Electroweak and QCD Physics at CMS

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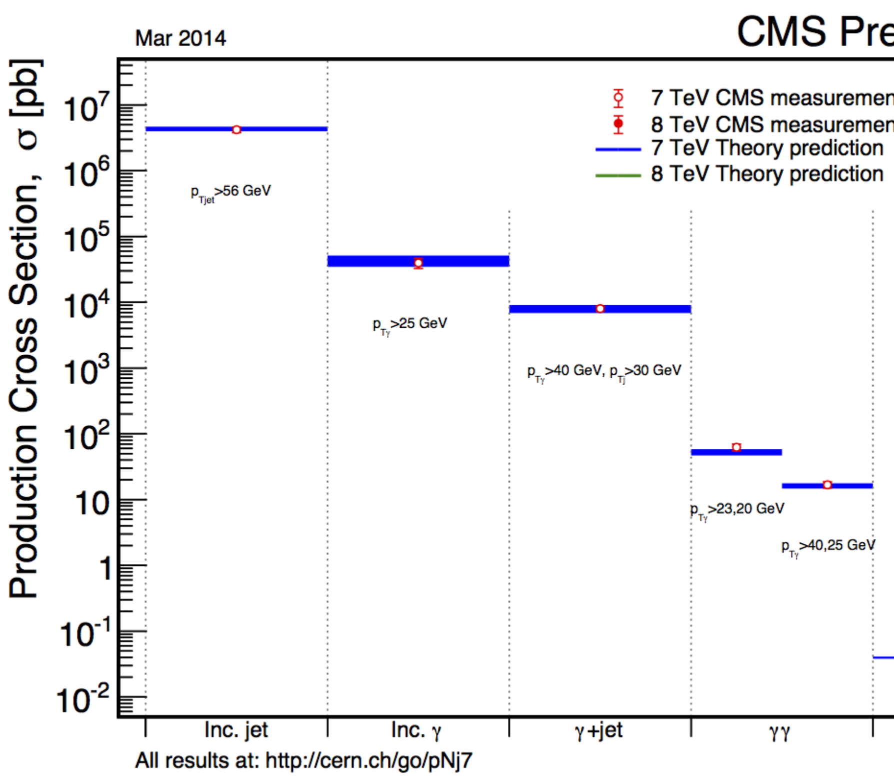
on behalf of the CMS Collaboration

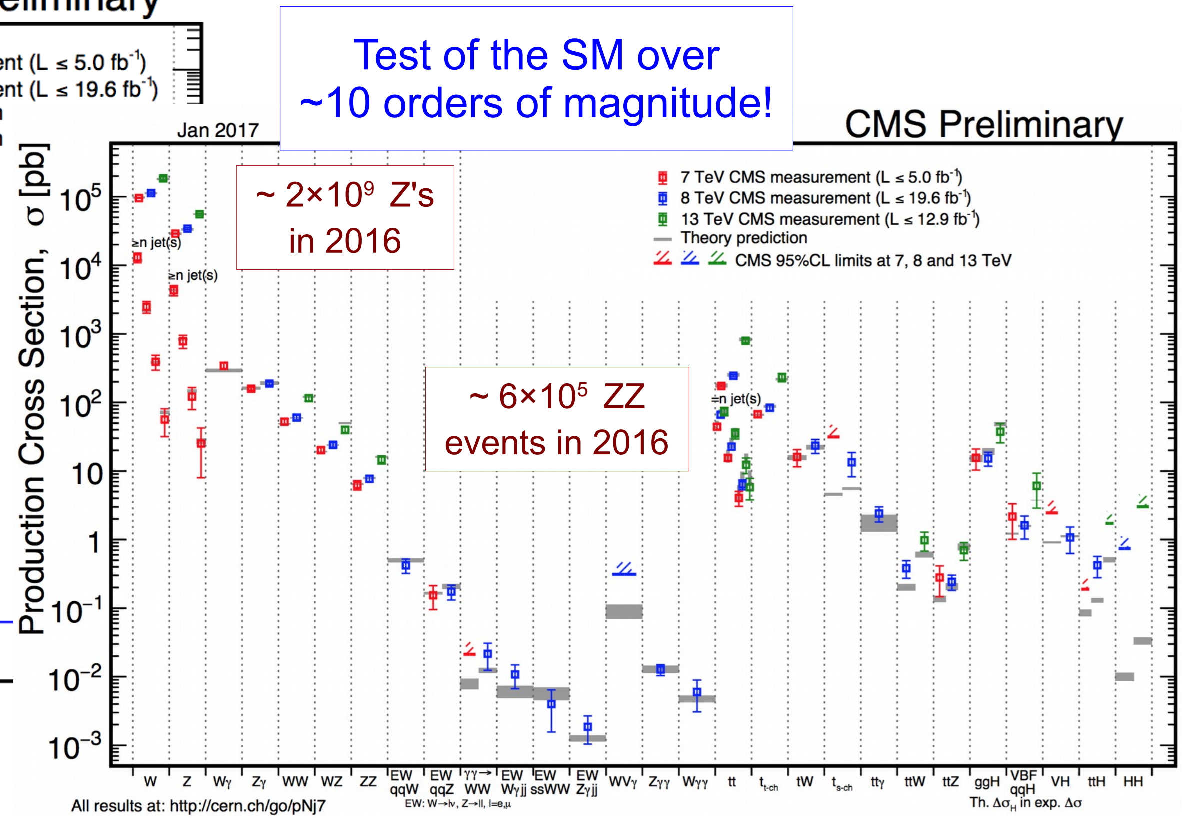
Les Rencontres de Physique de la Vallée d'Aoste

March 5–11, 2017 — La Thuile, Italy

Why Standard Model Physics?

- SM precision measurements are important at the LHC
  - test a wide range of QCD and EW predictions to the highest energies available
  - tune theoretical calculations and MC generators
  - provide precise modeling of backgrounds to many searches
    - any deviation from the SM expectation may be a sign of new physics!





LHC Data Taking

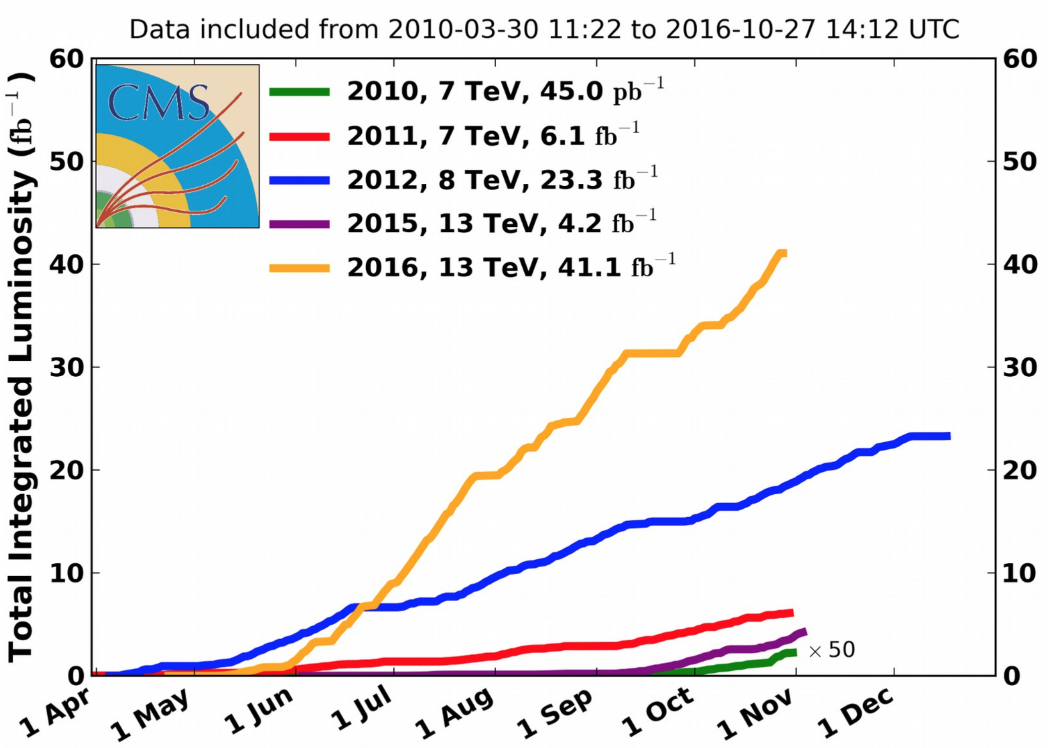
- LHC has delivered > 70 fb^{-1} of proton-proton collisions
  - 7 TeV: 6 fb^{-1} (2010-11)
  - 8 TeV: 23 fb^{-1} (2012)
  - 13 TeV: 4 fb^{-1} (2015) + 40 fb^{-1} (2016)

Run I

Run II

- The 2016 data will improve most of the Run-I results → *underway*!

I will focus on the main results at 8 and 13 TeV (2015)



Jets

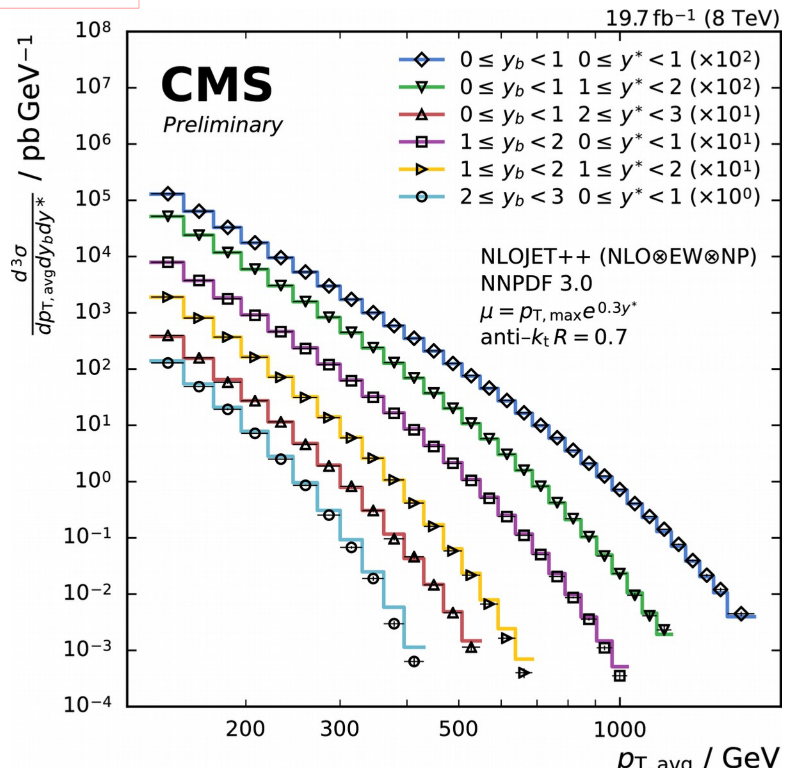
Measurement	(7) 8 TeV	13 TeV
double-differential inclusive jet	arXiv:1609.05331	EPJC 76 (2016) 451
triple-differential dijet	CMS-PAS-SMP-16-011	
α_S from R_{32}	CMS-PAS-SMP-16-008	
very-forward inclusive jet	CMS-PAS-FSQ-12-023 (7 TeV)	CMS-PAS-FSQ-16-003

** A short list of the latest jet studies — far from being exhaustive!*

Jet Production

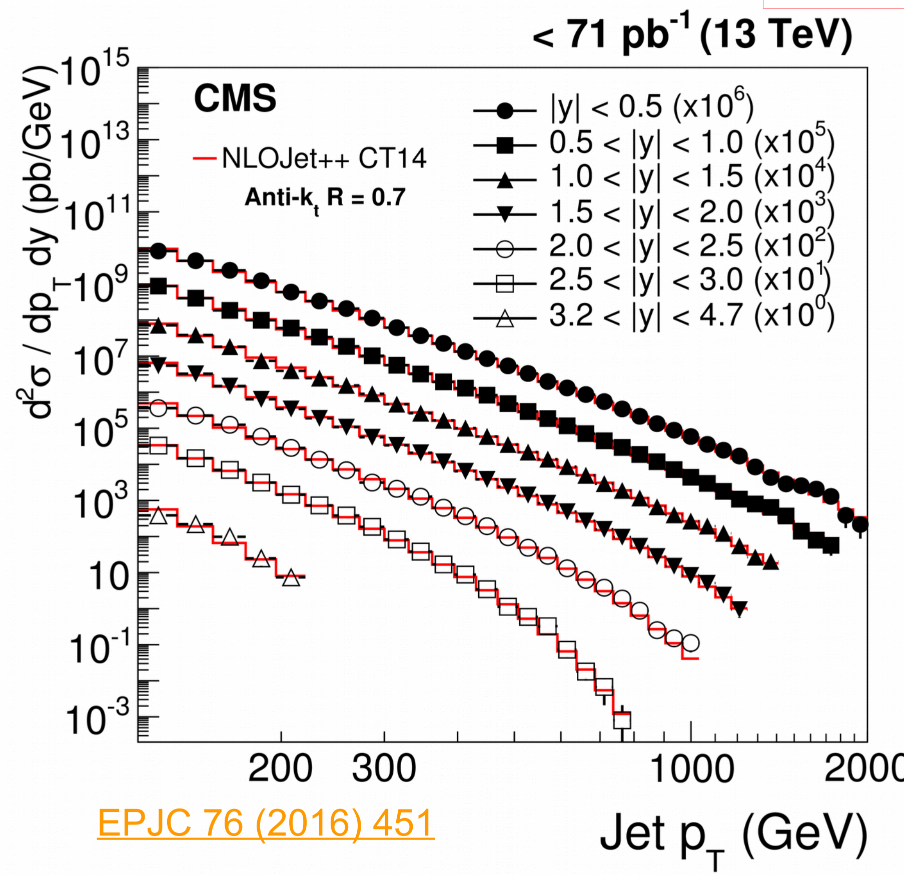
- Double- and triple-differential (di)jet cross section vs jet p_T and y ($|y_1 + y_2|$, $|y_1 - y_2|$)
  - measurement covers ~7 orders of magnitude, for jet p_T up to ~ 2 TeV
  - compared with NLO QCD predictions + NLO EW + nonperturbative effects
  - very good agreement over most of the phase space

Dijet, 8 TeV



CMS-PAS-SMP-16-011

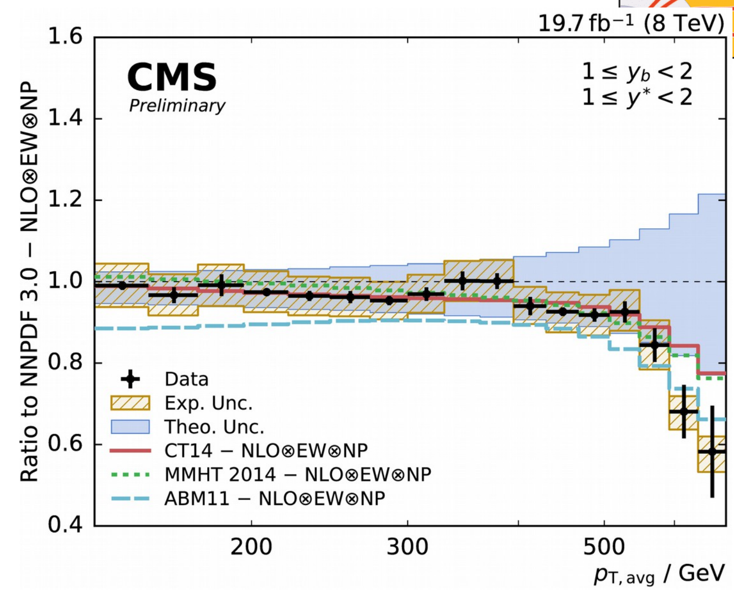
Inclusive, 13 TeV

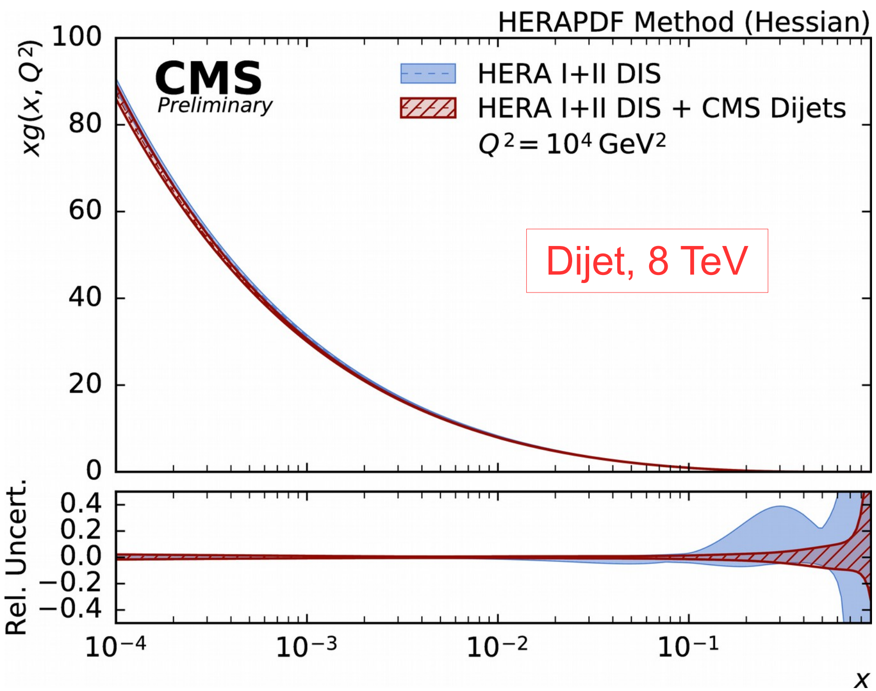


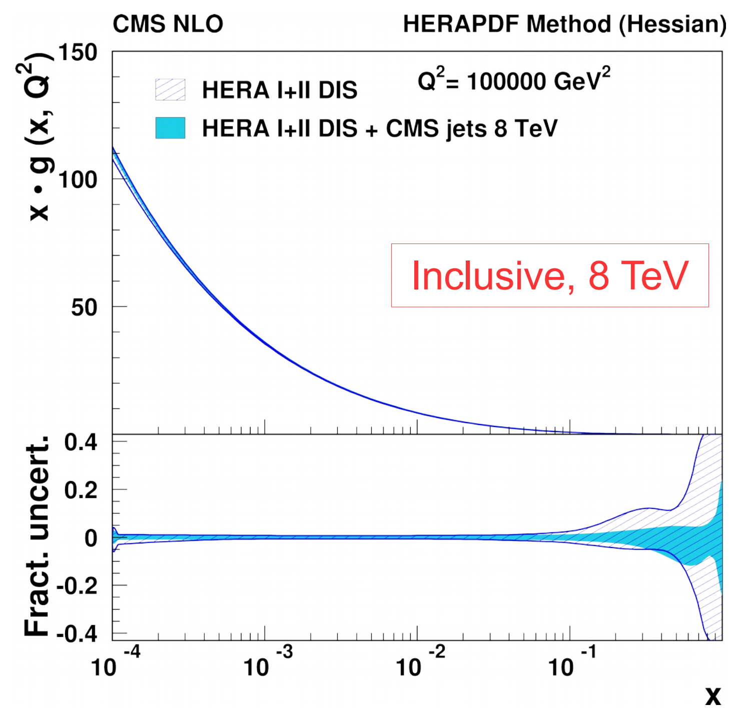
EPJC 76 (2016) 451

Jet Production: PDF Constraints

- Discrepancies for boosted dijet topologies:
  - high $|y_1 + y_2|$, high p_T ⇒ high x values
- Small experimental uncertainties
  ⇒ effective constrain on PDF at high x





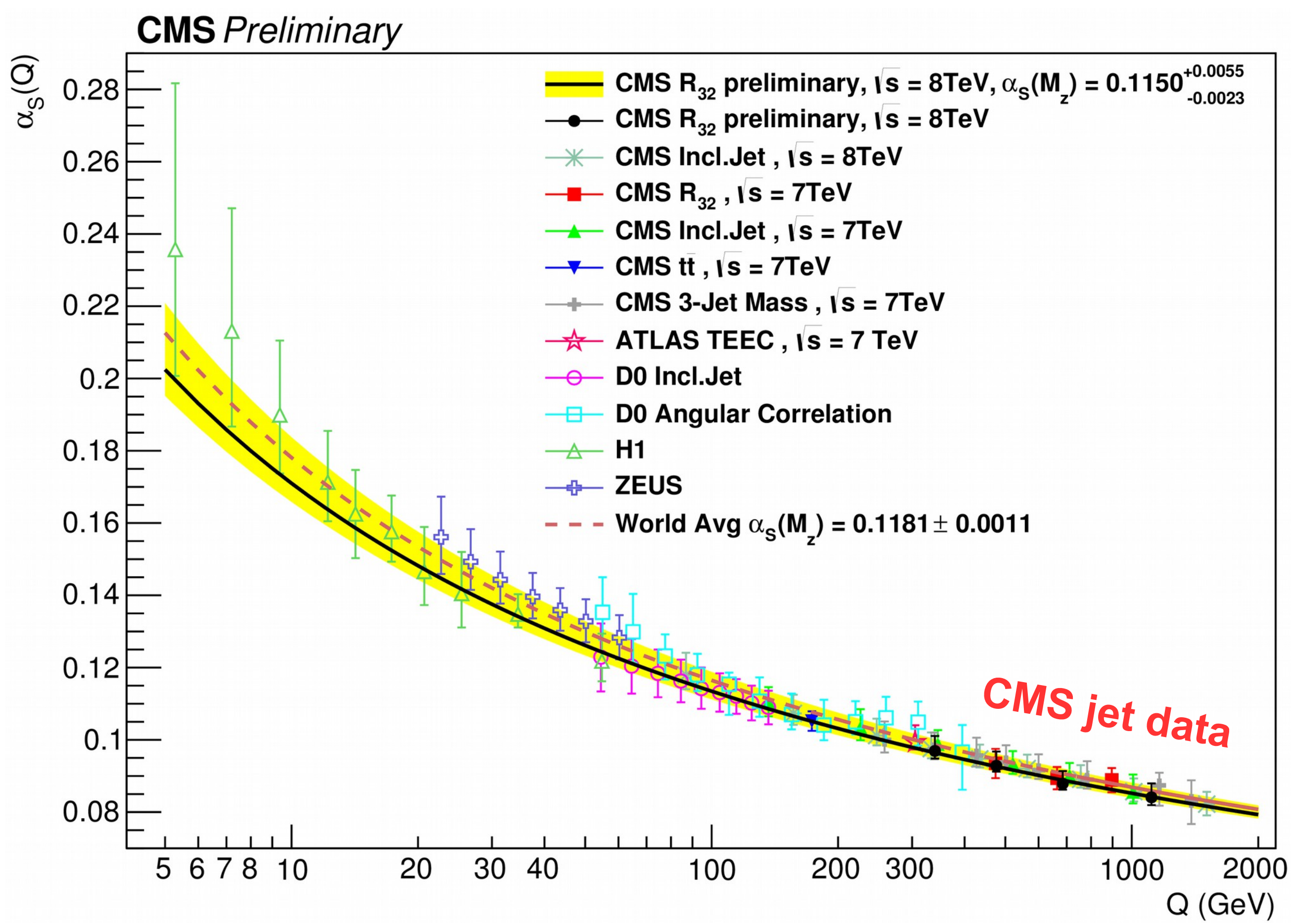


CMS-PAS-SMP-16-011

arXiv:1609.05331

Jet Production: α_S Measurement

- Jet differential cross sections are sensitive to α_S $\Rightarrow$ determine α_S from a fit of the theoretical predictions to the data
- Estimates of $\alpha_S(M_Z)$ are obtained from different measurements, e.g. the differential inclusive-jet and dijet cross sections, or the ratio of inclusive 3-jet to 2-jet cross sections

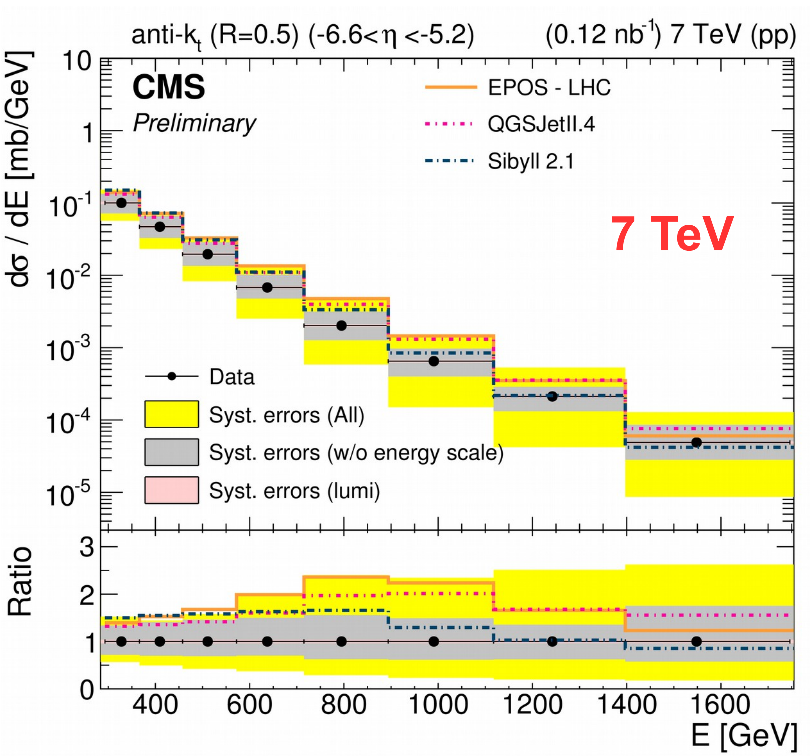


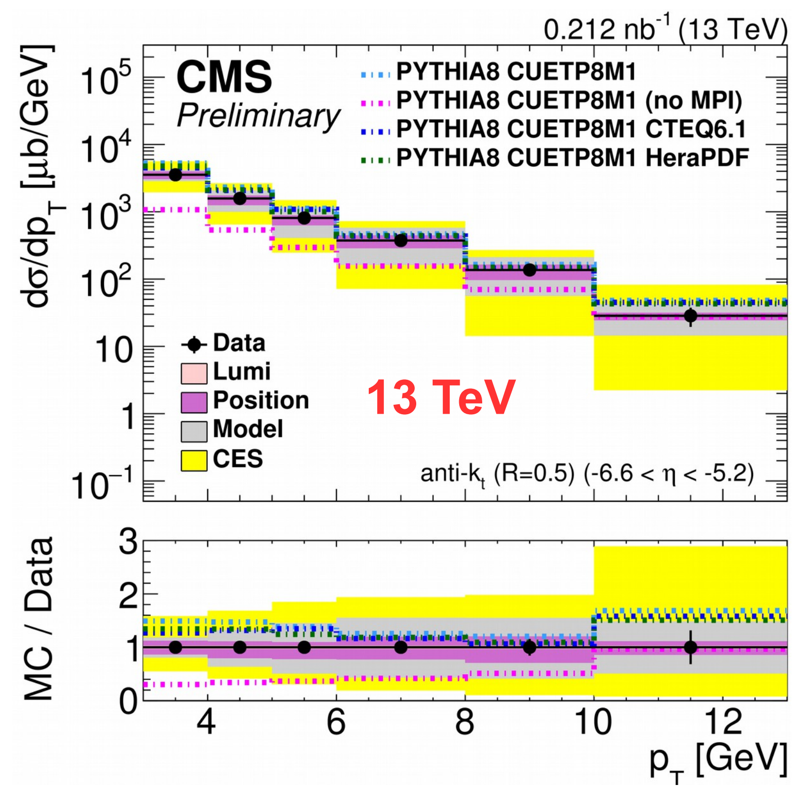
CMS-PAS-SMP-16-008

Very-Forward Jets

- The CASTOR calorimeter allows for jet measurements at $-6.6 < \eta < -5.2$
  - access to very low x (~10^{-6}), where DGLAP evolution is expected to break down
  - differential cross sections in jet energy or p_T compared to different MC models and tunes, based on either DGLAP or Gribov-Regge theory at low x
  - energy scale uncertainty currently too large to discriminate among models
  - low-energy region very sensitive to MPI contribution

CMS-PAS-FSQ-12-023





CMS-PAS-FSQ-16-003

W and Z Bosons (+ Jets)

Measurement	(7) 8 TeV	13 TeV
Z (+ jets)	CMS-SMP-14-012 PLB 750 (2015) 154 CMS-PAS-SMP-14-009	CMS-PAS-SMP-15-004 CMS-PAS-SMP-15-010 CMS-PAS-SMP-15-011
DY	CMS-PAS-SMP-15-002 EPJC 76 (2016) 325 EPJC 75 (2015) 147	CMS-PAS-SMP-15-004 CMS-PAS-SMP-16-009
W (+ jets)	JHEP 02 (2017) 096 arXiv:1610.04222	CMS-PAS-SMP-16-005
V + HF	EPJC 77 (2017) 92 arXiv:1611.06507 CMS-PAS-SMP-15-009 EPJC 77 (2017) 92	
VBF W/Z	JHEP 11 (2016) 147 EPJC 75 (2015) 66	
W-like Z mass	CMS-PAS-SMP-14-007 (7 TeV)	

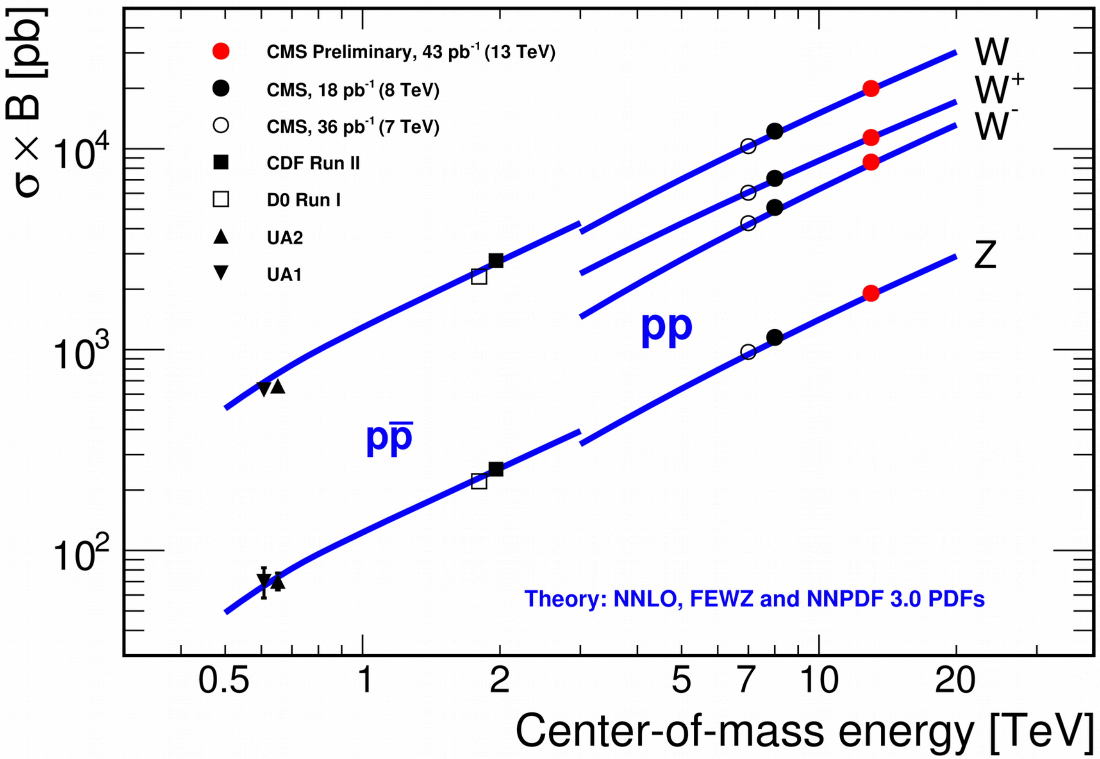
See also Kadir Ocalan's talk on Tuesday (W + jets)

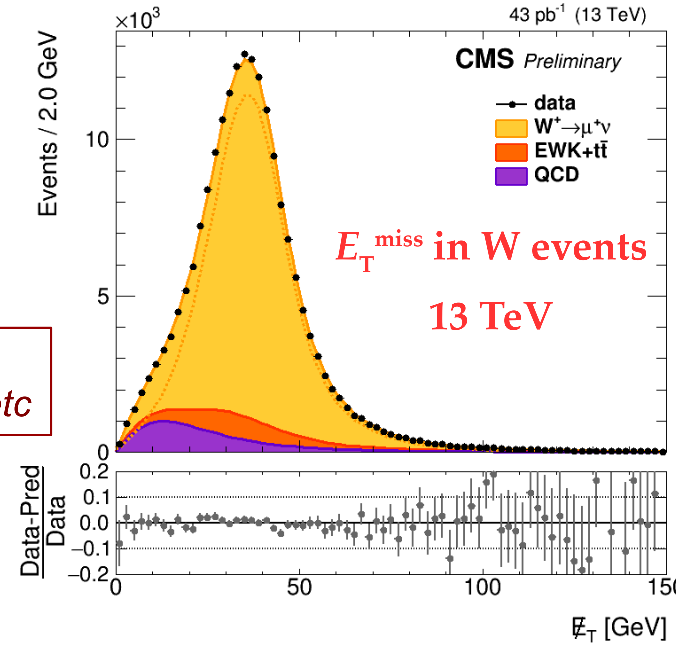
Single W/Z Cross Sections

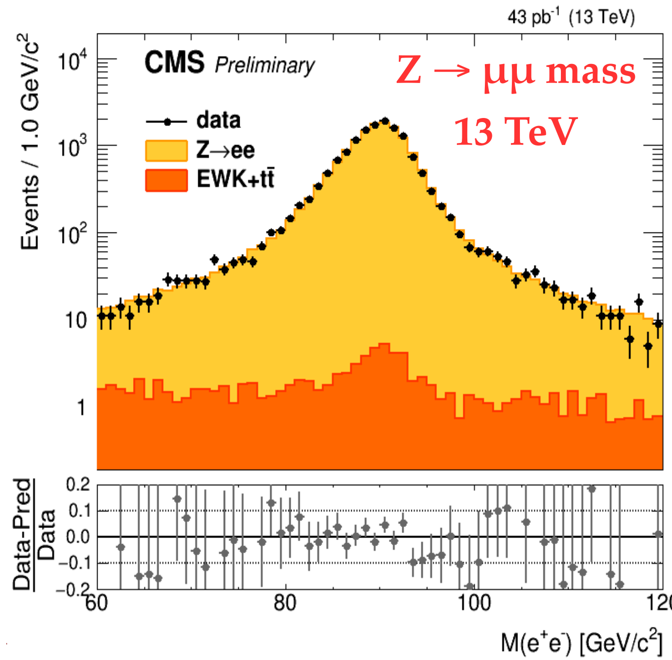
- Inclusive W and Z cross section measurements at c.o.m. energies of 7, 8, and 13 TeV
  - Precision tests of theoretical predictions
    ⇒ good agreement with NNLO

CMS-PAS-SMP-15-004

W, Z: standard candles used for detector calibration, efficiencies, etc



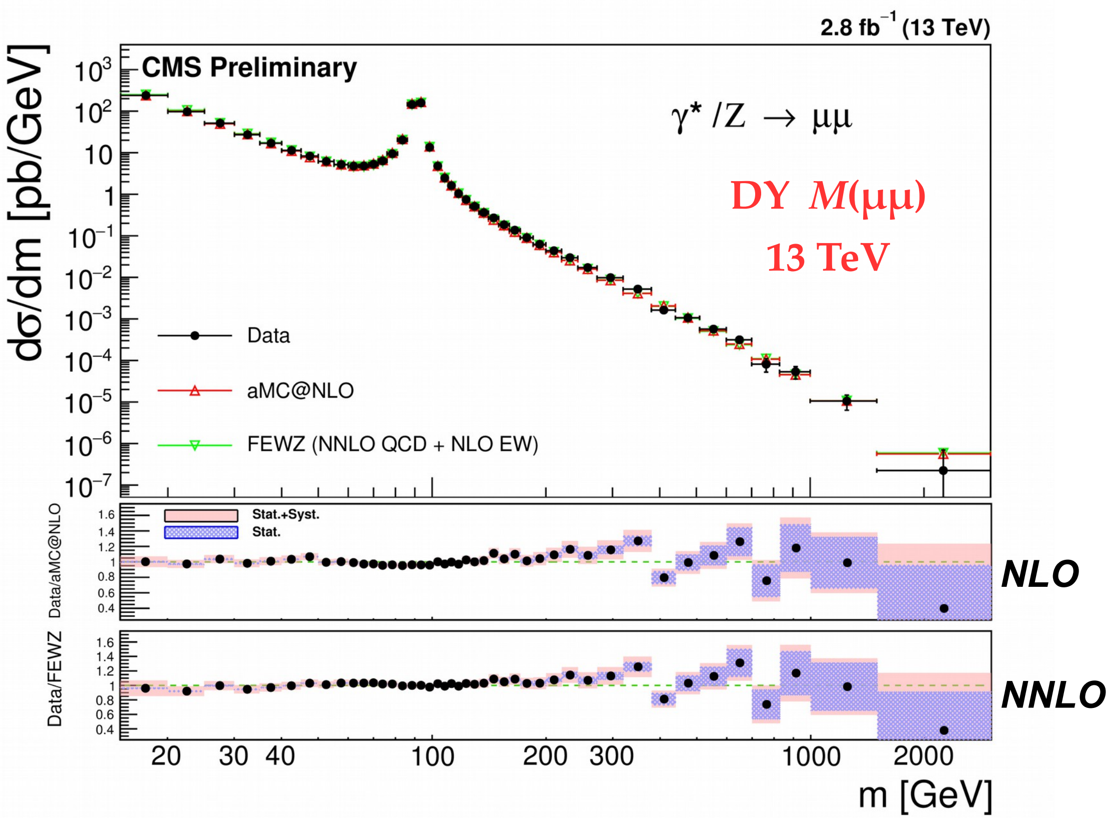


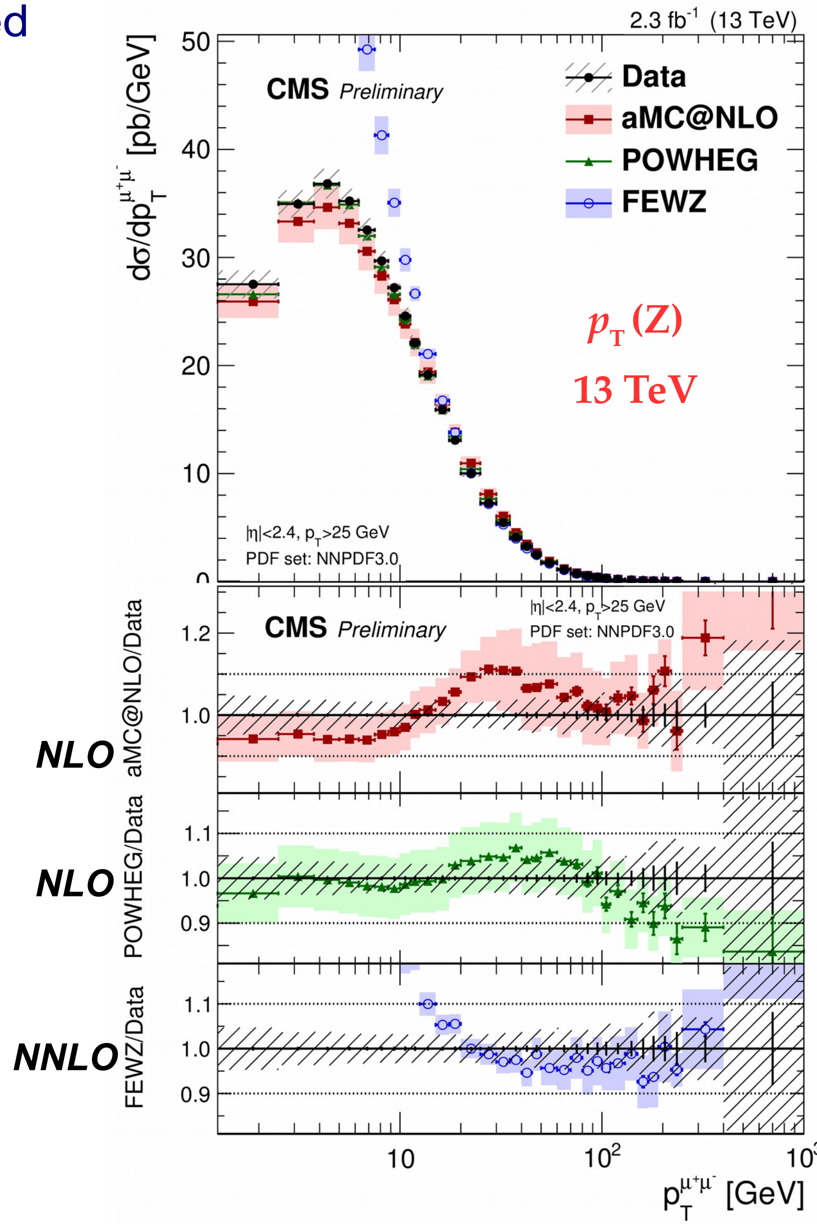


W/Z Differential Cross Sections

- A number of differential measurements compared to fixed-order calculations and MC generators
  - decent agreement with NLO and NNLO predictions within uncertainties
  - in general, NNLO (FEWZ) shows better agreement (e.g. at high $p_T(Z)$)

CMS-PAS-SMP-16-009



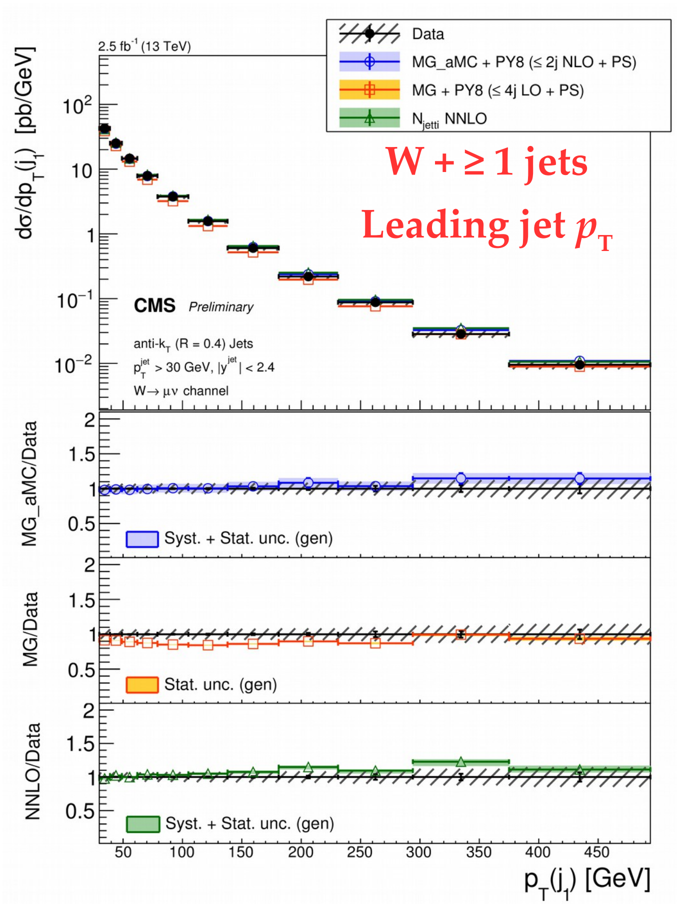


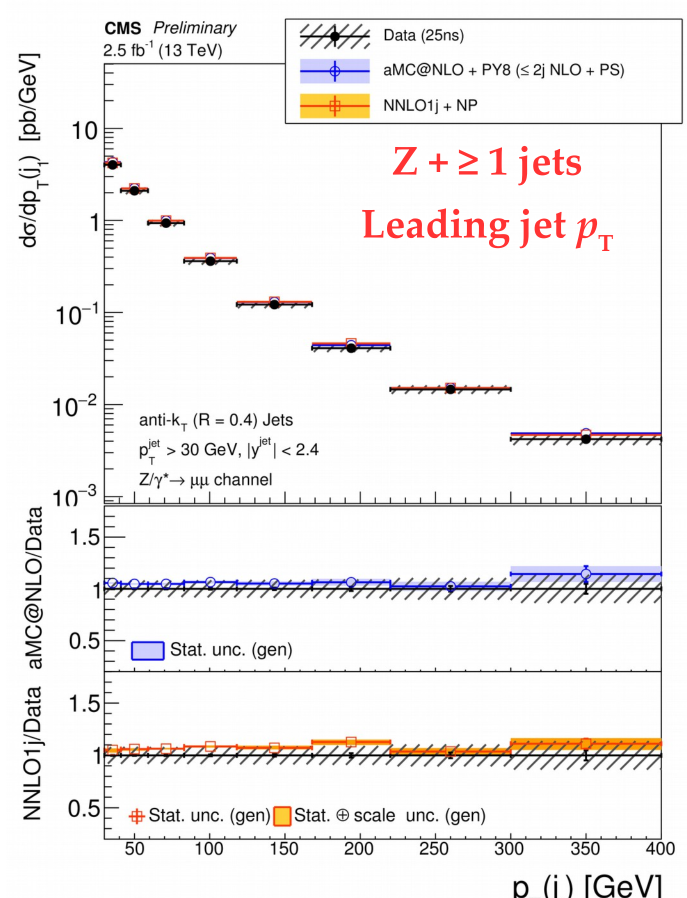
CMS-PAS-SMP-15-011

V + Jets Differential Cross Sections

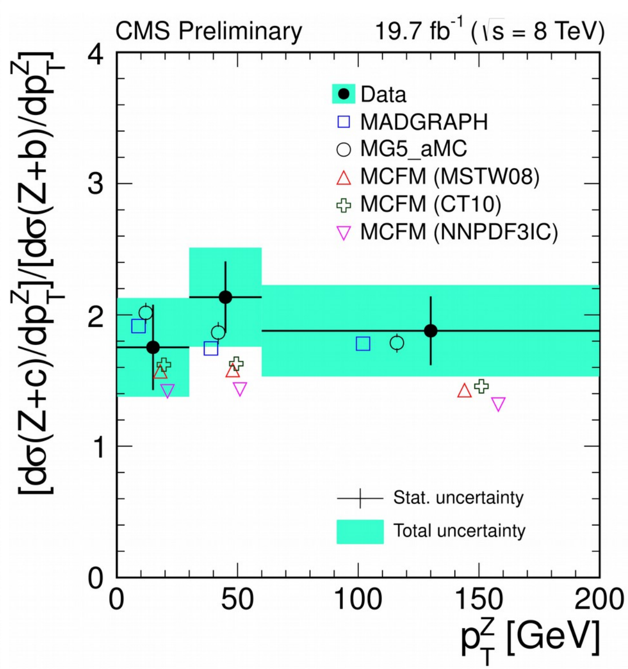
- Sensitive to higher-order corrections, but also soft-QCD effects (e.g. PS)
  - compared to MC simulations (ME + PS) and fixed-order calculations
  - in general, good agreement with NLO and NNLO predictions
- Measurements of V + b/c cross sections available at 8 TeV

See K. Ocalan's talk





$$\text{Ratio } \frac{\sigma(Z + \text{c-quark})}{\sigma(Z + \text{b-quark})}$$

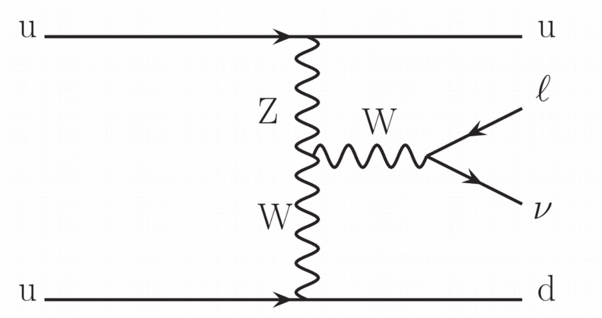


CMS-PAS-SMP-16-005 CMS-PAS-SMP-15-010 CMS-PAS-SMP-15-009

W Boson Electroweak Production

- Vector boson fusion (VBF) characteristic signature
  - 2 jets at high $|\eta|$
    - high dijet invariant mass m_{jj}
    - large rapidity separation $\Delta\eta$
    - little hadronic activity in the central part of the detector

    ➔ multivariate analysis to increase background discrimination



- Fiducial cross section from fits to m_{jj} distributions, using parametric models for all processes

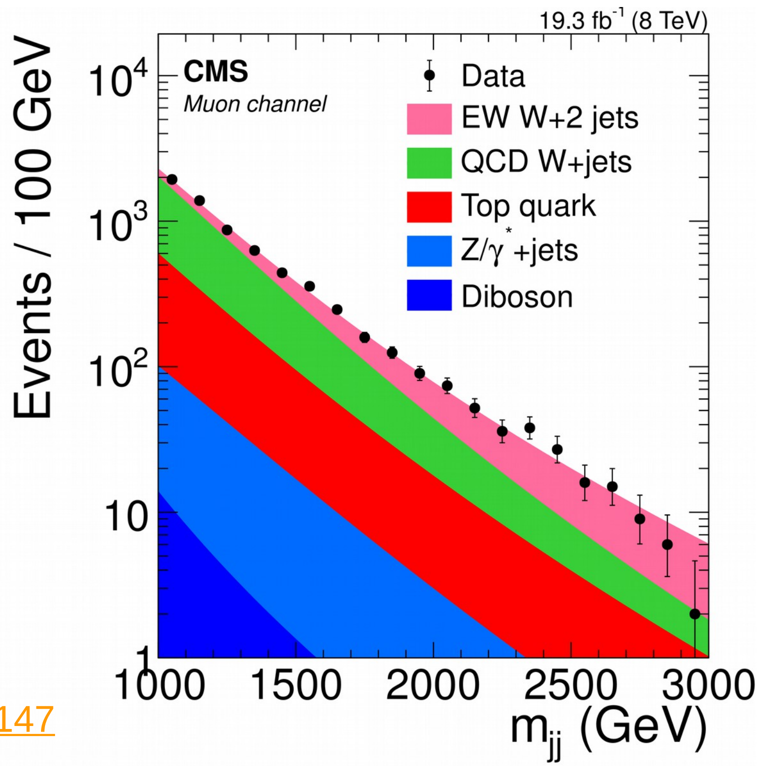
  $\sigma_{fid} = 0.42 \pm 0.04\ (\text{stat}) \pm 0.09\ (\text{syst}) \pm 0.01\ (\text{lumi})\ \text{pb}$

- Consistent with LO prediction

  $\sigma_{LO} = 0.50 \pm 0.02\ (\text{scale}) \pm 0.02\ (\text{PDF})\ \text{pb}$

See K. Ocalan's talk

JHEP 11 (2016) 147



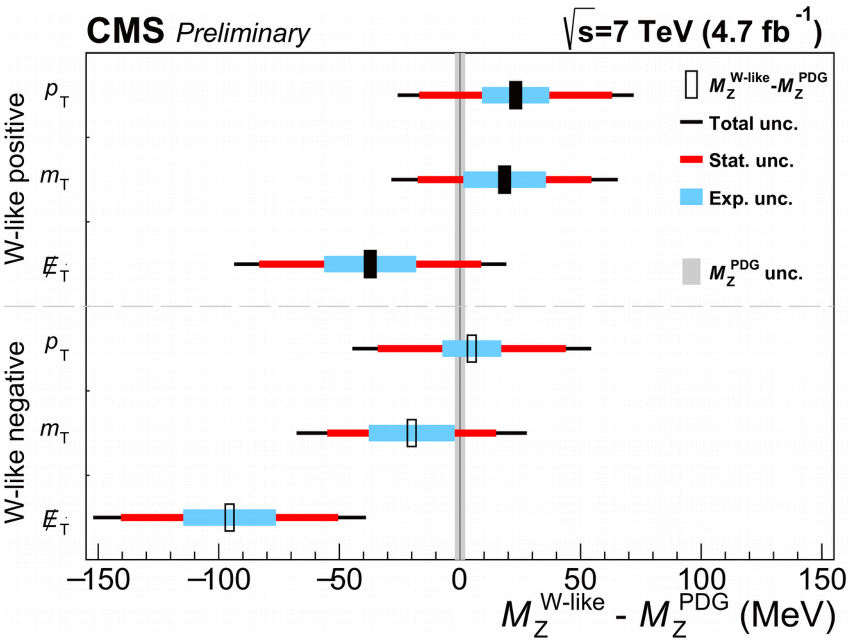
Towards a Measurement of W Mass

- "W-like" measurement of the Z boson mass in $\mu^+\mu^-$ events
  - μ^+ (μ^-) treated as a neutrino to form the W^--like (W^+-like) candidate
  - test of the W-mass measurement procedure and achievable precision

- Critical aspects
  - Muon momentum scale: ~ 2×10^{-4}
    - achieved thanks to a novel calibration algorithm using dimuons from J/ψ, $\Upsilon(1S)$
  - Hadronic recoil calibration: < 2×10^{-4}

- Final uncertainties ~ 20 MeV (exp)

  ~ 30 MeV (theo)



➔ Competitive with current W mass measurements!

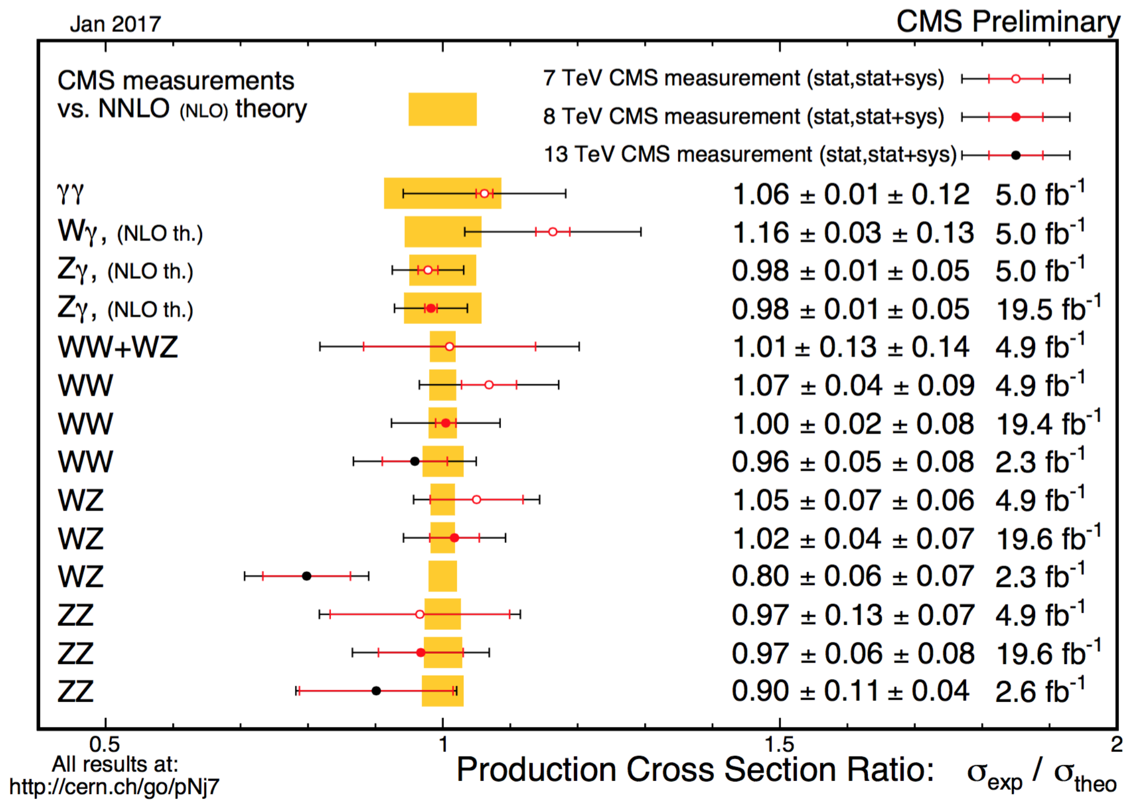
CMS-PAS-SMP-14-007

Multibosons

Measurement	(7) 8 TeV	13 TeV
$ZZ \rightarrow 4\ell$	PLB 740 (2015) 250	PLB 763 (2016) 280
$ZZ \rightarrow 2\ell 2\nu$	EPJC 75 (2015) 511	
$Z\gamma \rightarrow \ell\ell\gamma$	JHEP 04 (2015) 164	
$Z\gamma \rightarrow \nu\nu\gamma$	PLB 760 (2016) 448	CMS-PAS-SMP-16-004
$WW \rightarrow \ell\nu\ell\nu$	EPJC 76 (2016) 401	CMS-PAS-SMP-16-006
$WZ \rightarrow 3\ell\nu$	arXiv:1609.05721	PLB 766 (2017) 268
$WV \rightarrow \ell\nu J$	CMS-PAS-SMP-13-008	CMS-PAS-SMP-16-012
$WV\gamma \rightarrow \ell\nu jj\gamma$	PRD 90 (2014) 032008	
$V\gamma\gamma \rightarrow \ell\nu\gamma\gamma$ / $\ell\ell\gamma\gamma$	CMS-PAS-SMP-15-008	
$\gamma\gamma \rightarrow WW \rightarrow \ell\nu\ell\nu$	JHEP 08 (2016) 119	
VBS ss $WW \rightarrow \ell\nu\ell\nu$	PRL 114 (2015) 051801	
VBS $W\gamma \rightarrow \ell\nu\gamma$	arXiv:1612.09256	
VBS $Z\gamma \rightarrow \ell\ell\gamma$	arXiv:1702.03025	
VBS $WZ \rightarrow \ell\nu\ell\ell$	PRL 114 (2015) 051801	

Multiboson Measurements

- Important test of the SM $\rightarrow$ probes gauge-boson self-interactions
- Background to many Higgs searches and new physics searches
- Relatively large diboson rates at the LHC
  - use mainly W/Z leptonic decays for clean signatures and high trigger efficiencies
  - add hadronic decays where possible to increase statistics



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

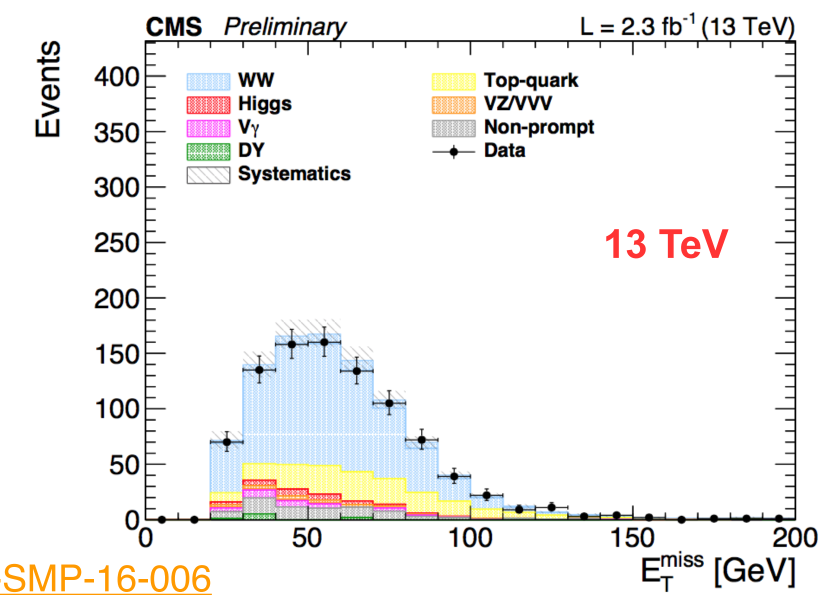
WW → ℓνℓ'ν

- Clean signature: exactly 2 charged leptons + E_T^{miss}
- Main background from $t\bar{t} \rightarrow \ell^+\nu\ell^-\bar{\nu}b\bar{b}$
  - no more than 1 jet, no b-tagged jets
  - jet veto efficiency sensitive to higher-orders

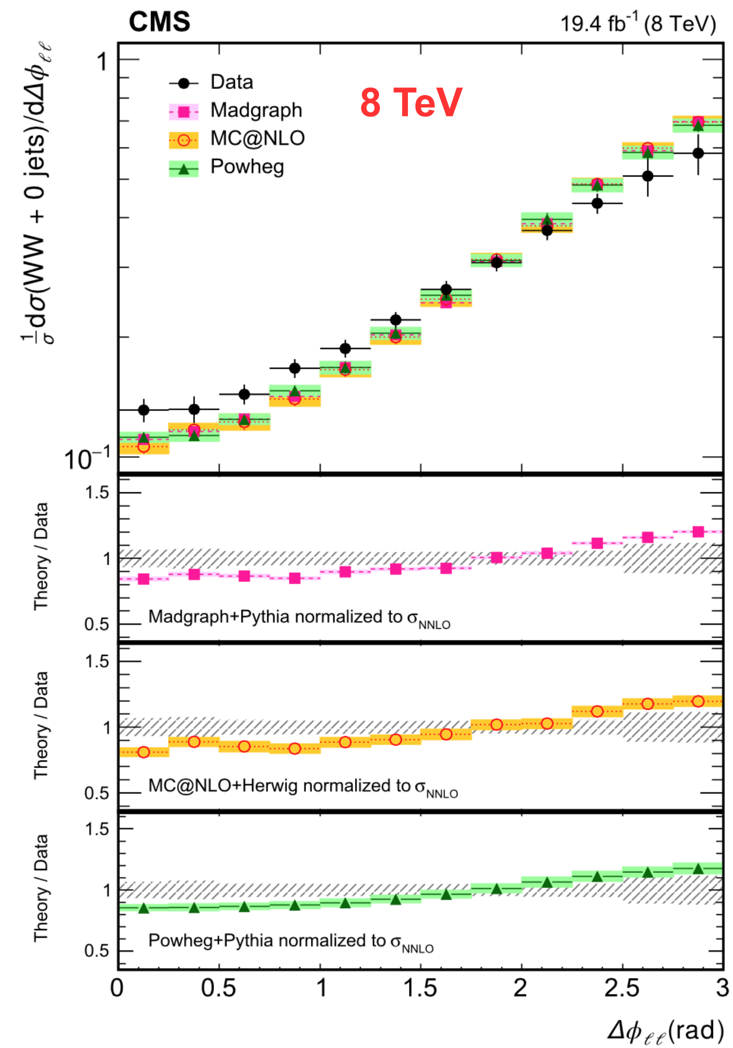
$$\sigma^{exp}_{13\,TeV} = 115.3 \pm 5.8\,(stat) \pm 5.7\,(exp) \pm 6.4\,(theo) \pm 3.6\,(lumi)\ pb$$

$$\sigma^{NNLO}_{13\,TeV} = 120.3 \pm 3.6\ pb \quad vs \quad \sigma^{NLO}_{13\,TeV} = 106.0 \pm 6.6\ pb$$

arXiv:1408.5243



CMS-PAS-SMP-16-006



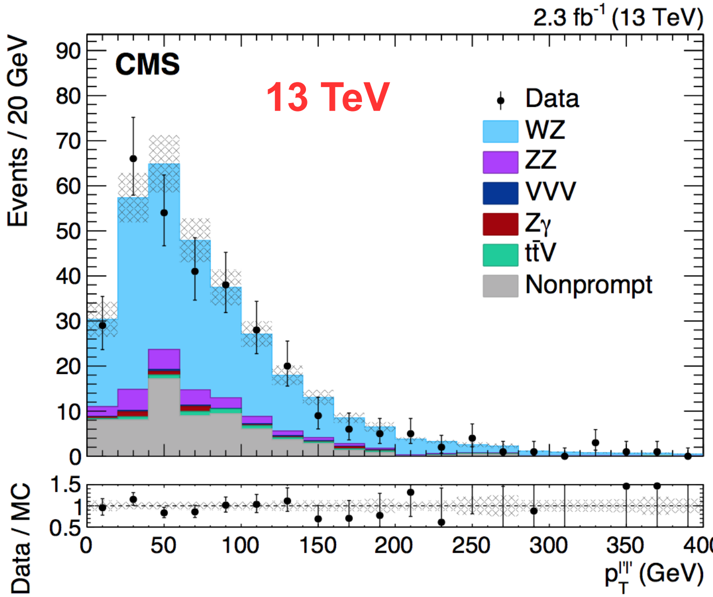
Differential cross sections at 8 TeV

Some discrepancies w.r.t. NLO predictions

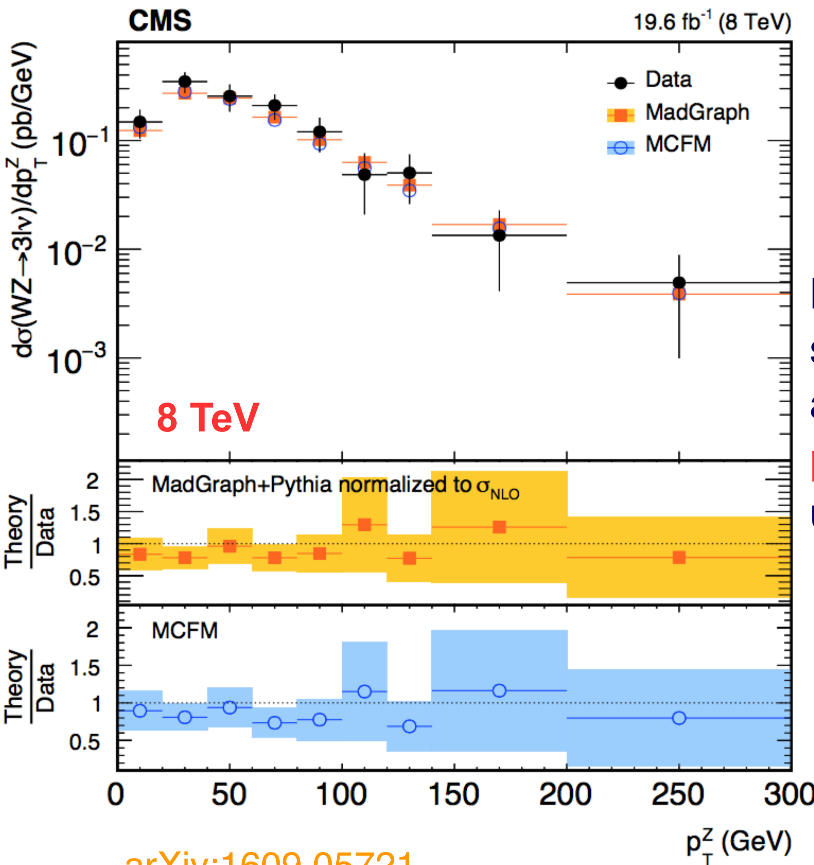
EPJC 76 (2016) 401

WZ → ℓνℓ'ℓ'

- Clean three-lepton signature
- Main backgrounds: Z + jets, $t\bar{t}$ with a mis-identified lepton

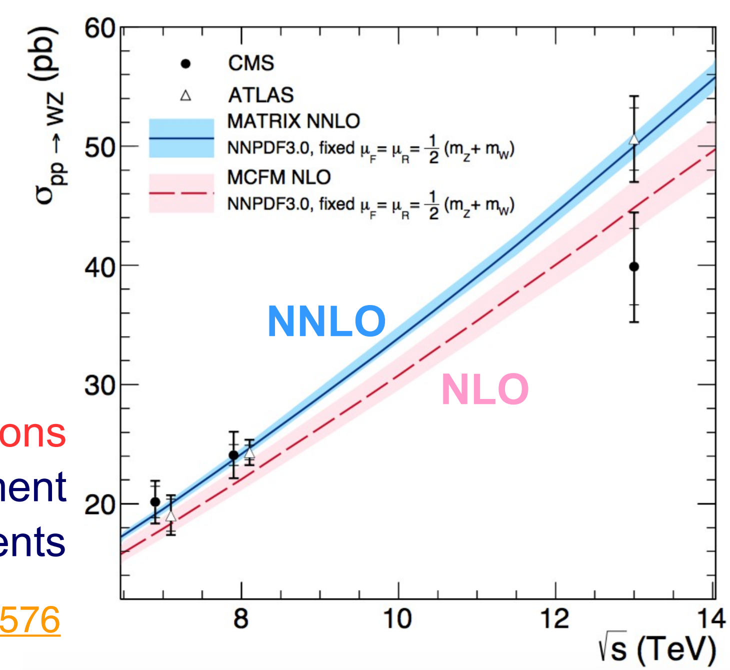


PLB 766 (2017) 268



arXiv:1609.05721

Differential cross sections at 8 TeV agrees with NLO predictions within uncertainties

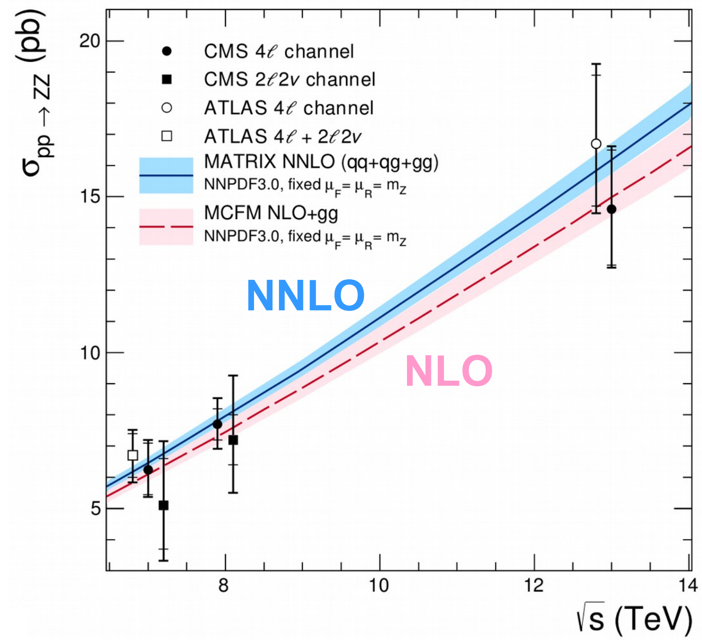


NNLO calculations improve agreement with measurements

arXiv:1604.08576

$ZZ \rightarrow \ell\ell\ell'\ell'$

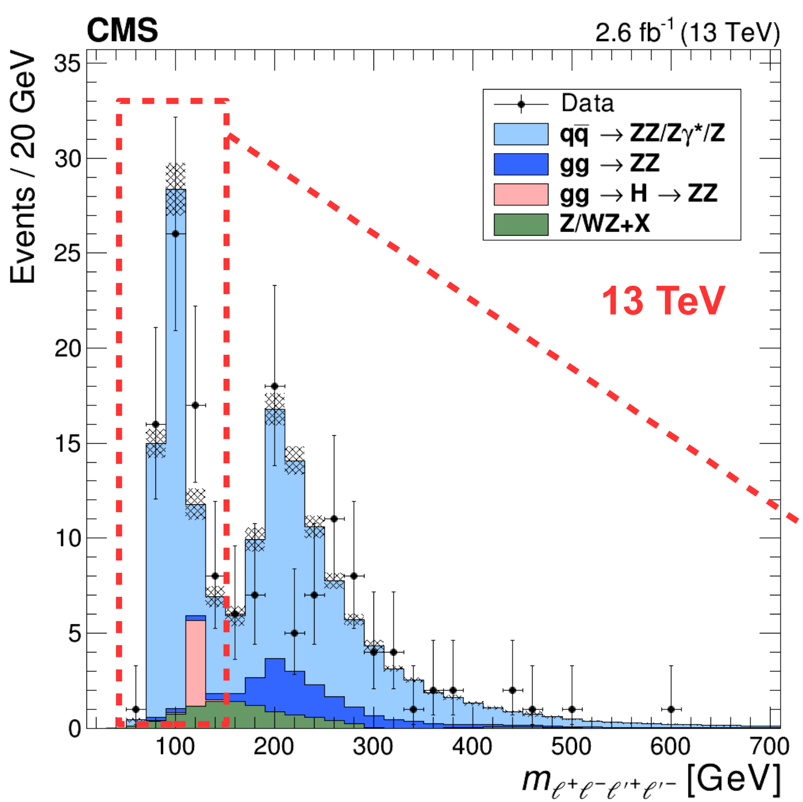
- Final states: $4e$, $2e2\mu$, 4μ (also $2e2\tau$, $2\mu2\tau$ at 8 TeV)
- Very small background with fake leptons
- Measurements agree with NLO and NNLO predictions

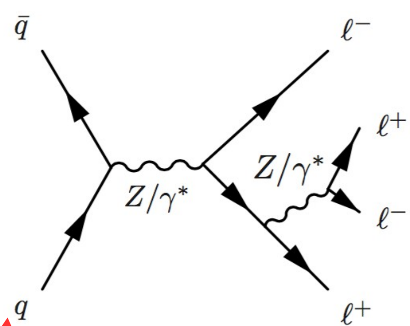


PLB 763 (2016) 280

PLB 740 (2015) 250

PLB 735 (2014) 311



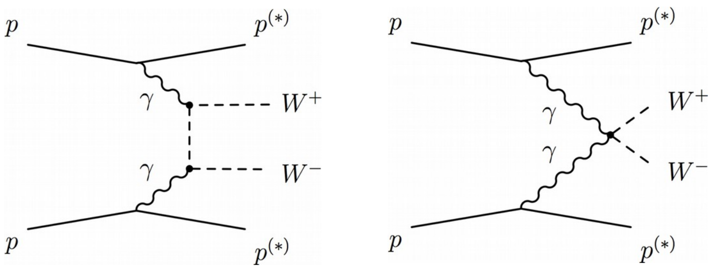


13 TeV: measurement of $Z \rightarrow 4\ell$ branching fraction

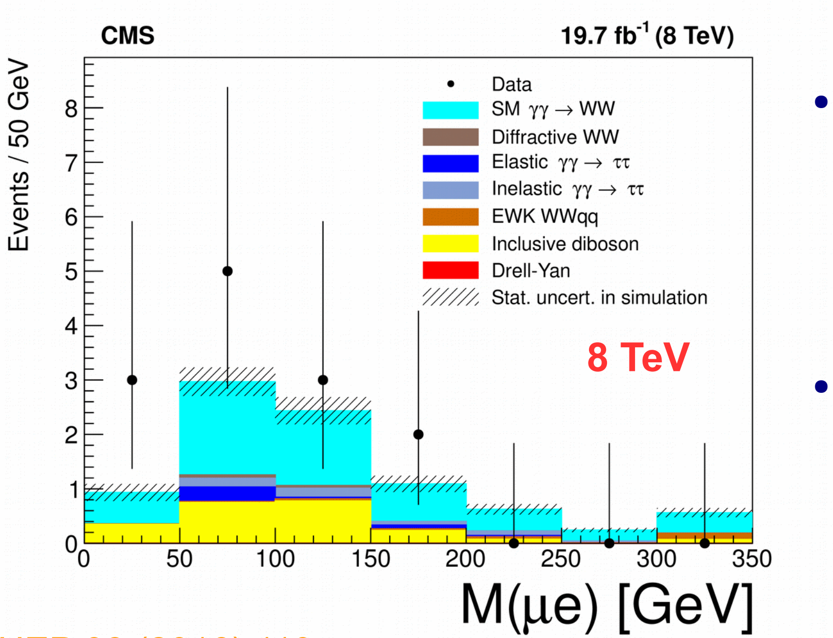
$$\mathcal{B} = 4.9\,^{+0.8}_{-0.7}\,\text{(stat)}\;^{+0.3}_{-0.2}\,\text{(syst)}\;^{+0.2}_{-0.1}\,\text{(theo)}\;\pm 0.1\,\text{(lumi)}\;\times 10^{-6}$$

Exclusive WW Production

- Exclusive or quasi-exclusive $\gamma\gamma \rightarrow WW$ production
  - no hadronic activity at the primary vertex, no additional tracks



- Use leptonic WW decays with different flavor, $e^{\pm}\mu^{\mp}$
  - ~10 times less background, eliminate exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$ production and DY



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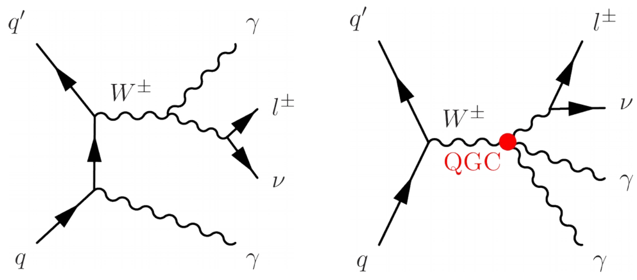
- Signal significance: 3.4σ (expected 2.8σ)
  - combined 7 and 8 TeV data sets
  - signal evidence!
- Cross section consistent with SM prediction

$$\sigma^{exp}_{8\ TeV}\left(pp \rightarrow p^{(*)}W^{+}W^{-}p^{(*)} \rightarrow p^{(*)}\mu^{\pm}e^{\mp}p^{(*)}\right) = 10.8^{+5.1}_{-4.1}\ \text{fb}$$

$$\sigma^{SM}_{8\ TeV} = 6.2 \text{ +- } 0.5\ \text{fb}$$

Triboson Production: $W\gamma\gamma$ and $Z\gamma\gamma$

- Select $W\gamma\gamma \rightarrow \mu\nu\gamma\gamma$ and $Z\gamma\gamma \rightarrow ee\gamma\gamma / \mu\mu\gamma\gamma$ events
- Main background: jets faking photons

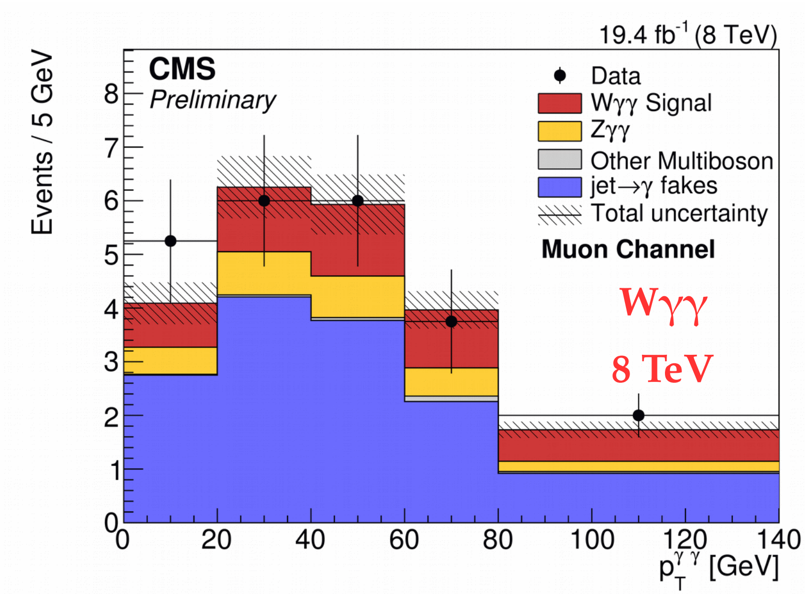


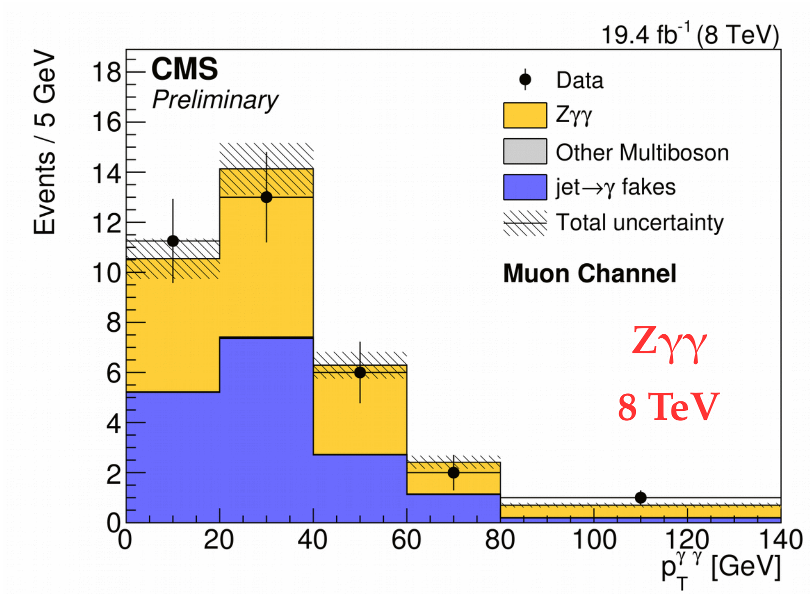
- Signal significance: 2.4σ for $W\gamma\gamma$, 5.9σ for $Z\gamma\gamma$
- Fiducial cross sections in agreement with NLO predictions

$$\sigma^{fid}_{W\gamma\gamma} \cdot B(W \rightarrow l\nu) = 6.0 \pm 1.8\ (stat) \pm 2.3\ (syst) \pm 0.2\ (lumi)\ fb \qquad \sigma^{NLO}_{W\gamma\gamma} \cdot B(W \rightarrow l\nu) = 4.76 \pm 0.53\ fb$$

$$\sigma^{fid}_{Z\gamma\gamma} \cdot B(Z \rightarrow ll) = 12.7 \pm 1.4\ (stat) \pm 1.8\ (syst) \pm 0.3\ (lumi)\ fb \qquad \sigma^{NLO}_{Z\gamma\gamma} \cdot B(Z \rightarrow ll) = 12.95 \pm 1.47\ fb$$

CMS-PAS-SMP-15-008

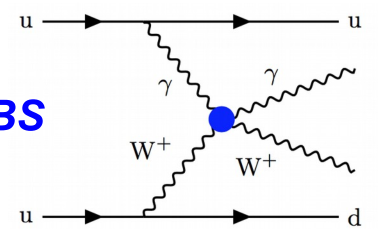




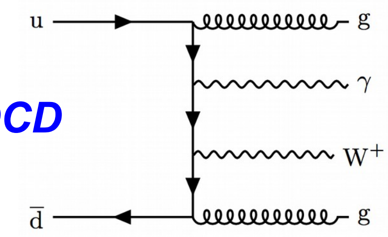
Electroweak Diboson Production

- $W\gamma + 2$ jets and $Z\gamma + 2$ jets produced via vector boson scattering (VBS)
  - Leptonic W or Z decays + VBS topology
  - Main background: QCD $W\gamma + 2$ jets and $Z\gamma + 2$ jets

VBS



QCD

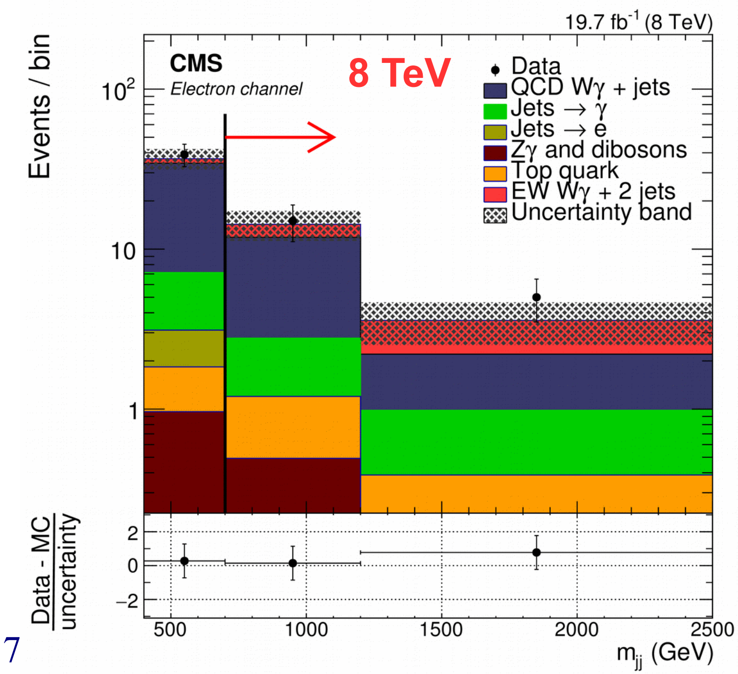


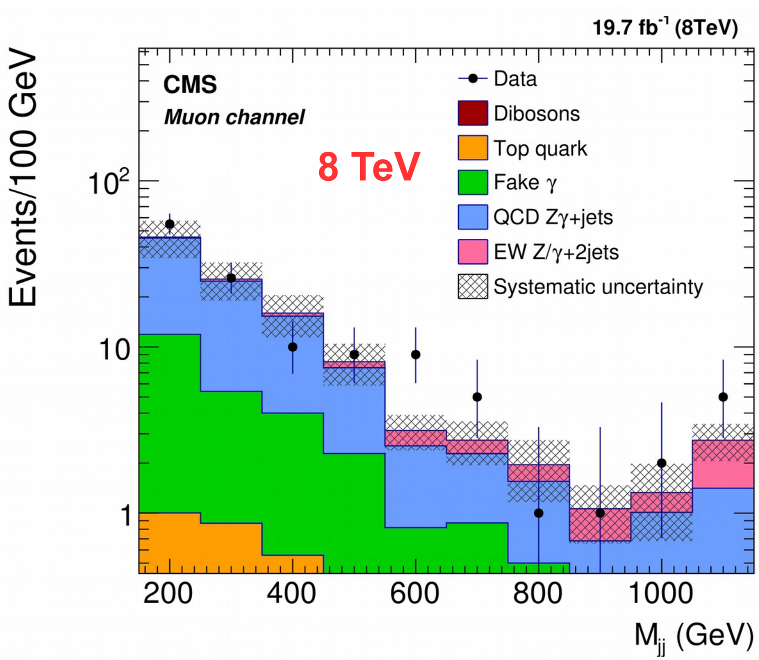
- Signal significance: 2.7σ for $W\gamma jj$, 3.0σ for $Z\gamma jj$
- Measured cross sections in agreement with LO predictions

$$\sigma^{fid}_{W\gamma jj} = 10.8 \pm 4.1 \text{ (stat)} \pm 3.4 \text{ (syst)} \pm 0.3 \text{ (lumi) fb}$$

$$\sigma^{fid}_{Z\gamma jj} = 1.86\,^{+0.89}_{-0.75} \text{ (stat)}\,^{+0.41}_{-0.27} \text{ (syst)} \pm 0.05 \text{ (lumi) fb}$$

arXiv:1612.09256





arXiv:1702.03025

Anomalous Gauge Couplings

- The SM predicts exact values for vector boson couplings
- New physics at very high energy scales — beyond the LHC reach — can manifest by modifying the vector boson couplings, e.g. through loops
- Anomalous triple and quartic gauge couplings (aTGC, aQGC) can be modeled with an effective Lagrangian or an effective field theory approach, e.g.

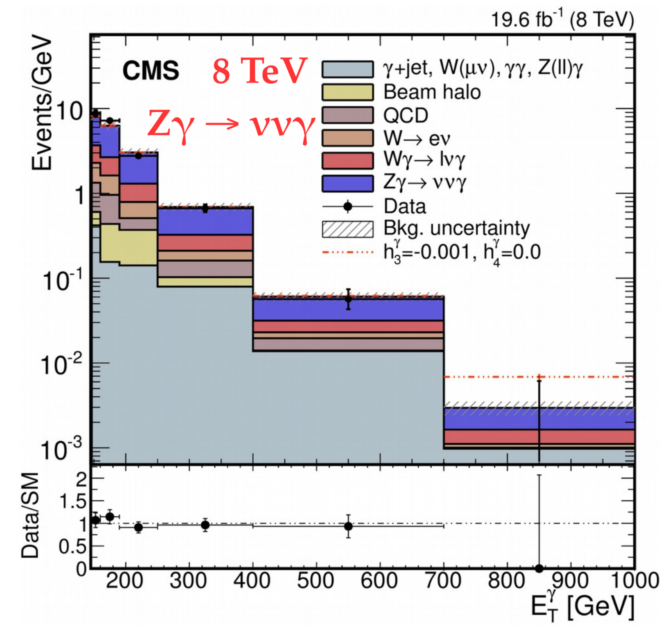
$$\mathcal{L}/g_{WWV} = ig_1^V [W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}] + i\kappa^V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda^V}{M_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu V^{\nu\lambda}$$

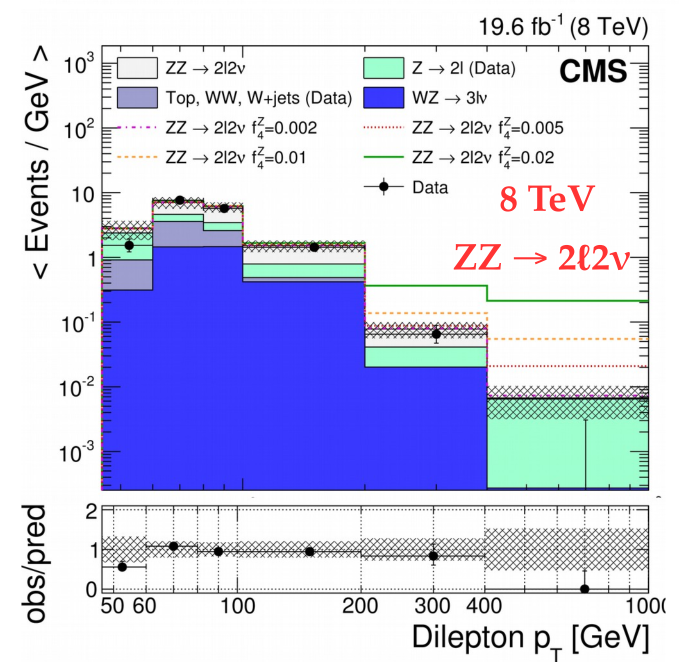
(WWγ and WWZ additional couplings)

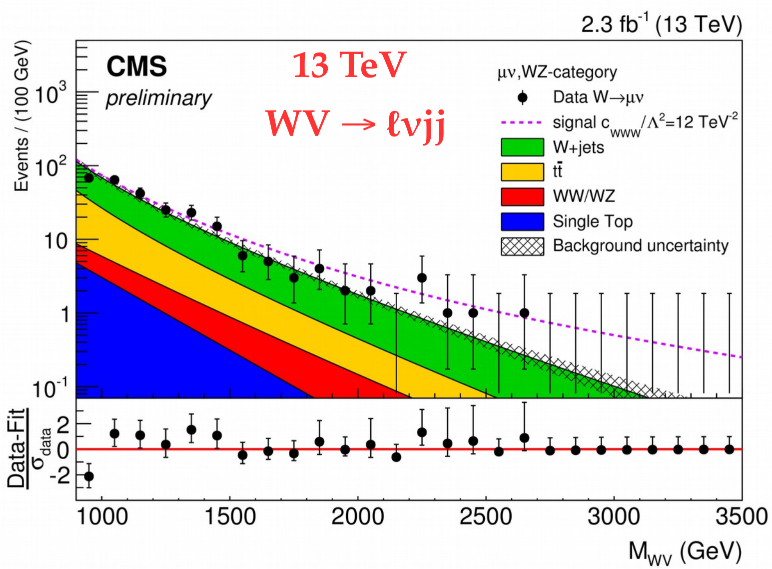
- Anomalous couplings result in an increase of cross sections at high energies
  - diboson invariant mass M_{VV} and boson transverse momentum p_{T} are suitable observables
- In the absence of deviations from the SM expectations, upper limits on aTGC/aQGC parameters can be set

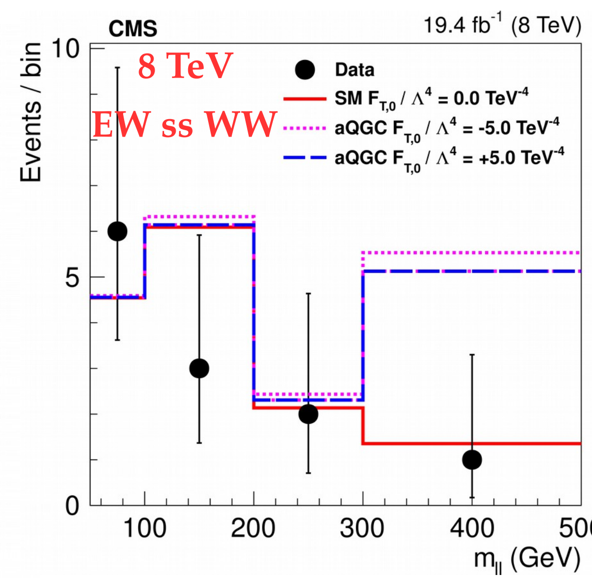
aTGC and aQGC Searches in Run-I

- Diboson and triboson measurements are the natural choice to search for anomalous gauge couplings
  - aTGC: inclusive diboson channels
  - aQGC: triboson and EW diboson processes
- Numerous searches performed during Run-I (and Run-II)
  - stringent limits on several couplings, comparable with or exceeding LEP results
- The analysis of 2016 data is expected to improve on Run-I results
  - higher energy and larger statistics → more data in the tails!



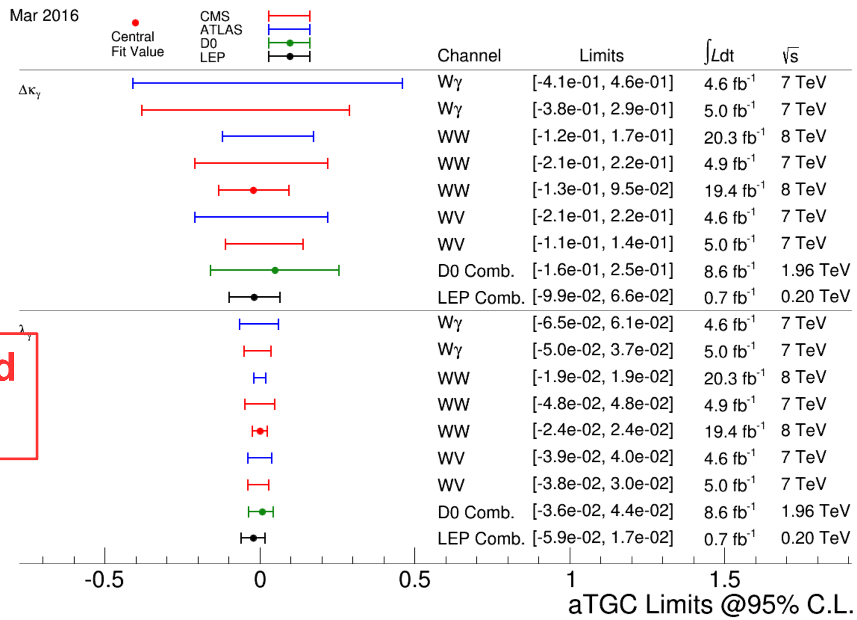




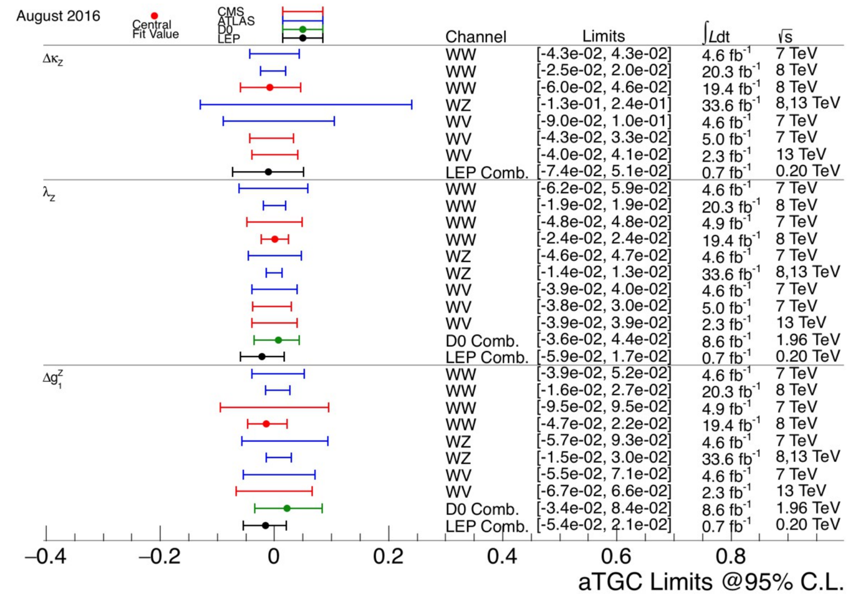


Summary of aTGC Limits

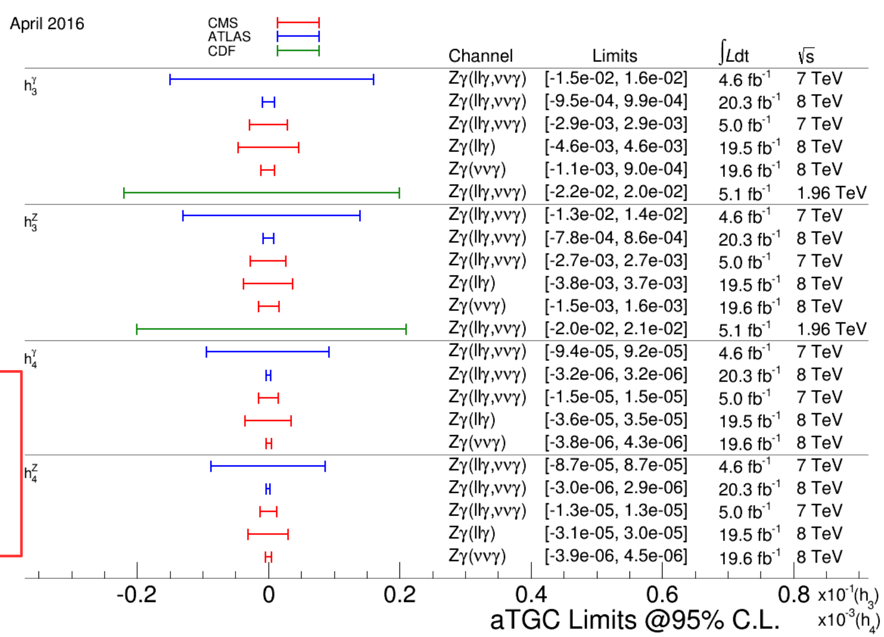
All results and references at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC



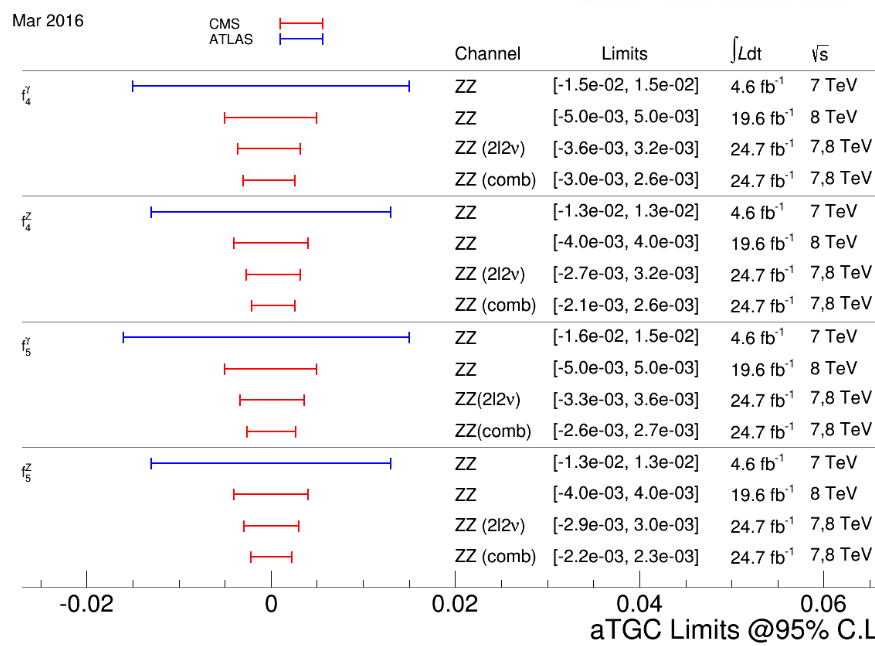
charged WWγ



charged WWZ



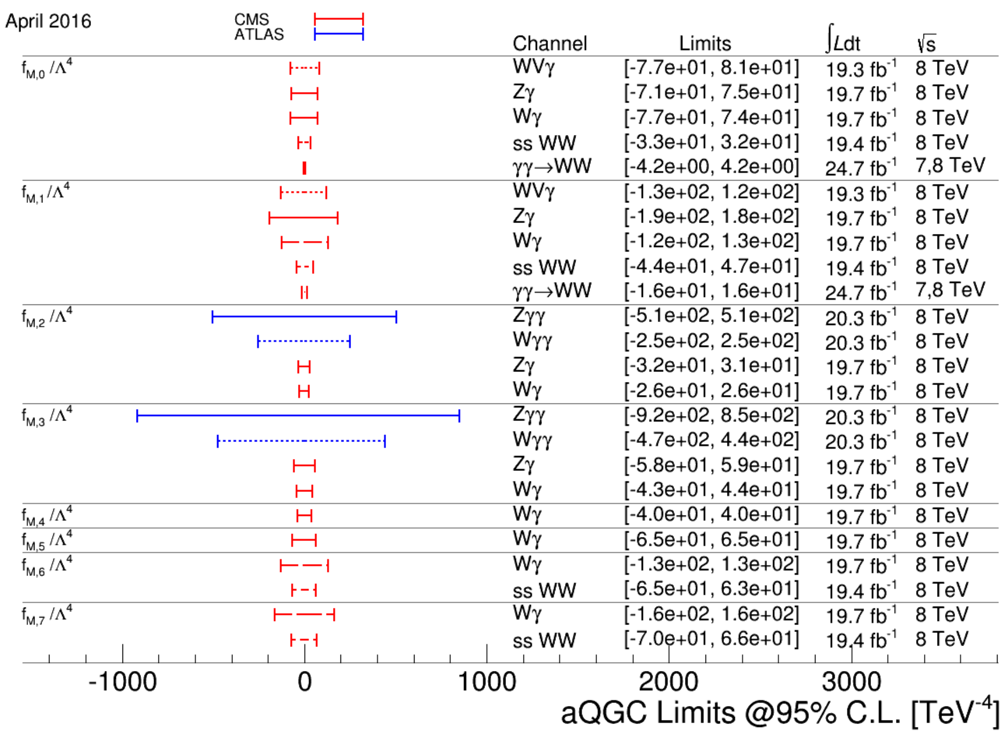
neutral ZZγ Zγγ



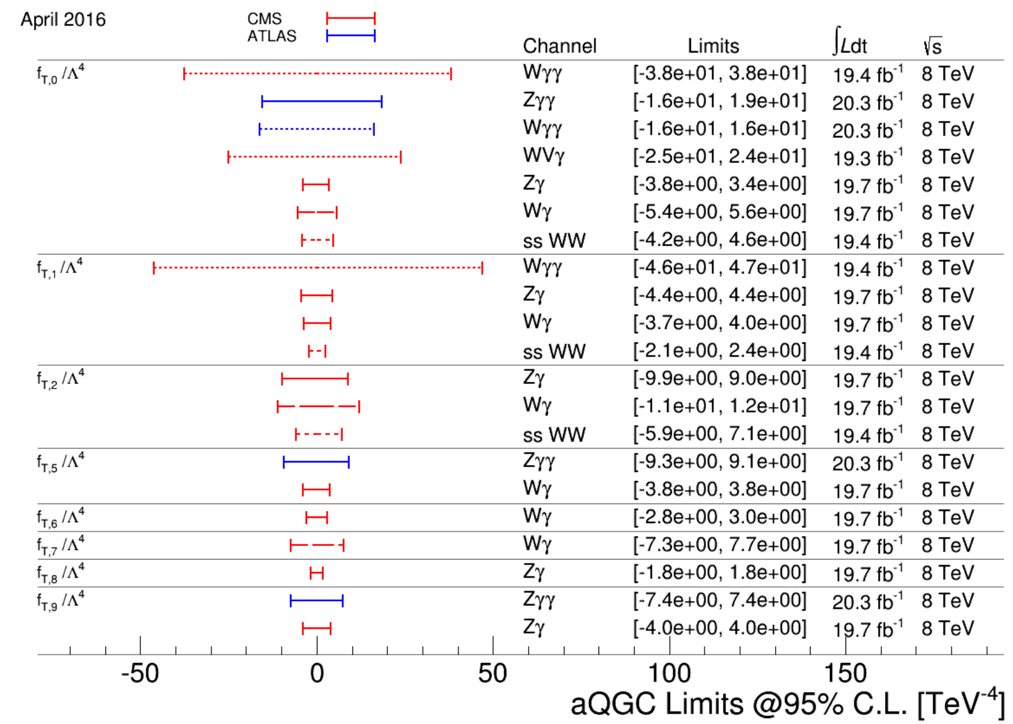
neutral ZZZ γZZ

Summary of aQGC Limits

All results and references at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC



Dimension-8 mixed transverse and longitudinal parameters $f_{M,i}$



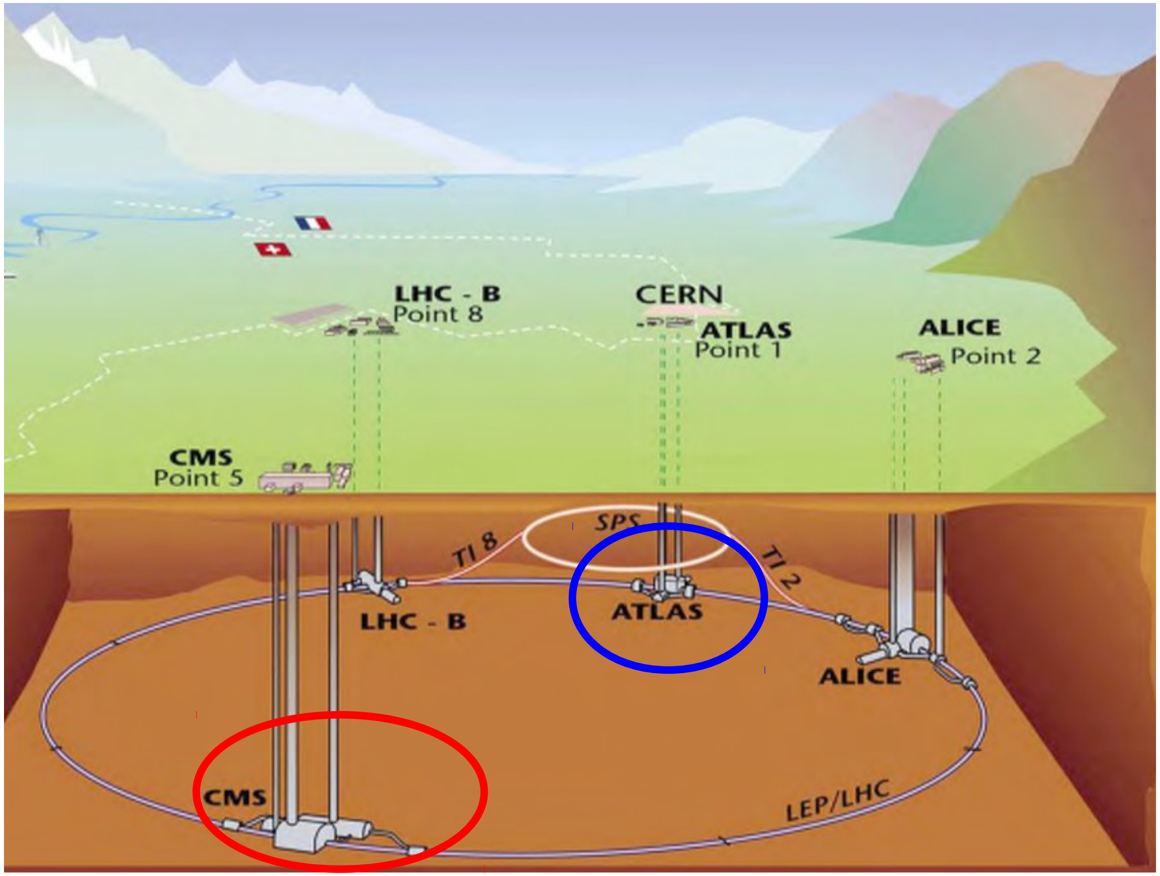
Dimension-8 transverse parameters $f_{T,i}$

Summary

- A lot of work has been done by CMS in the last years to understand the SM to ever higher precision
    - Known QCD and EW processes have been studied in greater detail
    - Our measurements benefit from (and drive) the advancements in theoretical calculations and MC generators
- Rare and yet-unseen processes are starting to emerge
    - First evidence and observations of rare processes, such as triboson and exclusive-boson production
- Not only understanding the SM, but searching for new physics
    - Increasing sensitivity to anomalous gauge boson couplings
- In 2016 the LHC delivered over 40 fb^{-1} of data, and more is expected this year!

Bonus Slides

The Large Hadron Collider (LHC)



CMS and **ATLAS**

two "general-purpose" detectors

⇒ *cross-check of results!*

The LHC accelerates and collides proton beams

- center-of-mass energy of 7 – 8 TeV (2011-12)

  ⇒ *high-mass particles O(TeV)!*

- instantaneous luminosity up to 7.5×10^{33} cm^{-2}s^{-1} (2012)

  ⇒ *rare processes!*

- machine rate 40 MHz, but collision rate ~1 GHz (pileup)

  ⇒ *need for a trigger system to reduce the rate to an acceptable level: ~400 Hz (2012)*

The Compact Muon Solenoid (CMS)

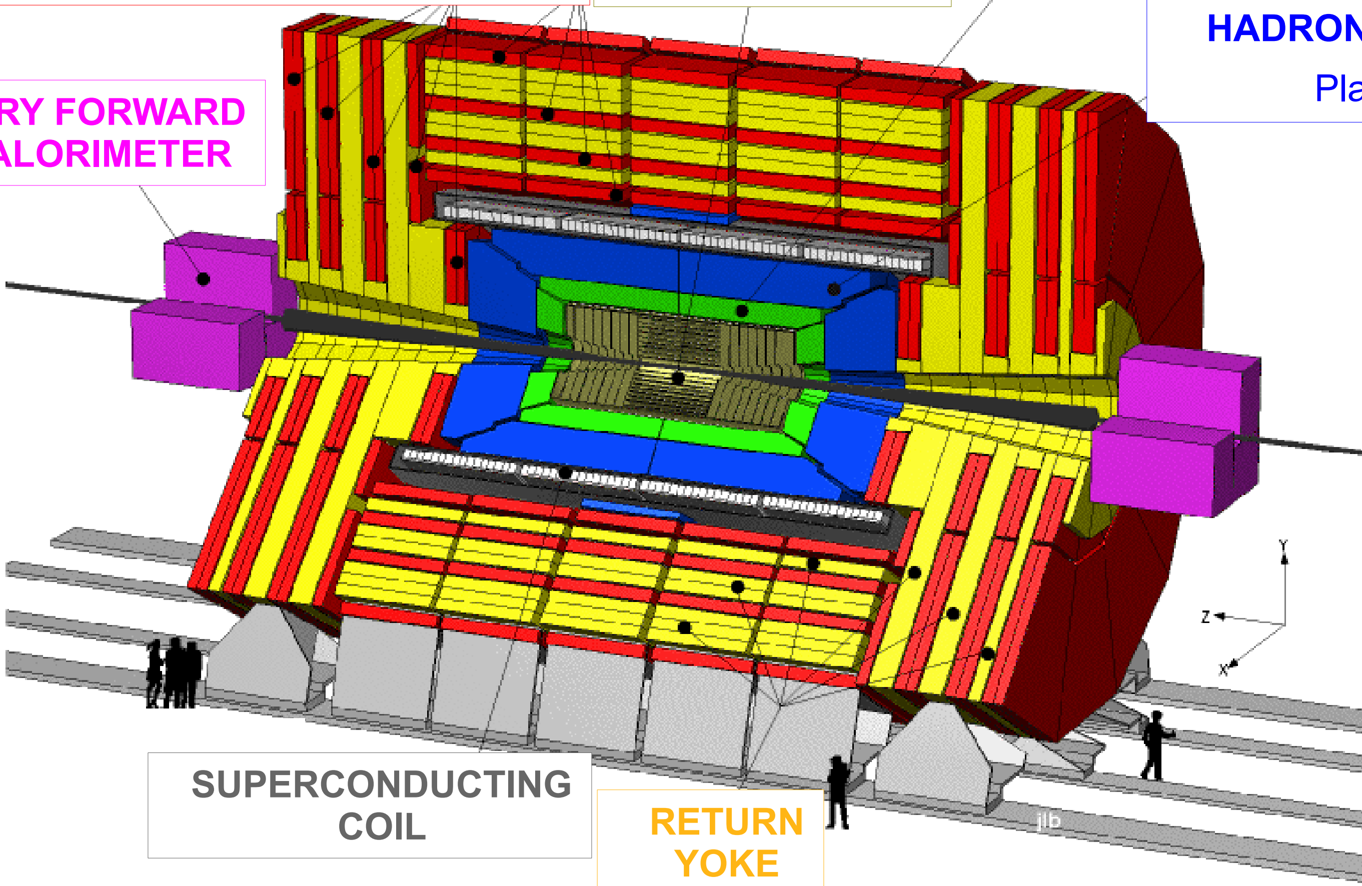
MUON CHAMBERS
drift tubes, cathode strip chambers, resistive plate chambers

INNER TRACKER
silicon pixel and μ-strip sensors

ELECTROMAGNETIC CALORIMETER (ECAL)
scintillating $PbWO_4$ crystals

HADRONIC CALORIMETER (HCAL)
Plastic scintillator / brass

VERY FORWARD CALORIMETER



SUPERCONDUCTING COIL

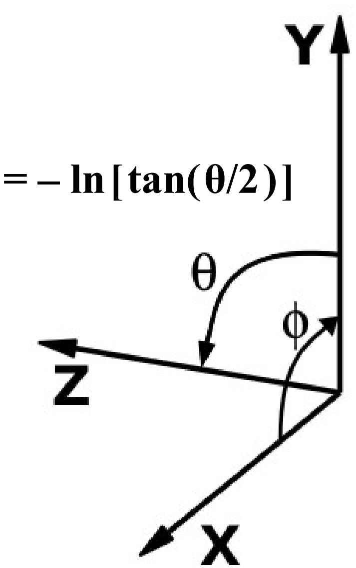
$B = 3.8$ T

RETURN YOKE

Z: beam axis (“longitudinal”)

X-Y: “transverse” plane

$$\eta = -\ln[\tan(\theta/2)]$$

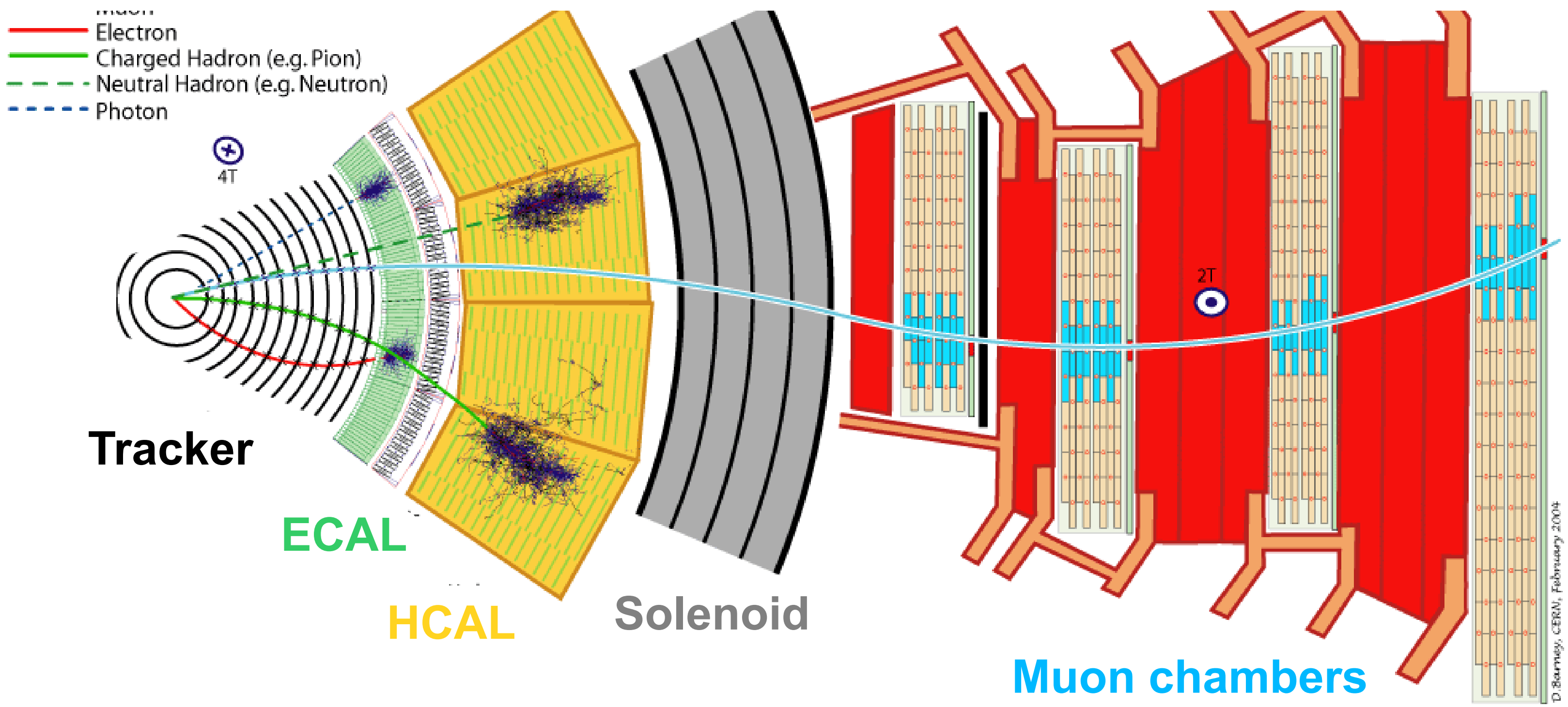


Event Reconstruction at CMS

Final-state particles:

- Electrons, photons ⇨ ECAL + tracker
- Hadrons (π, K, p, n) ⇨ HCAL + tracker
- Muons ⇨ Muon chambers + tracker

After reconstructing individual particles, the "particle-flow" algorithm uses the full-event information to refine the reconstruction and provide a coherent event description

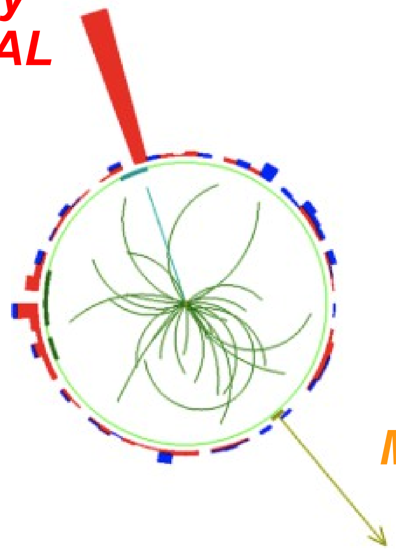


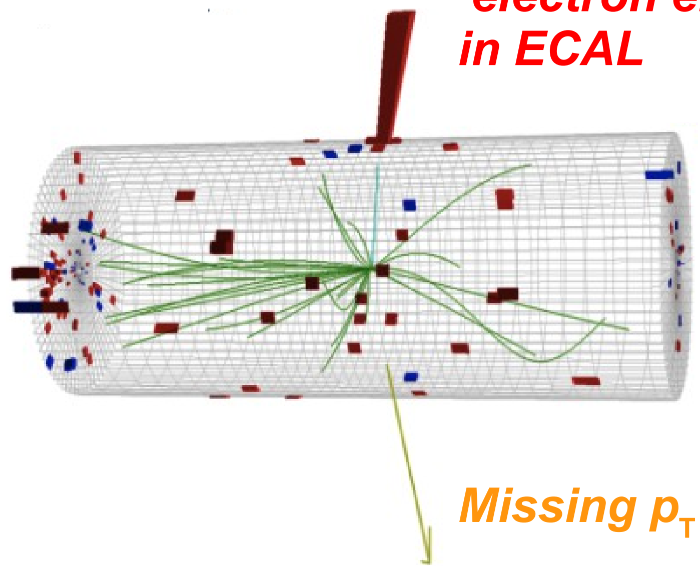
Missing Transverse Energy (MET)

- Undetectable particles (neutrinos, …?…) can be measured collectively as an imbalance in the transverse momentum of all detected particles
  - *initial state*: two partons of unknown longitudinal momentum and with negligible transverse momentum
  - *final state*: collision products must balance among themselves in the transverse plane no constraints along the beam axis

momentum conservation

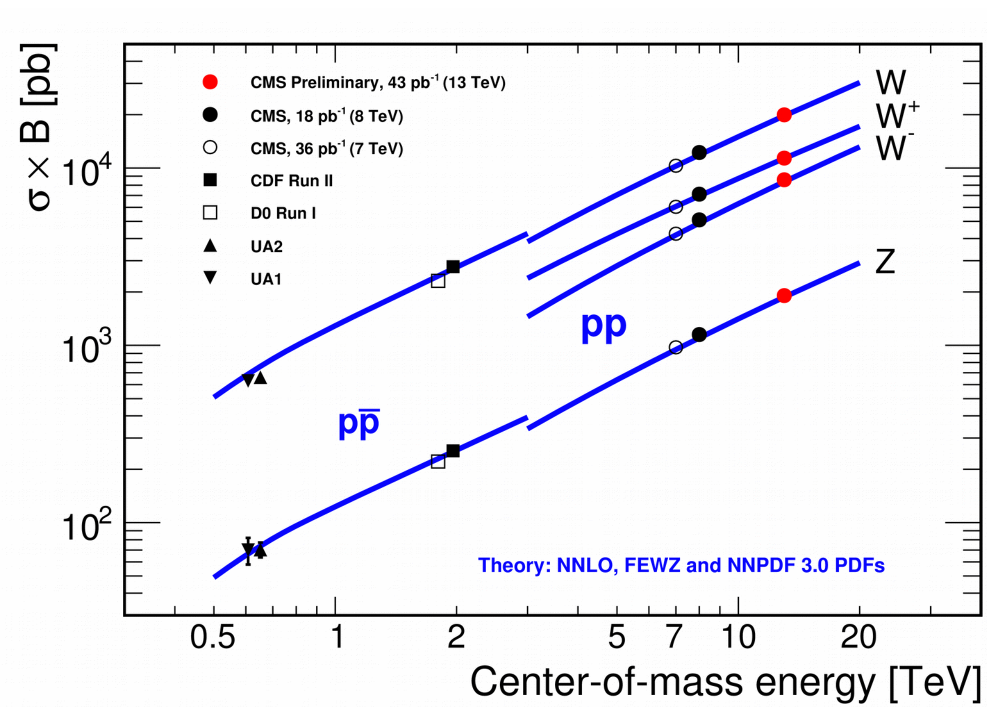
➔ missing transverse momentum (or energy): $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\sum_i \vec{p}_{\mathrm{T}}^{\,i}\,, \quad E_{\mathrm{T}}^{\mathrm{miss}} = \left|\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}\right|$

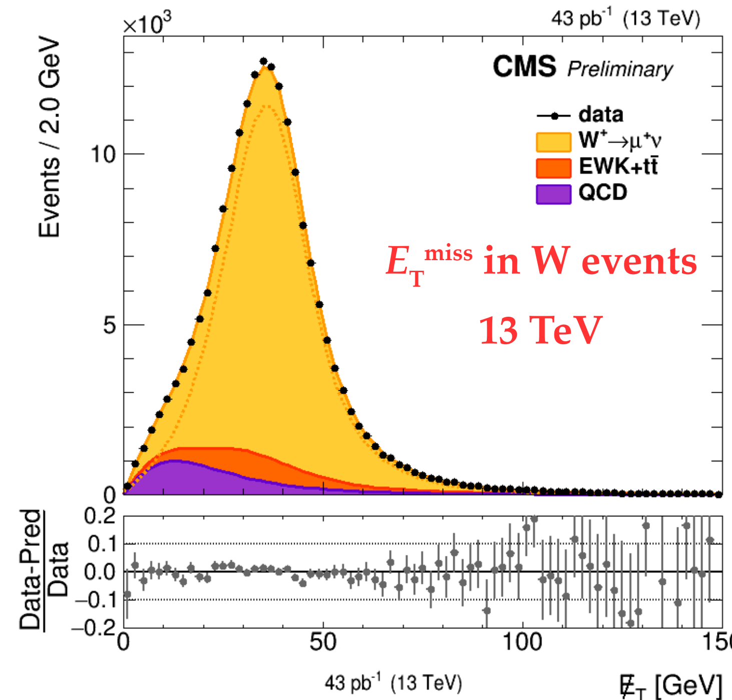


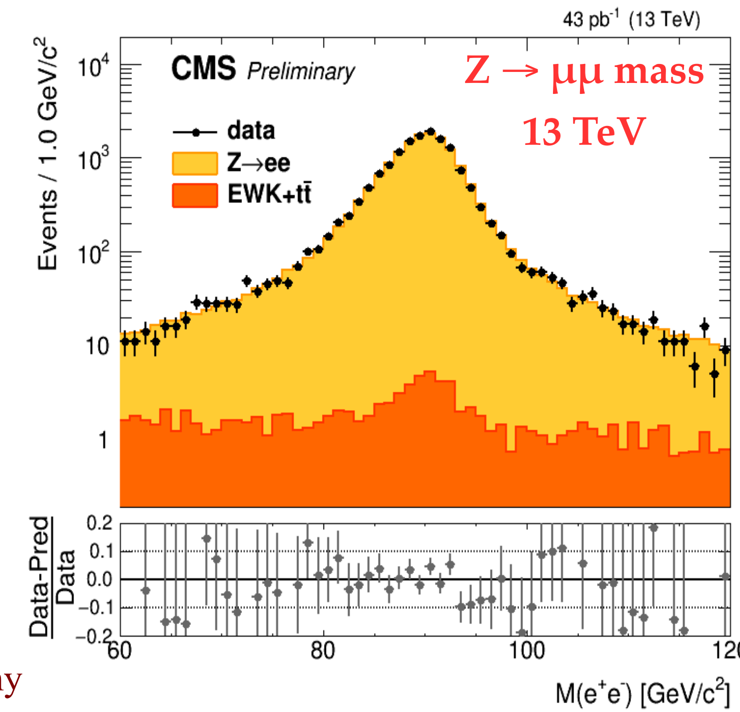


Single W/Z Cross Sections

- Inclusive W and Z cross section measurements at c.o.m. energies of 7, 8, and 13 TeV
  - Precision tests of theoretical predictions
    ⇒ good agreement with NNLO
  - Standard candles used for multiple purposes
    (e.g. detector calibration, efficiencies)

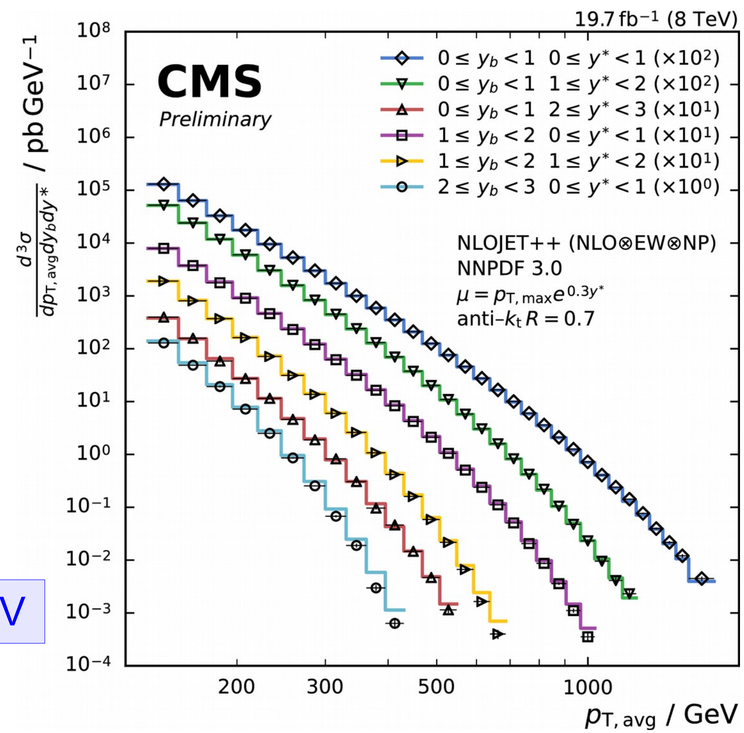




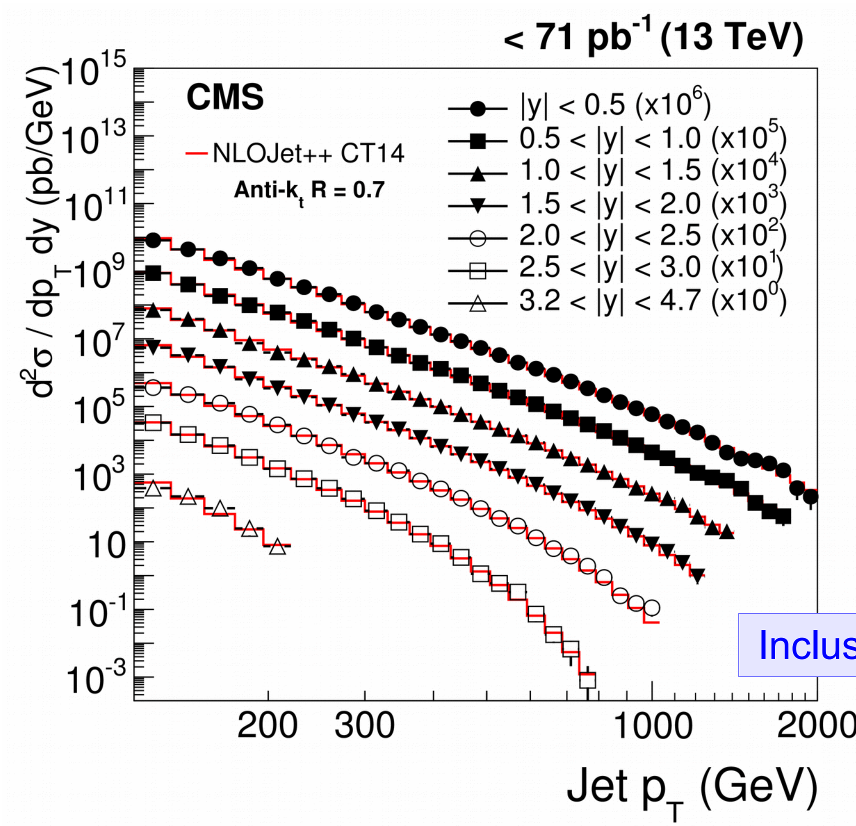


Jet Production

- Double- and triple-differential (di)jet cross section vs jet p_T and y ($|y_1 + y_2|$, $|y_1 - y_2|$)
  - measurement covers ~7 orders of magnitude, for jet p_T up to ~ 2 TeV
  - anti-k_T clustering algorithm, R = 0.7 or 0.4 → test radiative and nonperturbative effects
  - compared with NLO QCD predictions + NLO EW + nonperturbative effects
  - very good agreement over most of the phase space



Dijet, 8 TeV



Inclusive, 13 TeV

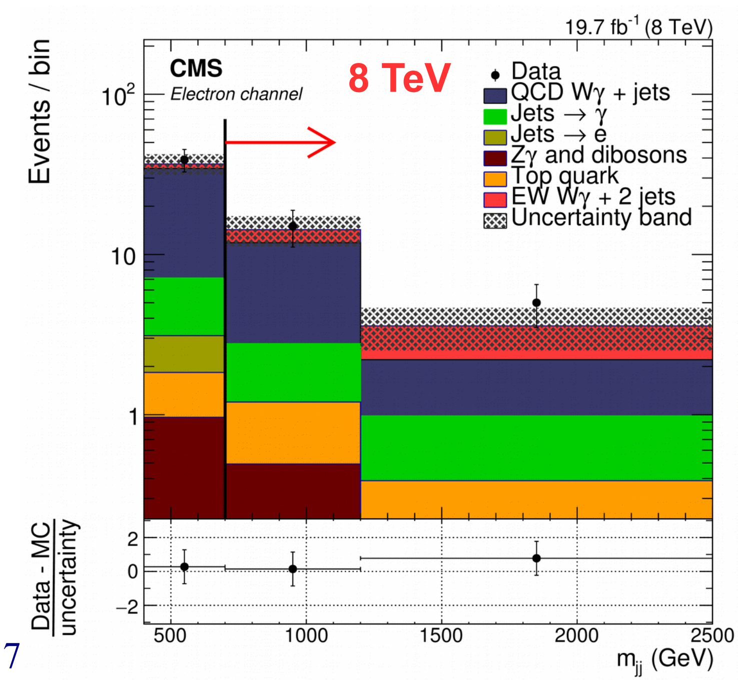
Electroweak Diboson Production

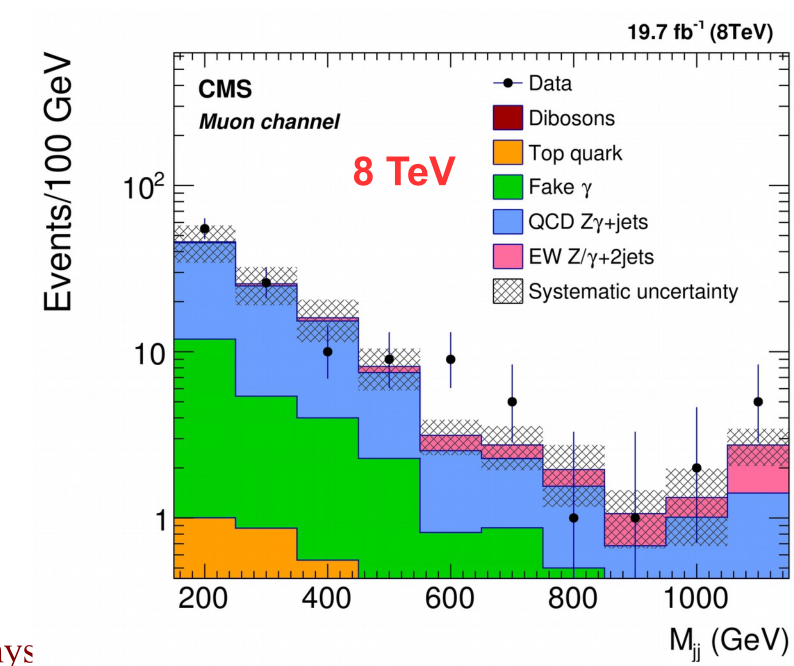
- $W\gamma + 2$ jets and $Z\gamma + 2$ jets produced via vector boson scattering (VBS)
  - Select events with one (two) electron(s) or muon(s), plus VBS topology requirements
  - Main background: QCD $W\gamma + 2$ jets and $Z\gamma + 2$ jets production
    - Normalization from low M_{jj} region
- Signal significance: $2.7\,\sigma$ for $W\gamma jj$, $3.0\,\sigma$ for $Z\gamma jj$
- Measured cross sections in agreement with LO predictions

$$\sigma^{fid}_{W\gamma jj} = 10.8 \pm 4.1\ (\text{stat}) \pm 3.4\ (\text{syst}) \pm 0.3\ (\text{lumi})\ \text{fb}$$

$$\sigma^{fid}_{Z\gamma jj} = 1.86\ ^{+0.89}_{-0.75}\ (\text{stat})\ ^{+0.41}_{-0.27}\ (\text{syst}) \pm 0.05\ (\text{lumi})\ \text{fb}$$

arXiv:1612.09256





arXiv:1702.03025