BNL Particle Physics Seminar

Jan. 10, 2019

Search for electroweak WZ vector boson scattering and new physics with the CMS Detector at the CERN LHC

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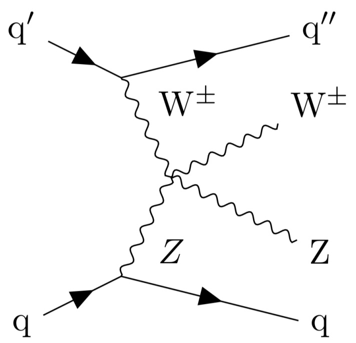
Outline

CMS-SMP-18-001

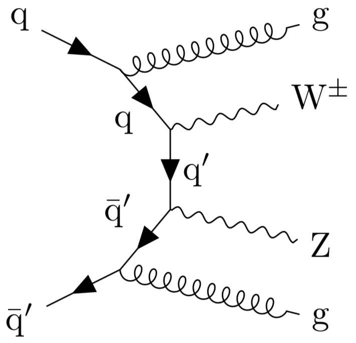
- Introduction and motivation
    - Electroweak WZ production in the SM
    - Searches for new physics with WZ VBS
- Common analysis procedures
    - Data collection
    - Event selection and backgrounds
    - Background estimation
- Measuring the WZjj cross section
- Search for electroweak WZ production in the SM
- Searches for new physics
- Conclusion

Introduction and motivation

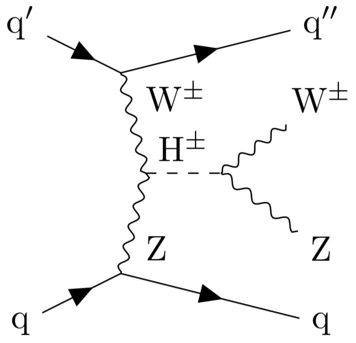
- WZ production via vector boson scattering
  - Important component of WZjj production proceeding entirely via EW interactions at tree level
  - Given SM Higgs, interactions with vector bosons, and V self-interactions precisely predicted
    - Deviations from predictions signal new physics in EW sector



VBS WZjj



Non-VBF WZjj



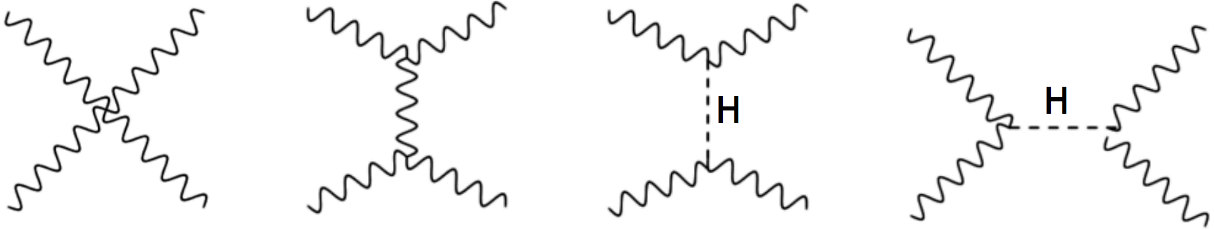
BSM H± Production

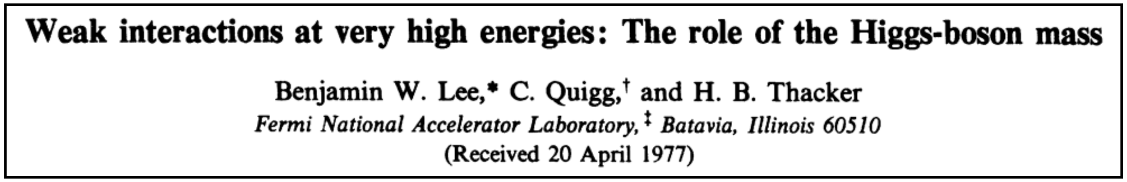
- Low cross sections for VBS just becoming accessible
  - Does VBS production occur with the rate predicted by the SM?
  - Do distributions show any signs of BSM physics?

VV interactions in the SM

- Arise due to non-Abelian structure of electroweak interaction
- Unitarity of VV ⟶ VV process ensured by Higgs interaction
  - ➡Major motivation for TeV-scale collider

$$\mathcal{A}(W_L W_L \to W_L W_L) \propto \left(-s - t + \frac{s^2}{s - m_H^2} + \frac{t^2}{t - m_H^2}\right)$$





Weak interactions at very high energies: The role of the Higgs-boson mass

Benjamin W. Lee,* C. Quigg,† and H. B. Thacker
Fermi National Accelerator Laboratory,‡ Batavia, Illinois 60510
(Received 20 April 1977)

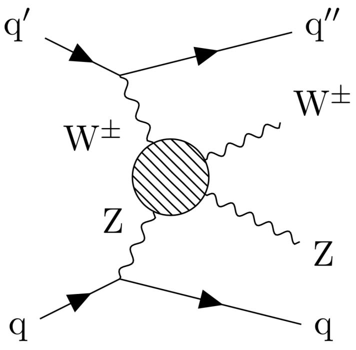
$$M_H{}^2 \leq \frac{8\pi\sqrt{2}}{3G_F} \equiv M_c{}^2 \simeq (1\ \mathrm{TeV}/c^2)^2$$

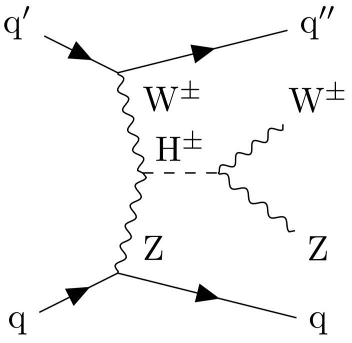
- Is the SM Higgs boson solely responsible for unitarization?
- Additional interactions could spoil cancelations
  - ➡Large effects possible!

New physics in WZ VBS topology

- Study deviations from SM from two perspectives
  - Explicit BSM models well-motivated by shortcomings in the SM
    - Example: charged Higgs bosons
    - Arise in extensions of the SM with extended Higgs sector
      - VBS production important when HV coupling dominant

Generic modification of WWZZ interaction





Charged Higgs production

- Generalized language for new physics in vector boson interactions
  - EFT expansion with Wilson coefficients c_i and New Physics scale Λ

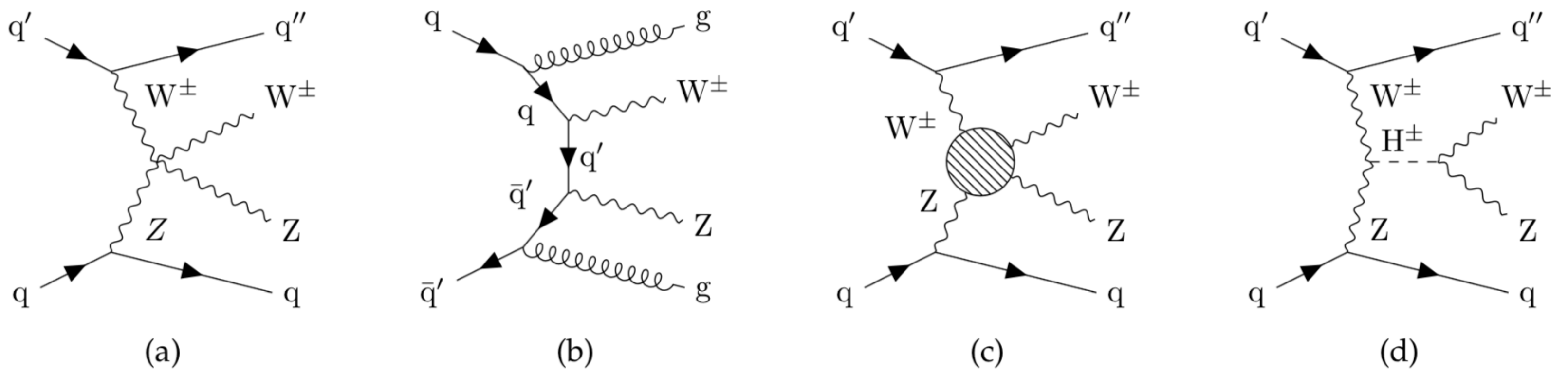
$$\mathcal{L}_{SM} \longrightarrow \mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_{i} \boxed{\frac{c_i^{(n)}}{\Lambda^n}} \mathcal{O}_i^{(n+4)}$$

  - Observed as deviations at high mass

Approaches are complementary!

Analysis overview

- Select $3\ell\nu jj$ events with VBS-like jets
  1. Measure WZjj cross section (treat (a) + (b) as signal) through cut-and-count analysis
  2. Distinguish EW and QCD production mechanisms through kinematics variables of two highest p_T jets
     - Treat (a) as signal, (b) as background
     - Fit to combined mjj and etajj distribution
  3. Look for new physics modifying the WWZZ interaction
     - Extract results in $m_T(WZ)$
     - Report results in terms of dimension-8 EFT (c) and charged Higgs production (d)

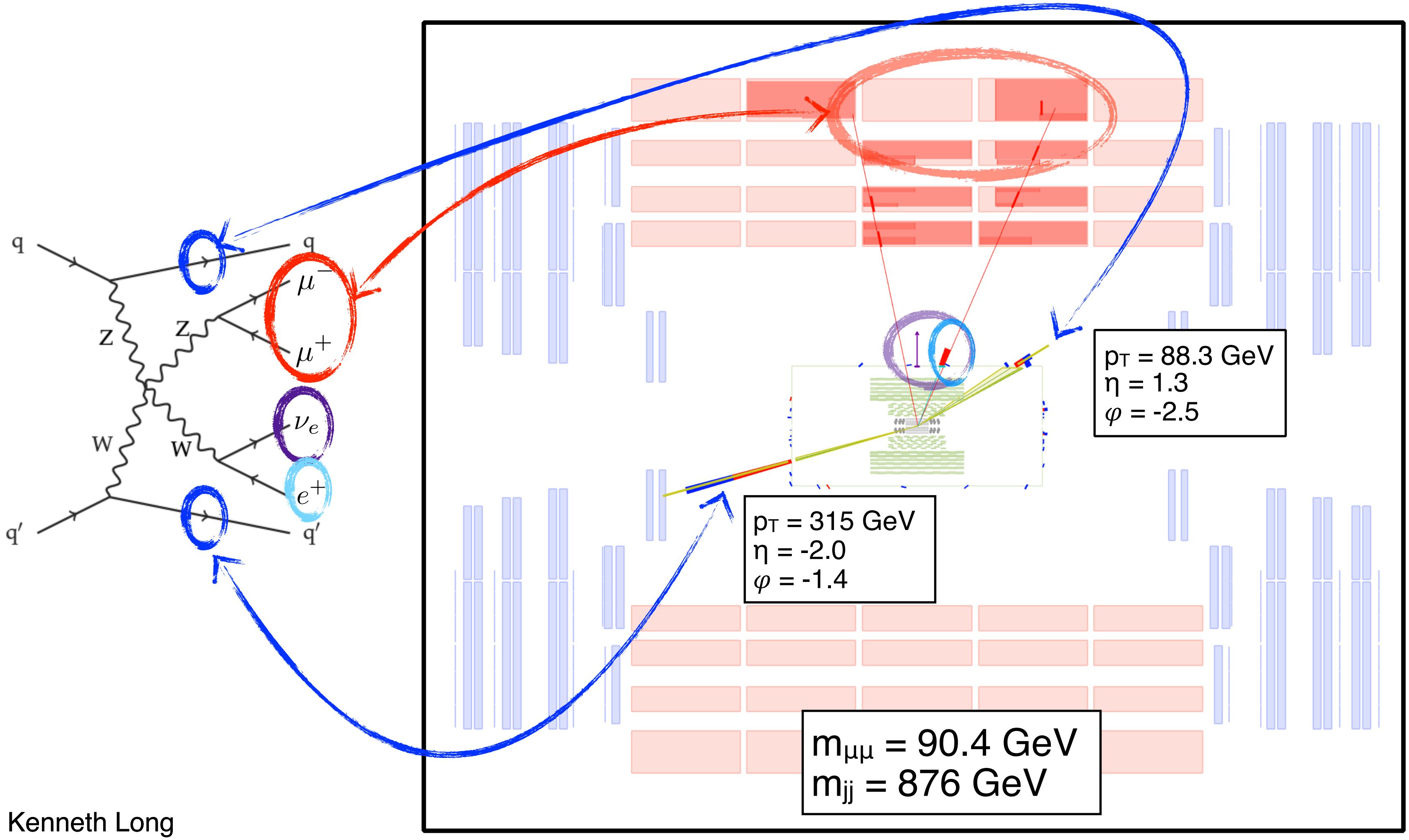


(a) (b) (c) (d)

Results from CMS-SMP-18-001, to appear on arXiv in next few days

Characteristics of WZ VBS events

- Radiation of vector bosons, lack of color flow between jets
  - ➡ Distinct kinematic signature for VVjj EW component
- Clean 3-lepton signature from leptonically decaying W and Z



p_T = 88.3 GeV
η = 1.3
φ = -2.5

p_T = 315 GeV
η = -2.0
φ = -1.4

$m_{\mu\mu}$ = 90.4 GeV
m_{jj} = 876 GeV

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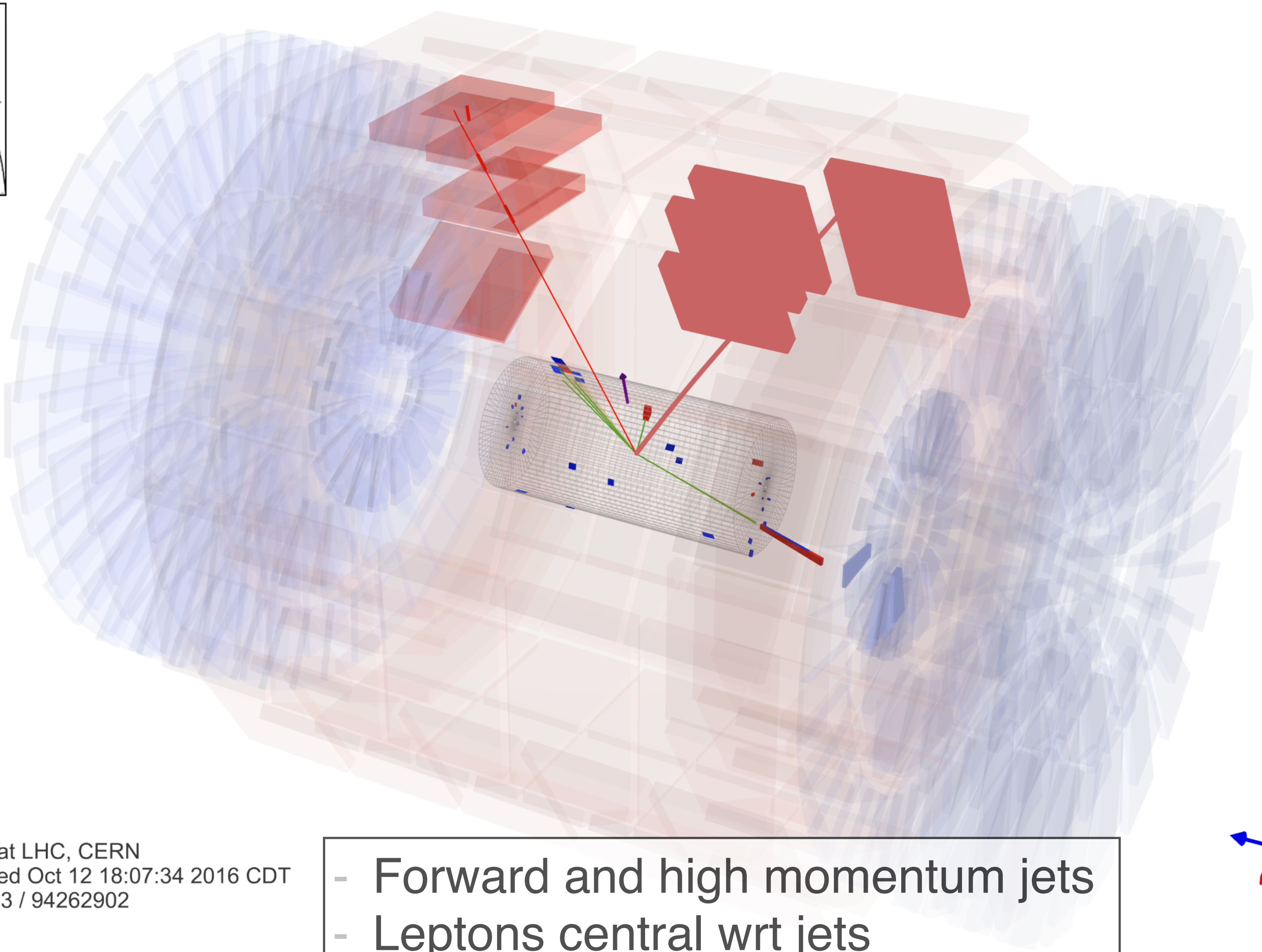
Picture of a candidate event



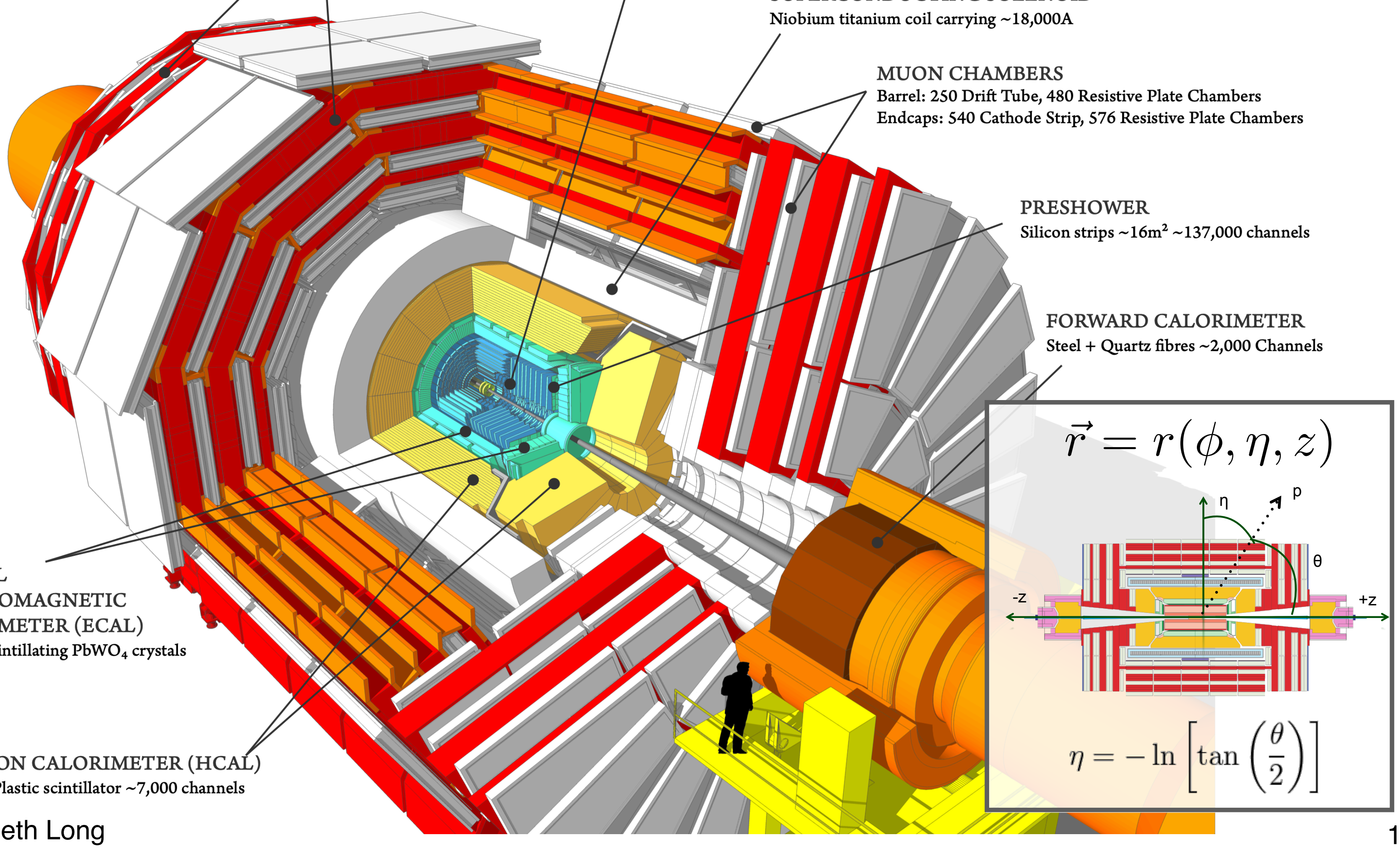
- Forward and high momentum jets
- Leptons central wrt jets

Analysis Procedure

The Compact Muon Solenoid

CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm) ~1m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
Silicon strips ~16m² ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

$$\vec{r} = r(\phi, \eta, z)$$

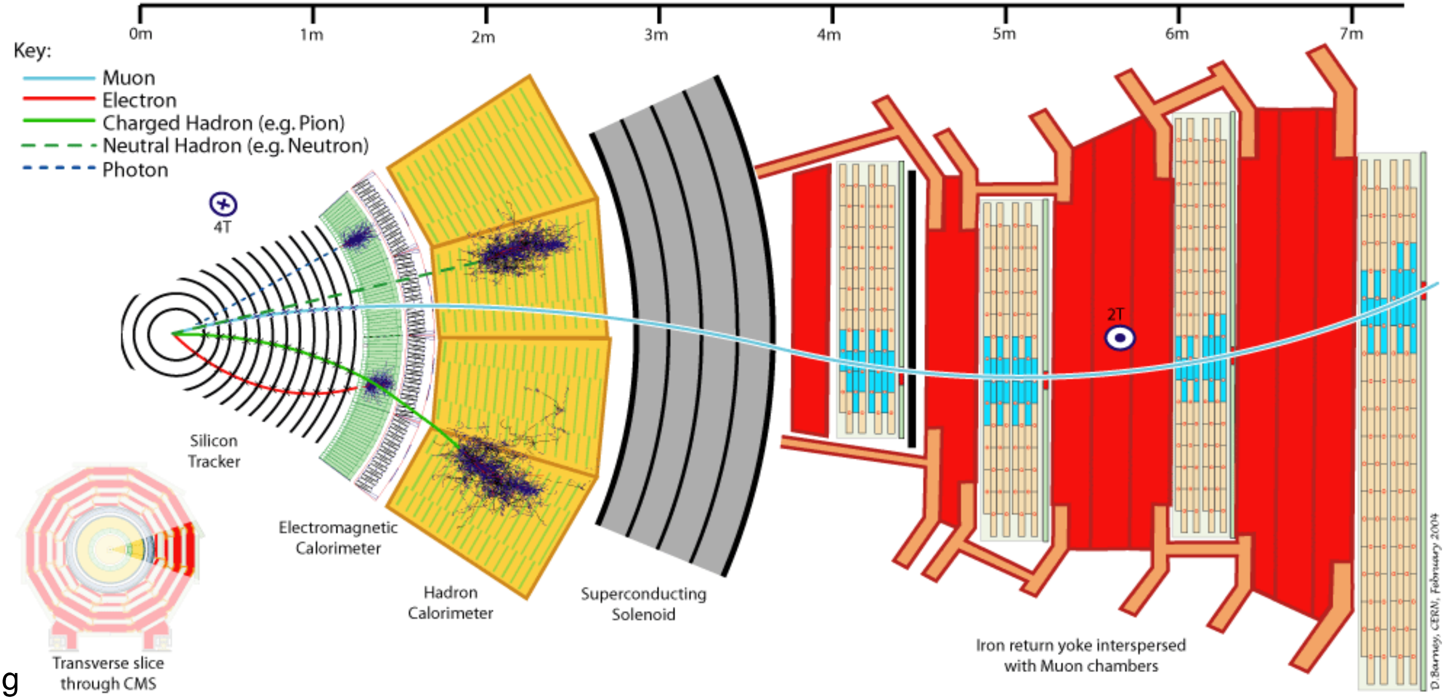
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

Particle Flow Reconstruction

- Provide unique identification and accurate kinematic measurements
- Start with systems essential for basic reconstructed
    1. Muons: Matched tracks in muon system and silicon tracker
    2. Electrons: Match tracks to ECAL energy deposits
    3. Charged Hadrons: Match tracks to ECAL and HCAL energy deposits
    4. Photons: Unmatched ECAL deposits

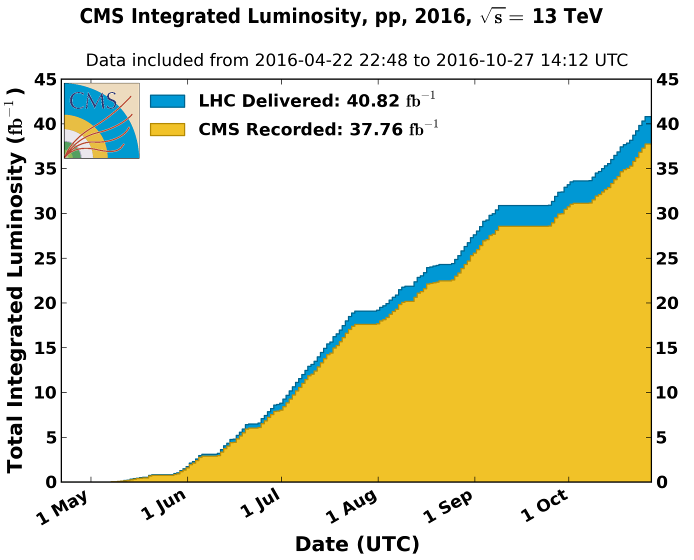
       Neutral Hadrons: Unmatched ECAL and HCAL deposits

➡ Refine with additional information: Isolation, ratio HCAL/ECAL energy, etc.



Data set

- Analysis performed with data collected in 2016 with the CMS Detector
- Events collected with double lepton triggers
  - Electrons: 23 (12) GeV threshold
  - Muons: 17 (8) GeV threshold
- Single lepton triggers included for efficiency near 100%

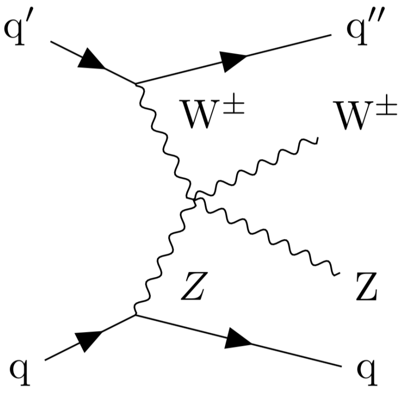


	Design	2016	2018
Beam energy (TeV)	7.0	6.5	6.5
Inst. luminosity (x 10^{34}cm^{-2}s^{-1})	1.1	1.3	2.0
Ave. collisions / bunch	20	23	38
Validated luminosity (fb^{-1})	—	35.9	> 60

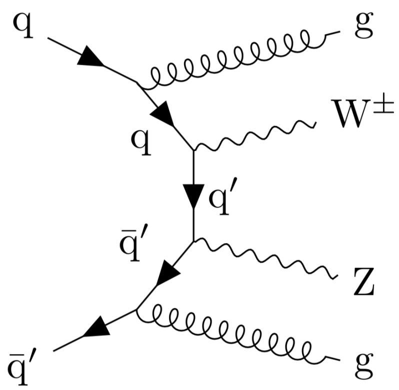
WZjj production

- WZjj 3/4 of yield in tight selection, 2/3 in loose
- EW-induced **(EW WZ)**
  - Entirely EW vertices at LO — $\mathcal{O}(\alpha^4)$
  - ~1/3 of WZjj in tight selection
  - Includes VBS, quartic WWZZ
    - VBS alone not gauge invariant
  - Signal for EW search
    - Background for new physics
- QCD-induced **(QCD WZ):** $\mathcal{O}(\alpha^2\alpha_s^2)$ at LO
  - 2/3 of WZ in tight selection
  - Final-state partons from QCD radiation
  - Considered signal for WZjj cross section
    - Leading background for EW search
- EW/QCD interference: $\mathcal{O}(\alpha^3\alpha_s)$ at LO
  - Observables ~ $|\mathscr{M}|^2$
  - Considered uncertainty in EW WZ process

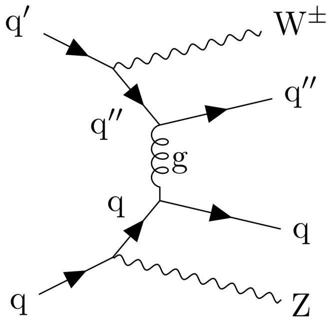
$\mathscr{M}_{\text{EW}} \propto$

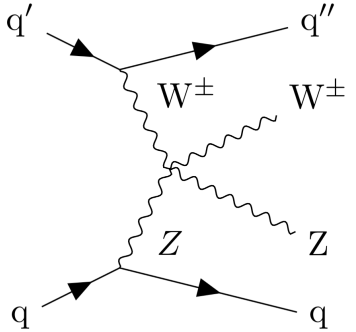


$\mathscr{M}_{\text{QCD}} \propto$



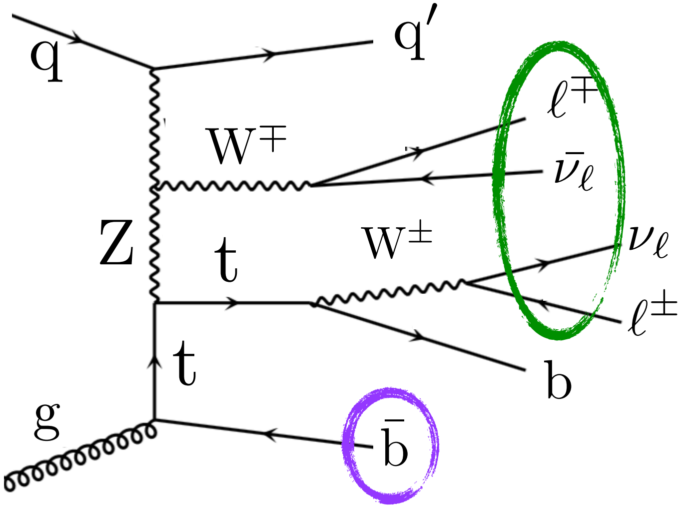
$\sigma_{\text{int}} \sim$



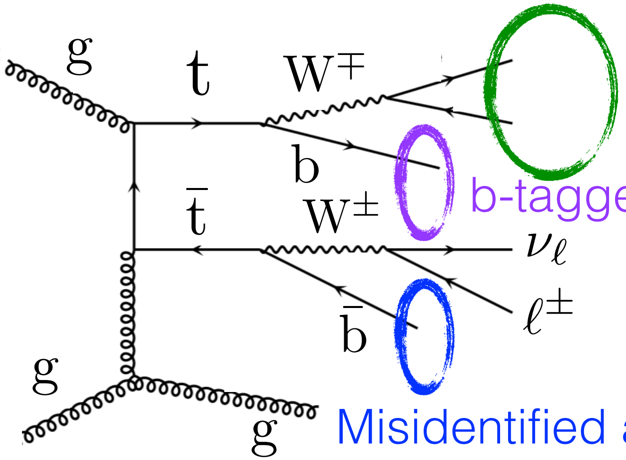


Major backgrounds to WZjj

- tZq production (~25% of non-WZ background)
  - Small rate of production
  - Can precisely mimic WZjj⟶3ℓvjj
  - Characterized by b jet
- Nonprompt backgrounds (~35% of non-WZ)
  - Large rate of production
  - Lepton “fake” from hadronic activity
  - ttbar (~20% of nonprompt)
    - No resonant decay of a Z
    - Suppress with b-veto
  - Z+jets (Drell-Yan) ~80% of nonprompt
    - Real Z candidate + 3 jets



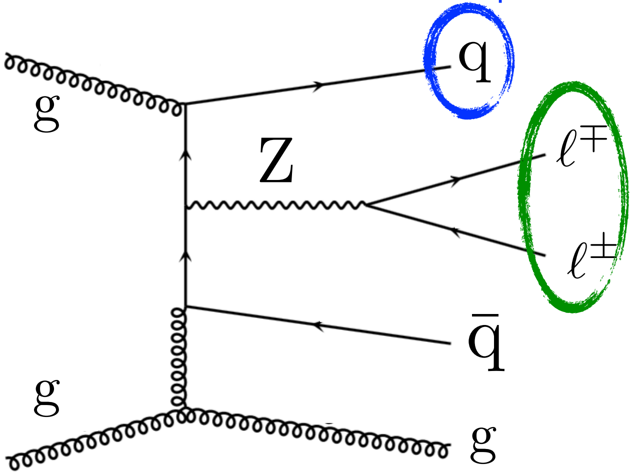
Mimics WZjj signal + b jet



b-tagged jet

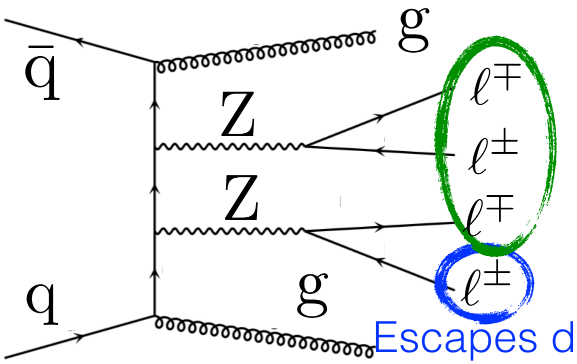
Misidentified as lepton

Misidentified as lepton

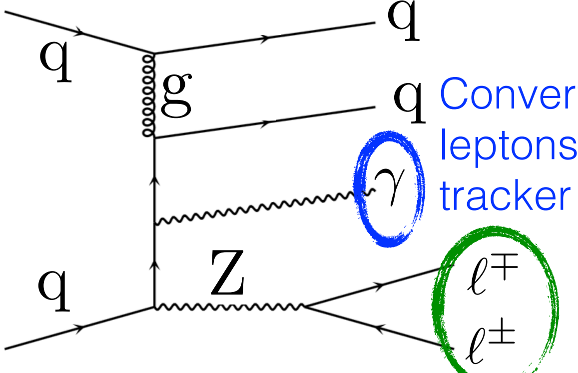


Other backgrounds

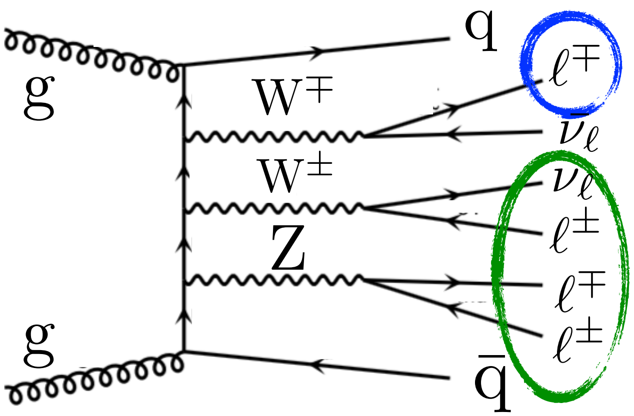
- Zγ production (~10% of non-WZ background)
  - True Z candidate
  - 3rd lepton from photon conversion in tracker
- ZZ⟶4ℓ production (~10% non-WZ)
  - Passes Z candidate requirement
  - Overlaps WZ⟶3ℓν signal when one lepton escapes detection
- VVV and ttV production (~5, 15% non-WZ)
  - Very small cross section
  - Can precisely mimic WZjj



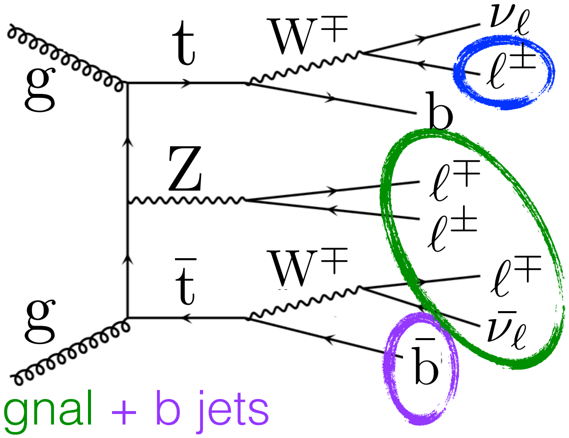
Escapes detector acceptance



Converts to leptons in tracker



Escapes detector acceptance



Escapes detector acceptance

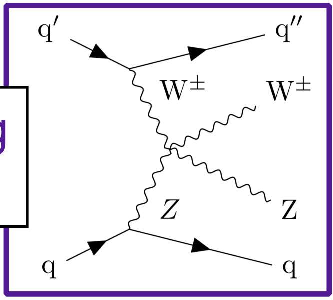
Mimics WZjj signal + b jets

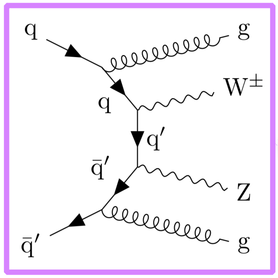
Event selection

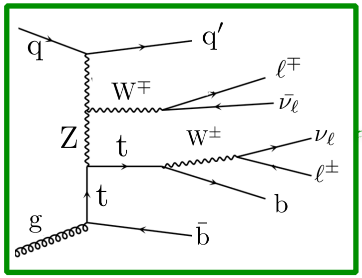
- Select events with 3 leptons + MET, + 2 forward and high momentum hadronic “jets”
  - Two leptons form composite object consistent with Z boson decay
  - Large rapidity separation between selected (forward) jets
  - Leptons central wrt jets

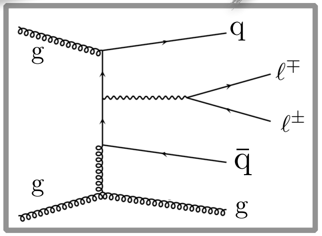
- 75 data events
  - Divided by WZ decay
- WZ/non-WZ ~ 3/1
- EW WZ / other ~ 1/3

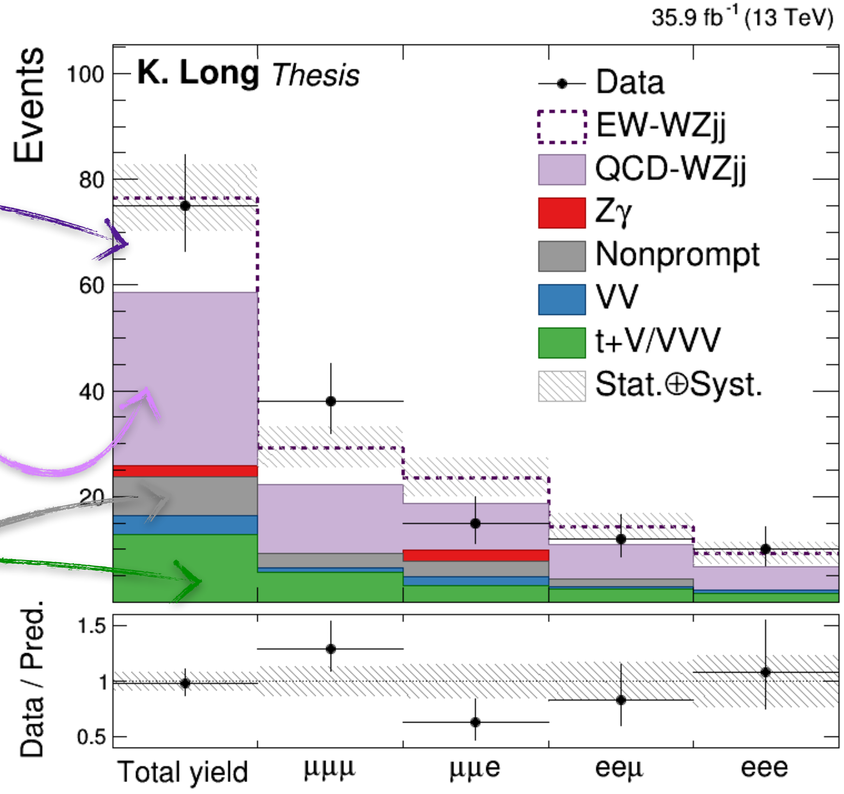
★Looking for this!





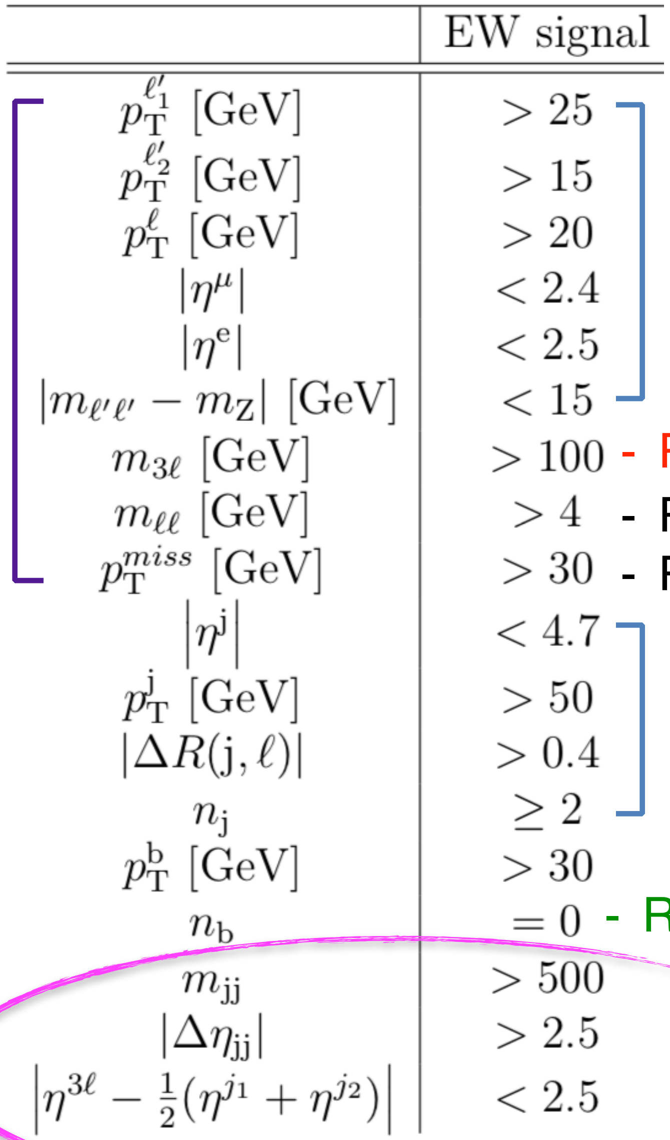






Detailed analysis selection

- Tight dijet kinematic cuts enhance EW WZ
- Loose selection for H± search
  - No $\eta^{3\ell}$ centrality requirement
  - Relax $p_T(j)$ to 30 GeV



	EW signal
$p_T^{\ell'_1}$ [GeV]	> 25
$p_T^{\ell'_2}$ [GeV]	> 15
p_T^{ℓ} [GeV]	> 20
$\lvert\eta^{\mu}\rvert$	< 2.4
$\lvert\eta^{e}\rvert$	< 2.5
$\lvert m_{\ell'\ell'} - m_Z\rvert$ [GeV]	< 15
$m_{3\ell}$ [GeV]	> 100
$m_{\ell\ell}$ [GeV]	> 4
p_T^{miss} [GeV]	> 30
$\lvert\eta^{j}\rvert$	< 4.7
p_T^{j} [GeV]	> 50
$\lvert\Delta R(j,\ell)\rvert$	> 0.4
n_j	≥ 2
p_T^{b} [GeV]	> 30
n_b	$= 0$
m_{jj}	> 500
$\lvert\Delta\eta_{jj}\rvert$	> 2.5
$\lvert\eta^{3\ell} - \frac{1}{2}(\eta^{j_1} + \eta^{j_2})\rvert$	< 2.5

- Consistent with Z boson (reduce non-res. background)
- Reduce Z $\longrightarrow \ell\ell\gamma \longrightarrow 3\ell + p_T^{miss}$
- Remove soft lepton
- Require W boson (reduce Z+jet)
- Require 2 jet events

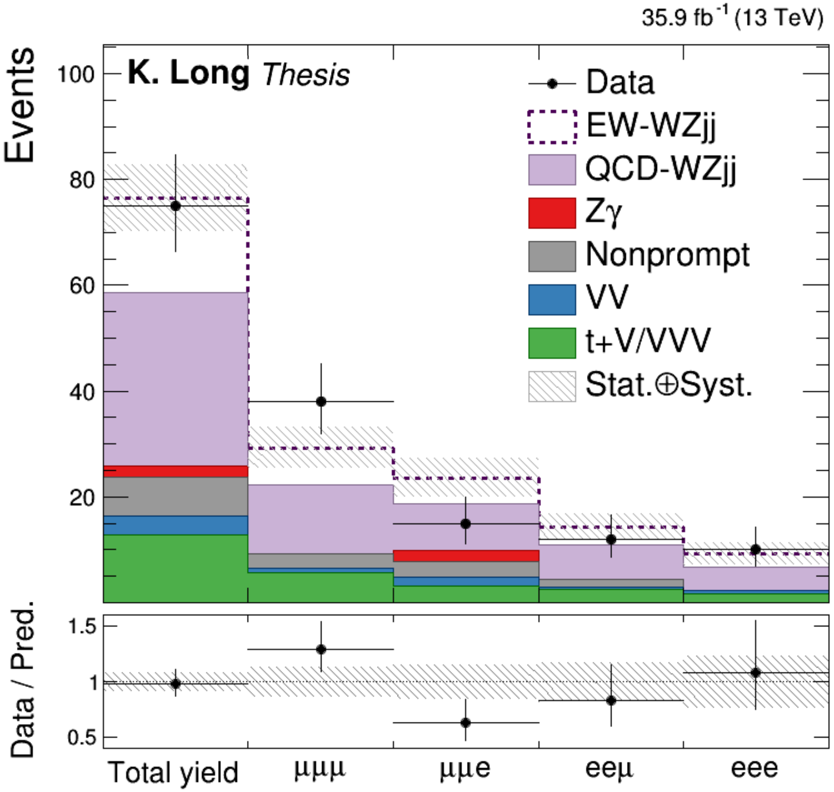
➡ Leptons “cleaned” from jets

- Reduce top background

VBS topology

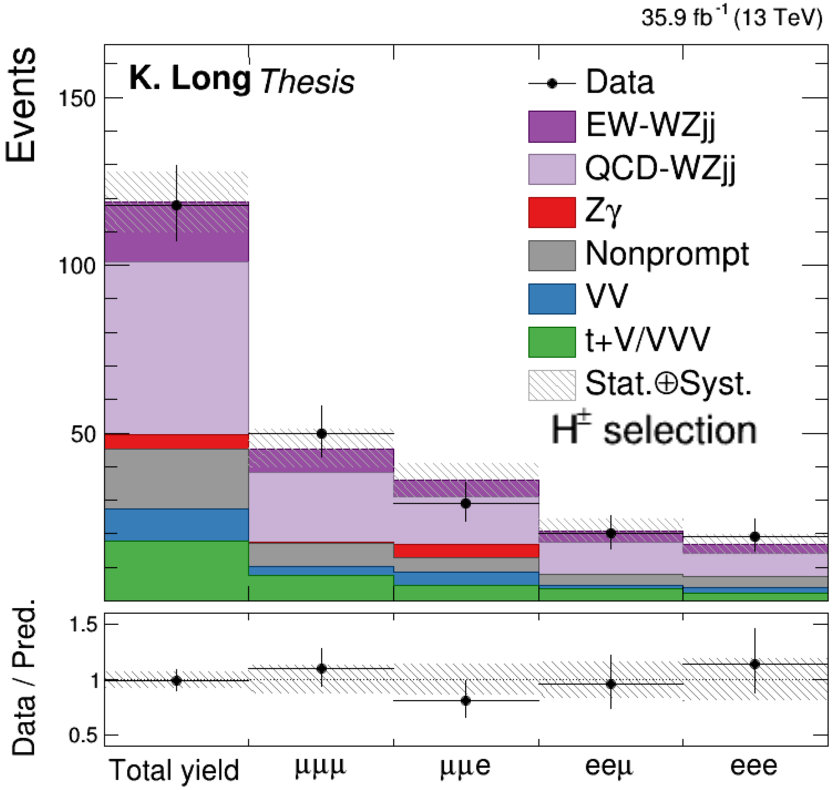
Event yields in signal regions

EW signal selection (tight)



- 75 data events
- Used for EW search, σ_{WZjj} , and aQGC search
- exp WZ/non-WZ ~ 3/1
- EW WZ / other ~ 1/3

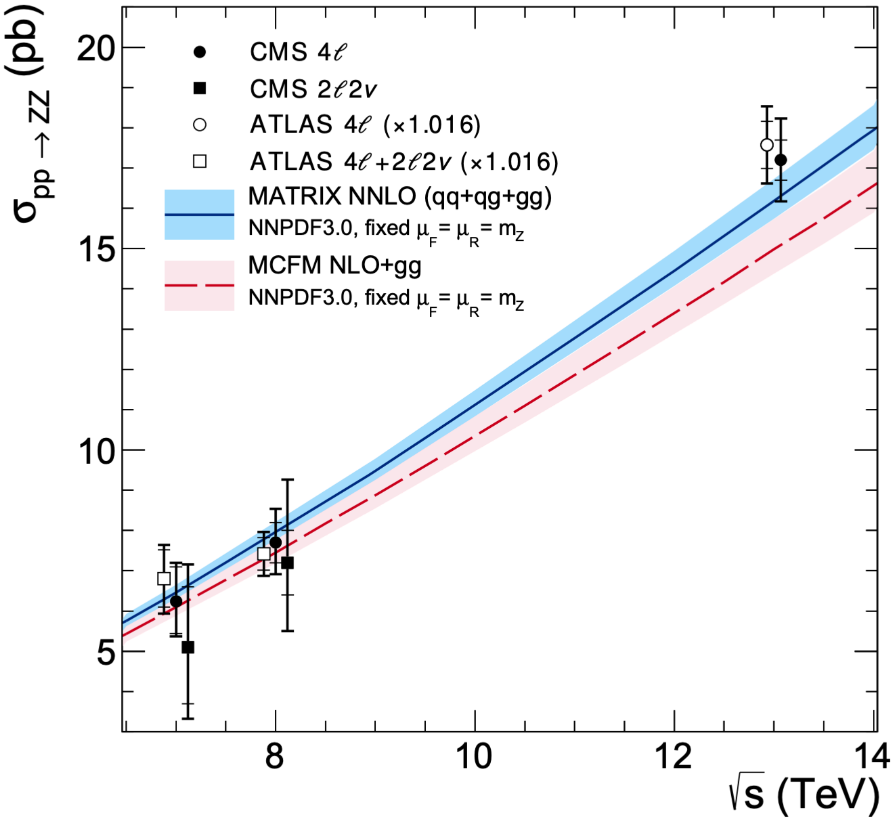
Charged Higgs selection (loose)



- 120 events
- Used for search for charged Higgs bosons
- exp. WZ/non-WZ ~ 2/1
- EW WZ / other ~ 1/5

Prompt background estimation

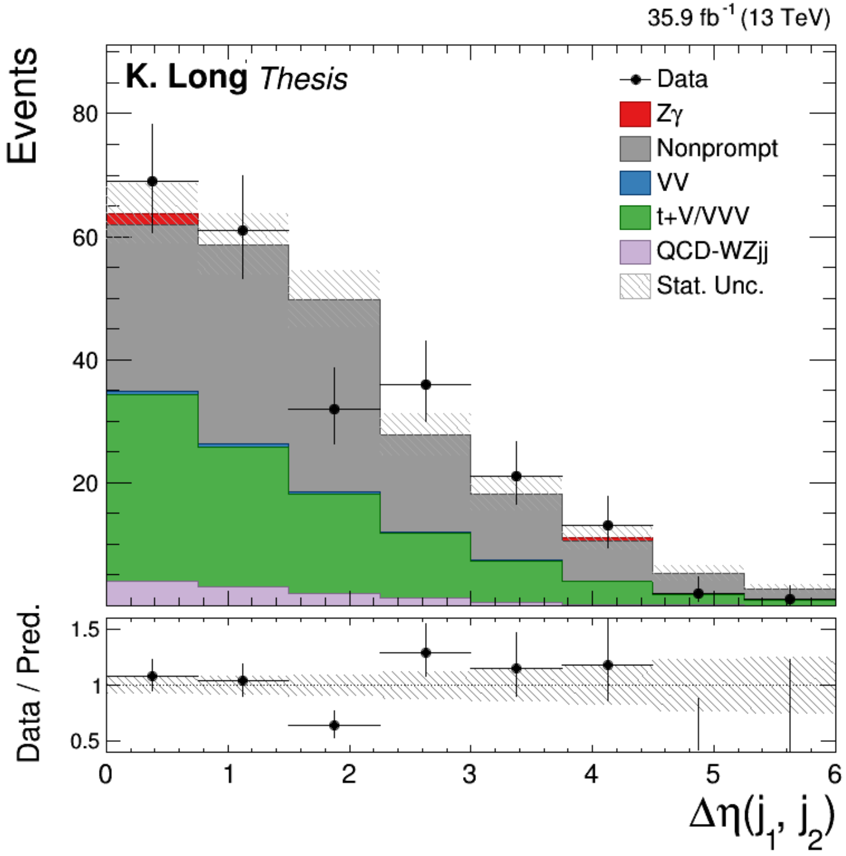
- Prompt backgrounds from MC simulation
  - MadGraph5_aMC@NLO for triboson processes, tZq, Zγ @NLO
  - Diboson processes from POWHEG v2
    - Best-available cross sections @NNLO via MATRIX
  - Pythia 8 parton shower+hadronization
  - Validated in control regions
- Several models considered for WZjj
  - Including Sherpa, Herwig 7, VBFNLO
  - Expanded discussion to follow



★CMS measurements confirm predictions

Nonprompt background estimation

- Nonprompt estimation
  1. Define “loose” ID with ID+isolation relaxed from “tight”
  2. Control regions: full analysis selection, with 1, 2, or 3 leptons passing loose <u>not</u> tight ID
  3. Remove contribution from prompt backgrounds in CR using MC
  4. Measure tight/loose ratio in Z+jet (dijet) events
  5. Apply loose ⟶ tight factors to events in control region
- Validation
  - Compare transfer factors from Z+jets and dijet events
  - Check data/prediction in regions dominated by Z+jets and ttbar



Validation selection (ttbar)

WZ+2j, ≥1 b jet

WZjj cross section measurement and search for EW WZ production

Systematic uncertainties

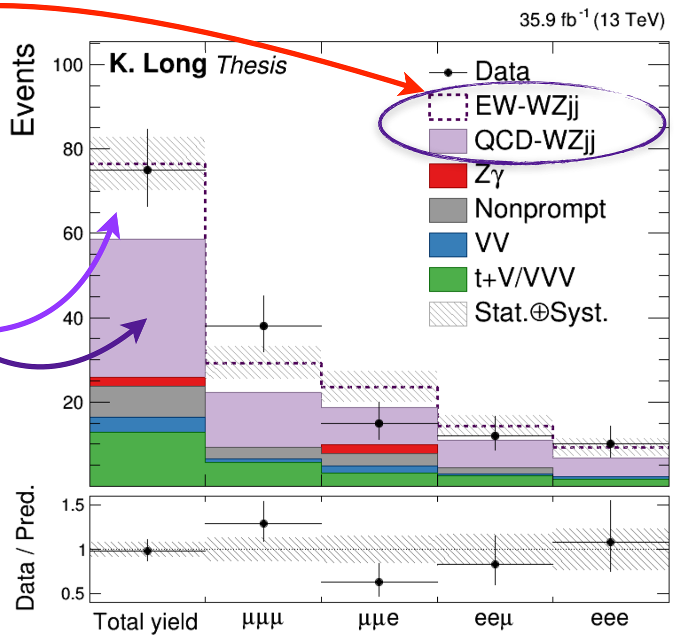
- Jet (JES), lepton energy scale (shape-based)
  - Vary momentum by uncertainty, recompute analysis qualities
  - JES: 5 (9)% on yield of QCD (EW) WZ — increases with η(j)
- Nonprompt background estimation
  - 30% normalization per channel, from differences in techniques
  - Statistical uncertainty of “loose lepton” control regions (dominant)
- Other theory (shape-based)
  - Scale/PDF uncertainties propagated to reconstructed events
- Contribution to σ_{WZjj}:
  - Freeze uncertainty to its central value and refit, compare to nominal

Source of systematic uncertainty	Relative systematic uncertainty [%] σ_{WZjj}
Jet energy scale	$+10.7\,/-8.1$
Jet energy resolution	$+1.9\,/-2.1$
QCD WZ modeling	N/A
Other background theory	$+2.2\,/-2.2$
Nonprompt normalization	$+2.5\,/-2.5$
Nonprompt event count	$+6.0\,/-5.8$
Lepton energy scale and eff.	$+3.5\,/-2.7$
b tagging	$+2.0\,/-1.7$
Integrated luminosity	$+3.6\,/-3.0$

WZjj cross section

- Measure WZjj EW+QCD cross section in VBS-enhanced phase space
  - Maximum likelihood fit to yields per channel in EW signal region

EW+QCD treated together as signal!



Fiducial Regions

	Tight fiducial	Loose fiducial
$p_T^{\ell_1'}$ [GeV]	> 25	> 20
$p_T^{\ell_2'}$ [GeV]	> 15	> 20
p_T^{ℓ} [GeV]	> 20	> 20
$\lvert\eta^{\mu}\rvert$	< 2.5	< 2.5
$\lvert\eta^{e}\rvert$	< 2.5	< 2.5
$\lvert m_{\ell'\ell'} - m_Z\rvert$ [GeV]	< 15	< 15
$m_{3\ell}$ [GeV]	> 100	> 100
$m_{\ell\ell}$ [GeV]	> 4	> 4
p_T^{miss} [GeV]	-	-
$\lvert\eta^{j}\rvert$	< 4.7	< 4.7
p_T^{j} [GeV]	> 50	> 30
$\lvert\Delta R(j,\ell)\rvert$	> 0.4	> 0.4
n_j	≥ 2	≥ 2
p_T^{b} [GeV]	-	-
n_b	-	-
m_{jj}	> 500	> 500
$\lvert\Delta\eta_{jj}\rvert$	> 2.5	> 2.5
$\lvert\eta^{3\ell} - \frac{1}{2}(\eta^{j_1} + \eta^{j_2})\rvert$	< 2.5	-

Tight $\boxed{\sigma^{\text{fid}}_{\text{WZjj}} = 3.18^{+0.57}_{-0.52}\,(\text{stat})^{+0.43}_{-0.36}\,(\text{syst})\text{ fb}}$

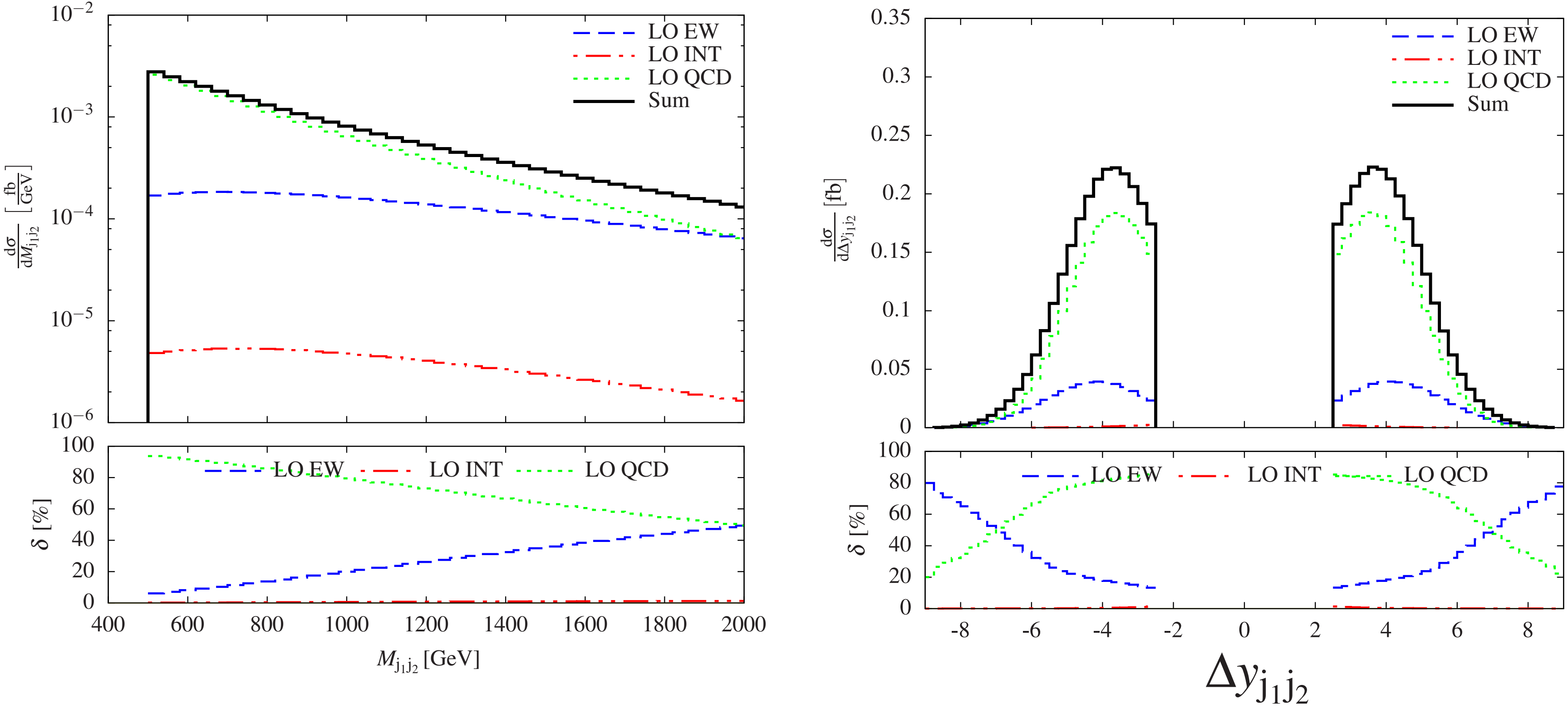
Loose $\boxed{\sigma^{\text{fid,loose}}_{\text{WZjj}} = 4.39^{+0.78}_{-0.72}\,(\text{stat})^{+0.60}_{-0.50}\,(\text{syst})\text{ fb}}$

Single signal strength, loose via theoretical acceptance

Compare tight fiducial to $\sigma_{\text{fid,MG}} = 3.27\,^{+0.39}_{-0.32}(\text{scale}) \pm 0.15\,(\text{PDF})$ fb

WZ QCD production as background

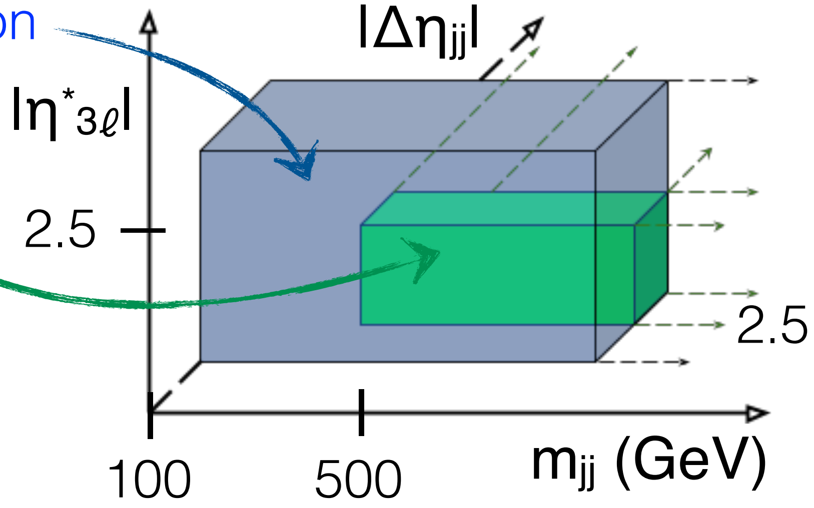
- QCD and EW WZ have indistinguishable signature in detector
- EW component distinguished by kinematics of dijet system
  - ➡Exploit to extract EW WZ component
  - Advantage: most sensitive to new physics, test of SM couplings
  - Disadvantage: depend on prediction for signal/background shapes

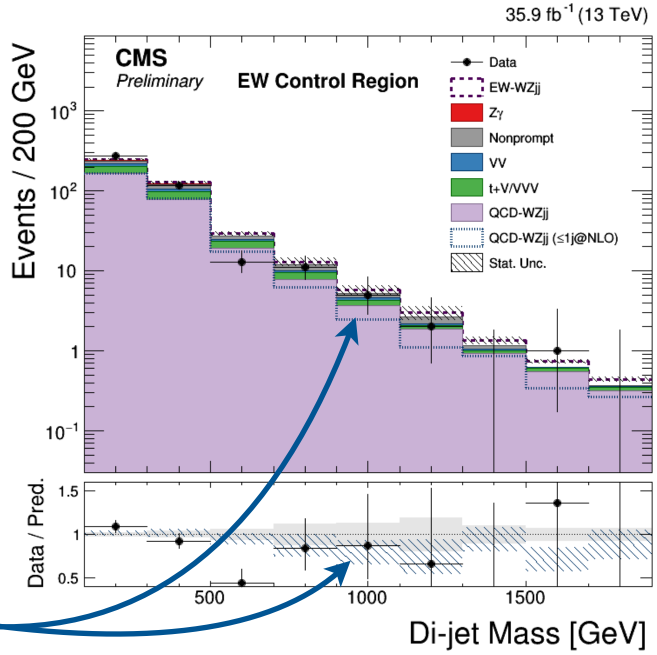


from Les Houches Study:
J. Bendavid, KL et. al. arxiv:1803.07977

Constraining modeling of QCD WZ

- Constrain normalization in sideband region
    - m_{jj} > 100 GeV, fail dijet signal cuts
    - Good agreement in CR
- Check that scale+PDF uncertainty covers uncertainty
- Nominal sample: simulated with MG5_aMC+Py8 WZ+≤3j@LO
    - Compare to predictions from MG5_aMC+Py8 WZ+≤1j@NLO,
        - each normalized to data in sideband region
    - Good agreement in sideband and signal regions
    - Uncertainty: LO scale+PDF+10% normalization covers largest differences

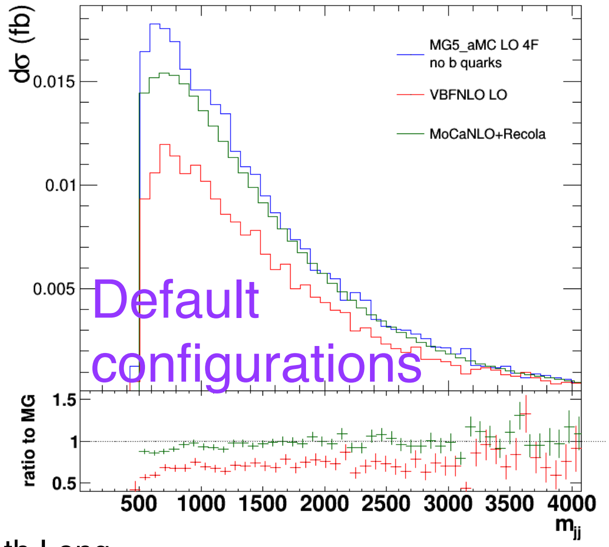




Alternative QCD-WZjj

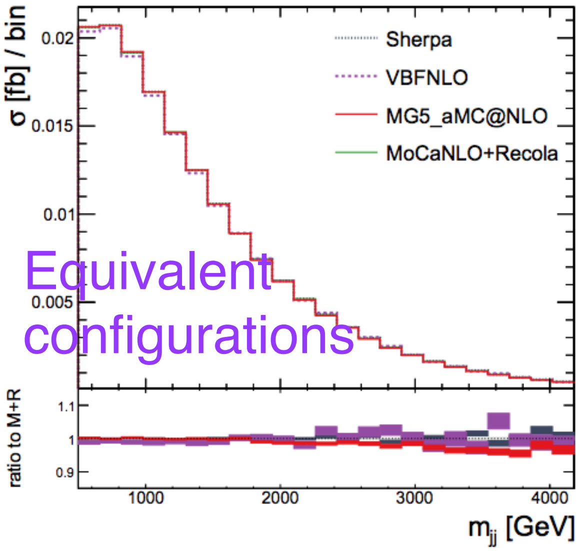
Understanding predictions for EW WZ

- Shape differences impact interpretation of results (shape-based analysis)
    - Significance and signal strength measured wrt input model
- $\sigma_{\text{pred.}}$ can't impact measurement, but may influence analysis approach
- Differences in MC predictions for EW WZ evolved into theory/experiment cross-study at Les Houches [1] (convened by KL and M. Pellen)
- Goal: technical comparison of generators + pheno study
    - When are differences uncertainties vs. misconfiguration?
    - With configuration of scale/PDF/inputs, very good agreement for $\Delta\eta_{jj}$, m_{jj}
- Conclusion: uncertainties covered by scale/PDF for validated MC
    - Avoid shower-dependent variables



Default configurations

Stat unc. only

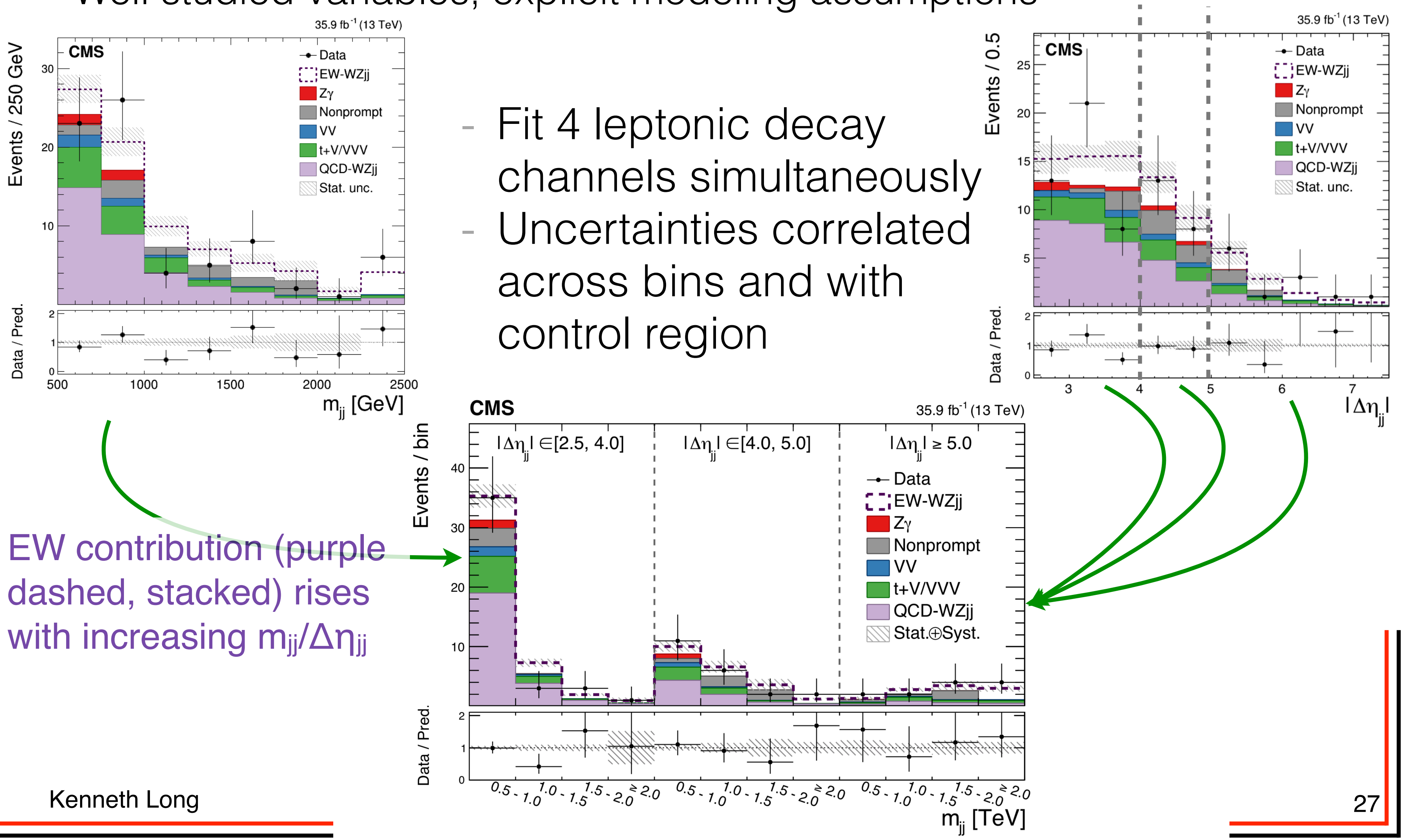


Equivalent configurations

[1] arxiv:1803.07977

WZ VBS at 13 TeV: EW Extraction

- Simultaneously fit to yield in control region and 2D dist. of m_{jj} and $\Delta\eta(j_1,j_2)$
  - Well studied variables, explicit modeling assumptions



- Fit 4 leptonic decay channels simultaneously
- Uncertainties correlated across bins and with control region

EW contribution (purple dashed, stacked) rises with increasing $m_{jj}/\Delta\eta_{jj}$

Results

- Observed (expected) significance of EW WZ 2.2σ (2.5σ)

$$\boxed{\mu_{\mathrm{EW}} = \sigma_{\mathrm{EW},\,obs}/\sigma_{\mathrm{EW},\,th} = 0.82^{+0.51}_{-0.43}}$$

- Consistent with SM expectation @LO: 1.48 ± 0.14 (scale + PDF) fb
- Uncertainty dominated by statistics of data
- Small difference from preliminary ICHEP result
  - Unanticipated trigger pre-firing in forward ECAL lead to loss of events with forward jets
- Downward fluctuation compatible with expectation
- EW corrections known to be large and negative
  - Schwan, Pellen, et. al., BOOST 2018 [1]
  - Observed significance stable when applying EW shape corrections

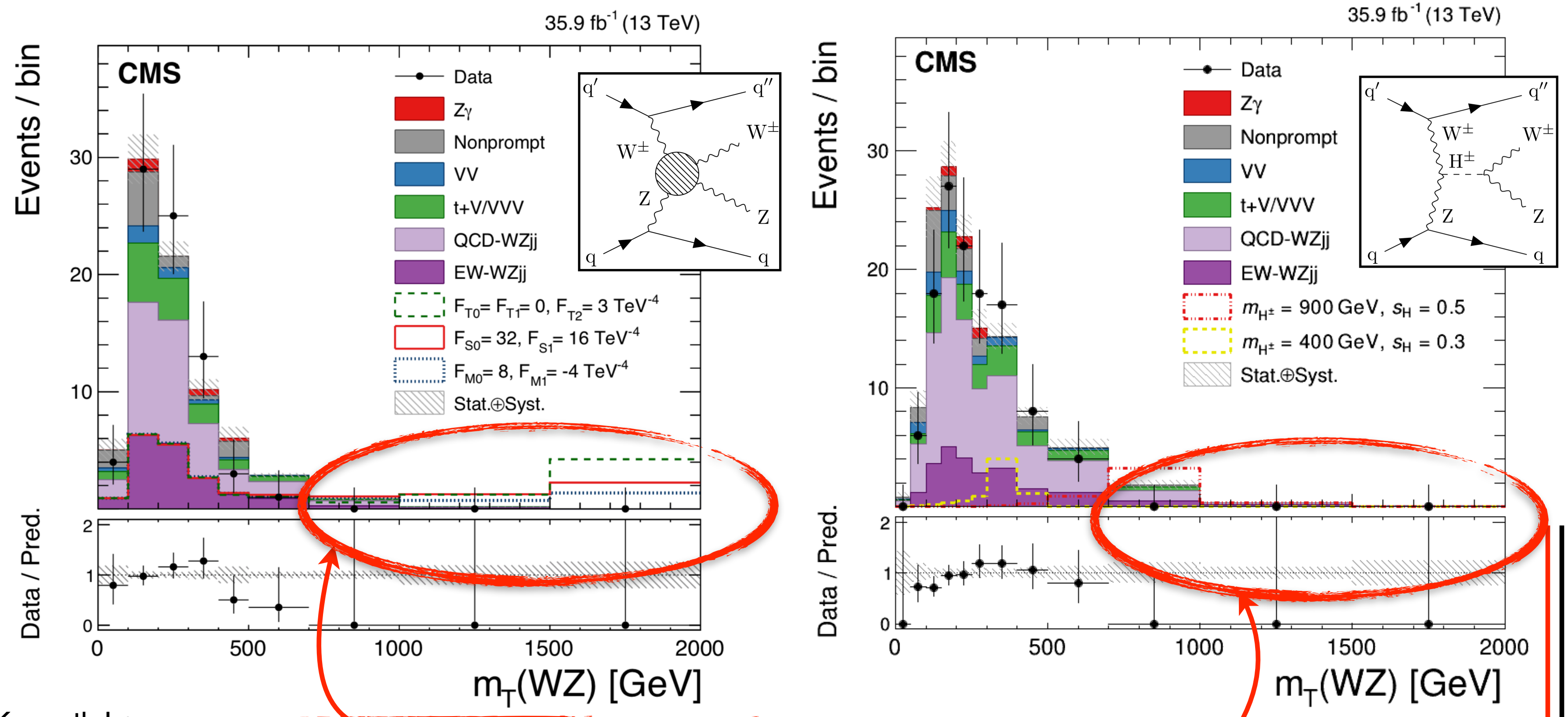
- Small tension with ATLAS result: $\mu = 1.77^{+0.49}_{-0.43}$, significance 5.3σ (3.2σ exp)
  - Analysis driven by multi-variate discriminant
  - On-going efforts to understand differences arising from MC inputs, data fluctuations, technique

[1] https://indico.cern.ch/event/702614/

Limits on new physics

Searches for new physics with WZ VBS

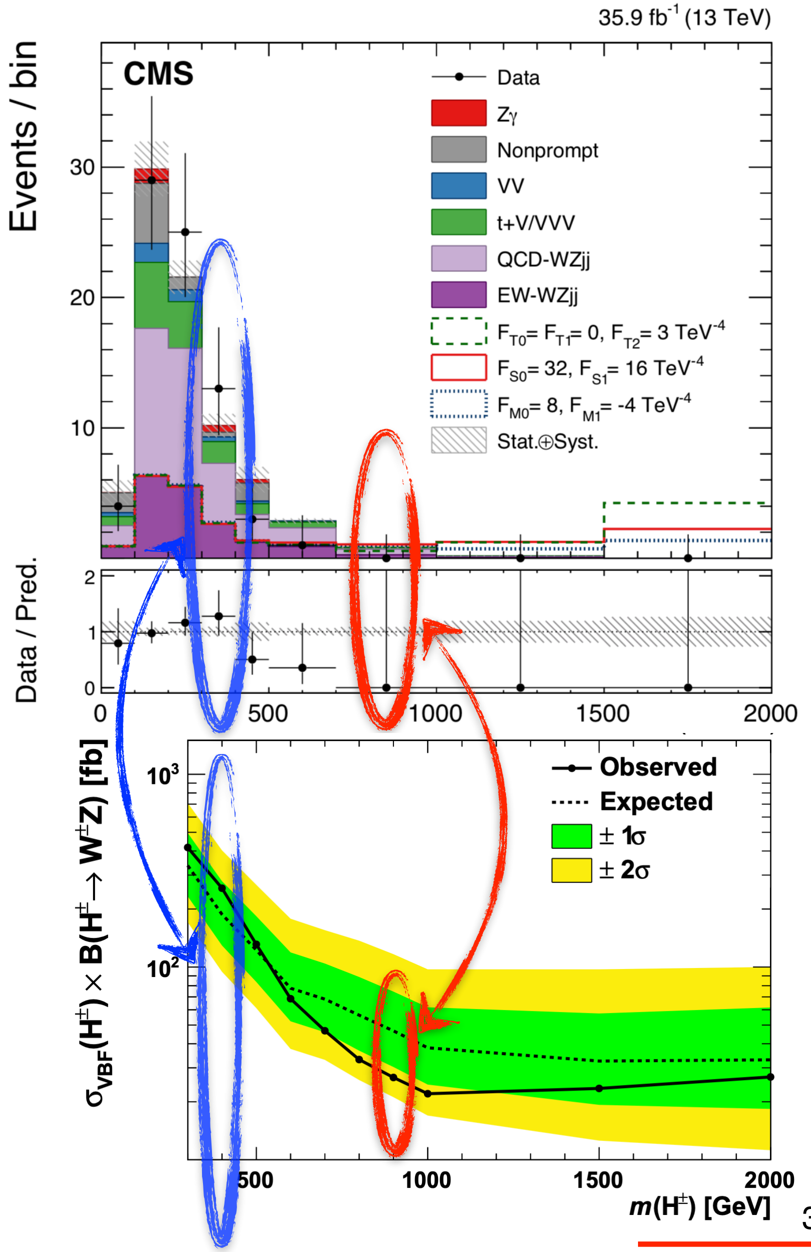
- New WWZZ interactions likely modify the m_T(WZ) spectrum
  - ➡Sensitive to center of mass energy of the scattering system
- Studied in specific and generic models
  - Charged Higgs bosons (Resonance-like)
  - Dimension-8 effective field theory operators (excess at high m_T)



No signs of new physics at high mass!

Quantifying nothing

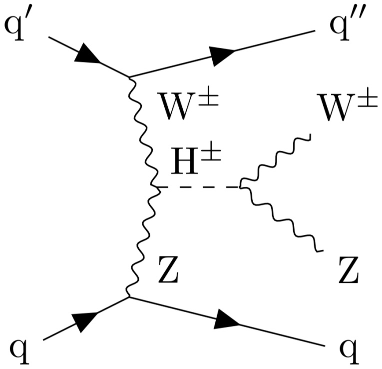
- We see no evidence of charged Higgs bosons
  - What if their production rate is just too low for us to see them?
- Place 95% confidence level limits on the production rate vs. mass
  - Model independent (with assumptions, e.g. narrow width)



Bottom plot: 5% chance of the data observation (e.g. no bump) given hypothetical production rate

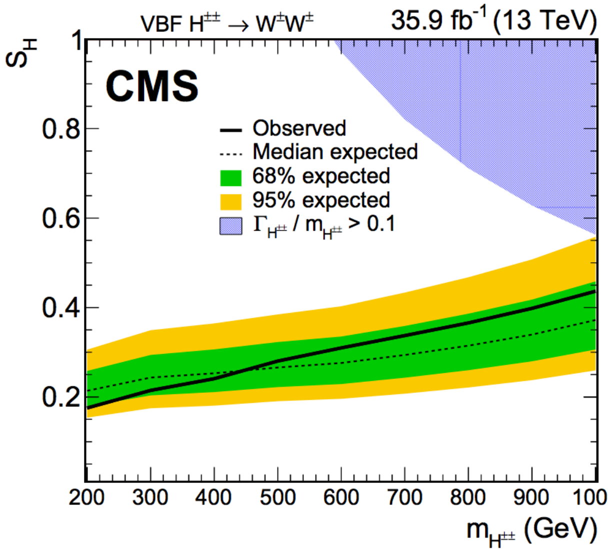
The Georgi-Machacek (GM) model

- Most limits on charged Higgs models favor leptonic decays
  - ➡ Dominant in models with Higgs sector extended by SU(2) doublets, e.g. MSSM
- Georgi-Machacek model
  - Extend Higgs sector with one real, one complex triplet
  - preserves custodial symmetry



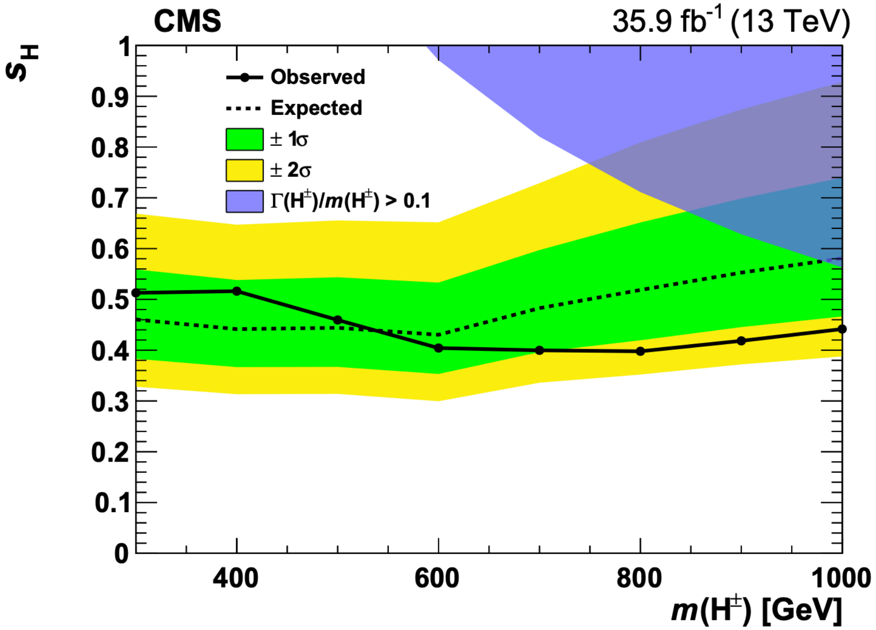
$$\rho = m_{\mathrm{W}}^2/(m_{\mathrm{Z}}^2 \cos^2\theta_{\mathrm{W}}) = 1$$ at tree level

  - 10 scalar states, fiveplet, triplet, 2 singlets (1 is SM h)
  - Fermiophobic H± produced by VBS
  - $\sigma_{H^\pm} \sim \sin^2(\theta_H)$
    - $\sin(\theta_H) \equiv s_H$, ratio of Higgs vevs
  - Limits from CMS with 15 fb^{-1} in WZ, in W±W± with 36 fb^{-1}, from ATLAS with WZ leptonic recently

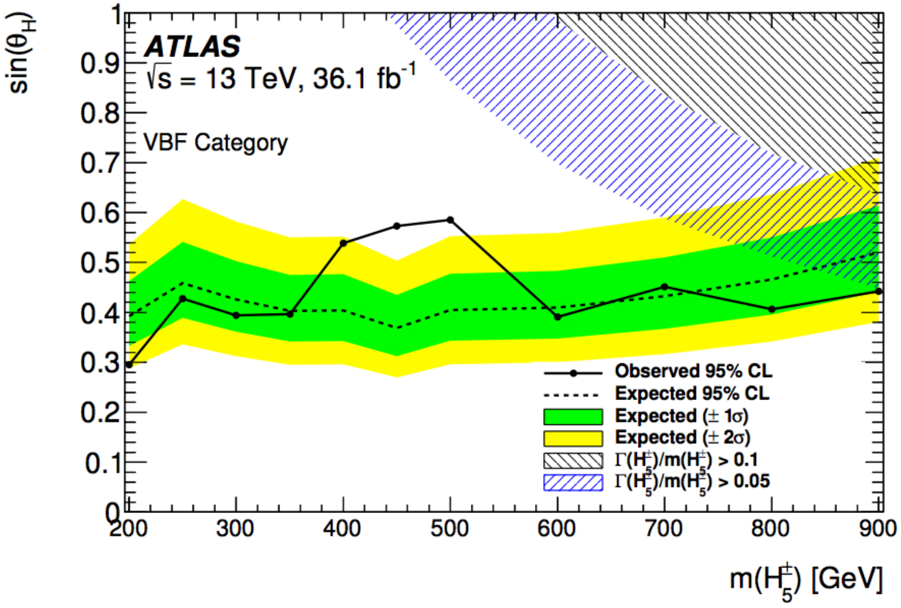


Limits on H± production in the GM model

- Charged Higgs limits improve from previous CMS study at 13 TeV, comparable to those from ATLAS
  - Similar sensitivity to ATLAS, slightly worse at low mass
  - ATLAS local excess at 450 GeV ~3σ,
    - CMS observed within 1σ of expected at $\sigma_{H^\pm}$ = 400 – 500 GeV



CMS-SMP-18-001



arXiv:1806.01532

New physics with dimension-8 EFT

- Studied using basis of Eboli, Gonzlez-Garcia, Mizukoshi [2]
  - All parity and charge conserving operators with pure V,H couplings

$$\mathcal{L}_{SM} \longrightarrow \mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty}\sum_{i} \frac{c_i^{(n)}}{\Lambda^n}\mathcal{O}_i^{(n+4)}$$

  - Operators constructed from Higgs fields only, gauge field only, and Higgs and gauge fields

e.g. $\boxed{\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]}$ $\boxed{\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]}$

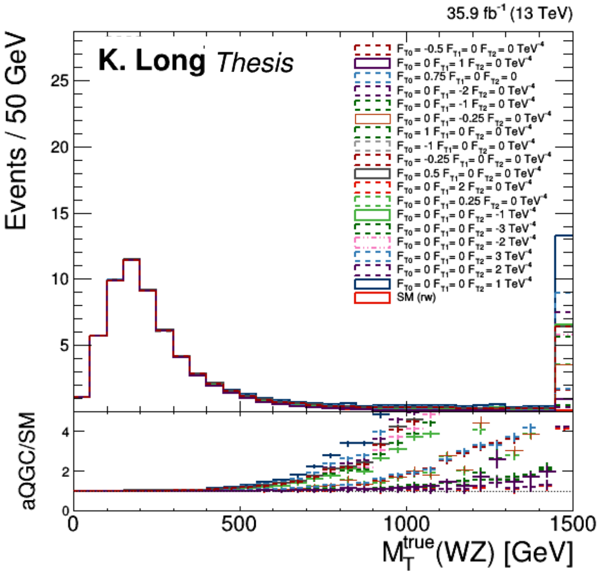
$\boxed{\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]}$ (Φ denotes H field)

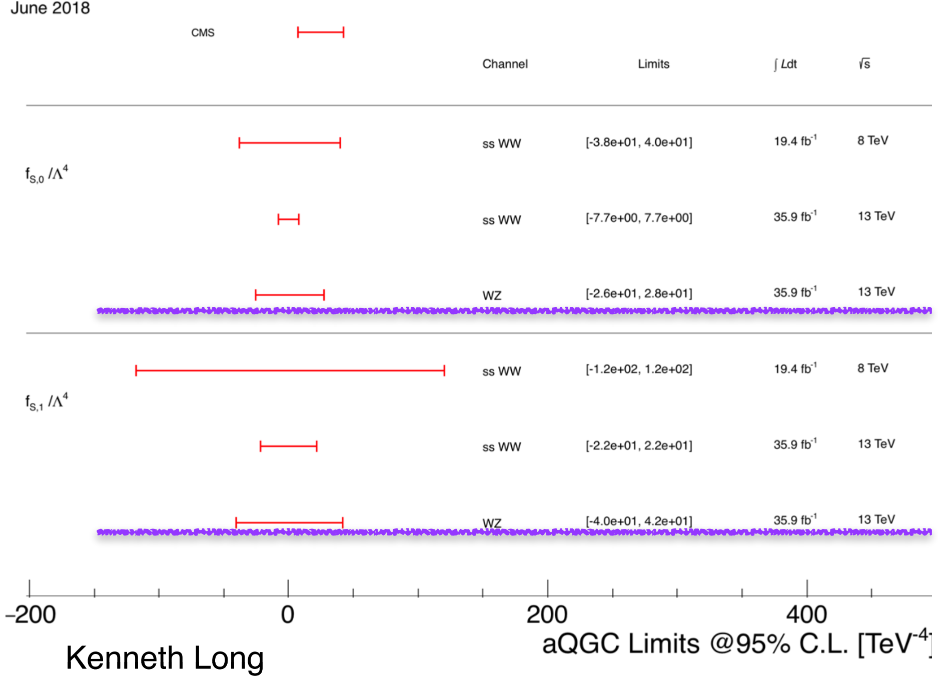
- All realized as excess at high m_{WZ}
- Generalizes V,H interactions
- With some caveats…
  - Assume dimension-6 operators (should dominate) are negligible
  - Applicability of EFT assumes $\hat{s} \ll \Lambda$
    - Operators violate unitarity when not satisfied
    - LHC limits often placed in non-unitary regime

[2] https://arxiv.org/abs/hep-ph/0606118

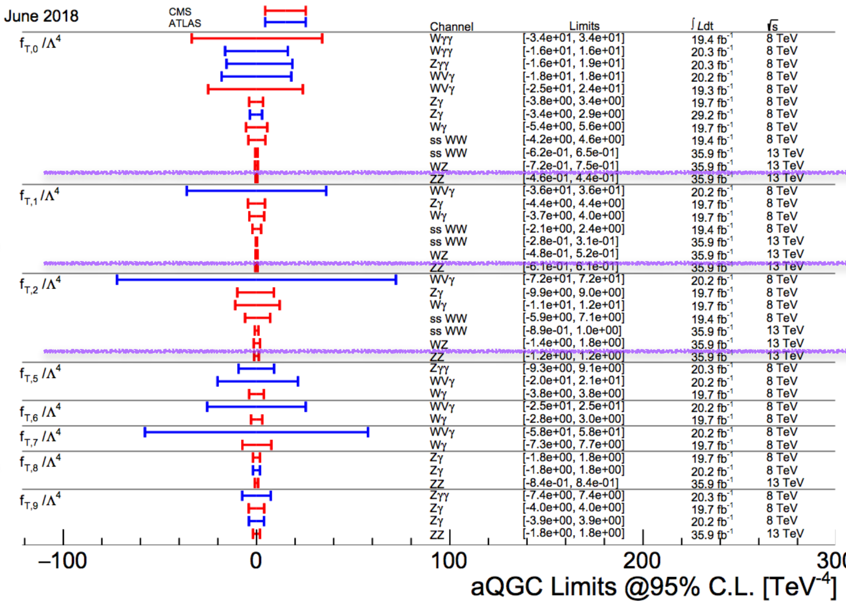
Limits on dimension-8 operators

- Simulated with MG5_aMC@NLO @LO with reweighted events to grid of aQGC parameters
    - Interpolate between parameter points with quadratic fit to yields
- Limits via CLs criterion
    - 1 floating parameter, all others fixed to 0
    - Complementary to other VBS analysis, competitive for several operators





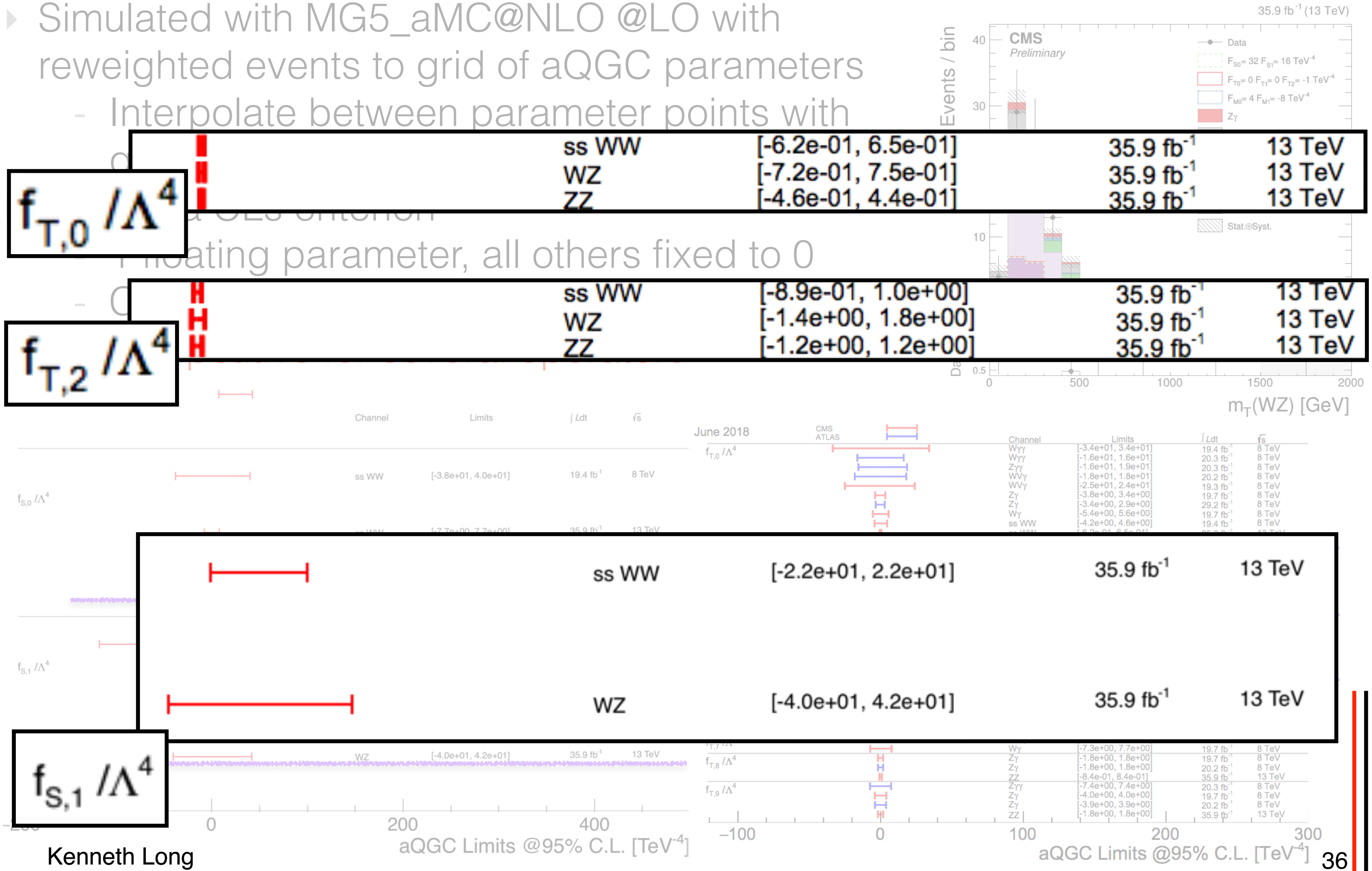
	Channel	Limits	$\int L dt$	$\sqrt{s}$
$f_{S,0}/\Lambda^4$	ss WW	[-3.8e+01, 4.0e+01]	19.4 fb^{-1}	8 TeV
	ss WW	[-7.7e+00, 7.7e+00]	35.9 fb^{-1}	13 TeV
	WZ	[-2.6e+01, 2.8e+01]	35.9 fb^{-1}	13 TeV
$f_{S,1}/\Lambda^4$	ss WW	[-1.2e+02, 1.2e+02]	19.4 fb^{-1}	8 TeV
	ss WW	[-2.2e+01, 2.2e+01]	35.9 fb^{-1}	13 TeV
	WZ	[-4.0e+01, 4.2e+01]	35.9 fb^{-1}	13 TeV



	Channel	Limits	$\int L dt$	$\sqrt{s}$
$f_{T,0}/\Lambda^4$	Wγγ	[-3.4e+01, 3.4e+01]	19.4 fb^{-1}	8 TeV
	Wγγ	[-1.6e+01, 1.6e+01]	20.3 fb^{-1}	8 TeV
	Zγγ	[-1.6e+01, 1.9e+01]	20.3 fb^{-1}	8 TeV
	WVγ	[-1.8e+01, 1.8e+01]	20.2 fb^{-1}	8 TeV
	WVγ	[-2.5e+01, 2.4e+01]	19.3 fb^{-1}	8 TeV
	Zγ	[-3.8e+00, 3.4e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-3.4e+00, 2.9e+00]	29.2 fb^{-1}	8 TeV
	Wγ	[-5.4e+00, 5.6e+00]	19.7 fb^{-1}	8 TeV
	ss WW	[-4.2e+00, 4.6e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-6.2e-01, 6.5e-01]	35.9 fb^{-1}	13 TeV
	WZ	[-7.2e-01, 7.5e-01]	35.9 fb^{-1}	13 TeV
	ZZ	[-4.6e-01, 4.4e-01]	35.9 fb^{-1}	13 TeV
$f_{T,1}/\Lambda^4$	WVγ	[-3.6e+01, 3.6e+01]	20.2 fb^{-1}	8 TeV
	Zγ	[-4.4e+00, 4.4e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-3.7e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	ss WW	[-2.1e+00, 2.4e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-2.8e-01, 3.1e-01]	35.9 fb^{-1}	13 TeV
	WZ	[-4.8e-01, 5.2e-01]	35.9 fb^{-1}	13 TeV
	ZZ	[-6.1e-01, 6.1e-01]	35.9 fb^{-1}	13 TeV
$f_{T,2}/\Lambda^4$	WVγ	[-7.2e+01, 7.2e+01]	20.2 fb^{-1}	8 TeV
	Zγ	[-9.9e+00, 9.0e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.1e+01, 1.2e+01]	19.7 fb^{-1}	8 TeV
	ss WW	[-5.9e+00, 7.1e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-8.9e-01, 1.0e+00]	35.9 fb^{-1}	13 TeV
	WZ	[-1.4e+00, 1.8e+00]	35.9 fb^{-1}	13 TeV
	ZZ	[-1.2e+00, 1.2e+00]	35.9 fb^{-1}	13 TeV
$f_{T,5}/\Lambda^4$	Zγγ	[-9.3e+00, 9.1e+00]	20.3 fb^{-1}	8 TeV
	WVγ	[-2.0e+01, 2.1e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-3.8e+00, 3.8e+00]	19.7 fb^{-1}	8 TeV
$f_{T,6}/\Lambda^4$	WVγ	[-2.5e+01, 2.5e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-2.8e+00, 3.0e+00]	19.7 fb^{-1}	8 TeV
$f_{T,7}/\Lambda^4$	WVγ	[-5.8e+01, 5.8e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-7.3e+00, 7.7e+00]	19.7 fb^{-1}	8 TeV
$f_{T,8}/\Lambda^4$	Zγ	[-1.8e+00, 1.8e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-1.8e+00, 1.8e+00]	20.2 fb^{-1}	8 TeV
	ZZ	[-8.4e-01, 8.4e-01]	35.9 fb^{-1}	13 TeV
$f_{T,9}/\Lambda^4$	Zγγ	[-7.4e+00, 7.4e+00]	20.3 fb^{-1}	8 TeV
	Zγ	[-4.0e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-3.9e+00, 3.9e+00]	20.2 fb^{-1}	8 TeV
	ZZ	[-1.8e+00, 1.8e+00]	35.9 fb^{-1}	13 TeV

Limits on dimension-8 operators

- Simulated with MG5_aMC@NLO @LO with reweighted events to grid of aQGC parameters
  - Interpolate between parameter points with
  - a CLs criterion
  - Floating parameter, all others fixed to 0



$f_{T,0}/\Lambda^4$

ss WW	[-6.2e-01, 6.5e-01]	35.9 fb^{-1}	13 TeV
WZ	[-7.2e-01, 7.5e-01]	35.9 fb^{-1}	13 TeV
ZZ	[-4.6e-01, 4.4e-01]	35.9 fb^{-1}	13 TeV

$f_{T,2}/\Lambda^4$

ss WW	[-8.9e-01, 1.0e+00]	35.9 fb^{-1}	13 TeV
WZ	[-1.4e+00, 1.8e+00]	35.9 fb^{-1}	13 TeV
ZZ	[-1.2e+00, 1.2e+00]	35.9 fb^{-1}	13 TeV

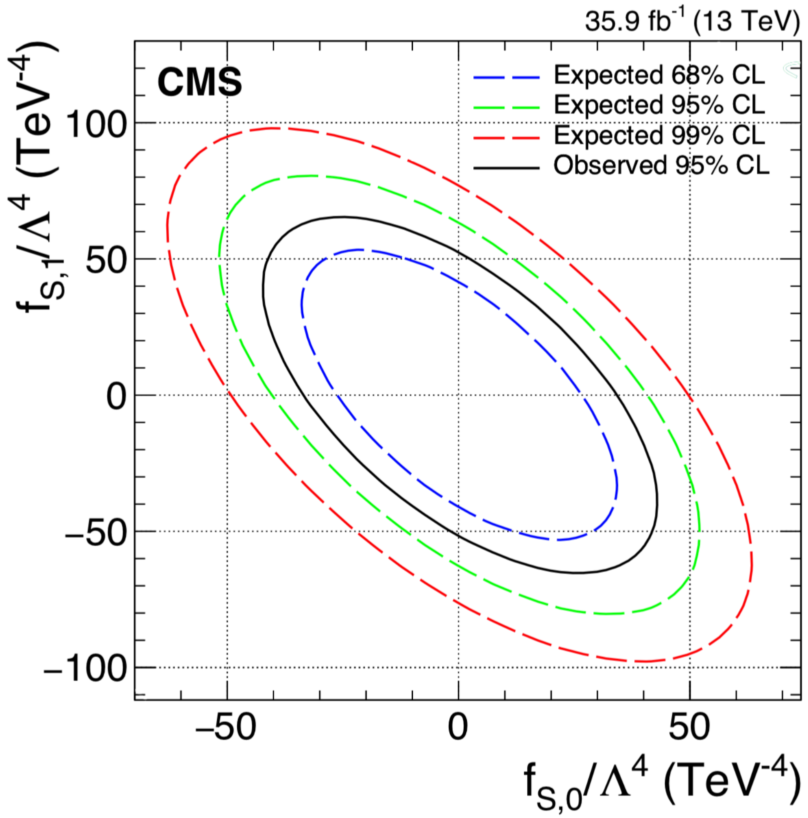
$f_{S,1}/\Lambda^4$

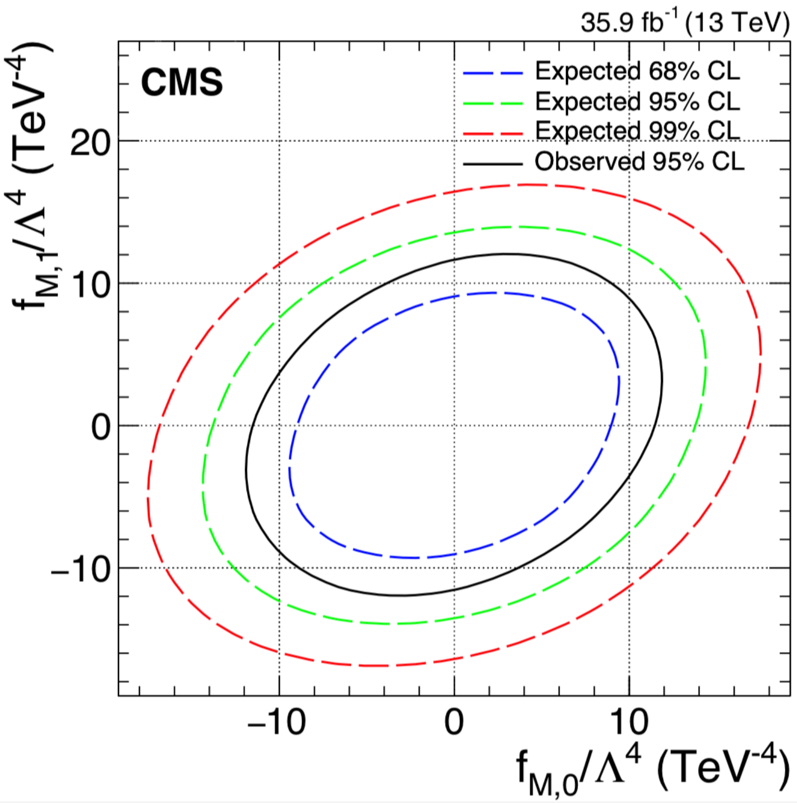
ss WW	[-2.2e+01, 2.2e+01]	35.9 fb^{-1}	13 TeV
WZ	[-4.0e+01, 4.2e+01]	35.9 fb^{-1}	13 TeV

Kenneth Long

2D limits on dimension-8 operators

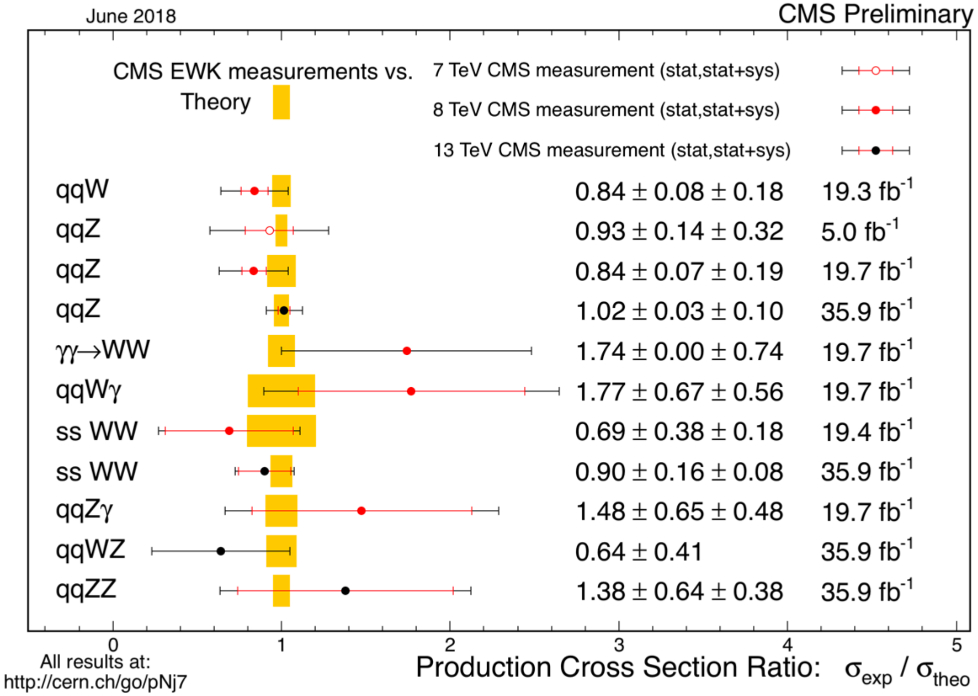
- Correlations between operators also important
  - Quartic WWZZ interaction linear combination of S0, S1 operators
  - Useful for conversion to other parameterizations/bases
- Form 2D confidence intervals by scanning likelihood with two parameters floating





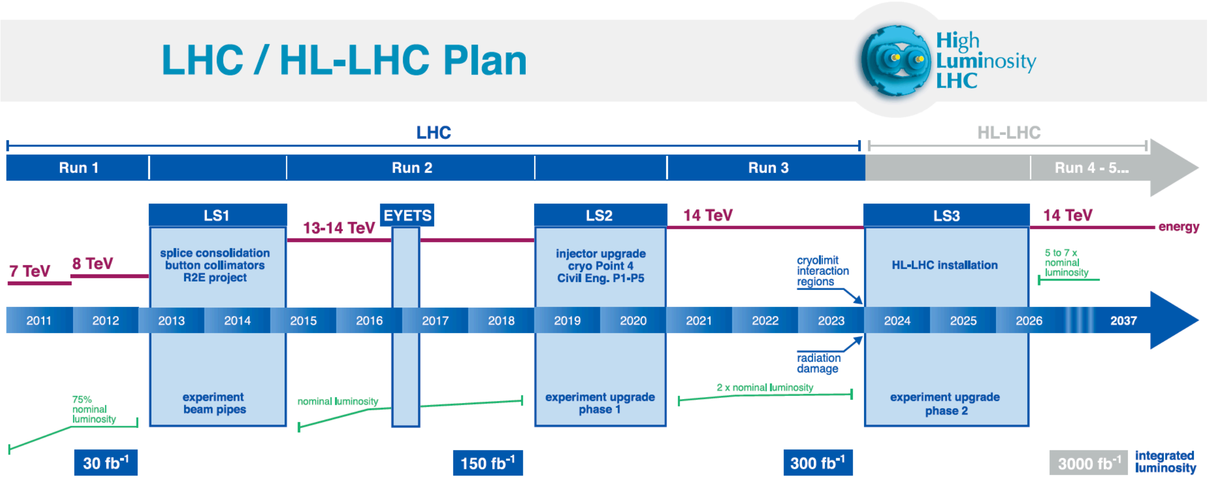
Conclusions

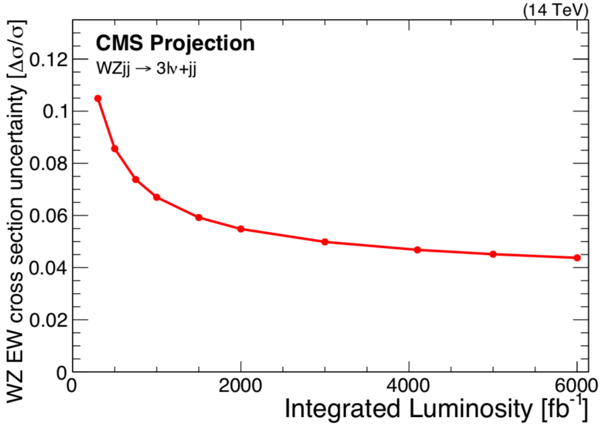
- Presented first search for EW WZ production at CMS
  - Results statistically limited but consistent with SM
  - Searches for new physics performed using generic and specific models
    - First 13 TeV limits on dimension-8 operators with WZ channel
    - Improved limits from previous CMS search for charged Higgs bosons
- New test of the SM… which the SM is withstanding
  - Deviations could be subtle
  - More data and improved techniques help look for cracks with increased precision and at higher energy scales



Outlook

- Full Run II data set of ~150 fb^{-1} will greatly improve sensitivity to EW WZ
  - Is observed μ_{EW} < 1 (> 1 ATLAS) statistical fluctuation, or is σ_{EW} notably different than $\sigma_{\text{EW, LO}}$?
  - 5σ significance with same approach likely, improvement possible!



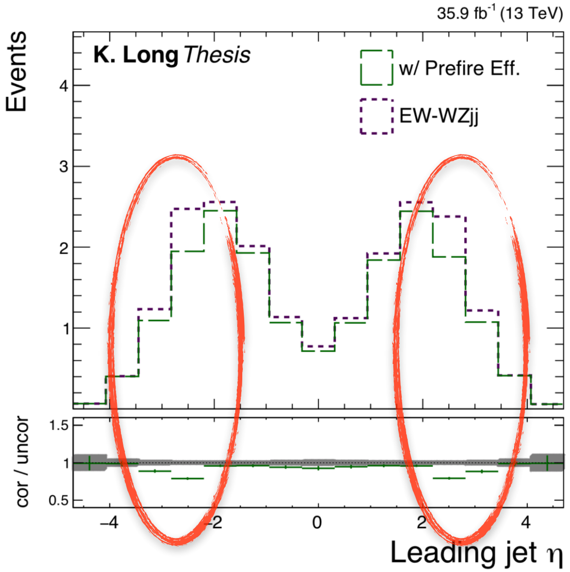


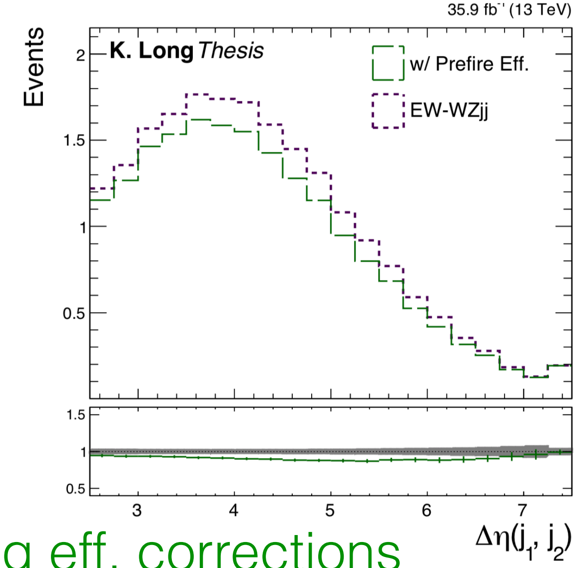
- VBS analyses will continue to evolve in Run III
  - Cross section with 5% uncertainty feasible
  - Measurements focusing on longitudinal polarization, sensitive to Higgs unitarization and some new physics models, become possible
  - Projections already ongoing!

Backup

Trigger pre-firing inefficiency

- Larger than anticipated aging effects in the forward ECAL ~(2.5 < |η| < 3.0)
  - ECAL pulse shape mistimed
  - High-energy forward jet triggers single-jet L1 trigger in BC-1
- Trigger throttling system prevents BC-0 triggering if BC-1 has triggered (buffer limiting)
  - Other objects in correct bunch crossing, e.g., 3ℓ+MET, cannot trigger
- If BC-1 event triggering L1 is rejected at HLT, all event content is lost
- Very difficult effect to observe and parameterize
  - Effect evaluated using jet dataset where trigger rules prevent pre-firing
  - Efficiency correction, binned in jet p_T and η applied to simulation





Pre-firing eff. corrections applied to EW WZjj simulation

Overview of ATLAS / CMS

- CMS and ATLAS both released new VBS WZ analyses for ICHEP
  - Similar expected significance (ATLAS higher by 20%)
  - Significantly different procedure and observed significance

- <u>Overview of analysis content</u>
  - CMS
    - Documentation: SMP-18-001, talk at ICHEP, arxiv in ~days
    - Significance of EW WZjj production: 2.2 obs. (2.5 exp.)
    - Fiducial WZjj EW and EW+QCD cross sections
    - Limits on anomalous couplings in dimension-8 EFT
    - Limits on charged Higgs boson production

  - ATLAS
    - Documentation: arxiv:1812.09740, talk at ICHEP
    - Significance of EW WZjj production: 5.3 obs. (3.2 exp.)
    - Fiducial WZjj EW cross section
    - Unfolded distributions for WZjj EW+QCD in VBS region

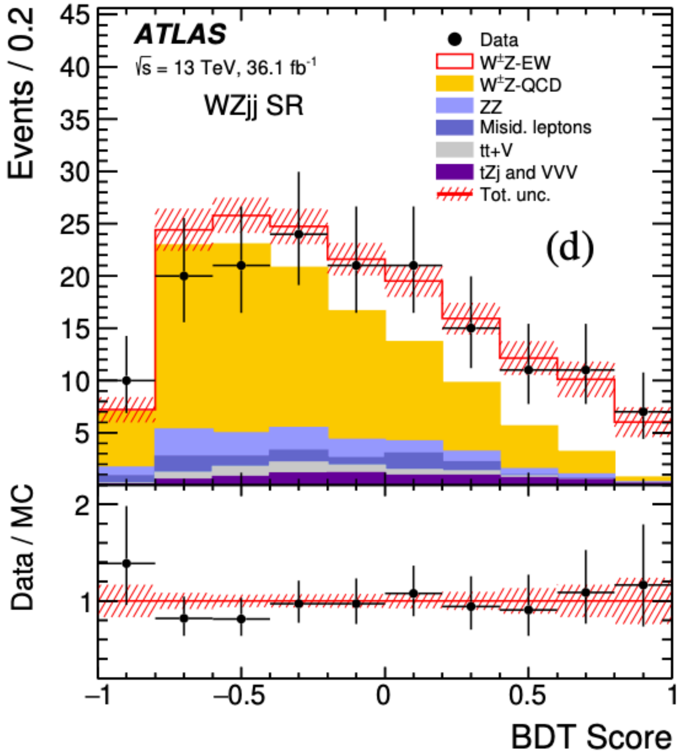
Monte Carlo Generators

- **CMS**: All samples use Pythia 8 for shower+had., with exception of GEN studies for signal modeling
  - Signal: MG5_aMC LO
  - QCD Background: MG5_aMC ≤3j@LO, MG5_aMC ≤1j@NLO
  - tZq: NLO MG5_aMC@NLO 4f, scaled to 5f NLO
  - ttV: NLO MG5_aMC@NLO
  - Others: Generally NLO MG

- **ATLAS**: Generally use Sherpa for ME+shower+had., otherwise shower from Pythia
  - Signal: Sherpa LO
  - QCD Background: Sherpa v2.2 with ≤1j@NLO+≤3j@LO,
    - POWHEG+Pythia,Herwig++
  - tZq: LO (??) MG5_aMC@NLO
  - ttV: LO MG5_aMC@NLO
  - Others: Generally Sherpa LO

ATLAS Analysis

- Train BDT for EW vs QCD discrimination on 15 variables (from 33 studied)
  - Jet kinematics
    - m_{jj}, N_{jets}, $p_T(j_1)$, $p_T(j_2)$, $\eta(j_1)$, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$
  - Vector boson kinematics
  - Jet/lepton kinematics
- Fit simultaneously:
  - m_{jj} in QCD-WZjj background region ($m_{jj} \in [150, 500]$ GeV)
  - number of bjets (ttV control)
  - m_{jj} in ZZ region (4th lepton)



➡Normalizations adjusted by unconstrained parameters

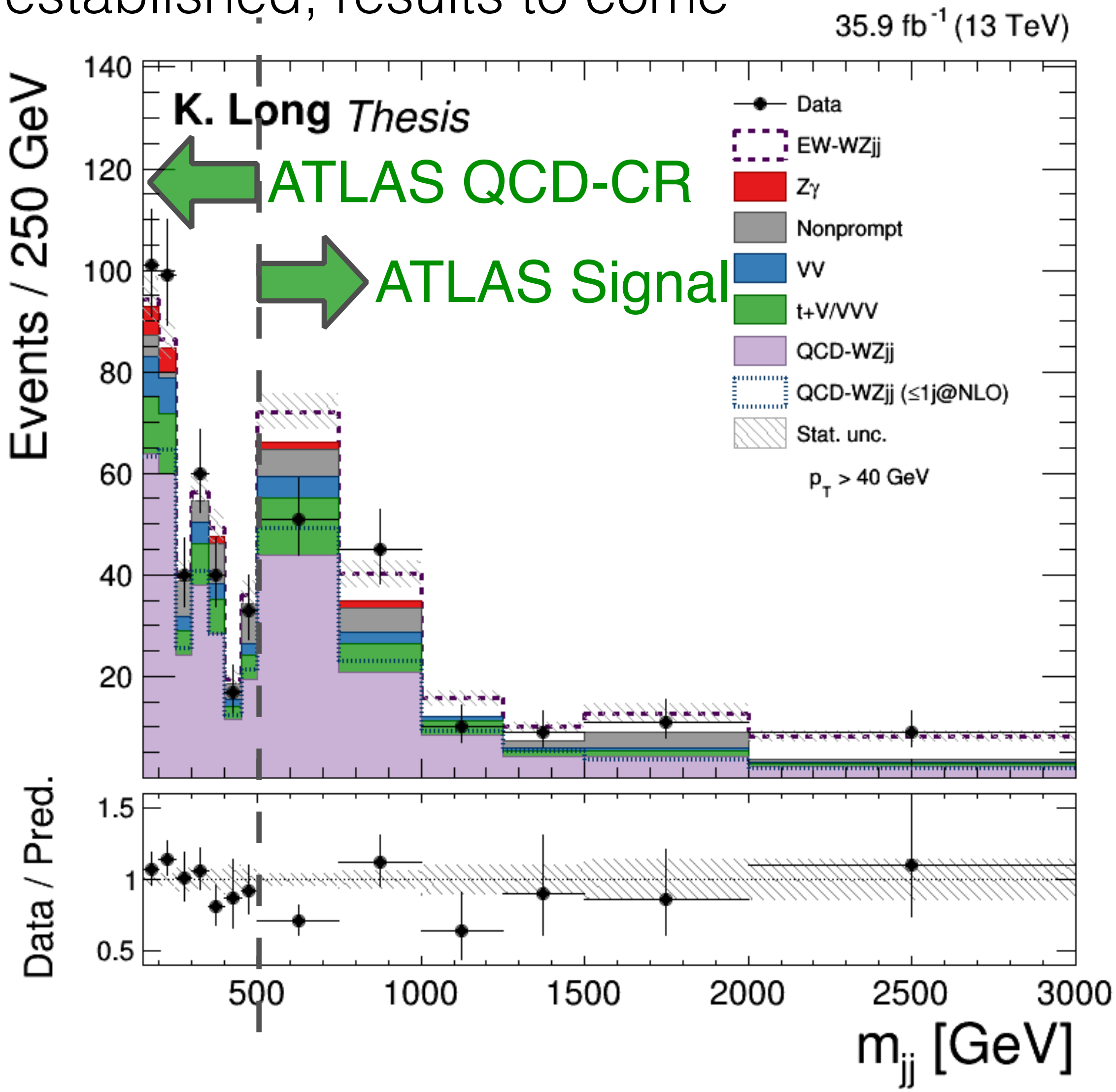
- Best fit results
  - $\mu_{QCD} = 0.6$
  - $\mu_{EW} = 1.77$

Significance of EW WZ: 5.3 obs (3.2 exp)

Do the MC normalizations agree?

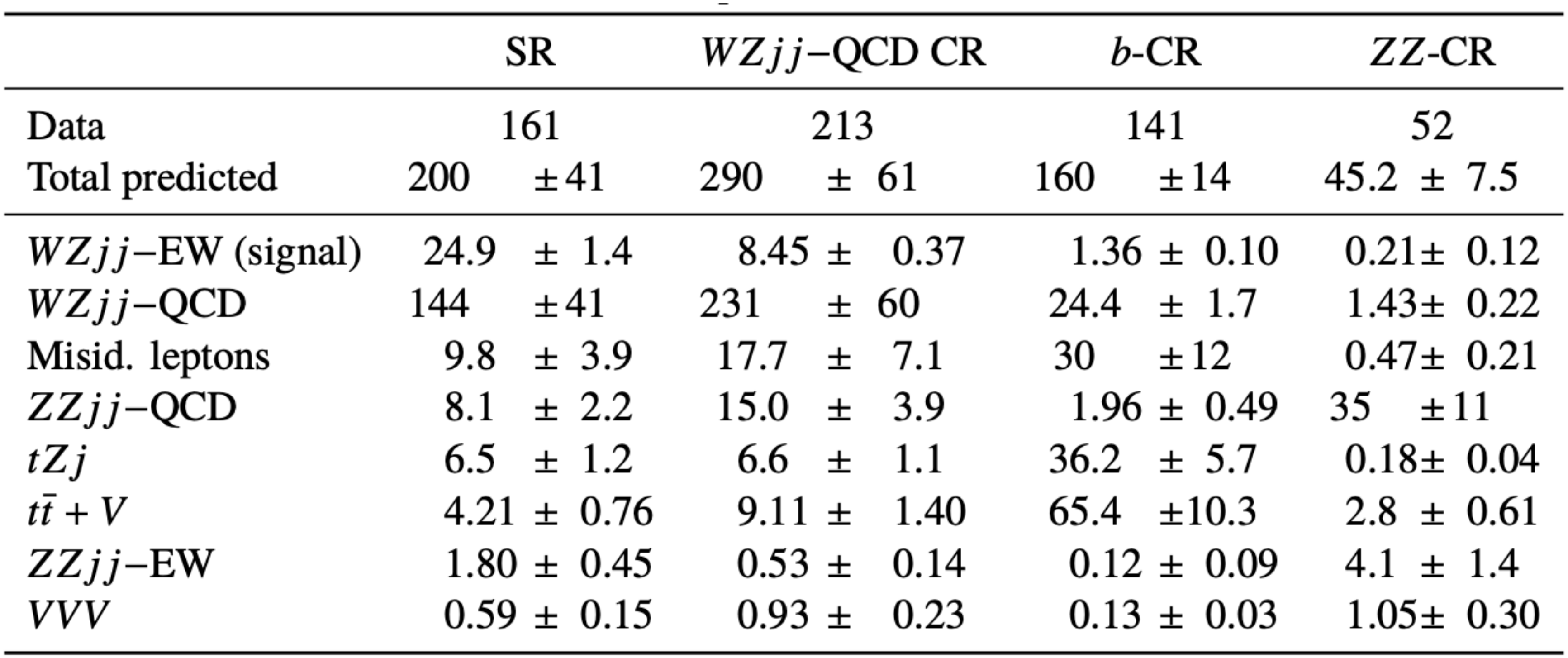
- Best approach: compare ATLAS and CMS MC directly (Rivet)
  - Planned and setup established, results to come

- CMS selection (leptons, MET) with ATLAS jet p_T
- Prefit, only stat. uncertainties
- Normalization ~1 in CR, < 1 in SR
  - Expected EW/QCD in signal region ~0.25
  - Not inconsistent with ATLAS WZ QCD correction



ATLAS Event Yields (prefit)

- From publication: “The expected signal purity in the WZjj signal region is about 13%, with a contribution of 72% of events arising from WZjj-QCD production.”



	SR	*WZjj*–QCD CR	*b*-CR	*ZZ*-CR
Data	161	213	141	52
Total predicted	200 ± 41	290 ± 61	160 ± 14	45.2 ± 7.5
WZjj–EW (signal)	24.9 ± 1.4	8.45 ± 0.37	1.36 ± 0.10	0.21 ± 0.12
WZjj–QCD	144 ± 41	231 ± 60	24.4 ± 1.7	1.43 ± 0.22
Misid. leptons	9.8 ± 3.9	17.7 ± 7.1	30 ± 12	0.47 ± 0.21
ZZjj–QCD	8.1 ± 2.2	15.0 ± 3.9	1.96 ± 0.49	35 ± 11
tZj	6.5 ± 1.2	6.6 ± 1.1	36.2 ± 5.7	0.18 ± 0.04
$t\bar{t}+V$	4.21 ± 0.76	9.11 ± 1.40	65.4 ± 10.3	2.8 ± 0.61
ZZjj–EW	1.80 ± 0.45	0.53 ± 0.14	0.12 ± 0.09	4.1 ± 1.4
VVV	0.59 ± 0.15	0.93 ± 0.23	0.13 ± 0.03	1.05 ± 0.30

- Best fit normalizations (unconstrained in the fit)
  - $\mu_{QCD} = 0.6$
  - $\mu_{EW} = 1.77$

CMS Event Yields (postfit)

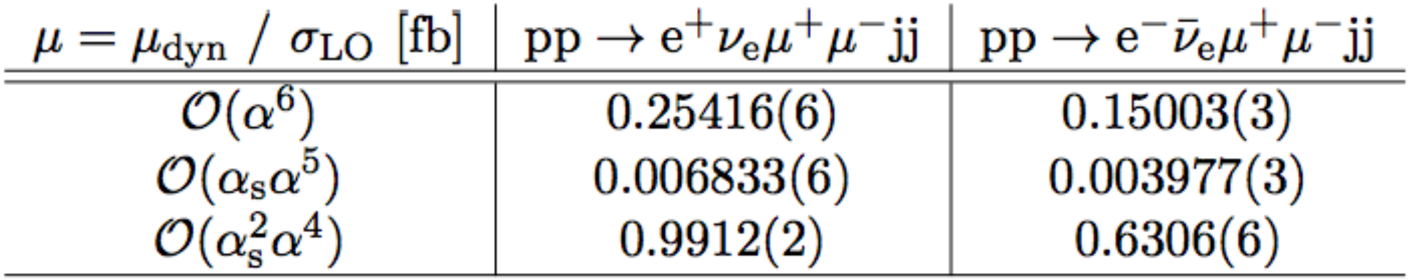
- Postfit ratios: 45% WZjj-QCD, 20% EW (25% prefit)
- (Significantly more aggressive than ATLAS selection)

Process	$\mu\mu\mu$	$\mu\mu e$	$ee\mu$	eee	Total yield
QCD WZ	13.5 ± 0.8	9.1 ± 0.5	6.8 ± 0.4	4.6 ± 0.3	34.1 ± 1.1
t+V/VVV	5.6 ± 0.4	3.1 ± 0.2	2.5 ± 0.2	1.7 ± 0.1	12.9 ± 0.5
Nonprompt	5.2 ± 2.0	2.4 ± 0.9	1.5 ± 0.6	0.7 ± 0.3	9.9 ± 2.3
VV	0.8 ± 0.1	1.6 ± 0.2	0.4 ± 0.0	0.7 ± 0.1	3.5 ± 0.2
$Z\gamma$	<0.1	2.1 ± 0.8	<0.1	<0.1	2.1 ± 0.8
Pred. background	25.2 ± 2.1	18.3 ± 1.6	11.2 ± 0.8	7.7 ± 0.5	62.4 ± 2.8
EW WZ signal	6.0 ± 1.2	4.2 ± 0.8	2.9 ± 0.6	2.1 ± 0.4	15.1 ± 1.6
Data	38	15	12	10	75

- Best fit normalizations (QCD is constrained around prediction in the fit)
    - $\mu_{QCD} = 1.02$
    - $\mu_{EW} = 0.82$

What EW/QCD ratio is expected?

- At fixed-order, with the same scale choice, and both the QCD and EW processes at LO
  - Fiducial definition: $p_T(\ell) > 20$ GeV; $\eta(\ell) < 2.5$; $|m_{\ell\ell} - m_Z| < 15$
    - $m_{jj} > 500$ && $\Delta\eta_{jj} > 2.5$ (more aggressive than ATLAS fiducial)



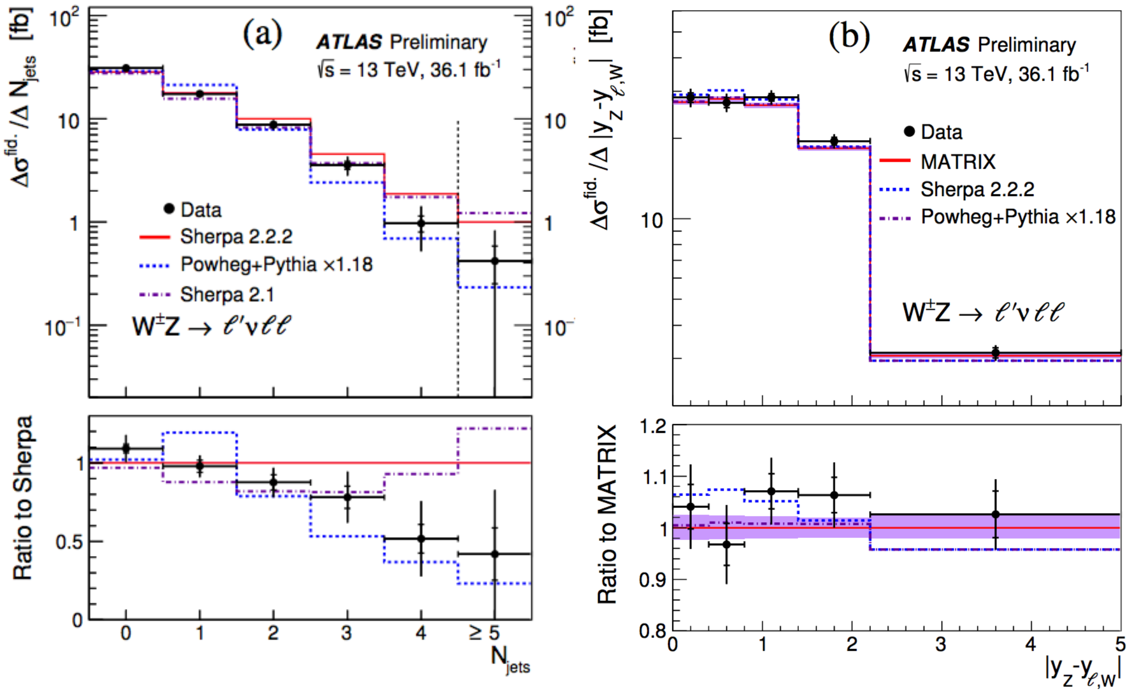
$\mu = \mu_{\mathrm{dyn}}$ / σ_{LO} [fb]	$\mathrm{pp} \rightarrow \mathrm{e}^+\nu_\mathrm{e}\mu^+\mu^-\mathrm{jj}$	$\mathrm{pp} \rightarrow \mathrm{e}^-\bar{\nu}_\mathrm{e}\mu^+\mu^-\mathrm{jj}$
$\mathcal{O}(\alpha^6)$	0.25416(6)	0.15003(3)
$\mathcal{O}(\alpha_s\alpha^5)$	0.006833(6)	0.003977(3)
$\mathcal{O}(\alpha_s^2\alpha^4)$	0.9912(2)	0.6306(6)

  - Expected ratio EW/QCD: ~0.25 (from Les Houches Report [1])
- Expect different behaviors with NLO and scale choice for EW and QCD
  - Factor of 2 difference surprising

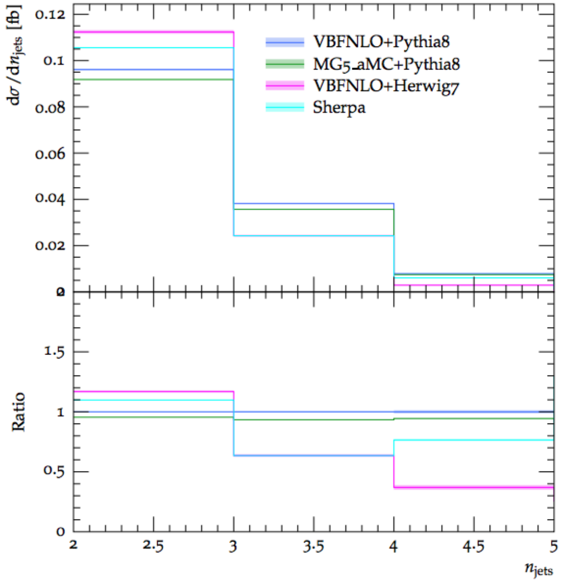
[1] https://arxiv.org/pdf/1803.07977.pdf

Modeling concerns for BDT training

- Poor MC modeling of signal/background can lead BDT to latch on to exaggerated “features” or artifacts of mis-modeling
- Very susceptible example: N_{jets}
  - Strong dependence on merging scheme and shower
- Some leptonic variables (ex: rapidity separations) have large (N)NLO corrections (inclusive)



[ATLAS inclusive WZ]



[Les Houches 2017 SM Report]

Overview of selections

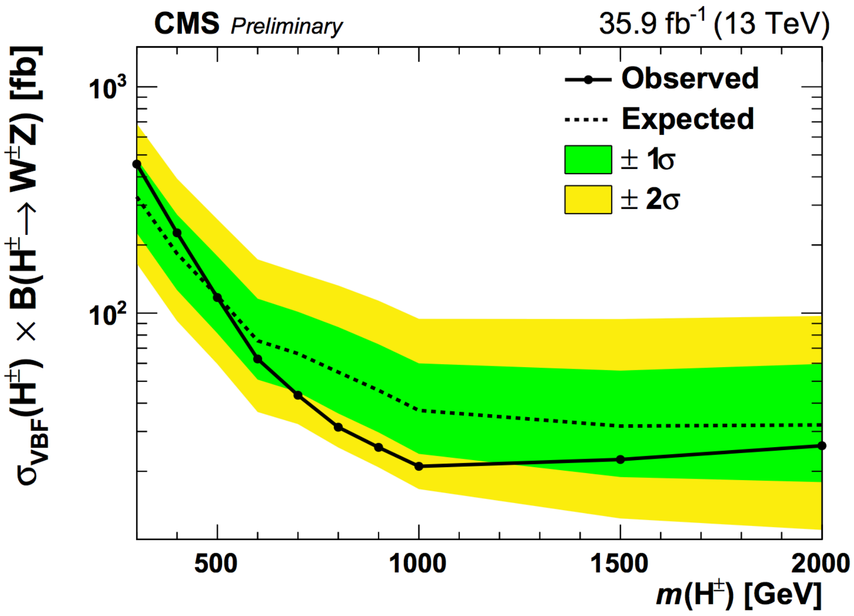
CMS

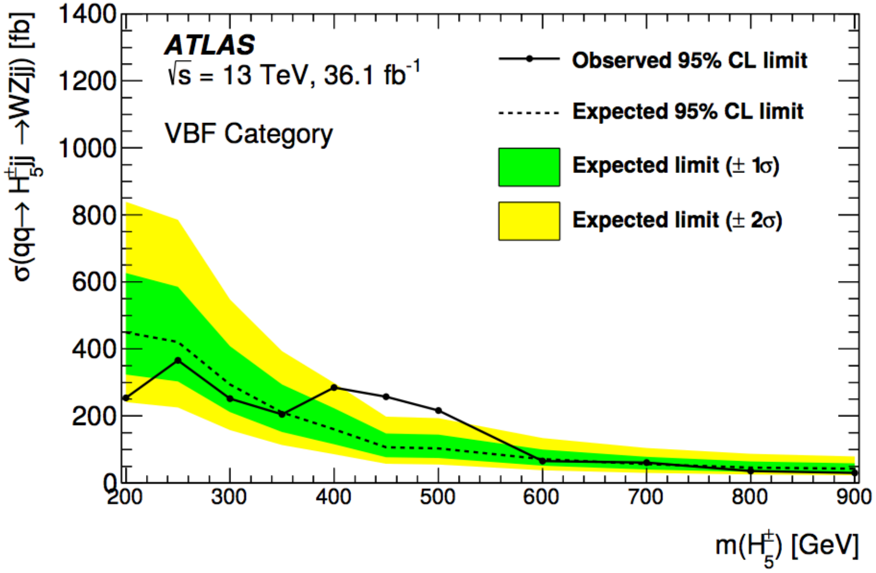
	Electroweak Signal
$p_{\mathrm{T}}(\ell_{\mathrm{Z},1})$ [GeV]	> 25
$p_{\mathrm{T}}(\ell_{\mathrm{Z},2})$ [GeV]	> 15
$p_{\mathrm{T}}(\ell_{\mathrm{W}})$ [GeV]	> 20
$\lvert\eta(\mu)\rvert$	< 2.4
$\lvert\eta(e)\rvert$	< 2.5
$\lvert m_{\mathrm{Z}} - m_{\mathrm{Z}}^{\mathrm{PDG}}\rvert$ [GeV]	< 15
$m_{3\ell}$ [GeV]	> 100
$m_{\ell\ell}$ [GeV]	> 4
p_{T}^{miss} [GeV]	> 30
$\lvert\eta(\mathrm{j})\rvert$	< 4.7
$p_{\mathrm{T}}(\mathrm{j})$ [GeV]	> 50
$\lvert\Delta R(\mathrm{j},\ell)\rvert$	> 0.4
n_{j}	≥ 2
$p_{\mathrm{T}}(\mathrm{b})$ [GeV]	> 30
$n_{\mathrm{b-jet}}$	$= 0$
m_{jj}	> 500
$\lvert\Delta\eta(\mathrm{j}_1,\mathrm{j}_2)\rvert$	> 2.5
$\lvert\eta_{3\ell} - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})\rvert$	< 2.5

ATLAS

- $p_T(\ell_{lead}) > 27$ GeV
- $p_T(\ell_Z) > 15$ GeV
- $p_T(\ell_W) > 20$ GeV
- $\eta(\mu, e) < 2.5, 2.47$
  - e: exclude [1.37, 1.52]
- $m_T(W) > 30$ GeV
- $p_T(j) > 40$ GeV
- mjj > 500 GeV (signal)
  - No other dijet cuts to define signal region

Model-indepedent limits on σH±



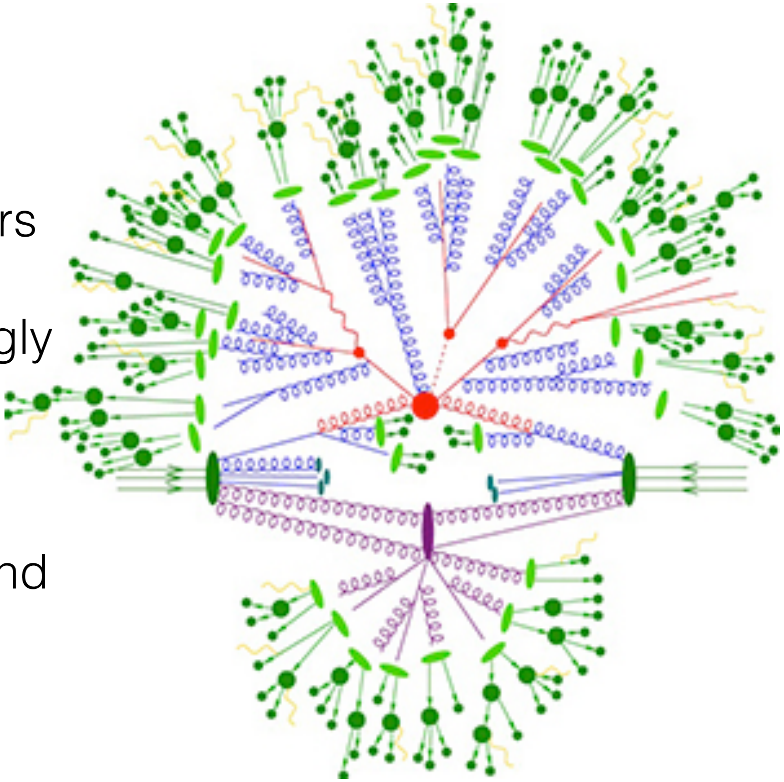


CMS-SMP-18-001

arXiv:1806.01532

Simulations for Precision Measurements

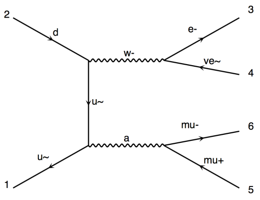
- Experimental measurements rely on precise theoretical predictions
  - Combine perturbative QFT with phenomenological models
  - Complex integrals calculated with Monte Carlo techniques
- Factorize calculations
  - Hard Processes
    - Matrix element calculations in perturbative QCD and QED
    - Increasingly complex at higher orders in coupling constants
    - Higher QCD orders contribute strongly
  - Soft processes
    - Parton shower model
    - Consider only soft/collinear contributions of higher order QCD and QED
  - Non-perturbative processes
    - Parton Distribution Functions
    - Hadronization
  - Decays



Monte Carlo Generators at CMS

- Event simulations at Next-to-leading order (NLO) in QCD are now the standard
- Two techniques for NLO event generation exist
  - POWHEG
    - Implemented in the POWHEG Box, a toolkit for NLO event generation
  - MC@NLO
    - Fully automated in MadGraph5_aMC@NLO
- Calculations inclusive and exclusive in QCD
  - Inclusive
    - Observables independent of the number of final state partons accurate at NLO
    - NLO calculation of pp ⟶ $3\ell\nu$

$\mathcal{M} =$



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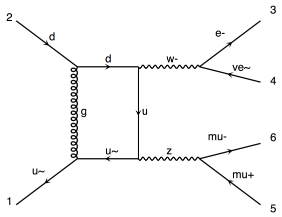

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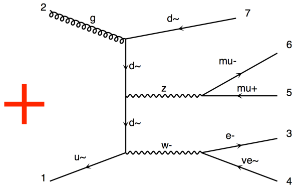
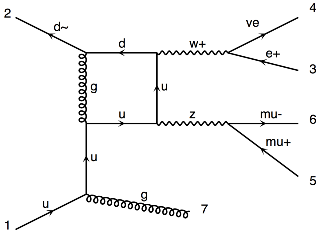


$+ \cdots$

- Exclusive
  - Observables dependent on the number of final state partons accurate at NLO
  - Merge calculations of pp ⟶ $3\ell\nu$ and pp ⟶ $3\ell\nu$ + q (q is a light quark or gluon)

$\mathcal{M} = \mathcal{M}_{3\ell\nu} + \cdots +$



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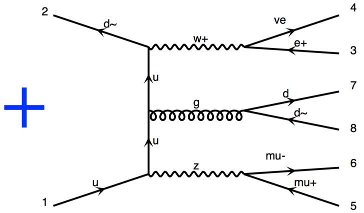
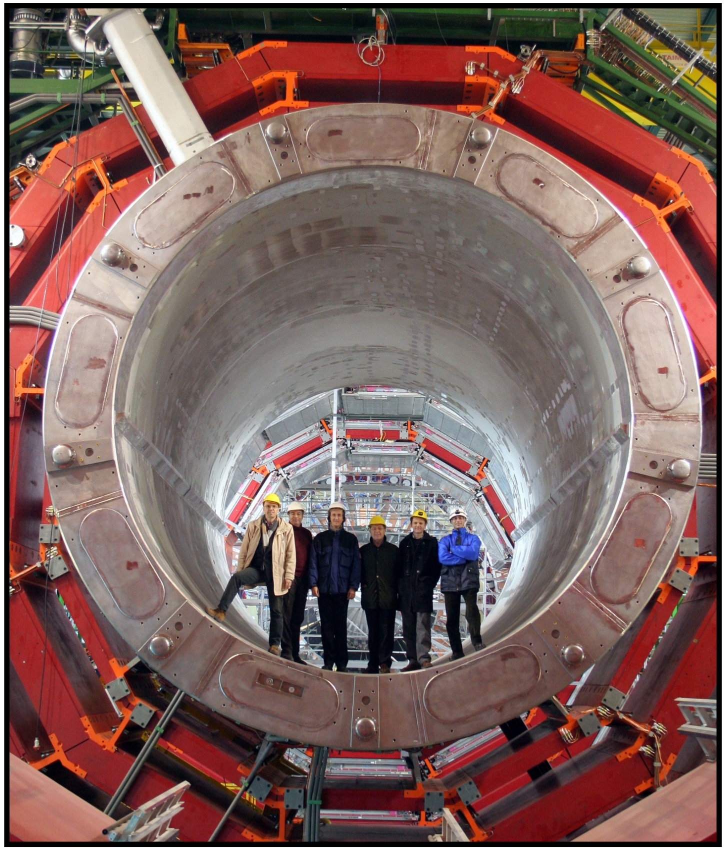
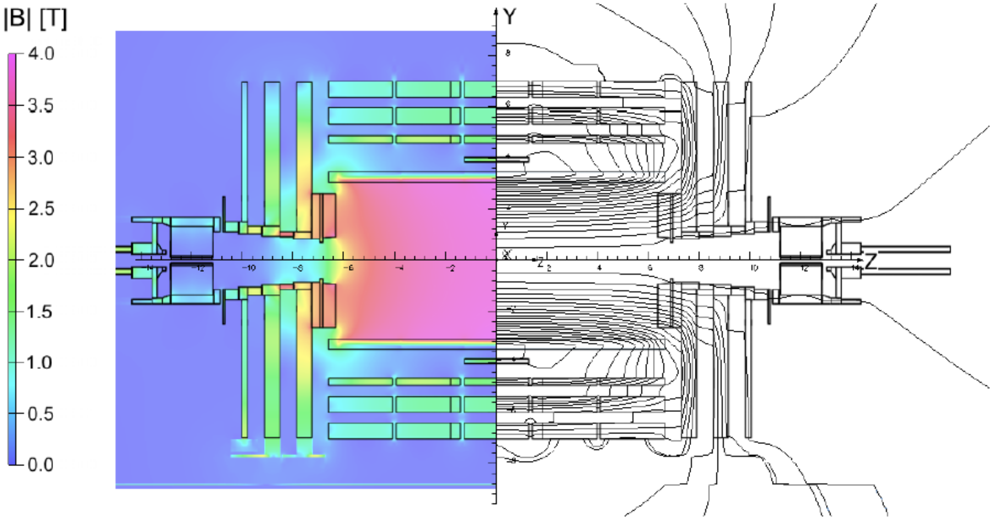


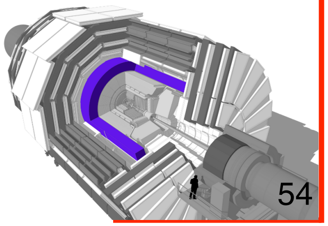
$+ \cdots$

Solenoid

- CMS detector designed around a 3.8 T superconducting solenoid magnet
  - 12.5 m length
  - 6.3 m diameter
  - Cooled to to 4.7 K
  - 2.0 T field in iron return yoke
- Allows precise measurement of transverse momentum (p_T) for charged particles



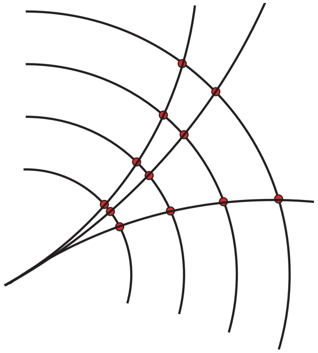


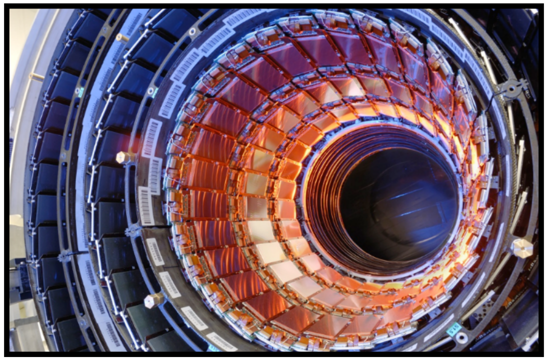


Silicon Tracker

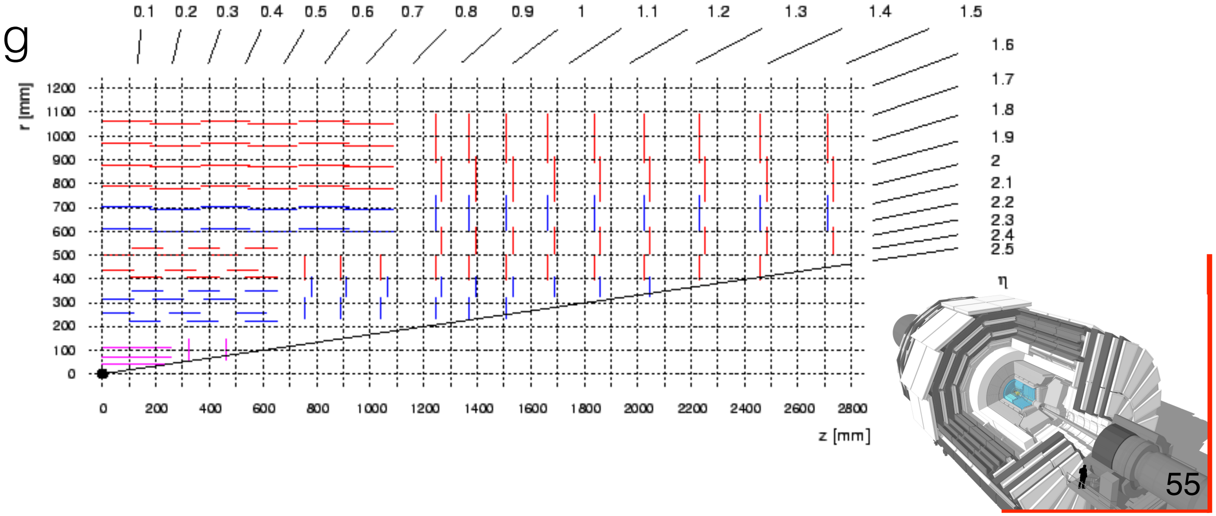
- Interactions of charged particles with silicon detectors used to reconstruct particle tracks
    - Magnetic field allows precise p_T measurement
    - Coverage: $|\eta| < 2.4$
    - Over 200 m^2 of silicon
    - Resolution (in barrel):

$$\frac{\delta p_T}{p_T} = \left(15\frac{p_T}{TeV} \oplus 0.5\right)\%$$





- Silicon pixel detector
    - 66M channels, fine grain resolution
    - 100 μm x 150 μm pixels
    - Important for identifying track vertex
- Silicon strip detector
    - 9.6M channels
    - 80 μm -180 μm x 4.3 cm -10 cm strips

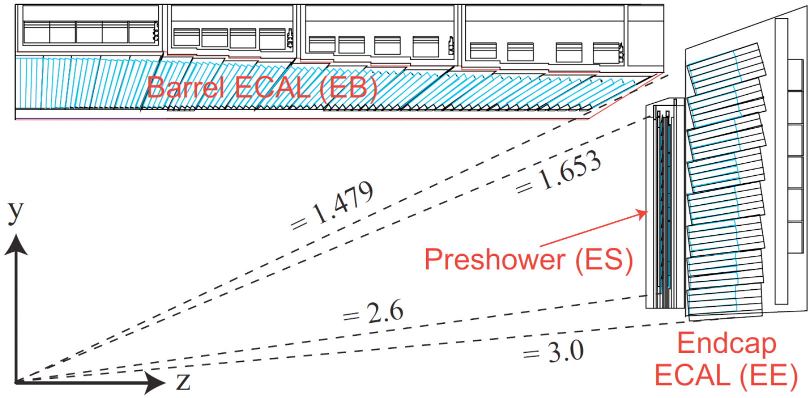


Electromagnetic Calorimeter

- Measures energy of electromagnetic particles
  - Crucial for electron and photon energy measurement and ID
  - High granularity provides position measurement
  - Coverage: $|\eta| < 3.0$
  - Resolution (in barrel):

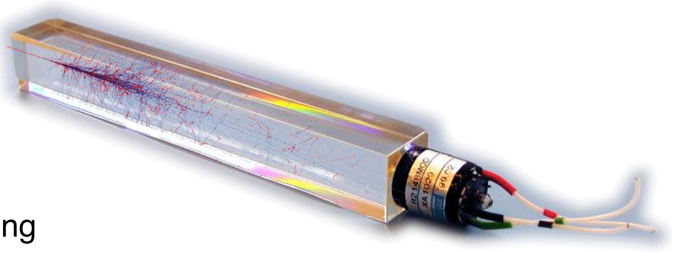
$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{0.128}{E} \oplus 0.3\%$$

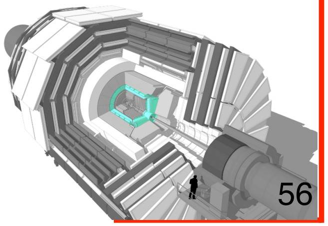
- Lead tungstate ($PbWO_4$) crystal scintillators read out by photodetectors
  - Dimensions: 2.2 cm x 2.2 cm x 23 cm
  - 61,200 crystals in barrel
  - 7,324 crystals in each endcap



Properties of $PbWO_4$

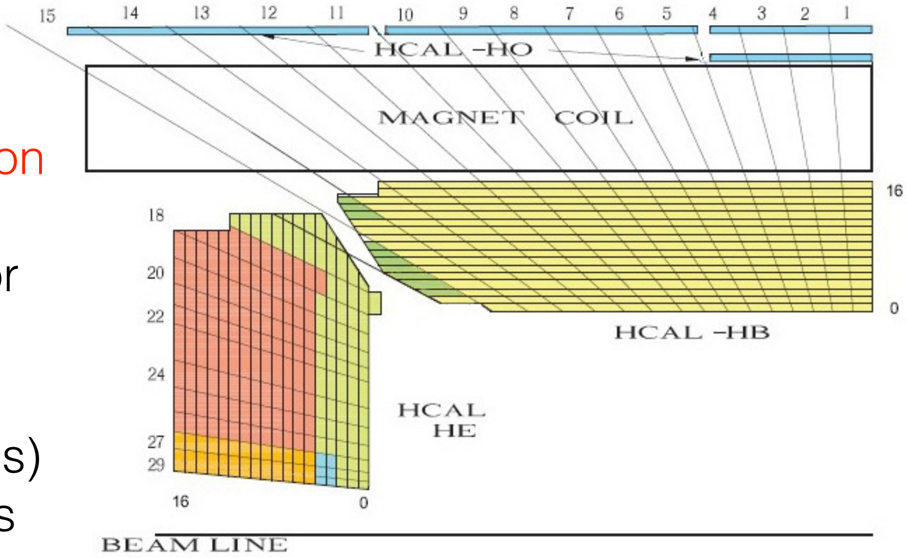
Density	8.3 g/cm^2
X_0	0.89 cm
Molière radius	2.19 cm
Peak Emission	430 nm
Light yield	~50 γ / MeV



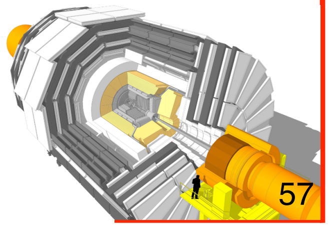


Hadronic Calorimeter

- Measures energy of charged and uncharged hadrons
  - Crucial for charged and neutral hadron energy measurement and ID
  - Hermeticity (up to |η| < 5.0) crucial for calculation of missing energy
- Sampling calorimeter
  - alternating layers of “absorber” (brass) and fluorescent “scintillator” materials
- HCAL Barrel (HB)
  - |η| < 1.3
- HCAL Endcap (HE)
  - 1.3 < |η| < 3.0
- HCAL Forward (HF)
  - 3.0 < |η| < 5.2
  - Cherenkov detector
  - Steel absorber

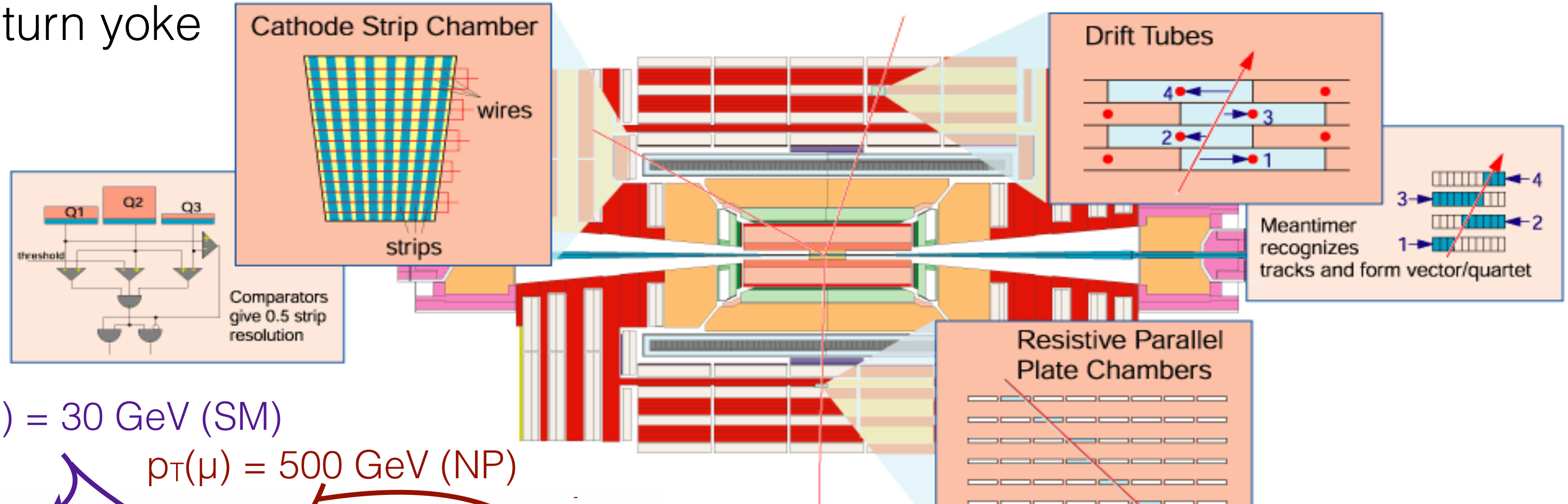


- Resolution
  - HB/HE: $\left(\frac{\sigma}{E}\right)^2 = \left(\frac{115\%}{\sqrt{E}}\right)^2 + (5.5\%)^2$
  - HF: $\left(\frac{\sigma}{E}\right)^2 = \left(\frac{280\%}{\sqrt{E}}\right)^2 + (11\%)^2$



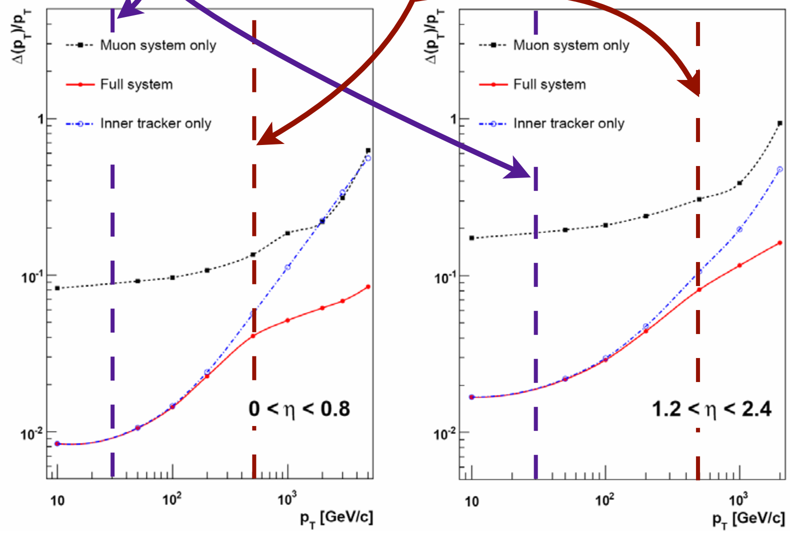
Muon System

- Combination of several detector technologies embedded within iron return yoke

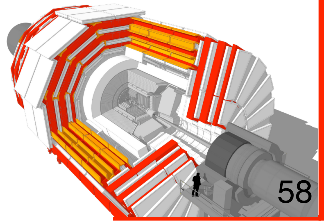


$p_T(\mu)$ = 30 GeV (SM)

$p_T(\mu)$ = 500 GeV (NP)



- Cathode Strip Chambers (CSC)
  - Endcap region, 0.9 < |η| < 2.4
  - 40 - 150 μm, ~2 ns
- Resistive Plate Chambers (RPC)
  - Barrel and endcap region, |η| < 1.6
  - ~2 ns
- Drift tubes (DT)
  - Barrel region, |η| < 1.2
  - 80 - 120 μm, ~3 ns



Kenneth Long