Moriond QCD:
Experimental Summary

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March 24th, 2018
A message for the summary speaker(s) for Moriond 2019...

“if you are debating whether to accept the invitation from the conference organizers or not...”
The organising committee is happy to invite you to the Conference Gala Dinner, Thursday evening.

You will be served at the "Table du Honneur" at 20:30.

Thursday 22 March

Appetizers
Local Cold Meat and Cheese with Homemade Mustards
Polenta with Yellow Pumpkin and Cheese Stuffings

First course
Crespella with Cheese
Mushroom Risotto with Tima Cheese

Main courses
Monkfish with Peas and Pea Puree
Cut Beef with Spinach and Berries
Baked Potatoes
Thank you to the organizers for the most amazing hospitality and for organizing such a productive conference!

Big thank you to all the speakers as well for the excellent talks and for your help in preparing this summary!

Disclaimer: impossible to summarize adequately all of the talks given this week; choices influenced by your suggestions, personal taste, new results, open questions...

Apologies if I missed your favorite result
Goals of experimental particle physics

“Sorry Doc, we had a load of Anti-Matter around 13 billion years ago, but it got lost when we moved”
“Greetings Earth-people. We have been monitoring your progress. Now that you have discovered the Higg’s boson you are qualified to join the Federation of Advanced Civilisations.”
Higgs Physics

• Why is the Higgs so light? Is $m_H$ stabilized by $\sim$TeV scale new physics or is it fine-tuned?

• Are there exotic Higgs decays?

• Are there additional Higgs bosons?

• Is the Higgs elementary or composite?

• Higgs couplings to light particles (e.g. $h \rightarrow J/\Psi+\gamma$)

• Higgs coupling to top:
  – known indirectly ($gg \rightarrow h$) or via difficult $tth$ channel
Higgs Highlights

- In the 6 years since its discovery there has been significant progress in the Higgs sector:
  - Firmly established $\gamma\gamma$, $ZZ$, $\tau\tau$, $WW$ decays
  - Single experiment observation (CMS): $H \rightarrow \tau\tau$
  - bottom-Higgs and top-Higgs Yukawa couplings
  - excellent mass measurement

$\begin{align*}
m_H &= 125.26 \pm 0.21 \, \text{(} \pm 0.20 \, \text{stat.} \pm 0.08 \, \text{sys.}\text{)} \, \text{GeV}
\end{align*}$
Higgs Highlights

Combined 13TeV results surpassing Run 1 precision in **key** measurements

Per production mode

- $\mu_{ggH} \approx 11\%$
- $\mu_{VBF} \approx 41\%$
- $\mu_{WH} \approx 27\%$
- $\mu_{ZH} \approx 51\%$
- $\mu_{ttH} \approx 26\%$
- $\mu_{bb} \approx 9\%$

**~30% more sensitive** than Run-1 ATLAS+CMS $\mu_{\gamma\gamma}$

**~50% more sensitive** than Run-1 ATLAS+CMS $\mu_{ZZ}$

Most precise measurement of gluon fusion, ttH, and total signal strength

(ATLAS+CMS Run 1 combination: $\mu_{ggH} = 1.03^{+0.16}_{-0.14}$)
Higgs Cross-sections

- Higgs physics has entered the **precision** era
  - Fiducial and differential cross section measurements comparing data to state-of-the-art calculations
  - Simplified template cross sections enable Higgs measurements that are less model dependent

**Best precisions of < 20% reached**
Higgs physics with hadronic signatures

- Working horse: $H \rightarrow bb$ channel
- Evidence for $VH(bb)$
- $ttH$ search: new results by CMS
- Di-Higgs: new result by ATLAS
- New approaches targeting $cc$ and light-quarks

Important sensitivity in hadronic final states
Sophisticated analysis methods to cope with challenging backgrounds
Over twenty years since its discovery, the top quark is still one of the hottest topics...
Top Quark

Top quark physics continues to be an important focus @ Tevatron and LHC

- Complementary measurements:
  - ~85% qq at Tevatron and >85% gg at LHC

Precision top physics @ LHCb soon

Forward region interesting for PDF constraints, charge asymmetries, ... less dilution, more quark-initiated prod.

Inclusive cross section well understood and agrees with NNLO predictions
Top production and properties

- Understanding the discrepancy in modelling of the top and ttbar system (e.g. in top $p_T$) continues to be a challenge
- Data softer at higher top quark transverse momentum than prediction:
  - Missing higher orders in pQCD: for production and/or decay?
  - EW corrections?
  - New physics...

- (Double) differential measurements may provide the answer to this puzzle
Jet substructure observables in ttbar events

Sensitive to modeling in MC

Underlying event in ttbar events

Crucial for understanding soft physics; can have significant effects on precision measurements (e.g. mass)
Top mass

- Diverse set of top mass measurements in different channels
  - Direct methods e.g. templates, matrix method, ideogram
  - Indirect methods e.g. extraction based on cross section

**ATLAS**: 0.9%; **CMS** precision at 1%
With ~5% theory uncertainty and ~2% exp → can reach 0.5% on pole mass)

Tevatron top mass:

\[ m_t = 174.30 \pm 0.35 \text{ (stat)} \pm 0.54 \text{ (syst)} \text{ GeV} \]

\[ \delta m / m_t = 0.37\% \]
Top asymmetry measurements

- Excitement over the past years related to Tevatron $l\!+\!\text{jets}$ $A_{FB}$ analyses showing departure from NLO SM expectations
- With updated NNLO+EW SM expectations, more data and more refined analyses, results are now compatible with SM

[ Charge asymmetry measured @ LHC First LHC top combination paper
  
  arxiv:1709.05327 ]
ttX Production at ATLAS and CMS

- ttZ and ttW cross-sections measurements reach interesting precision
  - Both ttW and ttZ observed > 5σ
  - CMS dominated by object-related uncertainties, ATLAS by statistical uncertainty
- ttττ cross-section measured and constraints on $y_t$ derived (CMS)
- Measurement of ttγ fiducial cross-section and first differential cross-section measurements for photon $p_T$, $\eta$
Single top at ATLAS and CMS

First measurement of diff. $tW$ cross sections

Stringent constraints on FCNC (in some cases approaching theory predictions e.g. $Hc$, $Hu$)

Evidence of $tZq$ production @ 13 TeV
W and Z at ATLAS and CMS

• Comprehensive W and Z results from ATLAS and CMS
  – New results available at 7, 8 and 13 TeV
  – Allow to test the SM w/ sub-precent uncertainties
  – Measured cross sections agree with NNLO QCD and NLO EW

• Results on single gauge boson production sensitive to PDFs
  – Differential uncertainties often well below 1%
  – ATLAS and CMS results provide constraints in PDFs
Multibosons at ATLAS and CMS

Diboson measurements are pushing for more precise theoretical calculations (NNLO or 3NLO QCD, NLO EWK, ...)

- Uncertainties on total cross section measurements are approaching lumi uncertainty
- Uncertainties on differential measurements still dominated by statistics
- Can mitigate lumi, theory uncertainties with ratios

Significant increase of sensitivity for indirect search for NP (aTGC)
Quarkonium results from Babar+Belle

First measurement of
\[ Br(J/\psi \to K_S^0K^\mp\pi^+\pi^-) = (5.7 \pm 0.3 \pm 0.4) \times 10^{-3} \]

Motivation: 4-quark component of \( \Upsilon (5S) \)
Reconstruct only the \( \eta \to \gamma \gamma \)
Fit the missing mass distribution

\[ M_{\text{miss}}^2(\gamma\gamma) = (\langle p_{e^+e^-} \rangle - p_\eta)^2 \]
**B_S^0π^± at Tevatron**

<table>
<thead>
<tr>
<th>Analysis</th>
<th>f_{BS/X(5568)}</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>First evidence</td>
<td>D0 (J/ψ φ)</td>
<td>8.6 ± 1.9 ± 1.4%</td>
</tr>
<tr>
<td>Confirmation</td>
<td>D0 (μ D_s)</td>
<td>7.3^{+2.8}<em>{-2.4}^{+0.6}</em>{-1.7}%</td>
</tr>
<tr>
<td>Limit set</td>
<td>CDF (J/ψ φ)</td>
<td>&lt; 6.7% (2.3 ± 1.9 ± 0.9%)</td>
</tr>
</tbody>
</table>

- Nominal ~2 sigma tension between CDF and D0 result
- Different kinematic ranges make “apples-to-apples” comparison difficult
LHC experiments (LHCb, ATLAS and CMS) do not observe the X(5568) resonance suggested by evidence from D0
CP Violation and mixing at LHCb

Several NEW measurements and UPDATES for gamma from LHCb

Search for CPV in b-baryon sector:

\[ \Lambda_b^0 \rightarrow pK^- \pi^+ \pi^- \]

\[ \Lambda_b^0 \rightarrow pK^- K^+ K^- \]
Recent results from HERA

- improvement in precision w.r.t previous HERA results for charm
- first combined HERA results for beauty
- enable precise determination of charm and beauty masses

\[ m_c(m_c) = 1290^{+46}_{-41} \text{(fit)}^{+62}_{-14} \text{(mod)}^{+3}_{-31} \text{(par)} \text{ MeV} \]
\[ m_b(m_b) = 4049^{+104}_{-109} \text{(fit)}^{+90}_{-32} \text{(mod)}^{+1}_{-31} \text{(par)} \text{ MeV} \]

Input data are consistent
combined result is much more precise
Explore effective theory of QCD @low energies, symm. breaking mechanisms in low-energy QCD, η, η’ electromagnetic structure, potential BSM physics

Explore structure of hadrons and interactions between photons & hadrons

\[ \psi(3686) \rightarrow e^+ e^- \chi_{cJ}, \chi_{cJ} \rightarrow e^+ e^- J/\psi \]

<table>
<thead>
<tr>
<th>decay mode</th>
<th>events</th>
<th>( B \times 10^4 )</th>
<th>remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta' \rightarrow \eta\pi^+\pi^- )</td>
<td>351016</td>
<td></td>
<td>prev 20k evts</td>
</tr>
<tr>
<td>( \eta' \rightarrow \eta\pi^0\pi^0 )</td>
<td>56249</td>
<td></td>
<td>prev 15k evts</td>
</tr>
<tr>
<td>( \eta' \rightarrow \pi^+\pi^-\gamma )</td>
<td>970000</td>
<td></td>
<td>prev 10k evts</td>
</tr>
<tr>
<td>( \eta' \rightarrow \pi^+\pi^-\pi^0 )</td>
<td>6067 ± 1</td>
<td></td>
<td>prev 20 evts</td>
</tr>
<tr>
<td>( \eta' \rightarrow (\pi^+\pi^-\pi^0_s) )</td>
<td>6580 ± 1</td>
<td></td>
<td>first data</td>
</tr>
<tr>
<td>( \eta' \rightarrow \pi^0\pi^0\pi^0 )</td>
<td>2015 ± 1</td>
<td></td>
<td>prev 235 evts</td>
</tr>
<tr>
<td>( \eta' \rightarrow e^+e^-\gamma )</td>
<td>864 ± 3</td>
<td></td>
<td>first data</td>
</tr>
<tr>
<td>( \eta' \rightarrow e^+e^-\omega )</td>
<td>60 ± 1</td>
<td></td>
<td>first data</td>
</tr>
<tr>
<td>( \eta' \rightarrow \gamma\gamma\pi^0 )</td>
<td>655 ± 6</td>
<td></td>
<td>first data</td>
</tr>
<tr>
<td>( \eta' \rightarrow \pi^+\pi^-\pi^+\pi^- )</td>
<td>199 ± 16</td>
<td>0.853 ± 0.069±0.069</td>
<td>first data</td>
</tr>
<tr>
<td>( \eta' \rightarrow \pi^+\pi^-\pi^0\pi^0 )</td>
<td>84 ± 16</td>
<td>1.82 ± 0.35±0.18</td>
<td>first data</td>
</tr>
</tbody>
</table>

Present statistics @ BESIII: \( 1.31 \times 10^9 J/\psi \leftrightarrow 7 \times 10^6 \eta' \)

1-2 orders of magnitude beyond world statistics, low level of background

Data taking at BESIII continues \( \rightarrow \) near future goal: \( 1 \times 10^{10} J/\psi \)
Observation of $\Xi_c(2930)$ @

- Weak evidence of $\Xi_c(2930)$ was reported by BaBar in $B^{-}\rightarrow \Xi_c(2930)\Lambda_c$, $\Xi_c(2930)\rightarrow \Lambda_c^+K^{-}$.
- Belle has performed the study with $\sim3$ times statistics.

<table>
<thead>
<tr>
<th></th>
<th>Mass (MeV/c²)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>2931±3±5</td>
<td>36±7±11</td>
</tr>
<tr>
<td>Belle</td>
<td>2928.9±3.0^{+0.8}_{-12.0}</td>
<td>19.5±8.4^{+5.4}_{-7.9}</td>
</tr>
</tbody>
</table>

Statistical significance of the peak at Belle is 5.1σ

First charmed baryon established in B-decay
Significant (12σ) signal in 13 TeV and 8 TeV data sets (7σ)

$$m(\Xi^{++}_{cc}) = 3621.40 \pm 0.72 \text{ (stat)} \pm 0.27 \text{ (syst)} \pm 0.14 \text{ (Λ^+)} \text{ MeV/c}^2$$

Mass difference with the SELEX measurement ($\Delta m = 103 \text{ MeV/c}^2$) is too large to be an isospin partner

Search for excited $B_c(2S)^+$ states:

$$B_c(2S)^+ \rightarrow B_c^+ \pi^+\pi^-$$

$$B_c(2S)^*+ \rightarrow B_c^{*+} (\rightarrow B_c^+ \gamma) \pi^+\pi^-$$

*not reconstructing the photon

Observation reported by ATLAS

$$m = 6842 \pm 4 \text{ (stat)} \pm 5 \text{ (syst)} \text{ MeV/c}^2$$

To be followed up... does CMS see it?
Heavy Flavor & New Physics searches
Rare decays

- Search both for small deviations in precisely predicted SM processes and for forbidden processes that can only occur through new physics
- New particles can appear at loop or tree level
- Flavor-changing neutral current (FCNC) processes
  - heavily suppressed → NP can appear at a similar or larger level as SM contributions

\[ B_s \rightarrow \mu^+\mu^- : \text{First single experiment observation (7.8}\sigma) \]

(previously achieved w/ LHCb+CMS combination)

Results consistent with SM predictions, set stringent limits on possible NP models
Anomalies in $b \to s \ell^+\ell^-$ transitions

• Differential branching fractions for a variety of $b \to s \ell^+\ell^-$ processes tend to be systematically lower than SM prediction
• Angular analyses [e.g. LHCb measurement of $P_5'$ from Run 1 data (3 fb$^{-1}$)] indicate tension with the SM

New physics? 

Or underestimated QCD uncertainties?
Lepton Flavor Universality: $b \to s \ell^+\ell^-$ transitions

The tension wrt to SM observed in muon final states

If the effect is real, does it appear only for muons or is it universal for all leptons?

LHCb, 3fb-1 [JHEP 08 (2017) 055]

Test in ratios of semi-leptonic decays

$R_K = \frac{BR(B^+ \to K^+ \mu^+\mu^-)}{BR(B^+ \to K^+ e^+e^-)}$

Analogously: $R_{K^*}$
ATLAS and CMS have analysed the angular distributions of $B^0 \rightarrow K^* \mu^+ \mu^-$

**ATLAS**: generally in good agreement with SM, except a \(\sim 2.5\) sigma deviation in 1 bin

**CMS**: data compatible with SM predictions in the whole range

Run 2 data being analyzed!
Lepton Flavor Universality: $b \rightarrow c \ell^+\nu$ transitions

$$R_{D^*} = \frac{BR(B^0 \rightarrow D^{*+} \tau^-\bar{\nu})}{BR(B^0 \rightarrow D^{*+} \mu^-\bar{\nu})}$$

$R(D^*)_{SM} = 0.252 \pm 0.003$ [PRD85(2012)094025]

- All measurements above SM prediction:
  - $R_{D^*}$ exceeds SM by $3.4\sigma$
  - $R_D$ by $2.3\sigma$
  - Combination: around $4\sigma$

- LHCb analyses presented use only $3\text{fb}^{-1}$
  - LHCb dataset on tape today contains factor 3 in number of B hadrons
  - LHCb upgrade in Run 3 \(\Rightarrow\) much improved trigger, e.g. \(~\) identical trigger for $\mu$- and $e$-

- Belle 2 ramping up!
Direct and indirect searches for new physics
Intriguing hints of new physics in B meson decays have renewed interest in leptoquark searches, particularly 2\textsuperscript{nd} and 3\textsuperscript{rd} generation.

CMS has a large and expanding program of leptoquark searches:

- Many channels push sensitivity above the TeV scale, favored by B physics anomalies.
- Warrants investigation of new/more complicated final states or model phase space (e.g. bigger couplings/widths).
- Searches adding and using 2017 data in progress.
Searches for di-lepton resonances @ CMS

High mass searches now using > 100 fb\(^{-1}\), limits extending beyond 4 TeV!

Uses 2017 data!

<table>
<thead>
<tr>
<th>Channel</th>
<th>Model</th>
<th>Obs. limit (TeV)</th>
<th>Exp. limit (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee (2017)</td>
<td>(Z'_{\text{SSM}})</td>
<td>4.10</td>
<td>4.15</td>
</tr>
<tr>
<td></td>
<td>(Z'_{\psi})</td>
<td>3.35</td>
<td>3.55</td>
</tr>
<tr>
<td>ee (2016 and 2017) + (\mu\mu) (2016)</td>
<td>(Z'_{\text{SSM}})</td>
<td>4.7</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>(Z'_{\psi})</td>
<td>4.1</td>
<td>4.1</td>
</tr>
</tbody>
</table>
Dijet Resonance Searches @ ATLAS and CMS

Novel “trigger-level analysis” [ATLAS] or “scouting” [CMS] allows to probe lower mass

Also take advantage of ISR, dedicated b-tagging triggers
Diboson searches @ ATLAS & CMS

- Substructure techniques (for jets, b-tagging) used for maximizing sensitivity to boosted topologies, large mass range
  - Includes using the Higgs as a discovery tool (“Higgs-tagging”)

Both experiments have comprehensive diboson search programs

Mild excess around 440 GeV in bbA search (3.6σ local, 2.4σ global)
Various searches are performed by ATLAS and CMS for exotic Higgs bosons beyond 2 Higgs Doublet Models (HDM) and MSSM:

- models with $H^{\pm \pm}$
- generic 2 HD + 1 Singlet models

Exotic Higgs Searches @ LHC

CMS-PAS-HIG-17-024, CMS-PAS-HIG-17-029

19.7 fb$^{-1}$ (8 TeV) + 35.9 fb$^{-1}$ (13 TeV)

CMS-Preliminary

ATLAS

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- $B(e^+e^-)$ = 30%
- $B(e^+\mu^-)$ = 40%
- $B(\mu^+\mu^-)$ = 30%

Observed 95% CL limit

Expected 95% CL limit

2HDM+S type III

$\tan\beta = 5.0$

Expected limit ± $\sigma$

Expected limit ± 2$\sigma$

$\sigma(pp \rightarrow H^+_1H^-_1)$

$\sigma(pp \rightarrow H^+_R H^-_R)$

arXiv:1802.03388
Searches w/ top quarks

- CMS: $T\bar{T}, B\bar{B} \rightarrow 1, 2, \text{and } 3 \text{ leptons}$
  - $1\ell$: boosted hadronic $W$ and $H$ bosons
  - $SS \ 2\ell \text{ and } 3\ell \text{ channels with low SM bkgd.}$
- ATLAS: $T\bar{T} \rightarrow Ht \ (H \rightarrow b\bar{b}), \ Zt \ (Z \rightarrow \nu\nu)$
  - Single lepton or high $p_T^{\text{miss}} + \text{multiple } b \text{ jets}$
  - Boosted hadronic tops and $H$ bosons

**Vector Like Quarks**

$T$ mass excluded below $1.2 - 1.4 \text{ TeV}$ for many benchmarks
Dark Matter Searches @ LHC

- Dark Matter (DM) searches @ LHC remain a thriving field of research.

- A large number of mono-X searches have been performed by ATLAS and CMS, already probing a large part of the parameter space.

- No evidence for BSM physics so far but significant progress in exploring a variety of final states:
  - incl. searches where Higgs mixes with new dark mediators

- LHC searches complementary to direct searches, providing improved sensitivity to low DM masses.
EWK SUSY @ ATLAS & CMS

Di/multileptons

Standard signatures well covered
Stau still hiding
Degenerate spectra demanding for e/µ reconstruction/ID...

Disappearing tracks

... or require unconventional analyses

Hadronic searches

First sensitivity to Higgsinos aided by non-leptonic signatures
Exotic searches @ NA62

NA62: fixed target experiment at CERN SPS with the main goal of collecting $\sim 20$ SM $K^+ \rightarrow \pi^+ \nu\nu$ events before LS2 (2018). [JINST 12 (2017), P05025]

Such high-intensity, high-performance setup also suitable for exotic searches (dark photons, heavy neutral leptons, axion-like particles)

Dark photon (NA62 preliminary)
Massive dark photon search, dimuon final state, prompt and displaced

World-best limits in 10.6 – 70 GeV/c²

First displaced limits
Muon g-2 @ FNAL

- Muon beam being delivered
- All major subsystems online, optimization ongoing
- Production data started Feb 2018
- Stay tuned for impactful results in next few years!
  - Expect 2 x BNL data soon!
  - Theory improvements expected from Lattice QCD calculations and analysis of data from BaBar, BES-III, Belle/Belle-II, CMD-3, SND, KLOE...

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**Anomalous Precession Frequency**

![Graph showing number of high energy positrons as a function of time]

![Graph showing integrated positrons FY18]
Production of low energy hadrons in $e^+e^-$ collisions remains an interesting experimental area due to its important contribution to the SM calculations of the muon anomalous magnetic moment and $\alpha(s)$.

Goal is to collect 1 fb$^{-1}$ of data in the next 3-5 years.
QCD & Heavy Ion Physics
QCD results from Tevatron

CDF - Extensive studies of Central Excl. Production (CEP) 
\( p\bar{p} \rightarrow p+\text{Excl. } X+p: \)

- \( f_2(1270) \), shoulder from \( f_0(1370) \) interference
- some structure around 1.4-2.4 GeV
- data falls monotonically above 2.4 GeV
Soft QCD @ ATLAS and CMS

- Measurements in soft QCD play an important role in validating theory predictions and tuning parameters for modelling hadron collisions.

Inelastic cross-section @ 13 TeV

Exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ production

JHEP 02 (2018) 032
Double parton scattering from same-sign $WW$ production
Probing QCD w/ multiplicity and UE studies

Valentina Zaccolo

Multiplicity

- Well described by theoretical calculations
- Used to study particle yields

Underlying Event

- semi-hard + soft interactions
- **General idea**: test soft-QCD dynamics excluding the hard sector
  
  Transverse region: rise due to MPI and flattens due to contributions from hard processes
<p>Particle production in high multiplicity collisions</p>

<math>
\langle p_T \rangle \text{ as a function of charge particle multiplicity and spherocity}
</math>

Jetty events (lowest 10% spherocity class)
Isotropic events (highest 10% spherocity class)

<math>K/\pi & p/\pi \text{ vs } p_T \text{ for jetty and isotropic events in high multiplicity class}
</math>

Comparison w/ MC models:
PYTHIA 8 & EPOS LHC
NLO predictions with non-perturbative and EW corrections are able to describe well data in huge phase-space regions. Detailed QCD interpretations are possible to an accuracy of about 5%.

NNLO predictions with full uncertainties are needed for precision QCD interpretation.

Soft and non-perturbative effects are typically described better by event generators compared to NLO model predictions.

Some work is needed in non-perturbative physics to keep up increased precision in particular for multi-final states and e.g. jet structure.
Photons and Jets @ ALICE

Jets & high $p_T$ hadrons in $p$–$Pb$: no observations of medium induced effects

Small jet mass

- collimated jets

Hard and electromagnetic probes in $Pb$–$Pb$:
- excess of direct $\gamma$ emitted from thermalised medium at low $p_T$
- suppressed high $p_T$ $\pi^0$ and $\eta$ yields

→ parton energy loss in QGP

PLB 776 (2018) 249-264
Measurements of open heavy-flavour (HF) particles and quarkonia performed in pp (\(\sqrt{s} = 2.76, 7, 8\) and 13 TeV), p-Pb (\(\sqrt{s_{NN}} = 5.02\) and 8.16 TeV) and Pb-Pb (\(\sqrt{s_{NN}} = 2.76\) and 5.02 TeV) collisions.

No significant suppression of open heavy flavor mesons found in measured p\(_{T}\) range

Suppression of charm yield observed at low p\(_{T}\) at forward rapidity

Model calculations that include cold dark matter effects show qualitative agreement with data
Heavy Ion measurements @ ATLAS & CMS

Completing the picture of QCD in a dense (and hot) medium:

- Initial state, fluctuations, hydrodynamics, parton interactions, flavor dependence, time evolution...
- Access to new processes (\(\bar{t}t\), \(\gamma\gamma \rightarrow \gamma\gamma\), ...)
- XeXe (2017) and more PbPb (2018) will bring further insights!

First top quark obs. in heavy ion collisions
In agreement with pQCD +nPDF expectations

Light-by-light scattering: new process
Fixed target collisions (p-Ar, p-He)

Interesting link with cosmic ray physics
- The AMS (ISS) experiment measures antiproton production
- Observed excess may be due to dark-matter candidates annihilation
- Predictions for $p$bar/$p$ currently limited by uncertainties on $p$bar production in p-He collisions
- LHCb has measured anti-proton cross-section in 110 GeV p-He collisions
- LHCb measurement permits to constrain MC generators
Quarkonium in heavy-ion collisions:
Deconfinement

Strong suppression of high-$p_T$ J/$\psi$
Point to QGP melting

$b \rightarrow e$ is less suppressed than $c \rightarrow e$ in Au+Au 0-10% central

>>> quark mass ordering of energy loss in QGP
The Future: near and long-term
Moriond predictions and achievements

RUN 2

Goal 60 fb$^{-1}$ ATLAS/CMS
2 fb$^{-1}$ for LHCb

with 131 days of p-p physics
55 fb$^{-1}$ and 1.8 fb$^{-1}$ if 119 days
keeping the LHC high availability and >50% stable beams

LHC 2018
Belle2 Physics Potential
• $e^+e^-$ machine at few $10^2$ GeV will measure Higgs and top properties
  • Precision $>>$ HL-LHC and less model dependent

• First CLIC stage at 350/380 GeV:
  • Higgs production: Higgsstrahlung and WW fusion
  • Top quark: threshold and continuum regions
  • Rare decays

• Higher-energy $e^+e^-$ collider has more BSM discovery potential
  • Direct detection up to kinematic limit
  • Indirect discovery via precise EW measurements up to $\sim$few x10 TeV
Discoveries in particle physics

<table>
<thead>
<tr>
<th>Facility</th>
<th>Original purpose, Expert Opinion</th>
<th>Discovery with Precision Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>P.S. CERN (1960)</td>
<td>$\pi N$ interactions</td>
<td>Neutral Currents $\rightarrow Z,W$</td>
</tr>
<tr>
<td>AGS BNL (1960)</td>
<td>$\pi N$ interactions</td>
<td>Two kinds of neutrinos</td>
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<td></td>
<td></td>
<td>Time reversal non-symmetry charm quark</td>
</tr>
<tr>
<td>FNAL Batavia (1970)</td>
<td>Neutrino Physics</td>
<td>bottom quark</td>
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<td></td>
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<td>top quark</td>
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<tr>
<td>SLAC Spear (1970)</td>
<td>ep, QED</td>
<td>Partons, charm quark</td>
</tr>
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<td></td>
<td></td>
<td>tau lepton</td>
</tr>
<tr>
<td>ISR CERN (1980)</td>
<td>pp</td>
<td>Increasing pp cross section</td>
</tr>
<tr>
<td>PETRA DESY (1980)</td>
<td>top quark</td>
<td>Gluon</td>
</tr>
<tr>
<td>Super Kamiokande (2000)</td>
<td>Proton Decay</td>
<td>Neutrino oscillations</td>
</tr>
<tr>
<td>Telescopes (2000)</td>
<td>SN Cosmology</td>
<td>Curvature of the universe</td>
</tr>
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<td>Dark energy</td>
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</table>

Often when we embark on an experiment with a goal in mind, we find something new.

(From an original slide by S.C.C. Ting.)
Final Words....

- We may not have seen an obvious sign of new physics in the data yet – however, what that implies is that we have to get cleverer and make sure we look in every corner and leave no stone un-turned.

- Develop and implement new ideas;

- Go in directions where no one has gone before!
Still round the corner there may wait,
A new road or a secret gate.

J. R. R. Tolkien