# Forward and High $p_{\mathrm{T}}$ Physics at HL-LHCb

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## outline

# introduction

# what have we done so far?

- forward and high-$p_{\mathrm{T}}$ physics covers a broad range of studies
  - electroweak and top physics
  - direct searches for exotic particles / Higgs
  - central exclusive production and soft qcd (minimum bias / underlying event)
- we've made a large number of measurement in this area in Runs 1 and 2
- most precise LHC measurements (at the time) of $W$ and $Z$ production and $\sin^2\theta_{\mathrm{W}}$
- number of measurements with jets, $W/Z+$jets, top production in Runs 1 and 2
- range of searches (LLPs, Dark Photons, $H \to c\bar{c}$ etc...)
- while CEP and Soft QCD are unlikely to benefit from Upgrade II*, significant potential in other areas

  *although maybe with special runs?

# what can we do at the HL-LHC?

**8. Forward and high-$p_{\mathrm{T}}$ physics**

8.1 Top physics in the forward region

8.2 Gauge-boson production and implications for PDFs

8.3 Measurement of the effective weak mixing angle

8.4 Prospects for $W$-mass measurement

8.5 Measurement of Higgs decays to $c\bar{c}$

8.6 Searches for prompt and detached dark photons

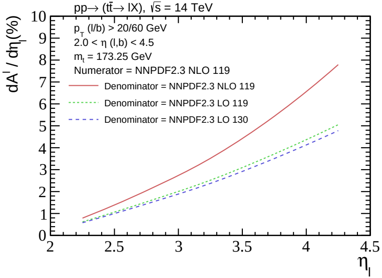
8.7 Searches for semileptonic and hadronic decays of long-lived particles

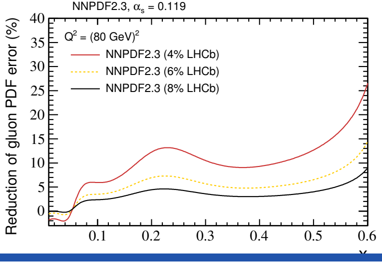
# top physics in the forward region

[*Phys. Rev.* (2015) D91:p. 054029]

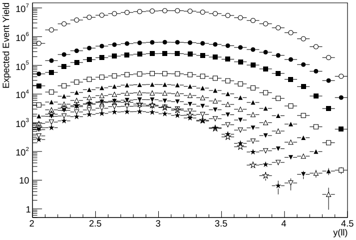
[*JHEP* (2014) 02:p. 126]

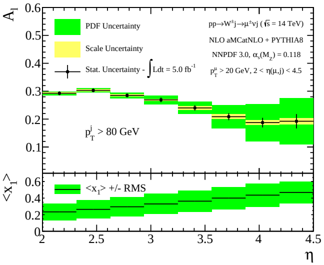
- top physics at LHCb is sensitive to new physics, probes gluon PDF at higher $x$ values than central region, and is more sensitive to charge asymmetry
- can extrapolate the Run 1 $\mu b$ and Run 2 $\mu e b$ analyses to HL-LHC
  - assume some improvements (selection, $b$-tagging efficiency)
- expect $\sim 200k$ events in $\mu b$ channel
  - statistical precision at the per-mille level, need to control backgrounds
  - can make differential measurements of asymmetry versus pseudo-rapdity
- expect >10k events in $\mu e b$ channel
  - statistical precision of $\sim 1\%$ on cross-section and asymmetry
  - high purity offers opportunity to make $< 5\%$ precision measurement to constrain gluon PDFs
  - can make asymmetry measurements in a pure environment
- maybe potential in the $\ell bb$ channel too

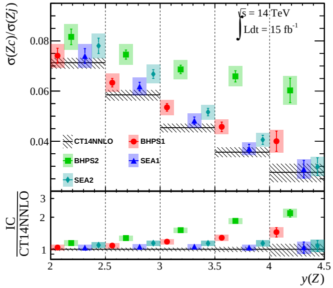


# $W/Z$ production and PDFs



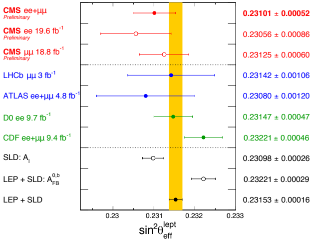



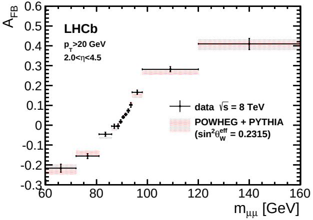

- extra statistics at the HL-LHC will allow us to get more precision on PDFs at large-$x$
- not 100% clear inclusive $W$ and $Z$ crosss-section measurements will benefit hugely from increase in statistics
  - but maybe more precision in very forward region and double-differential distributions?
  - can probe high-mass Drell-Yan at kinematic limit to high precision
- studies exist outlining our potential to constrain the large-$x$ $d$ PDF (with $W + jet$) [*Phys. Rev.* (2016) D93:p. 014008] and intrinsic charm (with $Z + c$) [*Phys. Rev.* (2016) D93:p. 074008]

# $A_{\mathrm{FB}}$ and $\sin^2\theta_W$

**CMS-PAS-SMP-16-007**

**[*JHEP* (2015) 11:p. 190]**

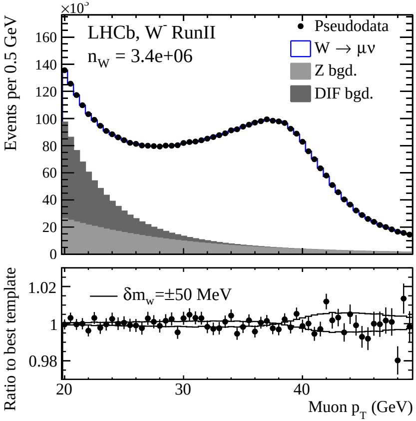



- two most precise measurements of $\sin^2\theta_{\mathrm{W}}$ differ by $3\sigma$
- LHCb is most sensitive at the LHC due to our forward acceptance
- Run 1 measurement was limited by statistics ($\delta_{\mathrm{stat.}} = 75 \cdot 10^{-5}$)
  - extrapolating the statistical precision to the end of Run 5 gives us $5 \cdot 10^{-5}$
  - extra statistics will also improve systematics, e.g. for momentum scale calibration
- **constraining PDFs will be crucial to making a precise measurement**
- will benefit from improved analysis techniques (in-situ PDF constraints, event weighting)
- adding electrons will be important to improve precision of measurement

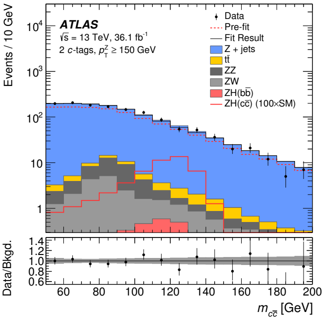
# $W$-mass Measurement

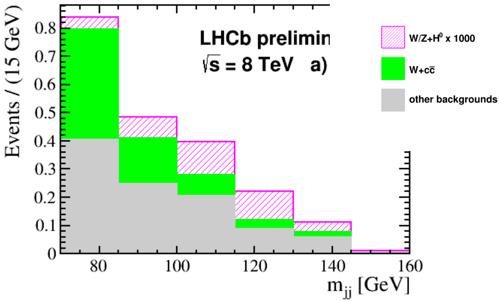
[*Eur. Phys. J.* (2015) C75:p. 601]




- LHCb can contribute to LHC-wide effort to measure the $W$ mass
  - exploit anti-correlation of PDF uncertainties in central and forward region
- huge samples of $Z$ bosons available at the HL-LHC for calibration / tuning of generators
- detector improvements may also help with precision
- difficult to project without existing measurement
- again, electrons can help improve precision

# $H \to c\bar{c}$

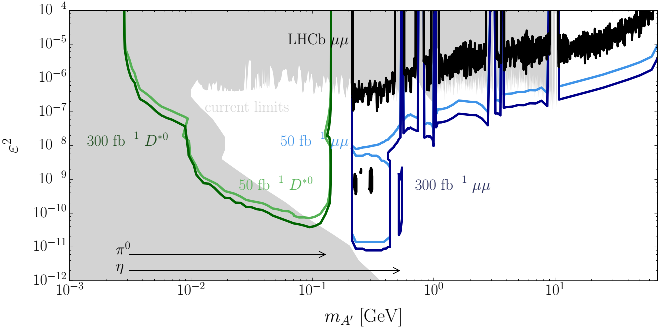



- ATLAS limit ∼100 times the SM with $36.1\,\text{fb}^{-1}$ at 13 TeV [[1802.04329 [hep-ex]] ]
- LHCb limit ∼8000 times the SM with $2.0\,\text{fb}^{-1}$ at 8 TeV [LHCb-CONF-2016-006 ]
- extrapolating current LHCb limit would give ∼50 SM with no changes to analyses
- however, we can improve...
  - significantly increase di-jet tagging efficiency (2% -> 30%)?
  - improve electron reconstruction and $b/c$-jet separation?

could expect as low as ∼4xSM with HL-LHC

# dark photons

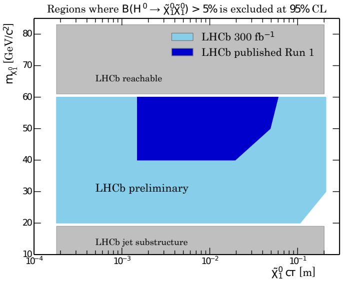


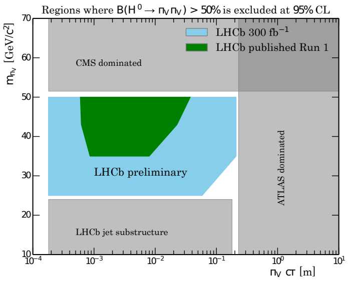

- Dark Photons at LHCb relies on vertex resolution, PID and turbo selection
- performed search for prompt and displaced in dimuon channel with Run 2 data
- search also underway in $D^{*0} \to D^0 e^+ e^-$ decays
- detailed studies already performed by Mike, Phil et al. ([*Phys. Rev.* (2015) D92:p. 115017],[*Phys. Rev. Lett.* (2016) 116:p. 251803] )
- 300 fb$^{-1}$ of data offers to opportunity to significantly improve LHCb's reach

# LLPs

[*Eur. Phys. J.* (2017) C77:p. 812]
[*Eur. Phys. J.* (2017) C77:p. 224]

- performed searches for long lived particles in muon + jets and di-jet final states in Run 1
- limits competitive with ATLAS/CMS despite factor 10 less luminosity



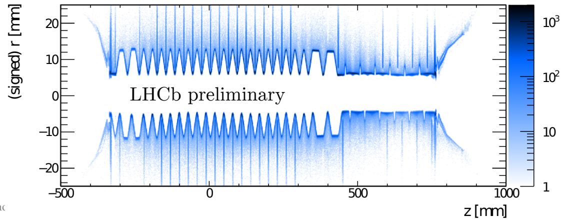

- extrapolate run 1 limits on displaced (left) $\mu$+jets and (right) di-jets
  - scale signal and background to 14 TeV
  - conservative estimates on detector performance, trigger, material interactions etc...
- will produce unique and complementary limits to those produced by ATLAS/CMS

# detector and running conditions

# forward and high-$p_{\mathrm{T}}$ physics with the upgraded detector

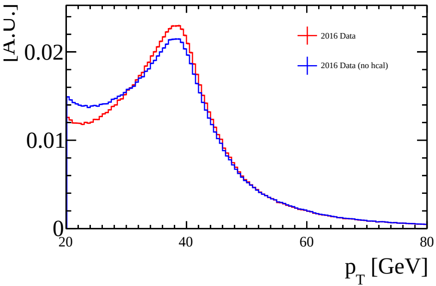
- of course, this will not be the same detector or conditions...
- how does the physics program cope with the changes?
  1. improvements in the VELO and tracking/ resolution ✓
  2. removal of RF foil / reduction of material ✓
  3. extended ECal dynamic range? ✓
  4. higher pile-up ✗
  5. no HCal? ✗

# tracking upgrades / material




- improved IP resolution and removal of RF foil will benefit analyses
  - more efficient flavour tagging of jets
  - reduced backgrounds from material interactions for LLP searches
- magnet-stations could benefit LLP searches (disappearing tracks?)
- improved momentum resolution can improve sensitivity to $\sin^2\theta_{\mathrm{W}}$
  - one of the largest systematic uncertainties in Run 1 analysis
- any increased (higher) $\eta$ coverage could benefit $W$ mass and $A_{\mathrm{FB}}$ measurements and top measurements

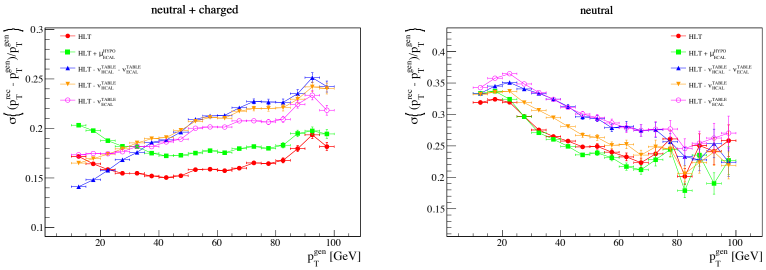
# $W$ and $Z$ Physics with no Hcal




- $W \to \mu\nu$ at LHCb may be the simplest final state measured at the LHC
  - a single muon, sensitive to any background producing a high $p_T$ muon or misidentified hadron
- the analysis requires low energy deposits in the Hcal and Ecal to reduce punchthrough
  - removing the Hcal energy will result in an increase in background

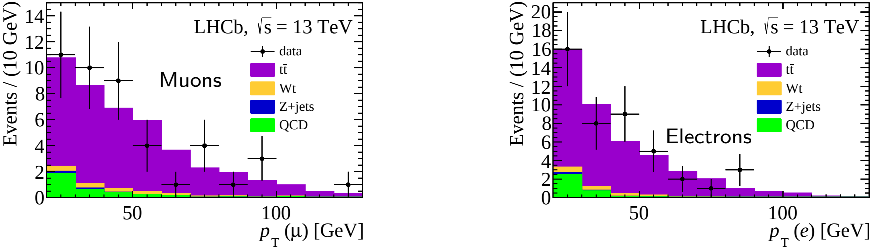
- Hcal is also used in the high $p_T$ electron id criteria
  - removing it increases background by $\sim 50\%$ for $Z \to ee$
- **could be difficult to deal with for electron final states...**

# Jet Physics with no Hcal




- for jet physics, no Hcal means less information on neutrals for the jet inputs
  - compare baseline with no HCal energy recovery
- clearly will result in a degradation in jet energy resolution
  - hard to quantify, number of competing effects
- will have an effect for long-lived particle searches, $H \to c\bar{c}$, etc..

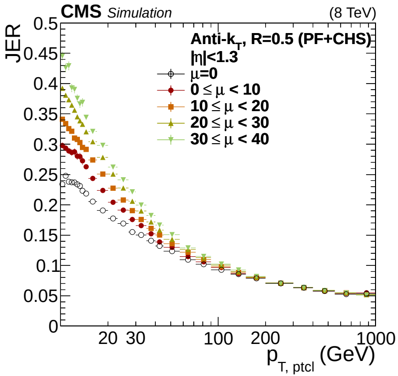
# Extended Ecal Dynamic Range




- saturation of Ecal readout for Run 1 limits a number of QEE analyses using electrons
  - lower efficiency, larger backgrounds, poorer momentum resolution
- improvements at the HL-LHC would have a number of benefits
- electrons can add another factor of 2 statistics to $\sin^2\theta_W$ and top asymmetry measurements
- can recover the 20% of events we lose to Bremsstrahlung for top dilepton final state or $WW$
- improved jet resolution
- could add $\gamma + c$ to $Z + c$ to probe intrinsic charm

# higher pile-up

[*JINST* (2017) 12:P02014]




- moving from $\sim 2$ to $\sim 50$
- don't expect that leptonic final states (e.g. $W/Z$) will be heavily affected by pile-up
- however, jet energy resolution will be impacted
  - neutral component most affected
- possibly small effect at high jet $p_T$, but could be significant for lower $p_T$ jets, e.g. for LLP searches
  - could consider "charged" jets only

# conclusions

## conclusions

- the extra statistics brings a lot of potential for forward and high-$p_T$ physics
  - top physics, precision EW physics, searches, etc....
- detector improvements will help high $p_T$ momentum resolution and jet tagging
  - high $p_T$ electrons would significantly improve a number of analyses!
- however, jet performance is a bit unclear, needs study
  - can affect LLP, $H \to c\bar{c}$ and top programs

# backup