Kruger 2022: Discovery Physics at the LHC

Standard model measurements at CMS: status & highlights

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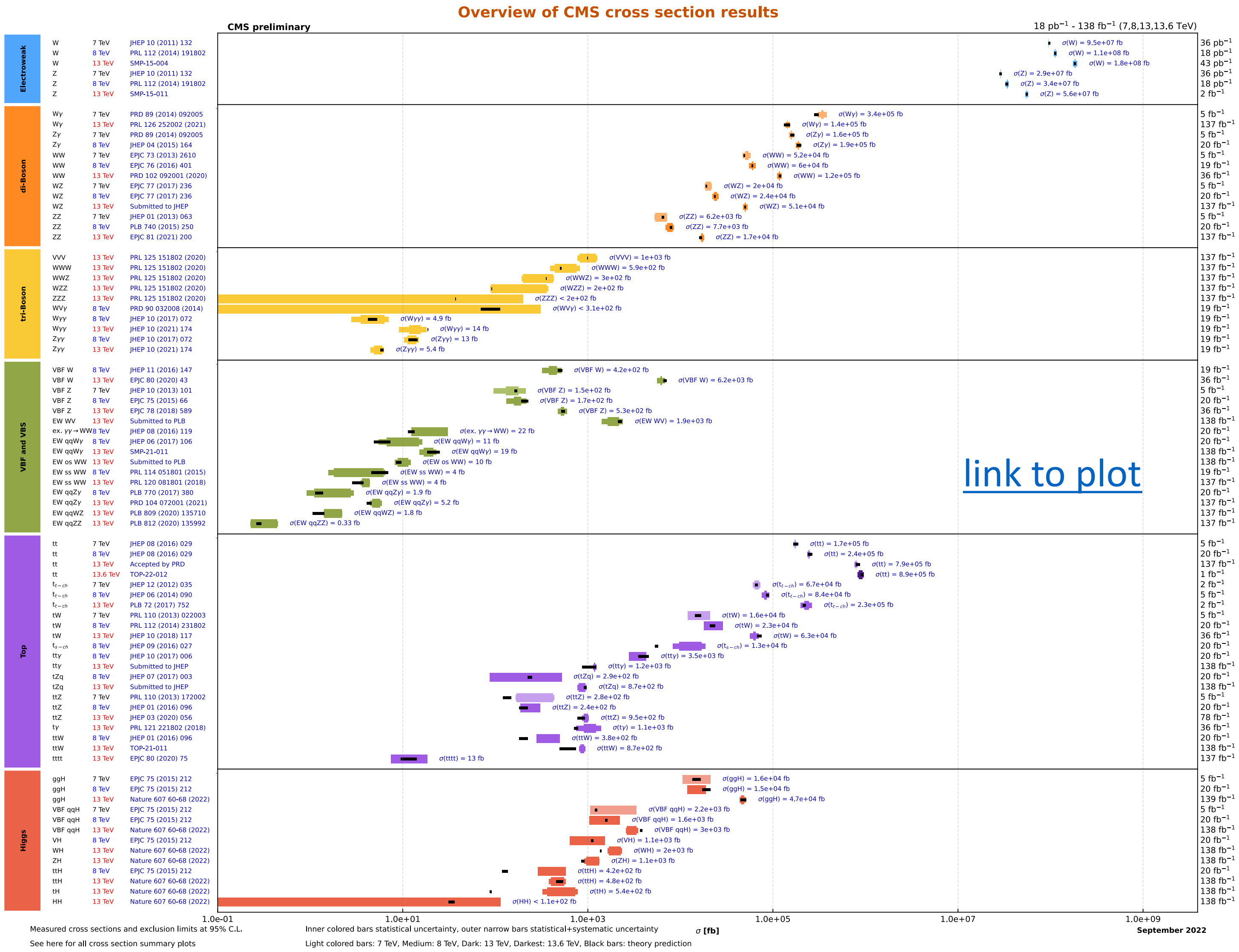
[1] University of Kansas

Where we stand

Precision measurements spanning over 9 orders of magnitude and different kinds of processes



link to plot

Events at CMS in Run 2 ($\sim$ 137 fb^{-1})

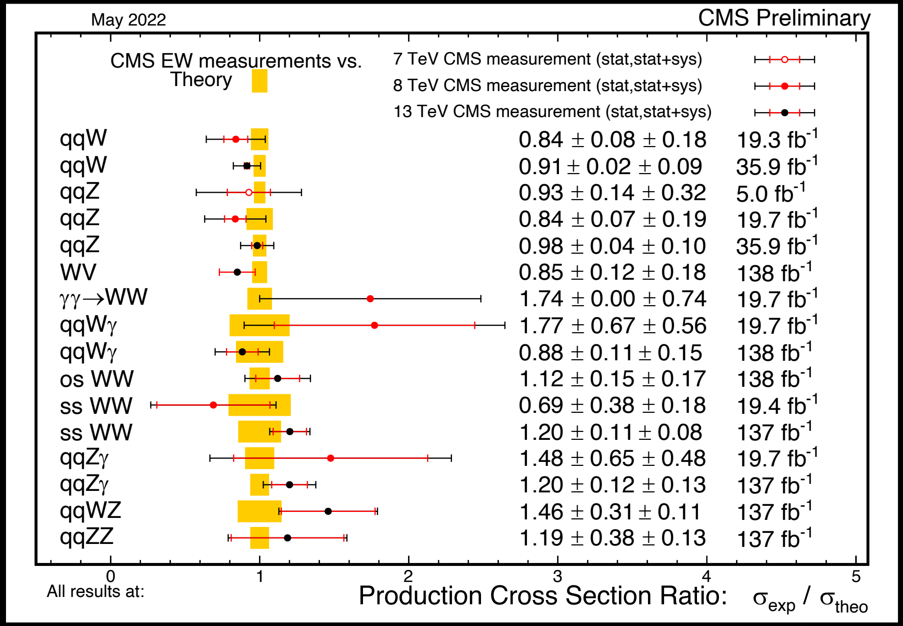
- W bosons 27000×10^6
- Z bosons 8000×10^6
- t quarks 130×10^6
- H bosons 8×10^6

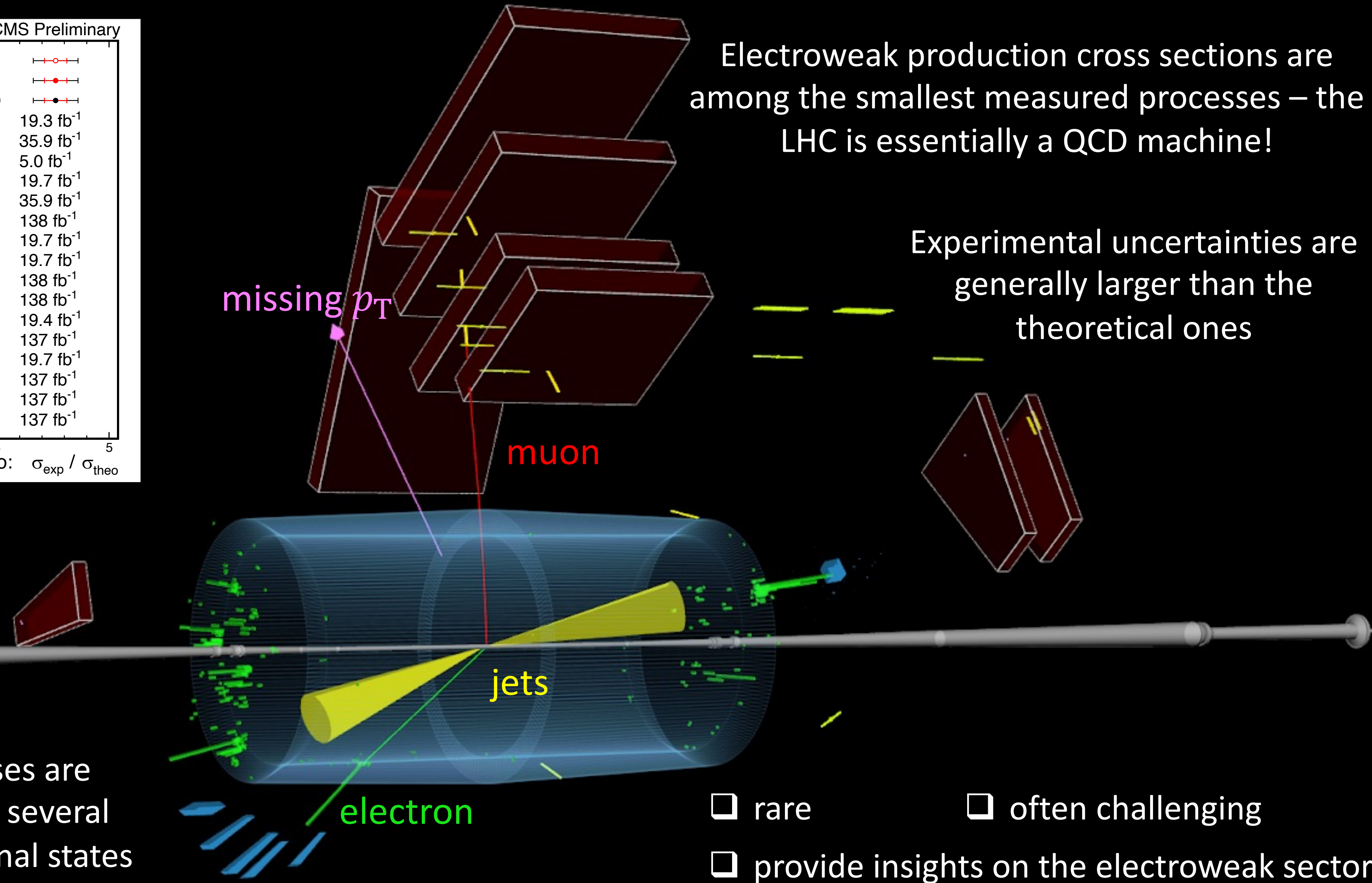
Will show interesting results published (or made public) in the last few months.

They all make use of Run 2 data.

As you can see on the left, we have started to add new points with Run 3 data!

The rare





Electroweak production cross sections are among the smallest measured processes – the LHC is essentially a QCD machine!

Experimental uncertainties are generally larger than the theoretical ones

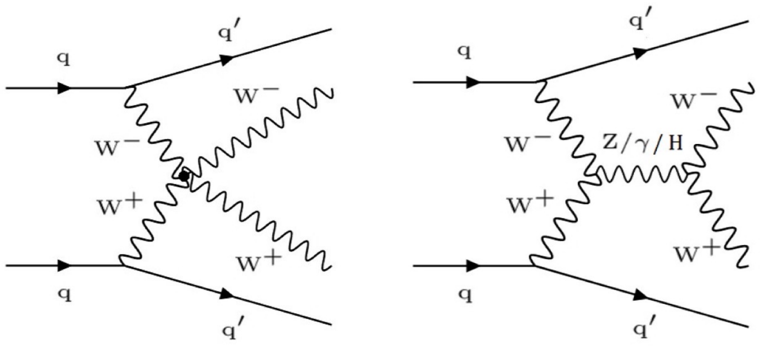
Vector boson scattering processes are extensively studied at the LHC, in several flavors of production modes and final states

- ❑ rare
- ❑ often challenging
- ❑ provide insights on the electroweak sector

Observation of W^+W^- VBS

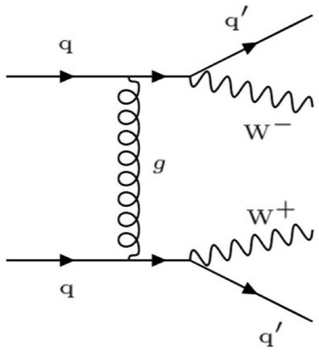
CMS-SMP-21-001

Higgs boson's role in adding diagrams that cancel divergences in theoretical calculations of VBS processes makes them a great probe of the Higgs sector



Electroweak production in OS final state

- Sensitive to potential new physics phenomena affecting H coupling to W
- Important for precisely determining several dimension-6 operators
  - Less sensitive wrt SS because of higher background (mainly from $t\bar{t}$)



QCD-induced production

- Irreducible background for the electroweak production measurement
- Has different kinematic properties wrt electroweak production

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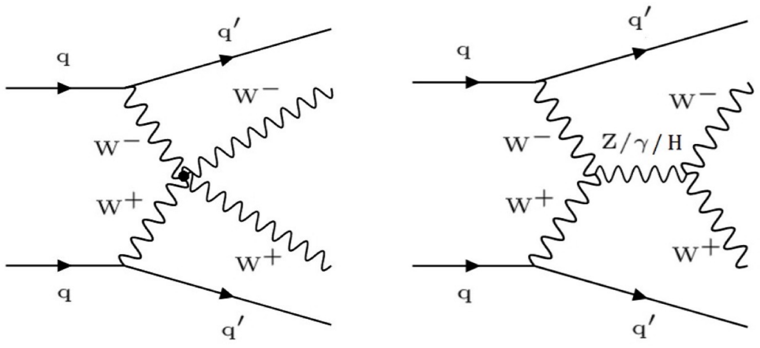

Electroweak production in OS final state

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WW VBS signature:

- Two jets at forward/backward rapidities
- Jets have large m_{jj}, $\Delta\eta_{\mathrm{jj}}$, suppressed hadronic activity in between
- Large $p_{\mathrm{T}}^{\mathrm{miss}}$ from neutrinos
- Final states: $\mathrm{e}^+\mathrm{e}^-, \mu^+\mu^-, \mathrm{e}^\pm\mu^\mp$ (including $\tau \rightarrow \ell\nu\bar{\nu}$)

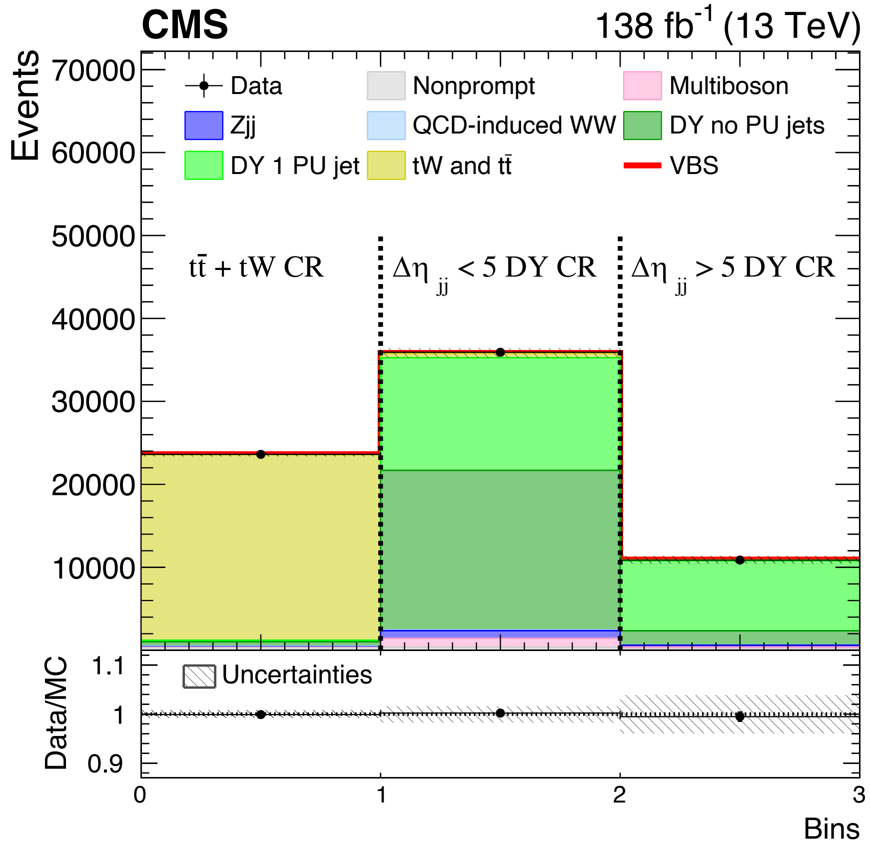
More sensitive due to lower Drell–Yan (+jets) contribution

Analysis strategy

CMS-SMP-21-001

Normalization of the major backgrounds measured by simultaneous fit to data, using dedicated control regions

ee, $\mu\mu$ channels



$t\bar{t}$ and tW → dominating backgrounds

DY background
- ≥ 1 jet from PU → CR with $|\Delta\eta_{jj}| > 5$
- jets from initial-state QCD radiation → CR with $|\Delta\eta_{jj}| < 5$

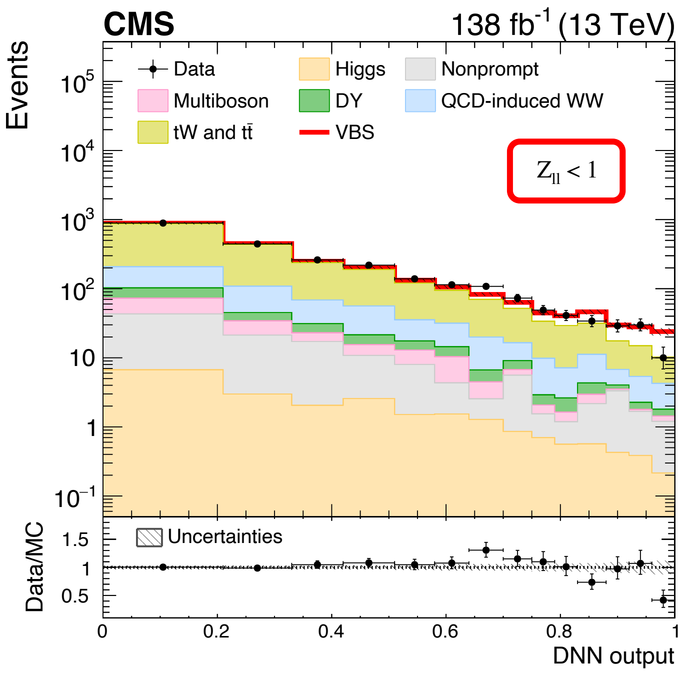
Analysis strategy

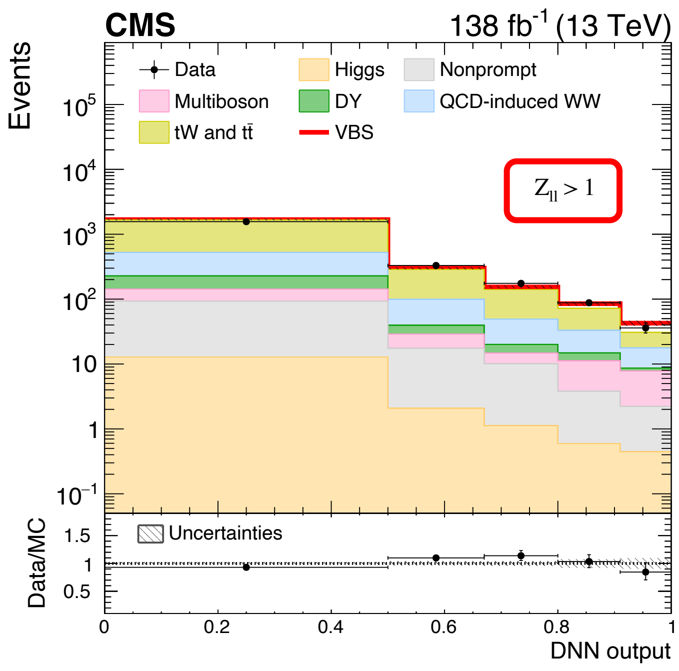
CMS-SMP-21-001

Normalization of the major backgrounds measured by simultaneous fit to data, using dedicated control regions

Deep neural network machine learning algorithm trained to identify signal-like events

$e\mu$ channel





Signal-enriched category

$t\bar{t}$ and tW → dominating backgrounds

DY → relatively negligible

QCD-induced WW → not negligible

Two separate DNNs for high ($Z_{\ell\ell} > 1$) and low ($Z_{\ell\ell} < 1$) values of Zeppenfeld variable

$$Z_\ell = \eta_\ell - \frac{1}{2}(\eta_{j1} + \eta_{j2}) \rightarrow Z_{\ell\ell} = \frac{1}{2}|Z_{\ell 1} + Z_{\ell 2}|$$

Centrality wrt the VBS jets

Analysis strategy

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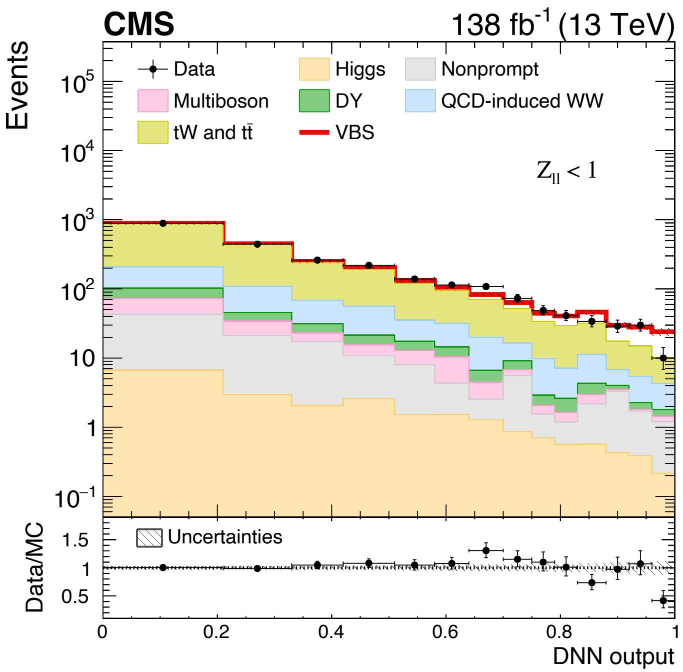
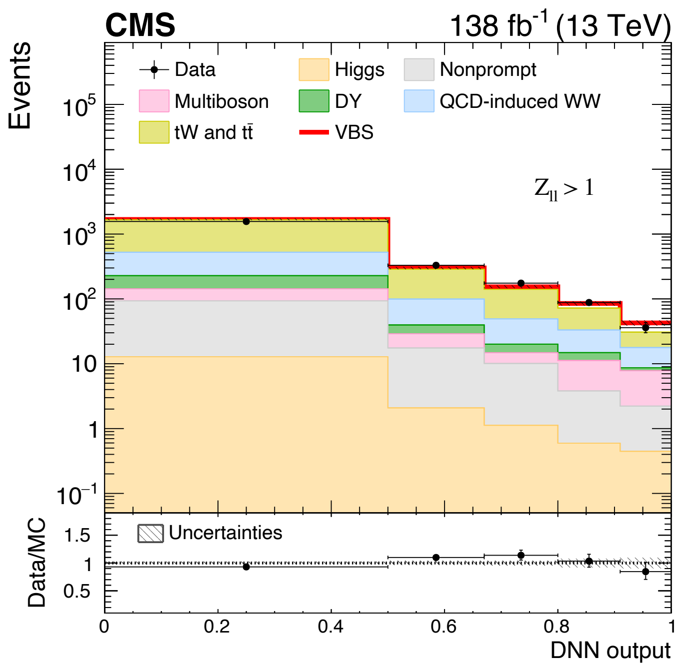
Observed (expected) statistical significance 5.6σ (5.2σ)





… and W^+W^- VBS cross section measured in two fiducial regions, by simultaneously fitting the DNN outputs and a several distributions of discriminating variables for ee and $\mu\mu$

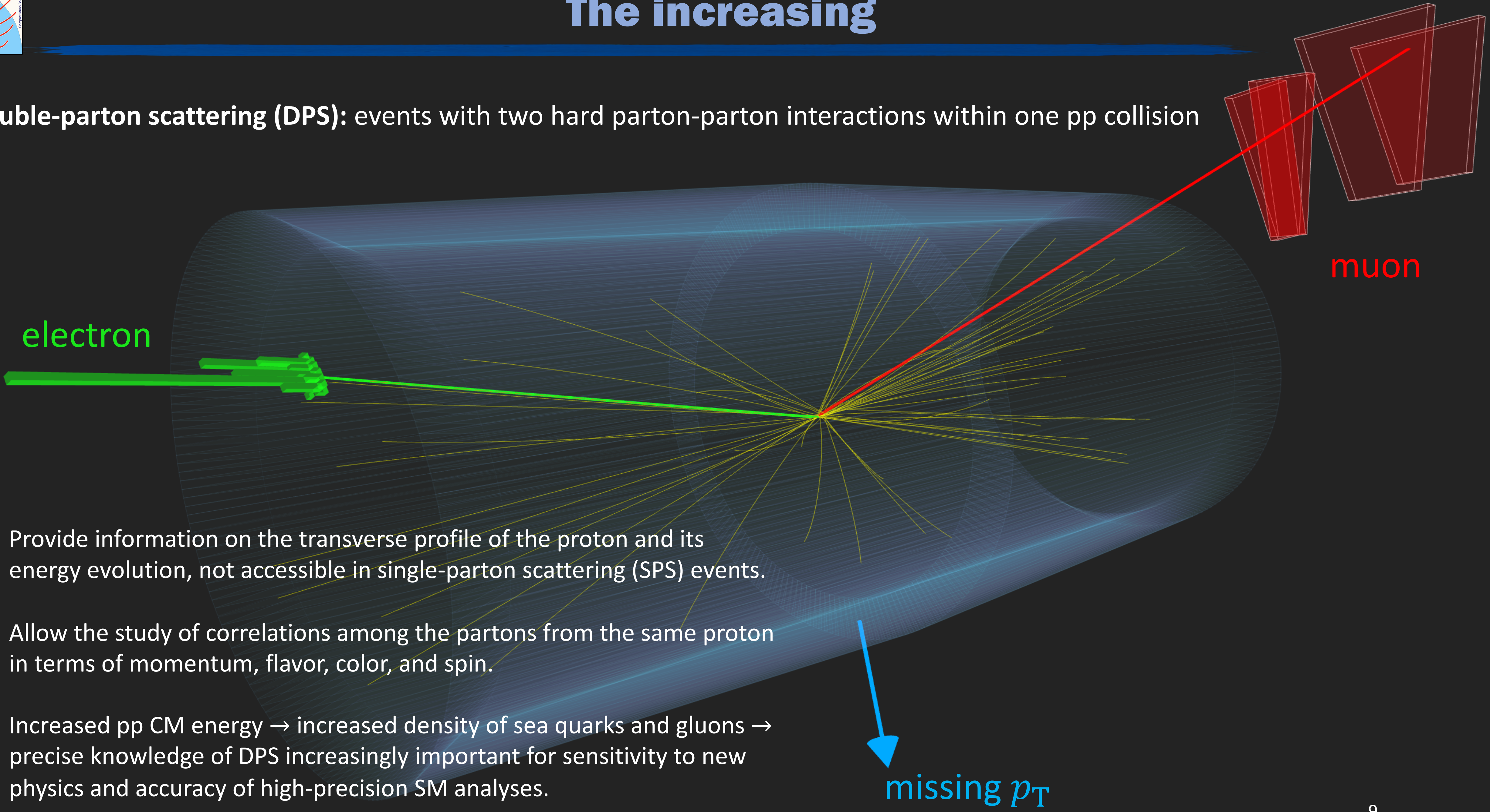
SR-like phase space:

Measurement: 10.2 ± 2.0 fb

Prediction at LO: 9.1 ± 0.6 fb

The increasing

Double-parton scattering (DPS): events with two hard parton-parton interactions within one pp collision

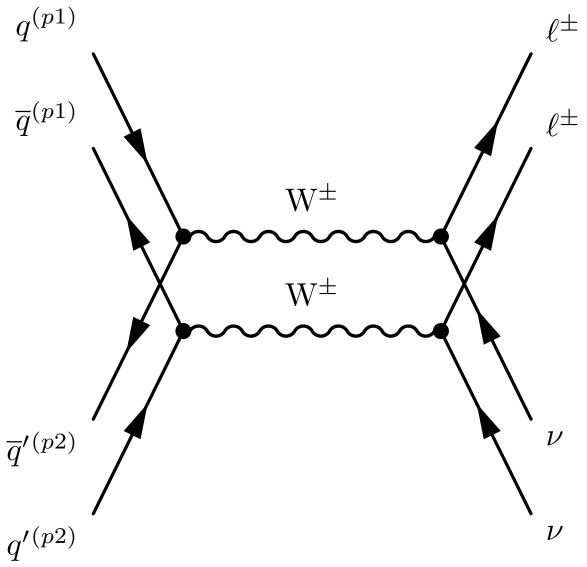


- ❑ Provide information on the transverse profile of the proton and its energy evolution, not accessible in single-parton scattering (SPS) events.
- ❑ Allow the study of correlations among the partons from the same proton in terms of momentum, flavor, color, and spin.
- ❑ Increased pp CM energy → increased density of sea quarks and gluons → precise knowledge of DPS increasingly important for sensitivity to new physics and accuracy of high-precision SM analyses.

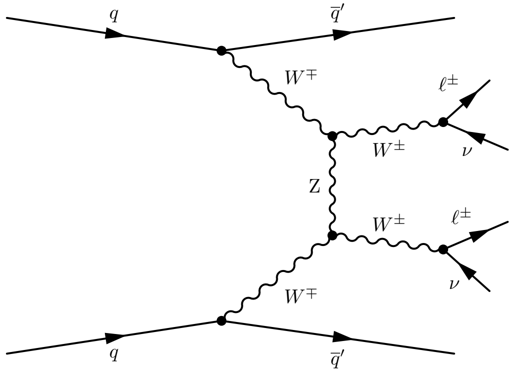
Observation of WW production from DPS

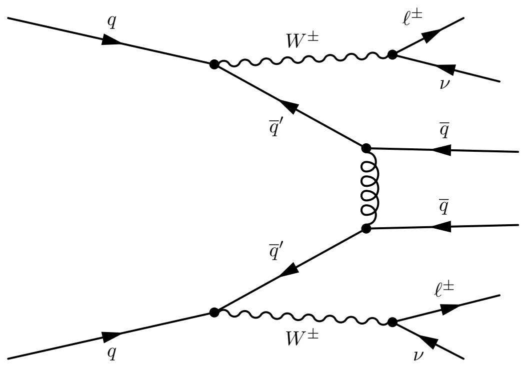
CMS-SMP-21-013

Simplest theoretical model: $\sigma_{AB}^{DPS} = \frac{n}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$



σ_A, σ_B = single-parton scattering (SPS) cross sections





n = 1 if A and B are the same process, n = 2 otherwise

σ_{eff} → proportional to average squared transverse distance between interacting partons. Measured at hadron colliders with rather large uncertainties

DPS $W^{\pm} W^{\pm} \rightarrow \ell^{\pm}\nu\, \ell^{\pm}\nu$ is very promising:

- SPS $W^{\pm} W^{\pm}$ suppressed at matrix element level
- Absence of jets in DPS $W^{\pm} W^{\pm}$
- “Clean” final state in the detector, easy to trigger on

Event selection

CMS-SMP-21-013

Dilepton final states considered (including leptonic τ decays): $\mu^{\pm}\mu^{\pm}$ $e^{\pm}\mu^{\pm}$ ~~$e^{\pm}e^{\pm}$~~ larger charge misID

Trigger

- A combination of dilepton and single-lepton triggers is used to increase the efficiency

Signal region selection

- Exactly two leptons of the same charge, with $p_{\mathrm{T}} > 25\ (20)\ \mathrm{GeV}$ for the leading (sub-leading) one
- Leptons must come from same primary vertex of the pp collision
- $p_{\mathrm{T}}^{\mathrm{miss}} > 15\ \mathrm{GeV}$ and $m_{\ell\ell} > 12\ \mathrm{GeV}$
- At most one jet with $p_{\mathrm{T}} > 30\ \mathrm{GeV}$ and veto events containing b-jets with $p_{\mathrm{T}} > 25\ \mathrm{GeV}$

BDT selection

- Two MVA classifiers trained to separate signal from **WZ production** and **processes with "non-prompt" leptons (W + jets, QCD multijet…)**

Similar lepton p_{T} spectra, but the bosons share a Lorentz boost along the z-axis

Very large cross section wrt the signal, but also larger kinematic differences

EPJC 80, 41 (2020)

Event classification and fit

CMS-SMP-21-013

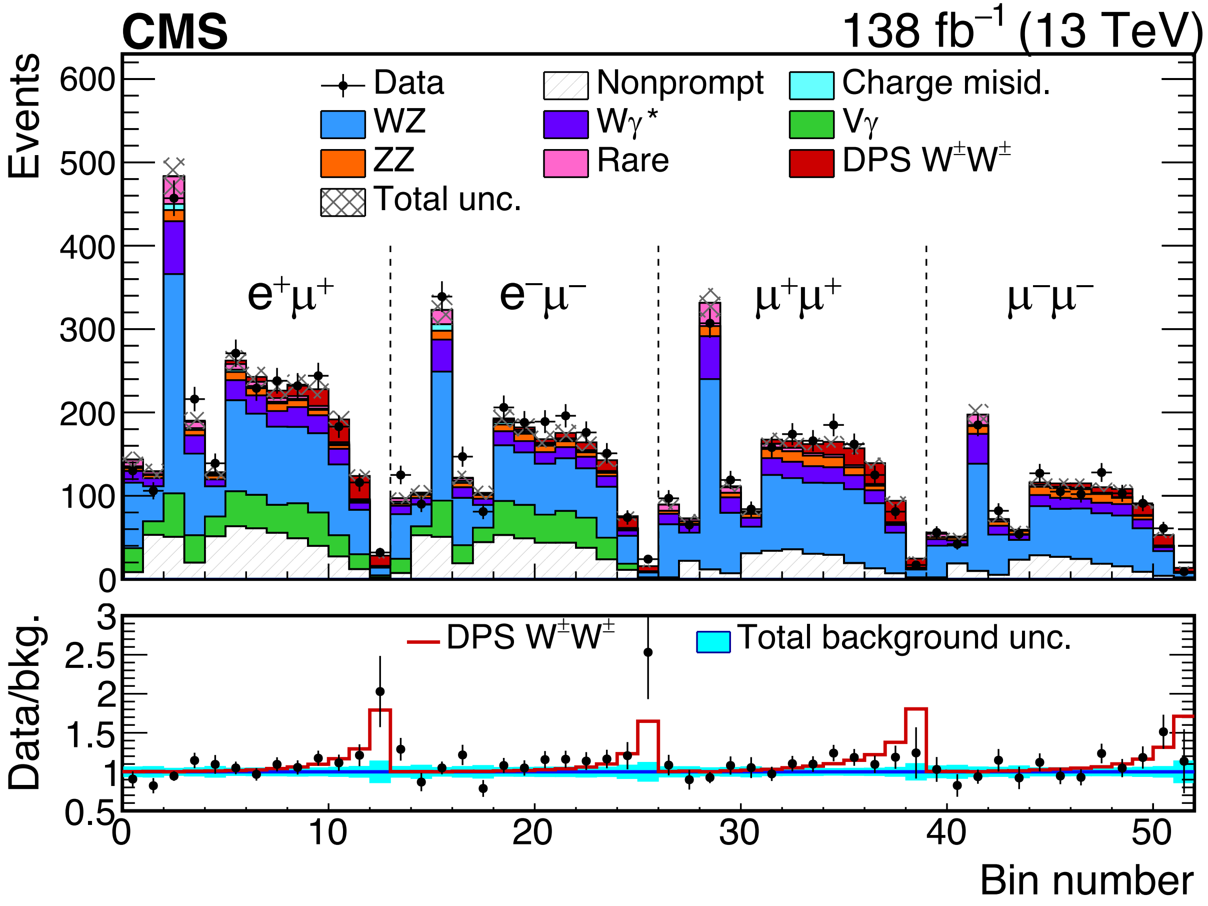
Background and signal processes are combined in two separate flavor ($e\mu$ and $\mu\mu$) and charge ($\ell^+\ell^+$ and $\ell^-\ell^-$) configurations

The two MVA classifiers are mapped into a 2D plane in both discriminants, further divided in 13 contiguous regions on which the fit is performed → optimization of expected signal significance

A ML fit is performed simultaneously on the four independent distributions of the final BDT classifier

Observed statistical significance is 6.2σ above bkg-only hypothesis

First observation!



Results

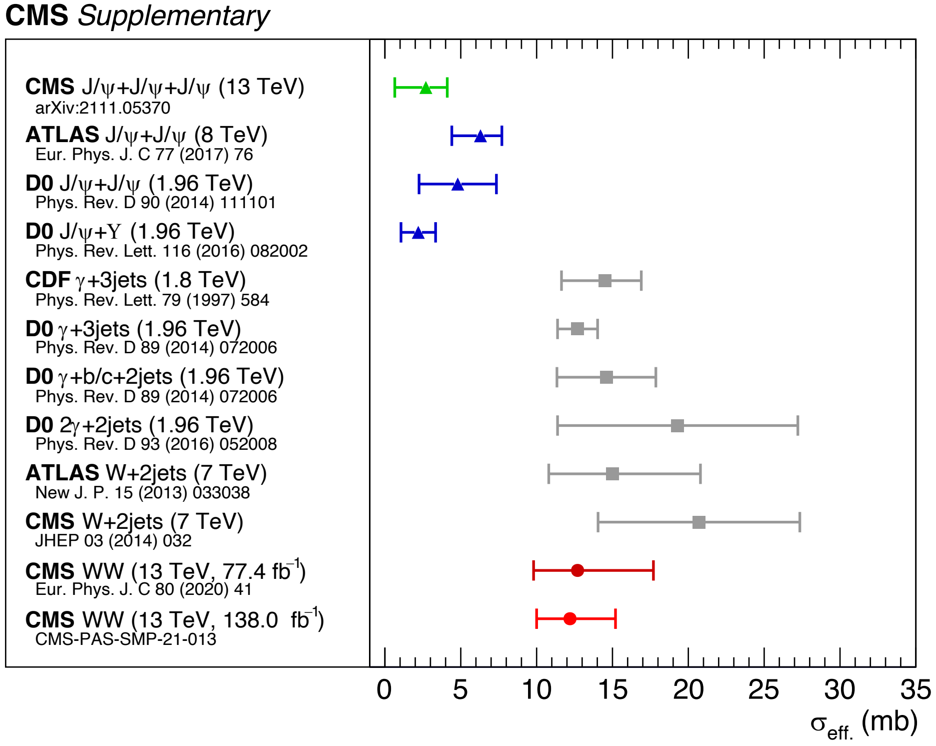
CMS-SMP-21-013

$$\sigma_{\mathrm{DPS}}^{\mathrm{W^\pm W^\pm}} = 80.7 \pm 11.2(\mathrm{stat})^{+9.5}_{-8.6}(\mathrm{syst}) \pm 12.1(\mathrm{model})\ \mathrm{fb}$$

Difference in cross sections obtained in the experimental acceptance region with the PYTHIA and HERWIG simulations

$$\textbf{Fiducial}\ \sigma_{\mathrm{DPS}}^{\mathrm{W^\pm W^\pm}} = 6.28 \pm 0.81(\mathrm{stat}) \pm 0.69(\mathrm{syst}) \pm 0.37(\mathrm{model})\ \mathrm{fb}$$

Fiducial volume defined using two generator-level SS "dressed" leptons (+photon momenta in $\Delta R(\ell,\gamma) < 0.1$) from W boson, passing SR kinematic selection



$$\sigma_{\mathrm{eff}} = 12.2^{+2.9}_{-2.2}\ \mathrm{mb}$$

Extracted using NNLO prediction for single $\mathrm{W}^\pm$ production cross section and leptonic branching fraction, and measured $\sigma_{\mathrm{DPS}}^{\mathrm{W^\pm W^\pm}}$

Consistent with previous measurements from final states with vector bosons

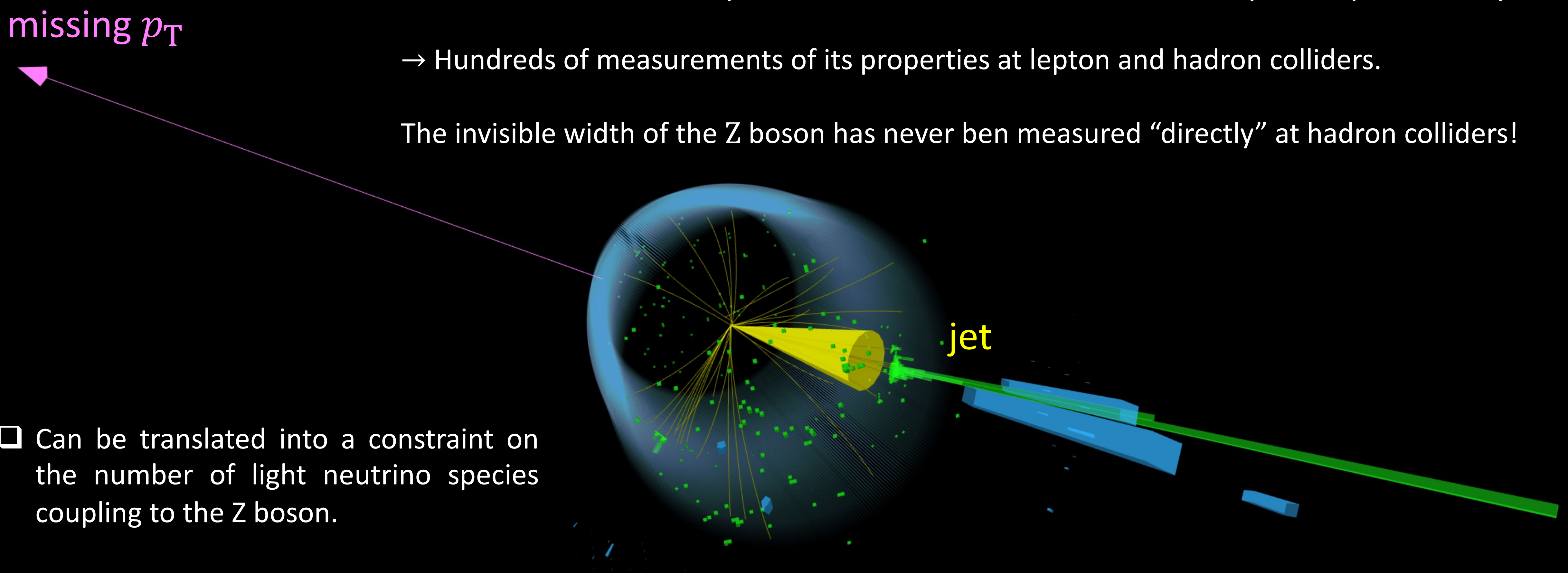
See Sanjay's talk for a comparison with σ_{eff} from gluon-initiated processes

The invisible

The Z boson is one of the particles we best understand, theoretically and experimentally

→ Hundreds of measurements of its properties at lepton and hadron colliders.

The invisible width of the Z boson has never ben measured “directly” at hadron colliders!



- ❑ Can be translated into a constraint on the number of light neutrino species coupling to the Z boson.
- ❑ Could reveal beyond-SM contributions from new physics scenarios (potentially different to those which the “indirect” measurement could be sensitive to)

Measuring the $Z \to$ invisible width

CMS-SMP-18-014

Precision measurement of the decay width of the Z boson to "invisible" particles, such as $\nu\bar{\nu}$

Historically, precision measurements of $Z \to$ invisible at LEP:

- **"direct"** → look for ISR photon from e^+e^- and s-channel production of Z ($e^+e^- \to \gamma Z \to \gamma\nu\bar{\nu}$)
- **"indirect"** → measure total Z width by studying Z lineshape. Subtract partial widths of decays with visible final states: $\Gamma_{inv} = \Gamma_{tot} - \Gamma_{vis}$. More precise than "direct" one at LEP

CMS performed the first measurement of the Z invisible width at hadron collider!

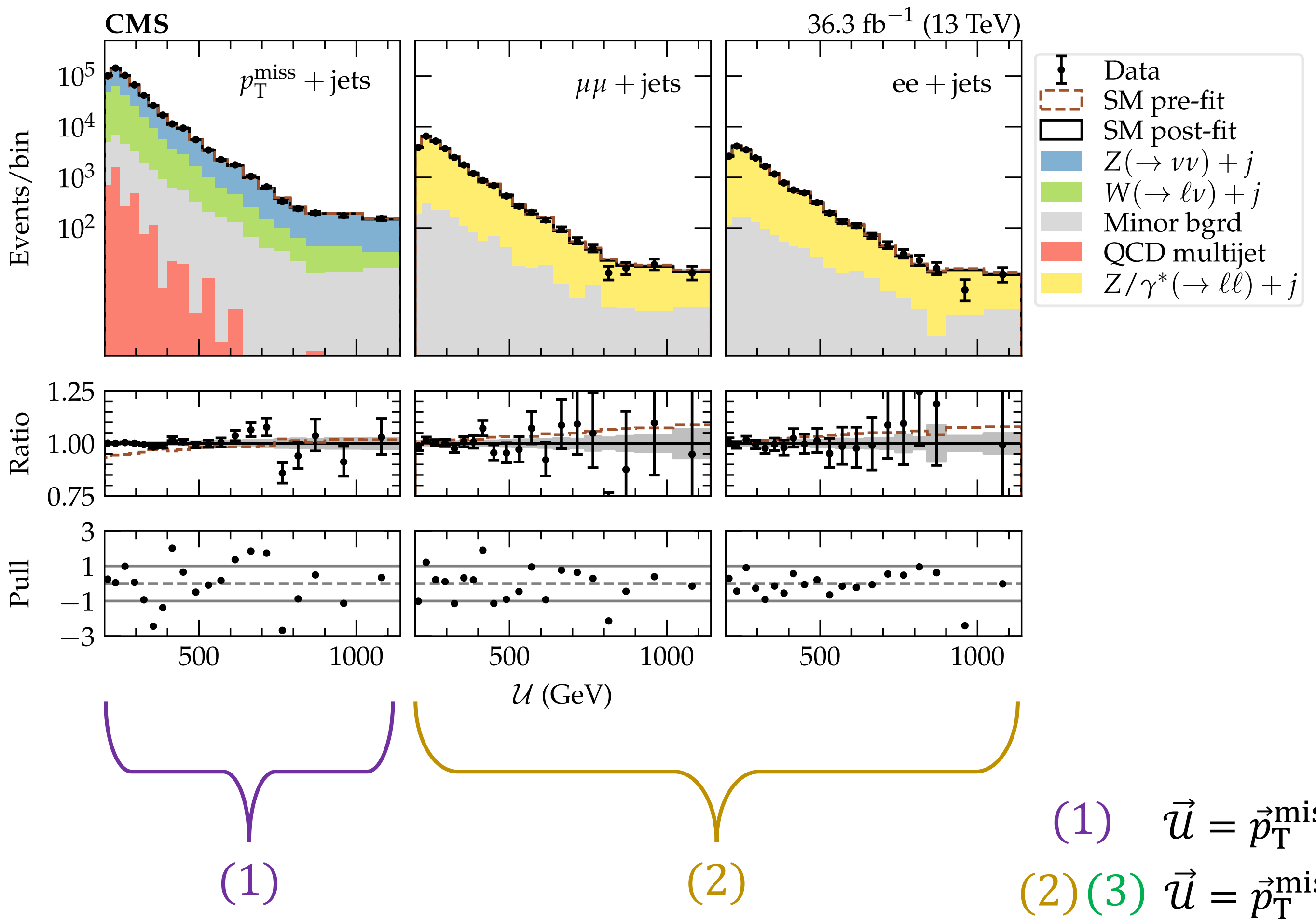
- Direct or indirect? The CMS way to measure it:

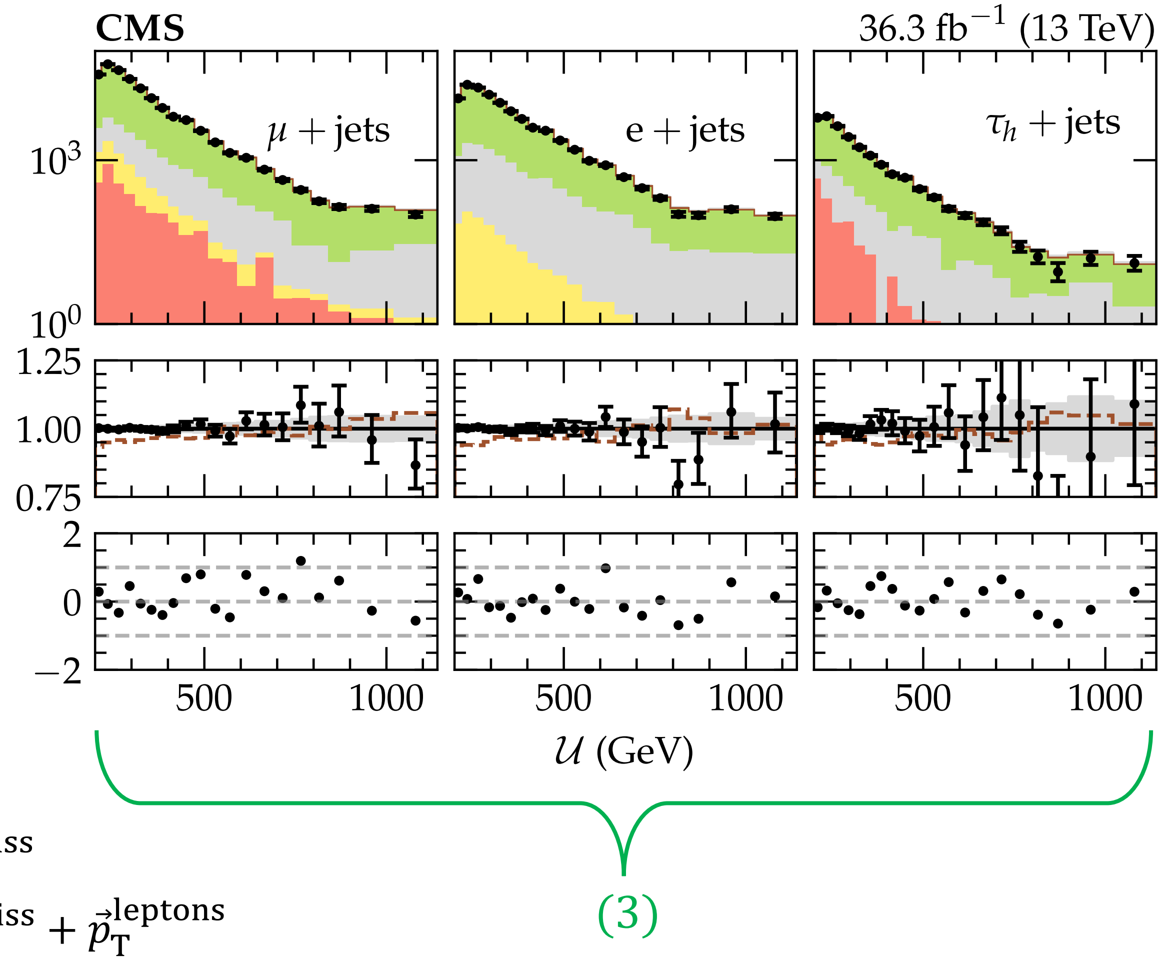
$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z + \text{jets})\mathfrak{B}(Z \to \nu\bar{\nu})}{\sigma(Z + \text{jets})\mathfrak{B}(Z \to \ell\ell)}\Gamma(Z \to \ell\ell) \qquad \ell = e, \mu$$

- Target $Z + $ jets production, with jets from initial state partons to favor a large p_T^Z
- Exploit similar kinematics of Z bosons decaying into $\ell^+\ell^-$ and $\nu\bar{\nu}$

Three analysis regions

CMS-SMP-18-014





(1) $\vec{\mathcal{U}} = \vec{p}_T^{miss}$

(2)(3) $\vec{\mathcal{U}} = \vec{p}_T^{miss} + \vec{p}_T^{leptons}$

(1) p_T^{miss} + jets ⟹ $Z \to \nu\bar{\nu}$

(2) $\ell\ell$ + jets ⟹ $Z/\gamma^* \to \ell\ell$

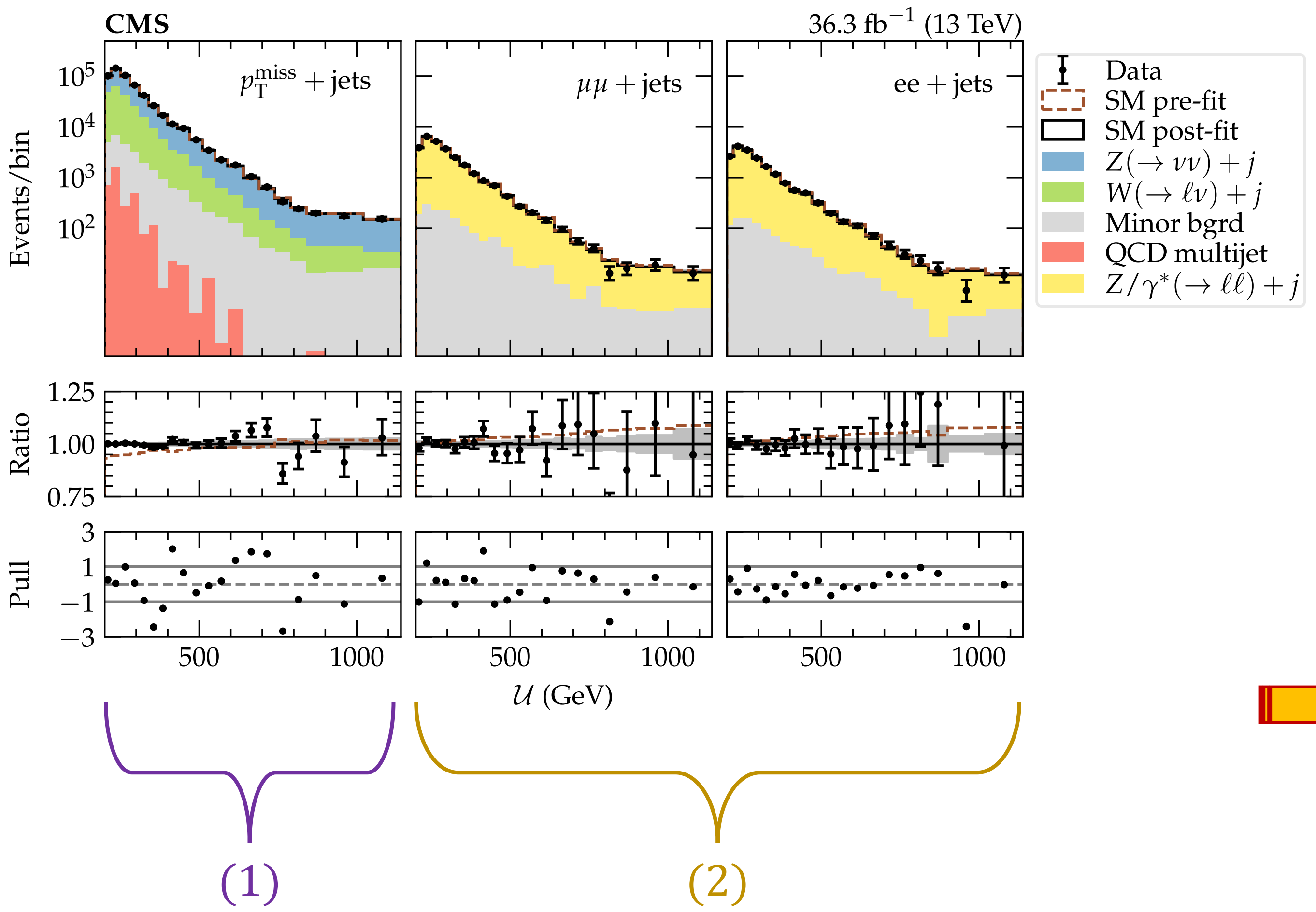
(3) ℓ + jets ⟹ $W \to \ell\nu$ (here $\ell = e, \mu, \tau_h$)

Trigger

- $p_T^{miss} > 90$ GeV && $H_T > 90$ GeV
- e > 27 GeV for ee + jets and e + jets

The technique

CMS-SMP-18-014



$$\Gamma(Z \rightarrow \nu\bar{\nu}) = \frac{\sigma(Z + \text{jets})\mathfrak{B}(Z \rightarrow \nu\bar{\nu})}{\sigma(Z + \text{jets})\mathfrak{B}(Z \rightarrow \ell\ell)} \Gamma(Z \rightarrow \ell\ell)$$

- Simultaneous fit to the tree analysis regions
- ℓ + jets regions are used for estimating the W + jets contribution to (1)
- Extract a scaling parameter $\Gamma(Z \rightarrow \nu\bar{\nu})/\Gamma_{inv}^{MC}$
- Scale Γ_{inv}^{MC} prediction obtained from simulation
- Assume same $\Gamma(Z \rightarrow \ell\ell)$ in data and simulation

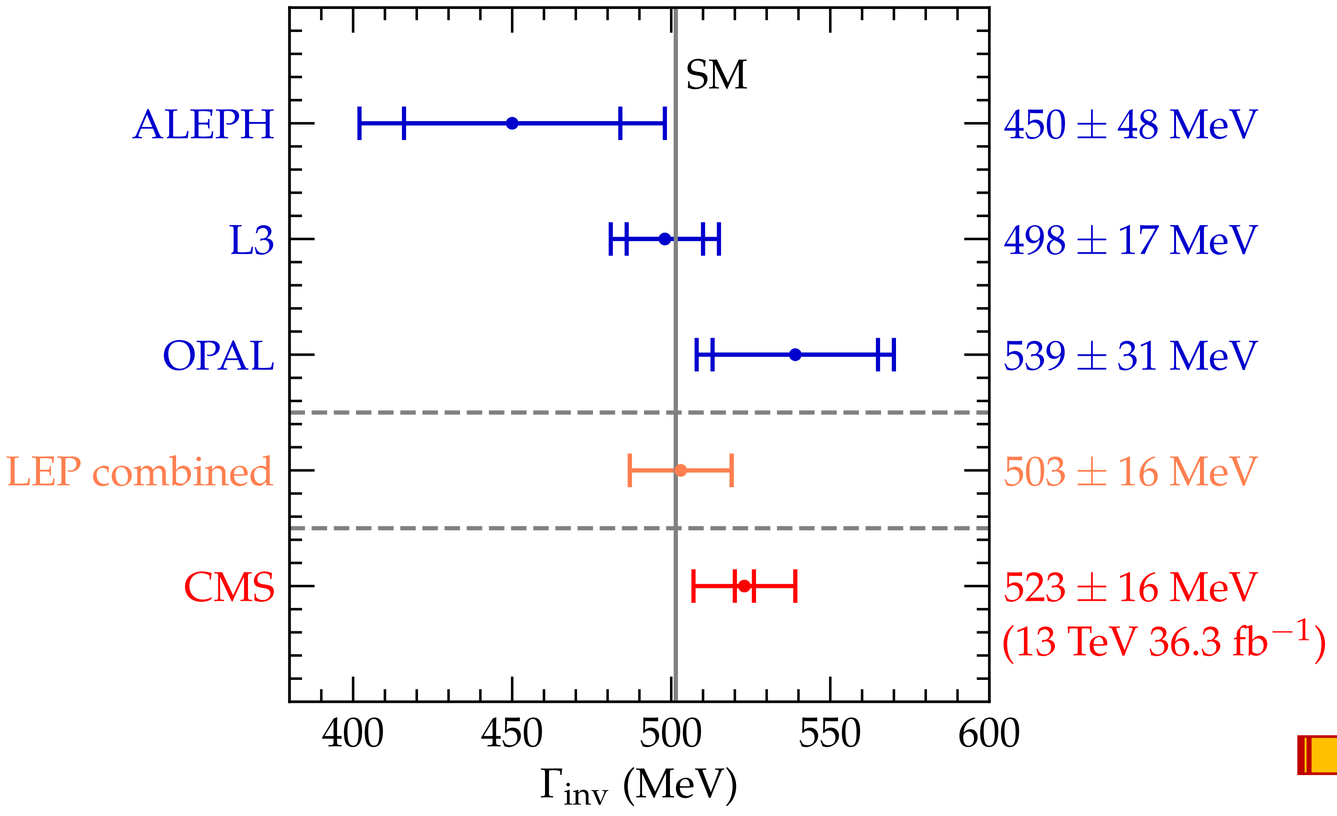
$$\Gamma(Z \rightarrow \nu\bar{\nu}) = 523 \pm 3\ (\text{stat}) \pm 16\ (\text{syst})\ \text{MeV}$$

Main systematics

- Muon and electron ID efficiencies
- Jet energy scale
- Pileup

Comparing with previous results

CMS-SMP-18-014



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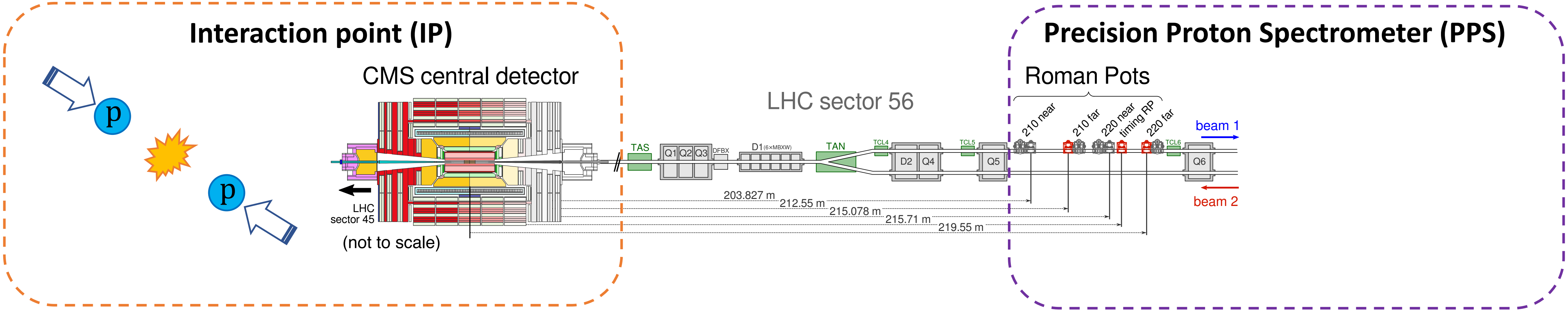
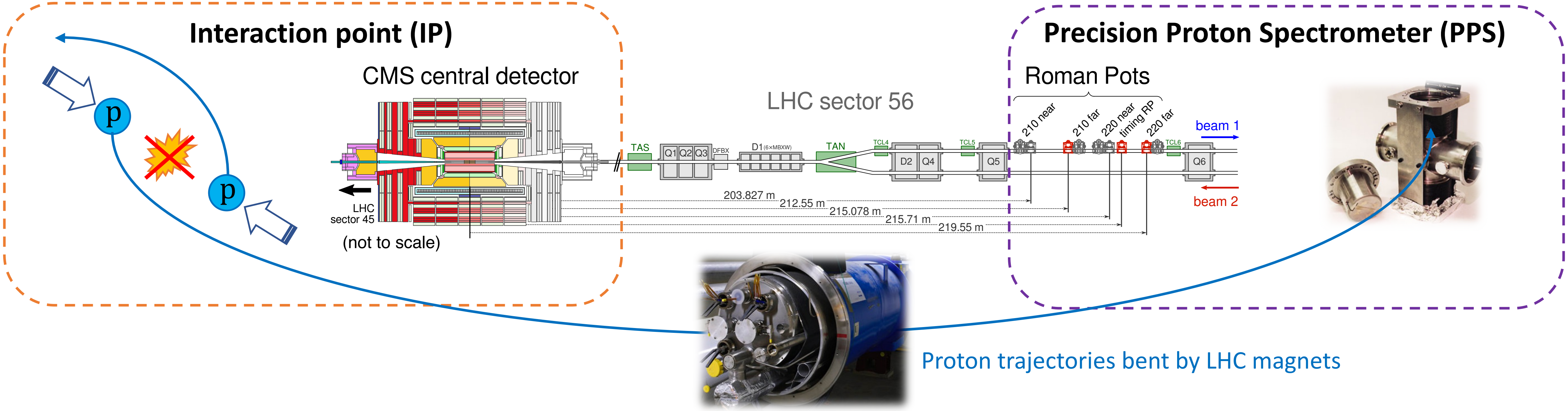
The intact



Interaction point (IP)
CMS central detector
p
p
LHC
sector 45
(not to scale)
LHC sector 56
Precision Proton Spectrometer (PPS)
Roman Pots
210 near
210 far
220 near
timing RP
220 far
beam 1
beam 2
TAS
Q1
Q2
Q3
DFBX
D1 (6×MBXW)
TAN
TCL4
D2
Q4
TCL5
Q5
TCL6
Q6
203.827 m
212.55 m
215.078 m
215.71 m
219.55 m

The intact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210 near
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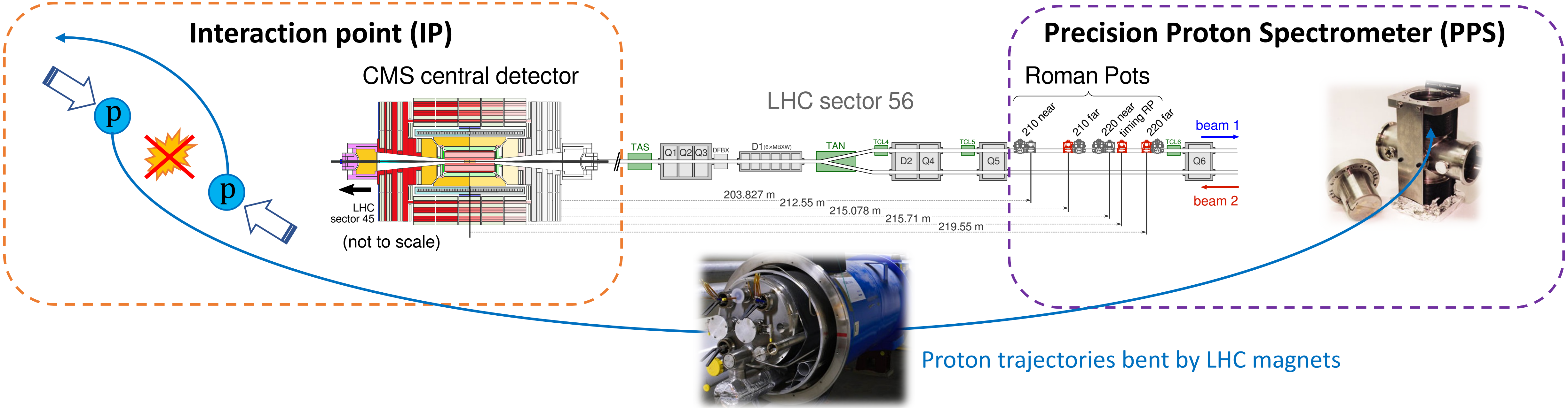
Proton trajectories bent by LHC magnets

The intact



- PPS is a magnetic spectrometer which detects protons that have lost part of their initial momentum in the IP and are bent by the LHC magnets

- Conceived to study $\mathrm{pp} \rightarrow \mathrm{pXp}$ processes: protons do not dissociate and interact via photon or color-singlet exchange to produce system X in central region

- Located $\approx 210\ \mathrm{m}$ from the IP in both directions, it consists of silicon tracking detectors (position, direction, momentum) and diamond-based timing counters (proton longitudinal position, pileup suppression) → measurement of mass and momentum of the centrally produced system, irrespectively of its decay mode

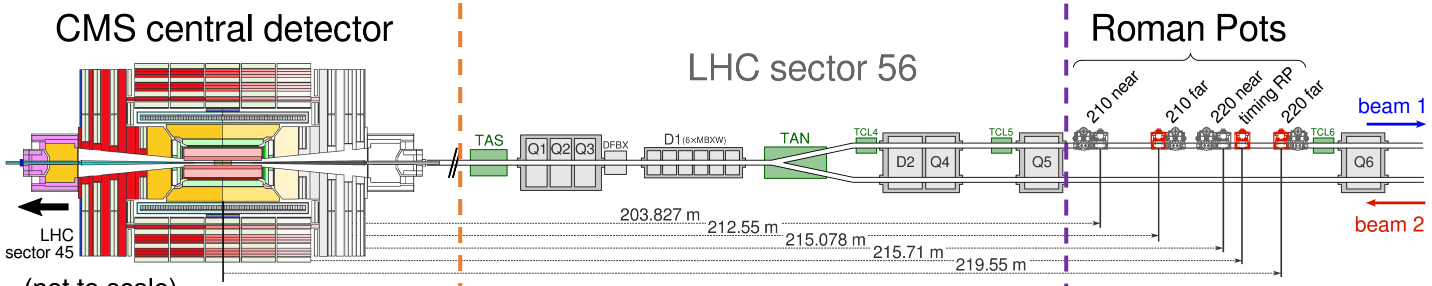
Search for exclusive $\gamma\gamma \rightarrow$ VV production

Interaction point (IP)

Reconstruct the two vector boson decays as boosted and merged jets

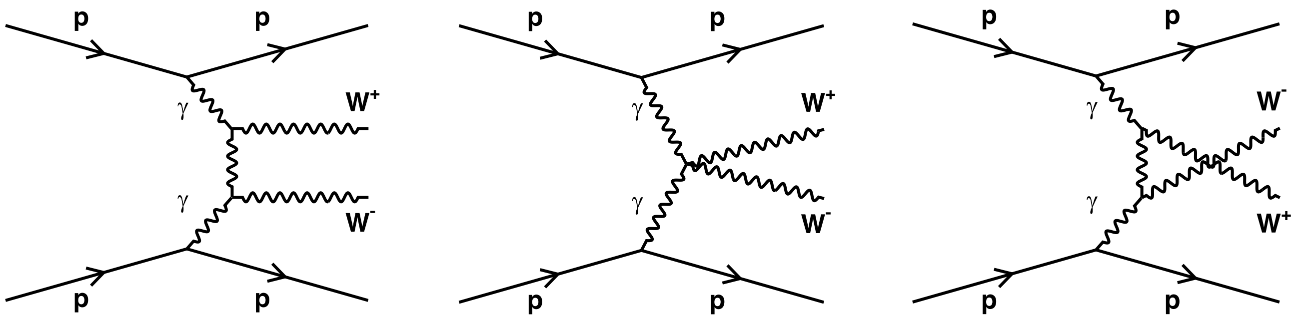
Precision Proton Spectrometer (PPS)

Look for two forward protons ("taggers")



(not to scale)

Look for pp scattering mediated by photons, with exclusive VV production: $\mathbf{pp \rightarrow pVVp}$



Quartic couplings involving two-photon production of charged gauge bosons are allowed at tree level within the SM

Predicted cross section with intact protons at 13 TeV: ≈ 50 fb (WW), ≈ 0.05 fb (ZZ) $\rightarrow$ hardly or no observation at all expected before HL-LHC

Any significant signal over the prediction could indicate BSM physics, especially at high $m(\mathrm{VV})$, where SM cross section is lower!

Protons, jets and their matching

CMS-SMP-21-014

Forward protons

"Multi-Roman pot" algorithm

↓

Combine tracks in each of the two tracking pots per arm of PPS

↓

- Proton scattering angle
- Proton fractional momentum loss $\xi = (p_{\mathrm{nom}} - p)/p_{\mathrm{nom}}$

↓

Sensitive to momentum loss $0.04 < \xi < 0.20$

Protons, jets and their matching

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Forward protons	***Jets***

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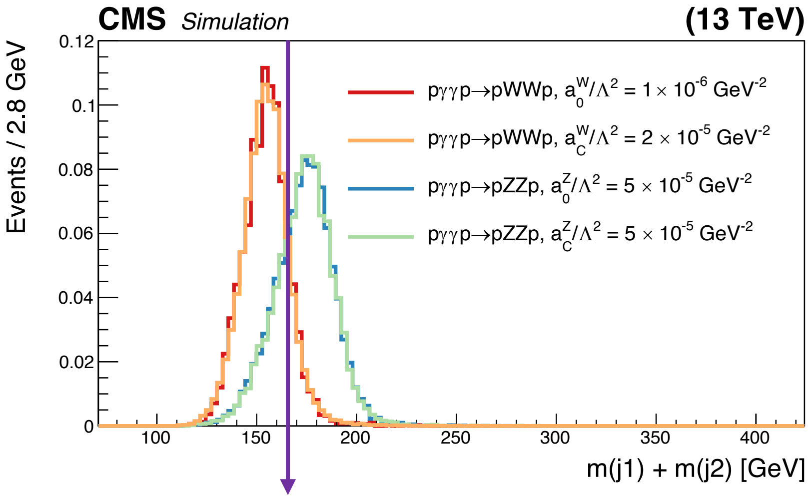
Select good candidates for merged jets from V decay

↓

Use N-subjettiness + pruning algorithm to reduce contribution from soft gluon radiation and pileup



Pruned jet mass used to achieve maximum discrimination of WW vs ZZ

$m(\text{jj}) > 1126$ GeV due to trigger requirements

Protons, jets and their matching

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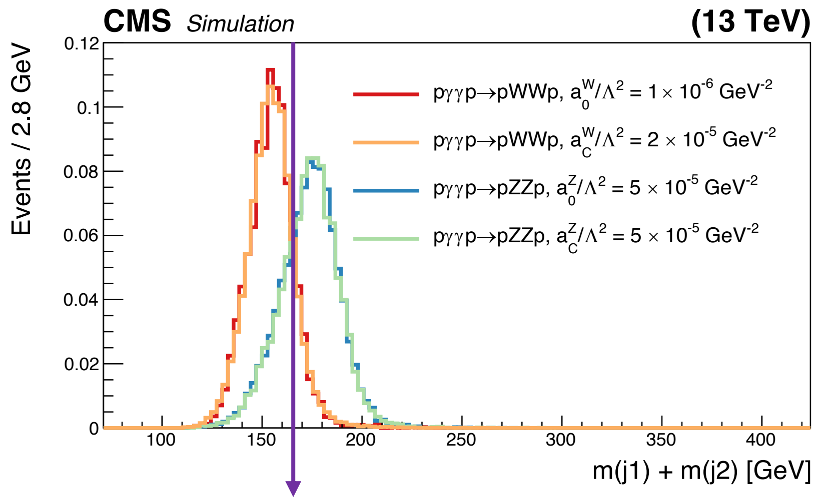

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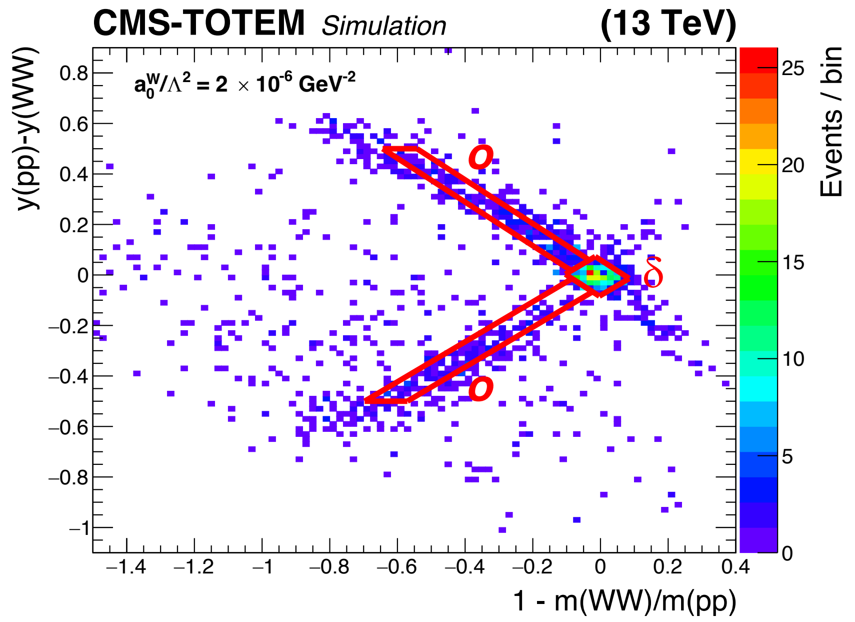
Matching

Two signal regions ($\boldsymbol{\delta}$, $\boldsymbol{o}$) based on invariant mass and rapidity of WW, ZZ and pp

$$m(\text{pp}) = \sqrt{s\,\xi_{\text{p1}}\xi_{\text{p2}}} \qquad y(\text{pp}) = \frac{1}{2}\ln\left(\frac{\xi_{\text{p1}}}{\xi_{\text{p2}}}\right)$$



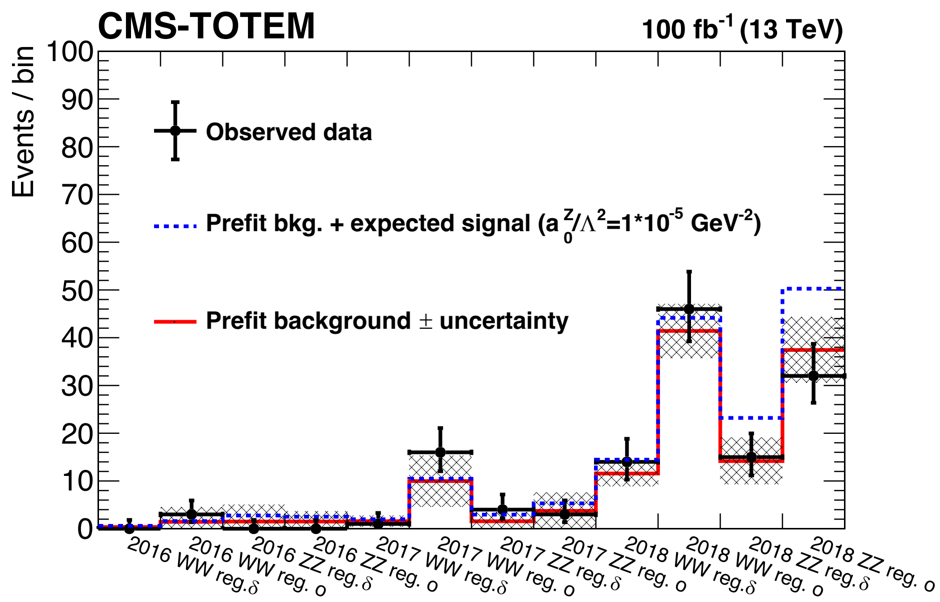
$\boldsymbol{\delta}$ → both protons correctly matched to jets

$\boldsymbol{o}$ → one proton from pileup

Results

CMS-SMP-21-014

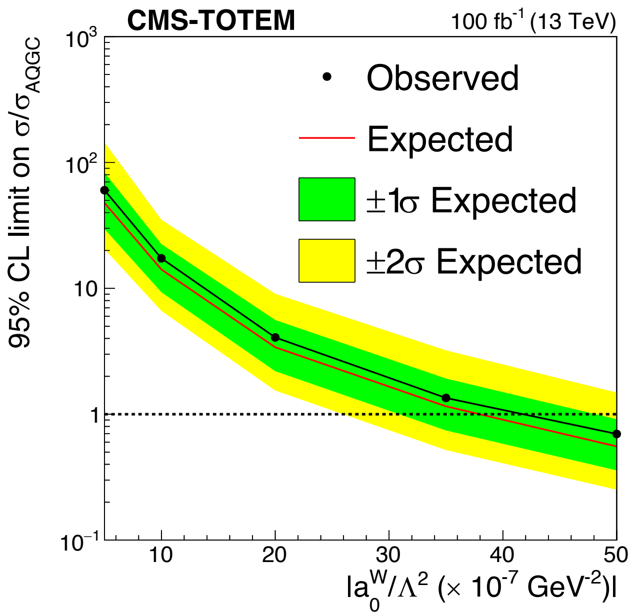
Binned fit to twelve analysis regions



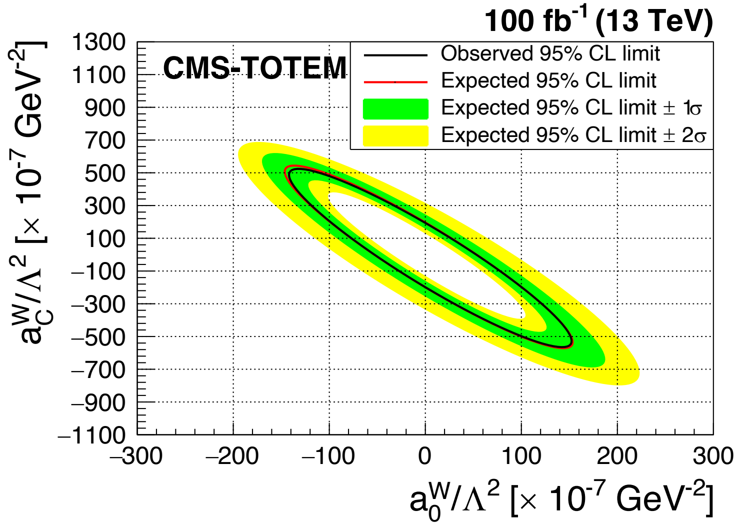
No significant excess

Interpretation in terms of several nonlinear dimension-6 and linear dimension-8 AQGC

Limits on anomalous coupling parameters



≈15–20 times more stringent than those obtained in Run 1 at the LHC for $\gamma\gamma \rightarrow$ WW without proton detection

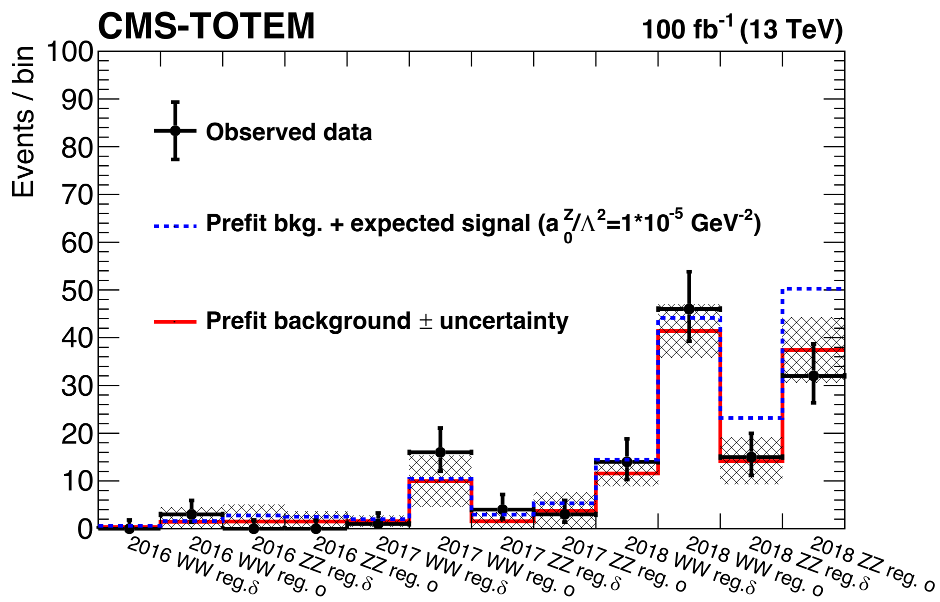


In WW channel, ***clipping*** applied to remove simulated signal above $\gamma\gamma$ interaction energy where predicted cross section becomes unphysically large and violates partial wave unitarity (i.e., for large values of coupling and large mass of diboson system)

Results

CMS-SMP-21-014

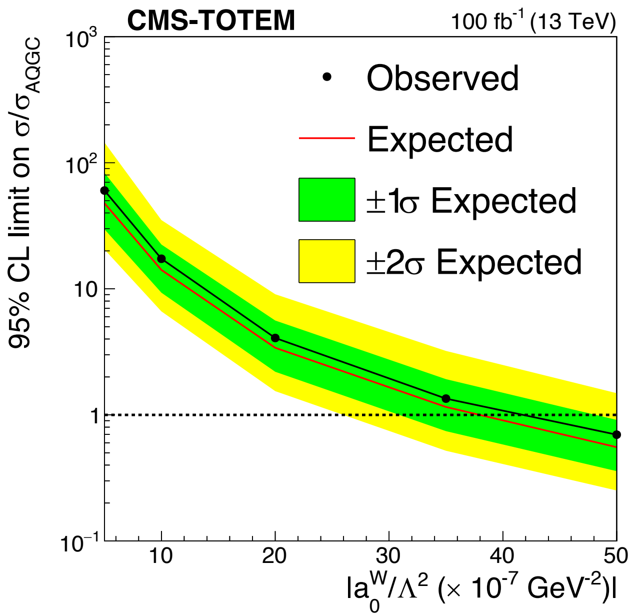
Binned fit to twelve analysis regions

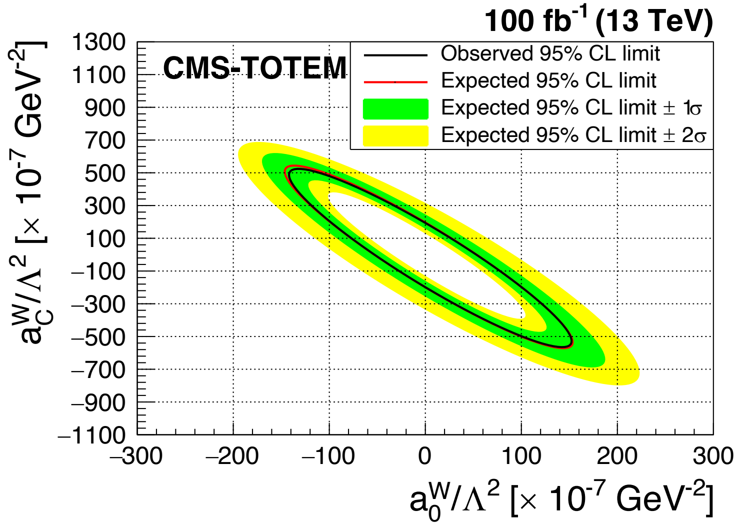


No significant excess

Interpretation in terms of several nonlinear dimension-6 and linear dimension-8 AQGC

Limits on anomalous coupling parameters





Limits on fiducial cross sections…

… for an AQGC-like signal and for $0.04 < \xi < 0.20$, $m(\mathrm{VV}) > 1$ TeV

$$\sigma(\mathrm{pp} \to \mathrm{pWWp}) < 67(53^{+34}_{-19})\ \mathrm{fb}$$
$$\sigma(\mathrm{pp} \to \mathrm{pZZp}) < 43(62^{+33}_{-20})\ \mathrm{fb}$$

95% CL

Summary

Presented some highlights among new standard model analyses at CMS:

- W^+W^- VBS
  - Observed a rare process with disfavored topology using machine learning techniques, interesting probe of electroweak sector

- $W^\pm W^\pm$ DPS
  - Observed for the first time a rare process, which becomes increasingly important as the CoM energy gets higher

- $Z \to \nu\bar{\nu}$
  - Achieved precision comparable with LEP combination for direct measurements

- $pp \to pVVp$
  - Probed the SM using the full capabilities of the CMS detector in events with no hard scattering, with potential to observe BSM effects

For more Run 2 results (and for a first glimpse of Run 3 too):

- CMS public webpage