CMS Results on H(inv) Decays: VBF Channel

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Boston University

DMWG Workshop

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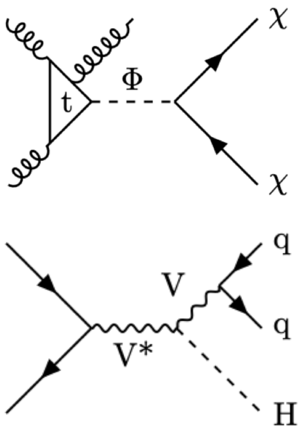
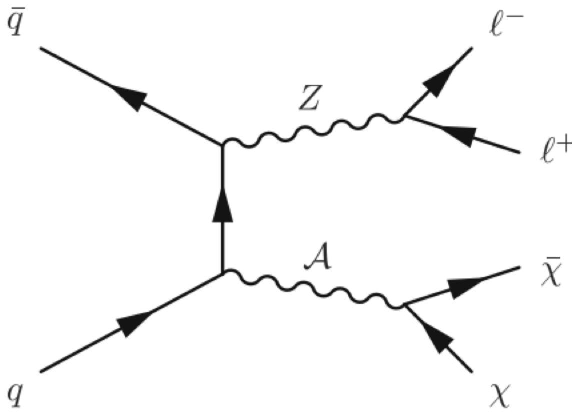
Overall: H(inv) Searches in CMS

$H \rightarrow inv$ searches with public Run2 results in CMS so far:



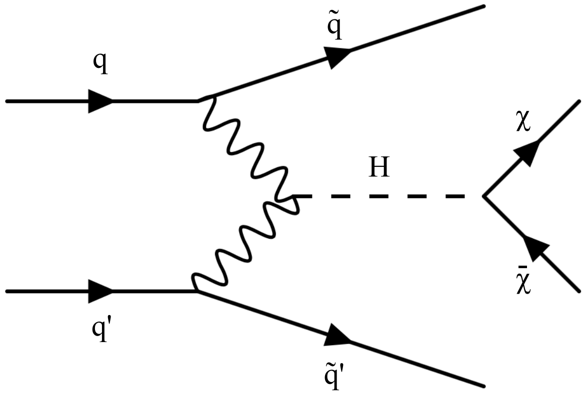
Monojet + Mono-V

arXiv:2107.13021



Mono-Z

EPJC 81, 13 (2021)



VBF H(inv)

CMS-PAS-HIG-20-003

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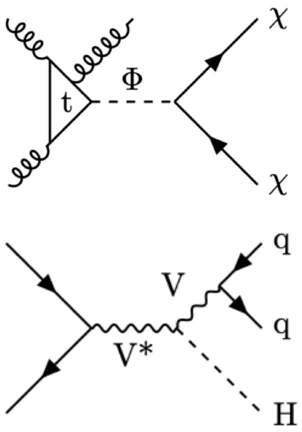

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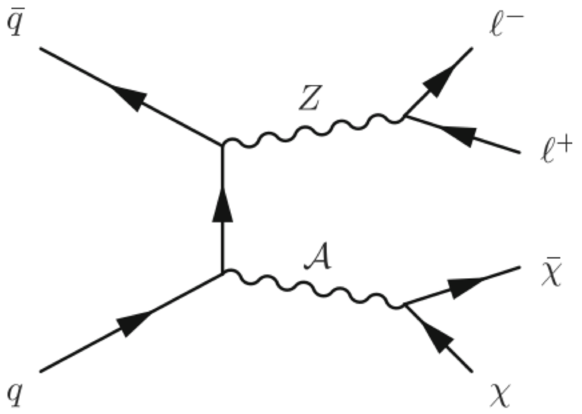

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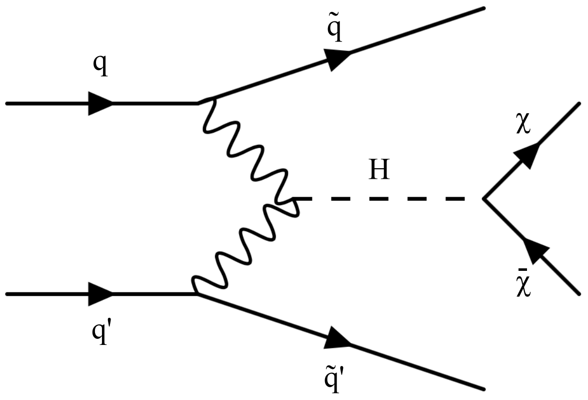


VBF H(inv)
CMS-PAS-HIG-20-003

Will focus on this channel in these slides

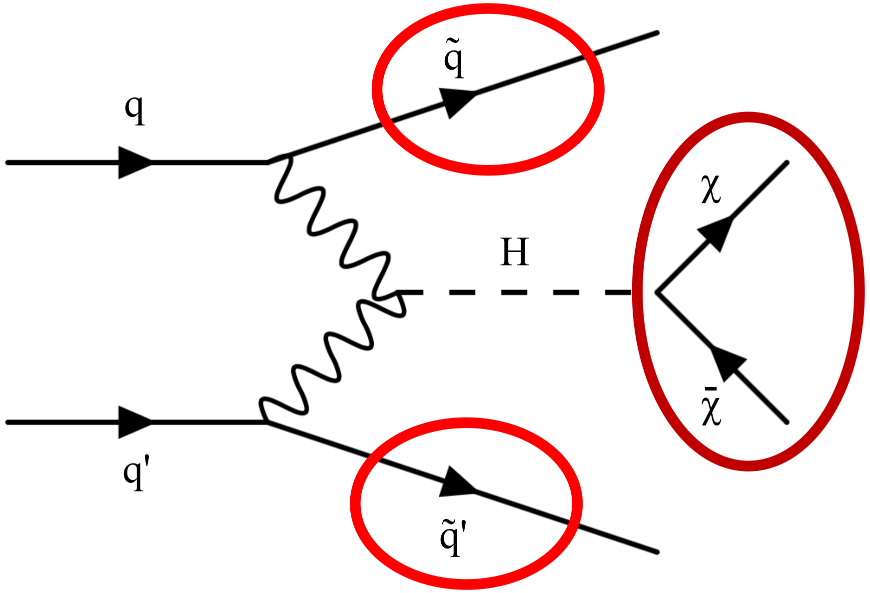
VBF H(inv):
Analysis Strategy

VBF H(inv): Strategy

CMS-PAS-HIG-20-003

Topology:

2 jets with large $m_{jj}, \Delta\eta_{jj} + p_T^{miss}$



$H \rightarrow inv$:
$\boldsymbol{p_T^{miss}}$

Two VBF jets

No leptons, photons, b-jets in the final state

VBF H(inv): Strategy

EWK V: Smaller XS, but looks more like signal!

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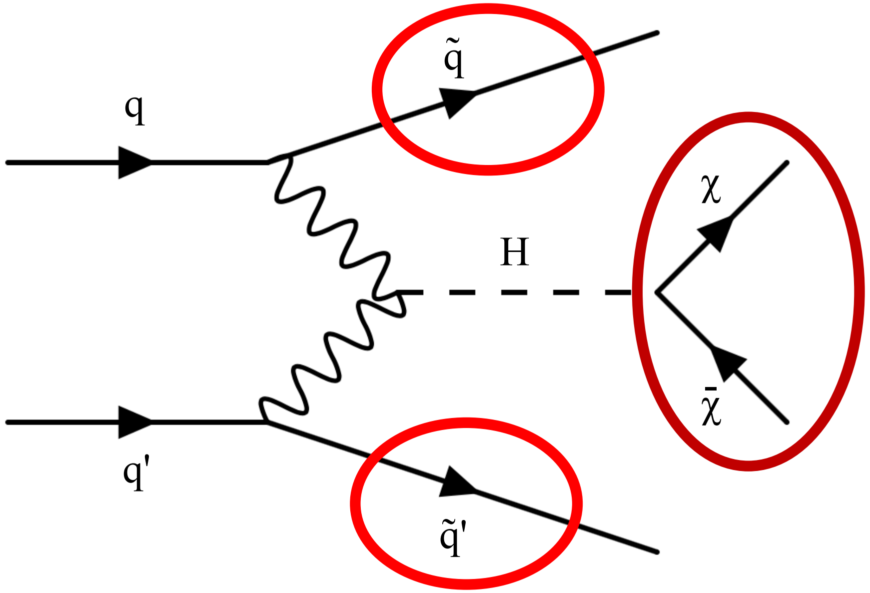
2 jets with large $m_{jj}, \Delta\eta_{jj} + p_T^{miss}$



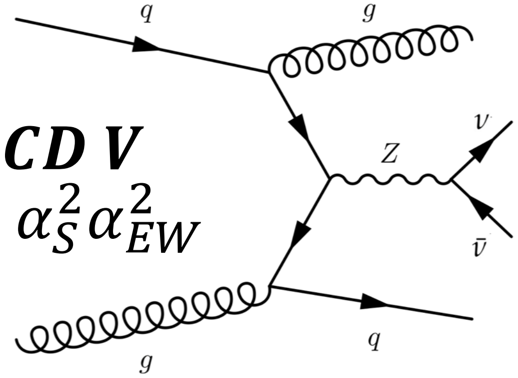
$H \rightarrow inv$: $\boldsymbol{p_T^{miss}}$

Two VBF jets

No leptons, photons, b-jets in the final state

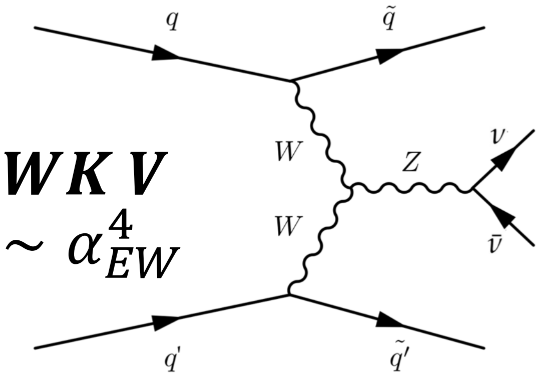
Dominating backgrounds:

$V + 2\ jets$



$\boldsymbol{QCD\ V}$

$\sigma \sim \alpha_S^2 \alpha_{EW}^2$



$\boldsymbol{EWK\ V}$

$\sigma \sim \alpha_{EW}^4$

Event Selection (Online)

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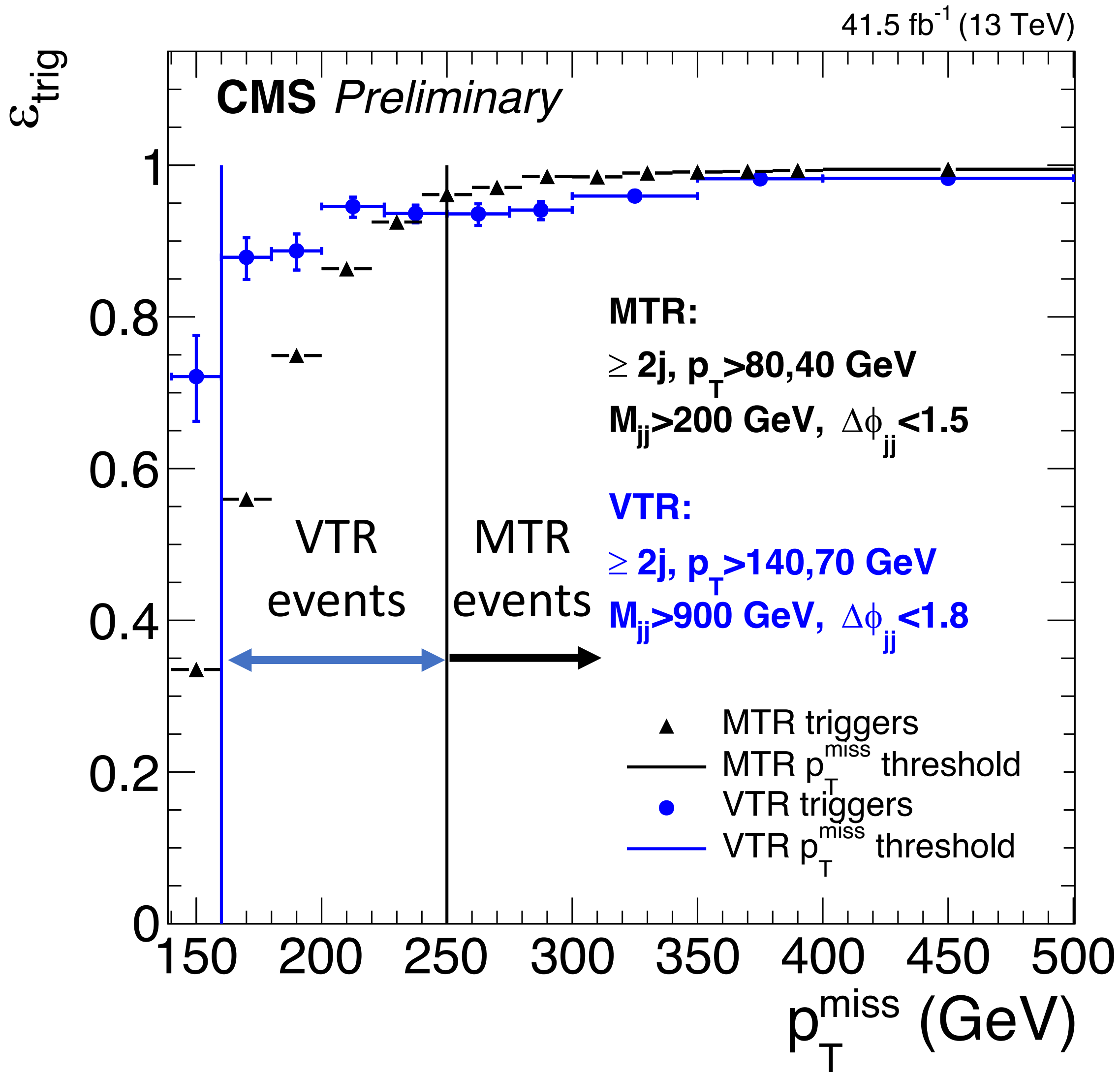

Two sets of triggers are used for two data taking categories:

- **MTR:** p_T^{miss} triggered category, target $p_T^{miss} > 250\ GeV$
- **VTR (new in 17+18):** VBF triggered category, target events @ lower p_T^{miss}

VBF triggers additionally cut on:
Online jet p_T, m_{jj}

→ VTR improves the sensitivity by ≈ 8%

Event Selection (Offline)

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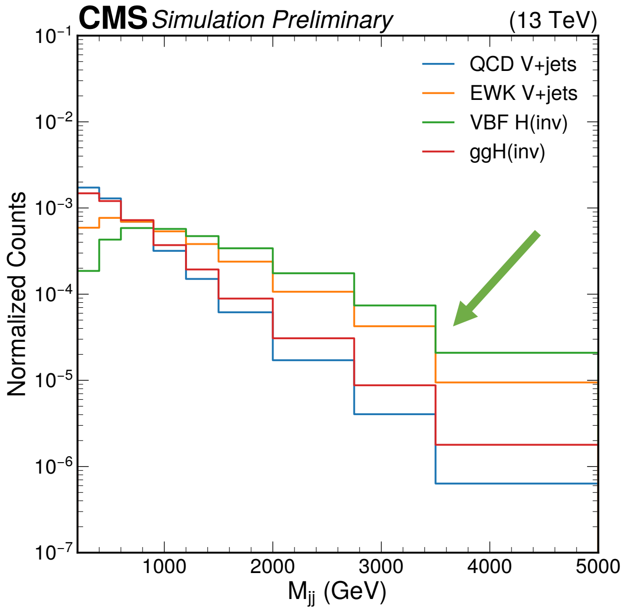
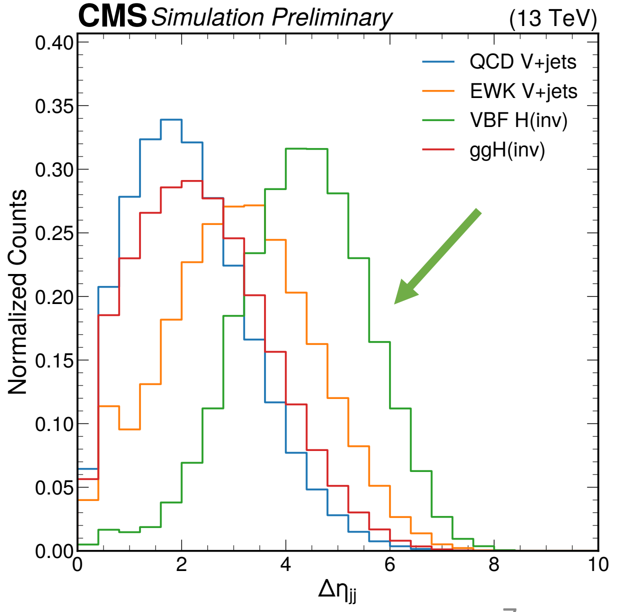
Distinguishing properties of the **VBF H(inv)** signal:
Two VBF jets have → Large m_{jj} & $\Delta\eta_{jj}$

Select events with di-jet + p_T^{miss} with:

	MTR	**VTR**
Jet p_T	$> 80, 40\ GeV$	$> 140, 70\ GeV$
m_{jj}	$> 200\ GeV$	$> 900\ GeV$
$\Delta\eta_{jj}$	> 1.0	> 1.0
$\Delta\phi_{jj}$	$< 1.5\ rad$	$< 1.8\ rad$
p_T^{miss}	$> 250\ GeV$	$[160, 250)\ GeV$
$\min\Delta\phi(j, p_T^{miss})$	$> 0.5\ rad$	$> 1.8\ rad$

Suppress multijet events





Background Estimation (V+Jets)

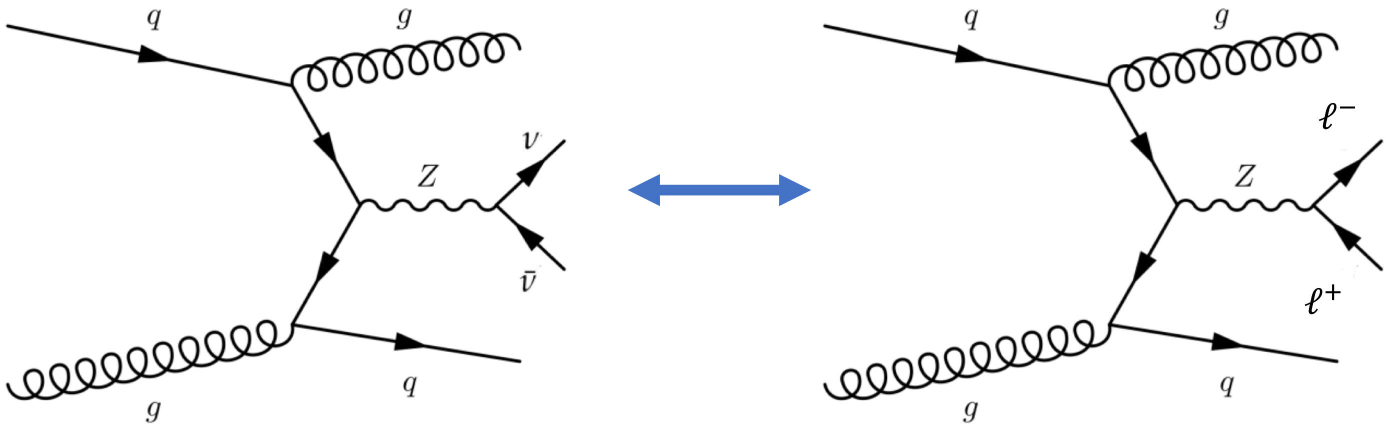
In CRs: $p_T^{miss} \rightarrow p_{T,no-\ell}^{miss}$

Define $V + jets$ **control regions (CR)** to model $V + jets$ backgrounds in **signal region (SR)**
Identical VBF kinematic selection together with:

Dilepton CRs: $Z(\rightarrow \ell\ell) + jets \rightarrow$ 2 oppositely signed $ee/\mu\mu$ with $|M_{\ell\ell} - M_Z| < 30\ GeV$

Aim to constrain the prediction in SR:

Collect in $Z(\ell\ell)$ CRs:



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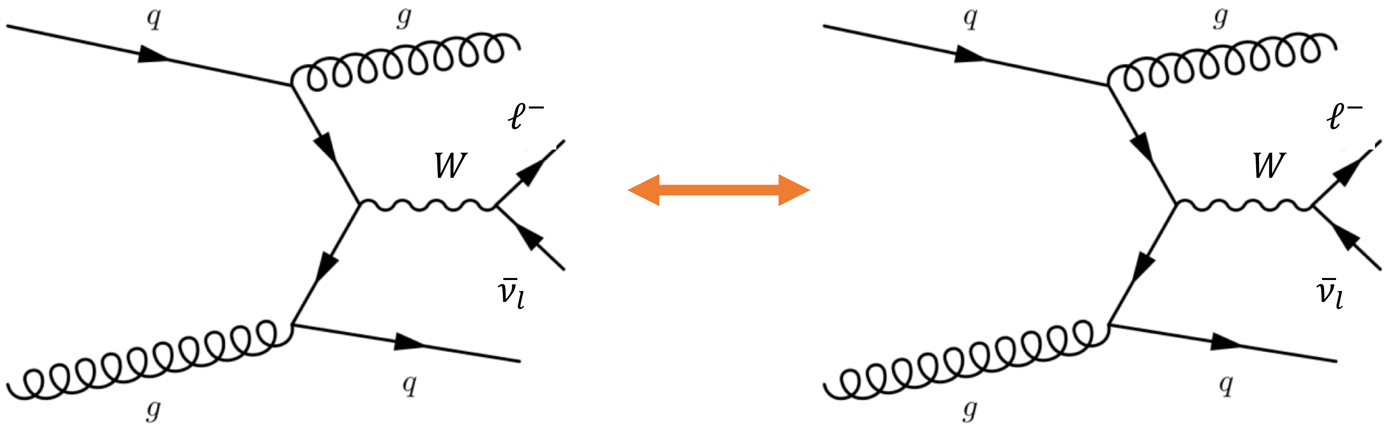
Single lepton CRs: $W(\rightarrow \ell\nu) + jets \rightarrow$ 1 e/μ with $p_T^{miss} > 80\ GeV$

Aim to constrain the prediction in SR:

Collect in $W(\ell\nu)$ CRs:



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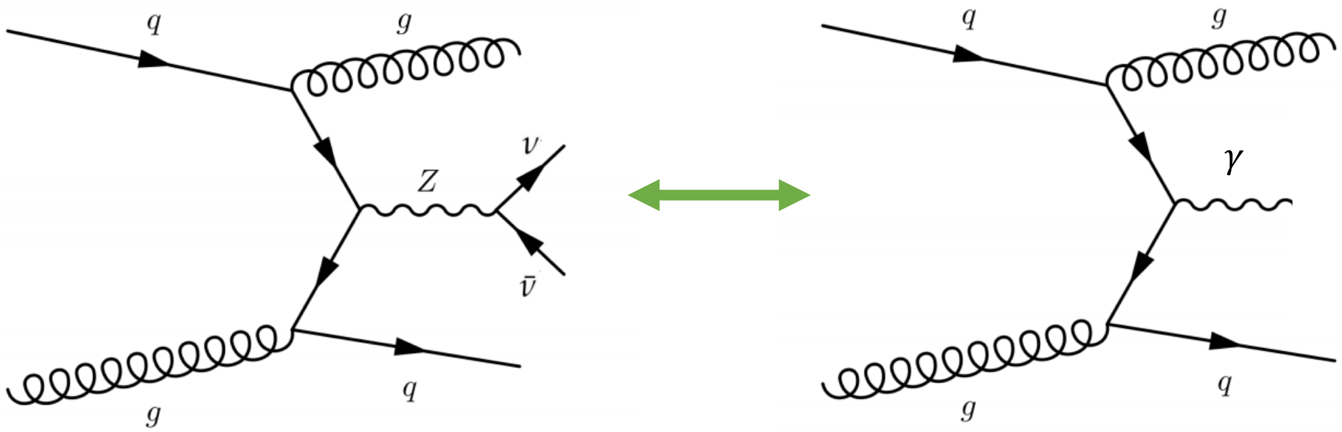
Identical VBF kinematic selection together with:

Dilepton CRs: $Z(\to \ell\ell) + jets \to$ 2 oppositely signed $ee/\mu\mu$ with $|M_{\ell\ell} - M_Z| < 30\ GeV$
Single lepton CRs: $W(\to \ell\nu) + jets \to$ 1 e/μ with $p_T^{miss} > 80\ GeV$
Photon CR: $\gamma + jets \to 1\ \gamma, p_T^{\gamma} > 230\ GeV$

Photon CR:
New in 2017+2018
Improves sensitivity by $\approx 11\%$

Aim to constrain the prediction in SR:

Collect in γ CR:

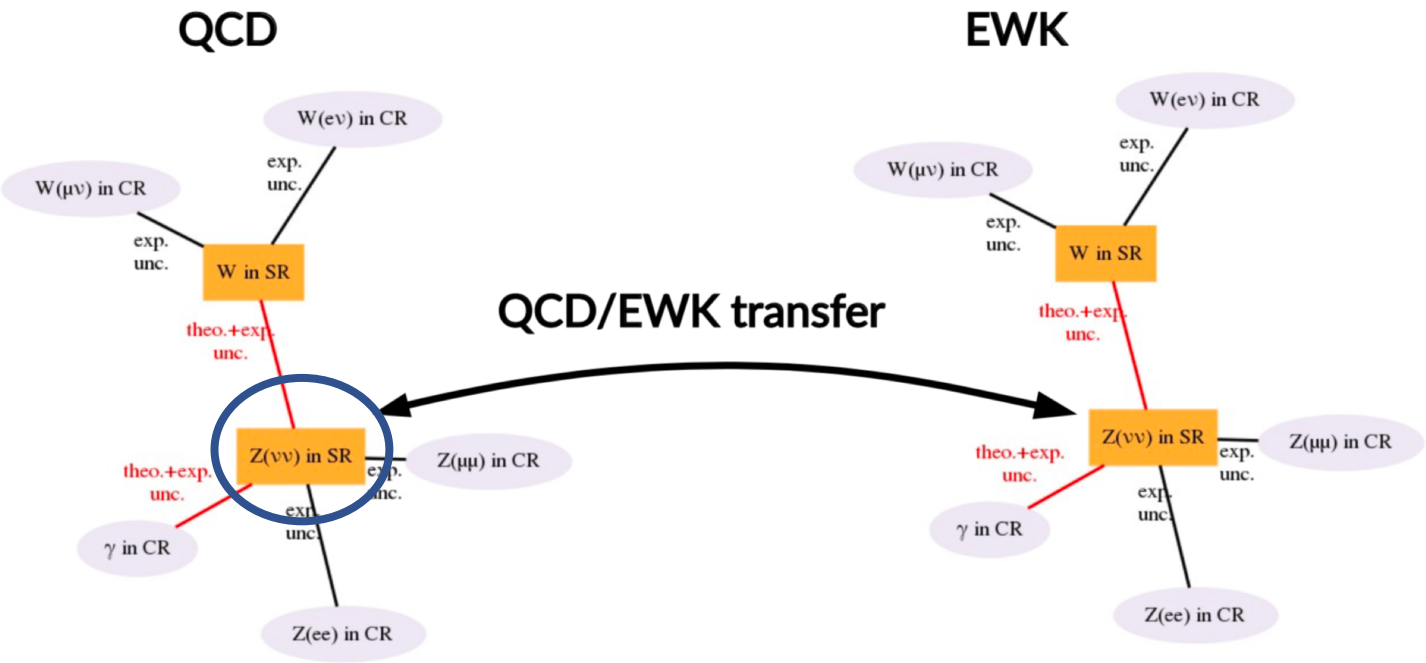


Background Estimation (V+Jets)

With the SR and CRs

→ Define transfer factors (TF) as ratios of the processes:

$$e.g.\ R_{Z(\mu\mu)/Z(\nu\nu)} = \frac{N^{i}_{Z(\mu\mu)}}{N^{i}_{Z(\nu\nu)}}$$



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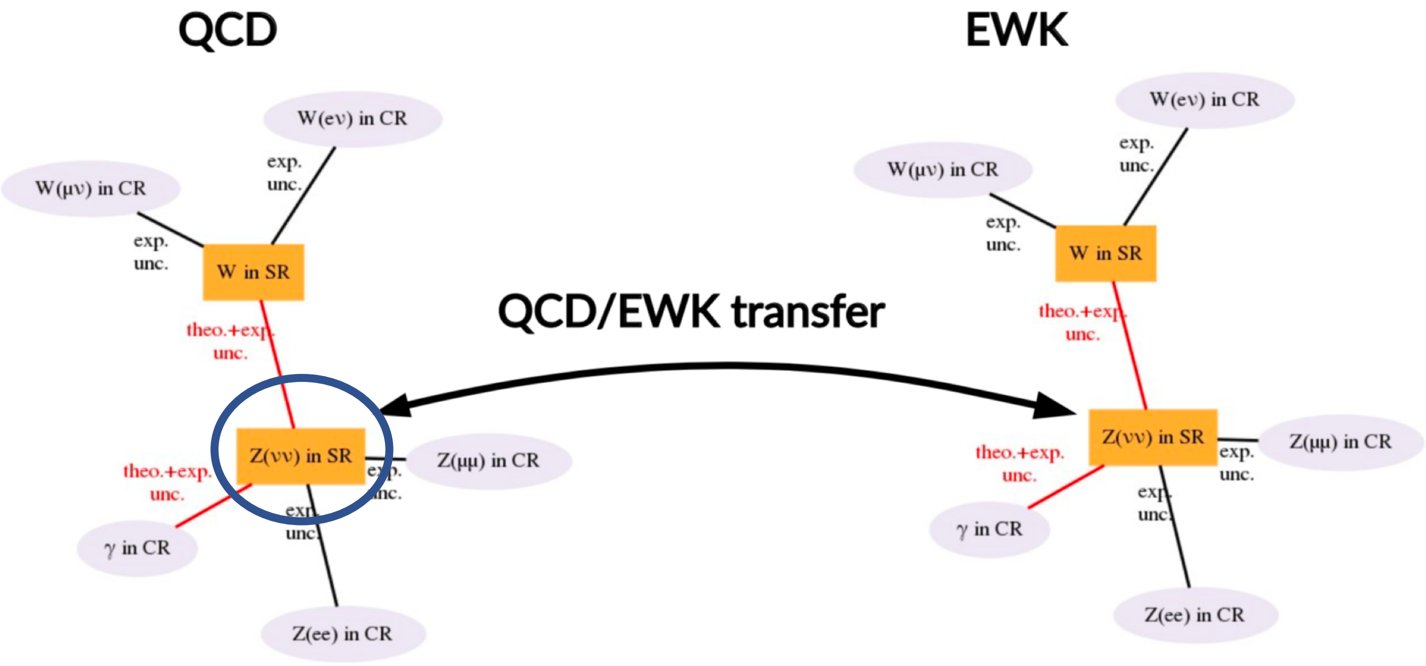

Using TFs: Can express all yields in terms of $Z(\nu\nu)$ in SR:

$$N^i_{Z(\mu\mu)} = R_{Z(\mu\mu)/Z(\nu\nu)} \times N^i_{Z(\nu\nu)}$$

Build a likelihood function L:

$$L(N^i_{Z(\nu\nu)}, \mu, \vec{\theta})$$

→ Simultaneous max. likelihood fit to get best-fit $N^i_{Z(\nu\nu)}$

TFs: Parametrized as a function of nuisance params (uncertainties)

Background Estimation (V+Jets)

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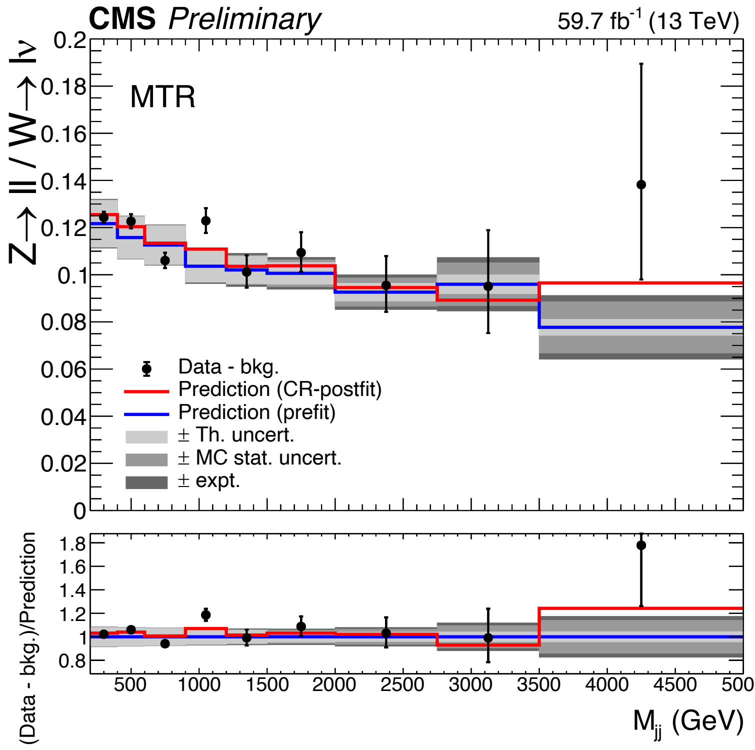
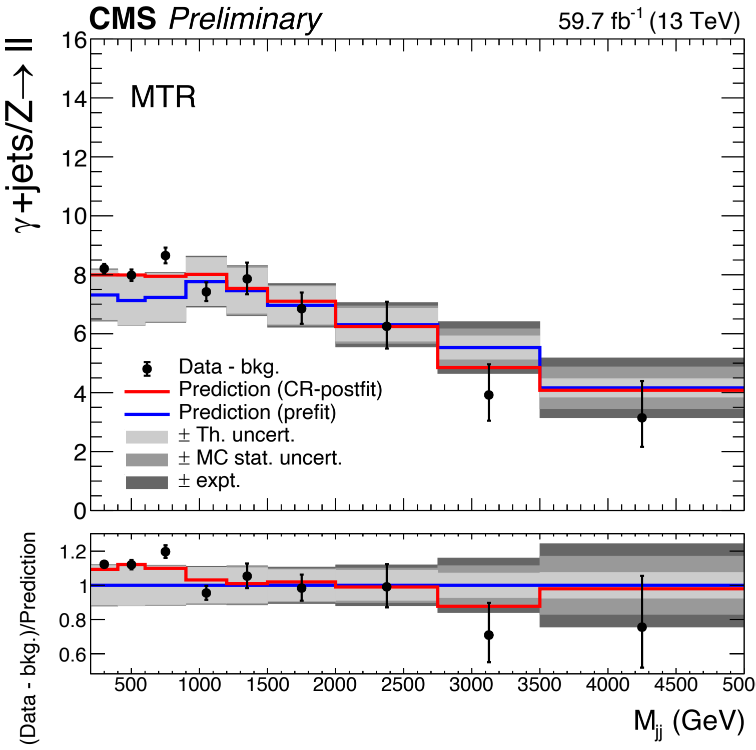
Validate the ratios predicted by simulation by comparing to the ratios measured in data:





Ratios predicted:

Blue: From simulation

Red: After a simultaneous fit to data on all CRs

Theory uncertainties especially important @ low m_{jj}:

Scale uncertainties: Partially-correlated between processes

PDF uncertainties: Fully-correlated

→ Predictions agree with data within the uncertainties

Background Estimation (QCD Multi-jet)

CMS-PAS-HIG-20-003

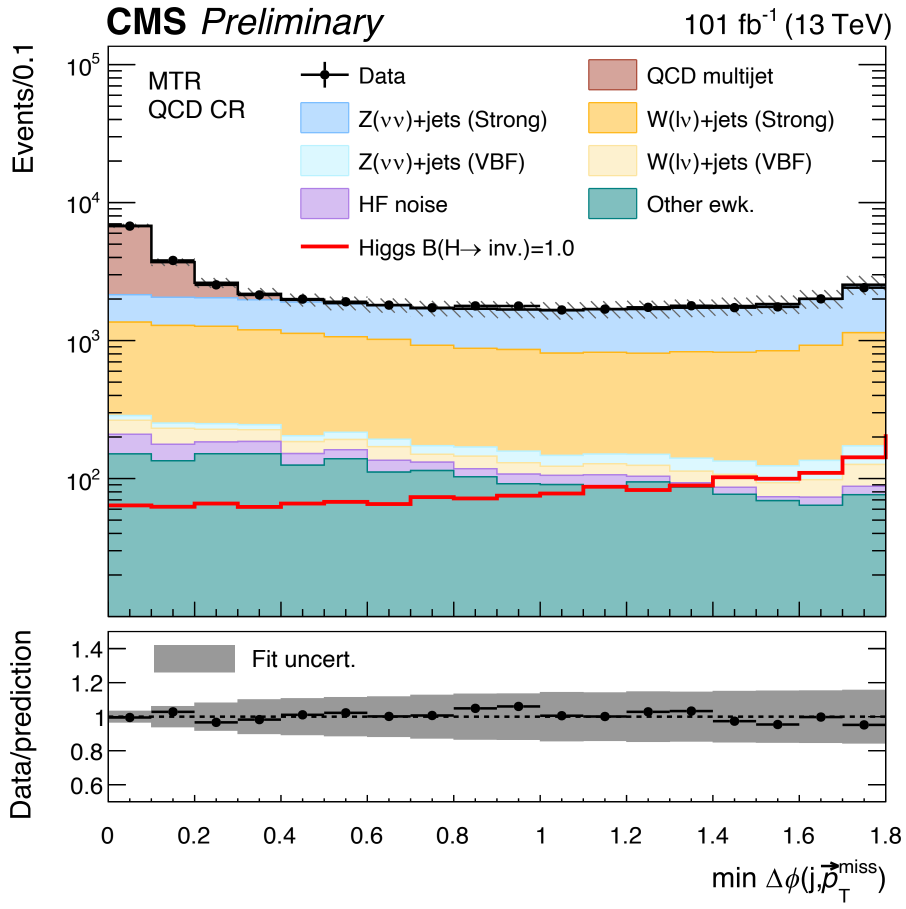
Aside from $V + jets$, additional backgrounds arise due to jet p_T mis-measurements

QCD multi-jet: Jet resolution effects result in high p_T^{miss} for QCD multi-jet events

Low probability of severe mis-measurement × **High** σ
→ Results in a small but non-negligible background to SR

Approach: Estimate this contribution using a QCD control region in data → $\min\Delta\phi\left(jet, p_T^{miss}\right) < 0.5$

→ Fit the distribution in data and extract the yields in SR i.e. $\min\Delta\phi\left(jet, p_T^{miss}\right) > 0.5$ (or 1.8 for VTR)



Background Estimation (QCD Multi-jet)

CMS-PAS-HIG-20-003

Aside from $V + jets$, additional backgrounds arise due to jet p_T mis-measurements

Forward calorimeter (HF) noise: High p_T^{miss} events due to jet p_T mis-measurements @ high η

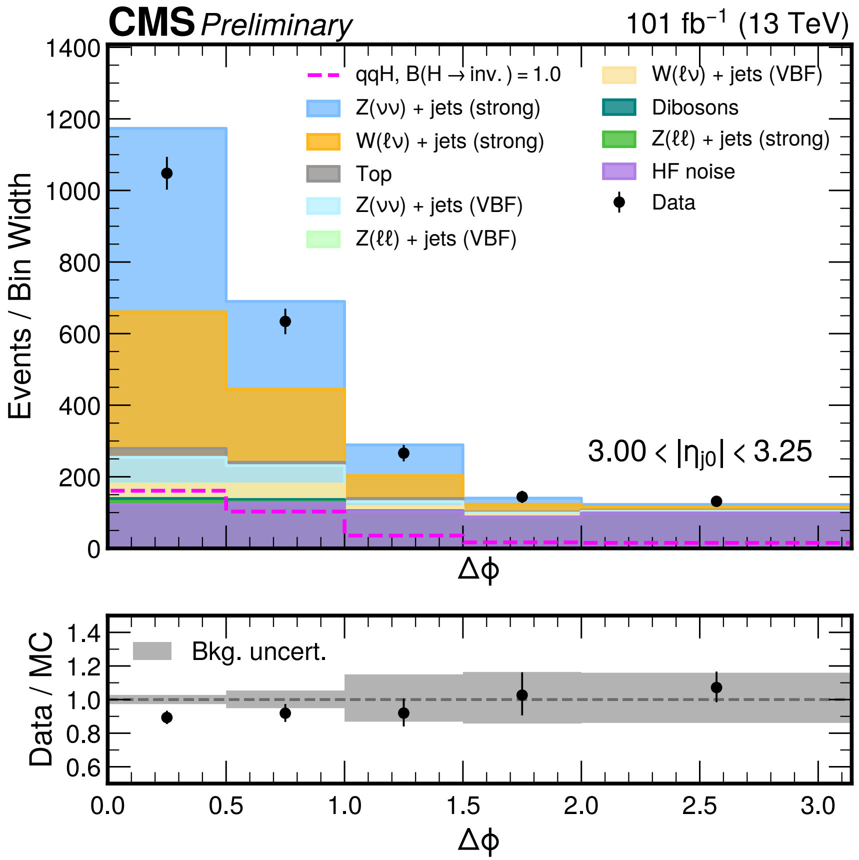
Mis-measured jets can be identified via their shower shapes:

- ✓ Typically, the η-width is larger than ϕ-width
- ✓ Larger # of PF candidates within $\Delta\phi(cand, jet) \approx 0.05$

→ These features are used to develop selections to reject events with such jets

Noise estimation: Invert the selection, compute the residual contribution from data

Estimation validated in VBF SR:



$\Delta\phi$: $\Delta\phi\left(p_{T,Trk}^{miss}, p_T^{miss}\right)$

20% norm uncertainty assigned

Results

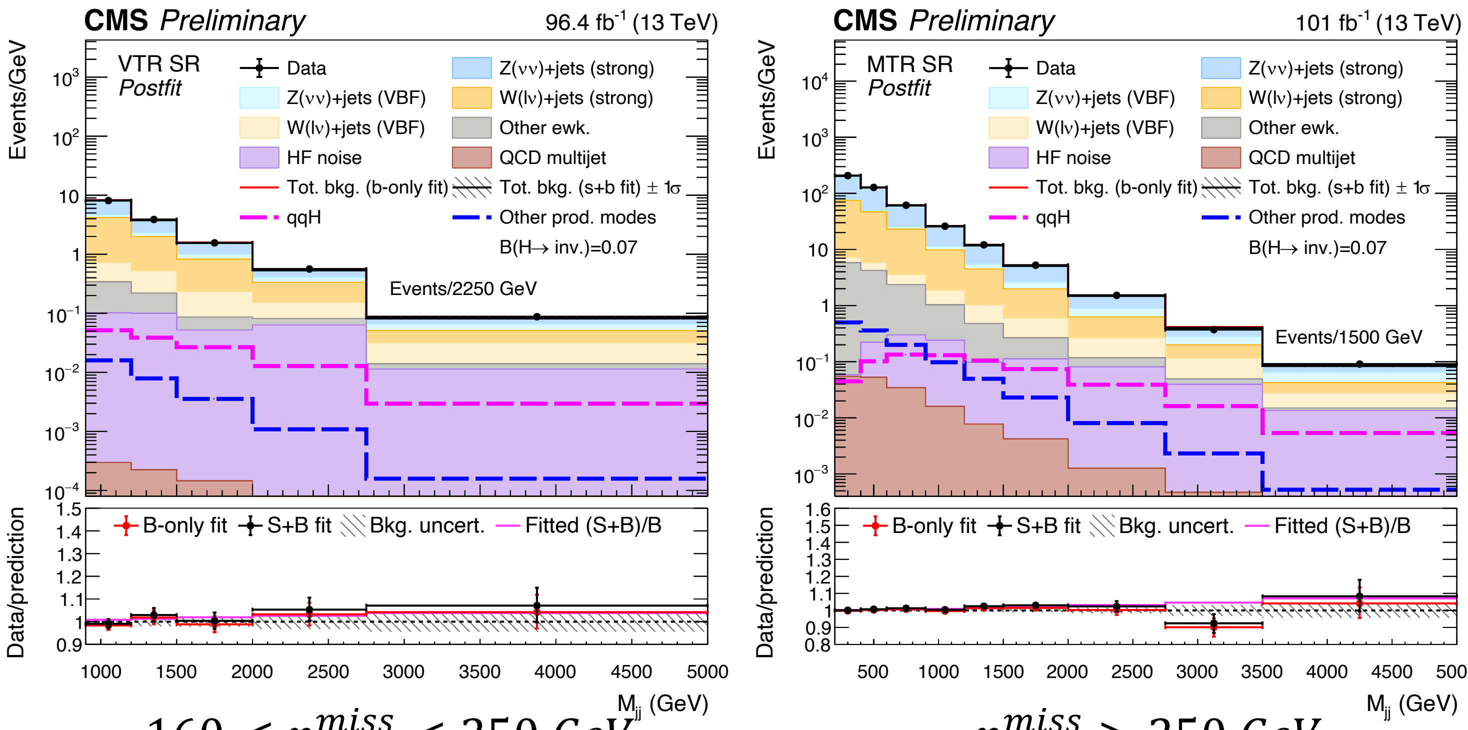
2017+2018 data is analyzed here, combination with the existing 2016 result is performed!

Results: Data vs Bkg. Predictions

Data & background estimation in signal region:

VTR 2017+2018:

MTR 2017+2018:



$160 < p_T^{miss} < 250\ GeV$

$p_T^{miss} > 250\ GeV$

Best-fit signal strength:

$$\mu = 0.076^{+0.057}_{-0.055}$$

Theoretical modeling, simulation & trigger efficiency uncertainties dominate:

Group of systematic uncertainties	Observed impact on $\mathcal{B}(\mathrm{H} \to \mathrm{inv})$
Theory	$^{+0.026}_{-0.025}$
MC stat.	$^{+0.024}_{-0.023}$
Triggers	$^{+0.021}_{-0.022}$
Leptons/photons/b	$^{+0.012}_{-0.011}$
QCD multijet mismodeling	± 0.013
Jet calibration	$^{+0.010}_{-0.007}$
Lumi/PU	± 0.005
Other systematic uncertainties	$^{+0.013}_{-0.010}$
Stat.	± 0.029

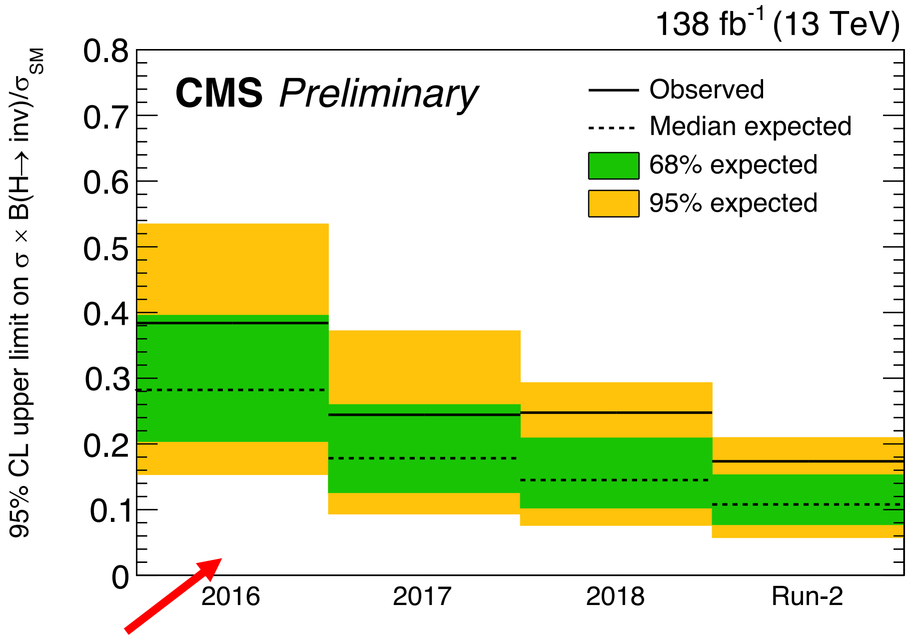
No excess of data over background predictions are observed in either category

→ Put constraints on $B(H \to inv)$

Results: Exclusion Limits

CMS-PAS-HIG-20-003

Exclusion limits on $B(H \rightarrow inv)$:



2016: Taken from arXiv:1809.05937
+ NLO correction on signal (backup)

Statistical combination with 2016 analysis:

Expected sensitivity: **11%**, observed: **17%**

→ Most stringent expected single-channel sensitivity to date!

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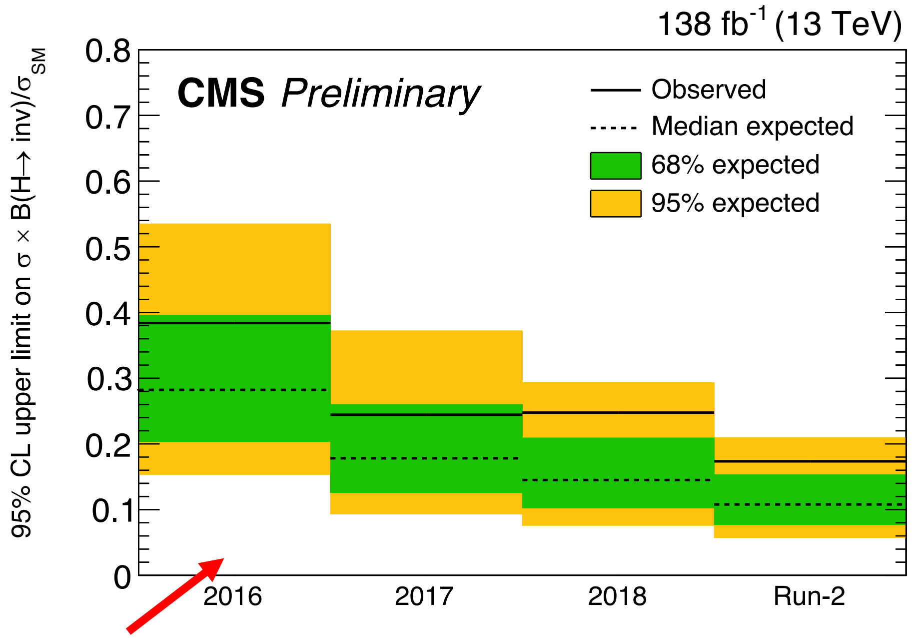

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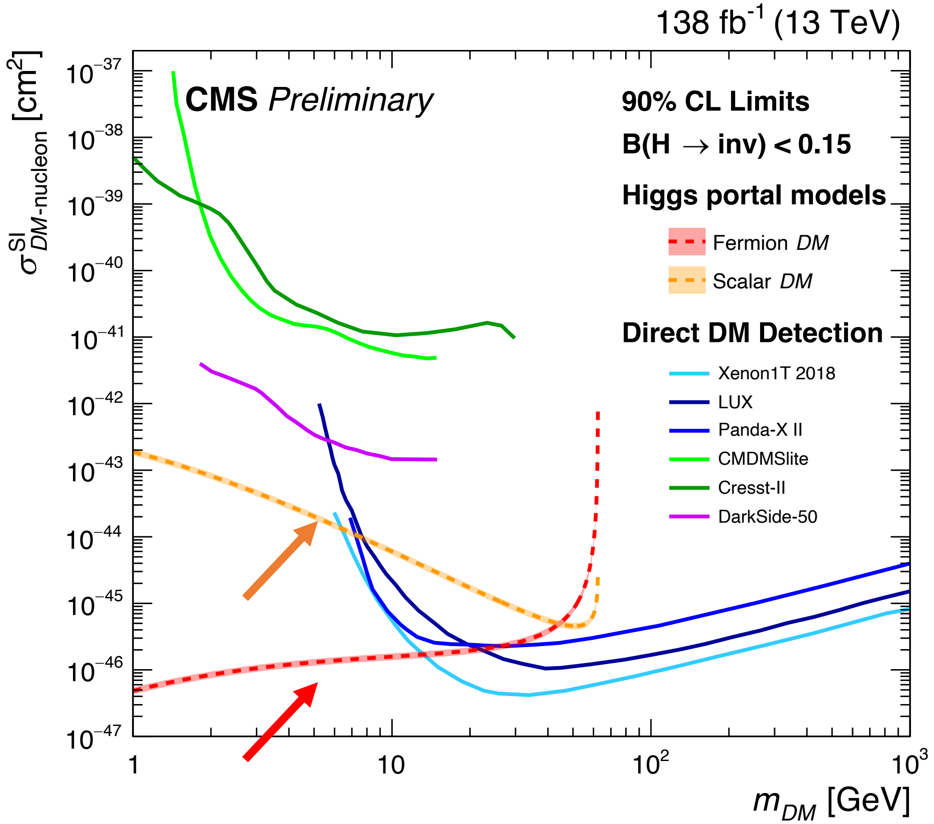
CMS-PAS-HIG-20-003

DM Interpretation

Can compare the results with direct detection:

Exclusion on $B(H \to inv)$ → Exclusion on σ_{DM}



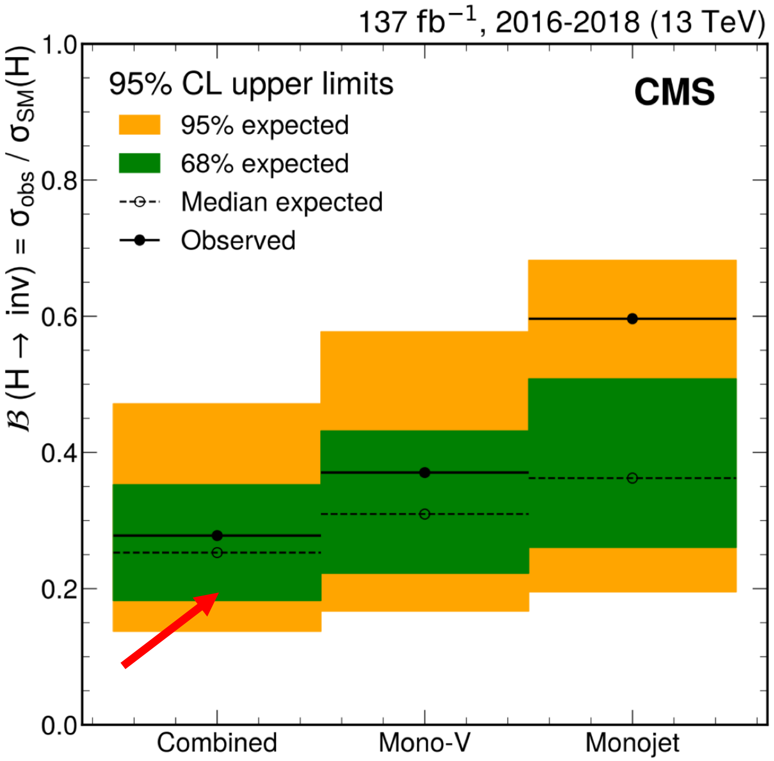
→ Results complement the direct-detection experiments nicely for $m_{DM} < O(10\ GeV)$

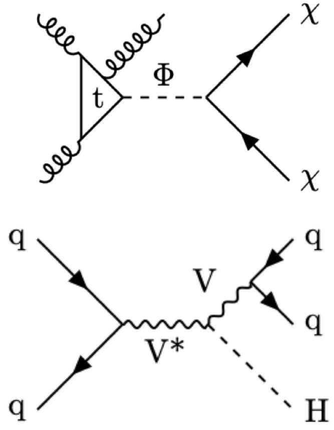
Results: More Channels!

[Eur. Phys. J. C (2021) 81:13](#)
[JHEP11 (2021) 153](#)

H(inv) interpretation results from other channels in CMS:

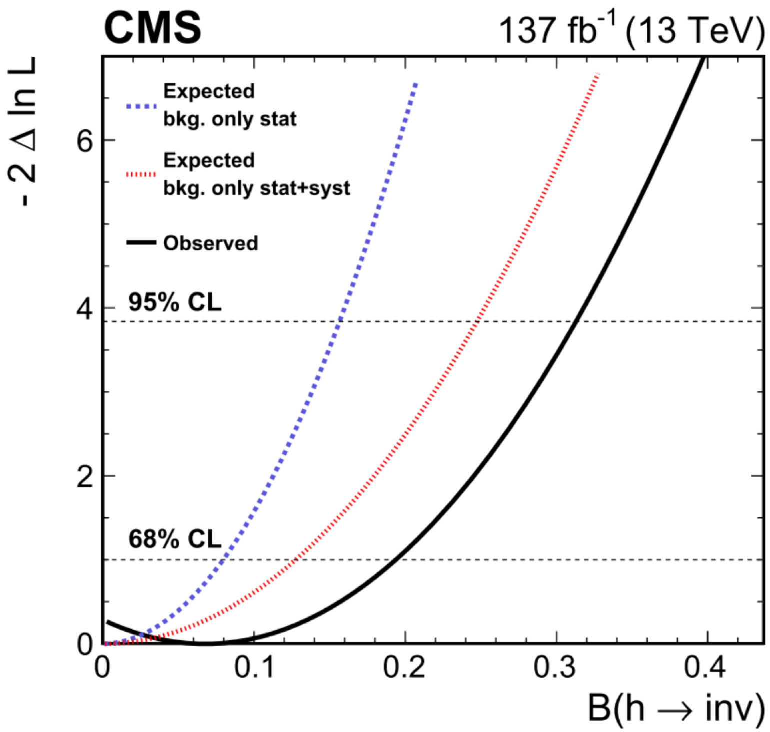
Exclusion limits on $B(H \rightarrow inv)$ from mono-jet + mono-V:

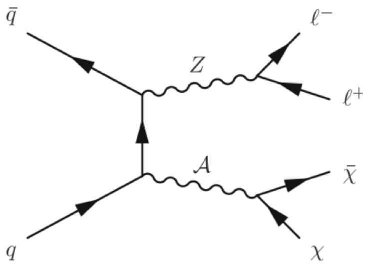




Two channels combined: 28% obs. limit

Mono-Z:





29% obs. (25% exp.) limit

Summary

A brief summary of the latest VBF H(inv) analysis

Important updates w.r.t. earlier analysis:

- ✓ Addition of the forward calorimeter (HF-HF) events!
- ✓ Addition of VBF triggered category (VTR)
- ✓ Addition of photon CR to MTR

→ Observed limit reaches to 17% with all years combined (exp. 11%)

Summary

CMS-PAS-HIG-20-003
CMS-PAS-HIG-18-008
JHEP11 (2021) 153
EPJC 81, 13 (2021)

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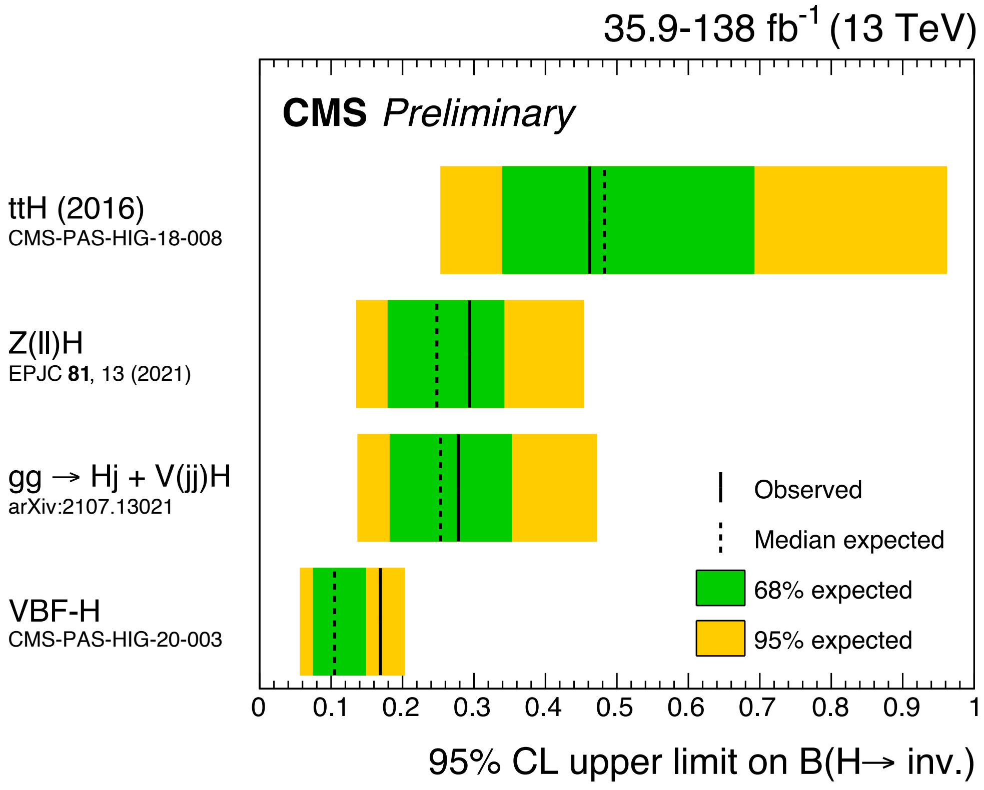
- ✓ Addition of VBF triggered category (VTR)
- ✓ Addition of photon CR to MTR

→ Observed limit reaches to 17% with all years combined (exp. 11%)

Can compare with other latest results from CMS:

- ✓ VBF is the most sensitive channel so far
- ✓ Mono-$Z(\ell\ell)$ and mono-jet + mono-V analyses are also out
- ✓ Mono-Z: 29% obs. limit
- ✓ Mono-jet + mono-V: 28% obs. limit

Exclusion limits from different channels:



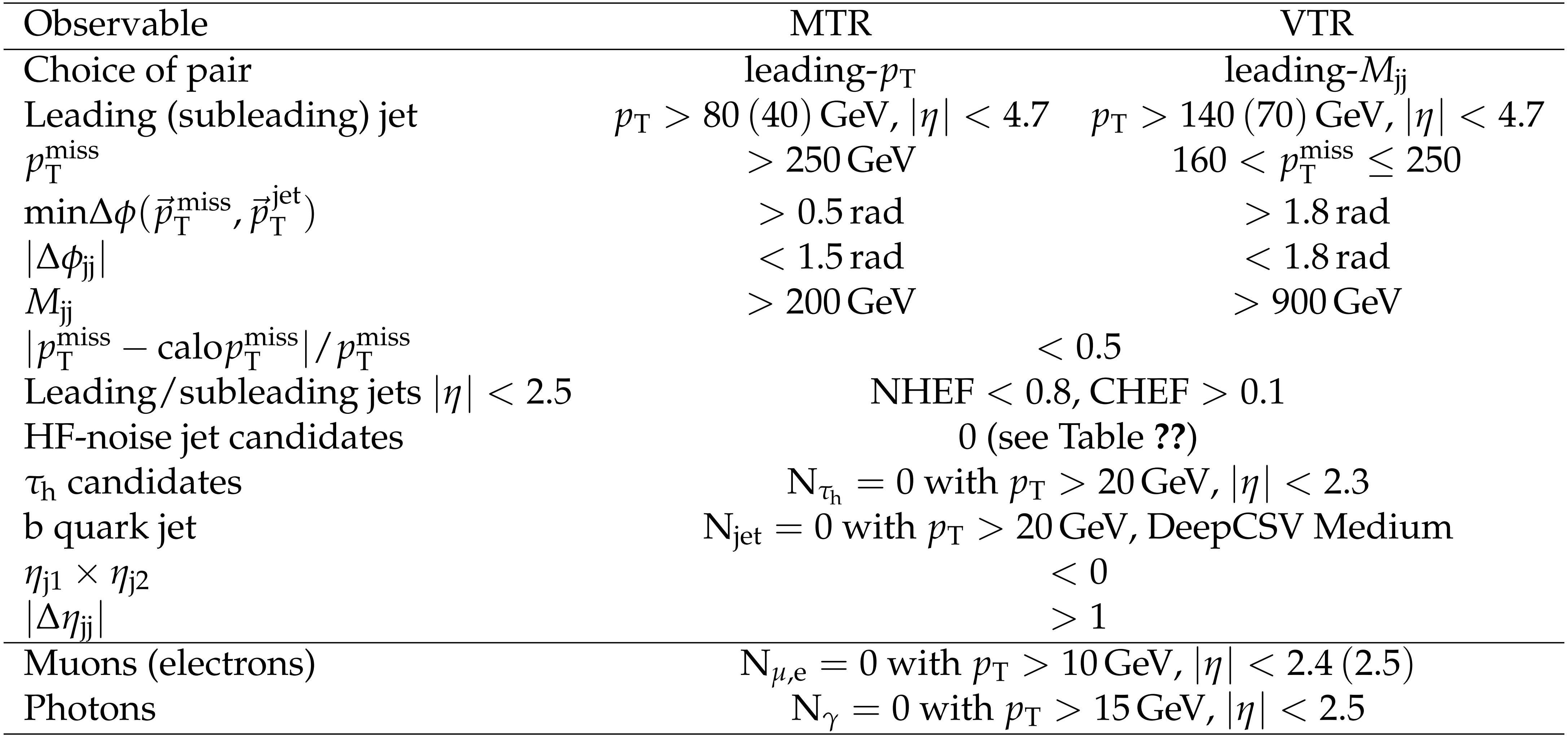
Backup

Event Selection: Signal Region

CMS-PAS-HIG-20-003

Object definitions are all according to POG recommendations

Event selection requirements for **MTR & VTR** signal regions are listed below:



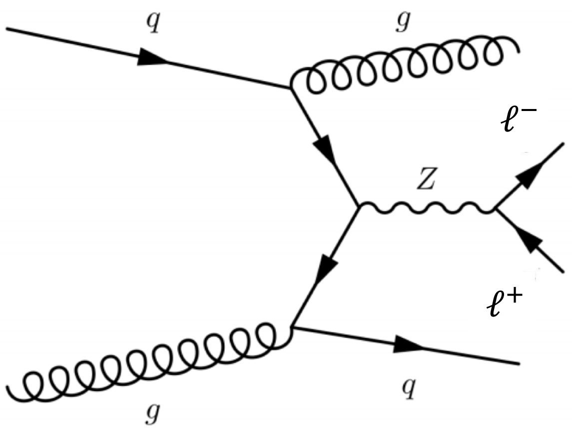
Observable	MTR	VTR
Choice of pair	leading-p_T	leading-M_jj
Leading (subleading) jet	$p_\mathrm{T} > 80\,(40)\,\mathrm{GeV}, \lvert\eta\rvert < 4.7$	$p_\mathrm{T} > 140\,(70)\,\mathrm{GeV}, \lvert\eta\rvert < 4.7$
$p_\mathrm{T}^\mathrm{miss}$	$> 250\,\mathrm{GeV}$	$160 < p_\mathrm{T}^\mathrm{miss} \leq 250$
$\min\Delta\phi(\vec{p}_\mathrm{T}^\mathrm{miss}, \vec{p}_\mathrm{T}^\mathrm{jet})$	$> 0.5\,\mathrm{rad}$	$> 1.8\,\mathrm{rad}$
$\lvert\Delta\phi_\mathrm{jj}\rvert$	$< 1.5\,\mathrm{rad}$	$< 1.8\,\mathrm{rad}$
M_jj	$> 200\,\mathrm{GeV}$	$> 900\,\mathrm{GeV}$
$\lvert p_\mathrm{T}^\mathrm{miss} - \mathrm{calo}p_\mathrm{T}^\mathrm{miss}\rvert / p_\mathrm{T}^\mathrm{miss}$	< 0.5	
Leading/subleading jets $\lvert\eta\rvert < 2.5$	NHEF < 0.8, CHEF > 0.1	
HF-noise jet candidates	0 (see Table **??**)	
τ_h candidates	$\mathrm{N}_{\tau_\mathrm{h}} = 0$ with $p_\mathrm{T} > 20\,\mathrm{GeV}, \lvert\eta\rvert < 2.3$	
b quark jet	$\mathrm{N}_\mathrm{jet} = 0$ with $p_\mathrm{T} > 20\,\mathrm{GeV}$, DeepCSV Medium	
$\eta_\mathrm{j1} \times \eta_\mathrm{j2}$	< 0	
$\lvert\Delta\eta_\mathrm{jj}\rvert$	> 1	
Muons (electrons)	$\mathrm{N}_{\mu,\mathrm{e}} = 0$ with $p_\mathrm{T} > 10\,\mathrm{GeV}, \lvert\eta\rvert < 2.4\,(2.5)$	
Photons	$\mathrm{N}_\gamma = 0$ with $p_\mathrm{T} > 15\,\mathrm{GeV}, \lvert\eta\rvert < 2.5$	

Event Selection: Control Regions

CRs built on top of the SR selections: VBF requirements are applied in all regions

Z CRs **2 CRs**

Collect $Z \rightarrow \ell\ell$ events to constrain $Z(\nu\nu)$ in SR



$p_{T,no-\ell}^{miss}$: $> 250\ GeV$ (MTR)

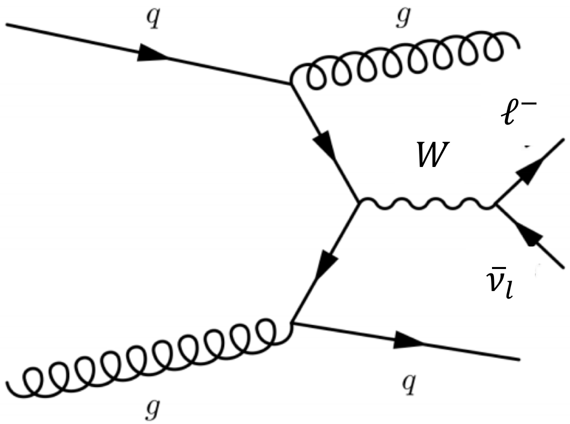
$\epsilon\ [160, 250]\ GeV$ (VTR)

$|M_{\ell\ell} - M_Z| < 30\ GeV$

$N_\ell = 2$ (at least 1 tight)

W CRs **2 CRs**

Collect $W \rightarrow \ell\nu$ events to constrain $W(\ell\nu)$ in SR



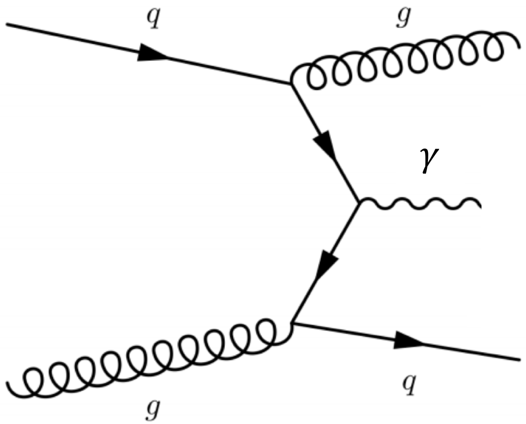
$p_{T,no-\ell}^{miss}$: $> 250\ GeV$ (MTR)

$\epsilon\ [160, 250]\ GeV$ (VTR)

$N_\ell = 1$ (tight)

$\gamma + jets$ CR **1 CR**

Collect $\gamma + jets$ events to further constrain $Z(\nu\nu)$



Only in MTR!

$p_{T,no-\gamma}^{miss} > 250\ GeV$

$p_T^\gamma > 230\ GeV$

$N_\gamma = 1$ (tight)

VBF: Total List Of Uncertainties

CMS-PAS-HIG-20-003

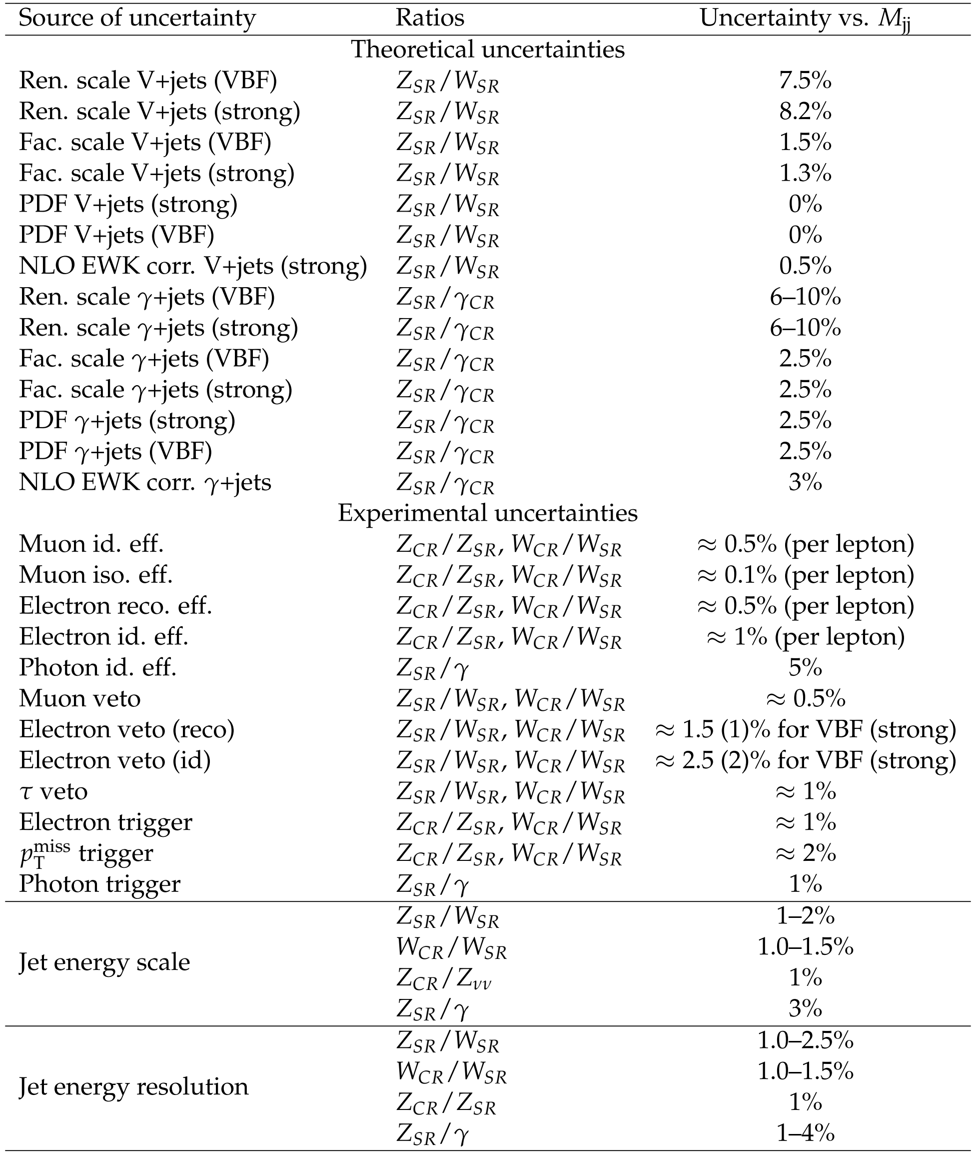
Total list of uncertainties for VBF H(inv) analysis is shown on the right

Theoretical uncertainties:

- Scale uncertainties taken as partially correlated between V+jets processes
- PDF uncertainties taken as fully correlated
- NLO EWK full correction applied as uncertainty

Experimental uncertainties:

- Uncertainties related to physics object identification + triggering



Source of uncertainty	Ratios	Uncertainty vs. M_{jj}
	Theoretical uncertainties	
Ren. scale V+jets (VBF)	Z_{SR}/W_{SR}	7.5%
Ren. scale V+jets (strong)	Z_{SR}/W_{SR}	8.2%
Fac. scale V+jets (VBF)	Z_{SR}/W_{SR}	1.5%
Fac. scale V+jets (strong)	Z_{SR}/W_{SR}	1.3%
PDF V+jets (strong)	Z_{SR}/W_{SR}	0%
PDF V+jets (VBF)	Z_{SR}/W_{SR}	0%
NLO EWK corr. V+jets (strong)	Z_{SR}/W_{SR}	0.5%
Ren. scale γ+jets (VBF)	Z_{SR}/γ_{CR}	6–10%
Ren. scale γ+jets (strong)	Z_{SR}/γ_{CR}	6–10%
Fac. scale γ+jets (VBF)	Z_{SR}/γ_{CR}	2.5%
Fac. scale γ+jets (strong)	Z_{SR}/γ_{CR}	2.5%
PDF γ+jets (strong)	Z_{SR}/γ_{CR}	2.5%
PDF γ+jets (VBF)	Z_{SR}/γ_{CR}	2.5%
NLO EWK corr. γ+jets	Z_{SR}/γ_{CR}	3%
	Experimental uncertainties	
Muon id. eff.	Z_{CR}/Z_{SR}, W_{CR}/W_{SR}	$\approx$ 0.5% (per lepton)
Muon iso. eff.	Z_{CR}/Z_{SR}, W_{CR}/W_{SR}	$\approx$ 0.1% (per lepton)
Electron reco. eff.	Z_{CR}/Z_{SR}, W_{CR}/W_{SR}	$\approx$ 0.5% (per lepton)
Electron id. eff.	Z_{CR}/Z_{SR}, W_{CR}/W_{SR}	$\approx$ 1% (per lepton)
Photon id. eff.	Z_{SR}/γ	5%
Muon veto	Z_{SR}/W_{SR}, W_{CR}/W_{SR}	$\approx$ 0.5%
Electron veto (reco)	Z_{SR}/W_{SR}, W_{CR}/W_{SR}	$\approx$ 1.5 (1)% for VBF (strong)
Electron veto (id)	Z_{SR}/W_{SR}, W_{CR}/W_{SR}	$\approx$ 2.5 (2)% for VBF (strong)
τ veto	Z_{SR}/W_{SR}, W_{CR}/W_{SR}	$\approx$ 1%
Electron trigger	Z_{CR}/Z_{SR}, W_{CR}/W_{SR}	$\approx$ 1%
p_{T}^{miss} trigger	Z_{CR}/Z_{SR}, W_{CR}/W_{SR}	$\approx$ 2%
Photon trigger	Z_{SR}/γ	1%
Jet energy scale	Z_{SR}/W_{SR}	1–2%
	W_{CR}/W_{SR}	1.0–1.5%
	$Z_{CR}/Z_{\nu\nu}$	1%
	Z_{SR}/γ	3%
Jet energy resolution	Z_{SR}/W_{SR}	1.0–2.5%
	W_{CR}/W_{SR}	1.0–1.5%
	Z_{CR}/Z_{SR}	1%
	Z_{SR}/γ	1–4%

NLO EWK Correction on VBF Signal

NLO EWK corrections on VBF signal are derived using HAWK generator

→ Was not applied previously

Corrections are computed as a function of Higgs boson p_T (with the VBF topology cuts applied):

HAWK

A Monte Carlo generator for the production of Higgs bosons Attached to Weak bosons

NLO EWK corrections:

- ✓ **Inclusive:** $\delta_{EWK}^{inclusive} \approx 5\%$ → Included in the VBF XS
- ✓ **Differential:** $\delta_{EWK}^{diff} > 7.5\%$

The remaining differential correction becomes:

$$\boxed{\epsilon^{NLO}(p_T^H) = (1 - 0.000372 \times p_T^H \; - 0.0304)/\, 0.95}$$

Total NLO EWK correction as a function of Higgs boson p_T

Impact on sensitivity: $\approx$ 15% loss in sensitivity

Note on 2016:
2016 signal templates are re-calculated with this correction for the final Run-2 result

→ $\approx$ 10% loss in sensitivity

List of URLs

Sorry, having issues with the PDF converters either modifying plots or removing links

If you're not able to click on the links on main slides, you can find the URLs here:

CMS-PAS-HIG-20-003: https://cms.cern.ch/iCMS/analysisadmin/get?analysis=HIG-20-003-pas-v3.pdf

CMS-PAS-HIG-18-008: http://cms.cern.ch/iCMS/analysisadmin/get?analysis=HIG-18-008-pas-v12.pdf

JHEP11 (2021) 153: https://link.springer.com/article/10.1007/JHEP11(2021)153

EPJC 81, 13 (2021): https://link.springer.com/content/pdf/10.1140/epjc/s10052-020-08739-5

HAWK Generator: https://hawk.hepforge.org/