LHC Run2 and Future Prospects

Nadia Pastrone

Maratea - June 29, 2018
Standard Model of Particle Physics

The SM works well up to an energy scale of a few hundred GeV

BUT it is incomplete, i.e.:

- Missing dark matter candidate

AND fundamental answers are still missing:

- Why 3 families of quarks and leptons?
- Why the masses of fundamental particles span several orders of magnitude?

Mass of quarks in MeV/c²

Drawing not in linear scale!!
The maximum achievable luminosity ($L$) is needed. 

RARE PROCESSES

$$R = L \sigma$$

$$L = f \frac{n_1 n_2}{A}$$

- Number of $p$ per beam
- Collision frequency
- Area of collision

→ The maximum achievable luminosity ($L$) is needed

1H/10^{12} events
New energy frontier

ratios of LHC parton luminosities: 13 TeV / 8 TeV

- gg
- Σqq
- qg

1 fb⁻¹ @ 13 TeV

3 fb⁻¹ @ 13 TeV

10 fb⁻¹ @ 13 TeV

<300 GeV

Mₙ (GeV)

MSTW2008NLO

~2 TeV

~3 TeV

~4 TeV
Outline

- The need of the Large Hadron Collider
- The experiments and the enabling technologies
- The physics: before LHC and Run1 – a short recap
- The ongoing Run2 – what’s new
  - Standard Model (SM)
  - BSM
  - Flavour physics
  - Heavy ions
- Prospects for near and far future
Large Hadron Collider (LHC)

Installed in 26.7 km LEP tunnel
Depth of 70-140 m
Multi-purpose, high resolution and hermetic detector
Magnets: Central Solenoid + 3 Toroids
Tracking: Silicon, Transition Radiation Tracker
Calorimeter: EM (LAr), Had Cal
Muon: Trigger + Precision chambers

Object Reconstruction
- leptons (e, \( \mu \), \( \tau \))
- photons
- jets
- b-jets
- Etmiss

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ATLAS: during construction
CMS Detector

- Pixels
- Tracker
- ECAL
- HCAL
- Solenoid
- Steel Yoke
- Muons

- **SILICON TRACKER**
  - Pixels (100 x 150 μm²) ~1m² ~66M channels
  - Microstrips (80-180μm) ~200m² ~9.6M channels

- **CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)**
  - ~76k scintillating PbWO₄ crystals

- **PRESHOWER**
  - Silicon strips ~16m² ~137k channels

- **SUPERCONDUCTING SOLENOID**
  - Niobium-titanium coil carrying ~18000 A

- **STEEL RETURN YOKE**
  - ~13000 tonnes

- **HADRON CALORIMETER (HCAL)**
  - Brass + plastic scintillator ~7k channels

- **FORWARD CALORIMETER**
  - Steel + quartz fibres ~2k channels

- **MUON CHAMBERS**
  - Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
  - Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers

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Total weight: 14000 tonnes
Overall diameter: 15.0 m
Overall length: 28.7 m
Magnetic field: 3.8 T
CMS tracker installation

Dec 2007
Compact Muon Solenoid slice

Key:
- Blue: Muon
- Red: Electron
- Green: Charged Hadron (e.g. Pion)
- Dark Green: Neutral Hadron (e.g. Neutron)
- Dashed Blue: Photon

Transverse slice through CMS

Iron return yoke interspersed with Muon chambers

\[ \text{PbWO}_4 \]
Large Hadron Collider beauty experiment

- LHCb is mainly (but not only) studying beauty (and charm) physics
  - At the LHC, the production of heavy quark pairs is peaked forward/backward
  - The detector is a single arm spectrometer
    - Both $b$-hadrons go together forward (or backward)
    - Acceptance $2 < \eta < 5$
  - A $b$-meson / baryon is boosted
    - It flies several millimetres before decaying
    - This is the main signature for selecting events
ALICE

→ to be installed in LS2
  - New Inner Tracking System (ITS)
    - MAPS: improved resolution, less material, faster readout
  - New Forward Muon Tracker (MFT)
    - vertex tracker at forward rapidity
  - New TPC Readout Chambers
    - 4-GEM detectors
  - New trigger detectors (FIT, AD)
    - + centrality, event plane
  - Upgraded read-out for TOF, TRD, MUON, ZDC, EMCal, PHOS, integrated Online-Offline system

record minimum-bias Pb-Pb data currently <1 kHz
→ at 50 kHz after LS2 upgrade
Standard Model re-discovery @ LHC

Original discovery

1933 1947 1964


2006 Dec Jan Feb Mar Apr May Jun Jul

CMS 2009 Preliminary

"Rediscovery" in CMS (dates approximate)

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First data

\[ \mu^+ \mu^- \]

\[ \rho, \omega, \phi, J/\psi, \eta, \psi', Y(1,2,3S), Z \]

CMS Preliminary

\[ \sqrt{s} = 7 \text{ TeV}, \ L_{\text{int}} = 40 \text{ pb}^{-1} \]
2013 Nobel Prize in Physics

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert
Université Libre de Bruxelles, Brussels, Belgium

Peter W. Higgs
University of Edinburgh, UK

“for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider”
A comparison to theory predictions

Production Cross Section, $\sigma_{tot}$

- $W$ with $\geq 1j$
- $Z$ with $\geq 1j$
- $W\gamma$ with $\geq 3j$
- $Z\gamma$ with $\geq 4j$
- $WW$ with $E_T > 15$ GeV, $|\eta^{jet}| < 2.4$
- $WZ$ with $E_T^{\gamma} > 30$ GeV, $\Delta R(\gamma,l) > 0.7$
- $ZZ$ with $36, 19$ pb$^{-1}$

7 TeV CMS measurement (stat+syst)
8 TeV CMS measurement (stat+syst)
7 TeV Theory prediction
8 TeV Theory prediction

CMS

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LHC: present schedule

Phase 1 Upgrade
ALICE, LHCb major upgrade
ATLAS, CMS minor upgrade

Heavy Ion Luminosity from $10^{27}$ to $7 \times 10^{27}$

HL-LHC, pp luminosity from $10^{34}$ (peak) to $5 \times 10^{34}$ (levelled)
Multi-annual integrated performance

03.06.2018

End of proton run

28.10.2018

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2017 pp collisions - luminosity

LHC 2017 RUN (6.5 TeV/beam)

Delivered integrated luminosity (fb⁻¹)

Month in 2017

(2018-05-28 20:32 including fill 6417; scripts by C. Barschel)
Excellent performance of the LHC

~25 fb$^{-1}$ delivered in RUN 1

~100 fb$^{-1}$ in Run 2

instantaneous luminosity in RUN 2 reached

$2 \times 10^{34}$ cm$^{-2}$s$^{-1}$ (twice the design value)
Run1-Run2 luminosity production

Peak Luminosity
2018 shows steepest increase in peak luminosity of all years

<table>
<thead>
<tr>
<th>Period</th>
<th>Int. Luminosity [fb⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>29.2</td>
</tr>
<tr>
<td>Run 2: 2015</td>
<td>4.2</td>
</tr>
<tr>
<td>Run 2: 2016</td>
<td>39.7</td>
</tr>
<tr>
<td>Run 2: 2017</td>
<td>50.2</td>
</tr>
<tr>
<td>Run 2: 2018</td>
<td>17.8</td>
</tr>
<tr>
<td>Total Run 1+ 2</td>
<td>141.1</td>
</tr>
</tbody>
</table>
LHC 2017: separation levelling

- Introduced separation levelling for all experiments

➔ Separation levelling is used since many years for ALICE and LHCb

- Initial spike before leveling reaching $2.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
Luminosity levelling

- In certain conditions and depending on the experiments request, it is desirable to adapt the luminosity dynamically with beams in collision – **levelling**
- Each levelling technique has its advantages and drawbacks

Levelling by beam offset / separation

Levelling by crossing angle

Levelling by $\beta^*$ (= beam size at IP)
Main levelling technique for HL-LHC

Luminosity evolution during $\beta^*$ levelling: back and forth between 30 cm and 40 cm. The beams remained head-on within $\sim 2 \mu$m!

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
(LHC high availability and >50% stable beams)
Pb-Pb run: 24 days + 4 days setting-up
Goal: > 600 $\mu$b$^{-1}$ ALICE (Run 2 > 1nb$^{-1}$)
# 2018 Machine beam parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch population $N_b$ [$10^{11}$ p]</td>
<td>1.15</td>
<td>$\sim 1.2$ ($\rightarrow 1.4$)</td>
</tr>
<tr>
<td>No. bunches per train</td>
<td>288</td>
<td>144</td>
</tr>
<tr>
<td>No. bunches</td>
<td>2780</td>
<td>2556</td>
</tr>
<tr>
<td>Emittance $\varepsilon$ [mm mrad]</td>
<td>3.5</td>
<td>$\sim 2.2$</td>
</tr>
<tr>
<td>Full crossing angle [$\mu$rad]</td>
<td>285</td>
<td>300 $\rightarrow$ 260</td>
</tr>
<tr>
<td>$\beta^*$ [cm]</td>
<td>55</td>
<td>30 $\rightarrow$ 27.5 $\rightarrow$ 25</td>
</tr>
<tr>
<td>Peak luminosity [$10^{34}$ cm$^{-2}$s$^{-1}$]</td>
<td>1.0</td>
<td>$\sim 2$</td>
</tr>
<tr>
<td>Integrated luminosity [fb$^{-1}$]</td>
<td></td>
<td>$\sim 60$</td>
</tr>
</tbody>
</table>

The “CMS bump” to compensate ground movement was increased from **-1.5 mm** to **-1.8 mm**
LHCb: Data Taking

- **RUN1**: 3 fb⁻¹ of data collected
  - ~3 x 10¹¹ b-anti-b pairs produced within LHCb @ √s = 7-8 TeV
- **RUN2**: operating at 13 TeV higher energy and at 25 ns bunch-crossing (+ detector improvements)
  - larger b-sample for same luminosity!
- Run 2 will go to end of 2018 – expect to increase the beauty sample by x3 or more.
LHCb running strategy for 2018

• Same strategy as 2017. Aim at maximum stability for maximum luminosity
• Last year for the current LHCb!

• TURBO was optimized in 2017
  – Selected data saved in a format ready for the analysis
  – An anticipation of the upgrade trigger

TURBO SP (2017 - 2018)
selective persistence: Save useful information “a la carte”
An application of Turbo: search for dark photons $A'\rightarrow\mu^+\mu^-$

A promising channel to detect dark photons is $A'\rightarrow\mu^+\mu^-$

![Graph showing candidates vs. $m(\mu\mu)$ with Direct trigger output, no offline analysis!][LHCb preliminary – 1.5 fb$^{-1}$]

Direct trigger output, no offline analysis!

[Phys. Rev. Lett. 120, 061801 (2018) Run 2, 1.6 fb$^{-1}$]
Run2 physics results

- Higgs Sector
  - Mass
  - Coupling to Bosons and Fermions
- Standard Model Precision measurements
  - W and Top Mass
  - Standard Model Fits
- Searches
  - Exotics
  - SUSY
- Flavour physics
  - CKM matrix and unitarity triangle tests
  - Spectroscopy and exotic hadronic states
  - Rare decays, FCNCs and $R(K^*)$
- Heavy ions results
Higgs sector
Higgs Boson Mass measured with high precision by ATLAS and CMS using the fully reconstructed final states: $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ\rightarrow 4l$ (e,μ)
All measurements in good agreement
Higgs Mass

CMS Mass Measurement using only H->4l
12% more precise than Run 1 ATLAS+ CMS comb.

\[ m_H = 125.26 \pm 0.21 \text{ (} \pm 0.20 \text{ stat.} \pm 0.08 \text{ sys.}) \text{ GeV} \]
Higgs Production and Branching fraction

- Different production mechanisms and decays to measure
- Use of different experimental signatures
- Some very clean decays with low BR ($\gamma\gamma$, $4l$), other very difficult with higher rates ($bb$, $WW$, $tt$)

@ 13 TeV

Higgs BR

- $gg$: 8.2%
- $\tau\tau$: 6.3%
- $Z\gamma$: 2.6%
- $\mu\mu$, $Z\gamma$, ...
- $WW$: 21.4%
- $bb$: 58.4%
- $YY$: 0.2%
- $cc$: 2.9%

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• The Higgs decay in $\gamma\gamma$ has a clean signature over a smooth background
• It is used to disentangle the different production mechanisms allowing a measurement of their signal strength : $\mu$
Bosons $H \rightarrow \gamma \gamma$: signal strength $\mu$

**CMS**

$$\mu = \mu_{\text{SM}}$$

$$\mu_{\text{combined}} = 1.18 \pm 0.17$$

$m_H$ profiled

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**ATLAS**

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

$H \rightarrow \gamma \gamma, \ m_H = 125.09 \text{ GeV}$

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{\text{top}}$</td>
<td>0.5</td>
<td>+0.6</td>
<td>+0.1</td>
<td>+0.1</td>
</tr>
<tr>
<td>$\mu_{\text{VH}}$</td>
<td>0.7</td>
<td>+0.9</td>
<td>+0.2</td>
<td>+0.2</td>
</tr>
<tr>
<td>$\mu_{\text{VBF}}$</td>
<td>2.0</td>
<td>+0.6</td>
<td>+0.3</td>
<td>+0.3</td>
</tr>
<tr>
<td>$\mu_{\text{ggH}}$</td>
<td>0.81</td>
<td>+0.19</td>
<td>+0.07</td>
<td>+0.07</td>
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<tr>
<td>$\mu_{\text{Run-2}}$</td>
<td>0.99</td>
<td>+0.15</td>
<td>+0.06</td>
<td>+0.07</td>
</tr>
<tr>
<td>$\mu_{\text{Run-1}}$</td>
<td>1.17</td>
<td>+0.28</td>
<td>+0.10</td>
<td>+0.12</td>
</tr>
</tbody>
</table>

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Coupling to Bosons $H \rightarrow ZZ$

- Very clean signature but very low rate
- Measurement of ggH and VBF production
- Measurement of total fiducial cross section

**ATLAS** Preliminary

- $\sigma_{pp \rightarrow H}$, $m_H = 125.09\text{ GeV}$
- QCD scale uncertainty
- Combined data
- Total uncertainty (scale $\oplus$ PDF $\oplus$ $\alpha_s$)

**CMS**

- Data (stat. $\oplus$ sys. unc.)
- Systematic uncertainty
- Standard model
- LHC HXSWG YR4, $m_H = 125.09\text{ GeV}$

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Coupling to Bosons $H \rightarrow WW$

- Larger usable branching fraction ($2l2\nu$) but much larger background
- No Higgs mass reconstruction, rely on lepton kinematics ($M_{t\bar{t}}, M_{ll}, \theta_{ll}$)

ATLAS Preliminary

$H \rightarrow WW^{*} \rightarrow e\nu\mu\nu, N_{W} \leq 1$

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

$ggF: 6.3 \sigma$ (exp: 5.2$\sigma$)

CMS

$\hat{\mu} = 1.28^{+0.18}_{-0.17} = 1.28 \pm 0.10$(stat) +0.11(syst) +0.10(theo.)

ATLAS

$\mu_{ggF} = 1.21^{+0.12}_{-0.11}$(stat.) +0.18(sys.) = 1.21^{+0.22}_{-0.21}$

$\mu_{VBF} = 0.62^{+0.30}_{-0.28}$(stat.) $\pm 0.22$(sys.) = 0.62^{+0.37}_{-0.36}$
Coupling to Fermions $H \rightarrow \tau \tau$

- Search for $H \rightarrow \tau \tau$ with $\tau$ decaying in $e\mu, \mu \tau_h, e\tau_h$ and $\tau_h \tau_h$
- Largest background from $Z \rightarrow \tau \tau$ and hadronic multijet events
- Search in categories aiming at $ggH$ and VBF production

Observation of $H \rightarrow \tau \tau$

$\mu = 1.09 \pm 0.26$

Significance: 4.9 $\sigma$ (5.9 $\sigma$ for comb. of 13 & 7-8 TeV)

First observed in run 1 by ATLAS and CMS Combination
Coupling to Fermions H→ bb

- Largest branching fraction (58.4%) but huge background from heavy flavour production
- Need to use exclusive (rare) production mechanism to gain sensitivity: VH H→bb (V=W or Z)
- Final states with 2 tagged b Jets and 0,1 or 2 leptons

Evidence of VH(bb) production

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Coupling to Fermions: ttH

- Very interesting:
  - give direct access to the Yukawa coupling between the top quark and the Higgs
- Very challenging:
  - Very small production cross section (O(0.5) pb @ 13 TeV)
  - Many complex final states and large irreducible backgrounds
- Complex analyses:
  - Use of BDTs, MVA, Deep Machine Learning techniques
- Results from ttH→ Multilepton final states and ttH, (H-bb)
ttH -> Multileptons

- Target Higgs decays to WW, ττ and ZZ
  - Two same sign or >=3 charged leptons + additional requirements on b-jet multiplicities (and/or τ_h for CMS)
    - CMS uses also 1 lepton and 2τ_h
- Irreducible background: ttW, ttZ, with prompt leptons
- Reducible background: mostly tt+γ with mis-reconstructed leptons

ATLAS comb. $\mu = 1.6^{+0.5-}$. CMS comb. $\mu = 1.23^{+0.5-}$

Evidence for ttH production in leptonic final states
 CMS: 3.2 $\sigma$ (2.8 $\sigma$ exp.)
 ATLAS: 4.1 $\sigma$ (2.8 $\sigma$ exp.)
ttH (H->bb) and Combination

- ATLAS and CMS use channels with 1 or 2 leptons and $N_{\text{jet}} \geq 4$, $\geq 3b$, to exploit leptonic $t$ decays to reduce huge backgrounds
- CMS also uses the all hadronic final state: higher rates but even larger background

Combined signal strength of all ttH channels in agreement with SM predictions

**ATLAS Combination Run2** $m=1.2^{+0.3}_{-0.2}$ Evidence ttH Prod. 4.2s (3.8σ exp.)

**CMS Combination Run2** $m=1.18^{+0.31}_{-0.27}$ Evidence ttH Prod 4.2σ

**CMS Combination Run1+Run2** $m=1.26^{+0.31}_{-0.26}$ Obs. of ttH with 5.2s (4.2σ exp)
The Higgs Sector summary

- CMS $\mu$ combination: $\mu = 1.17^{+0.10}_{-0.10}$
- Cross sections measurements in agreement with SM
- Differential Cross Sections also in good agreement with SM

Cross sections normalised to SM from ZZ and $\gamma\gamma$ combination

Higgs production

ATLAS Preliminary
\[ \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \]
\[ H \to \gamma\gamma \text{ and } H \to ZZ^* \to 4l \]
m$_H$ = 125.09 GeV, $|y_H|<2.5$

- $\mu_{ggH}$ ~ 11%
- $\mu_{VBF}$ ~ 41%
- $\mu_{WH}$ ~ 27%
- $\mu_{ZH}$ ~ 51%
- $\mu_{ttH}$ ~ 26%
- $\mu$ ~ 9%
SM precision measurements
SM and QCD

Impressive number of measured cross sections in very good agreement with expectations

Standard Model Production Cross Section Measurements

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

**Status:** March 2018

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**W boson mass**

**Early 2011 data with low Pile-Up**

4.6 fb\(^{-1}\) @ \(\sqrt{s} = 7\) TeV

\[
m_W = 80.370 \pm 0.019 \text{ GeV}
\]

\(\pm 7\) MeV statistical

\(\pm 11\) MeV systematic

\(\pm 14\) MeV modeling

Huge amount of work to understand detector response and the modelling of kinematic quantities (Mt, \(P_t\))

(relies on large \(Z \rightarrow \ell\ell\) sample)

Similar precision reached as for current best CDF measurement
Measurement of the Top Mass

- Large Top production cross section
  - Many precision measurements on Top Properties
- Many different methods and final states used to extract Top Mass
  - Direct methods, (Templates, Ideograms)
  - Indirect method (based on measured Xsect.)

ATLAS Combination $m_{\text{top}} = 172.51 \pm 0.5$

CMS Combination $m_{\text{top}} = 172.44 \pm 0.48$
Standard Model

- A precision measurement of $m_{\text{top}}$ $m_W$ and $m_H$ allows a stringent test of the SM
  - Aim at improving further the precision on $M_W$ with dedicated runs
- Precision measurement of $\sin^2 \theta_W$ by $A_{\text{fb}}$ consistent with previous measurements and with SM
BSM Searches
# ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

\[ \sqrt{s} = 8, 13 \text{ TeV} \]

### Model

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( E_{T}^{\text{miss}} )</th>
<th>( \mathcal{L} \text{dt} ) [fb(^{-1})]</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD ( G_{\chi} \pm e/q )</td>
<td>0, e, ( \mu )</td>
<td>1 - 4</td>
<td>Yes</td>
<td>36.1</td>
<td>( M_{\chi} )</td>
</tr>
<tr>
<td>ADD non-resonant ( \gamma \gamma )</td>
<td>2 ( \mu )</td>
<td>-</td>
<td>-</td>
<td>36.7</td>
<td>( M_{\chi} )</td>
</tr>
<tr>
<td>ADD QBF</td>
<td>-</td>
<td>2 ( \mu )</td>
<td>-</td>
<td>37.0</td>
<td>( M_{\chi} )</td>
</tr>
<tr>
<td>ADD BH high ( \Sigma pT )</td>
<td>( \geq 1 ), e, ( \mu )</td>
<td>( \geq 2 )</td>
<td>-</td>
<td>3.2</td>
<td>( M_{\chi} )</td>
</tr>
<tr>
<td>ADD BH multijet ( \geq 3 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.6</td>
<td>( M_{\chi} )</td>
</tr>
<tr>
<td>RS1 ( G_{\chi} \rightarrow \gamma \gamma )</td>
<td>2 ( \gamma )</td>
<td>-</td>
<td>-</td>
<td>36.7</td>
<td>( M_{\chi} )</td>
</tr>
<tr>
<td>Bulk RS ( G_{\chi} \rightarrow WW \rightarrow q\bar{q}l\nu )</td>
<td>1, e, ( \mu )</td>
<td>1 J</td>
<td>Yes</td>
<td>36.1</td>
<td>( M_{\chi} )</td>
</tr>
<tr>
<td>( Z \rightarrow \ell \ell )</td>
<td>0, e, ( \mu )</td>
<td>2 ( \mu ), ( 2 ) j</td>
<td>-</td>
<td>13.2</td>
<td>( M_{\chi} )</td>
</tr>
<tr>
<td>( \ell \rightarrow q \bar{q} )</td>
<td>-</td>
<td>2 ( \mu )</td>
<td>-</td>
<td>37.0</td>
<td>( M_{\chi} )</td>
</tr>
<tr>
<td>( \ell \rightarrow q \gamma \gamma )</td>
<td>-</td>
<td>2 ( \mu )</td>
<td>-</td>
<td>37.0</td>
<td>( M_{\chi} )</td>
</tr>
<tr>
<td>Vector mediator (Dirac DM)</td>
<td>0, e, ( \mu )</td>
<td>2 ( \mu ), ( 2 ) j</td>
<td>-</td>
<td>36.1</td>
<td>( M_{\chi} )</td>
</tr>
<tr>
<td>VV/\gamma EFT (Dirac DM)</td>
<td>0, e, ( \mu )</td>
<td>1 ( \mu ), ( 2 ) j</td>
<td>-</td>
<td>32.3</td>
<td>( M_{\chi} )</td>
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<tr>
<td>Scalar LO 1st gen</td>
<td>2 ( \mu )</td>
<td>( \geq 2 )</td>
<td>-</td>
<td>3.2</td>
<td>( M_{\chi} )</td>
</tr>
<tr>
<td>Scalar LO 2nd gen</td>
<td>2 ( \mu )</td>
<td>( \geq 2 )</td>
<td>-</td>
<td>3.2</td>
<td>( M_{\chi} )</td>
</tr>
<tr>
<td>Scalar LO 3rd gen</td>
<td>1, e, ( \mu )</td>
<td>( \geq 2 )</td>
<td>-</td>
<td>20.3</td>
<td>( M_{\chi} )</td>
</tr>
<tr>
<td>Heavy quark</td>
<td>0 or 1, e, ( \mu )</td>
<td>( \geq 2 )</td>
<td>-</td>
<td>13.2</td>
<td>( M_{\chi} )</td>
</tr>
<tr>
<td>Heavy quark</td>
<td>1, e, ( \mu )</td>
<td>( \geq 2 )</td>
<td>-</td>
<td>36.1</td>
<td>( M_{\chi} )</td>
</tr>
<tr>
<td>Heavy quark</td>
<td>2, e, ( \mu )</td>
<td>( \geq 2 )</td>
<td>-</td>
<td>36.1</td>
<td>( M_{\chi} )</td>
</tr>
<tr>
<td>Heavy quark</td>
<td>2, e, ( \mu )</td>
<td>( \geq 2 )</td>
<td>-</td>
<td>20.3</td>
<td>( M_{\chi} )</td>
</tr>
<tr>
<td>Heavy quark</td>
<td>1, e, ( \mu )</td>
<td>( \geq 2 )</td>
<td>-</td>
<td>36.1</td>
<td>( M_{\chi} )</td>
</tr>
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<td>( M_{\chi} )</td>
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<td>Heavy quark</td>
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<td>( \geq 2 )</td>
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<td>20.3</td>
<td>( M_{\chi} )</td>
</tr>
</tbody>
</table>

### Reference

- ATLAS-CONF-2017-060
- ATLAS-CONF-2017-027
- ATLAS-CONF-2017-006
- ATLAS-CONF-2016-072
- ATLAS-CONF-2017-014
- ATLAS-CONF-2017-017
- ATLAS-CONF-2017-055
- ATLAS-CONF-2017-029
- ATLAS-CONF-2017-023

*Only a selection of available mass limits on new states or phenomena is shown.

† Small-radius (large-radius) jets are denoted by the letter \( j \) (\( J \)).
New Bosons

- Di-lepton (ee, $\mu\mu$), ($e\nu, \mu\nu$) final states offer a very clean signature to searches of new Heavy Bosons eg $Z'$, $W'$

- No significant excess observed

- Results interpreted in many models e.g.:
  - $M(Z'_{SSM}) > 4.7$ TeV
  - $M(Z'_{\psi}) > 4$ TeV

Maratea - June 29, 2018
• Searches in the Mono-\( X \) final states
  – One well reconstructed object with large Missing Energy due to WIMP
  – Many models constrained up to 1-2 TeV

• Searches also in the Di-Jet final states exclude up to 2.7 TeV for almost whole DM range
Strong Production (Gluino and Squark) well tested: Limits in TeV range
Moving to electroweak production and non-conventional signatures

Maratea - June 29, 2018

Nadia Pastrone
Flavour physics
History of the Unitarity Triangle

1988

1995

2000

2003
In the presence of relevant new physics effects, the various contours would not cross each other in a single point.

Certainly that’s a great success of the Standard Model CKM picture, but there is still room for new physics at the 10% level.
Measurement of $\sin 2\beta$

- $CP$ violation due to interference between $B^0 - \bar{B}^0$ mixing and $b \rightarrow c\bar{c}s$ transitions

- LHCb has reached the precision of the $B$ factories and will soon surpass that with Run-2 data.

Maratea - June 29, 2018

Nadia Pastrone
\( \phi_s \) from \( b \to c\bar{c}s \) transitions

- Golden mode \( B_s \to J/\psi \phi \) proceeds (mostly) via a \( b \to ccs \) tree diagram

- Interference between \( B_s \) mixing and decay graphs

- Measures the phase-difference \( \phi_s \) between the two diagrams, precisely predicted from global CKM fits in the Standard Model to be

\[ \phi_s = -2\lambda^2 \eta = -37.4 \pm 0.7 \text{ mrad} \rightarrow \text{can be altered by new physics} \]
Measurement of $\phi_s$

- $\phi_s$ precision mostly driven by LHCb
- Latest HFLAV world average
  - $\phi_s = -21 \pm 31$ mrad
- Still compatible with the SM at the present level of precision

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Mode</th>
<th>Dataset</th>
<th>$\phi_s^{\text{tilt}}$</th>
<th>$\Delta \Gamma_s$ (ps$^{-1}$)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>$J/\psi \phi$</td>
<td>9.6 fb$^{-1}$</td>
<td>$[-0.60, +0.12]$, 68% CL</td>
<td>$+0.068 \pm 0.026 \pm 0.009$</td>
<td>[2]</td>
</tr>
<tr>
<td>D0</td>
<td>$J/\psi \phi$</td>
<td>8.0 fb$^{-1}$</td>
<td>$-0.55^{+0.38}_{-0.36}$</td>
<td>$+0.163^{+0.065}_{-0.064}$</td>
<td>[3]</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$J/\psi \phi$</td>
<td>4.9 fb$^{-1}$</td>
<td>$+0.12 \pm 0.25 \pm 0.05$</td>
<td>$+0.053 \pm 0.021 \pm 0.010$</td>
<td>[4]</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$J/\psi \phi$</td>
<td>14.3 fb$^{-1}$</td>
<td>$-0.110 \pm 0.082 \pm 0.042$</td>
<td>$+0.101 \pm 0.013 \pm 0.007$</td>
<td>[5]</td>
</tr>
<tr>
<td>ATLAS</td>
<td>above 2 combined</td>
<td></td>
<td>$-0.090 \pm 0.078 \pm 0.041$</td>
<td>$+0.085 \pm 0.011 \pm 0.007$</td>
<td>[5]</td>
</tr>
<tr>
<td>CMS</td>
<td>$J/\psi \phi$</td>
<td>19.7 fb$^{-1}$</td>
<td>$-0.075 \pm 0.097 \pm 0.031$</td>
<td>$+0.095 \pm 0.013 \pm 0.007$</td>
<td>[6]</td>
</tr>
<tr>
<td>LHCb</td>
<td>$J/\psi K^+ K^-$</td>
<td>3.0 fb$^{-1}$</td>
<td>$-0.058 \pm 0.049 \pm 0.006$</td>
<td>$+0.0805 \pm 0.0091 \pm 0.0032$</td>
<td>[7]</td>
</tr>
<tr>
<td>LHCb</td>
<td>$J/\psi \pi^+ \pi^-$</td>
<td>3.0 fb$^{-1}$</td>
<td>$+0.070 \pm 0.068 \pm 0.008$</td>
<td>—</td>
<td>[8]</td>
</tr>
<tr>
<td>LHCb</td>
<td>$J/\psi K^+ K^- \ ^a$</td>
<td>3.0 fb$^{-1}$</td>
<td>$+0.119 \pm 0.107 \pm 0.034$</td>
<td>$+0.066 \pm 0.018 \pm 0.010$</td>
<td>[9]</td>
</tr>
<tr>
<td>LHCb</td>
<td>above 3 combined</td>
<td></td>
<td>$+0.001 \pm 0.037$ (tot)</td>
<td>$+0.0813 \pm 0.0073 \pm 0.0036$</td>
<td>[9]</td>
</tr>
<tr>
<td>LHCb</td>
<td>$\psi(2S)\phi$</td>
<td>3.0 fb$^{-1}$</td>
<td>$+0.23^{+0.20}_{-0.28} \pm 0.02$</td>
<td>$+0.066^{+0.41}_{-0.44} \pm 0.007$</td>
<td>[10]</td>
</tr>
<tr>
<td>LHCb</td>
<td>$D_s^+ D_s^-$</td>
<td>3.0 fb$^{-1}$</td>
<td>$+0.02 \pm 0.17 \pm 0.02$</td>
<td>—</td>
<td>[11]</td>
</tr>
</tbody>
</table>

$^a m(K^+ K^-) > 1.05$ GeV/$c^2$.  

See HFLAV page for the list of references

http://www.slac.stanford.edu/xorg/hflav/
Measurement of $\gamma$

- $\gamma$ is the least known angle of the UT, although not for too long yet, measured via the interference between $b\rightarrow u$ and $b\rightarrow c$ tree-level transitions.

- Simple and clean theoretical interpretation, but statistically very challenging.
Searches for new physics in $b \to s \ell^+ \ell^-$ transitions

- Quark-level transitions entering some of the most relevant decay amplitudes to search for new physics effects

- The presence of new particles may lead to observable effects
$B^0 \rightarrow \mu^+ \mu^-$ and $B_s \rightarrow \mu^+ \mu^-$

- CMS and LHCb performed a combined fit to their full Run-1 data sets
  
  \[ \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9} \]
  
  \[ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10} \]

- $B_s \rightarrow \mu \mu$ $6.2\sigma$ significance was first observation
  – Well compatible with the Standard Model

- More recently, also ATLAS published a measurement with Run-1 data

EPJC 76 (2016) 513

Nature 522 (2015) 68
$B \rightarrow \mu \mu$ at LHCb with Run-2 data

- New measurement from LHCb using Run-2 data has led in 2017 to the first observation of the $B_s \rightarrow \mu \mu$ decay from a single experiment

$$B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

- Moreover, it starts to be possible to measure other properties, such as the “effective” lifetime, that will be useful for discriminating between new physics models
Lepton-flavour universality tests in $b \rightarrow s\ell^+\ell^-$

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

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

- For the moment at the 3σ-ish level from the SM

- Updates with Run-2 data as well as other new measurements with different decay modes expected during the course of the year
Other anomalies in the $b \rightarrow s \ell^+ \ell^-$ sector

- E.g., differential BFs consistently lower than SM expectations, although control of hadronic uncertainties in the predictions is matter of lively debates.
New physics searches in flavour in a nutshell

• Classic broad-range measurements
  – CKM physics, search for very rare decays
• Measurements in specific sectors where anomalies are emerging in recent years
  – Lepton-flavour universality in $b \rightarrow s \ell^+ \ell^-$ quark-level transitions, and related $b \rightarrow s \ell^+ \ell^-$ picture of decay rates
  – Lepton-flavour universality in semileptonic $b$-hadron decays
New physics searches in the flavour sector

• Instead of searching for new particles produced directly, look for their indirect effects to low energy processes (e.g. $b$-hadron decays)

• General amplitude decomposition in terms of couplings and scales

• By studying CP-violating and flavour-changing processes, two fundamental tasks can be accomplished
  – Identify new symmetries (and their breaking) beyond the Standard Model
  – Probe mass scales not accessible directly at a collider like the LHC
LFU tests in semileptonic $b$-hadron decays

- Measure ratio
  \[ R_D(\ast) = \frac{\text{BF}(B \rightarrow D(\ast)\tau\nu)}{\text{BF}(B \rightarrow D(\ast)\mu\nu)} \]

- Measurements of $R(D)$ and $R(D^*)$ by BaBar, Belle and LHCb
  - Overall average shows a $4\sigma$ discrepancy from the SM
  - LHCb has recently demonstrated to be able to make the measurement also with 3-prong $\tau$ decays [arXiv:1708.08856]

- LHCb can also perform measurements with other $b$ hadrons
  - Recent determination of $R(J/\psi) = \frac{\text{BF}(B_c \rightarrow J/\psi\tau\nu)}{\text{BF}(B_c \rightarrow J/\psi\mu\nu)}$ at about $2\sigma$ from the SM [arXiv:1711.05623]
  - Other modes with $B_s$ and $\Lambda_b$ decays will also come
Spectroscopy at LHCb

- LHCb particularly suitable for hadron spectroscopy:
  - Large production cross section
  - Excellent mass resolution
  - Excellent vertexing and PID (→ low background)

- Many new states have been observed in heavy flavor spectroscopy: see for example the charmonium spectrum

- Many of them can be interpreted as “standard” hadronic states while others require an “exotic” interpretation

The decay $\Xi^{-}_b \rightarrow J/\psi \Lambda K^-$

- Paper on observation of this decay just released on arXiv:1701.05274, subm. to PLB
- It may proceed through $P_c$ states with open strangeness:
- It is the analogous of $\Lambda_b \rightarrow J/\psi pK$ with an $s$ spectator quark

**only L candidates made with 2 long tracks**
Exotic states in $B^+ \rightarrow J/\psi \phi K^+$

- LHCb exploits the largest sample of $B^+ \rightarrow J/\psi \phi K^+$ decays so far, trying to shed light on these states.

![Graph showing signal region and sideband](image1)

![Graph showing signal region](image2)
Fixed target
Cosmic ray physics at LHCb: p+He→anti-p+X

- The recent AMS02 results provide unprecedented accuracy for measurement of anti-p/p ratio in cosmic rays at high energies [PRL 117, 091103 (2016)]
- Hint for a possible excess, and milder energy dependence than expected
- Prediction for anti-p/p ratio from spallation of primary cosmic rays on interstellar medium (H and He) is presently limited by uncertainties on anti-p production cross-sections, particularly for p-He
- No previous measurement of anti-p production in p-He, predictions from soft QCD models vary within a factor 2

The LHC energy scale and LHCb+SMOG are very well suited to perform this measurement.
CoSMic ray physics at LHCb: \( p+He \rightarrow \text{anti-p}+X \)

- LHCb took \( p-He \) collision data in May 2016, with proton energy 6.5 TeV, \( \sqrt{s_{NN}} = 110 \) GeV
- Anti-protons are identified using the RICH detectors
- The luminosity is measured using elastic scattering of protons on atomic electrons
  - Fully elastic regime in the LHCb acceptance
  - Very well known theoretically

- A luminosity measurement at the 10% level can be obtained (main uncertainty: gas contamination !)

- \( L = 0.443 \pm 0.011 \pm 0.027 \text{ nb}^{-1} \)
Antiproton production in fixed-target $p\text{He}$ collisions

- Antiproton cross section measured with 10% precision
- Theoretical interpretation on its way
- Additional production measurements are also important
  - E.g., antiprotons from $\Lambda$ decays
- Further results expected in the near future

LHCb-CONF-2017-002
(paper in preparation)
Heavy ions collisions

QGP properties
hadron chemistry
nucleosynthesis in QGP
increased precision on QGP parameters
new insights on jet quenching

collective effects in small systems
important progress in system-size dependence
properties, buildup of collective effects
closing in on medium effects in small systems?
rich input for pp modeling
LHCb Heavy Ions: J/ψ and D⁰ signals in PbPb collisions

- LHCb has an interesting HI physics program exploiting the complementary geometry and its PID capability

- Only pPb in Run 1
- In Run 2 we took data also in PbPb
- Challenging! But results coming out
Heavy ion and fixed target physics at LHCb

- LHCb can operate in collider mode, fixed target mode or both in parallel!

Collider mode

- \( \sqrt{s_{NN}} = 8.2 \) TeV
- \( \sqrt{s_{NN}} = 110 \) GeV

Fixed target mode

- Forward/backward coverage
- Central and backward coverage

@ \( \sqrt{s_{NN}} \) between SPS and RHIC
Ultrarelativistic Nuclear Collisions

basic idea: compress large amount of energy in small volume
→ produce a “fireball” of hot matter:
  temperature $O(10^{12} \text{ K})$
  ~ $10^5 \times T$ at centre of Sun
  ~ $T$ of universe @ ~ 10 µs after Big Bang

extreme conditions: how does matter behave?
→ phase transition
deconfined QCD medium (Quark-Gluon Plasma, QGP)
predicted by QCD
evidence for QGP already at lower energy
(CERN-SPS, BNL-RHIC)
LHC: high statistics and controlled probes
→ quantitative study of properties of QCD medium
  viscosity, opacity, transport, diffusion, ...
Status of data taking

<table>
<thead>
<tr>
<th>System</th>
<th>Year(s)</th>
<th>$\sqrt{s_{NN}}$ (TeV)</th>
<th>$L_{int}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb-Pb</td>
<td>2010-2011</td>
<td>2.76</td>
<td>~75 $\mu$b$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>5.02</td>
<td>~250 $\mu$b$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>by end of 2018</td>
<td>5.02</td>
<td>~1 nb$^{-1}$</td>
</tr>
<tr>
<td>Xe-Xe</td>
<td>2017</td>
<td>5.44</td>
<td>~0.3 $\mu$b$^{-1}$</td>
</tr>
<tr>
<td>p-Pb</td>
<td>2013</td>
<td>5.02</td>
<td>~15 nb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>2016</td>
<td>5.02, 8.16</td>
<td>~3 nb$^{-1}$, ~25 nb$^{-1}$</td>
</tr>
<tr>
<td>pp</td>
<td>2009-2013</td>
<td>0.9, 2.76, 7, 8</td>
<td>~200 $\mu$b$^{-1}$, ~100 nb$^{-1}$, ~1.5 pb$^{-1}$, ~2.5 pb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>2015,2017</td>
<td>5.02</td>
<td>~1.3 pb$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>2015-2017</td>
<td>13</td>
<td>~25 pb$^{-1}$</td>
</tr>
</tbody>
</table>

- 2018 campaign in full swing!
- high statistics Pb-Pb run in November!
Identified particles

Textbook-quality Run 2 data!
More and more species

Resonances, hyperons, ...

→ QGP hadronisation, radial expansion, freeze-out, ...
Deuterons

Coalescence probability decreases as system size grows

ALICE-PUBLIC-2017-006

ALICE Preliminary

< 0.5 lab η | | lab η / d ch N d 〈 1 10 2 10 3 10 2 10 1 10 0 | N s 1/6 − 10 5 − 10 4 − 10 3 − 10 2 − 10 1 − 10 0 = 5.02 TeV NN s pp INEL ALICE, Pb-Pb, \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) V0A Multiplicity Classes (Pb-side) ALICE, p-Pb, \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) ALICE Preliminary INEL normalisation uncertainty: 2.55% | < 0.5

\[ \frac{1}{N_{ev}} \frac{d^2N}{dp_T^2} (\text{GeV/c})^{-1} \]

\[ \frac{2d}{(p+p)} \]

\[ \langle dN_{\text{ch}} / d\eta \rangle |_{\eta_{\text{lab}} < 0.5} \]

ALICE, pp INEL, \( \sqrt{s} = 13 \text{ TeV} \)

ALICE, Pb-Pb, \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)

ALICE, Pb-Pb, \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) (PRC 93 (2015) 024917)

ALICE, pp INEL, \( \sqrt{s} = 7 \text{ TeV} \) (PRC 93 (2015) 024917)
Hypertriton: lifetime

\(^3\Lambda H\): \(pn\Lambda\) bound state

\(^3\Lambda H \rightarrow ^3\text{He} + \pi^-

One of the most precise determinations of the lifetime
Consistent with world data and with free \(\Lambda\) lifetime
Charm: constraining the QGP transport properties

\[ \frac{R_{AA}}{N_{\text{coll}}} \frac{dN}{dp_T} \times \left( 1 + 2v_1 \cos(\varphi - \psi_1) + 2v_2 \cos(2[\varphi - \psi_2]) + \ldots \right) \]

- powerful constraint from combination of \( R_{AA} \) and \( v_2 \)
Jet shape studies

e.g.: declustering: “peel apart” the shower (Soft Drop)

\[ z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} \quad z_g > 0.1 \]

sensitive to coherence of energy loss

→ suppression of symmetric splittings at large $\Delta R$
Xe-Xe: multiplicity

6-hour run in 2017

- $N_{\text{part}}$ scaling violated $\rightarrow N_{\text{quark}} \sim$ works
  - already known from Pb-Pb

- strong increase of $N_{\text{ch}}/N_{\text{part}}$ for central Xe-Xe
  - Xe-Xe: more $N_{\text{ch}}$ than Pb-Pb at same $N_{\text{part}}$
  - Xe deformation?
  - not fully understood yet...

[arXiv:1805.04432]
Energy loss in p-Pb?

- collective effects in p-Pb
  - long-range correlations ($v_2$)
  - mass-dependence similar to Pb-Pb
  - strangeness enhancement pattern
- but still no evidence of jet quenching
  - system size, hence effect, smaller
  - but some predictions of sizeable effect, e.g.:
  - dependence on event activity is important!
Charmonia in p-Pb collisions

- moderate $J/\psi$ suppression (consistent with shadowing)
- but $\psi(2S)$ more suppressed (especially in Pb hemisphere)

→ final-state effects?
Future prospects
Run3 and HL-LHC
LHC - heavy ions run

- **LS2:**
  - LHC injector upgrades, Pb-Pb rate $\rightarrow$ 50 kHz (now ~10 kHz)
  - ALICE upgrades
- **Run 3 + Run 4:**
  - experiments request $> 10$/nb (ALICE: $10}$/nb + $3}$/nb at 0.2 T)
  - in line with latest projections from machine group
ALICE upgrade @ Run3 and Run4

**PHYSICS GOAL:** x 100 statistics increase for Run 3 and Run 4!

- study heavy quark interaction in QCD medium
  - heavy flavour dynamics and hadronisation at low $p_T$
- study charmonium regeneration in QGP
  - charmonium down to zero $p_T$
- chiral symmetry restoration and QGP radiation
  - vector mesons and virtual thermal photons (di-leptons)
- production of nuclei in QGP
  - high-precision measurement of light nuclei and hypernuclei
TPC at high rate

- Goal: replace existing MWPC-based Readout Chambers and Front-End Electronics in LS2 to allow continuous readout of Pb-Pb collisions at 50 kHz in RUN3 and 4
- Technical solution: 4-layer GEM detectors

- currently: average time between collisions $\sim 125 \mu s \sim$ TPC drift time
  - 1 event in TPC at any given time $\rightarrow$ triggerable

- after upgrade: average time between collision $\sim 20 \mu s \ll$ TPC drift time
  - 5 events in TPC at any given time $\rightarrow$ continuous readout
O² System

Requirements
1. LHC min bias Pb-Pb at 50 kHz
2. very small signal over background
   → triggering not possible
3. support for continuous read-out

New computing system
→ read-out the data of all interactions
→ compress data intelligently
   → online reconstruction
→ common online-offline computing system → O²

Unmodified raw data of all interactions shipped from detector to online farm in triggerless continuous mode
HI run 3.5 TByte/s
Baseline correction and zero suppression
Data volume reduction by zero cluster finder.
No event discarded.
Average compression factor 6.6
500 GByte/s

Data volume reduction by online tracking.
Only reconstructed data to data storage.
Average compression factor 5
90 GByte/s

Data Storage
1 year of compressed data
120 GB/s

Tier 0, Tiers 1 and Analysis Facilities

Asynchronous (hours) event reconstruction with final calibration
200 GB/s

Detector Electronics
9000 GBTs links

270 First-Level Processors
Hw acc: FPGAs

Switching Network

1500 Event Processing nodes
Hw acc: GPUs

Switching Network

Data storage
Wr 120 GB/s Rd 320 GB/s
Capacity: 60 PB

Maratea - June 29, 2018
Nadia Pastrone
The LHCb upgrade in a snapshot

All sub-detectors read out at 40 MHz for a fully software trigger

- Upgraded detector
  - New silicon upstream tracker
  - New PIXEL vertex detector
  - New RICH optics and photodetectors
  - New scintillating fibre tracker
  - New electronics for muon and calorimeter systems
LHCb Upgrade II – not approved yet

- assumes a future upgrade to raise instantaneous luminosity to $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$
- First upgrade in LS2 $\Rightarrow$ instantaneous luminosity up to $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$
- Expression of Interest for a further upgrade during LS4 to reach $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$ (~50 fb$^{-1}$/year), called Upgrade II $\Rightarrow$ pileup ~50 - very challenging !!!
High Luminosity LHC

- a “landmark project” in the ESFRI roadmap
- formally approved by the CERN Council

LHC / HL-LHC Plan

TODAY 2018

FAV = Fabrication, Assembly and Verification
The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

Prepare machine for operation **beyond 2025 and up to 2035-37**

Devise beam parameters and operation scenarios for:

# enabling a total integrated luminosity of **3000 fb⁻¹**

# implying an integrated luminosity of **250-300 fb⁻¹ per year**,

# design for $\mu \sim 140 \ (\sim 200)$ (⇒ peak luminosity of $5 \ (7.5) \times 10^{34} \ \text{cm}^{-2} \ \text{s}^{-1}$)

# design equipment for ‘ultimate’ performance of $7.5 \times 10^{34} \ \text{cm}^{-2} \ \text{s}^{-1}$

and **4000 fb⁻¹**

=> **Ten times the luminosity reach of first 10 years of LHC operation**
Luminosity recipe:

\[ L = \frac{n_b \cdot N_1 \cdot N_2 \cdot \gamma \cdot f_{rev}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot F(\phi, \beta^*, \varepsilon, \sigma_s) \]

1) maximize bunch intensities
2) minimize the beam emittance
3) minimize beam size (constant beam power);
4) maximize number of bunches (beam power);
5) compensate for ‘F’;
6) Improve machine ‘Efficiency’

⇒ Injector complex
⇒ LIU ↔ IBS
⇒ triplet aperture
⇒ 25ns
⇒ Crab Cavities
⇒ minimize number of unscheduled beam aborts
11 Tesla dipole ($\text{Nb}_3\text{Sn}$) long prototype
Conclusions and outlook

- 2018 run restarted very well: LHC continues to provide a wealth of excellent physics results
- Already ~ 100 fb\(^{-1}\) delivered by LHC to ATLAS and CMS is only 3% of the full LHC program \(\Rightarrow\) precision measurements in the Higgs sector start to be feasible
- Flavor sector can complement with indirect measurements the direct searches while exploring SM and rare decays
- In the current state with fundamental physics, it is necessary to have a programme as diversified as possible: maintaining the broadest possible physics programme in the long term will be crucial
- LS2 shutdown for machine and experiments upgrade is close
- Looking into the far future seeking for new opportunities!!