Imperial College London

Science & Technology Facilities Council

CMS Compact Muon Solenoid

CMS Wildcard Talk:

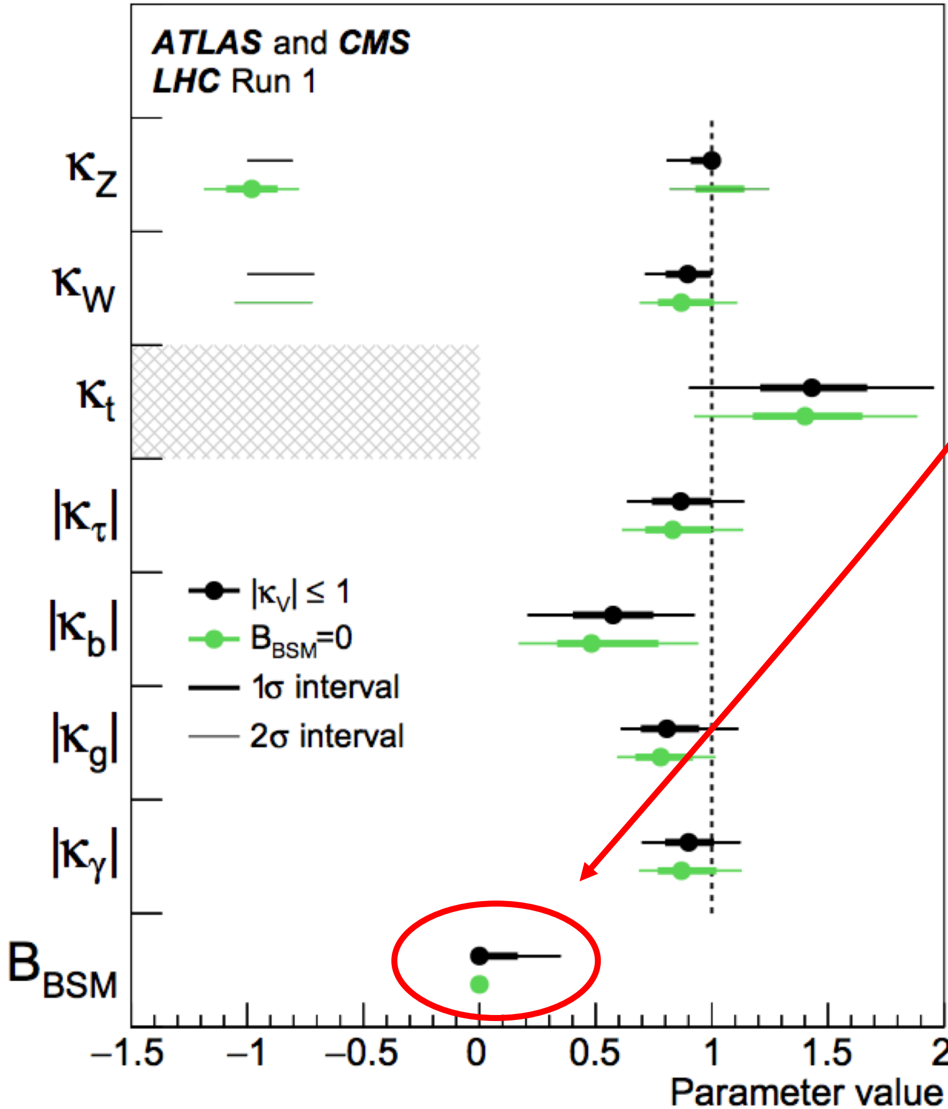
Search for invisible Higgs boson decays in VBF production at CMS

Nicholas Wardle

Higgs2021 – Stonybrook, USA

18th October 2021

BSM Higgs boson decays



Higgs boson coupling measurements leave room for Beyond SM (BSM) decays!*

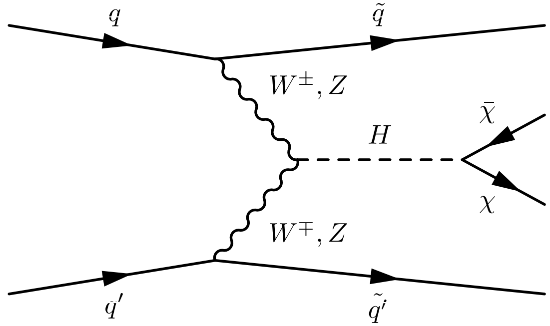
Several BSM models predict invisible contributions to Higgs boson width✦

Invisible Higgs boson decays in SM quite small B(H→4ν)~0.1%

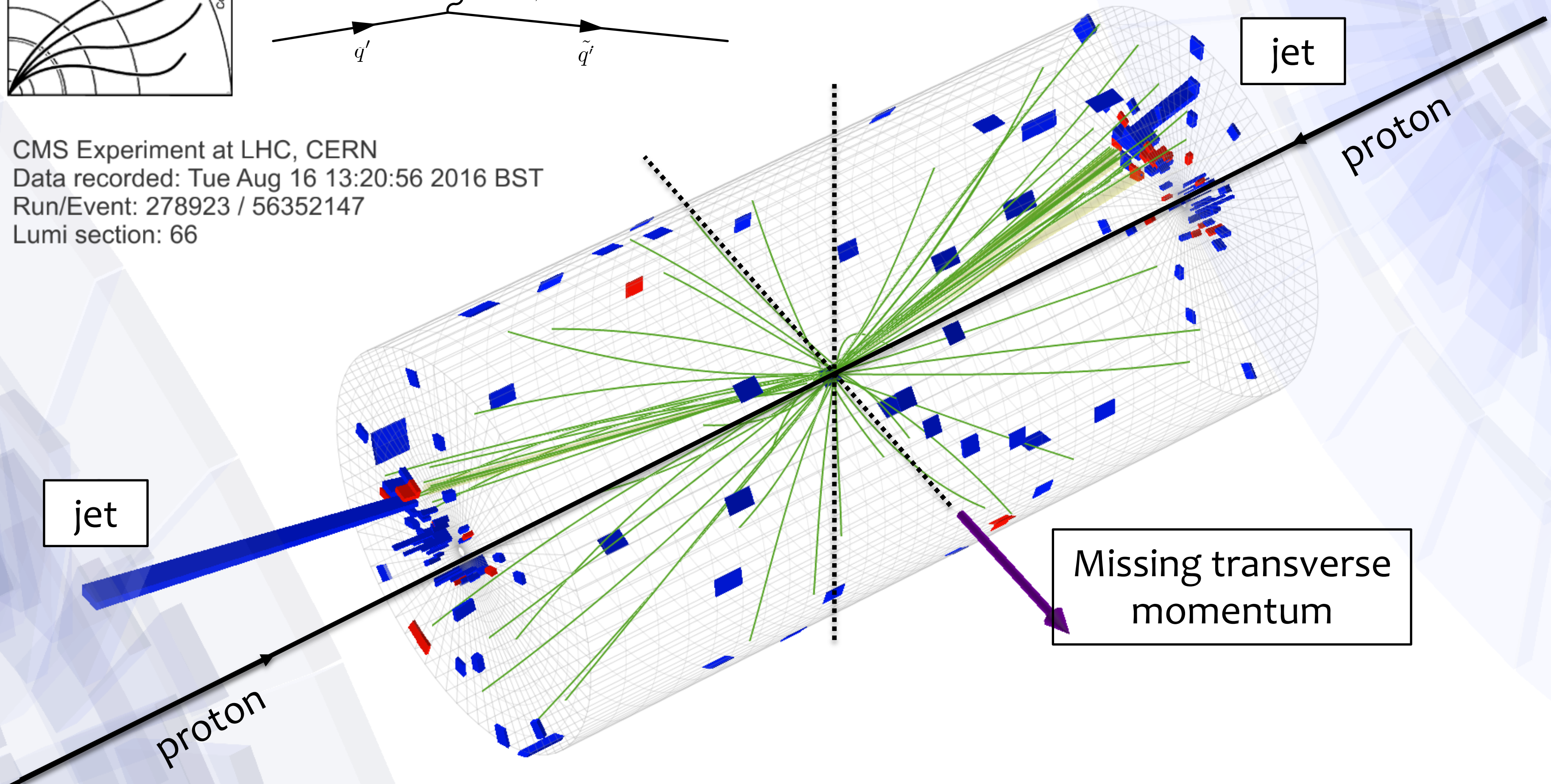
→ *Invisible Higgs boson decays will be a strong indication of new physics!*

*see talk by **Scott Snyder** on various searches for exotic Higgs decays
✦see talky by **Savvas Kyriacou** on constraints on the Higgs boson width

VBF Production



CMS Experiment at LHC, CERN
Data recorded: Tue Aug 16 13:20:56 2016 BST
Run/Event: 278923 / 56352147
Lumi section: 66



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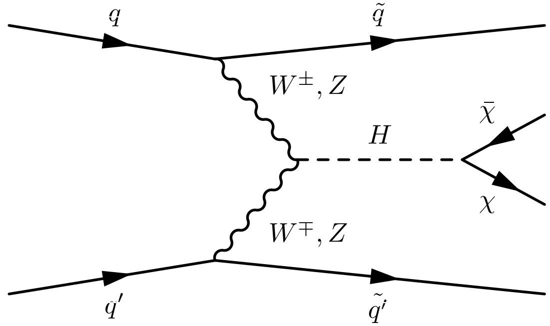

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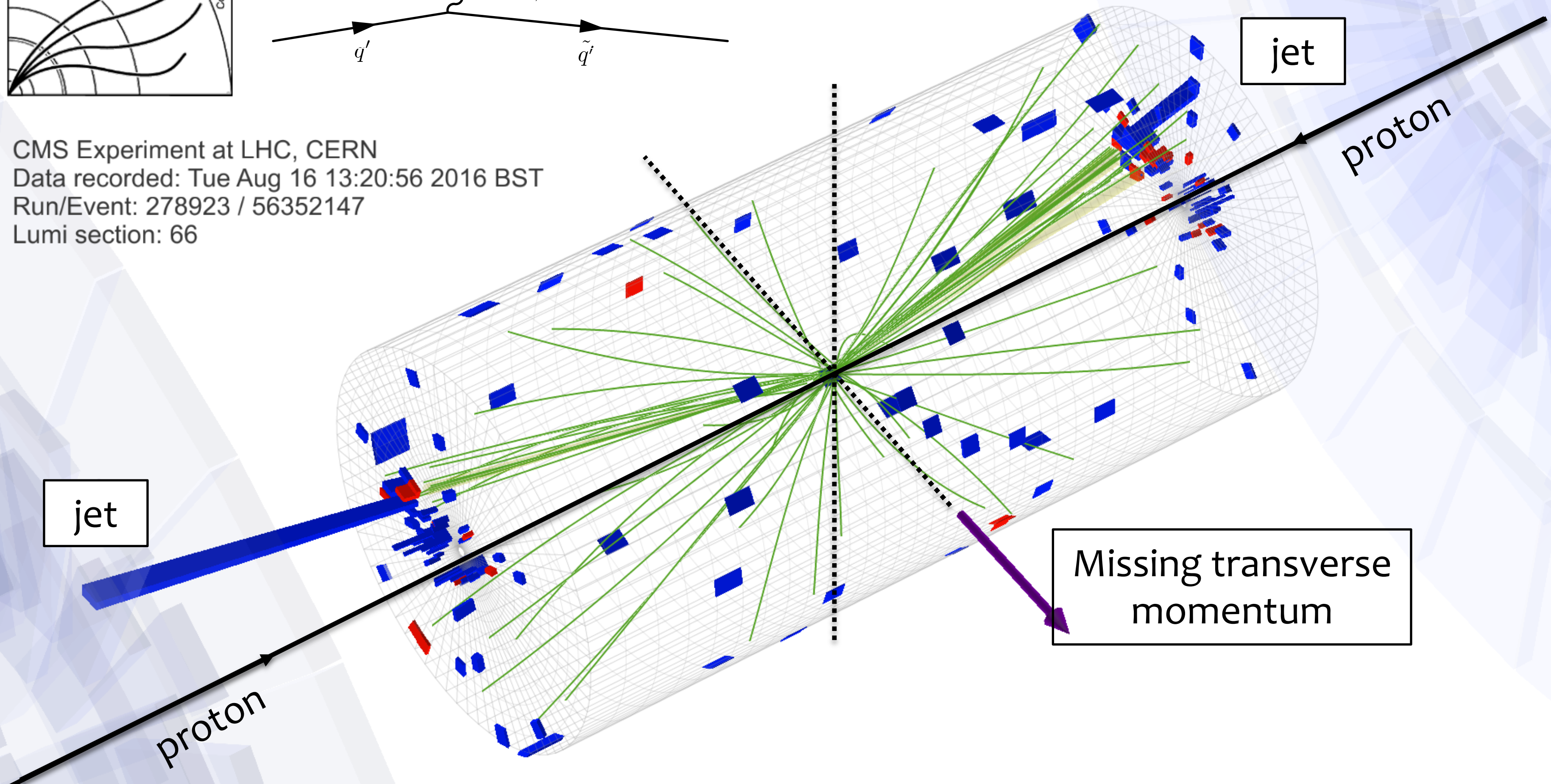
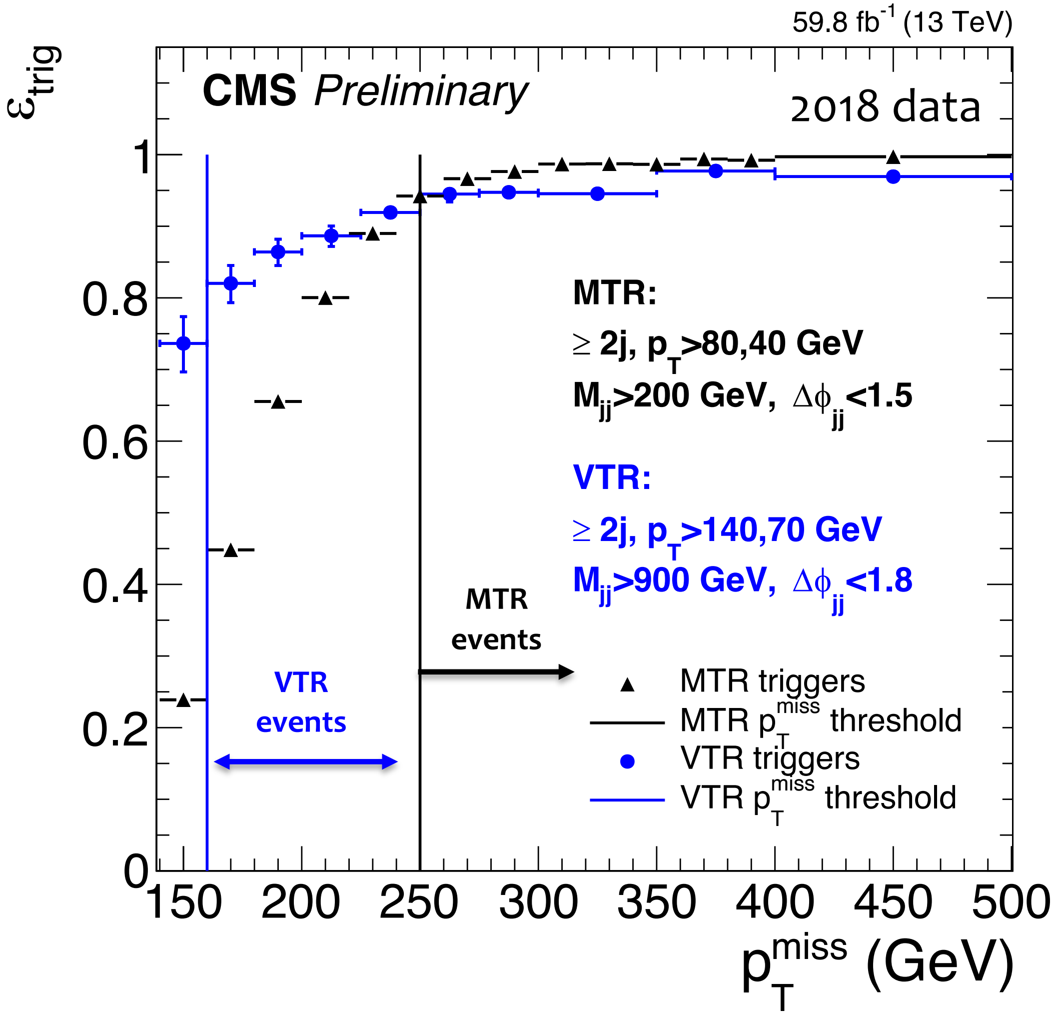


Today I will present a **new search for VBF H→invisible** at CMS with the full Run-2 dataset: CMS-PAS-HIG-20-003

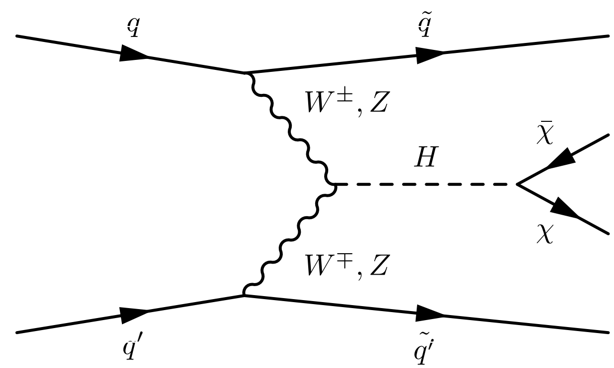
Event selection (online)



Event triggers require large missing momentum + jets

- **MTR** (missing-momentum trigger) target high p_T^{miss} events
- **NEW for 2017/2018: VTR** (VBF-trigger) provides improved efficiency at lower p_T^{miss} (improves sensitivity by ~8%)

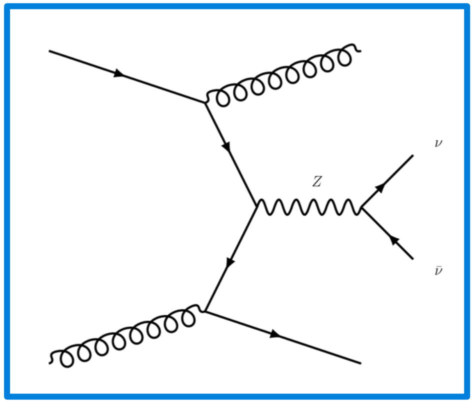
Events separated into two regions (MTR & VTR) based on reconstructed p_T^{miss} and jet/M_{jj} requirements

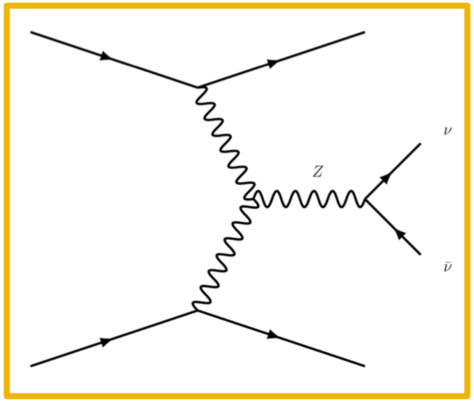


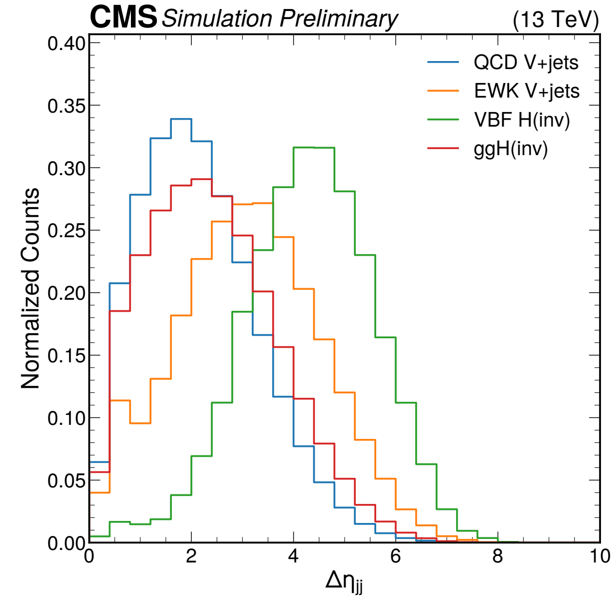
Using refined alignment/calibration for 2017/2018 analysis
→ Substantial performance gain for forward jets!

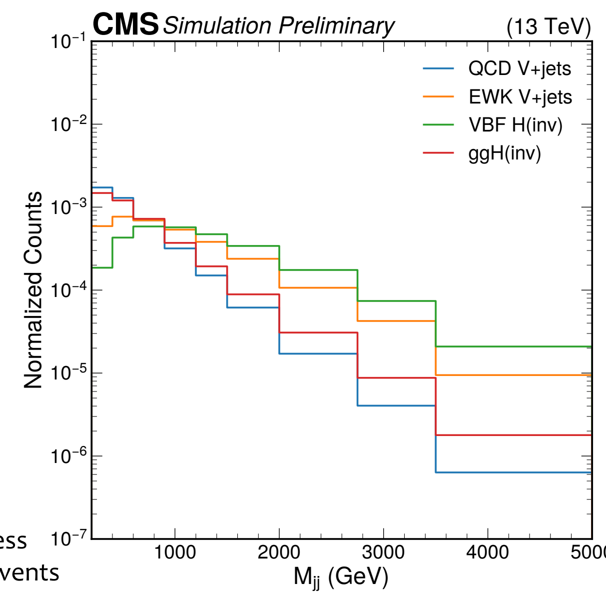
Event selection

Rely on VBF di-jet tagging to reduce contributions from SM Backgrounds (V+jets)









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

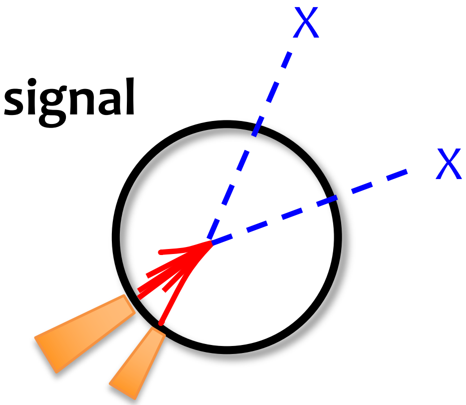
	MTR	VTR
p_T	> 80/40 GeV	> 140/70 GeV
M_{jj}	> 200 GeV	> 900 GeV
$\Delta\eta(j,j)$	> 1	> 1
$\Delta\varphi(j,j)$	< 1.5 rad	< 1.8 rad
Min $\Delta\varphi(j,p_T^{miss})$	> 0.5 rad	> 1.8 rad

} Suppress multijet events

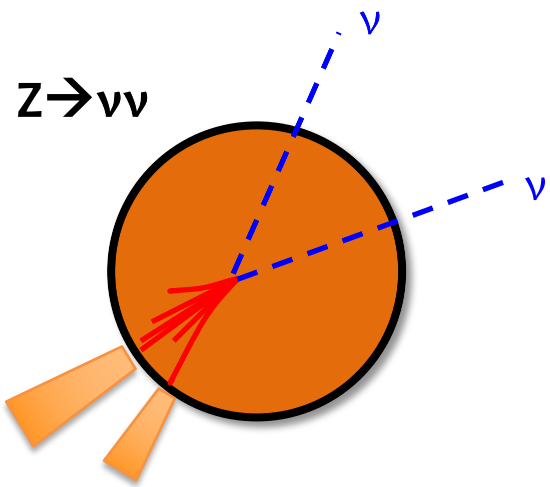
+ Veto events with leptons/photons/b-jets and additional spurious jets (noise)

Invisible backgrounds

H→inv signal



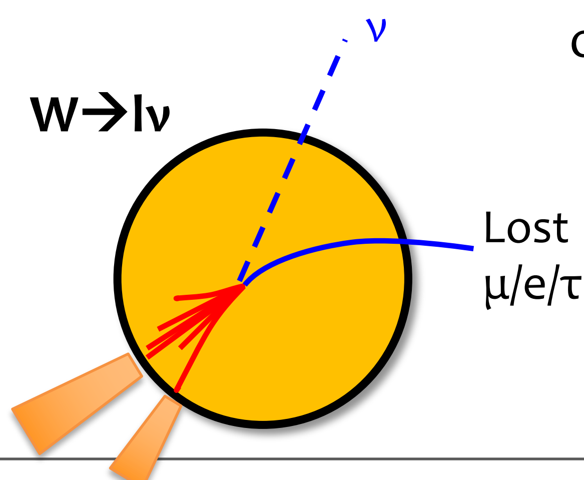
Z→νν



Neutrinos escape detection to mimic a DM signal!

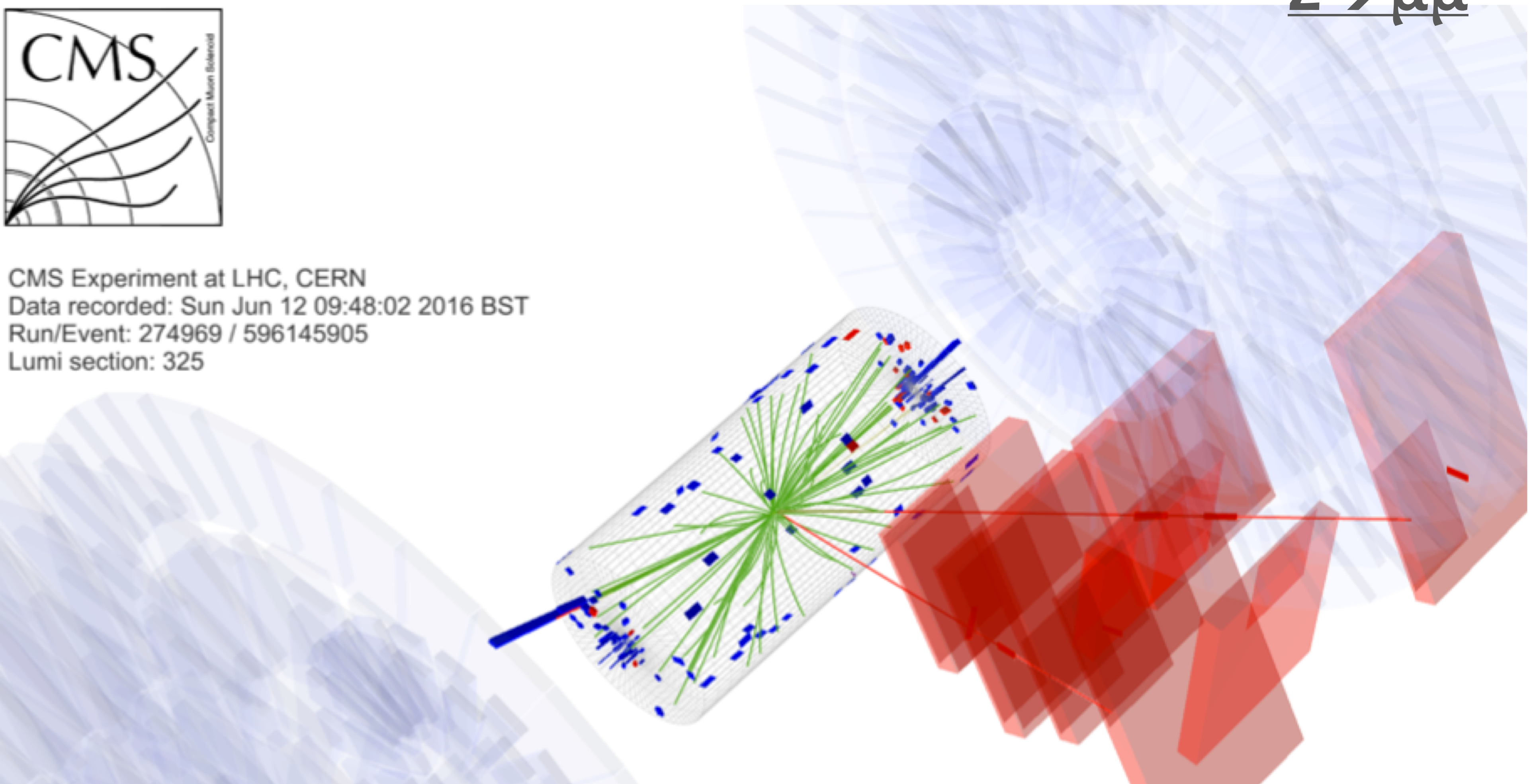
Most common are Z decays to neutrinos and leptonic W decays where the lepton falls outside of the acceptance or isn't reconstructed

W→lν



Relatively large cross-sections for these processes mean backgrounds are sizeable compared to H→inv signal

Z→μμ

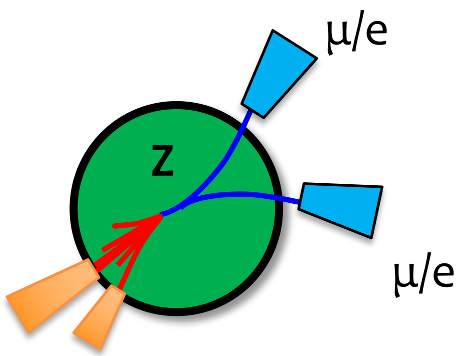


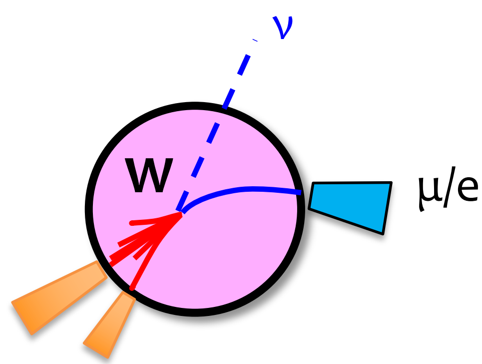
Lepton/Photon regions in data (eg Z→ll) used to model V+jets

- Kinematics similar between processes (strong correlation between visible object p_T and p_T^{miss})
- Systematics due lepton/photon efficiencies/vetos & theoretical modeling of cross-section ratios

Control regions in data

Define single & double-lepton control regions (CR) in data enriched in W and Z boson decays to model V+jets backgrounds in signal region (SR)

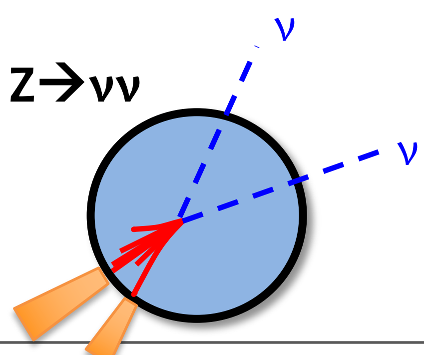




Select orthogonal regions with identical selection to signal region except

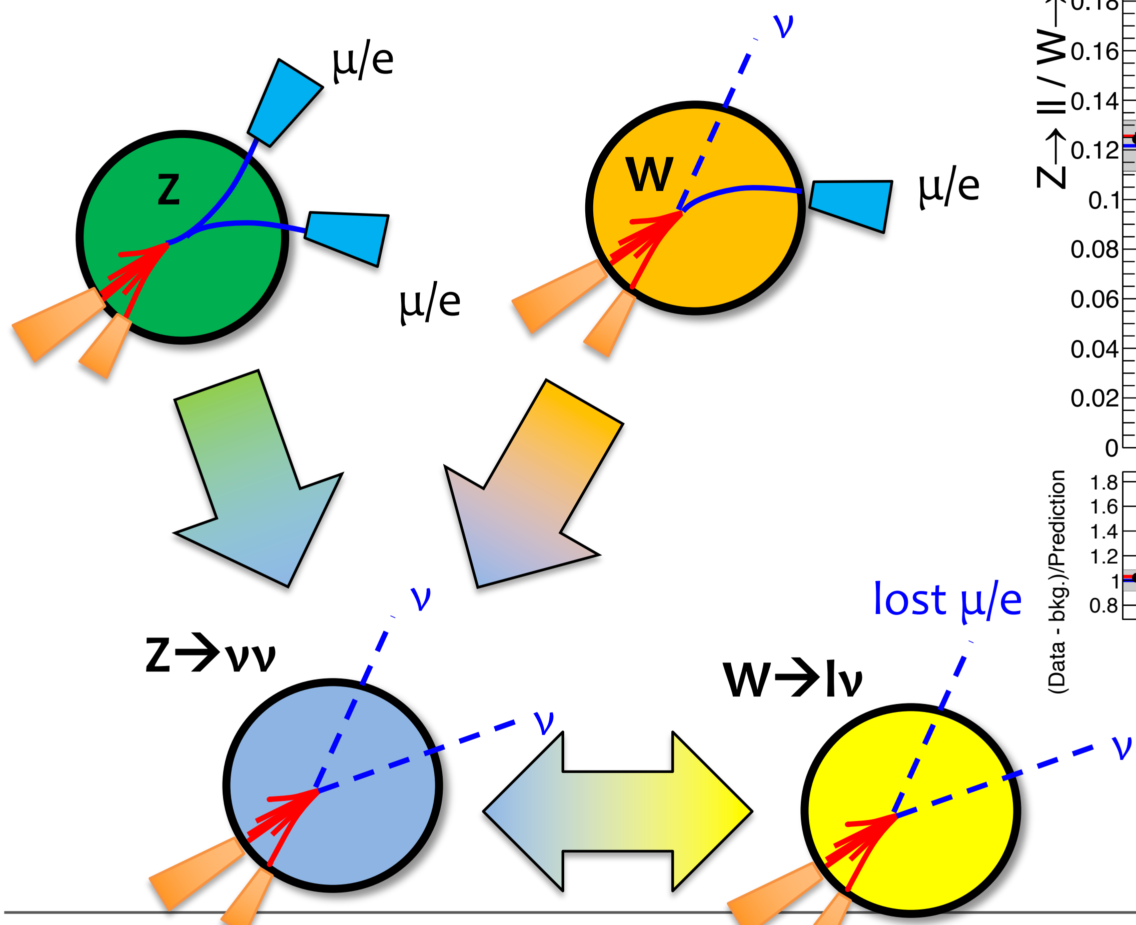
- Single-lepton: Exactly 1 μ/e + p_T^{miss} > 80 GeV
- Di-lepton : Exactly 2 opposite signed μμ/ee with 60 < m_{ll} < 120 GeV

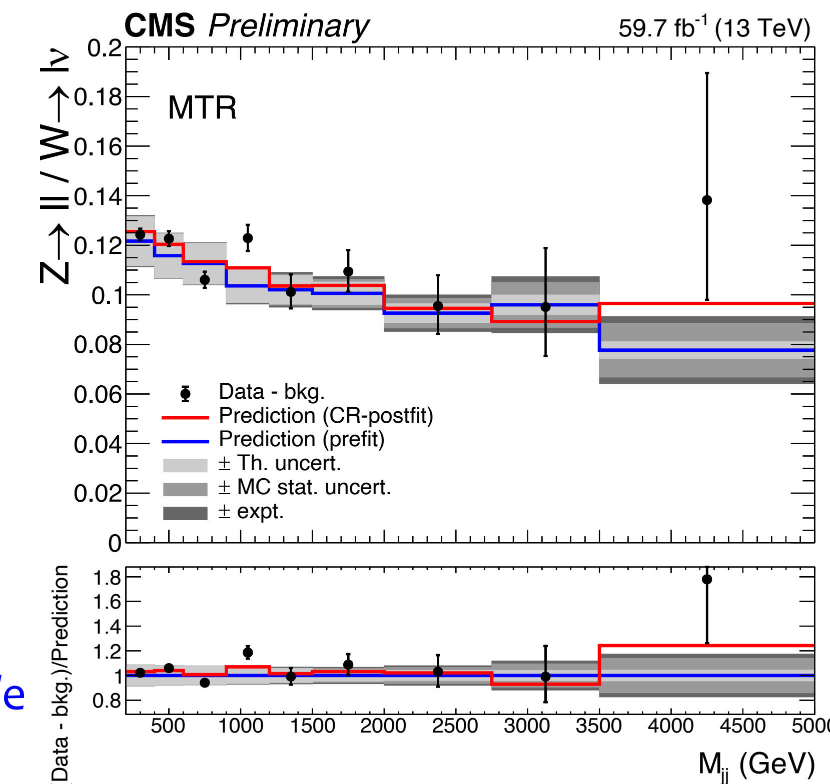
Redefine p_T^{miss} to include reconstructed leptons → mimics missing momentum in signal region!



Control regions in data

Ratio of W:Z processes in signal region predicted at NLO (QCD) + NLO EWK $p_T(V)$ dependent corrections → rely on ratios to best exploit constraints from lepton control regions

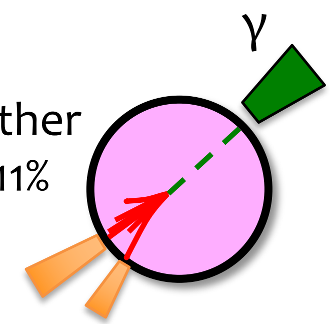


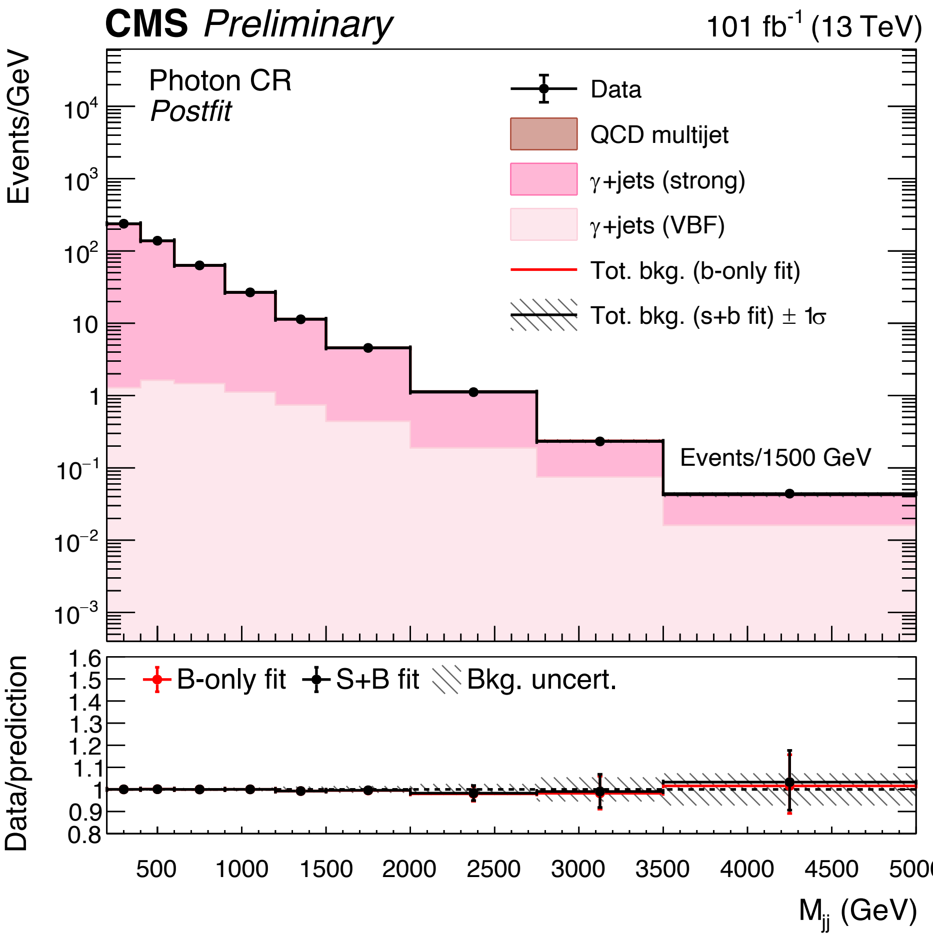


Predictions validated using measured ratios between lepton regions!

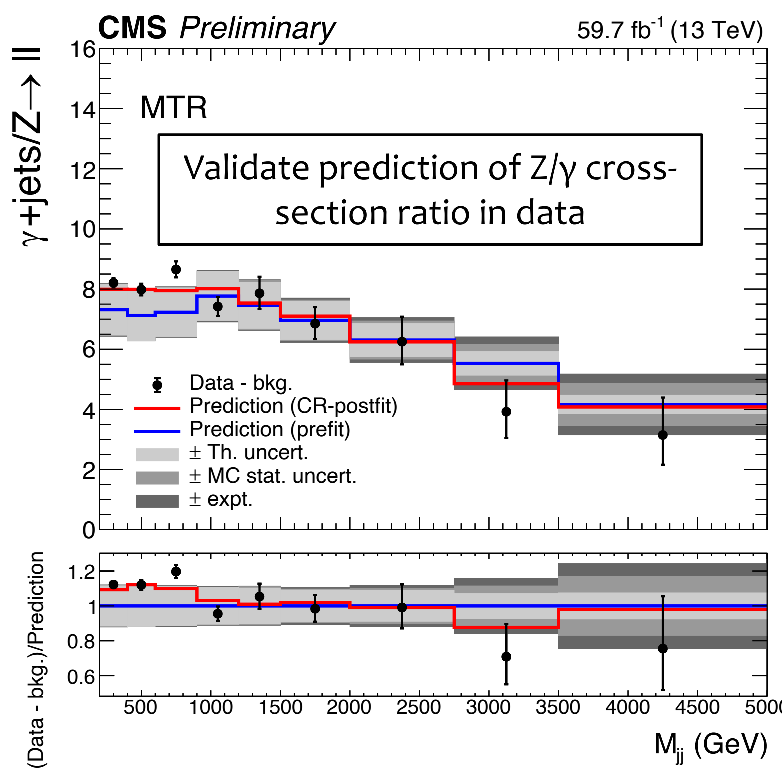
Photon+jets CR

New in 2017/2018 analysis: Inclusion of photon+jets* control region to further constrain V+jets backgrounds in signal regions – improves sensitivity by ~11%





- Exactly 1 photon $p_T > 230$ GeV
- Recoil ($p_T^{miss} + p_T^{\gamma}$) > 250 GeV

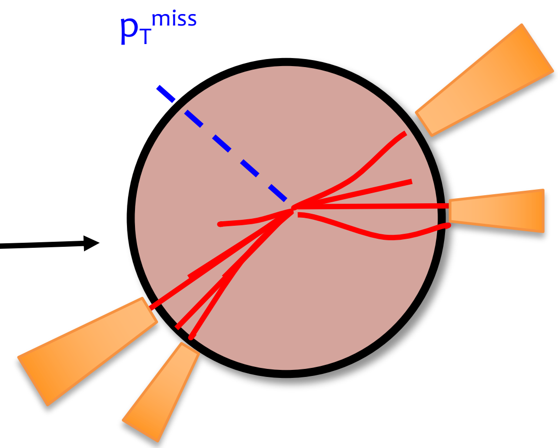


*only included for MTR due to photon trigger thresholds

Instrumental backgrounds

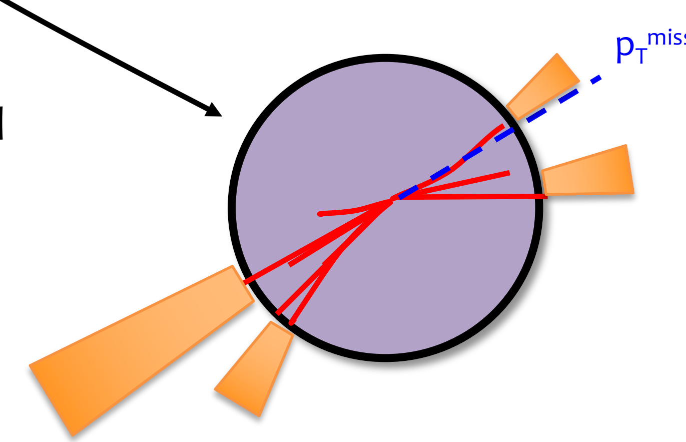
Large backgrounds from instrumental (mis-)measurement of jets

- Resolution effects in jet energies leads to large p_T^{miss} tails from QCD multijet events

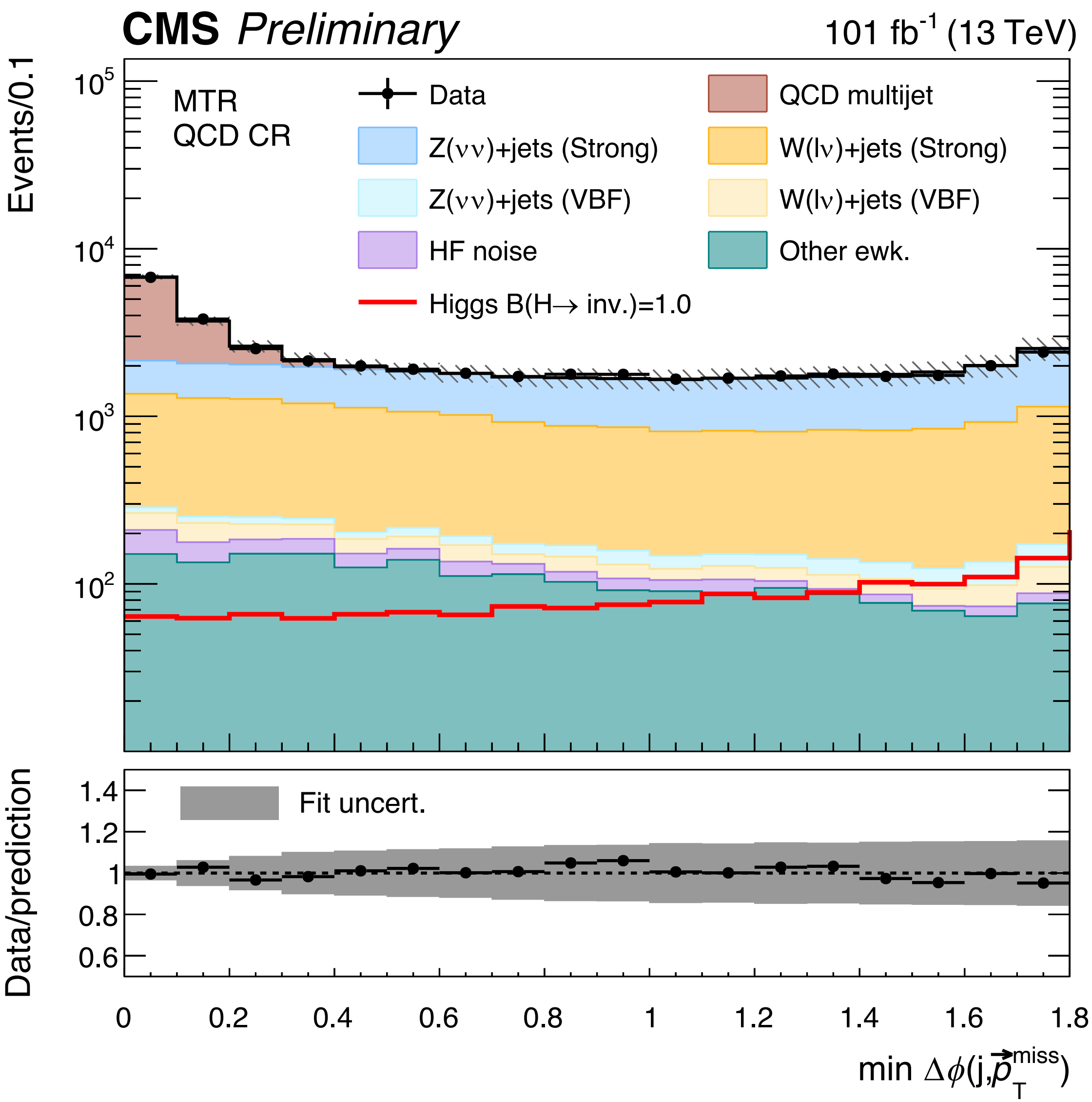


- Activity from calorimeter noise at large pseudo-rapidity aligned with missing momentum (HF-Noise)

Both contributions measured in dedicated control regions in data



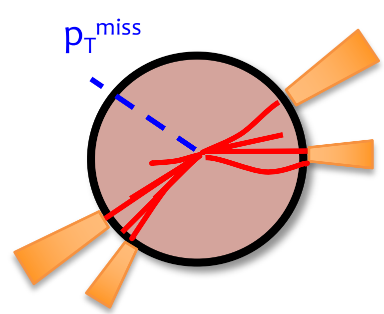
QCD multijet



QCD multijet region defined by inverting min $\Delta\varphi(j,p_T^{miss})$ selection.

Fit distribution of min $\Delta\varphi(j,p_T^{miss})$ in data with a resolution function for the QCD multijet component

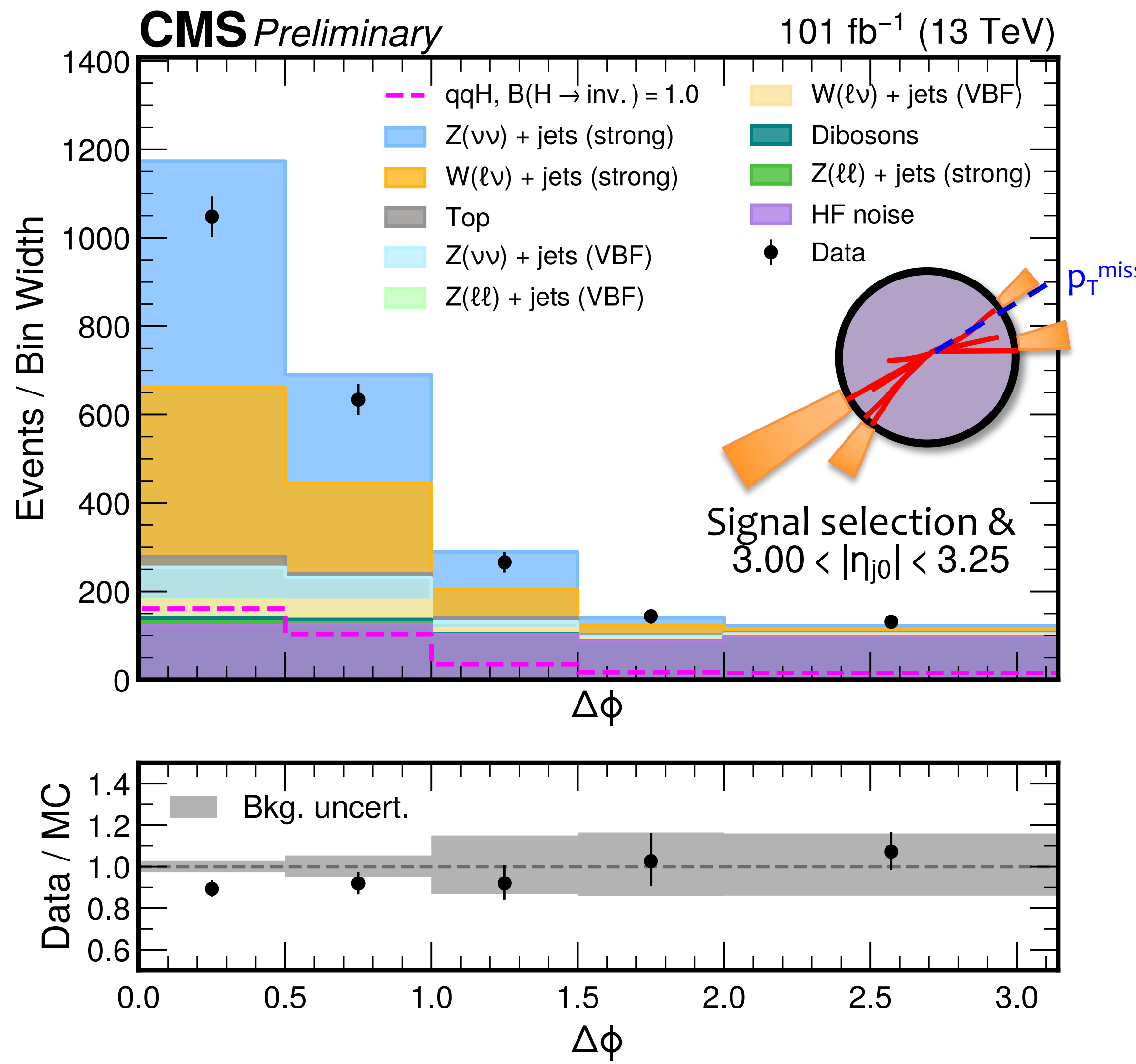
Fit used to normalize QCD multijet M_{jj} template in signal region from data



HF-Noise

Define **jet-shape variables** $\sigma_{\eta\eta}$, $\sigma_{\varphi\varphi}$ and veto events with jets satisfying …

Observable	$2.99 < \lvert\eta_{jet}\rvert < 4$	$4 < \lvert\eta_{jet}\rvert < 5$
$\sigma_{\eta\eta} - \sigma_{\phi\phi}$	< 0.02	—
$\sigma_{\eta\eta}$	> 0.02	< 0.1
$\sigma_{\phi\phi}$	> 0.02	
N^{cent}_{PFCand}	< 3	



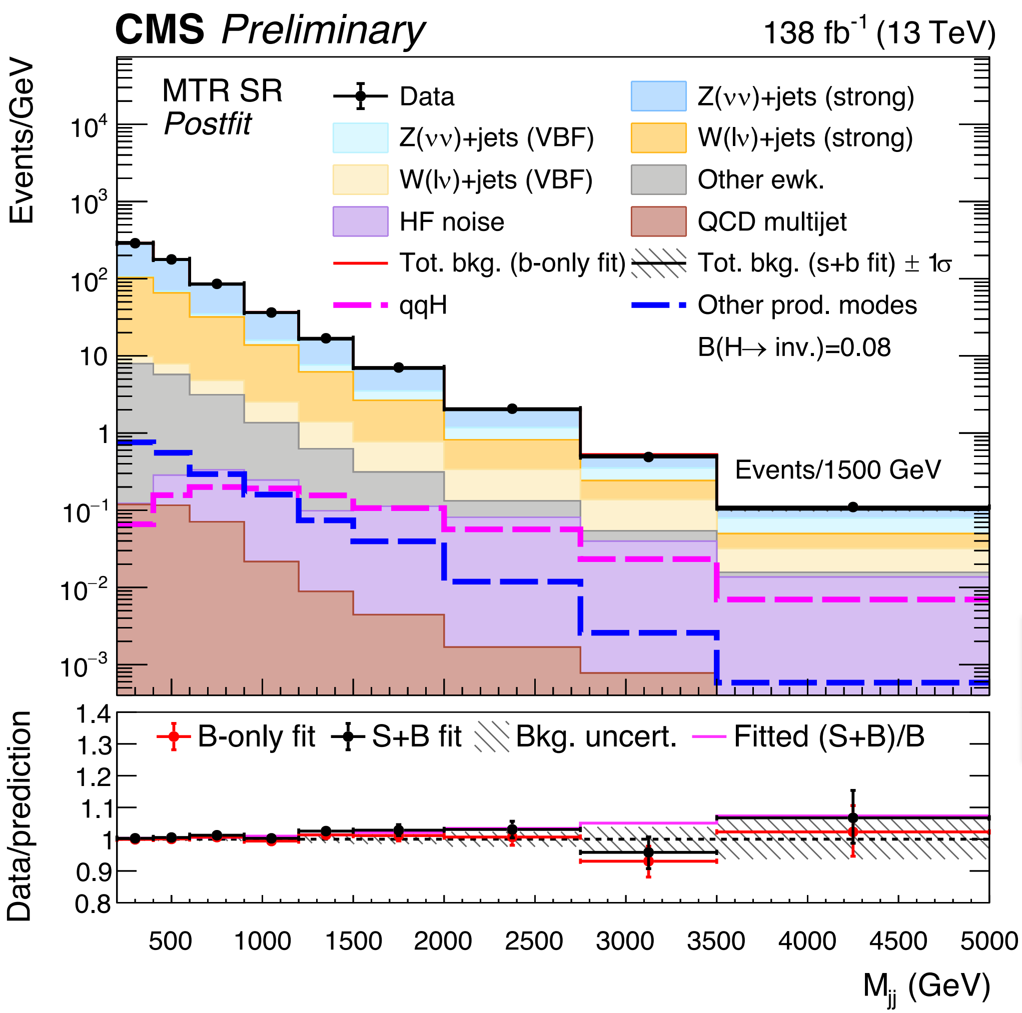
Invert selection (*noise-enriched data*) to estimate residual contributions in signal region.

Estimation validated at high $\Delta\Phi$ (p_T^{miss} –tracker only, p_T^{miss})

Include **20% uncertainty** on contribution in signal region

Signal Extraction

Signal extracted from **simultaneous fit** to M_{jj} distributions in MTR (&VTR) SR+CRs in 2016-2018 (2017-2018)



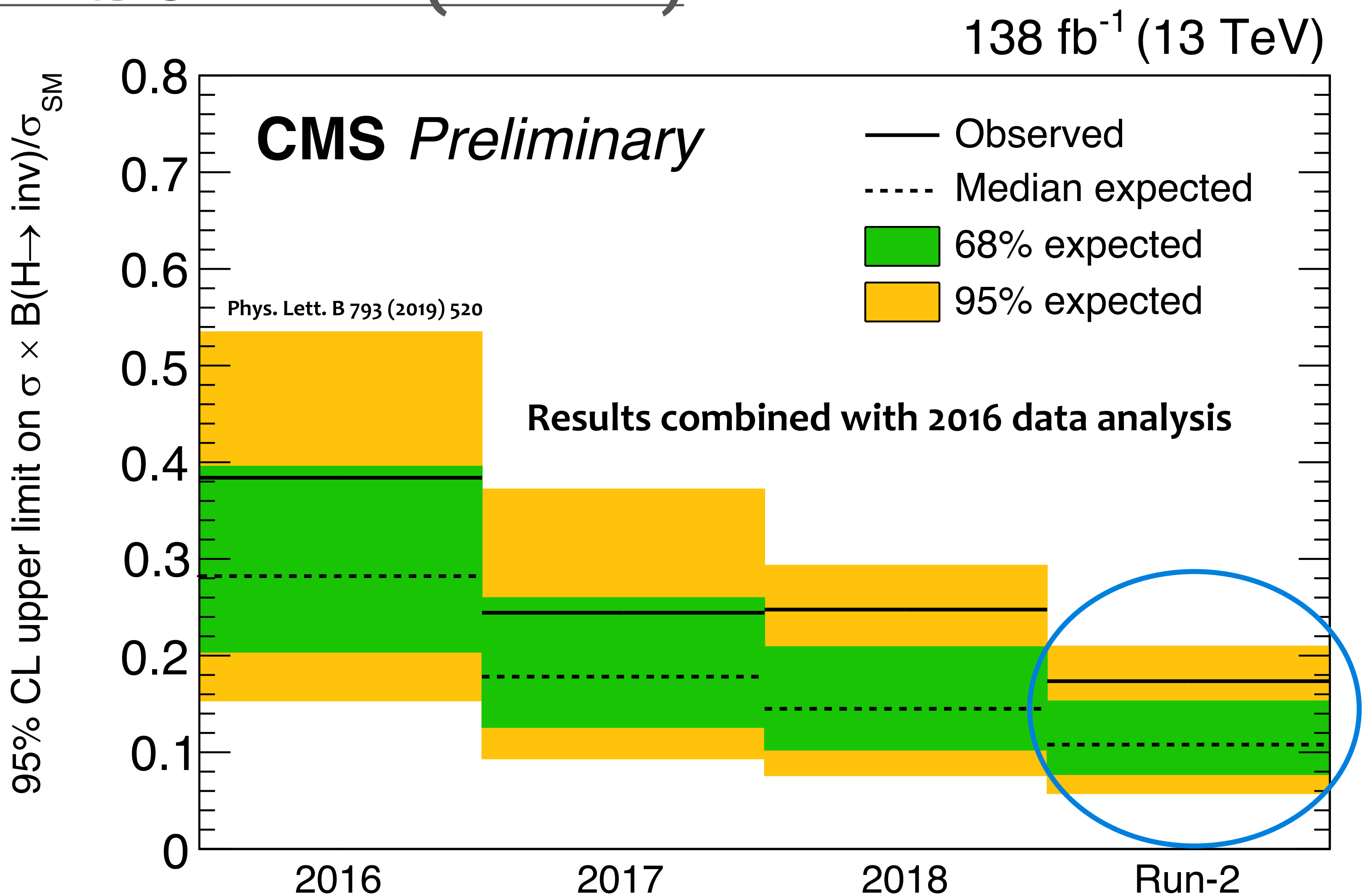
→ Overall good agreement between data and SM-background predictions
→ Mild signal-like excess observed (< 1.5σ)

$$B(H \to inv) = 0.076^{+0.057}_{-0.055}$$

Systematic uncertainties dominated by
- **Theoretical modeling + simulation**
- **Trigger efficiencies**

Group of systematic uncertainties	Observed impact on $\mathcal{B}(H \to \text{inv})$
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

Limits on VBF B(H→inv)

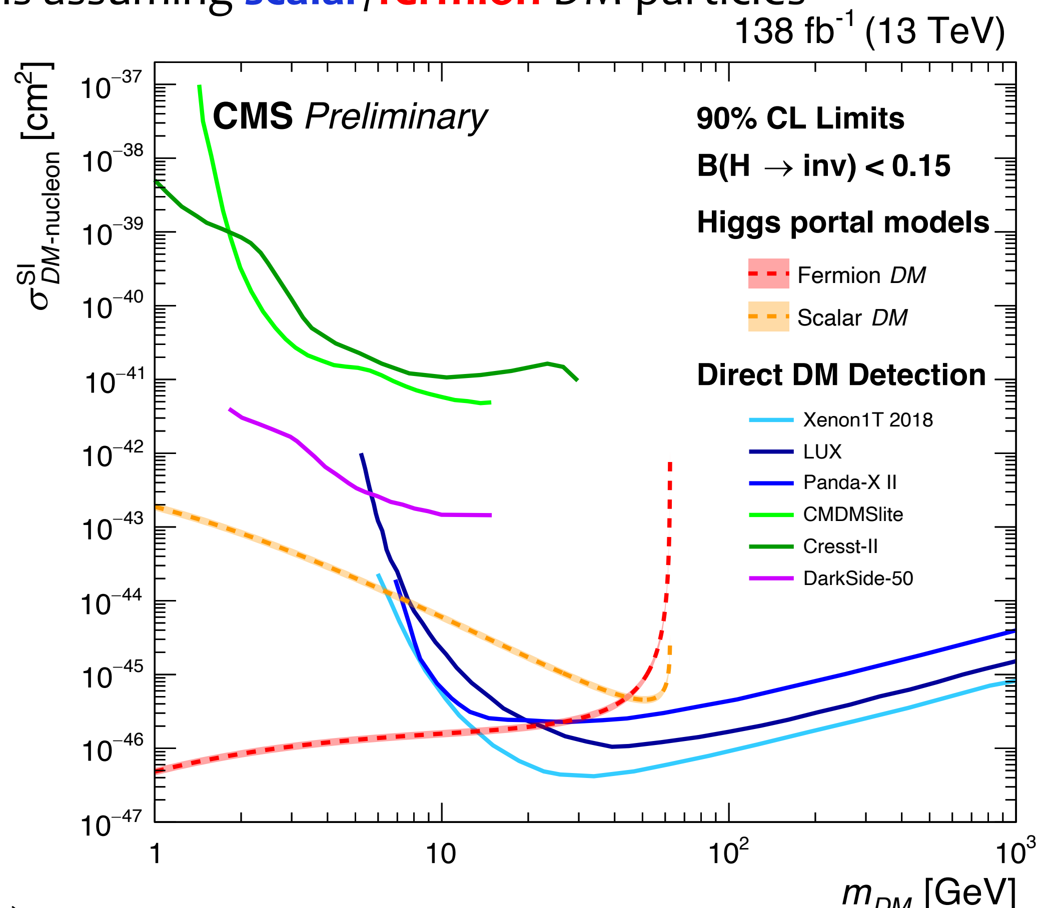


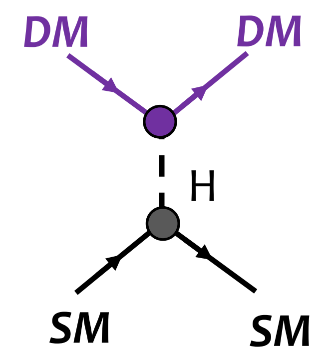
B(H→inv.) < 17% (11%) obs. (exp.) @ 95%CL !

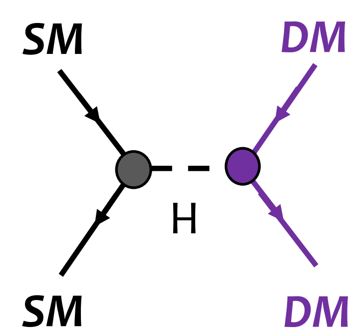
Higgs portal models for Dark Matter

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

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







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

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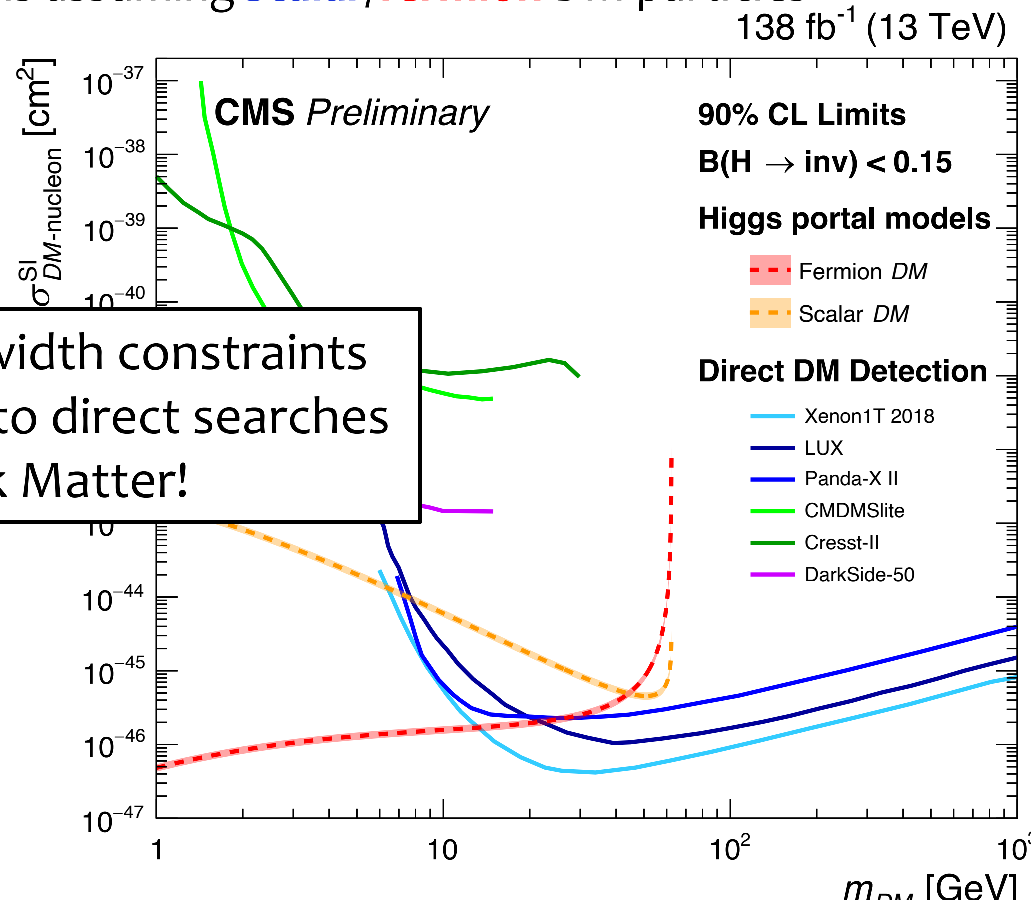
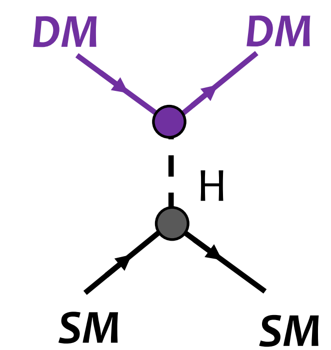
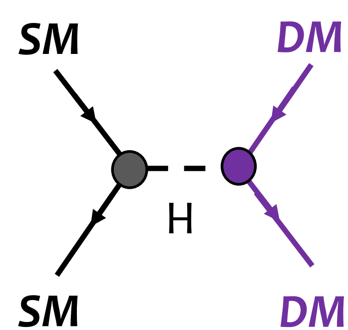


Higgs invisible width constraints complementary to direct searches for Dark Matter!





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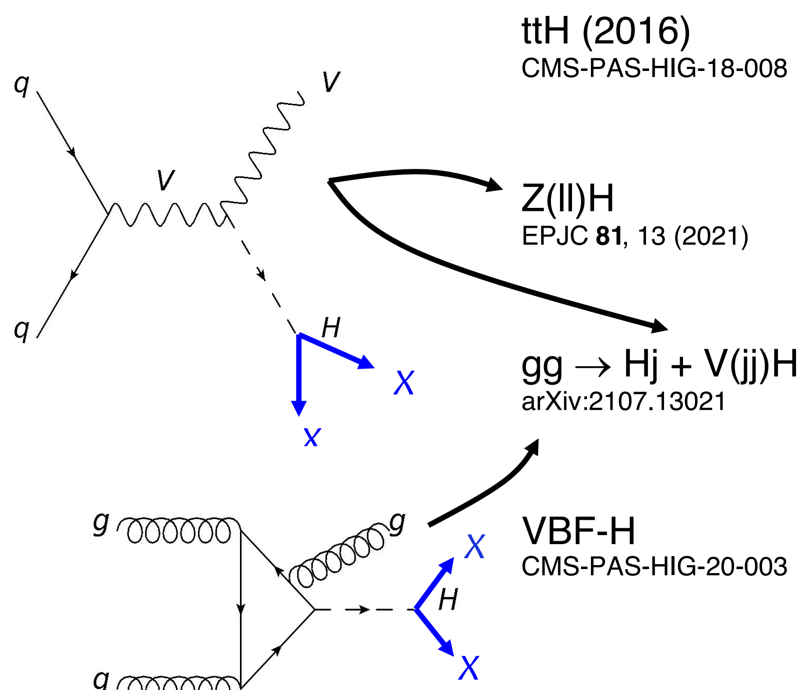
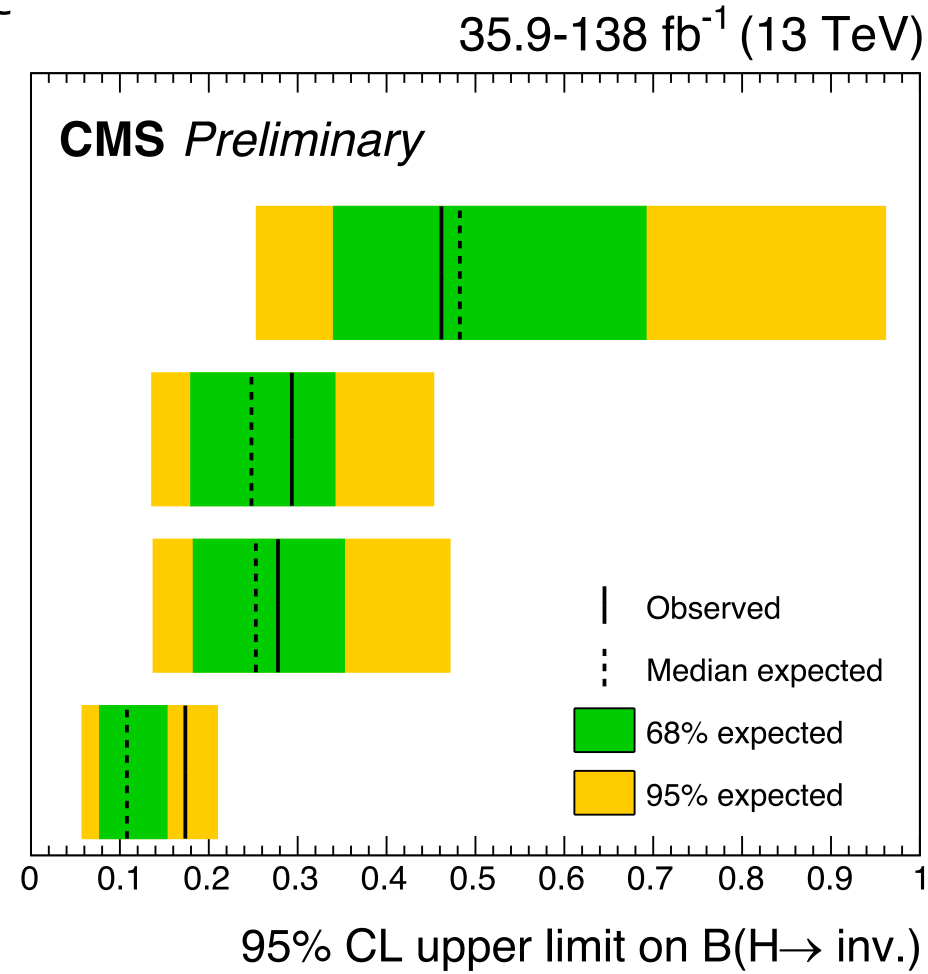
CMS H→inv. Summary

Other production modes exploited to search for invisible Higgs boson decays at LHC

See talks by **Alp Akpinar** and **Scott Snyder**



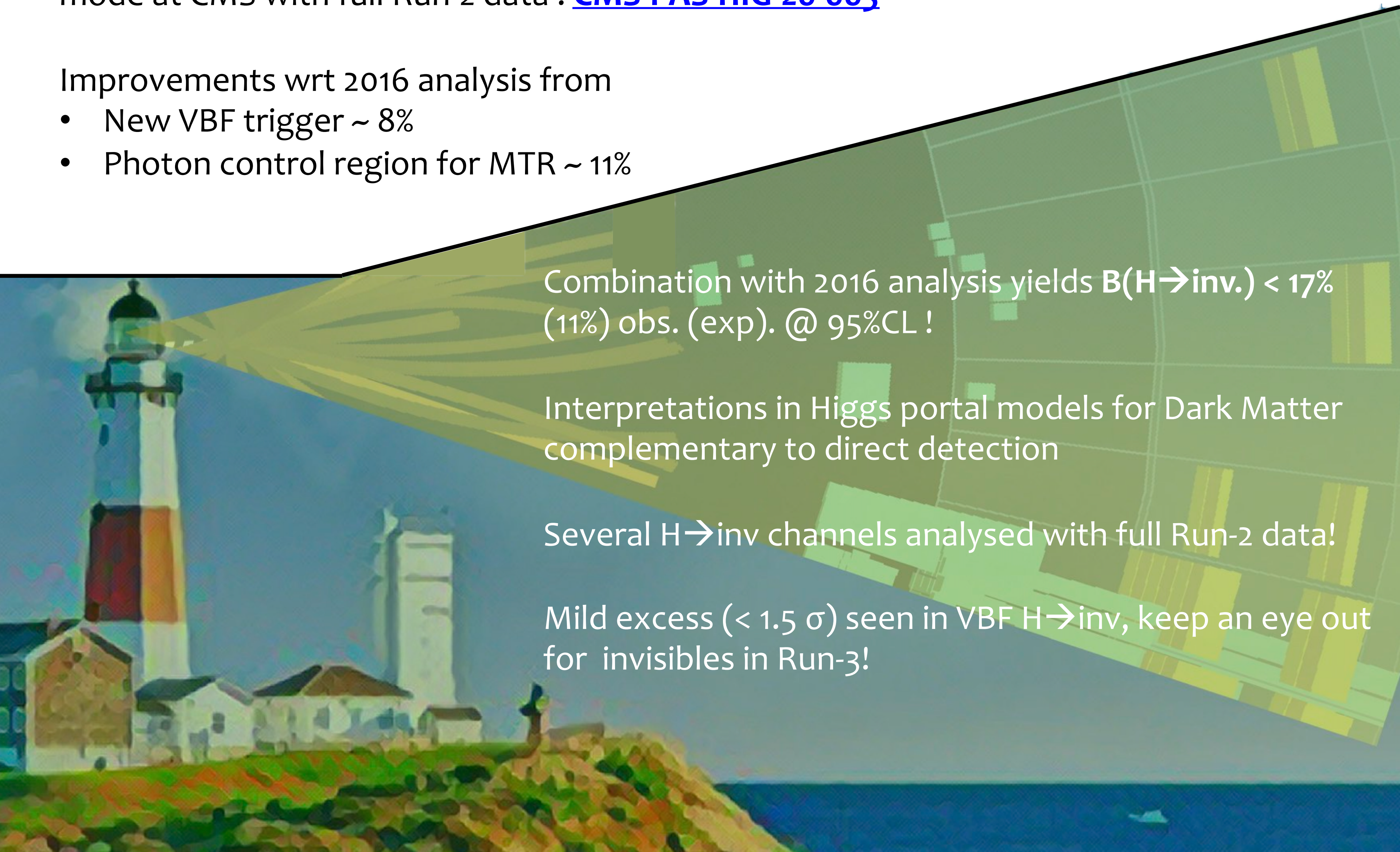


Summary

Presented a search for H→invisible decays in the VBF production mode at CMS with full Run-2 data : [CMS-PAS-HIG-20-003]

Improvements wrt 2016 analysis from

- New VBF trigger ~ 8%
- Photon control region for MTR ~ 11%



Combination with 2016 analysis yields **B(H→inv.) < 17%** (11%) obs. (exp). @ 95%CL !

Interpretations in Higgs portal models for Dark Matter complementary to direct detection

Several H→inv channels analysed with full Run-2 data!

Mild excess (< 1.5 σ) seen in VBF H→inv, keep an eye out for invisibles in Run-3!

Summary

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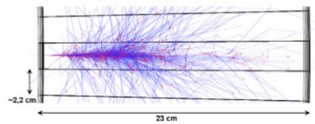
Thanks!

Backup Slides

CMS Detector

Hermetic design of CMS provides good coverage of interaction



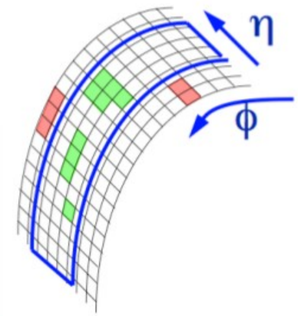
→ Vital for searches with missing energy

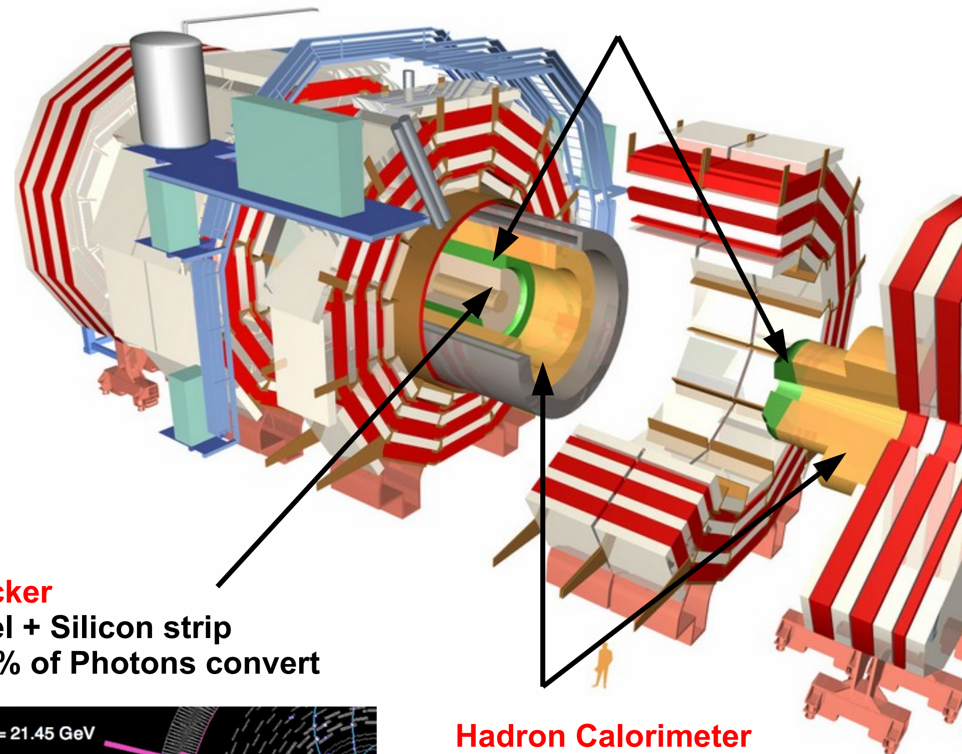
Triggers reduce 40 MHz (LHC)→ O(100) Hz

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

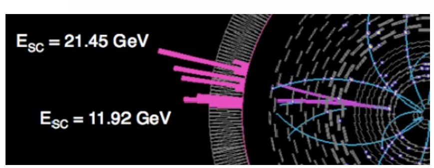
→ Upgrade Trigger for 2016 data taking performs PU subtraction at L1

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

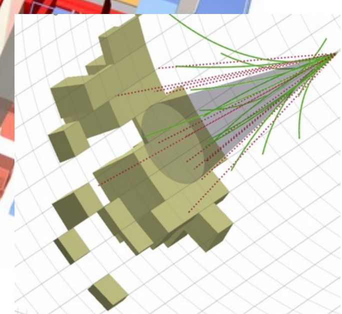




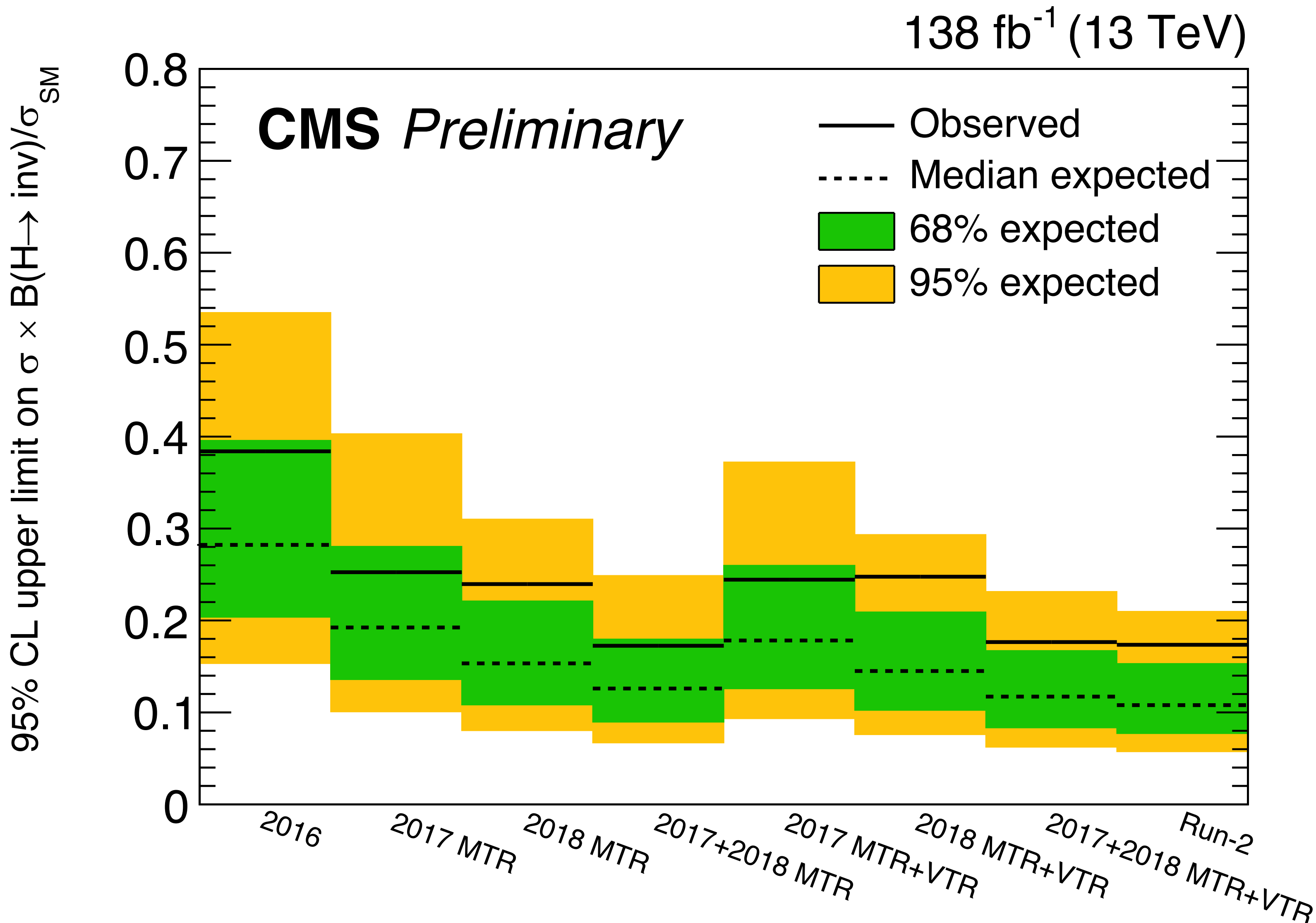
Tracker
Pixel + Silicon strip
~50% of Photons convert



Hadron Calorimeter
Scintillating Brass
Exploit jets from VBF production



Limit breakdown

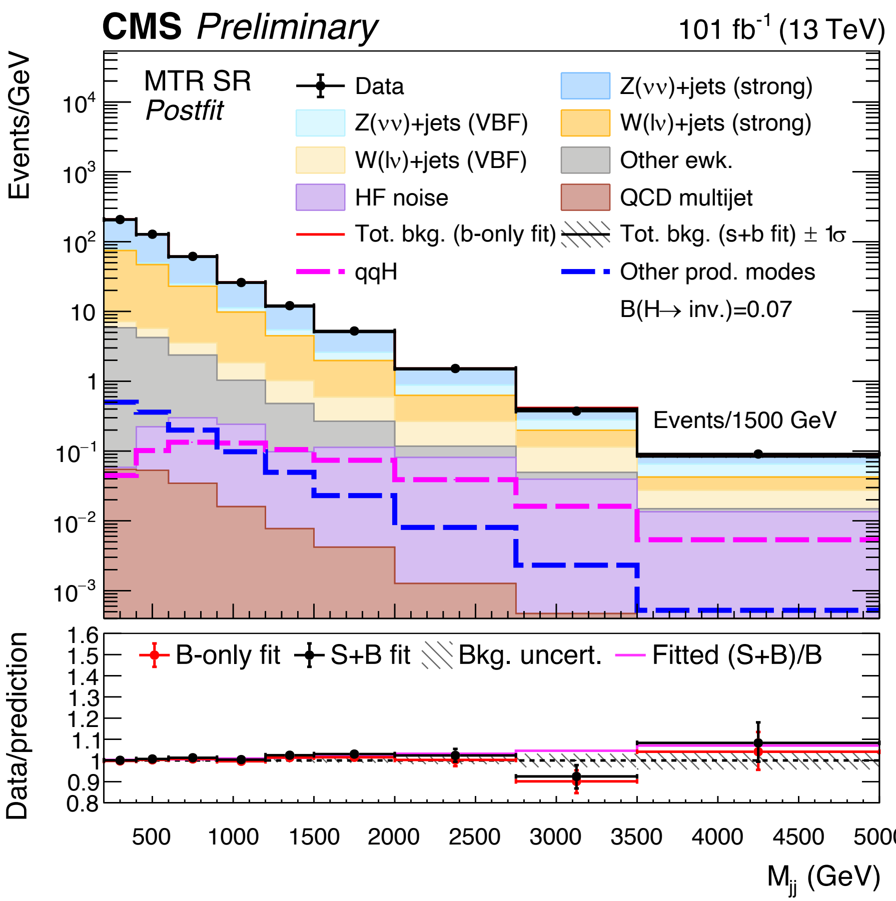


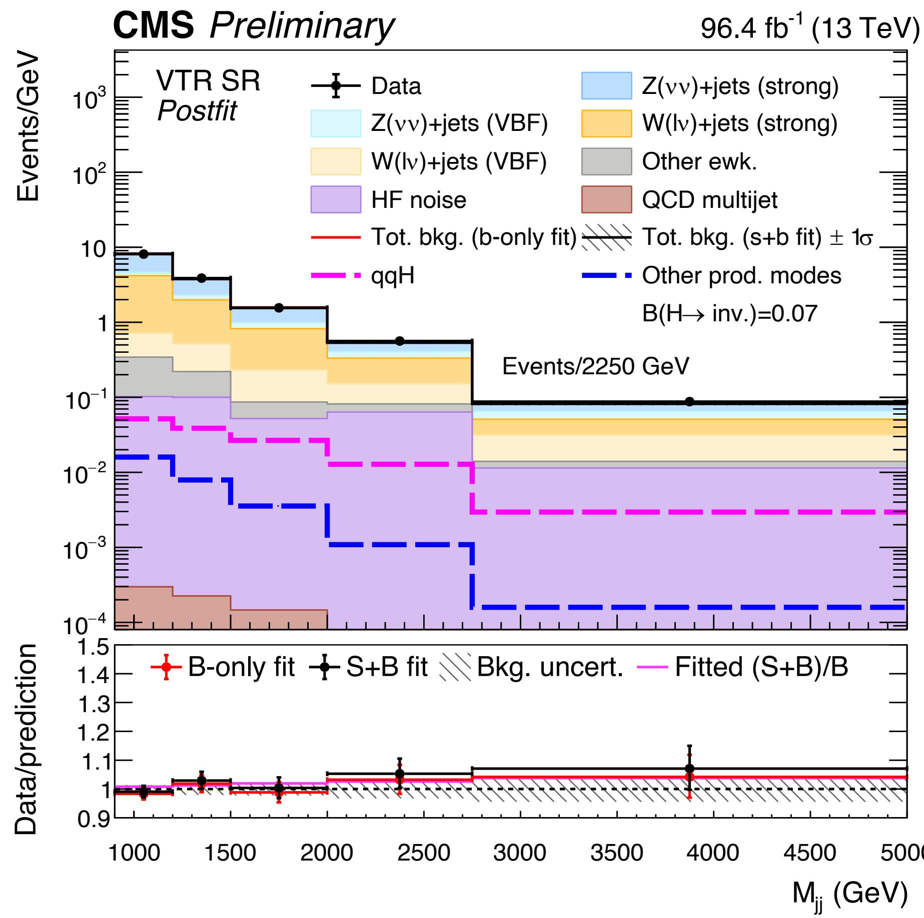
Signal regions

Signal extracted from (simultaneous) fit to M_{jj} distributions in MTR and VTR

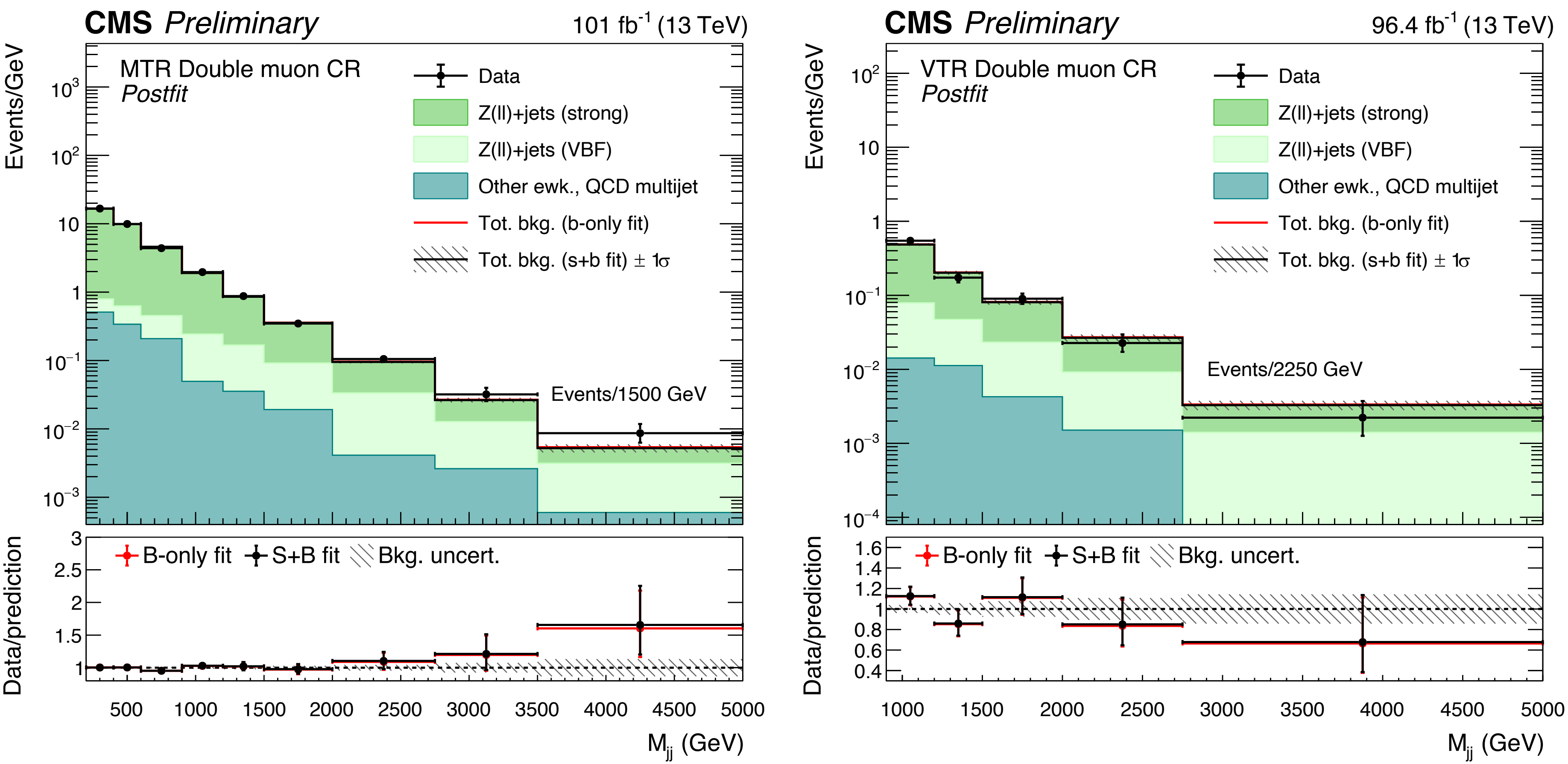
→ Overall good agreement between data and SM-background predictions

→ Mild signal-like excess observed (< 1.5σ)

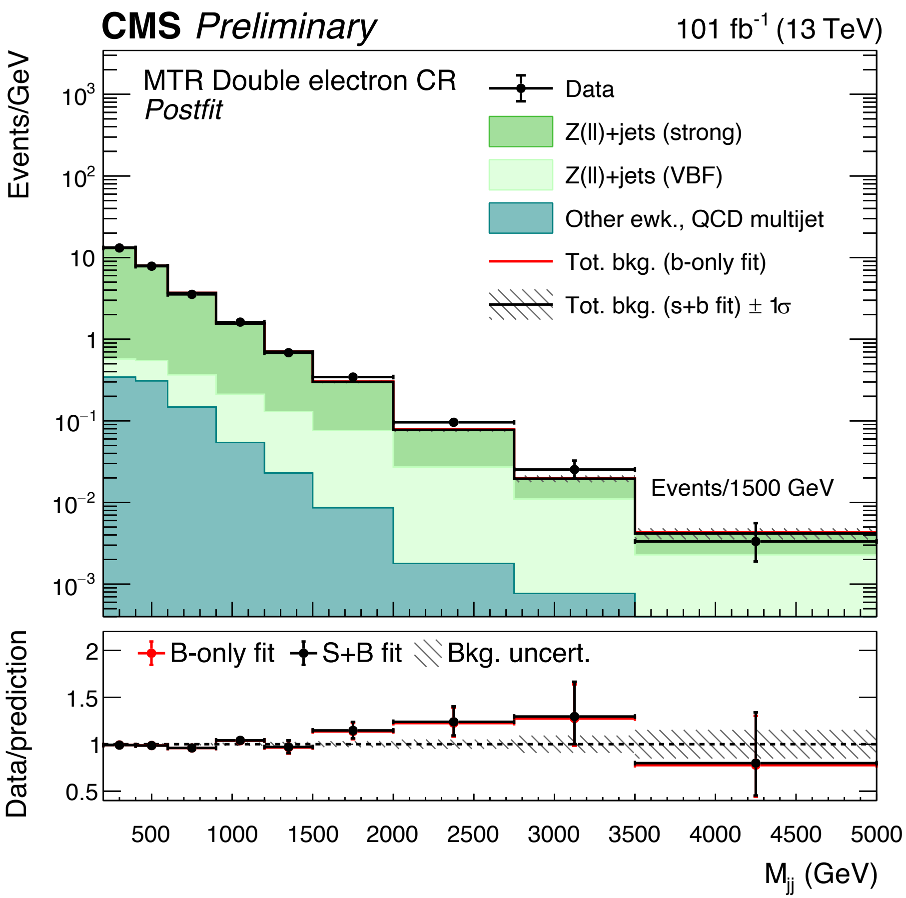


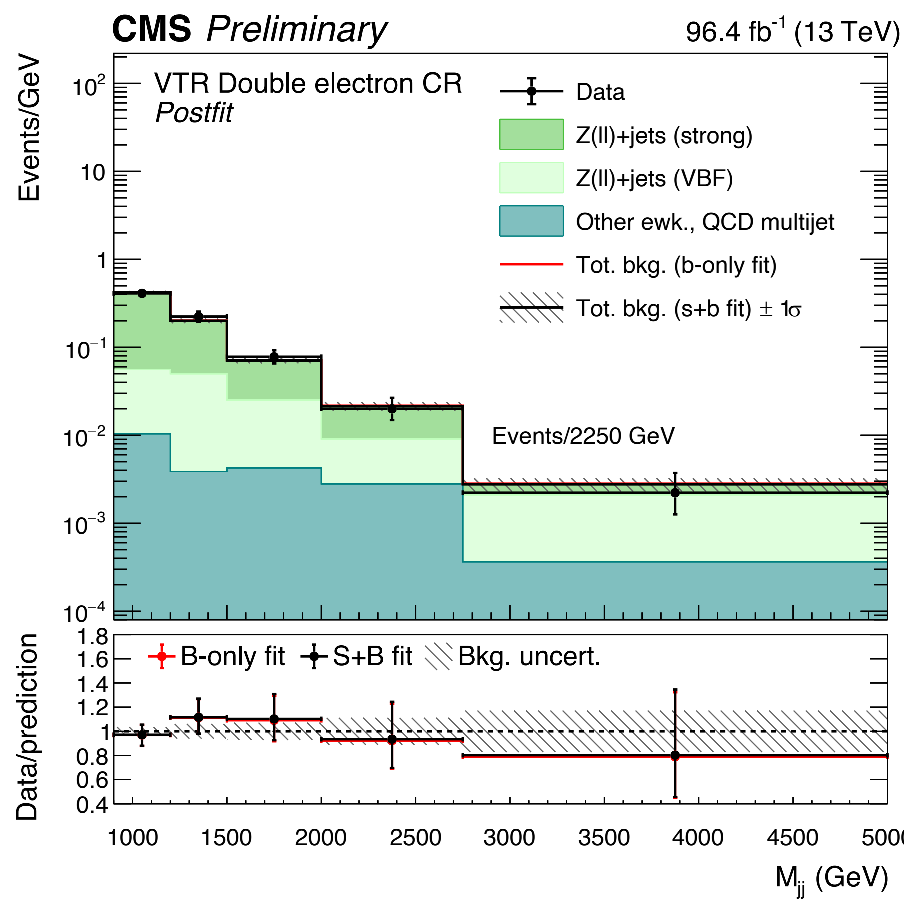


Control regions (di-muon)

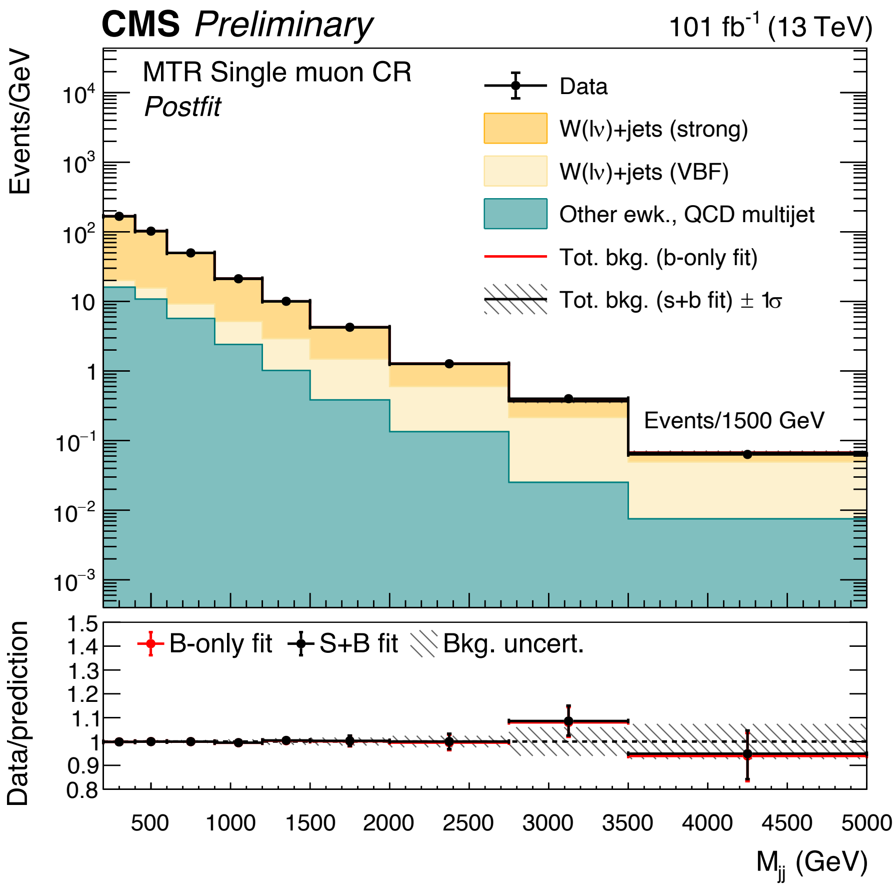


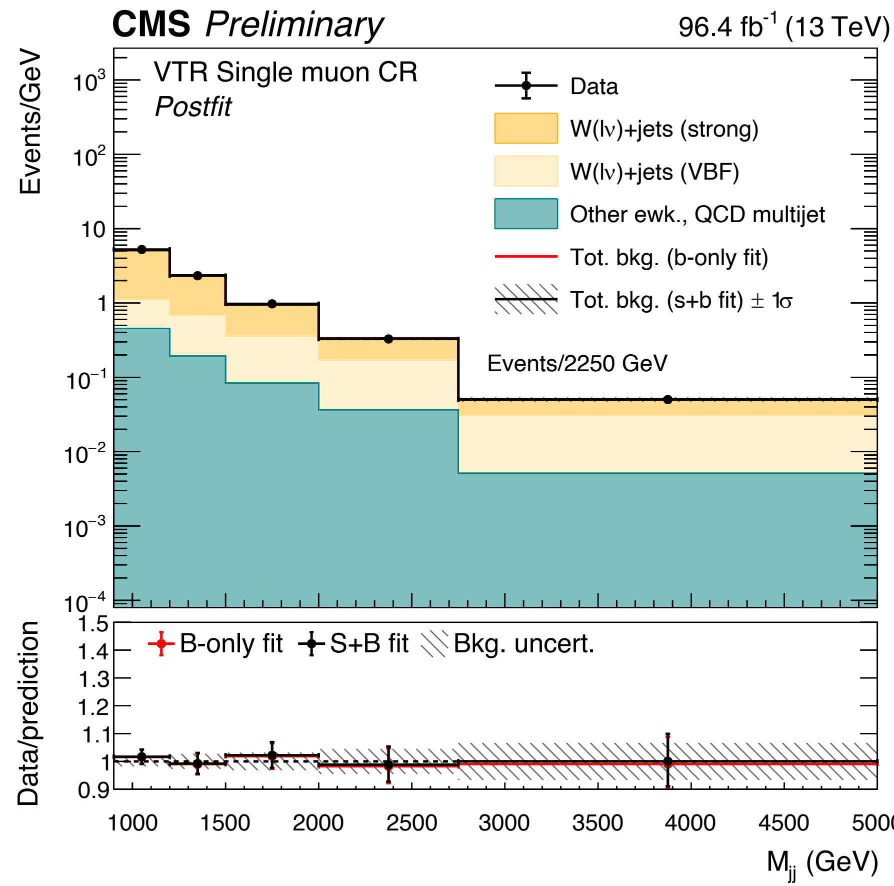
Control regions (di-electron)



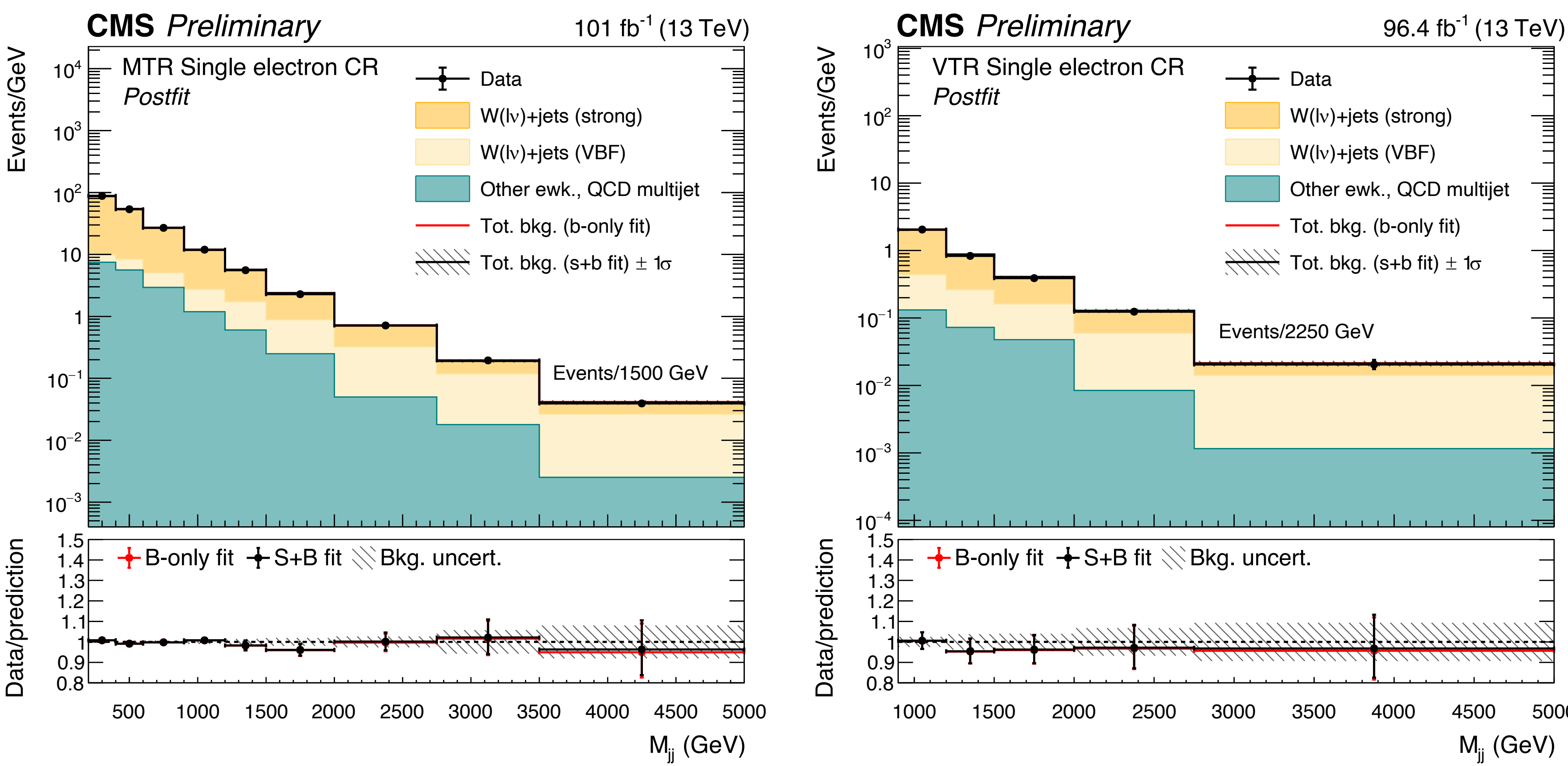


Control regions (single muon)

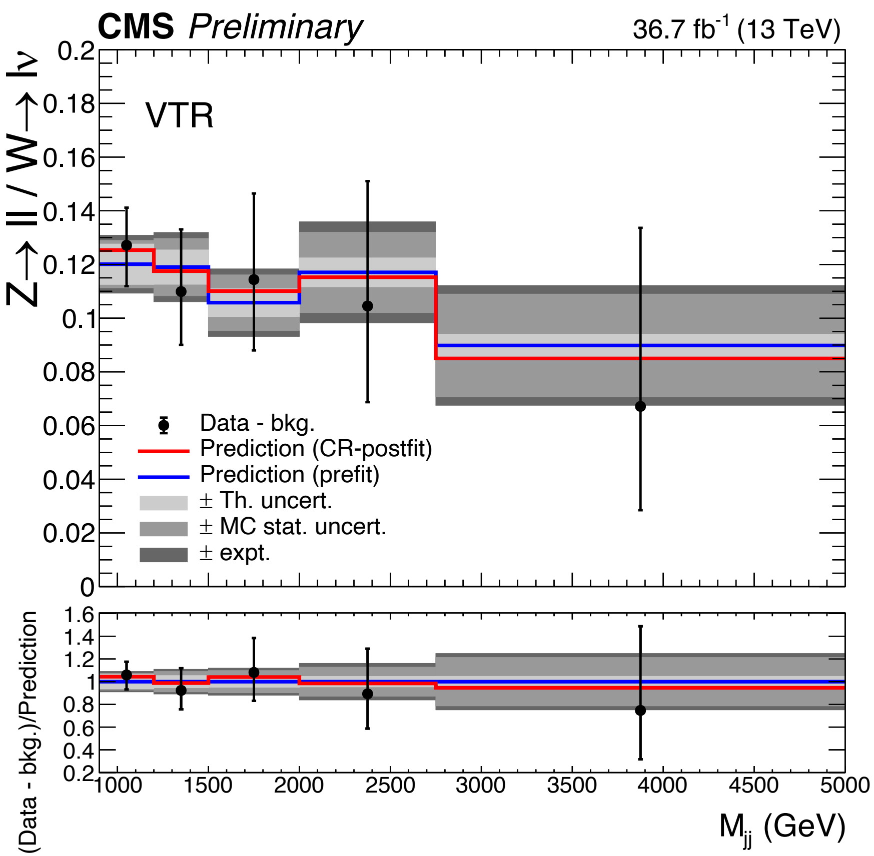


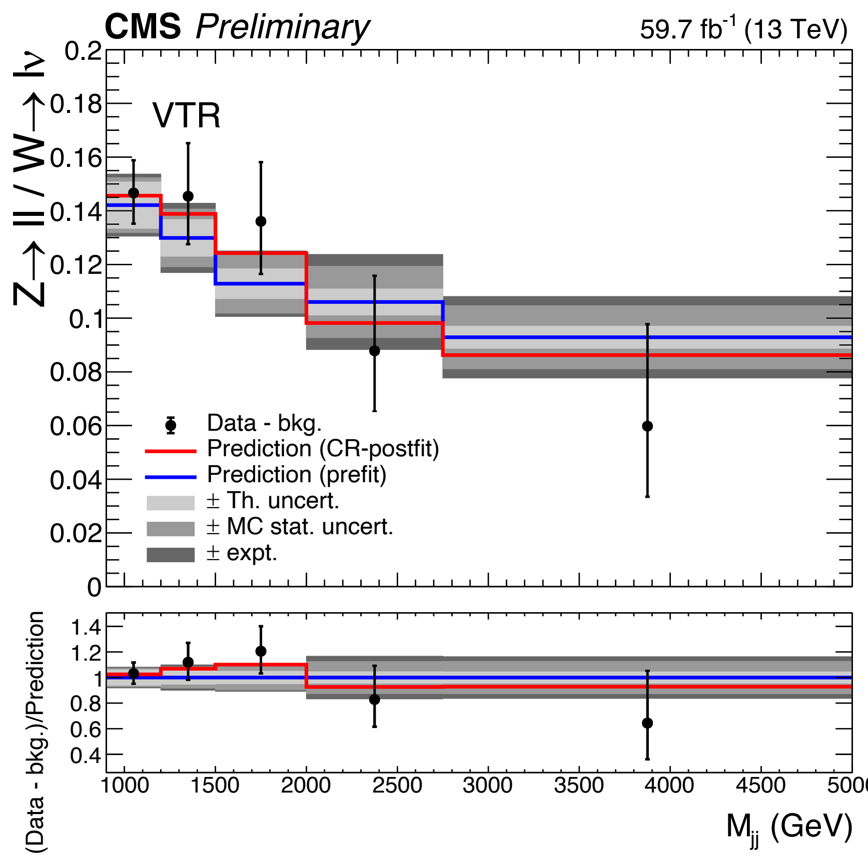


Control regions (single electron)

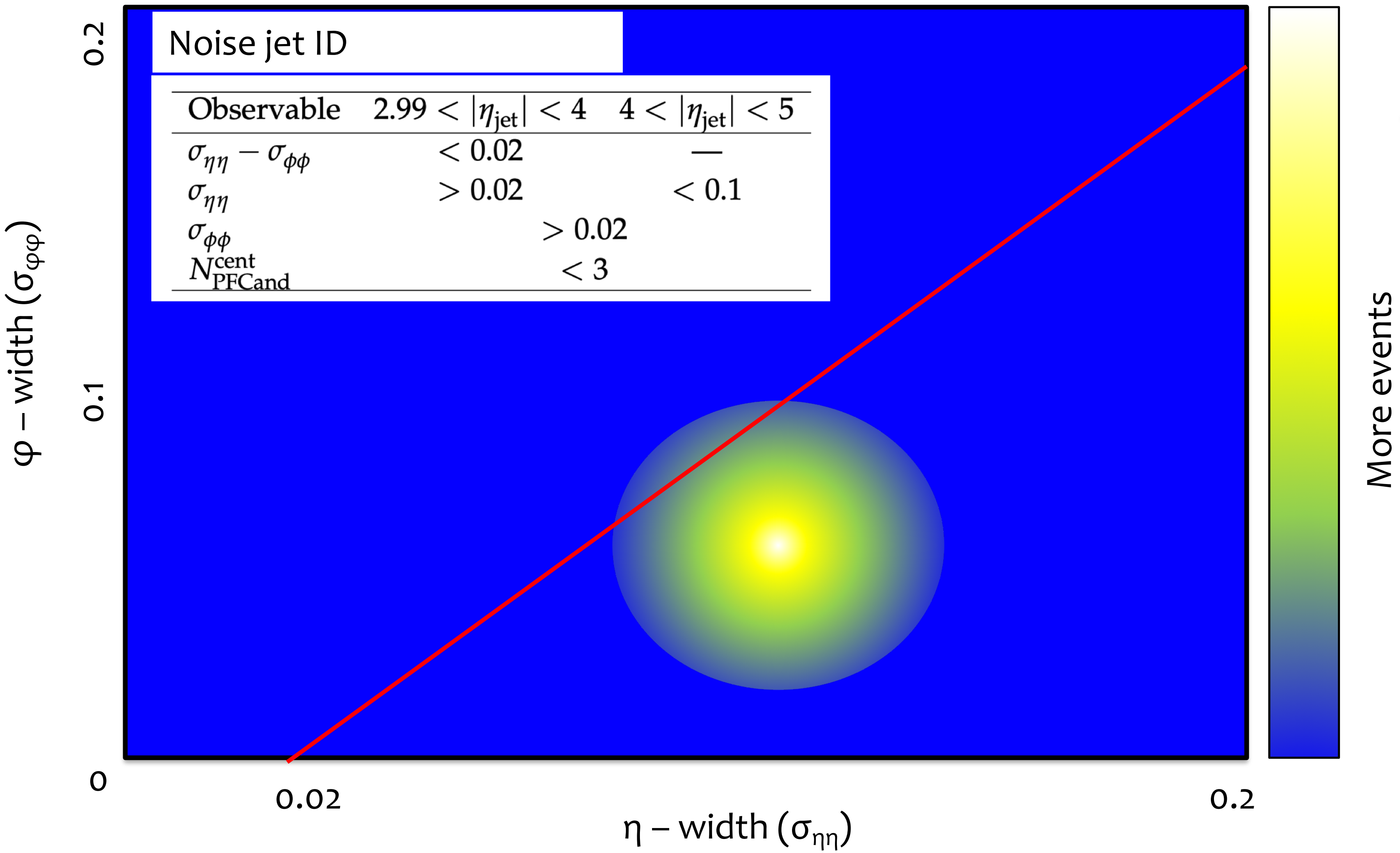


Validation (VTR)



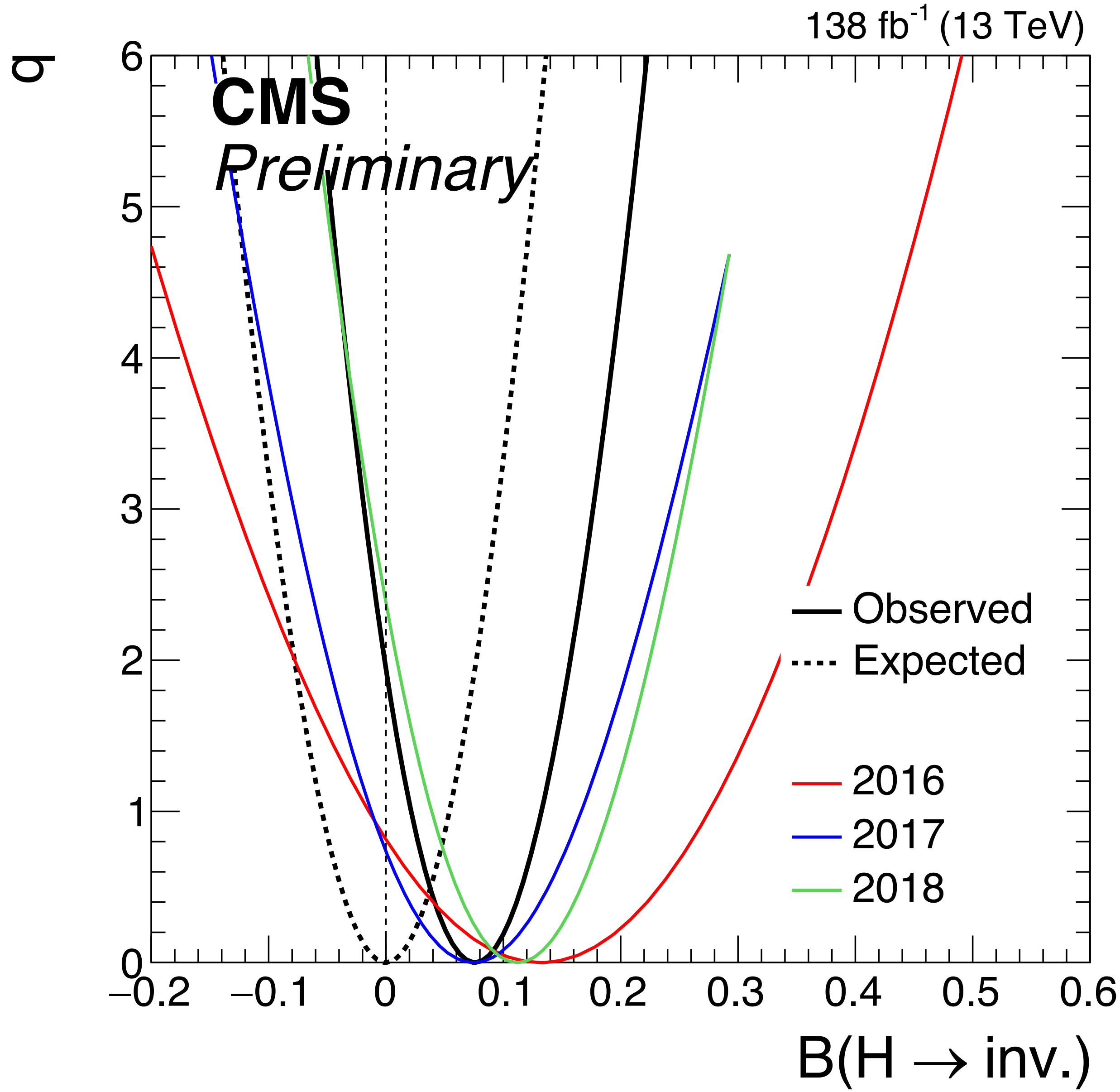


HF Noise rejection



Observable	$2.99 < \lvert\eta_{jet}\rvert < 4$	$4 < \lvert\eta_{jet}\rvert < 5$
$\sigma_{\eta\eta} - \sigma_{\phi\phi}$	< 0.02	—
$\sigma_{\eta\eta}$	> 0.02	< 0.1
$\sigma_{\phi\phi}$	> 0.02	
N^{cent}_{PFCand}	< 3	

Compatibility



Selections

Table 2: Summary of the kinematic selections used to define the SR for both the MTR and the VTR categories.

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

Likelihood function

$$
\begin{aligned}
\mathcal{L}(\mu, \kappa^{\nu\bar{\nu}}, \boldsymbol{\theta}) =& \prod_i \mathrm{P}\left(d_i \middle| B_i(\boldsymbol{\theta}) + \mathrm{Z}_i({\kappa_i}^{\nu\bar{\nu}}) + \mathrm{W}_i({\kappa_i}^{\nu\bar{\nu}}, \boldsymbol{\theta}) + \mu S_i(\boldsymbol{\theta})\right) \times \\
& \prod_{\mathrm{CR}} \left(\prod_i \mathrm{P}\left(d_i^{\mathrm{CR}} \middle| B_i^{\mathrm{CR}}(\boldsymbol{\theta}) + \mathrm{V}_i^{\mathrm{CR,strong}}({\kappa_i}^{\nu\bar{\nu}}, \boldsymbol{\theta}) + \mathrm{V}_i^{\mathrm{CR,VBF}}({\kappa_i}^{\nu\bar{\nu}}, \boldsymbol{\theta})\right)\right) \times \\
& \prod_j \mathrm{P}(\theta_j), \\
\mathrm{Z}_i({\kappa_i}^{\nu\bar{\nu}}) =& (1 + Z_i^{\frac{\mathrm{VBF}}{\mathrm{strong}}}) \times {\kappa_i}^{\nu\bar{\nu}} \\
\mathrm{W}_i({\kappa_i}^{\nu\bar{\nu}}, \boldsymbol{\theta}) =& (f_i^{\mathrm{W/Z,strong}}(\boldsymbol{\theta}) + Z_i^{\frac{\mathrm{VBF}}{\mathrm{strong}}} \times f_i^{\mathrm{W/Z,VBF}}(\boldsymbol{\theta})) \times {\kappa_i}^{\nu\bar{\nu}} \\
\mathrm{V}_i^{\mathrm{CR,strong}}({\kappa_i}^{\nu\bar{\nu}}, \boldsymbol{\theta}) =& \mathrm{C}_i^{\mathrm{CR,strong}}(\boldsymbol{\theta}) \times R_i^{\mathrm{CR}}(\boldsymbol{\theta}) \times {\kappa_i}^{\nu\bar{\nu}} \\
\mathrm{V}_i^{\mathrm{CR,VBF}}({\kappa_i}^{\nu\bar{\nu}}, \boldsymbol{\theta}) =& \mathrm{C}_i^{\mathrm{CR,VBF}}(\boldsymbol{\theta}) \times Z_i^{\frac{\mathrm{VBF}}{\mathrm{strong}}} \times R_i^{\mathrm{CR}}(\boldsymbol{\theta}) \times {\kappa_i}^{\nu\bar{\nu}}
\end{aligned} \tag{4}
$$

Systematics

Table 3: Experimental and theoretical sources of systematic uncertainties on the V+jets transfer factors. The second column highlights on which ratio specifically a given source of uncertainty acts, and its impact on M_{jj} is given in the 3rd column, either as a single value (if no dependence on M_{jj} is observed) or as a range of impact on low to high M_{jj} values.

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%