Physics at the HL-LHC

Andreas B. Meyer
Production Cross Section [pb]

- QCD
- Electroweak
- Top
- Higgs
- New Physics

CMS Preliminary

- 7 TeV CMS measurement ($L \leq 5.0 \text{ fb}^{-1}$)
- 8 TeV CMS measurement ($L \leq 19.6 \text{ fb}^{-1}$)
- 13 TeV CMS measurement ($L \leq 137 \text{ fb}^{-1}$)
- Theory prediction
- CMS 95% CL limits at 7, 8 and 13 TeV

Andreas B. Meyer

Physics at the High-Luminosity LHC

GK Seminar, Aachen, 25 May 2019
Production Cross Section [pb]

- Precision frontier: Improve systematics with more statistics and new ideas
- Statistics frontier: Discover / observe and explore
- QCD
- Electroweak
- Top
- Higgs
- New Physics

CMS Preliminary

- 7 TeV CMS measurement (L ≤ 5.0 fb⁻¹)
- 8 TeV CMS measurement (L ≤ 19.6 fb⁻¹)
- 13 TeV CMS measurement (L ≤ 137 fb⁻¹)
- Theory prediction

CMS 95%CL limits at 7, 8 and 13 TeV

Run-3 and HL-LHC: explore new frontiers

Andreas B. Meyer
Physics at the High-Luminosity LHC
GK Seminar, Aachen, 25 May 2019
Higgs Boson Production at LHC

source of background with the same leptonic final state is the production of top-quark pairs

With the exception of the

tt-bar final states are excluded because the corresponding events are already used

h channel. A discriminating variable combining a number of kinematic

variables, combining the outputs of two BDTs trained to discriminate the

tV and t+jets backgrounds respectively, is used in the 2

channels. Another

tt+jets background is used in the 1

channels. All six

production:

\( m_t = 1.23 \)

Experimental:

\( m_t = 1.09 \)

•

Flips

\( m_t \), which is most important in the e

tt+jets decay products because the missing

h decay products because the missing

H (\( m_t \)), is used.

Tree level measurement of top quark Yukawa

\( \mu \)

coupling can be effective or a mixture of          .

Direct measurement not possible since     appear in nominator and denominator of

Experimental:

\( m_t \)

\( m_t \)

Coupling

Higgs - τ
Summer 2017

Higgs - top
Spring 2018

Higgs - b
Summer 2018

First direct observations of Higgs-fermion couplings
LHC Run-2: A Few Highlights

**EWK Vector Boson Scattering W±W± (CMS)**

**Summer 2017**

5.5(5.7) σ

**TGC**

**QGC**

**EWK Vector Boson Scattering WZ→3ℓν (ATLAS)**

**Winter 2018**

5.3(3.2) σ

**4-Top Production**

**Spring 2019**

2.6(2.7) σ

Starting to scrutinize virtual Higgs boson
The High-Luminosity LHC

- 20 times more integrated luminosity than Run-2
- Better detectors, larger acceptance, better triggers
- Improved analysis methods and theory
# The High-Luminosity LHC

<table>
<thead>
<tr>
<th>Year</th>
<th>LHC</th>
<th>High-Luminosity LHC</th>
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<tbody>
<tr>
<td>2019</td>
<td>LS2 Run 3</td>
<td>LS3 Run 4</td>
</tr>
<tr>
<td>2020</td>
<td>ATLAS and CMS</td>
<td>Detector Upgrade</td>
</tr>
<tr>
<td>2021</td>
<td>Detector Upgrade</td>
<td>2 x 10^{33} ~50 \text{ fb}^{-1}</td>
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<tr>
<td>2022</td>
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<tr>
<td>2023</td>
<td>Detector Upgrade</td>
<td>2 x 10^{33} \ 50 \text{ fb}^{-1}</td>
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<tr>
<td>2024</td>
<td>LS4 Run 5</td>
<td>5-7 x 10^{34} \ 3000 \text{ fb}^{-1}</td>
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<tr>
<td>2034</td>
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</tr>
</tbody>
</table>

- 20 times more integrated luminosity than Run-2
- Better detectors, larger acceptance, better triggers
- Improved analysis methods and theory
Detector Upgrades

- Tracking up to $|\eta|<4.0$
- High granularity endcap calorimeter
- Muons up to $|\eta|<3.0$
- Improved triggering
- MIP Timing Layer (Barrel and Endcap)
- Fast tracking and vertexing
- Expect to collect 50 fb$^{-1}$ until end of Run 4
- Full 40 MHz readout into CPU farm
- Calorimeters
  - High grain timing detector
  - Tracking up to $|\eta|<4$
- Fwd Muon
- Trigger/DAQ HLT: 10 kHz
- New DAQ, Trigger (x50)
- Trigger/DAQ HLT: 7.5 kHz
Chapter 2
Overview of the Phase-2 Tracker Upgrade

2.1 Limitations of the present tracker

The present strip tracker was designed to operate with high efficiency at an instantaneous luminosity of \( 1.0 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1} \), with an average pileup of 20–30 collisions per bunch crossing, and up to an integrated luminosity of 500 fb\(^{-1}\). The tracker is indeed performing very well at current instantaneous luminosities that are well above the design value. Performance will however degrade due to radiation damage beyond 500 fb\(^{-1}\). The original pixel detector has already been replaced with a new device, the "Phase-1" pixel detector [17], during the extended year-end technical stop (EYETS) 2016/2017. As the instantaneous luminosity exceeded the original design value and is projected to increase further prior to LS3, this upgrade was needed to address dynamic inefficiencies in the readout chip at high rates. One quarter of the layout of the Phase-1 tracker is shown in Fig. 2.1. The radial region below 200 mm is equipped with pixelated detectors. Beyond 200 mm, the present tracker features single-sided strip modules and double-sided modules composed of two back-to-back silicon strip detectors with a stereo angle of 100 mrad. Double-sided modules provide coarse measurements of the \( z \) and \( r \) coordinates in the barrel and endcaps, respectively. The tracking system was designed to provide coverage up to a pseudorapidity of \(|\eta| < 2.4\).

Before the start of the HL-LHC both the strip tracker and the Phase-1 pixel detector will have to be replaced due to the significant damage and performance degradation they would suffer during operation at the HL-LHC, and to cope with the more demanding operational conditions. The performance degradation has been studied extensively and is documented in the Technical Proposal for the CMS Phase-2 Upgrade [13, 18].

Acceptance: \(|\eta| < 2.5\)

Example: Track Detectors
Chapter 2. Overview of the Phase-2 Tracker Upgrade

Figure 2.3: Sketch of one quarter of the tracker layout in \( r \)–\( z \) view. In the Inner Tracker the green lines correspond to pixel modules made of two readout chips and the yellow lines to pixel modules with four readout chips. In the Outer Tracker the blue and red lines represent the two types of modules described in the text.

Figure 2.4: Average number of module layers traversed by particles, including both the Inner Tracker (red) and the Outer Tracker (blue) modules, as well as the complete tracker (black). Particle trajectories are approximated by straight lines, using a flat distribution of primary vertices within \( |z| < 70 \text{ mm} \), and multiple scattering is not included.

The following section summarizes the main concepts and features of the upgraded tracking system. One quarter of the Phase-2 tracker layout can be seen in Fig. 2.3. Figure 2.4 shows the average number of active layers that are traversed by particles originating from the luminous region, for the complete tracker as well as for the Inner Tracker and the Outer Tracker separately.

The number of layers has been optimised to ensure robust tracking, i.e. basically unaffected performance when one detecting layer is lost in some parts of the rapidity acceptance. The six layers of the Outer Tracker are the minimum required to ensure robust track finding at the L1 trigger in the rapidity acceptance of \( |\eta| < 2.4 \), as discussed in more details in Section 3.1.

Much larger acceptance: \( |\eta| < 4 \)
less detector material and better resolution
Detector Performance

**Mass Resolution**

\[ H \rightarrow \mu\mu \]

**Suppression of PU-tracks using MIP Timing Detector**

**CMS Simulation preliminary**

13 TeV

**B-tagging with and w/o timing detector**

**CMS Phase-2 Simulation**

\[ t\bar{t}, PU = 200, jet p_T > 30 \text{ GeV} \]

**Generally similar or better performance under harsher conditions**

Swagato
Workshop on Physics at HL-LHC and Perspectives for HE-LHC

- Review, extend and refine our understanding of the HL-LHC physics potential
- **Begin** a study of physics at the HE-LHC, a possible pp collider with energy of ~27 TeV

### Working Group Report, “YR2018”

- **WG1: Standard Model**  
  arXiv:1902.04070  
  220 pages, ~200 authors
- **WG2: Higgs**  
  arXiv:1902.00134  
  364 pages, ~400 authors
- **WG3: BSM**  
  arXiv:1812.07831  
  281 pages, ~300 authors
- **WG4: Flavour**  
  arXiv:1812.07638  
  298 pages, ~300 authors
- **WG5: High-density QCD**  
  arXiv:1812.06772  
  209 pages, ~200 authors
- 78 notes from ATLAS and CMS  
  arXiv:1902.10229  
  1377 pages, >5000 authors

- Two 10-page executive summaries  
  >1000 authors each
  submitted to the European Strategy Update Group
  - HL-LHC  
    https://indico.cern.ch/event/765096/contributions/3295995/
  - HE-LHC  
    https://indico.cern.ch/event/765096/contributions/3296016/
HL-LHC Physics

- **Standard Model**
  - Ultimate precision measurements and constraints
  - Rare SM processes like (longitudinal) VBS, VVV, 4-Top

- **Higgs**
  - Precise determination of H(125) properties
  - Search for new phenomena in the Higgs sector

- **Direct Searches**
  - Heavy Resonances
  - Supersymmetry
  - Long-lived particles
  - Dark Matter

- **Flavour**
  - CKM metrology and QCD spectroscopy
  - Rare decays → flavour anomalies ?

- **Heavy Ions**
  - Precision study of material properties of QCD media
  - Study HI-like behaviour in small systems (pp and pA)
HL-LHC Projected Uncertainties

- Effort to make realistic projections, based on Run-2 analyses

- Systematic uncertainties will be limiting factor for more and more measurements

- ATLAS and CMS common approach
  - Statistical uncertainties scale as $1/\sqrt{L}$
  - Theory: assume reduction by factor 2
  - MC statistics assumed to give zero uncertainty
  - Experimental systematics scale as $1/\sqrt{L} \rightarrow$ until “floor”

- “Floor” values for all physics objects estimated and agreed
- Keeping “Run-2” and “stat-only” for comparison

Expecting to exceed expectations
Standard Model

Ultimate Precision Measurements
Parton density distributions based on differential cross sections at ultimate precision

Projection using pseudo-data $Z(\text{pt})$, high-mass DY, top quark pair, $W+$charm, direct photon and inclusive jets
Ultimate Precision Cross Sections

- Run-1 example: $\sigma_{\text{fid}}(Z/\gamma^* \rightarrow \ell\ell) = 502.2 \pm 0.3 \text{ (stat)} \pm 1.7 \text{ (syst)} \pm 9.0 \text{ (lumi)} \text{ pb}$

- Systematic uncertainties
  - Lepton ID: 0.3%
  - Lepton isolation: 0.15%
  - Signal modelling: 0.2%
  - Integrated luminosity: ~2%

- HL-LHC
  - Improved luminosity detectors (being designed)
  - Further refined Van-der-Meer analysis
  - Additional low-PU runs for cross section measurements (no uncertainty due to low-to-high PU extrapolation)

- Once measured at (sub-)percent level, Z-boson production rate can help luminosity measurement $\rightarrow$ planning for proof of concept in Run-3

Target luminosity uncertainty YR2018: 1%
Ultimate Precision W Mass

- $m_{\text{top}}$, $m_W$ and $m_H$ connected via loop corrections $\rightarrow$ constrain and test SM

- Current dominant uncertainty: PDF

- Low PU: high-resolution missing energy

- Extended $\eta$-range: measurements in central and forward regions are anti-correlated.

- Low-PU run ($\mu$~2) at HL-LHC:
  - 200 pb$^{-1}$, $|\eta|<2.4$: $2\times10^6$ evts. 16 MeV
  - 200 pb$^{-1}$, $|\eta|<4$: 12 MeV
  - 1 fb$^{-1}$, $|\eta|<4$: 9 MeV
  - + ultimate PDF: 5 MeV

![Diagram of $m_W$ and $m_t$](image-url)
Ultimate Precision Top Mass

- More statistics $\rightarrow$ samples and calibration
- Better systematics (both theory and experiment)
- Combination of different methods [arXiv:1807.06617]

$J/\psi$: $\delta m_{\text{top}} \sim 0.5 \text{ GeV}$

CMS-PAS-FTR-16-006

CMS Preliminary Projection

$m_{\text{pole}}$ from $\sigma(\text{tt})$

2ndary vertex

$J/\psi$

single top

$\ell$+jets

Run I 0.3/ab, 14 TeV 3/ab, 14 TeV

Total uncertainty on $m_t$ [GeV]
Higgs

Precise Properties and Couplings for H(125) Searches in the Higgs Sector
**Higgs Production and Decay**

- "k-model": Fit of scale-factors $\kappa$ to the data assuming SM processes

\[
\kappa_{Hff} = \frac{m_f}{v} \quad \kappa_{HVV} = \frac{2m^2_v}{v}
\]

---

Andreas B. Meyer  
Physics at the High-Luminosity LHC  
GK Seminar, Aachen, 25 May 2019
Higgs Measurements

Signal strength uncertainties: most channels ~3%, bb ~5%, µµ ~10%
After the discovery of the Higgs boson at the LHC, the first exploration of the couplings of the new particle at Run I and Run II has achieved an overall precision at the level of ten percent. One of the main goals of Higgs studies at the HL-LHC or HE-LHC will be to push the sensitivity to deviations in the coupling modifier parameters for the combination of ATLAS and CMS extrapolations. The first (S2) is the foreseen baseline scenario at HL-LHC, and the second (S2') for the theoretical and modelling systematic uncertainties are halved, which in many cases would correspond to uncertainties before the discovery of the Higgs boson at the LHC. The results are reported in Table 2.8 Higgs couplings precision overview in the Kappa-framework and the nonlinear EFT approach.

For each measurement, the total uncertainty is indicated by a grey box while the statistical, experimental and theory uncertainties are indicated by a blue, green and red line respectively. One of the main uncertainties in S2 (with YR18 systematic uncertainties) would also improve for S2'. The results for the relative expected uncertainty per experiment are given in Table 30. For the combination of ATLAS and CMS very consistent and there are roughly four times smaller than for current Run 2 analyses. It should be noted that HL-LHC measurements, whose precision is limited by systematic uncertainties, would also improve for S2'.

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ATLAS and CMS very consistent

μ: most channels ~3%, bb ~5%, μμ ~10%
**ttH → bb**

- For 3ab\(^{-1}\) CMS expects $\delta \mu \sim 7\%$
  - $tt+HF$ background constrained by data
  - dominant uncertainty on $\mu$: signal theory

- For ATLAS/CMS combination
  - CMS $tt+HF$ uncertainty set to 10%, no significant impact on $\kappa$-results
In the absence of the SM

The numbers are shown first for the entire SR, then for the last two bins of the BDT distribution where the background-only Asimov dataset. The signal is estimated using a fit to an Asimov dataset with selection criteria described in Section 3.3 Systematics and Results.

All sources of uncertainties are incorporated in the fit as nuisance uncertainties on the data-driven fake-systematic uncertainties are set to their Run 2 values unless otherwise stated. Analogously, the statistical uncertainties are set to their Run 2 values unless otherwise stated. In addition to the baseline scenario, an alternative conservative extrapolation is performed. Here, all sources of uncertainties are incorporated in the fit as nuisance uncertainties on the data-driven fake-systematic uncertainties are set to their Run 2 values unless otherwise stated.

---

- Ultimate goal: observation of trilinear coupling
- 120k HH events expected
- Best sensitivity (BR vs. bg): bbττ and bbγγ

---

**HH → bbμμ**

**CMS Phase-2 3000 fb⁻¹ (14 TeV)**

Simulation Preliminary

- Multijet
- Single τ
- Single Higgs
- Bkg. uncertainty
- SM HH (× 100)

**HH → bbbb**

**ATL-PHYS-PUB-2018-053**

ATLAS Preliminary

- SM HH → bbbbb
- 2b-tag
- 2-cut
- τ → τ had 2b-tag

**HH → bbττ**

**ATL-PHYS-PUB-2018-053**

ATLAS Simulation Preliminary

- SM HH → bbττ
- Single Higgs
- Others
- Reducible
- Others

**HH → bbγγ**

**CMS-FTR-18-019**

Simulation Preliminary

- Pseudo-data
- Nonresonant backgr.
- Full backgr.
- Sig. + Full backgr.

(a) m_γγ, high mass category

m_W [GeV]
- **Ultimate goal:** observation of trilinear coupling
- **120k HH events expected**
- **Best sensitivity (BR vs. bg):** $bb\tau\tau$ and $bb\gamma\gamma$

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$HH \rightarrow bbbb$</td>
<td>0.61</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\tau\tau$</td>
<td>2.1</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\gamma\gamma$</td>
<td>2.0</td>
</tr>
<tr>
<td>$HH \rightarrow bbVV(ll\nu\nu)$</td>
<td>-</td>
</tr>
<tr>
<td>$HH \rightarrow bbZZ(4l)$</td>
<td>-</td>
</tr>
<tr>
<td>combined</td>
<td>3.0</td>
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</table>

**Combined signal strength significance:** $4\sigma$ (stat. + syst.)

![Graph showing SM HH significance](Image)
Higgs Self-Coupling: HE-LHC combination

HE-LHC (15 ab\(^{-1}\) at 27 TeV) will be able to pin \(\kappa_\lambda\) down fully (~15%)
# Differential Higgs Measurements

**CMS FTR-18-020**

**CMS Phase-2 Simulation Preliminary**

3 ab⁻¹ (14 TeV)

<table>
<thead>
<tr>
<th>(fb/GeV)</th>
<th>Stat + exp. syst. + ggH+VH theo. uncert.</th>
<th>Hadronic categories only</th>
<th>Leptonic categories only</th>
<th>Expectation κₙ = 10</th>
<th>Expectation κₙ = -5</th>
<th>ttH+H theo. uncert.</th>
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</thead>
<tbody>
<tr>
<td>t(t)H → γγ</td>
<td><img src="graph.png" alt="Graph" /></td>
<td><img src="graph.png" alt="Graph" /></td>
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<td><img src="graph.png" alt="Graph" /></td>
<td><img src="graph.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

- **pₜ(Higgs) distribution:**
  - t(t)H: sensitive to self-coupling κₙ
  - ggH: sensitive to interference between quark loops → κₖ and κₗ

**CMS FTR-18-011**

**CMS Projection**

3000 fb⁻¹ (13 TeV)

![Graph](graph.png)

With 3000 fb⁻¹ constrain κₖ and κₙ to a few times SM
Higgs and Charm

- Summary of limits on $\kappa_{c,s,d,u}$ (for 2 x 3000 fb$^{-1}$)
  - global fit to production cross section ($\kappa$-fit)
  - direct search for a cc final state (VHcc)
  - differential cross-sections (e.g. previous page)
  - total width (off/on-sh & interf. in pp $\rightarrow 4\ell$ and $\gamma\gamma$)
  - exclusive decays (e.g. $H \rightarrow J/\psi\gamma$)

ZH $\rightarrow \ell\ell cc$
$\mu < 6.3 \times SM$

ZH $\rightarrow \ell\ell cc$  [arXiv:1802.04329]
- ATLAS (Run-2) HL-LHC: $\mu < (110) \ 6.3 \times SM @ 95CL$
- VH($\rightarrow$cc):  [LHCb-CONF-2016-006]
  - LHCb (Run-1) 300 fb$^{-1}$: $\mu < (7900) \ 5-10 \times SM$

With further improvements, Higgs-charm could be in reach
Vector Boson Scattering

- Longitudinal VBS, $V_L V_L \rightarrow V_L V_L$ cross section:
  - unitarized by scalar Higgs and/or new physics
  - in SM few percent of total EWK VBS

$V_L V_L$ discovery significance $\sim 3\sigma$ / experiment
BSM Higgs

- From kappa fit (for $\kappa_V < 1$): $B_{BSM} < 2.5\%$
- Direct $h \rightarrow$ invisible: $B_{inv} < 2.5\%$  
  [ATL-PHYS-PUB-2013-014  CMS-FTR-18-016]
- MSSM Higgs: $H/A \rightarrow \tau\tau$: $M_A$ limit increased to $\sim 2$ TeV
- CP-odd Hff couplings from $\tau\tau$ spin correlations (limits so far only for HVV)
  - $H \rightarrow \tau\tau$ with $\tau^{\pm} \rightarrow q^{\pm}\nu_{\tau} \rightarrow \pi^{\pm}\pi^{0}$
  - $\varphi_{CP}^* = \text{angle between the two } \tau \text{ decay planes}$
  - Sensitivity strongly depends on $\pi^0$ resolution and $\tau$-ID

Frame: $\Sigma p(\text{vis. dec. products}) = 0$

Possible exclusion of CP-odd $H\tau\tau$ coupling with this analysis alone: $\sim 2\sigma$
Direct Searches

Supersymmetry, Long-Lived Particles, Dark Matter, Heavy Resonances
Direct Searches

ATLAS Preliminary
Projection from Run-2 data
$\sqrt{s} = 14$ TeV, 3000 fb$^{-1}$
Sign region, 4-tag
Scaling from 4b simulation

CMS-FTR-18-001
Andreas B. Meyer                                     Physics at the High-Luminosity LHC                                 GK Seminar, Aachen, 25 May 2019

Phase-2 Simulation Preliminary
Expected 95% CL limit
$\sim 200 \chi_{-1}$

CMS
$pp \rightarrow 150 \chi_{-1} \rightarrow HH \rightarrow 4b$

ATL-PHYS-PUB-2018-028
1000 $Z \chi_{-1} \sim 200 = m \sim \chi_{-1}$

$\sim 200 \chi_{01}$
$1000 \chi_{01} \rightarrow 0$ lepton final state

CMS-FTR-18-004

Top-Quark FCNC
$3000 fb^{-1} (14$ TeV)

CMS Phase-2 Simulation Preliminary
$\sqrt{s} = 14$ TeV, 3 ab$^{-1}$

CMS-FTR-18-002

Electroweakinos

CMS Phase-2 Simulation Preliminary
3 ab$^{-1} (14$ TeV)

CMS-FTR-18-001

$pp \rightarrow 1200 \chi_{-1} \rightarrow HH \rightarrow 4b$

ATL-PHYS-PUB-2018-048

ATLAS Simulation Preliminary
Run-2 Uncertainties
$f=14$ TeV, 3000 fb$^{-1}$

ATLAS 13 TeV, 80 fb$^{-1}$
All limits at 95% CL

$\sim 200 \chi_{-1}$

CMS-FTR-18-016

Invisible Higgs

CMS Phase-2 Simulation Preliminary
$\sqrt{s} = 14$ TeV, 3 ab$^{-1}$

95% CL upper limit on $\sigma \times \text{BR}(H \rightarrow \text{inv}) / \sigma_{\text{SM}}$ (%)

CMS-FTR-18-003

Direct searches by ATLAS and CMS

Stop production

ATL-PHYS-PUB-2018-021

$TT \rightarrow \chi_{-1} \chi_{-1}$ - 0 lepton final state

CMS-FTR-18-002

$\sim 200 \chi_{-1}$

Stop production

ATL-PHYS-PUB-2018-021

$\sim 200 \chi_{-1}$

Stop production

ATL-PHYS-PUB-2018-021

$\sim 200 \chi_{-1}$
Heavy Resonances

- Heavy Vector Triplet (HVT) model: composite Higgs and three additional vector bosons $Z'$ and $W'^\pm$
  $Z'$ and $W'^\pm \rightarrow WW, WZ$ or $ZZ$

- Randall-Sundrum-Gluon: $RSG \rightarrow tt$

![Diagram of jet substructure variables with measurements at higher integrated luminosities.](image)

3 ab$^{-1}$ (14 TeV)

**CMS Phase-2 Simulation Preliminary**

<table>
<thead>
<tr>
<th>Event Channel</th>
<th>0 t tag</th>
<th>Other</th>
<th>RSG (3 TeV)</th>
<th>RSG (6 TeV)</th>
<th>RSG (12 TeV)</th>
<th>Bkg uncertainty</th>
</tr>
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<td></td>
<td>events</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

![ATLAS Simulation](image)

$\sigma(pp \rightarrow ZZ', WW)[pb]$ $q\bar{q}$ HVT

- Expected 95% CL Limit 3000 fb$^{-1}$
- Expected 95% CL Limit 300 fb$^{-1}$
- Expected Limit 3000 fb$^{-1}$ ($\pm 1\sigma$)
- Expected Limit 3000 fb$^{-1}$ ($\pm 2\sigma$)

**Z' $\rightarrow WW$**

![CMS-FTR-18-009](image)

15 ab$^{-1}$ (27 TeV)

**CMS HE-LHC Simulation Preliminary**

- Signal cross section
- Median expected
- 68% expected
- 95% expected

**RSG $\rightarrow tt$**

Mass reach: exclusion up to 5-6 TeV at HL-LHC — 10-11 TeV at HE-LHC

Andreas B. Meyer

Physics at the high-luminosity LHC

GK Seminar, Aachen, 25 May 2019
Supersymmetry

- Strong SUSY ($\sigma \approx 1$ pb at $m = 500$ GeV): many scenarios already excluded up to 1 TeV
- Electroweak SUSY ($\sigma < 0.1$ pb at $m = 500$ GeV): could still be light
Stau pairs:
- Final state: $\tau_h\tau_h$ or $\ell\tau_h$ + MET
- Run-2: No stringent limits yet
- HL-LHC excl. limit: 650 GeV

Electroweakinos:
- Degenerate mass scenarios $\rightarrow$ compressed spectra and/or long lifetimes
- Use ISR jet for triggering
- Detect disappearing track

Electroweak SUSY

**CMS** CMS-FTR-18-010 3 ab$^{-1}$ (14 TeV)

- Expected exclusion
- Expected discovery

### Sensitivity to new scenarios

**Mass $m(\chi^\pm_1)$ [GeV]**

**Disappearing Track Analysis**

ATLAS Simulation Preliminary
$\sqrt{s}=14$ TeV, 3000 $fb^{-1}$, $\mu = 200$
All limits at 95% CL

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Andreas B. Meyer

Physics at the High-Luminosity LHC

GK Seminar, Aachen, 25 May 2019
Long-Lived Particles

- Various scenarios: mass degeneracy, small couplings, heavy mediators
- Many SM particles are long-lived, too!
- Detect LLP signatures → creative analysis approaches (campaign since Run-2)
- Dedicated LHC experiments: Codex-b, Mathusla, MilliQan, Faser

Significant benefits from improved detectors
Dark Sector

Displaced muons from long-lived dark photons

H → 4µ + X

Dark photons in B decays

A' → µµ (or ee)

Excluded

ATLAS+CMS

Summary of dark photon limits

arXiv:1808.08865 extended WG3

LHC minimal

HL-LHC minimal

LHC B\(_{H \rightarrow A'A'} = 10\%

HL-LHC B\(_{H \rightarrow A'A'} = 10\%

m\(_{A'}\) [GeV]
Dark Matter …

- … is known to exist: → uncover its elementary nature at the LHC (?)
- Simplified models for comparison with direct detection experiments

** mono-Z: **

** mono-top: **

** Figure 5:** Expected 95% CLs upper limits on the signal cross-section as a function of the mass of the mediator for the non-resonant model assuming $m_{\chi} = 1$ GeV, $a = 0.5$ and $g = 1$ using a BDT analysis. The MC statistical uncertainty is not considered but the full set of systematics, extrapolated from the 13 TeV analysis is considered.

** Limit on $m_{V} \sim 4.5$ TeV (for $m_{DM} = 1$ GeV, $a=0.5$ and $g=1$) **

** CMS-FTR-18-007**

** CMS Projection 3.0 ab$^{-1}$ (14 TeV)**

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<th>Vector mediator, Dirac DM</th>
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** Expected 95% CL limit on $\mu$ (YR18)**

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** Expected 95% CL limit on $\mu$ (YR18)**
Flavour

Low $p_T$ / High $p_T$ Complementarity
Flavour Physics

expectation using 50fb⁻¹ LHCb and 50ab⁻¹ Belle II data

ATLAS and CMS can help in a few channels

In several areas LHCb (also Belle) w/o cross check

Classical CKM metrology

excluded area has CL > 0.95

γ(α)

|Vub|

γ & γ(α) & |Vub|

HFLAV

CMS-FTR-18-013

Simulation Preliminary

Toy events

B⁻→µ⁺ν

B⁻→µ⁻ν

B⁻→ν⁻µ⁺

B→ν⁻µ⁺

Combinatorial bkg

Semileptonic bkg

B→ν⁻µ⁺ bkg

Peaking bkg

B⁰(τ)→µµ

P⁺ from B→K⁺μμ

LHCb data

ATLAS data

Belle data

SM from DHMV

SM from ASZB

HFLAV Moriond 2019

ΔαCP

HFLAV

arXiv:1903.08726

Simplicity:精彩的观察到的角动量分析

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LHCb

Ω⁺(3030)

Ω⁺(3090)

Ω⁺(3140)

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Spectroscopy
Flavour Anomalies: Low $p_T$

- Tension in current measurements
  - $R(K^*)$, $b\rightarrow s\mu\mu$: 2-3$\sigma$ below expectation
  - $R(D^*)$, $b\rightarrow c\tau\nu$: 3-4$\sigma$ above expectation
  - $P_5'$ from $B\rightarrow K^+\mu\mu$: LHCb also in tension

- LHCb will measure several more channels, also with $B_S, \Lambda_b$ and $B_c$
-- Flavour Anomalies: High $p_T$ --

- **R($K^*$) $b \rightarrow s \ell \ell$**
  - Theoretically very clean
  - Could be explained by LQ or flavour violating $Z'$
  - However, $Z' \rightarrow \mu \mu$ already excluded (EFT)

- **R($D$) and R($D^*$): $b \rightarrow c \ell \nu$**
  - Good fits for $W'$ vector, scalar or vector-like
  - Full range of LQ searches,
    Exclude LQ$\rightarrow t \ell$ up to $M_{LQ} \sim 2$ TeV

  LQ could explain R($D^*$) and R($K^*$)
  Could this be a no-lose theorem?
Heavy Ion Physics

Precise Differential Measurements
Heavy Ion Physics

- Determine material properties of QCD media (Flow behaviour, long-range correlations, nPDF)
- Study HI-like behaviour also in pp and pA
- Future HI running (Run-3 and Run-4):
  - Factor ~20 (100) more data for CMS, ATLAS (Alice)
  - Allow for precise differential measurements

Exclusion limits on Axion-like particle (ALP) masses vs coupling from light-by-light scattering in UPC

![Graph showing exclusion limits on Axion-like particle (ALP) masses vs coupling from light-by-light scattering in UPC](image)

**CMS**

**Projection**

**CMS-FTR-18-024**

- $B^+$, 10 nb$^{-1}$
- Non-prompt J/ψ, 10 nb$^{-1}$
- $B_s$, 10 nb$^{-1}$

**CMS-FTR-18-027**

- $\sqrt{s_{NN}} = 5.02\text{ TeV}$

**CMS**

**Simulation**

- $pp + PbPb (2000\text{ pb}^{-1}, \sqrt{s_{NN}}=8.16\text{ TeV})$
- Pseudo-data
- $pPb \rightarrow t\bar{t}$ Powheg (EPPS16)

**ATL-PHYS-PUB-2018-018**

**CMS-FTR-18-024**

**CMS-FTR-18-027**

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**CMS-FTR-18-027**
Summary

- **HL-LHC**: superior detectors, refined analyses, advanced theory
  - Recent detailed update and extension of HL-LHC projections

- **3000 fb$^{-1}$ of extremely rich and exciting physics**
  - Standard model: ultimate precision and rare processes
  - Higgs: precise determination of the H(125) properties and searches
  - Direct searches: discover new physics or close a few chapters
  - Flavour: high/low $p_T$ complementarity
  - Heavy Ion: precise differential measurements

**Expecting to exceed expectations**