PROSPECTS FOR QCD, EWK AND TOP PHYSICS AT THE (HL-)LHC

R. Schöfbeck, HEPHY Vienna
### LHC Long Term Schedule

#### 2021 - 2029

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>Run 3</td>
<td>~2x10^{34} cm^{-2}s^{-1}</td>
</tr>
<tr>
<td>2022</td>
<td></td>
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<tr>
<td>2023</td>
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<td>2024</td>
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<td>2025</td>
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<td>2026</td>
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<td>2027</td>
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<td>2028</td>
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<tr>
<td>2029</td>
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</tr>
</tbody>
</table>

**Note:** Last significant low PU run of PU 40-60

Run 3(+2): 300-350 fb^{-1}

![Calendar image with Run 3 and Run 4 marked]

#### 2030 - 2038

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030</td>
<td>Run 4</td>
<td>(~5-7) 10^{34} cm^{-2}s^{-1}, 3-4 ab^{-1}, PU 140-200</td>
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<tr>
<td>2031</td>
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<tr>
<td>2032</td>
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<tr>
<td>2037</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2038</td>
<td>Run 5</td>
<td></td>
</tr>
</tbody>
</table>

**Note:** Major detector upgrades in LS3

![Calendar image with Run 4, LS4, and Run 5 marked]

Last updated: January 2022

- Shutdown/Technical stop
- Protons physics
- Ions
- Commissioning with beam
- Hardware commissioning/magnet training
CMS UPGRADES FOR HL-LHC

**Improved muon coverage and trigger**

- Increased RPC coverage ($1.5 < |\eta| < 2.4$)
- New electronics

[CMS-TDR-016]

**New precision timing detector**

- Timing resolution of 30-40 ps for MIPs
- Full coverage of $|\eta| < 3.0$

[CMS-TDR-020]

**New endcap calorimeters**

- High granularity
- Can reconstruct showers in 3D

CMS-TDR-019

**Updates to calorimeter and trigger**

- Higher granularity
- Electronics for trigger

**New inner tracker**

- All silicon tracker
- 4 layers of pixels
- 5 layers of strips
- Coverage to $|\eta| < 4$

[L1: CMS-TDR-021]

[DAQ/HLT: CMS-TDR-022]

**Upgrade to trigger and DAQ**

- L1 rate increased to 750 kHz
- High Level trigger rate to 7.5 kHz
- Track information at L1
ATLAS UPGRADES FOR HL-LHC

Inner Tracking Detector (ITk)
All silicon, strips and Pixels up to $|\eta| \leq 4$
[ATLAS-TDR-025, ATLAS-TDR-030]

Muon system upgrade
New chambers in the Inner barrel region ($|\eta| \leq 2.7$)
[ATLAS-TDR-026]

High granularity timing detector (HGTD) $2.4 \leq |\eta| \leq 4.0$ with 30ps
[ATLAS-TDR-031]

Upgraded Trigger and Data Acquisition System
[ATLAS-TDR-029]
FURTHER READING

• HL/HE-LHC WG Yellow report (2018-19)
  • [SM Physics] [Higgs Physics] [Beyond the SM] [Flavour Physics] [High-density QCD]
• European Particle Physics Strategy Update (EPPSU) [Physics Briefing Book]
• Snowmass Community Planning Exercise (until Oct. 2022) & [Snowmass White paper]
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FREQUENTLY MADE ASSUMPTIONS

• “more data”: scale statistical uncertainties with luminosity
• “can afford computing”: no statistical uncertainty in simulation
• “anticipate accompanying theory developments”: reduce theoretical uncertainties to 50%
  • cross sections, ISR/FSR scale, PDF, tuning, b-fragmentation, ren./fact. scales, color reconnection
• “detector upgrades balance harsh conditions”: 1) nominal exp uncertainties from Run II analyses 2) statistical component reduced with lumi 3) lumi at 1%
RECONSTRUCTION PERFORMANCE

- ATLAS ITk nuclear interaction length vs. $\eta$ with extended tracking coverage.
- Impacts $b$-tagging performance similar to Run II (200PU & up to $|\eta| < 4$).
- Excellent & stable PU jet rejection across all PU densities.
- $E_T^{\text{miss}}$ resolution not much worse than in Run II.

Puppi $E_T^{\text{miss}}$ resolution for $p_T(Z) > 30$ GeV.

Hard-scatter jet efficiency vs. PU density.

[ATL-PHYS-PUB-2021-024, ATL-PHYS-PUB-2021-023]
TOP QUARK MEASUREMENTS

• A great many things have to come together
  1. state of the art theoretical tools/calculations
  2. low-level understanding of sub-detector performance
  3. object performance – realistic projections
  4. novel analysis ideas that incorporate 1-3

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• kinematic reach
  • NNLO QCD for HL-LHC 14 TeV with 3/ab
  • EWK corrections essential for precision
  • increase reach by several TeV

Cumulative $M_{tt}$ distribution for HL-LHC

≈10 events $M_{tt} > 7$ TeV
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• kinematic reach
  • NNLO QCD for HL-LHC 14 TeV with 3/ab
  • EWK corrections essential for precision
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Cumulative $p_T(t)$ distribution for HL-LHC

≈20 events

$p_T > 2.5$ TeV

TeV scale jets/leptons collimated to slim jets: $\Delta R \approx 0.13$

(16cm @ CMS ECAL)
**PRECISION FROM THE BULK AND FROM HIGH ETA**

- uncertainty on differential top x-sec O(5%)
- significant impact on high x gluon PDF

![Graph showing differential cross section vs. p_{T}(t) for CMS Phase-2 simulation and preliminary parton level with various uncertainties.

![Graph showing CMS Phase-2 Simulation Preliminary events / 40 GeV with NLO NNPDF3.1 and NLO NNPDF3.1 + tt with experimental uncertainty.

[M. Guzzi: tt+jets on CT18]

[arXiv:1311.1810]
[arXiv:1808.08865]
• uncertainty on differential top x-sec $O(5\%)$
• significant impact on high x gluon PDF
• complemented with forward tops:
  1. 300/fb LHCb data probe high-x PDFs with partially reconstructed top quarks
  2. quark PDFs: use differential charge asymmetry vs. lepton $\eta$

quark PDFs:
  - differential $l^\pm b$ charge asymmetry vs $\eta_l$
  - (300/fb for HL/LHC)
PDFs AT HL-LHC

- ultimately: Drell-Yan at all $m(\ell\ell)$, top quarks, W+charm, direct $\gamma$, forward W+Z, inclusive jets

- ATLAS direct $\gamma$ up to $E_T^\gamma \approx 2$ TeV with good statistics

- differential high- $E_T^\gamma$ x-sec ratio for different PDF sets

- “ultimate” PDF precision for projected measurements: > factor 2
• simple concept:
  1. pick out jets from top
  2. pair up the right jets to each top
  3. calculate mass

• challenges (a selection)
  • efficient b tagging (combinatorics)
  • moderate $p_T$ triggers
  • relate the ‘MC mass’ to a well defined parameter in a ren. scheme to 100 MeV [e.g. here]  
  • precision JES & $E_T^{miss}$, lepton E scale

• top mass measurement requires precision on all fronts!
TOP MASS

- simple concept:
  1. pick out jets from top
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  - moderate $p_T$ triggers
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  - precision JES & $E_T^{miss}$, lepton E scale

- Mitigate JES by considering 0.04% BR with a J/Psi: $t\bar{t} \rightarrow (W^+ b)(W^- b) 
  \rightarrow (\ell\nu\ell J/\psi(\rightarrow \mu^+\mu^-)X)(qq')$

ATLAS J/$\Psi$ projection 
± 0.14 (stat) ± 0.48 sys
(fragmentation modelling)

0.17 GeV → 0.1 % dominated by JES

0.3 ab$^{-1}$, 14 TeV  3 ab$^{-1}$, 14 TeV

Run I

Precision mass measurement requires precision on all fronts!
SPIN CORRELATION

- Fully reconstructed **dileptonic top pairs** provide access to polarization and **spin correlation observables**.
- Projection based on **Run II analysis**, 50% theory unc.

- 40% improvement for the most sensitive measurement of the **spin correlation strength**
- Set limits in SUSY top squark using a **parametric DNN**, trained on 19 kinematic features
- Improving SUSY mass limits by x10 where $M_{\text{stop}} \gtrsim M_{\text{top}}$ (corridor) and traditional SUSY searches are inefficient

[CMS-FTR-18-034]
[CMS-TOP-18-006]
FOUR TOP PRODUCTION

- complete NLO cross section $15.8 \text{ fb} \pm 20\%$ known (EWK: 11\%)
  - Enhanced in BSM scenarios (SUSY gluinos, sgluons, 2HDM)
  - Relevant for $\gamma_t$ measurement, and 4-fermion operators in SM-EFT

$$\sigma(t\bar{t}t\bar{t}) = 13.14 - 2.01\kappa_t^2 + 1.52\kappa_t^4 \text{ [fb]} \ (13 \text{ TeV})$$

- ATLAS Run II observes $4.7\sigma \ (2.6\sigma)$, $1.9\sigma$ above SM

$$\mu = 2.2 \pm 0.7 \text{ (stat.)}^{+1.5}_{-1.0} \text{ (syst.)} = 2.2^{+1.6}_{-1.2}$$
  - important: ttW + 7/≥ 8 jets modelling

1. Run II (ttW nuisance post-fit)
2. Run II “improved”
   - 50\% theory uncertainties
   - scale down ttX+HF uncertainties with $\mathcal{L}$
   - keep exp. uncertainties

- CMS limits on 4-top contact interactions

[EPJC 80 (2020) 1085, CMS-PAS-FTR-18-031]
[ATL-PHYS-PUB-§2022-004, JHEP 11 (2021) 118]
FOUR TOP PRODUCTION

- complete NLO cross section $15.8 \text{ fb} \pm 20\%$ known (EWK: 11\%)
  - Enhanced in BSM scenarios (SUSY gluinos, sgluons, 2HDM)
  - Relevant for $y_t$ measurement, and 4-fermion operators in SM-EFT

\[
\sigma(t\bar{t}t\bar{t}) = 13.14 - 2.01\kappa_t^2 + 1.52\kappa_t^4 \ [\text{fb}] \ (13 \text{ TeV})
\]

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\[\mu = 2.2 \pm 0.7 \text{ (stat.)} ^{+1.5}_{-1.0} \text{ (syst.)} = 2.2 ^{+1.6}_{-1.2}\]
  - important: $t\bar{t}W + 7/\geq 8$ jets modelling

1. Run II (ttW nuisance post-fit)
2. Run II “improved”
   - 50\% theory uncertainties
   - scale down $ttX+HF$ uncertainties with $\mathcal{L}$
   - keep exp. uncertainties

- CMS limits on 4-top contact interactions

[EPJC 80 (2020) 1085, CMS-PAS-FTR-18-031]
TOP-Z/γ COUPLING MEASUREMENTS

- ATLAS/CMS study using $p_T(Z)$ and $p_T(γ)$ with Delphes
  - Constrain t-Z/γ coupling modifications
- ATLAS projects constraints for ttγ (1l/2l)
  - 5-7% uncertainty up to $p_T(γ) \approx 1$ TeV
- CMS ttZ (3ℓ): Up to factor 4 sensitivity improvements for EWK interactions of the top quark
• $M_W$: dedicated low-PU runs @ $\langle \mu \rangle \approx 2$
  • $200 \text{ pb}^{-1} \approx O(\text{weeks}), 1\text{ fb}^{-1} \approx O(\text{months})$

• projection study by ATLAS
  • realistic combination of $m_T$ & $p_T(\ell)$ fits
  • comparing different PDF sets
  • “HL-LHC” incorporates future constraints
  • high $\eta$ bins important – 40% improvement
    • anti-correlation between different $\eta$ bins
    • also expected for ATLAS/CMS/LHCb combination
      M.Pernas, LHCb talk!
DIBOSON VBS PRODUCTION

• Higgs observation established that W and Z acquire mass via BEH mechanism

• Vector boson scattering (VBS) is crucial in testing the fundamentals of the BEH
  • pert. non-unitarity for $W_L W_L$ at $s \sim 1.2$ TeV
DIBOSON VBS PRODUCTION

- Higgs observation established that W and Z acquire mass via BEH mechanism
- Vector boson scattering (VBS) is crucial in testing the fundamentals of the BEH
  - pert. non-unitarity for $W_L W_L$ at $s \sim 1.2$ TeV
- LHC “laboratories”: VBS systems
  - 2 jets, large $M_{jj}$, larger rapidity separation
  - Small deviations lead to large changes in predictions for EW induced VBS
VBS DIBOSON SIGNATURES NOW AND IN THE FUTURE

$W^\pm W^\pm$

$W^\pm Z$

$ZZ$

$Z\gamma$

$\sigma_{[13 \text{ TeV}]} = 6.5\sigma$

$\sigma_{[13 \text{ TeV}]} = 5.7\sigma$

$\sigma_{[13 \text{ TeV}]} = 5.3\sigma$

$\sigma_{[13 \text{ TeV}]} = 6.8\sigma$

$\sigma_{[13 \text{ TeV}]} = 5.5\sigma$

$\sigma_{[13 \text{ TeV}]} = 4\sigma$

$\sigma_{[13 \text{ TeV}]} > 5\sigma$
VBS DIBOSON SIGNATURES NOW AND IN THE FUTURE

\[ W^\pm W^\pm \]

- \([13 \text{ TeV}] 6.5\sigma\]
- \([13 \text{ TeV}] 5.7\sigma\]
- \([\text{projection}] \sigma(\text{x-sec}) = 6\% \]
- \(\sigma(W_LW_L) = 1.8\sigma\]

\[ W^\pm Z \]

- \([13 \text{ TeV}] 5.3\sigma\]
- \([13 \text{ TeV}] 6.8\sigma\]
- \([\text{projection}] \sigma(\text{x-sec}) = 3\% \]
- \(\sigma(W_LW_L) = 2.7\sigma\]

\[ ZZ \]

- \([13 \text{ TeV}] 5.5\sigma\]
- \([13 \text{ TeV}] 4\sigma\]
- \([\text{projection}] \sigma(\text{x-sec}) = 20\% - 100\% \]
- \(\sigma(Z_LZ_L) : 4\sigma\]

\[ Z\gamma \]

- \([13 \text{ TeV}] 4.1\sigma\]
- \([13 \text{ TeV}] >5\sigma\]
- \([\text{projection}] \sigma(\text{x-sec}) \approx 10\% \]

\[ W^\pm Z \]

- \([13 \text{ TeV}] +27\% \text{ purity from MVA ind. pol., } F_0(W^+) : 2.5\sigma\]
- \([\text{projection}] \sigma(\text{x-sec}) = 3\% - 5\% \]
- \(W_LZ_L \approx 1.5\sigma\]

\[ W^\pm L^\pm \]

- \([13 \text{ TeV}] \sigma(\text{x-sec}) = 6\% \]
- \(\sigma(W_LW_L) = 1.8\sigma\]

\[ ZZ \]

- \([13 \text{ TeV}] \sigma(\text{x-sec}) = 3\% \]
- \(\sigma(Z_LZ_L) : 4\sigma\]
- \([\text{projection}] \sigma(\text{x-sec}) \approx 10\% \]

\[ ZZ \]

- \([13 \text{ TeV}] \sigma(\text{x-sec}) = 6\% \]
- \(\sigma(Z_LZ_L) : 4\sigma\]
- \([\text{projection}] \sigma(Z_LZ_L) : 4\sigma\]

CMS EXTRAPOLATION FOR $W^\pm W^\pm$ AND WZ

- targets EWK production of $W^\pm W^\pm$, Run II based
  - same-sign WW: comparably low backgrounds
  - YR study by ATLAS YR [ATLAS-PHYS-PUB-2018-052]
- $W_L$ radiated closer to the quark direction
  - lower $p_T$ and changes in decay angle distributions
  - $W_L^\pm W_L^\pm$ ($10.9\%$), $W_L^\pm W_T^\pm$ ($31.9\%$), $W_T^\pm W_T^\pm$ ($57.2\%$)
- Extrapolation: Follows Run II strategy
  - Fit in BDT discriminants, sensitive to differences in polarized components
- significance of $\sigma_{WLWL} \approx 4\sigma$
  - $>5\sigma$ in ATLAS combination
  - one of the last LHC discoveries could tackle one of the earliest SM LHC predictions
SUMMARY

• With $3ab^{-1}$ HL-LHC will be the workhorse for many years to come
  • We’re now convinced that PU$_{140-200}$ is a challenge we can meet
  • Detector upgrades enlarge the physics scope
  • Highly energetic tails and low-xsec processes pose many sensitive tests of the SM – many of them new

• Improvements on theoretical and modelling uncertainties crucial!

• The value of upgrade studies is to facilitate new ideas!
  • The best is yet to come!
MW UNCERTAINTY CORRELATIONS

\[ m_W \text{ from } m_T, \text{ CT10 PDF} \]

**ATLAS Simulation Preliminary**

\[ \sqrt{s} = 27 \text{ TeV} \]

\[ \sqrt{s} = 14 \text{ TeV} \]

\[ |\eta| \]
$M_W$ UNCERTAINTY EVOLUTION (FULL FIT)

$[M_W$ extrapolation$]$
## Uncertainty Details (Top Mass)

<table>
<thead>
<tr>
<th>Source</th>
<th>8 TeV, 19.7 fb$^{-1}$</th>
<th>14 TeV, 0.3 ab$^{-1}$</th>
<th>14 TeV, 3 ab$^{-1}$</th>
<th>Comment</th>
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<tbody>
<tr>
<td>Method calibration</td>
<td>±0.04</td>
<td>±0.02</td>
<td>±0.02</td>
<td>MC stat. ×4</td>
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<tr>
<td>Lepton energy scale</td>
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<td>±0.01</td>
<td>±0.01</td>
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<tr>
<td>Global JES</td>
<td>±0.13</td>
<td>±0.12</td>
<td>±0.04</td>
<td>3D fit, differential</td>
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<tr>
<td>Flavor-dependent JES</td>
<td>±0.19</td>
<td>±0.17</td>
<td>±0.06</td>
<td>3D fit, differential</td>
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<tr>
<td>Jet energy resolution</td>
<td>−0.03</td>
<td>±0.02</td>
<td>&lt; 0.01</td>
<td>differential</td>
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<td>$E_T$\text{miss} scale</td>
<td>+0.04</td>
<td>±0.04</td>
<td>±0.04</td>
<td>unchanged</td>
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<tr>
<td>b tagging efficiency</td>
<td>+0.06</td>
<td>±0.03</td>
<td>±0.03</td>
<td>improved with data</td>
</tr>
<tr>
<td>Pileup</td>
<td>−0.04</td>
<td>±0.04</td>
<td>±0.04</td>
<td>unchanged</td>
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<tr>
<td>Backgrounds</td>
<td>±0.03</td>
<td>±0.01</td>
<td>±0.01</td>
<td>cross sections</td>
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<tr>
<td>ME generator</td>
<td>−0.12 ± 0.08</td>
<td>−</td>
<td>−</td>
<td>NLO ME generator</td>
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<tr>
<td>Ren. and fact. scales</td>
<td>−0.09 ± 0.07</td>
<td>±0.06</td>
<td>±0.06</td>
<td>NLO ME generator, MC stat.</td>
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<td>ME-PS matching</td>
<td>+0.03 ± 0.07</td>
<td>±0.06</td>
<td>±0.06</td>
<td>MC stat.</td>
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<td>Top quark $p_T$</td>
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<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
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<tr>
<td>b fragmentation</td>
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<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>unchanged</td>
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<td>Semileptonic b hadron decays</td>
<td>−0.16</td>
<td>±0.11</td>
<td>±0.06</td>
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<tr>
<td>Underlying event</td>
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<td>±0.14</td>
<td>±0.09</td>
<td>improved with data, MC stat.</td>
</tr>
<tr>
<td>Color reconnection</td>
<td>+0.01 ± 0.09</td>
<td>±0.05</td>
<td>&lt; 0.01</td>
<td>improved with data</td>
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<tr>
<td>PDF</td>
<td>±0.04</td>
<td>±0.03</td>
<td>±0.02</td>
<td>improved with data</td>
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<tr>
<td>Systematic uncertainty</td>
<td>±0.48</td>
<td>±0.30</td>
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<tr>
<td>Statistical uncertainty</td>
<td>±0.16</td>
<td>±0.04</td>
<td>±0.02</td>
<td></td>
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<tr>
<td>Total</td>
<td>±0.51</td>
<td>±0.31</td>
<td>±0.17</td>
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</tr>
</tbody>
</table>
COMMON SYSTEMATICS

- Renormalization and factorization scales (includes ME and PS): factor 1/2 (improve with more data and more studies)
- Top pt: factor 1/3 or even less (more differential cross sections, NLO generators, 2D-differential NNLO predictions used for differential k-factors.)
- MC statistics: no uncertainty
- https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCCommonSystematics

<table>
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<tr>
<th>Object Efficiency</th>
<th>uncertainty</th>
<th>Recommendation</th>
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<tbody>
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<td>Muons</td>
<td></td>
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<tr>
<td>muon reco+ID (all WP)</td>
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<td>0.1%</td>
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<tr>
<td>muon reco+ID+isolation (all WP)</td>
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<td>0.5%</td>
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<tr>
<td>Electrons/photons</td>
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</tr>
<tr>
<td>electron reco+ID (incl. isolation), all WP (pt &gt; 20 GeV)</td>
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<td>0.5%</td>
</tr>
<tr>
<td>photon reco+ID+incl. isolation)</td>
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<td>~2% (?)</td>
</tr>
<tr>
<td>tau</td>
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<tr>
<td>tau reco+ID+isolation (all WP)</td>
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<td>5% as in Run2</td>
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<td>flavor tagging</td>
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<tr>
<td>b-jets (all working points)</td>
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<td>~1% for 30&lt;pt&lt;300 GeV, 2-6% for pt&gt;300 GeV</td>
</tr>
<tr>
<td>c-jets (all working points)</td>
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<td>~2%</td>
</tr>
<tr>
<td>light jets (loose WP)</td>
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<td>5%</td>
</tr>
<tr>
<td>light jets (medium WP)</td>
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<td>10%</td>
</tr>
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<td>light jets (tight WP)</td>
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<td>15%</td>
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<td>Jets</td>
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<td></td>
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<tr>
<td>JES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>abs. scale</td>
<td></td>
<td>0.1-0.2%</td>
</tr>
<tr>
<td>rel. scale</td>
<td></td>
<td>0.1-0.5%</td>
</tr>
<tr>
<td>Pile up</td>
<td></td>
<td>0-2%</td>
</tr>
<tr>
<td>Jet Flavour</td>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td>JER</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet substructure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet mass scale uncertainty</td>
<td></td>
<td>1%</td>
</tr>
<tr>
<td>Jet mass resolution</td>
<td></td>
<td>10%</td>
</tr>
<tr>
<td>W tagging efficiency</td>
<td></td>
<td>10% (governed by Herwig vs Pythia)</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td></td>
<td>1%</td>
</tr>
</tbody>
</table>
Fig. 70: Expected signal yields (top-left), migration matrices (top-right), and its properties (bottom) for measurements of $p_T(t_h)$ for the HL-LHC (Phase-2) simulation. The purity is defined as the fraction of parton-level top quarks in the same bin at the detector level, the stability as the fraction of detector-level top quarks in the same bin at the parton level, and the bin efficiency as the ratio of the number of events found in a certain bin at detector level and the number of events found at parton-level in the same bin.
# CMS $W^\pm W^\pm$ VBS SELECTION

Table 2: Selection to define the $W^\pm W^\pm$ and WZ SRs. The looser lepton $p_T$ requirement on the WZ selection refers to the trailing lepton from the Z boson decays. The $|m_{\ell\ell} - m_Z|$ requirement is applied to the dielectron final state only in the $W^\pm W^\pm$ SR.

<table>
<thead>
<tr>
<th>Variable</th>
<th>$W^\pm W^\pm$</th>
<th>WZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of leptons</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>$p_T^{\ell}$</td>
<td>$&gt; 25/20$ GeV</td>
<td>$&gt; 25/10/20$ GeV</td>
</tr>
<tr>
<td>$p_T^{j}$</td>
<td>$&gt; 50$ GeV</td>
<td>$&gt; 50$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>m_{\ell\ell} - m_Z</td>
<td>$</td>
</tr>
<tr>
<td>$m_{\ell\ell}$</td>
<td>$&gt; 20$ GeV</td>
<td>-</td>
</tr>
<tr>
<td>$m_{\ell\ell\ell}$</td>
<td>-</td>
<td>$&gt; 100$ GeV</td>
</tr>
<tr>
<td>$p_T^{\text{miss}}$</td>
<td>$&gt; 30$ GeV</td>
<td>$&gt; 30$ GeV</td>
</tr>
<tr>
<td>Anti b-tagging</td>
<td>Applied</td>
<td>Applied</td>
</tr>
<tr>
<td>$\tau$ veto</td>
<td>Applied</td>
<td>Applied</td>
</tr>
<tr>
<td>$max(z^*_\ell)$</td>
<td>$&lt; 0.75$</td>
<td>$&lt; 1.0$</td>
</tr>
<tr>
<td>$m_{jj}$</td>
<td>$&gt; 500$ GeV</td>
<td>$&gt; 500$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\Delta\eta_{jj}</td>
<td>$</td>
</tr>
</tbody>
</table>
Table 3: Selection to define the nonprompt, WZb, and ZZ CRs. The looser lepton $p_T$ requirement on the WZb CR selection refers to the trailing lepton from the Z boson decays. The $|m_{\ell\ell} - m_Z|$ requirement is applied to the dielectron final state only in the nonprompt CR. The lepton $p_T$ requirements in the ZZ CR are ordered by the $p_T$ values themselves.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Nonprompt</th>
<th>WZb</th>
<th>ZZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of leptons</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$p_T^{\ell}$</td>
<td>$&gt; 25/20$ GeV</td>
<td>$&gt; 25/10/20$ GeV</td>
<td>$p_T &gt; 25/20/10/10$ GeV</td>
</tr>
<tr>
<td>$p_T^{j}$</td>
<td>$&gt; 50$ GeV</td>
<td>$&gt; 50$ GeV</td>
<td>$&gt; 50$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>m_{\ell\ell} - m_Z</td>
<td>$</td>
<td>$&gt; 15$ GeV (ee)</td>
</tr>
<tr>
<td>$m_{\ell\ell}$</td>
<td>$&gt; 20$ GeV</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$m_{\ell\ell\ell}$</td>
<td>-</td>
<td>$&gt; 100$ GeV</td>
<td>-</td>
</tr>
<tr>
<td>$p_T^{miss}$</td>
<td>$&gt; 30$ GeV</td>
<td>$&gt; 30$ GeV</td>
<td>-</td>
</tr>
<tr>
<td>Anti b-tagging</td>
<td>Inverted</td>
<td>Inverted</td>
<td>-</td>
</tr>
<tr>
<td>$\tau$ veto</td>
<td>Applied</td>
<td>Applied</td>
<td>-</td>
</tr>
<tr>
<td>$\max(z_{\ell}^*)$</td>
<td>$&lt; 0.75$</td>
<td>$&lt; 1.0$</td>
<td>$&lt; 0.75$</td>
</tr>
<tr>
<td>$m_{jj}$</td>
<td>$&gt; 500$ GeV</td>
<td>$&gt; 500$ GeV</td>
<td>$&gt; 500$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \eta_{jj}</td>
<td>$</td>
<td>$&gt; 2.5$</td>
</tr>
</tbody>
</table>
FLAVOR CHANGING NEUTRAL CURRENTS

- FCNC BR suppressed to $10^{-12} – 10^{-15}$ in SM by GIM mechanism
- sensitive probe BSM models (2HDM, SUSY, RPV, ...)
- traditionally use anomalous coupling Lagrangian:

\[
\mathcal{L}_{\text{FCNC}} = \sum_{q=u,c} \left[ \sqrt{2} g_s \frac{\kappa_{tqg}}{\Lambda} \left( \bar{q} \sigma^{\mu\nu} T^a \left( f_{gq}^L P_L + f_{gq}^R P_R \right) t \right) G_\mu^a \right. \\
+ \frac{g}{\sqrt{2}} \kappa_{tqH} \left( \bar{q} \left( f_{Hq}^L P_L + f_{Hq}^R P_R \right) t \right) H \\
+ e \frac{\kappa_{tq\gamma}}{\Lambda} \left( \bar{q} \sigma^{\mu\nu} \left( f_{\gamma q}^L P_L + f_{\gamma q}^R P_R \right) i \right) F_{\mu\nu} \\
+ \frac{g}{\sqrt{2} c_W} \frac{\kappa_{tqZ}}{\Lambda} \left( \bar{q} \sigma^{\mu\nu} \left( f_{Zq}^L P_L + f_{Zq}^R P_R \right) t \right) Z_{\mu\nu} \\
+ \frac{g}{4 c_W} \zeta_{tqZ} \left( \bar{q} \gamma^\mu \left( f_{Zq}^L P_L + f_{Zq}^R P_R \right) t \right) Z_{\mu} \left] + h.c. \right. \\
\]

- In practice, often simplify chiral structure, e.g. $f_R = 1$
- $q = u, c$ with more sensitivity to $u$ (higher x-sec)
ATLAS AND CMS ON FCNC

- Comprehensive studies by ATLAS (tZq) and CMS (tqg)
- Both simulate dedicated signal and background samples and follow the Run-II strategies
- CMS uses BNN on kinematic input
- ATLAS uses $\chi^2$ constructed under FCNC hypothesis
- Improvement typically one order of magnitude

<table>
<thead>
<tr>
<th>Operator</th>
<th>Expected limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>C_{uB}^{(31)}</td>
</tr>
<tr>
<td>$</td>
<td>C_{uW}^{(31)}</td>
</tr>
<tr>
<td>$</td>
<td>C_{uB}^{(32)}</td>
</tr>
<tr>
<td>$</td>
<td>C_{uW}^{(32)}</td>
</tr>
</tbody>
</table>

- SM-EFT limits:
• W boson helicity measurements, asymmetries and single top production are able to constrain potential anomalous $W_{tb}$ couplings:

$$\mathcal{L}_{W_{tb}} = -\frac{g}{\sqrt{2}} b \gamma^\mu (V_L P_L + V_R P_R) t W_{\mu} = -\frac{g}{\sqrt{2}} b \frac{i \sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) t W_{\mu} = h.c.$$

• comprehensive list of measurements
  • W boson helicity from Tevatron & LHC (8 TeV)
  • $A_{FB}$ from LHC (8 TeV)
  • single top x-sec from Tevatron and LHC (7/8/13)

• Extrapolate to 3/ab & include scaled results
  • Reconstruction level uncertainties were kept (b-tagging was divided by two)
$\sin^2 \theta_{\text{eff}}$ AND THE MASS OF THE W BOSON

- tackle important discrepancies, profit from ITk at $|\eta| \leq 4$
  - $\sin^2 \theta_{\text{eff}}$ di-electron Drell-Yan events
  - fitting rapidity dependence of $A_{\text{FB}}$ and $m(\ell\ell)$
  - Benefit from $\eta \sim 4$ extension of the ATLAS Itk upgrade
  - Can resolve LEP/SLD disagreement with similar precision

- $M_W$: dedicated low-PU runs @ $<\mu> \approx 2$
  - Combine $m_T$, $p_T(\ell)$ fits
  - “HL-LHC” incorporates future constraints
Figure 1 – Parton-level $|\Delta \phi_{\ell\ell}|$ distributions measured by ATLAS$^7$ (left) and CMS$^8$ (right), compared with various predictions. In the centre, the ATLAS measurement is compared with fixed-order calculations$^3,^{11}$. 