Prospects for QCD, EW and Top Physics at the HL-LHC

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Outline

- Introduction: the future of HEP and the High-Luminosity LHC (HL-LHC)
- The upgraded ATLAS and CMS detectors
  - a sample of key expected performance results
- Physics prospects:
  - Jets and Photons
  - EWK physics: Precision observables
  - EWK physics: Vector-boson scattering
  - Forward Physics
  - Top-quark Physics
  - In back-up slides: double-parton scattering and dibosons (TGCs) projections
- Conclusions

The future of high-energy particle physics

- Several planning processes being carried out in these years, notably:
  - European Strategy planning [PHYSICS BRIEFING BOOK] – 2020
  - Snowmass planning exercise (leading to P5 recommendation) – ongoing

see also J. Mnich's talk

coming soon ATLAS and CMS plan to submit new contributions in this timescale (see experiments' LoI: ATLAS and CMS)

Particle Physics is global:

Snowmass process involves the international community and strategies/plans from other regions

- Strong interplay with similar planning exercises in other regions and countries

The High-Luminosity LHC

- THE only future high-energy collider we are certain to build and operate
  - expected to operate from ~2027 until at least 2036, with two long-shutdowns in between
  - a baseline reference for any future collider physics experiment

HL-LHC key parameters

$\sqrt{s}$ = 14 TeV
$\mathcal{L} = 5 – 7 \cdot 10^{34}$ cm^{-2}s^{-1}
$\rightarrow$ pile-up (<μ>) = 140–200
L = 3 – 4 ab^{-1}

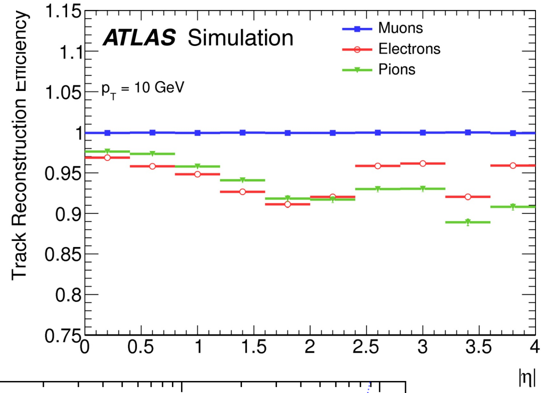
- Most projections shown today are from the HL-LHC CERN Yellow Report
  - ATLAS/CMS have similar reach in most benchmarks, using one or the other to give an example

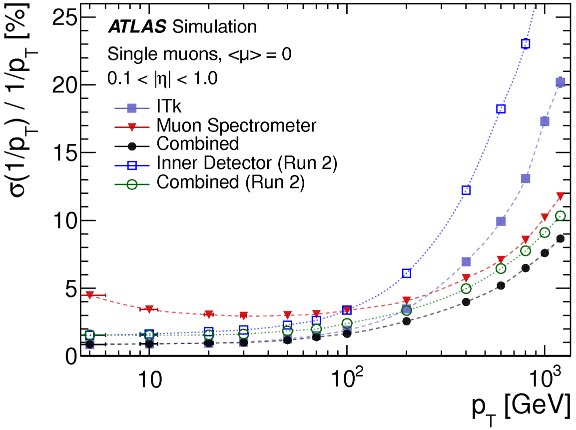
The upgraded ATLAS and CMS detectors

- Vast upgrade program to simultaneously **address challenges** of an harsher environment and **increase the capabilities** of the present detectors

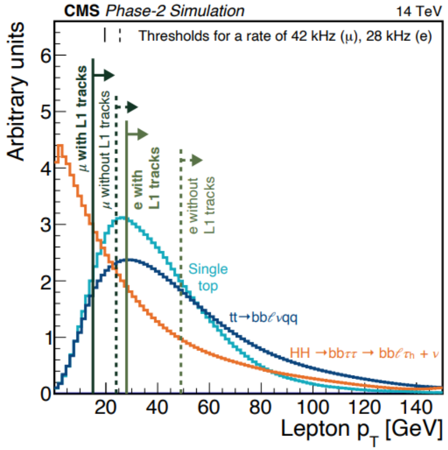
ATLAS	System	CMS
All new Silicon Tracker Pixel TDR, Strips TDR	Inner Tracker	All new Silicon Tracker Tracker TDR
10 kHz output rate TDAQ TDR	Trigger	L1 Track-trigger L1 Trigger TDR
30 ps / track fwd timing HGTD TDR	Timing Detector	MIP central timing layer MIP TDR
New FE electronics Tile TDR, LAr TDR	Hadronic/EM Calorimeters	New high-granularity + timing fwd HGCAL New FE electronics Barrel
New chambers, FE electronics Muon TDR	Muon Spectrometer	New FE electronics Muon TDR

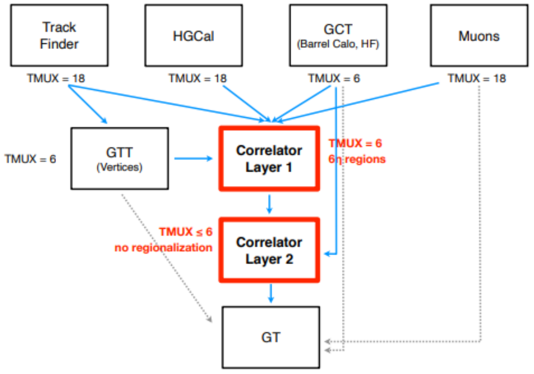
- Vast upgrade program to simultaneously **address challenges** of an harsher environment and **increase the capabilities** of the present detectors





System
Inner Tracker
Trigger
Timing Detector
Hadronic/EM Calorimeters
Muon Spectrometer

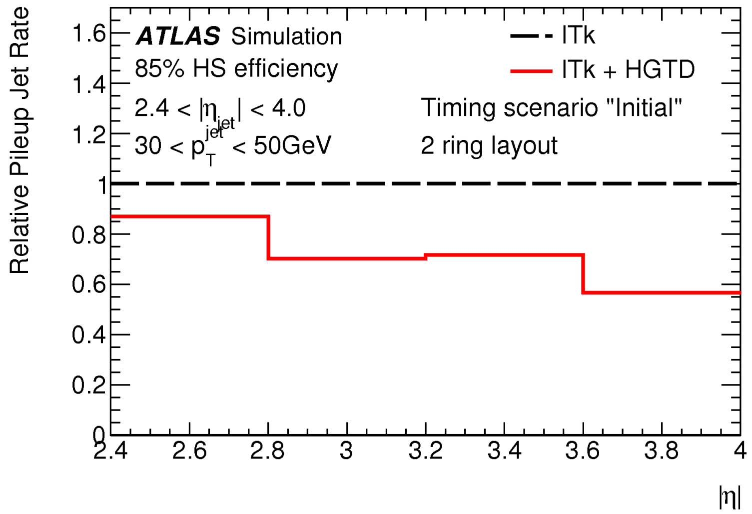




The upgraded ATLAS and CMS detectors

- Vast upgrade program to simultaneously **address challenges** of an harsher environment and **increase the capabilities** of the present detectors

Fwd pile-up jets rejection



System
Inner Tracker
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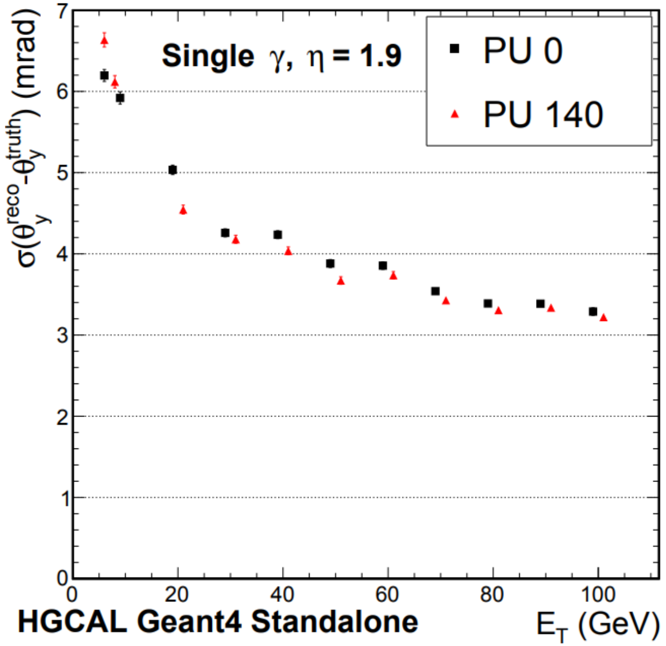
Timing Detector
Hadronic/EM Calorimeters
Muon Spectrometer

see also C. Mills's talk

Pointing capability + PU robustness



HL-LHC Projections strategies

- (S) **Full simulation** to assess/optimize performance of reconstructed objects in detail
  — Very resource consuming. Only in very few cases used to derive physics projections
- (F) "**Fast simulation**": parametrized detector performance or fast reconstruction (DELPHES)
  — Allows re-optimization of selections, usually at the price of simplified data analysis
- (E) **Extrapolation** from existing run-2 analyses
  — Captures full complexity of analyses, only minor tweaks possible
- Treatment of **systematic uncertainties** harmonized between experiments and extrapolated →

	Full sim	Fast sim	Extrap.
Faster		✓	✓✓
Allows re-optimization of selections	✓	✓	
Complex analyses w/ multiple SR			✓
Extended tracker acceptance/upgrades	✓	✓	
Modeling and stat. of large bkg		✓	✓

General guiding principles for systematic uncertainties:

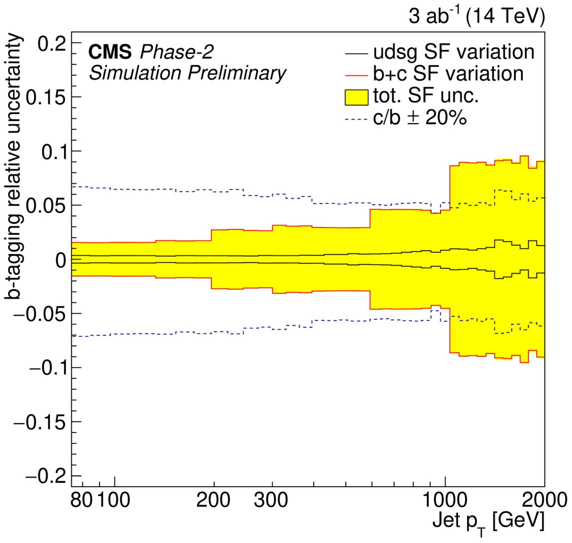
- Statistics-driven sources: data → $\sqrt{L}$, simulation → 0
- Intrinsic detector limitations stay ~constant
- Theory uncertainties tentatively halved
- PDF uncertainties based on dedicated analysis
  arXiv:1810.03639
- Extrapolation based mostly on methods available now

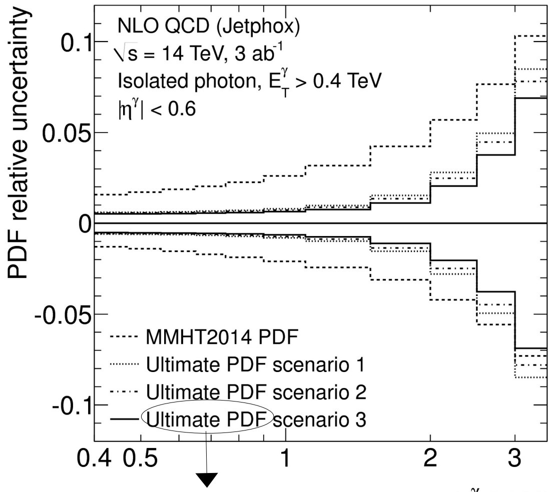
Jets and Photons

- Push boundaries of high energy jets and photon production
- Particular care in estimating the expected size of systematics and their effect on the measurements
  - Experimental as well as theoretical uncertainties discussed
  - Interplay with PDF knowledge and sensitivity

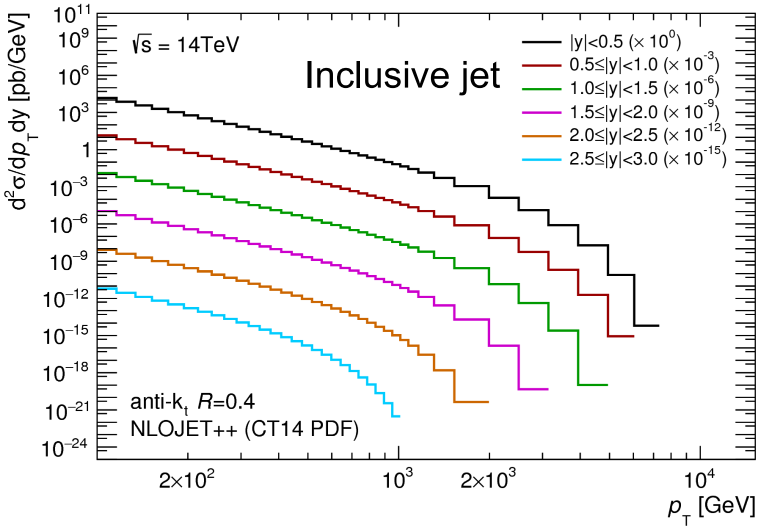
coming soon jet substructure, α_s, DPS,...

Observable	Max p_T
Inclusive jet	~ 4 TeV
Inclusive γ	~ 3.5 TeV
b-jet	~ 3 TeV
W-bosons (had.)	~ 2.5 TeV
top-quarks	~ 2 TeV



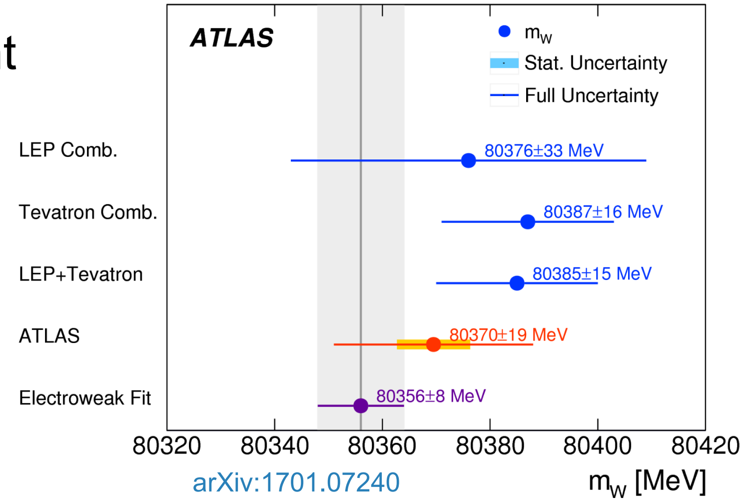


arXiv:1810.03639

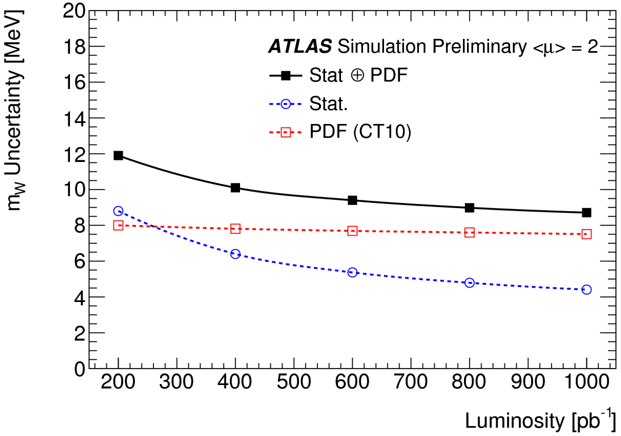


EWK Physics: W mass

- Indirect constraints more accurate than direct measurement
  - Systematics-dominated, PDF uncertainties play a key role
- At HL-LHC, plan to take advantage of improved detector in collecting data also at low pile-up
  - Optimal reconstruction of missing transverse momentum
  - Extended rapidity coverage (|η| < 2.4 → 4.0) is key in reducing PDF uncertainties



arXiv:1701.07240

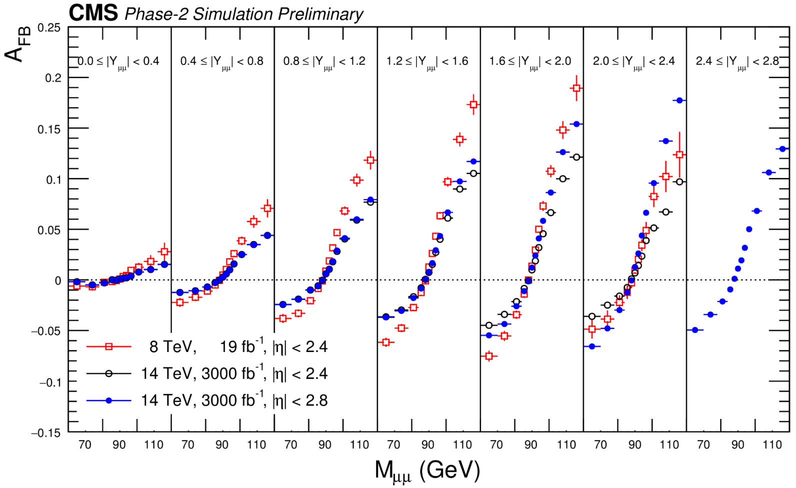


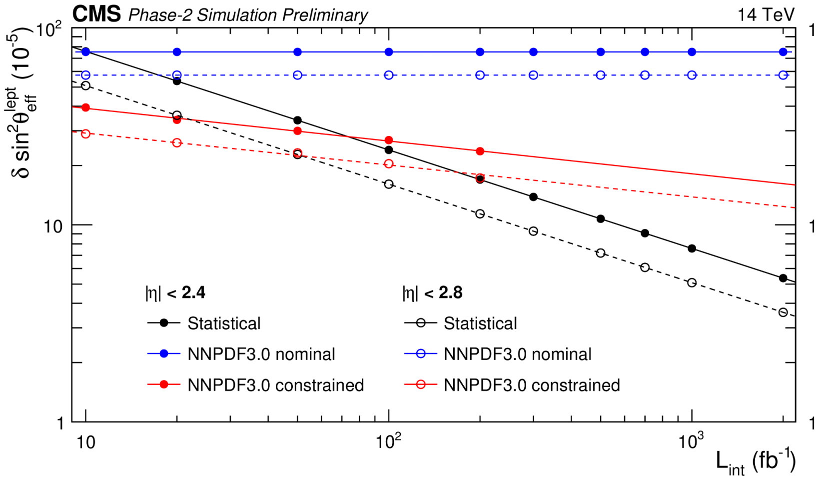
$\sqrt{s}$ [TeV]	Lepton acceptance	Uncertainty in m_W [MeV]		
		CT10	CT14	MMHT2014
14	$\lvert\eta_\ell\rvert < 2.4$	16.0 (10.6 ⊕ 12.0)	17.3 (11.4 ⊕ 13.0)	15.4 (10.7 ⊕ 11.1)
14	$\lvert\eta_\ell\rvert < 4$	11.9 (8.8 ⊕ 8.0)	12.4 (9.2 ⊕ 8.4)	10.3 (9.0 ⊕ 5.1)

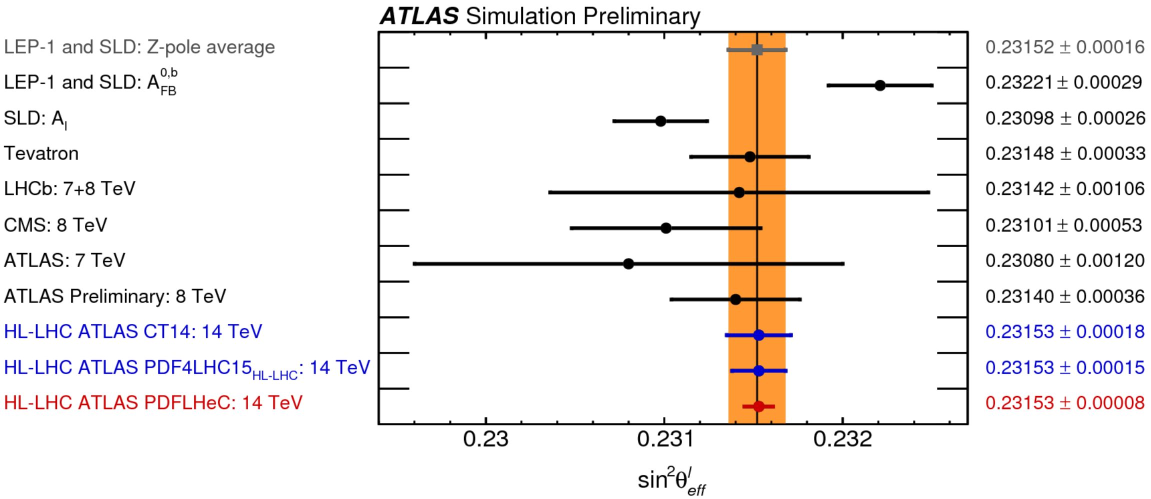
Table above assumes 200 pb^{-1}, uncertainty is *total (stat ⊕ PDF)*

EWK Physics: weak mixing angle

- Measured using forward/backward asymmetry in di-lepton production at Z resonance
- Constraining PDF uncertainties also a key component for the success of this measurement
  - Extended lepton acceptance and large statistics
- Expect sensitivity to resolve long-standing discrepancy

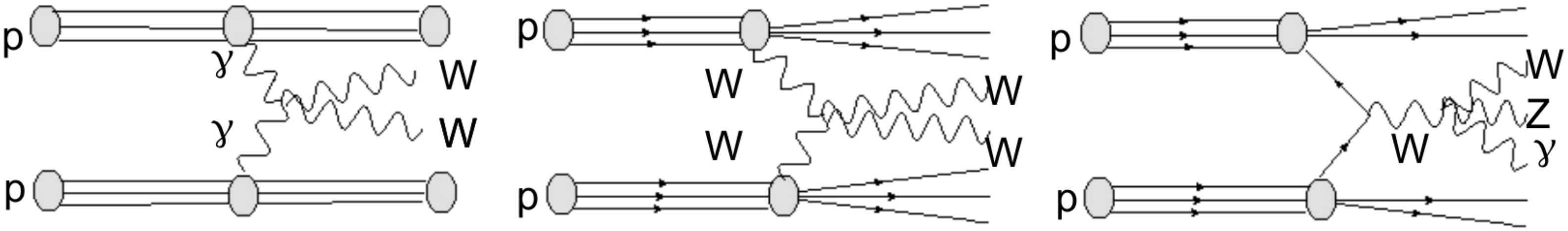






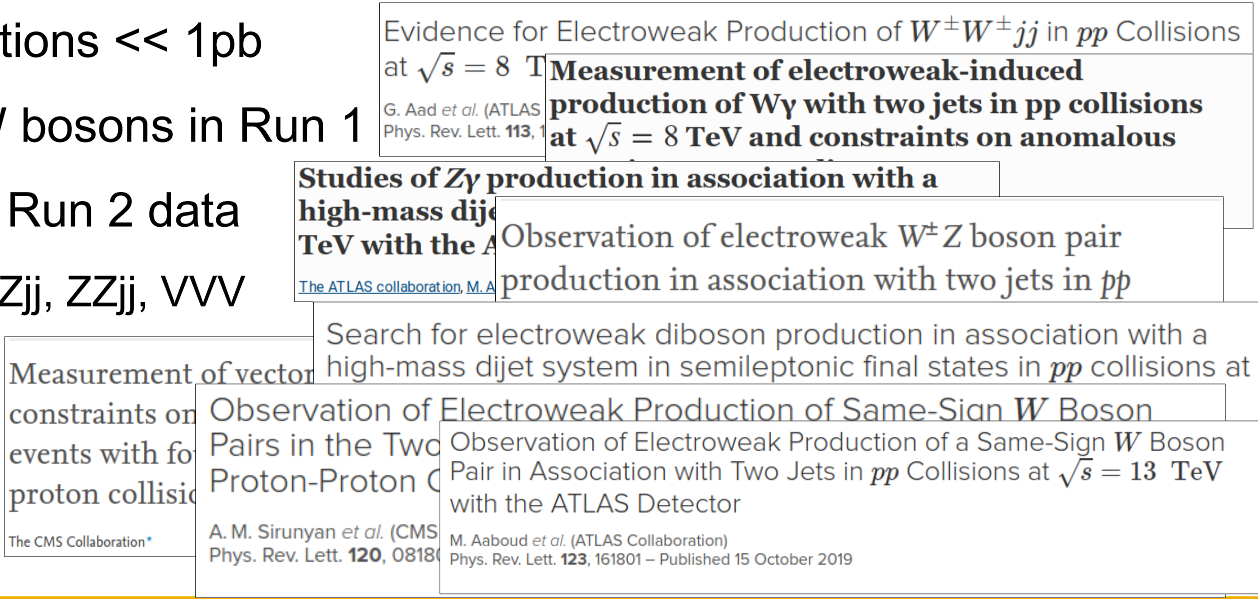
EWK Physics: quartic gauge couplings

- Three main classes of processes to study quartic gauge couplings at the LHC



Exclusive production | Di-bosons | Tribosons

- Very rare processes with cross sections << 1pb
- First evidence of same-charge WW bosons in Run 1
- The field is growing very fast using Run 2 data
  - Observation of same-charge WWjj, WZjj, ZZjj, VVV
  - Evidence of Zγjj, WWW, WWZ
  - Observation of pp → p (γγ→)WW p
- Paving the road for detailed measurements at the HL-LHC!


Evidence for Electroweak Production of $W^{\pm}W^{\pm}jj$ in pp Collisions at $\sqrt{s}=8$ T

G. Aad et al. (ATLAS

Phys. Rev. Lett. 113, 1

Measurement of electroweak-induced production of Wγ with two jets in pp collisions at $\sqrt{s}$ = 8 TeV and constraints on anomalous

Studies of $Z\gamma$ production in association with a high-mass dije

TeV with the A

The ATLAS collaboration, M. A

Observation of electroweak $W^{\pm}Z$ boson pair production in association with two jets in pp

Search for electroweak diboson production in association with a high-mass dijet system in semileptonic final states in pp collisions at

Measurement of vector

constraints on

events with fo

proton collisi

The CMS Collaboration*

Observation of Electroweak Production of Same-Sign W Boson Pairs in the Two

Proton-Proton C

A. M. Sirunyan et al. (CMS

Phys. Rev. Lett. 120, 0818

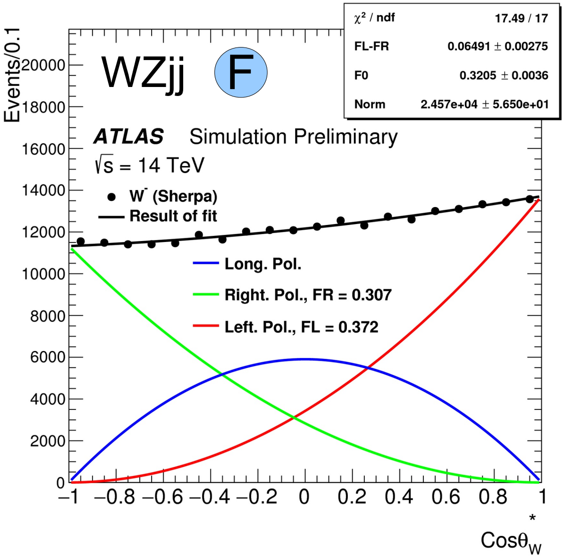
Observation of Electroweak Production of a Same-Sign W Boson Pair in Association with Two Jets in pp Collisions at $\sqrt{s}=13$ TeV with the ATLAS Detector

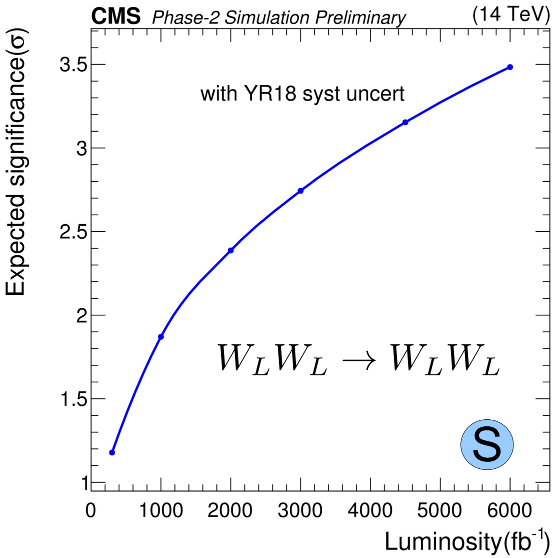
M. Aaboud et al. (ATLAS Collaboration)

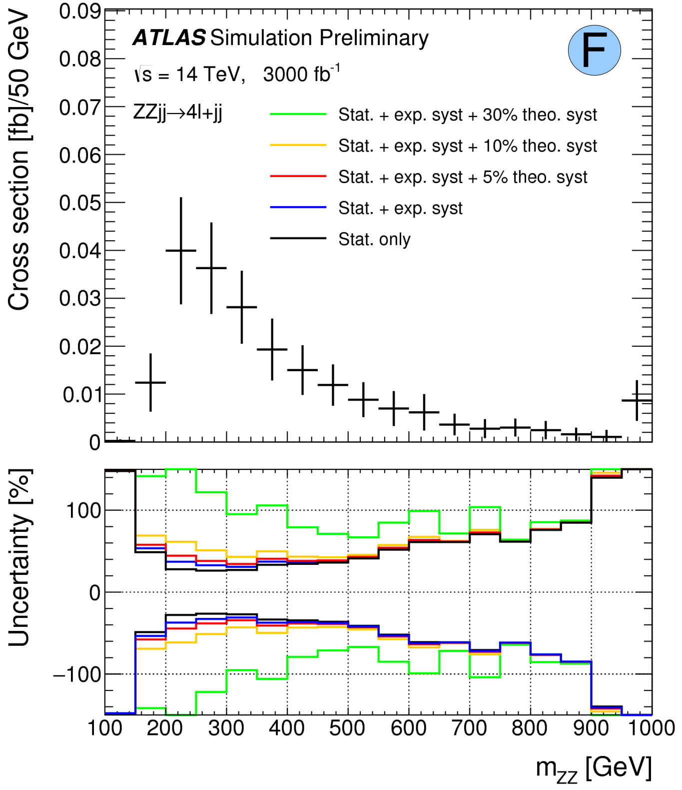
Phys. Rev. Lett. 123, 161801 – Published 15 October 2019

Vector Boson Scattering: VVjj (lep.)

- Large dataset allows differential measurements even for the very rare ZZjj → 4l jj production
  - Theoretical uncertainties dominates if no further improvements
- Studied sensitivity to the longitudinally-polarized VV scattering → very sensitive to SM cancellations
  - Expect enough sensitivity for observation for $W_L W_L \rightarrow W_L W_L$

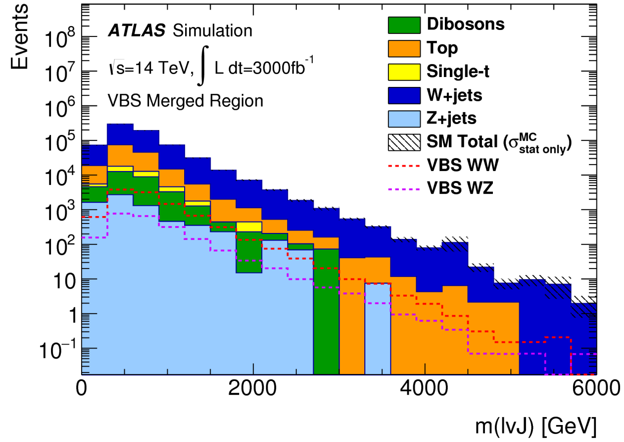




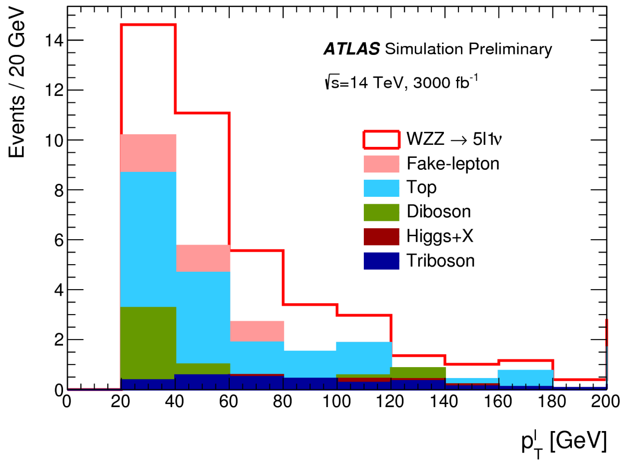


coming soon Updated projections on WZ,ZZ,VVV

VVjj (had.), and tribosons



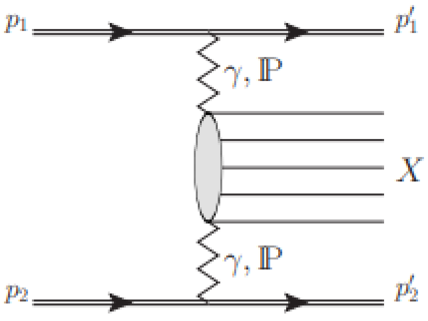
- Hadronically decays V bosons allow to probe very large √s of VV interaction, but suffer from large backgrounds → studied in both resolved (V → jj) and boosted (V → J) modes
- Multivariate techniques to separate signal from backgrounds
  - Expect better than 5% accuracy on EWK VVjj cross section when combining boosted/resolved regimes and lv, ll,vv final states



- Expect to study in details triboson processes separately
  - Sensitivity also for the most statistically-limited channels as WZZ in the 5 leptons final state!

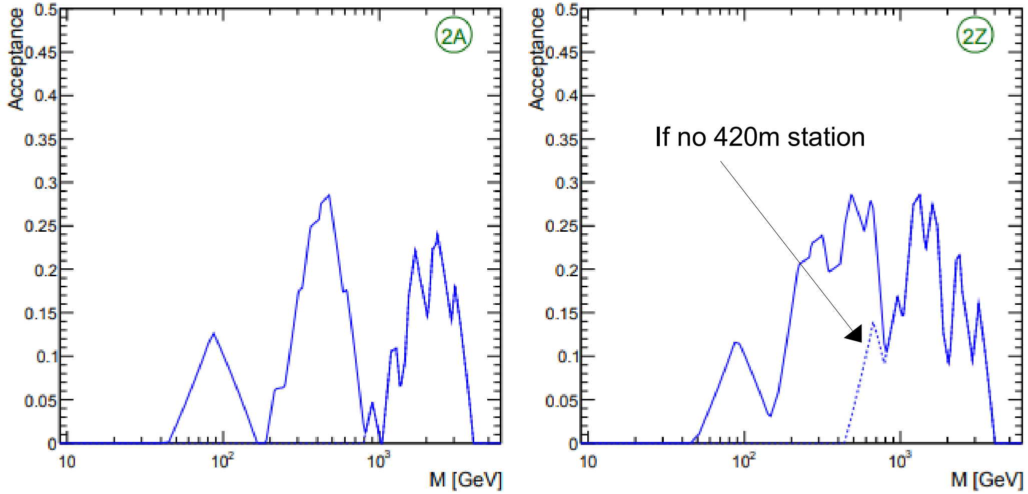
Channel	$\frac{\Delta\mu}{\mu}$ (3000 fb^{-1})	$\frac{\Delta\mu}{\mu}$ (4000 fb^{-1})
$WWW \to 3\ell\ 3\nu$ (0SFOS)	11%	10%
$WWZ \to 4\ell\ 2\nu$ (DFOS)	27%	25%
$WZZ \to 5\ell 1\nu$	36%	31%

Forward Physics



- Central exclusive production mechanism offers unique probes of the SM
  - Primary example: quartic γγWW gauge coupling when X = WW
- CMS expressed interest in a new near-beam proton spectrometer
  - Detect intact protons from exclusive production
  - Timing plus tracking detectors @ $\underbrace{196/220/234}_{0.133 - 2.7\ \text{TeV}}/\underbrace{420\text{m}}_{0.043 - 2.7\ \text{TeV}}$
  - Detector position sets acceptance in terms of invariant mass of the system (X)
  - Vertical beam crossing angle more favorable → adopted for HL-LHC
- ATLAS also exploring opportunities for forward-physics detectors at the HL-LHC

2A/Z: 250μrad half x-ing angle, β*=15/60cm

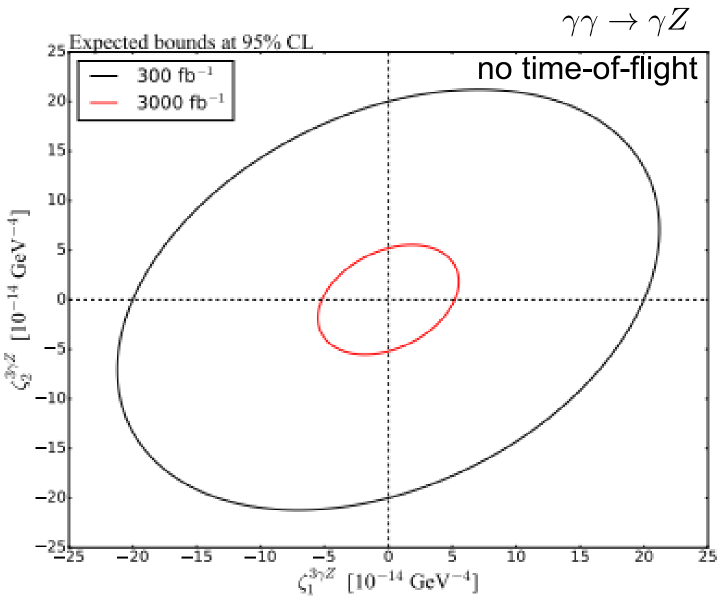


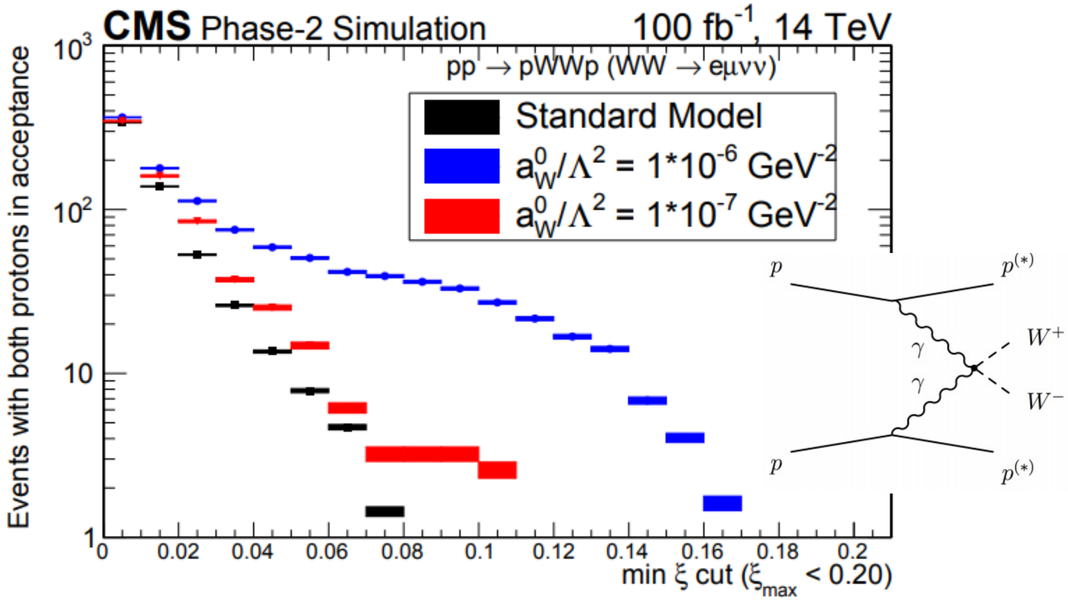
coming soon Projections for HL-LHC as γγ collider

Forward Physics - II

- Acceptance studies for:
  - γγ → ll, γγ → WW, γγ→ tt, γγ→ jj (fragmentation studies)
  - Higgs physics (w/ 420m station)
  - BSM (e.g. axions, dark-matter, etc..)

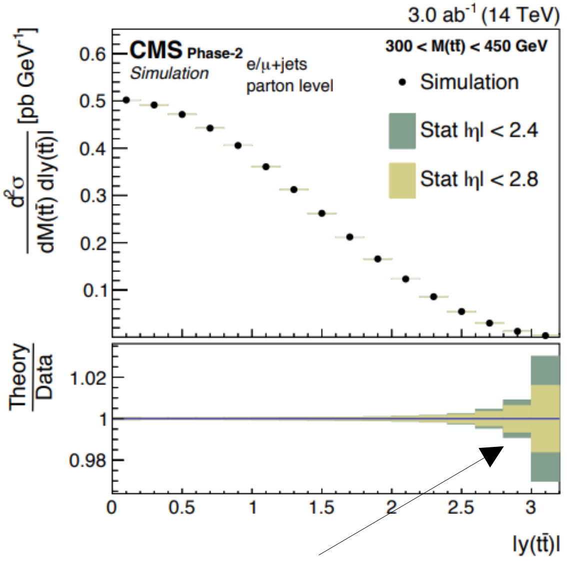
Process	fiducial cross section [fb] all stations		fiducial cross section [fb] w/o 420	
	$\mathbb{P}-\mathbb{P}$	$\gamma-\gamma$	$\mathbb{P}-\mathbb{P}$	$\gamma-\gamma$
jj	$\mathcal{O}(10^6)$	60	$\mathcal{O}(10^4)$	2
W^+W^-	—	37	—	15
$\mu\mu$	—	46	—	1.3
$t\bar{t}$	—	0.15	—	0.1
H	0.6	0.07	0	0
$\gamma\gamma$	—	0.02	—	0.003



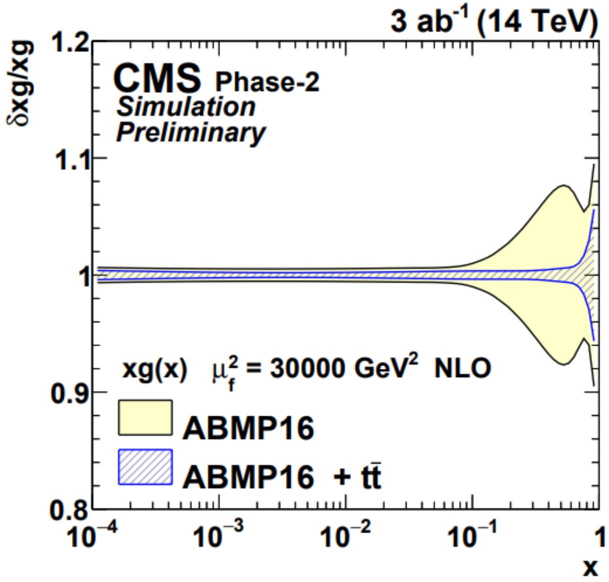


Top Physics: top-quark

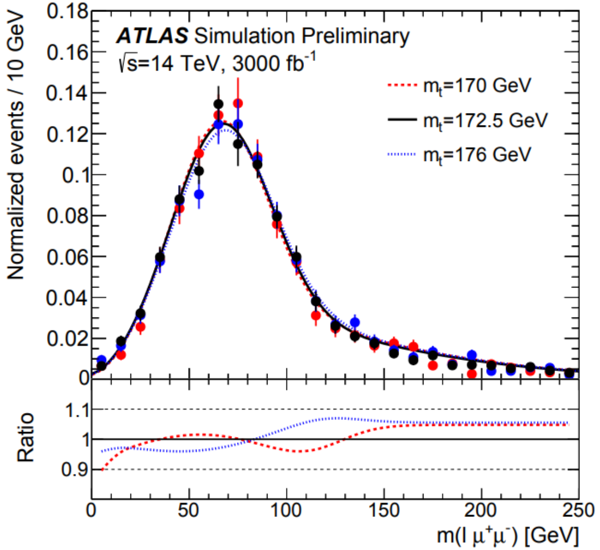
- Precision of double-differential cross section (m_{tt}, y_{tt}) will profit from the large amount of data and the extended η-range
  - Sensitivity to constrain PDFs



Increased stat due to extended single-lepton trigger



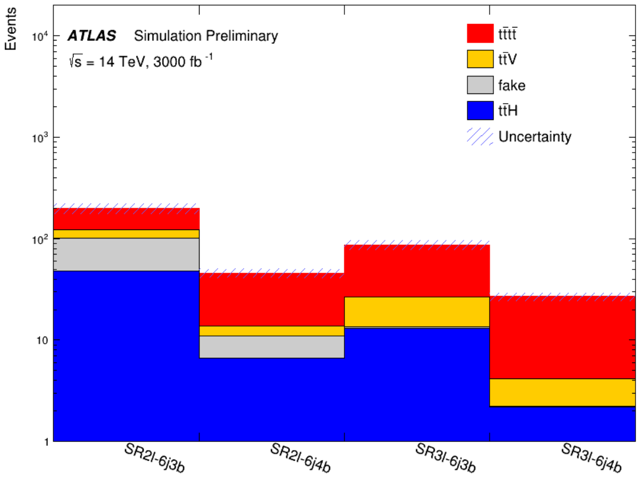
- **top** quark **mass** using tt→ lepton+jets events with J/ψ→$\mu^+\mu^-$ in the final state
  - Exploit correlation of m(t) and m(l J/ψ)
  - Method needs large statistics



Expected uncertainty:
±0.14 (stat.) ±0.48 (syst.) GeV

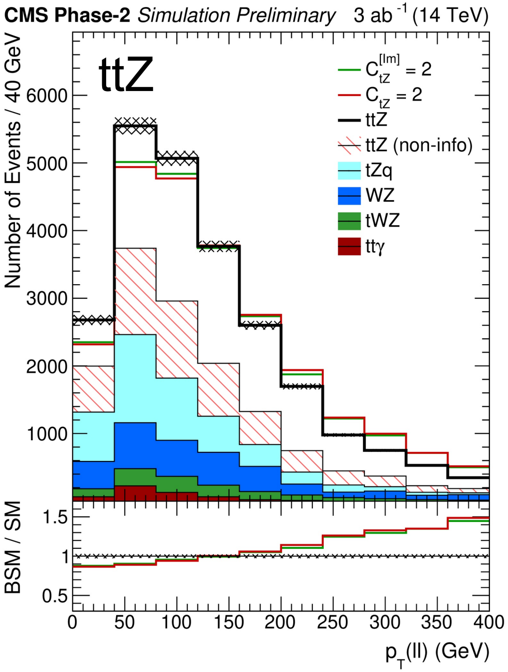
Top physics: rare processes

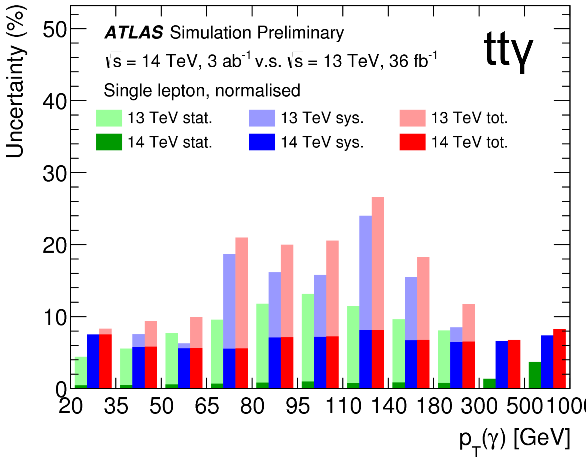
- Projections for 4-top process expect ~10-30% uncertainty in cross-section
  - Already evidence of this process with full Run 2 analysis
  - Expect much more sophisticated methods will end up outperforming projections



coming soon Updated projection

- Associated production of top pairs with W, Z and γ can be studied differentially
  - Probing e.g. tZ and tγ couplings





coming soon Updated projection and anomalous couplings constraints

Conclusions

- ATLAS and CMS upgrades brings robustness as well as new features for HL-LHC

- Large dataset enables precision and differential measurements of processes we barely have observed (or haven't yet) now

- Projections tend to inherently be conservative, although a significant effort was put to harmonize assumptions and show the importance of reducing systematics for HL-LHC

- Overall HL-LHC promises a vast and rich precision physics program throughout the QCD, EWK and Top sectors of the Standard Model
  - only a subset of available results shown, see dedicated ATLAS and CMS pages for more!
  - and more physics projections are expected to come soon in the context of Snowmass

Backup

DPS at HL-LHC

- The naive probability of having double-parton scattering production of a process AB is

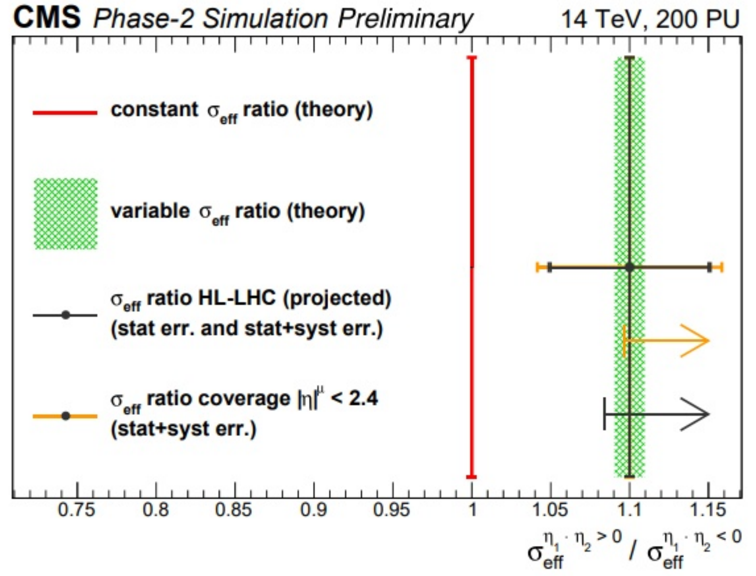
$$\sigma_{\rm DPS}^{AB} \simeq \frac{\sigma_{\rm SPS}^{A}\sigma_{\rm SPS}^{B}}{\sigma_{\rm eff}}$$

  – in practice seff is not necessarily universal
  – other effects can easily complicate the picture, e.g. "competing" valence quarks for processes A,B; correlations in momentum fraction between partons

- Studied in the context of same-charge WW production, using correlation between leptons from the W decay

$$a_{\eta_l} = \frac{\sigma(\eta_1 \cdot \eta_2 < 0) - \sigma(\eta_1 \cdot \eta_2 > 0)}{\sigma(\eta_1 \cdot \eta_2 < 0) + \sigma(\eta_1 \cdot \eta_2 > 0)},$$

  – Calculation taking into account the double-parton distribution functions
  – HL-LHC has sensitivity to start probing these effects!



- Studied in the context of the HL-LHC Yellow-Report, projecting based on external fits of LHC data.

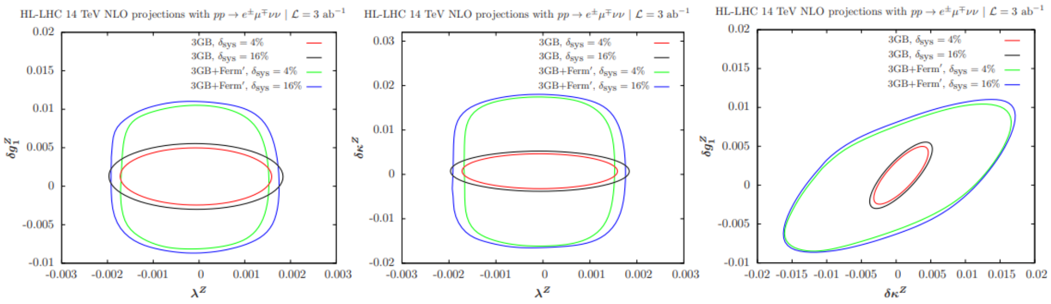


Fig. 40: Projections for 14 TeV with 3 ab^{-1}. $p_{T,cut}$ = 750 GeV, corresponding to δ_{stat} = 16% with δ_{sys} = 4% and δ_{sys} = 16%. The curves labelled 3GB have SM Z-fermion couplings, while the curves labelled 3GB +Ferm' allow the Z-fermion couplings to vary around a central value of 0.

$$\mathcal{L}_V = -ig_{WWV}\Big\{(1+\delta g_1^V)\left(W^+_{\mu\nu}W^{-\mu}V^\nu - W^-_{\mu\nu}W^{+\mu}V^\nu\right) + (1+\delta\kappa^V)W^+_\mu W^-_\nu V^{\mu\nu}) + \frac{\lambda^V}{M_W^2}W^+_{\rho\mu}W^{-\mu}{}_\nu V^{\nu\rho}\Big\},$$

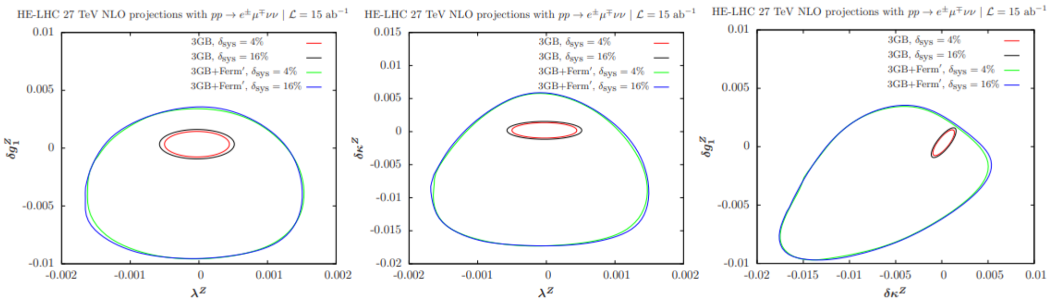


Fig. 41: Projections for 27 TeV with 15 ab^{-1}. $p_{T,cut}$ = 1350 GeV, corresponding to δ_{stat} = 16% with δ_{sys} = 4% and δ_{sys} = 16%. The curves labelled 3GB have SM Z-fermion couplings, while the curves labelled 3GB +Ferm' allow the Z-fermion couplings to vary around a central value of 0.

CMS L1 Trigger Menu

L1 Trigger seeds	Offline Threshold(s) at 90% or 95% (50%) [GeV]	Rate $\langle PU \rangle = 200$ [kHz]	Additional Requirement(s) [cm, GeV]	Objects plateau efficiency [%]
Single/Double/Triple Lepton (electron, muon) seeds				
Single TkMuon	22	12	$\lvert\eta\rvert < 2.4$	95
Double TkMuon	15,7	1	$\lvert\eta\rvert < 2.4, \Delta z < 1$	95
Triple TkMuon	5,3,3	16	$\lvert\eta\rvert < 2.4, \Delta z < 1$	95
Single TkElectron	36	24	$\lvert\eta\rvert < 2.4$	93
Single TkIsoElectron	28	28	$\lvert\eta\rvert < 2.4$	93
TkIsoElectron-StaEG	22, 12	36	$\lvert\eta\rvert < 2.4$	93, 99
Double TkElectron	25, 12	4	$\lvert\eta\rvert < 2.4$	93
Single StaEG	51	25	$\lvert\eta\rvert < 2.4$	99
Double StaEG	37,24	5	$\lvert\eta\rvert < 2.4$	99
Photon seeds				
Single TkIsoPhoton	36	43	$\lvert\eta\rvert < 2.4$	97
Double TkIsoPhoton	22, 12	50	$\lvert\eta\rvert < 2.4$	97
Taus seeds				
Single CaloTau	150(119)	21	$\lvert\eta\rvert < 2.1$	99
Double CaloTau	90,90(69,69)	25	$\lvert\eta\rvert < 2.1, \Delta R > 0.5$	99
Double PuppiTau	52,52(36,36)	7	$\lvert\eta\rvert < 2.1, \Delta R > 0.5$	90
Hadronic seeds (jets,H_T)				
Single PuppiJet	180	70	$\lvert\eta\rvert < 2.4$	100
Double PuppiJet	112,112	71	$\lvert\eta\rvert < 2.4, \Delta\eta < 1.6$	100
PuppiH_T	450(377)	11	jets: $\lvert\eta\rvert < 2.4, p_T > 30$	100
QuadPuppiJets-PuppiH_T	70,55,40,40,400(328)	9	jets: $\lvert\eta\rvert < 2.4, p_T > 30$	100,100
E_T^{miss} seeds				
PuppiE_T^{miss}	200(128)	18		100
Cross Lepton seeds				
TkMuon-TkIsoElectron	7,20	1	$\lvert\eta\rvert < 2.4, \Delta z < 1$	95, 93
TkMuon-TkElectron	7,23	3	$\lvert\eta\rvert < 2.4, \Delta z < 1$	95, 93
TkElectron-TkMuon	10,20	1	$\lvert\eta\rvert < 2.4, \Delta z < 1$	93, 95
TkMuon-DoubleTkElectron	6,17,17	0.1	$\lvert\eta\rvert < 2.4, \Delta z < 1$	95, 93
DoubleTkMuon-TkElectron	5,5,9	4	$\lvert\eta\rvert < 2.4, \Delta z < 1$	95, 93
PuppiTau-TkMuon	36(27),18	2	$\lvert\eta\rvert < 2.1, \Delta z < 1$	90, 95
TkIsoElectron-PuppiTau	22,39(29)	13	$\lvert\eta\rvert < 2.1, \Delta z < 1$ $\Delta R > 0.3$	93, 90

L1 Trigger seeds	Offline Threshold(s) at 90% or 95% (50%) [GeV]	Rate $\langle PU \rangle = 200$ [kHz]	Additional Requirement(s) [cm, GeV]	Objects plateau efficiency [%]
Cross Hadronic-Lepton seeds				
TkMuon-PuppiH_T	6,320(250)	4	$\lvert\eta\rvert < 2.4, \Delta z < 1$	95,100
TkMuon-DoublePuppiJet	12,40,40	10	$\lvert\eta\rvert < 2.4, \Delta R_{j\mu} < 0.4,$ $\Delta\eta_{jj} < 1.6, \Delta z < 1$	95,100
TkMuon-PuppiJet-PuppiE_T^{miss}	3,100,120(55)	14	$\lvert\eta\rvert < 1.5, \lvert\eta\rvert < 2.4,$ $\Delta z < 1$	95,100, 100
DoubleTkMuon-PuppiJet-PuppiE_T^{miss}	3,3,60,130(64)	4	$\lvert\eta\rvert < 2.4, \Delta z < 1$	95,100, 100
DoubleTkMuon-PuppiH_T	3,3,300(231)	2	$\lvert\eta\rvert < 2.4, \Delta z < 1$	95,100
DoubleTkElectron-PuppiH_T	10,10,400(328)	0.9	$\lvert\eta\rvert < 2.4, \Delta z < 1$	93,100
TkIsoElectron-PuppiH_T	26,190(124)	9	$\lvert\eta\rvert < 2.4, \Delta z < 1$	93,100
TkElectron-PuppiJet	28,40	34	$\lvert\eta\rvert < 2.1, \lvert\eta\rvert < 2.4,$ $\Delta R > 0.3, \Delta z < 1$	93,100
PuppiTau-PuppiE_T^{miss}	55(38),190(118)	4	$\lvert\eta\rvert < 2.1$	90,100
VBF seeds				
Double PuppiJets	160,35	40	$\lvert\eta\rvert < 5, m_{jj} > 620$	100
B-physics seeds				
Double TkMuon	2,2	12	$\lvert\eta\rvert < 1.5, \Delta R < 1.4,$ $q1 * q2 < 0, \Delta z < 1$	95
Double TkMuon	4,4	21	$\lvert\eta\rvert < 2.4, \Delta R < 1.2$ $q1 * q2 < 0, \Delta z < 1$	95
Double TkMuon	4.5,4	10	$\lvert\eta\rvert < 2.0, 7 < m_{\mu\mu} < 18,$ $q1 * q2 < 0, \Delta z < 1$	95
Triple TkMuon	5,3,2	7	$0 < m_{\mu 5 \mu 3, q1*q2<0} < 9$ $\lvert\eta\rvert < 2.4, \Delta z < 1$	95
Triple TkMuon	5,3,2.5	6	$5 < m_{\mu 5 \mu 2.5, q1*q2<0} < 17$ $\lvert\eta\rvert < 2.4, \Delta z < 1$	95
Rate for above Trigger seeds				346
Total Level-1 Menu Rate (+30%)				**450**