Moriond QCD 2019
Experimental summary

Vincenzo Vagnoni
INFN Bologna

(the last winter first spring conference of the year)
Moriond QCD today

• QCD is everywhere...
Moriond QCD today

• QCD is everywhere...

• It can be the main character of our studies...
Moriond QCD today

• QCD is everywhere...

• It can be the main character of our studies...

• ...or an annoying antagonist that pollutes the measurements of our interest!
Moriond QCD today

• For the joy of summary speakers
  – About 90 talks covering Higgs physics, electroweak physics, top physics, BSM physics, soft QCD, jets, PDFs, heavy ions, heavy flavours, spectroscopy, ...
The (damned) Standard Model

• The SM is a stubborn animal, indeed!
  – Although it has been working beautifully so far up to a few hundred GeV, we know it must be an effective theory valid up to some energy scale

• The good reasons to believe that it is incomplete are still there, e.g.
  – Hierarchy problem?
  – Dark matter candidate?
  – Unification of gauge couplings?
  – $CP$ violation for dynamical BAU?
  – Three generations of quarks and leptons?
  – Origin of mass hierarchy?
  – Origin of CKM hierarchy?
  – ...

Fortunately we have powerful tools...

Frederick Bordry

Peak luminosity

76 % availability

ATLAS/CMS: ~66 fb\(^{-1}\)

- Despite some problems LHC performance record in 2018 → Peak luminosity steadily at ~2\(\times10^{34}\) cm\(^{-2}\)s\(^{-1}\)
  - x2 w.r.t. the design value
Higgs physics
Higgs: from observation to measurement

• Seems with us since ages, but it’s just a **seven year-old baby**

• Measurements of Higgs properties with increasing precision are a **formidable tool to look for new-physics manifestations**

Main production mechanisms: $ggH$, $VBF$, $VH$, $t\bar{t}H$

Main decays: $\gamma\gamma$, $ZZ$, $WW$, $\tau\tau$, $bb$
Simplified template cross-sections (STXS)

- Framework for cross-section measurements with reduced model dependence, targeting Higgs production
- Split Higgs production into the main production modes
- Split further into fine-grain kinematic regions of phase space

\[ + \text{bbH} + \text{tH} \]

- gluon fusion (87%)
- vector boson fusion (7%)
- VH (4%)
- ttH (2%)

\[ \begin{align*}
  g &\rightarrow t, b, h \\
  q &\rightarrow W^\pm, Z \\
  g &\rightarrow W^\pm, Z \\
  q &\rightarrow W, Z \\
  g &\rightarrow t, \bar{t} \\
\end{align*} \]
Vector-boson + H with $H \rightarrow b\bar{b}$

Kurt Brendlinger

80 fb$^{-1}$, 13 TeV [arXiv:1903.04618]

- Measure associated production of $H \rightarrow b\bar{b}$ and W or Z decaying into leptons as a function of $p_T(V)$ with STXS
- Cross-sections used to constrain parameters in an effective Lagrangian framework, adding terms like $c_i^{(D)} O_i^{(D)}/\Lambda^{D-4}$
  - Only dimension 6 operators are considered in this study
Higgs-top measurements

Kurt Brendlinger

140 fb$^{-1}$, 13 TeV [ATLAS-CONF-2019-004]

- Measure coupling to the top quark using $H \rightarrow \gamma\gamma$ decays
  - Simultaneous fit in seven signal-enriched event categories

- $ttH$ production observed at $4.9\sigma$ relative to the background-only hypothesis

All channels $\log(1+S/B)$ weighted

Fit results in the 7 BDT bins

Measured signal strength: $\mu_{ttH} = 1.38^{+0.33}_{-0.31} \text{ (stat.)}^{+0.13}_{-0.11} \text{ (exp.)}^{+0.22}_{-0.14} \text{ (th.)}$
Measurements of $H \rightarrow ZZ \rightarrow 4\ell$

Meng Xiao

137 fb$^{-1}$, 13 TeV [CMS-PAS-HIG-19-001]

- Several new measurements in the four-lepton final state
  - All main production modes: $ggH$, VBF, VH, $ttH$
    - Little sensitivity to $bbH$ or $tH$, but they are also considered explicitly
- Differential cross sections measured as a function of the Higgs $p_T$ and $y$, the number of associated jets, and the $p_T$ of the leading associated jet

Measured signal strength:

$$\mu = 0.94^{+0.07}_{-0.07} \text{(stat.)} +^{0.08}_{-0.07} \text{(syst.)}$$
H → J/ψJ/ψ and YY

Martin Flechl

37.5 fb⁻¹, 13 TeV [CMS-PAS-HIG-18-025]

• With more and more statistics, searches for Higgs rare decays becoming increasingly important
• Exclusive decays of the Higgs boson to mesons interesting to study Yukawa couplings to quarks and for BSM searches
• New physics could affect direct Higgs-qq couplings or enter through loops, and modify interference patterns between the various amplitudes
• SM predictions very small and uncertain

\[
\begin{align*}
B(H \to J/\psi J/\psi) &\times 10^{3} & 1.8 & 1.8^{+0.2}_{-0.1} \\
B(H \to YY) &\times 10^{3} & 1.4 & 1.4 \pm 0.1 \\
B(Z \to J/\psi J/\psi) &\times 10^{6} & 2.2 & 2.8^{+1.2}_{-0.7} \\
B(Z \to YY) &\times 10^{6} & 1.5 & 1.5 \pm 0.1
\end{align*}
\]

SM: \( B(H \to J/\psi J/\psi) \approx 1.5 \cdot 10^{-10} \)

\( B(H \to YY) \approx 2 \cdot 10^{-9} \)

PRD 79 (2009) 114015
Higgs status and outlook

• So far it looks, swims and quacks like a Standard Model Higgs

• But transition from observation to detailed measurements has only started
  – Now also in the STXS framework, with finer granularity to probe deviations from the Standard Model

• Several new Higgs results presented at winter conferences
  – Only a few with full Run-2 statistics and many others with partial Run-2 statistics

• Looking forward to significant improvements with the full set of analyses and the full Run-2 data set

• I am personally amongst those who would be very surprised if with Run 3 and then with the HL-LHC, at latest, we will conclude that the Higgs is purely Standard Model!
Electroweak and top
**EW tests of the Standard Model**

- In the SM three parameters define the EW sector
  - U(1), SU(2) couplings and VEV

- The electroweak sector of the SM is overconstrained and the strength of global fits can be exploited to predict key observables, such as the W mass and the effective electroweak mixing angle, with a precision exceeding that of direct measurements

- Stringent consistency test of the SM!
$M^2_W \left( 1 - \frac{M^2_W}{M^2_Z} \right) = \frac{\pi \alpha}{\sqrt{2} G_F} (1 + \Delta r)$

- $M_W$ sensitive to $M_H$ and $M_t$ via radiative corrections
- Precise determination of the W mass is of great importance in testing the internal consistency of the Standard Model
- The global EW fit yields $M_W$ with an uncertainty
  \[ \Delta m^\text{theory}_W = 8 \text{ MeV} < \Delta m^\text{exp}_W = 15 \text{ MeV} \rightarrow \text{Need to improve experimental uncertainty} \]
- Only $M_W$ measurement at LHC so far from ATLAS
  - $M_W = 80370 \pm 7 \text{ (stat.)} \pm 11 \text{ (exp. syst.)} \pm 14 \text{ (mod. syst.) MeV}$
  - Precision 0.02%, dominating uncertainty from theory: QCD, PDF

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<tbody>
<tr>
<td>$m_T-p_T^f$, $W^\pm$, $\mu$</td>
<td>80369.5</td>
<td>6.8</td>
<td>6.6</td>
<td>6.4</td>
<td>2.9</td>
<td>4.5</td>
<td>8.3</td>
<td>5.5</td>
<td>9.2</td>
<td>18.5</td>
<td>29/27</td>
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- ATLAS measurement alone competes with Tevatron combination
  - Measurement at LHC affected by PDFs more than Tevatron
Double Z production

Louis Helary

101 fb$^{-1}$, 13 TeV [CMS-PAS-SMP-19-001]

- In the SM, ZZ production proceeds mainly through quark-antiquark $t$- and $u$-channel scattering diagrams
  - At higher orders in QCD also $gg$ fusion contributes via box diagrams with quark loops
- Recent CMS study of 4-lepton production $pp \rightarrow (Z/\gamma^*)(Z/\gamma^*) \rightarrow 4\ell$, where $\ell = e$ or $\mu$, at 13 TeV
- By combining with the 2016 results, CMS measured $\sigma(pp \rightarrow ZZ)$ to be $17.1 \pm 0.3 \text{ (stat)} \pm 0.4 \text{ (syst)} \pm 0.4 \text{ (theo)} \pm 0.3 \text{ (lumi)} \text{ pb}$
- Measured cross-section value is found to be consistent with the Standard Model predictions
LHC as a top factory

- Produced predominantly in pairs at the LHC: $\sigma_{tt} \approx 0.8$ nb at 13 TeV
  - Single top quark production via electroweak interactions is rarer, but theoretically very clean
- Heaviest fundamental particle by far: $m_t \approx 173$ GeV
  - Similar mass scale to H, W and Z related to electroweak symmetry breaking?
- Short lifetime: $\tau \approx 10^{-25}$ s
  - Decays before hadronization → unique opportunity to study a quasi-free quark
  - Spin decorrelation time much longer → can study spin correlation via decay products, e.g. ATLAS [arXiv:1903.07570]
- Decays almost exclusively to Wb in the Standard Model
  - Categorize events by the decays of the W bosons: all-hadronic, $\ell$+jets, di-lepton
Top mass measurement

Dominic Hirschbuhl

- $M_H$ at 125 GeV is close to the minimum value that ensures absolute vacuum stability within the Standard Model
- Precise top-mass measurement very relevant → several different techniques

Ideogram method, 35.9 fb$^{-1}$, 13 TeV [EPJC 78 (2018) 891]

$$m_t^{hyb} = 172.25 \pm 0.08 \text{ (stat+JF)} \pm 0.62 \text{ (syst) GeV}$$

All-jets final state, 35.9 fb$^{-1}$, 13 TeV [arXiv:1812.10534]

$$m_t^{hyb} = 172.34 \pm 0.20 \text{ (stat+JF)} \pm 0.70 \text{ (syst) GeV}$$

Inclusive cross-section, 35.9 fb$^{-1}$, 13 TeV [arXiv:1812.10505], different PDF sets

<table>
<thead>
<tr>
<th>PDF set</th>
<th>$m_t^{pole}$ [GeV]</th>
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<tbody>
<tr>
<td>ABMP16</td>
<td>$169.9 \pm 1.8 \text{ (fit + PDF + } \alpha_s) \pm 0.8$ (scale)</td>
</tr>
<tr>
<td>NNPDF3.1</td>
<td>$173.2 \pm 1.9 \text{ (fit + PDF + } \alpha_s) \pm 0.9$ (scale)</td>
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<tr>
<td>CT14</td>
<td>$173.7 \pm 2.0 \text{ (fit + PDF + } \alpha_s) \pm 0.9$ (scale)</td>
</tr>
<tr>
<td>MMHT14</td>
<td>$173.6 \pm 1.9 \text{ (fit + PDF + } \alpha_s) \pm 0.9$ (scale)</td>
</tr>
</tbody>
</table>

Differential cross-section, 35.9 fb$^{-1}$, 13 TeV [arXiv:1812.10505]

$$m_t^{pole} = 170.5 \pm 0.7 \text{ (fit)} +0.1_{-0.1}(\text{mod}) +0.0_{-0.1}(\text{par}) +0.3_{-0.3}(\text{scale}) \text{ GeV} = 170.5 \pm 0.8 \text{(total) GeV}$$
Associated production of $t\bar{t}$+VB

Imma Riu

- $t\bar{t}Z$ and $t\bar{t}W$ are rare processes
  - $\sigma \approx 1$ pb at 13 TeV
- Very useful to test QCD predictions
- Deviations in the measurements might indicate new physics
  - Vector-like quarks
  - Strongly coupled Higgs bosons
  - Exotic quarks with $Q = -4/3$
  - Anomalous dipole moments of top quark

ATLAS, 36.1 fb$^{-1}$, 13 TeV [arXiv:1901.03584]

CMS, 35.9 fb$^{-1}$, 13 TeV [JHEP 08 (2018) 011]

CMS, 77.5 fb$^{-1}$, 13 TeV [CMS-PAS-TOP-18-009]

- Results in line with NLO predictions
- CMS result on $t\bar{t}Z$ has better precision than NLO $\rightarrow$ resummed calculations now reaching NNLL+NLO accuracy

$\sigma_{t\bar{t}Z} = 0.95 \pm 0.08$ (stat) $\pm 0.10$ (syst) pb
$\sigma_{t\bar{t}W} = 0.87 \pm 0.13$ (stat) $\pm 0.14$ (syst) pb

$\sigma_{t\bar{t}W} = 0.77^{+0.12}_{-0.11}$ (stat) $^{+0.13}_{-0.12}$ (syst) pb

$\sigma_{t\bar{t}Z} = 1.00^{+0.06}_{-0.05}$ (stat) $^{+0.07}_{-0.06}$ (syst) pb
Search for 4-top production

Willem Verbeke

- Very rare process
  - $\sigma \approx 10$ fb at 13 TeV

- Very large jet, b-jet multiplicities and hadronic activity

- Latest search by CMS in same-sign dilepton and multilepton events using full Run-2 statistics

- A multivariate analysis yields a significance of $2.6\sigma$ relative to the background-only hypothesis, and a cross-section of $12.6^{+5.8}_{-5.2}$ fb

- Results used to constrain the top Yukawa coupling with respect to the Standard Model value

$|y_t| / |y_t^{SM}| < 1.7$ (95% C.L.)
Search for FCNC with top

Elizabeth Brost

• Top is also a tool to look directly for BSM physics
• E.g., in FCNC processes the top can couple to a light quark (up or charm) and a neutral boson (γ, Z, H, g)
  – Forbidden at tree-level in the Standard Model → not observable with present data set
• Observation of FCNC would be indicative of new physics
• Recent measurement by ATLAS in $t\to uH$ and $t\to cH$
  – No evidence for the process found
• Combining the search with other ATLAS searches in diphoton and multilepton final states at 95% C.L. one gets
  – $\text{BR}(t\to uH) < 1.1 \times 10^{-3}$
  – $\text{BR}(t\to cH) < 1.2 \times 10^{-3}$
• Nothing unexpected in exotic physics with top quarks yet but the full Run-2 dataset has still to be analyzed!
Forward top-pair production

Pavel Krokovny

• Forward acceptance of the LHCb detector allows measurements in a phase space inaccessible to ATLAS and CMS

• Events containing a high-\(p_T\) muon and electron of opposite charge in addition to a high-\(p_T\) jet are selected

Selection: \(p_T(l) > 20\ \text{GeV}/c\), \(\Delta R(ll) > 0.1\), jet building by anti-\(k_T\) algorithm FASTJET,

\[
2.2 < \eta(\text{b-jet}) < 4.2, \quad p_T(\text{b-jet}) > 20\ \text{GeV}/c, \quad \Delta R(\text{b,l}) > 0.5,
\]

Measurement in fiducial region:

\[
\sigma_{t\bar{t}} = 126 \pm 19 \text{ (stat)} \pm 16 \text{ (syst)} \pm 5 \text{ (lumi)} \text{ fb}
\]

Extrapolating from the fiducial region using predictions from aMC@NLO

1.9 fb\(^{-1}\), 13 TeV [JHEP 08 (2018) 174]
BSM searches
BSM searches at the LHC

• BSM searches are amongst the most important (and challenging) analyses at the LHC

• First searches: BSM models predict new resonances decaying to a pair of objects
  – Two-body resonances like di-photons, di-leptons, di-bosons, di-jets

• Once the multiplicity of the final states gets larger, or one goes for exotic signatures like LLPs, analyses become increasingly more complex and model-dependent, requiring better understanding of the underlying physics models being tested and of the detector response

• Many signatures already probed with full Run-2 statistics
  – First analyses did not reveal evidence for new physics yet, but a lot of phase space still to be explored
BSM searches at the LHC

- A comprehensive discussion of the many searches which are being performed is beyond the possibilities of what a human being can do with a few slides...

- ...but let’s have a look at a few examples of recent analyses presented during the conference
Di-lepton searches

Marcus Morgenstern

- Recent search by ATLAS for new resonances decaying to electron and muon pairs using full Run-2 statistics
- Background fit with parametric function exhibits excellent description of di-lepton spectra up to several TeV
- No significant excess over SM expectation
  - Cross-section limits are set for generic resonances with a relative natural width between zero and 10%

139 fb^{-1}, 13 TeV [arXiv:1903.06248]
**Di-jet searches**

Yiming Abulaiti

- New heavy particles that decay to partons are predicted in many BSM models
  - For example, excited quarks are predicted in compositeness models and are a typical benchmark used in many di-jet searches

- Partons shower and hadronise, creating collimated jets
- BSM phenomena may produce a resonance di-jet signal up to masses that are a significant fraction of the total collision energy
- Two recent searches for new resonances in di-jet invariant mass by ATLAS and CMS shown here
- No significant excess over SM expectation
Searches with multileptons

Stephanie Beauceron

137 fb\(^{-1}\), 13 TeV [CMS-PAS-EXO-19-002]

- **Moving to a more complex analysis**
  - Three or more electrons and muons in the final states
- **Look for non-resonant excesses in the tails of the sum of lepton \( p_T \) + missing transverse momentum**
- **Observed data consistent with SM expectation**

Upper limits on the production cross section of heavy fermion pair \( \Sigma \Sigma \) as a function of mass

Type-III seesaw heavy fermions are excluded for masses below 880 GeV

Red-curve: prediction for \( \Sigma \) pair production via the Type-III seesaw
Unconventional signatures

- While phase space for easy discovery is reducing, growing interest emerging for new-physics searches with unconventional signatures

  - Beasts like: emerging jets, heavy charged LLPs, delayed jets, displaced jets, disappearing tracks, displaced muons

  - Community white paper “Searching for long-lived particles beyond the Standard Model at the LHC” [arXiv:1903.04497]
Dimuon search around the $\Upsilon$

Pavel Krokovny

3 fb$^{-1}$, 7/8 TeV [JHEP 09 (2018) 147]

- Search for a spin-0 boson using prompt decays to $\mu^+\mu^-$
- The LHCb detector has good sensitivity to light spin-0 particles due to its high-precision spectrometer and its capability of triggering on objects with small transverse momenta

- No evidence for a signal is observed and limits are placed
Outlook for BSM searches

• BSM searches are very challenging as they look for corners and tails of Standard Model physics
  – Continuously developing new techniques and adding new models, phase-space regions, correlations with Standard Model background

• Many results anticipated to come out soon with Run-2 statistics, while preparing for Run 3

• Phase space narrowed down for some models, but still many others to study
  – Far to be the end of the searches!
(Some) hard and soft QCD processes
Relevance of QCD measurements at the LHC

• Important for good modelling of hadronic collisions and to test our understanding of QCD
  – Probing PDFs and NLO predictions
  – Study event topologies in interesting phase space regions
    • i.e. multijet production, di-jet decorrelations, very forward region
  – Study jet substructure
  – Understand backgrounds for EW analyses, BSM searches, ...
  – Multiple parton interactions, e.g. double particle scattering (DPS)
  – ...

• In addition, accurate knowledge crucial for the development of future projects, as ATLAS and CMS phase II upgrades, etc.

• Several recent measurements by ATLAS and CMS, the latter also using CASTOR to study very forward energy flow and jets
DPS in inclusive 4-lepton production


Merijn van de Klundert

- Simultaneous Drell-Yan production with four leptons in the final state
- Particular relevant as background to Higgs in four lepton decays
- A simplified model for a DPS cross-section can be written as
  \[ \sigma_{DPS} = \frac{n \sigma_A \sigma_B}{2 \sigma_{eff}} \]
- \(\sigma_{eff}\) assumed to be process and energy independent
- No signal of double-parton scattering is observed
- Upper limit on the fraction of the DPS contribution to the inclusive four-lepton final state translates into a lower limit of 1.0 mb on the effective cross section
DPS in same sign WW production

77 fb⁻¹, 13 TeV [CMS-PAS-SMP-18-015]

Merijn van de Klundert

• Important channel to test DPS predictions
  – Both hard scatterings lead to the production of a W boson, and particularly interesting is the final state with two same-charge W bosons
  – W decay provides relatively clean signal
  – Background processes well understood
    • WZ production main background

• Perform fit in different flavour-sign categories separately
  – μ⁺μ⁻, e⁺μ⁺

• This result presents the first experimental evidence of the DPS WW process

![Diagram showing DPS WW process with W± and W± particles, and a CMS Preliminary graph comparing observed and predicted cross-sections for different channels.](image)
Isolated-photon cross-section

Jonathan Bossio

20.2 fb⁻¹ and 3.2 fb⁻¹, 8 and 13 TeV [arXiv:1901.10075]

- Production of prompt photons in $pp \rightarrow \gamma + X$ allows pQCD tests with a hard colourless probe
- Dominant production mechanism at the LHC is $qg \rightarrow q\gamma$
  - Cross-section sensitive to the gluon density in the proton
- Isolation cut needed to reduce background from neutral-hadron decays and from fragmentation where the emitted photon is close to a jet
- In this analysis, the ratio between cross-sections at 13 and 8 TeV $R_{13/8}^\gamma$ is measured as a function of the $E_T^\gamma$ in different $\eta^\gamma$ ranges
- Predictions using several PDFs agree well with data
Heavy Ions
Hard probes

- **One of the pillars** to study **hot and dense QCD matter** created in HI collisions
- **Perturbative processes take place before the QGP forms**, e.g. heavy-quark production
  - On the other hand, heavy quarks decay weakly so that their lifetime is greater than that of the QGP and they experience the full system evolution
- In addition, quarkonium states have binding energies of the order of a few hundred MeV, and **interactions with hard gluons in a QGP can overcome this threshold breaking the quarkonium system**
- The modification of the jet structures while traversing the hot medium is also another relevant example (jet quenching)
Quarkonium suppression

Javier Castillo

- **J/ψ at high p_T strongly suppressed in PbPb w.r.t. to pp collisions**
  - Suppression increases as a function of the centrality of the collision

- **Also strong Υ suppression is observed, and higher Υ states even more suppressed**

\[
\frac{R_{AA}(\Upsilon(2S))}{R_{AA}(\Upsilon(1S))} = 0.28 \pm 0.12 \text{ (stat)} \pm 0.06 \text{ (syst)}
\]

**PLB 790 (2019) 89**
Quarkonium suppression

CMS observes a similar spectacular behaviour

The $R_{AA}$ of the $\Upsilon(3S)$ state is measured to be below 0.096 at 95% C.L. → the strongest suppression observed for a quarkonium state in HI collisions to date
Quarkonium regeneration

- At low $p_T$, smaller suppression for the $J/\psi$ at the LHC than at RHIC
- New regenerated $J/\psi$ produced by recombination of charm quarks, with larger regeneration occurring at higher $c\bar{c}$ pair density and higher energy density
$\Lambda_c / D^0$ production

- Ratio of $\Lambda_c$ to $D^0$ meson measured by ALICE in pp, pPb, and PbPb collisions
- Similar ratio in pp and pPb whereas enhanced production of $\Lambda_c$ with respect to $D^0$ mesons in PbPb
  - Still limited in precision to draw a firm conclusion, but intriguing
- Also STAR seems to observe a larger $\Lambda_c / D^0$ ratio in AuAu

arXiv:1809.10922
Open beauty in pPb

Daniele Marangotto

- As a dedicated heavy-flavour experiment, LHCb has obvious advantages in measuring b-hadron decays (at pPb event multiplicities)
- Beauty hadrons cleanly reconstructed in exclusive decay modes
  - First measurements in nuclear collisions down to very low $p_T$
- Confirmed $R_{pPb}$ suppression pattern seen in $J/\psi$ from $b$
- LHCb can also inject gas into the beampipe to measure cross-sections in fixed-target mode
  - See e.g. antiproton production in pHe [PRL 121 (2018) 222001] or charm production in pAr and pHe [arXiv:1810.07907]
Muon flow with heavy flavours

Krzysztof Woźniak

- ATLAS measured the flow of muons from heavy flavour decays in pp and PbPb collisions at 2.76 TeV

- $R_{AA}$ is found to be less than 1
  → suppressed production of heavy-flavour muons in PbPb collisions
  - For 10% most central PbPb events, $R_{AA}$ is ~0.35

- Furthermore, lower values of the elliptic flow for particles with heavy quarks than with the lighter quarks
  - Information useful for analysis of interactions of quarks in the medium
Light-flavor production

Giacomo Volpe

- Charged hadron production in PbPb and XeXe collisions at 5.02 and 5.44 TeV
- Production of (most) light-flavour hadrons in PbPb at 5.02 TeV is described by thermal model
- Differences between protons and strangeness sector are confirmed
- Hydrodynamic properties studied with spectral shape and azimuthal anisotropy
  - Hydrodynamics works at low $p_T$ for central collisions
  - Agreement worsens towards peripheral collisions
Collectivity in small systems

Tamás Novák

In recent years, momentum anisotropies have been measured in pp and pA collisions, despite expectations that the volume and lifetime of the medium produced would be too small.

PHENIX observed elliptic and triangular flow patterns in pAu, dAu and \(^3\)HeAu collisions:

- The three initial geometries and two flow patterns provide powerful model discrimination.

In the PHENIX analysis, hydrodynamical models, based on the formation of short-lived QGP droplets, provide the best simultaneous description of the measurements.
Heavy (and less heavy) flavours
Consistency of global CKM fits

• Each coloured band defines the allowed region of the apex of the unitarity triangle according to the measurement of a specific process

• Tremendous success of the CKM paradigm!
  – All of the available measurements agree in a highly profound way to the current level of precision
  – In presence of BSM physics affecting the measurements, the various contours would not cross each other into a single point

• The quark flavour sector is generally well described by the CKM mechanism ➔ we must look for small discrepancies
Observation of CP violation in charm

Last week at Moriond EW
Observation of CP violation in charm

Andrea Contu

6 fb$^{-1}$, 13 TeV [arXiv:1903.08726]

- Using full Run-2 statistics, LHCb measured
\[ \Delta A_{CP} \equiv A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+) \]

- To perform the measurement, the flavour of the $D^0$ meson is tagged either using the charge of the pion in $D^{*+} \rightarrow D^0 \pi^+$ decays, or using the charge of the muon in $\bar{B} \rightarrow D^0 \mu^- \nu_\mu X$ decays
Observation of CP violation in charm

Andrea Contu

6 fb⁻¹, 13 TeV [arXiv:1903.08726]

- Run-2 results:
  - Well compatible with previous LHCb results and world average

\[
\Delta A_{\pi\text{-tagged}}^{CP} = [-18.2 \pm 3.2 \text{ (stat.)} \pm 0.9 \text{ (syst.)}] \times 10^{-4}
\]

\[
\Delta A_{\mu\text{-tagged}}^{CP} = [-9 \pm 8 \text{ (stat.)} \pm 5 \text{ (syst.)}] \times 10^{-4}
\]

- Combination of Run-1 and Run-2 data gives
\[
\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}
\]

- CP violation observed at 5.3σ!

- Roughly compatible with the SM, which however is way more uncertain than data
New measurements of $\phi_s$

- Golden mode $B_s \rightarrow J/\psi \phi$ is the $B_s$ analogue to $B^0 \rightarrow J/\psi K_S$
- Interference between $B_s$ mixing and decay graphs

- One measures the phase-difference $\phi_s$ between the two diagrams, precisely predicted in the SM to be $\phi_s = -2 \lambda^2 \eta = -37.4 \pm 0.7 \text{ mrad} \rightarrow$ very small, can receive sizeable contributions from new physics
New measurements of $\phi_s$

- New measurement by ATLAS using $B_s \rightarrow J/\psi \phi$ and by LHCb using $B_s \rightarrow J/\psi \phi$ and $B_s \rightarrow J/\psi \pi \pi$
  - ATLAS: 80.5 fb$^{-1}$, 13 TeV [ATLAS-CONF-2019-009]
  - LHCb: 1.9 fb$^{-1}$, 13 TeV [LHCb-PAPER-2019-013]
  - LHCb: 1.9 fb$^{-1}$, 13 TeV [arXiv:1903.05530]

- The combination of Run-1 and Run-2 data gives
  - ATLAS: $\phi_s = -0.076 \pm 0.034 \text{(stat)} \pm 0.019 \text{(syst)} \text{ rad}$
  - LHCb: $\phi_s = -0.040 \pm 0.025 \text{ rad}$

New HFLAV average $\phi_s = -0.0544 \pm 0.0205$

- Approaching the sensitivity to observe a nonzero value
- Eagerly waiting for analyses with full Run-2 data and CMS results
Rare radiative decays $b \rightarrow s \gamma$

Clara Alepuz

3 fb$^{-1}$, 7/8 TeV [LHCb-PAPER-2019-015]

- Chiral structure of the $W$ boson leads to a photon polarization mostly left-handed in the SM, with a small right-handed component
- But new physics might significantly alter the contribution of the right-handed component to the total amplitude
- LHCb now measured for the first time direct and mixing-induced CP violation in $B_s \rightarrow \phi \gamma$ decays

$$\Gamma(t) \propto e^{-\Gamma_{s}t} \left[ \cosh \left( \frac{\Delta \Gamma_{s}t}{2} \right) - A_{\phi\gamma} \sinh \left( \frac{\Delta \Gamma_{s}t}{2} \right) \pm C_{\phi\gamma} \cos (\Delta m_{s}t) \mp S_{\phi\gamma} \sin (\Delta m_{s}t) \right]$$

$$S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11$$
$$C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11$$
$$A_{\phi\gamma}^\Delta = -0.67^{+0.37}_{-0.41} \pm 0.17$$

- Compatible with the SM at 1.3, 0.3 and 1.7$\sigma$
Measurements of $B \rightarrow \mu^+ \mu^-$ decays

- Highly suppressed in the SM
  - FCNC- and helicity-suppressed, proceed via $Z$ penguin and $W$ box.
- BR particularly sensitive to new physics scalar contributions, such as extra Higgs doublets.
- CMS and LHCb performed in 2015 a combined fit to their full Run-1 data sets
  - $B_s \rightarrow \mu \mu$ observed for the first time at 6.2σ.
- In 2017 first measurement by LHCb using Run-2 data.
  - In the same year ATLAS published with Run-1 data [PRL 118 (2017) 191801]


Measurements of $B\rightarrow \mu^+\mu^-$ decays

Alessandro Cerri

• New measurement by ATLAS with Run-2 data

• By combining Run-1 and Run-2 data:

\[ \mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9} \]

\[ \mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 2.1 \times 10^{-10} \]

  – Compatible with SM at 2.4σ

• 2016+2017 CMS analysis in preparation

  – Expect 433 $B_s / 54 B_d$ candidates at the end of Run 2 (assuming 300 fb\(^{-1}\))
LFU tests in $b \rightarrow s \ell^+\ell^-$ transitions

- **Measure ratios**
  \[
  R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+\mu^-)}{\mathcal{B}(B^+ \rightarrow K^+e^+e^-)}
  \]
  \[
  R_{K^*} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+\mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0}e^+e^-)}
  \]

- **Theoretically very clean**
  - Observation of non-LFU would be a clear sign of new physics

- **3σ-ish level from the SM**

- **Complementing a range of anomalies in $b \rightarrow s \ell^+\ell^-$**
  - Branching fractions in various decays, angular analysis of $B \rightarrow K^*\mu\mu$
LFU tests in $b \rightarrow s \ell^+ \ell^-$ transitions

Rolf Oldeman

3 fb$^{-1}$ at 7/8 TeV + 2 fb$^{-1}$ at 13 TeV [arXiv:1903.09252]

• New measurement of $R_K$ by LHCb in the dilepton mass-squared range $1.1 < q^2 < 6.0$ GeV$^2$/c$^4$
  – Adding 2 fb$^{-1}$ of Run-2 data to 3 fb$^{-1}$ of Run-1 data
  – Statistics of previous measurement doubled

• Measure the double ratio

$$R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow J/\psi (\rightarrow \mu^+ \mu^-)K^+)} / \frac{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}{\mathcal{B}(B^+ \rightarrow J/\psi (\rightarrow e^+ e^-)K^+)}$$

Non-resonant

Resonant

e channel

μ channel
LFU tests in $b \to s \ell^+\ell^-$ transitions

$3 \text{ fb}^{-1}$ at 7/8 TeV + $2 \text{ fb}^{-1}$ at 13 TeV [arXiv:1903.09252]

$R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$

2.5σ from the SM

- Situation practically unchanged after the new measurement
  - Reduced uncertainty but central value closer to the SM
- Outlook
  - Inclusion of 2017 and 2018 data doubles statistics
  - More channels
    - $R_{K^*}$ but also $B_s$ and $\Lambda_b$ channels
LFU tests with semitauonic decays $B \rightarrow D(\ast)\tau\nu$

- Ratio $R_D(\ast) = \mathcal{B}(B \rightarrow D(\ast)\tau\nu) / \mathcal{B}(B \rightarrow D(\ast)\mu\nu)$ sensitive to new physics at tree-level

- Measurements of $R_D$ and $R_{D\ast}$ by BaBar, Belle and LHCb
  - Overall average shows a discrepancy from the SM around 3.8σ

- LHCb can also perform measurements with other $b$ hadrons
  - e.g. $B_s$, $B_c$ and $\Lambda_b$ decays will help better understand the global picture
LFU tests with semitauonic decays $B \rightarrow D^{(*)} \tau \nu$

- New Belle measurement presented last week at Moriond EW
  \[ R(D) = 0.307 \pm 0.037 \pm 0.016 \]
  \[ R(D^*) = 0.283 \pm 0.018 \pm 0.014 \]

- Most precise measurement of $R(D)$ and $R(D^*)$ to date and first $R(D)$ measurement performed with semileptonic tag

- Compatible with SM at 1.2σ

- $R(D)\!-\!R(D^*)$ Belle average is now at 2σ from the SM prediction

- Overall tension with SM expectation decreases to about 3.1σ
• **Belle II** has successfully concluded the phase 2 pilot run
  – Basic detector performance → OK
  – Nano-beam scheme first tests → OK
Belle II starting to ramp-up

• Phase 3 target
  – Full physics run
  – 20 fb\(^{-1}\) by Summer 2019

• Crucial years to demonstrate the capability of the machine to provide the required luminosity keeping background under control → good luck colleagues!!!

Brute force: Increase the current \((x2)\)
Precision: denser beams, smaller \(\beta^*\) \((x20)\)
Dark photon in $\pi^0$ decays

• While waiting for $\text{BR}(K^+ \to \pi^+ \nu \bar{\nu})$ ...not only heavy flavours $\to$ use NA62 kaon beam as a source of $\pi^0$s
  – Search for an invisible massive dark photon $A'$

$$\frac{\text{BR}(\pi^0 \to \gamma A')}{{\text{BR}(\pi^0 \to \gamma\gamma)}} = 2\varepsilon^2 \left(1 - \frac{M_{A'}^2}{M_{\pi^0}^2}\right)^3$$

• Basic idea

![Diagram showing the decay process and experimental setup]
Dark photon in $\pi^0$ decays


- No statistically significant excess is detected
  - Using only 1% of the available statistics collected by NA62 in 2016-2018
  - Observed upper limits at 90% C.L. compatible with fluctuations from the background-only hypothesis
- Improving on the previous limits over the mass range 60-110 MeV/c$^2$
K$^\pm \rightarrow \pi^\pm \pi^0 e^+ e^-$ decay

Cristina Biino


- Rare decay proceeding through virtual photon exchange: $K^\pm \rightarrow \pi^\pm \pi^0 \gamma^* (\rightarrow e^+ e^-)$

- 4919 candidates $\rightarrow$ first observation

$$BR = (4.237 \pm 0.063 \text{ (stat.)} \pm 0.033 \text{ (syst.)} \pm 0.126 \text{ (ext.)}) \times 10^{-6}$$

- Several CP-violating asymmetries and a long-distance P-violating asymmetry have been measured and found to be consistent with zero
Muon magnetic anomaly
$a_\mu$ in the Standard Model

\[ a_\mu \equiv \frac{g_\mu - 2}{2} \]

- **QED**
  - < 1 ppb precision
  - dominant contribution

- **HVP**
  - 0.4% precision
  - 60 ppm contribution

- **HLbL**
  - 25% precision
  - \( \sim 1 \) ppm contribution

- **Electroweak**
  - 0.7% precision
  - \( \sim 1 \) ppm contribution

- Hadron vacuum polarization and hadronic light-by-light scattering dominate the theoretical uncertainty
The muon g-2 experiment at FNAL

Aaron Fienberg

- E821 measured $a_\mu$ at 550 ppb
- The discrepancy with the SM is (statistically dominated) at $3.7\sigma$
  \[ a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (26.6 \pm 7.24) \times 10^{-10} \]
- E989 will reduce the experimental uncertainty down to 140 ppb
- Need to reduce the hadronic theoretical uncertainties to cope with the increased experimental precision
e^+e^- → light hadrons

• The contribution of hadron vacuum polarisation to $a_\mu$ is calculated through a dispersion relation using the experimental information on the cross-section $\sigma(e^+e^-) \rightarrow \text{hadrons}$, as the relevant energy scale is too low for applying perturbative QCD

$$a_\mu^{\text{had}} = \frac{1}{4\pi^3} \int_{4m_p^2}^{\infty} ds \ K(s) \sigma_0^{\text{hadrons}}(s)$$

• ~20% reduction in uncertainty since 2013, mostly owing to results from BaBar and VEPP-2000

• Hadronic light-by-light scattering contribution remains an open issue
  – LQCD calculations and MUonE proposal to measure elastic reaction $\mu e \rightarrow \mu e$ and constrain $a_\mu^{\text{HLO}}$ from data

• Additional physics motivations for light-resonance spectroscopy
  – Hadronic decays of charmonium via $e^+e^- \rightarrow \gamma\psi (\rightarrow \text{hadrons})$
  – Other hadronic resonances
  – Dark-photon decays
Spectroscopy
Spectroscopy with heavy flavours

Excited $B_c$ states

- A renaissance of QCD in the non-perturbative regime in the last decade
- CMS observed two excited $B_c$ states in the $B_c \pi \pi$ final state, with $B_c \rightarrow J/\psi(\mu \mu)\pi$, using full Run-2 statistics

$\Delta M_{\text{exp}} = 29.1 \pm 1.5 \pm 0.7$ MeV
$M(B_c^{+}(2S)) = 6871.0 \pm 1.2$ (stat) $\pm 0.8$ (syst) $\pm 0.8$ ($B_c^+$) MeV

- Result also confirmed by LHCb

LHCb, 8.5 fb$^{-1}$, 7/8/13 TeV [LHCb-PAPER-2019-007]
Spectroscopy at BESIII

• Dedicated \(e^+ e^-\) open charm and charmonium factory at BEPC
• A plethora of spectroscopy measurements through the years, notably including tetraquark states \(\Xi\ \Psi\ \Omega\)
• E.g., recent observation of \(X(3872) \rightarrow \omega J/\psi\) [arXiv:1903.04695]
  – Cross-section measurement of \(\gamma X(3872)\) suggests a connection between \(X(3872)\) and \(Y(4260)\)

• Also very active in searching for/studying glueball candidates
  – \(0^{++}: f_0(1700), f_0(1500)\) with \(J/\psi \rightarrow \gamma \eta\eta, \gamma K_S K_S, \gamma \pi^0 \pi^0\)
  – \(0^{-+}: X(2370)\) with \(J/\psi \rightarrow \gamma \pi\pi \eta', \gamma K K \eta\)
  – \(2^{++}: f_2(2340)\) with \(J/\psi \rightarrow \gamma \eta\eta, \gamma K_S K_S, \gamma \Phi \Phi\)
Near-threshold $D \bar{D}$ spectroscopy

Tomasz Skwarnicki

- New state observed, likely to be $\psi(1^3D_3)$
  - First observation of a spin-3 charmonium state

\[ M = 3842.71 \pm 0.16 \pm 0.12 \text{ MeV} \]
\[ \Gamma = 2.79 \pm 0.51 \pm 0.35 \text{ MeV} \]
Pentaquark news

Tomasz Skwarnicki

- First pentaquarks observed by LHCb four years ago using $\Lambda_b \rightarrow J/\psi pK$ decays as a proxy
  - Two charged states: one narrow dubbed $P_c(4450)$ and one broader dubbed $P_c(4380)$, decaying into $J/\psi p$
- Great theoretical interest in understanding the nature of the new states
  - Tightly bound vs molecular

3 fb$^{-1}$, 7/8 TeV [PRL 115 (2015) 072001]
Pentaquark news

Tomasz Skwarnicki

9 fb⁻¹, 7/8/13 TeV [LHCb-PAPER-2019-014]

- Update by LHCb using full Run-2 statistics
- x9 increase w.r.t. the Run-1 analysis
  - Improvements in data selection (x2), integrated luminosity (x3) and cross-section (13 TeV vs 7-8 TeV)
- Narrow bump hunting analysis with empirical background shape
  - Full amplitude analysis ongoing, especially needed to confirm $P_c(4380)$
- The previously found $P_c(4450)$ reveals a finer structure with two close peaks, and a new peak is found at 4312 MeV
- Important novel input to shed light into the nature of pentaquarks

<table>
<thead>
<tr>
<th>State</th>
<th>$M$ [MeV]</th>
<th>$\Gamma$ [MeV]</th>
<th>(95% CL)</th>
<th>$\mathcal{R}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c(4312)^+$</td>
<td>$4311.9 \pm 0.7^{+6.8}_{-0.6}$</td>
<td>$9.8 \pm 2.7^{+3.7}_{-4.5}$</td>
<td>($&lt; 27$)</td>
<td>$0.30 \pm 0.07^{+0.34}_{-0.09}$</td>
</tr>
<tr>
<td>$P_c(4440)^+$</td>
<td>$4440.3 \pm 1.3^{+4.1}_{-4.7}$</td>
<td>$20.6 \pm 4.9^{+8.7}_{-10.1}$</td>
<td>($&lt; 49$)</td>
<td>$1.11 \pm 0.33^{+0.22}_{-0.10}$</td>
</tr>
<tr>
<td>$P_c(4457)^+$</td>
<td>$4457.3 \pm 0.6^{+4.1}_{-1.7}$</td>
<td>$6.4 \pm 2.0^{+5.7}_{-1.9}$</td>
<td>($&lt; 20$)</td>
<td>$0.53 \pm 0.16^{+0.15}_{-0.13}$</td>
</tr>
</tbody>
</table>
Breaking news from Moriond 2119!
S'chn T'gai Spock

You still don’t know, but there’s plenty of life in the Universe. And, more importantly, the Standard Model is wrong!
Muon mystery?

Ralf Ulrich

What are we observing here?

- Strange fireball? PRD 95 (2017) 063005
- ???

→ still unsolved!

arXiv:1902.08124

- Maybe first signals of new-physics processes will be seen using particles from natural accelerators lost in some corner of the Universe...
Thank you Moriond QCD!

• For now the SM is still making fun of us!
• How long shall we wait?
Thank you Moriond QCD!

• For now the SM is still making fun of us!
• How long shall we wait?
• Spock didn’t tell us, but we know that it won’t be forever, and we’ll never give up!