Experimental Highlights

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Disclaimer

➤ 33 plenary experimental talks
   – \(O(10^2)\) parallel session talks

➤ Remarkable number of new results, ideas, upgrades despite challenging past 16 months

➤ A very personal and non-comprehensive narrative
   – apologies if your favorite result not included

Many thanks to all speakers for providing the material for this talk

Name omissions and mistakes purely due to sleep deprivation and will be fixed in the public version on the conference website
Executive Summary

- Flavor anomalies still alive and need further input
- Jet substructure tools widely used from rare searches to dense QGP
- Consolidation of Machine Learning for analysis and future detectors
- Rich program across energy and mass scales to detect rare processes
  - indirect search for New Physics
- Vibrant and diversified direct search program for New Particles
- Taking a stab at some of rarest processes already with Run 2
- Higgs, top, and vector bosons constraining effective theories with Standard Model as low-energy limit
  - SMEFT is here to stay

\[ \mathcal{L}_{\text{eff}} = \frac{\Lambda^4}{g^2} \mathcal{L} \left( \frac{D_\mu}{\Lambda}, \frac{g_H H}{\Lambda}, \frac{g_{f L, R} f_{L, R}}{\Lambda^{3/2}}, \frac{g_{F_{\mu \nu}}}{\Lambda^2} \right) \approx \mathcal{L}_4 + \mathcal{L}_6 + \cdots \]

- **dimension-4 terms:** The SM
- **dimension-6 terms:** Leading deviations from the SM
Standard Model

- Extremely predictive theory since its inception

- Last missing piece discovered just 9 years ago
  - Compare to gravitational waves and general relativity

- Has successfully resisted 50 years of falsification

- *We already know it is incomplete*
  - Neutrinos are massive

- It cannot address some basic curiosities and questions about *our* Universe
Questions and Curiosities

➢ What is the origin of mass?
➢ Have we found the Higgs boson?
➢ What is the origin of mass hierarchy?
➢ Do all leptons behave equally?
➢ Where is all the anti-matter in our Universe?
➢ What is Dark Matter?

LHC provides broad spectrum of measurements to tackle almost all these questions!
Means of Falsification

- Multiple and redundant measurements of well known quantities
  - different methods, contexts, technologies
  - differential and fiducial cross sections

- Measurement of very small and precise predictions
  - variety of such observables across the spectrum
  - typically referred to as indirect search for New Physics
  - At LHC now merging with standard Physics thanks to amount of data

- Search for the exotic
  - chasing more or less crazy ideas by theory friends
    - often motivated by some big question
  - Taking advantage of capabilities of detectors for unconventional signatures

- New computational tools for more efficient data mining and increasing sensitivity

- New technologies to improve detection techniques and try new avenues
CP Violation

What & Why

• CKM matrix: connects the "weak" and the "mass" states of the quarks
• Complex and unitary triangles

\[ V_{ud} V_{us} |V_{ub}|, \gamma \]
\[ V_{cd} V_{cs} |V_{cb}| \]
\[ \Delta m_d, \beta \]
\[ \Delta m_s, \beta_s \]
\[ |V_{tb}| \]

\[ \gamma(=65.7^{+1.0}_{-2.5})^\circ \]

\[ \gamma = (67 \pm 4)^\circ \]

• Beauty decays: excellent terrain to test CKM picture
• CP violation: CKM complex phase
• Mixing and Semileptonic rates: CKM's amplitudes
• Laboratory to study LFU anomalies (Alessandra's Talk on Tuesday)

Tensions are a clear sign for New Physics

B. Khanji (Dortmund)
B-hadrons: CPV and semileptonic decays
June 10, 2021

\[ B^+ \rightarrow D^0 h^-, D^0 \rightarrow hh\pi^0/\phi\pi^0 \]
\[ B^+ \rightarrow D^0 h^+, D^0 \rightarrow K^0_S h^+ \]
\[ B^+ \rightarrow D^0 h^+, D^0 \rightarrow h^0 h^- \]

Full LHCb Combination

\[ B^+ \rightarrow D^0 h^+, D^0 \rightarrow h^0 h^- \]

\[ B^+ \rightarrow D^0 h^+, D^0 \rightarrow \phi h^- \]

\[ B^+ \rightarrow D^0 h^+, D^0 \rightarrow h^+ h^- \]

\[ B^+ \rightarrow D^0 h^+, D^0 \rightarrow h^+ h^- \]

\[ B^+ \rightarrow D^0 h^+, D^0 \rightarrow \phi h^- \]

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\[ B^+ \rightarrow D^0 h^+, D^0 \rightarrow \phi h^- \]

\[ B^+ \rightarrow D^0 h^+, D^0 \rightarrow h^0 h^- \]
\[ \Phi_s \text{ and } B_s^0 \rightarrow J/\Psi \phi \]

- Golden mode for Bs
  - clean experimental signature and theoretical prediction

\[ \phi_s^{SM} \simeq -2\beta_s = -36.89^{+0.70}_{-0.81} \text{ rad} \ [\text{CKMfitter}] \]

- Different trigger strategies for ATLAS and CMS
  - uncertainties competitive with LHCb

- LHCb provides measurement with several channels

\[ \phi_s = -0.041 \pm 0.025 \text{ rad}, \Delta\Gamma_s = 0.082 \pm 0.005 \text{ ps}^{-1} \]
$B^0_S$ oscillation and time-dependent CPV

- Most precise measurement oscillation frequency in $B^0_S \to D_s^- \pi^+$

$$\Delta m_s = 17.7656 \pm 0.0057 \text{ ps}^{-1}$$

- First observation of time-dependent CP violation in $B^0_{s,d} \to h^+ h^-$

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**Flavor Changing Neutral Currents**

- Forbidden in Standard Model at tree level
- Typically small predicated rates and hence sensitive to new particles in strong and electroweak penguin loops
- Rich area of probe in b, c, s, and now also top decays

![Diagram of Flavor Changing Neutral Currents](image)

- $\text{BR}(t \rightarrow qH) \sim 10^{-15}$
- $\text{BR}(t \rightarrow qZ) \sim 10^{-14}$

**New CMS-PAS-TOP-20-007**

- $B(t \rightarrow Hu) < 1.9 \times 10^{-4}$
- $B(t \rightarrow Hc) < 7.3 \times 10^{-4}$
Lepton Flavor Universality

B-physics anomalies, measured in b-flavor observables and deviations from SM prediction. Leptoquarks possible solution.

Leptoquarks at CMS...
Long Standing Anomalies

\[ R(D^*) = \frac{BF(B \rightarrow D^* \tau \nu)}{BF(B \rightarrow D^* \mu \nu)} \]

\[ R_K = \frac{BR(B^+ \rightarrow K^+ \mu^+ \mu^-)}{BR(B^+ \rightarrow K^+ e^+ e^-)} \]

\[ B^0 \rightarrow K^{*0}(K^+ \pi^-) \mu^+ \mu^- \]
Anomaly stands still

New angular analysis in $B_S^0 \to \phi \mu^+ \mu^-$
- Discrepancy wrt predictions similar to $K^{*0} \mu^+ \mu^-$
- CP Asymmetries and averages compatible with SM
Tackling Anomalies at High Mass

- Tree-level explanation of B anomalies with preferred coupling to 2\textsuperscript{nd} and 3\textsuperscript{rd} generations
- Pair- and single-production of leptoquarks
Lepton Universality in W decays

- Compare W branching fraction in $e, \mu, \tau$

$\tau/\mu$

$\tau/e$

- Very good agreement between LHC and Standard Model
DM INTERACTIONS WITH ORDINARY MATTER

- Dark Matter interactions are important to get the right relic abundance.
- Then why not?
- Dark Matter as a particle hints at many interactions with ordinary matter.

**Direct Detection**

**Production at Colliders**

The Dark Matter Mass Spectrum

**Dark Matter**

The known unknown
In addition to classic MET + SM-object(s) search, also constraining mediator mass and coupling in simplified models also visible decays

Search for hidden sector also at very low mass
LHC Physics Program

- Intense scrutiny of Higgs and Yukawa sector

\[ \mathcal{L} = -\frac{1}{4} F_{\mu \nu} F^{\mu \nu} + i \bar{\psi} D \psi + |D_\mu \phi|^2 - V(H) + Y_{ij} \psi_i \psi_j \phi + h.c. \]

- While keeping a wide open eye on new phenomena

\[ + \mathcal{L}_{New} \]

- Precision Electroweak
- QCD
- Higgs properties
- Higgs self interaction

- Higgs coupling to bosons and fermions
- CKM matrix and CP Violation

- New light and heavy particles
- Lepton flavour universality violation
- Leptoquarks
- SUSY
- Long-lived particles
- Dark matter
Quantum Chromo Dynamics

Quark-Gluon Plasma and Spectroscopy

Relativistic Heavy-Ion Collisions

made by Chun Shen

Initial energy density

QGP phase

Hadron gas phase

Hadronization

Kinetic freeze-out

final detected particle distributions

\[ \gamma \]

\[ \pi \]

\[ K \]

\[ p \]

\[ e^+ \]

\[ e^- \]

\[ \tau \sim 0 \text{ fm/c} \quad \tau \sim 1 \text{ fm/c} \]

\[ \tau \sim 10 \text{ fm/c} \quad \tau \sim 10^{15} \text{ fm/c} \]

pre-equilibrium dynamics

viscous hydrodynamics

collision evolution

free streaming

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Jet substructure

- Internal radiation pattern used in pp and ion-ion collisions
  - reliable predication
  - valuable probe in both high density matter and rare searches
    - distinguish QCD jets from W/Z/H

- Systematic study of radiation versus opening (Lund Plane)
  - complementary kinematic regions in ALICE and ATLAS+CMS

- Jets with heavy flavor to probe mass dependency

\[ R(\theta) = \frac{1}{N^{D0{\text{jets}}} \frac{d\ln N^{D0{\text{jets}}}}{d\ln(1/\theta)}} \left( \frac{1}{N^{\text{inclusive jets}}} \frac{d\ln N^{\text{inclusive jets}}}{d\ln(1/\theta)} \right) \]

Relative ratio to gluons and light flavor quarks

Hadron level beauty \( \ln(k_\perp) > 0 \)

\( \theta_2 = m_k / E \)

\( \theta = 2 k_\perp^{\text{min}} / E \)

Radiator: quark lead prong

Leticia Cunqueiro Mendez
Interaction in QGP

Probing interactions with medium with W/Z, jets, and heavy flavor
- Use W/Z and p-p as reference
- measure energy loss and jet widening

\[ R_{AA} = \frac{\text{Pb-Pb}}{\text{scaled@pp}} \]

Quarkonium \( R_{AA} \) (Re)generation

QGP melting

Energy Density

\[ R_{AA}(J/\psi) \]

- ALICE PbPb 5.02 TeV, \( p_{T} > 0 \) GeV
- PHENIX AuAu 0.2 TeV, \( p_{T} > 0 \) GeV
- STAR AuAu 0.2 TeV, \( p_{T} > 0.15 \) GeV
- CMS PbPb 5.02 TeV, \( p_{T} > 6.5 \) GeV
- ATLAS PbPb 5.02 TeV, \( p_{T} > 9 \) GeV

CMS & ATLAS high-\( p_{T} \)

Smaller suppression at LHC

Gradual decrease vs \( N_{\text{part}} \) in RHIC

\[ R_{AA}(\text{RHIC}) \sim R_{AA}(\text{LHC}) \text{ at high-} p_{T} \]

Agreement between RHIC and high \( p_{T} \) LHC despite different energy density
Observation of odderon

- Structure in differential cross section of elastic scattering
  D0 measured elastic $p\bar{p} \, d\sigma/dt$ at 1.96 TeV.
  TOTEM measured elastic $pp \, d\sigma/dt$ at: 2.76, 7, 8 and 13
  – odderon: C-odd gluon compound

- Combination of TOTEM and D0 excludes models w/o odderon exchange

D0 and TOTEM elastic scattering data: D0 measured elastic $p\bar{p} \, d\sigma/dt$ at 1.96 TeV.
TOTEM measured elastic $pp \, d\sigma/dt$ at: 2.76, 7, 8 and 13 TeV.

pp elastic $d\sigma/dt$ characterized by a diffractive minimum and a secondary maximum.

Extrapolate “characteristic” points of TOTEM $d\sigma/dt$ to predict $pp \, d\sigma/dt$ at D0 energy.

D0 and TOTEM: ArXiv:2012.03981

Comparison of extrapolated $pp \, d\sigma/dt$ with $p\bar{p}$ D0 data:

2-test of difference: 3.4 significance for Odderon exchange
Significance confirmed by a combined Kolmogorov-Smirnov and normalization test

Previous evidence from TOTEM (EPJC (2019) 785):
Using very low $|t|$ data at 13 TeV TOTEM measured $\r_{\text{tot}}$ and $\r_{\text{real}}$ (ratio of real to imaginary part of elastic amplitude at $t = 0$).
Combination of the measured $\r_{\text{tot}}$ and $\r_{\text{real}}$ values not compatible with any set of models without Odderon exchange at 4.6 significance.
Combination of independent evidences of Odderon exchange from TOTEM $\r_{\text{tot}}$ and $\r_{\text{real}}$ with $pp$ and $p\bar{p}$ comparison excludes available models without Odderon exchange at 5.2-5.7 leading to observation of Odderon.
Spectroscopy

▷ New Age of spectroscopy and fruitful collaboration with theory
  – systematic study of tetra- and penta-quarks

▷ Interesting discrepancy in baryon lifetimes confirmed
  – interesting to see theory prediction and previous measurement
Electroweak Sector

New Physics through Precision

Inclusive W and Z

WW, WZ, ZZ

top pair

tt+X

SUSY

Higgs self interaction

Triple and Quartic Gauge Coupling

Vector boson scattering

WWW, ZZZ

All results at: http://cern.ch/go/pNj7

Electroweak Sector

New Physics through Precision
Vector Boson Scattering

- Quartic gauge couplings known exactly in SM and sensitive to new physics contributions
  - Disentangle QCD and EW contribution through jet kinematics
  - Suppress QCD background with novel ML techniques

- Important milestone for longterm LHC program towards study of WW scattering
  - Observation of Same-sign WW in 2017!

- First observation of $\gamma\gamma \rightarrow W^+W^-$

- Comprehensive input with various VV modes to constrain EFT operators
Top agreement with theory

- Competing precision between theory and experiment in ttZ

- tt+bb production now exceeding theoretical knowledge!
  - Important background in study of top-Higgs Yukawa coupling

- Now also tt+cc with 19% precision
  - Key role of c-tagging

- Precision theory input needed to reduce uncertainties
  - Important ingredient for rare Higgs and other processes

First tt+cc measurements!

\[ \sigma_{ttcc} \sim 19\% \]
\[ \sigma_{ttbb} \sim 15\% \]

-8% precision
-6% precision

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top and W properties

- Infer spin of weakly-produced single-top from angular analysis in $t \rightarrow b l \nu$
  - polarisation consistent with SM prediction and sensitive to new physics contributions

- Measurement of W helicity to approach W mass
  - differential cross section for $W^+$ and $W^-$
  - Aim at reduced uncertainty in W mass by constraining also PDFs
    - correct and abundant simulation a key ingredient
4-top production

- SM cross section: 12 fb @ 13 TeV
- Several final states combined
  - key role of BDT discriminants in this search

Dominant uncertainties:
- $t\bar{t}+\geq 1b$ modelling, (±8 fb), $t\bar{t}+\geq 1c$ cross-section (±5 fb)
In the confidence intervals for a Higgs boson coupling to a coupling strength modifiers (June 7, 2021)

For the first time, meaningful 68% and 95% kappa framework for $m=1$.

$H$ second generation fermion = $\pm 125.38 \pm 0.22$ (at 68%CL)

Probing Higgs Couplings at the LHC

4 main production modes

Higgs boson production

49 pb $\sigma$ [pb]

Higgs boson decays

4 main production channels

Higgs BR + Total Uncert

$\sigma$ [pb]

#Higgs produced during Run-2

From Discovery to Precision

Higgs

$Y_{ij}\psi_i\psi_j\phi$
Higgs Physics

- A standard candle of Standard Model in just a decade since its discovery
  - compare to top, W, and Z

- Higgs now used as a probe in searches for new phenomena
  - FCNC in top decays
  - Search for Supersymmetry
  - Search for Dark Matter WIMP candidates
  - Decay of heavy new particles to H+X

- Couplings to 3rd generation established
  - taus in 2017, top and b in 2018

- Coupling to 2nd generation under way!
  - evidence for muons, tackling also charm

- So far it walks and talks like the Standard Model Higgs

- Falsification of the Higgs mechanism a critical component of High Energy Frontier program
Higgs precision studies

- Extensive measurement of differential and fiducial cross sections
  - STXS framework as the basis for reporting results

- Study of spin and CP also in agreement so far with Standard Model precisions

- Theory and experimental uncertainties now comparable
  - Fruitful collaboration with theory
H \rightarrow c\bar{c}

- Higgs produced together with vector bosons

- Remarkable achievement thanks to novel tagging techniques
  - Higgs Branching fraction 3%!

- Within reach with future improvements and copious data at HL-LHC
Understanding Higgs sector requires measurement of its self-interaction

- Updated search in bbbβ now excluding x4 SM (expected x7 SM)

- Cornerstone of Run3 and HI-LHC
  - currently limited by statistics
  - room for even more sophisticated analysis techniques
Experimental Results on Exotic Searches - LHCP 2021

Tri-body resonances: \( WKK \rightarrow \text{Trijets} \)

- First LHC search on a triboson resonance
  - KK excited massive W boson (bulk RS WED model):
  - Targets events triggered by a lepton, with additional "large-R jets" (AK8)
    - 2 \( W \)-tagged jets
    - 1 "WW"-tagged jets including merged hadronic+leptonic \( WW \) decays (lepton-in-jets)
  - Event categorization based on jet masses and the NN tagger score (substructure)
  - Need consistency with SM

- A lepton+jets resonant peak is sought after.

95% C.L. upper limit on cross section for \( \sigma_{\text{WWW}} \rightarrow \text{WR} \rightarrow \text{kk} \)

For \( m_R \), masses are excluded below 3.3 TeV

For \( m_W \), masses are excluded below 3.3 TeV

For \( m_K \), masses are excluded below 3.3 TeV

Credits: J. Antonelli
The Higgs or A Higgs?

- In BSM models with more Higgs bosons, some can resemble the Higgs
- Direct search for additional light and heavy Higgs bosons

2HDM has 5 Higgs bosons
- $h$: "SM" Higgs
- $H$: heavy Higgs
- $A$: pseudoscalar
- $H^\pm$: charged Higgs

High-Luminosity LHC two provide x20 increase in statistics

So far no excess or evidence and only exclusion in theory parameter space

High-Luminosity LHC two provide x20 increase in statistics

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Long-Lived Particles

small coupling
e.g. coupling to gravitino

off-shell decays
e.g. squark mass > 10 TeV

phase space
e.g. small mass splitting

direct LLP detection
observable track

indirect LLP detection
observe decay products

Tracks only in inner tracker and possible calorimetric veto
Supersymmetry

- Many new searches targeting both strong and electroweak production
  - No significant excess observed so far

- Strong SUSY searches targeting masses ~ 2 TeV

- Searches now using also H→γγ and exotic Higgs decays in electroweak production

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Elodie Ressegui
Machine-Assisted Intelligence

- Machine-Learning methods percolating not-only data analysis at fast rate
- Several processes already accessible in Run 2 thanks to advance techniques
  - flavor tagging for both b and c with deep learning
  - Boosted Decision Trees a crucial ingredient in top, Higgs, and electroweak sector
  - Significant impact also in direct searches
- Highest pay-off for deployment at low level to better understand detector response and particle or event identification
  - Upgraded detectors to rely on ML for low-level reconstruction
- Appropriate use of these tools and our experience with Run2 lay the foundations for improved sensitivity in Run 3 and HL-LHC
- Past experience tells us we always do better than $1/\sqrt{\mathcal{L}}$ in our projections
  - just pick any physics book from LHC or B factories
Outlook

- Standard Model continues to stand strong in this Universe
- Flavor anomaly still there and to be pursued at low and high mass
  - Redundant measurements and revamped interest for Z’ and LQ
- Higgs coupling to 2nd generation fermion ahead of schedule
  - Take a look at physics TDRs released 15 years ago
- Top, W, Z, Higgs entering *precision era in pp* and constraining new physics
  - Maximise impact through concerted effort with EFT approach to SM
- Expected increase in ion-ion collisions Run 3 to allow differential studies
  - Order of magnitude increase in statistics in addition to powerful ML techniques
- Human ingenuity assisted by Artificial Intelligence is putting us *further* ahead of statistics-only pace

Nice overview by Sergo Jindariani
LHC in 2021

▷ Life during Run 1 of LHC

▷ In Run 2/3 day-to-day life can be challenging
  – harvesting copious data
  – upgrading magnificent detectors
  – produce copious high quality results

▷ Do not forget the 30’000 feet view
  – 90% of data yet to be delivered and collected
  – room for novel ideas and techniques