Vector Boson Production and Properties at CMS

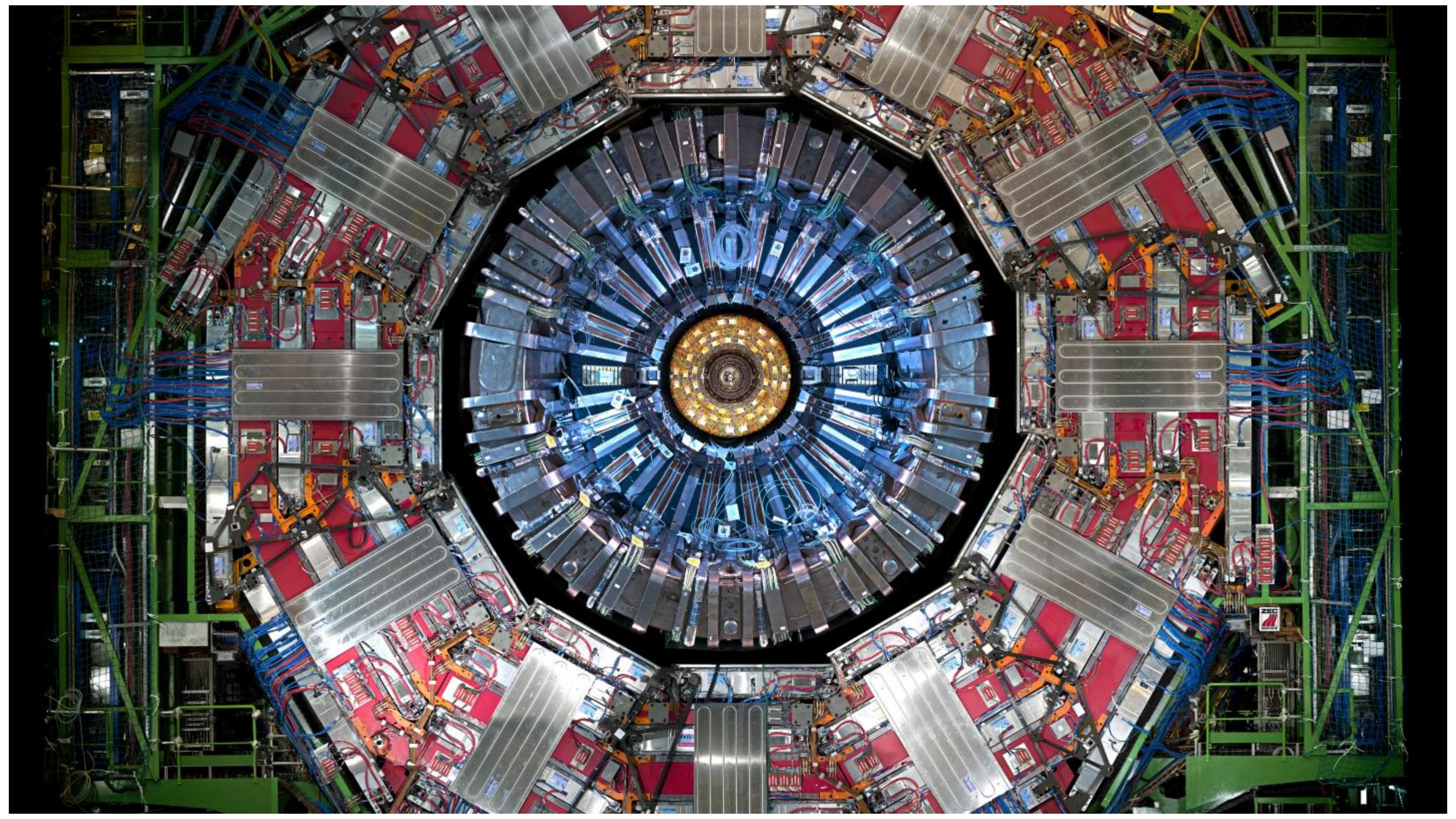
selection of recent results

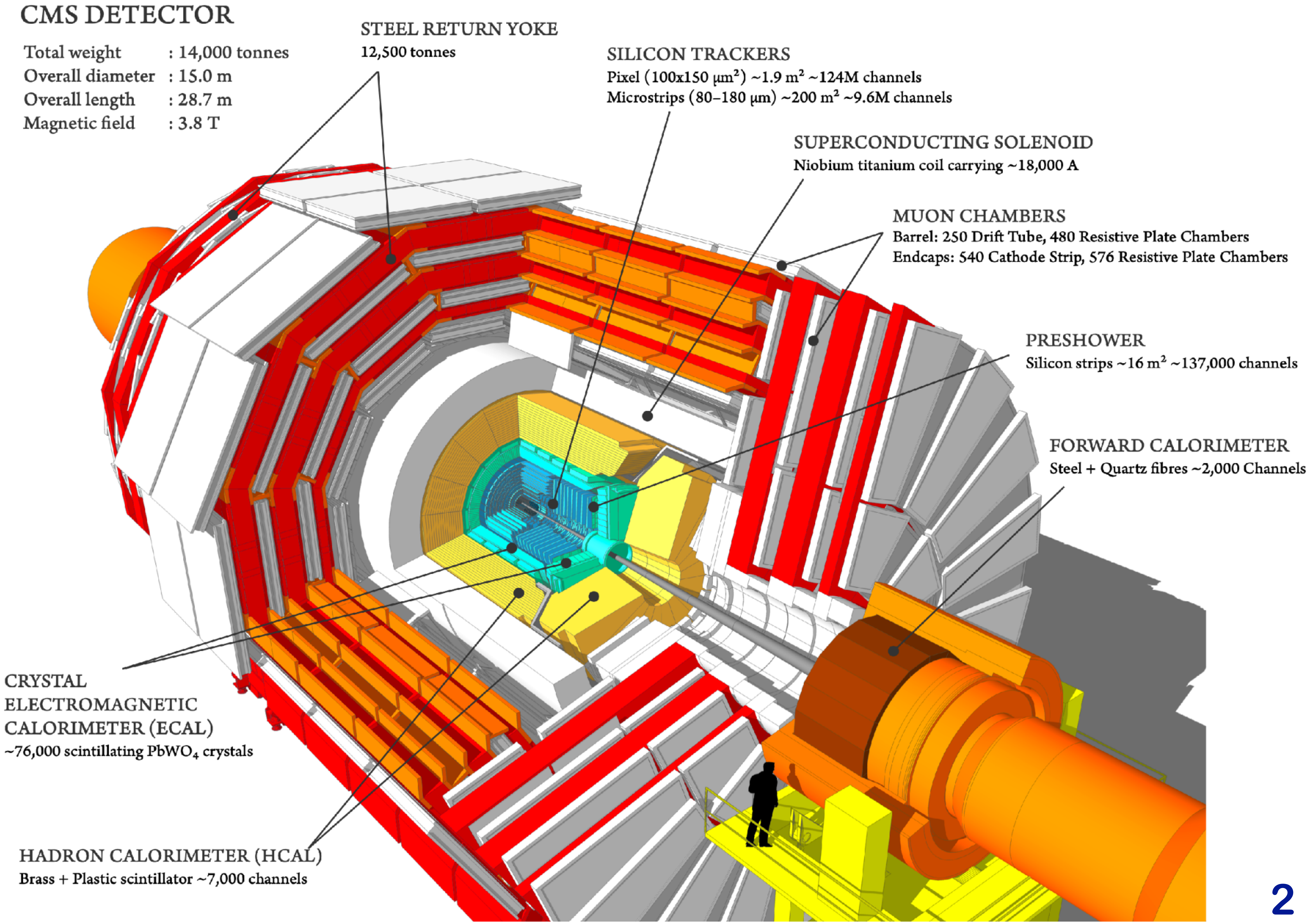
LLWI, 19-24 Feb 2024

Patrizia Azzi (INFN Padova)
on behalf of the CMS Collaboration

The CMS experiment

At CERN LHC

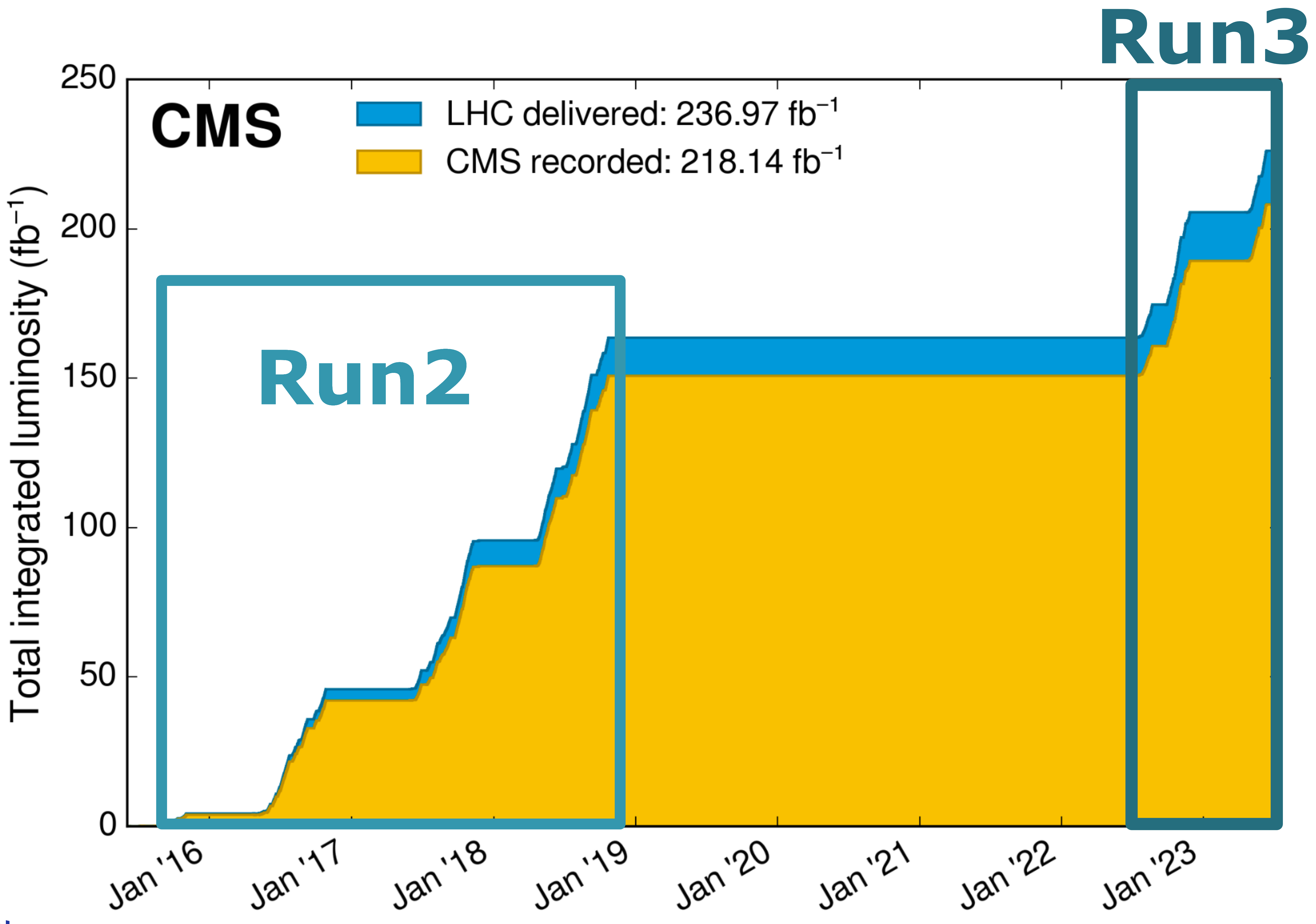


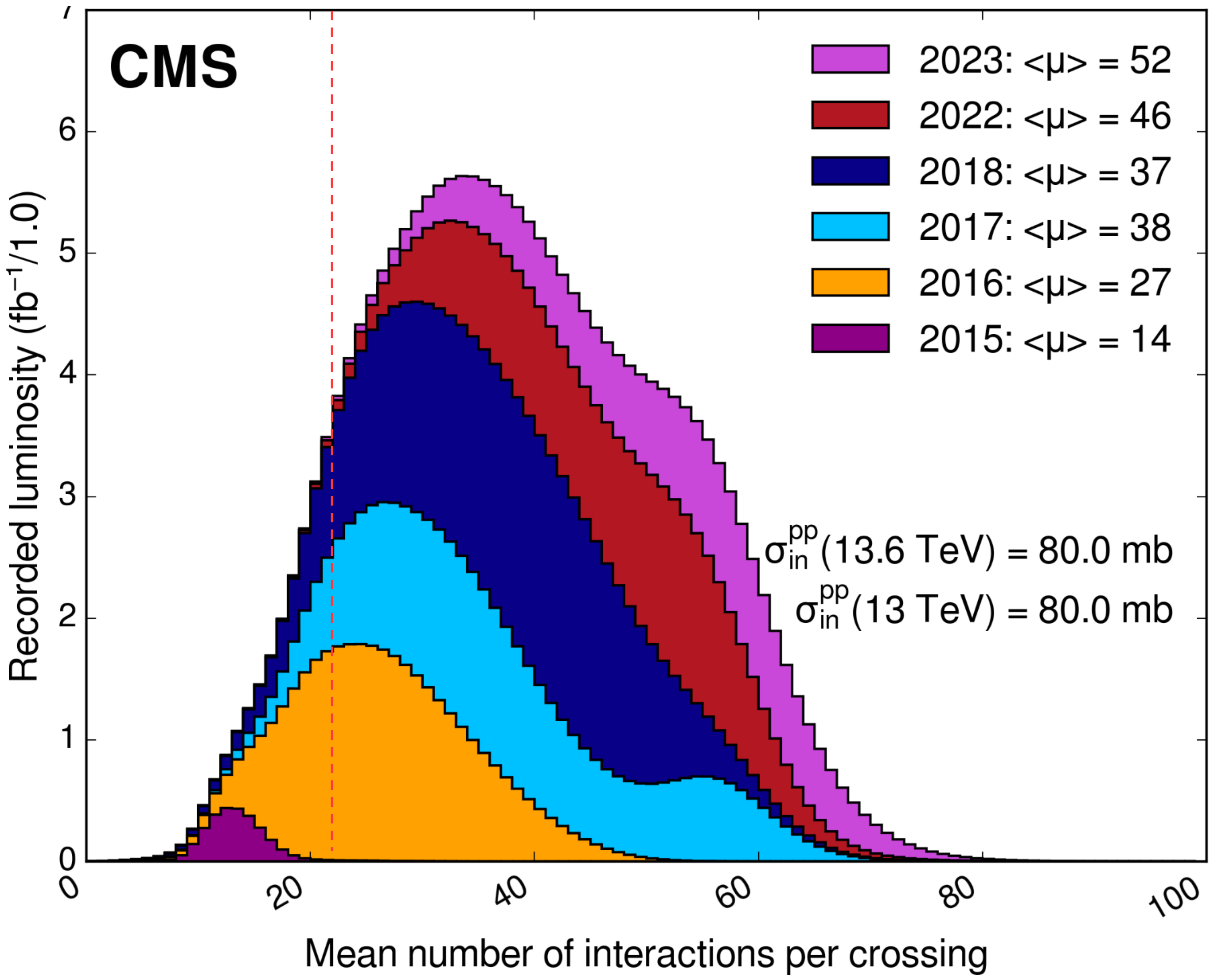


[CMS-PRF-21-001 (submitted to JINST)]

Status of data taking

Collisions to restart in April 2024



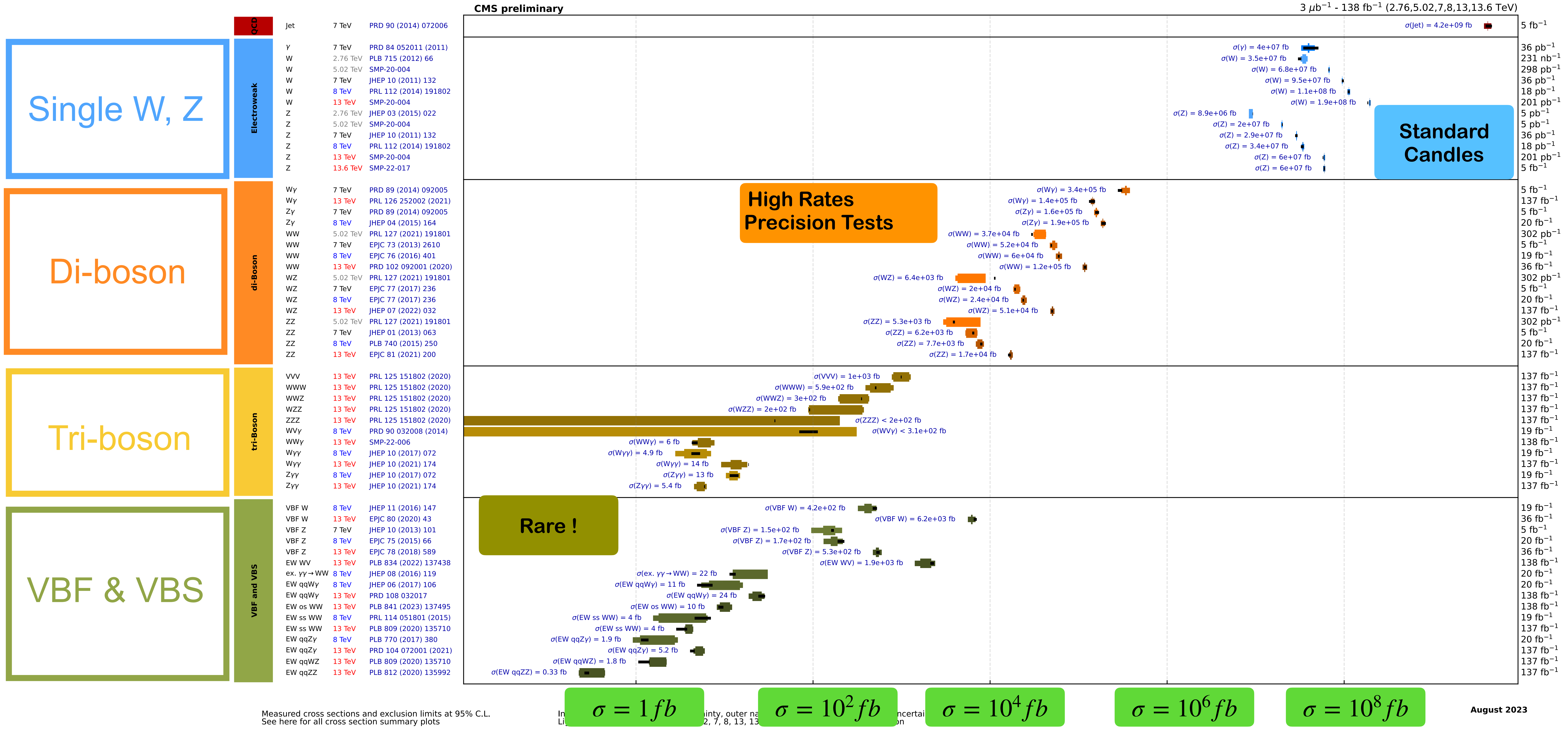


Vector Bosons Measurements @CMS

A snapshot

https://twiki.cern.ch/twiki/pub/CMSPublic/

Overview of CMS cross section results



Jet	7 TeV	PRD 90 (2014) 072006	5 fb⁻¹
γ	7 TeV	PRD 84 052011 (2011)	36 pb⁻¹
W	2.76 TeV	PLB 715 (2012) 66	231 nb⁻¹
W	5.02 TeV	SMP-20-004	298 pb⁻¹
W	7 TeV	JHEP 10 (2011) 132	36 pb⁻¹
W	8 TeV	PRL 112 (2014) 191802	18 pb⁻¹
W	13 TeV	SMP-20-004	201 pb⁻¹
Z	2.76 TeV	JHEP 03 (2015) 022	5 pb⁻¹
Z	5.02 TeV	SMP-20-004	5 pb⁻¹
Z	7 TeV	JHEP 10 (2011) 132	36 pb⁻¹
Z	8 TeV	PRL 112 (2014) 191802	18 pb⁻¹
Z	13 TeV	SMP-20-004	201 pb⁻¹
Z	13.6 TeV	SMP-22-017	5 fb⁻¹
Wγ	7 TeV	PRD 89 (2014) 092005	5 fb⁻¹
Wγ	13 TeV	PRL 126 252002 (2021)	137 fb⁻¹
Zγ	7 TeV	PRD 89 (2014) 092005	5 fb⁻¹
Zγ	8 TeV	JHEP 04 (2015) 164	20 fb⁻¹
WW	5.02 TeV	PRL 127 (2021) 191801	302 pb⁻¹
WW	7 TeV	EPJC 73 (2013) 2610	5 fb⁻¹
WW	8 TeV	EPJC 76 (2016) 401	19 fb⁻¹
WW	13 TeV	PRD 102 092001 (2020)	36 fb⁻¹
WZ	5.02 TeV	PRL 127 (2021) 191801	302 pb⁻¹
WZ	7 TeV	EPJC 77 (2017) 236	5 fb⁻¹
WZ	8 TeV	EPJC 77 (2017) 236	20 fb⁻¹
WZ	13 TeV	JHEP 07 (2022) 032	137 fb⁻¹
ZZ	5.02 TeV	PRL 127 (2021) 191801	302 pb⁻¹
ZZ	7 TeV	JHEP 01 (2013) 063	5 fb⁻¹
ZZ	8 TeV	PLB 740 (2015) 250	20 fb⁻¹
ZZ	13 TeV	EPJC 81 (2021) 200	137 fb⁻¹
VVV	13 TeV	PRL 125 151802 (2020)	137 fb⁻¹
WWW	13 TeV	PRL 125 151802 (2020)	137 fb⁻¹
WWZ	13 TeV	PRL 125 151802 (2020)	137 fb⁻¹
WZZ	13 TeV	PRL 125 151802 (2020)	137 fb⁻¹
ZZZ	13 TeV	PRL 125 151802 (2020)	137 fb⁻¹
WVγ	8 TeV	PRD 90 032008 (2014)	19 fb⁻¹
WWγ	13 TeV	SMP-22-006	138 fb⁻¹
Wγγ	8 TeV	JHEP 10 (2017) 072	19 fb⁻¹
Wγγ	13 TeV	JHEP 10 (2021) 174	137 fb⁻¹
Zγγ	8 TeV	JHEP 10 (2017) 072	19 fb⁻¹
Zγγ	13 TeV	JHEP 10 (2021) 174	137 fb⁻¹
VBF W	8 TeV	JHEP 11 (2016) 147	19 fb⁻¹
VBF W	13 TeV	EPJC 80 (2020) 43	36 fb⁻¹
VBF Z	7 TeV	JHEP 10 (2013) 101	5 fb⁻¹
VBF Z	8 TeV	EPJC 75 (2015) 66	20 fb⁻¹
VBF Z	13 TeV	EPJC 78 (2018) 589	36 fb⁻¹
EW WV	13 TeV	PLB 834 (2022) 137438	138 fb⁻¹
ex. γγ→WW	8 TeV	JHEP 08 (2016) 119	20 fb⁻¹
EW qqWγ	8 TeV	JHEP 06 (2017) 106	20 fb⁻¹
EW qqWγ	13 TeV	PRD 108 032017	138 fb⁻¹
EW os WW	13 TeV	PLB 841 (2023) 137495	138 fb⁻¹
EW ss WW	8 TeV	PRL 114 051801 (2015)	19 fb⁻¹
EW ss WW	13 TeV	PLB 809 (2020) 135710	137 fb⁻¹
EW qqZγ	8 TeV	PLB 770 (2017) 380	20 fb⁻¹
EW qqZγ	13 TeV	PRD 104 072001 (2021)	137 fb⁻¹
EW qqWZ	13 TeV	PLB 809 (2020) 135710	137 fb⁻¹
EW qqZZ	13 TeV	PLB 812 (2020) 135992	137 fb⁻¹

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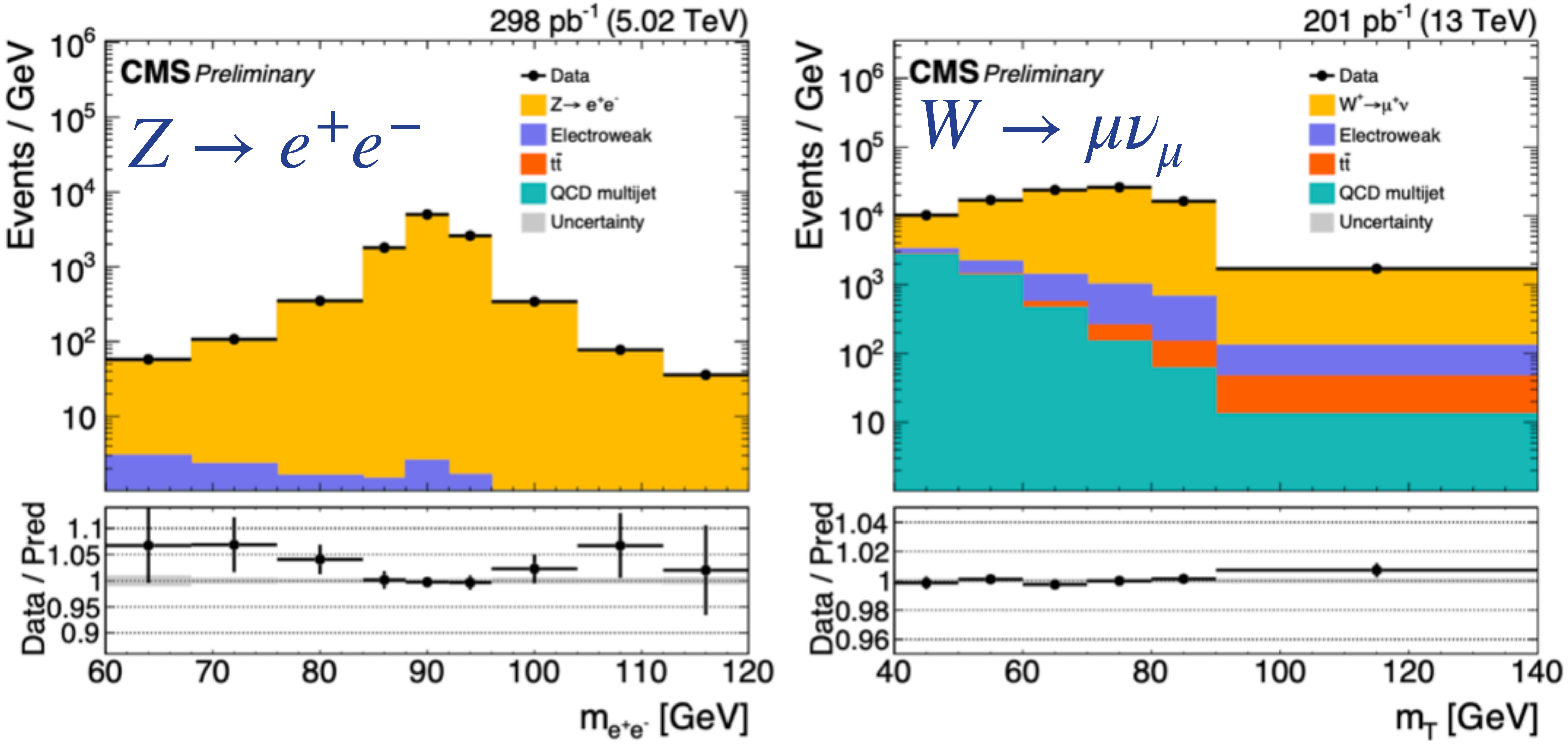
CMS-PAS-20-004

Single Boson production cross-sections

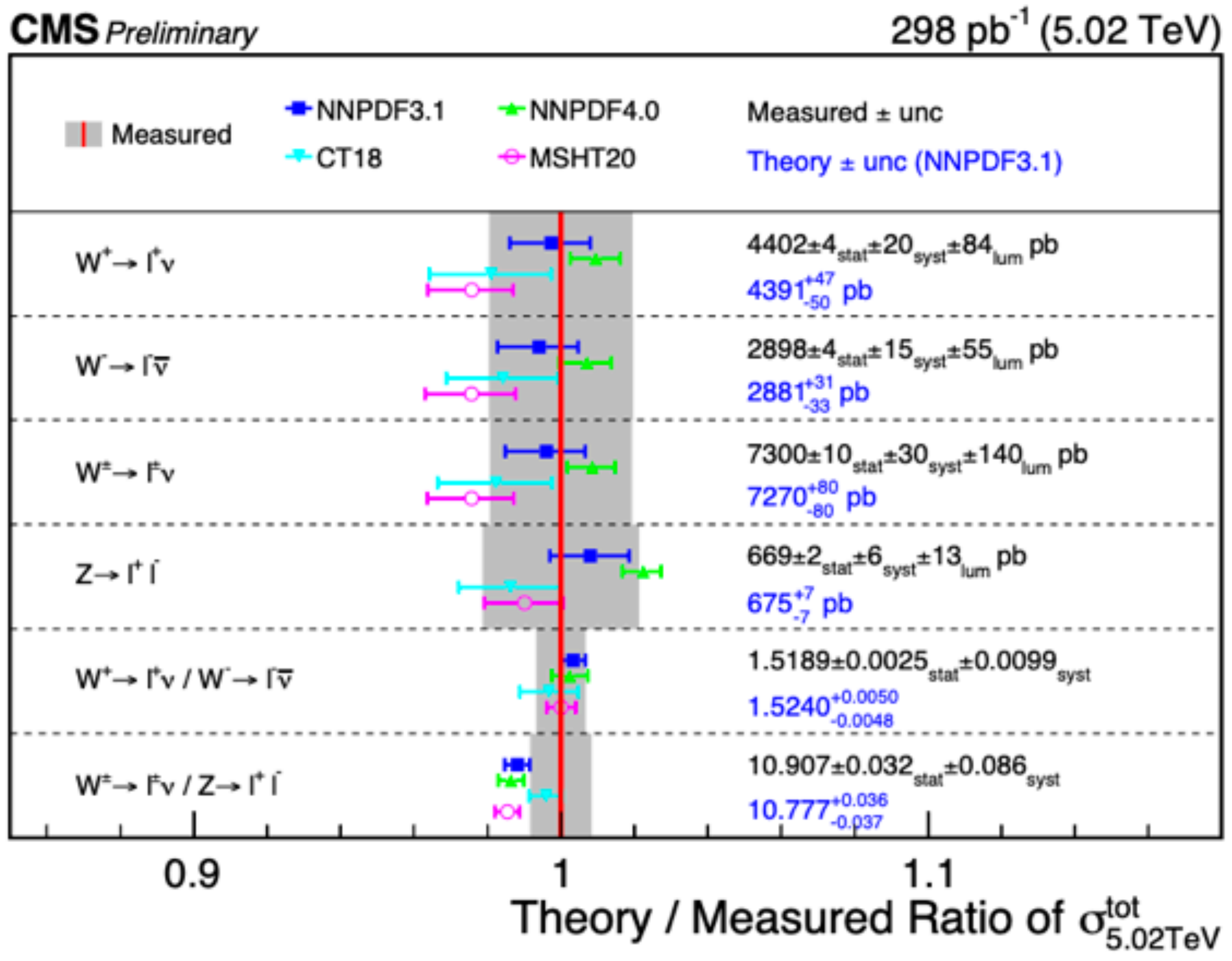
Standard Candles

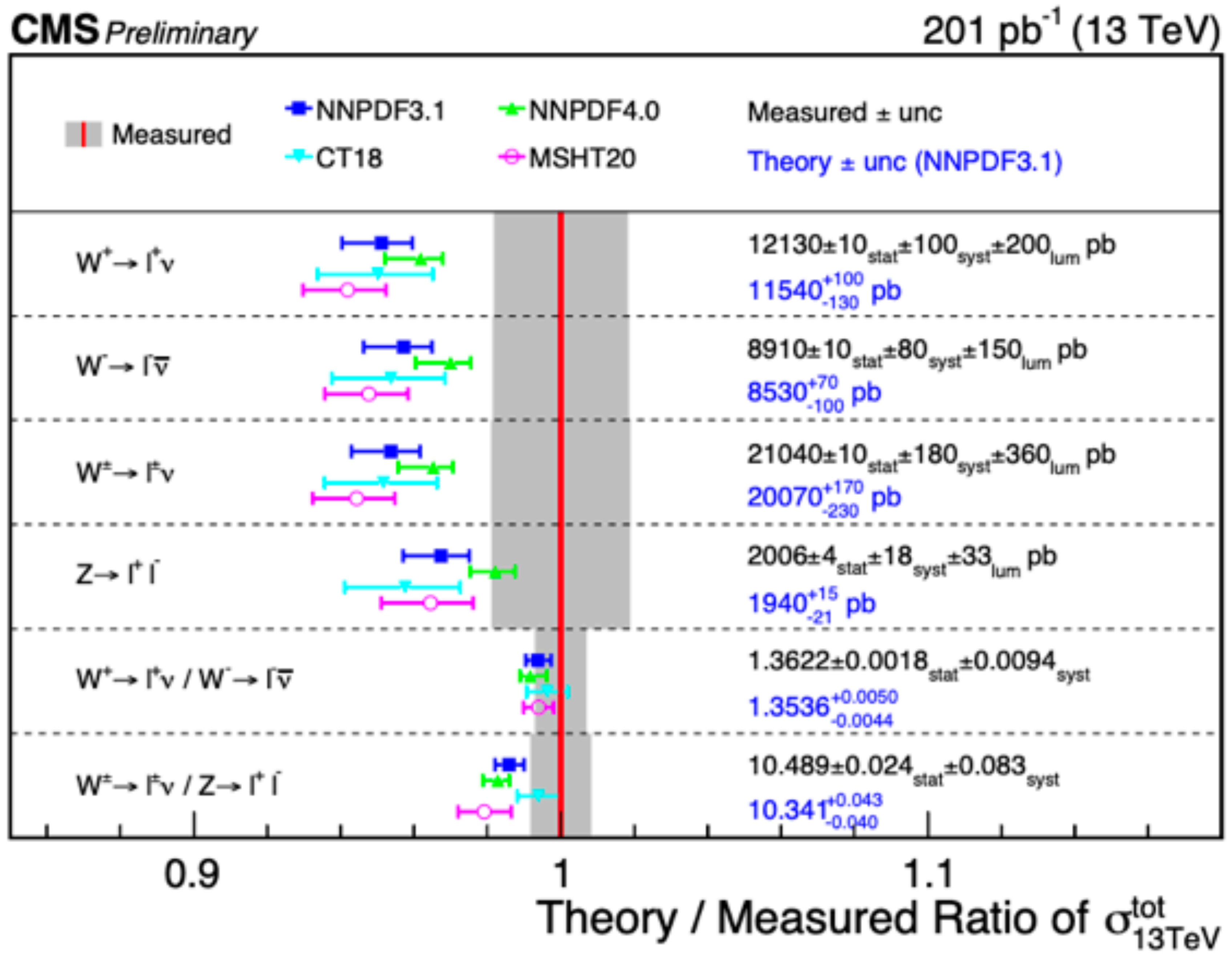


- Production cross section $\sigma = N^{obs}/(A \cdot \epsilon \cdot \mathcal{L})$
  - N^{obs} = observed events, A = acceptance, ϵ = efficiency, $\mathcal{L}$ = integrated luminosity
- Z boson fully reconstructed from 2 charged leptons, W boson partially from lepton + p_T^{miss}
- Measurement in low-PU data: $\langle N_{PU} \rangle = 3 \to$ better p_T^{miss} resolution
- Fitting signal strength of MC predictions to data, backgrounds from MC or data sidebands

CMS-PAS-20-004

W & Z production at 5 & 13 TeV



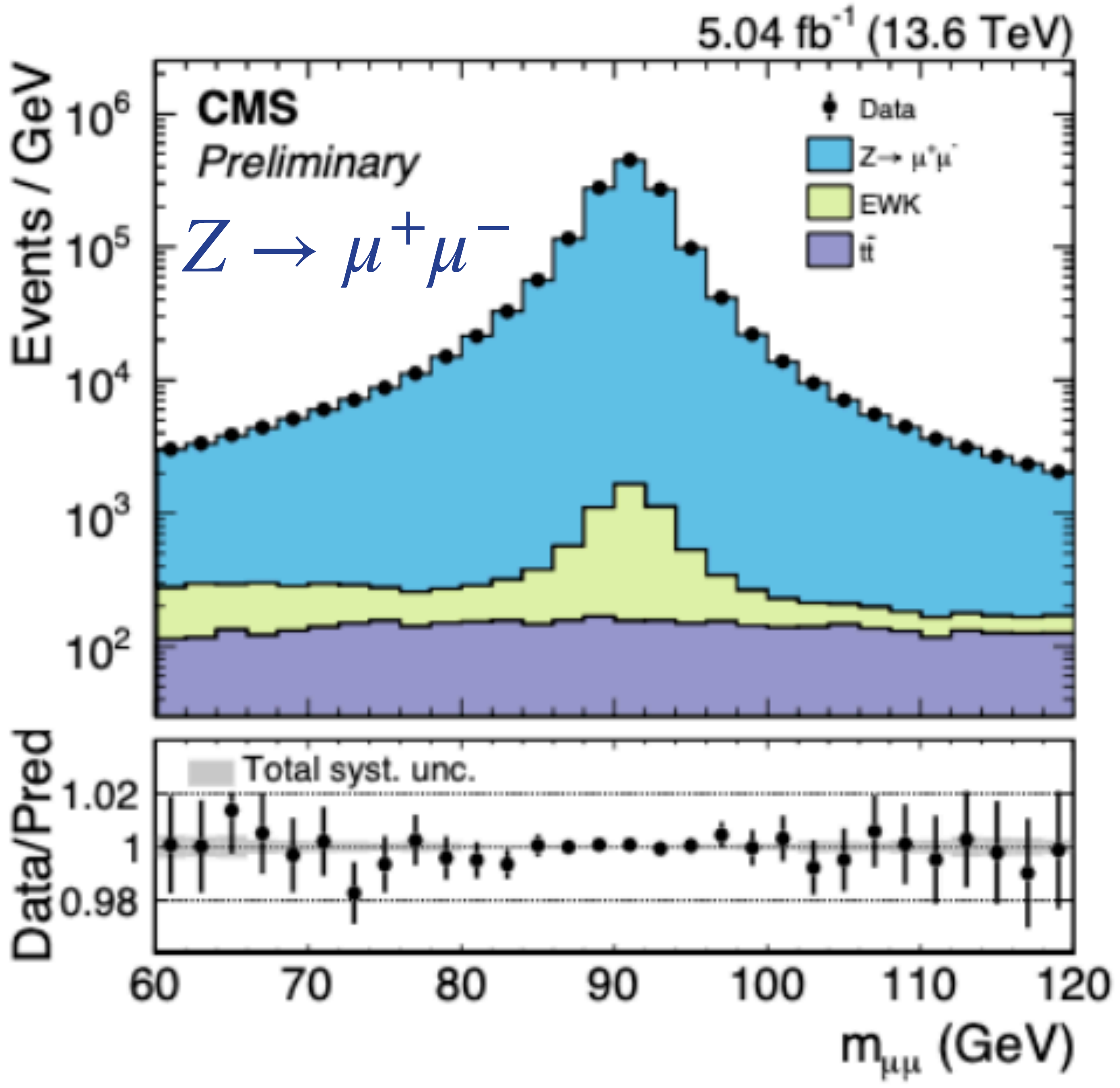


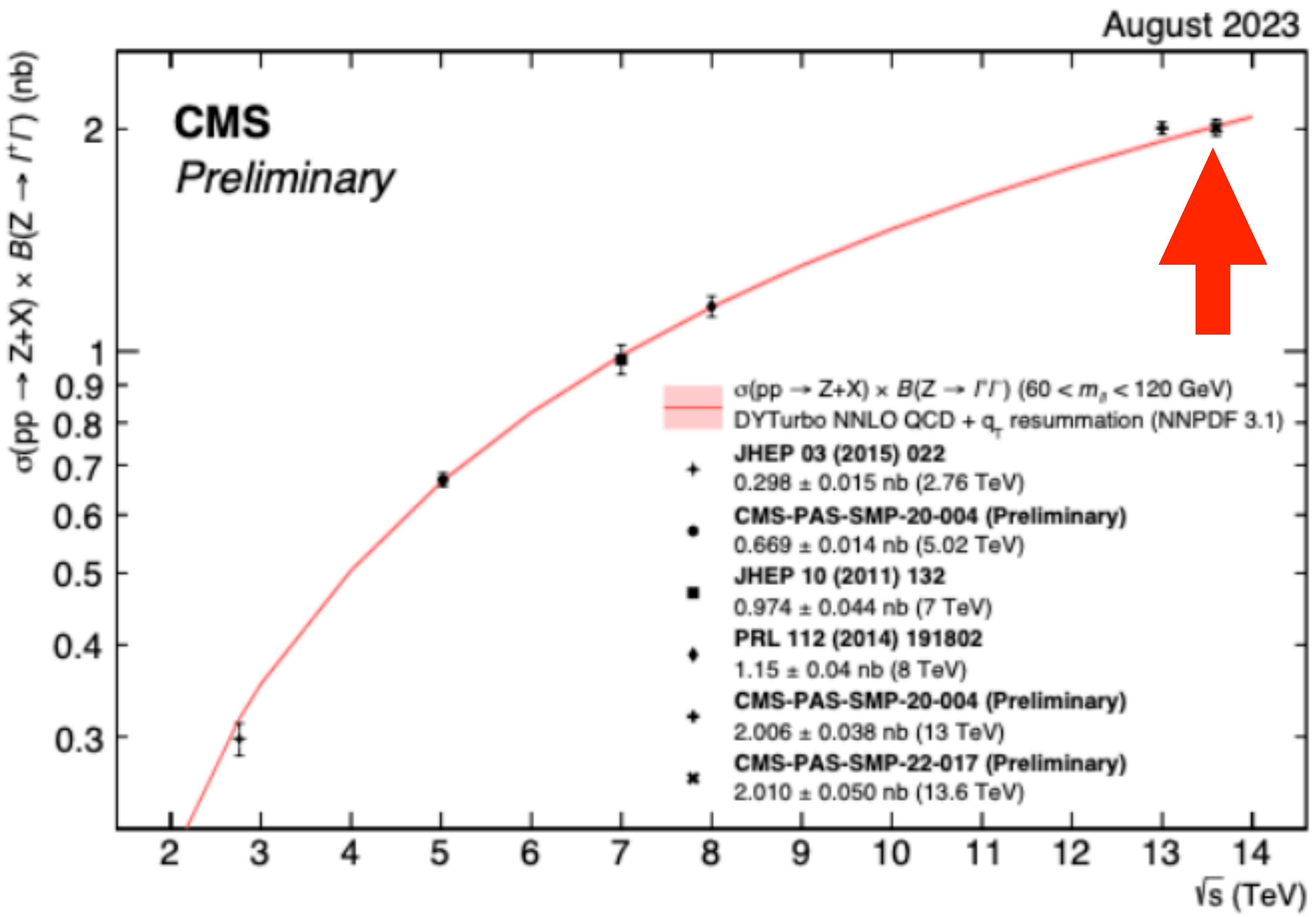
- Special runs with low instantaneous luminosity, N(PU)=3, taken at different energies to measure W and Z production cross section
- 5TeV results agree well with the predictions (using NNPDF3.1)
- 13 TeV results (right) show a cross section about 5% higher than expected, not covered by uncertainties (mostly = Lumi)

CMS-PAS-22-017

Z production cross section at 13.6 TeV

First measurement with early 2022 data





- Preliminary calibration for muon efficiency, muon momentum scale and luminosity
- Excellent agreement with NNLO predictions for $Z/\gamma^* \to \ell^+\ell^-$ with $60 < M(\ell\ell) < 120\,GeV$ suggest the 13TeV result was an outlier.

$$(\sigma_{\text{tot}}\mathcal{B})_{\text{measured}} = (2.010 \pm 0.001(\text{stat}) \pm 0.018(\text{syst}) \pm 0.046(\text{lumi}) \pm 0.007(\text{theo}))\,\text{nb},$$

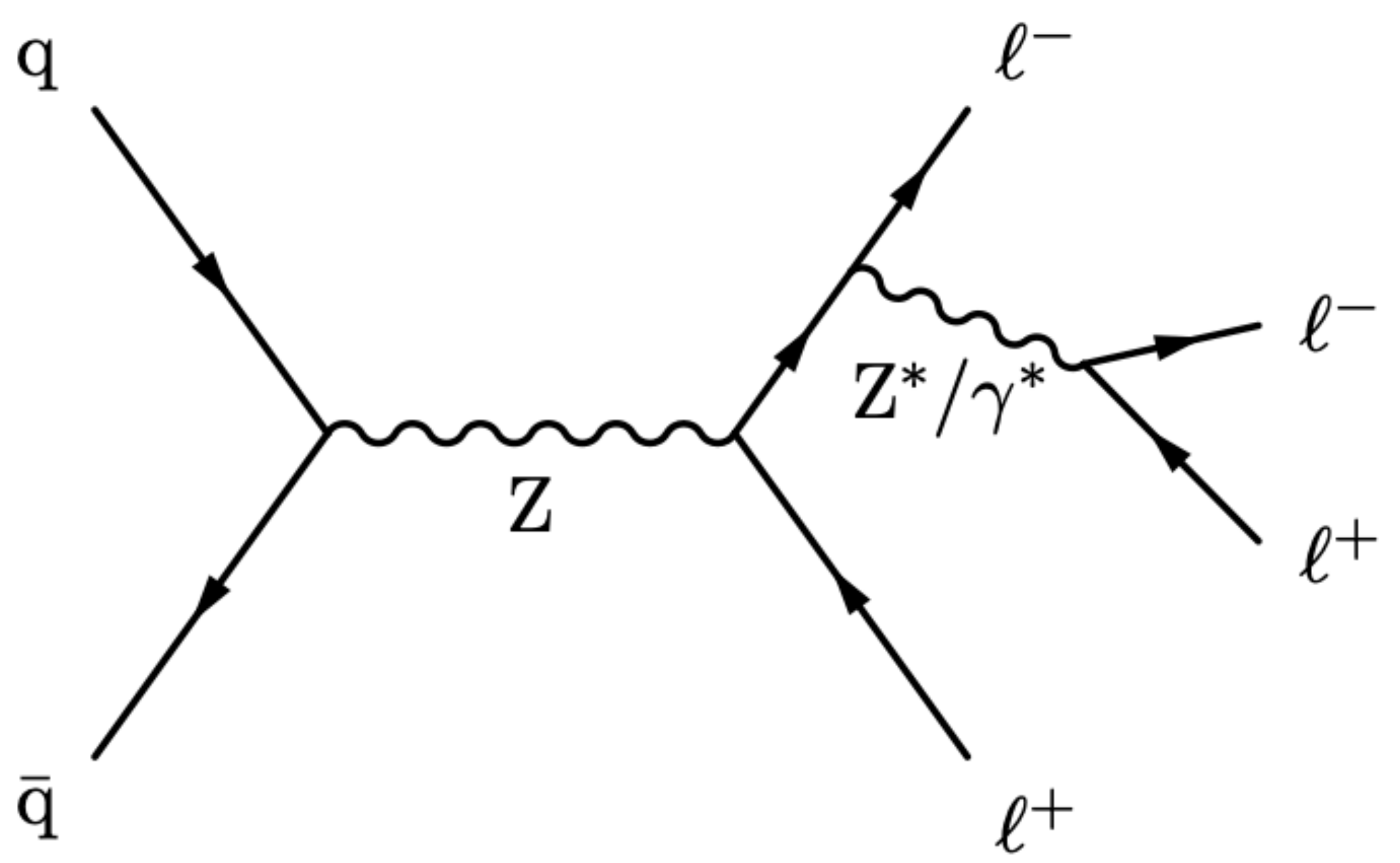
$$(\sigma_{\text{tot}}\mathcal{B})_{\text{predicted}} = (2.018 \pm 0.012(\text{PDF})^{+0.018}_{-0.023}(\text{scale}))\,\text{nb},$$

CMS-PAS-19-007

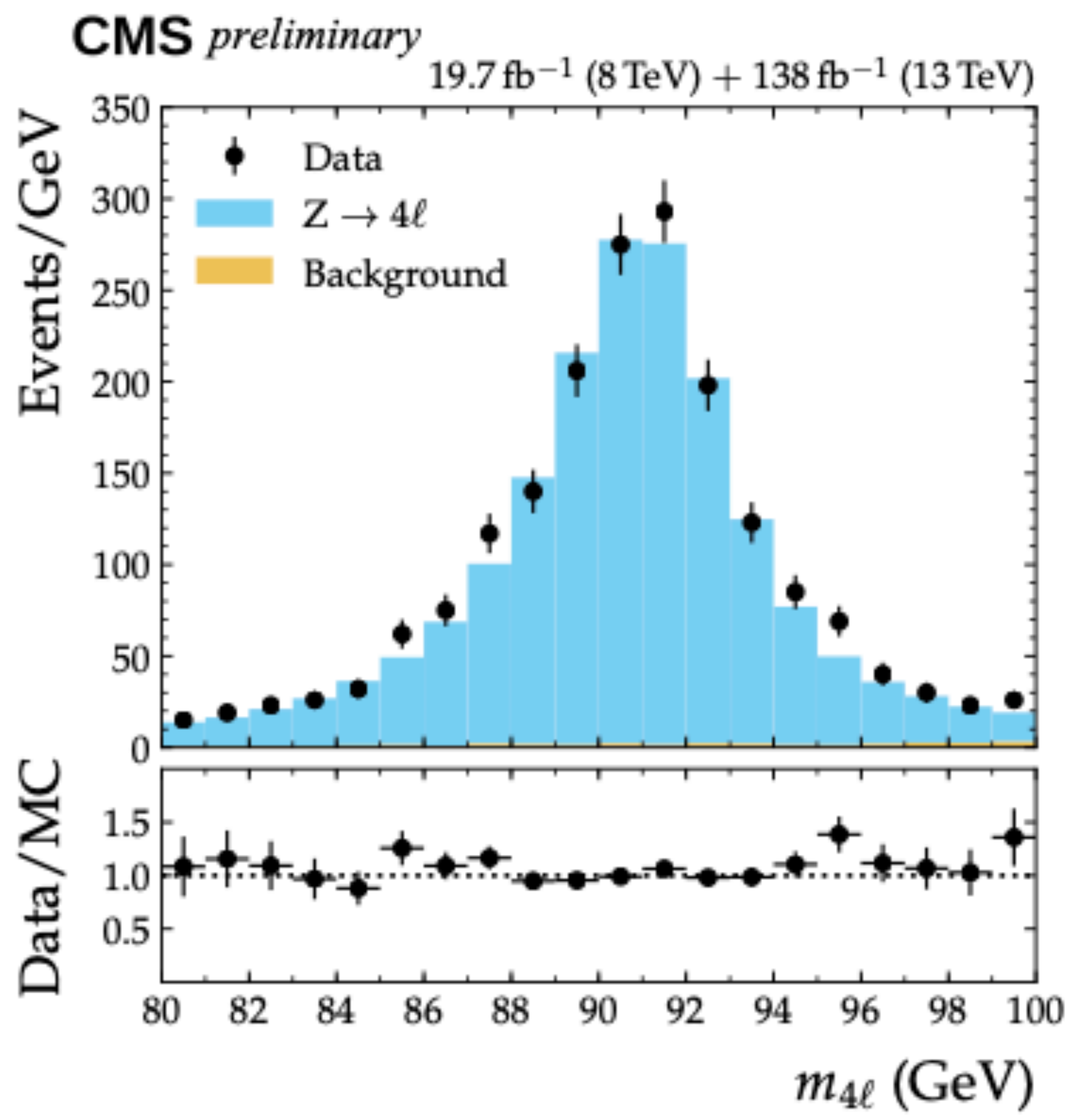
CMS-EXO-18-008

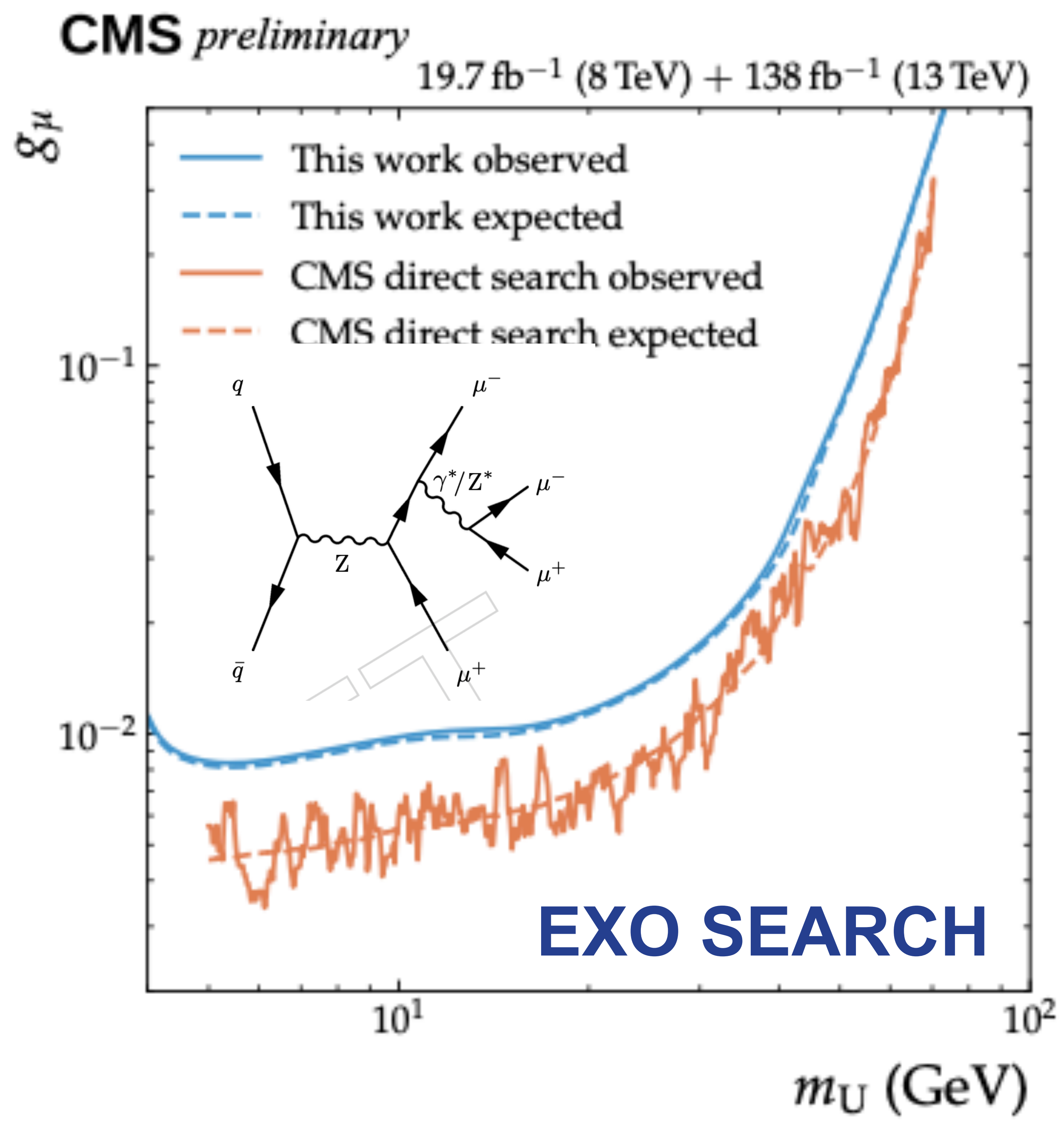
Z decays to 4 leptons (e,μ)

Rare process



$Z \to \ell^+\ell^-\ell^+\ell^-$

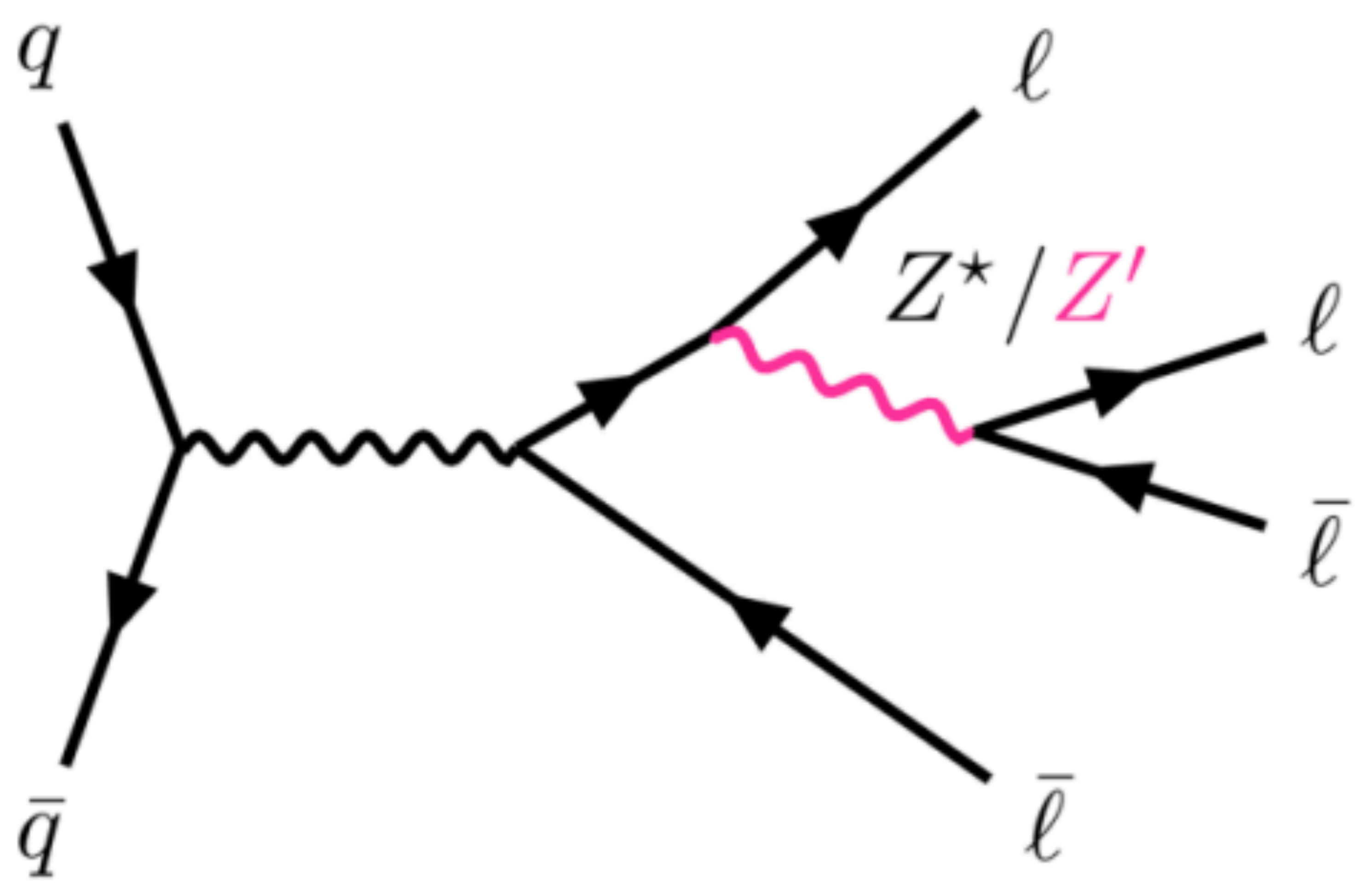


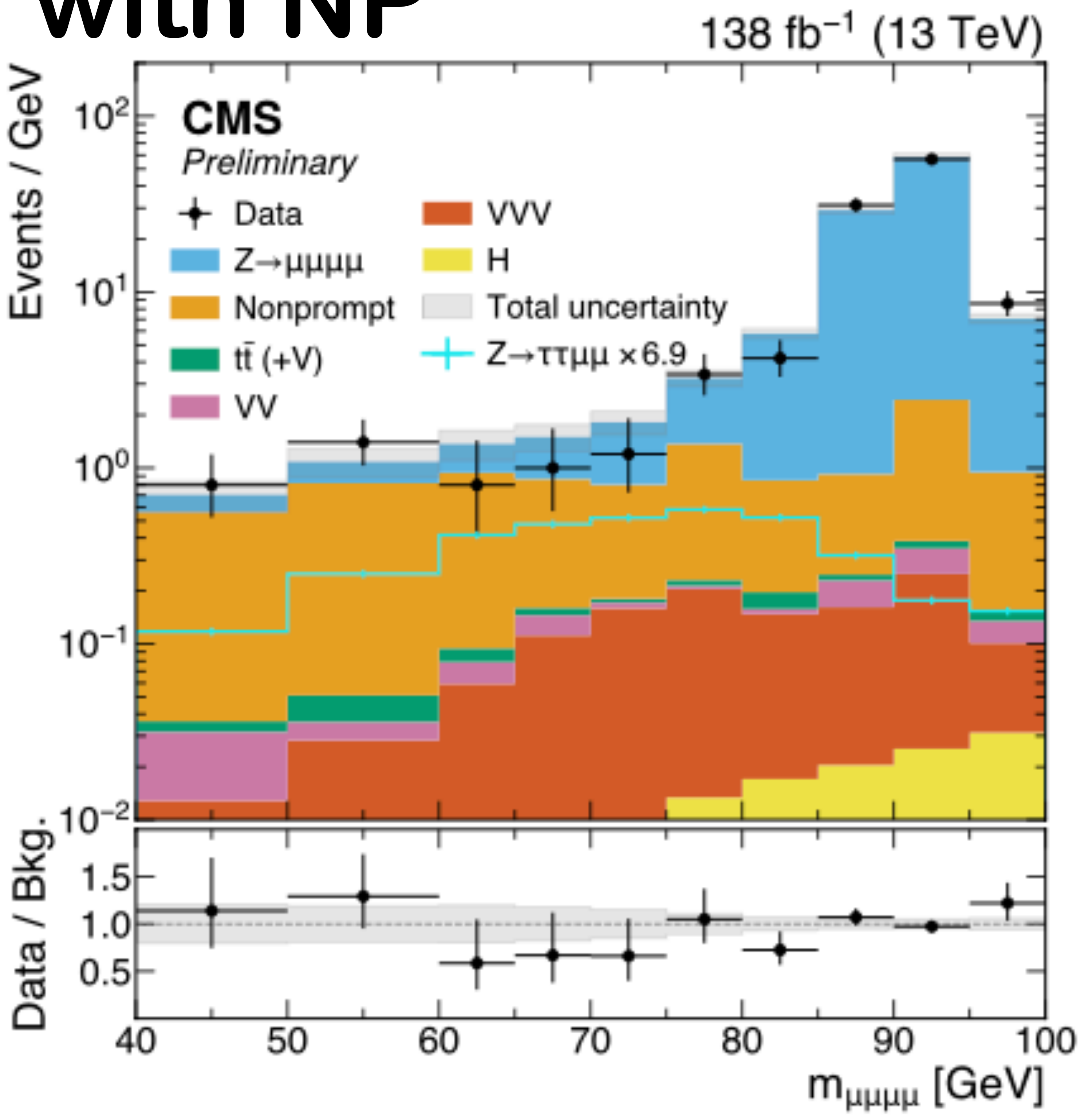


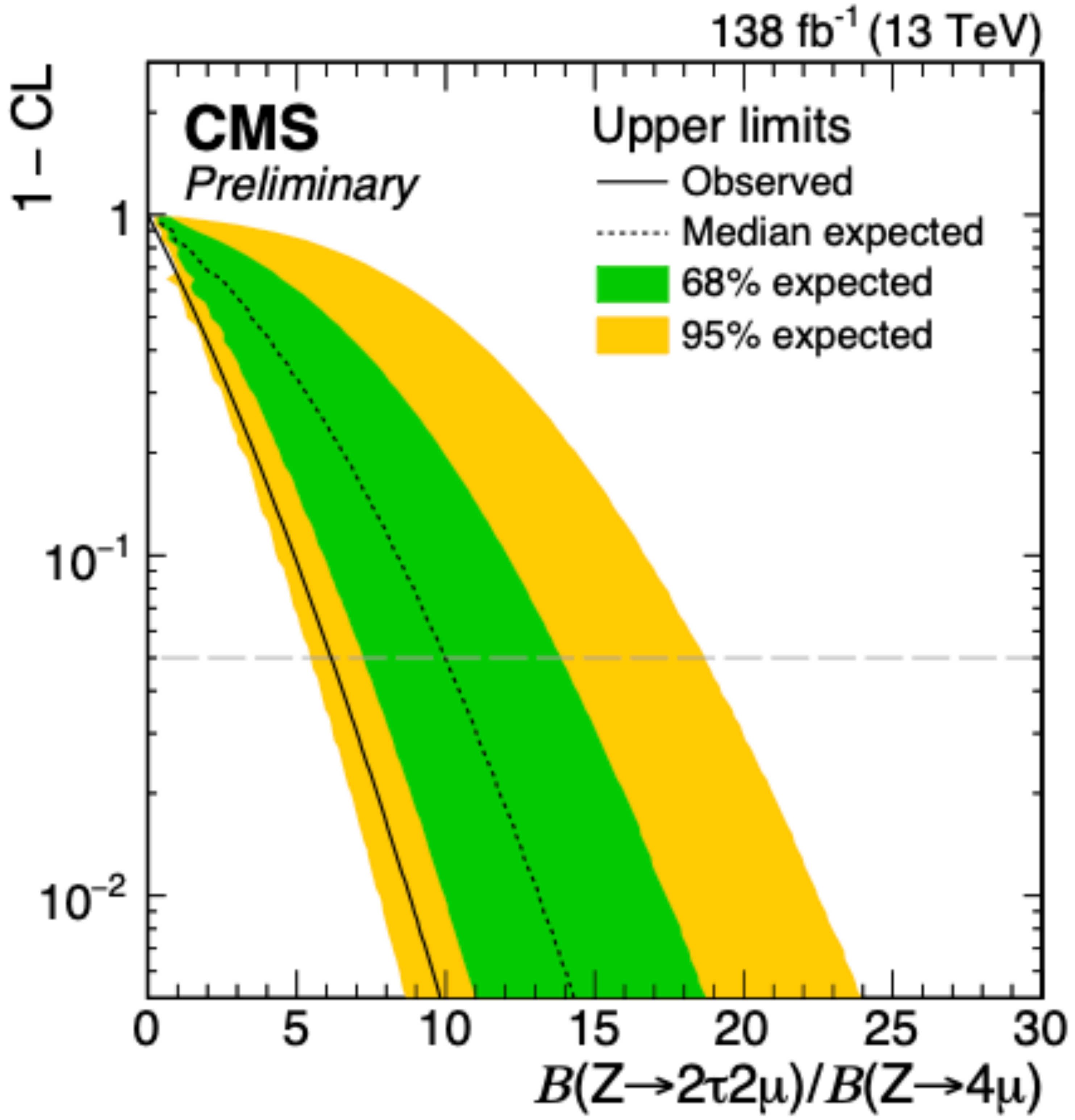
- Select events with 4 e or μ with $80 < M(4\ell) < 100\,GeV$
- Minimize uncertainties by normalising to $Z \to 2\ell$ proces
- Result: $\mathcal{B}(Z \to 4\ell) = (4.67 \pm 0.11(stat) \pm 0.10(syst)) \times 10^{-6}$, expected $(4.70 \pm 0.02) \times 10^{-6}$
- Reinterpretation in term of limits on couplings and mass of new light gauge boson U (motivated by g-2 anomaly) does exclude lare part of the favoured region

Search for Z decays to 4 leptons (μ, τ)

3rd gen tighter connection with NP





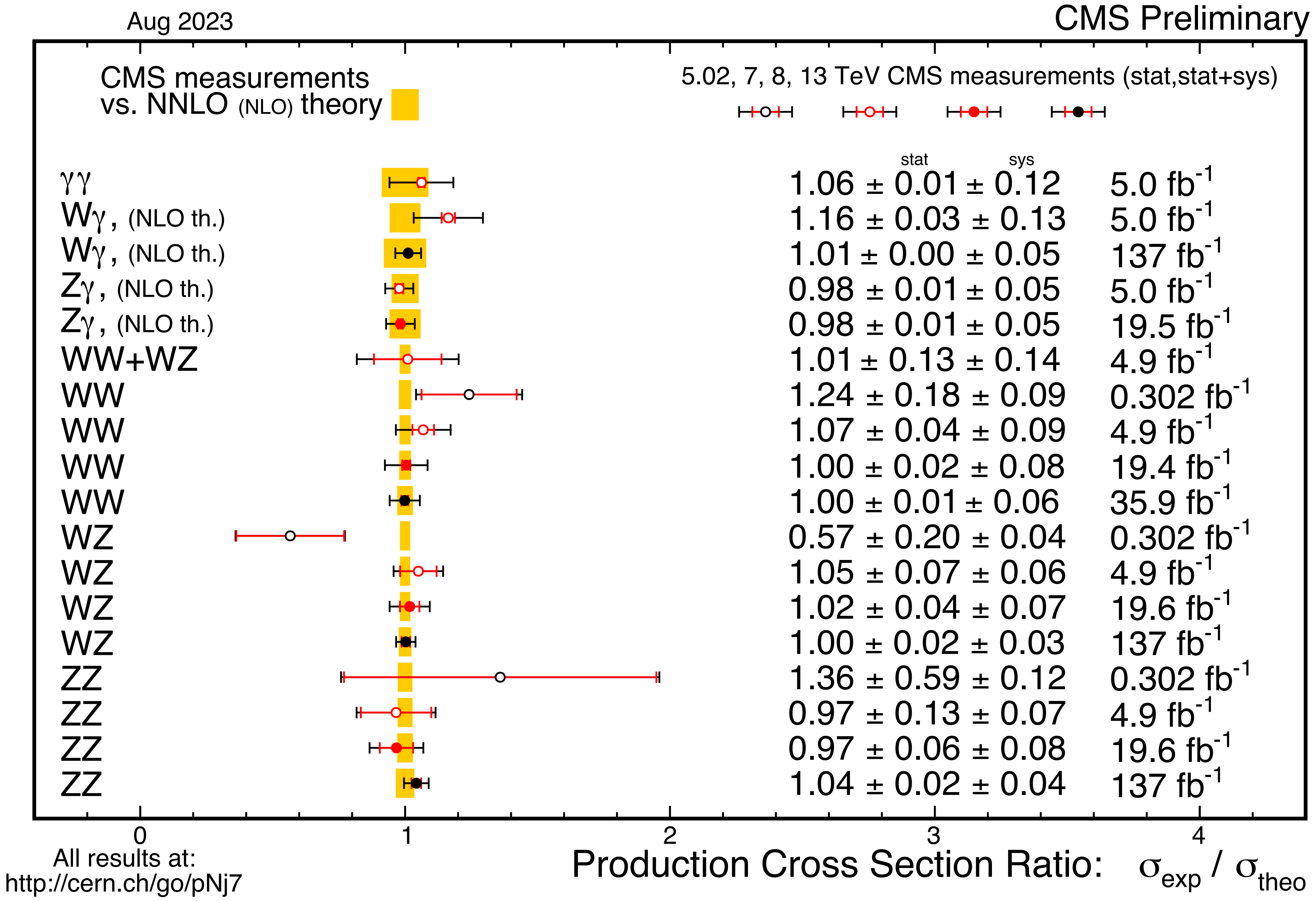


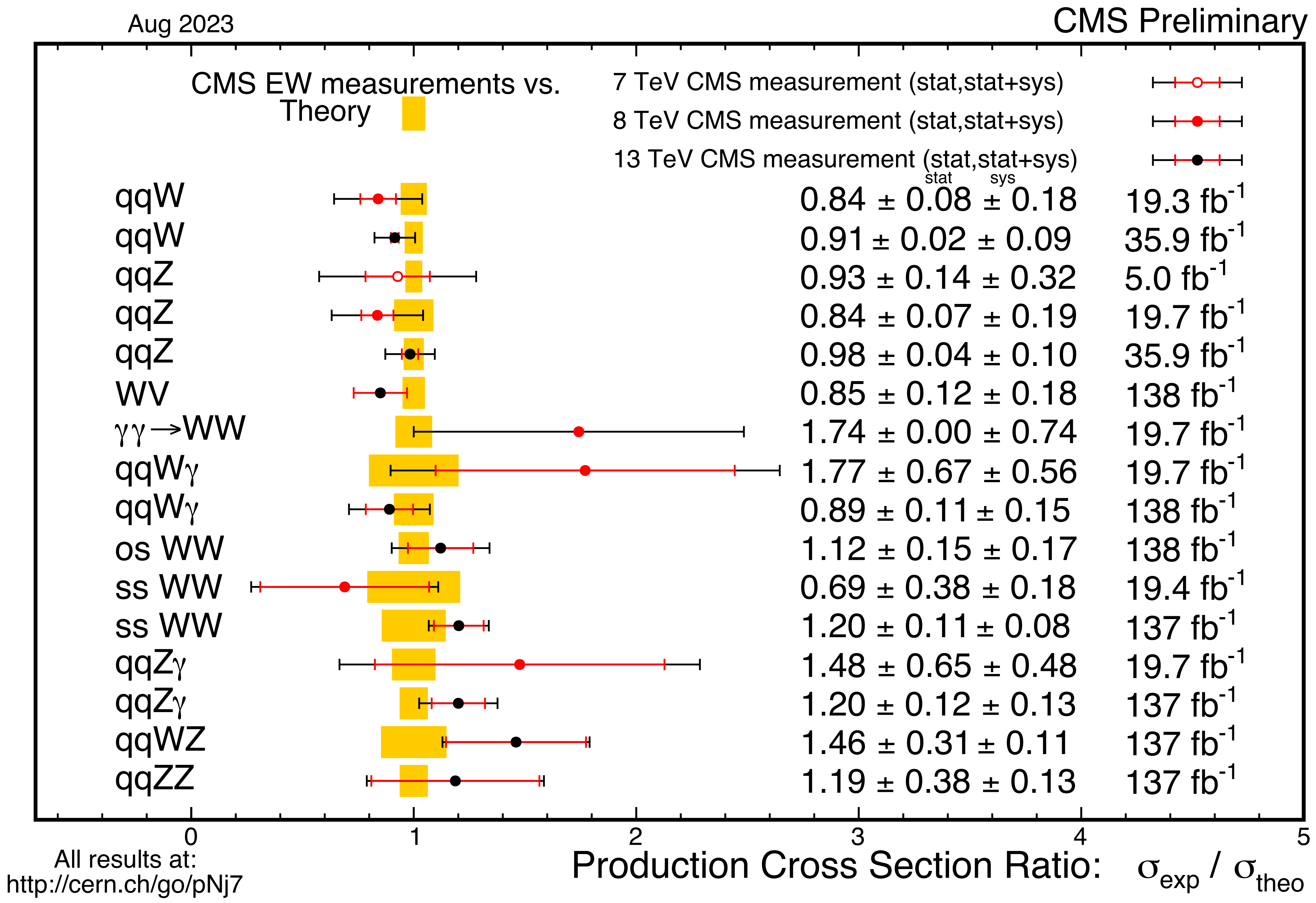
- Search for Z' boson in the process: $Z \to \tau^+\tau^-\mu^+\mu^-$ where $\tau \to \mu\bar{\nu}_\mu\nu_\tau$
- Systematics cancel if we evaluate the ratio $\dfrac{\mathscr{B}(Z \to \tau\tau\mu\mu)}{\mathscr{B}(Z \to \mu\mu\mu\mu)}$
- No signal observed, actually deficit in signal region. **Limit on BR<6.9 x SM [95%CL]**

Di-Boson Measurements

crucial tests of the Standard Model (SM)

- **Vector boson self-interactions are fundamental prediction of SM resulting from non-Abelian nature of the SU(2)xU(1) gauge theory**
- Di-boson processes are important backgrounds for Higgs measurements and NP searches
- Anomalous triple and quartic gauge boson couplings (aTGC and aQGC) would imply New Physics





QCD PRODUCTION

Experiment demands $\mathcal{O}(1\%)$ theoretical precision

EWK PRODUCTION

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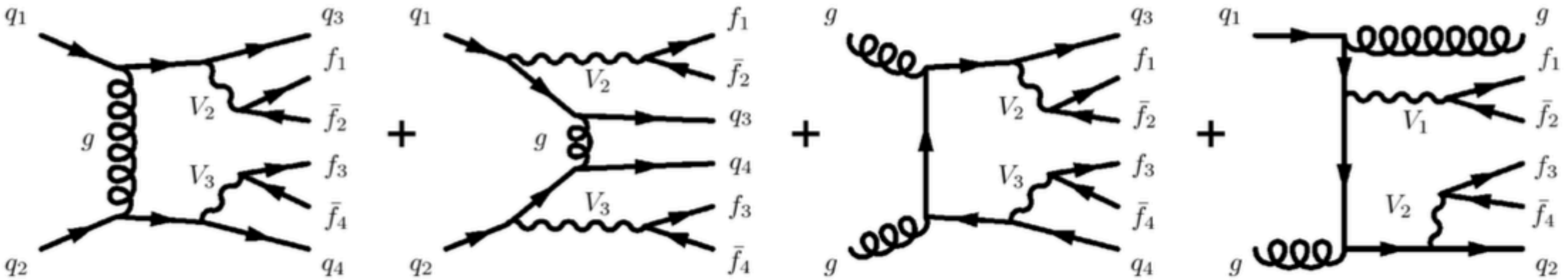
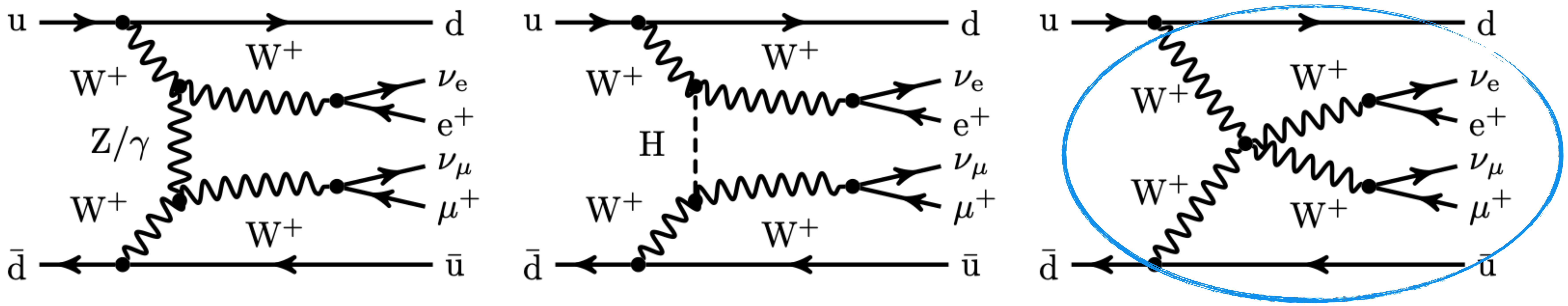
https://arxiv.org/pdf/1708.00268.pdf

Di-boson production processes

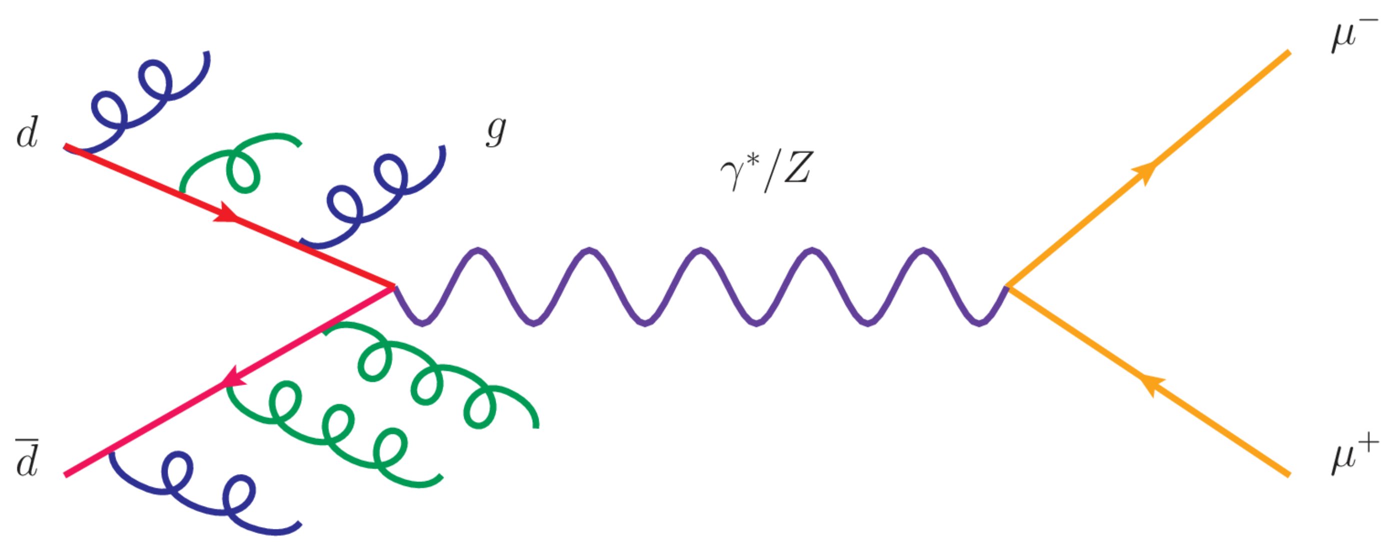
Theory perspective



- $\mathcal{O}(\alpha_s^2\alpha_{ew}^4)$ QCD induced process



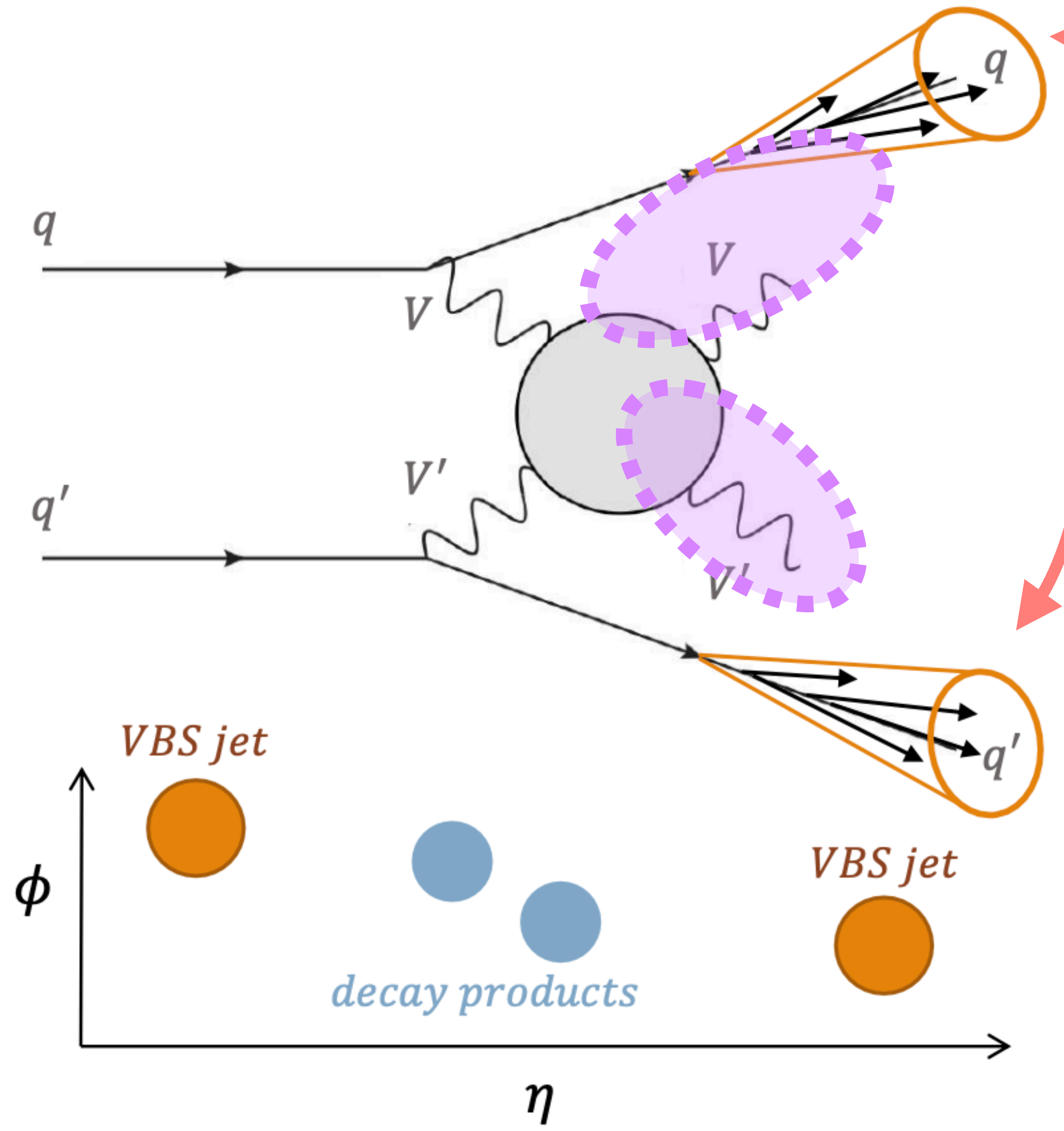
- $\mathcal{O}(\alpha_{ew}^6)$ **process: quartic diagrams** + gauge invariant diagrams



- Typical Background $\mathcal{O}(\alpha_s^4\alpha_{ew}^2)$ V+jets

VBS di-boson production

Pure EWK process: small cross section (few fb)



TWO FORWARD JETS (large η) W/ LITTLE HADRONIC ACTIVITY IN BETWEEN (rapidity gap)

TWO CENTRALLY PRODUCED BOSONS

- Experimental selection based on:
  - VBF jets with large $\Delta\eta_{jj}$ and large M_{jj}
  - Triggering on boson decay products
- S/B heavily depending on boson decay
- Profit of ML techniques to extract signal

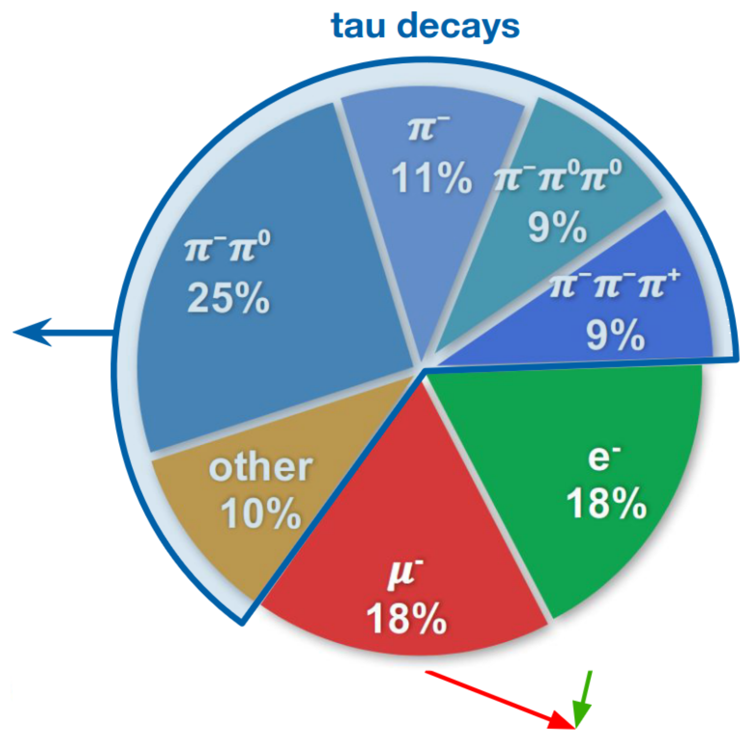
VBS ssWW dilepton with tau

CMS-PAS-22-008

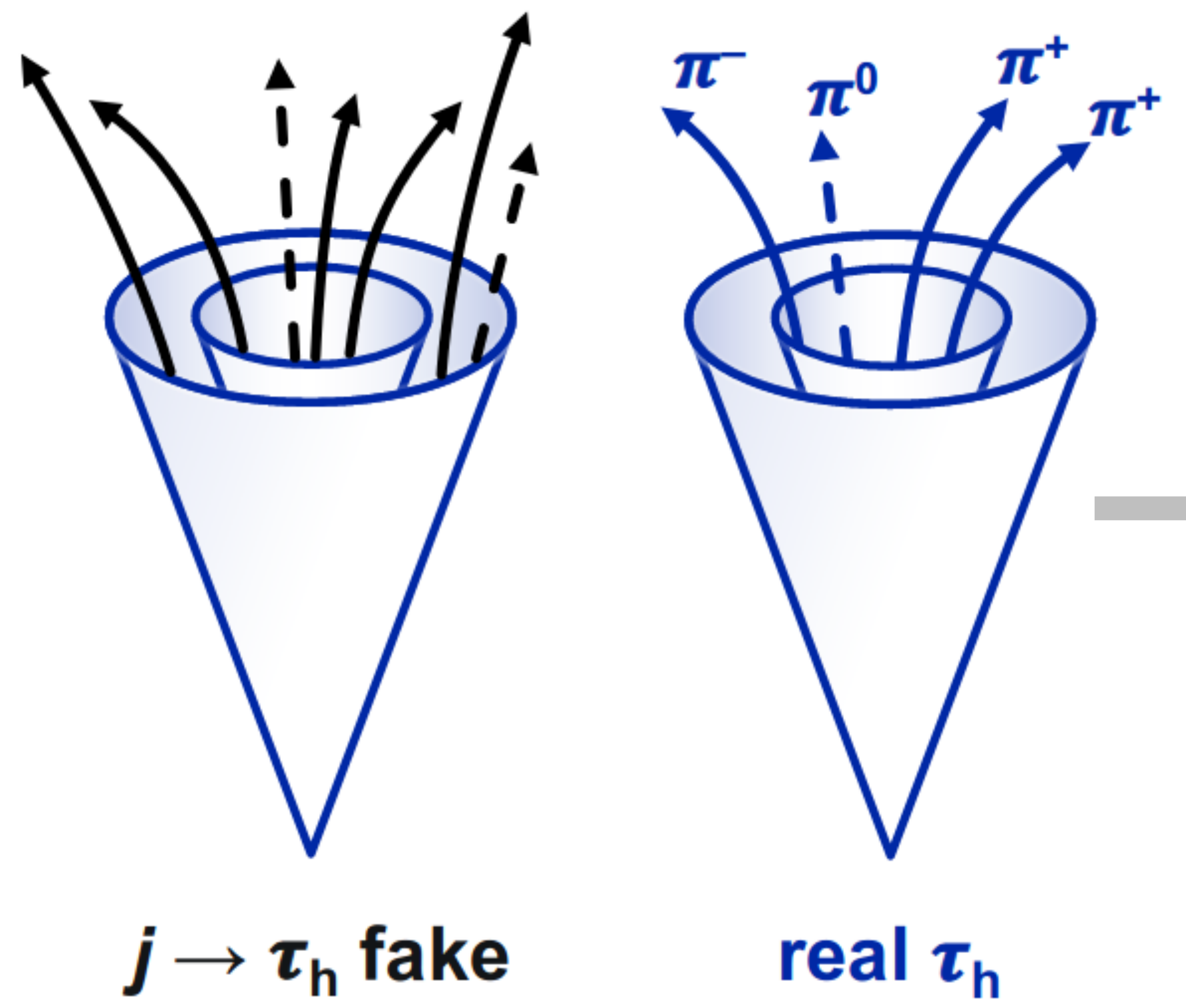
First measurement with a τ_{had} in the final state

~64% BR to hadrons

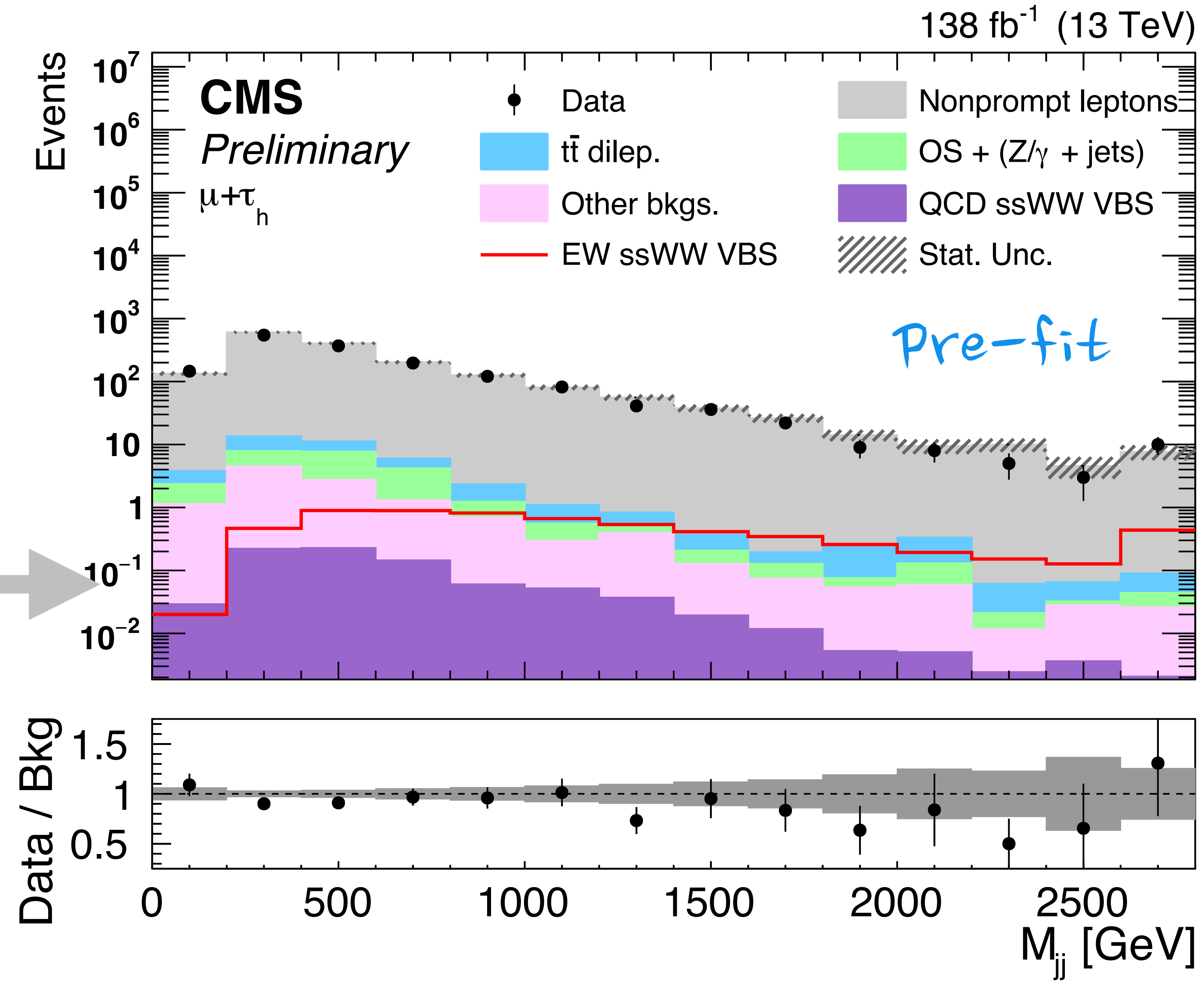
$$q\bar{q} \rightarrow W^{\pm}W^{\pm}q\bar{q} \rightarrow \tau_h^{\pm}\nu_{\tau}\ell^{\pm}\nu_{\ell}q\bar{q}$$



- Large BR but suffering large experimental background:
  - ~95% of the events with non-prompt leptons from jets misreconstructed as e,μ, or τ_h. Data estimate needed
  - ~2% are from Z/γ*+jets
  - 1% from dileptonic $t\bar{t}$ events



"Non-prompt leptons" background estimated from data. Validated in a CR close to the SR



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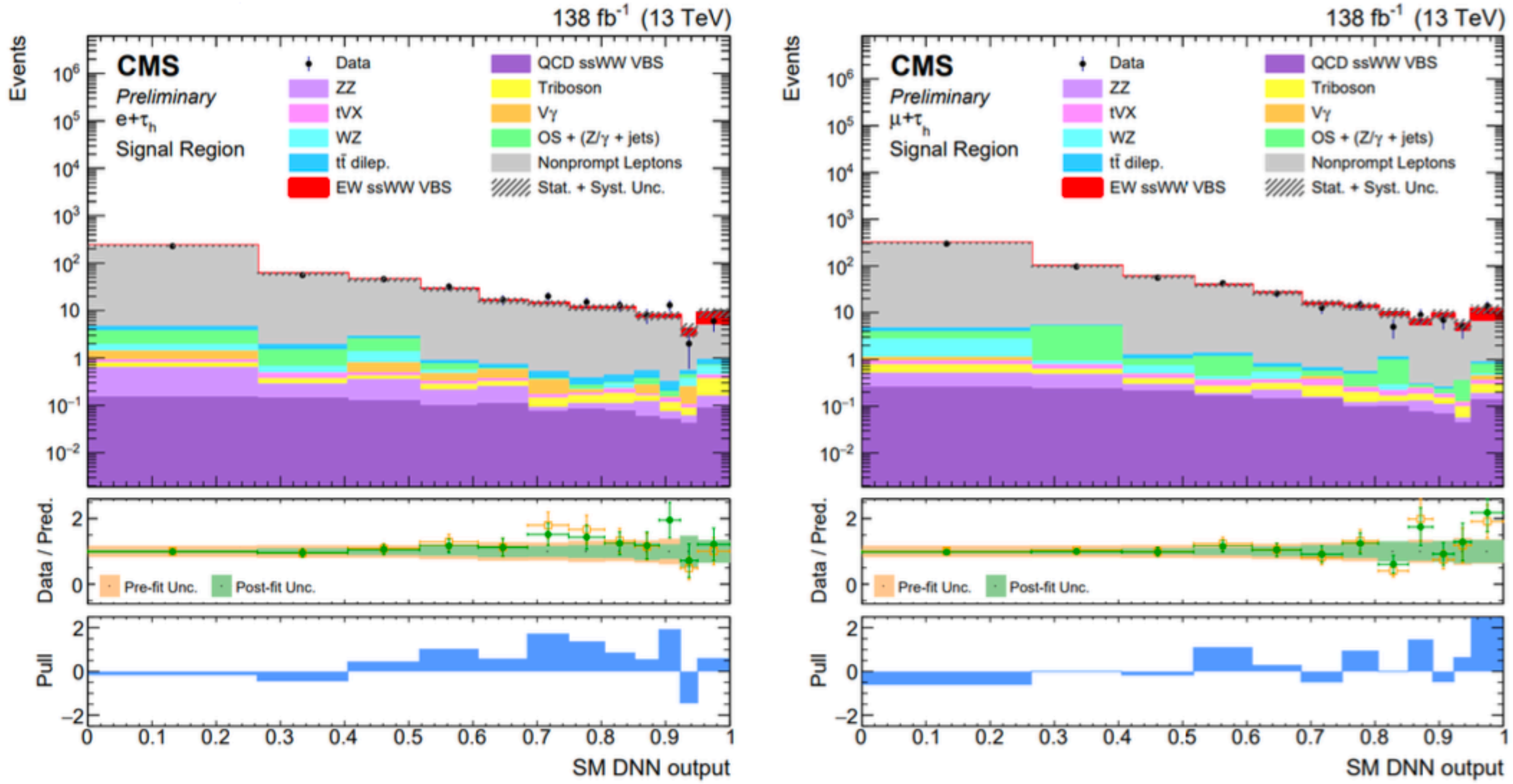
VBS ssWW dilepton with tau

Result

- Simultaneous fit using DNN templates from SR and CRs
- **Two separate measurements: with purely-EW signal strength and one scaling together the EW and QCD ssWW signal strength**
- *Statistical uncertainty dominates: will profit of Run 3 data!*



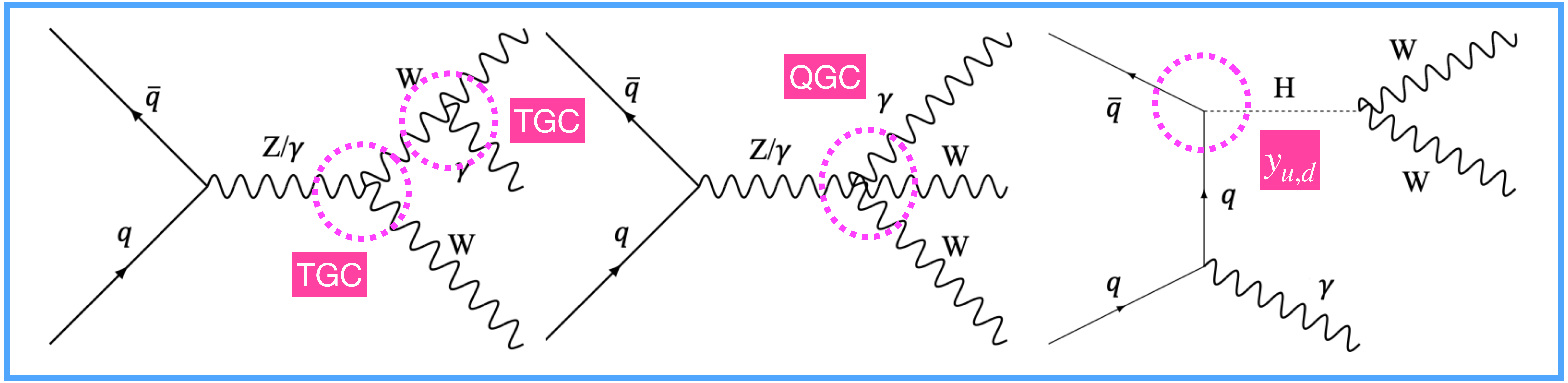
	Significance [#σ] (expected)	μ (expected)
EW	**2.7** (1.9)	$\mathbf{1.44^{+0.63}_{-0.56}}\left(1.00^{+0.60}_{-0.53}\right)$
EW + QCD	**2.9** (2.0)	$\mathbf{1.43^{+0.60}_{-0.54}}\left(1.00^{+0.57}_{-0.51}\right)$

EFT interpretation in progress

CMS-PAS-22-006

$W^+W^-\gamma \rightarrow e^{\pm}\nu_e\mu^{\mp}\nu_\mu\gamma$

Just published!

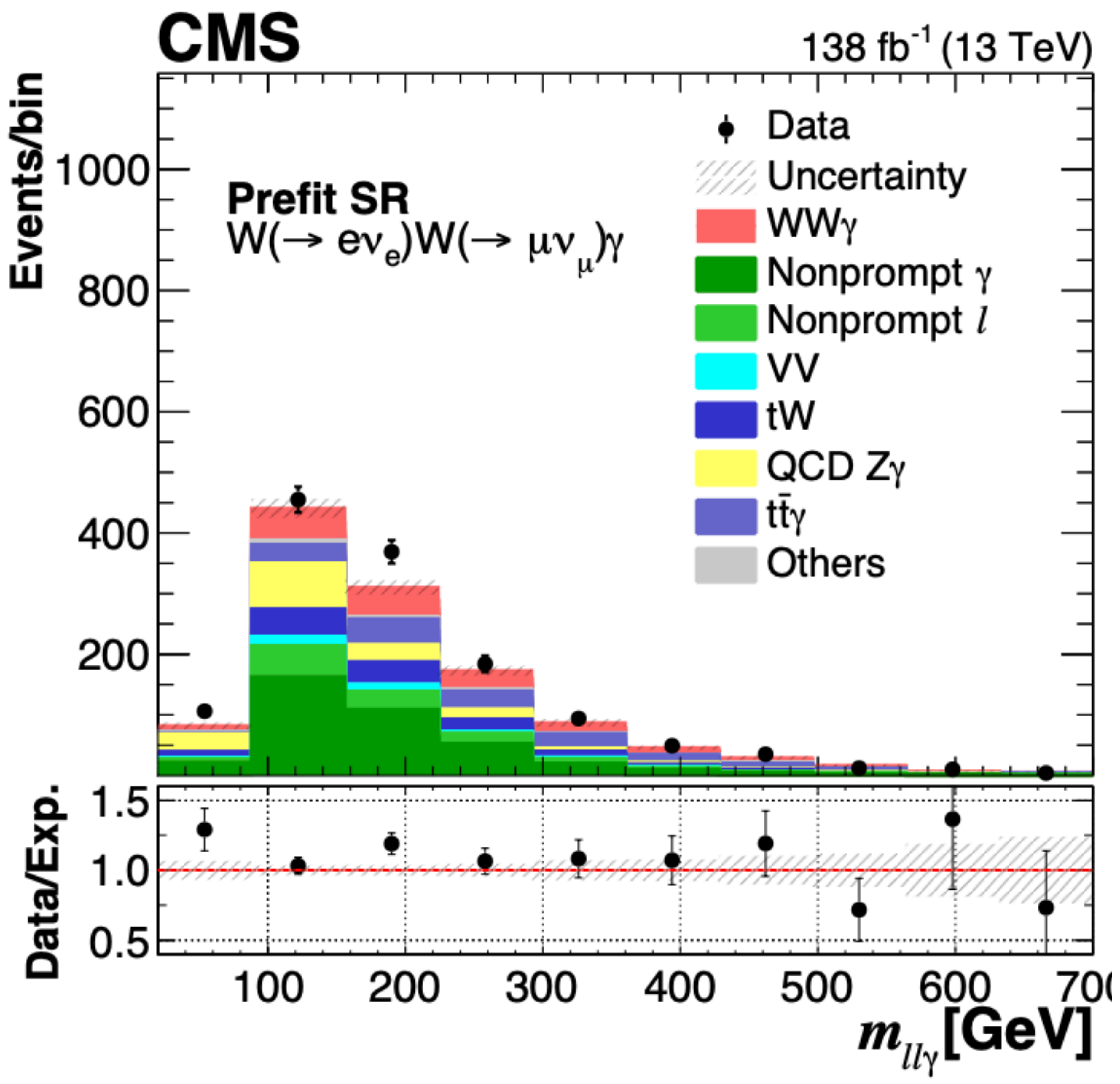


- **Sensitive to Triple and Quartic-gauge couplings**
- Unique opportunity to search for the Higgs+photon production obtaining **constraints on Higgs coupling to light quarks**
- Data driven estimate of non-prompt background(leptons, photons) with specific control regions ($ssWW\gamma$ and $tt\gamma$ respectively) used in the simultaneous final fit
- Result obtained with maximum likelihood fit of 2D binned distributions in the (m^T_{WW}, $m_{\ell\ell\gamma}$) plane

$W^+W^-\gamma \to e^{\pm}\nu_e\mu^{\mp}\nu_\mu\gamma$

CMS-PAS-22-006

Result



Process observed with 5.6 s.d. significance

$$\sigma_{fid} = 6.0 \pm 0.8(stat) \pm 0.7(syst) + 0.6(th)\, fb$$

$$\sigma_{th} = 4.61 \pm 0.34(scale) \pm 0.05(PDF)\, fb$$

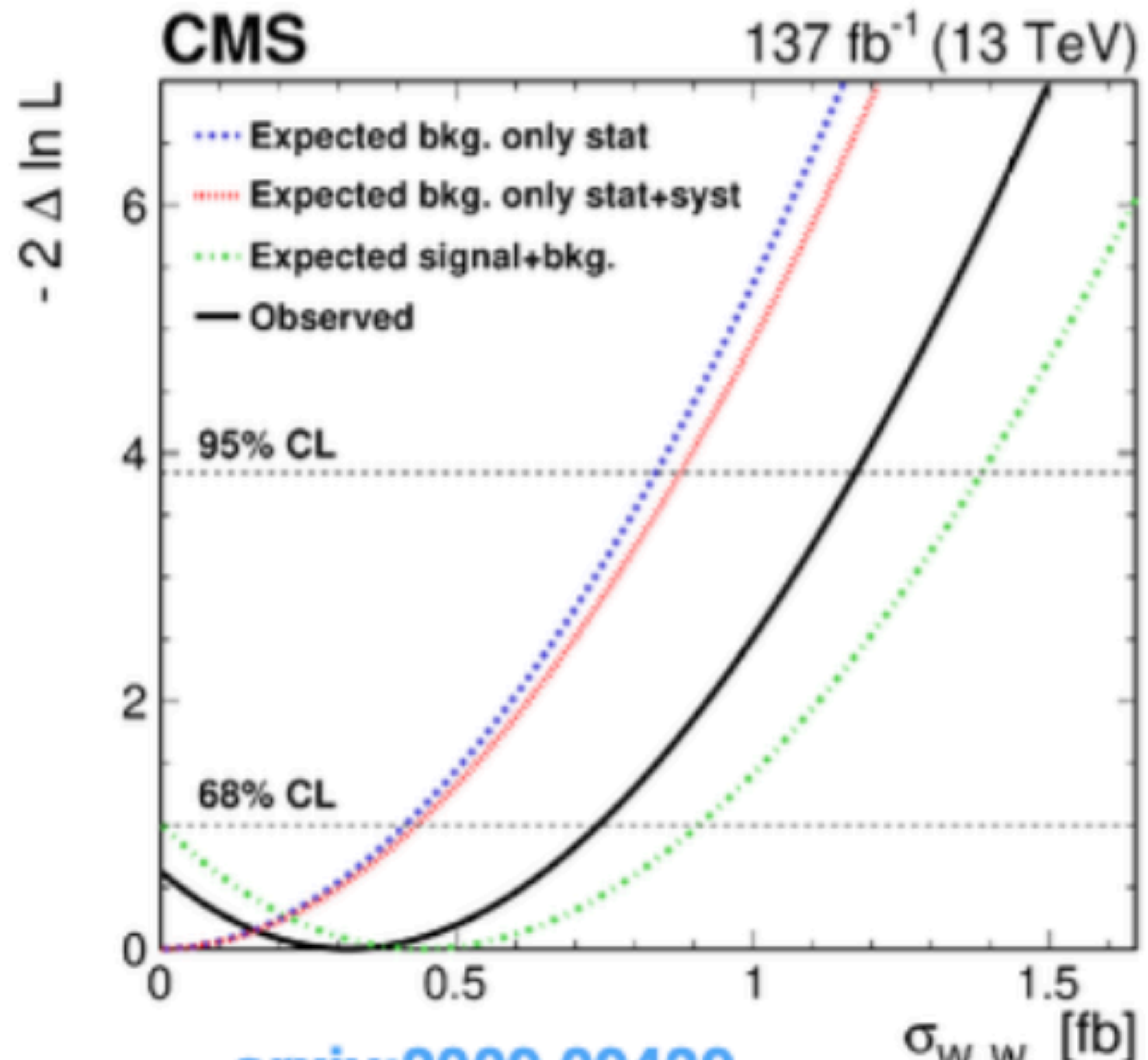
- Targeted search for $H\gamma$ where the $WW\gamma$ is a bkg.
- Fit to $\Delta R_{\ell\ell}$ and m^T_{WW} to extract limits on y_q

Process	σ upper limits obs. (exp.) [fb]	κ_q limits obs. (exp.) at 95% CL
$u\bar{u} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	85 (67)	$\lvert\kappa_u\rvert \leq 16000$ (13000)
$d\bar{d} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	72 (58)	$\lvert\kappa_d\rvert \leq 17000$ (14000)
$s\bar{s} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	68 (49)	$\lvert\kappa_s\rvert \leq 1700$ (1300)
$c\bar{c} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	87 (67)	$\lvert\kappa_c\rvert \leq 200$ (110)

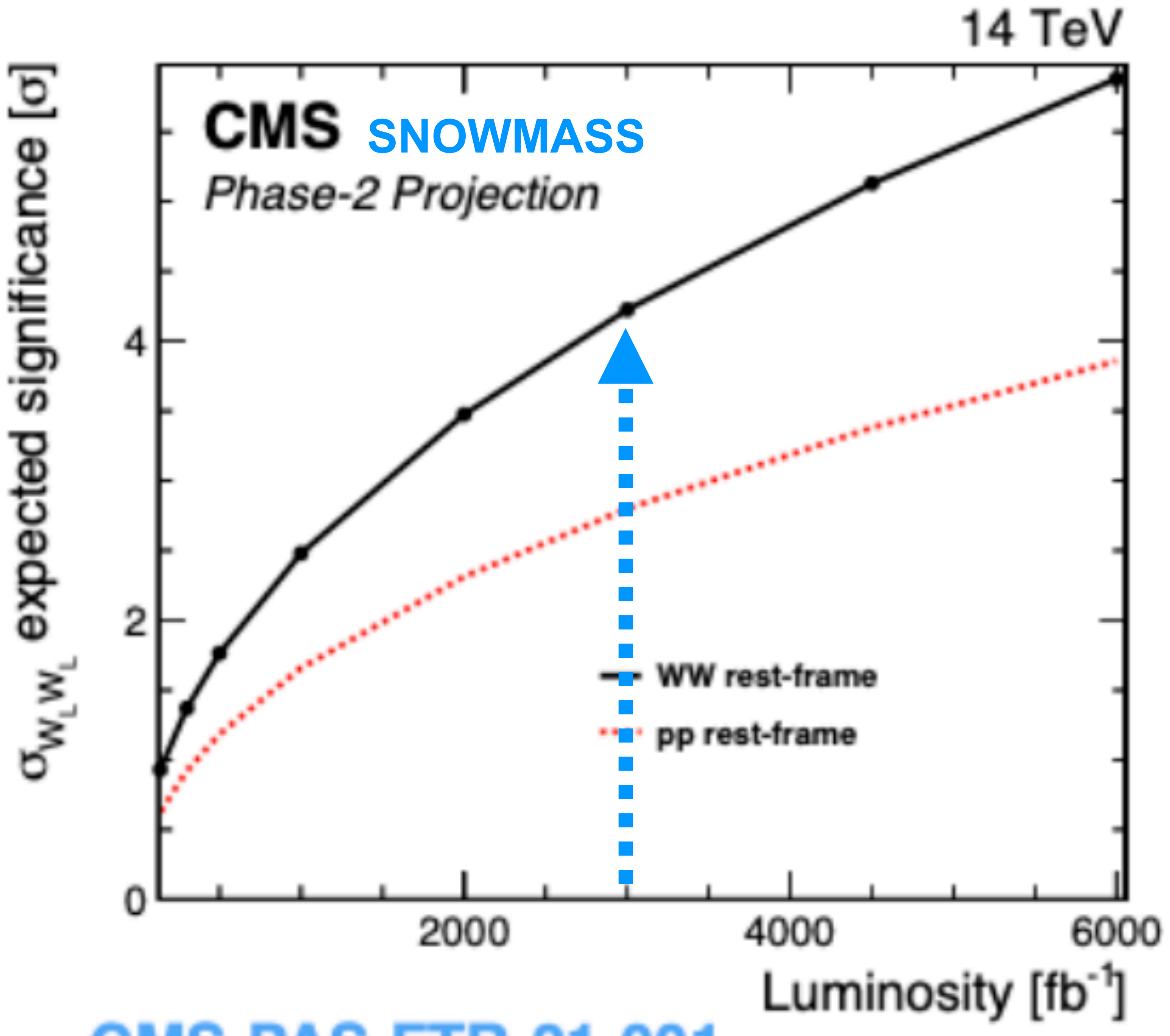
The far future of boson physics

HL-LHC & FCC

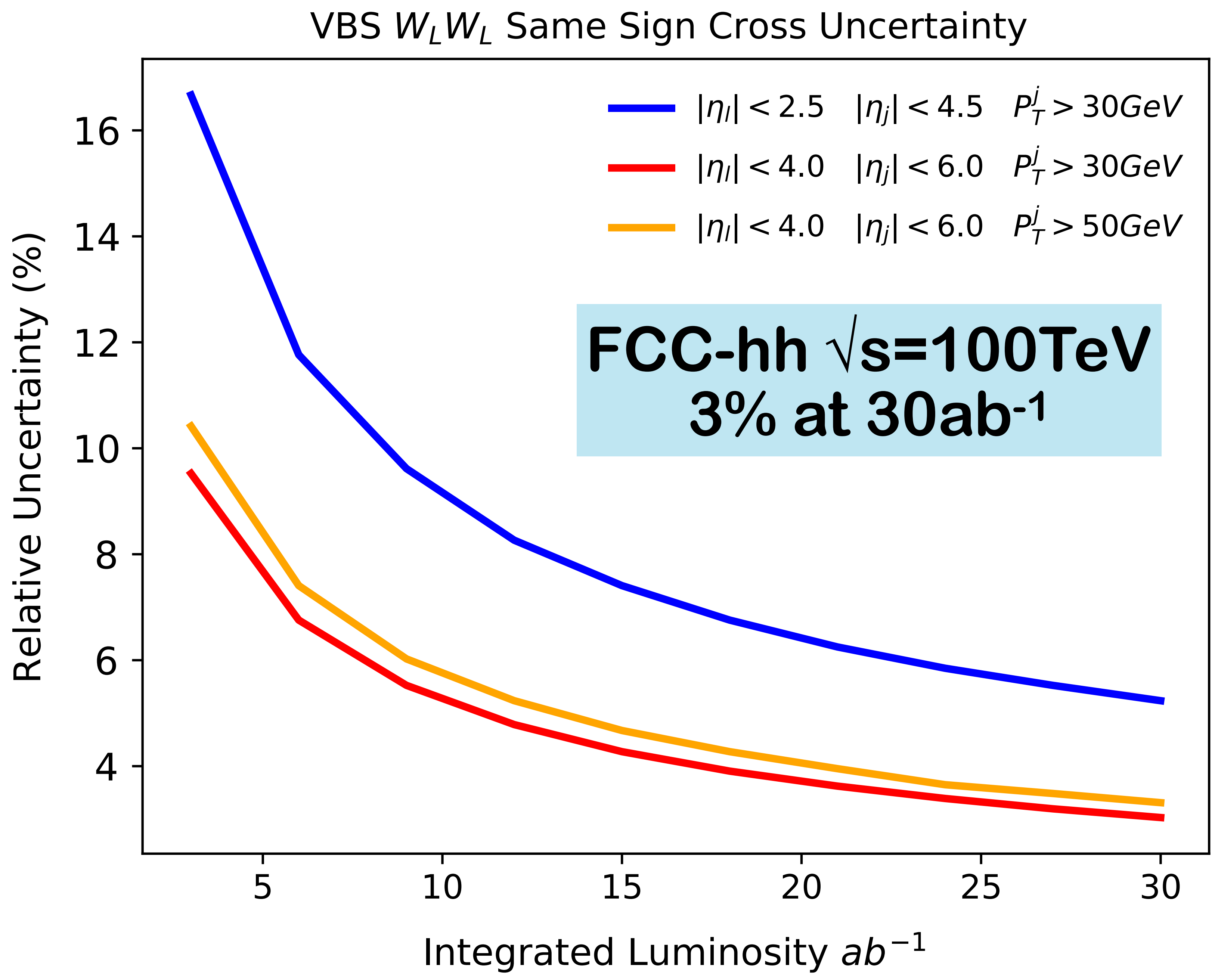
- **Next steps will be to observe the $V_L V_L$ scattering process that is at the heart of the EWSB.**
- Extrapolations have been made for the HL-LHC that show how difficult this will be even with the larger statistics
- During Run3 though, CMS will deploy new triggers and new analysis techniques that should improve the efficiency
- *Will need a collider such as the FCC at a 100TeV to be able to observe this process.*



arxiv:2009.09429



CMS-PAS-FTR-21-001



Conisderations

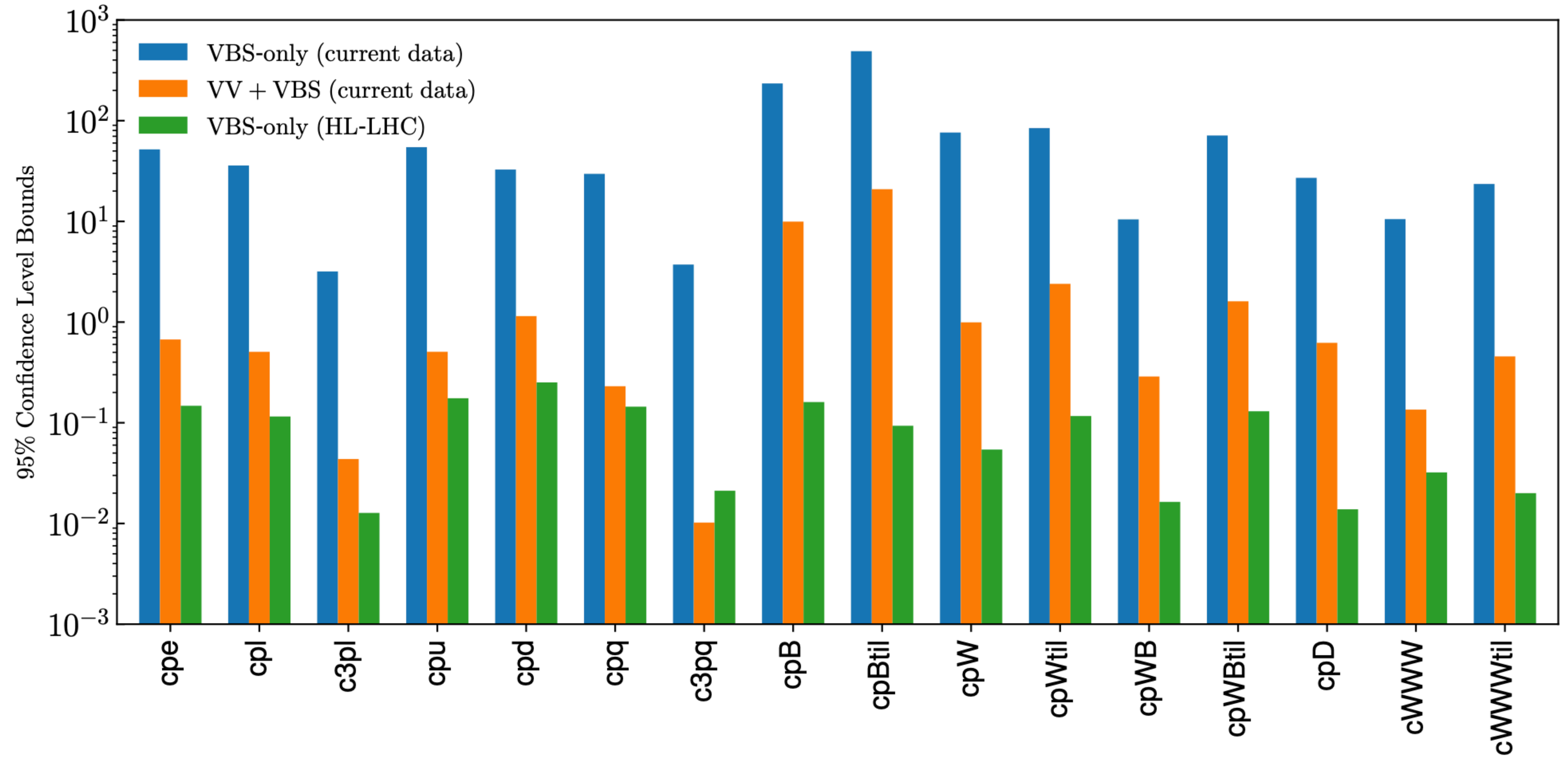
Boson physics is the heart of precision physics at pp collider

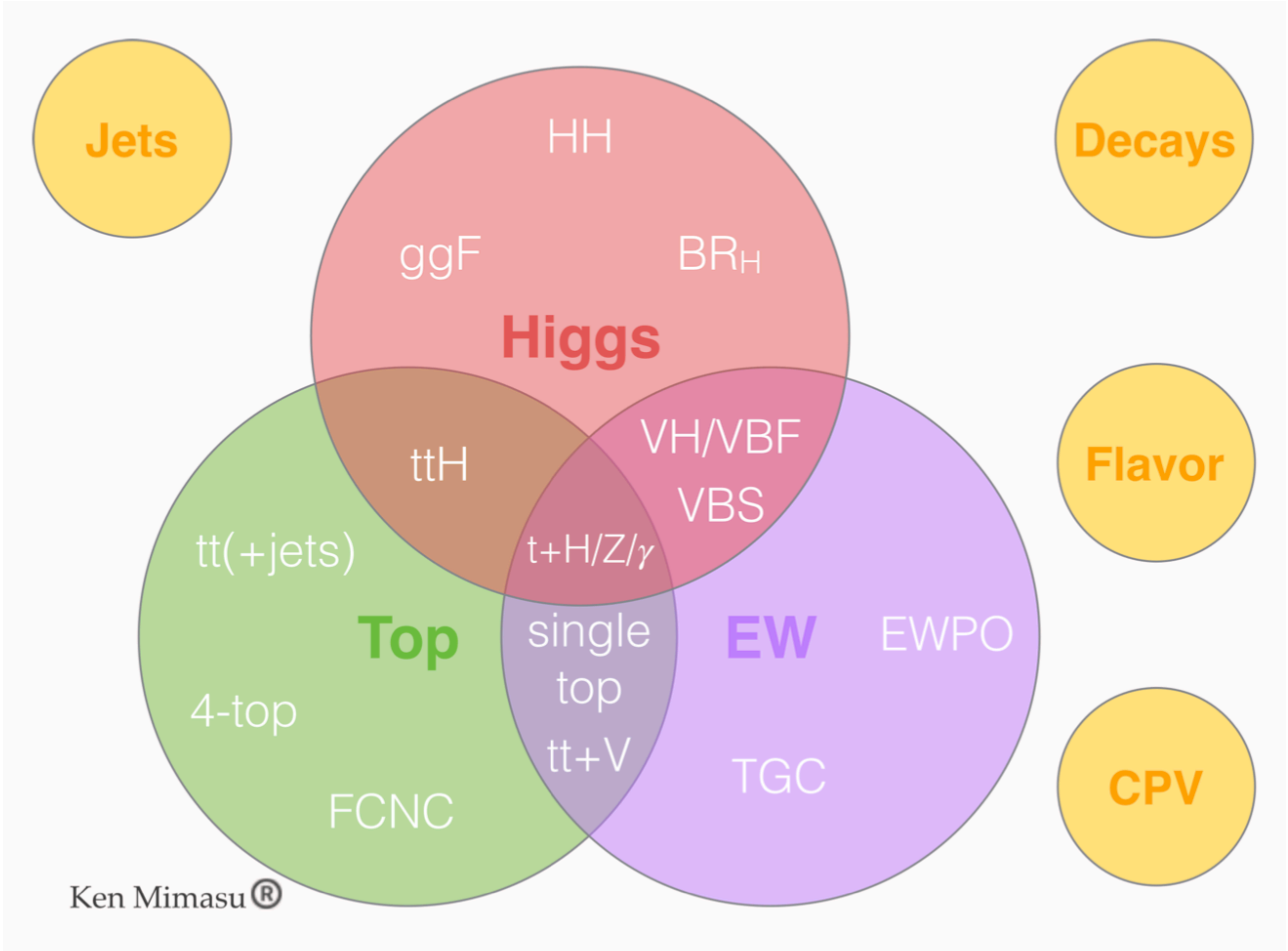
- **Precisely measuring the properties of the SM bosons allows to understand the inner workings of the Standard Model.**
  - This is a *challenge also for the theorists* to provide higher order corrections
- Larger statistics and new analyses techniques will allow to reduce the systematics uncertainties, both theoretical and experimental
- Large statistics, also due to new trigger strategies, will expand the phase space that can be explored and reach observation of rare processes
- **…LHC has collected only 10% of its statistics**

Forward look

Higher precision of EWK measurements

- EFT framework becoming a stronger ally with increasing number of measurement and their precision
- EW measurements of boson properties help improving the sensitivity of an EFT interpretation





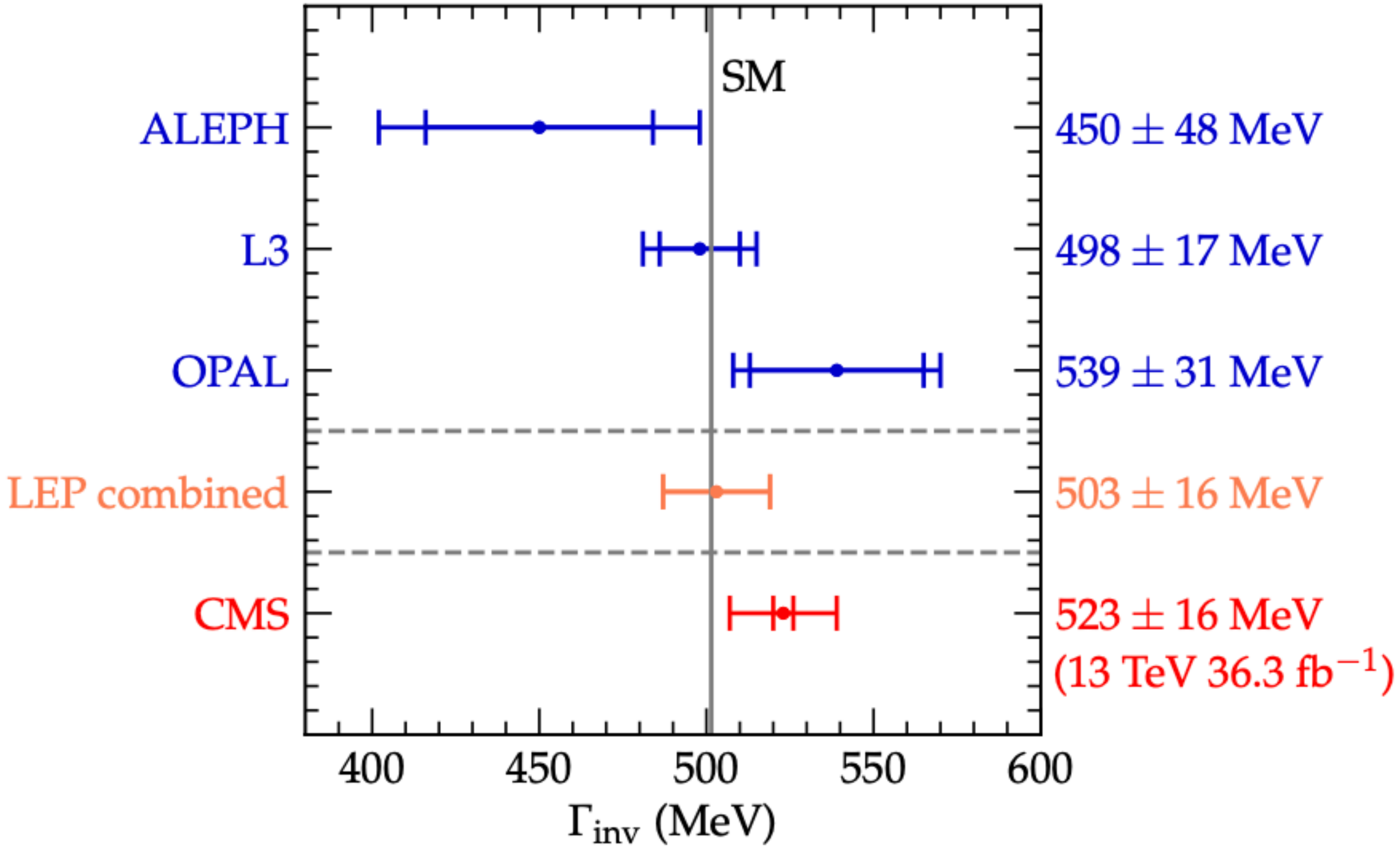
Moving toward a global EFT framework complementary to direct searches to push the reach of the full LHC program

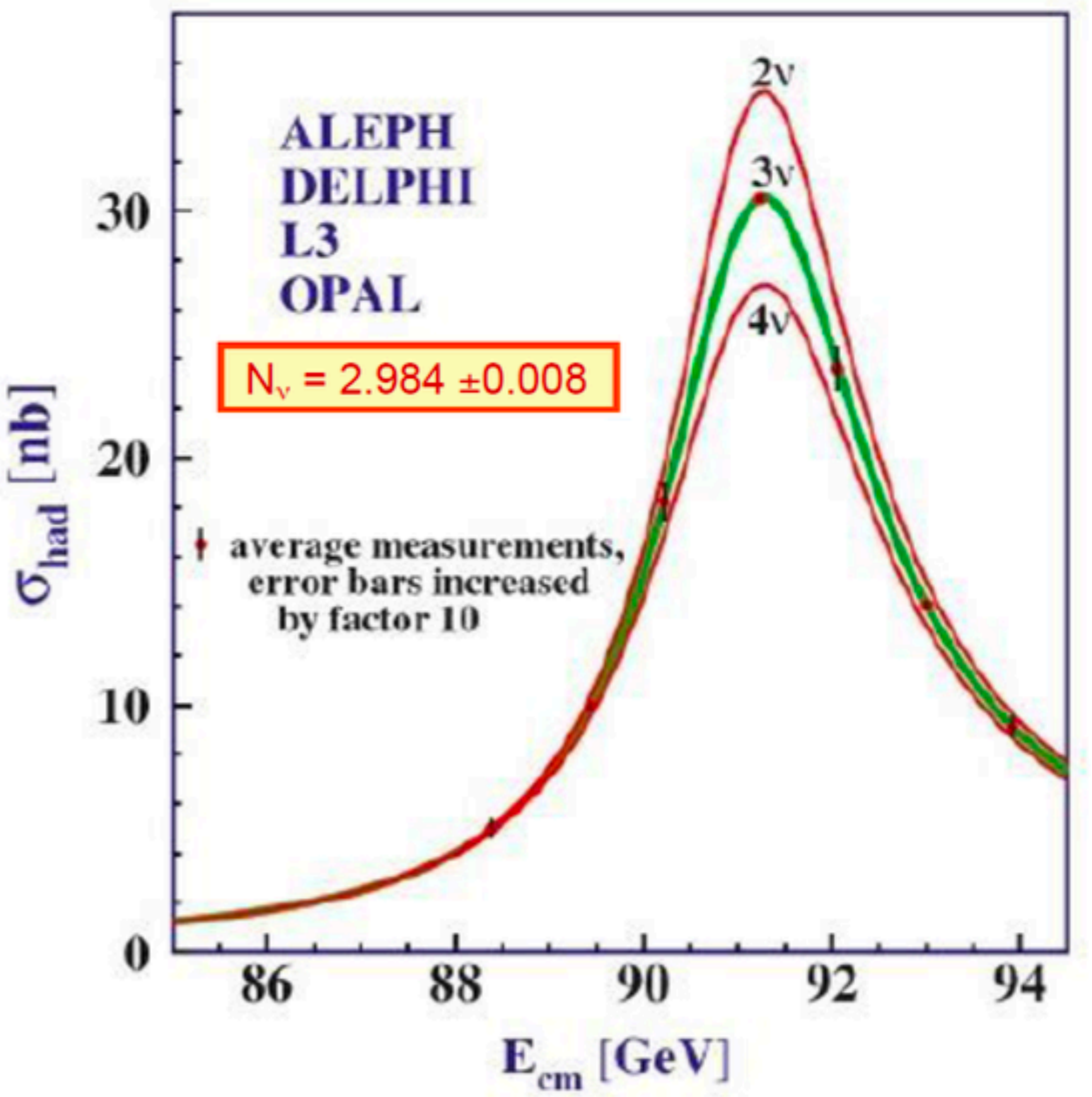
Backup

Invisible Z width

CMS SMP-18-014

- Determine invisible width as $\Gamma(Z \to \nu\bar{\nu}) = \mathcal{B}(Z \to \nu\bar{\nu}) / \mathcal{B}(Z \to \ell^+\ell^-) \times \Gamma(Z \to \ell^+\ell^-)$





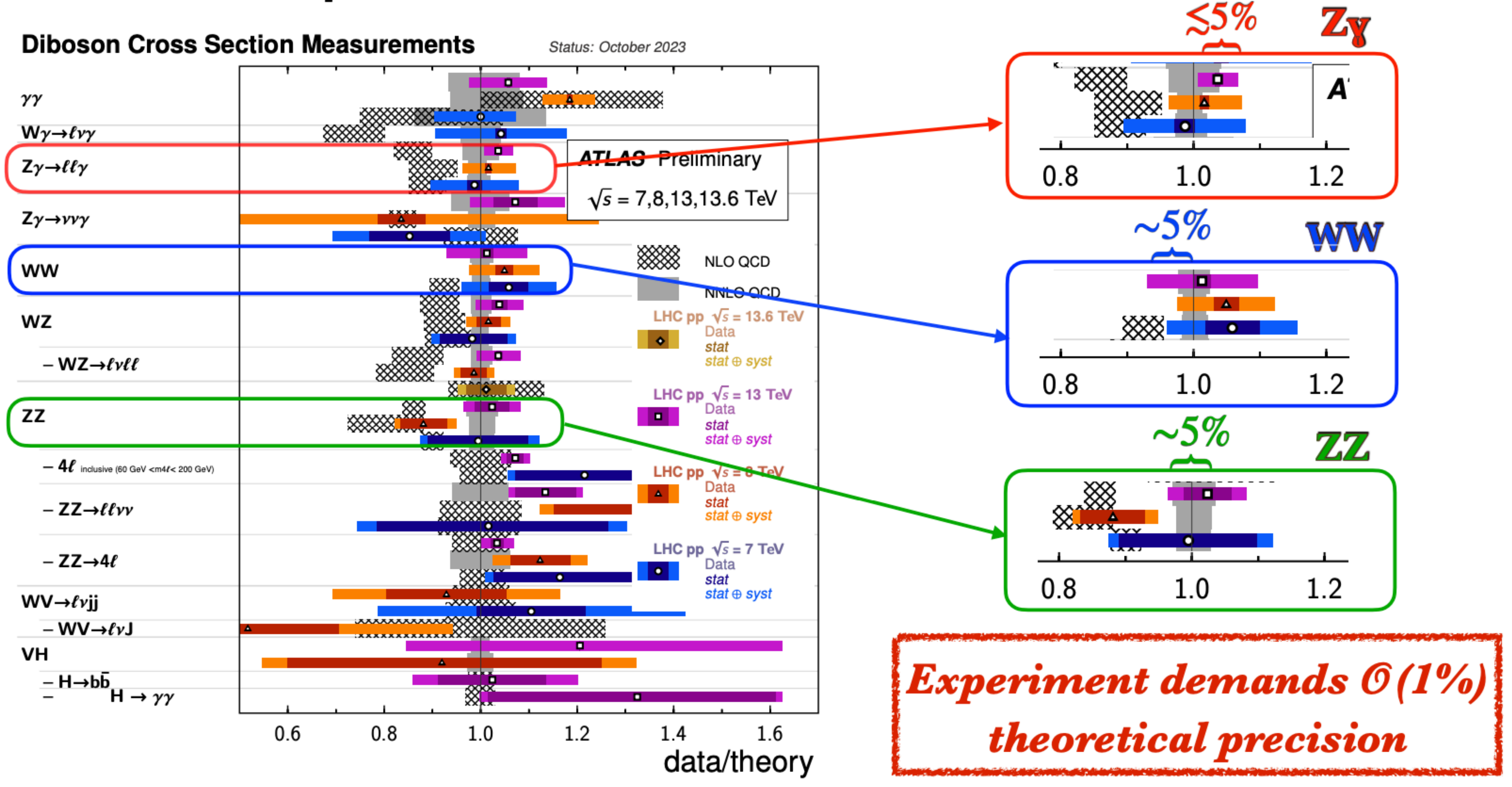
- Uncertainties mainly from lepton identification and jet energy scale
- Single most precise measurement of $\Gamma(Z \to \nu\bar{\nu})$, competitive with LEP combination
- Compatible with Standard Model, no sign of Z decays to unknown light fermions

Di-Boson Measurements

Pushing theoretical precision

Stolen from M. Wiesemann

Diboson precision measurements at the LHC

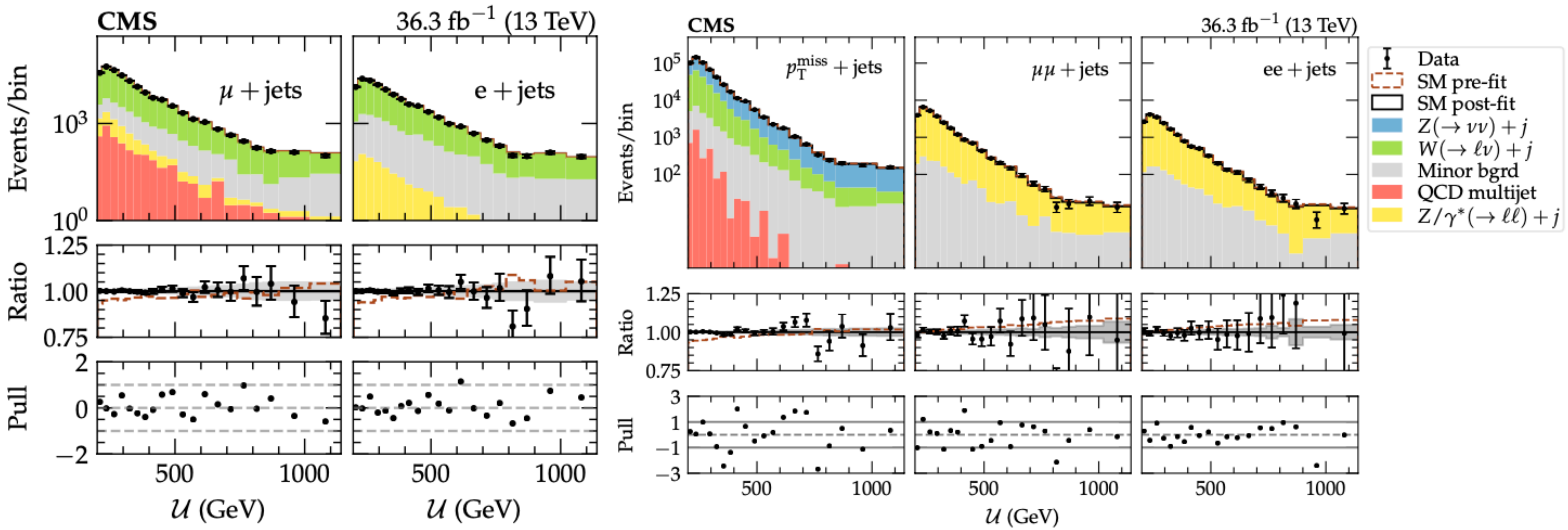


Marius Wiesemann (MPP Munich) Status of vector-boson pair production at the LHC January 17, 2024 2

Invisible Z width

CMS SMP-18-014

- Measure $Z \to \nu\bar{\nu}$ in events with large missing p_T and jets
- Using observable $\mathcal{U} = p_T^{miss}$ or hadronic recoil (in dilepton events), $\mathcal{U} > 200\,\text{GeV}$



ℓ+jets region — signal region — $\ell^+\ell^-$+jets region

- ℓ+jets control region → W+jets background prediction
- Signal shape from $(Z \to \ell^+\ell^-)$ +jets region
- QCD multijet from events where missing p_T in direction of a jet