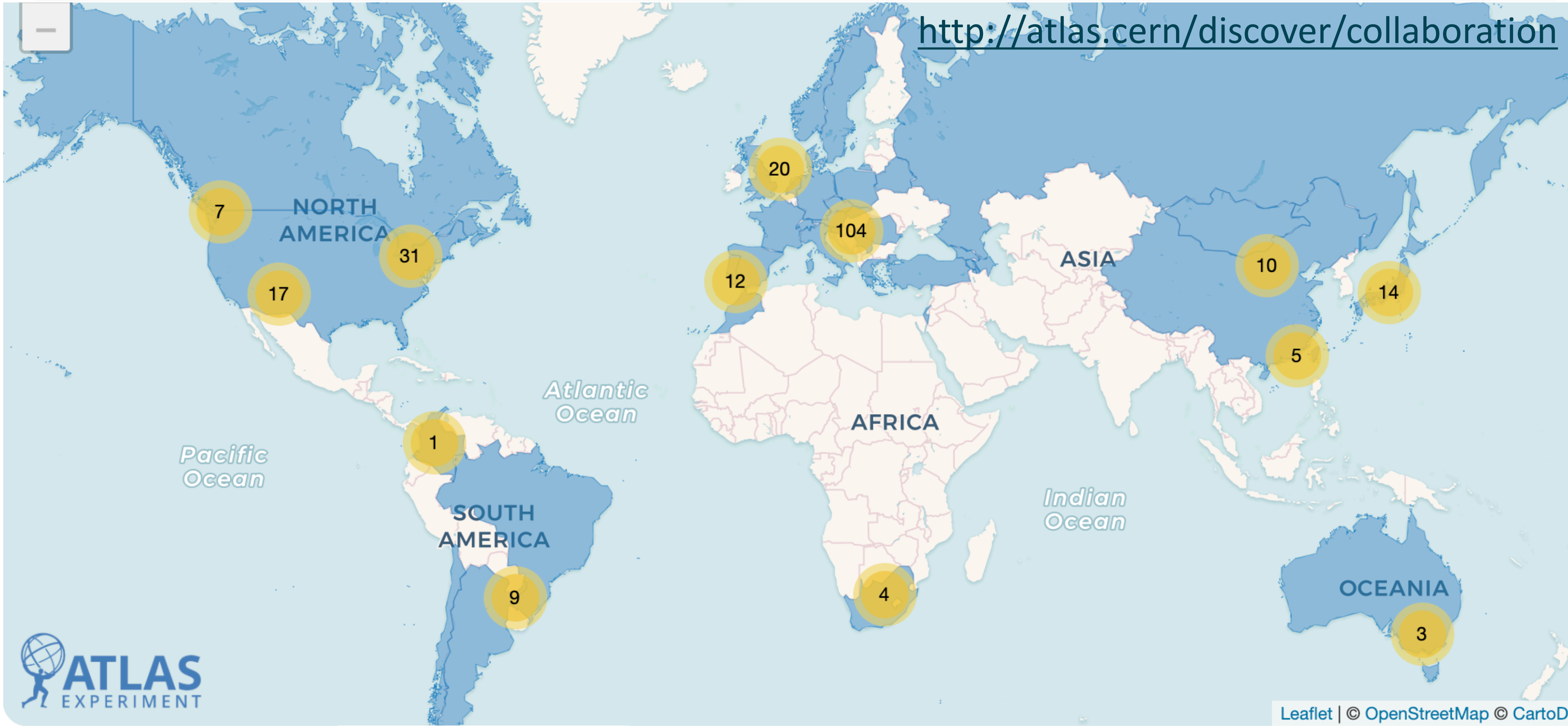
Highlights from the ATLAS experiment

Heather Russell, McGill University

CAP-PPD 2020 – 8 – 9 June 2020

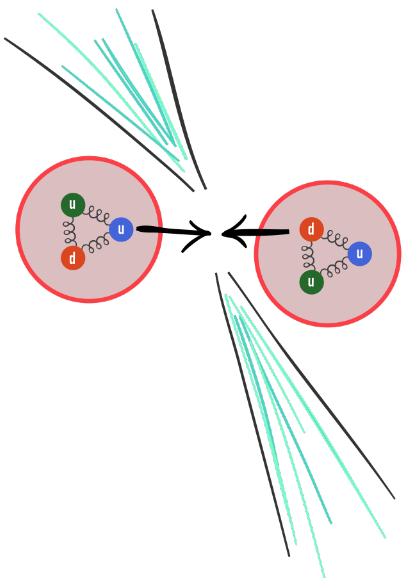
The ATLAS collaboration

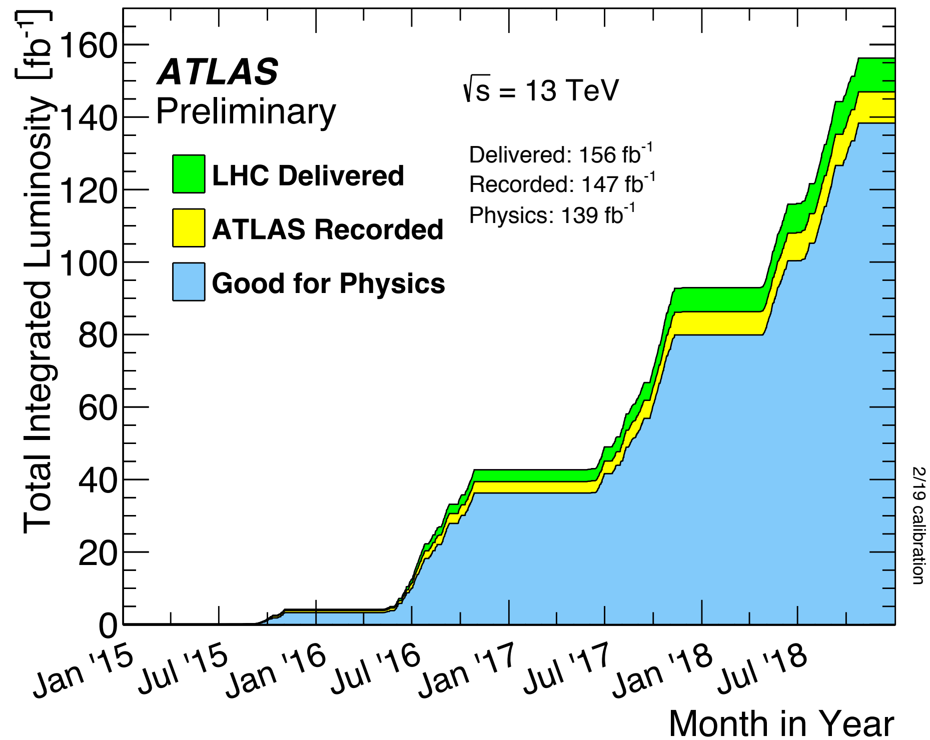


University of Alberta
Carleton University
Université de Montréal
University of Toronto
York Université University
The University of British Columbia
McGill University
SFU Simon Fraser University
University of Victoria
TRIUMF

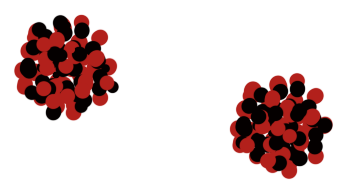
Overview of datasets

139 fb^{-1} of 13 TeV proton-proton collision data collected from 2015-2018





But also special low-pileup data, 5 TeV proton-proton collision data, proton-lead, lead-lead collisions, and xenon-xenon collisions, and more!



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

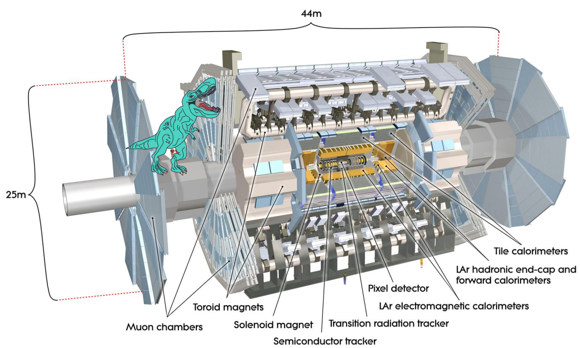
A tour of ATLAS physics*

*with proton-proton collisions

Precision measurements of the Standard Model

Studies of top quark properties

Searches for rare standard model processes



Studies of beauty and charm physics

Studies of Higgs boson properties

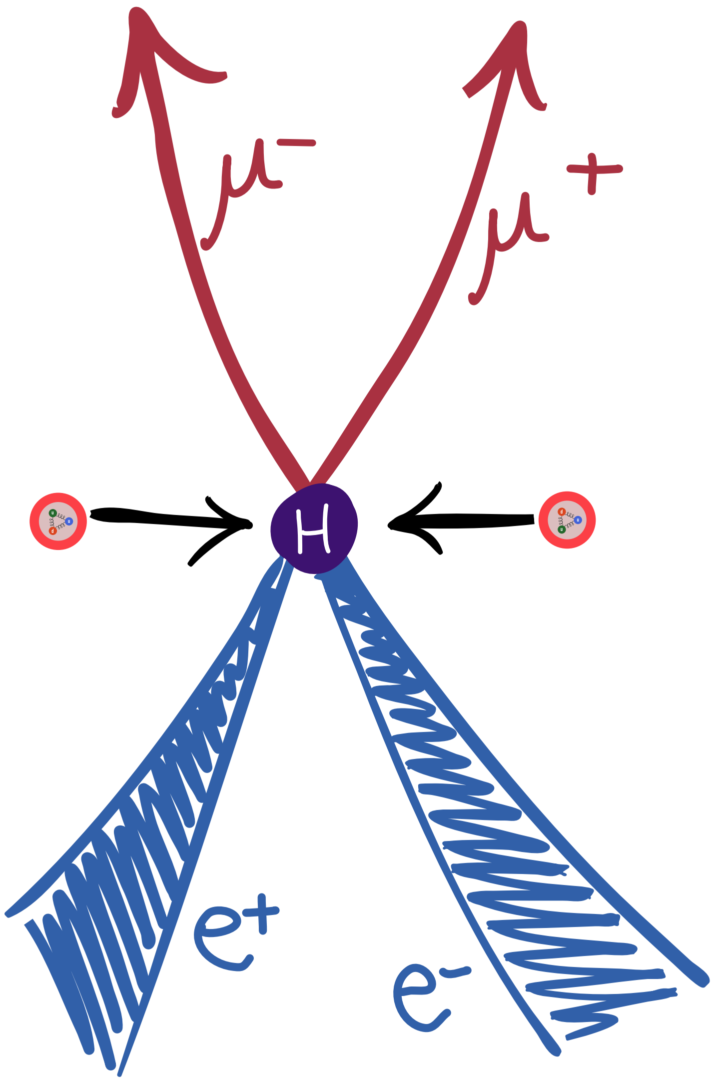
Searches for new physics

Searches for supersymmetry

Searches for exotic Higgs boson decays

Searches for dark matter

Searches for unconventional signatures



Higgs →ZZ* measurements

Two same-flavour, opposite-charge lepton pairs:

$2e2\mu$, $2e2e$, $2\mu2\mu$

One SFOC pair close to the Z-boson mass

Four-lepton mass close to the Higgs boson mass

CONF-2020-005
arXiv:2004.03969

Overview: $H \to ZZ^* \to 4l$

arXiv:2004.03969

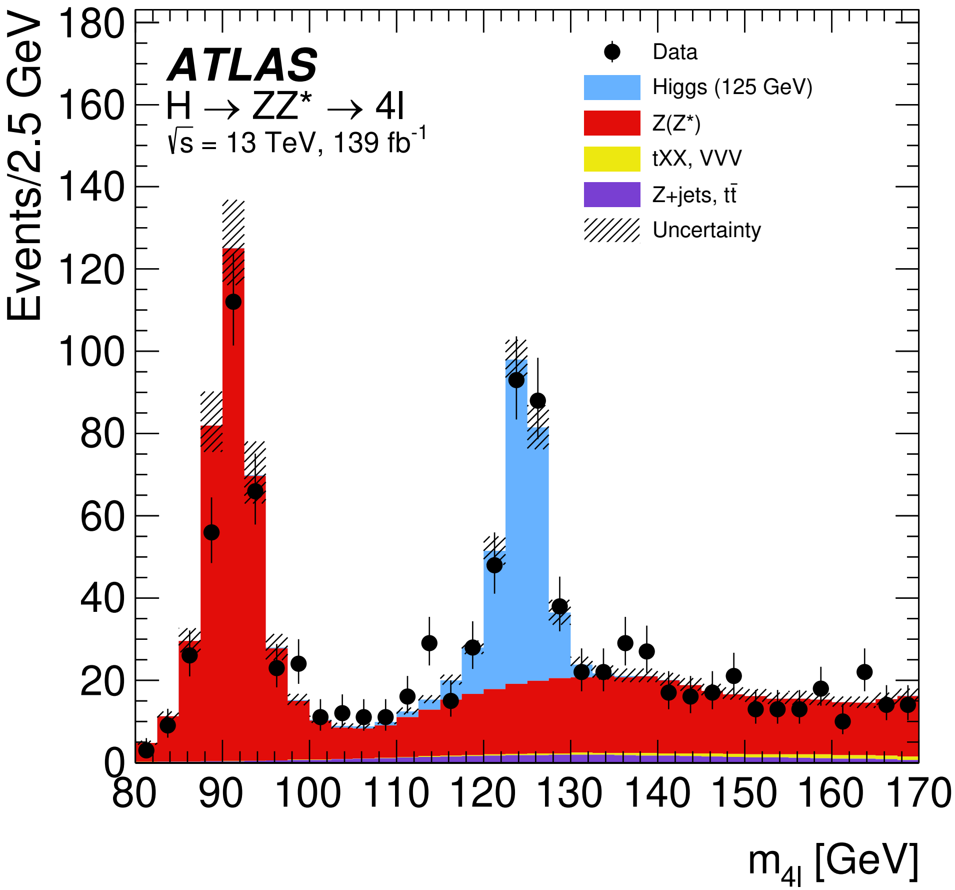
Low branching ratio: only 0.17% of all Higgs boson decays!

...but a very distinct signal, and high purity in the Higgs boson mass window:

Background from SM Z(Z*) → 4l production: simulation constrained by fitting regions outside the Higgs boson mass window

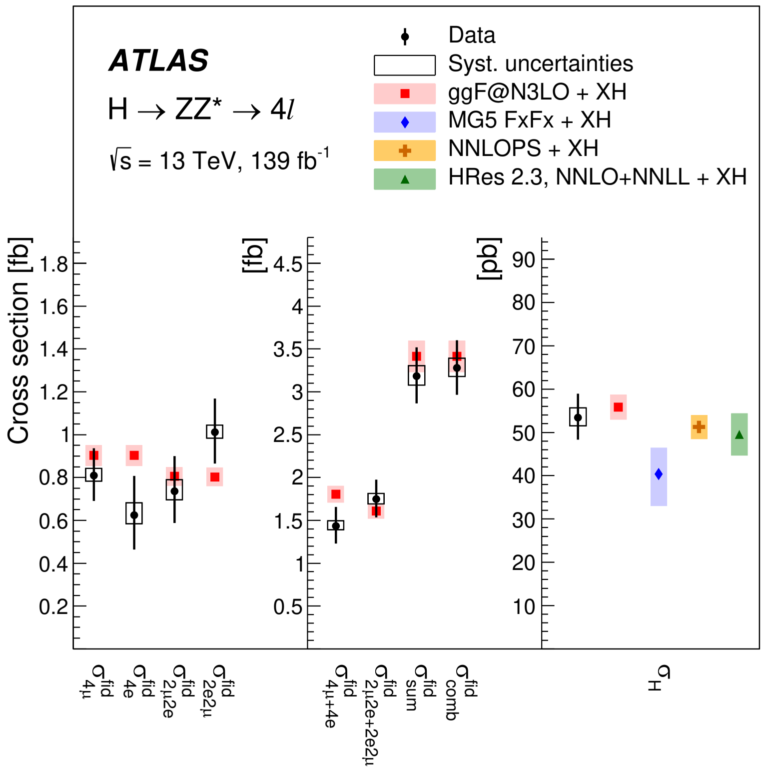
Multi-boson and *tXX* (*X=t, V*) are estimated from simulation

Backgrounds from fake and non-prompt leptons are measured using a data-driven method



$H \rightarrow ZZ^* \rightarrow 4l$ cross sections

arXiv:2004.03969



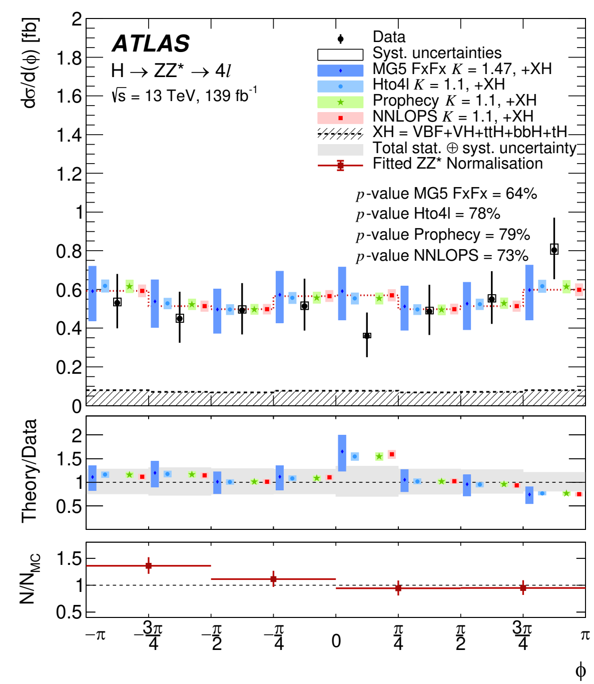
Unfolded, fiducial cross sections are measured for each channel and combined

Inclusive Higgs boson production cross section σ_H measured using SM branching ratios

→ Overall good agreement with SM predictions

Differential cross sections for many variables, compared to different theoretical predictions, including jet-related variables and angular variables

Showing here the azimuthal angle between the two Z bosons



Higgs boson mass: $H \to ZZ^* \to 4l$

CONF-2020-005

Improvements over the cross-section measurement:

FSR photons added to m_{4l}: 1% improvement in resolution

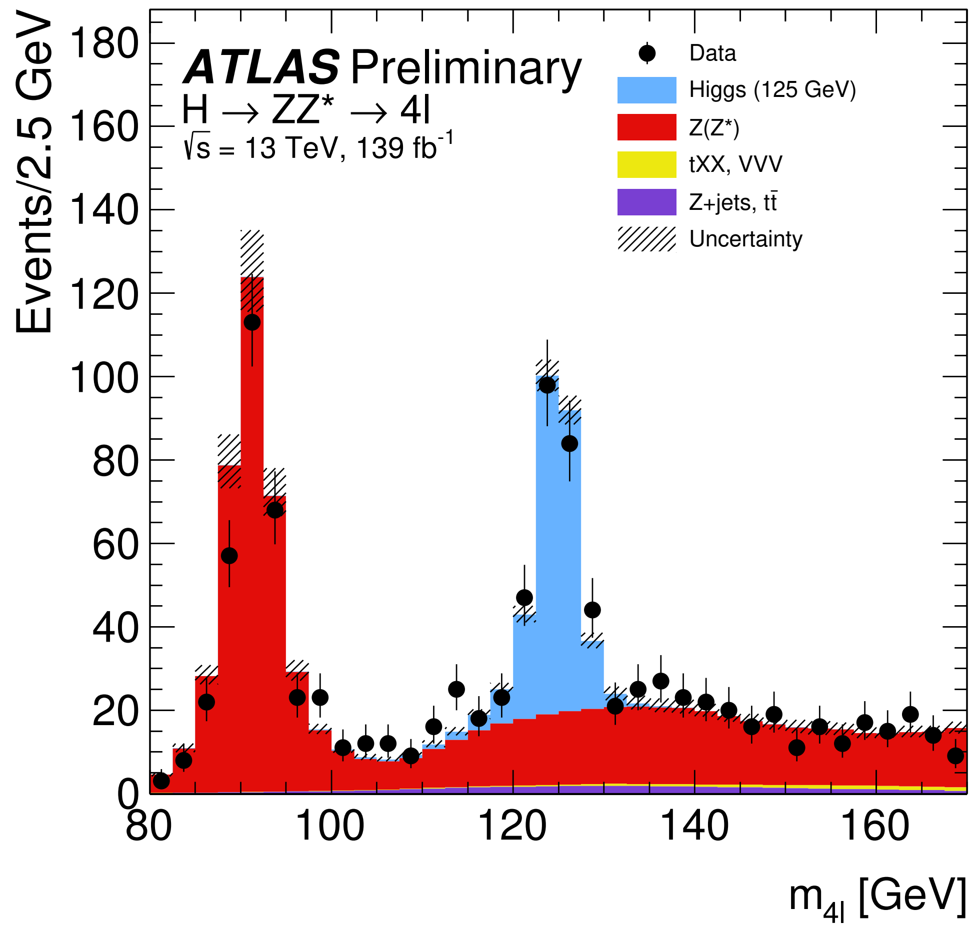
Kinematic fit used to constrain m_{12} to the Z boson mass: 17% improvement in resolution

Mass constraint:

$115 < m_{4l} < 130$ GeV

316 ± 14 events, 66% signal

Signal lineshape dominated by detector response: m_{4l} distribution is modelled with a double-sided crystal ball distribution



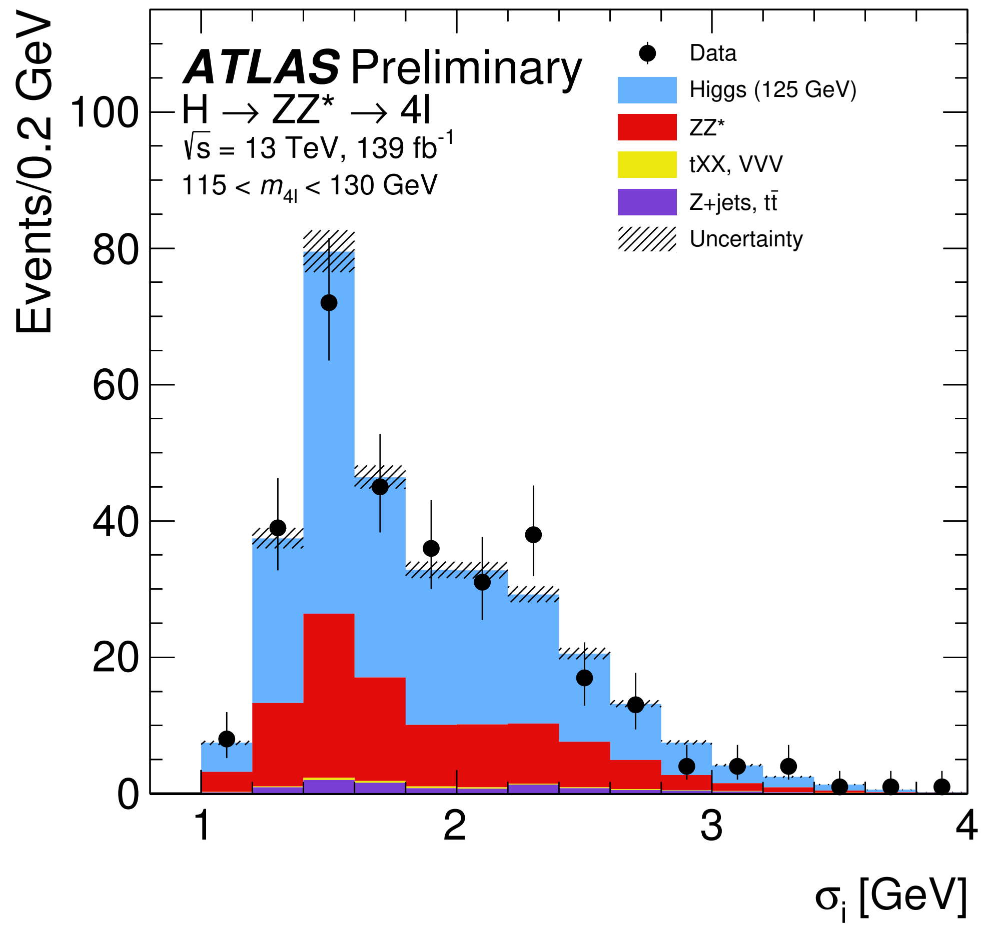
Higgs boson mass: $H \rightarrow ZZ^* \rightarrow 4l$

CONF-2020-005

Use the event-level resolution σ_i instead of the average resolution σ in the fit

Estimate σ_i using a quantile regression neural network:

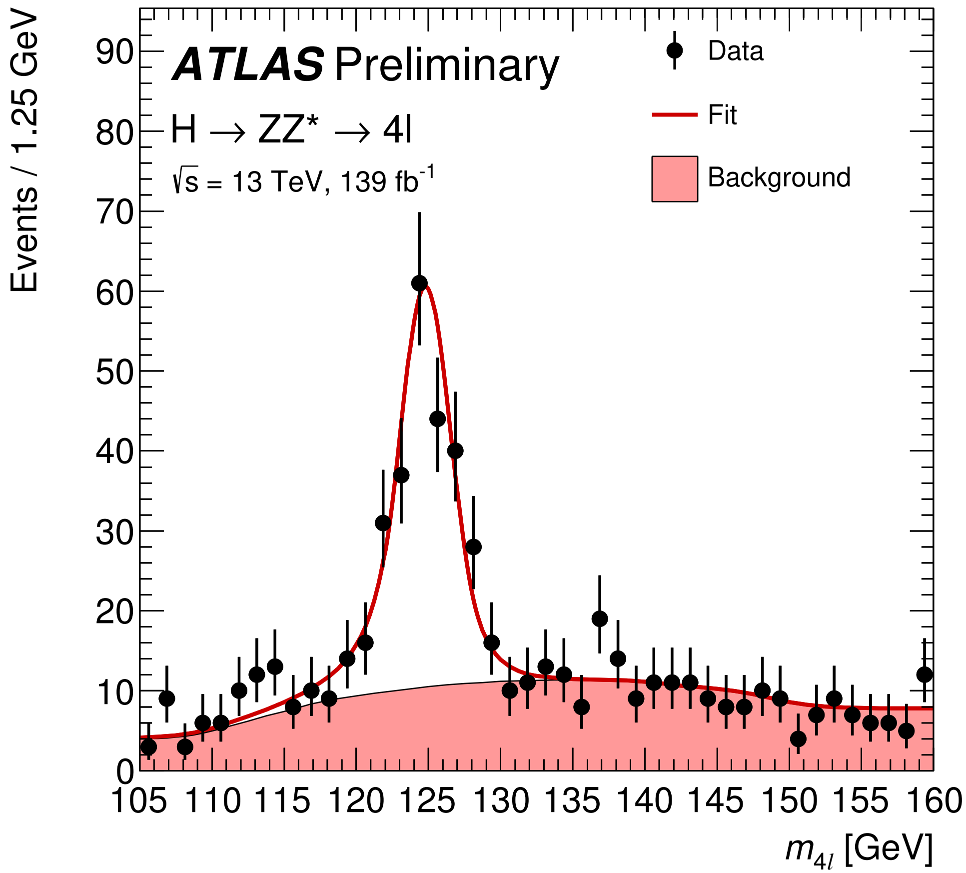
- Input individual lepton kinematics and the four-lepton momentum and its uncertainty

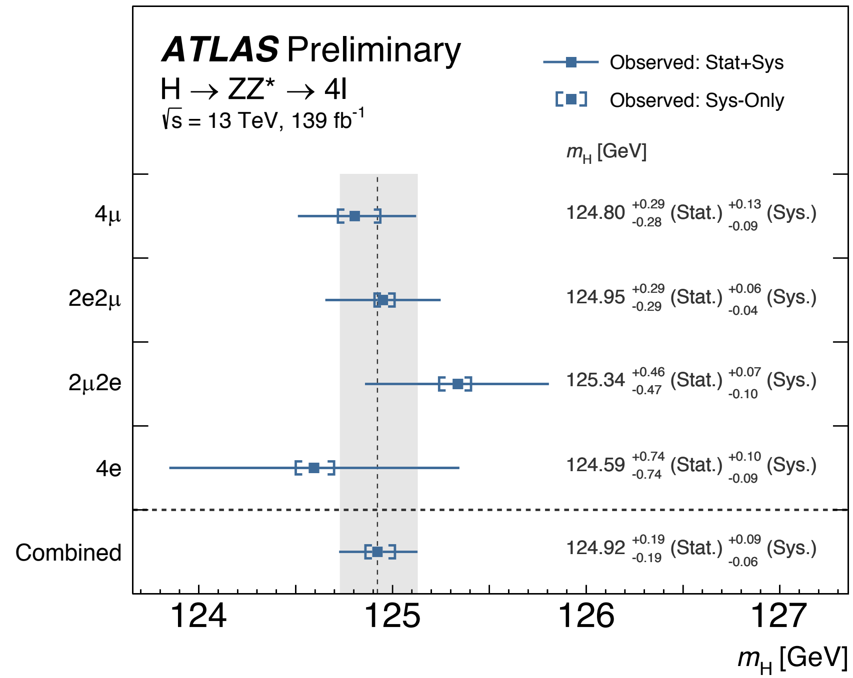


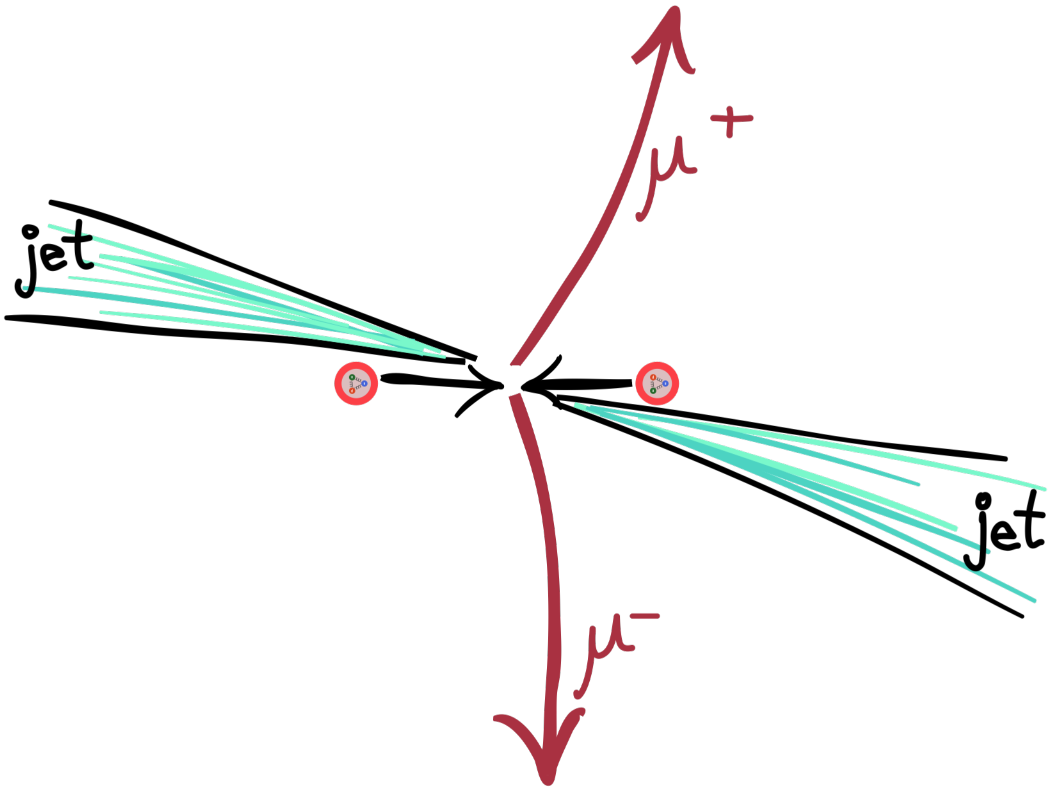
Higgs boson mass: $H \rightarrow ZZ^* \rightarrow 4l$

CONF-2020-005

Measured m_H = $124.92^{+0.19}_{-0.19}$ (Stat.) $^{+0.09}_{-0.06}$ (Sys.) GeV







Electroweak *Zjj* production

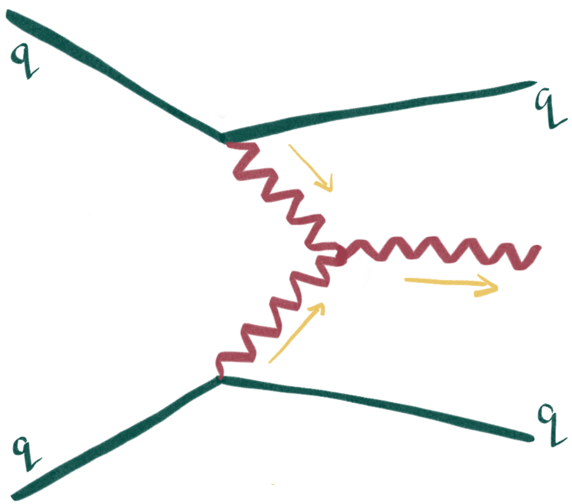
Z boson decaying leptonically (2e/2μ)

Two jets

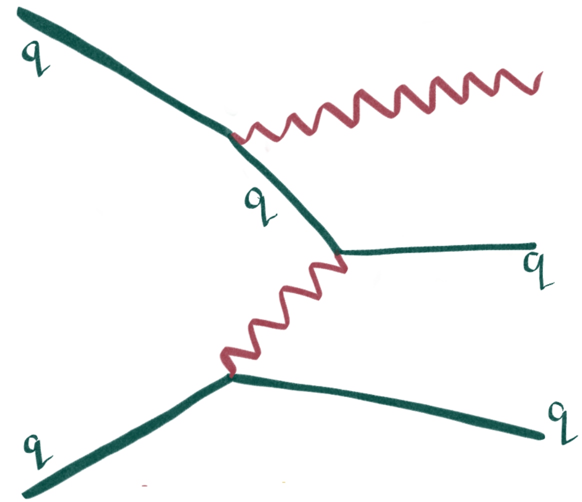
- Large rapidity separation
- Large invariant mass

No jets in the gap

Electroweak *Zjj* production



vector boson **fusion**
$\mathcal{O}(\alpha_{EW}) = 3$



Zjj production
$\mathcal{O}(\alpha_{EW}) = 3$

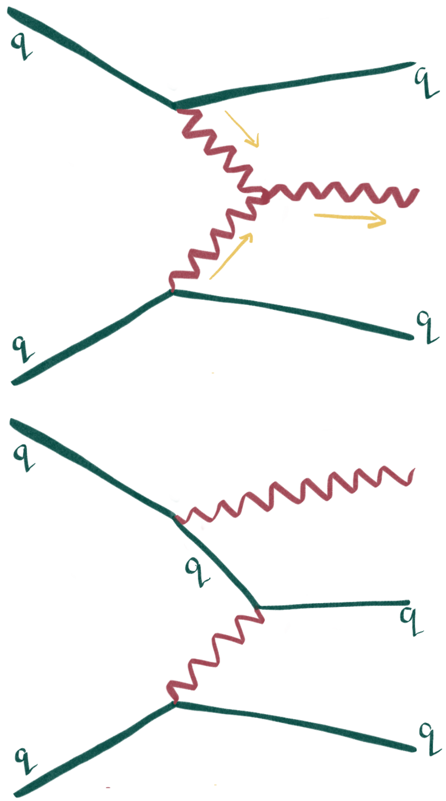
We cannot directly measure vector boson fusion – there is **significant interference** with other diagrams of the same order in α_{EW}, and extracting the VBF component is not a gauge invariant operation

➔ Measure **electroweak production** of Zjj

Electroweak Zjj production

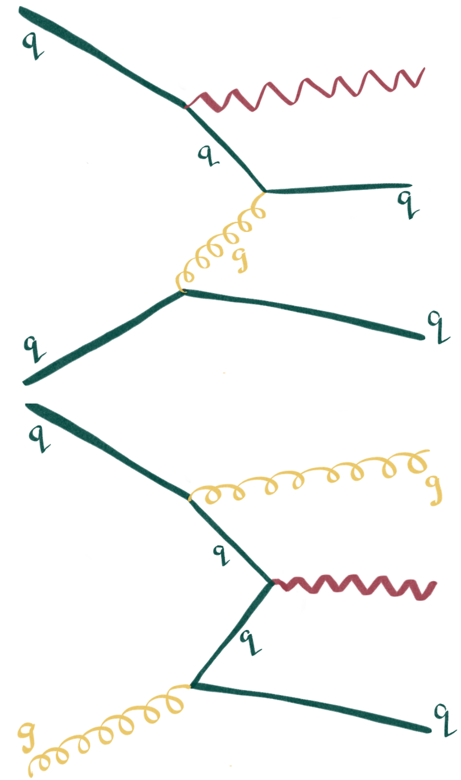
Electroweak Vjj production

$\mathcal{O}(\alpha_{EW}) = 3$



Strong Vjj production

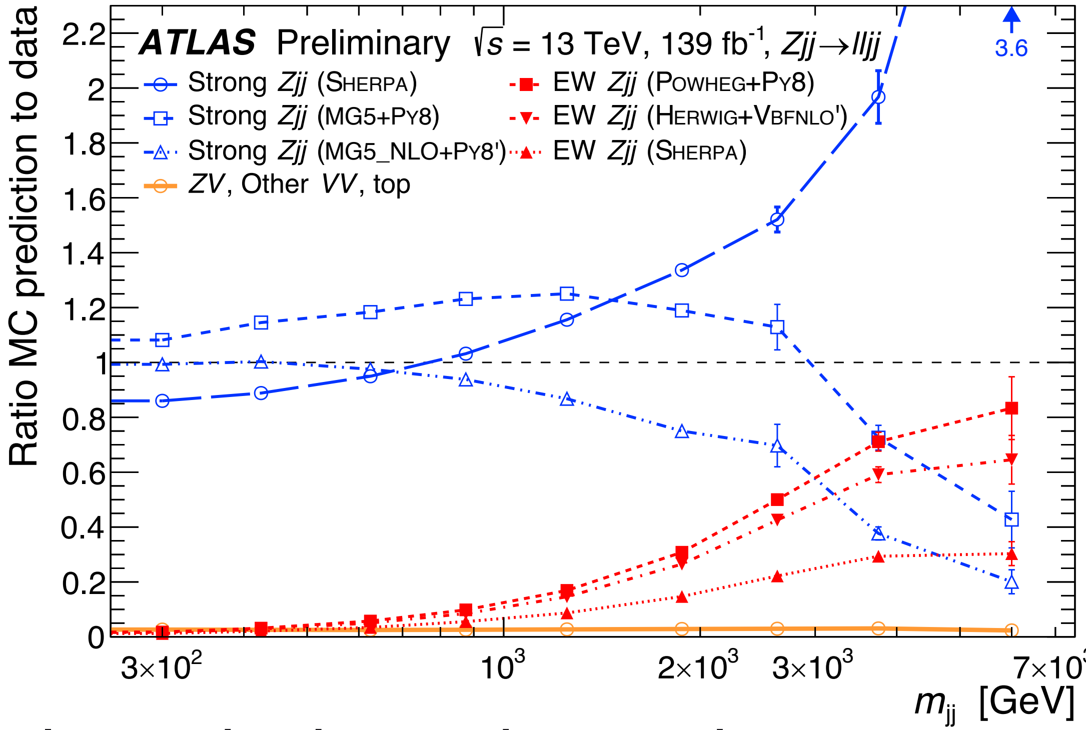
$\mathcal{O}(\alpha_{EW}) = 1$, $\mathcal{O}(\alpha_S) = 2$



Strong production has the same final state and a higher cross-section

Electroweak Zjj production

CERN-EP-2020-045



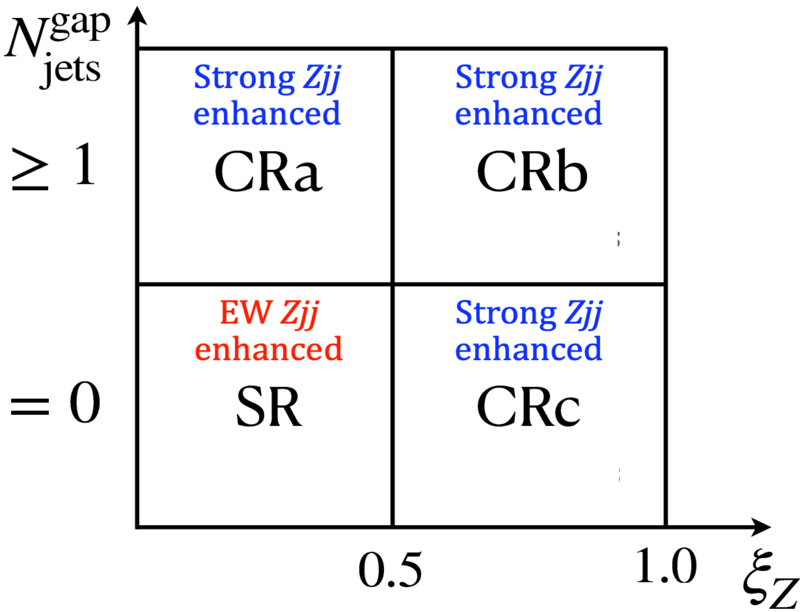
Strong Zjj is the largest background across the spectrum

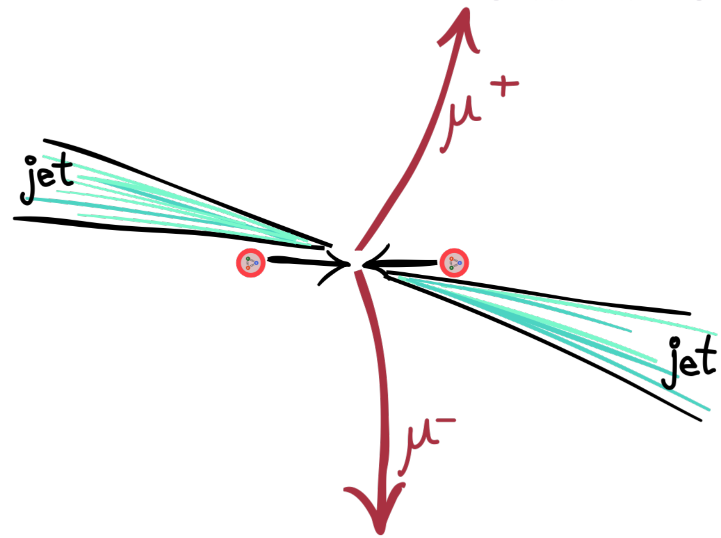
Monte Carlo modelling of both strong electroweak Zjj shows discrepancies between generators

Modelling of strong Zjj is especially poor, particularly in the high-m_{jj} signal-enriched region

Data-driven background modelling

CERN-EP-2020-045





Analysis is split into four regions with two uncorrelated variables:

number of jets between the leading and subleading jets

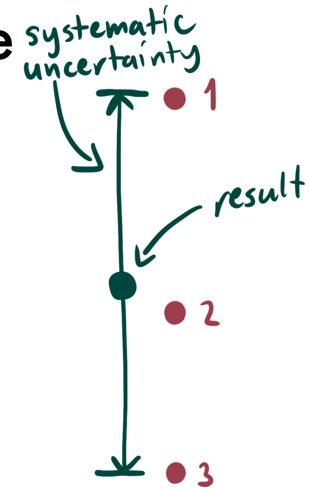
centrality of the reconstructed Z boson:

$$\xi_Z = \left|y_{\ell\ell} - 0.5(y_{j1} + y_{j2})\right| / \left|\Delta y_{jj}\right|$$

➔ three background-enhanced regions and one signal region fit to reduce dependence on mismodelling

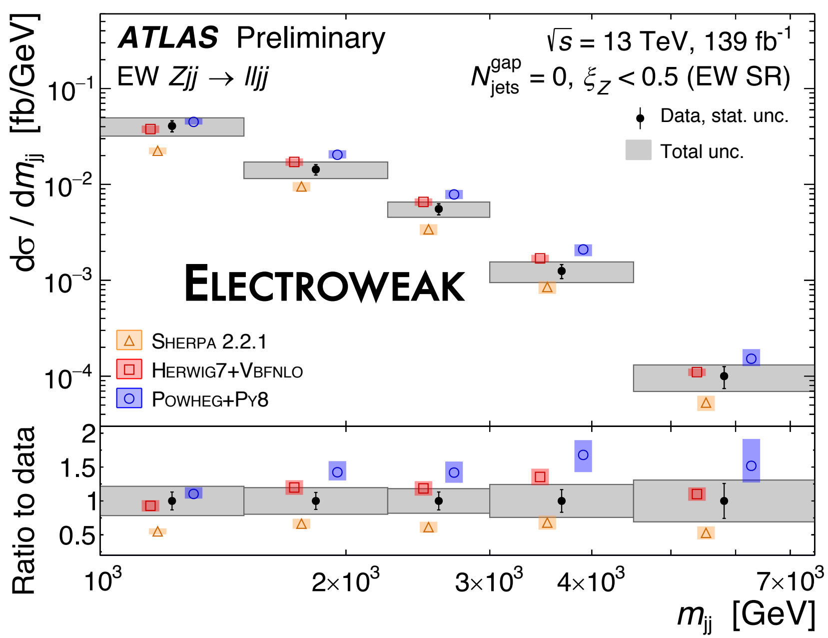
Results

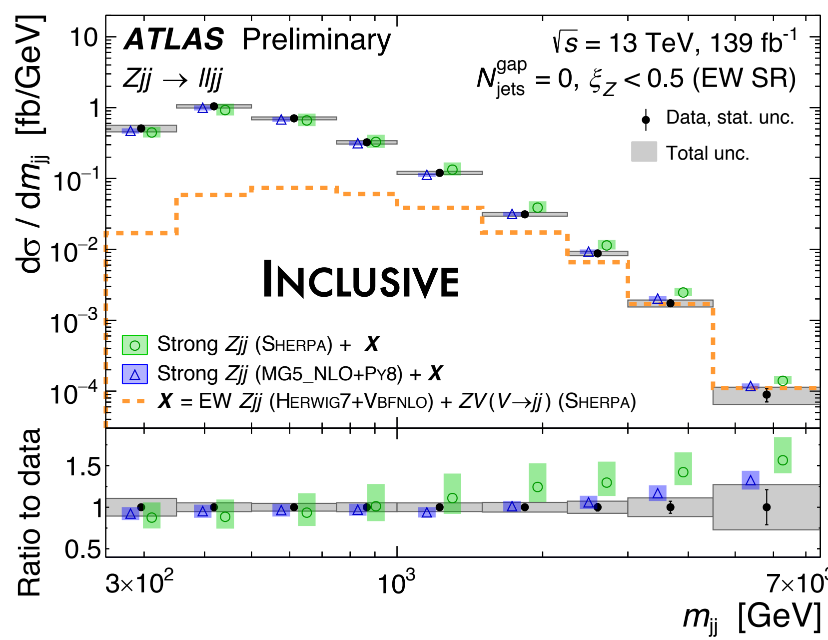
Extract the electroweak Zjj signal once for each of the three strong *Zjj* MC generators:



result is the midpoint of the envelope

Signal and control regions are unfolded for both electroweak and inclusive *Zjj* yields:

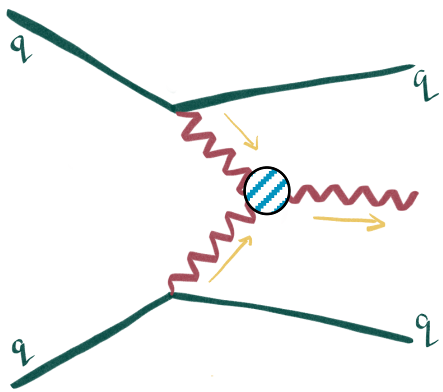




Effective field theory interpretation

CERN-EP-2020-045

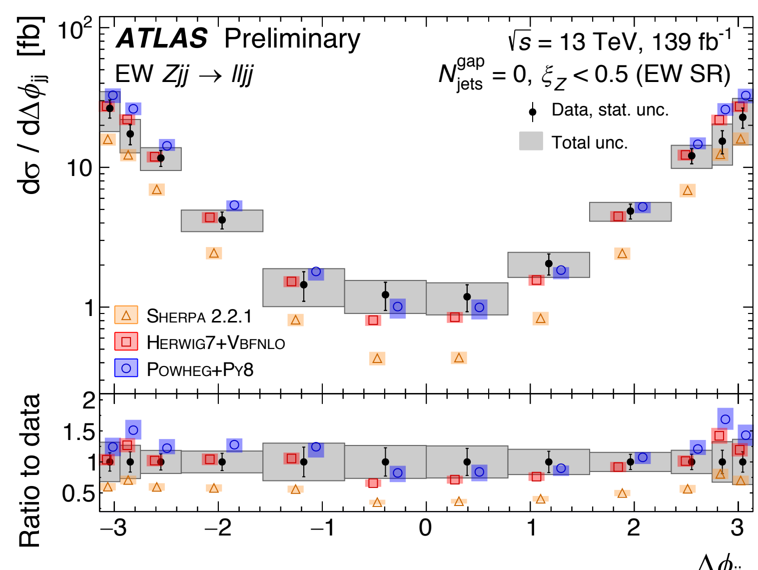
$$\sigma_{EFT} = \sigma_{SM} + \sum \frac{c_j}{\Lambda^2} \sigma^{\text{interf.}}_{SM,j} + \sum_j \frac{c_j^2}{\Lambda^4} \sigma^{\text{NP}}_{j} + \sum_{j \neq k} \frac{c_j c_k}{\Lambda^4} \sigma^{\text{NP - interf.}}_{jk}$$



Wilson coefficient	Linear EFT	95 % confidence limit [TeV^{-2}] Expected (Asimov)	Observed
c_W/Λ^2	yes	[−0.30, 0.30]	[−0.19, 0.41]
	no	[−0.31, 0.29]	[−0.19, 0.41]
$\tilde{c}_W/\Lambda^2$	yes	[−0.12, 0.12]	[−0.11, 0.14]
	no	[−0.12, 0.12]	[−0.11, 0.14]
c_{HWB}/Λ^2	yes	[−2.45, 2.45]	[−3.78, 1.13]
	no	[−3.11, 2.10]	[−6.31, 1.01]
$\tilde{c}_{HWB}/\Lambda^2$	yes	[−1.06, 1.06]	[0.23, 2.34]
	no	[−1.06, 1.06]	[0.23, 2.35]

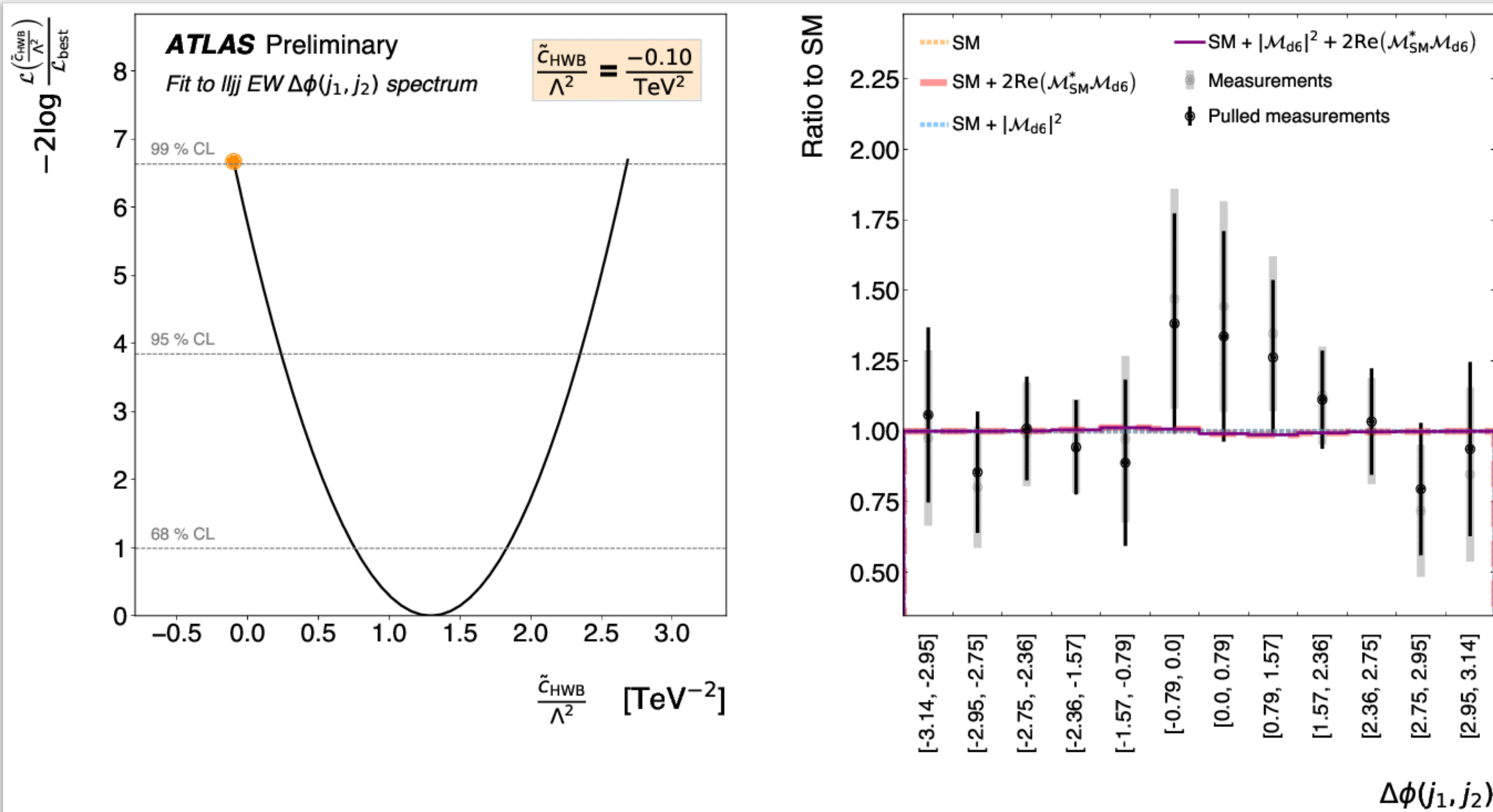
Two CP-even and two CP-odd operators were tested

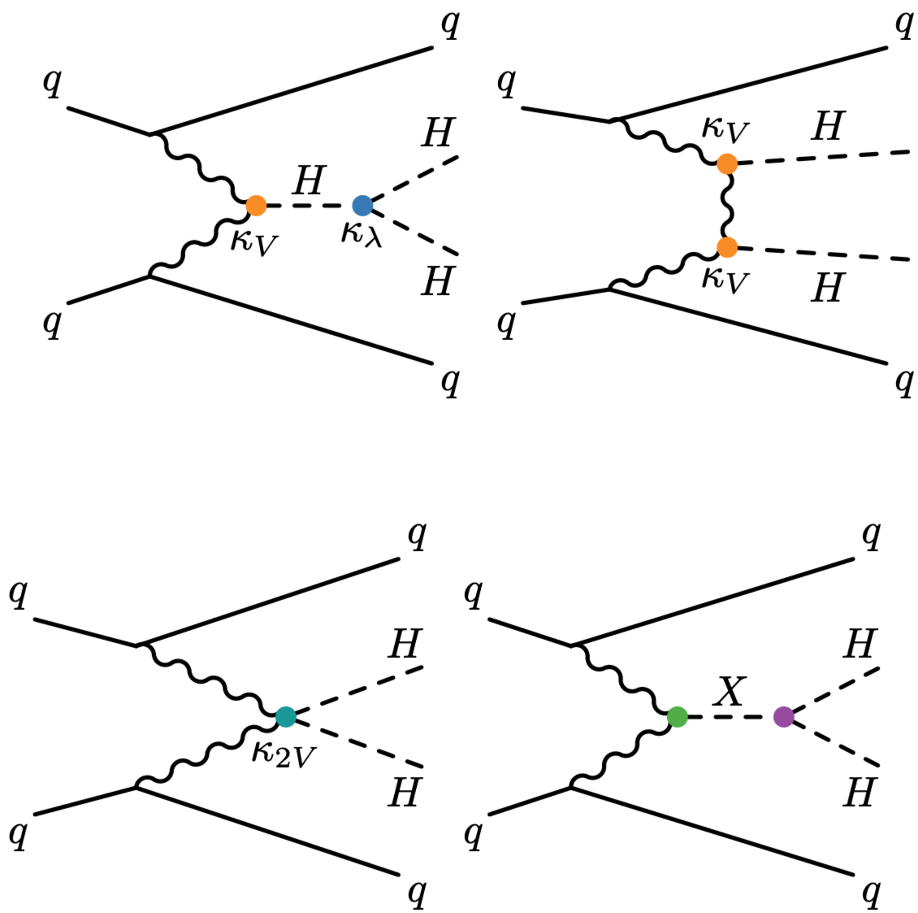
→ sensitivity to CP-odd operators through the parity-odd observable $\Delta\varphi_{jj} = \varphi_{\text{higher rapidity jet}} - \varphi_{\text{lower rapidity jet}}$, where jj = the two leading jets



Effective field theory interpretation

CERN-EP-2020-045





VBF di-Higgs searches

Four central *b*-tagged jets

Two jets

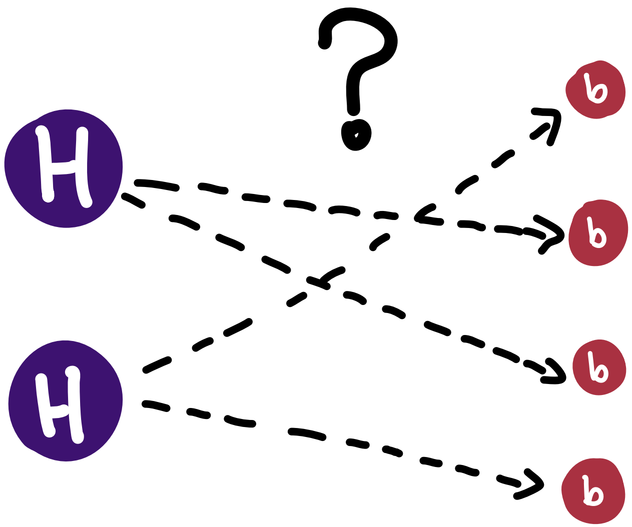
- Large rapidity separation
- Opposite sides of the detector
- Large invariant mass

arXiv:2001.05178

VBF di-Higgs – finding the Higgs

arXiv:2001.05178

Two Higgs bosons decay into four *b*-jets:



Exactly 4 b-tagged jets with $p_T > 40$, $|\eta| < 2.0$	
If $m_{4b} < 1250$	$\frac{360}{m_{4b}} - 0.5 < \Delta R_{bb}^{\text{lead}} < \frac{653}{m_{4b}} + 0.475$ $\frac{235}{m_{4b}} < \Delta R_{bb}^{\text{subl}} < \frac{875}{m_{4b}} + 0.35$
If $m_{4b} \geq 1250$	$\Delta R_{bb}^{\text{lead}} < 1$ $\Delta R_{bb}^{\text{subl}} < 1$
Pairs with minimum $D_{HH} = \sqrt{(m_{2b}^{\text{lead}})^2 + (m_{2b}^{\text{subl}})^2} \left|\sin\left(\tan^{-1}\left(\frac{m_{2b}^{\text{subl}}}{m_{2b}^{\text{lead}}}\right) - \tan^{-1}\left(\frac{116.5}{123.7}\right)\right)\right|$	

Criteria based on pairs of *b*-jets, forming Higgs boson candidates

Pair of pairs with minimum D_{HH} is chosen:

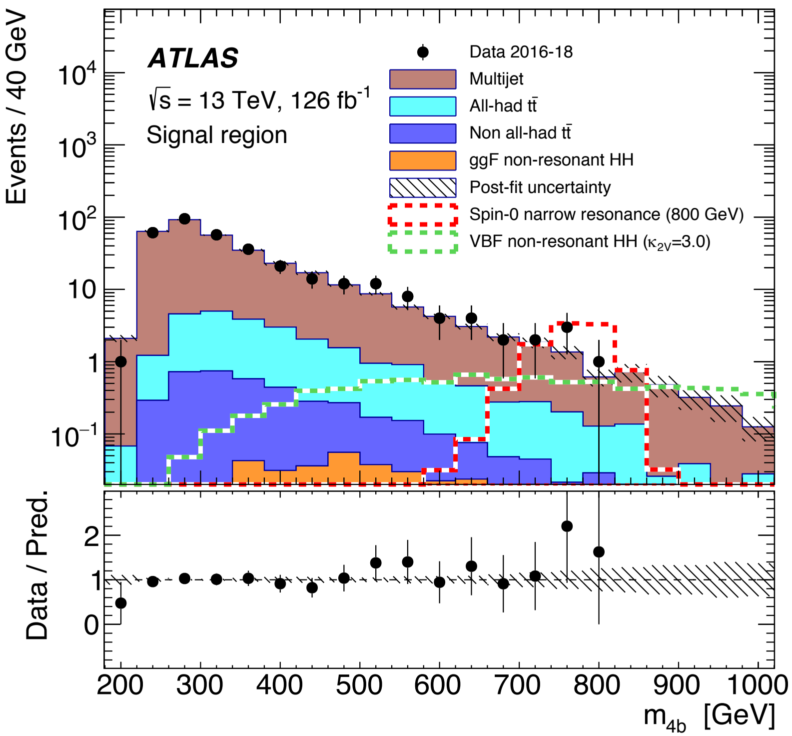
correct 83% of the time for SM non-resonant HH

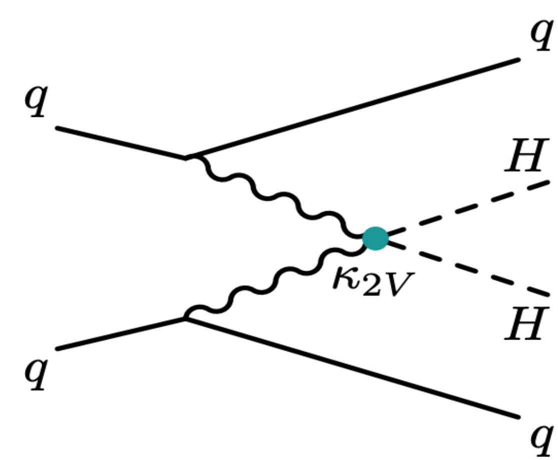
correct 91% of the time for broad BSM resonance → HH

VBF di-Higgs – results

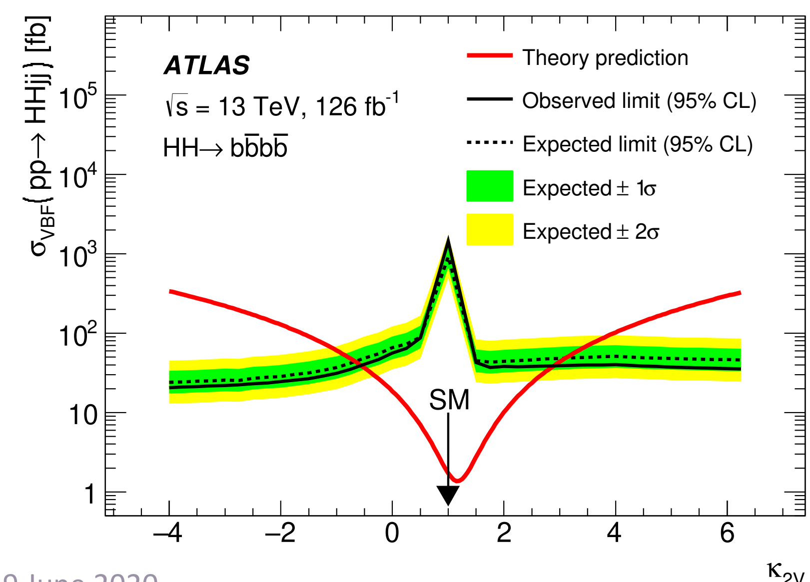
arXiv:2001.05178

Observed 95% CL upper limit of 1450 fb on SM VBF HH production (σ_{SM} = 1.73 fb)

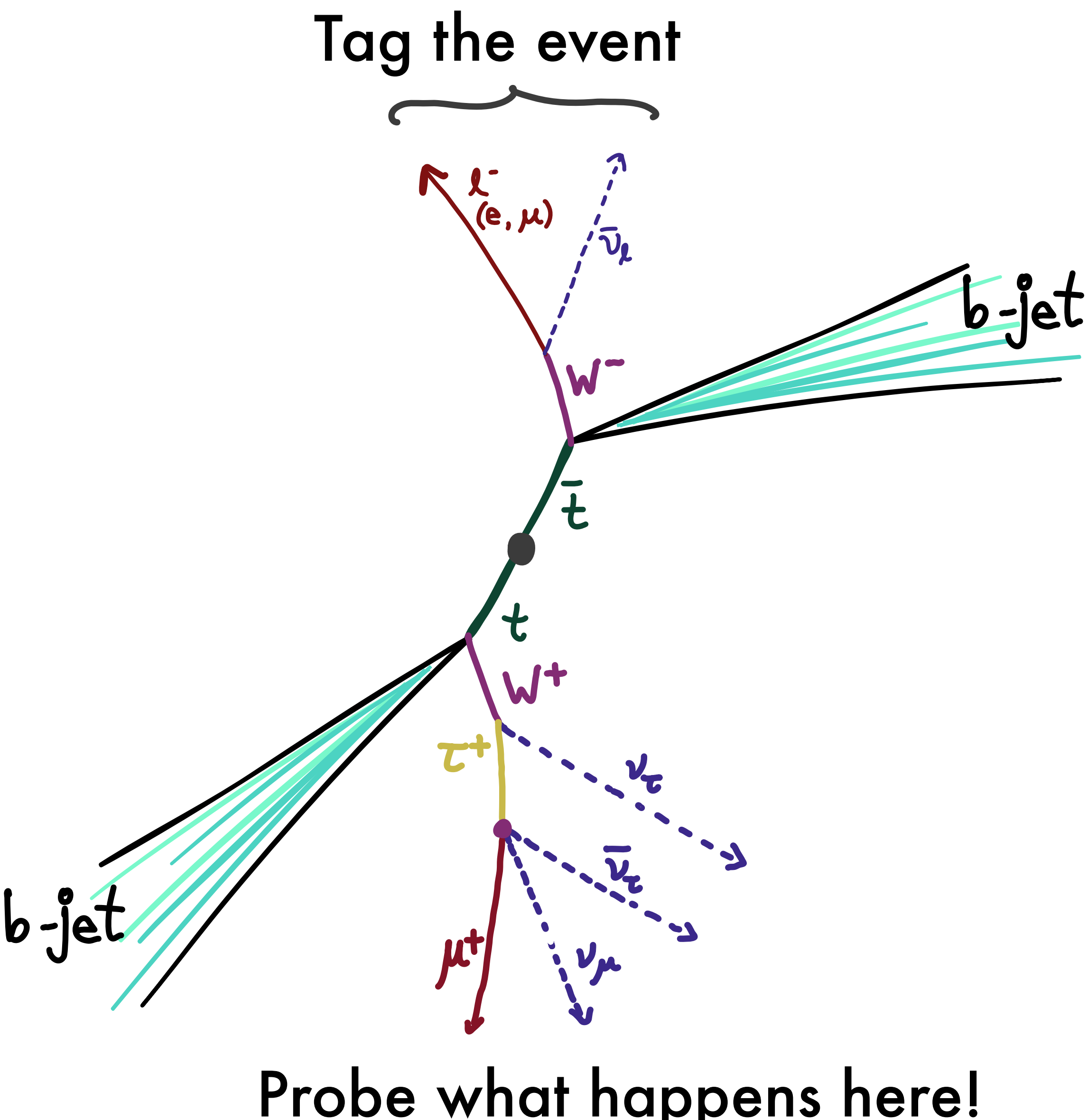




Sensitivity to HHVV coupling (κ_{2V}) unique to VBF HH searches



Not shown: limits also set on narrow and broad BSM X → HH resonances



Universality of lepton couplings in W boson decays

tt events: two *b*-jets

One leptonically decaying W (e/μ) as a tag

Second opposite-sign leptonically decaying W ($\mu\nu$ or $\tau\nu$ → $\mu\nu\nu\nu$)

Z mass veto

CONF-2020-014

LFU in W boson decays

CONF-2020-014

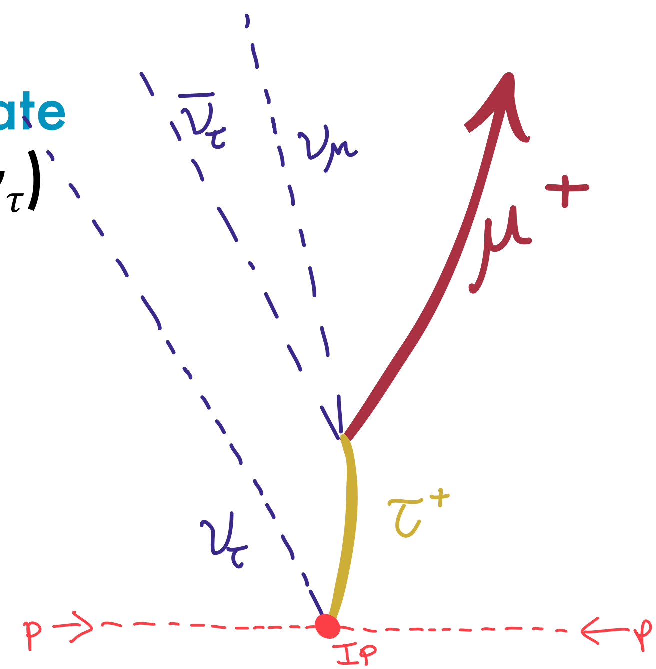
In the SM, gauge boson decays exhibit
lepton flavour universality

Measure the ratio of tau decays to muon decays: Only previous measurement is from LEP, which shows a 2.7σ discrepancy from the SM

$$R(\tau/\mu) = \frac{\mathrm{BR}(W \to \tau\nu)}{\mathrm{BR}(W \to \mu\nu)}$$

Use $\tau \to \mu$ decays to have the muon final state for both lepton flavours ($W \to \tau\nu_\tau \to \mu\nu_\mu\nu_\tau\nu_\tau$)

Properties of muons from $W \to \mu\nu$ vs. $W \to \tau\nu$ differ: form templates for each decay channel and fit to data

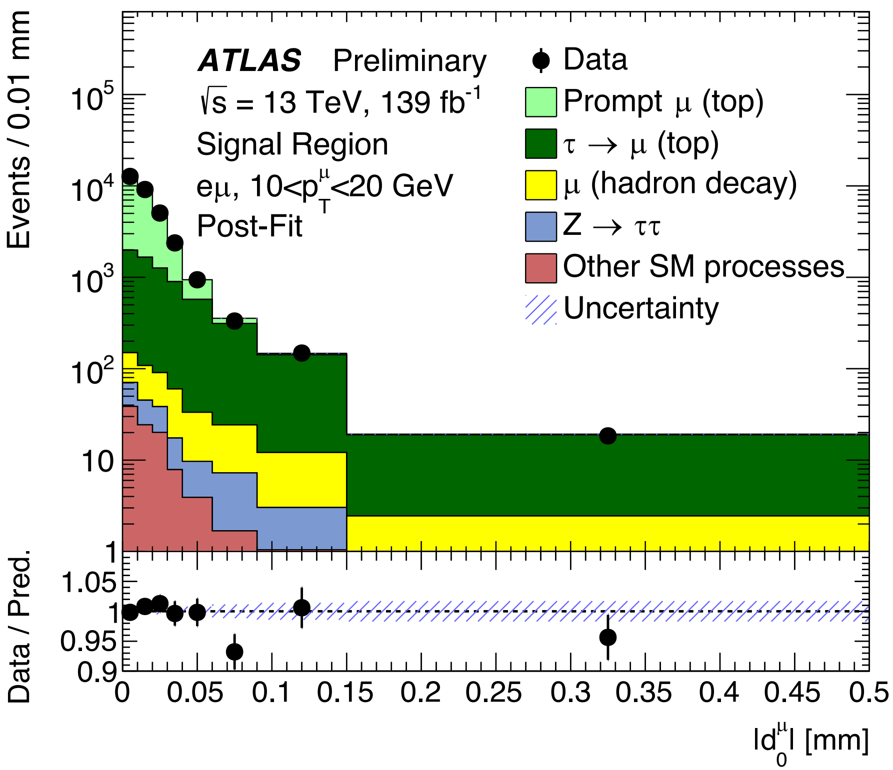


LFU in W boson decays

CONF-2020-014

48-bin fit (3 muon p_T bins, 8 muon d_0 bins, two tag-lepton channels) to extract two parameters:

- R(τ/μ): parameter of interest, applied to $\tau\rightarrow\mu$ (top) component
- *k(tt)*: normalization applied to both tt and Wt



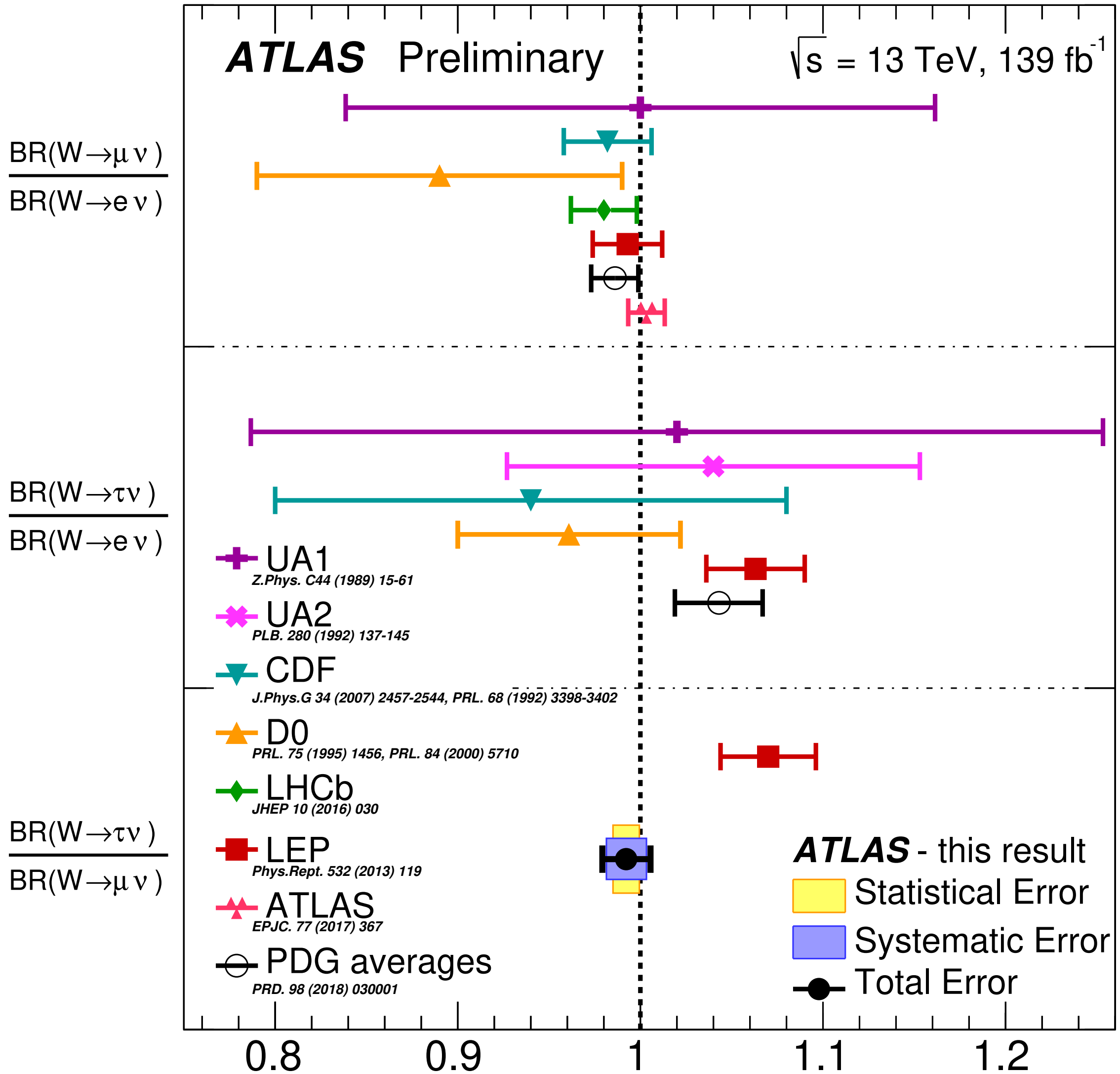
$$R(\tau/\mu) = 0.992 \pm 0.013$$

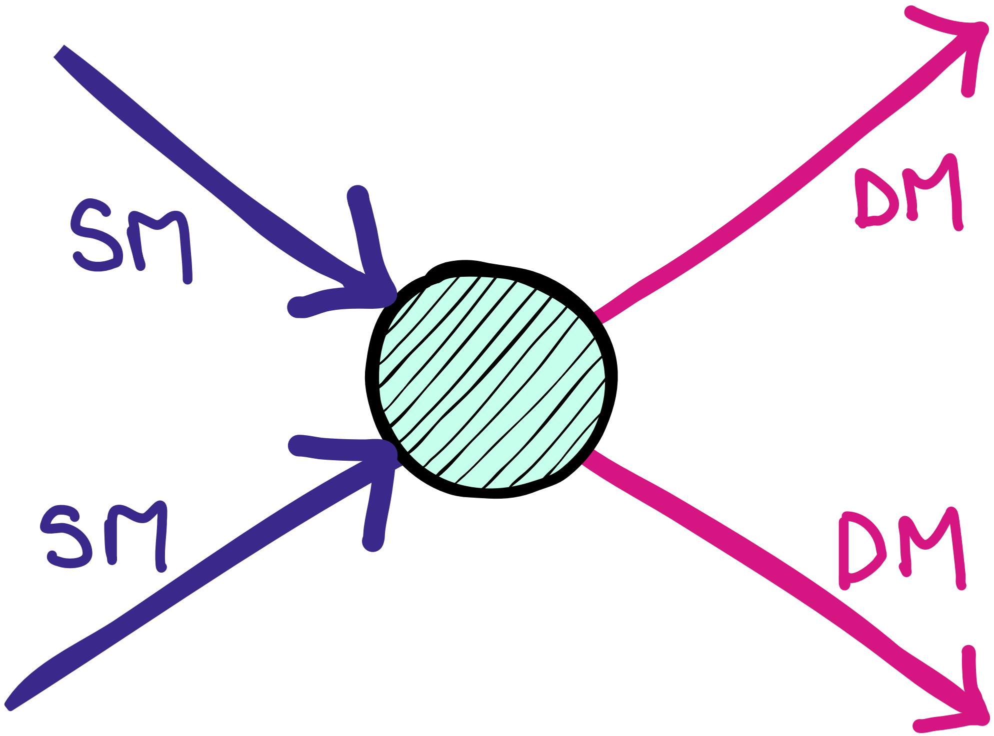
$$[\pm 0.007\ (\mathrm{stat}) \pm 0.011\ (\mathrm{syst})]$$

Most precise value to-date!

LFU in W boson decays

CONF-2020-014





Searches for Dark Matter

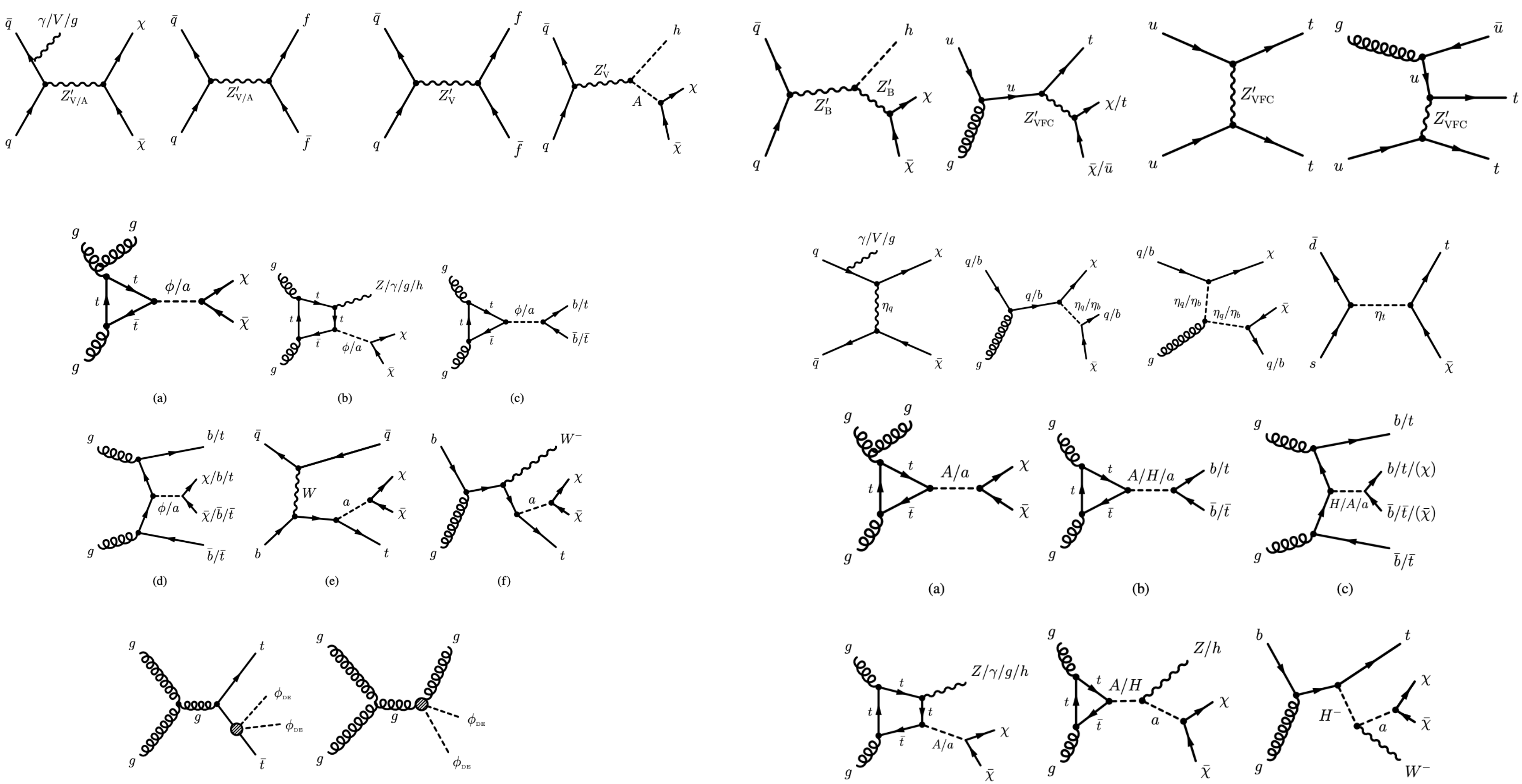
Many, many possibilities!

CONF-2020-008
JHEP 05 (2019) 142

Dark matter summary

JHEP 05 (2019) 142

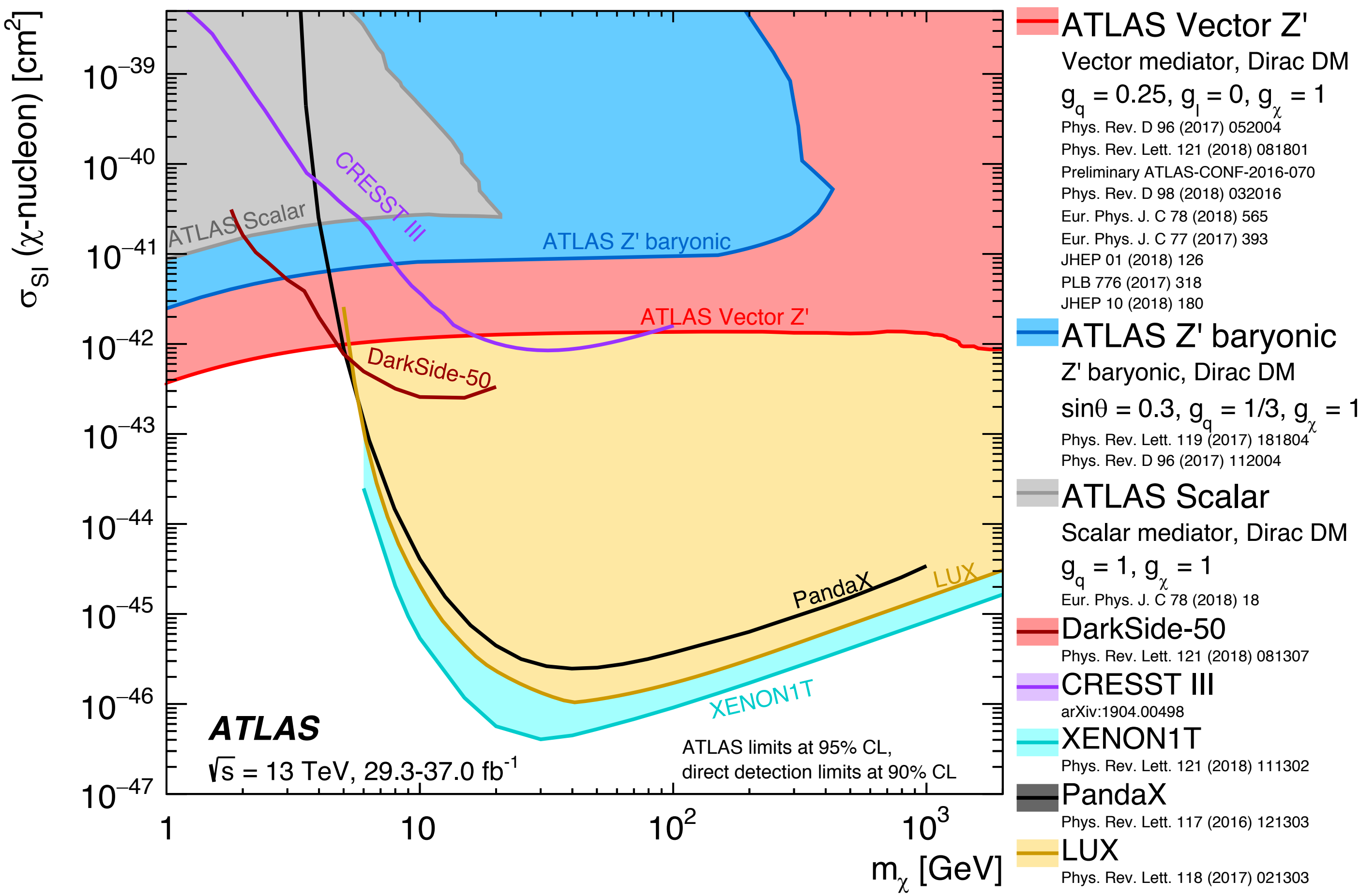
Dark matter could be produced in many, many ways at the LHC:



Dark matter summary

JHEP 05 (2019) 142

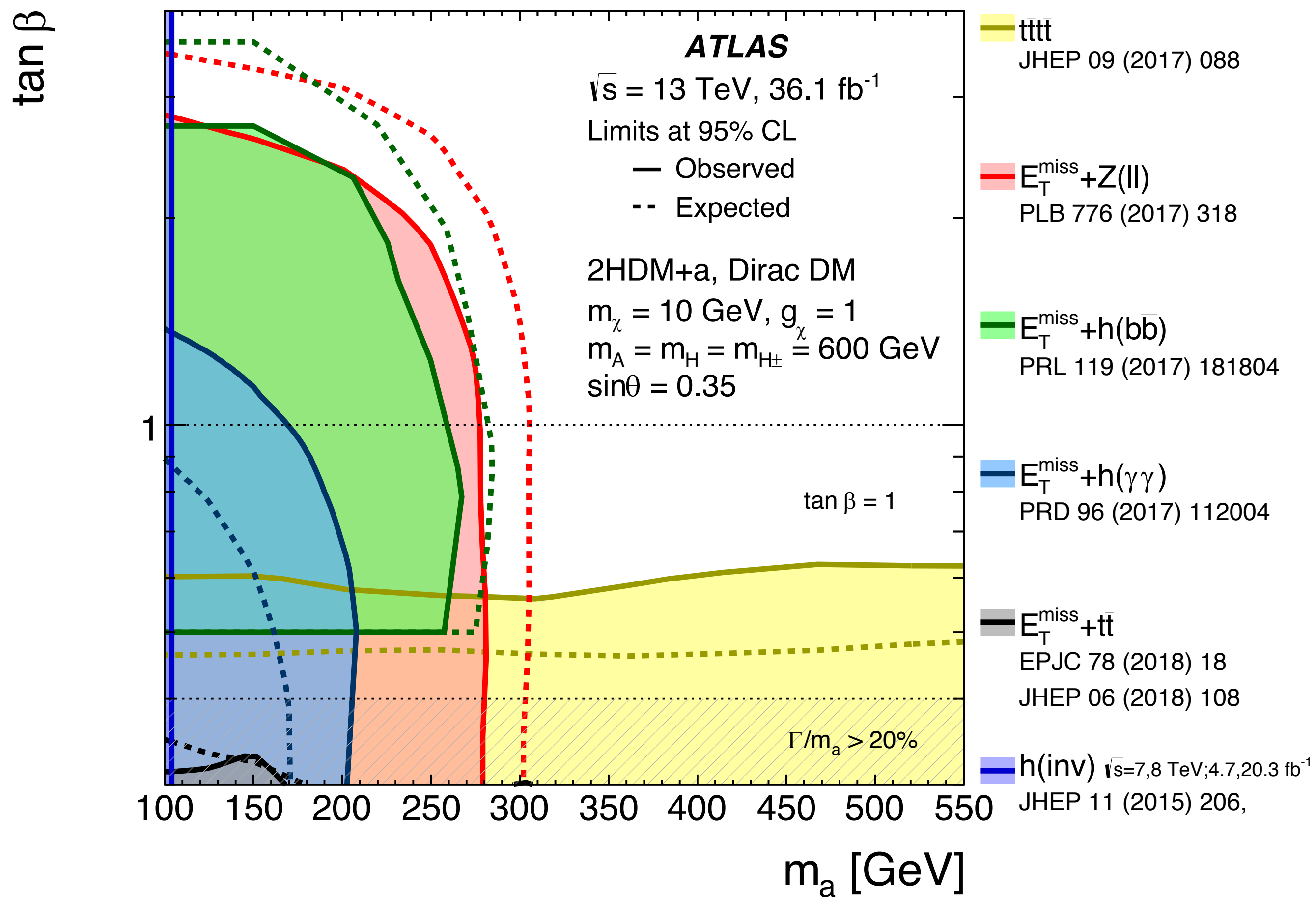
Important to understand how ATLAS compare to other experiments:



Dark matter summary

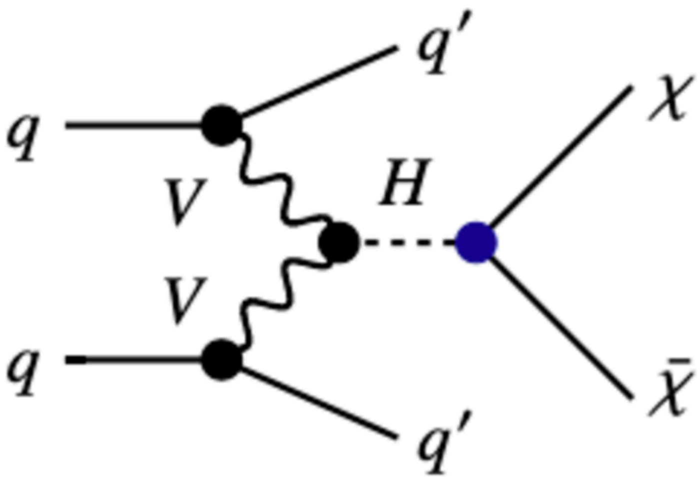
JHEP 05 (2019) 142

Important to understand how searches in different channels are complementary, and what areas of phase space we still need to focus on:



DM in invisible Higgs boson decays

CONF-2020-008

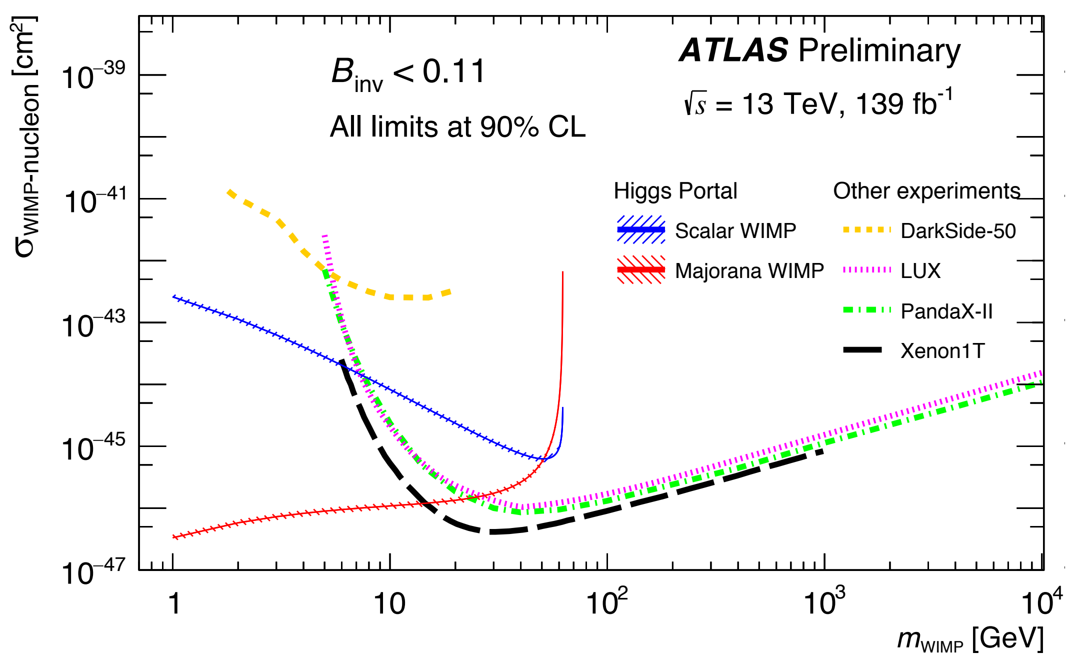


In the SM, the Higgs boson decays invisibly 0.12% of the time

Previous best fit measurement: < 26% at 95% CL PRL 122, 231801 (2019)

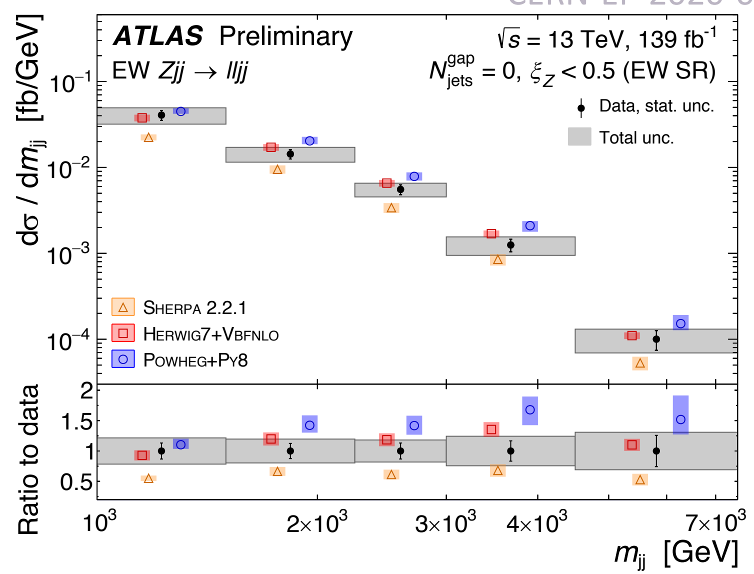
Full Run 2 preliminary result has limited this to < 13% at 95% CL!

Strong $BR_{invisibles}$ limit can be interpreted as strong constraints on Higgs portal DM:



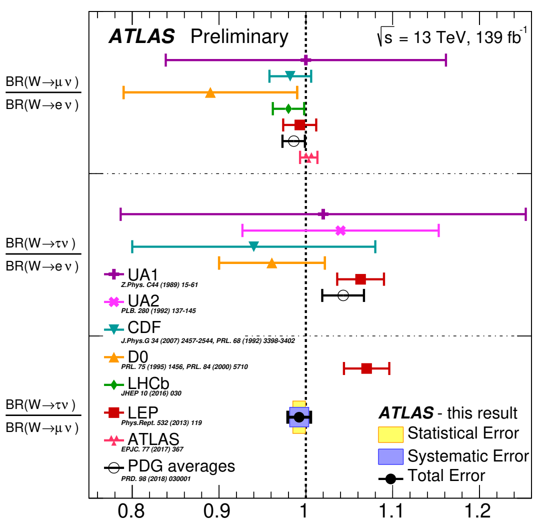
Summary

CERN-EP-2020-045



ATLAS has a hugely diverse physics program

Many results using the full Run 2 dataset are already complete

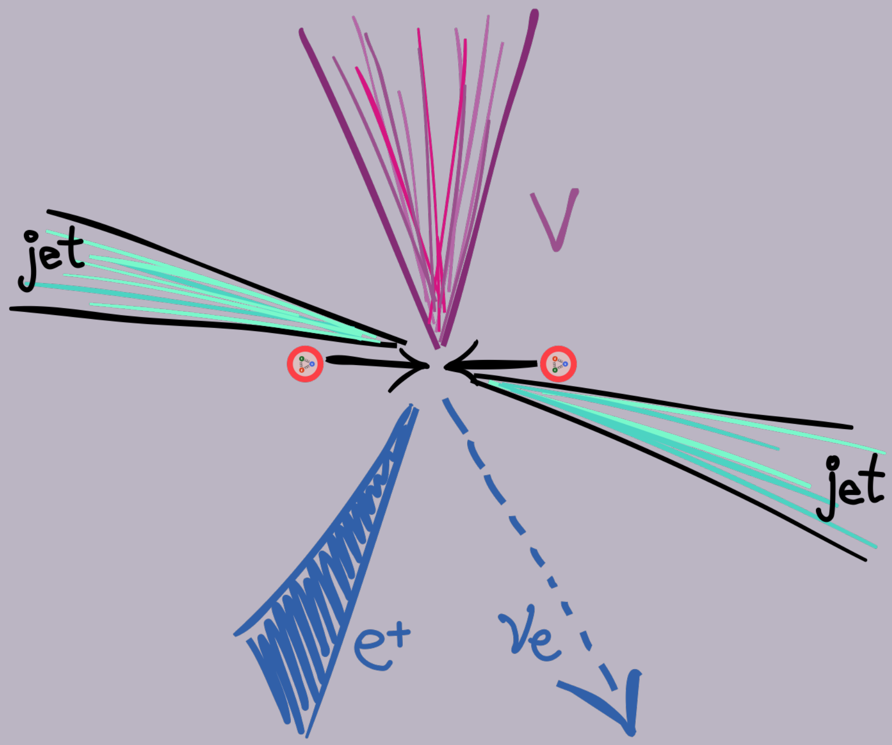


CONF-2020-014

I've only shown a small handful of what we have:

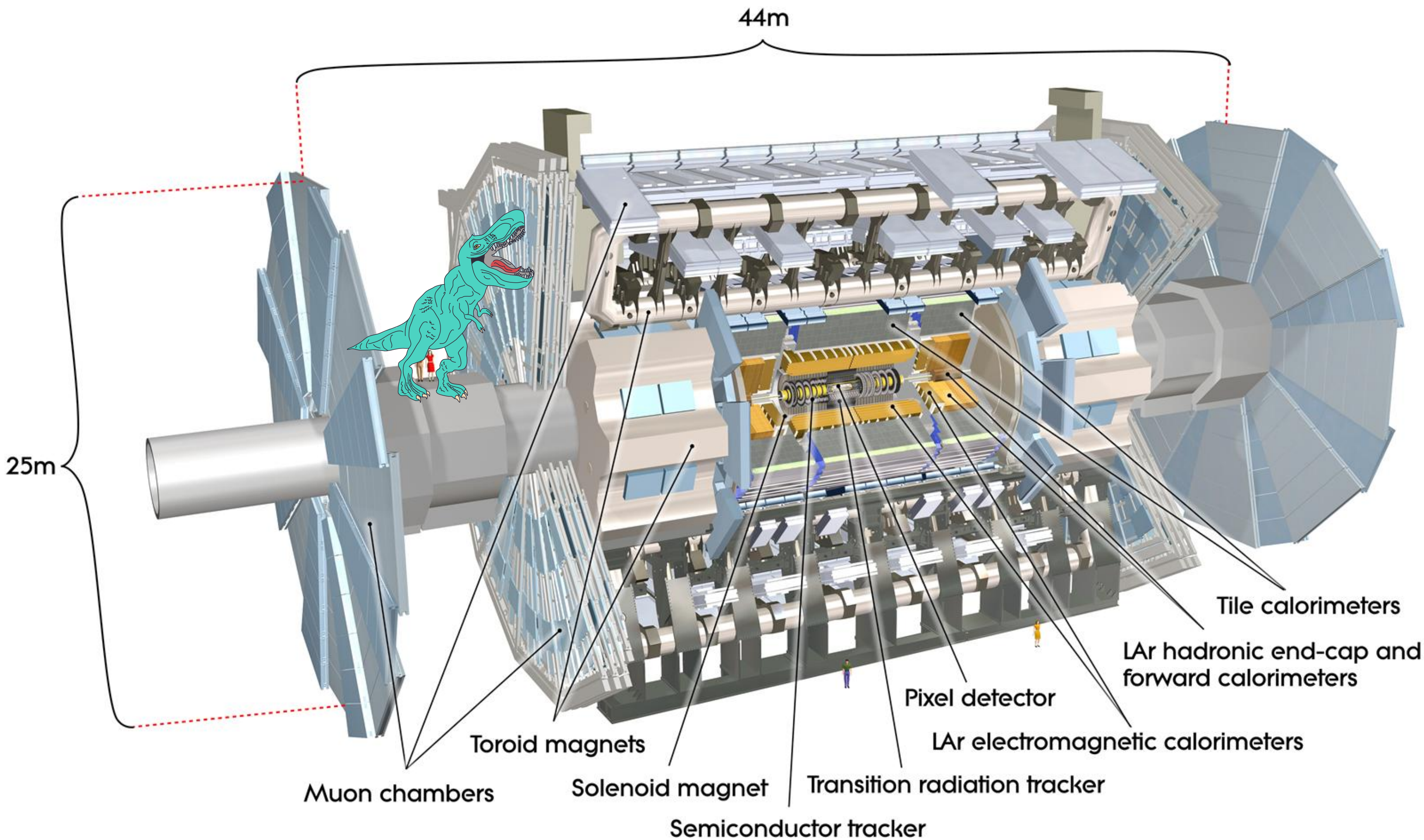
- Higgs → ZZ* → 4l
- VBF HH
- VBF Z
- R(tau/mu) in W decays
- Dark matter searches

…and many more interesting results are still to come!

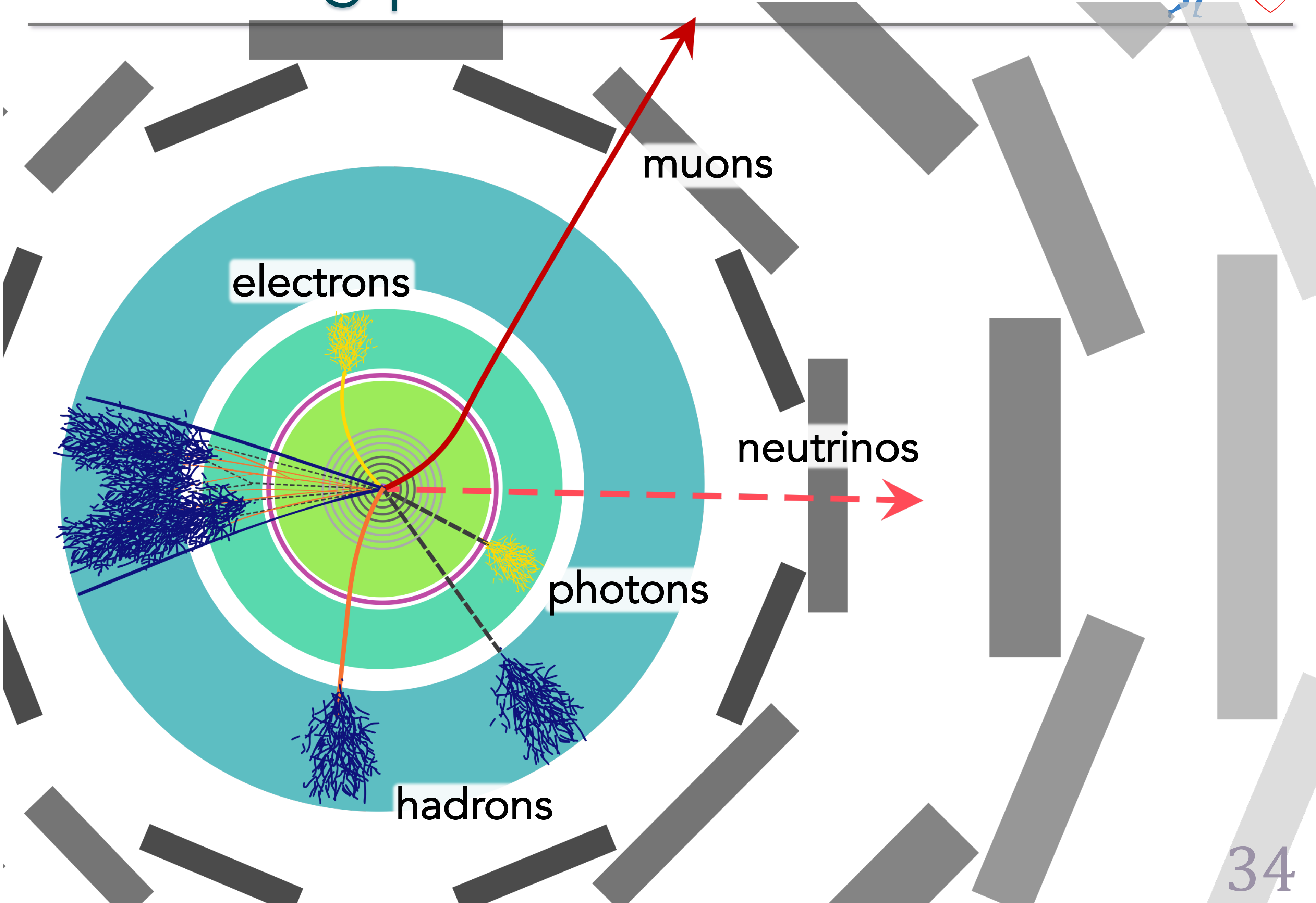


Backup

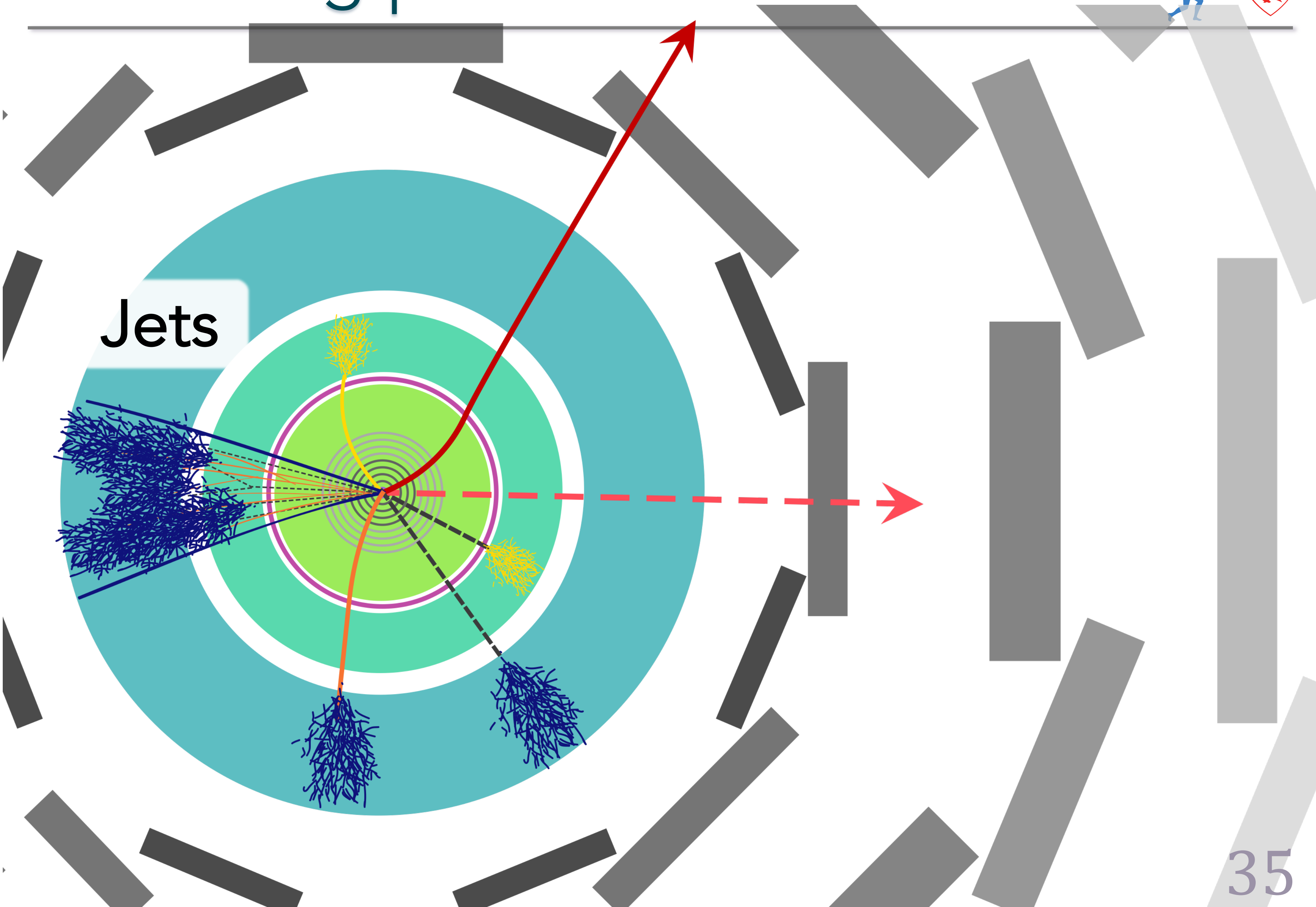
The ATLAS detector



Detecting particles with ATLAS

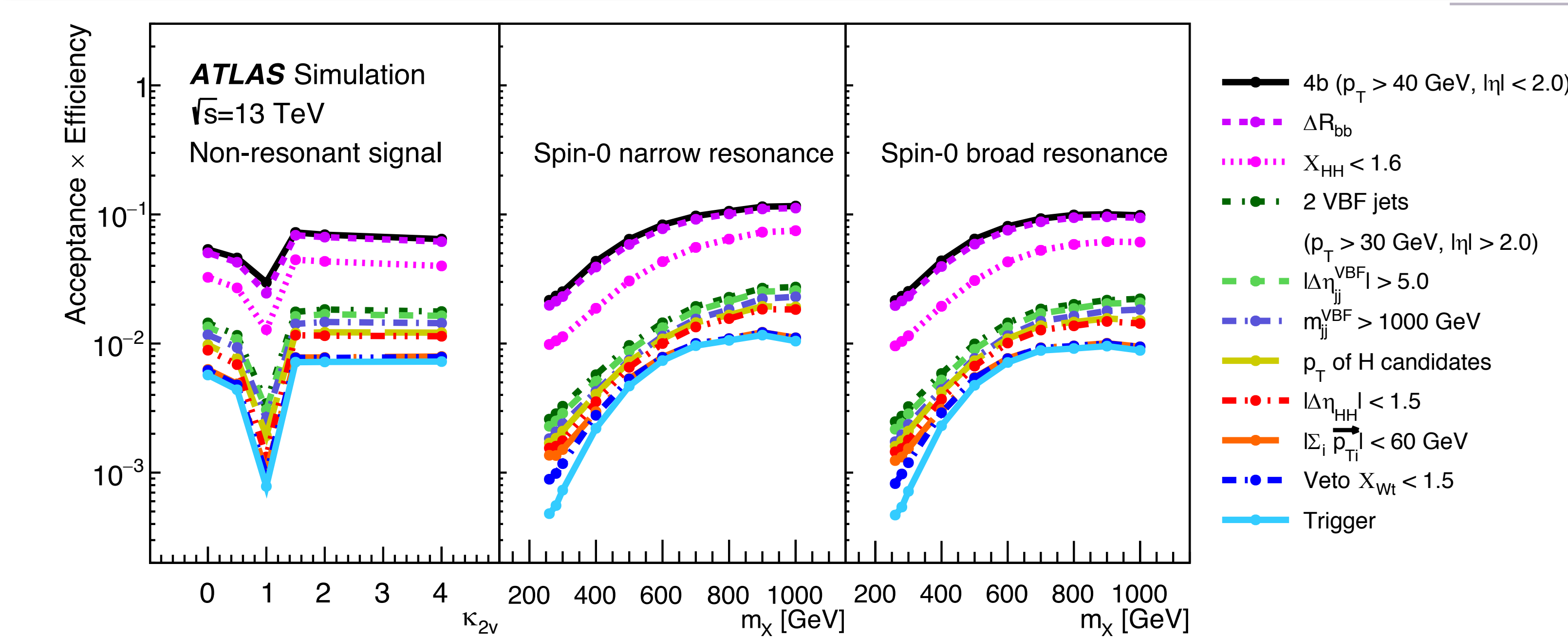


Detecting particles with ATLAS



VBF HH: acceptance x efficiency

arXiv:2001.05178

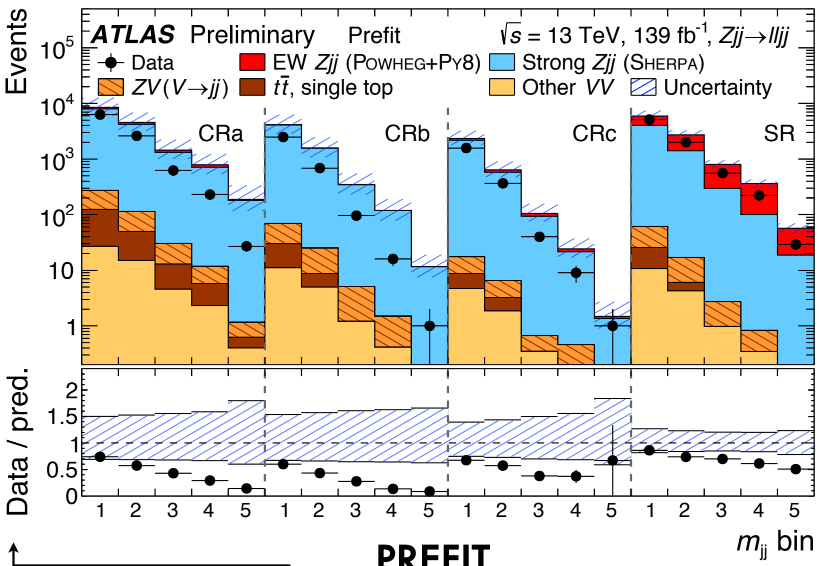


"For κ_{2V} values deviating from the SM prediction, growing non-cancellation effects result in a harder m_{HH} spectrum, and thereby higher-pT *b*-jets, which in turn lead to increased signal acceptance times efficiency as shown in Figure 2.

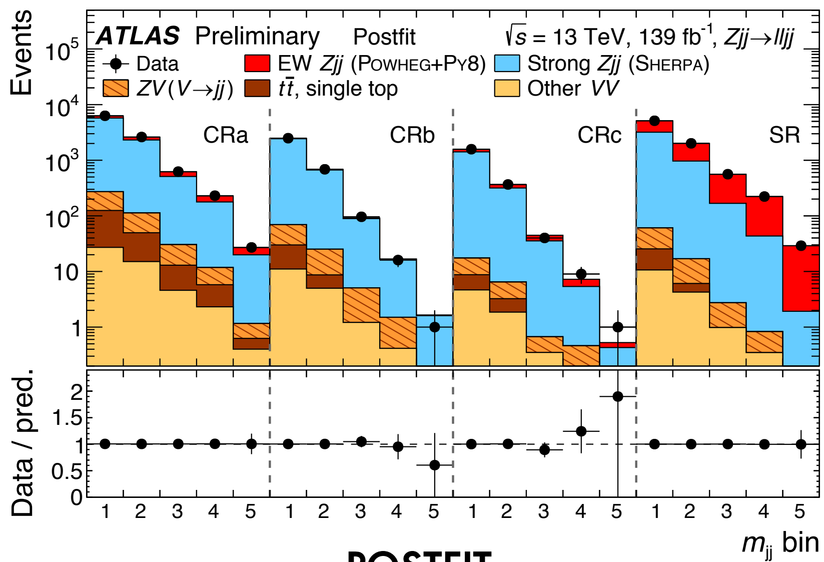
This search is therefore not sensitive to the region close to the SM prediction, corresponding to $\kappa_{2V} = 1$"

Extracting the EW Zjj signal

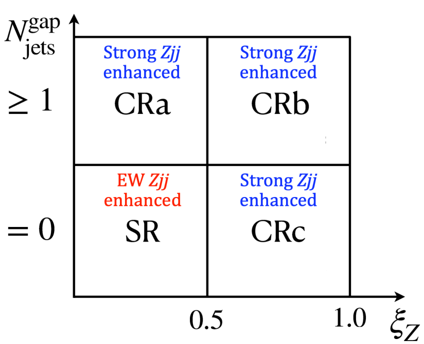
CERN-EP-2020-045



PREFIT



POSTFIT



Binned maximum likelihood fit is performed to reduce dependence on MC mismodelling, with $3 * N_{\text{bins}} + 2$ free parameters:

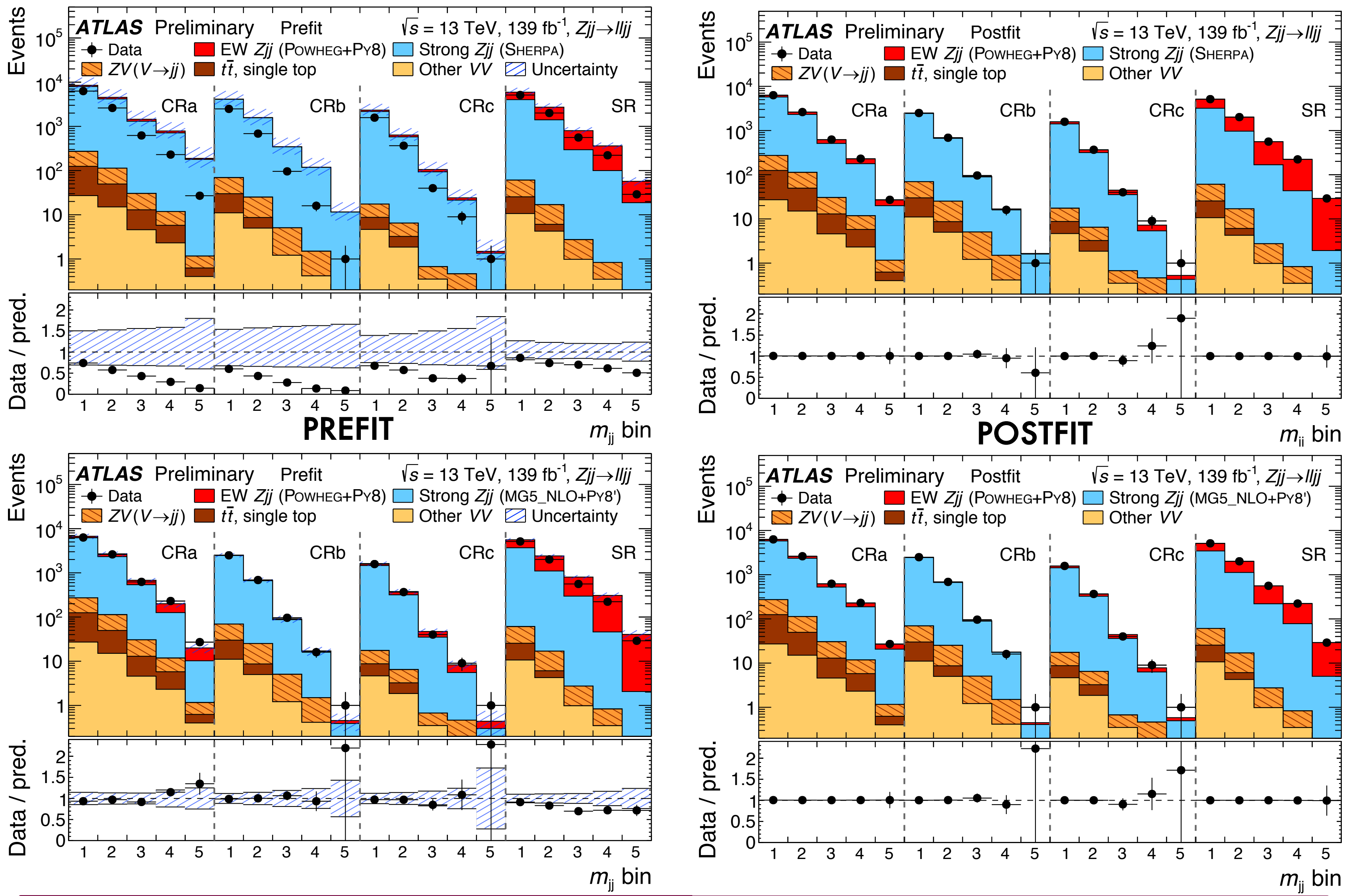
(1) bin-by-bin weights for strong Zjj, separate for low and high centrality but linked between $N_{\text{jets}}^{\text{gap}} \geq 1$ and $N_{\text{jets}}^{\text{gap}} = 0$

(2) linear f(x) applied to strong Zjj to correct for residual $N_{\text{jets}}^{\text{gap}}$ dependence

(3) bin-by-bin electroweak Zjj signal strengths (same in all regions)

Extracting the EW Zjj signal

CERN-EP-2020-045



→ Perform fit again with alternative generators for strong Zjj component