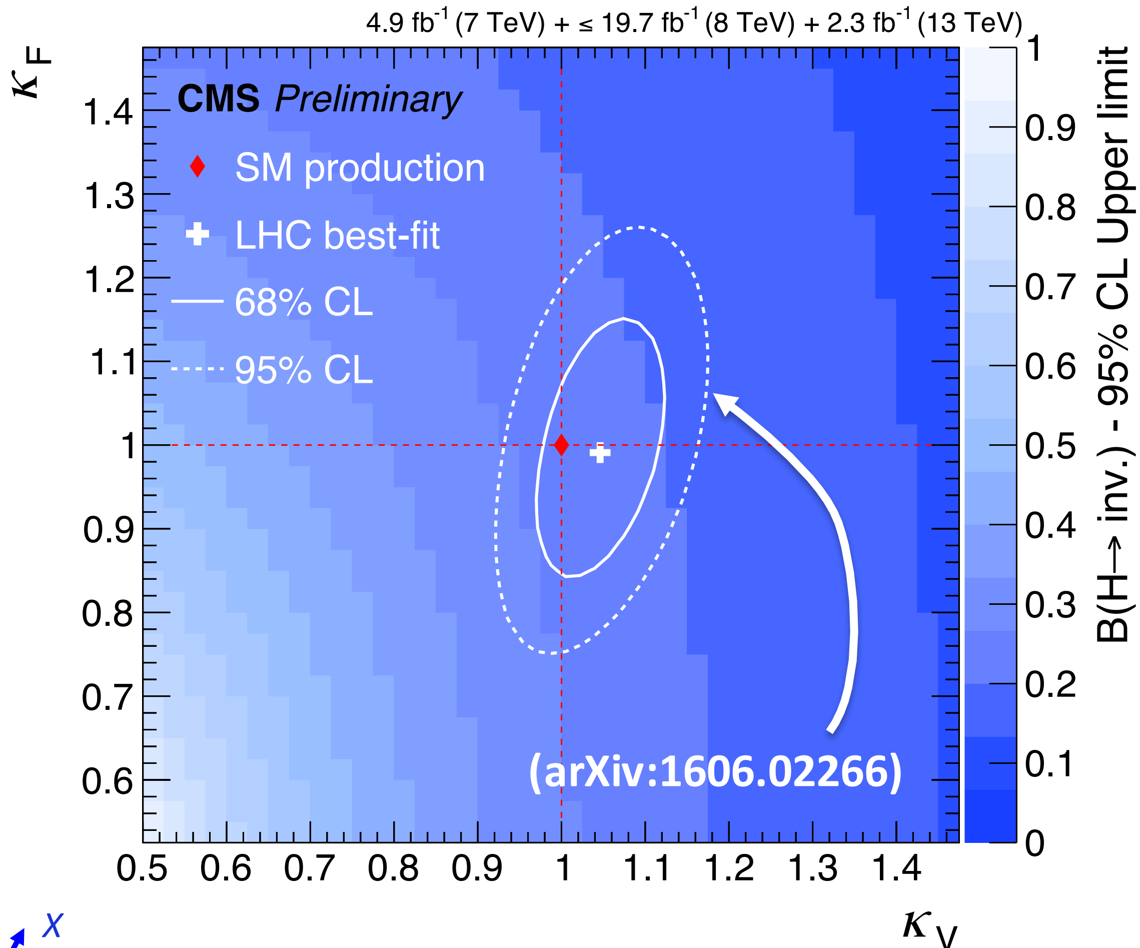
Assume SM values for ratios of production cross-sections

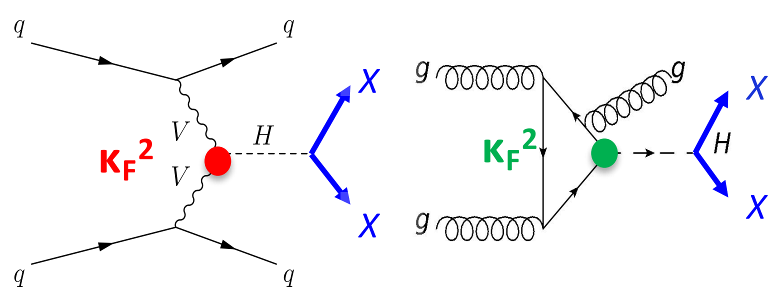
Non-SM production

95% Upper limit on B(H->inv) expressed as for different assumptions on production

Vary coupling modifiers of Higgs boson to SM fermions (κ_F) and vector bosons (κ_V)

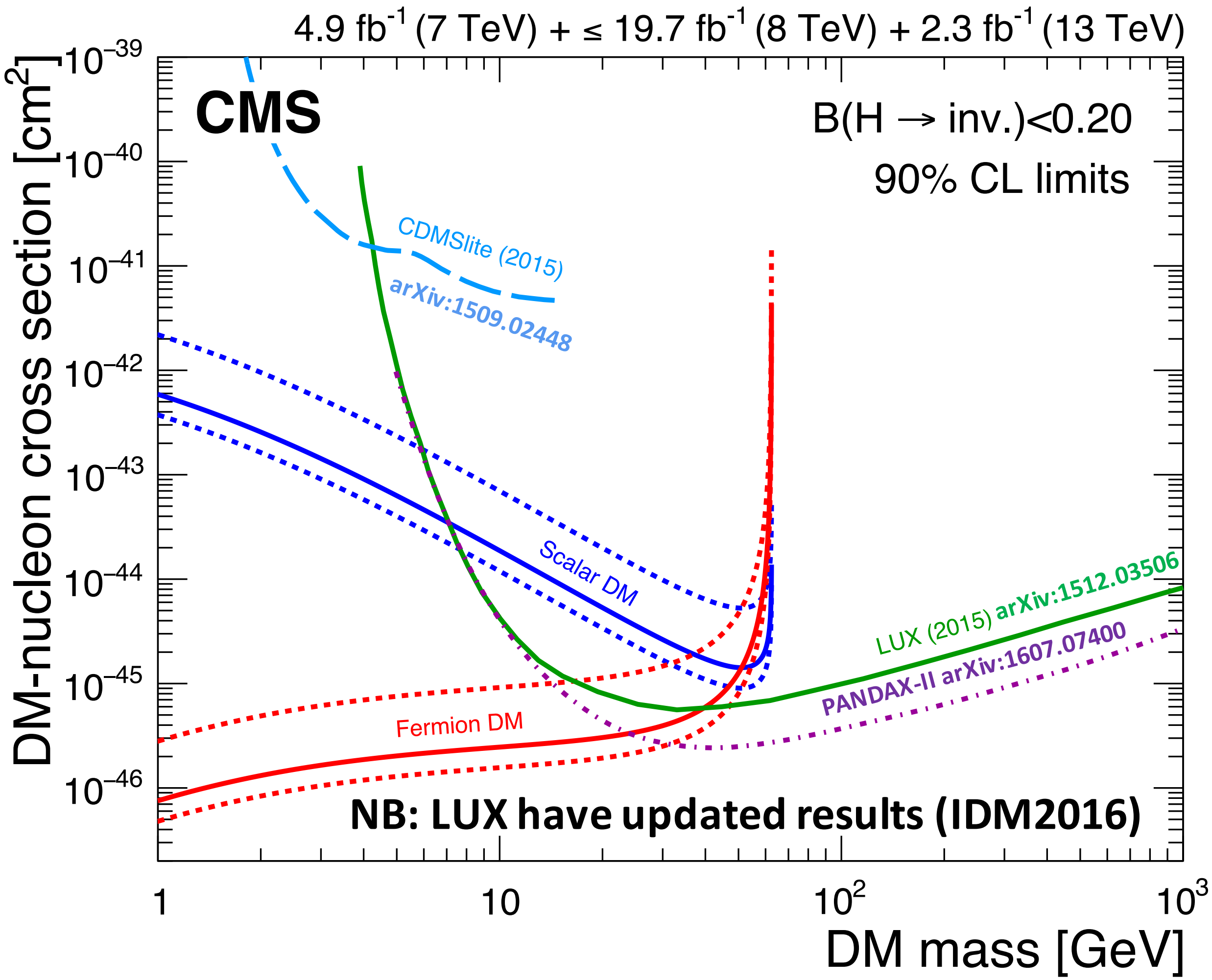
- Non trivial scaling for gg->ZH component
- ZH(H->bb) background in Z(bb) channel also modified





95% upper limit on B(H->inv) varies between 20-30 % within LHC couplings constraints

DM interpretation



B(H->inv.) translated into DM-nucleon spin-independent cross section limits as a function of DM mass

Use Higgs-Portal* models assuming **scalar**/**fermion** DM

90% CL to compare to direct detection experiments

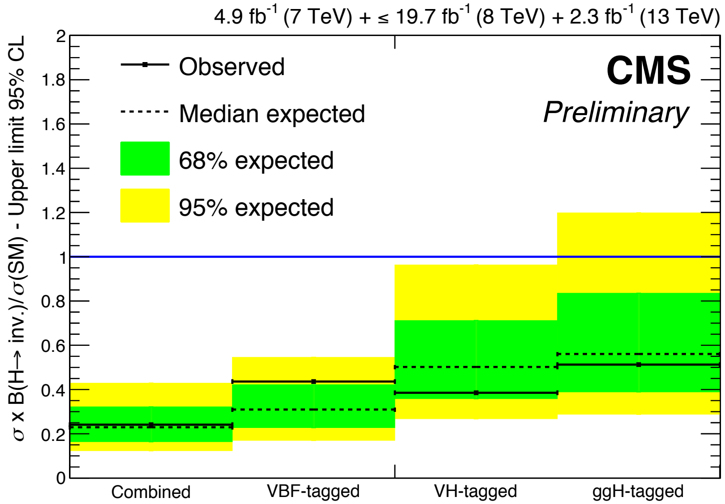
CMS limits more stringent for small DM masses

*A. Djouadi et al, *Phys. Lett. B* **709** (2012)

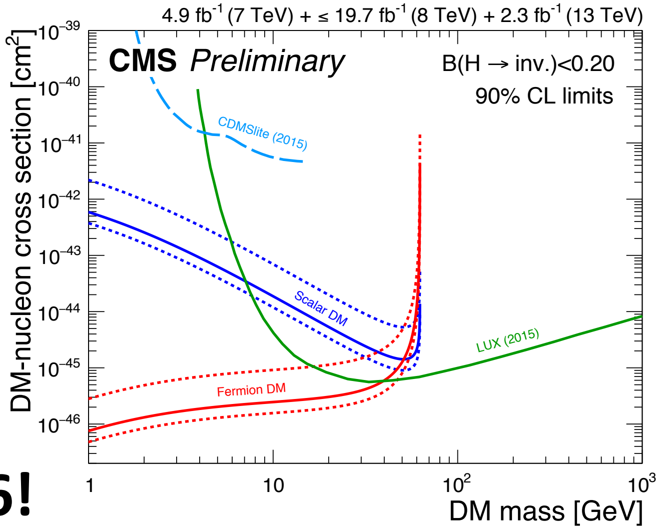
Summary

Presented searches for Higgs decaying to invisibles at CMS

- Run-2 data @ 13 TeV, including some new results with 12.9 fb^{-1}
- Search channels include VBF, Z(ll)H, V(jj)H and gluon-fusion tags
- Combination of searches between Run-1 and 2015 data provide direct constraint on B(H->Inv)



B(H->inv) < 24% observed (23% expected) @ 95% CL



- Non SM-production scenarios and DM interpretations presented
- Sensitivity is statistics dominated but systematics are becoming more important

Look forward to additional data from 2016!

BACKUP

CMS detector

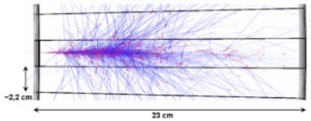
Hermetic design of CMS provides good coverage of interaction

→ Vital for searches with missing energy

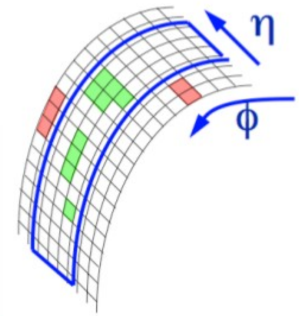
Triggers reduce 40 MHz (LHC)→ O(100) Hz

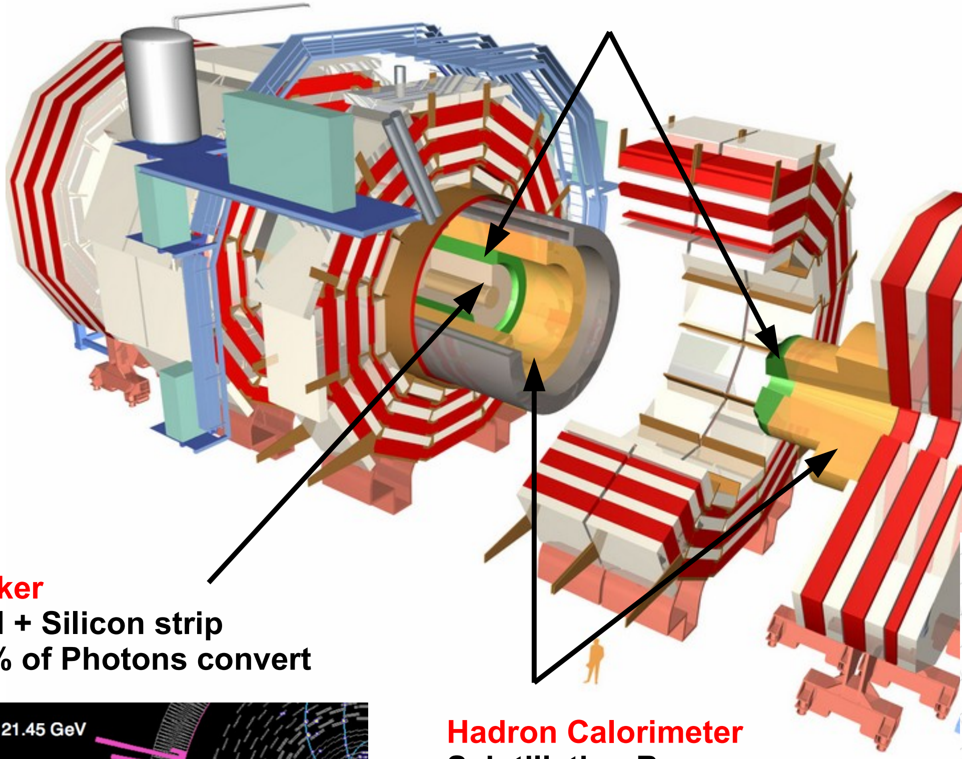
High multiplicity from multiple, pile-up interactions (PU)

→ Upgrade Trigger for 2016 data taking performs PU subtraction at L1

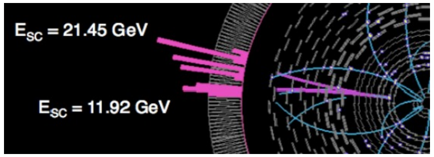


EM Calorimeter
Lead tungstate (PbWO4) crystals
61 200 (EB) / 7 324 (EE)

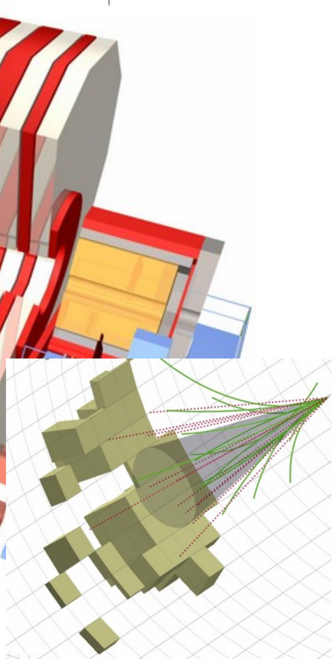


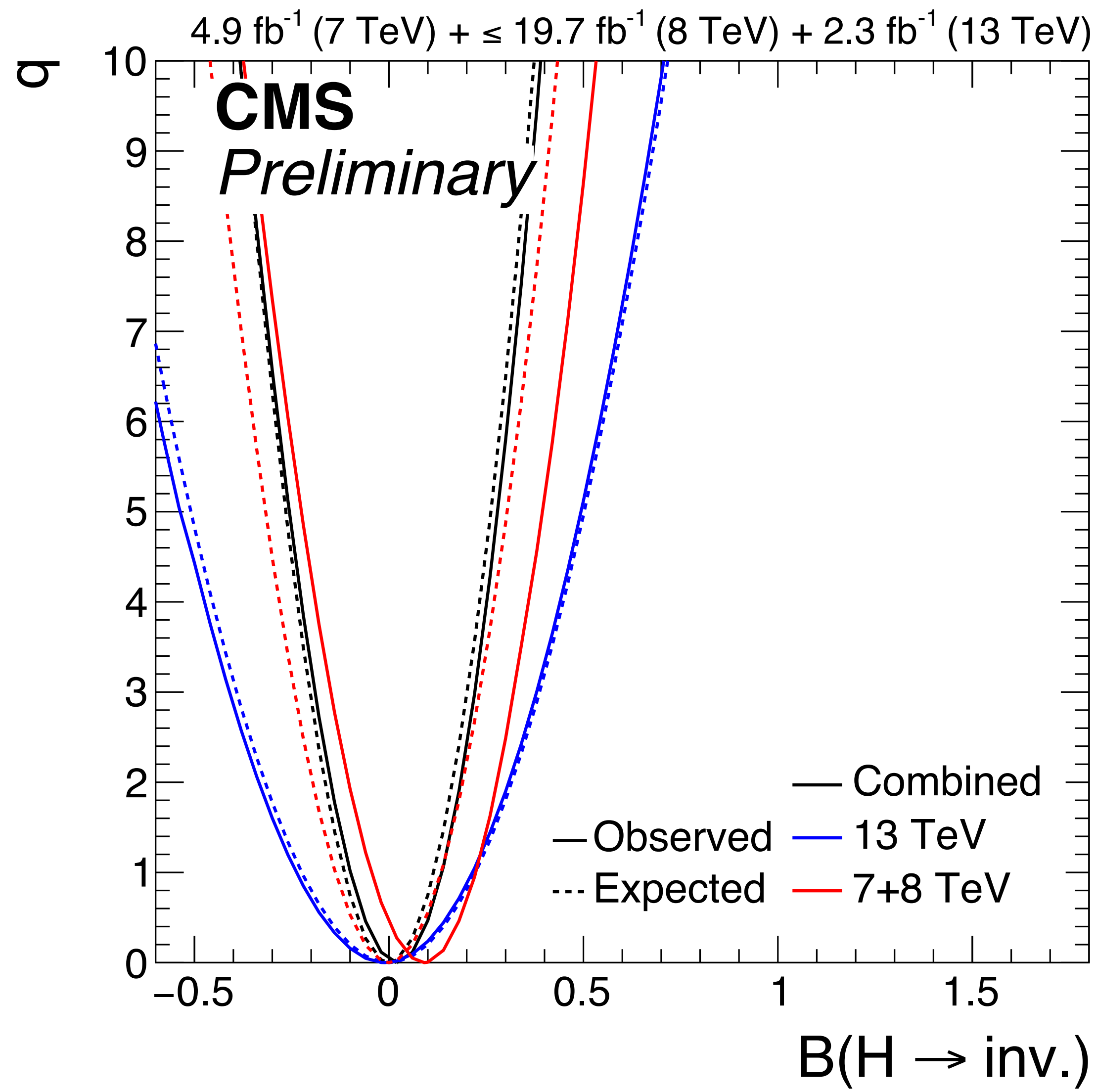


Tracker
Pixel + Silicon strip
~50% of Photons convert



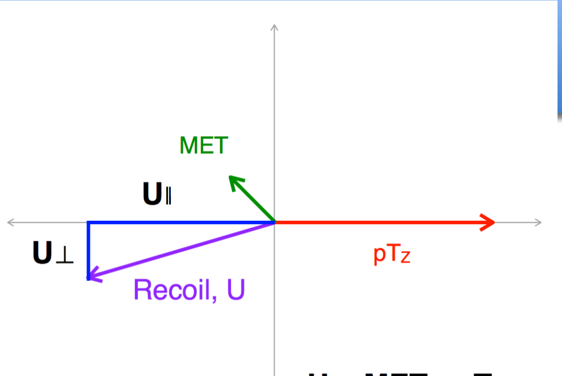
Hadron Calorimeter
Scintillating Brass
Exploit jets from VBF production



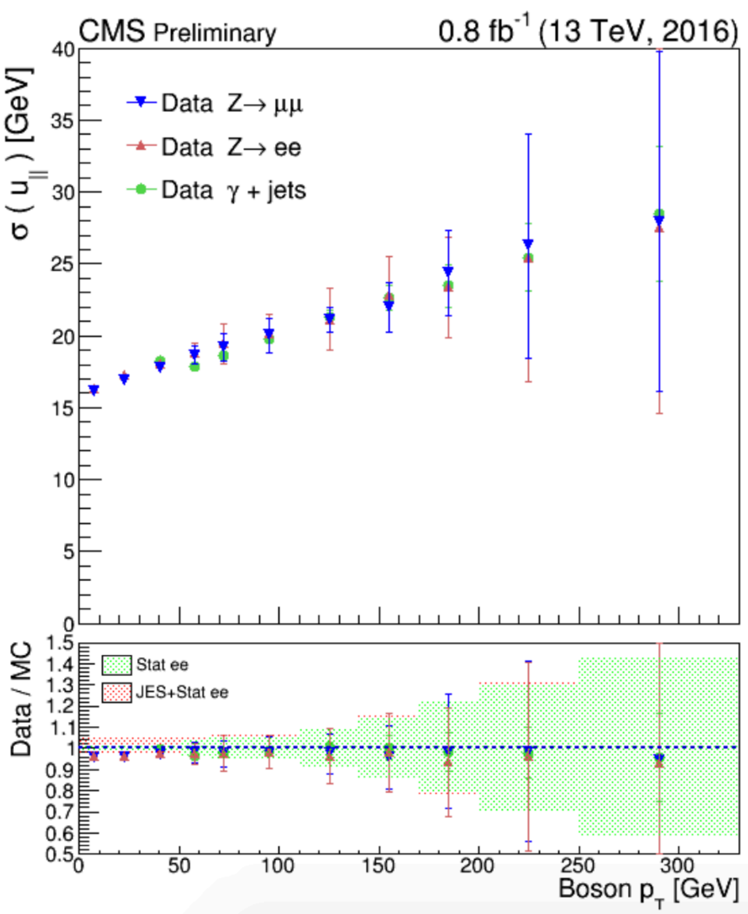


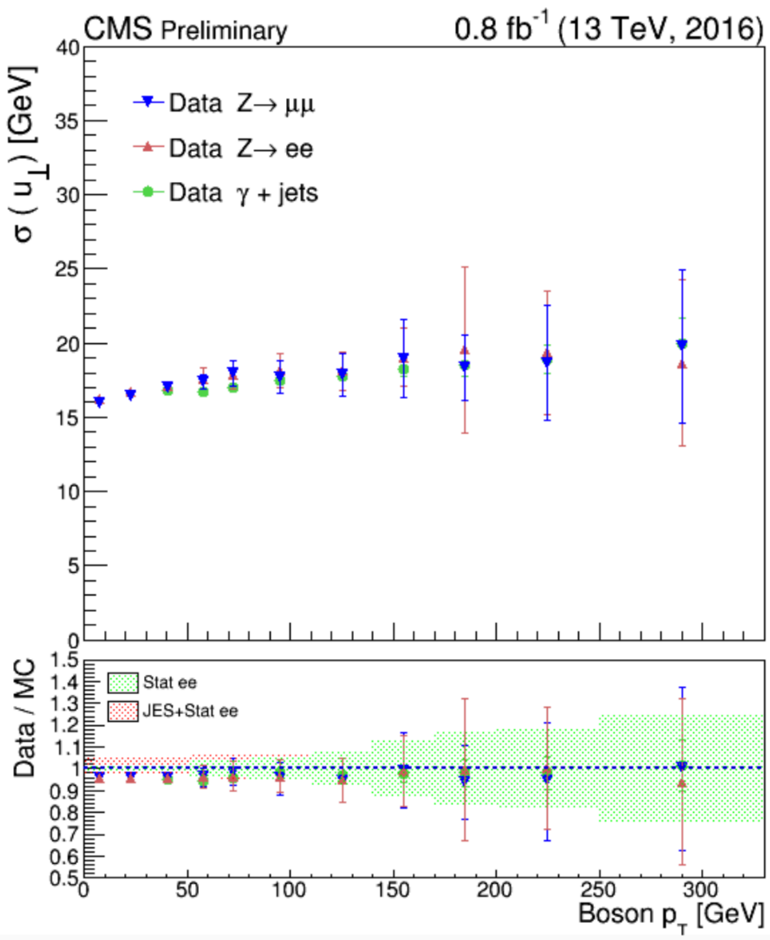
4.9 fb^{-1} (7 TeV) + ≤ 19.7 fb^{-1} (8 TeV) + 2.3 fb^{-1} (13 TeV)
CMS
Preliminary
q
B(H → inv.)
Combined
13 TeV
7+8 TeV
Observed
Expected

E_T^{miss} Resolution

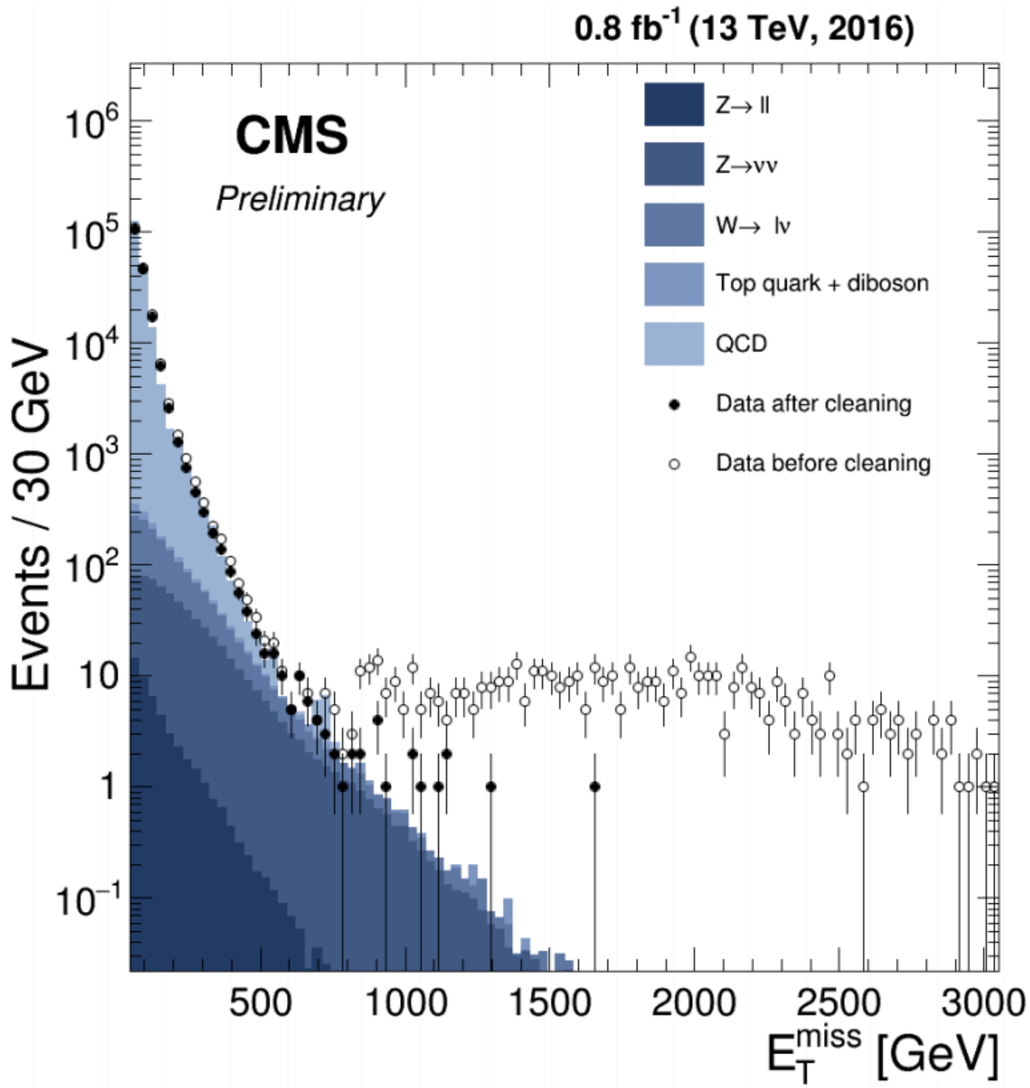


U = MET - pTz





E_T^{miss} Tails



Dedicated noise filters remove events with spurious missing energy

-> Remove E_T^{miss} Resolution fake contributions in high tails.

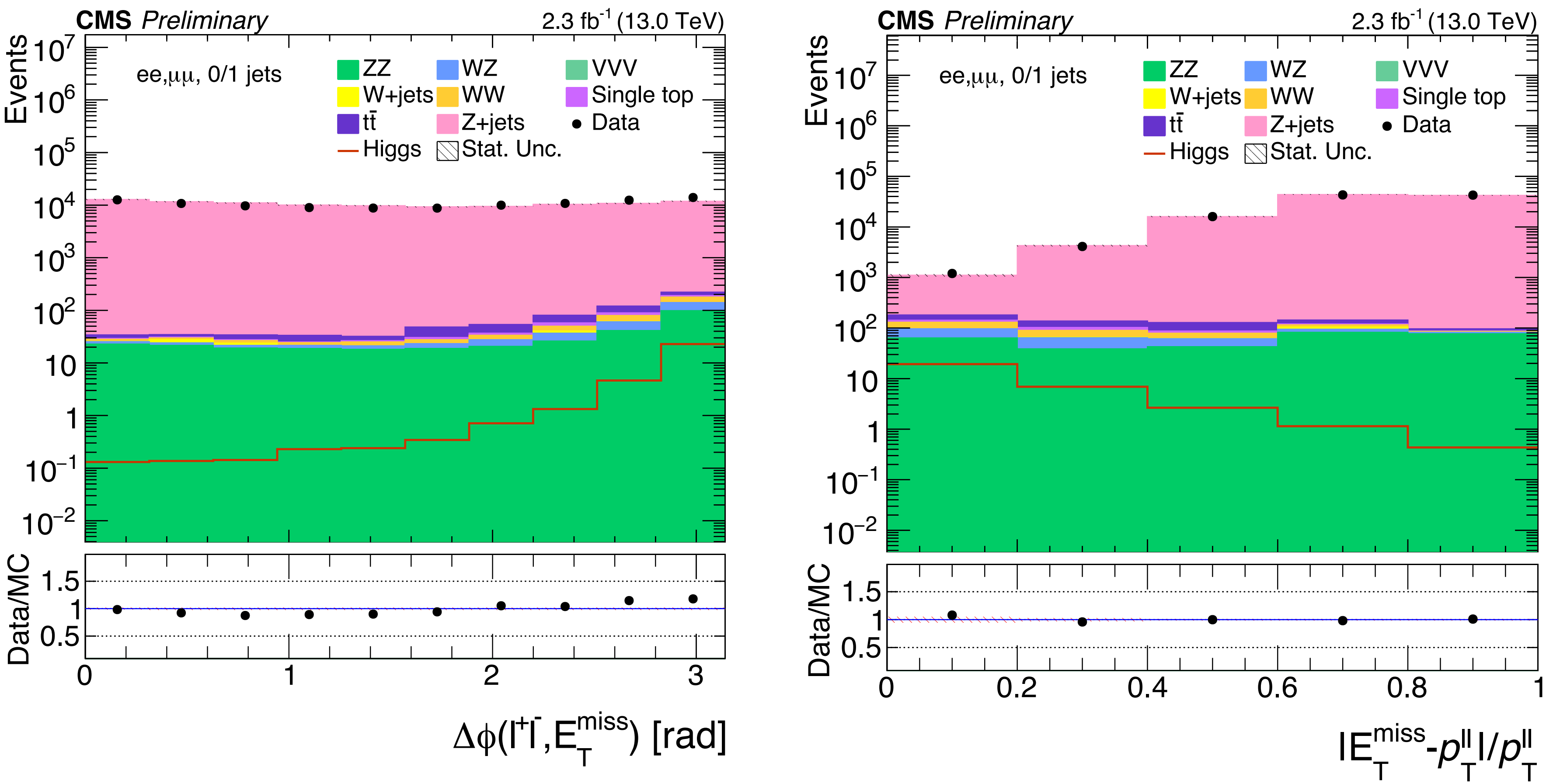
Z(ll) H

Backgrounds dominated by **diboson processes**: ZZ(2l2v) (70%), WZ(lvll) (25%)

-> Estimated from simulationNLO with POWHEG+MCFM

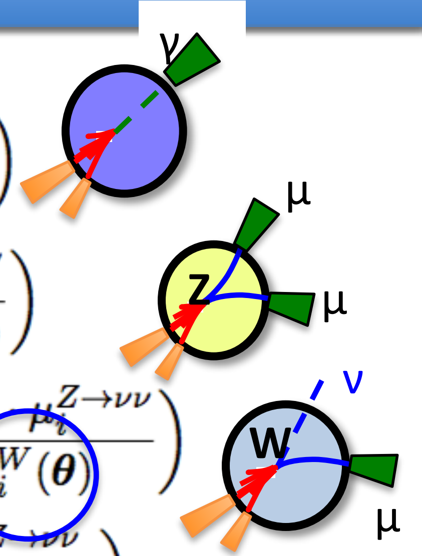
Process	0 jets		1 jet	
	$\mu^+\mu^-$	e^+e^-	$\mu^+\mu^-$	e^+e^-
ZH, $m_H = 125$ GeV	5.97 ± 0.55	4.27 ± 0.39	1.29 ± 0.20	0.98 ± 0.15
$Z(l^+l^-)$+jets	0.45 ± 0.45	0.30 ± 0.30	0.45 ± 0.45	0.30 ± 0.30
$ZZ \rightarrow ll\nu\nu$	10.4 ± 1.14	7.46 ± 0.81	2.04 ± 0.31	1.49 ± 0.23
$WZ \rightarrow l\nu ll$	3.42 ± 0.28	2.40 ± 0.19	1.04 ± 0.10	1.00 ± 0.10
Top/WW/$\tau\tau$	0.69 ± 0.23	0.88 ± 0.29	0.44 ± 0.22	0.26 ± 0.13
VVV	-	-	0.13 ± 0.06	0.07 ± 0.03
Total background	15.0 ± 1.28	11.0 ± 0.93	4.10 ± 0.60	3.12 ± 0.41
Data	18	8	5	1

Event balance variables



Likelihood Model

$$\mathcal{L}_c(\mu, \boldsymbol{\mu}^{Z\rightarrow\nu\nu}, \boldsymbol{\theta}) = \prod_i \text{Poisson}\left(d_i^{\gamma} | B_i^{\gamma}(\boldsymbol{\theta}) + \frac{\mu_i^{Z\rightarrow\nu\nu}}{R_i^{\gamma}(\boldsymbol{\theta})} \right)$$
$$\times \prod_i \text{Poisson}\left(d_i^{Z} | B_i^{Z}(\boldsymbol{\theta}) + \frac{\mu_i^{Z\rightarrow\nu\nu}}{R_i^{Z}(\boldsymbol{\theta})} \right)$$
$$\times \prod_i \text{Poisson}\left(d_i^{W} | B_i^{W}(\boldsymbol{\theta}) + \frac{f_i(\boldsymbol{\theta}) \cdot \mu_i^{Z\rightarrow\nu\nu}}{R_i^{W}(\boldsymbol{\theta})} \right)$$
$$\times \prod_i \text{Poisson}\left(d_i^{Zee} | B_i^{Zee}(\boldsymbol{\theta}) + \frac{\mu_i^{Z\rightarrow\nu\nu}}{R_i^{Zee}(\boldsymbol{\theta})} \right)$$
$$\times \prod_i \text{Poisson}\left(d_i^{We\nu} | B_i^{We\nu}(\boldsymbol{\theta}) + \frac{f_i(\boldsymbol{\theta}) \cdot \mu_i^{Z\rightarrow\nu\nu}}{R_i^{We\nu}(\boldsymbol{\theta})} \right)$$
$$\times \prod_i \text{Poisson}\left(d_i | B_i(\boldsymbol{\theta}) + (1 + f_i(\boldsymbol{\theta}))\mu_i^{Z\rightarrow\nu\nu} + \mu S_i(\boldsymbol{\theta}) \right)$$



Number of observed events

Expected 'other background' contamination in CR

Expectation of number of Z/W/γ given TF (R)

$$\mu_i^{c,W\rightarrow l\nu} \rightarrow f_i(\boldsymbol{\theta}) \cdot \mu_i^{c,Z\rightarrow\nu\nu}$$

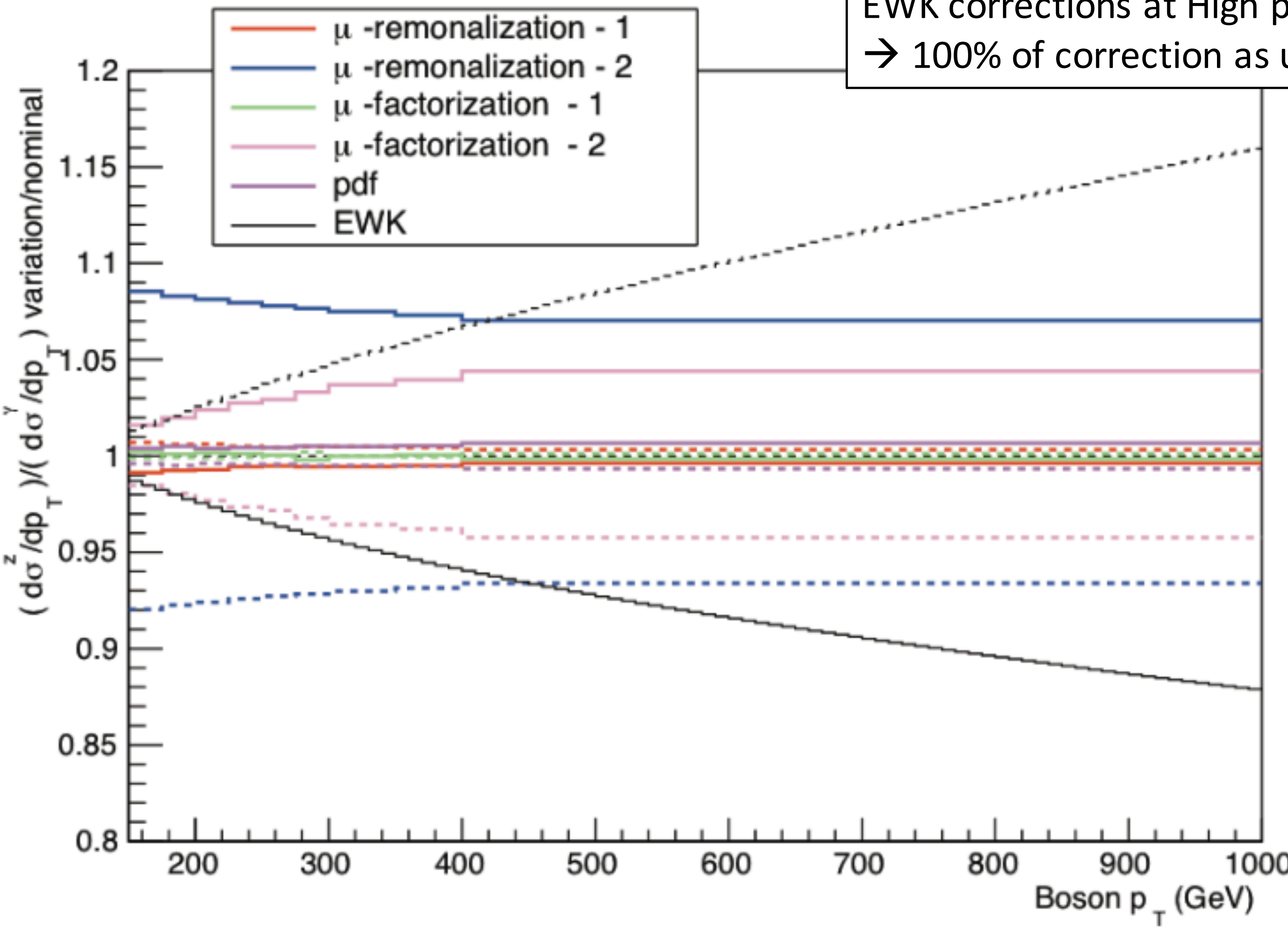
f_i → ratio of W→lv / Z→vv in the signal region :

- Relies on theoretical prediction for differential cross-sections and lepton acceptance!
- Transfer factors (R) are unchanged (easy to switch back and forth between this and old likelihood definition

V+jets theory systematics

arXiV:1505:05704

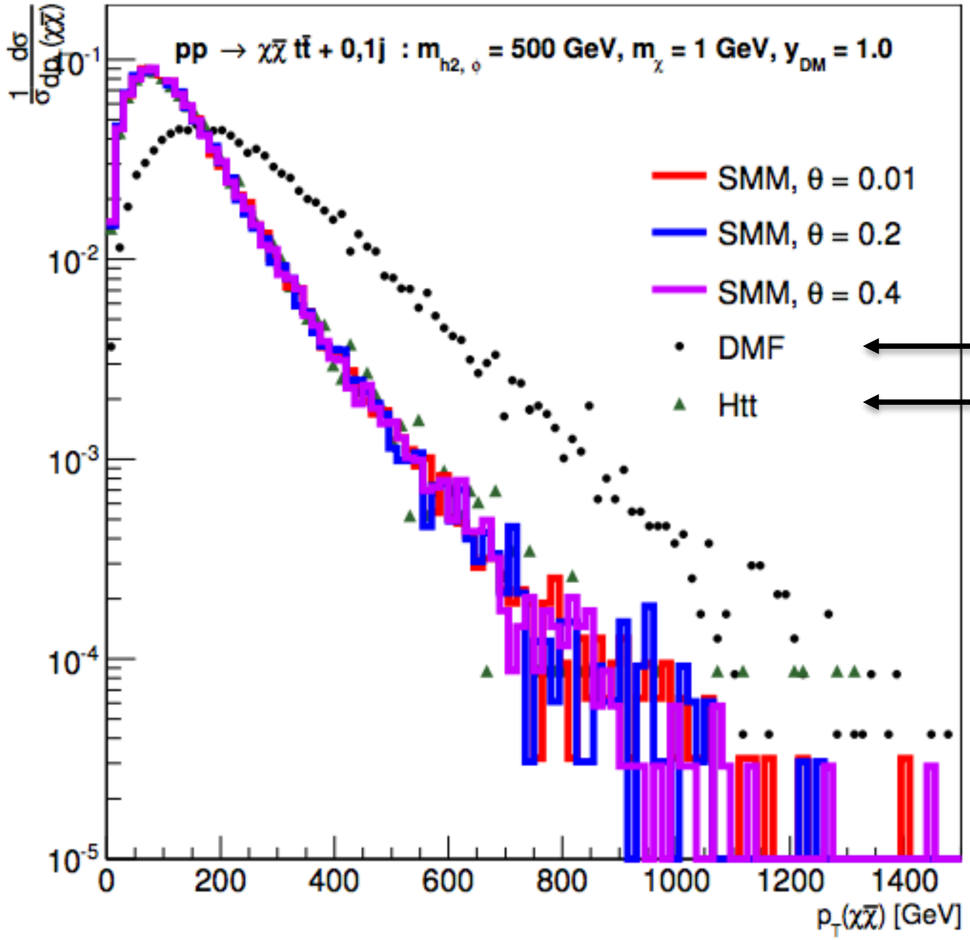
EWK corrections at High pT are large!
→ 100% of correction as uncertainty



DM Scalar + mixing with 125

arXiv:1607.06680

If DM is light, H(125) will dominate kinematics when mixing is allowed
-> Rescale B(H->Inv) constraints to constrain generic scalar DM models)



Mixing

"Heavy Higgs" (no mixing)

ttH(125) (no mixing)

Combination

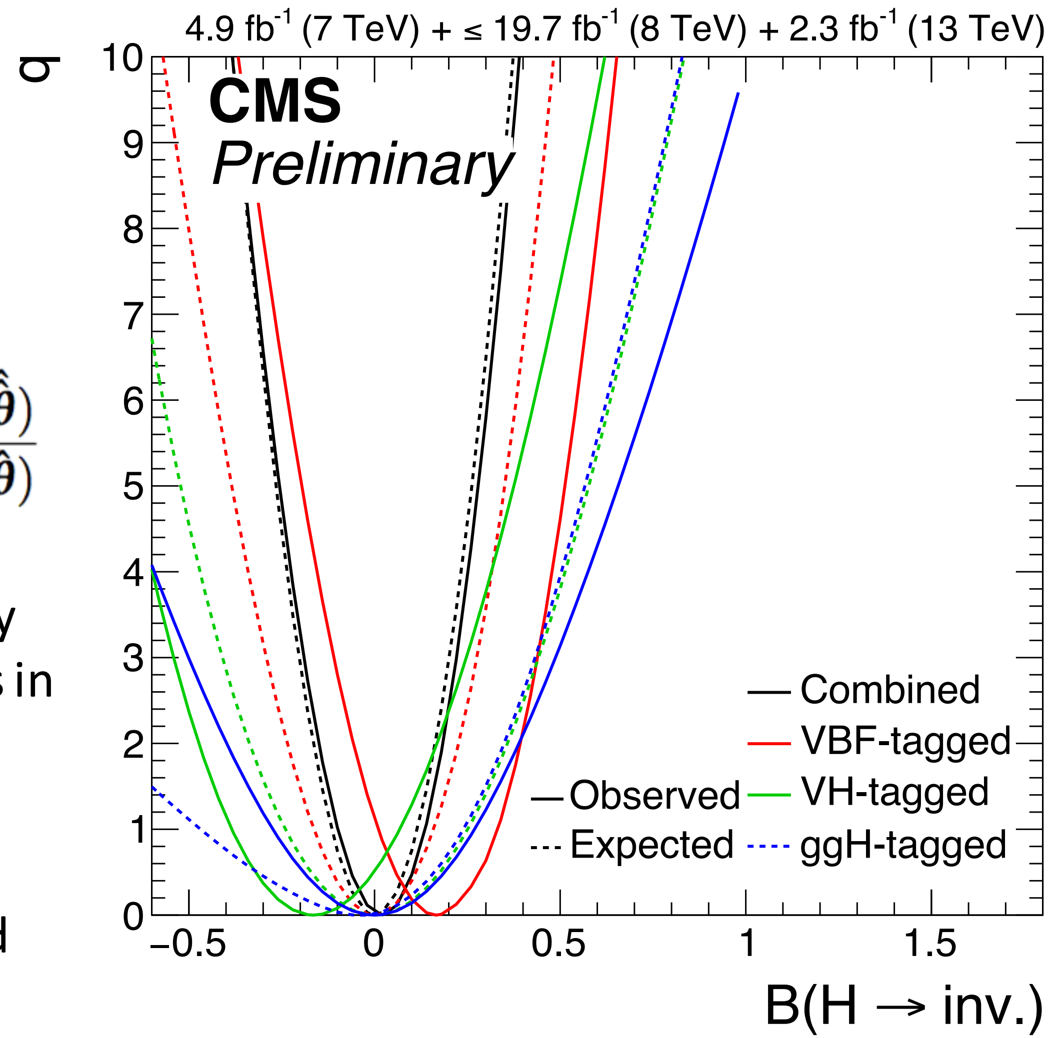
Assuming SM values for production cross sections
-> Interpret potential signal as Invisible Higgs branching ratio

Profile likelihood ratio

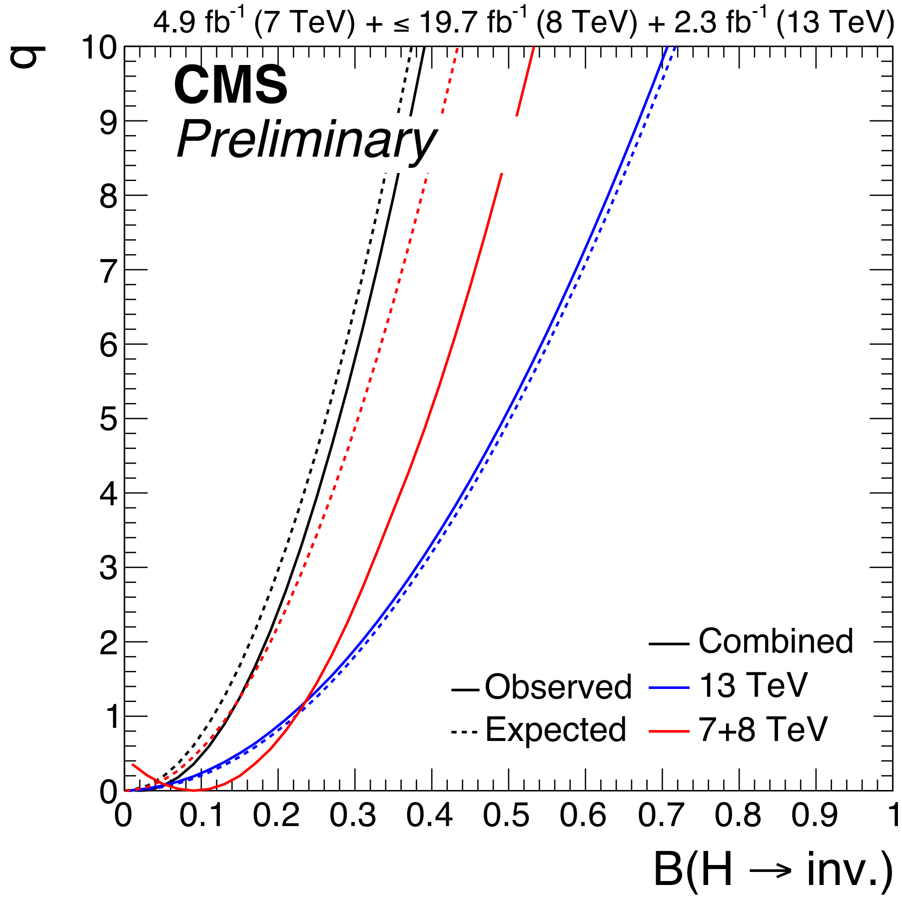
$$q = -2\ln\frac{L(\text{data}|\mathrm{B}(\mathrm{H}\to\text{inv.}),\hat{\hat{\theta}})}{L(\text{data}|\hat{\mathrm{B}}(\mathrm{H}\to\text{inv.}),\hat{\theta})}$$

Expected sensitivity dominated by **VBF** but small excess (<1σ) results in less stringent limit

Deficit of events in **VH** tagged channels yields stronger observed limit

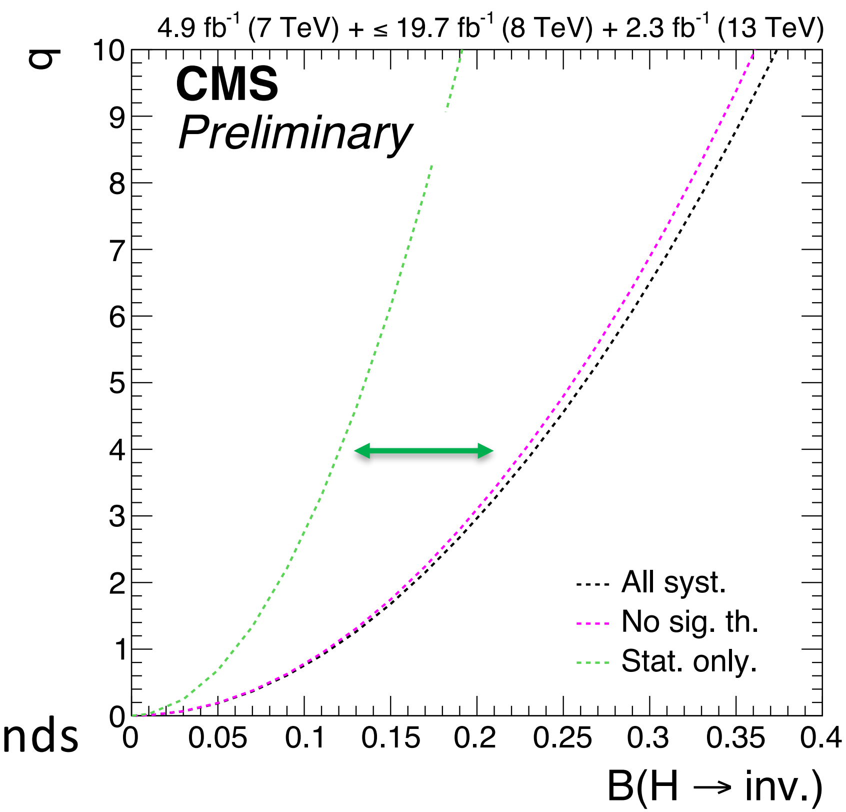


Combination



Sensitivity dominated by **Run-1 analyses**

Excess in VBF at 8 TeV yields slightly worse improvement in observed limit



Systematic uncertainties play a large role

-> Large impacts from CR<->SR transfer theory uncertainties to constrain backgrounds

1D projections