

Perspectives for forward physics with electroweak bosons at LHCb

Philip Ilten
on behalf of the LHCb Collaboration

Massachusetts Institute of Technology

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PHYSICS AT THE HIGH-LUMINOSITY LHC



Luminosity and Detector

- projected luminosity (see V. Vagnoni (2015) HL-LHC)

LHC era				HL-LHC era	
Run 1(a) 2011	Run 1(b) 2012	Run 2 2015 - 2018	Run 3 2020 - 2022	Run 4 2025 - 2028	Run 5 2030 - ?
1 fb^{-1}	2 fb^{-1}	5 fb^{-1}	15 fb^{-1}	23 fb^{-1}	54 fb^{-1}

- LHCb upgrade during LS 2
 - LHCb-PUB-2014-040**
 - replacement of ring imaging Cherenkov detectors
 - replacement of tracking detectors
 - full software trigger**, see **LHCB-TDR-016**
 - currently limited by hardware readout at 1 MHz
 - upgrade will read out entire detector at 40 MHz
- no dedicated electroweak boson performance studies (yet)
 - assume Run 1 performance for EWK objects
 - trigger on anything *reasonable*

Run 1 Analyses

- excellent constraints on low- x and high- x PDFs
- forward tests of pQCD, precision measurements

measurement	publication
$W[\mu] + j, c, b$ ratios at 7 and 8 TeV	LHCb-PAPER-2015-021
$Z[\mu\mu]$ cross-section at 7 TeV	LHCb-PAPER-2015-001
$Z[ee]$ cross-section at 8 TeV	arXiv:1503.00963 [hep-ex]
$Z[ee]$ cross-section at 7 TeV	JHEP 1302 (2013) 106
$Z[\mu\mu] + b$ cross-section at 7 TeV	JHEP 1501 (2015) 064
$W[\mu]$ cross-section at 7 TeV	JHEP 1412 (2014) 079
$Z[\mu\mu]$ cross-section in proton-lead	JHEP 1409 (2014) 030
$Z[\mu\mu] + D$ cross-section at 7 TeV	JHEP 1409 (2014) 030
$Z[\mu\mu] + j$ cross-section at 7 TeV	JHEP 1401 (2014) 033
$Z[\tau\tau]$ cross-section at 7 TeV	JHEP 1301 (2013) 111
$H[\tau\tau]$ limits at 7 TeV	JHEP 1305 (2013) 132

Run 4+ Analyses

- inclusive W and Z
- di-boson production
- top and $W + b$
- Higgs

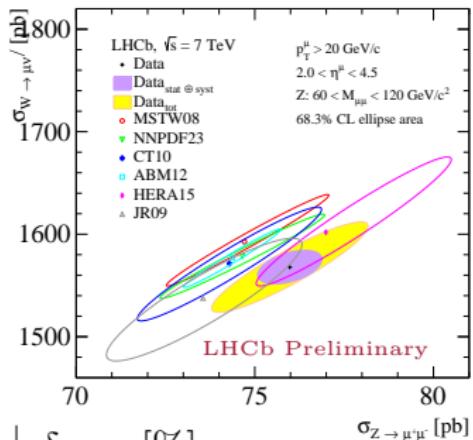
Assumptions

- physics objects with $p_T > 20 \text{ GeV}$ and $2 < \eta < 5$
 - leptons (ℓ) are electrons and muons
 - jets are anti- k_T with $R = 0.5$
 - Z -boson mass within $60 < m < 120 \text{ GeV}$
- theory predictions are performed with MC@NLO at NLO
 - fiducial definitions above used
 - **these are estimates!**
- detector performance similar to Run 1
 - lepton and jet reconstruction $\approx 95\%$
 - b -jet tagging $\approx 65\%$, c -jet tagging $\approx 25\%$
 - photon reconstruction $\approx 50\%$
 - hadronic τ reconstruction $\approx 60\%$ (assumed from CMS and ATLAS), branching $\approx 65\%$
 - **100% trigger efficiency!**
- 150 fb^{-1} of integrated luminosity

$Z[\ell\ell]$ Run 1

LHCb-PAPER-2015-001

- muon channel, 7 TeV, 1 fb^{-1}
- 5.8×10^4 events selected
- 18 bins of rapidity, 14 bins of p_T
- statistical $\approx 2\%$, systematic $\approx 1\%$



source	$\delta_{\sigma(Z)} [\%]$
trigger efficiency	0.07
identification efficiency	0.23
tracking efficiency	0.53
FSR	0.11
purity	0.22
global event cut efficiency	0.26

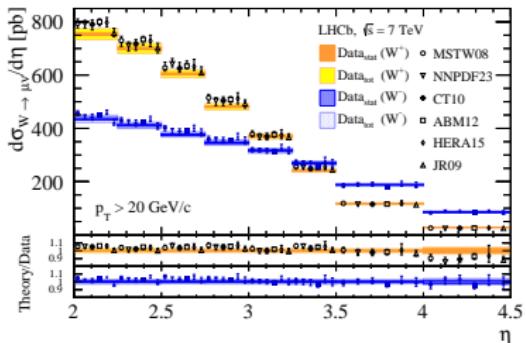
Z[$\ell\ell$] Run 4+

- expected cross-section 4.7×10^5 fb
 - $\rightarrow 6.4 \times 10^7$ events
- keep the same binning of 18 bins
 - statistical precision $\approx 0.05\%$
- keep the same statistical precision of 2%
 - single differential: ≈ 25000 bins (y)
 - double differential: ≈ 160 bins (y, p_T)
 - triple differential: ≈ 30 bins ($y, p_T, ?$)
- FSR uncertainty currently at 0.11%, more important at 14 TeV
- all other uncertainties statistically driven from data

$W[\ell]$ Run 1

JHEP 1412 (2014) 079

- muon channel, 7 TeV, 1 fb^{-1}
- 8.1×10^5 events selected
- 8 bins of pseudo-rapidity
- statistical $\approx 1\%$, systematic $\approx 2\%$



source	$\delta_{\sigma(W^+)} [\%]$	$\delta_{\sigma(W^-)} [\%]$
template shape	0.28	0.39
template normalization	0.10	0.10
reconstruction efficiency	1.20	1.20
selection efficiency	0.33	0.32
acceptance and FSR	0.18	0.12
luminosity	1.17	1.17

$W[\ell]$ Run 4+

- expected cross-section 7.9×10^6 fb
 - $\rightarrow 4.3 \times 10^8$ events
- keep the same binning of 8 bins
 - statistical precision $\approx 0.01\%$
- keep the same statistical precision of 1%
 - single differential: ≈ 40000 bins (η)
 - double differential: ≈ 200 bins (η, p_T)
 - triple differential: ≈ 40 bins ($\eta, p_T, ?$)
- limited by current theory driven systematic of $\approx 0.3\%$
- reconstruction efficiency systematic may not reduce as expected

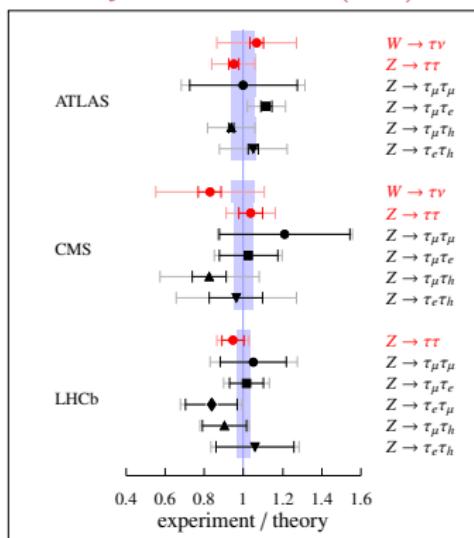
$W[\tau]$ Production

- interest from LEP measurements, [hep-ex/0511027](#)

$$\frac{2\sigma(W[\tau])}{\sigma(W[\mu]) + \sigma(W[e])} = 1.077 \pm 0.026$$

- looking at $W \rightarrow \tau[\mu]$ in Run 1 (no trigger for hadronic τ)
 - systematic uncertainty will not be competitive
- expected cross-section 4.0×10^6 fb
 - $\rightarrow 1.6 \times 10^6$ hadronic τ events
- systematic uncertainties
 - hadronic τ reconstruction, partially driven by $Z \rightarrow \tau\tau$ statistics
 - FSR corrections
 - hadronic τ acceptance

Nucl. Phys. Proc. 253-255 (2014) 163



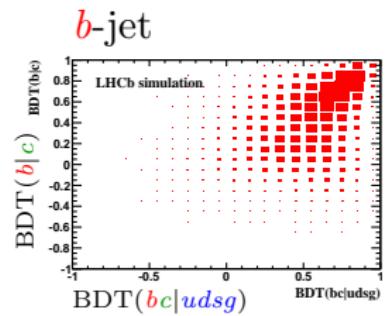
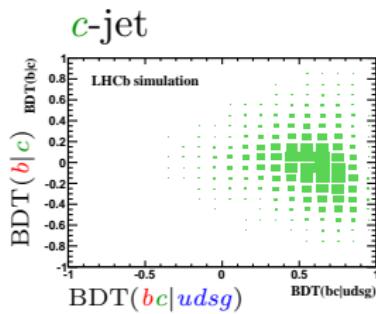
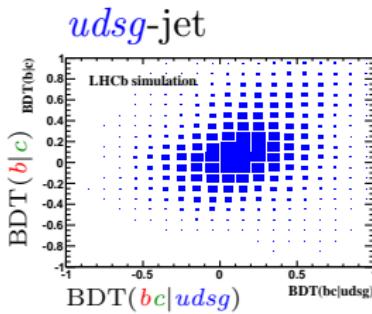
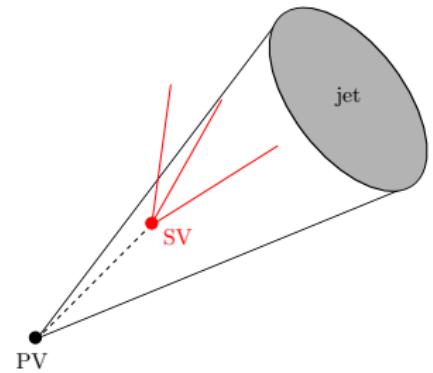
WW , WZ , ZZ , $W\gamma$, and $Z\gamma$ Production

- no Run 1 di-boson measurements
- expected $WW[\ell, \ell]$ cross-section 300 fb
 - $\rightarrow 2.0 \times 10^4$ events ($[e, \mu]$ final state)
 - clean signature, precision measurement
 - backgrounds primary systematic uncertainty ($Z \rightarrow \tau\tau[e, \mu]$)
- expected $WZ[\ell, \ell, \ell]$ cross-section 16 fb
 - $\rightarrow 2000$ events
- expected $ZZ[\ell, \ell, \ell, \ell]$ cross-section 3.1 fb
 - $\rightarrow 380$ events
- $V\gamma$ measurements difficult with current detector (ECAL response)
- expected $W\gamma[\ell, \gamma]$ cross-section 3700 fb
 - $\rightarrow 2.6 \times 10^5$ events
- expected $Z\gamma[\ell, \ell, \gamma]$ cross-section 780 fb
 - $\rightarrow 5.6 \times 10^4$ events

Jet Tagging Run 1

arXiv:1504.07670

- n -body secondary vertex algorithm
- require vertex flight direction within jet, $\Delta R(\text{SV}, \text{jet}) < 0.5$
- two BDTs
 - $\text{BDT}(\textcolor{red}{b}\textcolor{blue}{c}|\textit{udsg})$: separates \textit{udsg} -jet from b, c -jet
 - $\text{BDT}(\textcolor{red}{b}|\textcolor{blue}{c})$: separates b -jet from c -jet

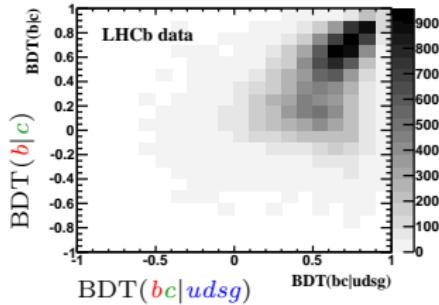


Jet Flavor Run 1

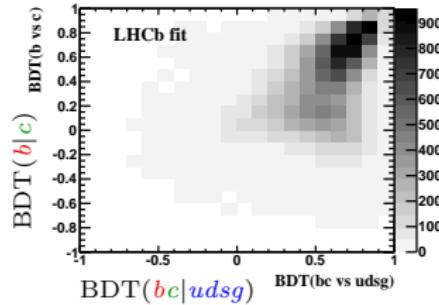
arXiv:1504.07670

b-enhanced ($B + \text{jet}$) data sample

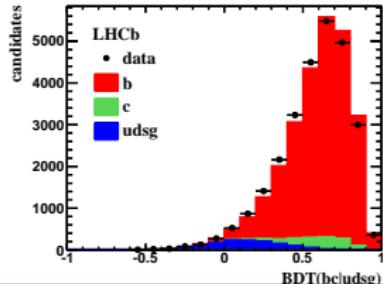
data distribution



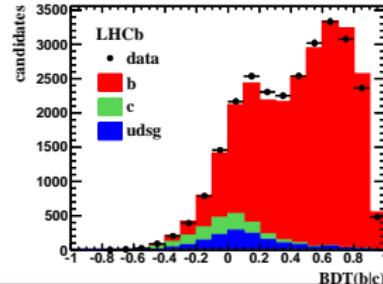
fit distribution



BDT($bc|udsg$) proj.



BDT($b|c$) proj.



Jet Tagging Run 4+

arXiv:1504.07670

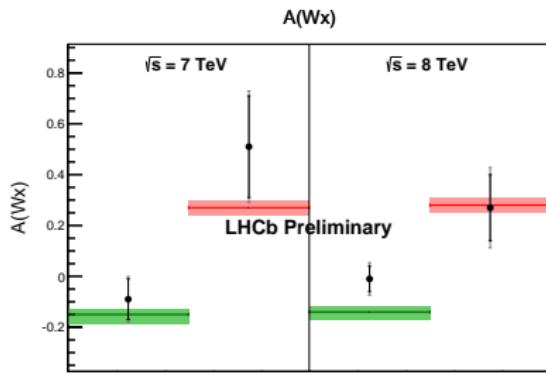
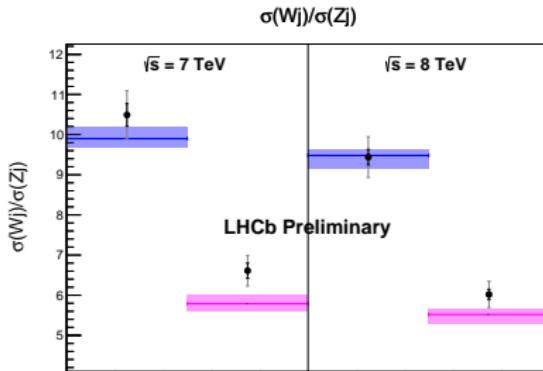
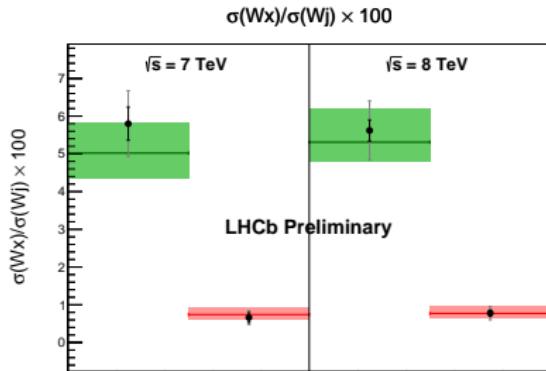
source	$\delta_{\varepsilon(b)} [\%]$	$\delta_{\varepsilon(c)} [\%]$
BDT templates*	≈ 2	≈ 2
<i>udsg</i> -jet large IP component*	≈ 5	$\approx 10 - 30$
hadron-as-muon (hardest- μ only)	5	20
gluon splitting	1	1
total (combined fit)	≈ 10	≈ 10

*dependent on jet type and p_T

- possible inclusion of s -tagging
 - utilize RICH information and vertexing
- primary uncertainty from χ^2_{IP} fit (denominator of efficiency)
 - not dependent on statistics
 - s -tagging development could reduce this
- work needed for precision measurements

$W + j, b, c[\mu]$ Run 1

LHCb-PAPER-2015-021



- points data (total, stat)
- fills MCFM NLO theory
- CT10 (scale + PDF)
- green $W + c\text{-jet}$
- red $W + b\text{-jet}$
- blue $W^+ + \text{jet}$
- magenta $W^- + \text{jet}$

$W + j, b, c[\ell]$ Run 4+

LHCb-PAPER-2015-021

source	$\frac{\sigma(Wb)}{\sigma(Wj)}$	$\frac{\sigma(Wc)}{\sigma(Wj)}$	$\frac{\sigma(Wj)}{\sigma(Zj)}$	$\mathcal{A}(Wb)$	$\mathcal{A}(Wc)$
(b, c)-tag efficiency	10%	10%	—	—	—
isolation templates	10%	5%	4%	0.08	0.03
top	13%	—	—	0.02	—
SV-tag BDT templates	5%	5%	—	0.02	0.02
$Z \rightarrow \tau\tau$	—	3%	—	—	—

- expected $W + j[\ell, j]$ cross-section 9.4×10^5 fb
 - $\rightarrow 1.3 \times 10^8$ events
- expected $W + c[\ell, c]$ cross-section 6.9×10^4 fb
 - $\rightarrow 2.3 \times 10^6$ events
- expected $W + b[\ell, b]$ cross-section 7300 fb
 - $\rightarrow 6.4 \times 10^5$ events
 - 10^2 bins $\rightarrow \approx 1\%$ statistical uncertainty
- excellent potential for constraints on s and b PDFs

Top Production Run 4+

- Run 1 analysis coming soon!
- lepton and b -jet final state
 - expected $t\bar{t}[\ell, b]$ 2600 fb
 - 2.5×10^5 events
 - expected $t[\ell, b]$ (t -channel) 1800 fb
 - 1.5×10^5 events
 - expected $t[\ell, b]$ (s -channel) 210 fb
 - 1.8×10^4 events
 - expected $Wt[\ell, b]$ 60 fb
 - 5300 events
 - expected $Wt[\ell, \ell, b]$ 20 fb
 - 1600 events
 - expected $t\bar{t}[\ell, \ell, b, b]$ 317 fb
 - 1.6×10^4 events

V_{ts} Run 4+

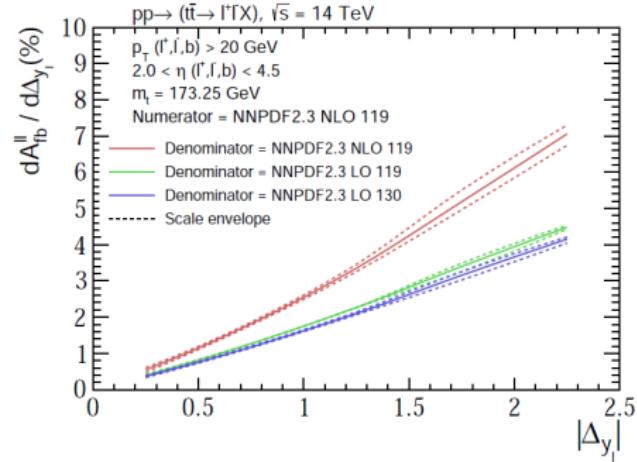
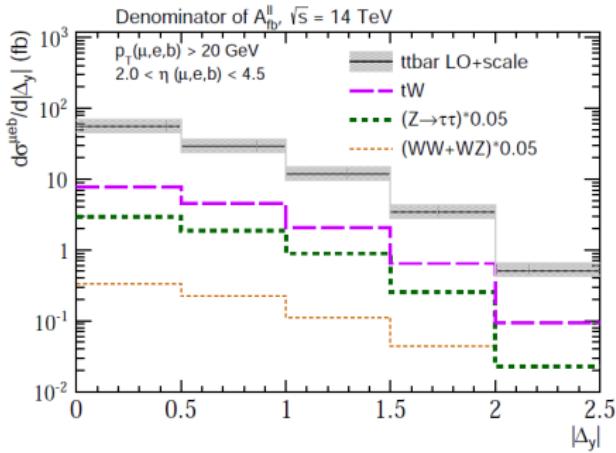
- best indirect (single) result from precision $B_s^0 - \bar{B}_s^0$ measurement by LHCb, **New J. Phys.** **15** (2013) 053021
 - $|V_{ts}| = (40.0 \pm 2.7) \times 10^{-3}$
- no tree level measurements (yet)
- look for s -channel production with lepton and 2 b -jet final state
 - requires s -jet tagging with excellent b -jet rejection
 - needs further investigation
- expected $t[\ell, b, b]$ (s -channel) 150 fb
 - assume 10% s -tag efficiency, 0.1% fake rate
 - 50 s -tagged signal, 10 mis-tagged b -jet events
 - ignoring other backgrounds ...

Top Asymmetry Run 4+

arXiv:1409.8631

- use electron, muon, and b -jet final state

$$\frac{dA_{\text{FB}}^{\ell\ell}}{d|\Delta_y|} = \frac{(d\sigma(\mu eb, \Delta y > 0) - d\sigma(\mu eb, \Delta y < 0))/d\Delta y}{d\sigma(\mu eb)/d\Delta y}$$

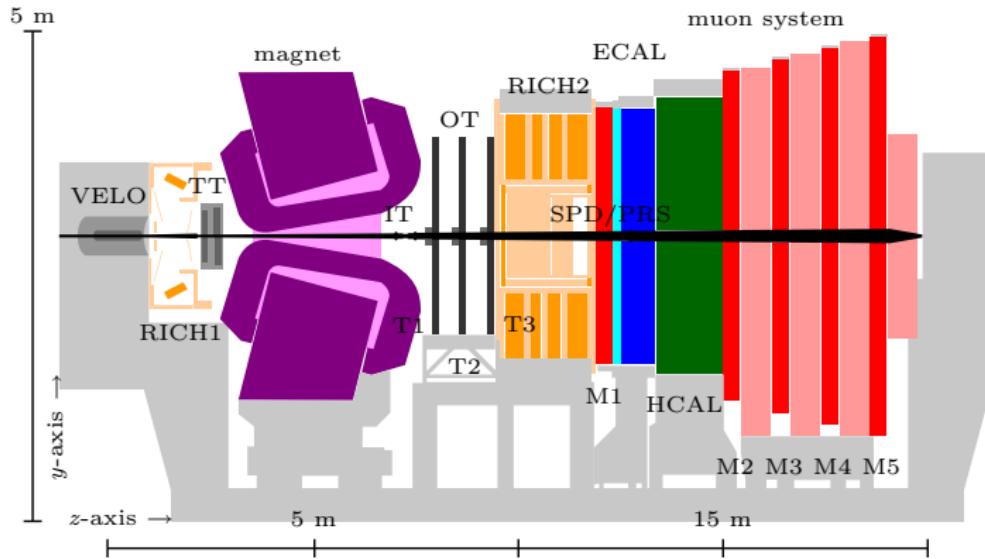


Higgs Production Run 4+

- no Run 1 Higgs observations from LHCb (only limits)
- possibility of $H \rightarrow c\bar{c}$ via VBF or associated vector?
- four-lepton modes still largely out of reach
- expected $H[b, b, j]$ (VBF) cross-section 70 fb
 - $\rightarrow 3800$ events
- expected $H[\tau, \tau, j]$ (VBF) cross-section 7.9 fb
 - $\rightarrow 150$ events
- expected $H[c, c, j]$ (VBF) cross-section 3.6 fb
 - $\rightarrow 27$ events
- expected $H + W[b, b, \ell]$ cross-section 12 fb
 - $\rightarrow 680$ events
- expected $H + W[\tau, \tau, \ell]$ cross-section 1.4 fb
 - $\rightarrow 30$ events

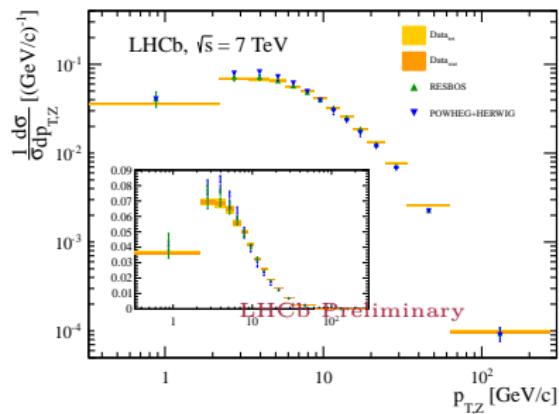
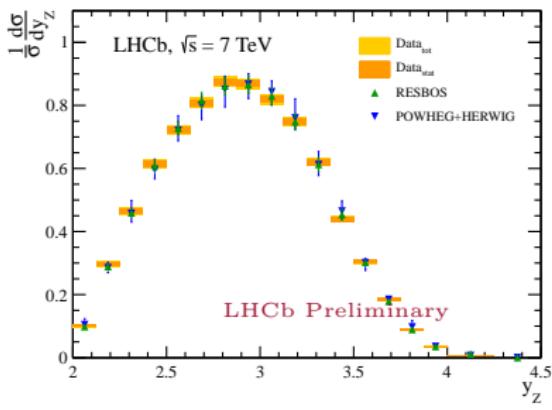
Summary

- double differential precision measurements with W and Z possible
 - Drell-Yan to very low masses also possible
 - provide comprehensive low- x and high- x dataset for PDFs
- forward di-boson cross-section measurements possible, particularly $WW[e, \mu]$
- vector boson and photon measurements (assuming updated ECAL)
 - not explored here but very interesting, vector boson CEP
- precision differential $W + j, b, c$ measurements
 - absolute cross-sections will be dominated by tagging
 - high precision with normalized
- enough top events for interesting forward measurements
- forward observation of the Higgs within reach

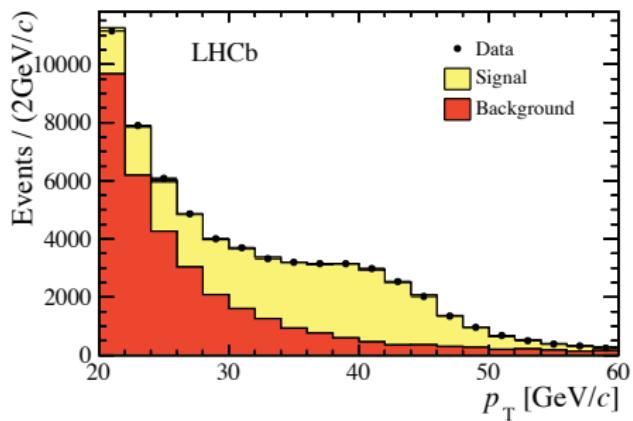
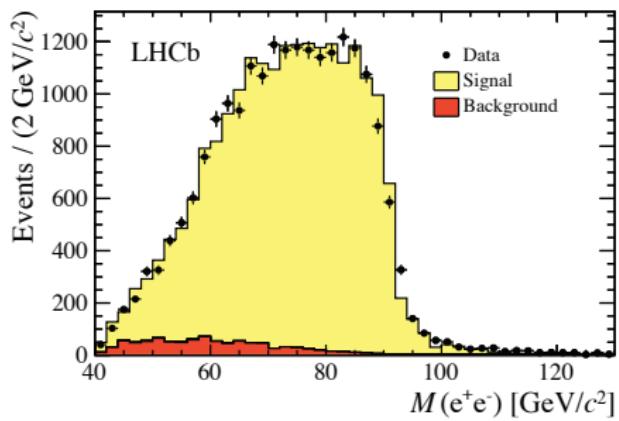


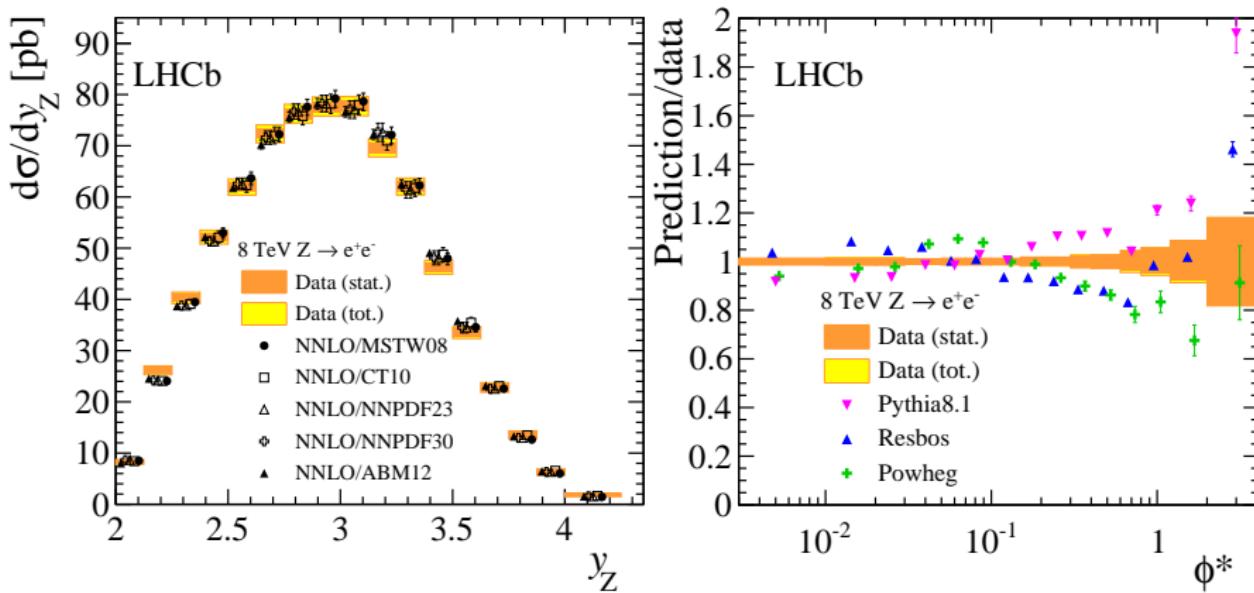
- fully instrumented between $2 < \eta < 5$
- momentum resolution between 0.4% at 5 GeV to 0.6% at 100 GeV
- impact parameter resolution of 13 – 20 μm for tracks
- secondary vertex precision of 0.01 – 0.05(0.1 – 0.3) mm in $xy(z)$

- muon reconstruction and trigger efficiencies from tag-and-probe
- heavy flavor background from displaced and non-isolated sidebands
- muon mis-identification from minbias, validated against same-sign

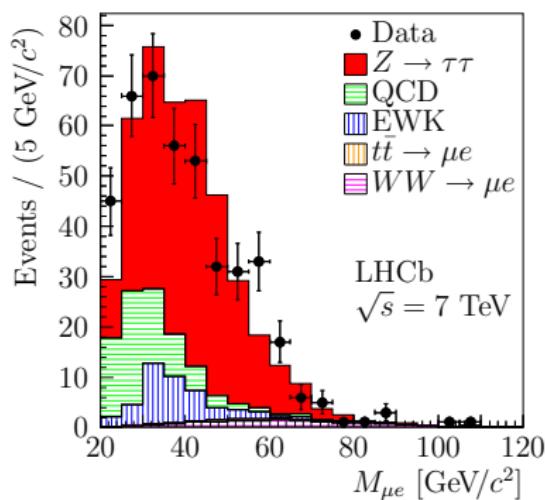
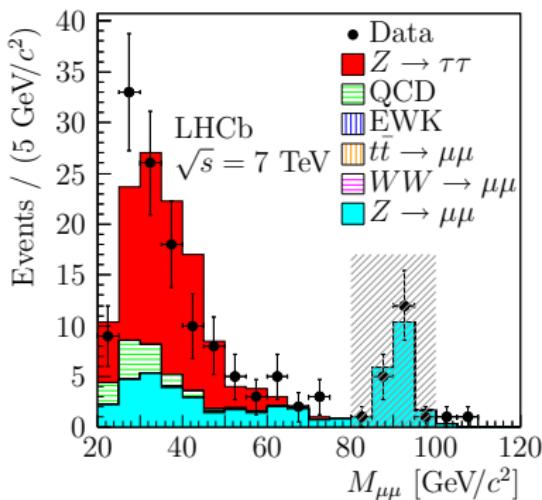


- ECAL saturation leads to smeared Z peak shape
- electron tracking efficiency large systematic uncertainty
 - can be determined from data, but not as a function of momenta

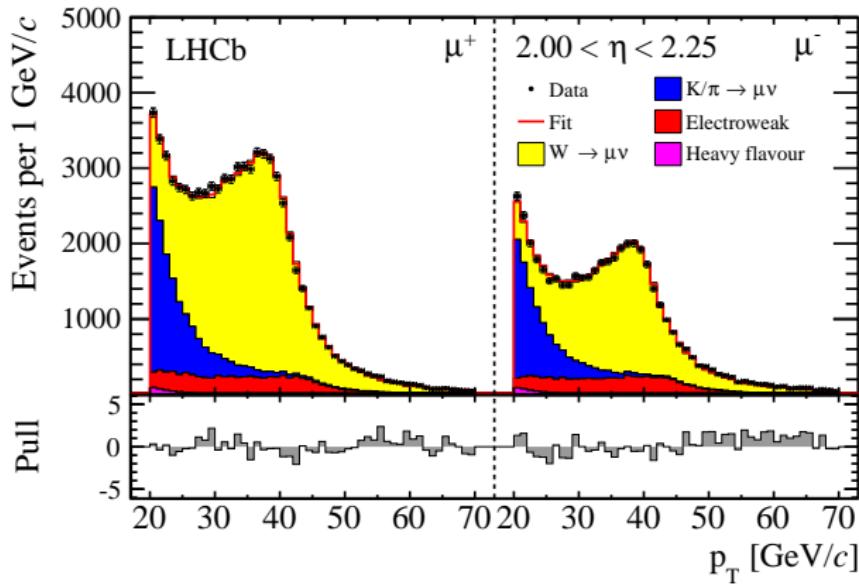




- utilized $\mu\mu$, $e\mu$, $h\mu$, and eh final states
- only selected single prong τ decays



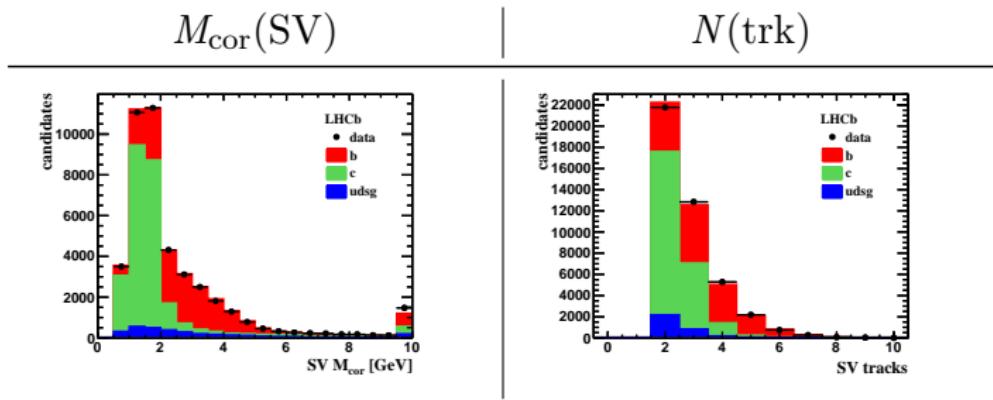
- search for isolated high p_T muons
- bin as a function of η and charge
- fit the muon p_T spectrum



Jet Tagging Run 1 (1)

arXiv:1504.07670

variable	separation	variable	separation		
$M(\text{SV})$	<i>udsgc</i>	<i>b</i>	$M_{\text{cor}}(\text{SV})$	<i>udsgb</i>	<i>c</i>
$\min(\text{FD}_T(\text{SV}))$	<i>udsg</i>	<i>cb</i>	$p_T(\text{SV})/p_T(\text{jet})$	<i>udsg</i>	<i>cb</i>
$\Delta R(\text{SV}, \text{jet})$	<i>udsg</i>	<i>cb</i>	$N(\text{trk})$	<i>udsgc</i>	<i>b</i>
$N(\text{trk} \in \text{jet})$	<i>udsgc</i>	<i>b</i>	$ Q(\text{SV}) $	<i>udsgb</i>	<i>c</i>
$\log(\chi^2_{\text{FD}}(\text{SV}))$	all		$\log(\chi^2_{\text{IP}}(\text{SV}))$	all	

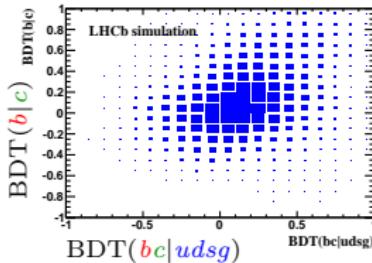


Jet Tagging Run 1 (2)

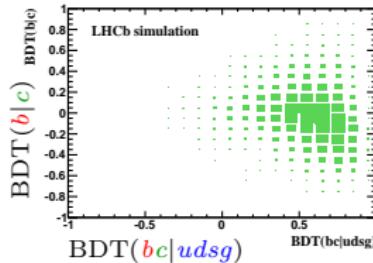
arXiv:1504.07670

- fit 2-dimensional $\text{BDT}(bc|udsg)$ versus $\text{BDT}(b|c)$ distributions

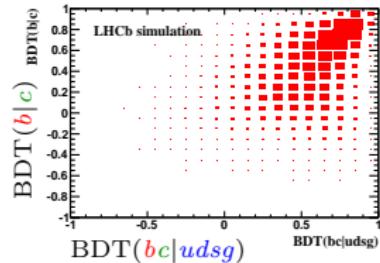
$udsg$ -jet



c -jet

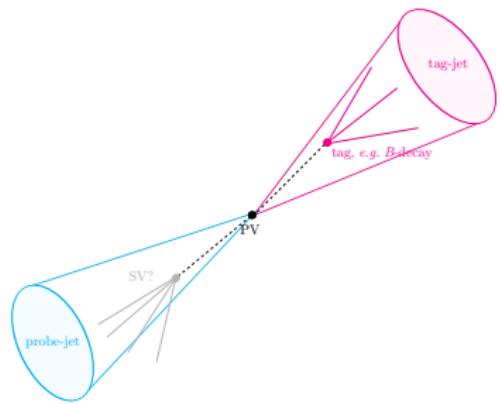


b -jet



- validate with four **tag+probe** data sub-samples

- $B + \text{jet}$: b -enhanced
- $D + \text{jet}$: c and b -enhanced
- displaced- $\mu + \text{jet}$:
 c and b -enhanced
- $W + \text{jet}$: use prompt isolated μ ,
 $udsg$ -enhanced



Jet Tagging Run 1 (3)

arXiv:1504.07670

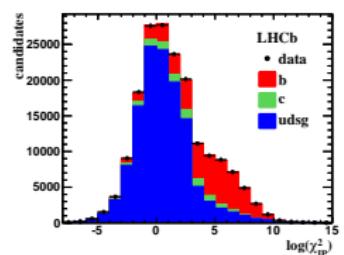
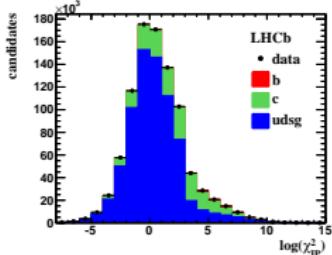
- determine efficiency with:

$$\frac{N_x(\text{SV})}{N_x(\chi_{\text{IP}}^2)}, x \in \text{udsg}, \text{c}, \text{b}$$

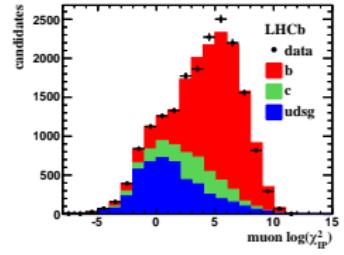
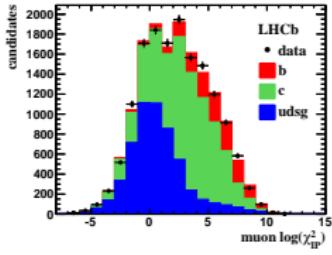
c-enhanced ($D + \text{jet}$)

b-enhanced ($B + \text{jet}$)

χ_{IP}^2 of hardest- p_T track (large initial $udsg$ -background)



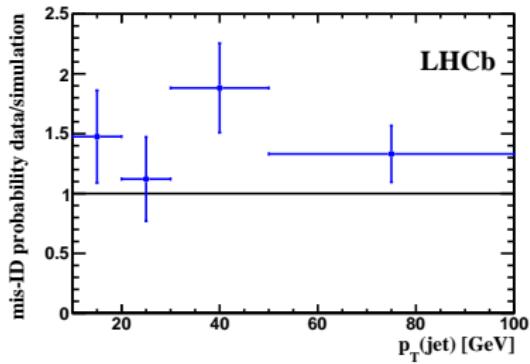
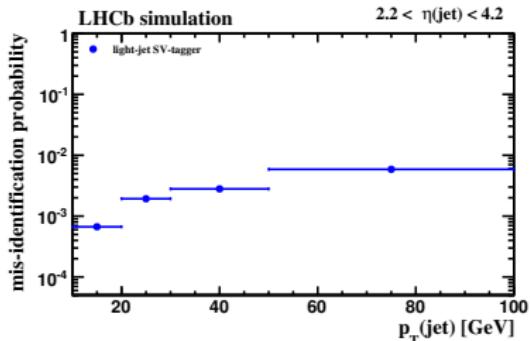
χ_{IP}^2 of hardest- p_T muon (only $\mathcal{O}(10\%)$ of jets)



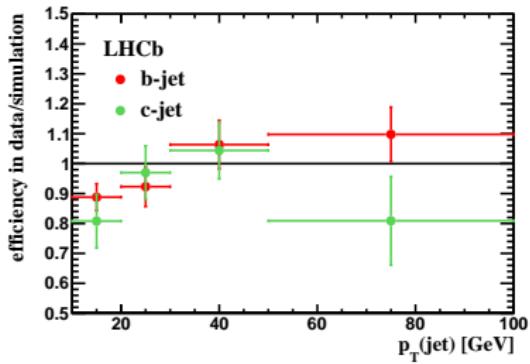
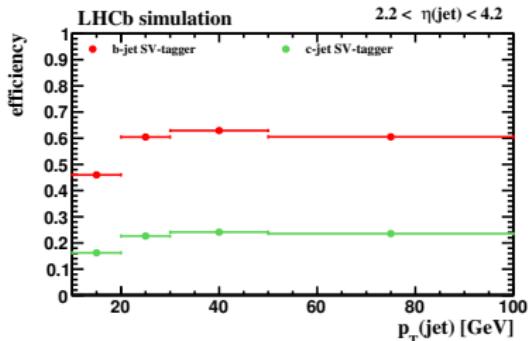
Jet Tagging Run 1 (4)

arXiv:1504.07670

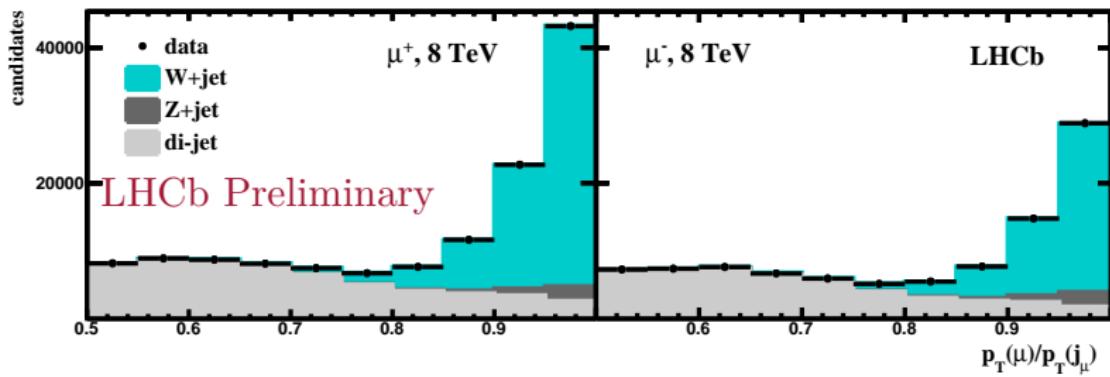
uds-g-jet



c-jet and b-jet



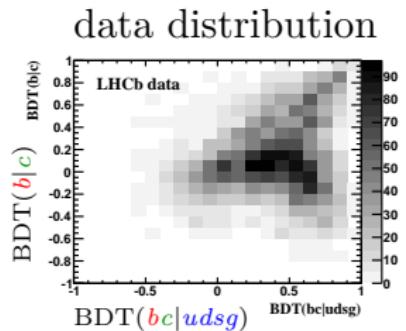
- isolation defined as $p_T(\mu)/p_T(j_\mu)$
- fit in bins of \sqrt{s} and muon charge
 - di-jet template from p_T -balanced events, $p_T(j_\mu + j) < 10$ GeV
 - $Z + \text{jet}$ yield and template extrapolated from di-muon $Z + \text{jet}$ data
 - $W + \text{jet}$ template from di-muon $Z + \text{jet}$ data, corrected to $W + \text{jet}$ with simulation



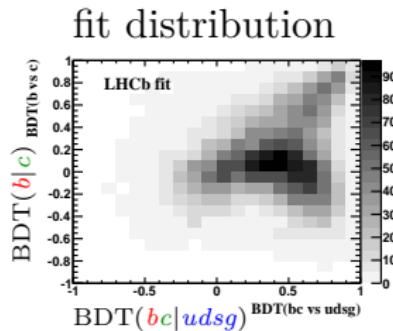
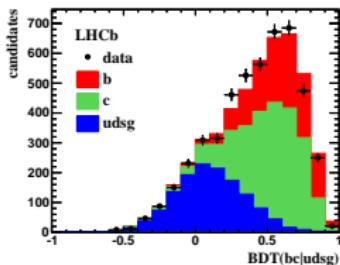
$W + j, b, c[\mu]$ Run 1 (2)

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- fit $\text{BDT}(\textcolor{red}{bc}|\textcolor{blue}{udsg})$ versus $\text{BDT}(\textcolor{red}{b}|\textcolor{green}{c})$ distribution in each bin of \sqrt{s} , muon charge, and $p_T(\mu)/p_T(j_\mu)$ (bin of 0.9 – 1.0 below)



BDT(b c | uds g) proj.



BDT($b|c$) proj.

