Recent CMS experimental results

Qun Wang
On behalf of the CMS collaboration

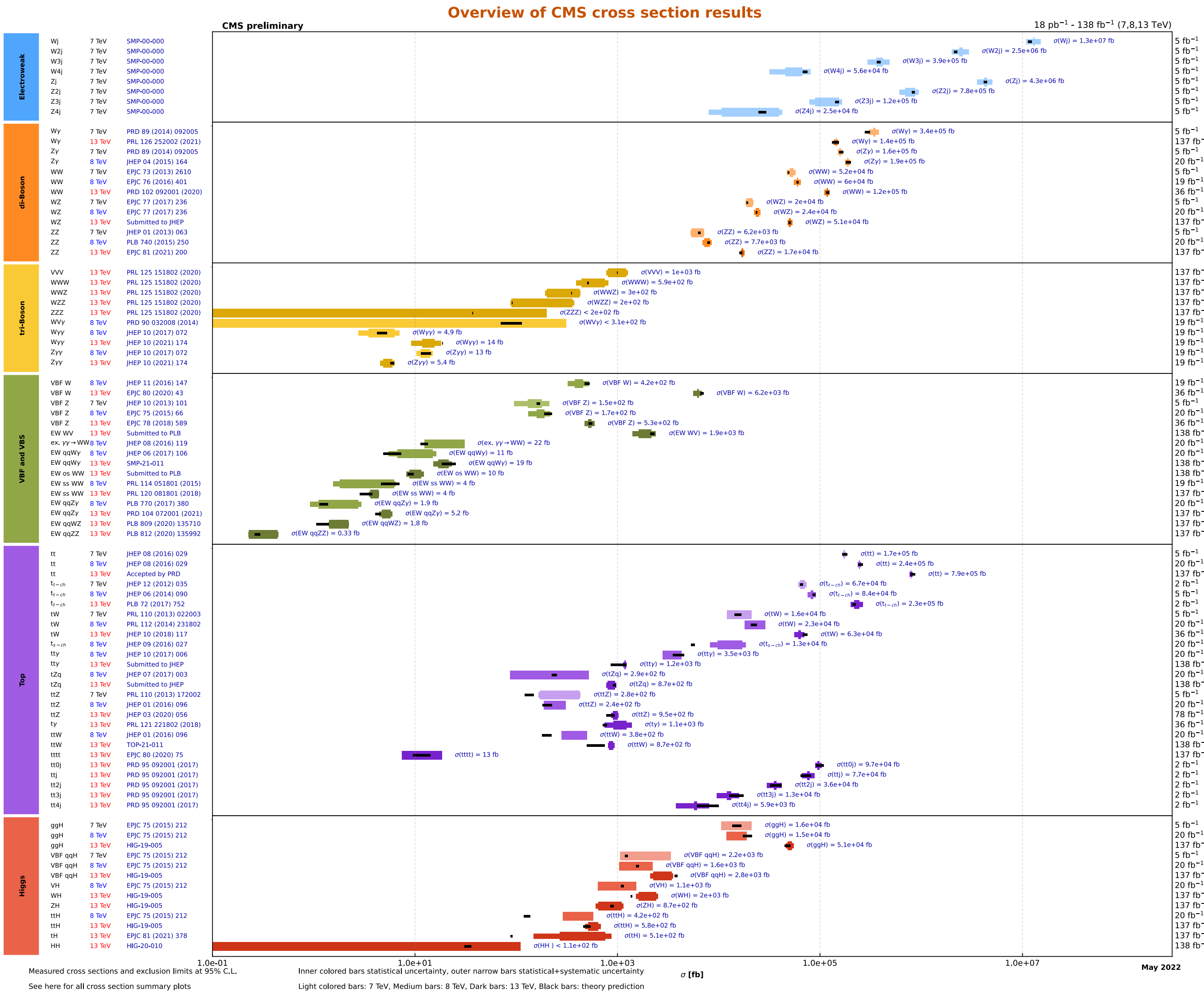
Lecce, 29 June 2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Outline

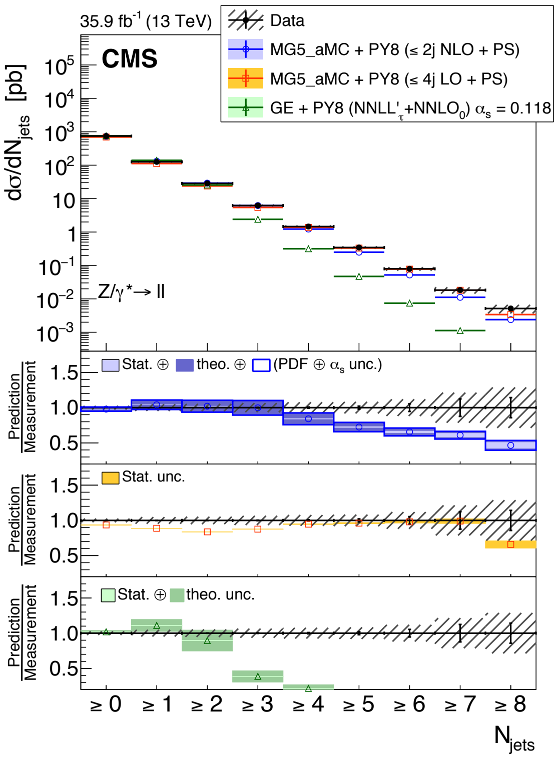
- This talk covers some highlights and recent results.

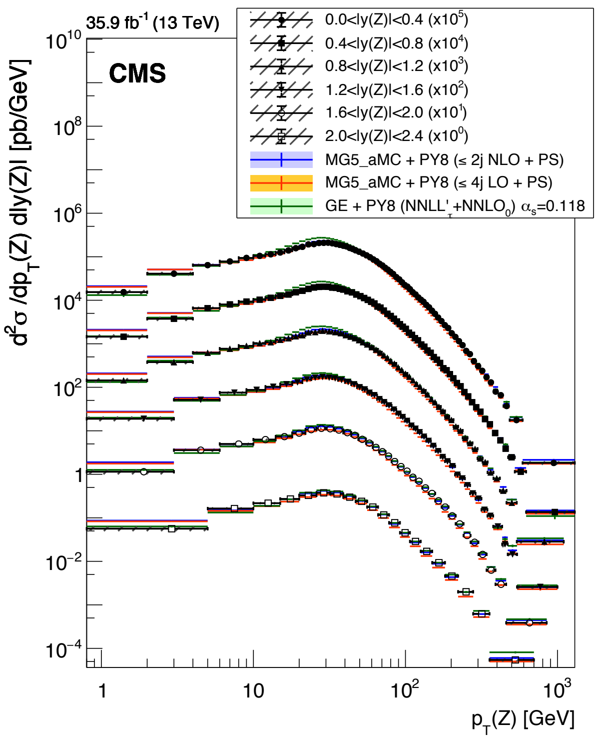


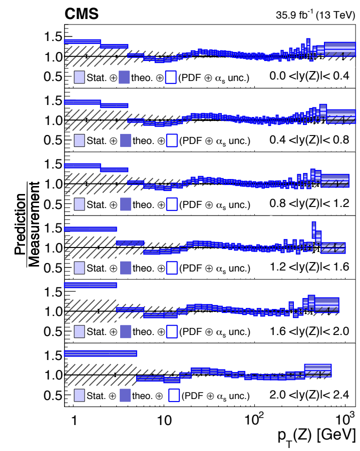
Multi-differential Z+jets cross sections at 13 TeV

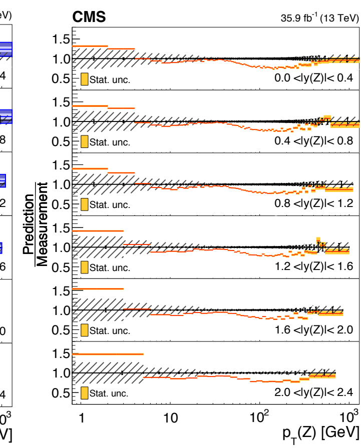
CMS-SMP-19-009; submitted to Phys. Rev. D

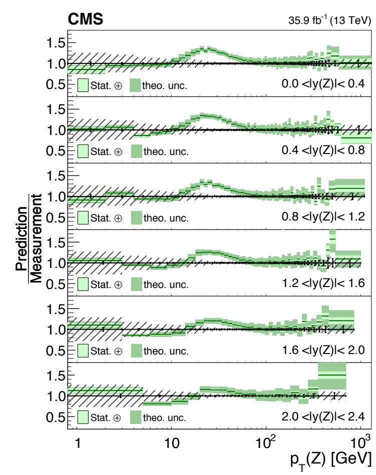
- Z+jets provides a sensitive evaluation of the accuracy of QCD modeling.
- Clean event selection with percent level background and well understood recoil object with the Z
- measure the differential cross section: double differential of Z pT and |y|; jet multiplicity up to 8 jets …









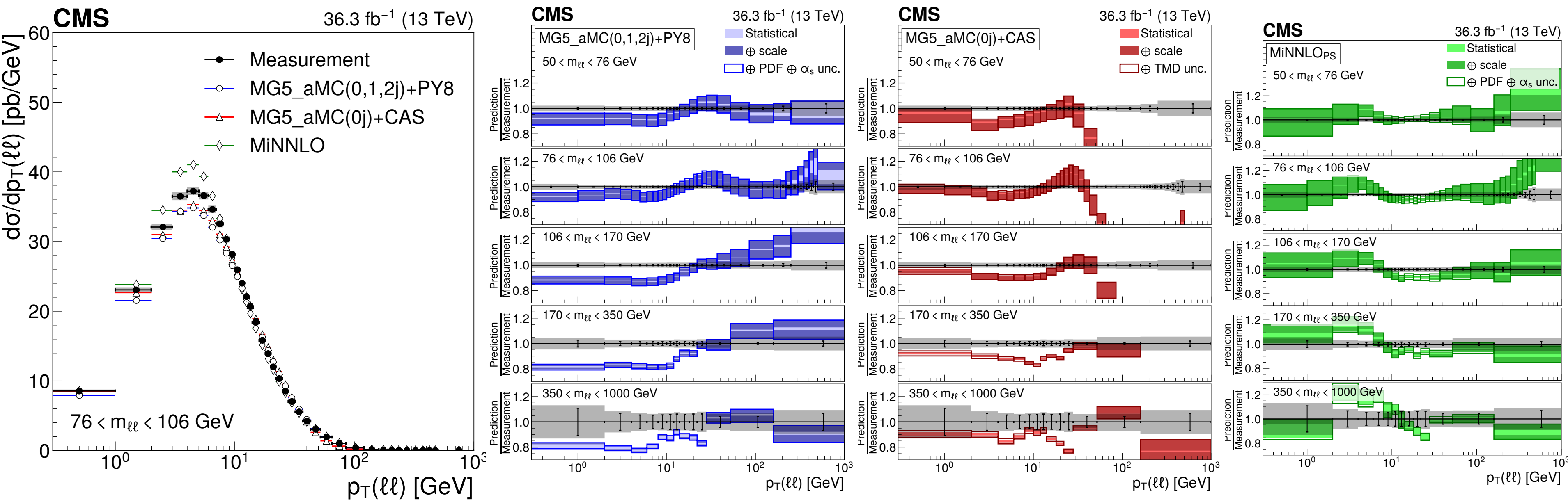


- All the predictions are in agreement with data.
- The NLO prediction provides a better description than LO and GENEVA for double differential cross sections.

DY over a wide mass range

CMS-SMP-20-003; submitted to Eur. Phys. J. C

- Measure pT (Z) and phi* distributions in 5 mass bins, in di-electron and di-muon channels
- Low pT region is of interest because it is sensitive to TMDs and resummation effects.



- MG5+Py8: describes the data well globally, although it predicts a too small cross section for pT(ℓℓ) value below 30 GeV. The disagreement is more pronounced at higher m(ℓℓ).
- CASCADE: produces a better description in low-pT(ℓℓ) part, which is valid for all m(ℓℓ) bins. The high pT(ℓℓ) part is not described due to missing higher fixed-order calculations.
- MiNNLOps: provides the best global description of the data.

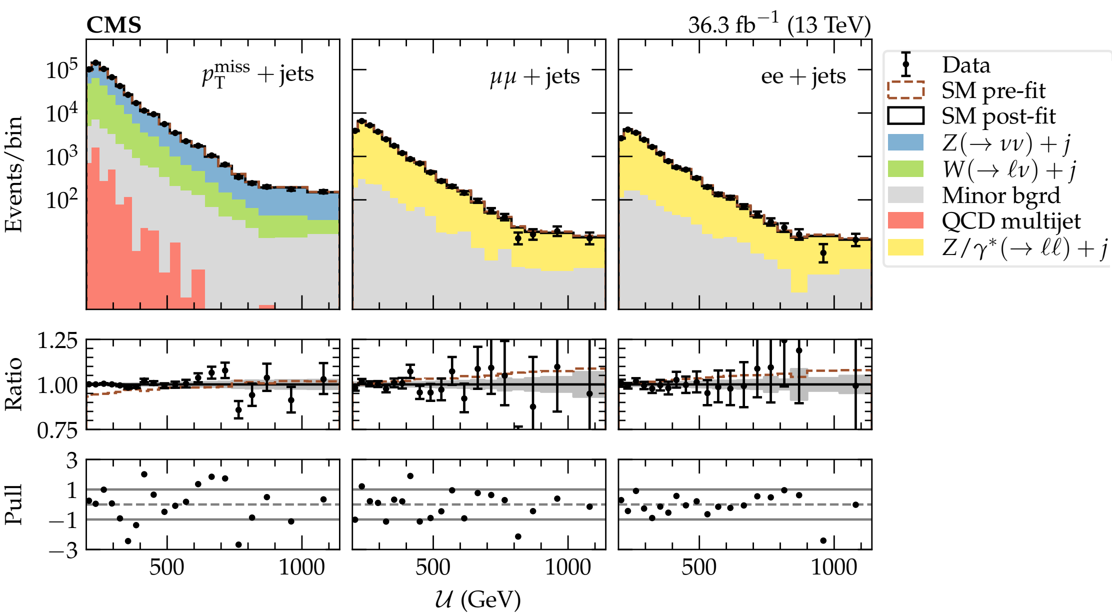
Precision measurement of the Z invisible width at 13 TeV

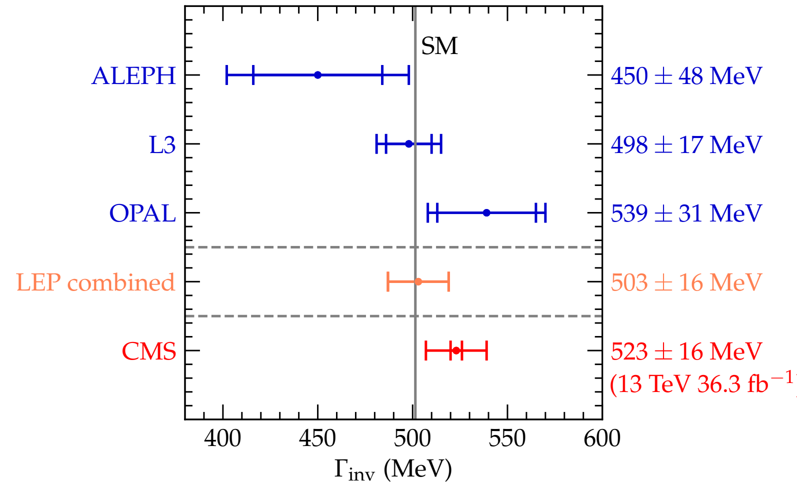
CMS-SMP-18-014; submitted to Phys. Lett. B

- Invisible width extracted from simultaneous likelihood fit to the jets+MET, $\ell\ell$+jets, ℓ+jets regions

$$\Gamma(\mathrm{Z} \to \nu\bar{\nu}) = \frac{\sigma(\mathrm{Z}+\mathrm{jets})\mathcal{B}(\mathrm{Z} \to \nu\bar{\nu})}{\sigma(\mathrm{Z}+\mathrm{jets})\mathcal{B}(\mathrm{Z} \to \ell\ell)}\Gamma(\mathrm{Z} \to \ell\ell)$$

- The transfer factor estimating the W+jets background is implemented as a global unconstrained parameter scaling the W+jets process in jets+MET and ℓ+jets.





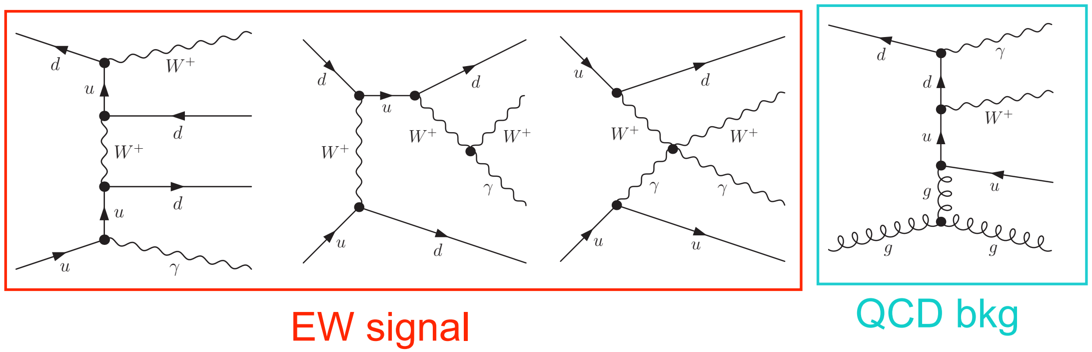
$$\Gamma_{\mathrm{inv}} = 523 \pm 3\,(\mathrm{stat}) \pm 16\,(\mathrm{syst})\,\mathrm{MeV}$$

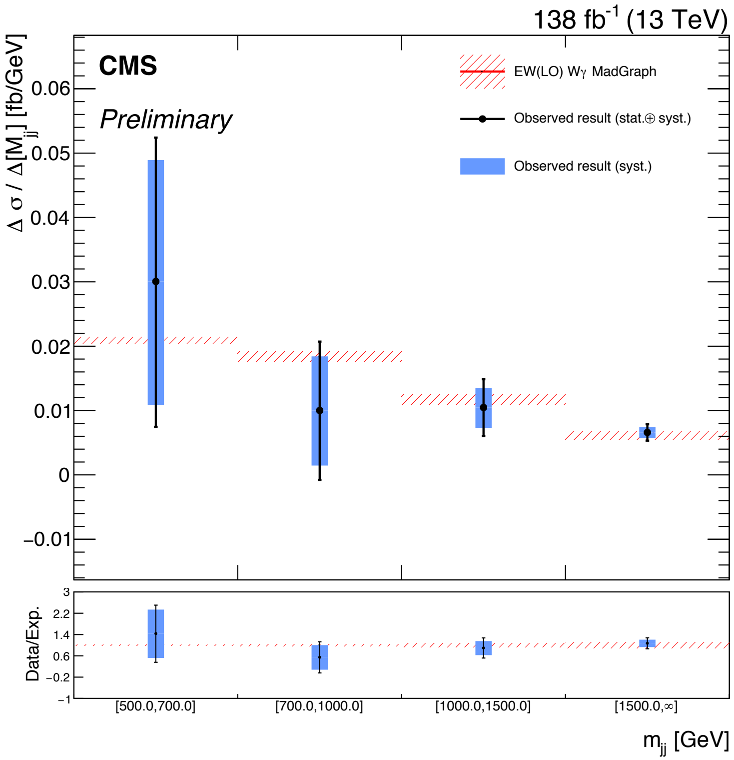
- First direct measurement of invisible Z width at CMS
- Precision competitive with LEP direct measurement
- Most precise single direct measurement

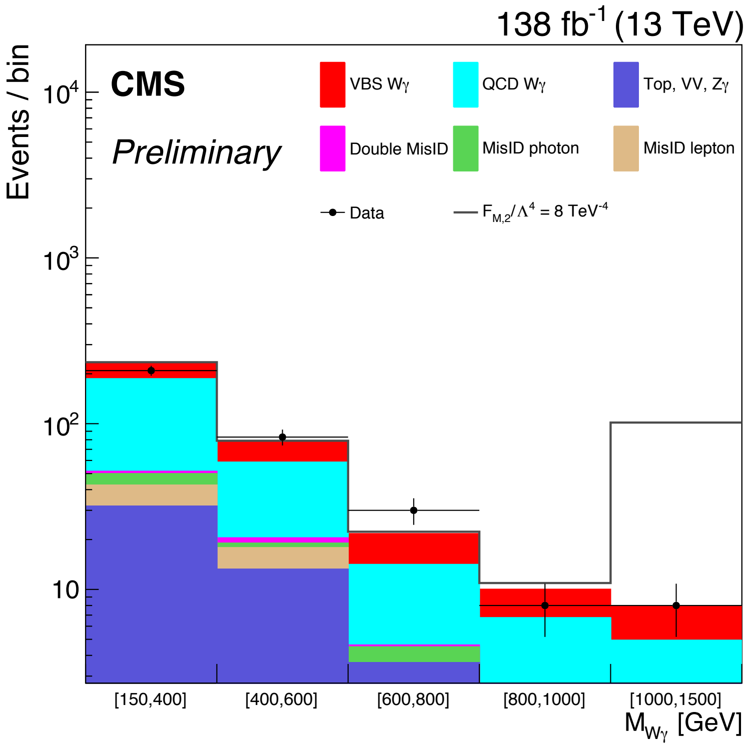
EW Wgamma plus 2 jets at 13 TeV full run 2

CMS-PAS-SMP-21-011

- Measure for EW production of Wgamma and measure fiducial cross section.
- Competitive limits on anomalous QGCs in dim-8 EFT





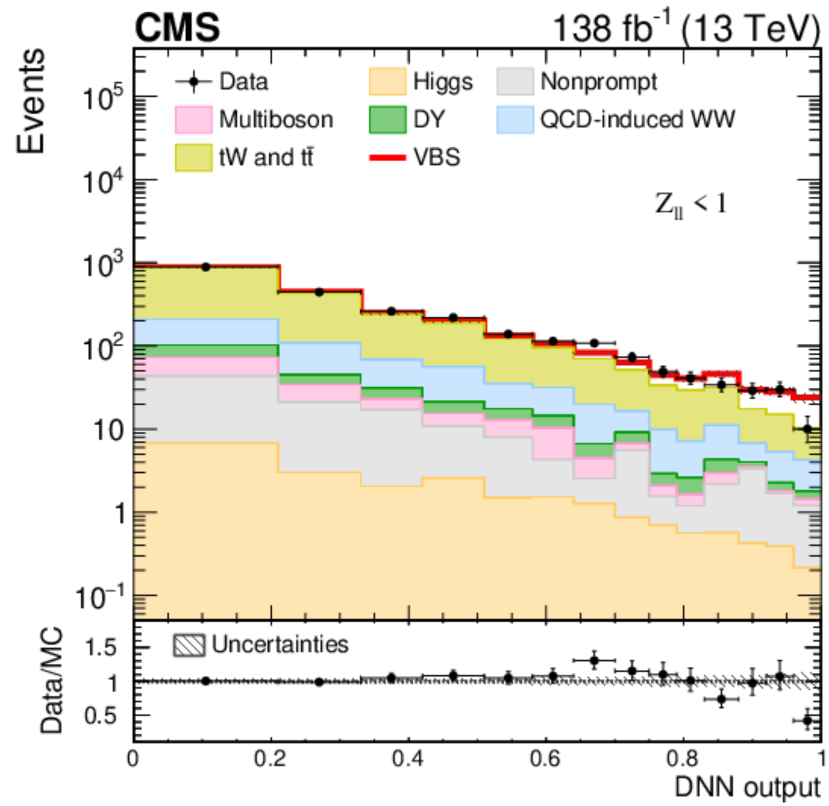


- First differential cross-sections unfolded to parton level

EW W+W- pair production in association with two jets

CMS-SMP-21-001

- Provides complementary information to the Higgs sector and probes the EW symmetry breaking mechanism
- First observation with same-sign W±W± [PRL 120(2018)081801]
    - W+W- more challenging ; large ttbar+tW background



- Deep neural network (DNN) to disentangle signal from top and QCD WW background.
- First observation: **5.6σ obs.** (5.2σ exp.)
- The cross section:

$$\sigma_{EW}^{obs} = 10.2 \pm 2.0 \text{ fb}$$

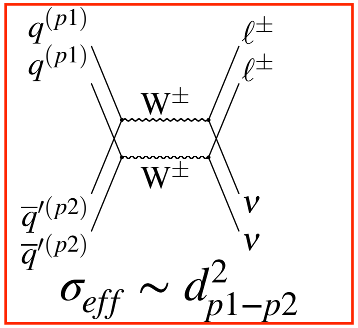
$$\sigma_{EW}^{theo} = 9.1 \pm 0.6 \text{ (scale) fb}$$

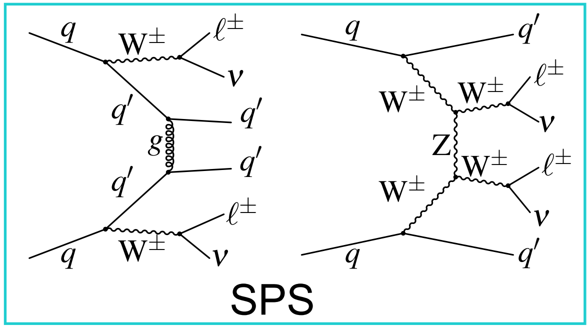
Same-sign WW production from double parton scattering (DPS)

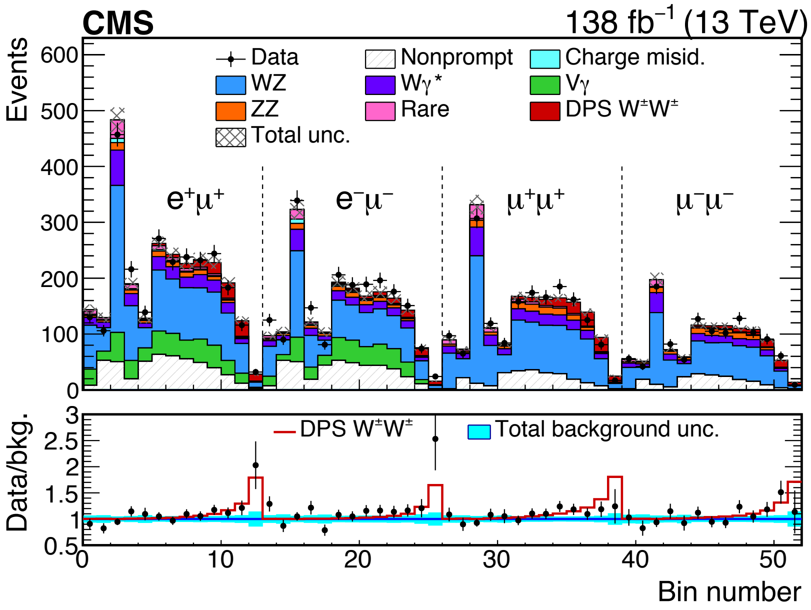
CMS-SMP-21-013; submitted to PRL

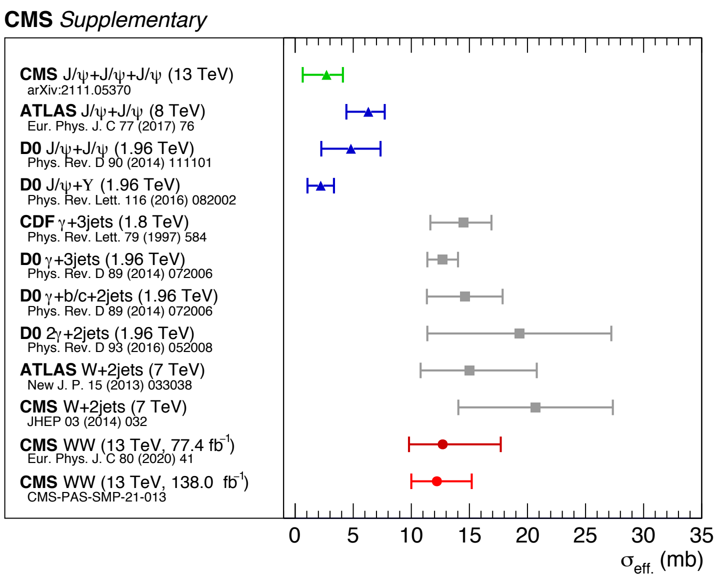
- Provides information about the proton structure & parton correlations inside protons
- Golden channel for DPS studies as single parton scattering (SPS) production suppressed at matrix element level

$$\sigma_{AB}^{DPS} = \frac{n}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$$





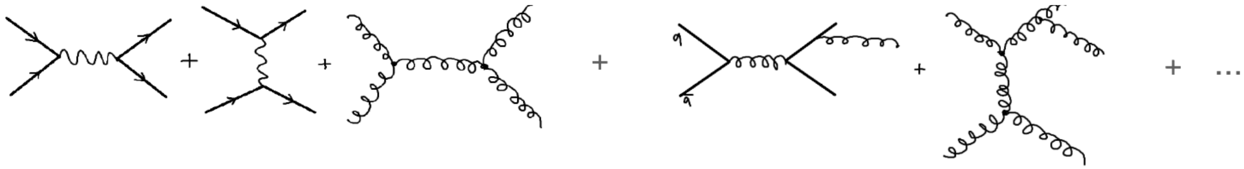


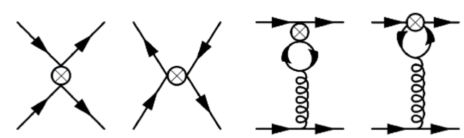


- First observation: **6.2σ obs.** (6.7σ expected)

Simultaneous constraints on QCD and BSM

Inclusive jets in pp collisions at 13 TeV: extract PDF + **probe of New Physics**

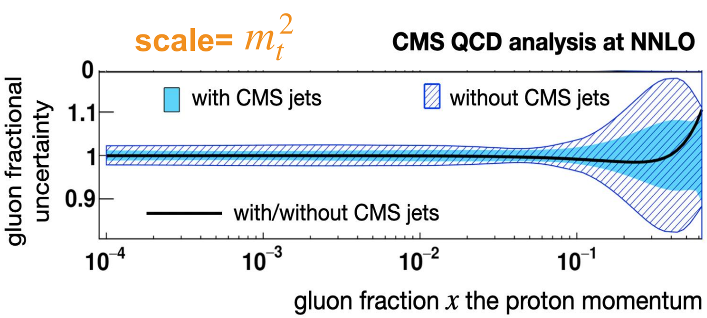


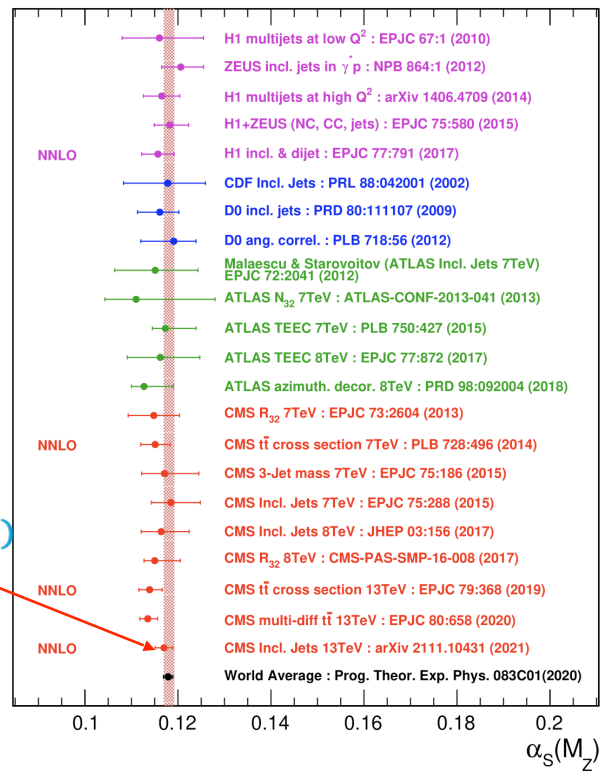


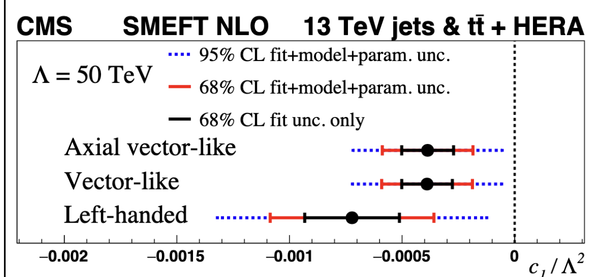
contact interactions

First NNLO interpretation of jets in pp

Unbiased SMEFT interpretation







Simultaneous constraints on PDFs and $\alpha_S(m_Z)$

most precise $\alpha_S(m_Z)$ at a hadron collider

95% CL exclusion for (=-1):

Left-handed : > 24 TeV

Vector-like: > 32 TeV

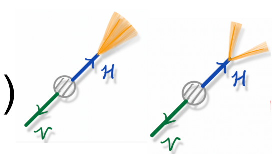
Axial-vector like > 31 TeV

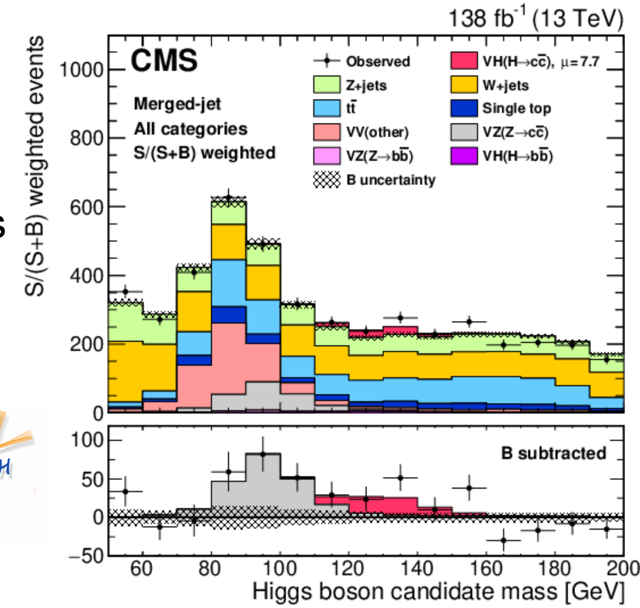
JHEP 02 142 (2022)

Search for the SM Higgs boson decaying to a charm quark-antiquark pair

CMS-HIG-21-008; submitted to PRL

- LHC is now measuring 2nd generation couplings to the Higgs
- Target VH production mode, the presence of leptons suppresses QCD to negligible levels.
- Analysis split based on pT(H) to further exploit decay topologies
  - Merged analysis: one large jet (AK15)
  - Resolved analysis: two fully resolved jets (AK4)





- Measure observed signal strength of

$$\mu_{VZ(Z\to c\bar{c})} = 1.01^{+0.23}_{-0.21} \quad (5.7\sigma)$$

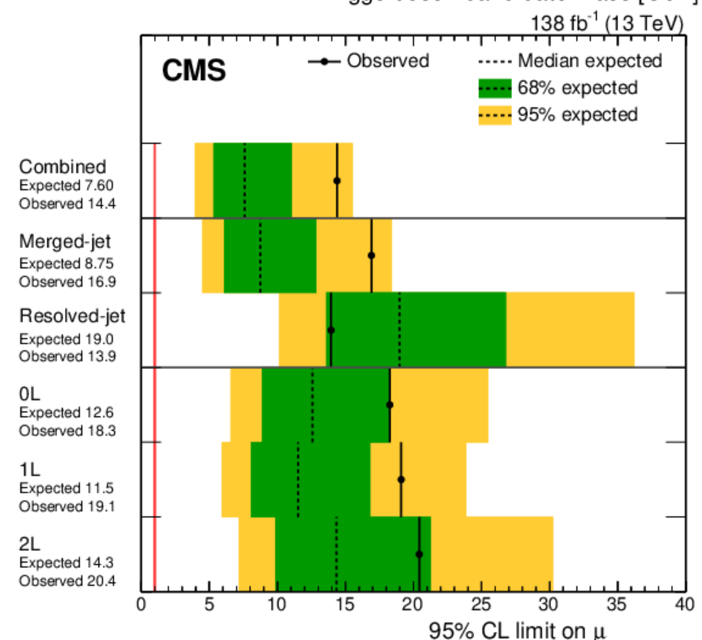
  - First observation of Z->cc at hadron collider!

- Observed upper limit on VH (H->cc) signal strength at 95%

$$\mu_{VH(cc)} < 14\ (7.6)$$

- Constraints on

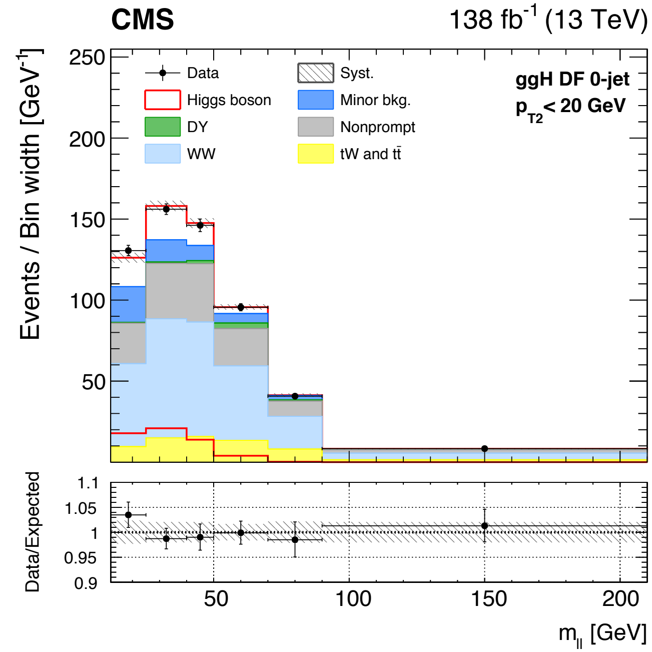
$$1.1 < |\kappa_c| < 5.5 \text{ obs } (|\kappa_c| < 3.4 \text{ exp})$$

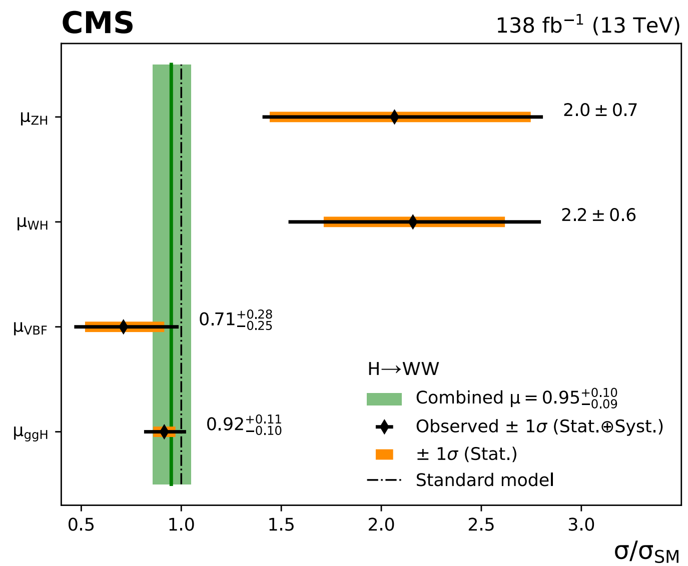


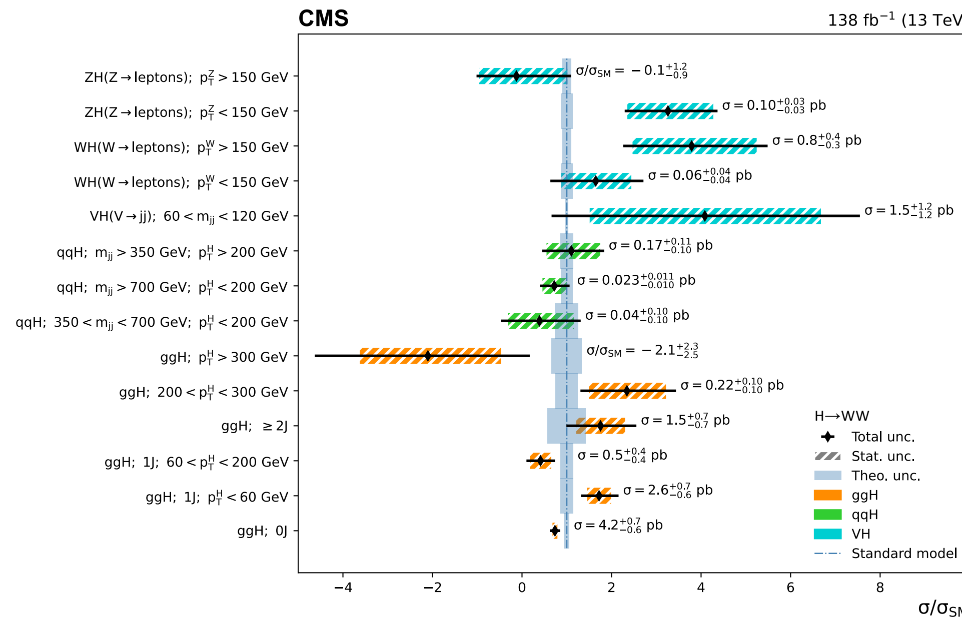
Higgs boson in the W boson pair

CMS-HIG-20-013; Submitted to EPJC

- HWW decays in the ggH, VBF and VH production modes
- Measure signal strengths, kappas and simplified template cross section (STXS) stage 1.2 cross sections
- Signal extracted from 2D fit to (mll, m_TH) in various event categories
- **10% precision on inclusive ggH production**
- **Excellent sensitivity in various STXS bins**





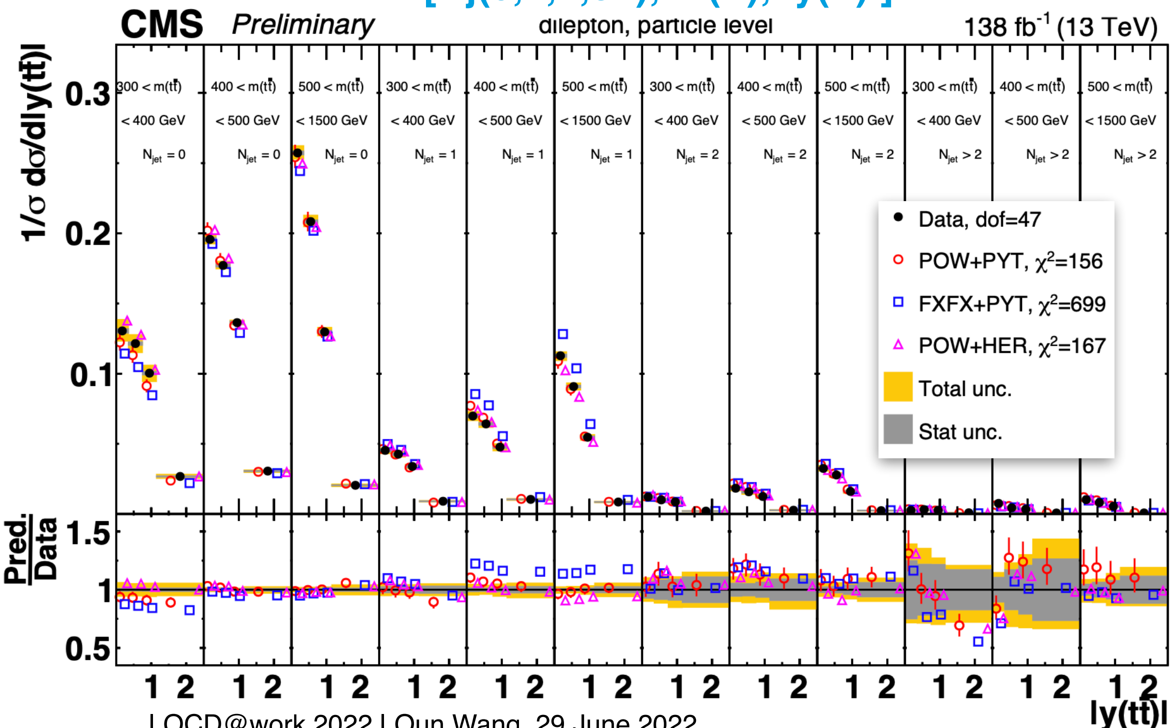


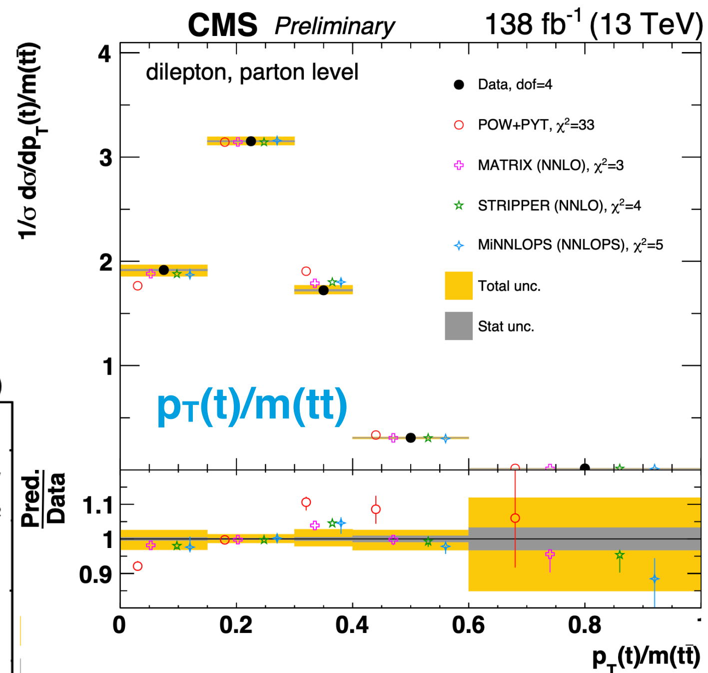
Multi-differential tt cross sections

CMS-PAS-TOP-20-006; Scrutinizing tt production in different regions of the phase space

- 1D —3D differential cross sections of tt, top, decay products, and additional jets
- Several **first-ever measurements** (eg. ratio observables, new 2D & 3D xsecs), **improved precision** by factor ~2 wrt previous results
- Comparison to newest beyond-NLO predictions

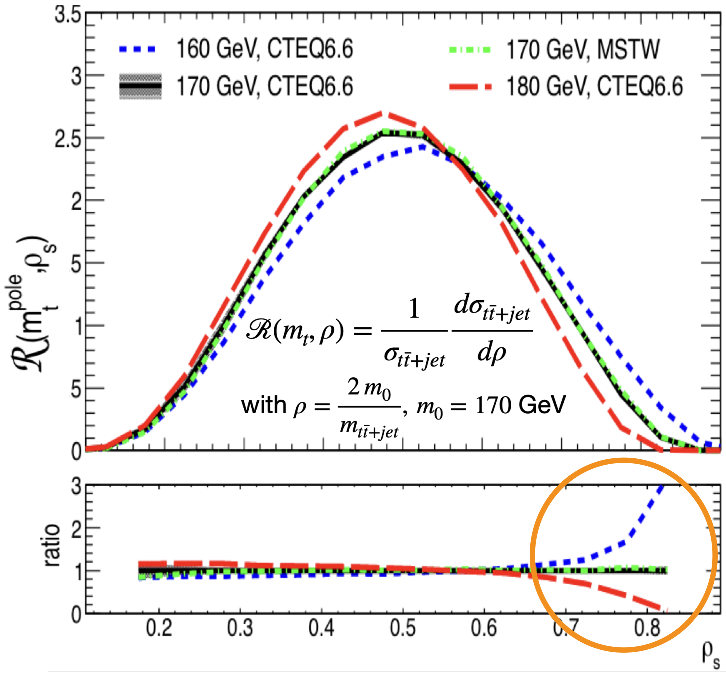
[Nj(0,1,2,3+), m(tt), ly(tt)l]





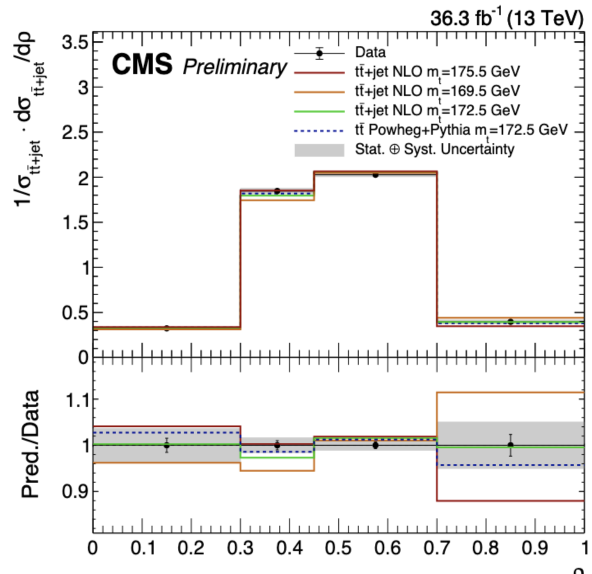
Top pole mass using tt+jet production

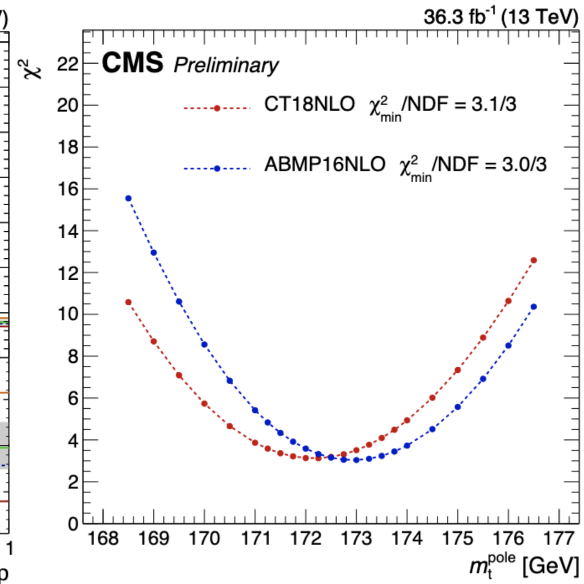
CMS-PAS-TOP-21-008; Probing novel observable to extract the top pole mass



Sensitivity to m_t^{pole}

- Exploit ML techniques (NN) to reconstruct ρ observable and optimize event selection
- Likelihood-fit-based unfolding to constrain systematics
- Extract pole mass by comparing to first-ever tt+jet NLO prediction employing dynamic scales





Results for different PDFs:

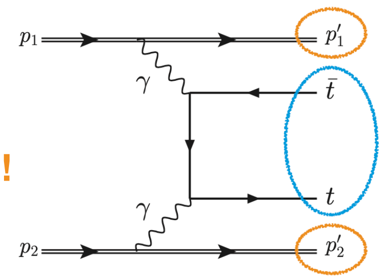
$m_t^{pole} = 172.16 \pm 1.35$ (fit+PDF+extr) $^{+0.50}_{-0.40}$ (scale) (CT18NLO)

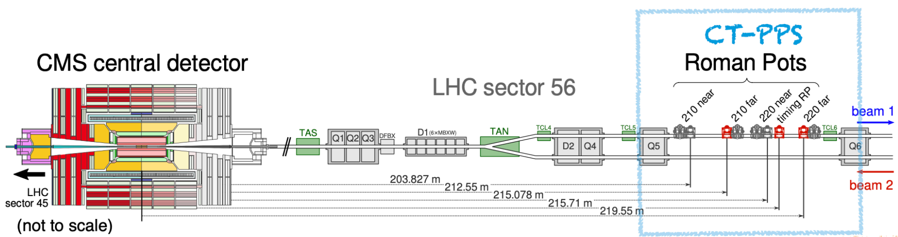
$m_t^{pole} = 172.94 \pm 1.27$ (fit+PDF+extr) $^{+0.51}_{-0.43}$ (scale) (ABMP16NLO)

Exclusive tt production using CMS + TOTEM Precision Proton Spectrometer (CT-PPS)

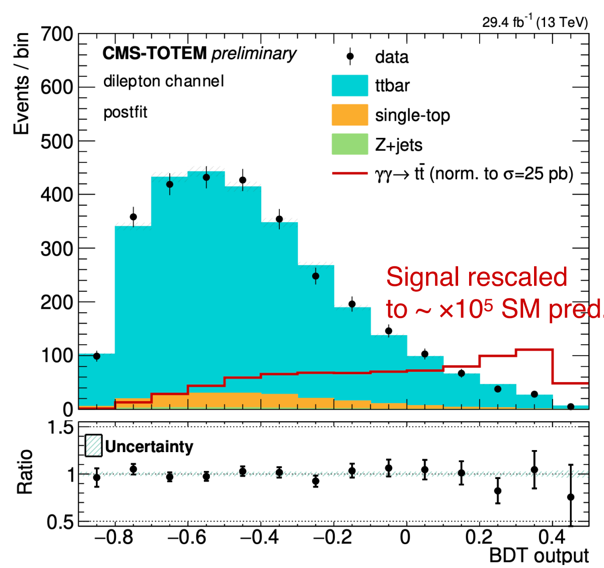
CMS-PAS-TOP-21-007; Detecting the creation of top quarks out of light

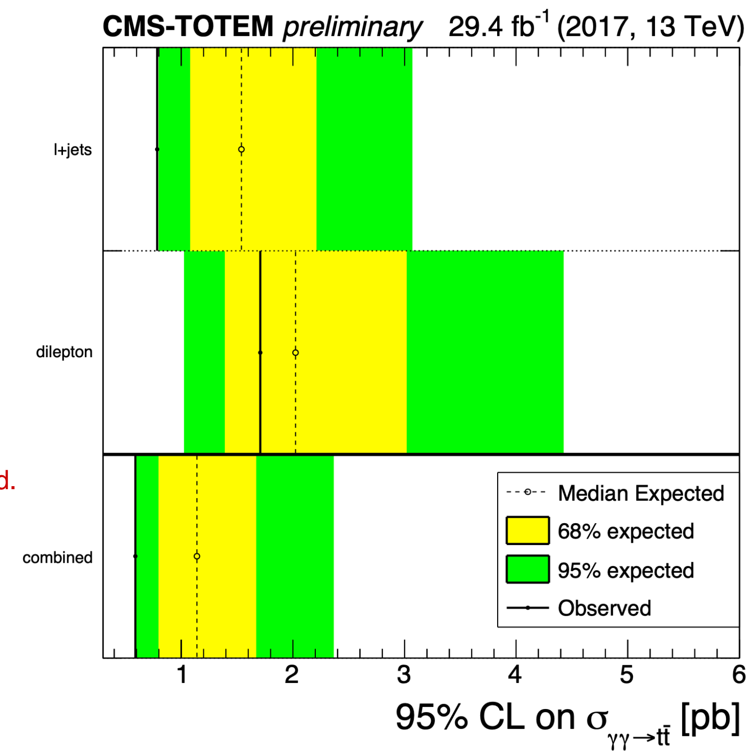
- Allows for full reconstruction of tt due to escaping intact protons
- Sensitive to anomalous top-γ couplings
- SM cross section predictions very small (~0.3 fb), **first-ever search!**





- Select events with 1 or ≥2 leptons, 2 b-tags, 1 proton on each CT-PPS arm
- BDT to separate signal from background (mainly tt overlapping with unrelated pileup protons)

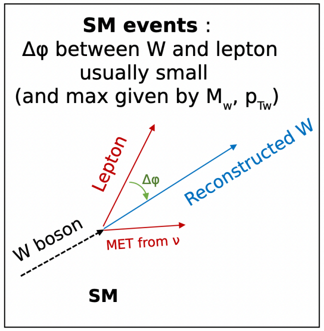


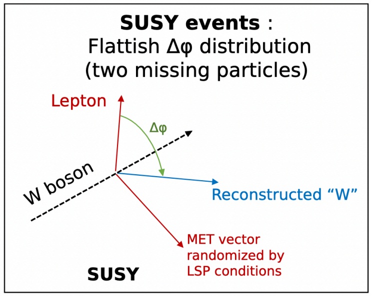


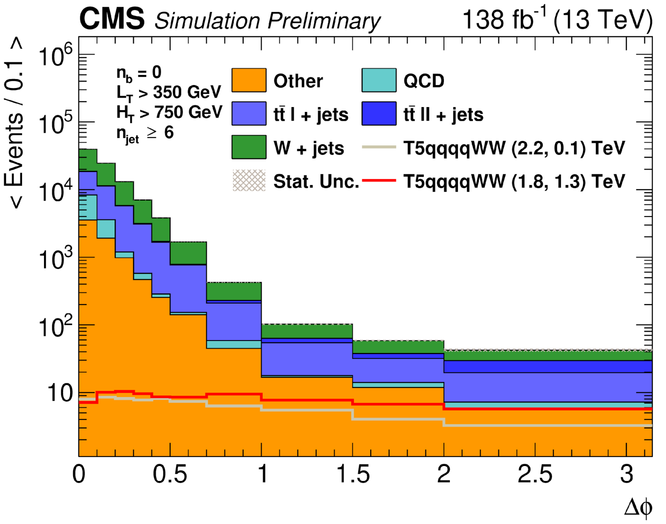
Search for gluino pair production

CMS-PAS-SUS-21-007;Single lepton final states

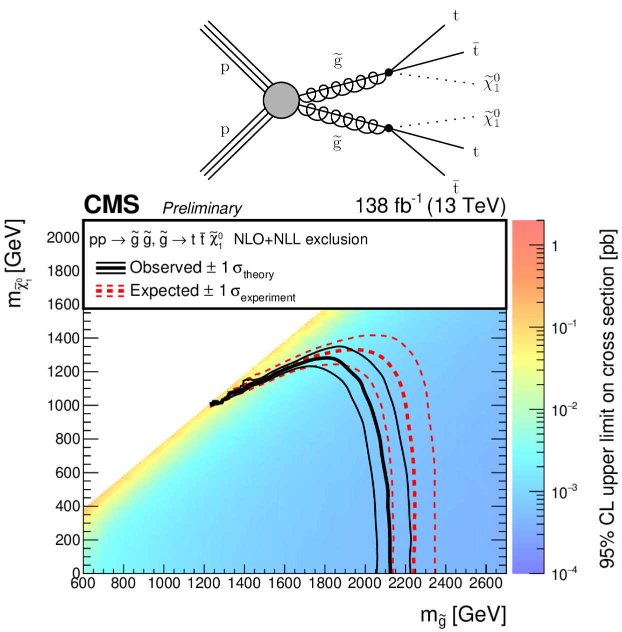
- Main discriminating observable:
  $\Delta\Phi$, the angle between the lepton and the reconstructed "W boson" (vector sum of the 1 lepton and MET)
- The signal-sensitive regions have large $\Delta\Phi$ and a high number of jets

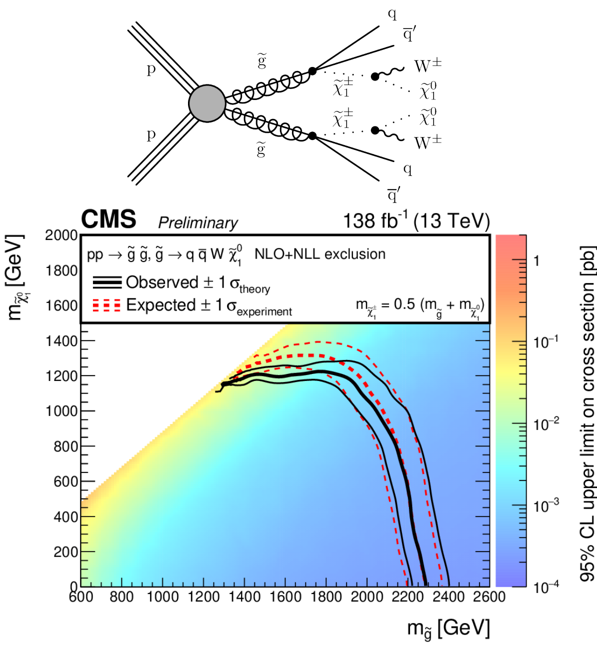






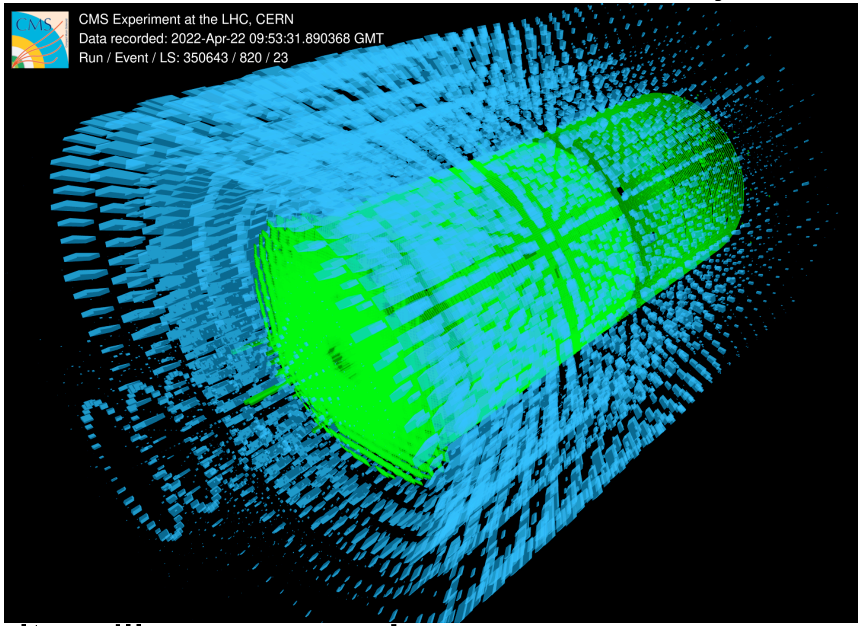
- 2130 GeV for multi-b search
- 2280 GeV for zero-b search





Summary

- Some of the highlights from CMS are presented.
- CMS continues to exploit the Run2 data set with a broad physics program.
  - Benefit from excellent performance and calibration of leptons, photons and jets.
  - Machine learning techniques enhance S/B separation
  - Increasing interpretation within the effective field theory framework



- CMS is ready for Run3!
- Many more exciting results will come soon!

Thanks a lot for your attention!

Thank you

Precision measurement of the Z invisible width at 13 TeV

SMP-18-014

- Goal: turns generic jets+MET dark matter search on its head to make precise measurement of Z invisible width.
- Z invisible width extracted from ratio of experimentally measured cross sections of Z(νν)+jets to Z($\ell\ell$)+jets and LEP measured partial width for Z->$\ell\ell$.

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

- Using 36.3 fb-1 of 13 TeV data
  - Jets+MET topology to select Z->νν events
  - μμ+jets and ee+jets to select Z->$\ell\ell$ events
  - μν+jets, eν+jets and τ_h ν+jets for W+jets
- Backgrounds:
  - W+jets events, estimated using data driven approach and ℓ+jets control regions.
  - QCD background is estimated using data driven.
  - Contribution from γ*—>$\ell\ell$ and interference between γ*—>$\ell\ell$ and Z->$\ell\ell$ is evaluated.

Precision measurement of the Z invisible width at 13 TeV

SMP-18-014

Baseline

MET filters
$p_T^{miss} > 200$ GeV
$|p_{T,PF}^{miss} - p_{T,Calo.}^{miss}|/p_T^{miss} < 0.5$
Lead jet $p_T > 200$ GeV and $|\eta| < 2.4$ and $0.1 <$ Ch. Had. EF < 0.95
Veto jets $p_T > 40$ GeV and $|\eta| \geq 2.4$
Loose photon veto $p_T > 25$ GeV and $|\eta| < 2.5$
Medium CSVV2 b-jet veto $p_T > 40$ GeV and $|\eta| < 2.4$

Jets+MET

Baseline
Loose muon veto $p_T > 10$ GeV and $|\eta| < 2.5$
Veto electron veto $p_T > 10$ GeV and $|\eta| < 2.5$
Very loose tau veto $p_T > 20$ GeV and $|\eta| < 2.3$
$\min[\Delta\phi(j_{1,2,3,4}, p_T^{miss})] > 0.5$

Double Muon

Baseline
2 medium muons $p_T > 25$ GeV and $|\eta| < 2.4$
Veto electron veto $p_T > 10$ GeV and $|\eta| < 2.5$
Very loose tau veto $p_T > 20$ GeV and $|\eta| < 2.3$
$71 < M_{\mu\mu} < 111$ GeV
$\min[\Delta\phi(j_{1,2,3,4}, p_T^{miss})] > 0.5$

Double Electron

Baseline
2 medium electrons $p_T > 30$ GeV and $|\eta| < 2.4$
Loose muon veto $p_T > 10$ GeV and $|\eta| < 2.5$
Very loose tau veto $p_T > 20$ GeV and $|\eta| < 2.3$
$71 < M_{ee} < 111$ GeV
$\min[\Delta\phi(j_{1,2,3,4}, p_T^{miss})] > 0.5$

Single Muon

Baseline
1 medium muon $p_T > 25$ GeV and $|\eta| < 2.4$
Veto electron veto $p_T > 10$ GeV and $|\eta| < 2.5$
Very loose tau veto $p_T > 20$ GeV and $|\eta| < 2.3$
$30 \leq M_T(\mu, p_{T,PF}^{miss}) < 125$ GeV
$\min[\Delta\phi(j_{1,2,3,4}, p_T^{miss})] > 0.5$

Single Electron

Baseline
1 medium electron $p_T > 30$ GeV and $|\eta| < 2.4$
Loose muon veto $p_T > 10$ GeV and $|\eta| < 2.5$
Very loose tau veto $p_T > 20$ GeV and $|\eta| < 2.3$
$p_{T,PF}^{miss} > 100$ GeV
$30 \leq M_T(e, p_{T,PF}^{miss}) < 125$ GeV
$\min[\Delta\phi(j_{1,2,3,4}, p_T^{miss})] > 0.5$

Single Tau

Baseline
1 tight tau $p_T > 40$ GeV and $|\eta| < 2.3$
Loose muon veto $p_T > 10$ GeV and $|\eta| < 2.5$
Veto electron veto $p_T > 10$ GeV and $|\eta| < 2.5$
$\min[\Delta\phi(j_{1,2,3,4}, p_T^{miss})] > 0.5$

QCD sideband

Baseline
Loose muon veto $p_T > 10$ GeV and $|\eta| < 2.5$
Veto electron veto $p_T > 10$ GeV and $|\eta| < 2.5$
Very loose tau veto $p_T > 20$ GeV and $|\eta| < 2.3$
$\min[\Delta\phi(j_{1,2,3,4}, p_T^{miss})] \leq 0.5$

5

Precision measurement of the Z invisible width at 13 TeV

SMP-18-014

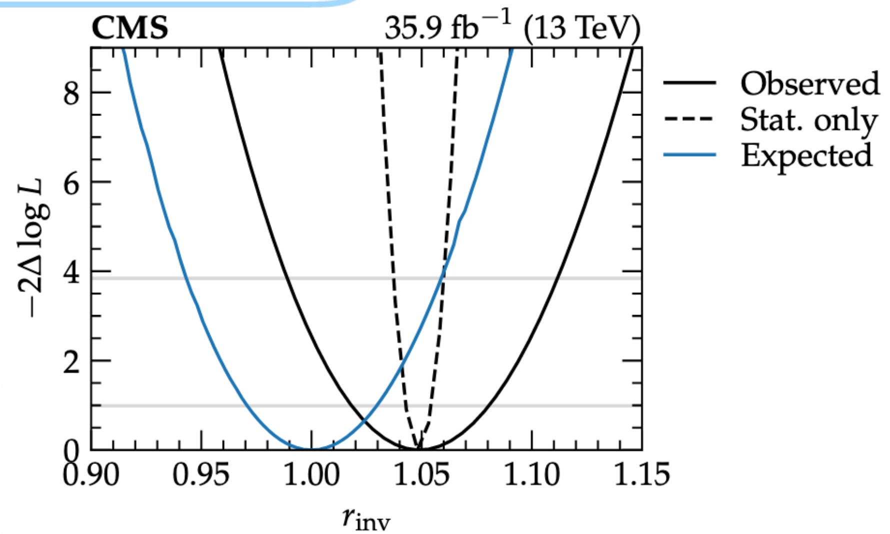
- Invisible width extracted from simultaneous likelihood fit to the jets+MET, $\ell\ell$+jets, ℓ+jets regions

$$\mathcal{L}(n_j, n_\ell, n_{\ell\ell} | r, r_Z, r_W, \boldsymbol{\theta}) =$$
$$\text{Poisson}\left(n_j \,\middle|\, r \cdot r_Z \cdot s_{Z,j}(\boldsymbol{\theta}) + r_W \cdot b_{j,W}(\boldsymbol{\theta}) + b_{\text{bkg.},j}(\boldsymbol{\theta})\right)$$ Jets+MET
$$\text{Poisson}\left(n_\ell \,\middle|\, r_W \cdot b_{\ell,W}(\boldsymbol{\theta}) + b_{\text{bkg.},\ell}(\boldsymbol{\theta})\right)$$ Single lepton
$$\text{Poisson}\left(n_{\ell\ell} \,\middle|\, r_Z \cdot s_{Z,\ell\ell}(\boldsymbol{\theta}) + \sqrt{r_Z} \cdot s_{\text{int.},\ell\ell} + s_{\gamma^*,\ell\ell}(\boldsymbol{\theta}) + b_{\text{bkg.},\ell\ell}(\boldsymbol{\theta})\right)$$ Double lepton
$$\cdot\, p(\tilde{\boldsymbol{\theta}}, \boldsymbol{\theta})$$

$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z+\text{jets}) \cdot B(Z \to \nu\bar{\nu})}{\sigma(Z+\text{jets}) \cdot B(Z \to \ell\ell)} \Gamma(Z \to \ell\ell)$$
$$= \frac{\varepsilon_{\ell\ell}\mathcal{A}_{\ell\ell}}{\varepsilon_{\nu\nu}\mathcal{A}_{\nu\nu}} \frac{r \cdot r_Z \cdot s_{Z,j}(\boldsymbol{\theta})}{r_Z \cdot s_{Z,\ell\ell}(\boldsymbol{\theta})} \Gamma(Z \to \ell\ell)$$
$$= r \frac{\varepsilon_{\ell\ell}\mathcal{A}_{\ell\ell}}{\varepsilon_{\nu\nu}\mathcal{A}_{\nu\nu}} \frac{s_{Z,j}(\boldsymbol{\theta})}{s_{Z,\ell\ell}(\boldsymbol{\theta})} \Gamma(Z \to \ell\ell).$$

$$\Gamma_{\text{MC}}(Z \to \nu\bar{\nu}) = \frac{\varepsilon_{\ell\ell}\mathcal{A}_{\ell\ell}}{\varepsilon_{\nu\nu}\mathcal{A}_{\nu\nu}} \frac{s_{Z,j}(\boldsymbol{\theta})}{s_{Z,\ell\ell}(\boldsymbol{\theta})} \Gamma_{\text{MC}}(Z \to \ell\ell)$$

$$r_{\text{inv}} \equiv r = \frac{\Gamma(Z \to \text{inv})}{\Gamma_{\text{MC}}(Z \to \text{inv})}$$



$$r_{\text{inv}} = 1.052 \pm 0.006(\text{stat})^{+0.032}_{-0.031}(\text{syst})$$

Using input Z width of 510 MeV:

$$\Gamma_{\text{inv}} = 523 \pm 3\,(\text{stat}) \pm 16\,(\text{syst})\,\text{MeV}$$

Precision measurement of the Z invisible width at 13 TeV

SMP-18-014

Systematic uncertainties:

Source of systematic uncertainty	Uncertainty (%)
Muon identification efficiency (syst.)	2.1
Jet energy scale	1.8–1.9
Electron identification efficiency (syst.)	1.6
Electron identification efficiency (stat.)	1.0
Pileup	0.9–1.0
Electron trigger efficiency	0.7
τ_h veto efficiency	0.6–0.7
p_T^{miss} trigger efficiency (jets plus p_T^{miss} region)	0.7
p_T^{miss} trigger efficiency ($Z/\gamma^* \to \mu\mu$ region)	0.6
Boson p_T dependence of QCD corrections	0.5
Jet energy resolution	0.3–0.5
p_T^{miss} trigger efficiency (μ+jets region)	0.4
Muon identification efficiency (stat.)	0.3
Electron reconstruction efficiency (syst.)	0.3
Boson p_T dependence of EW corrections	0.3
PDFs	0.2
Renormalization/factorization scale	0.2
Electron reconstruction efficiency (stat.)	0.2
Overall	3.2

- First direct measurement of invisible Z width at CMS
- Precision competitive with LEP direct measurement
- Most precise single direct measurement

Multi-differential Z+jets cross sections at 13 TeV

SMP-19-009

- Z+jets provides a sensitive evaluation of the accuracy of QCD modeling
- Using 35.9 fb-1 data to measure the differential cross section:
  - Double differential of Z pT and |*y*|
  - Jet multiplicity up to 8 jets
  - Transverse momentum and rapidities of 5 jets
  - Double differential of leading jet pT and |*y*|
  - Angular variables…

Event selections:

Opposite sign leptons with pT > 30/20GeV, |η|< 2.4

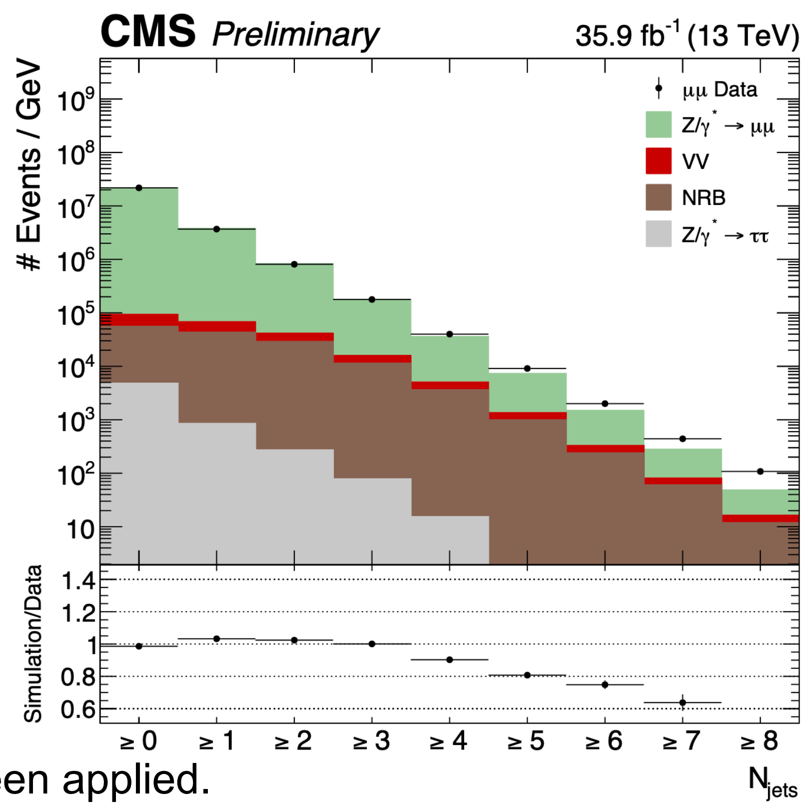
|mℓℓ −mZ |< 20GeV

Medium ID (+ 0.15 Isolation for muon)

AK4PF chs jets with pT > 30GeV, |η|< 2.4

Jets pass Loose ID and Tight WP for PU MVA

ΔR (ℓ,jets) < 0.4



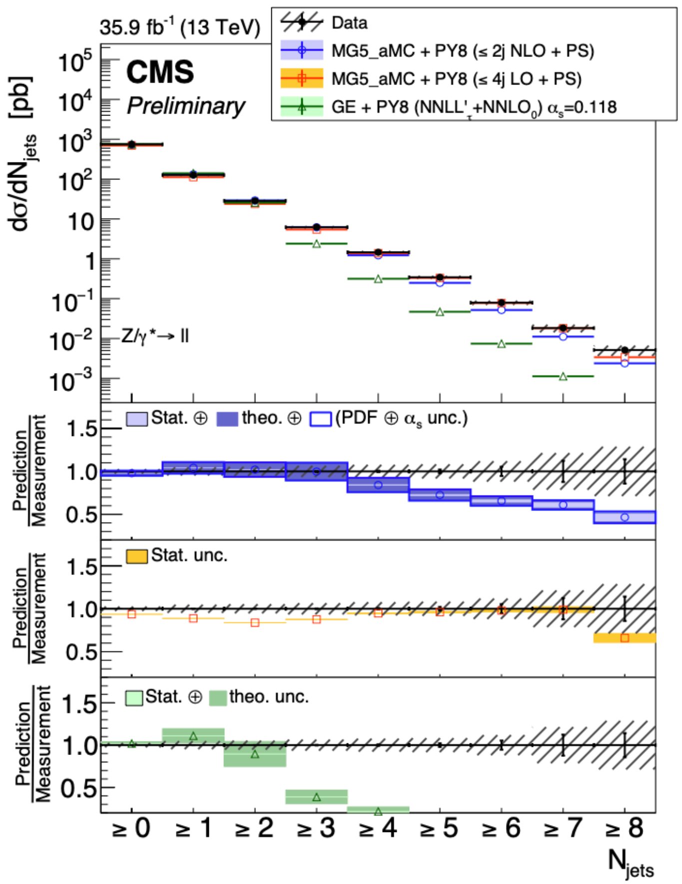
Corresponding corrections and scale factors have been applied.

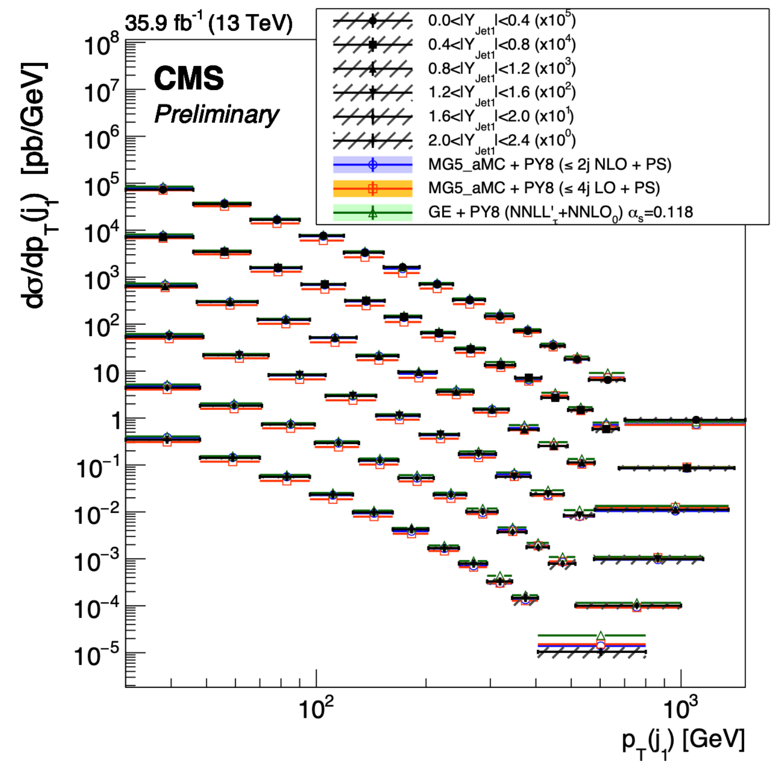
Multi-differential Z+jets cross sections at 13 TeV

SMP-19-009

Predictions:

- Madgraph5 NLO (Labeled NLO MG 5 aMC)
- Madgraph5 LO (Labeled LO MG 5 aMC)
- GENEVA (NNLO + NNLL resummation)



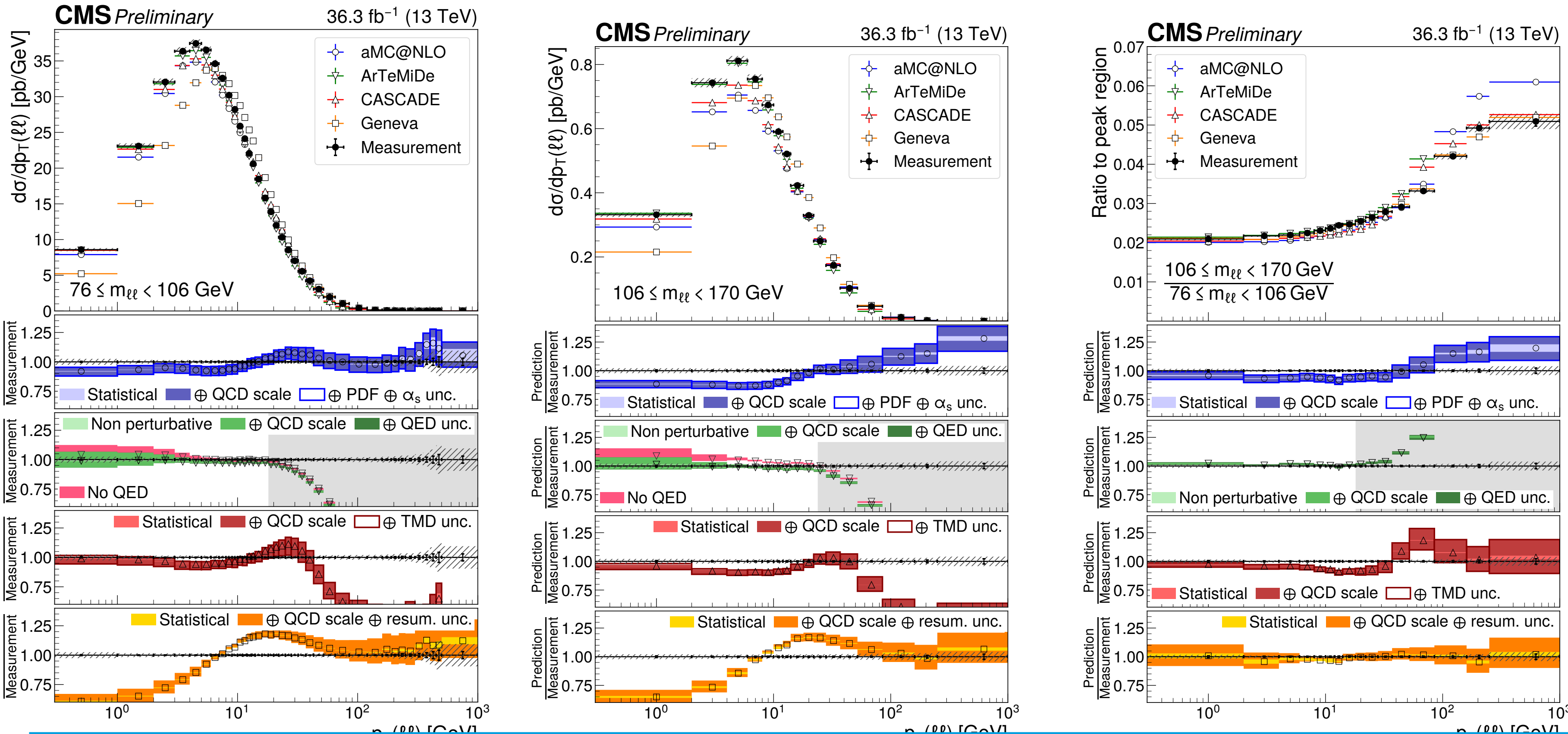


- All the predictions are in agreement with data.
- The NLO prediction provides a better description than LO and GENEVA for double differential cross sections.

DY over a wide mass range

CMS-SMP-20-003; submitted to Eur. Phys. J. C

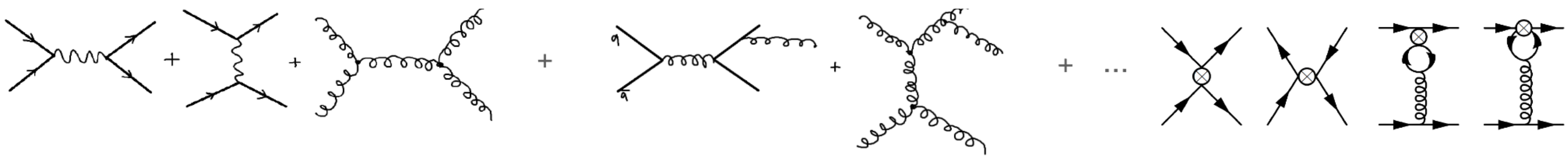
- Measure pT (Z) and phi* distributions in 5 mass bins, in di-electron and di-muon channels
- Low pT region is of interest because it is sensitive to TMDs and resummation effects.



MG5+Py8: shows a generally good agreement, except at pT(ℓℓ) value below 10 GeV.
ArTeMiDe: provides good descriptions in its range of validity (pT<0.2Mass), except highest mass bin
CASCADE: gives a better description at the low pT region, missing higher fixed-order calculations at high pT
Geneva: predicts a harder pT(ℓℓ) spectrum. It gives an overall good agreement for the ratio measurements.

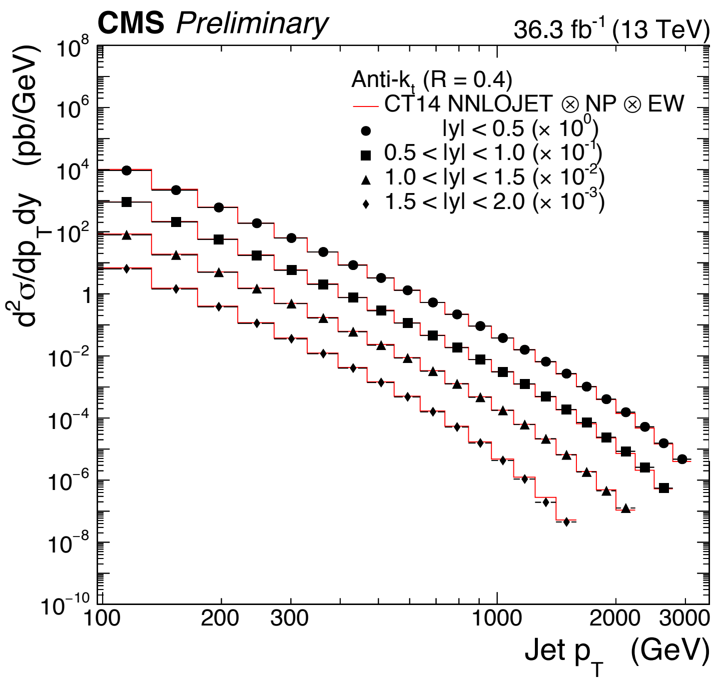
Simultaneous constraints on QCD and BSM

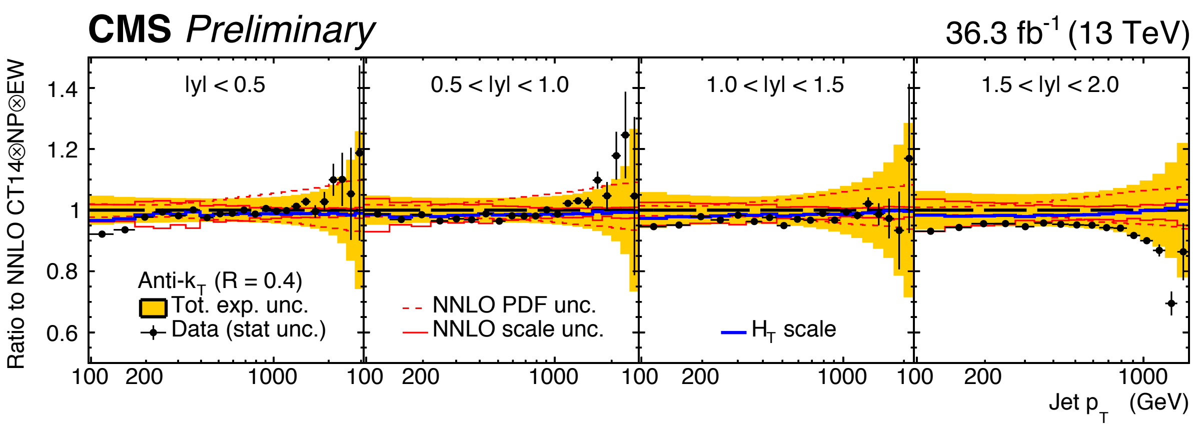
Inclusive jets in pp collisions at 13 TeV: extract PDF + **probe of New Physics**



contact interactions

- Key process to test the predictions of perturbative QCD over a wide region.
- Double differential cross section as a function of jet transverse momentum and absolute rapidity





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