Collider physics at the intensity and energy frontier

The HL-LHC and beyond

Federico Meloni (DESY), on behalf of the ATLAS and CMS collaborations

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DISCRETE 2018, Vienna
Introduction

The success of the Standard Model

Standard Model Production Cross Section Measurements

**ATLAS** Preliminary
Run 1,2 $\sqrt{s} = 7,8,13$ TeV

**Status:** July 2018

### Measurement of the W Boson Mass

- Uses 4.6 fb$^{-1}$ of 7 TeV data
- Huge amount of work since 2011 to understand detector response and modeling of kinematic quantities, e.g. lepton $p_T$, $E_T$ miss
- Similar precision to best previous single experiment measurement (from CDF)
- Result consistent with SM expectation
- Further progress requires improved modeling

$$m_W = 80.370 \pm 0.019 \text{ GeV}$$

$\pm 7$ MeV (stat.)

$\pm 11$ MeV (syst.)

$\pm 14$ MeV (modeling)
Standard Model shortcomings

Even with such a successful description of Nature, a few, but major, pieces are missing in the puzzle:

• Neutrino masses (and flavour oscillation) not predicted
• Matter-antimatter imbalance
• Unification of forces
• No gravity
• Missing dark matter/energy candidates
• Hierarchy problem
• …

Dark Energy 68%

Dark Matter 27%

Ordinary Matter 5%
But...

**CMS Preliminary**

- **Leptoquarks**
  - LQ1(ee) x2
  - LQ1(μμ) x2
  - LQ2(ττ) x2
  - LQ2(μμ) + LQ1(ττ) β = 0.5
  - LQ3(μμ) x2
  - LQ3(ττ) x2
  - Single LQ1 (λ = 1)
  - Single LQ2 (λ = 1)

- **RS Gravitons**
  - RS1(μμ), k = 0.1
  - RS1(ττ), k = 0.1
  - RS1(ττ), k = 0.1

- **Heavy Gauge Bosons**
  - SSM Z'(ττ)
  - SSM Z'(μμ)
  - SSM Z'(ee) + Z'(μμ)
  - SSM W'(μμ)
  - SSM W'(ττ)
  - SSM Z'(bb)

- **Excited Fermions**
  - e* (M = Λ)
  - μ* (M = Λ)
  - q* (ag)
  - q* (qy) f = 1
  - b*

- **13 TeV**
- **8 TeV**

**Multijet Resonances**

- coloron(μμ) x2
- coloron(ττ) x2
- gluino(3) x2
- gluino(μμ) x2

**Large Extra Dimensions**

- dijets, Λ+ LL/RR
- dijets, Λ- LL/RR
- dimuons, Λ+ LLIM
- dimuons, Λ- LLIM
- dielectrons, Λ+ LLIM
- dielectrons, Λ- LLIM
- single e, Λ HnCM
- single μ, Λ HnCM
- inclusive jets, Λ+
- inclusive jets, Λ-

**Compositeness**

**CMS Exotica Physics Group Summary – ICHEP, 2016**
Where to look?

LHC (and future colliders) offer a unique place where to look directly for new particles.

**Precision measurements of SM**
- Each deviation could be an hint of new physics!

**Direct BSM searches**
- A plethora of kinematic regions and possible new resonances from heavy particles

Other focused experiments give alternative and fundamental opportunities!
Particle physics at colliders

Why?

Broad exploration potential

- target well justified BSM scenarios but also have sensitivity to the unknown

Flexibility

- if (indirect) hints of NP arise somewhere, need to be able to re-direct efforts

Guaranteed deliverables

- if not a discovery, precision measurements!

Physics at Colliders fulfils all the above conditions, so it’s important to guarantee a continuous progression in this direction with sufficient complementarity
(Possible) future colliders
Options for the next 30+ years

**High Energy - LHC** \( \sqrt{s} = 27 \text{ TeV} \), beyond 2038

**FCC - hh** \( \sqrt{s} = 100 \text{ TeV} \), beyond 2045 (after FCC-ee), up to 30/ab

**ILC** \( \sqrt{s} \approx 500 \text{ GeV} \) with staging at 250 GeV

**CLIC** three stages \( \sqrt{s} \approx 380 \text{ GeV}, 1.5 \text{ TeV} \) and 3 TeV for 500/fb, 1.5/ab and 3/ab respectively, data taking after HL-LHC for ~ 20 yrs

**CepC >=** two stages, \( \sqrt{s} \approx 91 \) and 240 GeV, data-taking 2030-2040 (upgradable to pp, with ep and HI options)

**FCC - ee** beyond 2045, 5 different stages and luminosities

**LHeC** \( E_e = 60 \text{ GeV} \), p from LHC, up to 1/ab, running at the same time as HL-LHC

**FCC-eh** \( E_e = 60 \text{ GeV} \) vs 50 TeV, up to 3/ab
The HL-LHC and the 2018 Yellow Report

$\sqrt{s} = 14$ TeV, up to 3000 or 4000 fb$^{-1}$ (300fb$^{-1}$ for LHCb)

The only facility approved so far, on which most studies have been made

• ATLAS, CMS and LHCb detectors upgrade well on-going

• Data taking: 2025-2038

• Yellow Report for EU strategy expected in December 2018 summarize studies and projections by experiments and theory community on SM&Top, Higgs, BSM, Heavy Flavor and Heavy Ions

ESPP update due for approval by CERN council in May 2020

• Feedback gathered and discussed at the HL-/HE-LHC Workshops
Yellow report studies

Some commonalities

Three main approaches:

• Full simulation
• Analysis with parameterized detector performance (e.g. DELPHES with up-to-date phase-2 detector performance)
• Projections using Run-2 signal and background samples scaled at 14 TeV

Harmonised treatment of detector and theory uncertainties evolution with time

• Agreement between experimental collaborations and theorists involved in the Yellow Report
• General “rule of thumb”: detector and theory/modelling uncertainties will be halved, MC statistics are supposed to be infinite
Outline

I will discuss a personal (arbitrary/incomplete) selection of physics goals that we can achieve by the end of HL-LHC and complementarities with other facilities.

Start with indirect searches

- Precision measurements in the electro-weak sector
- Characterisation of the Higgs boson and its potential

Close with direct searches

- Supersymmetry
- New resonances
- Simplified dark matter models
Precision physics

Weak mixing angle
W boson mass
Vector boson scattering
Higgs boson properties
Measurement of the Weak Mixing Angle

Measure the leptonic effective weak mixing angle ($\sin^2\theta_{\text{lept}}$) in dilepton events.

- Tension of about 3$\sigma$ between the two most precise measurements (LEP and SLD)
- Minimizing the $\chi^2$ value between the simulated data and template $A_{FB}$ distributions in 72 dilepton mass and rapidity bins
- The analysis is done at the generator level

\[
\cos \theta^* = \frac{2(p_1^+ p_2^- - p_1^- p_2^+)}{\sqrt{M^2(M^2 + P_T^2)}} \times \frac{P_z}{|P_z|}
\]

\[
A_{FB} = \frac{N(\cos \theta^* > 0) - N(\cos \theta^* < 0)}{N(\cos \theta^* > 0) + N(\cos \theta^* < 0)}
\]
Measurement of the W boson mass

W boson mass measurement by ATLAS

- study potential of low pile-up data
- extended pseudo-rapidity range effect on decorrelation of PDF
- include PDF uncertainties from different sets

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [TeV]</th>
<th>Lepton acceptance</th>
<th>Uncertainty in $m_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CT10</td>
</tr>
<tr>
<td>14</td>
<td>$</td>
<td>\eta_\ell</td>
</tr>
<tr>
<td>14</td>
<td>$</td>
<td>\eta_\ell</td>
</tr>
<tr>
<td>27</td>
<td>$</td>
<td>\eta_\ell</td>
</tr>
<tr>
<td>27</td>
<td>$</td>
<td>\eta_\ell</td>
</tr>
<tr>
<td>14+27</td>
<td>$</td>
<td>\eta_\ell</td>
</tr>
</tbody>
</table>
Vector boson scattering

Electroweak production of a Z boson pair plus two jets

VBS is crucial for probing the mechanism of electroweak symmetry breaking in the Standard Model.

- At the HL-LHC, evidence of the EW-ZZjj processes becomes possible

**Four lepton channel:** two high-energy jets in the back and forward regions, with two vector bosons.

- Exploit the ZZ centrality

$$ZZ \text{ centrality} = \frac{|y_{ZZ} - (y_{j1} + y_{j2})/2|}{|y_{j1} - y_{j2}|}$$
## Future colliders (FCC-ee)

<table>
<thead>
<tr>
<th>Observable</th>
<th>Measurement</th>
<th>Current precision</th>
<th>FCC-ee stat.</th>
<th>FCC-ee syst.</th>
<th>Dominant exp. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_z) (keV)</td>
<td>(Z) Lineshape</td>
<td>91187500 ± 2100</td>
<td>5</td>
<td>&lt; 100</td>
<td>Beam energy</td>
</tr>
<tr>
<td>(\Gamma_z) (MeV)</td>
<td>(Z) Lineshape</td>
<td>2495200 ± 2300</td>
<td>8</td>
<td>&lt; 100</td>
<td>Beam energy</td>
</tr>
<tr>
<td>(R_l (\times 10^3))</td>
<td>(Z) Peak ((\Gamma_{had}/\Gamma_{lep}))</td>
<td>20767 ± 25</td>
<td>0.06</td>
<td>0.2 – 1</td>
<td>Detector acceptance</td>
</tr>
<tr>
<td>(R_b (\times 10^6))</td>
<td>(Z) Peak ((\Gamma_{bb}/\Gamma_{had}))</td>
<td>216290 ± 660</td>
<td>0.3</td>
<td>&lt; 60</td>
<td>(g \rightarrow bb)</td>
</tr>
<tr>
<td>(N_v (\times 10^3))</td>
<td>(Z) Peak ((\sigma_{had}))</td>
<td>2984 ± 8</td>
<td>0.005</td>
<td>1</td>
<td>Lumi measurement</td>
</tr>
<tr>
<td>(\sin^2 \theta_W^{eff} (\times 10^6))</td>
<td>(A_{FB}^{\mu\mu}) (peak)</td>
<td>231480 ± 160</td>
<td>3</td>
<td>2 – 5</td>
<td>Beam energy</td>
</tr>
<tr>
<td>(1/\alpha_{QED}(m_z) (\times 10^3))</td>
<td>(A_{FB}^{\mu\mu}) (off-peak)</td>
<td>128952 ± 14</td>
<td>4</td>
<td>&lt; 1</td>
<td>Beam energy</td>
</tr>
<tr>
<td>(\alpha_s(m_z) (\times 10^4))</td>
<td>(R_l)</td>
<td>1196 ± 30</td>
<td>0.1</td>
<td>0.4 – 1.6</td>
<td>Same as (R_l)</td>
</tr>
<tr>
<td>(m_w) (MeV)</td>
<td>WW Threshold scan</td>
<td>80385 ± 15</td>
<td>0.6</td>
<td>0.3</td>
<td>Beam energy</td>
</tr>
<tr>
<td>(\Gamma_w) (MeV)</td>
<td>WW Threshold scan</td>
<td>2085 ± 42</td>
<td>1.5</td>
<td>0.3</td>
<td>Beam energy</td>
</tr>
<tr>
<td>(N_v (\times 10^3))</td>
<td>(e^+e^- \rightarrow \gamma Z, Z \rightarrow \nu\nu, \mu\mu)</td>
<td>2920 ± 50</td>
<td>0.8</td>
<td>small</td>
<td>?</td>
</tr>
<tr>
<td>(\alpha_s(m_w) (\times 10^4))</td>
<td>(B_l = (\Gamma_{had}/\Gamma_{lep})_W)</td>
<td>1170 ± 420</td>
<td>2</td>
<td>small</td>
<td>CKM Matrix</td>
</tr>
<tr>
<td>(m_{top}) (MeV)</td>
<td>Top Threshold scan</td>
<td>173340 ± 760 ± 500</td>
<td>17</td>
<td>&lt; 40</td>
<td>QCD corr.</td>
</tr>
<tr>
<td>(\Gamma_{top}) (MeV)</td>
<td>Top Threshold scan</td>
<td>?</td>
<td>45</td>
<td>&lt; 40</td>
<td>QCD corr.</td>
</tr>
<tr>
<td>(\lambda_{top})</td>
<td>Top Threshold scan</td>
<td>(\mu = 1.28 ± 0.25)</td>
<td>0.10</td>
<td>&lt; 0.05</td>
<td>QCD corr.</td>
</tr>
<tr>
<td>(ttZ) couplings</td>
<td>(\sqrt{s} = 365) GeV</td>
<td>± 30%</td>
<td>0.5 – 1.5%</td>
<td>&lt; 2%</td>
<td>QCD corr.</td>
</tr>
</tbody>
</table>

Table credit: A. Blondel
Characterising the Higgs boson

Complementarity and availability of results

Based as much as possible on the knowledge gathered from most recent analyses

- projections from the coupling combination
- dedicated truth-smearing studies for key analyses

Collaboration with LHC Higgs cross section Working Group

- 14 TeV and 27 TeV
- evaluated theory systematics

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Couplings</strong></td>
<td>✓✓✓</td>
<td>✓✓✓</td>
</tr>
<tr>
<td><strong>Differential xsec</strong></td>
<td>✓✓</td>
<td>✓✓</td>
</tr>
<tr>
<td><strong>Width</strong></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td><strong>CPV</strong></td>
<td>✓</td>
<td>✓✓</td>
</tr>
<tr>
<td><strong>Rare decays</strong></td>
<td>✓✓✓</td>
<td>✓✓</td>
</tr>
<tr>
<td><strong>Di-Higgs</strong></td>
<td>✓✓✓</td>
<td>✓✓✓</td>
</tr>
<tr>
<td><strong>BSM</strong></td>
<td>✓✓</td>
<td>✓✓</td>
</tr>
</tbody>
</table>

**Legend:** Past studies, 2017 TDRs, 2018 YR

Latest results: ATLAS CMS
Higgs to pairs of muons
Couplings to second-generation fermions

- Opposite-charge muons with \( p_T > 15 \text{ GeV} \) and \( |\eta| < 2.5 \)
- Leading muon \( p_T > 25 \text{ GeV} \)
- \( 110 < m_{\mu\mu} < 160 \text{ GeV} \)

Split the selected sample in subsets with different signal-to-background ratios

- a maximum likelihood fit to the di-muon invariant mass
- Systematic uncertainties are incorporated as nuisance parameters in the final fit

<table>
<thead>
<tr>
<th>Scoping Scenario</th>
<th>( \langle \mu \rangle )</th>
<th>Overall significance</th>
<th>( \Delta \mu ) w/ syst. errors</th>
<th>( \Delta \mu ) w/o syst. errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>reference</td>
<td>200</td>
<td>9.5</td>
<td>( \pm 0.13 )</td>
<td>( \pm 0.12 )</td>
</tr>
<tr>
<td>middle</td>
<td>200</td>
<td>9.4</td>
<td>( \pm 0.14 )</td>
<td>( \pm 0.12 )</td>
</tr>
<tr>
<td>low</td>
<td>200</td>
<td>9.2</td>
<td>( \pm 0.14 )</td>
<td>( \pm 0.13 )</td>
</tr>
</tbody>
</table>
Double Higgs production

Ultra-rare processes

Plan to perform a combination to probe the expected reach for di-Higgs

- Measure $\lambda_{HHH}$ (and $k_t$)
- Combination with CMS crucial
- Exploit three decay channels: $bb\gamma\gamma$, $bb\tau\tau$ and $bb$  

**ATLAS Simulation**

$\sqrt{s} = 14$ TeV, $L = 3000$ fb$^{-1}$

0.2 $< \lambda_{HHH}/\lambda_{HHH}^{SM} < 6.9$

- Limited sensitivity ($\sim 1\sigma$)
- Expect improvements and channel combination for YR
Higgs boson couplings
HL-LHC and beyond

CMS prospects for measuring Higgs boson couplings.

- Extrapolated from Run-2 results with 36 fb\(^{-1}\)
- Identical detector performances
- Two systematic uncertainty scenarios (Run-2 and halved)

### Table: Higgs Couplings

<table>
<thead>
<tr>
<th>g_{Hxx}</th>
<th>FCC-ee</th>
<th>FCC-hh</th>
<th>FCC-eh</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>0.15%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WW</td>
<td>0.20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Γ(_{H})</td>
<td>1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>γγ</td>
<td>1.5%</td>
<td>&lt;1%</td>
<td></td>
</tr>
<tr>
<td>Zγ</td>
<td>--</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>tt</td>
<td>13%</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td>bb</td>
<td>0.4%</td>
<td></td>
<td>0.5%</td>
</tr>
<tr>
<td>ττ</td>
<td>0.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cc</td>
<td>0.7%</td>
<td></td>
<td>1.8%</td>
</tr>
<tr>
<td>μμ</td>
<td>6.2%</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>uu,dd</td>
<td>H→ργ?</td>
<td>H→ργ?</td>
<td></td>
</tr>
<tr>
<td>ss</td>
<td>H→φγ?</td>
<td>H→φγ?</td>
<td></td>
</tr>
<tr>
<td>ee</td>
<td>ee→H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HH</td>
<td>30%</td>
<td>~3%</td>
<td>20%</td>
</tr>
<tr>
<td>inv, exo</td>
<td>&lt;0.45%</td>
<td>10^{-3}</td>
<td>5%</td>
</tr>
</tbody>
</table>

Table credit: A. Blondel
Beyond the Standard Model

Supersymmetry
New resonances
Searches for dark matter

Image credit xkcd: https://xkcd.com/1621/
Supersymmetry

Theoretically sound, predictive framework

But where is SUSY?

• Barbieri-Giudice 3% naturalness
  \[ m(\tilde{g}) \lesssim 1000 \text{ GeV} \]
  \[ m(\tilde{t}_1) \lesssim 500 \text{ GeV} \]

• LHC limits severely constraining these models

Is SUSY unnatural? Is it dead? Not really…

• Considering the electroweak fine-tuning \( (\Delta_{EW}) \), SUSY is natural (3-10%) with:
  \[ m(\tilde{g}) \lesssim 5-6 \text{ TeV} \]
  \[ m(\tilde{t}_1) \lesssim 2-3 \text{ TeV} \]
  \[ m(\tilde{q}) \lesssim 10-20 \text{ TeV} \]

• Need low \( \mu \sim 100-300 \text{ GeV} \)
Search for Higgsinos

One of the focuses of the HL-LHC programme

\[ \tilde{\chi}_2^0, \tilde{\chi}_1^0, \tilde{\chi}_2^-, \tilde{\chi}_1^-, \tilde{\chi}_1^+, \tilde{\chi}_1^\pm \] production, \( \tan\beta = 5, \mu > 0 \)  

Pure Higgsino

ATLAS Simulation Preliminary
\( \sqrt{s} = 14 \) TeV, 3000 fb\(^{-1}, \mu = 200 \)

All limits at 95% CL

Exploit ISR jet + \( E_T^{miss} \) + soft leptons

- Challenging lepton identification

Gap that needs to be filled!

- Mono photon from FSR? VBF?

Disappearing tracks (long-lived charginos)

- New reconstruction options

- Challenging tracking environment!

\[ \tilde{\chi}_1^0 \]
The hunt for the natural spectrum

**HE-LHC**

Various projections available beyond the HL-LHC

---

**Stop Mass [GeV]**

- Stop (compressed)
- Stop
- Gluino (compressed)
- Gluino

**σ [ab]**

- 5σ (0.3 ab⁻¹)
- 5σ (1 ab⁻¹)
- 5σ (3 ab⁻¹)
- 95% CL (0.3 ab⁻¹)
- 95% CL (1 ab⁻¹)
- 95% CL (3 ab⁻¹)

**Stop Mass [GeV]**

- CLIC
- ILC/FCC-ee
- FCC-hh (3/ab)
- HE-LHC (3/ab)
- HL-LHC (3/ab)
- LHC (current)

**σ [ab]**

- Stop (compressed)
- Stop
- Gluino (compressed)
- Gluino

**Stop Mass [GeV]**

- Staus
- Sleptons (all)
- Higgsinos
- NLSP (C1/N2)

**σ [ab]**

- CLIC
- ILC/FCC-ee
- FCC-hh (3/ab)
- HE-LHC (3/ab)
- HL-LHC (3/ab)
- LHC (current)

---

**JHEP04 (2014) 117**

**m_g [TeV]**

- 5σ discovery

**m_0 [TeV]**

- 100 TeV, 3000 fb⁻¹
- 33 TeV, 3000 fb⁻¹
- 14 TeV, 3000 fb⁻¹
- 14 TeV, 300 fb⁻¹

Image credit: M. D’Onofrio
Heavy W prime

Search in tb channel

Projection assumes narrow width approximation from early Run-2 analyses.

- Studied dependency on uncertainty evolution

Heavy resonances at future colliders: the higher the energy, the better…
Dark Matter searches

Foreseen by full theories as SUSY but also searched with ‘simplified models’

**Strategy:** search for associated production with one of many SM tags:

- jet, photon, Z, single/double top, bottom, Higgs

---

**ATLAS Simulation Preliminary**

\[ \sigma(pp \rightarrow t\bar{t} \rightarrow b\bar{b} V) \times BR(t\rightarrow bV) \] [pb]

- **Theory**
- **95% CL Exp. Limit**
- **Non-resonant model**
- **95% CL Exp. ± 1σ**
- **95% CL Exp. ± 2σ**

**Mono-top+MET**

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**CMS Projection**

3.0 ab\(^{-1}\) (14 TeV)

- **with YR18 syst. uncert.**
- **with Run 2 syst. uncert.**
- **with stat. uncert. only**

**Vector mediator, Dirac DM**

\[ g_q = 0.25, g_{DM} = 1.0 \]

**Mono-Z+MET**

\[ \Omega h^2 = 0.12 \]
Four top quarks in 2HDM+a

Search in multi-lepton channel

2HDM+a models are considered

• type-II coupling structure
• the lightest CP-even state of the Higgs-sector, $h$, can be identified with the SM Higgs boson

Select at least two leptons with the same electric charge or at least three or more leptons

• Potential observations for a range of masses and mixings
• Adding the fully hadronic, semi-leptonic can further improve
Complementarity with Direct Detection

Recasting a di-lepton search for DM+top quark pairs

- Search for scalar/pseudoscalar mediator decaying to invisible
- Yukawa-like interactions

**ATLAS** Simulation Preliminary
All Limits at 90% CL

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**ATLAS**
- Limit Run 2
  - $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
  - Scalar mediator, Dirac DM, $g = 1.0$

**ATLAS** 5$\sigma$ Discovery
- $\sqrt{s} = 14$ TeV, 3000 fb$^{-1}$, $t\bar{t}+\phi$
  - Scalar mediator, Dirac DM, $g = 1.0$

**ATLAS** Expected Limit
- $\sqrt{s} = 14$ TeV, 3000 fb$^{-1}$, $t\bar{t}+\phi$
  - Scalar mediator, Dirac DM, $g = 1.0$
Dark matter at the FCC-hh

Assume wino-like DM particles

- Extrapolation of mono-jet and disappearing track searches are expected to start covering the multi-TeV range
- Higgsino-like sensitivity just below the TeV
Summary

Several SM shortcomings require investigations that are expected to extend beyond the scope of the LHC.

I have presented some examples highlighting the reach of:

• Crucial SM precision measurements
• Direct searches for BSM phenomena

in the context of a variety of (possible) future collider facilities.

Other 50+ years of interesting physics lie ahead!
Thank you