LHCP Experimental Summary

Highlights

Few selected highlights and perspectives

Andreas Hoecker (CERN)

LHCP, Everywhere, 30 May 2012
This conference was …

- **Pioneering** — the first virtual of the large HEP conferences
- **Rich** — a showcase for first rate research under difficult circumstances
- **Important** — huge thanks to the organisers for bringing the community together

LHCP Experimental Highlights

Few selected highlights and perspectives

Disclaimer: I apologise for not adding names on these slides. I have used so many talks/posters for the material presented here that I rather choose to sincerely thank ALL speakers and poster presenters!
We are celebrating 10 years of physics and technological prowess

- The Higgs boson exists
- There is — so far — no proof of physics beyond the SM up to the TeV scale
- Numerous discoveries within the SM were made involving rare processes, flavour, spectroscopy, high-density strong matter
- Accelerators, detectors, computing & analysis performed beyond expectations
- The LHC has prompted prodigious progress in particle theory
Cern experiment: Machine switched on. No Big Bang. It works

The world watched and waited for the greatest experiment in history to begin. Impressive though it was, it was also a bit like booting up a sulky PC, says Andy McSmith who was at Cern

Thursday 11 September 2008 00:00
Remember

The First Year: 2009/10
\[ \sqrt{s} = 0.9, 7 \text{ TeV (35 pb}^{-1}) \]
2.76 TeV/NN (9 µb}^{-1})

First candidate collisions in CMS 23 Nov 2009

High-multiplicity collision event seen in ALICE
The First Year: 2009/10

\( \sqrt{s} = 0.9, 7 \text{ TeV (35 pb}^{-1}) \)

\( 2.76 \text{ TeV/NN (9 } \mu \text{b}^{-1}) \)

\( \sigma(pp \to H b X) = 75 \pm 14 \mu \text{b} \)

Charged particle multiplicity at 900 GeV


CMS: arXiv:1009.4122, September 2010

(d) CMS N \( \geq 110, 1.0 \text{ GeV/c}p < 3.0 \text{ GeV/c} \)

Long-range correlations in pp

**Jet quenching in PbPb collisions**

Remember
Now — after an outstanding Run 2 — the LHC experiments have in their hands the richest hadron collision data sample ever recorded

<table>
<thead>
<tr>
<th>Particle</th>
<th>Produced in 140 fb⁻¹ pp at √s = 13 TeV</th>
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<tbody>
<tr>
<td>Higgs boson</td>
<td>7.8 million</td>
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<tr>
<td>Top quark</td>
<td>275 million (115 million t̅t)</td>
</tr>
<tr>
<td>Z boson</td>
<td>8 billion (→ ℓℓ, 270 million per flavour)</td>
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<tr>
<td>W boson</td>
<td>26 billion (→ ℓν, 2.8 billion per flavour)</td>
</tr>
<tr>
<td>Bottom quark</td>
<td>~160 trillion (significantly reduced by acceptance)</td>
</tr>
</tbody>
</table>

Broad physics potential by probing with high-precision Higgs and other Standard Model processes, detecting very rare processes, and exploring new physics via direct and indirect measurements.
Precision calibration of data

The results presented this week rely on excellent detector and reconstruction performance, exploiting more and more low-level machine learning algorithms, but most importantly on the meticulous calibration of the algorithms with data.

Crucial is also precise luminosity measurement: ~1.7% for ATLAS and CMS for all Run-2
Theory so far agrees with all measured cross sections — Across widely different processes

Harvest of cross section measurements confirms the predictive power of the Standard Model

Also huge progress on theoretical calculations (NNLO QCD revolution, NLO EW corrections, towards full DY NNLO QCD-EW)

Many more detailed fiducial and differential cross section measurements
ATLAS & CMS explore ever rarer processes — New probes for anomalous couplings or new particles

**CMS Preliminary**

<table>
<thead>
<tr>
<th>Process</th>
<th>Signal Strength $\mu$</th>
<th>$5.7\sigma$</th>
<th>$3.3\sigma$</th>
<th>$3.4\sigma$</th>
<th>Allowed</th>
<th>&lt; 5.4</th>
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<tbody>
<tr>
<td>Combined</td>
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<td>WWW</td>
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<td>ZZZ</td>
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</tbody>
</table>

137 fb$^{-1}$ (13 TeV)

**CMS observes massive triboson production**

Involves (among others) quartic gauge coupling vertex

All results at: http://cern.ch/go/pHJ7

CMS PAS SMP-19-014
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CMS PAS SMP-19-014

ATLAS & CMS explore ever rarer processes — New probes for anomalous couplings or new particles
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Somewhere here at 12 fb we expect 4-top production, a spectacularly massive state of almost 700 GeV
ATLAS & CMS explore ever rarer processes — New probes for anomalous couplings or new particles

ATLAS finds strong evidence for 4-top production

\[ \sigma(tttt) = 24^{+7}_{-6} \text{ fb} \]

Obs. (exp) significance: 4.4\(\sigma\) (2.4\(\sigma\))

For triboson and 4-top measurements with many leptons and jets as well as MET, good physics modeling and control of fake leptons crucial: among the big analysis challenges for the coming years!
Hadron colliders enable high-precision — See W & top mass, $\sin^2 \theta_W$, W, Z, top cross sections, flavour, etc.

Longstanding 2.7\(\sigma\) LEP puzzle of $R = B(\text{W} \to \tau \nu)/B(\text{W} \to \mu \nu) = 1.070 \pm 0.026$

— Driven (a.o.) by high $B(\text{W} \to \tau \nu)$ and low $B(\text{W} \to \mu \nu)$ measurements from L3 ($R_{[\text{L3}]} = 1.19 \pm 0.05$)

ATLAS used top-pair events as clean probe for W’s to measure the ratio of prompt to softer delayed muons from tau decays

Result $0.992 \pm 0.013$ is twice more precise than LEP and in agreement with lepton universality

… as are LEP $\tau_T$, $\tau \to \mu \nu$, $\tau \to e \nu \nu$ measurements within 0.14% precision (but at lower energy, off-shell W)
The Higgs boson

The LHC’s magnum opus

Discovery allows to access new sector of SM Lagrangian:

- Yukawa couplings
- Gauge–scalar boson interactions
- Higgs potential (incl. self coupling)
Run 2 provided proof & measurements of Higgs couplings to 3rd generation fermions, with results on full Run-2 dataset being released.

Also progress on probing Higgs dynamics, rare decays, CP violation, dark matter.

Yukawa force between elementary particles: new form of interaction — not a gauge force, non-universal, driving the fate of the universe.

Just think what happens had the electron the mass of a muon (answer here: R. Cahn, Rev. Mod. Phys. 68, 951)
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Uncertainties 3~12%
Striking example of the **power of our detectors**, also exploited in many high-mass searches: analysis of jet substructure by combining precise vertexing, tracking and calorimeter information measured in a dense environment.
Probing Higgs properties in four-lepton channel

ATLAS and CMS move towards predefined less model-dependent fiducial cross-section (STXS) measurements and effective field theory interpretations.
ATLAS & CMS explore ever rarer processes — $J^\text{CP}(H) = 0^{++}$ established, but CP-odd admixture possible

Matter–antimatter asymmetry of universe remains a mystery. SM far insufficient, lepton sector (“baryogenesis via leptogenesis”) offers elegant but speculative solution → must look further

CMS & ATLAS looked for CP-odd contribution ($\alpha$) in Higgs–top coupling using $\text{ttH}(\rightarrow \gamma\gamma)$
Top Yukawa coupling

Combined fit of Higgs couplings constrains $\kappa_t$ coupling modifier to 11%, $ttH$ alone to about 15%

New CMS study indirectly determines $Y_t = \kappa_t$ from top-pair kinematics in the dilepton final state sensitive to virtual Higgs boson exchange (part of EW corrections)

Result: $Y_t = 1.16^{+0.24}_{-0.35}$ (dominated by systematic effects from EW corr. and FSR)

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Simulation of $M_{bb}$ spectrum versus $Y_t$

Fit result

Post-fit distribution

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Figure 1: Sample diagrams for weak contributions to gluon-induced and quark-induced top quark pair production, where $y_{\nu}$ and $y_{\tau}$ are Goldstone bosons.

Figure 2: Effect of the weak corrections on $t\bar{t}$ production, showing the impact on the lepton+jets and Drell-Yan channels.

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Table: Summary of constraints on $Y_t$ from different processes and years.

<table>
<thead>
<tr>
<th>Year</th>
<th>Channels</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>$t\bar{t}$+jets</td>
<td>$Y_t &lt; 1.04$</td>
</tr>
<tr>
<td>2017</td>
<td>$t\bar{t}$+jets</td>
<td>$Y_t &lt; 1.06$</td>
</tr>
<tr>
<td>2018</td>
<td>$t\bar{t}$+jets</td>
<td>$Y_t &lt; 1.08$</td>
</tr>
</tbody>
</table>

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Graphs showing the $\Delta M_b$ distribution at various $Y_t$ values, with shaded regions indicating uncertainties.

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CMS HATHOR Preliminary

Graph showing the $\Delta M_b$ distribution for reconstructed events compared to simulations.
Rare Higgs decays — Sensitivity to 2nd generation fermion couplings and new physics

Tightly linked to detector momentum & energy resolution capabilities

New ATLAS result on $H \rightarrow Z\gamma$: $\mu = 2.0^{+1.0}_{-0.9} \ (2.2\sigma)$

HL-LHC studies: $\sigma(\mu) \sim 20\%$ for ATLAS & CMS combined (6 ab$^{-1}$)

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HL-LHC studies: $\sigma(\mu) \sim 20\%$ for ATLAS & CMS combined (6 ab$^{-1}$)
Higgs as probe of Dark Matter — DM massive, could (should?) couple to Higgs boson

Invisible Higgs decays can be probed by associated production (VBF, VH, …)

\[
\begin{align*}
q & \rightarrow H \rightarrow \chi \chi \\
q' & \rightarrow H \\
q & \rightarrow W/Z \rightarrow \ell \nu
\end{align*}
\]

Missing energy

Sensitivity to WIMP mass < \(m_H/2\), complementary to direct dark matter searches

\[B(H \rightarrow \text{invisible}) < 0.13\text{ at }95\% \text{ CL} \]

Precision obtained depends crucially on control of \(Z \rightarrow \nu \nu\) and \(W \rightarrow \ell \nu\) backgrounds (theory input and very large MC statistics needed)

\(\Omega_B \sim \Omega_{DM}\) may suggest other than gravity interaction

\[\Omega_B \sim \Omega_{DM}\]

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The scalar sector is directly connected with profound questions: naturalness, vacuum stability & energy, flavour.

The Higgs boson discovery allows us to directly study this sector, requiring a broad experimental programme that will extend over decades.

And the Higgs boson does more …
Higgs boson moderates high-energy longitudinal vector boson scattering

**Unitarity:** if only Z and W are exchanged, the amplitude of (longitudinal) \( W_LW_L \) scattering violates unitarity

\[
A_{Z,W} (W^+W^- \rightarrow W^+W^-) \propto \frac{1}{u^2} (s+t)
\]

Higgs boson restores unitarity of total amplitude:

\[
A_H (W^+W^- \rightarrow W^+W^-) \propto -\frac{m_H^2}{u^2} \left( \frac{s}{s-m_H^2} + \frac{t}{t-m_H^2} \right)
\]

Same-sign WW selection greatly reduces background from strong production and removes s-channel Higgs process:

- EW VBS production
- Non-VBS production
- Strong production

Look for EW production (and VBS) at high dijet mass

Observation of EW production during Run 2:

- **WW+jj** (CMS, 2017, ATLAS 2019)
- **WZ+jj, ZZ+jj** (ATLAS 2018, 2019)
New electroweak production results on Wyjj and ZZjj from CMS

Electroweak Wyjj processes:

Electroweak ZZjj processes:

5.8σ (4.8σ exp.) after combining with 8 TeV
In agreement with SM

Very rare but clean mode using Z decays to charged leptons

4.0σ (3.5σ exp.)
EW and EW+QCD in agreement with SM
New electroweak production results on Wyjj and ZZjj from CMS

Electroweak Wyjj processes:

Electroweak ZZjj processes:

Run 2 has seen the observation of electroweak qq → qqVV (and VVV) processes

Probing Higgs moderation requires higher-mass studies (→ Run 3) and eventually the isolation of the longitudinally polarised components at large Δφ(jj) → HL-LHC

Also more theoretical work needed for precise predictions of these complex processes

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In agreement with SM

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EW and EW+QCD in agreement with SM
New electroweak production results on Wyjj and ZZjj from CMS

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Electroweak ZZjj processes:

Also more theoretical work needed for precise predictions of these complex processes
Flavour physics & spectroscopy

Success of SM flavour structure is since long a source of discomfort for BSM physics, as are the anomalies a source of excitement.
CKM — LHCb is greatly contributing to CKM metrology, in particular through a large set of $\gamma$ measurements

LHCb also seriously contributes to direct $|V_{cb}|$ and $|V_{ub}|$ determinations, where longstanding tensions between exclusive and inclusive results exist

New $|V_{cb}|$ measurement from $B_s \rightarrow D_s^{(*)}\mu\nu$ decay rate vs recoil (novel approach to estimate recoil momentum)

HFLAV combination of exclusive results

LHCb*: $|V_{ub}|/V_{cb}$

Dependence on theoretical form factor

Also measured recoil shape
Time-dependent CP violation in $B_s$ system and rare decays

Phase $\phi_s$ precisely predicted in SM — platin channel to look for new physics

New CMS result on 2017+2018 data (96 fb$^{-1}$) using 11 physics-par. fit (incl. direct CPV parameter $|\lambda|$ and $\Delta m_s$) and combination with Run-1 [CMS-PAS-BPH-20-001]

Rare decays are powerful tools to look for new physics (loop amplitudes, small BSM contributions could be measurable)

New LHCb search for FCNC process $K^0_S \to \mu\mu$ [arXiv:2001.10354]

SM BR: $(5.2 \pm 1.5) \times 10^{-12}$, uncertainty due to $K^0_S \to \pi\pi \to \gamma\gamma \to \mu\mu$ [corresponding $K^0_L$ decay already measured in agreement with SM: $6.8 \times 10^{-9}$]

Some tensions among parameters to be understood

Result: $B(K^0_S \to \mu\mu) < 2.1 \times 10^{-10}$ combined 2011 and 2012 data
Status of flavour anomalies:

\[ R_{D(*)} = \frac{B(B \to D(*)\tau\nu)}{B(B \to D(*)\ell\nu)} \]

Possible new physics in charged current in tree diagram

Tension reduced after 2019 Belle result \[\text{[1904.08794]}\]
in agreement with SM

Remaining tension (HFLAV): 3.1σ

Corresponding \( R_{J/\psi\tau/\mu} \sim 2\sigma \) above SM \[\text{[LHCb: 1711.05623]}\]

\[ R_{K(*)} = \frac{B(B \to K(*)\mu\mu)}{B(B \to K(*)ee)} \approx 1 \]

Experiments measure double ratio involving J/\( \psi \)

New results by LHCb:

\[ R_{pK} = \frac{B(\Lambda_b^0 \to pK^-\mu\mu)}{B(\Lambda_b^0 \to pK^-ee)} \approx 1 \]

LHCb measures double ratios to J/\( \psi \)

Result: \( R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05 \)
in agreement with SM (but also lower)

\( B \to K^*\mu\mu \) angular analysis

New result from LHCb with 4.7 fb\(^{-1} \) (Run 1 + 2016 data)

Full fit to all angular observables

Global fit by LHCb to SM model varying Re(C\(_9\)) only gives 3.3σ discrepancy
Status of anomalies

Status of flavour anomalies:

\[ R_{D^{(*)}} = \frac{B(B \to D^{(*)}\tau\nu)}{B(B \to D^{(*)}\ell\nu)} \]

Possible new physics in charged current in tree diagram

Expected new results by LHCb:

\[ R_{pK} = \frac{B(\Lambda^0_b \to pK^-\mu\mu)}{B(\Lambda^0_b \to pK^-ee)} \approx 1 \]

Only one firm conclusion here:

More data needed
New decays and states!

Observation of $B_s^0 \rightarrow X(3872)(\rightarrow J/\psi\pi\pi)\phi$ decay

BR consistent with $B_d^0 \rightarrow X(3872)K^0$, but 1/2 of $B^+ \rightarrow X(3872)K^+$
This differs from $\psi(2S)$ for which $B_s^0/B^+$ ratio is 0.87

Observation of excited $\Omega_b^- (ssb)$ states in decay to $\Xi_b^0 (usb)K^-$
$\Omega_b^- (6.0$ GeV) discovered by CDF in 2009, $\Xi_b^0 \rightarrow \Xi_c^+ (\rightarrow pK^-\pi^+\pi^-)$

Consistent with expectation from $L=1$ excitations of ground state

Observation of excited $\Xi^0 (dsc)$ states in decay to $\Lambda_c^+ (udc) (\rightarrow pK^-\pi^+)K^-$

Qualitatively similar $\Omega_b^- \rightarrow \Xi_b^0 K^-$ spectrum as for $\Omega_c^- \rightarrow \Xi_c^+ K^-$

Possible structure here (TBC)
Heavy Ion Physics
High-density strong Matter

... and physics of strong electromagnetic fields!
Understanding of Heavy Ion collisions has hugely evolved since start of LHC

Seminal plot from ALICE with rich physics

- Hadron / pion ratio smoothly evolves across multiplicity reaching thermal values in Pb-Pb
- Rise of strangeness (the stranger the steeper)
- No √s dependence
- Low multiplicity pp data described by Pythia (but remains constant towards higher \(N_{ch}\))
- Increase of ratio could indicate thermal production of strangeness independent of size of system
- High-multiplicity pp ~ same hadro-chemistry as fully thermalized system
- Is it possible to understand behavior of large systems from parton (re-)scattering in small systems?
- Theoretical models allow quantitative description
Understanding of Heavy Ion collisions has hugely evolved since start of LHC

![Graph showing multiplicity dependence of flow in pp collisions](image)

True collectivity (flow) in small systems established: revealed by applying techniques from heavy ion physics to pp (and p-Pb)

Theoretical analysis of precise Pb-Pb flow data shows that shear viscosity of QGP is 10 × lower than for any other form of matter \(\rightarrow\) almost perfect fluid [S. Bass et al., Nature Phys 15, 1113 (2019)]
Hard probes — Suppression of strongly interacting probes in Pb-Pb collisions uniformly observed

Colourless probes not suppressed

→ Useful as reference and for measurement of nuclear PDFs

But what is jet quenching?

→ Redistribution of energy to large angles from the jet axis observed in Pb-Pb

→ Energy goes out of the cone

Jet suppression in QGP up to TeV scale. No R dependence

R_{AA} = \text{Pb-Pb cross section} / \text{scaled pp cross section}

**ATLAS** Preliminary

Pb+Pb 5.02 TeV, 0.49 nb^{-1} + 1.38 nb^{-1}

\text{pp} 5.02 TeV, 25 pb^{-1} + 260 pb^{-1}
Quarkonia — Suppression versus recombination in deconfined medium (QGP)

Colour screening at high temperature dissociates ("melts") quarkonia in QGP
But, quarkonia also regenerated in QGP by re-combination of heavy $Q\bar{Q}$ pairs

Balanced effects at low $p_T$
Reproduced by theoretical models

Stronger suppression for loosely bound system
Bottomia less affected by recombination due to lower $b\bar{b}$ cross section
For open flavours, hierarchical energy loss
$\text{gluons} > \text{charm} > \text{bottom}$
(dead-cone effect + colour factor)
High data statistics allows to look for new probes

Top pair production in Pb-Pb collisions

→ Decays before QGP creation, reconstructed $m(tt)$ carries information on time structure of medium [arXiv:1711.03105]

Light (anti)nuclei production and absorption

→ Ratio of (anti)deuteron, (anti)triton, (anti)$^3$He production to protons increases smoothly across colliding systems

Measurement of low-$p_T$ $\bar{d}$ cross section in p-Pb

→ Novel method exploits detector as absorber. Measurement relevant for antinuclei production from cosmic rays
Observation of light-by-light scattering in 5.02 TeV ultraperipheral Pb-Pb collisions taken in 2018

Look for low-energy back-to-back photon pair with no additional activity in detector

59 $\gamma \gamma \rightarrow \gamma \gamma$ events observed for $12 \pm 3$ expected background (8.2$\sigma$)

Field strength of up to $10^{25}$ V/m reached in UPC Pb-Pb collisions

Photon flux / nucleus $\sim Z^2$

This opened the door to new studies and searches using the interaction of quasi-real photons in Pb-Pb collisions
This week: measurement of light-by-light scattering in 5.02 TeV ultraperipheral Pb-Pb collisions taken in 2015 + 2018.

Measurement of differential cross sections and constraints on ALP-photon coupling versus ALP mass.
Searches for New Physics

Broad and deep searches continue, many exploiting the detectors in new ingenious ways not always envisioned by their designers, but possible thanks to system redundancy.
**Searches for heavy resonances** decaying via pairs of W, Z, H bosons or top quarks benefit from significantly improved boson and top tagging algorithms using machine learning.

Backgrounds derived from data using smooth functions — requires faithful description.
Searches for heavy resonances decaying via pairs of W, Z, H bosons or top quarks benefit from significantly improved boson and top tagging algorithms using machine learning. Backgrounds derived from data using smooth functions — requires faithful description.

**VV → qqqq resonance search**

Novel method: 3D fit to the two large-R-jet masses & dijet mass → up to 30% better sensitivity

High — Low
**Purity category**

Limit $H_{VT_B} W'(Z') > 3.8$ (3.5) TeV

arXiv:1906.05977
Searches for Supersymmetry are significantly improving sensitivity in difficult areas of compressed spectra, and deepen quest for R-parity violating scenarios.

Look for Z+lepton (3\ell) resonance:

Excluding charginos up to 1 TeV

Look for many jets & b-jets, no leptons:

Excluding top squarks up to 950 GeV
Searches for Supersymmetry: state-of-the-art sensitivity and limits for gluino, top squark and electroweak pair production.
Dark sector and long-lived particle searches

Number of new experiments around LHC and SPS proposed or approved to look for long-lived neutral particles (e.g., heavy neutral leptons (“sterile neutrinos”), dark photons, dark scalars, axion-like particles)

One possibility: dark photon ($A'$) portal

Recent LHCb search for prompt and long-lived $A' \rightarrow \mu\mu$ (5.5 fb$^{-1}$)

arXiv:1910.06926
Dark matter searches at the LHC — Direct through recoil (incl. SUSY), indirect through mediator

If produced at the LHC, DM interactions will be mediated by particles that can also be directly searched for — complementarity

Interpretation depends strongly on values of $g_q$, $g_X$
The next steps
Upgrades during LS2: improve Run-3 physics and prepare for HL-LHC

**Accelerators**

LHC Injector Upgrade (LIU): Linac 4, PSB, SPS
For improved beam brightness and reliability

LHC: consolidation of interconnections & diode boxes
Two 11 T dipoles at P7 to make room for collimator
Unclear whether will be installed

Civil engineering for HL-LHC

**ALICE**

Main theme: trigger-less readout
50-100 times min bias, 50 kHz readout (was 1 kHz)

New Pixel Inner (ITS2) and Fwd muon tracker (MFT) — 13B pixels
Pioneers monolithic MAPS (CMOS) technology

GEM-based TPC readout + Fast Interaction Trigger, new Online-Offline computing system, …

**ATLAS**

Main theme: refine trigger selection
In view of Run-3 and the HL-LHC

LAr upgrade for better L1Calo granularity
Exploited by more powerful L1 trigger boards

Muon New Small Wheel (NSW), …
Improved fake muon rejection at trigger level

**CMS**

Many upgrades already during Run-2
New Pixel, DCDC, L1 trigger, PPS, HCAL elec.

Finalise this work during LS2
Plus for HL-LHC: new beampipe, civil eng., muon electronics & GEMs, beam & Fwd systems

Additional consolidation tasks

**LHCb**

Main theme: 5 times luminosity and pileup
Maintain performance of detector — update ~all systems
– New tracking detectors: pixel, strips, outer (SciFi)
– New RICH optical system and photo detectors

40 MHz all-software trigger (current HW: 1.1 MHz)
New RICH, calorimeter, muon readout (L0 trigger removal)
HLT1 (first level) reconstruction on GPUs
Surface data centre for event filter and building
Upgrades during LS2: improve Run-3 physics and prepare for HL-LHC

Accelerators

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Two 11 T dipoles at P7 to make room for collimator
Unclear whether will be installed
Civil engineering for HL-LHC

Run 3 will be a game changer for ALICE (×50 of Run 1+2) and LHCb (×5)

For ATLAS and CMS, the LS2 upgrades prepare for the game changing HL-LHC

ALICE

ATLAS

CMS

LHCb

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New Pixel, DCDC, L1 trigger, PPS, HCAL elec.
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40 MHz all-software trigger (current HW: 1.1 MHz)
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Surface data centre for event filter and building
Upgrades during LS2: improve Run-3 physics and prepare for HL-LHC

We have heard this week that much of this work is affected by the necessary COVID-19 measures. In addition to the restrictions at CERN, the international experiments depend on the situation at production sites and travel of experts. **There will be delays.** Reassessment of schedule performed over the summer.

As soon as possible experts restarted urgent work wearing their protective equipment and keeping distance.

Photos shown by Matt Charles (LHCb) and Miguel Jimenez (LHC & Injectors)
Miguel Jimenez confirmed on Monday that the additional time needed by the experiments due to COVID-19 will be used for magnet training.
ATLAS & CMS Phase-II upgrades entering construction phase

No time to summarise the many innovating and challenging projects here

Simulated VBF Higgs event with 200 pileup interactions in CMS

HL-LHC: monumental upgrades of LHC, ATLAS & CMS, proposals by ALICE & LHCb

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$\mathcal{L}_{\text{inst}}$ [$10^{34}$ cm$^{-2}$ s$^{-1}$]</th>
<th>$\langle \mu \rangle$</th>
<th>$\int \mathcal{L}$ per year [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>5</td>
<td>140</td>
<td>250</td>
</tr>
<tr>
<td>Ultimate</td>
<td>7.5</td>
<td>200</td>
<td>&gt;300</td>
</tr>
</tbody>
</table>

With 3 ab$^{-1}$: 190 million H and 120 thousand HH (ggF) produced (SM)

© P. Ferreira da Silva at Moriond EW, 2016
Among the many things I did not discuss

- Many, many, many other beautiful results (among these, the suit of new and ingenious long-lived particle searches, an utterly creative field as we heard today)

- Further progress on theoretical calculations and modelling is critical for exploiting the physics of Run-3 and the HL-LHC

- SMEFT, SMEFT, SMEFT: theorists and experimentalists are moving to a global and coherent BSM interpretation framework of measurements and searches — this is an excellent development

- The importance of outreach for particle physics: go and speak to policy makers, your colleagues at universities and labs, and the public about this exciting and important science!
A decade after the start, the LHC and its experiments have exceeded all performance promises and transformed particle physics

We have discovered many new tools to approach the big questions:

- Nature of dark matter and energy
- Hierarchy of scales and stability of the scalar sector
- Matter-antimatter asymmetry in Universe
- Strong CP problem

...to which — unfortunately — direct experimental probes are yet elusive

But there is huge progress on "answerable questions" through measurement (G. Salam, LHCP 2018)

We live in data-driven times, experiment must guide us to the next stage. The LHC and its experiments represent the flagship of particle physics at the energy frontier for the decade to come.
Conclusions

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The unprecedented COVID-19 crisis hits our societies hard with human suffering and huge societal as well as economic challenges.

In this situation, we are extremely grateful to Giovanni, Roberto and all the LHCP 2020 Organisers as well as CERN for allowing this important conference with many fascinating talks and posters to happen.

Thank you!