LHCb: a general purpose detector in the forward region

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Outline

✦ Introduction: LHCb, not only flavour (or spectroscopy)!
✦ SM and top physics
✦ Direct searches
✦ Fixed target physics
✦ Conclusions
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Introduction
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Collision region!

Electroweak, top and exotics physics at LHCb: present and future

X. Cid Vidal

Introduction to LHCb

Electroweak physics

Z and W production at LHCb

Z+X

Exotics physics

Limits on H0

H0 decays to long-lived particles

A C in b\bar{b}

Future

Prospects on EW

How about top?

Towards H0!

b\bar{b}

Conclusions
Introduction

- LHCb takes significantly less data than ATLAS/CMS (factor of ~8 at Run 1) but
  - Precise integrated luminosity computation
  - Stable conditions (trigger)
  - Advantage in vertexing, PID, $p$ resolution...

Collision region!

- JINST3(2008)S08005
Important and very well known contributions to flavour physics and spectroscopy

First single experiment observation of the decay $B_s \rightarrow \mu \mu$

Observation of $J/\psi p$ resonances consistent with pentaquark states

Also doing SM and top physics, direct searches (à la ATLAS and CMS)... Will be the focus in this talk!
... and pPb, PbPb and **fixed target** physics!

will show an example!
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Physics with EW bosons at LHCb

- LHCb EW production measurements probe two Bjorken $x$ – $Q^2$ regions
  - Low $x$, high $Q^2$ previously unexplored. Overlap region allows direct ATLAS/CMS comparison
  - LHCb produces $W/Z$ by collisions between low-$x$ and high-$x$ partons

\[ \sigma(x, Q^2) = \sum_{a,b} \int_0^1 dx_1 dx_2 f_a(x_1 Q^2) f_b(x_2 Q^2) \times \hat{\sigma}(x_1, x_2, Q^2) \]

where

- $x$ parton longitudinal momentum fraction
- $Q^2$ momentum transfer
LHCb results are useful!

- LHCb results so far on EW gauge bosons have already been used to constrain different proton PDFs

![Graphs showing NNPDF3.1 NNLO, Q = 100 GeV and Q = 1.7 GeV](image)

- Uncertainty on \(d\) PDF reduced a factor of 2 at \(x \sim 0.2\)

- Models where non-perturbative charm can carry much more than 1% of the total proton’s momentum are strongly disfavoured by the LHCb data
Measurement using $\mu\mu$ and $ee$ final states

- Selecting leptons with $p_T > 20 \text{ GeV/c}$ and $2 < \eta < 4.5$, $60 < m_{ll} < 120 \text{ GeV/c}^2$
- For $\mu\mu$, purities above 99%, for $ee$ above 92%
- Analysis using $\sim 300 \text{ pb}^{-1}$
- Efficiencies determined from data, using tag and probe
- Dominating uncertainty from integrated luminosity ($\sim 4\%$)
Absolute and differential cross sections determined

Results in agreement with theory predictions

Also, good agreement between ee and μμ results!
Measure $A_{FB}$ using $Z \rightarrow \mu\mu$. High rapidities: enhancement of $A_{FB}$, increased sensitivity to $\sin^2\theta_{W,\text{eff}}$ (proportional to $\sin^2\theta_W$)

- Less ambiguity over choice of z-axis in forward region: quark tends to travel towards LHCb!

Get $\sin^2\theta_{W,\text{eff}}$ from measured $A_{FB}$

More to come (statistically limited!)

$\sin^2\theta_{W,\text{eff}} = 0.23142 \pm 0.00073$ (stat.) $\pm 0.00052$ (syst.) $\pm 0.00056$ (th.)

**Figure 3:** Difference between the di\(\sigma\)erence and the minimum $\chi^2$ obtained by comparing the final $A_{FB}^{(m\mu\mu)}$ measurements in data to $A_{FB}^{(\text{pred})}$ calculated using values of $\sin^2\theta_W$ ranging from 0.22 to 0.24, indicated by the crosses on the plot. A quadratic fit is used to determine the minimum value for $\sin^2\theta_W$ and the corresponding uncertainty, and is shown for the different centre-of-mass energies and the combination. The black dashed horizontal line corresponds to one unit of $\chi^2$ from the minimum and the intersecting $\sin^2\theta_W$ for the combination are indicated by the vertical red dashed lines.

**JHEP 11 (2015) 190**
Jet reconstruction at LHCb

- **Particle Flow** approach, with neutral recovery
  - Jets reconstructed using anti-$k_T$
  - $R = 0.5$
  - Calibration in data, using $Z \rightarrow \mu \mu +$ jets
  - Efficiency above 90% for jets with $p_T$ above 20 GeV/c
  - Jets reconstructed both online and offline!

JHEP01 (2014) 033
b and c jet tagging

- Require jets with a secondary vertex reconstructed close enough
  - light jet mistag rate < 1%, $\varepsilon_b \sim 65\%$, $\varepsilon_c \sim 25\%$
  - SV properties (displacement, kinematics, multiplicity,...) and jet properties combined in two BDTs.
  - $\text{BDT}_{bc|udsg}$ optimised for heavy flavour versus light discrimination.
  - $\text{BDT}_{b|c}$ optimised for b versus c discrimination.

![Figure 1: SV-tagger algorithm](image)

3.3 Performance in simulation

Figure 1 shows the SV-tagger BDT distributions obtained from simulated $W+\text{jet}$ events for each jet type. The distributions in the two-dimensional BDT plane of SV-tagged $b$, $c$, and light-parton jets are clearly distinguishable. The full two-dimensional distribution is fitted in data to determine the jet flavor content. However, to aid in comparison to other jet-tagging algorithms, a requirement of $\text{BDT}_{bc|udsg} > 0.2$ is applied to display the performance obtained from simulated events in Fig. 2. This requirement is about 90% efficient on SV-tagged ($b$, $c$) jets and highly suppresses light-parton jets. The ($b$, $c$)-jet efficiencies are nearly uniform for jet $p_T > 20$ GeV and for $2 < \eta < 4$. But are lower for low-$p_T$ jets and for jets near the edges of the detector. The misidentification probability of light-parton jets is less than 0.1% for low-$p_T$ jets and increases to about 1% at 100 GeV.

Figure 3 shows the ($b$, $c$)-jet efficiencies versus the mistag probability of light-parton jets obtained by increasing the $\text{BDT}_{bc|udsg}$ cut.

For the TOPO algorithm, in the trigger a BDT requirement is always applied; the requirement is looser when the SV contains a muon. In the LHCb measurement of the charge asymmetry in $b\bar{b}$ production [23], this same looser BDT requirement was applied to tag a second jet in the event. Figure 2 shows the performance of the TOPO algorithm, obtained from simulated events, for both the nominal and loose BDT requirements. The nominal trigger BDT requirement strongly suppresses $c$ and light-parton jets, with the misidentification probability of light-parton jets being 0.01% for low-$p_T$ jets. Such a strong suppression is required during online running due to output rate limitations.

The jet-tagging performance is measured in simulated events with one pp collision and two or more pp collisions and found to be consistent. The tagging performance is also studied in simulation using different event types, e.g. top-quark and QCD di-jet events, with only small changes in the tagging efficiencies and BDT templates observed for $(b, c)$ jets. The mistag probability of light-parton jets is found to be higher for high-$p_T$ jets in events that also contain $(b, c)$ jets. This is discussed in detail in Sec. 5.
Lepton + 2 b/c jets (I)

- Measurement using 2 fb\(^{-1}\) dataset
  - Events with high \(p_T\) isolated lepton (electron or muon) and two heavy flavour tagged jets (> 12.5 GeV/c)

- Strategy → Simultaneous 4D fit to \(\mu^+, \mu^-, e^+, e^-\) samples. Variables:
  - Di-jet mass
  - BDT(b|c) for both jets
  - MVA (uGB) to separate \(W+bb\) from \(tt\): Use topology and kinematic variables and sub-combination masses

- In the fit:
  - \(W+bb, W+cc\) and \(tt\) floated. Background fixed to theory
  - Nuisance parameters included in fit

Lepton + 2 b/c jets (II)

- Results: cross sections and theoretical predictions in LHCb fiducial region
  - NLO theory prediction: MCFM with PDF set CT10 interleaved with Pythia8
  - Uncertainties dominated by statistics!

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

\[
\begin{array}{l}
\sigma(W^+ + b\bar{b}) \\
\sigma(W^- + b\bar{b}) \\
\sigma(W^+ + c\bar{c}) \\
\sigma(W^- + c\bar{c}) \\
\sigma(t\bar{t})
\end{array}
\]

\[
\begin{array}{l}
\text{Data}_{\text{stat}} \\
\text{Data}_{\text{tot}}
\end{array}
\]

\[
\sigma \ [\text{pb}]
\]

\[ \text{Sample} \quad \text{Significance} \]

\[
\begin{array}{l|c}
\text{tt} & 4.9\sigma \\
W^+ + b\bar{b} & 7.1\sigma \\
W^- + b\bar{b} & 5.6\sigma \\
W^+ + c\bar{c} & 4.7\sigma \\
W^- + c\bar{c} & 2.5\sigma
\end{array}
\]


Higgs searched for in association to W or Z at 8 TeV

- Same samples as W+bb, tighter $p_T$ cuts on jets (20 GeV/c)
- Fix backgrounds to theory predictions
- Use CL$_s$ method to extract limits
- For H→bb, best limit at LHCb on a Higgs search, good prospects for the future
- For H→cc, exploratory study (first direct limit ever from experiment). Use BDT(b|c) to separate from H→bb
Brand new analysis: Measurement of the fraction of $p_T$ carried by $J/\psi$ when reconstructed within a jet

- Useful to study QCD phenomenology, e.g., $J/\psi$ isolated if produced directly in parton-parton scattering
- Analysis with 2016 data: Use of $J/\psi$ selected at trigger level! Then reconstruct jets and apply usual LHCb cuts
- Separate $J/\psi$ if produced from $b$ or prompt using pseudo-lifetime

$$z(J/\psi) \equiv p_T(J/\psi)/p_T(\text{jet})$$

$$\tilde{t} \equiv \Delta(PV - SV)m(J/\psi)/p_L(J/\psi)$$
J/ψ in jets (II)

- Unfolding of detector response: perform 2D unfolding in z and $p_T(j)$ (iterative Bayesian)
- Measurement: distribution of z, independent for detached and prompt J/Ψ

- Comparison to Pythia 8 predictions performed

Paper just published... but already produced reaction in the theory community!

Alternatives to Pythia provided, better qualitative description of prompt $z(J/\psi)$ achieved:

*arxiv:1702.05525*
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✦ Conclusions
Increasing interest in **direct searches** at LHCb

- Can be competitive in certain domains (specially low mass, low \( p_T \) objects)
- Two main types of searches

**Searches for exotic resonances in B/D decays**

**Direct production of new particles**


Exp. considerations

- Obvious disadvantage: LHCb collects less data than ATLAS/CMS and has worse acceptance for several searches
- But softer triggers (for instance, can trigger detached di-muons with $p_T \sim 1$ GeV/c), other advantages already mentioned
- In practice that means we can look into complementary phase space regions
- In general, sensitive to BSM predicting light exotic particles (prompt or detached). Examples: composite dark sector, dark photons or simplified models predicting that kind of resonances

Long lived particles

- Sensitivity to **long lived particles** (LLPs)

- **reconstructable** decay-lengths are:
  - within VELO: ideally ~50 cm (*standard* more like ~20 cm)
  - up to TT: ~200 cm
  - minimum detachment sensitivity ~ around $\tau$ lifetime
LLP to $\mu$+jets (I)

- **Signature**: single displaced vertex with several tracks and a high $p_T$ muon. Use Run-1 dataset
- Model: mSUGRA neutralino decaying to a lepton and two quarks
- LLP $m=[20-80]$ GeV/$c^2$, $\tau=[5-100]$ ps
- Background dominated by $bb$
  - tight selection + MVA classifier
  - Number of candidates from fit to LLP mass

* $R_{xy}$ = distance to beam axis
Result: no excess found: result interpreted in various models

Example: 125 GeV Higgs decay

Rejecting BR(H→χχ)>10% down to m_χ = 30 GeV/c^2, τ_χ = 5 ps
**Signature:** single displaced vertex with two (b-) jets

- Model: Hidden valley V-pions from SM Higgs decay
- Use Run 1 dataset, trigger on displaced vertex.

**Selection:**
- Find two associated jets, quality requirement on jets, di-jet pointing
- Material veto + selection optimised as a function of $R_{xy}$
- Main remaining background: QCD
- Signal from di-jet mass fit in 6 bins of $R_{xy}$
Again, no excess found

- Tested the region: $m_n = [25-50]$ GeV, $\tau = [2-500]$ ps

Compatible search in Eur. Phys. J. C (2016) 76664 (look for both LLPs in the same event)
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SMOG system

- **SMOG**: System for Measuring the Overlap with Gas

  - SMOG device used initially for beam-gas imaging (integrated luminosity measurement)
  - Done by injecting noble gas into the interaction region: He, Ne, Ar.
  - **Fixed target physics** in pA and PbA configurations
  - Physics: Strangeness production, cosmic rays physics and cosmology,....
p/\bar{p} ratio in astroparticle experiments is sensitive probe to dark matter in the Universe

- Current data seems compatible with background from standard sources
- Largest uncertainty from antiproton production cross-section: extrapolated from pp and p+C
- No data yet on pHe \rightarrow \bar{p} process
Dataset and selection

- **Collisions of 6.5 TeV beam on He**, nucleon-nucleon $\sqrt{s} = 110.5$ GeV. 0.4 nb$^{-1}$ data acquired in 2016

- **Selection**: good quality PVs, suppress material interactions and secondaries

- Particle identification from combined detectors response. Fraction of anti-protons via **2D PID fit**

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LHCb Preliminary
Results

- No precise determination of gas density: **Normalisation** with elastic $pe$ scattering with He atoms
  - Signature: single low-momentum electron in the detector

- **Results:**
  - 33.7 million reconstructed $pHe$ collisions for about 1.4 million antiprotons
  - Double differential cross-section in $p$ and $p_T$
  - Spectrum in agreement with EPOS MC but absolute value around factor of 50% larger
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Conclusions and prospects

✦ LHCb: general purpose detector in the forward region!
  ➔ SM physics and top
  ➔ Direct searches
  ➔ Fixed target physics

✦ Much more to come in Run II and beyond
  ➔ Will take \( \sim 5 \text{ fb}^{-1} \) in Run II (3 fb\(^{-1}\) in Run I)
  ➔ Increased cross sections and better acceptance for many of the physics presented
  ➔ After LS2: **LHCb upgrade**. 50 fb\(^{-1}\) of data expected with purely software trigger! 300 fb\(^{-1}\) possible?
Thank you!
Introduction

Electroweak, top and exotics physics at LHCb: present and future

X. Cid Vidal

Introduction to LHCb

Electroweak physics
Z and W production at LHCb
Z+X

Exotics physics
Limits on H₀!⧷+⧷
H₀ decays to long-lived particles

Future
Prospects on EW
How about top?
Towards H₀!b¯b

Conclusions

LHCb complementarity

• LHCb can offer unique coverage at the LHC
• However b physics imposes dealing with lower luminosities

2010: 37 pb
2011: 1 fb
2012: 2 fb

• As a benefit, very stable conditions in terms of trigger/luminosity (luminosity leveling)
Main pp datasets (LHC Run I and Run II)

- 1 fb\(^{-1}\) at \(\sqrt{s}=7\) TeV (2011)
- 2 fb\(^{-1}\) at \(\sqrt{s}=8\) TeV (2012)
- 0.3 fb\(^{-1}\) at \(\sqrt{s}=13\) TeV (2015)
- 1.7 fb\(^{-1}\) at \(\sqrt{s}=13\) TeV (2016)
Integrated luminosity determination

- Most precise at the LHC in Run 1! ($\sim 1\%$)

- Bunch intensity ($N_1N_2$) measured by LHC instrumentation (uncertainties: $\sim 0.3\%$).

- Overlap integral depends on beams properties (e.g. beam width, position, angle, shape)

- Determined with 2 independent methods:
  - Classic “van der Meer scan” (VDM) used by all 4 LHC experiments
  - Beam-gas imaging (BGI): new method exclusive to LHCb

\[ L = f \cdot N_1N_2 \cdot \text{Overlap} \]

*2014 JINST 9 P12005*
Discrepancy b/t data and theory in the same rapidity bin as LHCb

CMS-PAS-SMP-15-011
Absolute and differential cross sections

**Theory references**

Motivation: measuring the electroweak mixing angle. Is this process dependent (not in SM!)?

Asymmetry definition

\[ A_{FB} \equiv \frac{N_F - N_B}{N_F + N_B} \]

where
- \( N_F \) : number of forward decays
- \( N_B \) : number of backward decays

\( \cos \theta^* > 0 \)

\( \cos \theta^* < 0 \)

The raw asymmetry \( A_{FB,\text{raw}} \), is corrected for:

- Efficiency of trigger, track reconstruction and muon identification (almost negligible).
- Detector mis-alignment curvature/momentum bias that shifts the Z peak.

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The true (at proton level) asymmetry $A_{FB}$ is obtained from the measured asymmetry through a Bayesian unfolding technique.

Systematic error dominated by curvature/momentum (PDFs uncertainties for $\sin^2 \theta_{W,\text{eff}}$)

$A_{FB}$ at 7 and 8 TeV compared to theory:

![Graphs showing $A_{FB}$ as a function of dimuon invariant mass for data compared to SM predictions for (left) $\sqrt{s} = 7$ TeV and (right) $\sqrt{s} = 8$ TeV. The SM predictions are calculated using POWHEG interfaced with PYTHIA for parton showering with the world average value for $\sin^2 \theta_W = 0.2315$. The data include both statistical and systematic uncertainties, and the SM predictions include the theoretical uncertainties described in Sec. 5.](image-url)
Forward-backward asymmetry in $Z \to \mu\mu$ (III)

- High rapidities: enhancement of $A_{FB}$, increased sensitivity to $\sin^2\theta_{W,\text{eff}}$ (proportional to $\sin^2\theta_W$)

- Less ambiguity over choice of z-axis in forward region: quark tends to travel towards LHCb!

- Simulation samples generated with different values of $\sin^2\theta_{W,\text{off}}$

- Compare simulations with measured $A_{FB}$, using $\chi^2$

- More to come (statistically limited!)

\[
\sin^2\theta_{W,\text{eff}} = 0.23142 \pm 0.00073 \text{ (stat.)} \pm 0.00052 \text{ (syst.)} \pm 0.00056 \text{ (th.)}
\]
Examples of fit projection

- $W+bb$, $W+cc$ and $tt$ floated. Background fixed to theory
- Nuisance parameters included in fit

Projection in $\mu^+$ the sample

Projection in $e^+$ the sample
Lepton + 2 b/c jets at $\sqrt{s} = 8$ TeV (II)

- **Examples of fit projection**
  - $W + bb, W + cc$ and $tt$ floated. Background fixed to theory
  - Nuisance parameters included in fit

Projection in $\mu^-$ the sample  
Projection in $e^-$ the sample

Examples of fit projection

- $W+bb, W+cc$ and $tt$ floated. Background fixed to theory
- Nuisance parameters included in fit

Lepton + 2 b/c jets at $\sqrt{s} = 8$ TeV (II)

Projection in $\mu$ the sample

Projection in $e$ the sample

Proton PDFs

\[ \sigma = \int x f(x, x_1, Q^2) x f(x, x_2, Q^2) \hat{\sigma} \, dx_1 \, dx_2, \quad Q^2(x) = e^{\pm 2y x^2 s} \]
Unfolding of detector response:

- correct for $z$ resolution and $p_{T}(j)$ resolution, $\sim 20 - 25\%$
- perform 2D unfolding in $z$ and $p_{T}(j)$ (iterative Bayesian)
Recasting result

- This result has just been recast to look for sterile neutrinos!

- arxiv just came out!

- 95% confidence level exclusion plot

- world best limit for masses in the 5-10 GeV/c$^2$ range. Excellent prospects!
In general, sensitive to BSM predicting light exotic particles (prompt or detached). Examples

**Dark photons**

- massive dark sector photon $A'$ couples to SM photon via kinetic mixing
- signature: resonance in (prompt or displaced) di-lepton spectrum
- di-muon direct search [arXiv:1603.08926]
- look for $A' \rightarrow e^+ e^-$ in $D^{*0} \rightarrow D^0$ $A'$ decays [arXiv:1509.06765]
**Simplified models** with spin-0 di-muon light resonances

- Connects directly with hints from outer-space experiments (Fermi-LAT, AMS, ...)
- Includes dark-photons but also other simple models, such as THDMII, NMSSM
- In [arXiv:1601.05110], recast using small fraction of LHCb’s Run 1 data
- Models with a **composite dark sector**
  
  - parton shower in the dark sector followed by displaced decays of dark pions back to SM jets
  - **Emerging jets** composed of displaced tracks and many different vertices within the jet cone
  - LHCb could also measure exclusively new particles (e.g., dark pions)

[arXiv:1502.05409]
Can also use RICH to look for new exotic particles!

- Likelihood to separate particles according to their masses
- In this case, separate Exotic heavy particles from Drell-Yan muons