Standard Model Measurements : (EWK and Top Physics)

Marjorie Shapiro (UC Berkeley & LBNL)

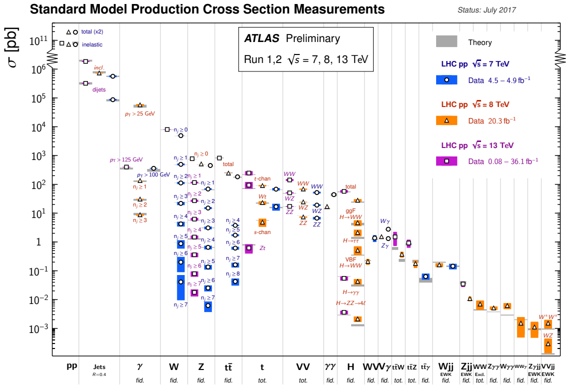
presenting results from ATLAS, CMS, LHCb, and D0
plus new Tevatron averages

10 July 2017

The Role of SM Measurements in Hadron Colliders

- Confront SM in regions of calculational complexity
  - Higher order corrections
  - EW corrections with (N)NLO QCD
  - Resummation techniques
  - Merging of pQCD and parton showers
- Constrain (or observe) new physics contributions via virtual corrections or modified gauge couplings
  - Precision measurements of Top and W mass
  - Anolomous rates for Triple and Quartic gauge interactions
- Provide accurate and precise predictions of background rates for BSM searches and for Higgs measurements
  - Top pairs and Vector Boson+Jet events often most important backgrounds
  - Tails of distributions and production with additional objects (heavy flavor, additional jets, vector bosons) often important

Standard Model Landscape



Outline

- Achievements in Experiment and Theory
- Recent Cross Section Measurements
  - Top
  - W and Z bosons
  - Multiboson final states
- Search for New Physics Via Virtual Corrections
  - W mass
  - top mass
  - $\sin^2\theta_W^{eff}$
- Gauge Boson Vertices and Limits on Anomolous Couplings
- Conclusions

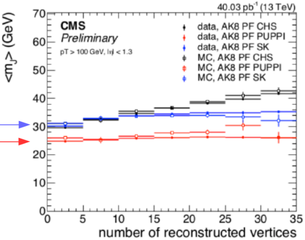
Technical Advances: Experiment

Maintaining Calibrations with High Pileup

Improved algorithm removes dependence on pileup

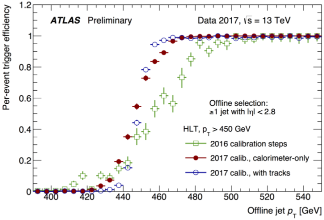
Standard Pileup Suppression

Pileup per Particle Suppression



Mean Jet Mass as function of # primary vertices

Improved Trigger Performance



Improved calibration corrects jet energy using longitudinal shower shape and track characteristics without changing overall energy scale

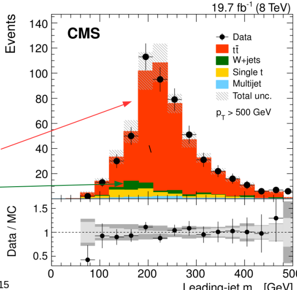
ATL-COM-DAQ-2017-063

Identifying Heavy Boosted Objects

Identify top quarks in boosted region using mass of "fat" jet

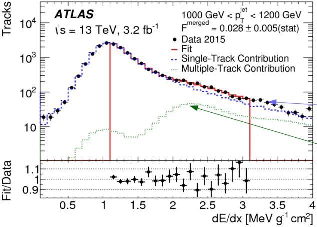
Jet mass: top quark template

Jet mass: W+Jet template



CMS-PAS-TOP-15-015

Reconstructing Tracks in Dense Environments



Measure 2-track resolution by finding merged pixel hits

Energy loss: Single tracks

Energy loss: Two tracks

arXiv:1704.07983

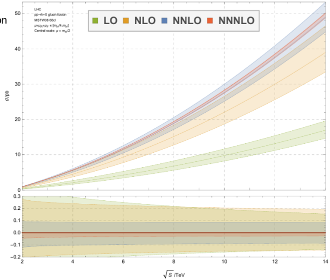
dE/dx used to identify clusters originating from multiple tracks

Technical Advances: Theory

N^3LO Perturbation Theory

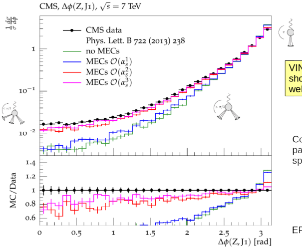
Higgs Boson gluon-fusion production at N^3LO

Scale uncertainty: 3%
A factor of 3 reduction over N^2LO



Anastasiou et al
Phys. Rev. Lett 114, 212001 (2015)

Improved Treatment of Parton Showers



VINCIA: A parton shower integration of well-separated jets

Corrects radiation pattern splitting-by-splitting to full LO

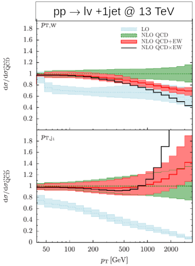
EPJC 76 (2016) 11 589

https://indico.cern.ch/event/588781/contributions/2547586/attachments/1453677/2242861/talk20170504-revised.pdf

NLO+EW Corrections

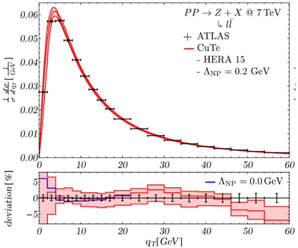
NLO QCD+EW Corrections for V+Jets including off-shell decays and Multijet Merging

- NLO EW corrections: tens of percent at TeV scale
- Comparable in size to NLO QCD
- Offshell contributions also large
- Approximate method implemented in MePS@NLO framework



Kallweit et al
JHEP 04 (2016) 021

Processes with Multiple Scales: Resumming large logs



q_T spectrum of Z boson at N^3LL+N^2LO

- Resummation of large $\log(q_T^2/M_Z^2)$ terms at low q_T
- Matching to FO calculation at large q_T

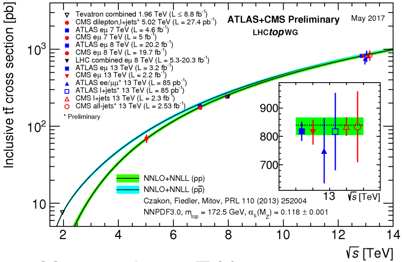
CuTe 2.0
Result in preparation
See: Thomas Becher, Aspen 2016

Top Cross Section: $\sigma_{t\bar{t}}$ vs $\sqrt{s}$

- Measurements in many channels yield consistent results
- Full NNLO+NNLL Calculation:

  High precision $\Rightarrow$

  $\sigma_{t\bar{t}}$ provides information on:
  - Gluon PDF at high x
  - Top mass (more later)



Most precise 13 TeV measurements:

ATLAS dilepton $e\mu$: Phys Lett. B761 (2016) 136

Fit $\sigma_{t\bar{t}}$ and ϵ_b using # b-jets

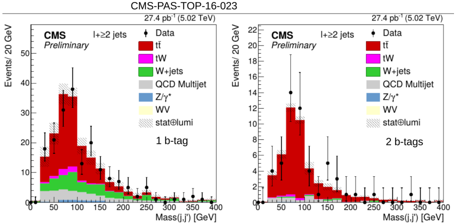
CMS dilepton $e\mu$: EPJC 77 (2017) 172

Count events after background subtraction

CMS lepton+jets: arXiv:1701.06228

Likelihood fit in 11 categories

Short 5.02 TeV pp run (heavy-ion reference)



- Combine dilepton and single lepton channels; Single lepton channel categorized by # b-jets
- $W \to jj$ contribution obtained from $\Delta(r_{jj})$

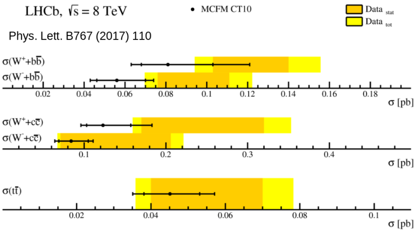
New for EPS:

ATLAS Inclusive $t\bar{t}$ cross section in ℓ+Jets (8 TeV) ATLAS-CONF-2017-054

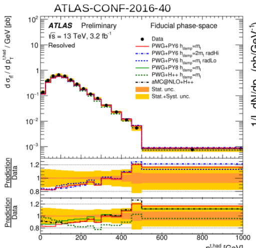
Top Cross Section: Probing Kinematic Extrema

Large Pseudorapidity

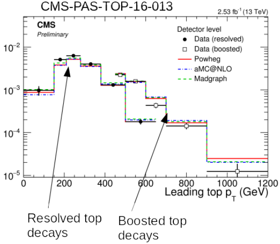
- Unique measurement from LHCb in forward region $2.2 < \eta < 4.2$
- Select ℓ + 2 Heavy Flavor jets
- Multi-dimensional fit to m_{jj} and 3 multivariate distributions separate:
  - $t\bar{t}$
  - $W + c\bar{c}$
  - $W + b\bar{b}$



Large Transverse Momentum

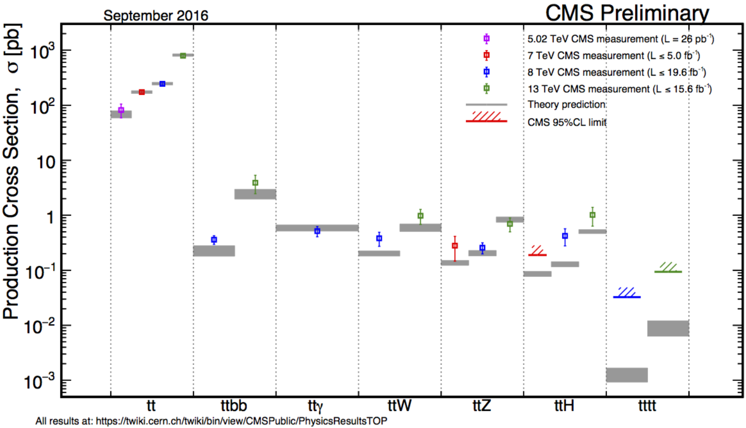


P_T of hadronic top



- Data softer than predictions of NLO Monte Carlo generators
- NNLO calculation significantly improves agreement
- Some tension between ATLAS and CMS measurements

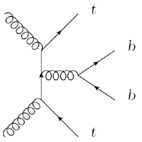
$t\bar{t} + X$ Overview



- $t\bar{t}$ production with additional objects probes top couplings
- Highest profile example: $t\bar{t} + H$
- Significant challenge to theory
  - Multi-scale problem: large logs
  - Precision matters

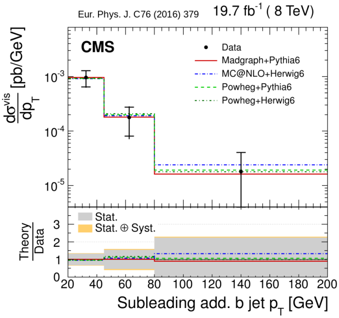
Of increasing importance with large data samples

$t\bar{t}+$ Heavy Flavour (HF)



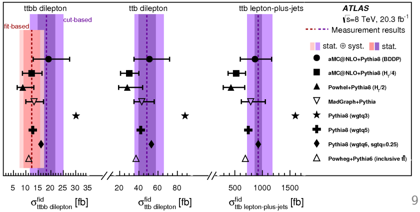
- Observation of $t\bar{t}+H$ production a major goal for ATLAS and CMS
  - Both experiments searching in many modes, including $t\bar{t}+H$ $(H \to b\bar{b})$
- Correct modelling of $t\bar{t}+$ HF essential
  - Detailed comparisons of differential distributions of data and MC required
- $\sigma(t\bar{t}+HF)$ measured at 8 TeV (ATLAS and CMS) and 13 TeV (CMS)
- Good agreement among measurements
- Data consistent with predictions of several event generators

Differential $tt+b$ and $tt+bb$ measurements

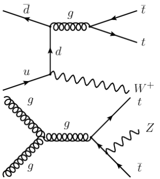


Comparisons with many theory predictions

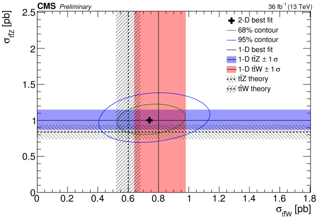
Eur. Phys. J. C76 (2016) 11



Top+Vector Boson Production

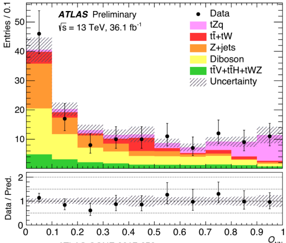


$t\bar{t} + W/Z$

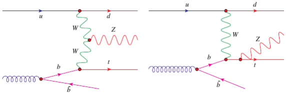


CMS-PAS-TOP-17-005

$t + Zq$



ATLAS-CONF-2017-052



- 13 TeV measurements from ATLAS and CMS
- $\sigma(t\bar{t} + Z)$: extraction of ttZ coupling
- $\sigma(tt + W/Z)$: sensitive to BSM physics (eg vector-like quarks)
- Current comparisons to NLO QCD. But improved calculations available:
  - NLO QCD+EW corrections
  - NLO+NNLL

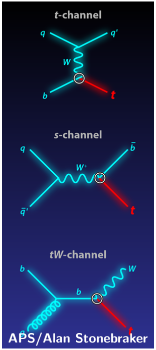
  No discrepancies with SM (to date)

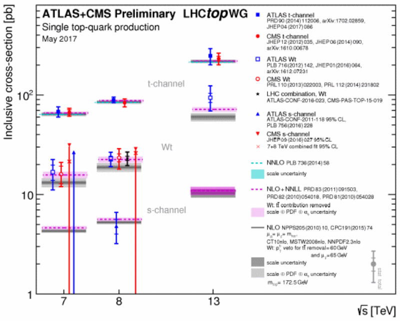
- $\sigma(tZq)$ sensitive to WWZ triple gauge couplings and tZ coupling
- tZ constrained by $t\bar{t}Z$
- Multivariate technique to isolate signal
- New for EPS:

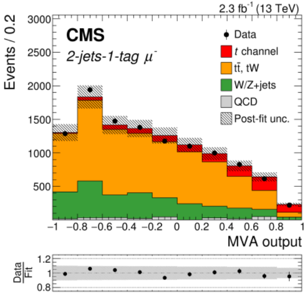
  4.2σ evidence for t-channel tZq:

  $\sigma(tZq) = (600 \pm 170 \pm 140)$ fb

Single Top Production

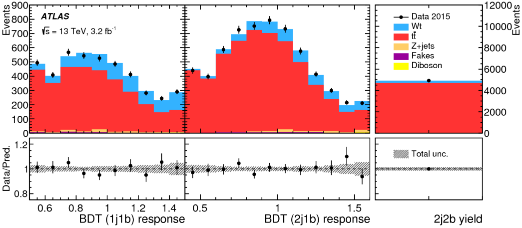






CMS-PAS-TOP-16-003

- Three production channels
- Extraction of σ relies on multivariate techniques
- All channels observed at 7 TeV and 8 TeV
- First measurements of t-channel and Wt at 13 TeV



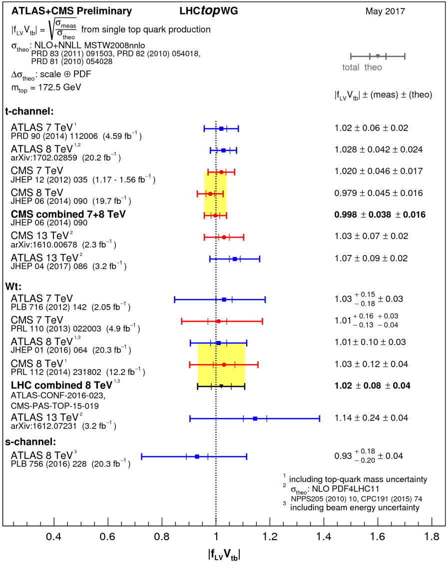
arXiv:1612.07231

Single Top and $|V_{tb}|$

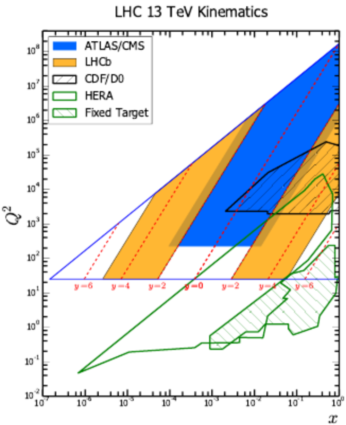
$$|V_{tb} \cdot f_{LV}|^2 = \frac{\sigma^{obs}}{\sigma^{theory}}$$

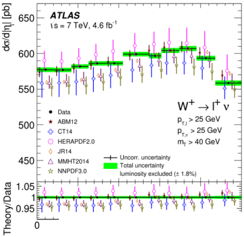
f_{LV}: Form Factor for BSM contributions

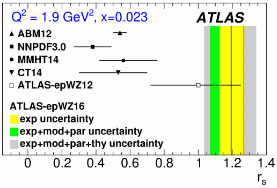
Consistent with $f_{LV} \cdot V_{tb} = 1$



W Production and PDFs



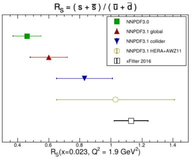




Eur. Phys. J. C 77 (2017) 367

Effect of including LHC W/Z data in PDF fits for strange quark density

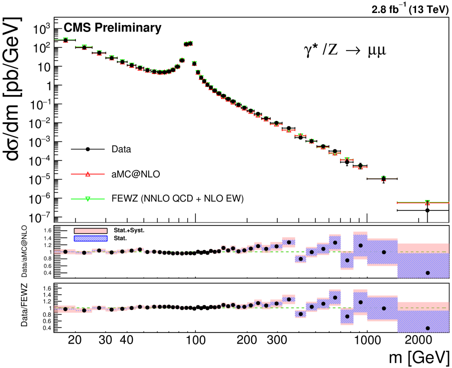
NNPDF collaboration
arXiv:1706.00428



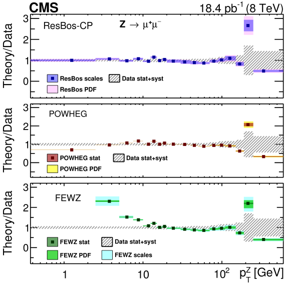
- Calculated to NNLO
- W^+/W^- asymmetry: difference in u and d PDFs
- LHCb reduces d PDF uncertainty by $\sim \frac{1}{2}$ for $x \sim 0.2$

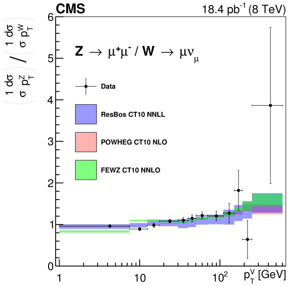
- $\sigma(W)$: constrains s-quark content $r_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}} \sim 1$
- Similar trend from $W + c$ production
- Some tension between collider and other data (eg ν-scattering)

γ/Z Production



CMS-PAS-SMP-16-009





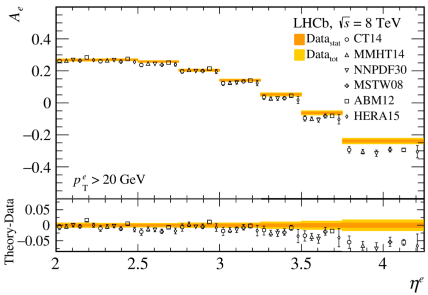
JHEP 02 (2017) 096

- Drell-Yan cross section well described by NLO and NNLO theory over full mass range
- Modelling of $P_T(Z)$ requires soft-gluon resummation (eg ResBos)
- $p_T(Z)/p_T(W)$ reasonably well described
- High precision measurement of $p_T(Z)$ an important input to W-mass measurement

Vector Bosons at Large Rapidity

LHCb: $p_T^\ell > 20$ GeV, $2 < \eta^\ell < 4.5$

W Production

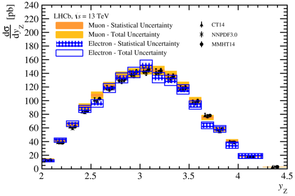


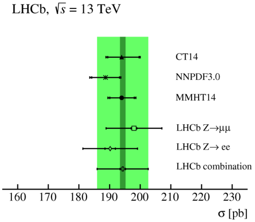
JHEP 10 (2016) 030

$$A_\ell = \frac{(\sigma(W^+) - \sigma(W^-))}{(\sigma(W^+) + \sigma(W^-))}$$

- Charge asymmetry changes sign due to V-A structure of WI

Z Production

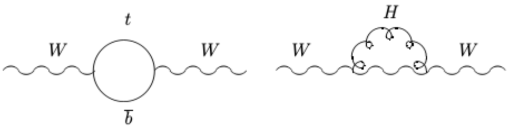


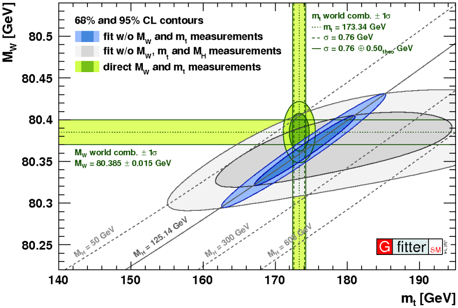


JHEP 09 (2016) 136

- Consistent with modern PDFs

Search for New Physics Via Virtual Corrections: M_W vs M_t





Fit as of July 2014

- Gauge sector of SM constrained by 3 parameters:

$$\begin{aligned} \alpha &= 1/137.035999139(31) \\ G_F &= 1.16637(1) \times 10^{-5}\ \mathrm{GeV}^{-2} \\ m_Z &= 91.1876(21)\ \mathrm{GeV} \end{aligned}$$

- At leading order:

$$m_W \sin^2\theta_W \frac{\pi\alpha}{\sqrt{2}G_F} \quad \sin^2\theta_W = 1 - m_W^2/m_Z^2$$

- HO corrections modify this:

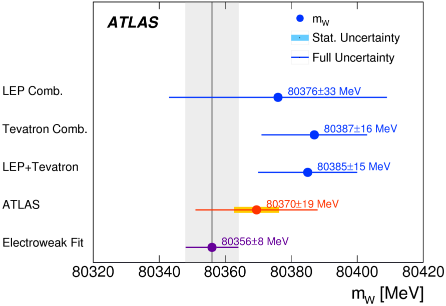
$$m_W \sin^2\theta_W \frac{\pi\alpha}{\sqrt{2}G_F}\frac{1}{1-\Delta r}$$

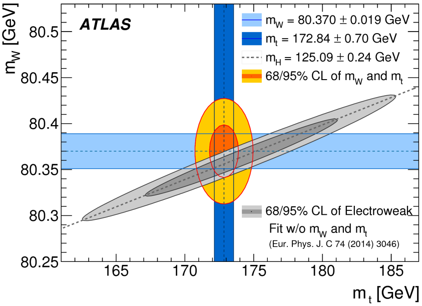
Precision measurements of m_t and M_W sensitive to presence of new particles in loops

W Mass: First LHC Measurement

$$m_W = 80370 \pm 7(\text{stat}) \pm 11(\text{exp sys}) \pm 14(\text{modelling sys}) \ \text{MeV}$$
$$= 80370 \pm 19 \ \text{MeV}$$

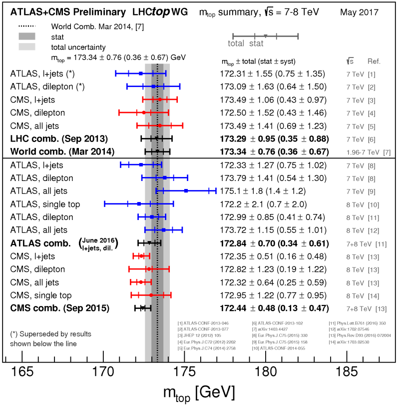
- Use low pile-up $\sqrt{s} = 7$ TeV data
  - Huge effort to control systematic uncertainties
- Uncertainty comparable to previous best measurement from CDF
- Expect future improvements
  - Larger statistics 8 TeV and 13 TeV samples
  - Reduction of modelling uncertainies (theory and W kinematics (eg p_T^W)
- But higher pileup will be a challenge!





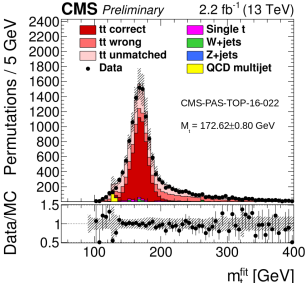
arXiv:1701.07240

Direct Measurements of the Top Mass

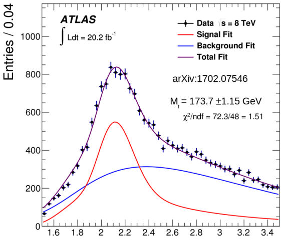


Recent Results:

CMS: μ+Jets, $\sqrt{s} = 13$ TeV



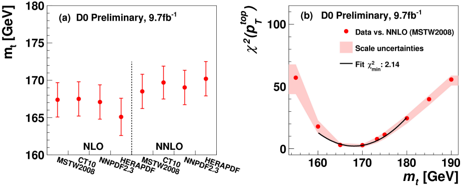
ATLAS: All hadronic $\sqrt{s} = 8$ TeV



- ATLAS and CMS in good agreement:
  - $m_t^{\text{ATLAS}} = 172.84 \pm 0.70$ GeV
  - $m_t^{\text{CMS}} = 172.44 \pm 0.48$ GeV
- Some tension with Tevatron average:

  $m_t^{\text{Tev}} = 174.30 \pm 0.65$ GeV
  - $m_t^{CDF} = 173.16 \pm 0.95$
  - $m_t^{D0} = 174.95 \pm 0.75$

Measurements of the Top Quark Pole Mass



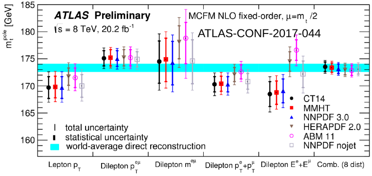
FERMILAB-CONF-16-383-PPD

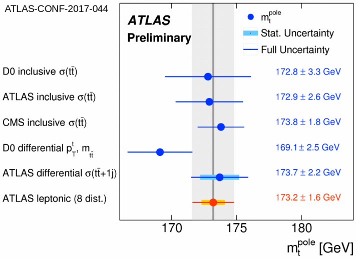
- Most precise m_t measurements from direct mass reconstruction
  - m_t^{direct} MC generator scheme dependent
  - Can differ by 1 GeV from m_t^{pole}
- m_t^{pole} obtained from $\sigma_{t\bar{t}}$ and its differential distributions
  - Sensitive to order of calculation and choice of PDF
  - NLO $\rightarrow$ NNLO: Scale Uncertainty $10\% \rightarrow 5\%$

- New for EPS: ATLAS m_t^{pole} from 8 TeV dileptons (using NLO prediction)

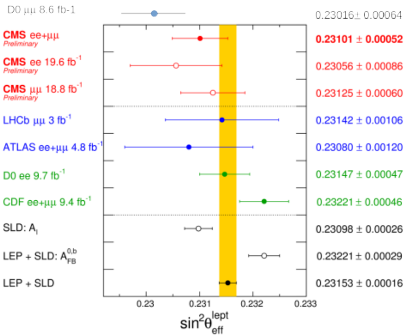
$$m_t^{pole} = 173.2 \pm 1.6 \;\; \text{GeV}$$

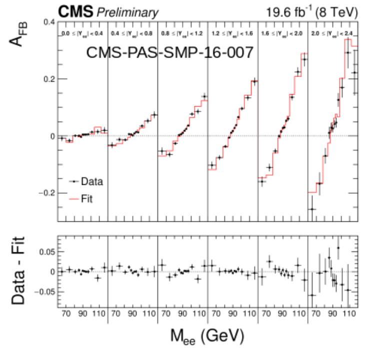
  - Fit to 8 differential distributions (NNLO kinematic dist. not yet available)





Building for the Future: $\sin^2\theta_W^{\text{eff}}$





- $p\bar{p}$: A_{FB} as fn of $m_{\ell\ell}$

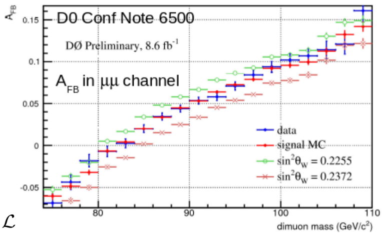
  New from D0 ($\mu\mu$): 0.23016 ± 0.00064

  New Tevatron Average: 0.23148 ± 0.00033 (FNAL-CONF-17-201-E)

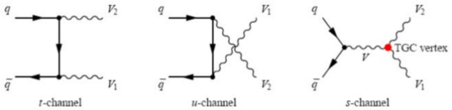
- pp: Z boost preferentially selects direction of valence quark

  New from CMS (8 TeV $ee + \mu\mu$): 0.23101 ± 0.00052

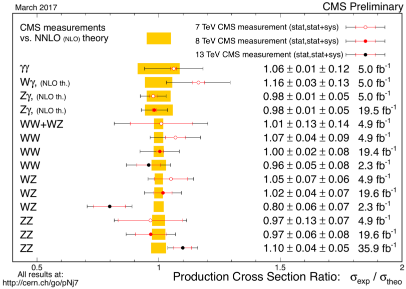
- Best measurements remain LEP+SLD: ± 0.00016
- Uncertainties for LHC measurements will decrease as $\int \mathcal{L}$ increases

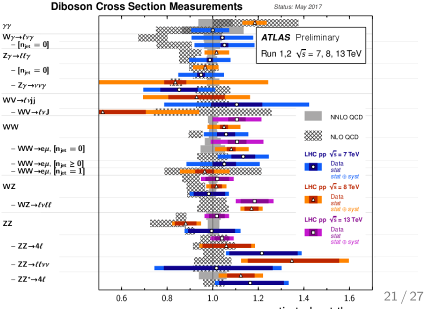


Diboson Production

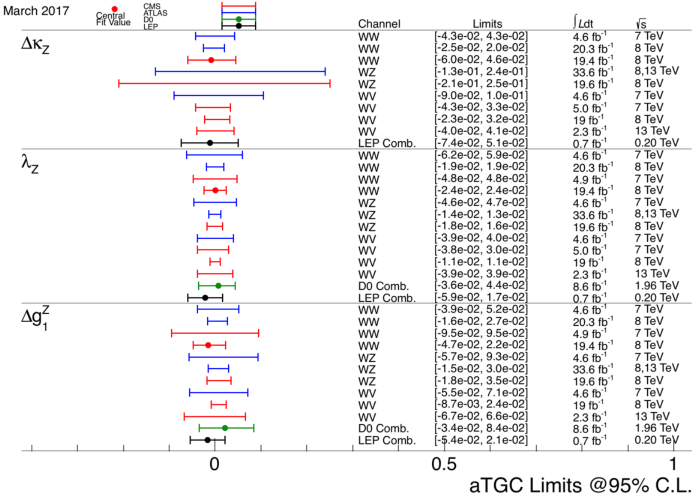


- Test of NLO EW corrections and NNLO QCD calculation
- Sensitive to new physics from triple gauge couplings
  - No single channel sensitive to all possible BSM contributions
- Large number of measurements
- Agreement with SM good to date
  - See next page for example aTGC limits
- Increased luminosity of Run2 and beyond will further improve precision



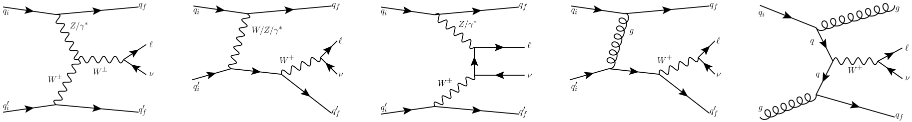


aTGC Limits from Diboson Production: WWZ Vertex



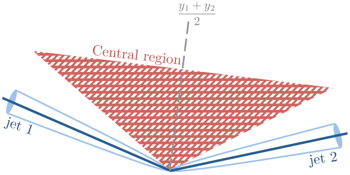
See https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC for additional results

Isolating EW Single and Di-boson Production with 2 Jets



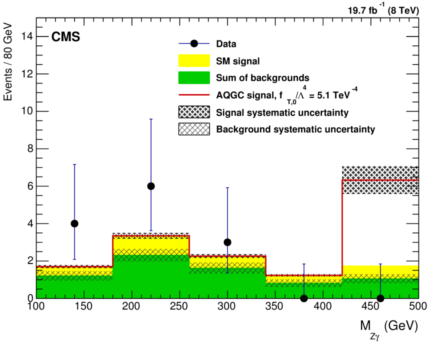
EW: Signal   Strong: Background

- Can use LHC as a boson-boson collider
- Single W/Z production through Vector Boson Fusion (VBF) and diboson production through Vector Boson Scattering (VBS)
  - Sensitive to new physics in the 3 or 4 boson vertex
- VBF and VBS tagged by presence of 2 jets at large separation in rapidity
  - Colorless objects in scattering $\Rightarrow$ low jet activity in central region
  - Large m_{jj} for leading two jets
- QCD production defined as "background'



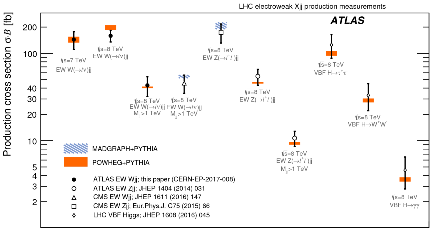
Probing Anomolous Couplings: EW X+2 Jets

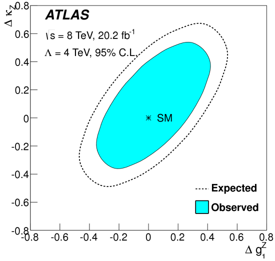
- VBF signals observed in many channels
- Measurements exist at 7, 8 and 13 TeV
- All results consistent with SM
- Limits on anomolous couplings set



Quartic gauge coupling constraint from $m - Z\gamma$

CMS-SMP-14-018



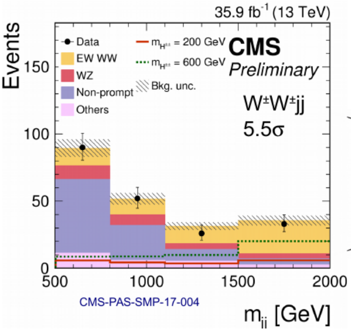


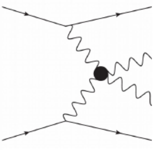
Triple gauge coupling constraints from Wjj

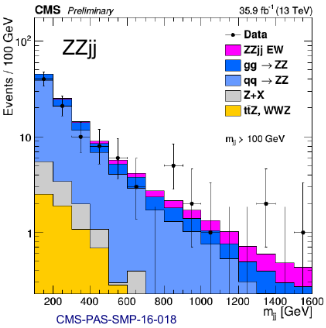
arXiv:1703.04362

Observation of EW Boson Scattering

- Observation of Vector Boson Scattering a milestone in studies of EW Sector
- S:N for EW:QED production for same-sign W scattering
  - First 5σ observation of $W^{\pm}W^{\pm}jj$ EWK production
  - Discriminating variable: m_{jj}
- First studies of $ZZjj$ EWK production
  - Larger contributions from Strong production in this channel
- Rich program of precision measurements anticipated with larger datasets available in the future







Summary and Conclusions

- Outstanding performance of LHC collider and experiments
  - Large data samples collected, with timely analysis underway
  - Techniques to mitigate pileup in place and working
- Large integrated luminosity enables:
  - Exploration of differential distributions in a variety of kinematic regimes
    - $t\bar{t}$ and $t\bar{t} + X$
    - Bosons and Dibosons
  - Observation of exciting low cross section processes
    - VBF production in many channels
    - First 5σ measurement of Vector Boson Scattering
  - Precision measurements to constrain virtual corrections
    - Top mass in many channels
    - First W mass measurement at the LHC
    - Progress on measurements of weak interaction parameters
  - Major advances in techniques for theoretical calculations
    - Control of uncertainties in challenging regions of phase space
- We are still at the beginning
  - Current data samples only $\sim 2\%$ of expectations for HL-LHC

Exciting times to come!

New Results for EPS

- ATLAS
  - ATLAS-CONF-2017-031: ZZ cross-section measurements and aTGC search in 13 TeV collisions with the ATLAS detector
  - ATLAS-CONF-2017-044: Measurement of lepton differential distributions and the top quark mass in $t\bar{t}$ production in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector
  - ATLAS-CONF-2017-048: Measurement of inclusive-jet and dijet cross-sections in proton-proton collisions at sqrt(s)=13TeV centre-of-mass energy with the ATLAS detector
  - ATLAS-CONF-2017-049: Measurement of Tau Polarisation in Z/gamma*-¿tautau Decays in Proton-Proton Collisions at sqrt(s)=8 TeV with the ATLAS Detector
  - ATLAS-CONF-2017-052: Measurement of the production cross-section of a single top quark in association with a Z boson in proton-proton collisions at 13 TeV with the ATLAS detector
  - ATLAS-CONF-2017-054: Measurement of the inclusive $t\bar{t}$ cross-section in the lepton+jets channel in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector
  - ATLAS-CONF-2017-056: Direct top-quark decay width measurement in the $t\bar{t}$ lepton+jets channel at $\sqrt{s} = 8$ TeV with the ATLAS experiment
  - ATLAS-CONF-2017-059: First measurement of isolated photon plus jet production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector
- LHCb
  - https://arxiv.org/abs/1707.01621 Observation of the doubly charmed baryon
- CMS
  - CMS-PAS-TOP-16-014: Measurement of the differential cross sections of top quark pair production as a function of kinematic event variables in pp collisions at $\sqrt{s} = 13$ TeV
  - CMS-NOTE-TOP-2017-004 Object definitions for top quark analyses at the particle level
  - CMS-PAS-SMP-16-010: Measurement of the differential jet production cross section with respect to jet mass and transverse momentum in dijet events from pp collisions at $\sqrt{s} = 13$ TeV
  - CMS-PAS-SMP-16-007: Measurement of the weak mixing angle with the forward-backward asymmetry of Drell-Yan events at 8 TeV
- D0
  - D0-CONF-1650: Measurement of the Effective Weak-Mixing Angle
- Tevatron Combination
  - FNAL-CONF-17-201-E: Combination of the CDF and D0 effective leptonic electroweak mixing angles