Recent SM results from CMS

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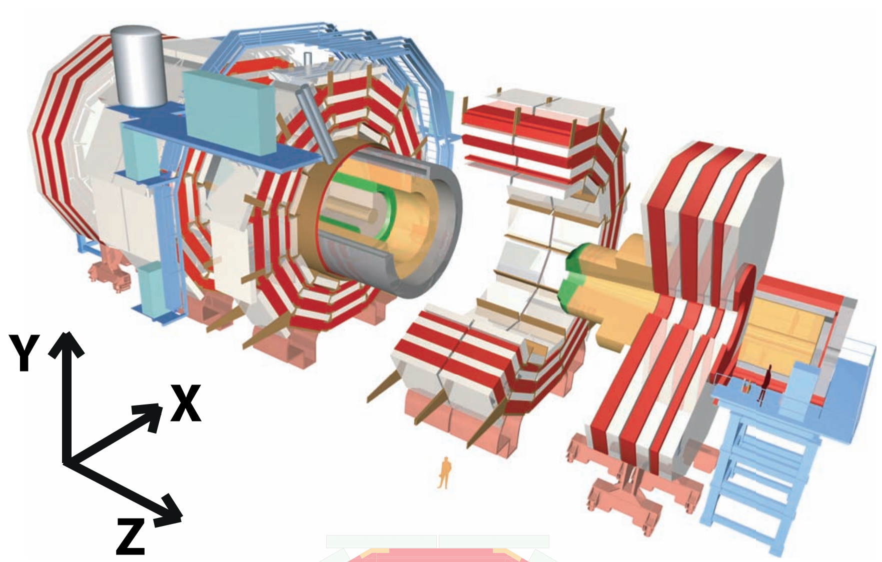
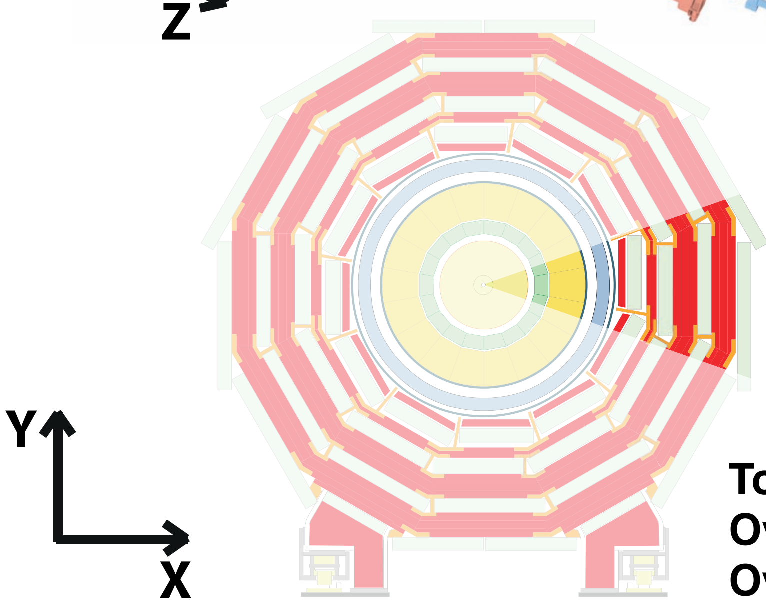
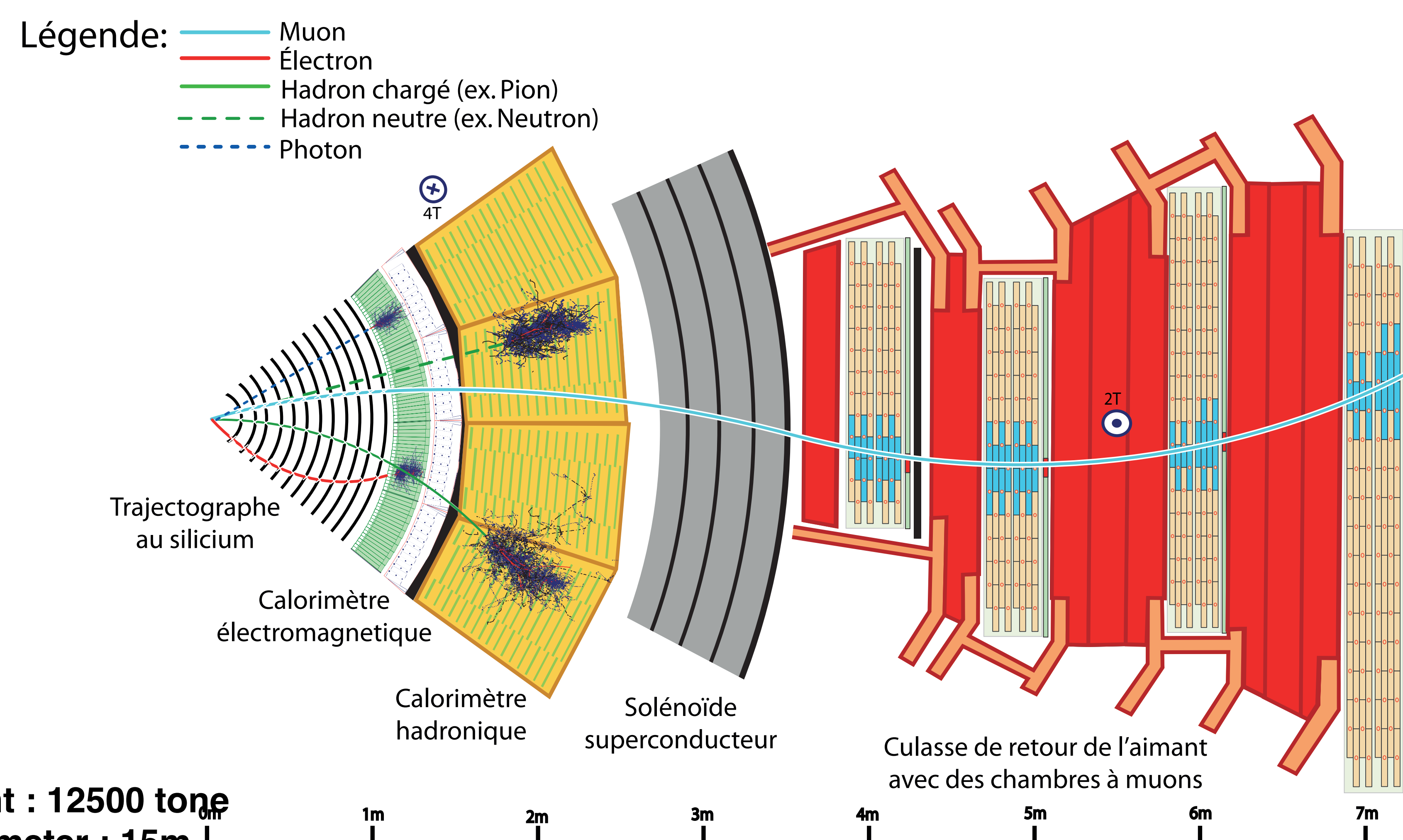
CMS

- General purpose design to detect all particles. Wide reaches of physics potential



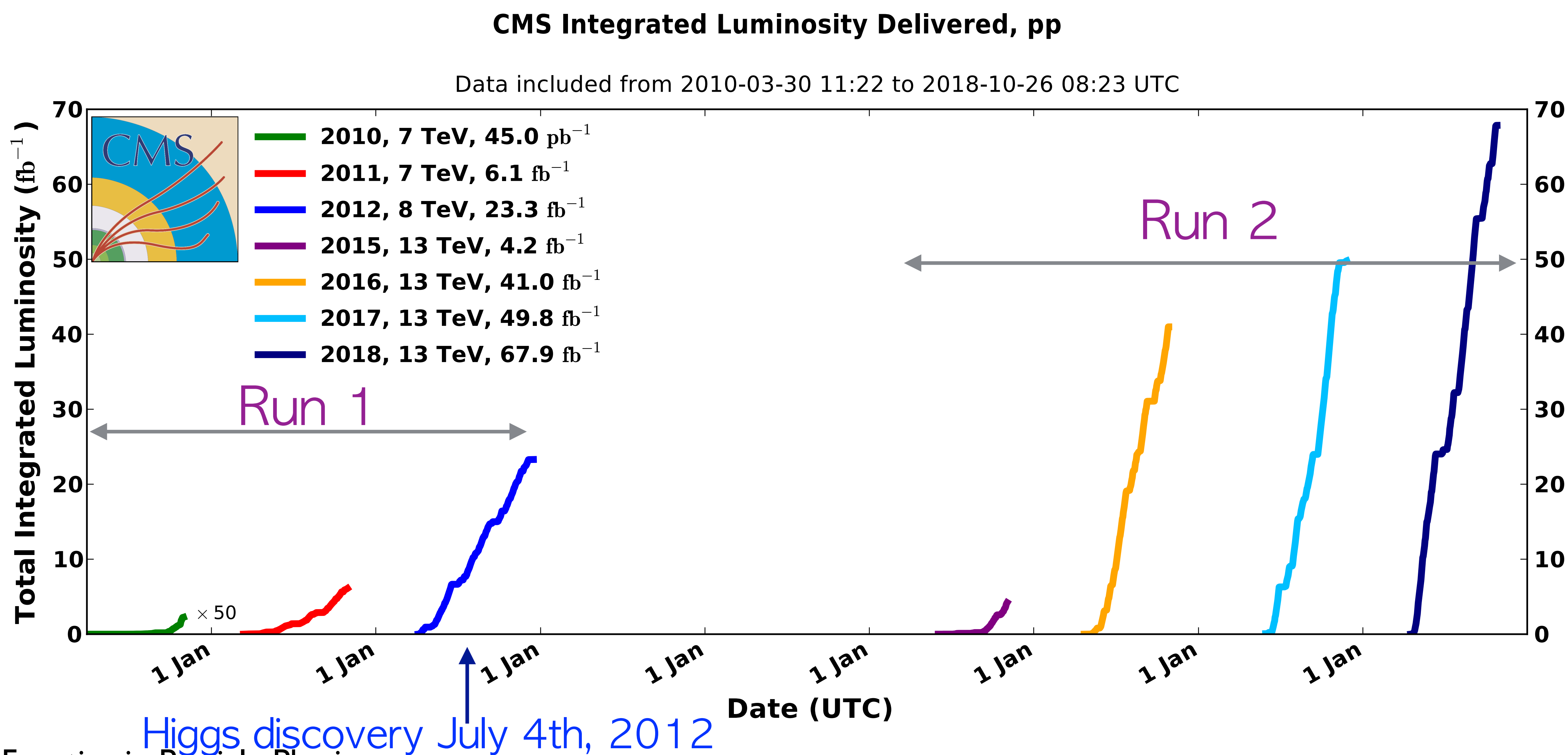




Total weight : 12500 tone
Overall diameter : 15m
Overall length : 21.5m
Magnetic field : 3.8 Tesla

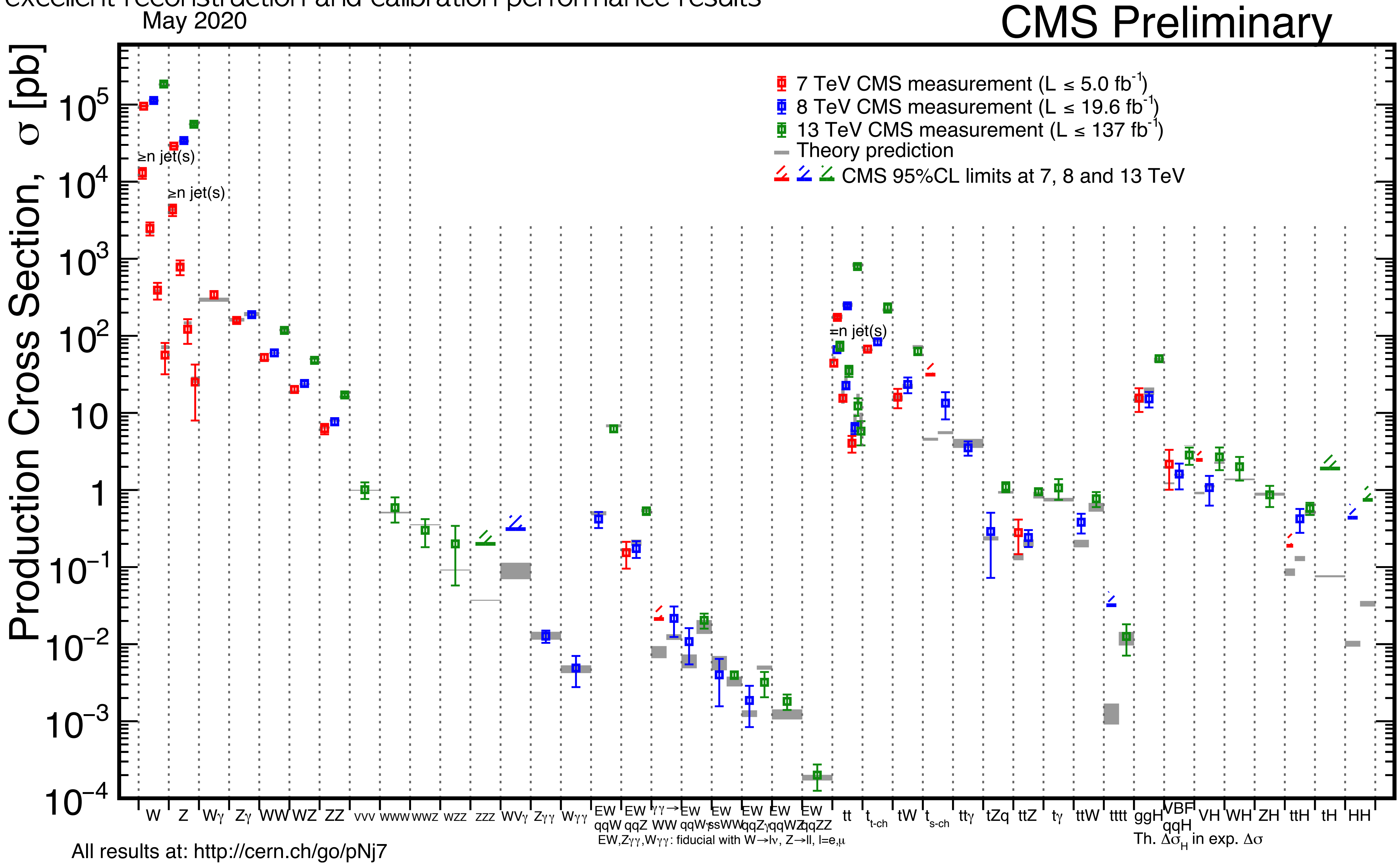
CMS Luminosity

- In Run1, CMS recorded 6.1fb^{-1} @7TeV and 23.3 fb^{-1} @8TeV.
- Run 2, CMS recorded 163 fb^{-1} @13TeV.



SM results of CMS

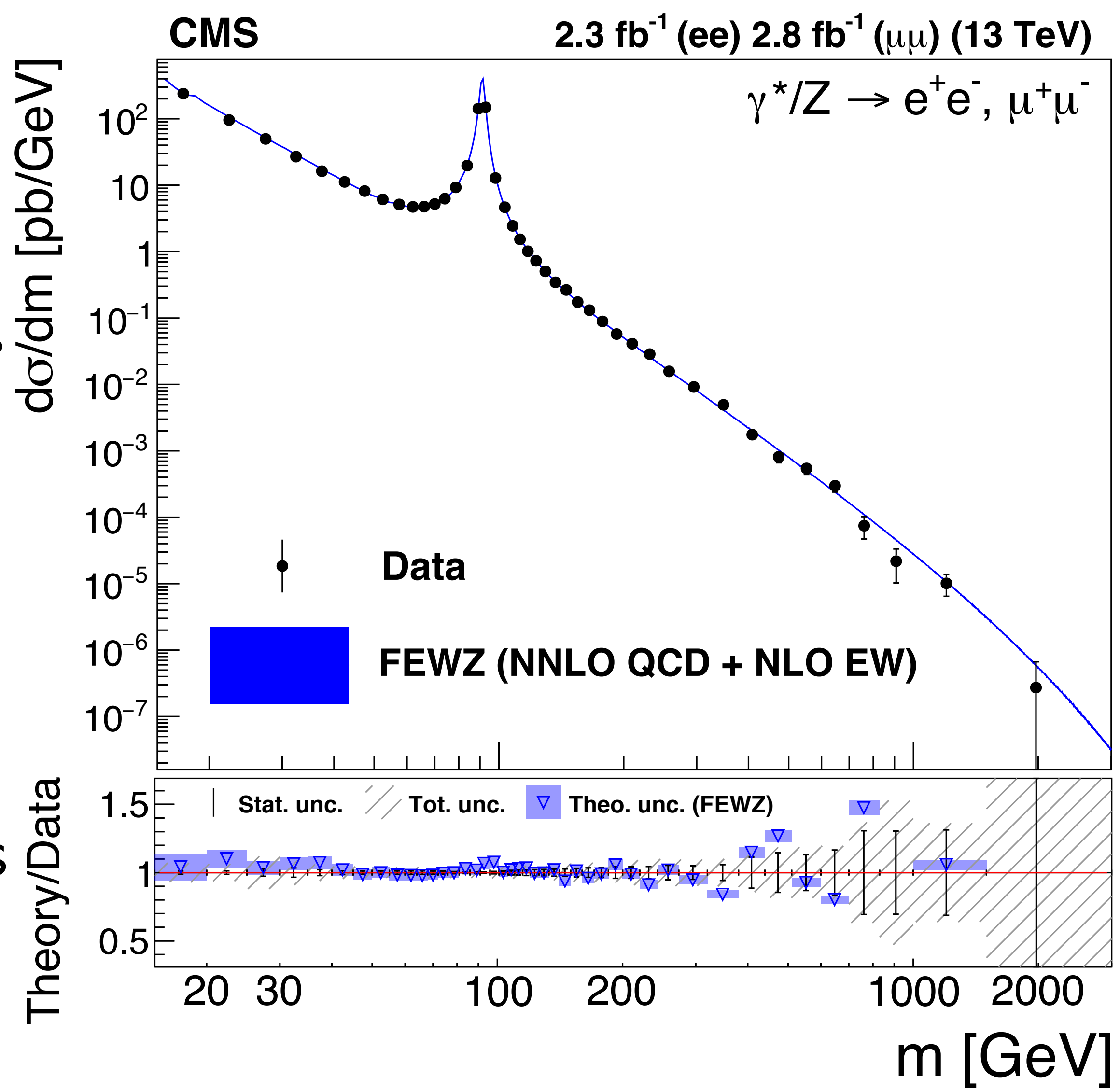
- Numerous "Standard Model measurements", use almost Full Run2 data, performed by CMS
- Good agreement for many processes, over 15 orders of magnitude
- Testing the Standard Model through rare processes and differential/precision measurements possible due to excellent reconstruction and calibration performance results



Drell-Yan from leptons

- The production of lepton pairs in pp-collisions is described by the s-channel exchange of γ^*Z. Theoretical calculations are well established up to NNLO order
- The measurement provides
  - Testing Standard model (SM)
  - Constraining parton distribution functions (PDFs)
  - Extracting parameters ($\sin^2\theta_W$, A_{FB}, angular coefficients etc.)
  - Background evaluation for BSM models
  - Testing different Monte Carlo models
  - Testing production mechanism dynamics
  - searches for new physics
- Precision measurements with a hadron collider!

JHEP 12(2019) 059

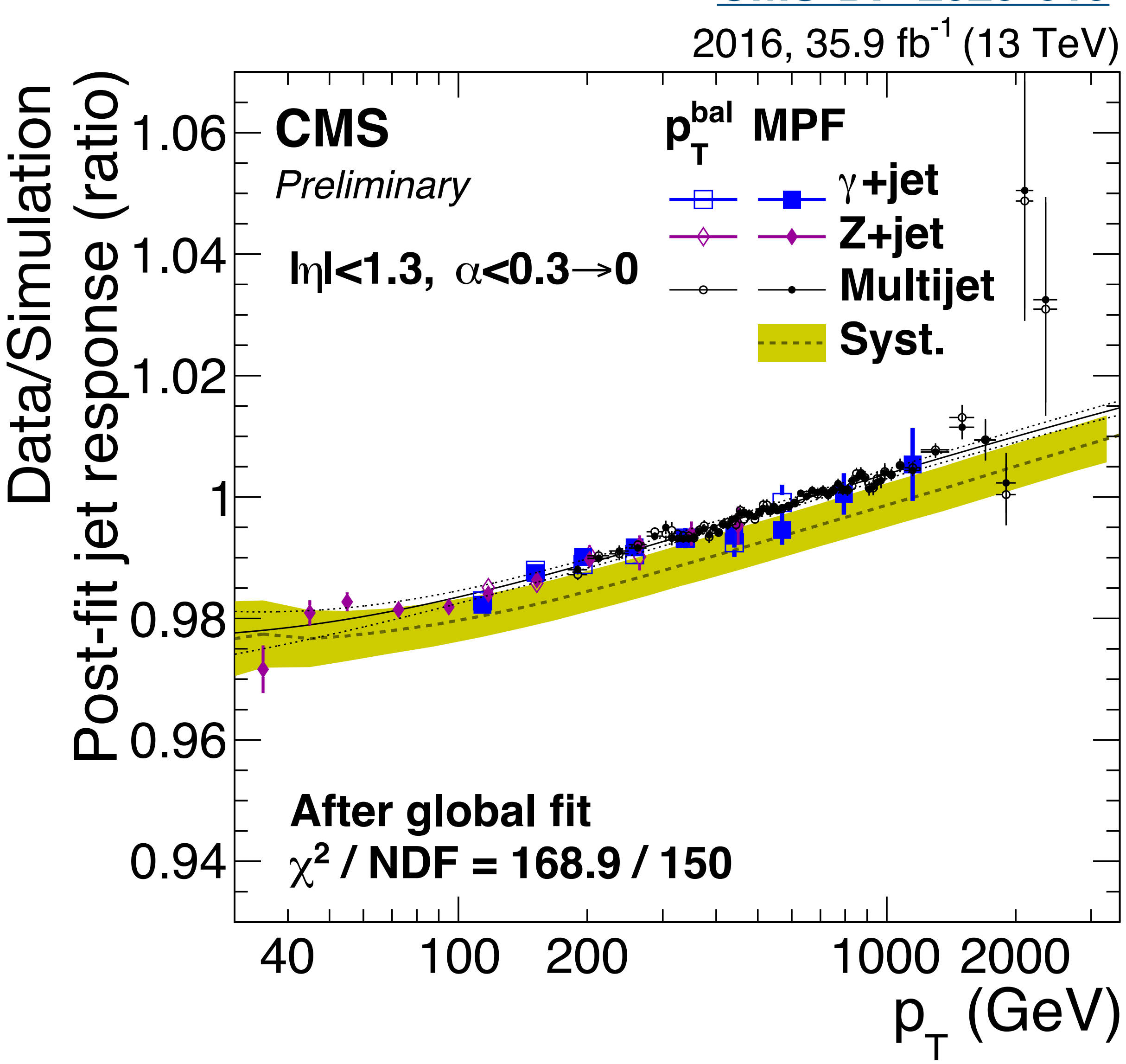


Jets

Jet Energy Correction agreement at per mill level;
MPF stands for Missing Transverse Energy Projection Fraction

PileUp Jet ID

CMS-DP-2020-019



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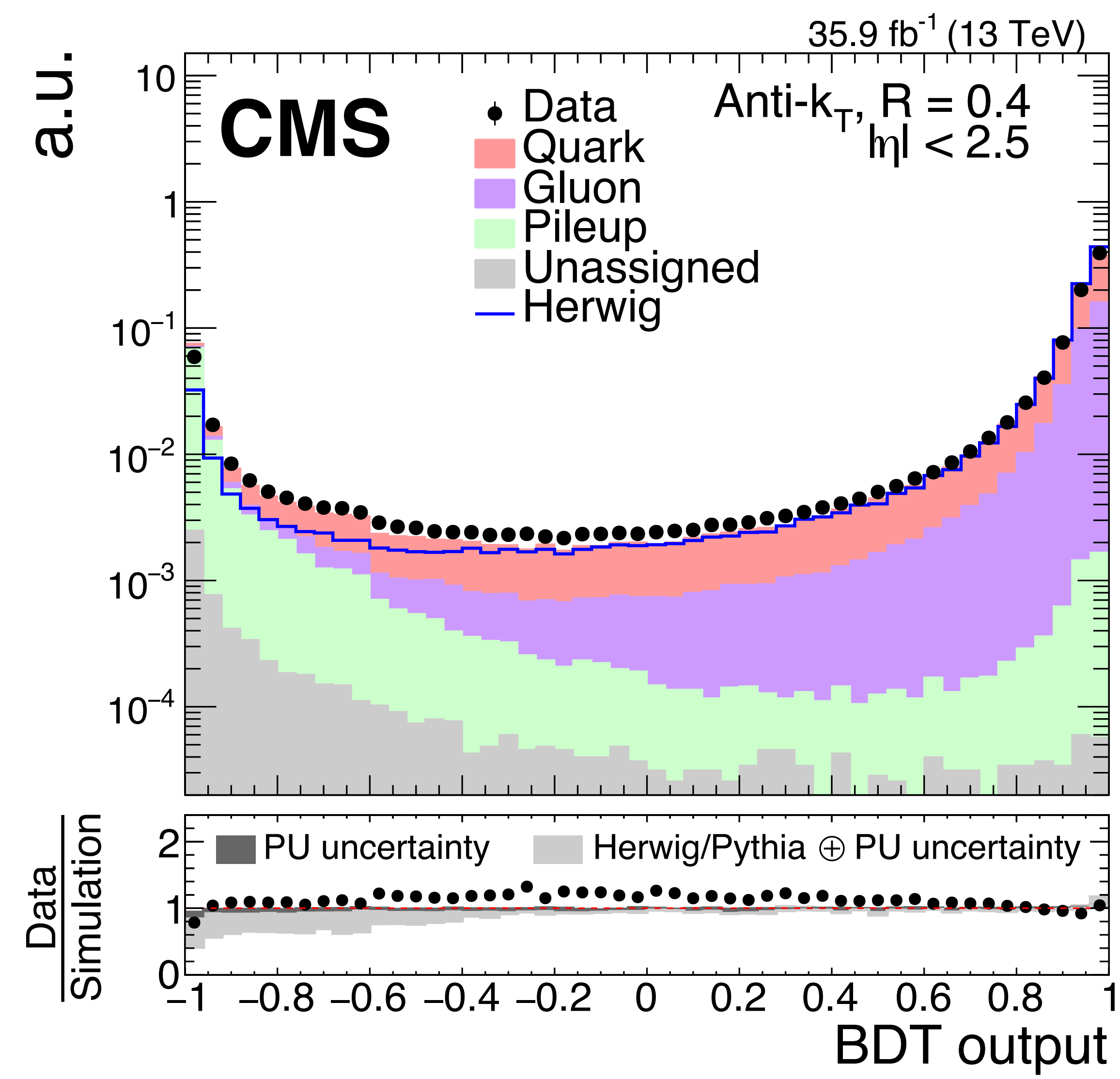
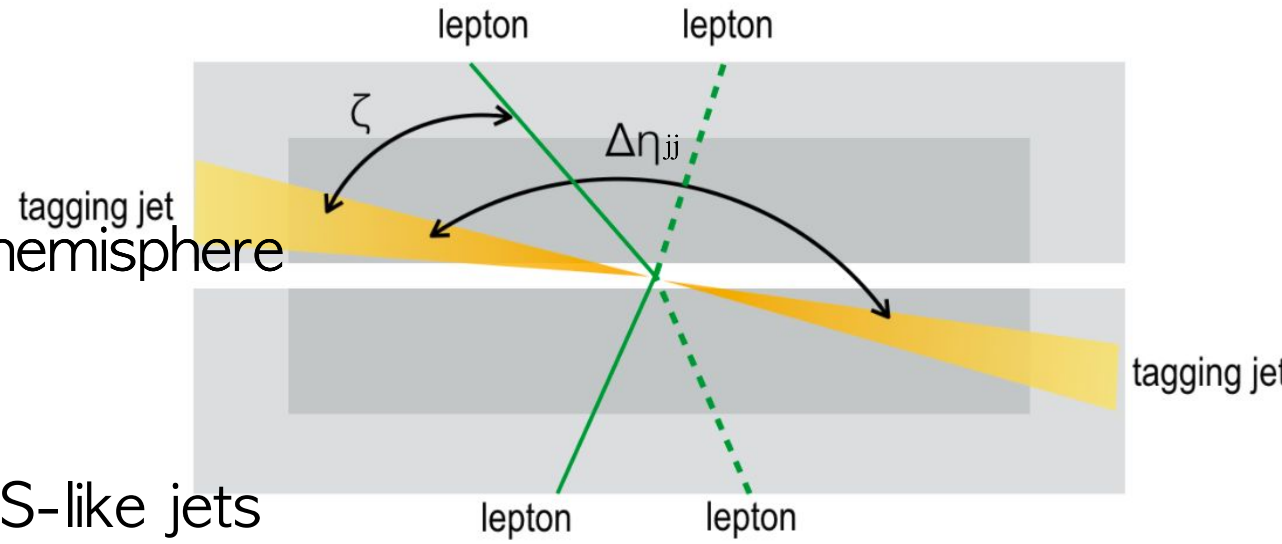


Vector Bonson Scattering

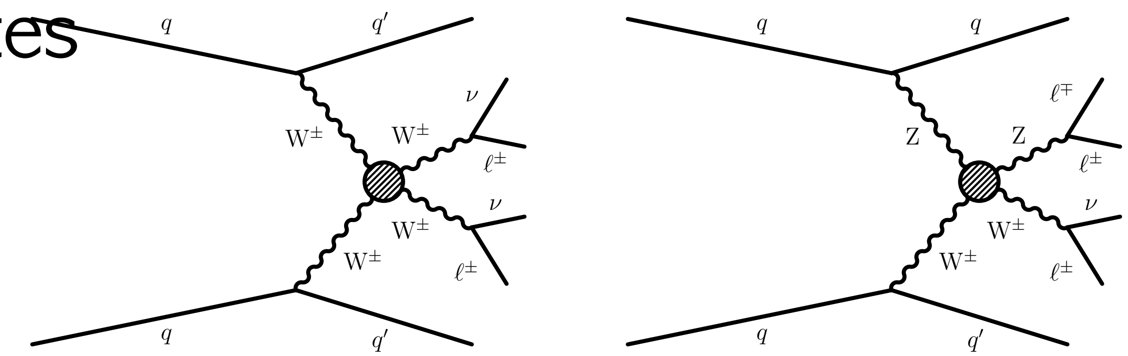
- Measurements of vector boson scattering (VBS) processes → Key process to experimentally probe nature of EWSB
  - complementary to direct Higgs boson measurements
- The LHC makes it possible to measure many rare processes predicted by the SM



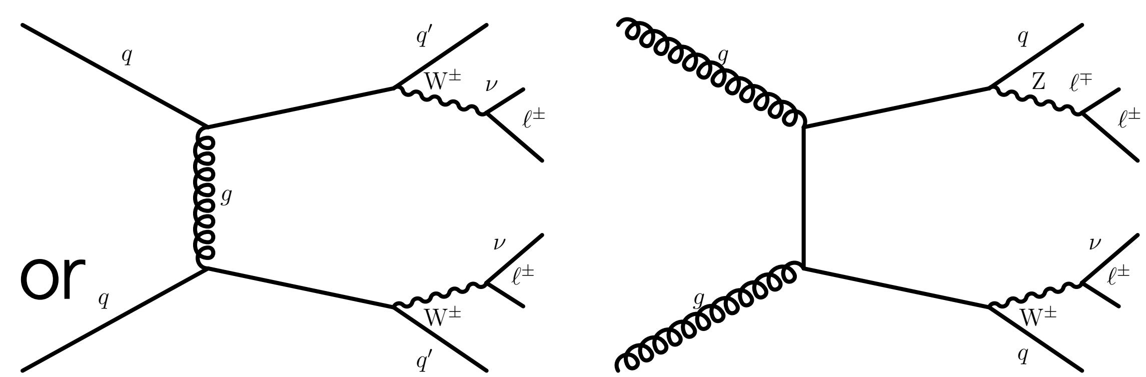
- VBS topology
  - two energetic forward jets in opposite hemisphere
  - large dijet mass and $\Delta\eta_{jj}$
- Experimental Analysis
  - Select VV (V=W, Z, γ) events with VBS-like jets
  - Estimate non-VV backgrounds
  - Non prompt/fake (reducible) due to mis-ID $\Longrightarrow$from data
  - Prompt (irreducible) $\Longrightarrow$ from MC
- Measurements
  - Inclusive and Differential Cross section Measurements
  - Search for anomalous Quartic Gauge Couplings

$W^{\pm}W^{\pm}$ & WZ VBS

- First simultaneous $W^{\pm}W^{\pm}$jj & WZjj analyses using fully leptonic final states
- Why $W^{\pm}W^{\pm}$jj ?
  - EW production dominant over QCD-induced
  - Distinct same-sign (SS) lepton state with low background
- Why WZjj ?
  - sensitive to charged resonances or couplings
  - Clean signature but higher background compared to $W^{\pm}W$



EWK production



QCD production

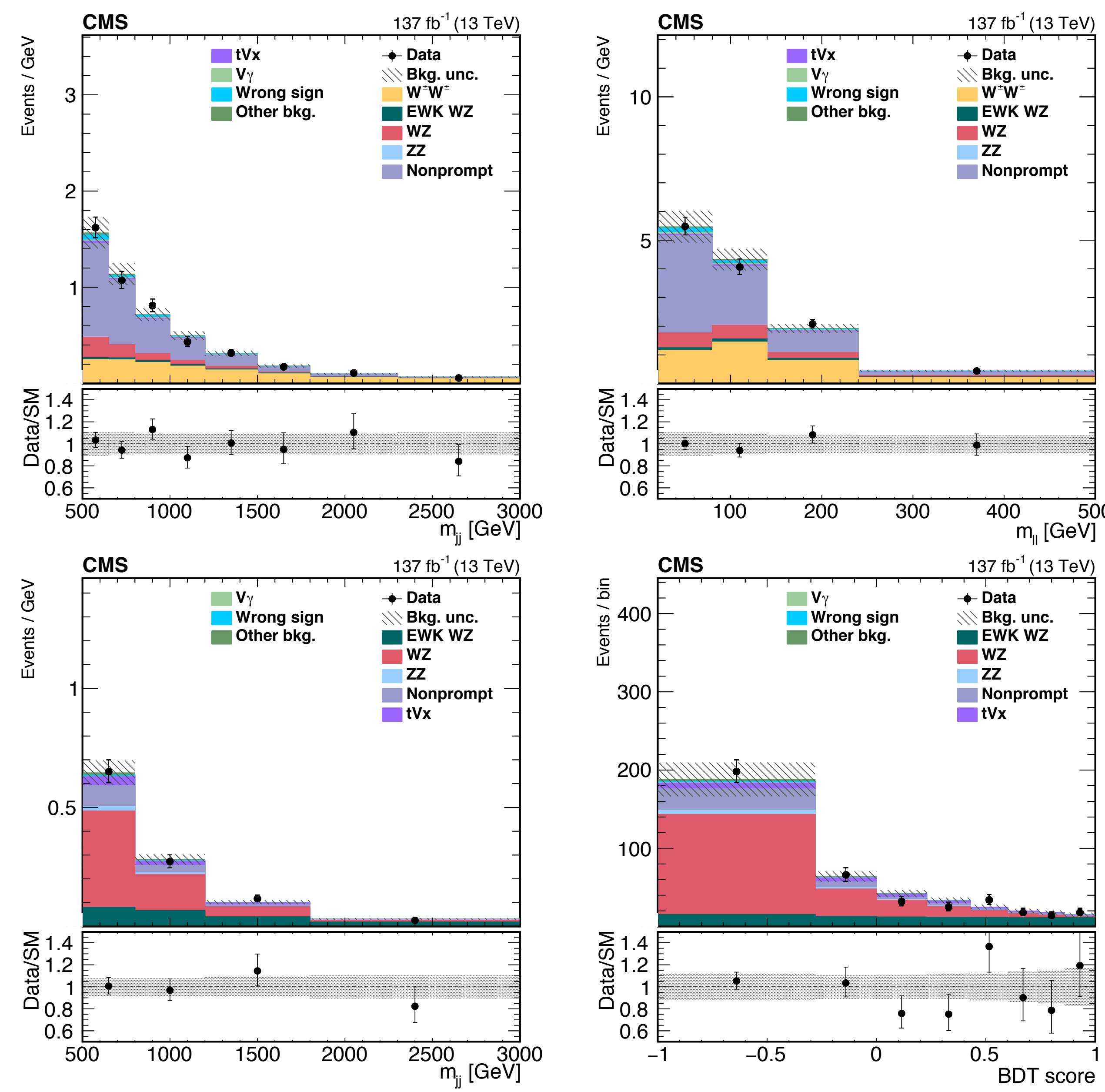
W±W± & WZ VBS: Analysis Strategy

- Statistical analysis by simultaneously fitting signal yields in WW & WZ signal regions as well as background yields in control Regions (Non prompt, WZb(tZq) and ZZ), to assess normalization from data

PLB 809(2020) 135710

Process	$W^{\pm}W^{\pm}$ SR		WZ SR	
	Pre-fit	Post-fit	Pre-fit	Post-fit
EW $W^{\pm}W^{\pm}$	209 ± 22	210 ± 26	—	—
QCD $W^{\pm}W^{\pm}$	13.6 ± 2.3	13.7 ± 2.2	—	—
Interference $W^{\pm}W^{\pm}$	8.4 ± 2.3	8.7 ± 2.3	—	—
EW WZ	14.1 ± 1.7	17.8 ± 3.9	54.3 ± 5.7	69 ± 15
QCD WZ	42.9 ± 4.7	42.7 ± 7.4	117.9 ± 6.8	117 ± 17
Interference WZ	0.3 ± 0.1	0.3 ± 0.2	2.2 ± 0.6	2.7 ± 1.0
ZZ	0.7 ± 0.1	0.7 ± 0.2	6.1 ± 0.4	6.0 ± 1.8
Nonprompt	211 ± 55	193 ± 40	14.6 ± 7.6	14.4 ± 6.7
tVx	9.0 ± 3.1	7.4 ± 2.2	15.1 ± 1.9	14.3 ± 2.8
$W\gamma$	7.8 ± 2.0	9.1 ± 2.9	1.1 ± 0.5	1.1 ± 0.4
Wrong-sign	13.5 ± 7.1	13.9 ± 6.5	1.6 ± 0.7	1.7 ± 0.7
Other background	5.0 ± 2.4	5.2 ± 2.1	3.3 ± 0.7	3.3 ± 0.7
Total SM	535 ± 60	522 ± 49	216 ± 12	229 ± 23
Data	524		229	

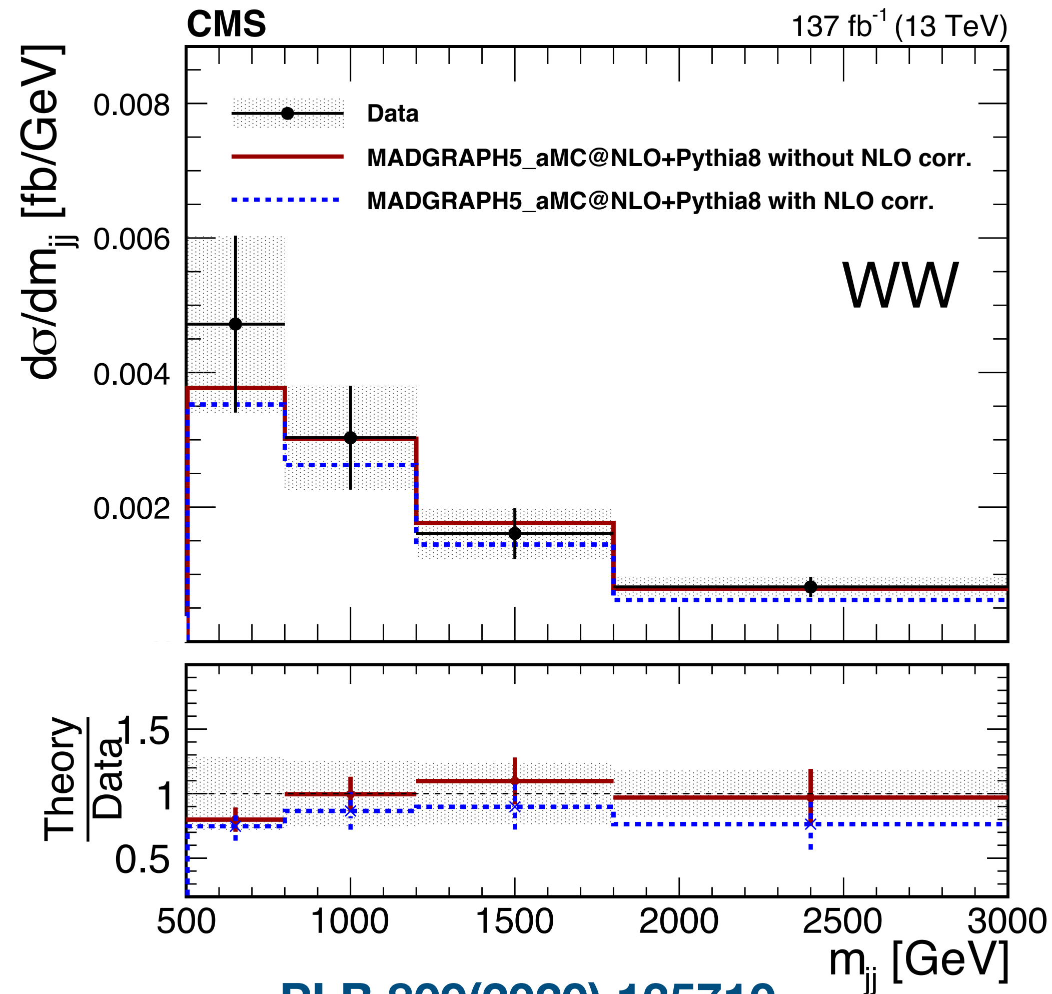
Source of uncertainty	$W^{\pm}W^{\pm}$ (%)	WZ (%)
Theory	1.9	3.8
Total systematic uncertainty	5.7	7.9
Statistical uncertainty	8.9	22
Total uncertainty	11	23



W±W± & WZ VBS Full Run II : Results

- Measured inclusive and differential cross section measurements on m_{jj}, $m_{\ell\ell}$, and p_T^{max} for WW and m_{jj} for WZ
- Obtained obs(exp) significance of 6.8(5.3)σ for EWK WZ and far above 5σ for EWK WW.

Process	$\sigma\mathcal{B}$ (fb)	MadGraph5_amc@nlo predictions at LO: Theoretical prediction without NLO corrections (fb)	Theoretical prediction with NLO corrections (fb)
EW W±W±	3.98 ± 0.45 0.37 (stat) ± 0.25 (syst)	3.93 ± 0.57	3.31 ± 0.47
EW+QCD W±W±	4.42 ± 0.47 0.39 (stat) ± 0.25 (syst)	4.34 ± 0.69	3.72 ± 0.59
EW WZ	1.81 ± 0.41 0.39 (stat) ± 0.14 (syst)	1.41 ± 0.21	1.24 ± 0.18
EW+QCD WZ	4.97 ± 0.46 0.40 (stat) ± 0.23 (syst)	4.54 ± 0.90	4.36 ± 0.88
QCD WZ	3.15 ± 0.49 0.45 (stat) ± 0.18 (syst)	3.12 ± 0.70	3.12 ± 0.70



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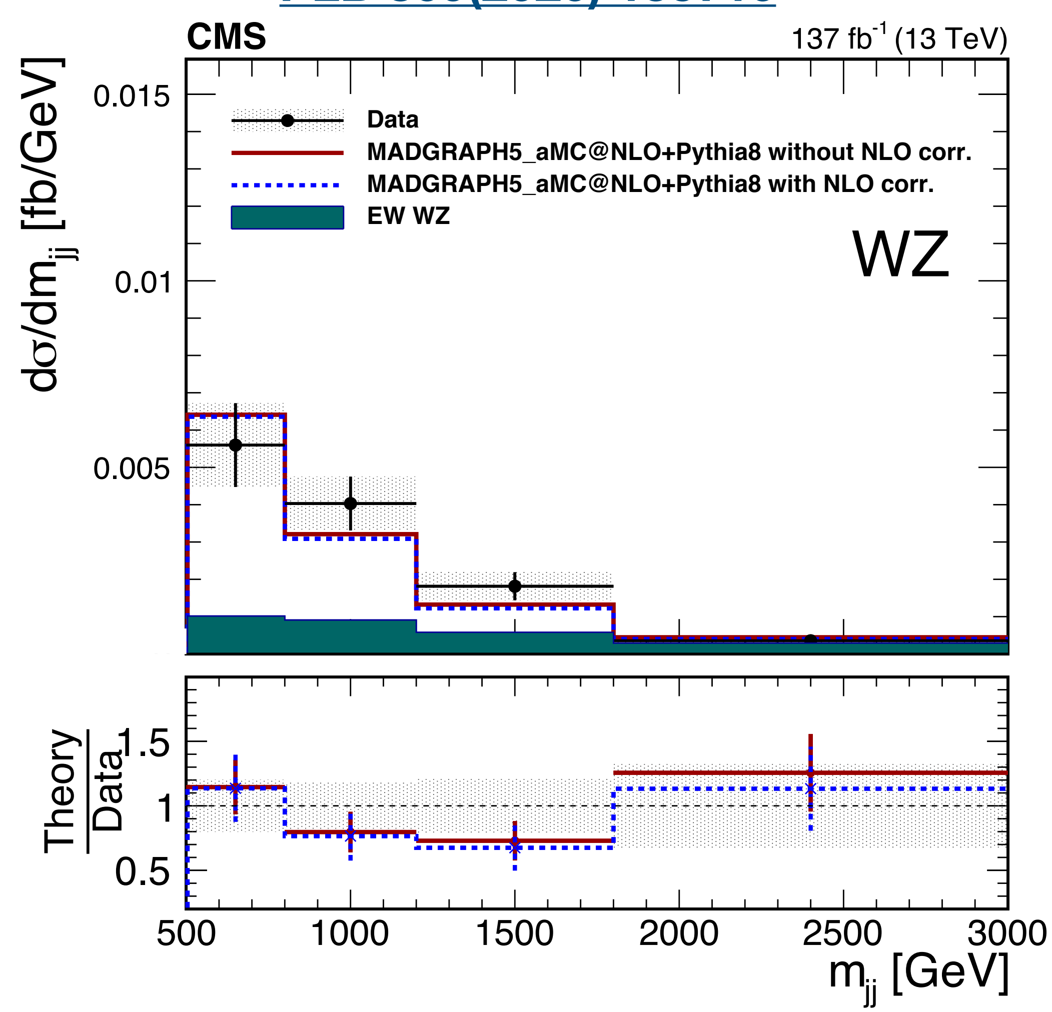
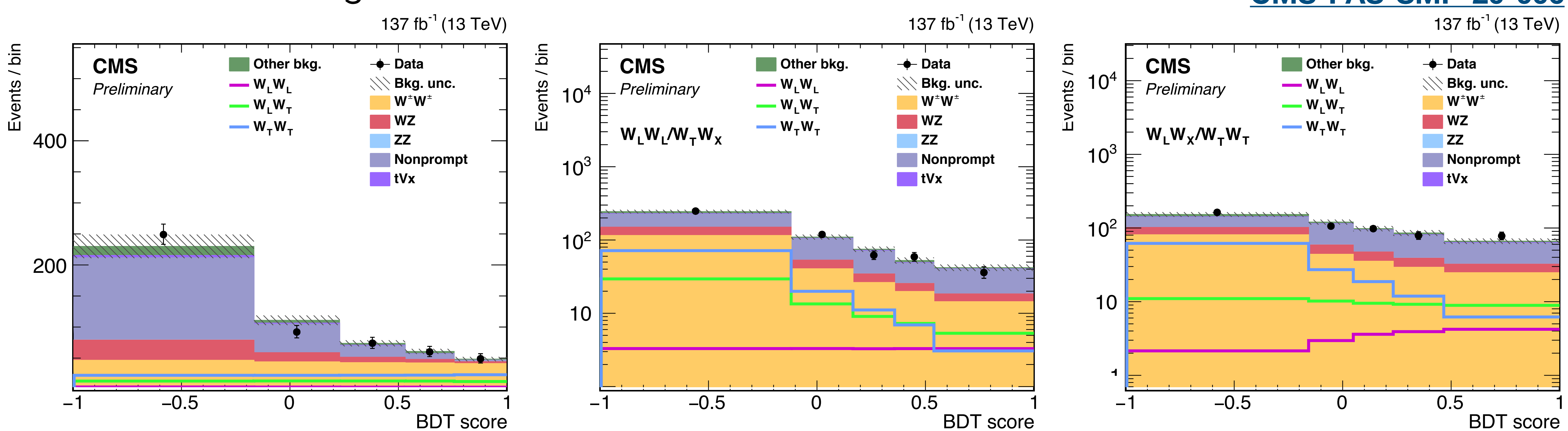


Polarized $W^{\pm}W^{\pm}$ VBS Full Run II : Overview

- First measurements of EW production cross sections of polarized $W^{\pm}W^{\pm}$
- VBS scattering amplitude is dominated by transverse gauge components. In SM, W_LW_L contribute bout 10% of total EW WW cross section. Significant excess in the longitudinally polarized channel would point to new interactions in the EWSB sector
- Same Event Selection & Background Estimation with WW VBS analysis
- Analysis Strategy : simultaneous fit with
  - WW signal region (2D) : inclusive BDT (to separate EW from SM bkg) vs signal BDTs (to measure W_LW_L against W_XW_T and W_LW_X agains W_TW_T)
  - Control regions

CMS-PAS-SMP-20-006

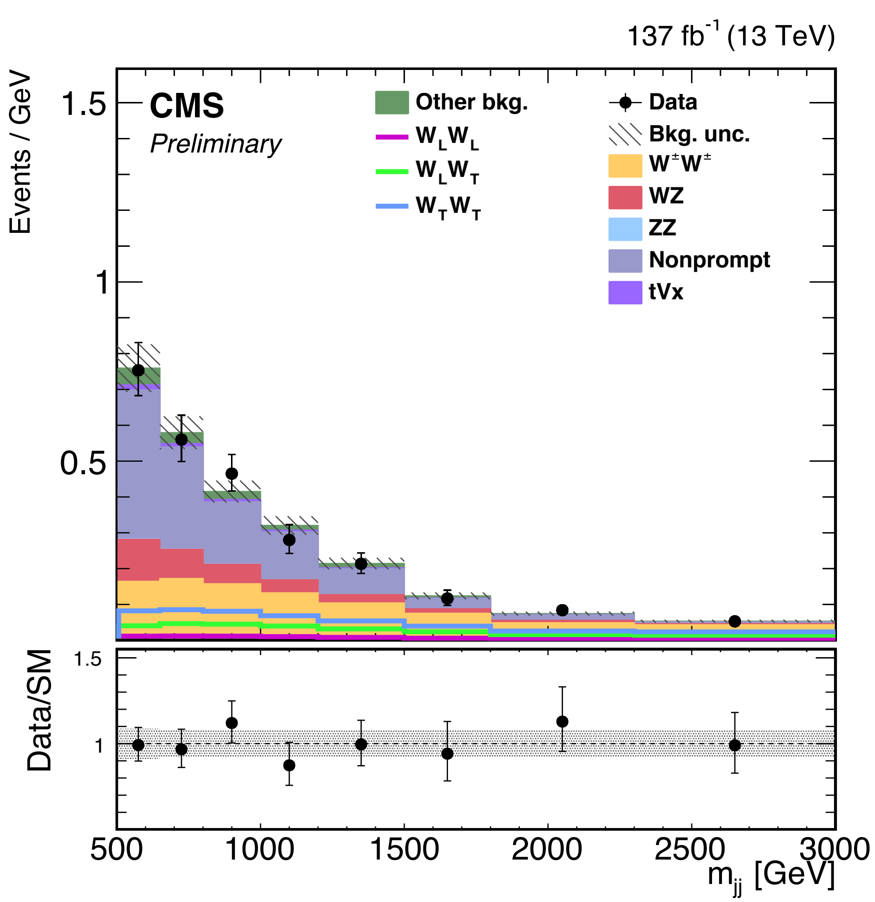


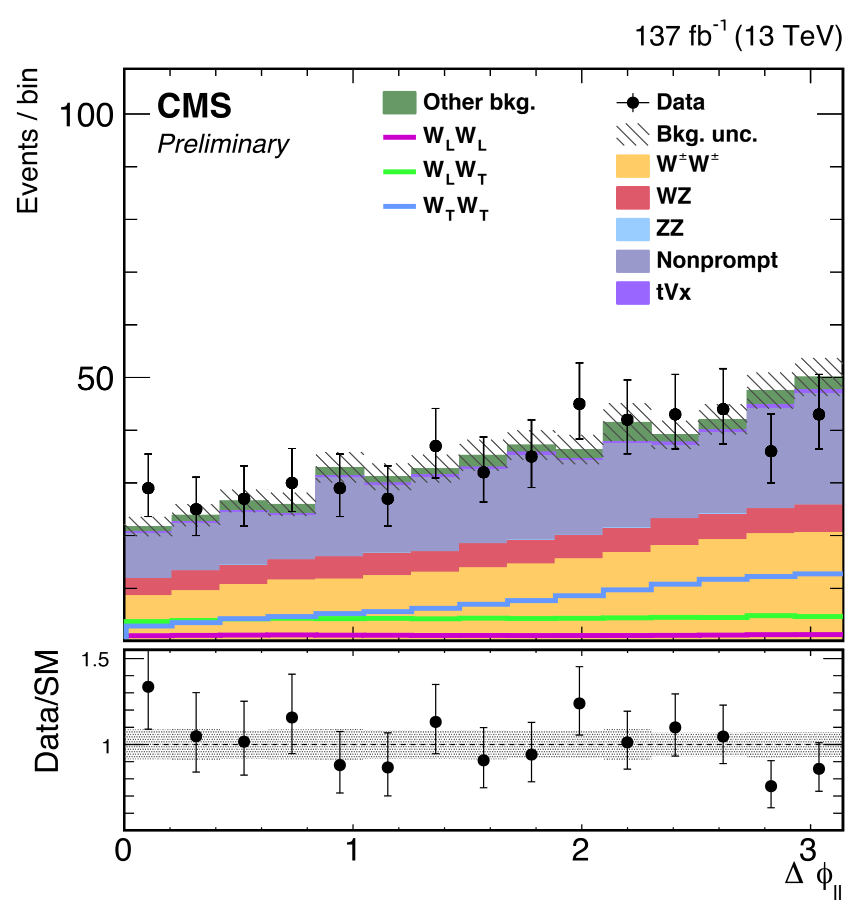
Polarized $W^{\pm}W^{\pm}$ VBS Full Run II : Results

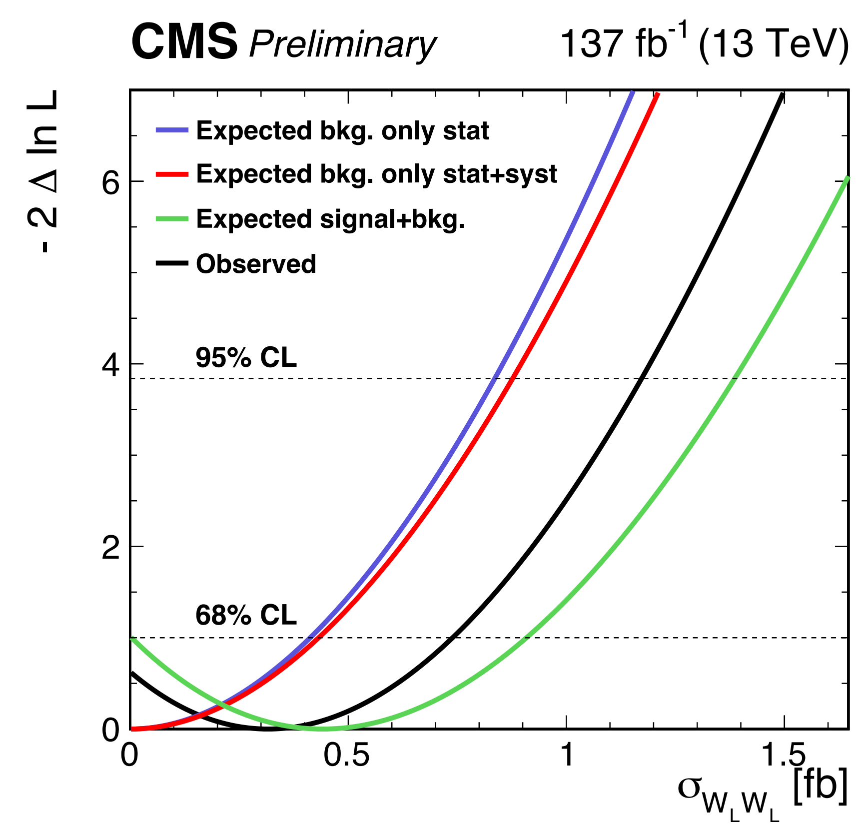
- Fiducial cross sections Measurement for the helicity eigenstates in the parton-parton center-of-mass frame
- The observed (expected) upper limit 95% CL of $W_L W_L$ is 1.17 (0.88) fb.

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^{\pm}_{L}W^{\pm}_{L}$	$0.24^{+0.40}_{-0.37}$	0.28 ± 0.03
$W^{\pm}_{X}W^{\pm}_{T}$	$3.25^{+0.50}_{-0.48}$	3.32 ± 0.37
$W^{\pm}_{L}W^{\pm}_{X}$	$1.40^{+0.60}_{-0.57}$	1.71 ± 0.19
$W^{\pm}_{T}W^{\pm}_{T}$	$2.03^{+0.51}_{-0.50}$	1.89 ± 0.21

CMS-PAS-SMP-20-006







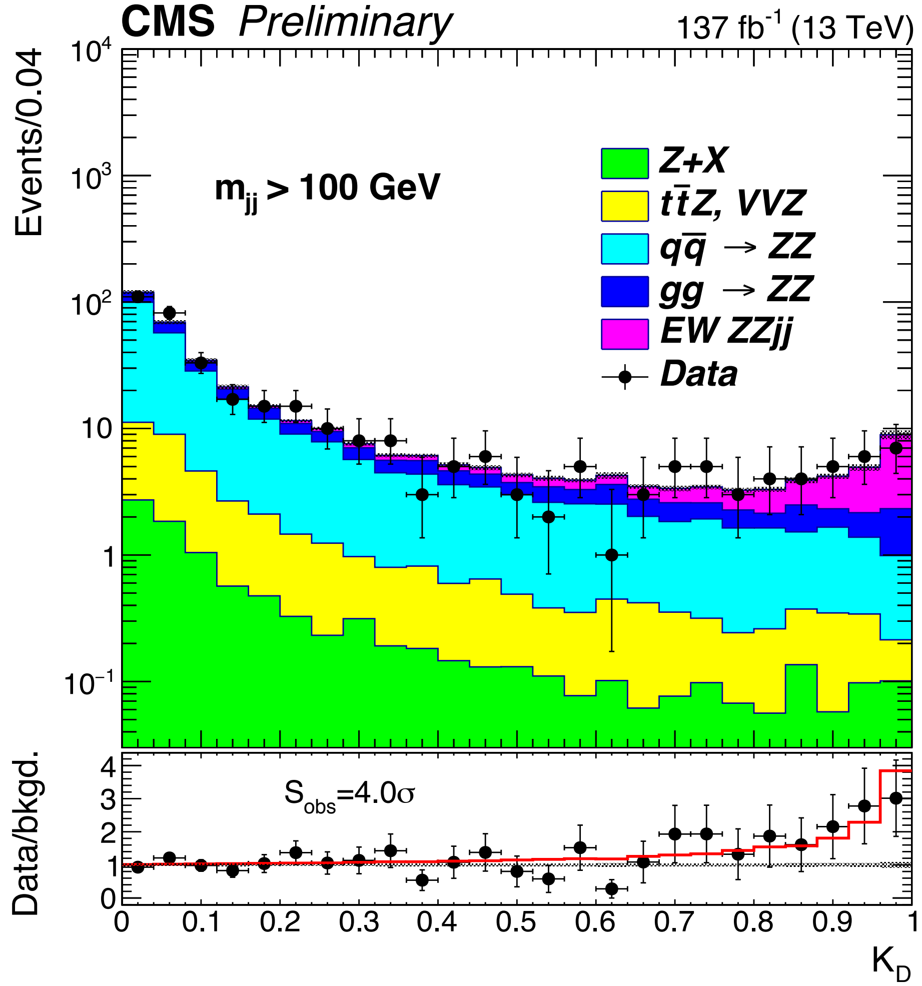
Profile likelihood scan as a function of the $W_L W_L$ cross section

ZZ VBS Full Run II

- Measurement of EW ZZjj production using 4ℓ events
- Really clean , fully reconstructable final state. Small instrumental background
- Making use of a matrix-element discriminant (K_D) to enhance EW production
- BDT was also studied - gave consistent results
- Observed (expect) EWK ZZ 4.0(3.5)σ
- $\mu_{\text{EW}} = 1.21^{+0.47}_{-0.40}$, $\mu_{\text{EW+QCD}} = 0.99^{+0.13}_{-0.12}$

	SM σ (fb)	Measured σ (fb)
	ZZjj inclusive	
EW	0.275 ± 0.021 (theo)	$0.33\ ^{+0.11}_{-0.10}$ (stat) $^{+0.04}_{-0.03}$ (syst)
EW+QCD	5.35 ± 0.51 (theo)	$5.29\ ^{+0.31}_{-0.30}$ (stat) ± 0.46 (syst)
	VBS-enriched (loose)	
EW	0.186 ± 0.015 (theo)	$0.200\ ^{+0.078}_{-0.067}$ (stat) $^{+0.023}_{-0.013}$ (syst)
EW+QCD	1.21 ± 0.09 (theo)	$1.00\ ^{+0.12}_{-0.11}$ (stat) $^{+0.06}_{-0.05}$ (syst)
	VBS-enriched (tight)	
EW	0.050 ± 0.005 (theo)	$0.06\ ^{+0.05}_{-0.04}$ (stat) ± 0.01 (syst)
EW+QCD	0.171 ± 0.012 (theo)	0.17 ± 0.04 (stat) ± 0.01 (syst)

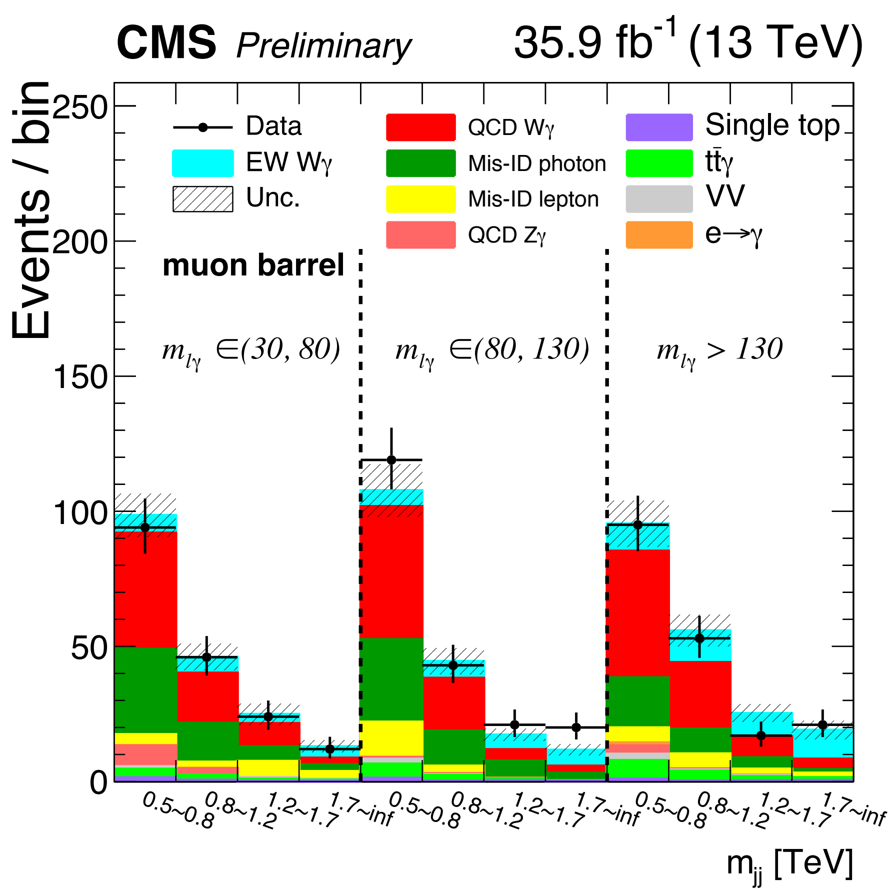
CMS-PAS-SMP-20-001

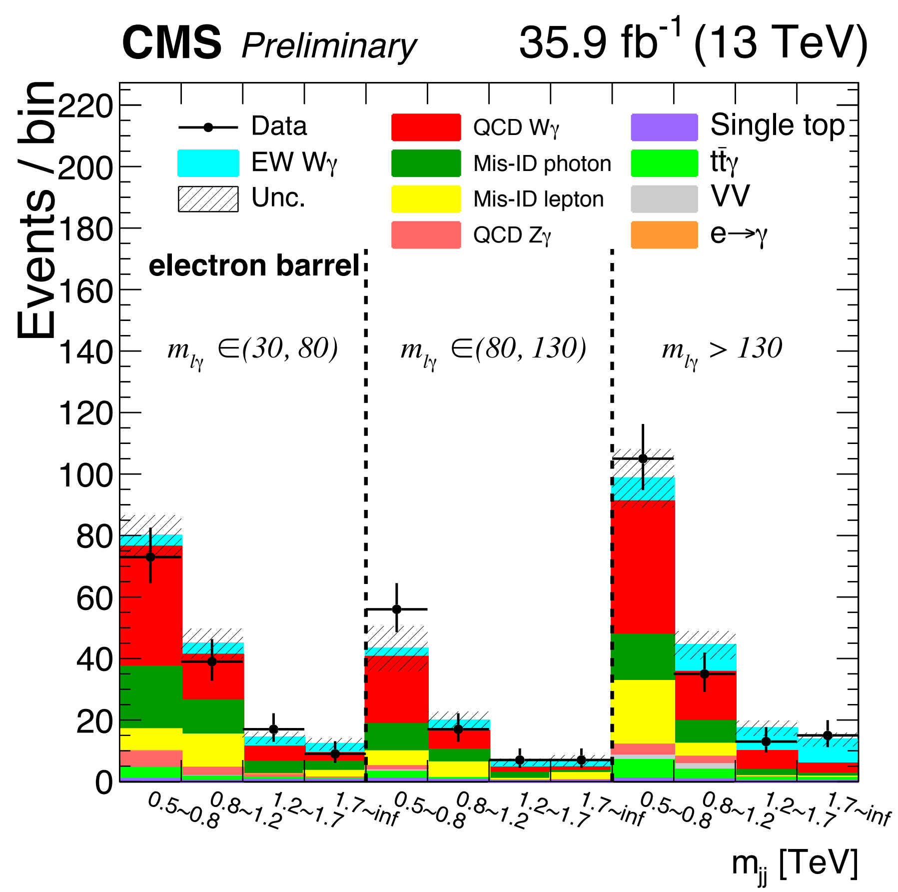


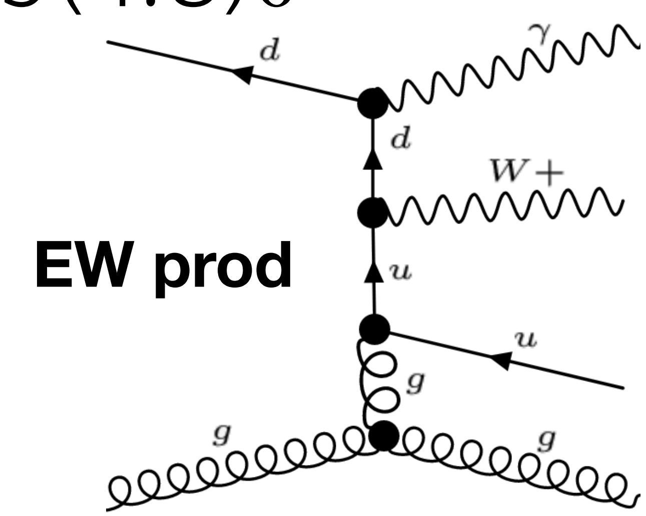
Wγ VBS 2016 dataset

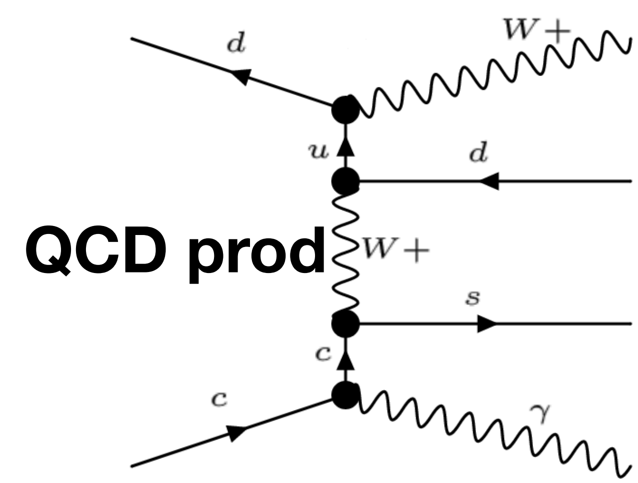
CMS-PAS-SMP-19-008

- Wγ measurement is difficult by itself
- Large QCD irreducible Wγjj background, and fakes
- Fiducial XS $\sigma^{\text{fid}}_{\text{EW}} = 20.4 \pm 0.4\,(\text{lumi}) \pm 2.8\,(\text{stat}) \pm 3.5\,(\text{syst})\,\text{fb}$
- Combine 13+8 TeV and obtain EW Wγ 5.3(4.8)σ observed (expect) significance





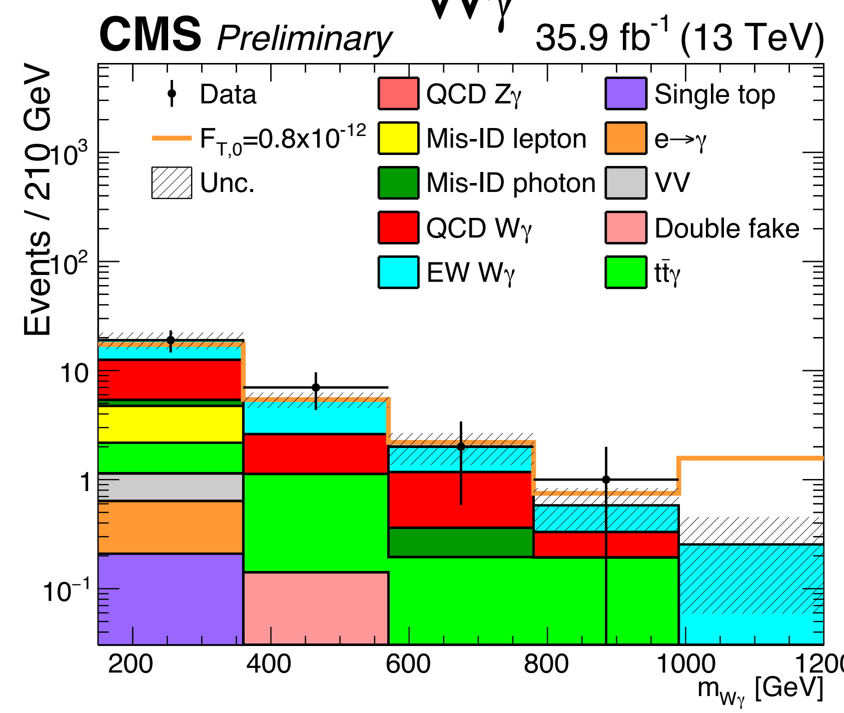




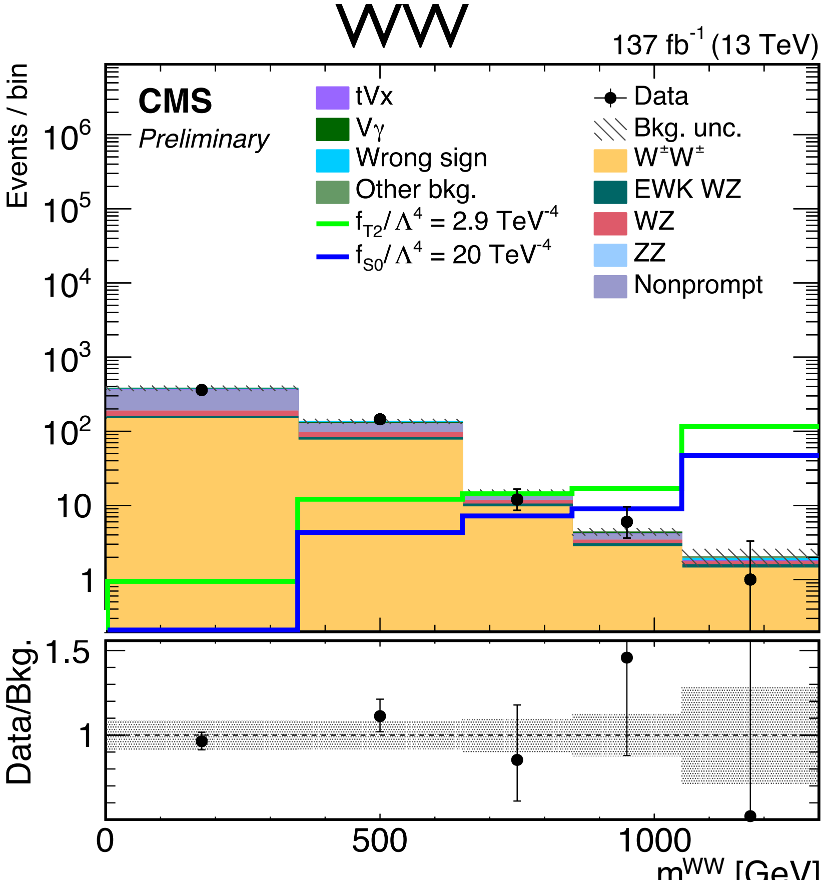
aQGCs

- Traces of heavy states from Beyond Standard Model Physics can be parameterized in terms of the Effective Field Theory (EFT) approach.
- Limits on aQGCs are set via EFT approach. Dimension-8 operators that can modify VVjj production through aQGCs are considered, one at a time.

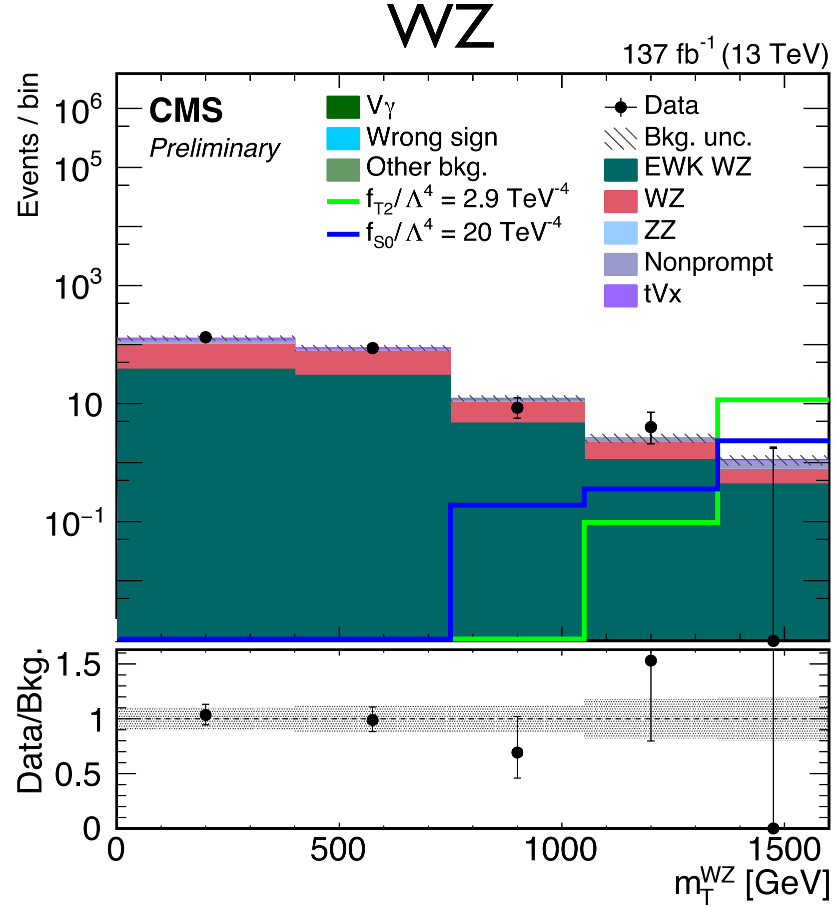
Wγ



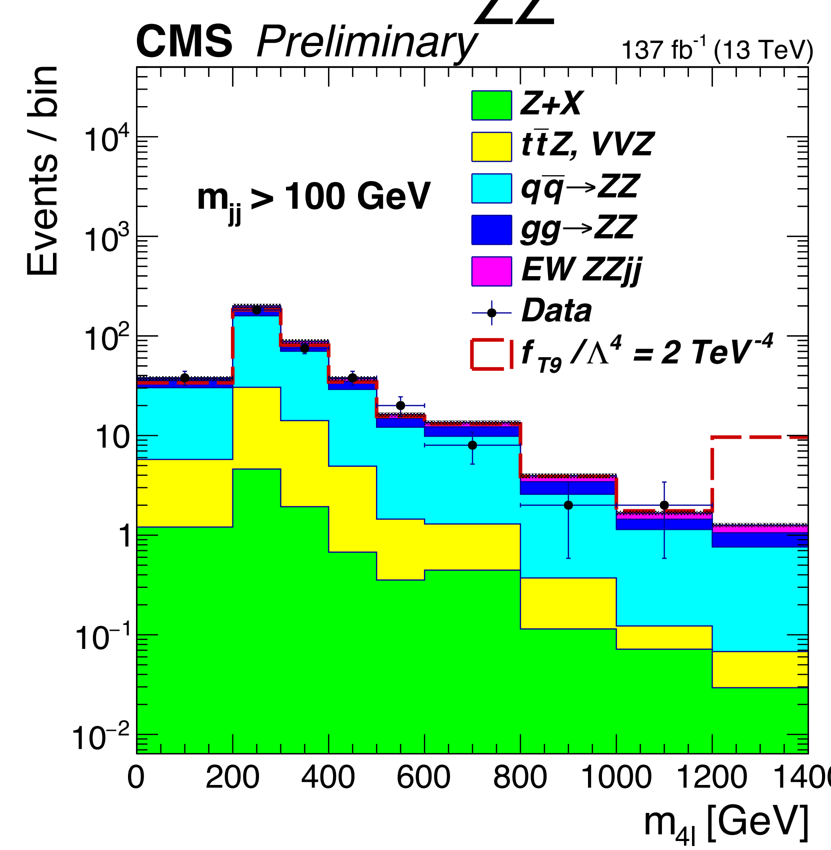
WW



WZ



ZZ



aQGCs : Results

WW & WZ

	Observed ($W^\pm W^\pm$) (TeV^{-4})	Expected ($W^\pm W^\pm$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-1.53,2.31]	[-2.05,2.73]	[-1.65,1.90]	[-2,2.25]	[-1.10,1.63]	[-1.58,1.99]
f_{T1}/Λ^4	[-0.81,1.16]	[-0.98,1.42]	[-1.32,1.54]	[-1.59,1.81]	[-0.69,0.97]	[-0.94,1.27]
f_{T2}/Λ^4	[-2.14,4.45]	[-2.65,5.25]	[-2.73,3.44]	[-4.42,5.47]	[-1.62,3.06]	[-2.25,3.82]
f_{M0}/Λ^4	[-13.4,15.9]	[-18.6,18.3]	[-16.2,16.1]	[-18.9,18.8]	[-10.5,12.2]	[-14.9,14.9]
f_{M1}/Λ^4	[-20.3,18.9]	[-22,24.8]	[-19.1,19.6]	[-23.3,23.8]	[-15,13.8]	[-18,19.6]
f_{M6}/Λ^4	[-27.3,31.8]	[-37.4,36.5]	[-33.6,33.4]	[-39,38.6]	[-21.7,24.8]	[-30.6,30]
f_{M7}/Λ^4	[-21.5,24.2]	[-26.6,24.9]	[-22.2,22]	[-28.2,28]	[-15.7,17.8]	[-21.9,20.9]
f_{S0}/Λ^4	[-35,36.1]	[-31.3,30.9]	[-82.5,85.4]	[-87.9,91.1]	[-33.8,35]	[-31,30.6]
f_{S1}/Λ^4	[-100,118]	[-102,110]	[-107,109]	[-122,126]	[-86.3,99.8]	[-91,97]

ZZ

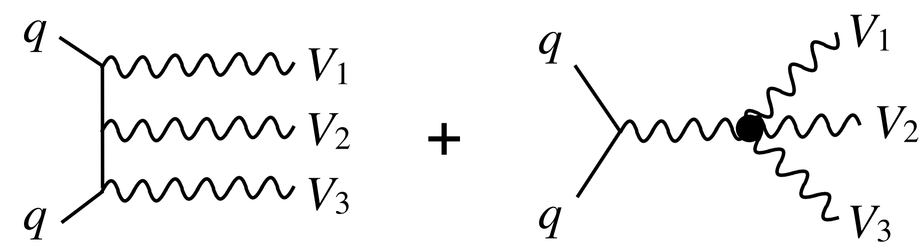
Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	-0.37	0.35	-0.24	0.22	2.9
f_{T1}/Λ^4	-0.49	0.49	-0.31	0.31	2.7
f_{T2}/Λ^4	-0.98	0.95	-0.63	0.59	2.8
f_{T8}/Λ^4	-0.68	0.68	-0.43	0.43	3.3
f_{T9}/Λ^4	-1.46	1.46	-0.92	0.92	3.3

Wγ

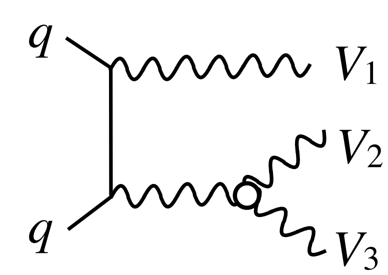
Observed limits [TeV^{-4}]	Expected limits [TeV^{-4}]	Unitarity bound [TeV]
$-8.07 < F_{M,0}/\Lambda^4 < 7.99$	$-7.67 < F_{M,0}/\Lambda^4 < 7.55$	1.0
$-11.8 < F_{M,1}/\Lambda^4 < 12.1$	$-10.8 < F_{M,1}/\Lambda^4 < 11.3$	1.2
$-2.81 < F_{M,2}/\Lambda^4 < 2.81$	$-2.68 < F_{M,2}/\Lambda^4 < 2.68$	1.3
$-4.41 < F_{M,3}/\Lambda^4 < 4.49$	$-4.04 < F_{M,3}/\Lambda^4 < 4.10$	1.5
$-4.99 < F_{M,4}/\Lambda^4 < 4.95$	$-4.70 < F_{M,4}/\Lambda^4 < 4.67$	1.5
$-8.27 < F_{M,5}/\Lambda^4 < 8.31$	$-7.85 < F_{M,5}/\Lambda^4 < 7.73$	1.8
$-16.2 < F_{M,6}/\Lambda^4 < 16.0$	$-15.4 < F_{M,6}/\Lambda^4 < 15.1$	1.0
$-20.8 < F_{M,7}/\Lambda^4 < 20.2$	$-19.4 < F_{M,7}/\Lambda^4 < 18.7$	1.3
$-0.62 < F_{T,0}/\Lambda^4 < 0.64$	$-0.60 < F_{T,0}/\Lambda^4 < 0.62$	1.4
$-0.35 < F_{T,1}/\Lambda^4 < 0.39$	$-0.34 < F_{T,1}/\Lambda^4 < 0.38$	1.5
$-0.99 < F_{T,2}/\Lambda^4 < 1.18$	$-0.98 < F_{T,2}/\Lambda^4 < 1.16$	1.5
$-0.45 < F_{T,5}/\Lambda^4 < 0.46$	$-0.43 < F_{T,5}/\Lambda^4 < 0.44$	1.8
$-0.36 < F_{T,6}/\Lambda^4 < 0.38$	$-0.34 < F_{T,6}/\Lambda^4 < 0.36$	1.7
$-0.87 < F_{T,7}/\Lambda^4 < 0.93$	$-0.83 < F_{T,7}/\Lambda^4 < 0.89$	1.8

VVV

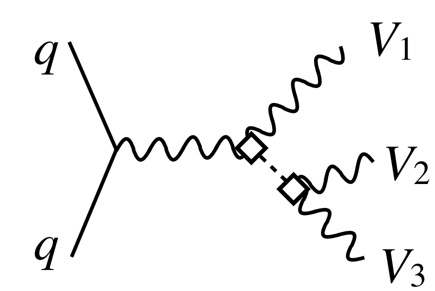
- Are multi-boson interaction SM? First observation VVV and evidences of individual channels.
- Fit four signal strength across 21 categories in lepton number(2~6)/charge/flavour ….
- Observed the production of heavy triboson production with a significance of 5.7σ (5.9σ expected).
- Evidences for the WWW 3.3σ (3.1σ expected) and WWZ 3.3σ (4.1σ expected). Hints for WZZ 1.7σ (0.7σ expected)
- signal strength of VVV production $\mu = 1.02^{+0.26}_{-0.23}$



Quartic gauge coupling (QGC)

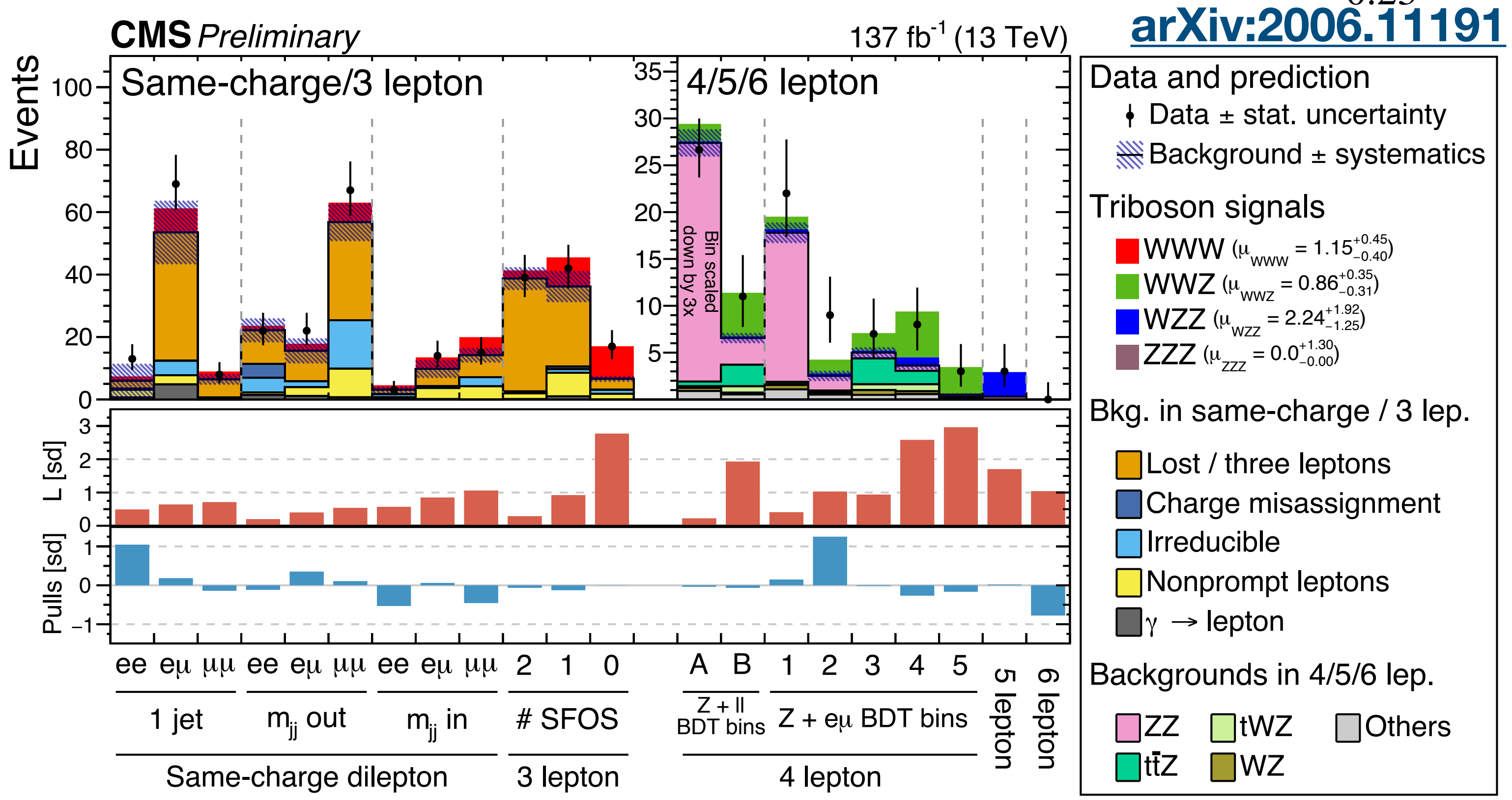


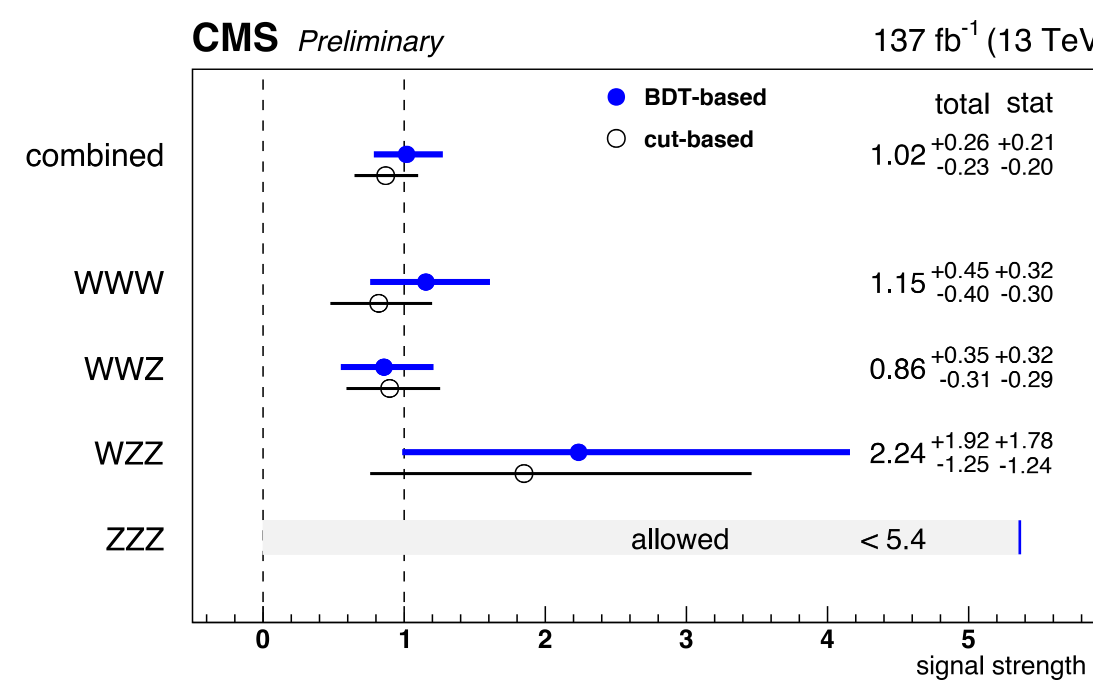
Triple gauge coupling (TGC)



Higgs-gauge coupling (HGC)

arXiv:2006.11191

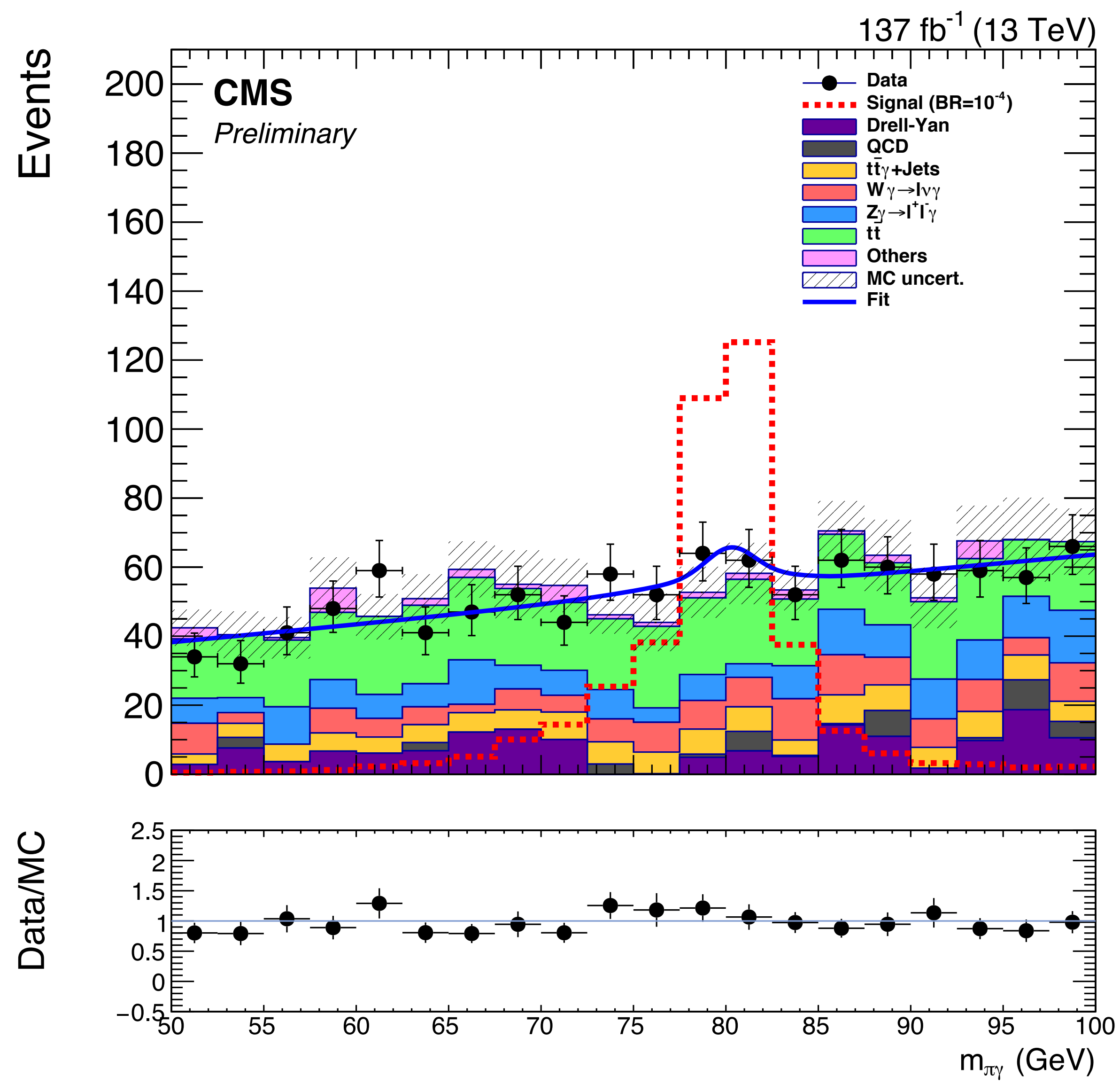




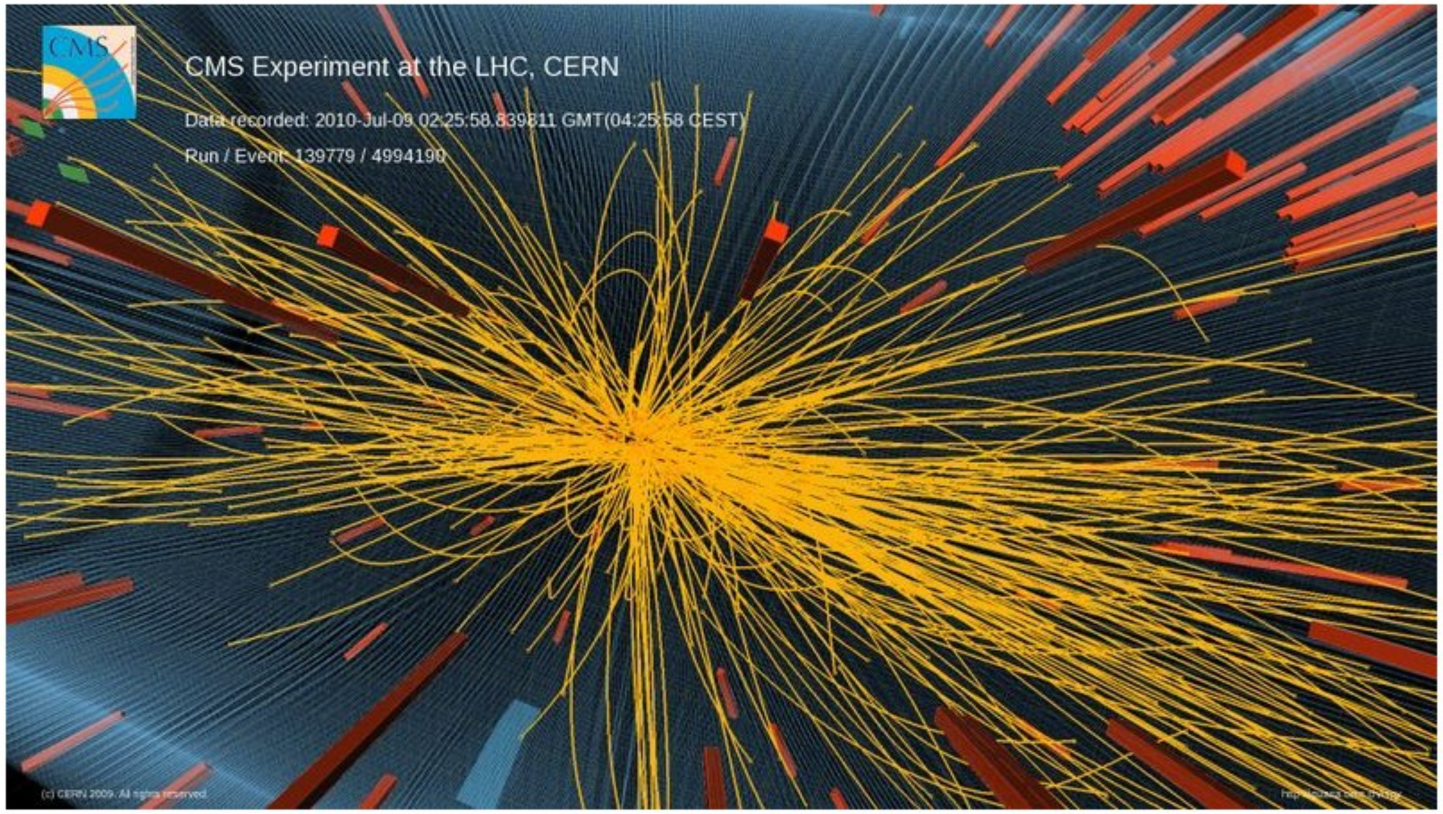
Search for W$^{\pm} \rightarrow \pi^{\pm}\gamma$ in $t\bar{t}$ events

- Exclusive hadronic decay of W boson
- provide insights on QCD factorization and meson form factors at high energy scales
- possible a new precision measurement of the W boson
- Large theoretical range of branching fraction in the range of 10^{-9}-10^{-6}
- Isolated single track + photon in tt enriched sample.
- Expect limit 0.86×10^{-5} and observe $\mathcal{B}(W \rightarrow \pi\gamma) < 1.51 \times 10^{-5}$

CMS-PAS-SMP-20-008

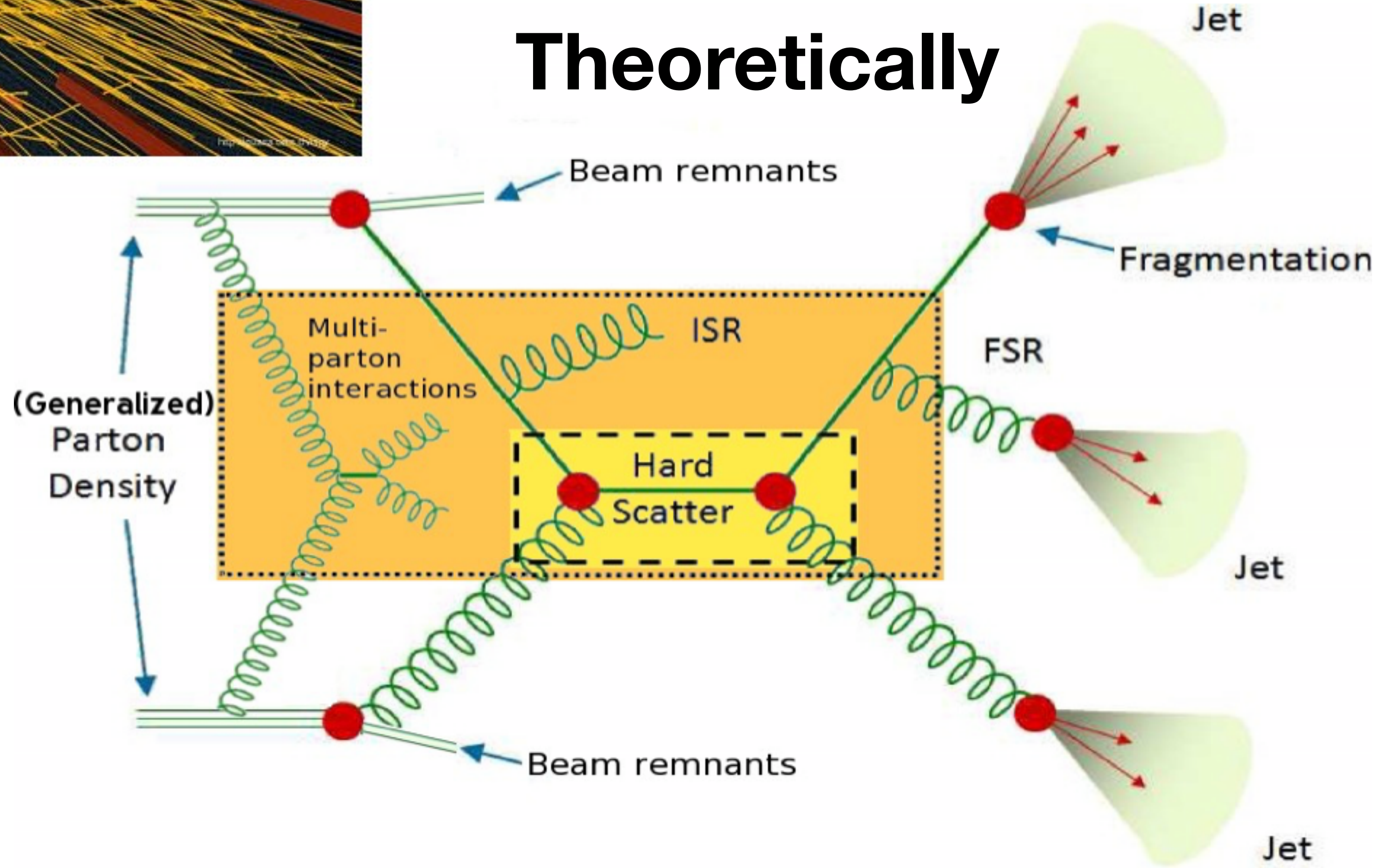


LHC pp physics is QCD physics

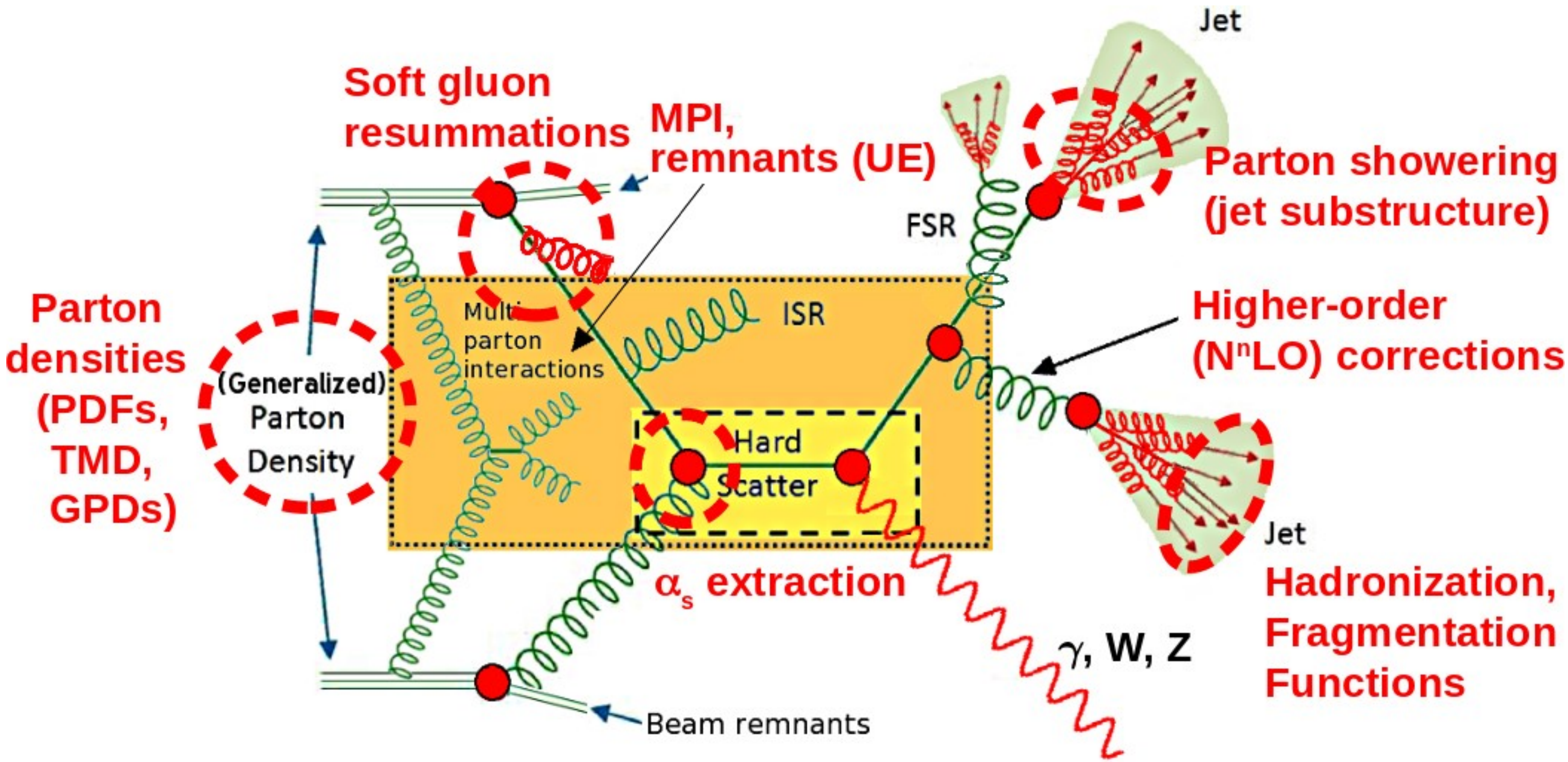


Experimentally

Theoretically

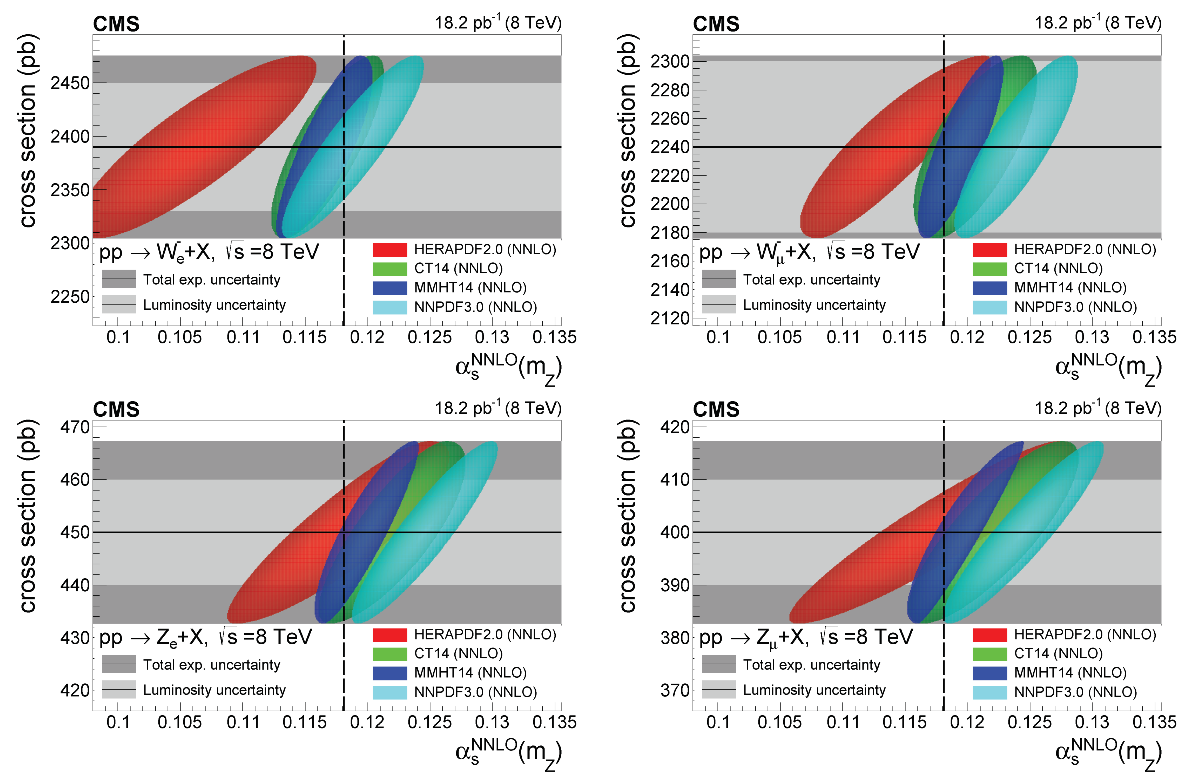


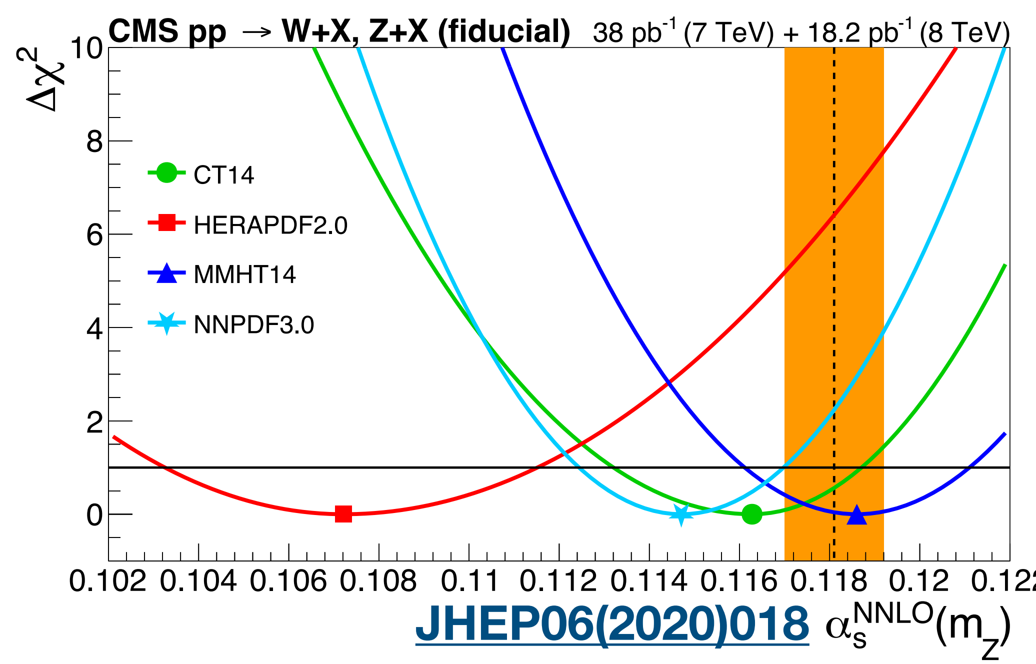
LHC pp physics is QCD physics



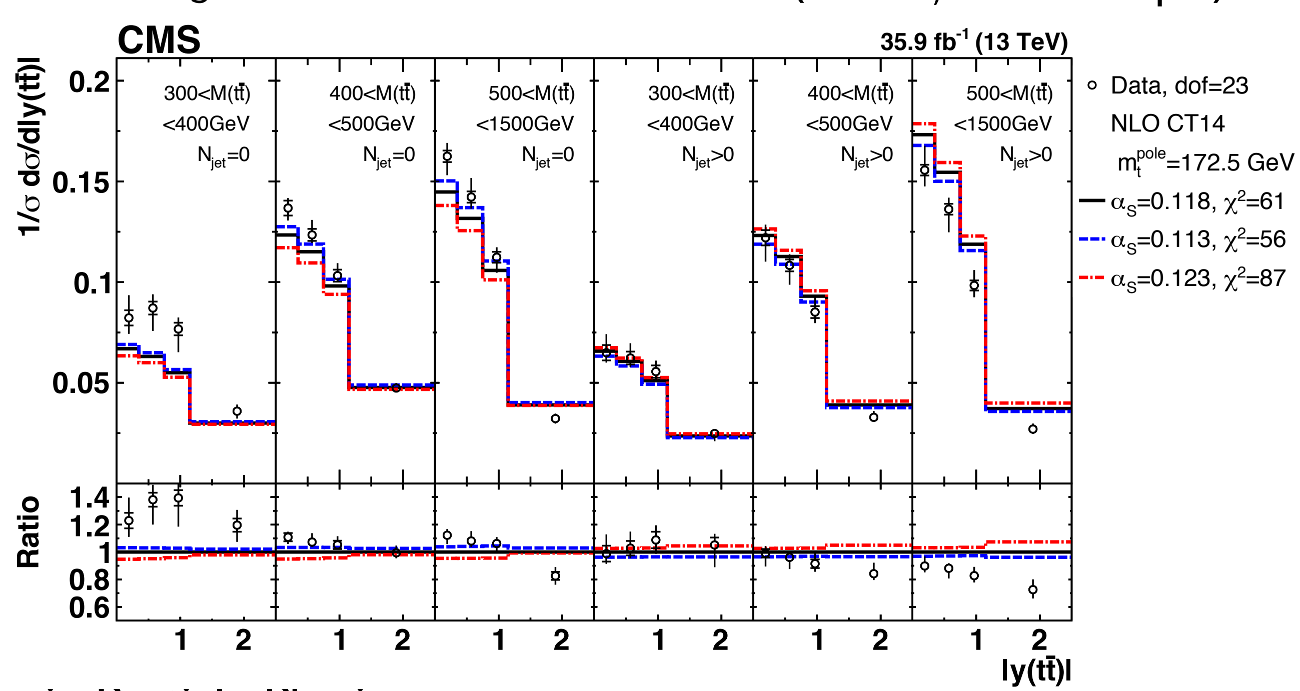
Extraction of α_s

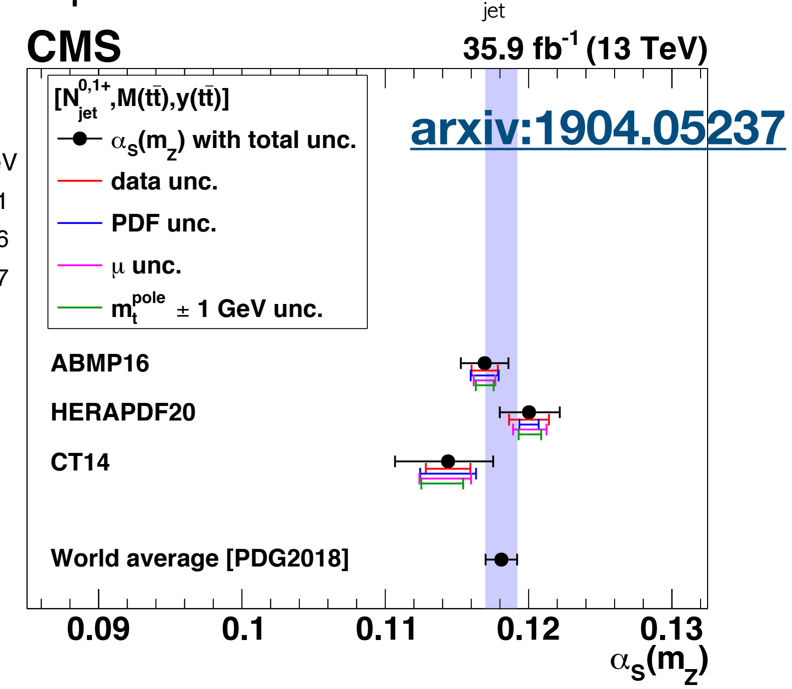
- Extracted $\alpha_s = 0.1175 \pm 0.0026$ (NNLO, $\pm 2.3\%$) via 12 precise W,Z x-sections:





- Extracted $\alpha_s = 0.1135 \pm 0.0020$ (NLO, PDF dep.) via precise ttbar+N_{jet} x-sections:

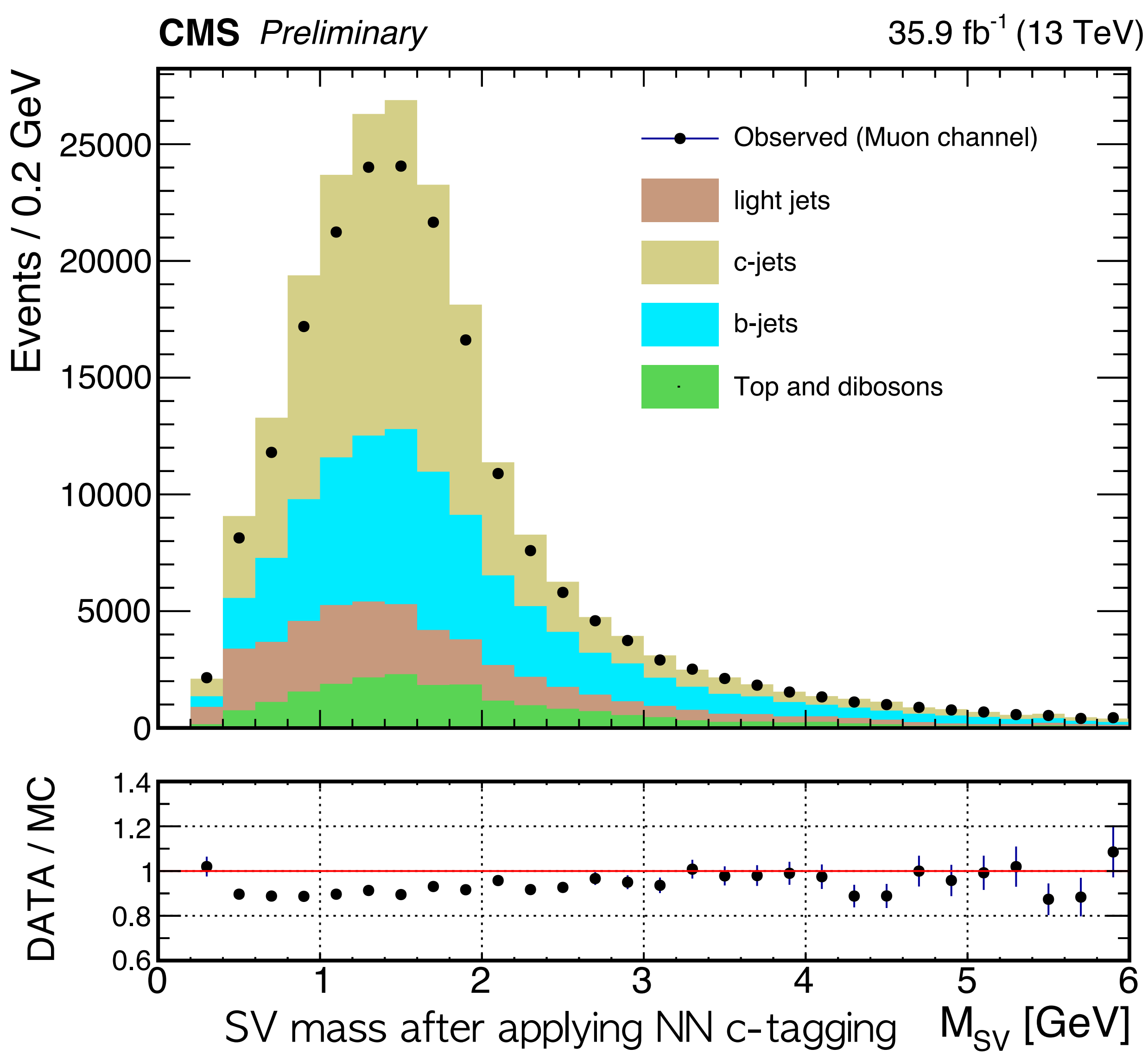


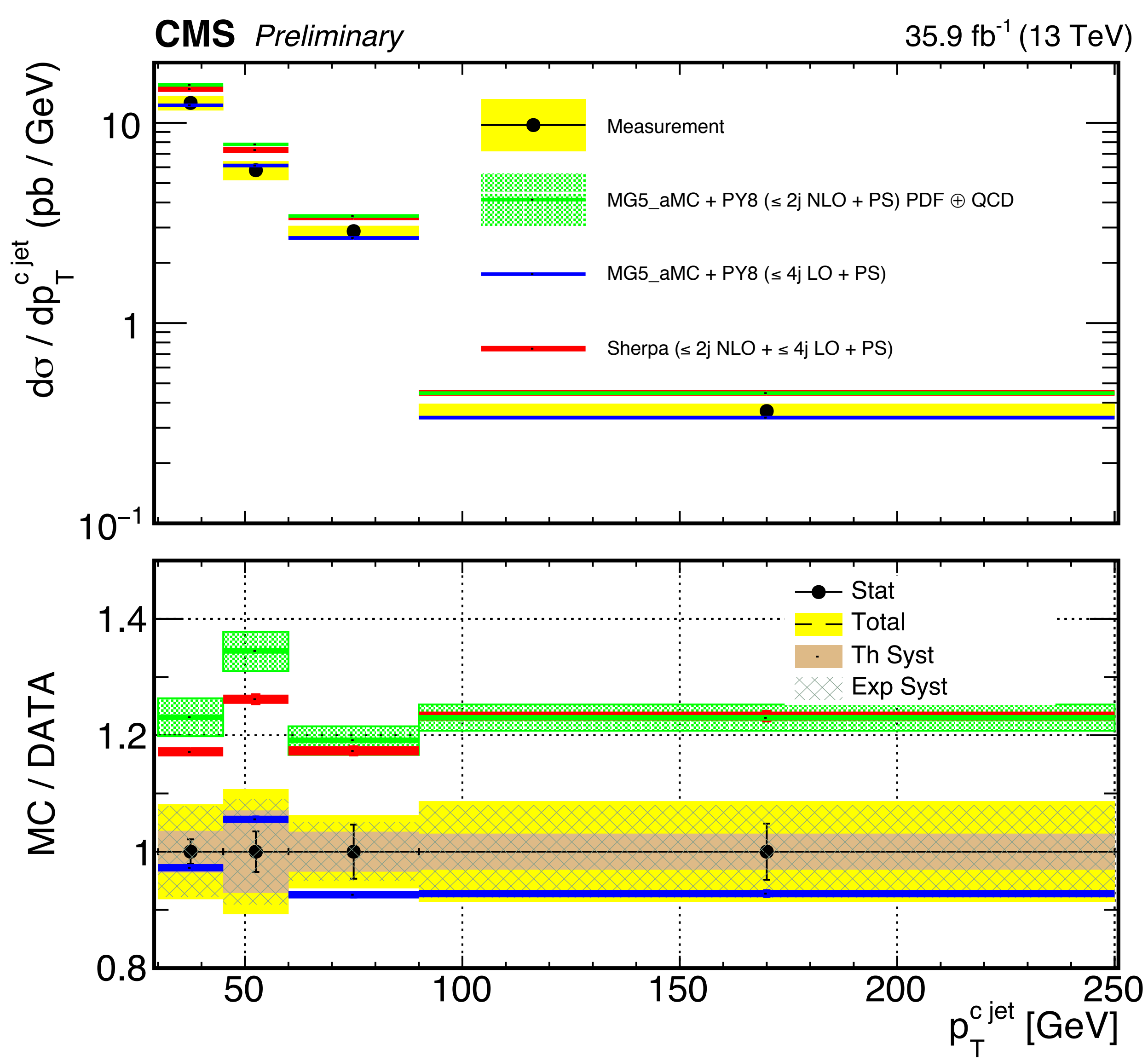


Data vs pQCD @N^nLO

- Z+c in good agreement with Madgraph LO predictions. Madgraph NLO and Sherpa tend to overestimate the data.

CMS-PAS-SMP-19-011

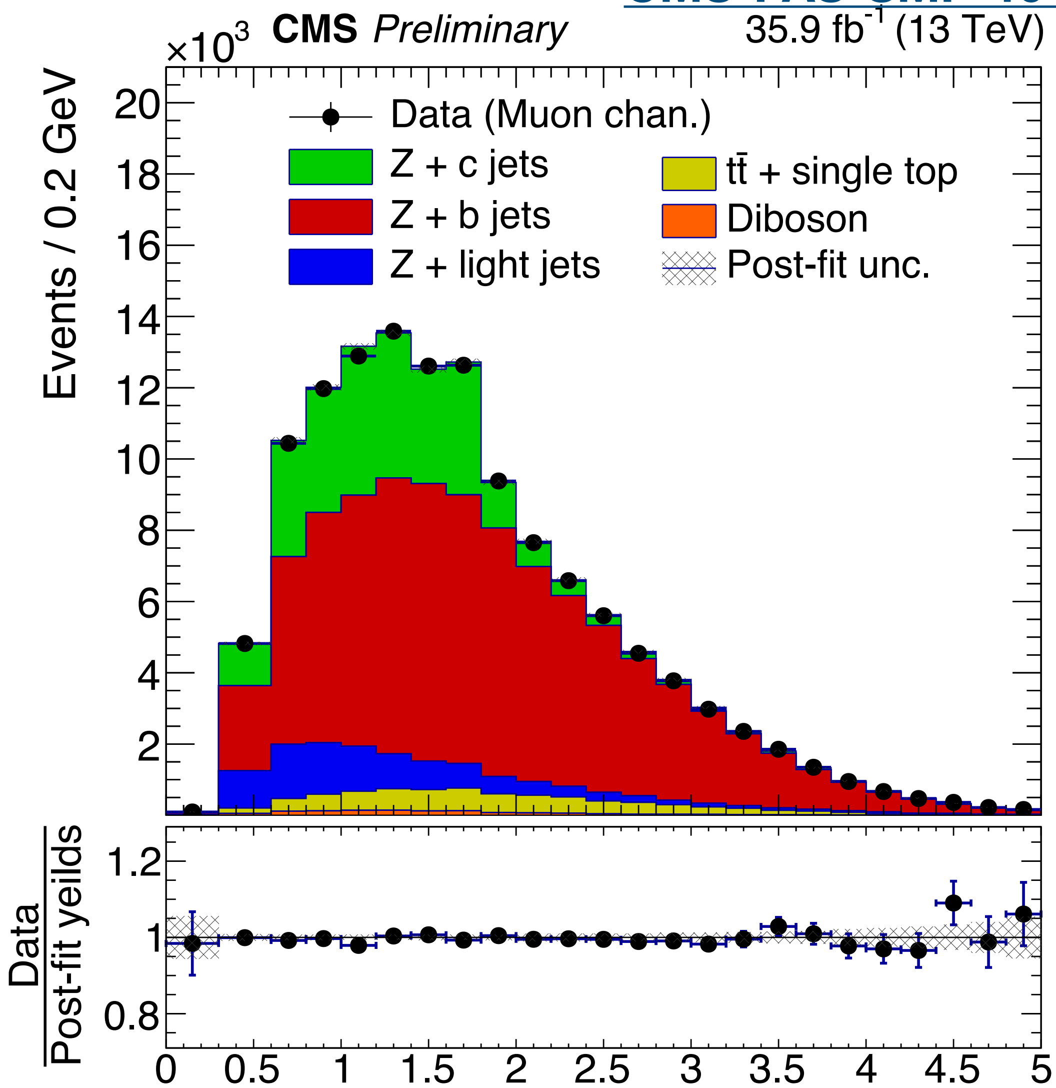




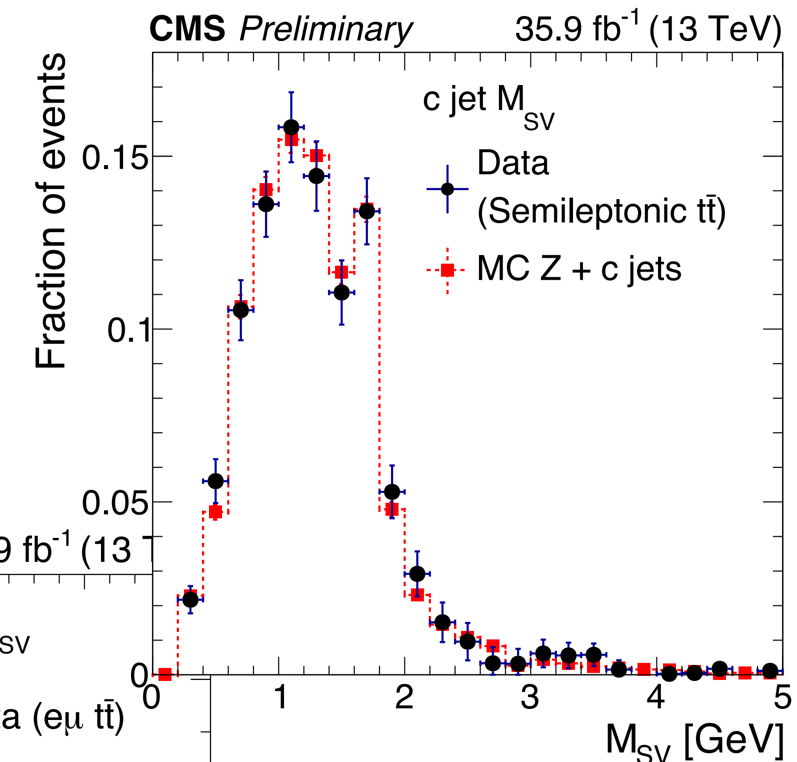
Data vs pQCD - Z+c/b

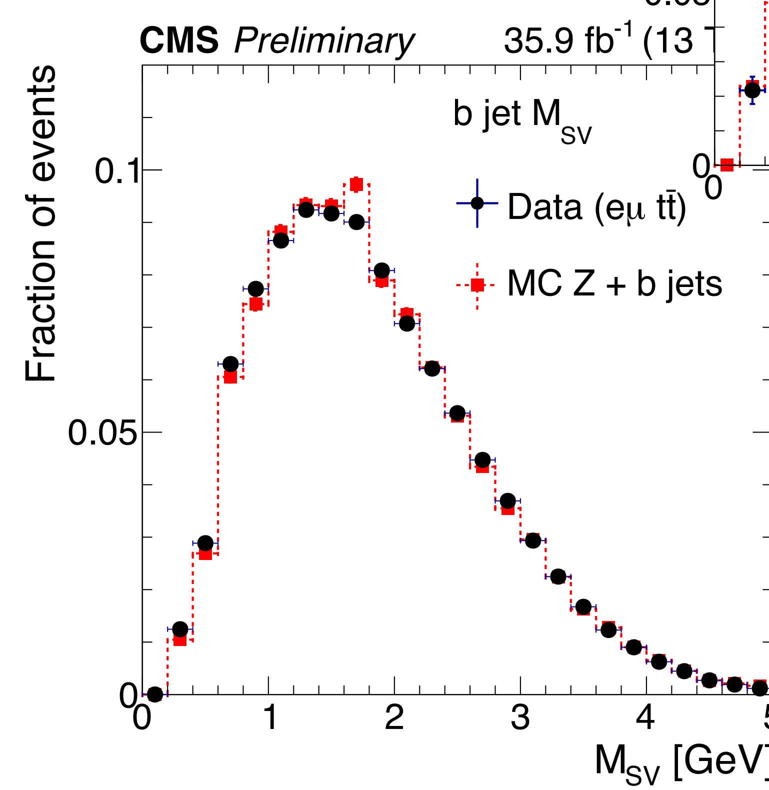
- Z+c/b measurements observe some disagreement between measurements and theoretical predictions, e.g. for R(c/j) for madgraph LO and NLO and R(b/j) for MCFM. R(c/b) is OK.

CMS-PAS-SMP-19-004



SV mass after applying NN b-tagging



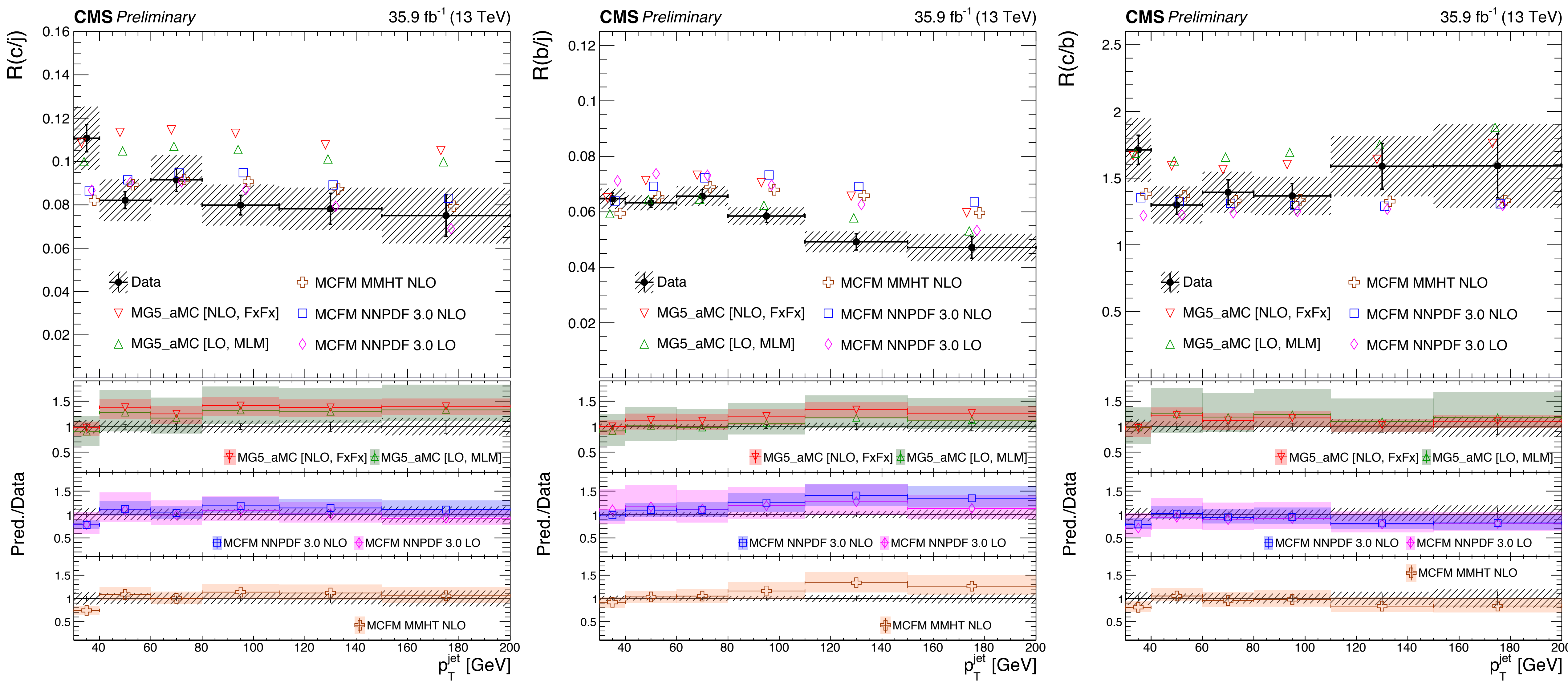


c/b jets in tt samples

Data vs pQCD - Z+c/b

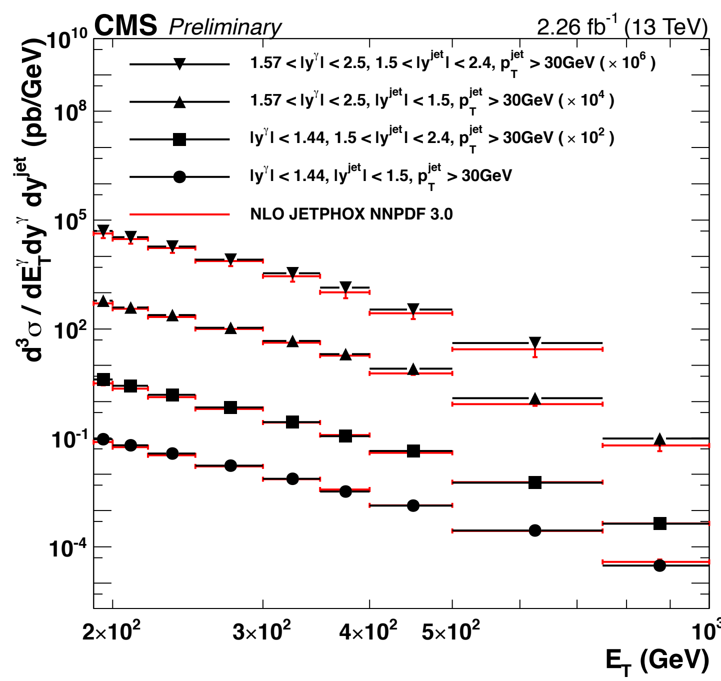
- Z+c/b measurements observe some disagreement between measurements and theoretical predictions, e.g. for R(c/j) for madgraph LO and NLO and R(b/j) for MCFM. R(c/b) is OK.

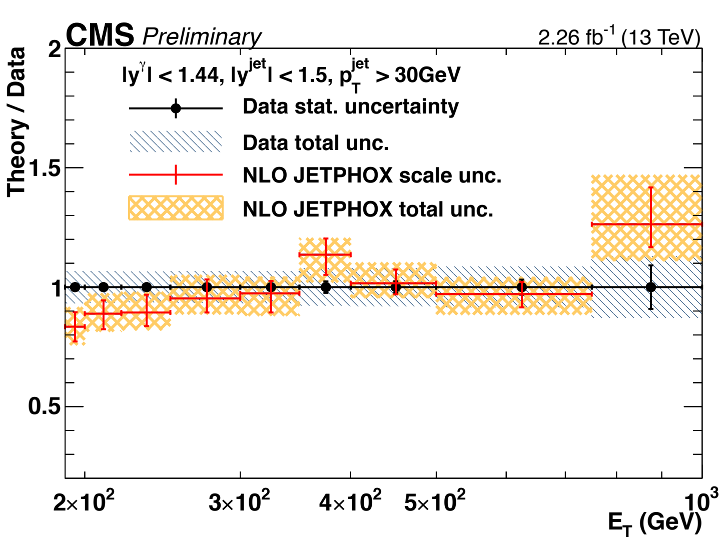
CMS-PAS-SMP-19-004

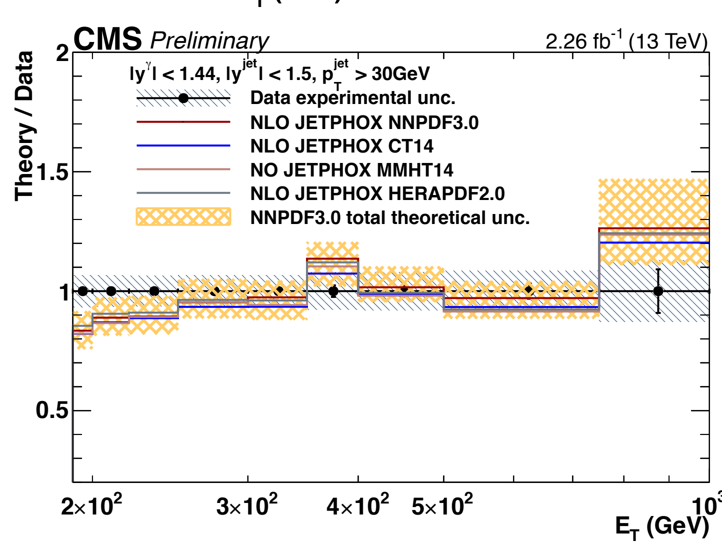


Data vs pQCD - Z/γ+jets

- γ+jets measurement directly test pQCD @NLO and is also sensitive to the gluon PDF over a wide range of x (momentum fraction) and Q2 (energy scale)

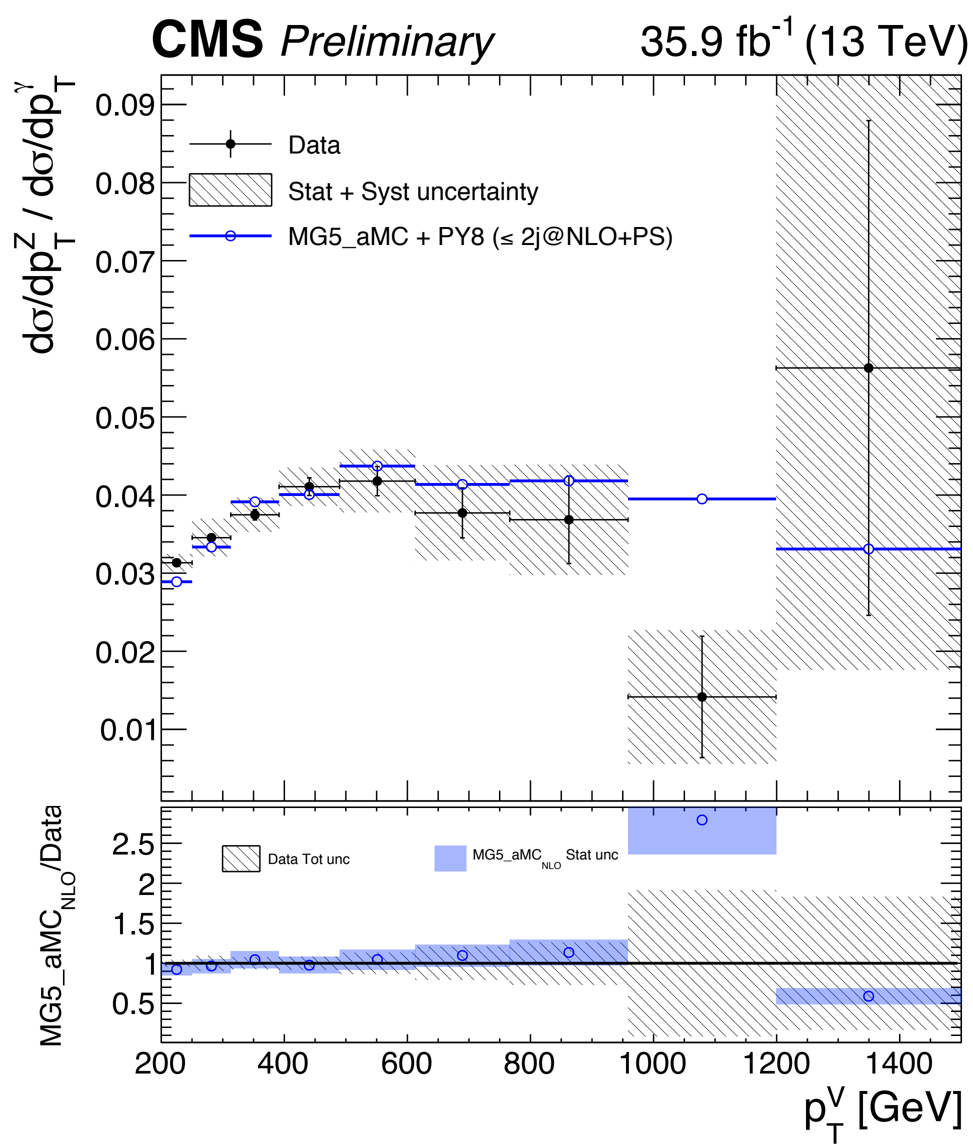






[EPJC 79(2019) 20](#)

- Differential measurement of cross section ratio of Z/γ vs boson pT
- Ratio can constrain higher order QCD and electroweak corrections that vary with boson pT



[CMS-PAS-SMP-19-010](#)

Other QCD measurements

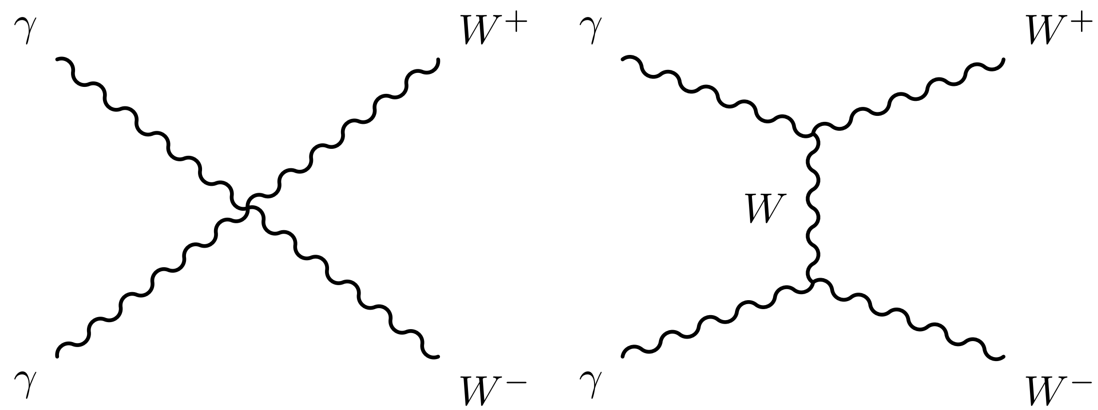
- Parton Distribution Functions constraint : All differential cross-sections :
  - dijet, W, Z, γ, $t\bar{t}$ ···
  - W/Z/γ + jets/ c/ b
- Jet substructure : dijet & $t\bar{t}$ events
- MPI : same sign WW, double ϒ; UE : Z+jet

Summary

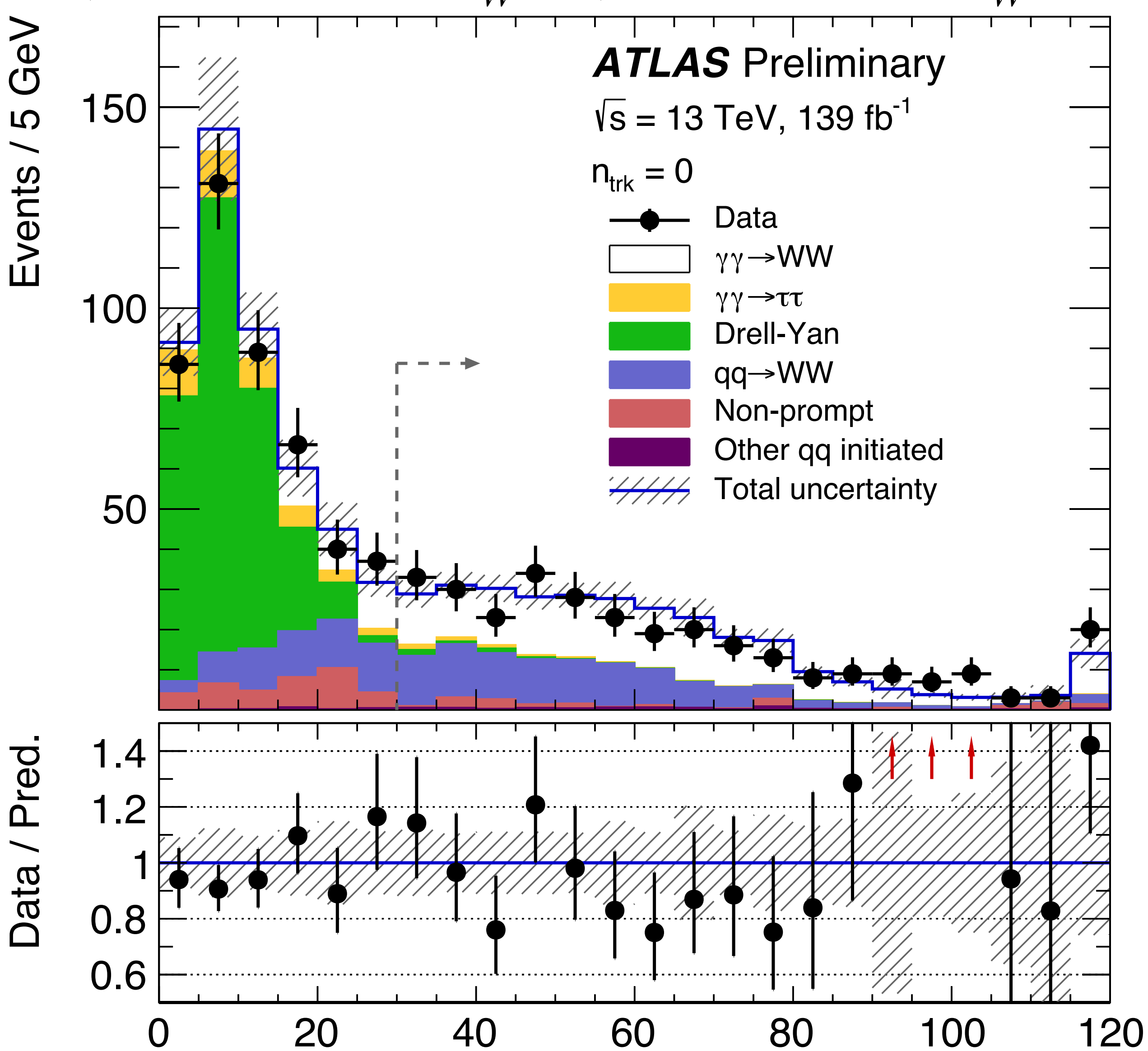
- CMS performs analyses on testing fundamental aspects of the Standard Model.
- The precision measurements study its EFT-based extensions if any hint
- Increasingly precise QCD observables are experimentally studied. It leads to improved analytic and MC models and better control of pQCD.

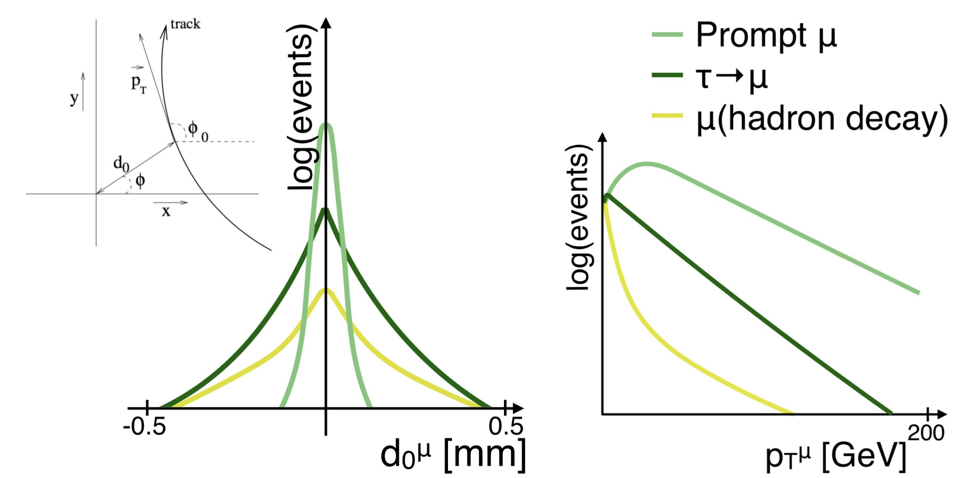
Back up slides

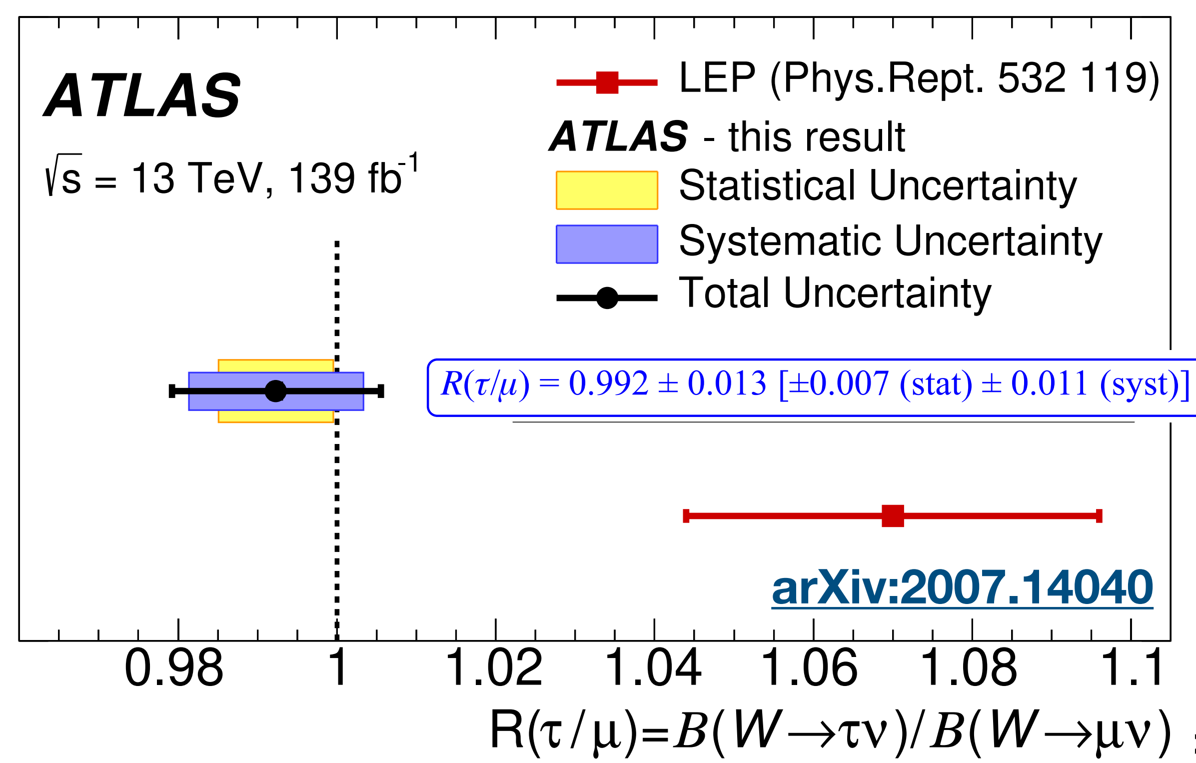
ATLAS γγ->WW and R(τ/μ) from W decay



- Probing universality of W coupling to charged leptons: fundamental property of SM
- di-lepton (eμ, μμ) $t\bar{t}$ events provide a sample of probe W-bosons
- differentiate W->τν and W→ μννν: $p_{T\mu}$ and $|d_\mu|$







ATLAS-CONF-2020-038

$W^{\pm}W^{\pm}$ & WZ VBS: Event Selection & Background Estimation

- WZ SR is dominated by QCD WZ events after the kinematic selection
- MultiVariate Analysis for WZ → enhance WZ EWK production w.r.t large WZ QCD production
- Overall good separation between EWK signal and background
- BACKGROUND ESTIMATION :
  - Backgrounds estimated from simulation marked with (*) have normalization assessed from data, others are normalized to the best theoretical cross section prediction

EVENT SELECTION IN SIGNAL REGIONS

Variable	$W^{\pm}W^{\pm}$	WZ
Leptons	2 leptons, $p_T > 25/20$ GeV	3 leptons, $p_T > 25/10/20$ GeV
p_T^j	>50 GeV	>50 GeV
$\|m_{\ell\ell} - m_Z\|$	>15 GeV (ee)	<15 GeV
$m_{\ell\ell}$	>20 GeV	—
$m_{\ell\ell\ell}$	—	>100 GeV
p_T^{miss}	>30 GeV	>30 GeV
b quark veto	Required	Required
$\max(z_\ell^*)$	<0.75	<1.0
m_{jj}	>500 GeV	>500 GeV
$\|\Delta\eta_{jj}\|$	>2.5	>2.5

Category	Estimation
Non Prompt	From Data-Driven technique
Wrong sign	From charge mis-ID scale factors and simulated opposite sign events
QCD WZ[*], ZZ[*], tZq[*], WW QCD, WW DPS, VVV	From simulation