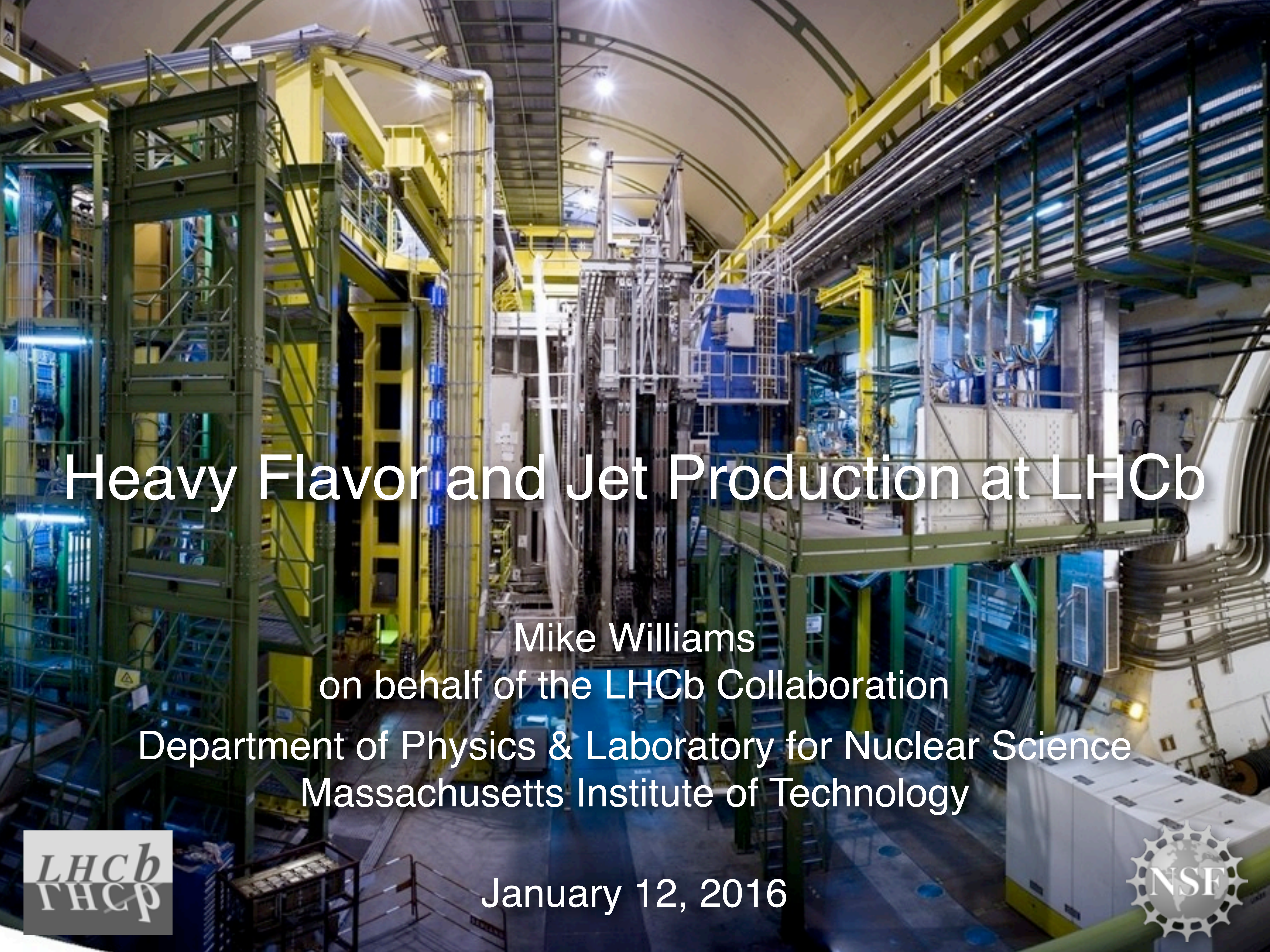


Heavy Flavor and Jet Production at LHCb

Mike Williams
on behalf of the LHCb Collaboration
Department of Physics & Laboratory for Nuclear Science
Massachusetts Institute of Technology

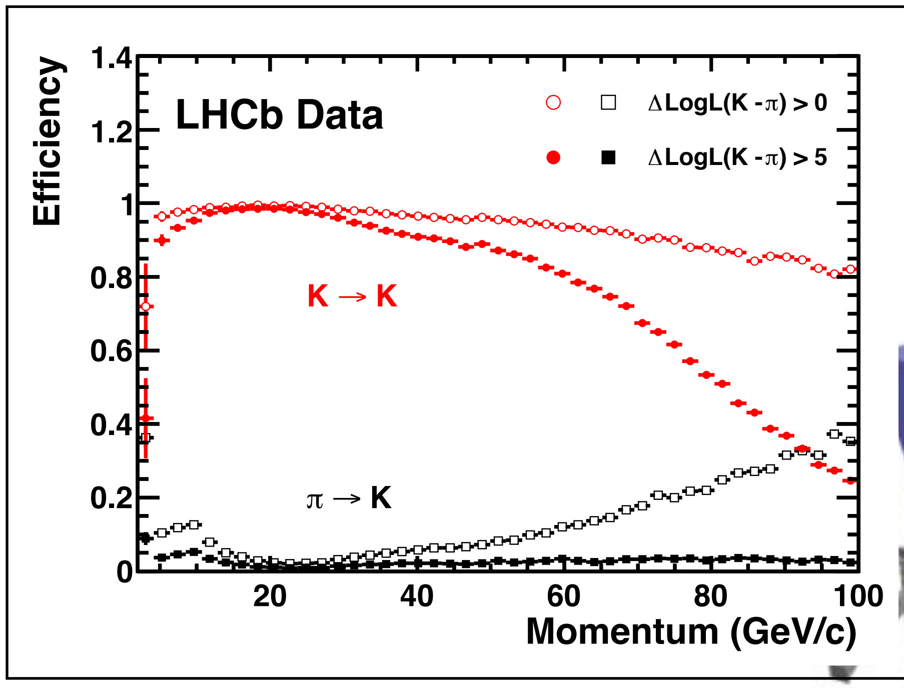
January 12, 2016

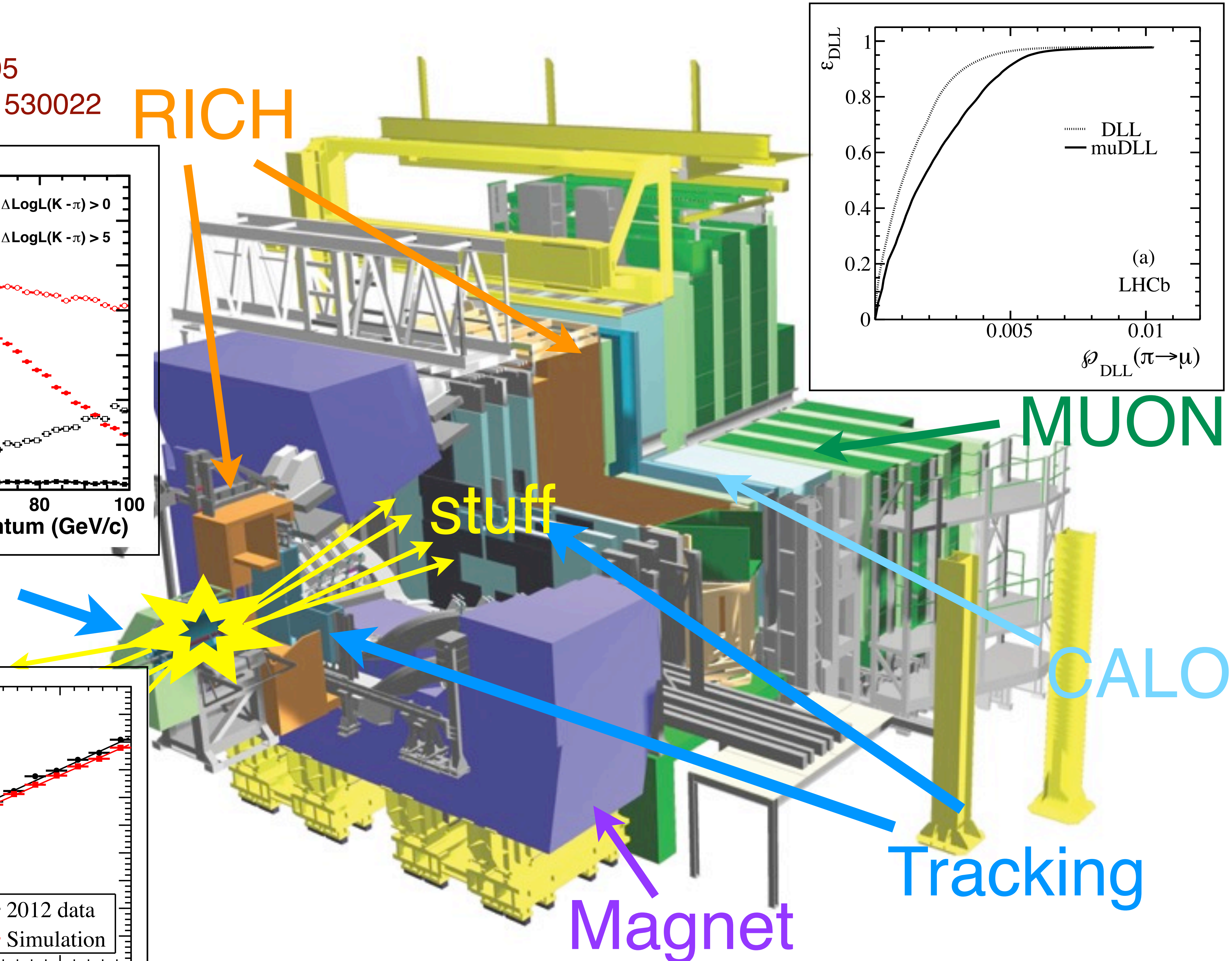

The Large Hadron Collider
Outline
LHCb overview
open beauty & charm
jets (V+j,b-jets,c-jets,...)
quarkonia
fixed-target running

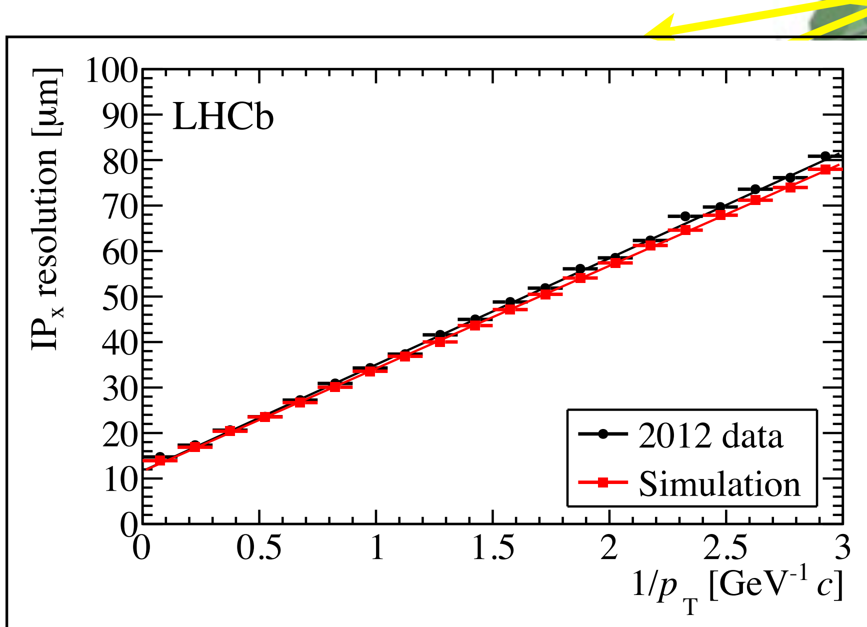
LHCb Detector

LHCb is a forward Spectrometer ($2 < \eta < 5$)

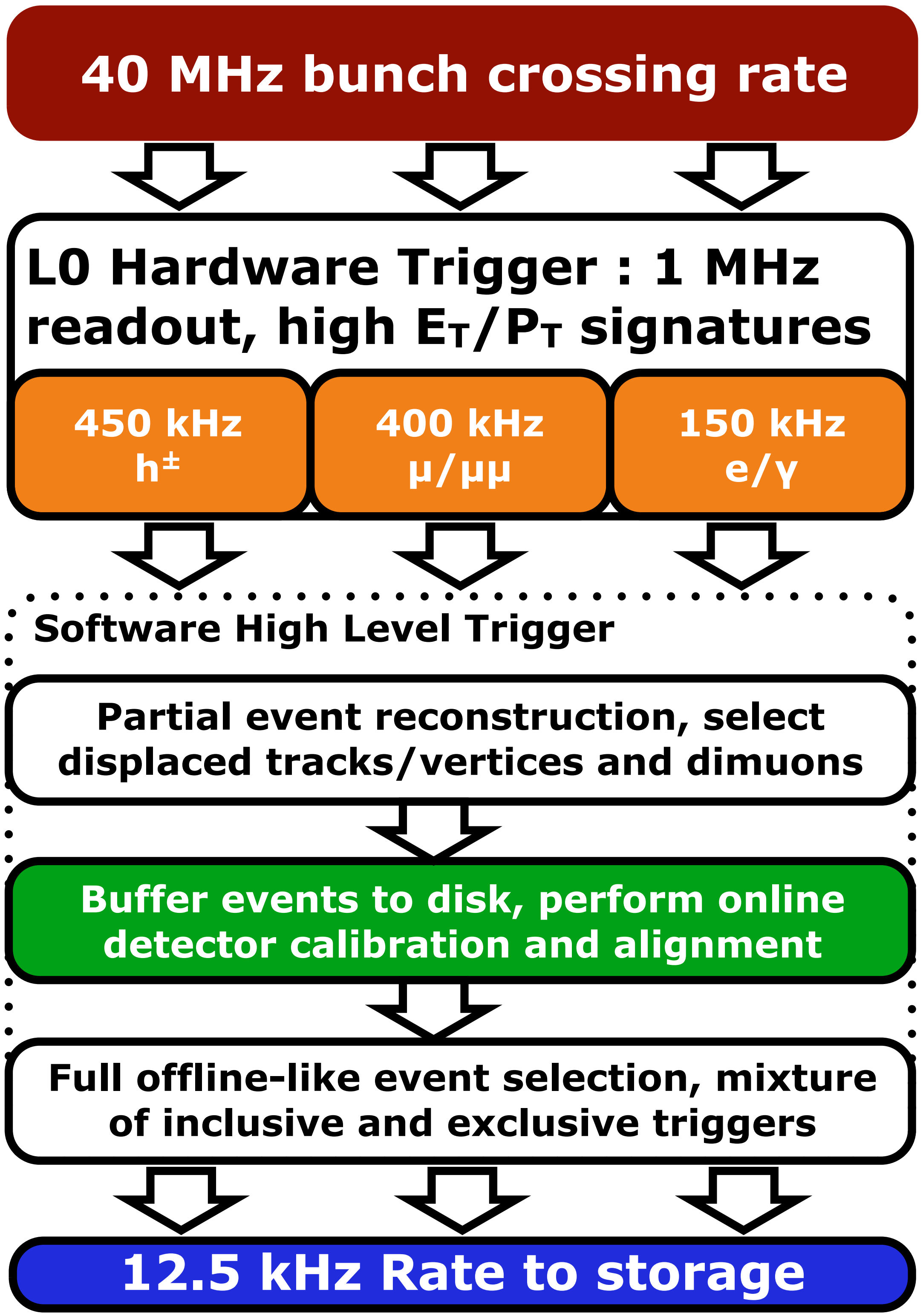
JINST 3 (2008) S08005
Int.J.Mod.Phys. A 30(2015) 1530022







LHCb Trigger



Precision measurements benefit greatly from using the final (best) reconstruction in the online event selection -- need real-time calibration!

JINST 8 (2013) P04022

all tracks $p_T > 0.5$ GeV (no IP requirements)

same calibration constants used online & offline

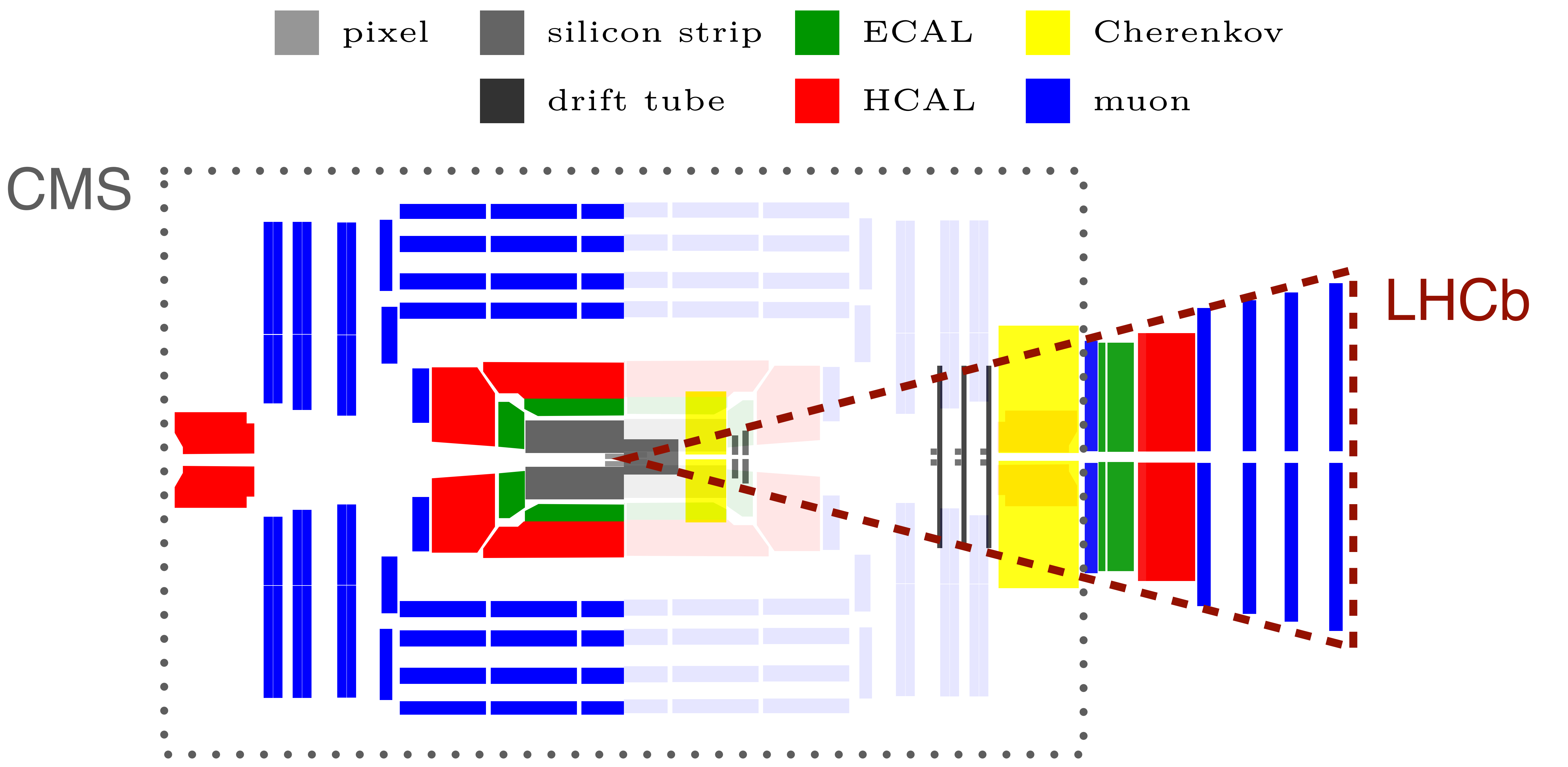
full reconstruction, offline-like particle ID, track quality, etc.

Heavy use of machine learning algorithms throughout the Run 1 and Run 2 trigger.

V.Gligorov, MW, JINST 8 (2012) P02013.

Plan to move to a triggerless-readout system in Run 3!

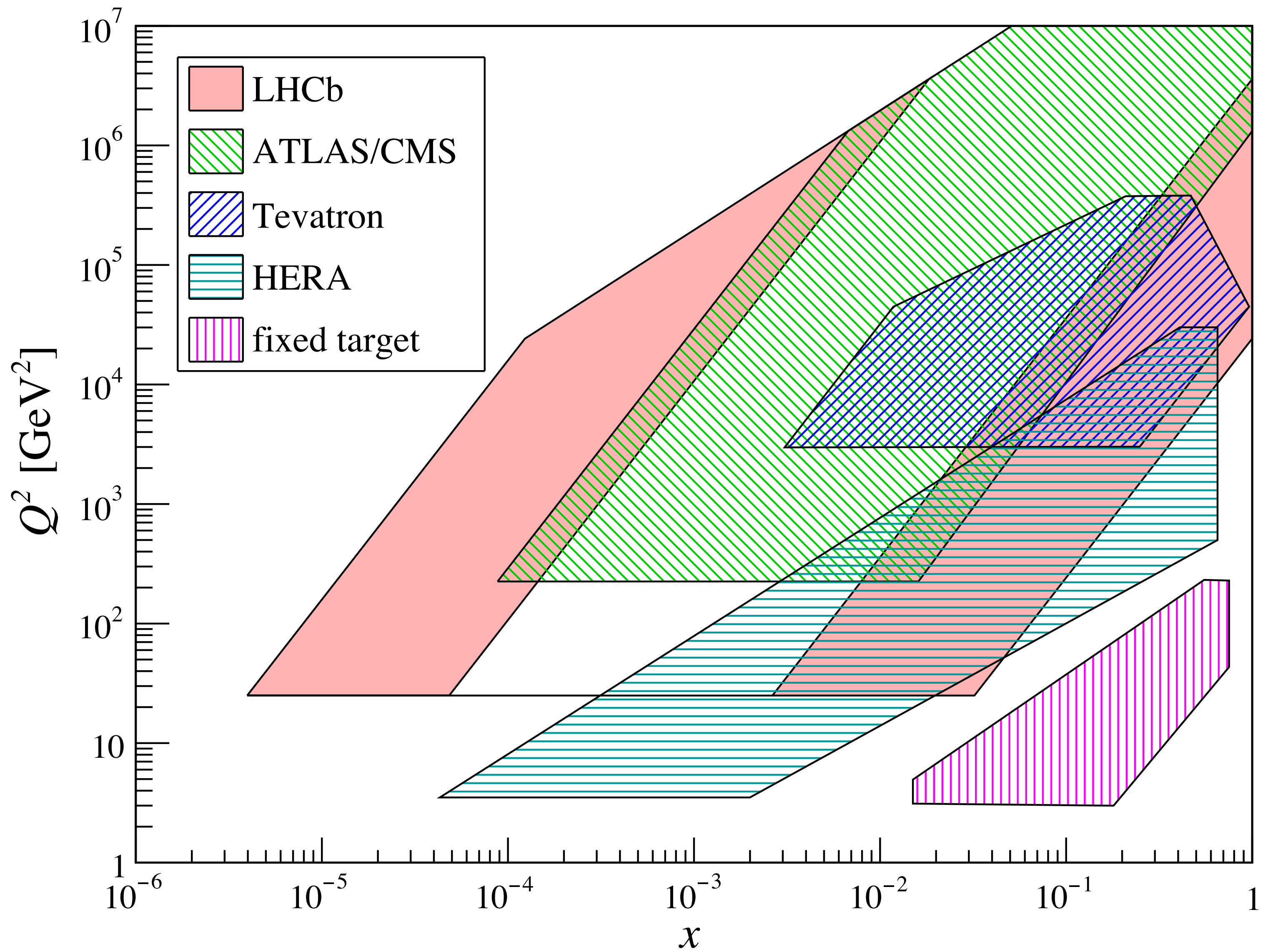
LHCb Detector



Complimentary kinematical coverage to CMS & ATLAS.

LHCb Physics

Core physics program involves searching for BSM physics in the decays of heavy-flavor hadrons -- but their production is also of great interest!



$$Q^2(x) = e^{\pm 2y} x^2 s$$

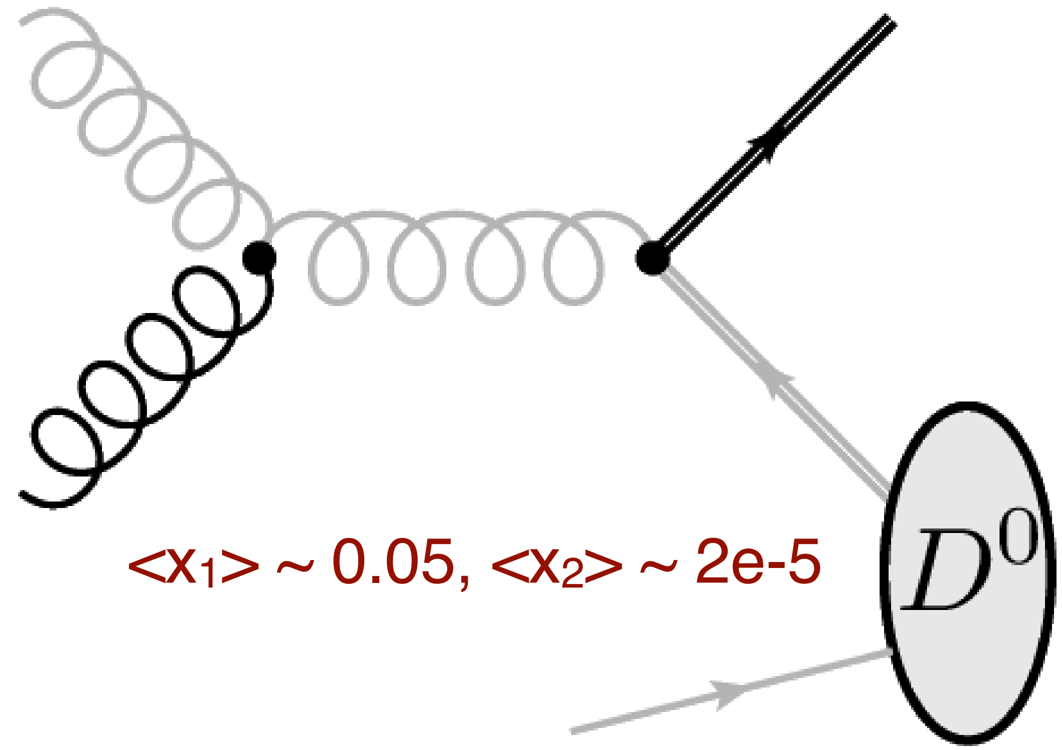
LHCb probes unique regions of (x,Q) so there are many measurements we can (potentially) make that are sensitive to (largely unknown) PDFs*.

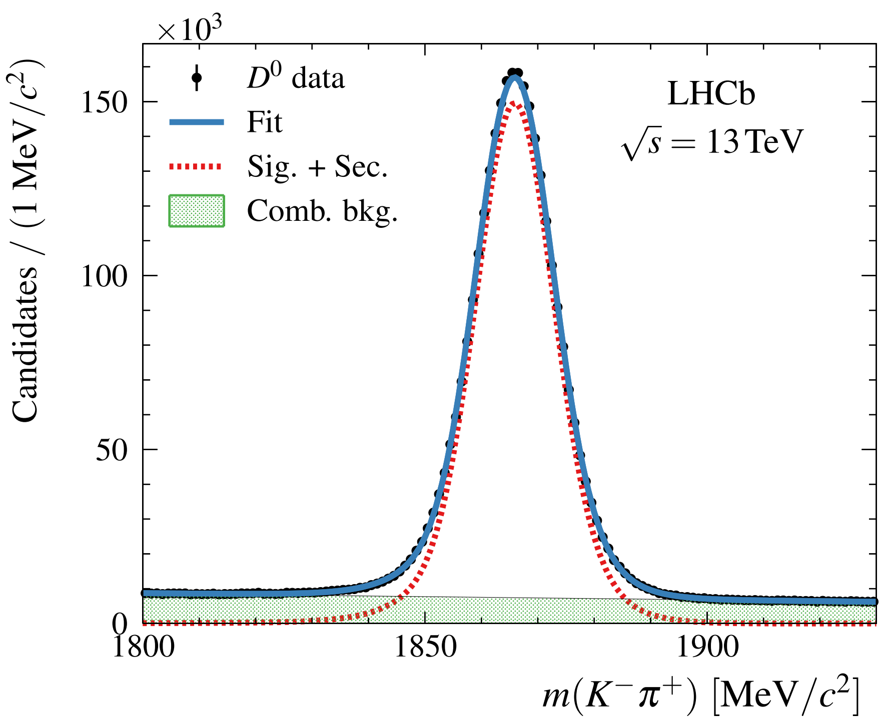
*PDFs means “parton distribution functions” throughout this talk.

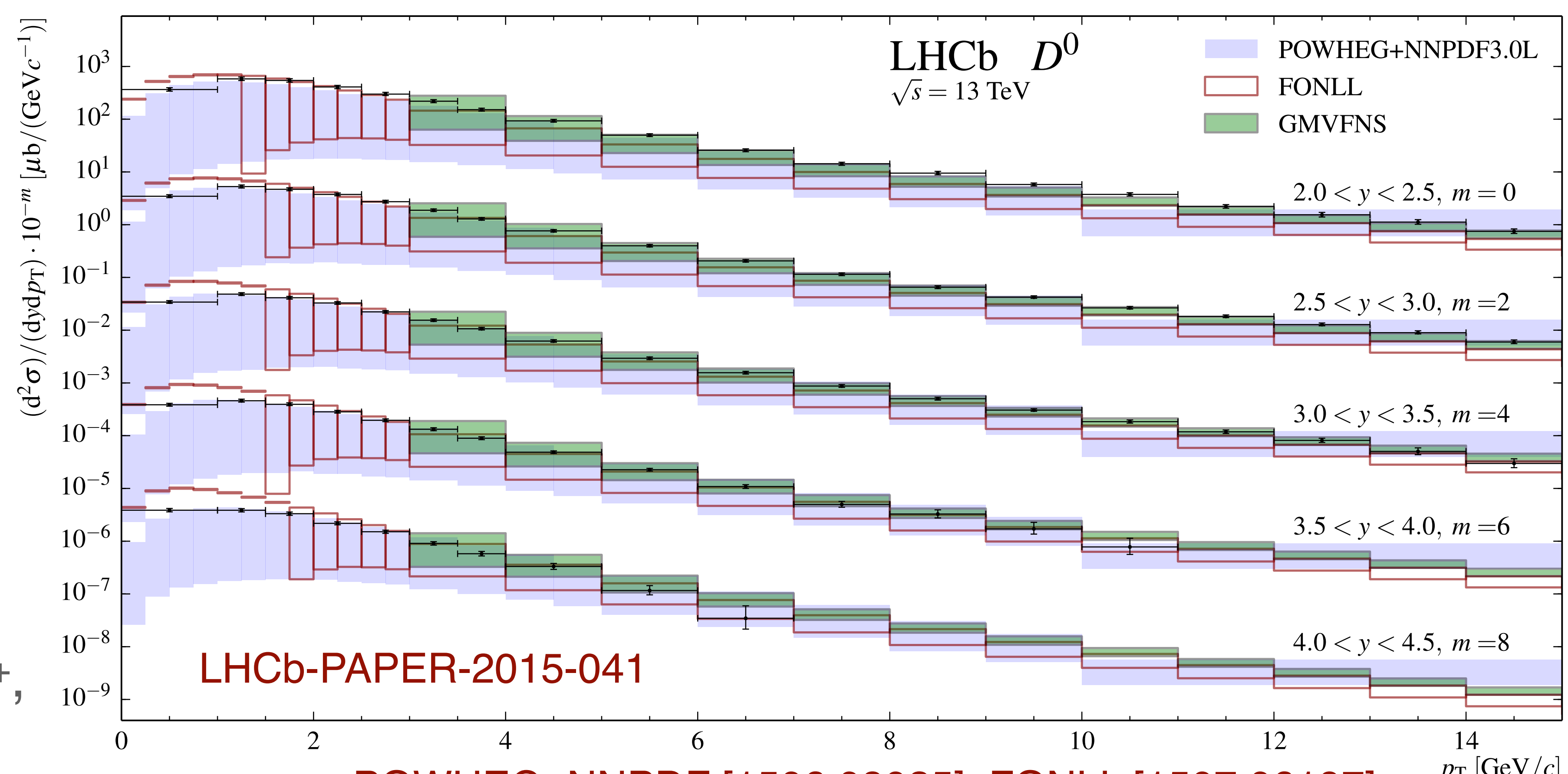
Open Charm

σ(cc)[13TeV] shown @ EPS (2015) within a week of recording the data; it was measured using online-reconstructed data.

Excellent probe of the small-x gluon PDF.







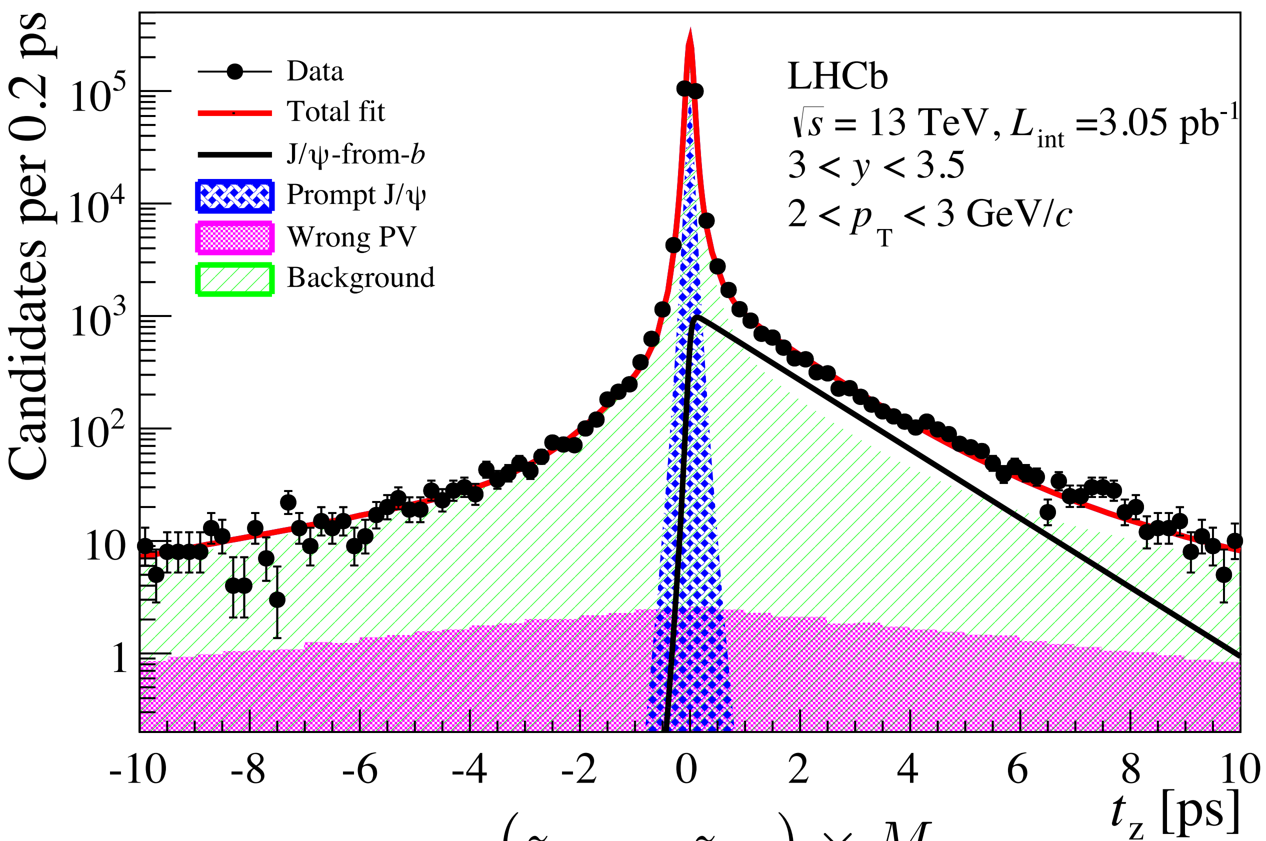
POWHEG+NNPDF [1506.08025], FONLL [1507.06197], GMVFNS [1202.0439]

Results also published for D^+, D_s, D^* at both 7 and 13 TeV.

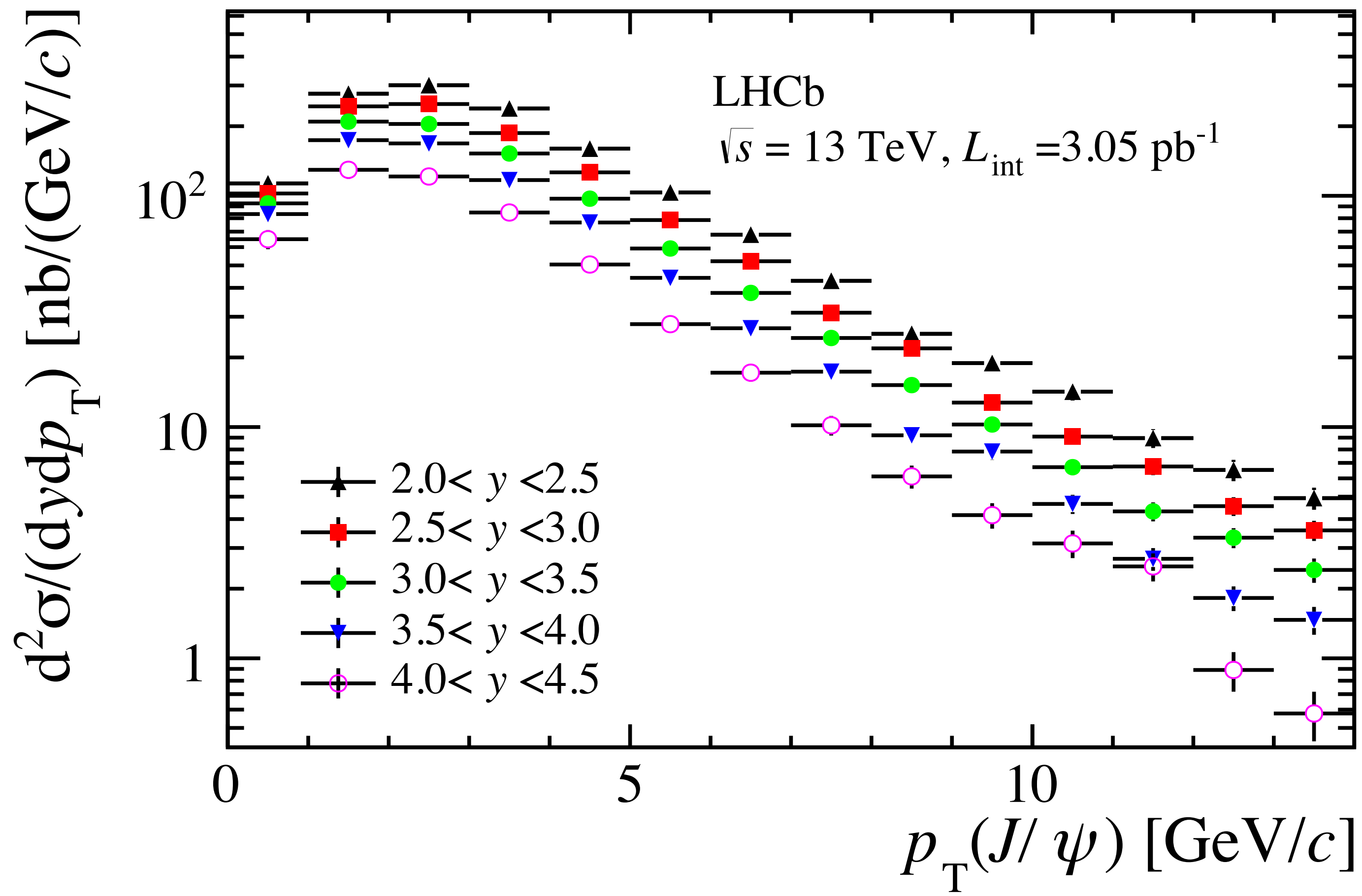
Open Beauty

σ(bb)[13TeV] also shown at EPS, and previously measured at lower energies.

LHCb-PAPER-2015-037: JHEP 10 (2015) 172



$$t_z = \frac{\left(z_{J/\psi} - z_{\rm PV}\right) \times M_{J/\psi}}{p_z}$$



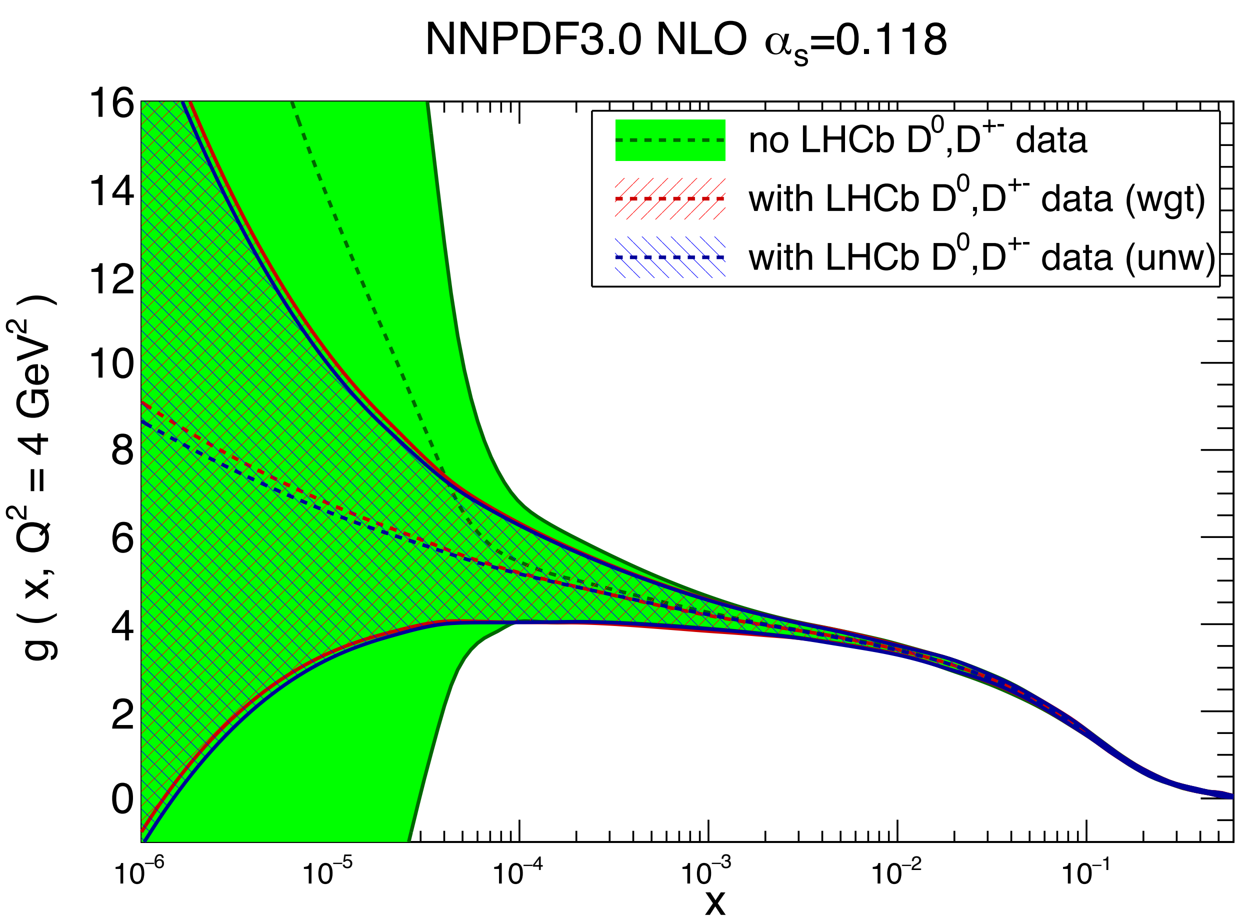
The pseudo-lifetime distribution of J/ψ's is fitted to determine both the prompt and "from b" content. LHCb has also measured production of many open-beauty meson and baryon species separately.

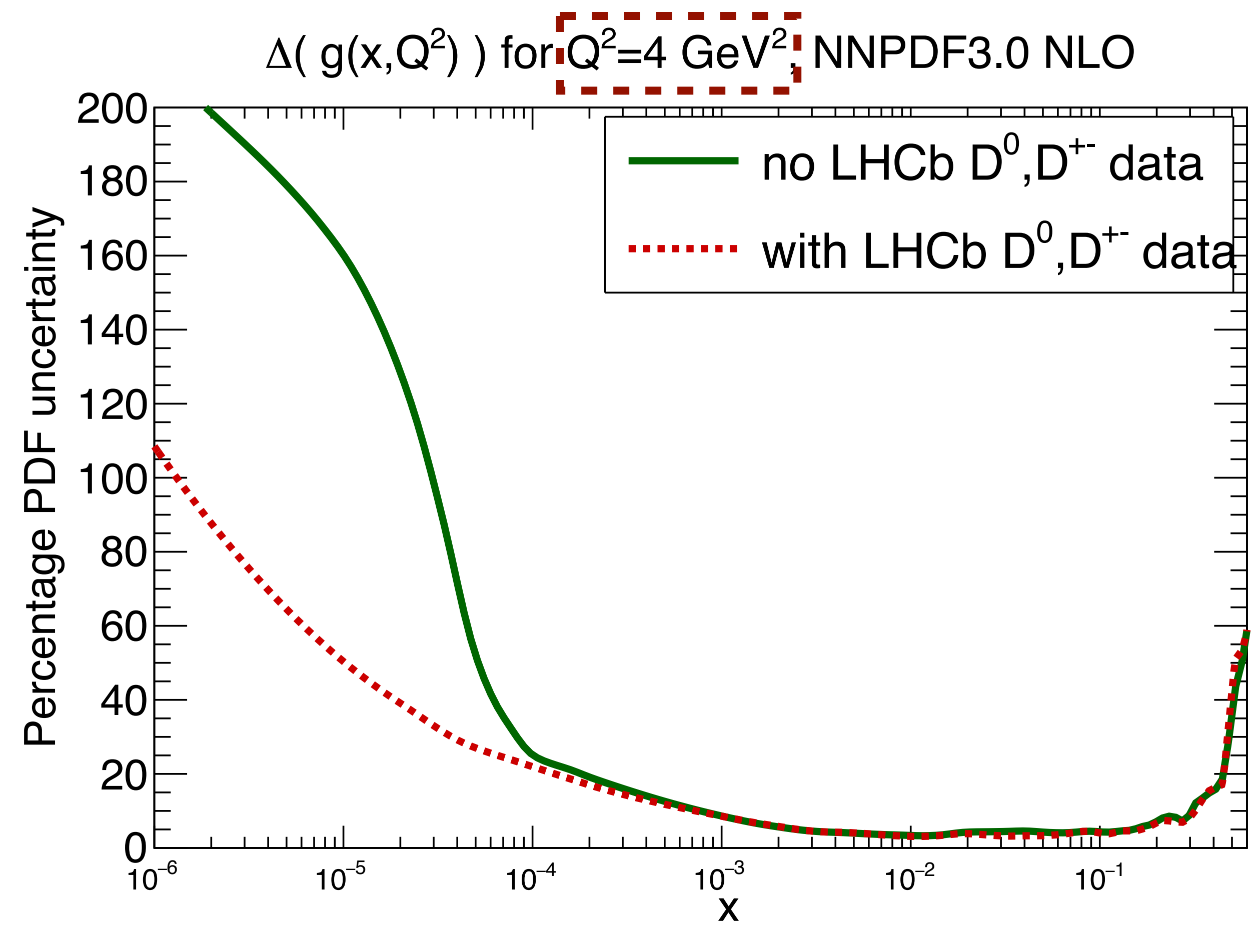
See http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_all.html for all LHCb publications.

Example Impact

Impact of 7 TeV prompt-charm* results on the low-x gluon PDF:

Gauld, Rojo, Rittoli, Talbert [1506.0825]





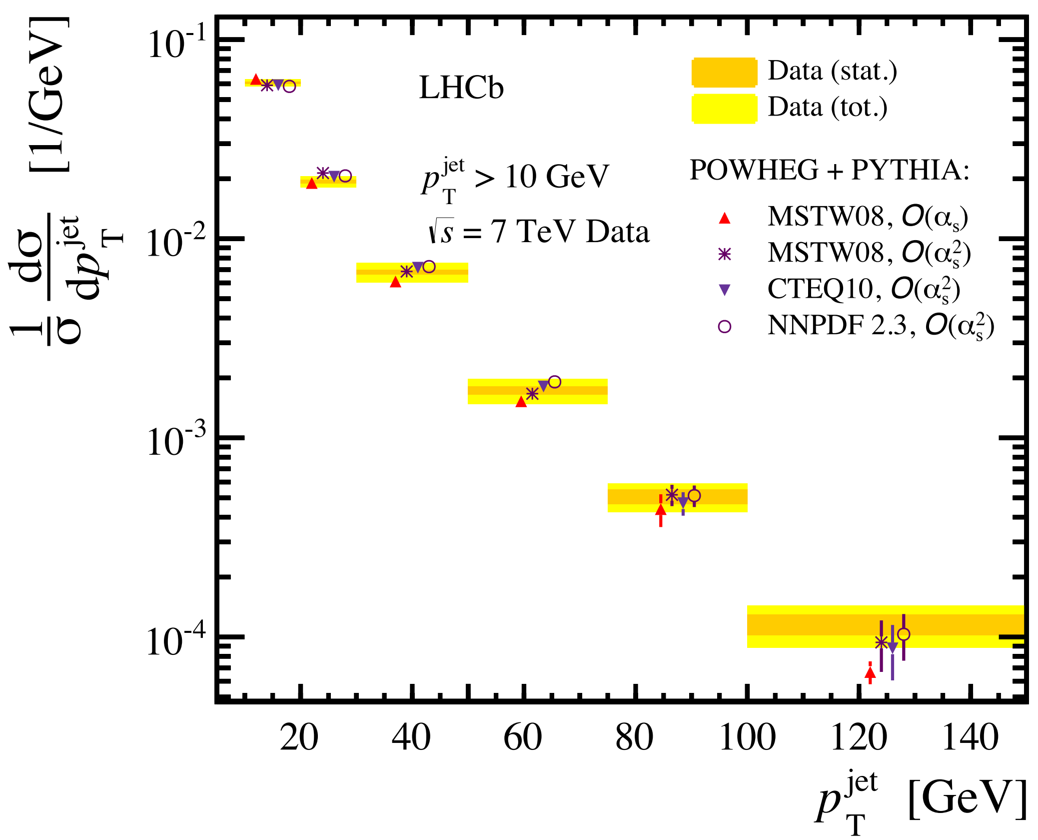
See also Gauld et al [1511.06346] for updated prompt atmospheric neutrino flux predictions for IceCube constrained by LHCb prompt-charm data.

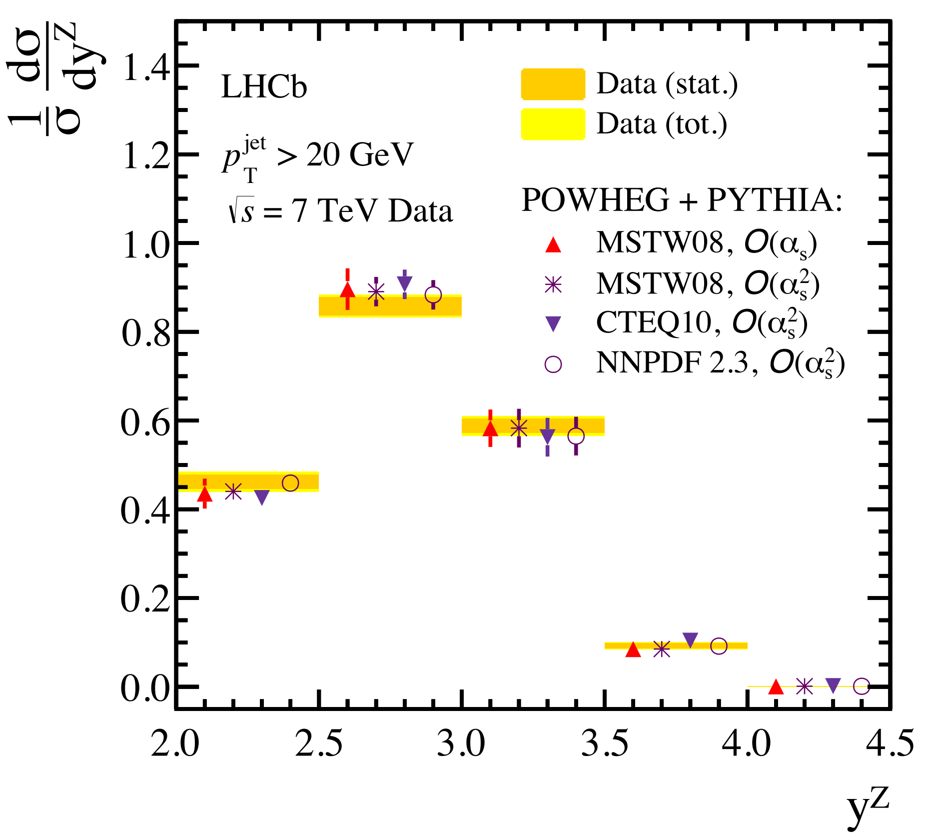
*LHCb-PAPER-2012-041: Nucl. Phys. B871 (2013) 1

Vector Boson + Jet

Jets @ LHCb: anti-k_T, R=0.5, particle flow. First LHCb jet paper provides differential measurements of Z+jet production:

LHCb-PAPER-2013-058: JHEP 01 (2014) 33





$\sigma(W^+j)/\sigma(Zj)$ and $\sigma(W^-j)/\sigma(Zj)$ also measured integrated over LHCb acceptance for $p_T(j) > 20$ GeV; these also agree with NLO SM predictions. LHCb-PAPER-2015-021 PRD 92 (2015) 052001

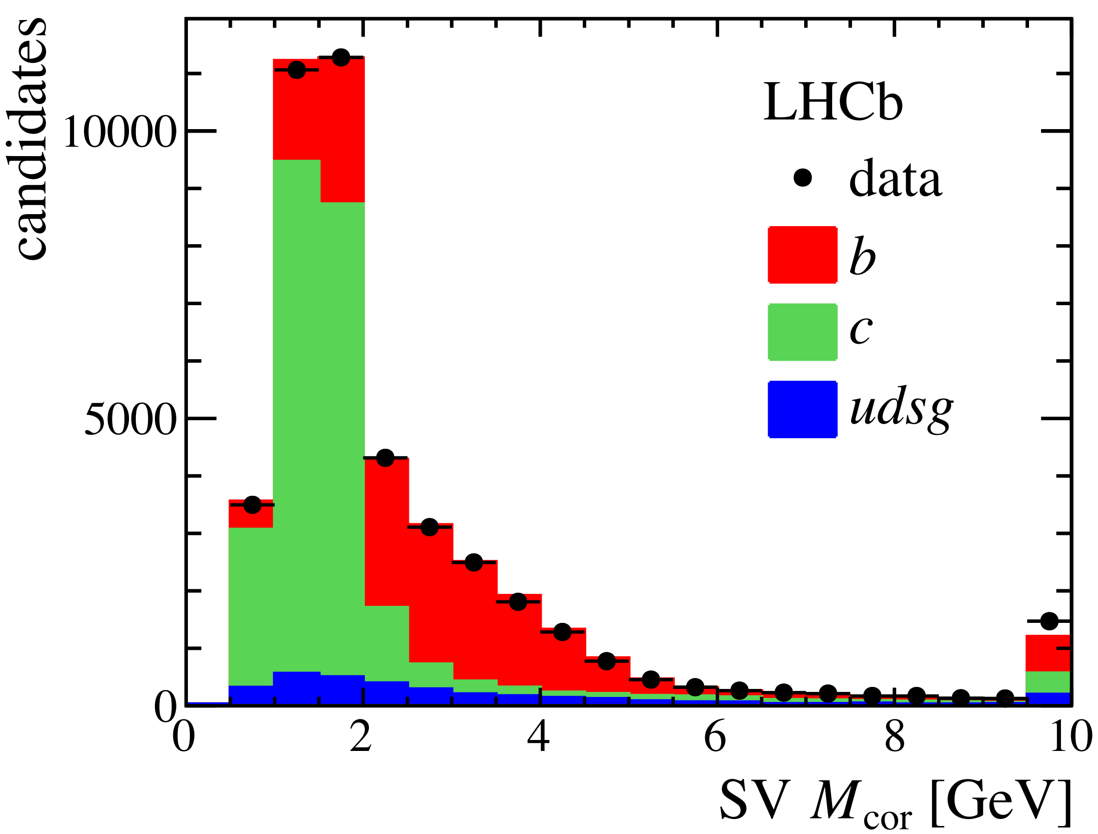
Run 1 differential W+jet measurements are in preparation. Such measurements in Runs 2 & 3 will enable strongly constraining d/u at large-x. Farry, Gauld [1505.01399]

Jet Tagging

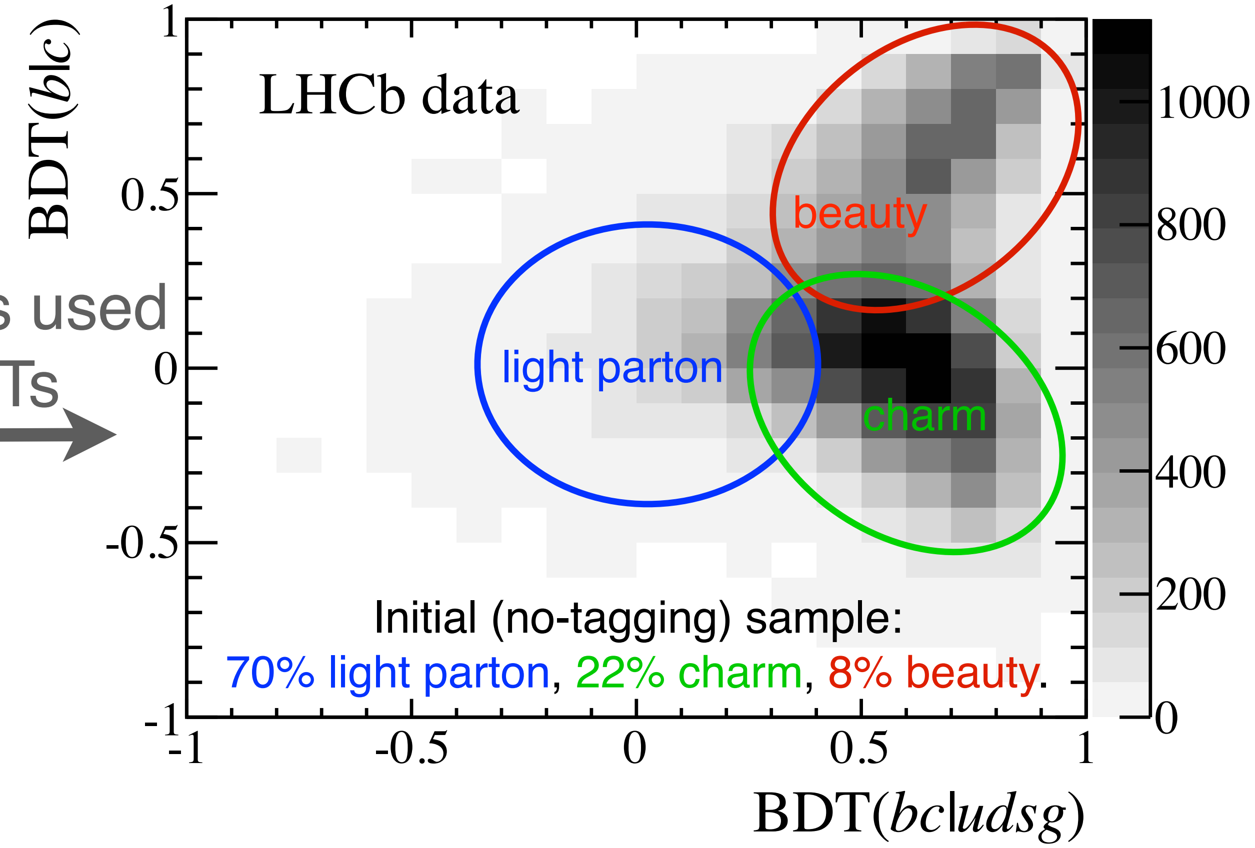
Use a SV-based algorithm to identify b and c jets (leveraging LHCb VELO):

JINST 10 (2015) P06013
LHCb-PAPER-2015-016

example SV feature: “corrected mass”



SV features used in 2 BDTs

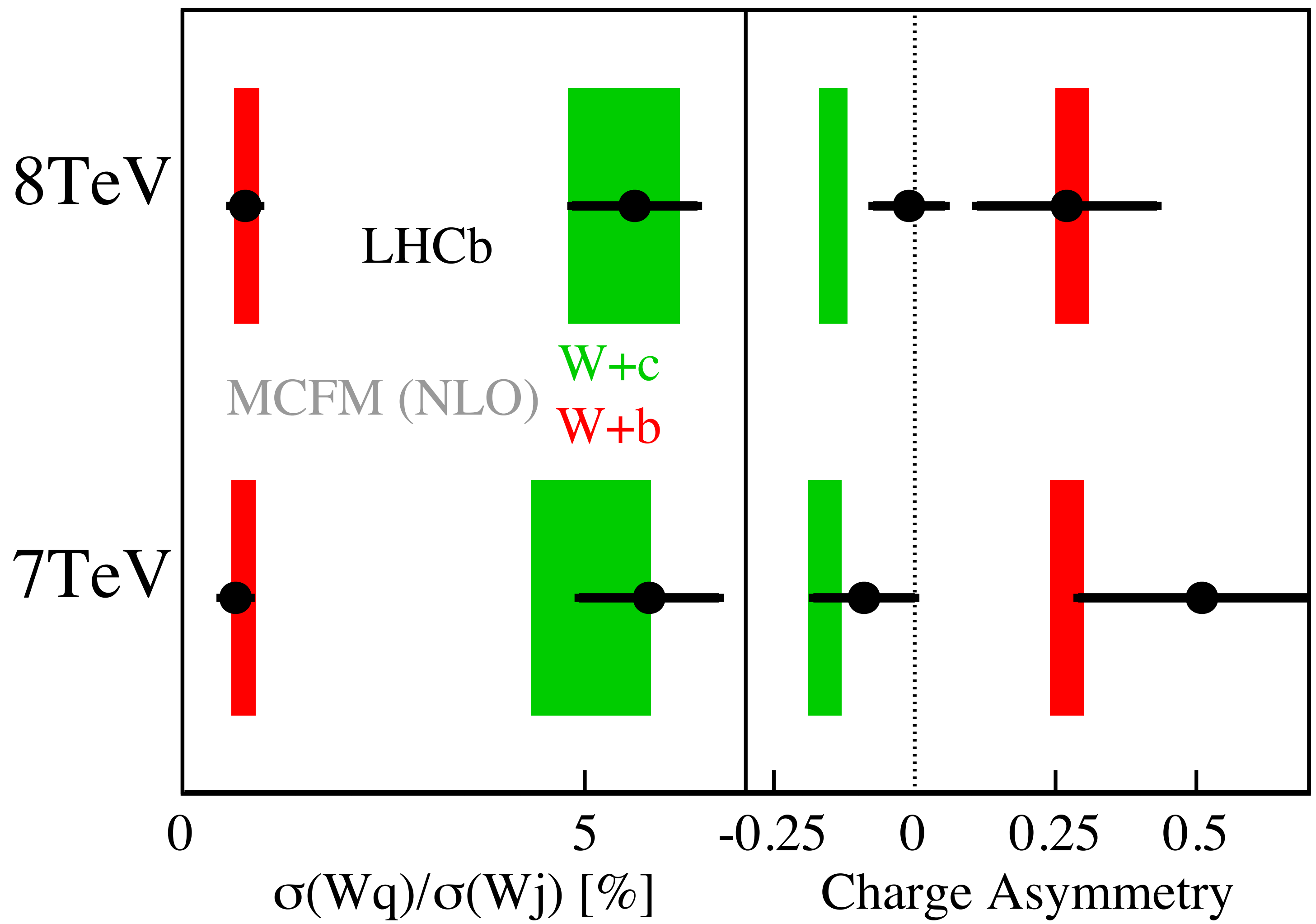


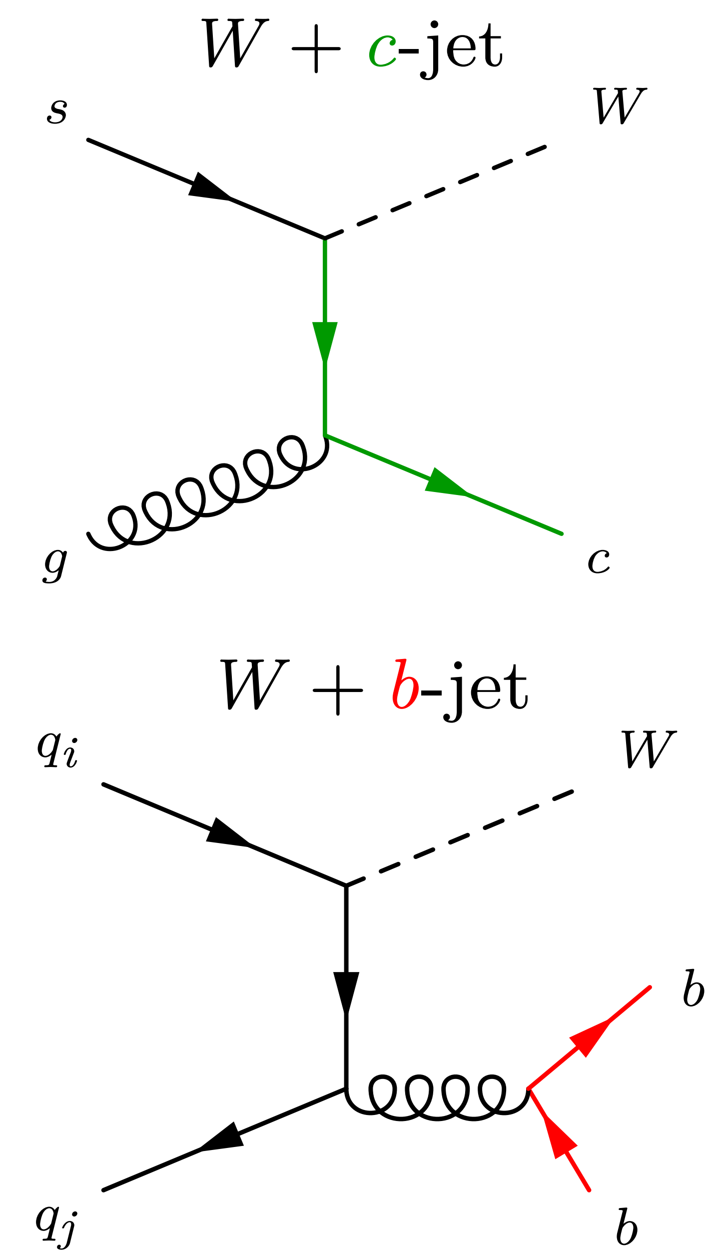
Performance validated & calibrated using large heavy-flavor-enriched jet data samples. Two-D BDT distributions fitted to extract SV-tagged jet flavor content; c-jet and b-jet yields each precisely determined simultaneously.

W+b & W+c

W+charm production probes the strange content of the proton. In the forward region, this includes large-x s vs s-bar.

PRD 92 (2015) 052001
LHCb-PAPER-2015-021

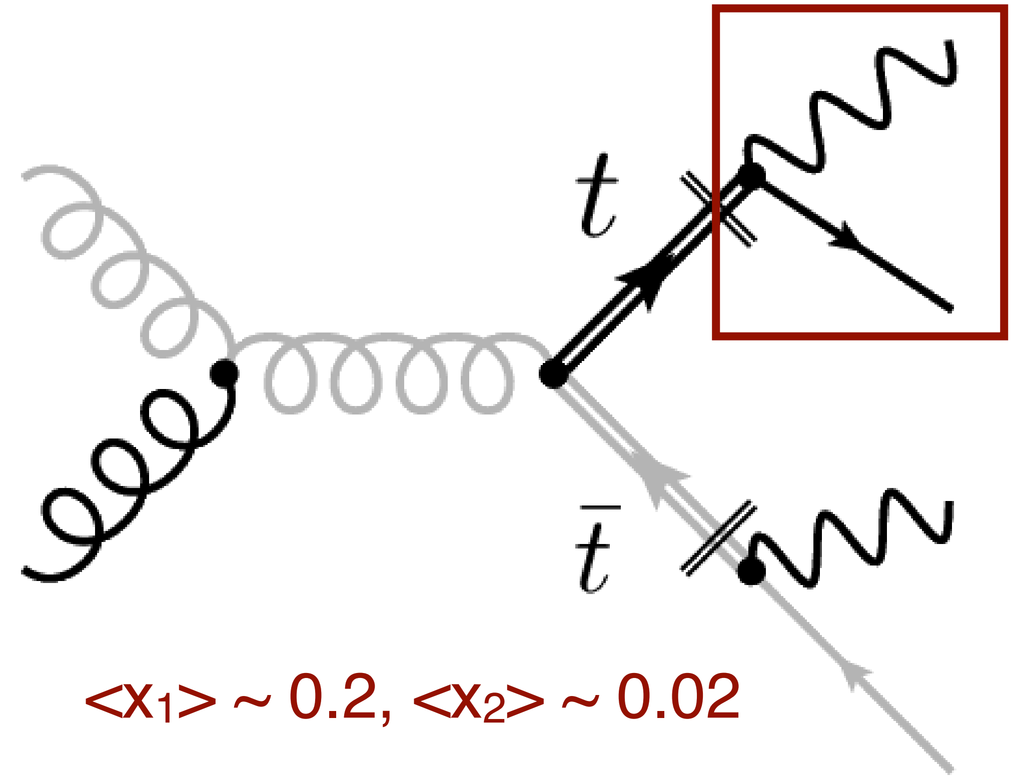




Expect ~10x larger stats in Run 2; will be able to probe s vs s-bar PDFs using differential measurements of W+c.

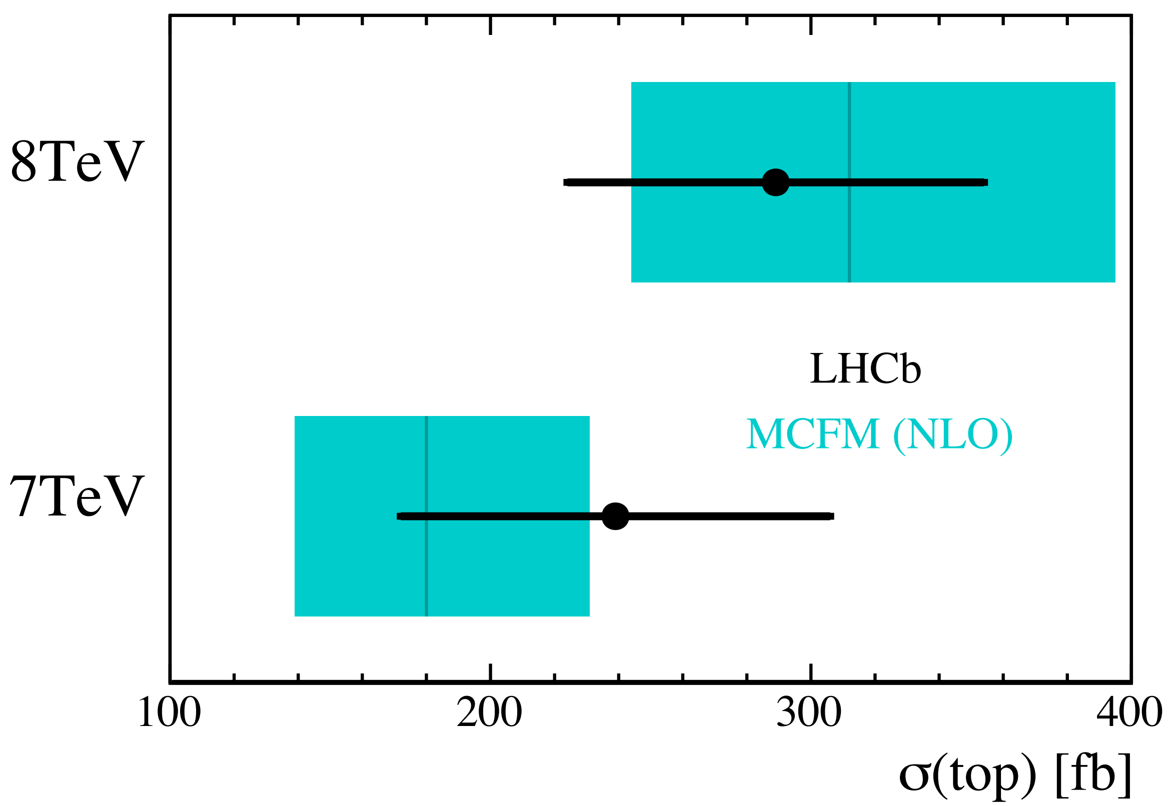
Top

Top production in the forward region probes the large-x gluon PDF and may be more sensitive to BSM. Kagan, Kamenik, Perez, Stone [1103.3747]



$\langle x_1 \rangle \sim 0.2$, $\langle x_2 \rangle \sim 0.02$

LHCb made the first observation of forward top production in Run 1:



PRL 115 (2015) 112001, LHCb-PAPER-2015-022

Results for σ(tt+t+t-bar):

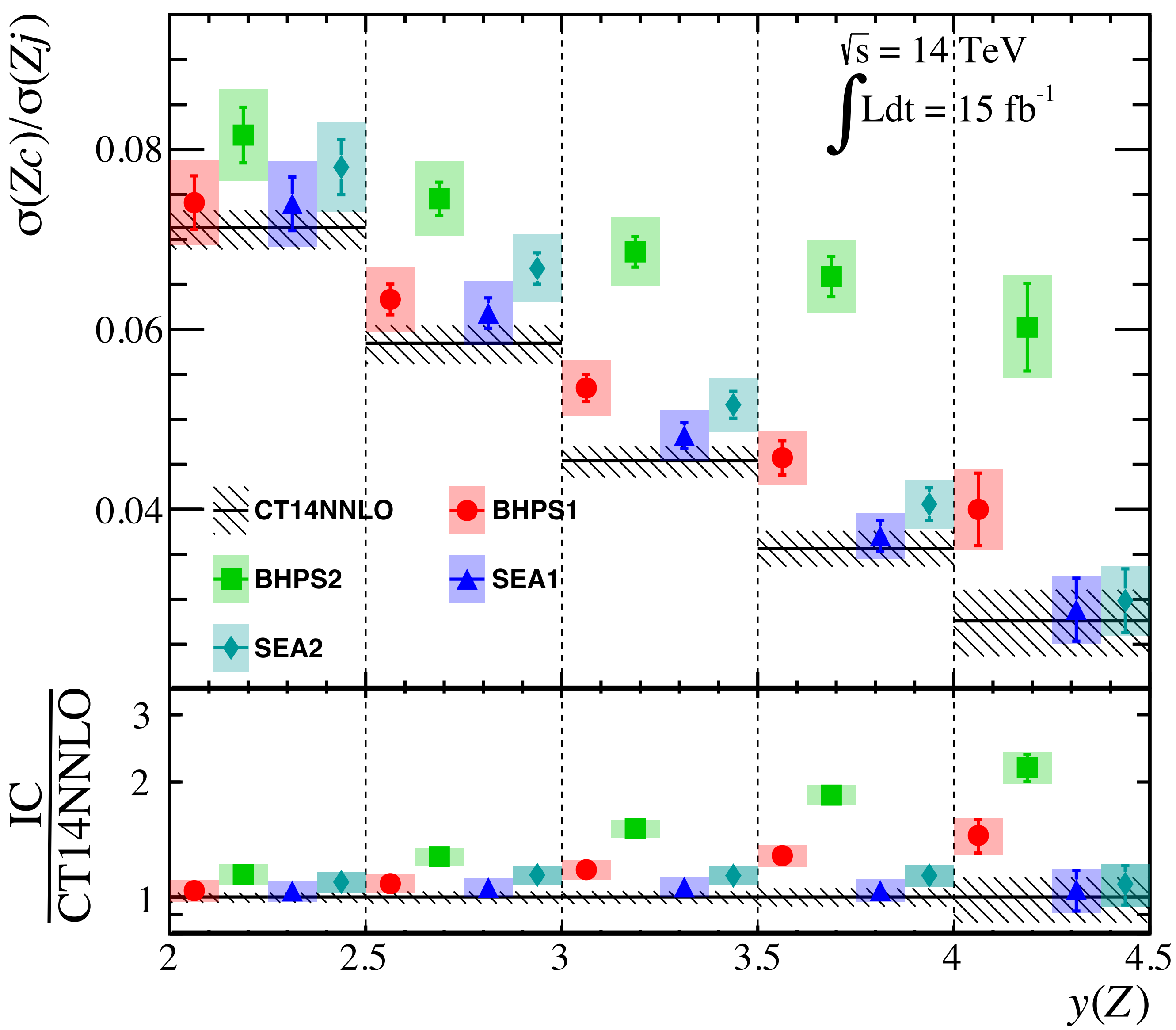
$$\sigma(\text{top})[7\,\text{TeV}] = 239 \pm 53\,(\text{stat}) \pm 33\,(\text{syst}) \pm 24\,(\text{theory})\,\text{fb}\,,$$
$$\sigma(\text{top})[8\,\text{TeV}] = 289 \pm 43\,(\text{stat}) \pm 40\,(\text{syst}) \pm 29\,(\text{theory})\,\text{fb}\,.$$

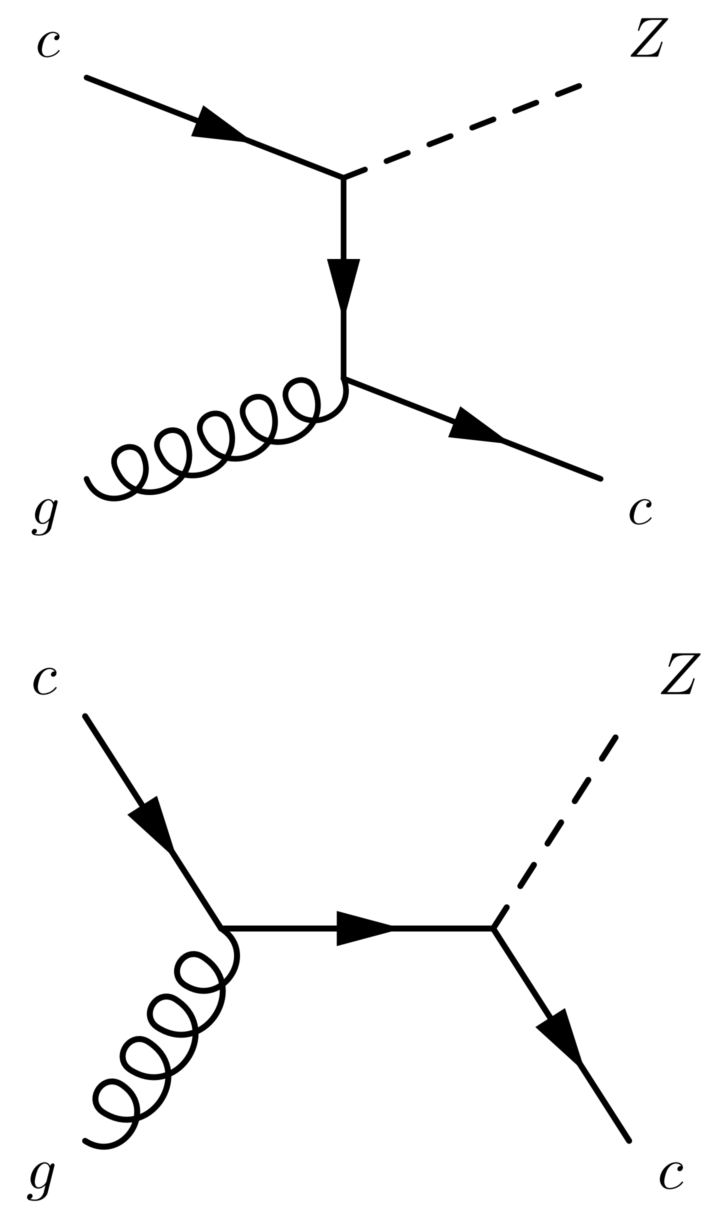
Expect ~20x more stats in Run 2; will explore separating pair and single-top production, and differential measurements. Should reduce the large-x gluon PDF uncertainty by ~20% [Gauld, 1311.1810].

Z+c

Whether there exists “intrinsic” (non-perturbative) charm content in the proton has long been debated. LHCb can say a lot here in Runs 2 and 3.

Boettcher, Ilten, MW [arxiv:1512.06666]

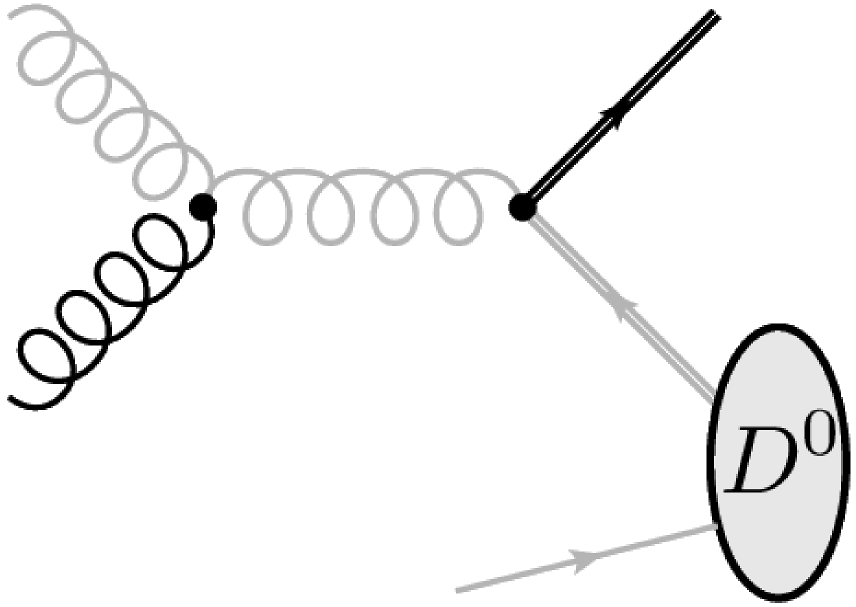




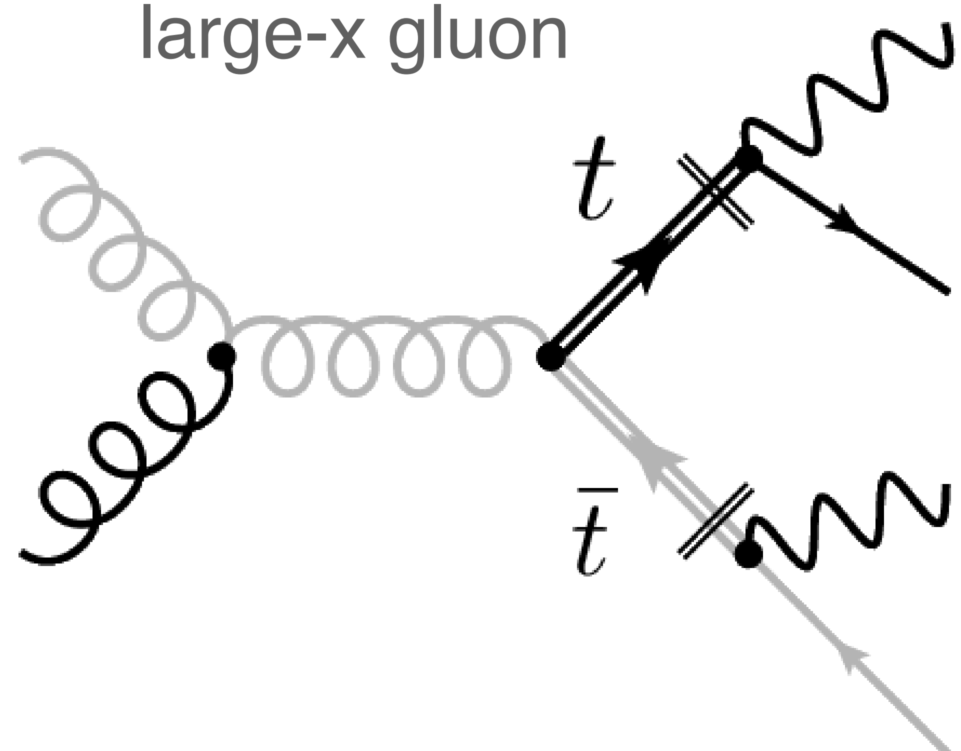
Also effects Higgs production by ~2% (more for H+c), direct dark matter detection (assuming H exchange), and prompt atmospheric neutrino rates.

PDFs Summary

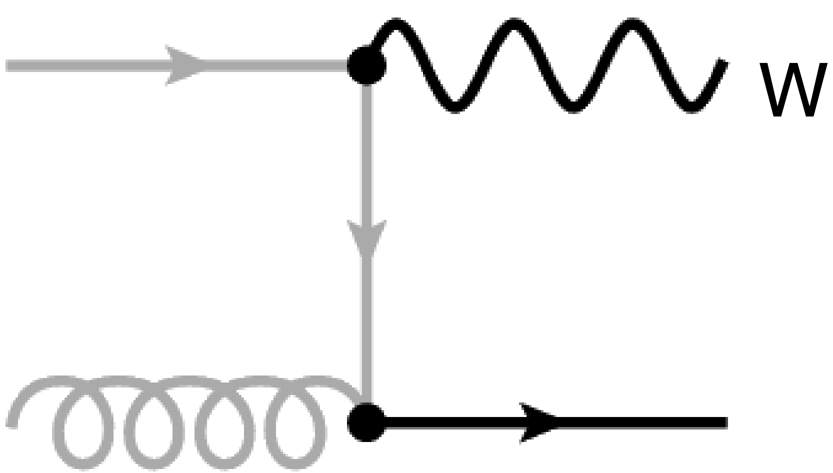
small-x gluon



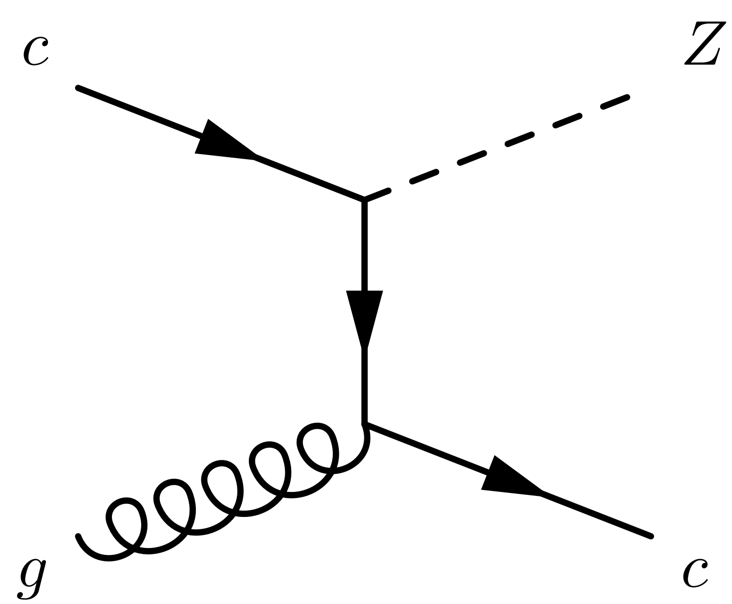
large-x gluon



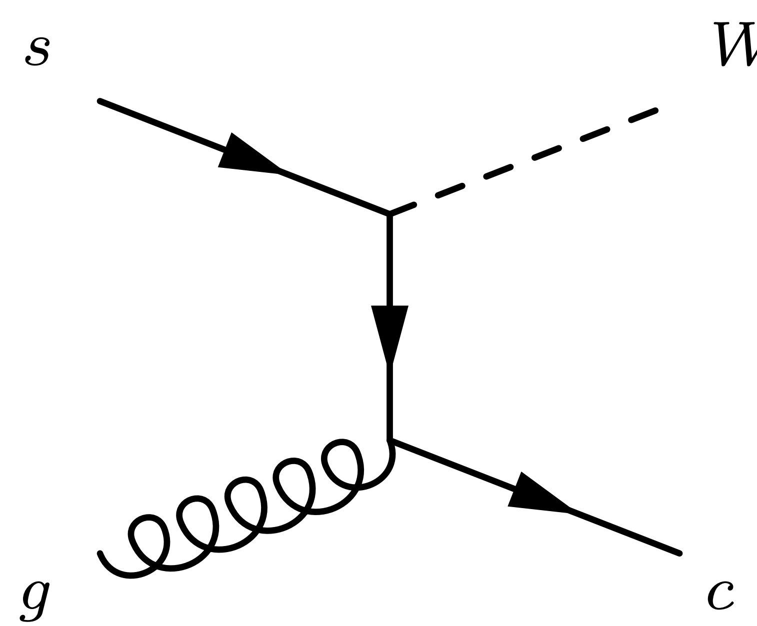
large-x d/u



intrinsic charm



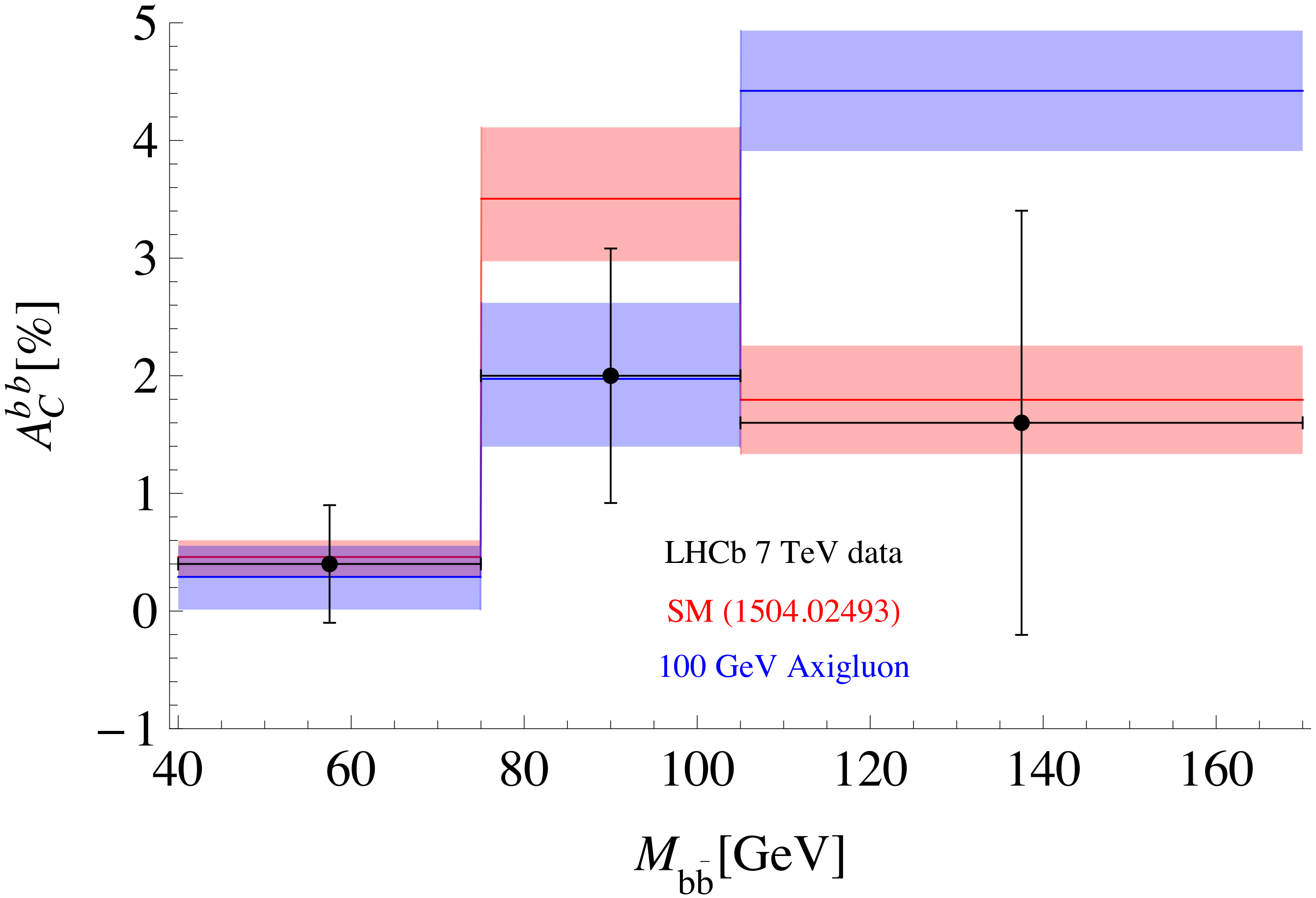
s vs s-bar



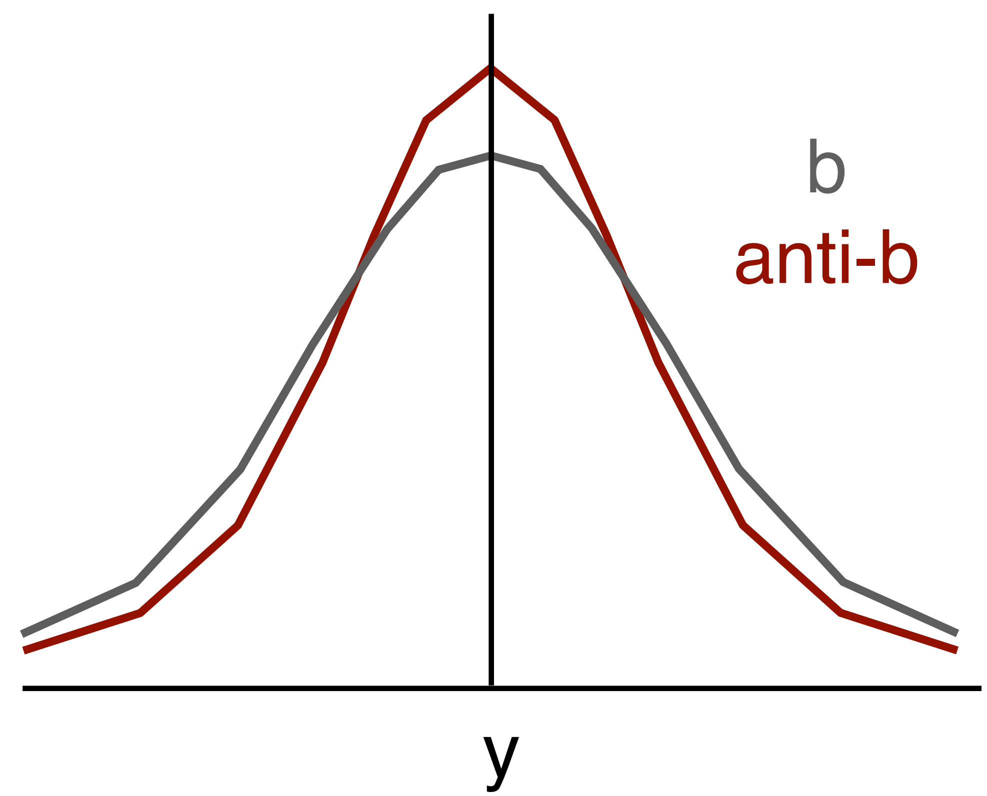
Dijets

Di-heavy-flavor jet production provides a standard candle measurement, is useful for constraining tagging efficiencies, and probes BSM physics.

LHCb-PAPER-2014-023: PRL 113 (2014) 082003.



$$A_{\mathrm{C}}^{b\bar{b}} \equiv \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)},$$

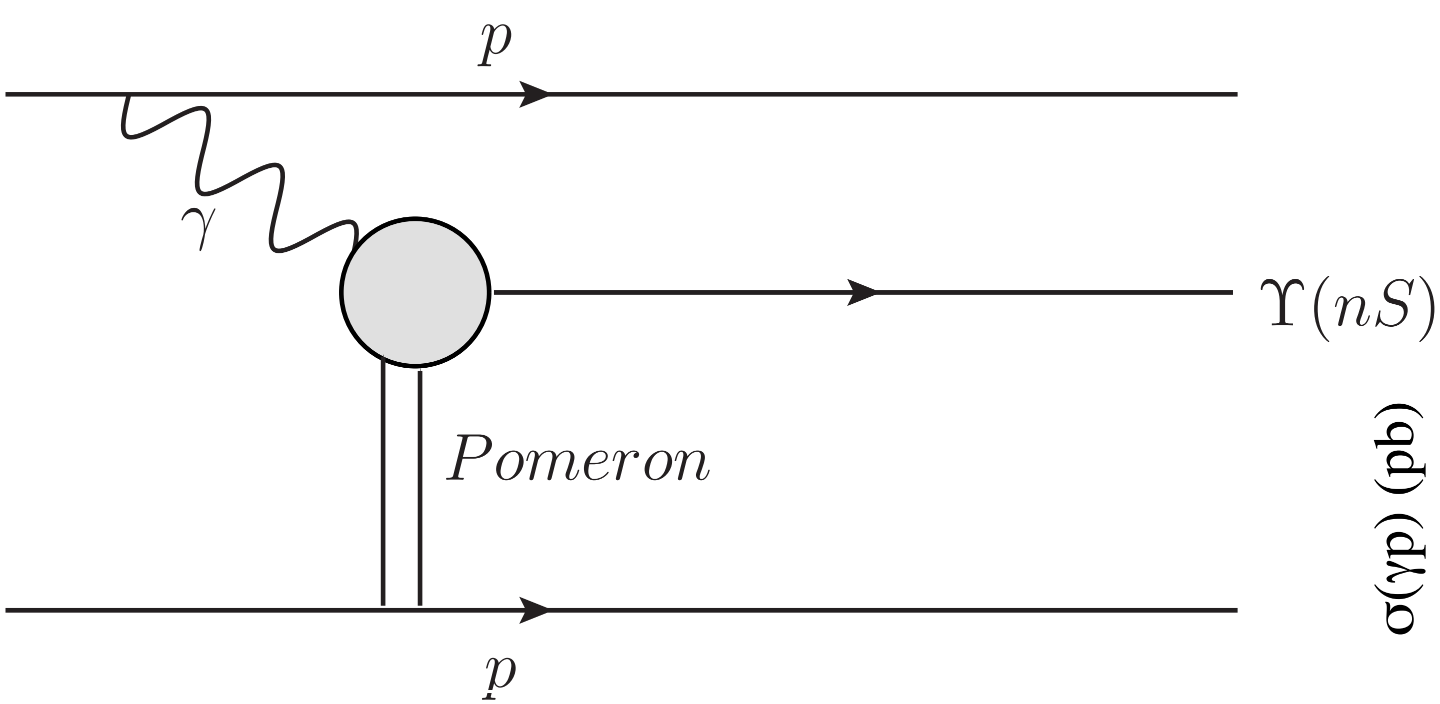


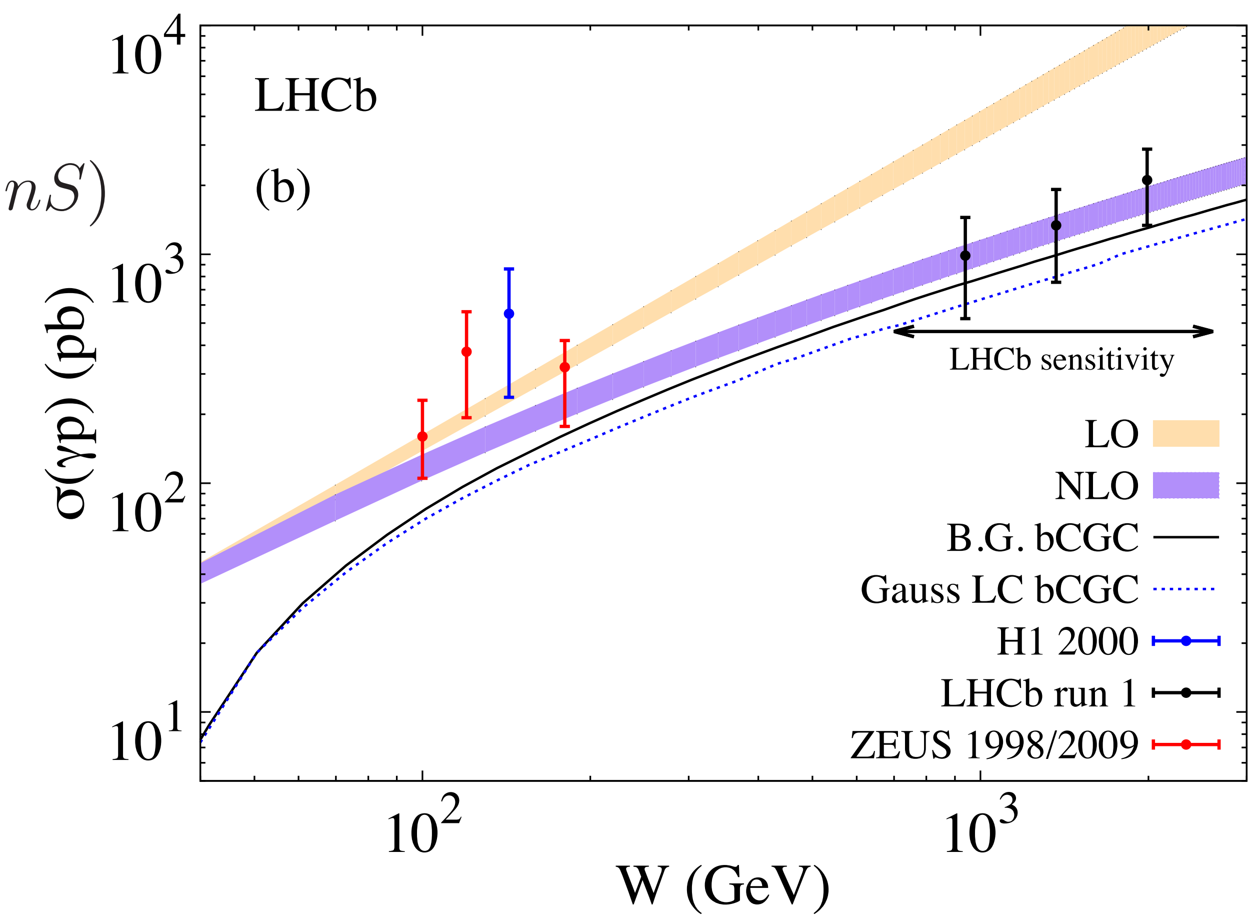
Expect much larger stats in Run 2; plan to also measure A_C(cc), along with σ(bb) and σ(cc) differentially.

Quarkonia

LHCb has published detailed differential measurements of ψ, ϒ, η_c, $\chi_{c,b}$ states. One of the more unique ones is via Central Exclusive Production:

LHCb-PAPER-2015-011: JHEP 09 (2015) 084





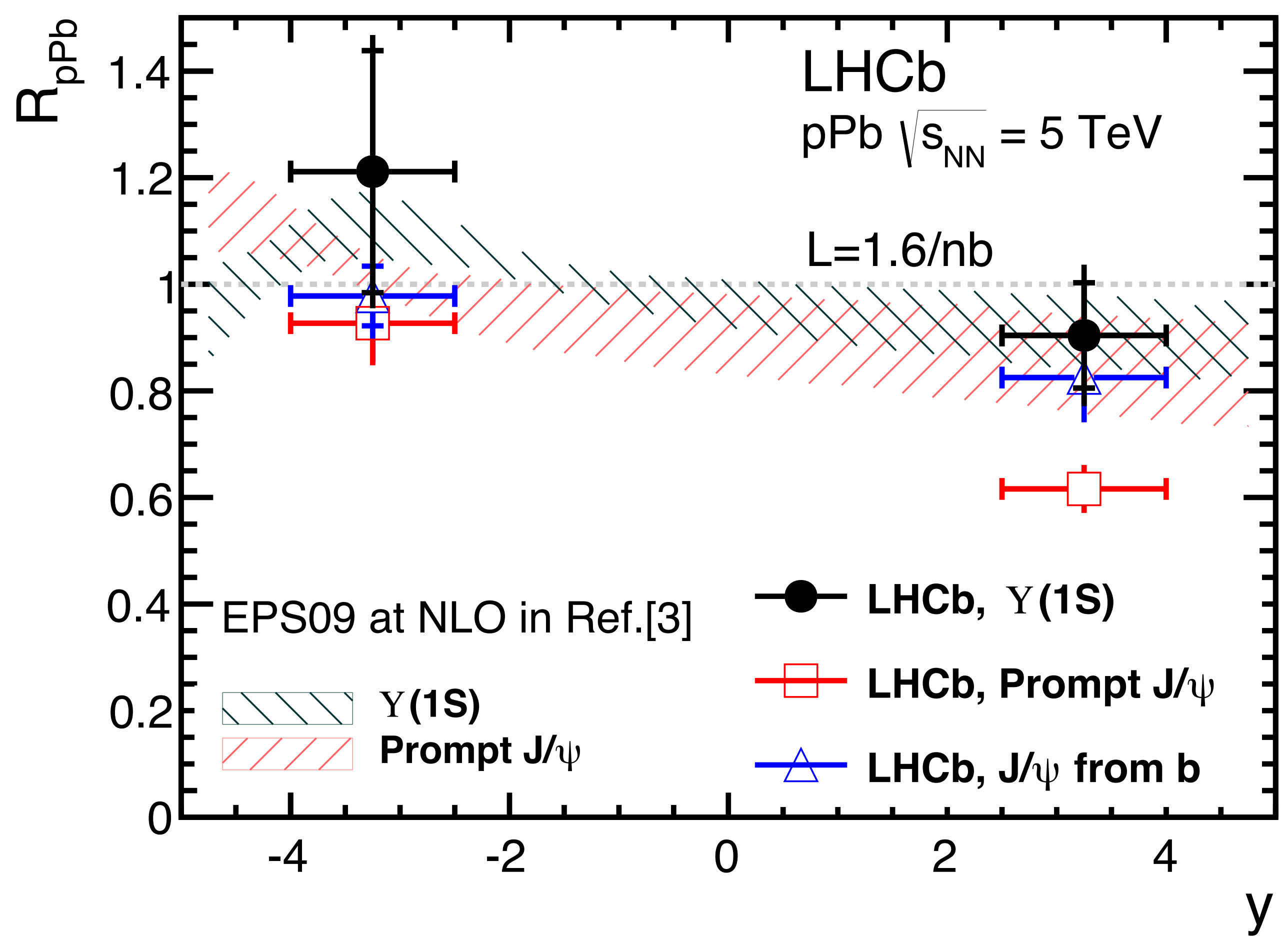
LHCb has also measured associated production of J/ψ + open charm and double open charm (c-c and c-cbar); these data are qualitatively consistent with double-parton scattering.

LHCb-PAPER-2012-003: JHEP 01 (2013) 90
LHCb-PAPER-2015-046

Heavy Ions

Cold nuclear matter effects studied in Pb-p vs p-Pb, each compared to reference p-p data, show a large suppression in the forward region:

Pb-p vs p-Pb
LHCb-PAPER-2014-015: JHEP 07 (2014) 094
LHCb-PAPER-2013-052: JHEP 02 (2014) 72



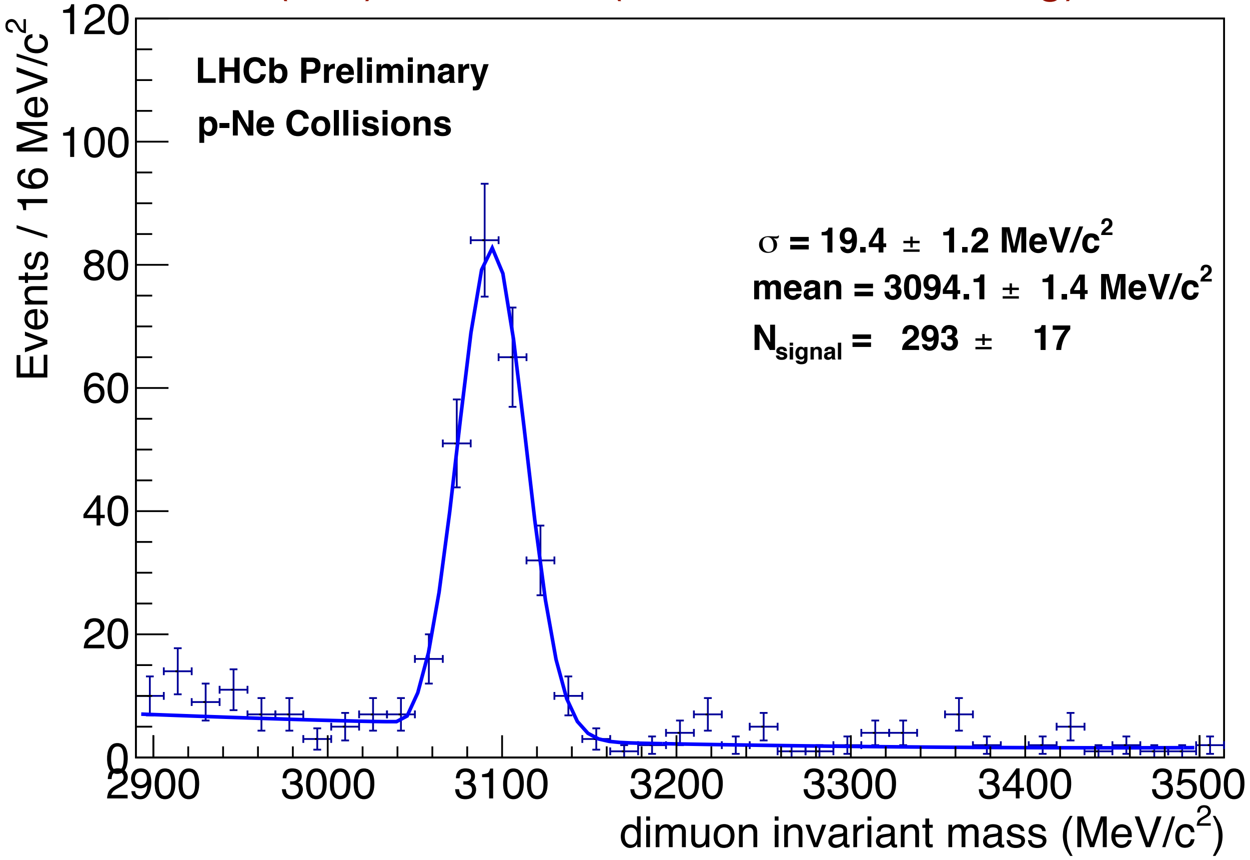
Ref [3] is Albacete et al [1301.3395]

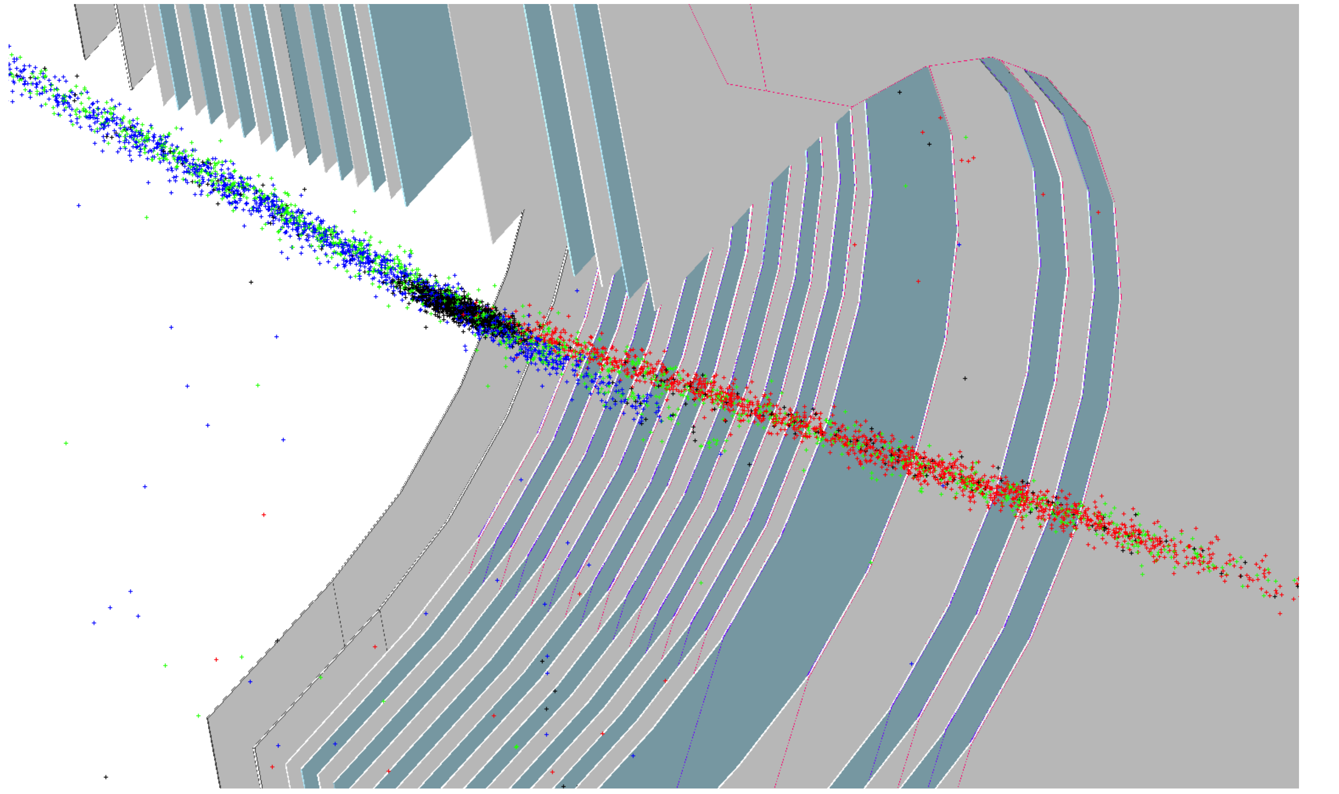
LHCb recently took Pb-Pb data too and we expect our heavy-ion program to continue to expand in the coming years.

SMOG

LHCb developed the **S**ystem for **M**easuring the **O**verlap with **G**as to obtain a high-precision (1%) luminosity measurement by injecting a noble gas into the VELO to profile the beams -- but also permits running in fixed-target mode!

E(CM)=110 GeV (~20 hours of running)



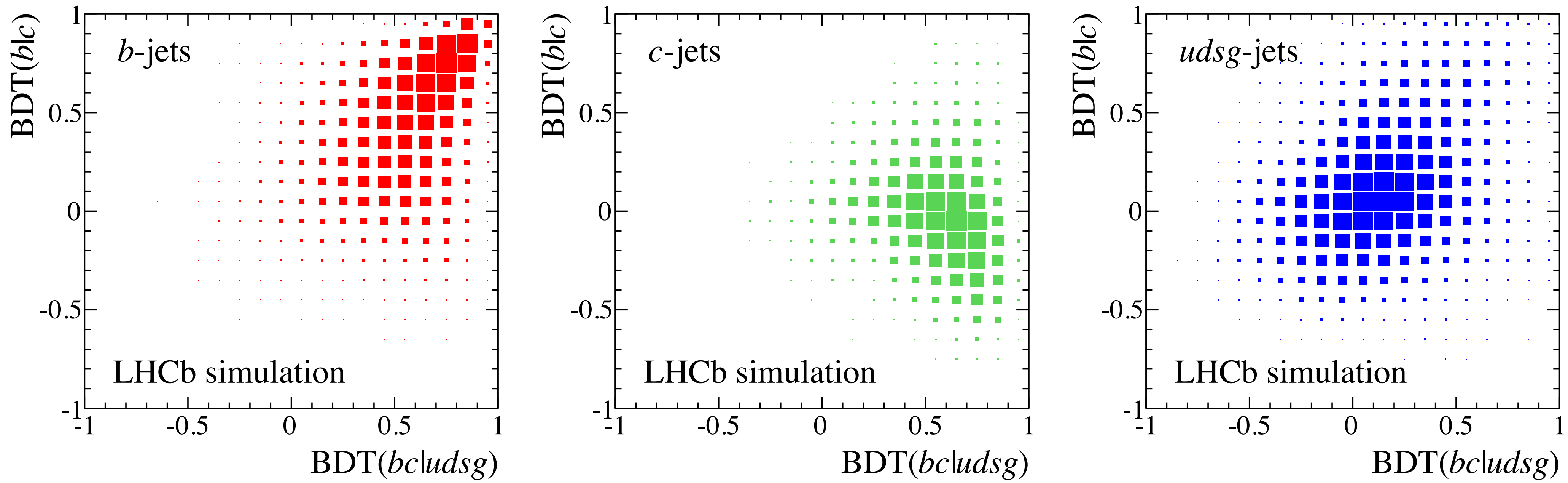


In fixed-target mode, LHCb is a central-backward detector that probes energy densities between that of the SPS and RHIC. Data collected: p-He, p-Ne, p-Ar and Pb-Ne, Pb-Ar.

Summary

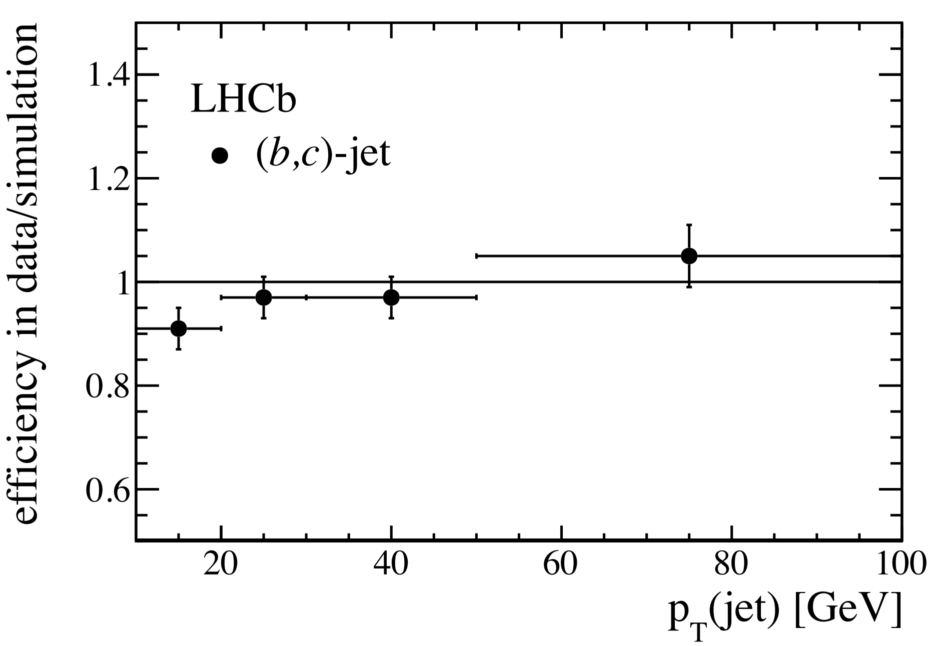
LHCb is a general-purpose detector in the forward region.

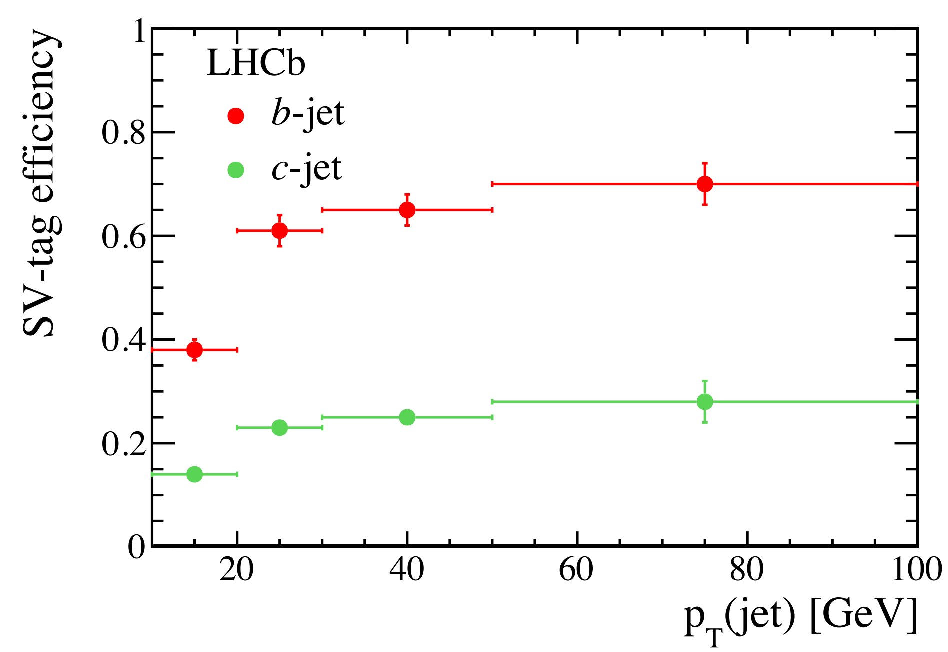
Jet Tagging



JINST 10 (2015) P06013
LHCb-PAPER-2015-016

Efficiencies are for 0.3% light-jet mis-tag.

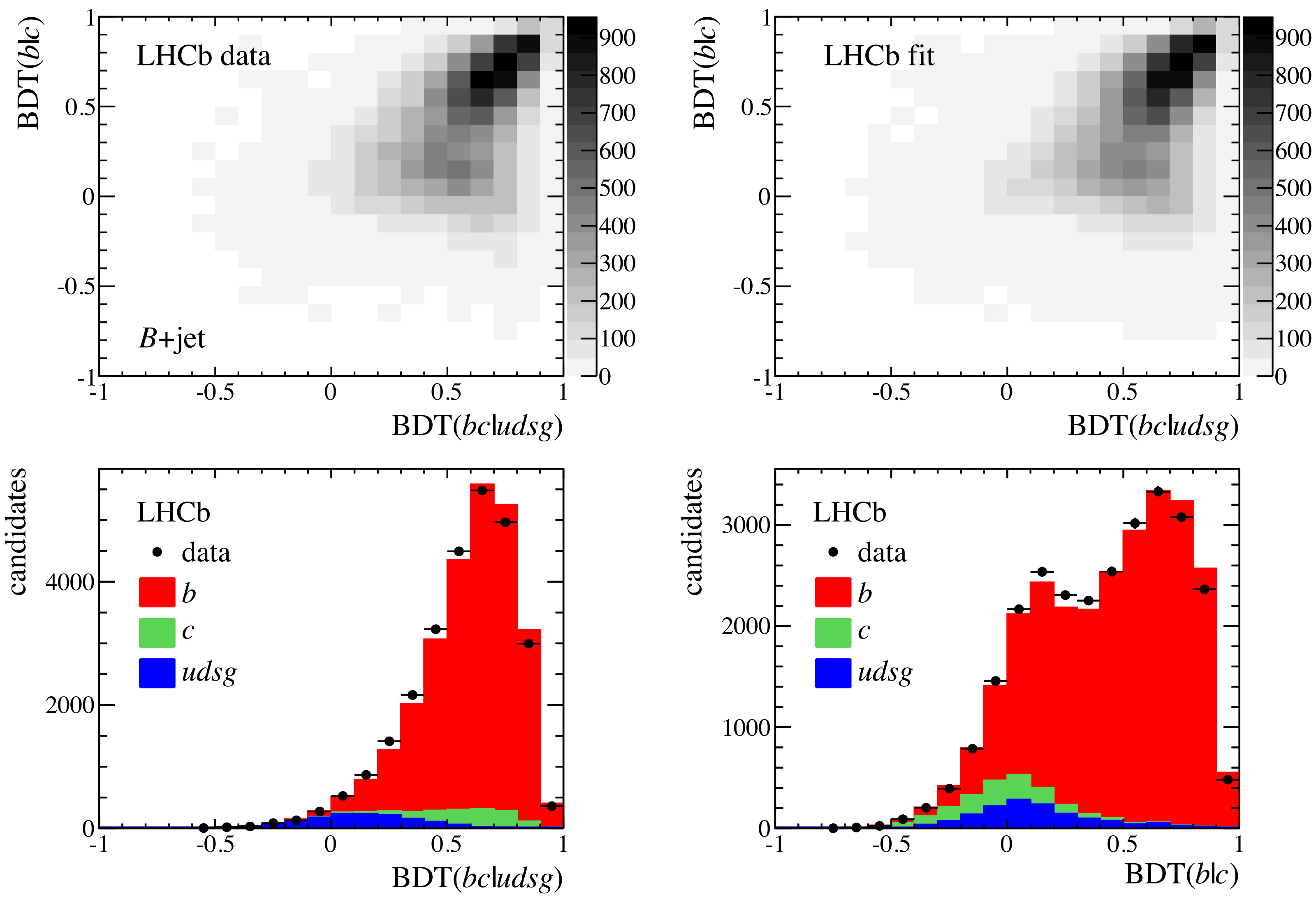




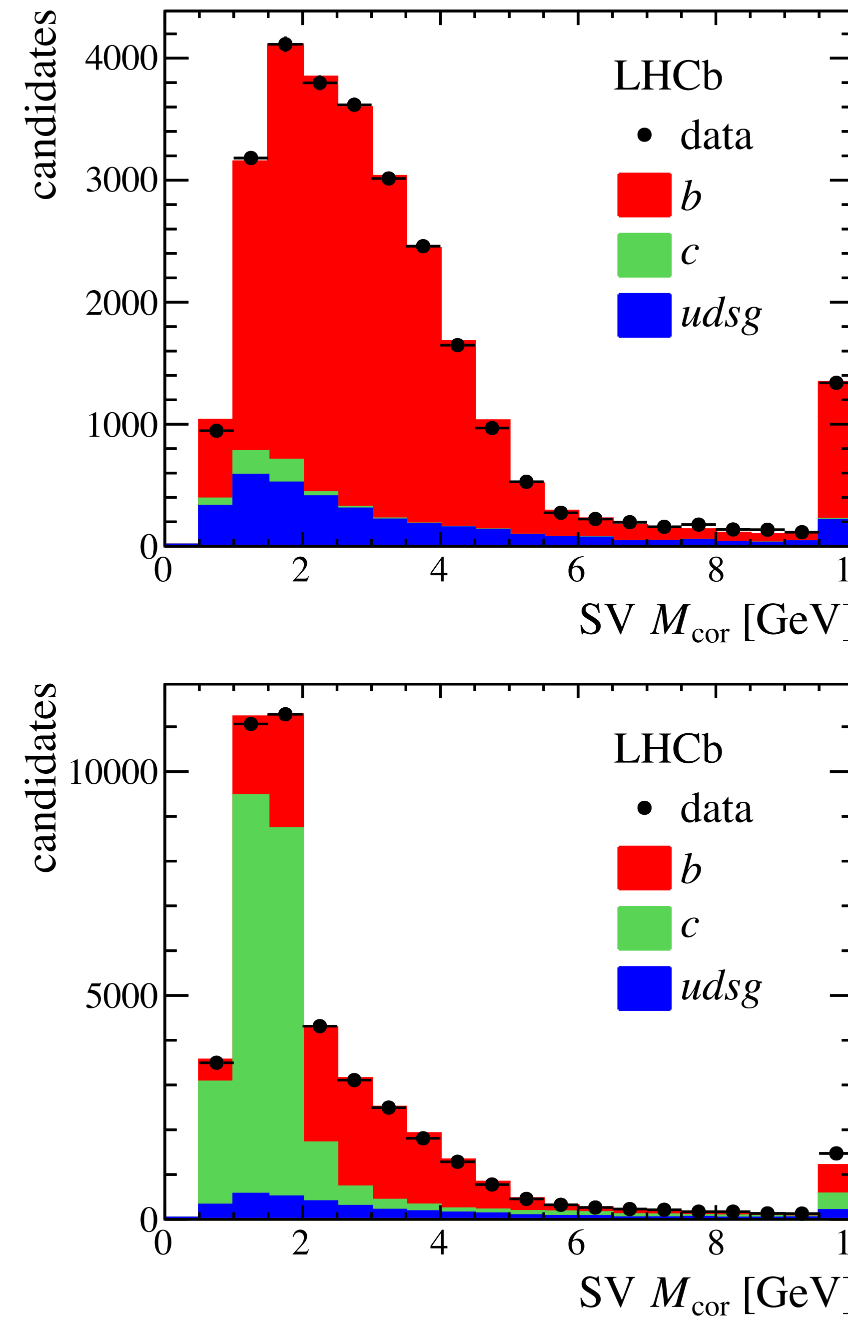
Jet Tagging

JINST 10 (2015) P06013
LHCb-PAPER-2015-016

BDT distributions for b-jet enriched data.



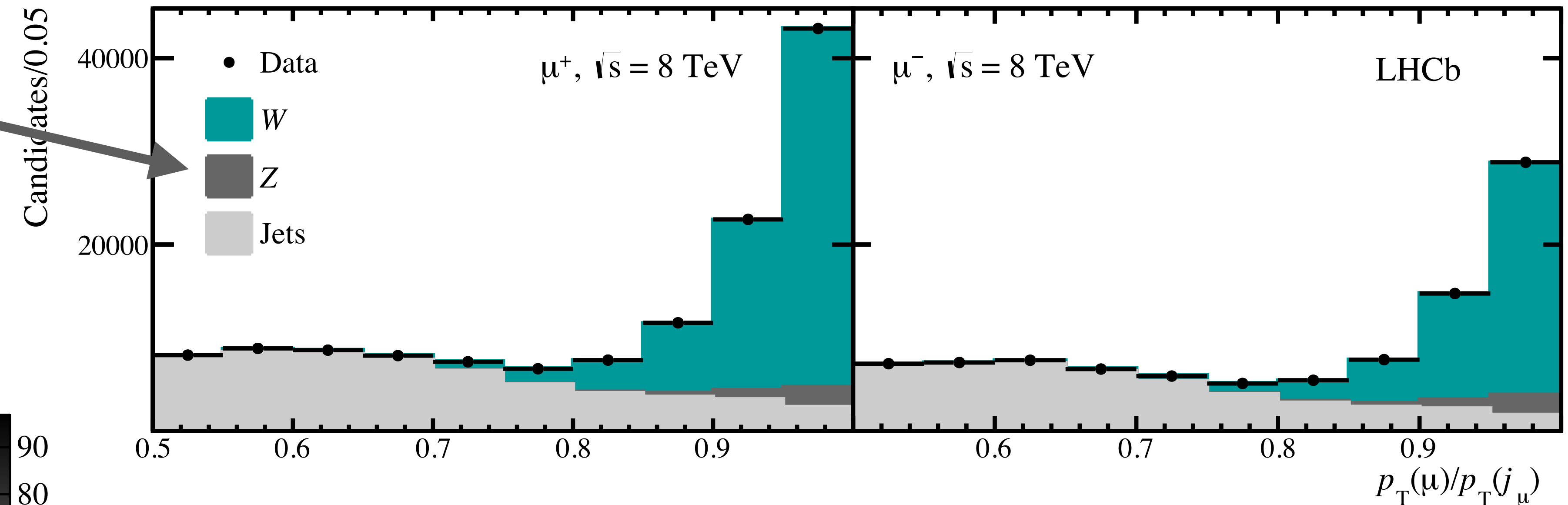
corrected mass in data for (top) b-jet enriched and (bottom) heavy-flavor enriched.



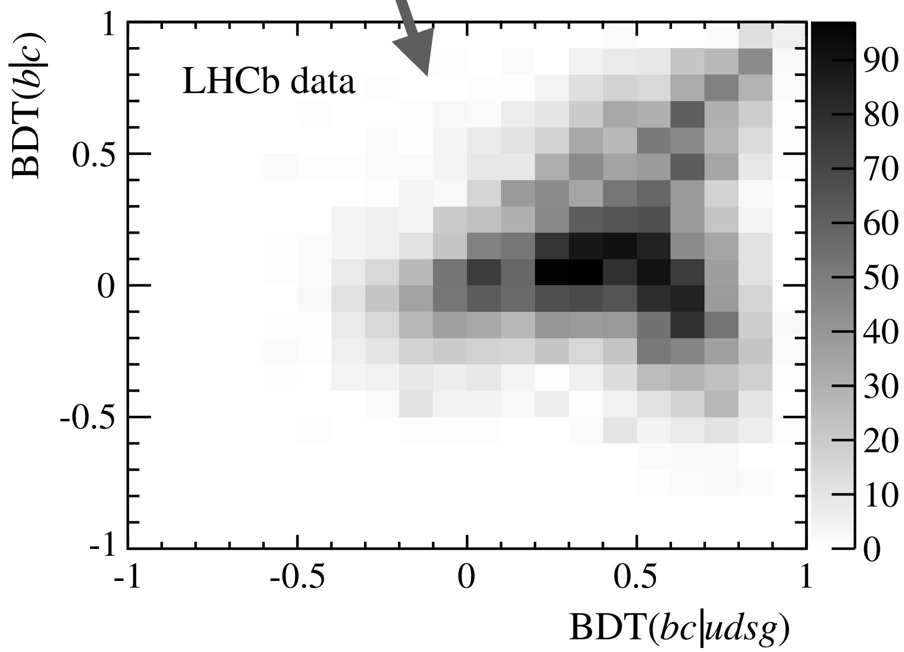
W+jet

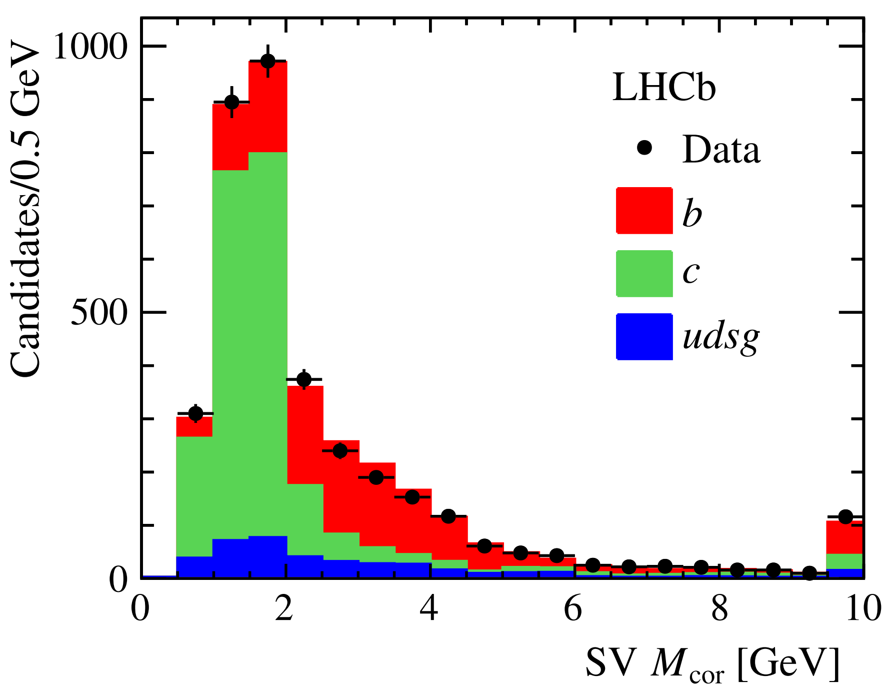
PRD 92 (2015) 052001
LHCb-PAPER-2015-021

W from fits to muon isolation.

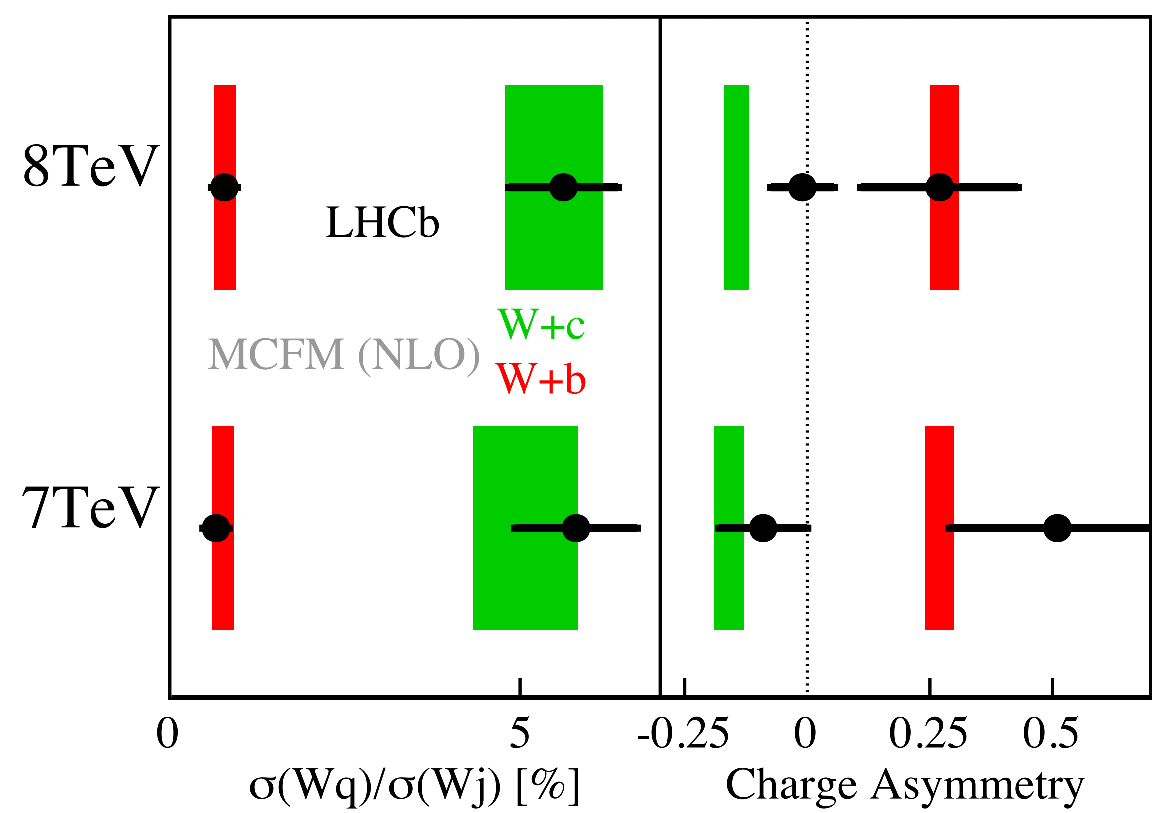


Jet flavor from 2-D BDT fits.





Run 1 results agree SM(CT10) predictions but stat limited.



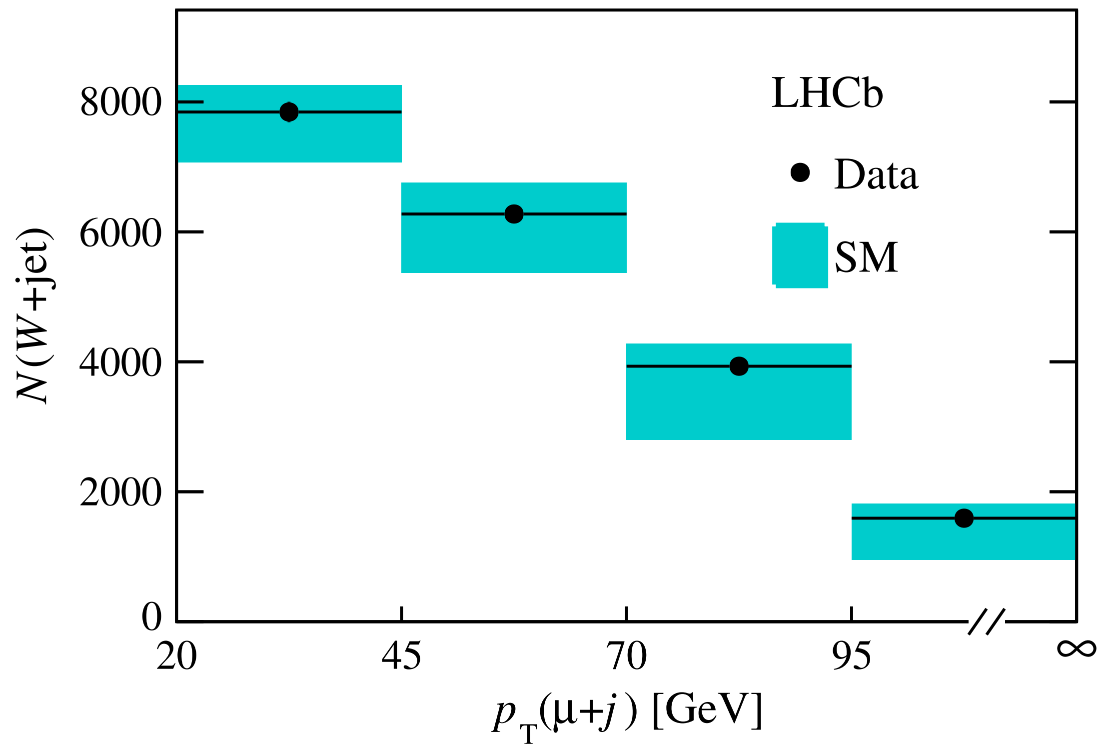
Expect much greater stats in Run 2; will be able to probe s vs s-bar PDFs using differential measurements.

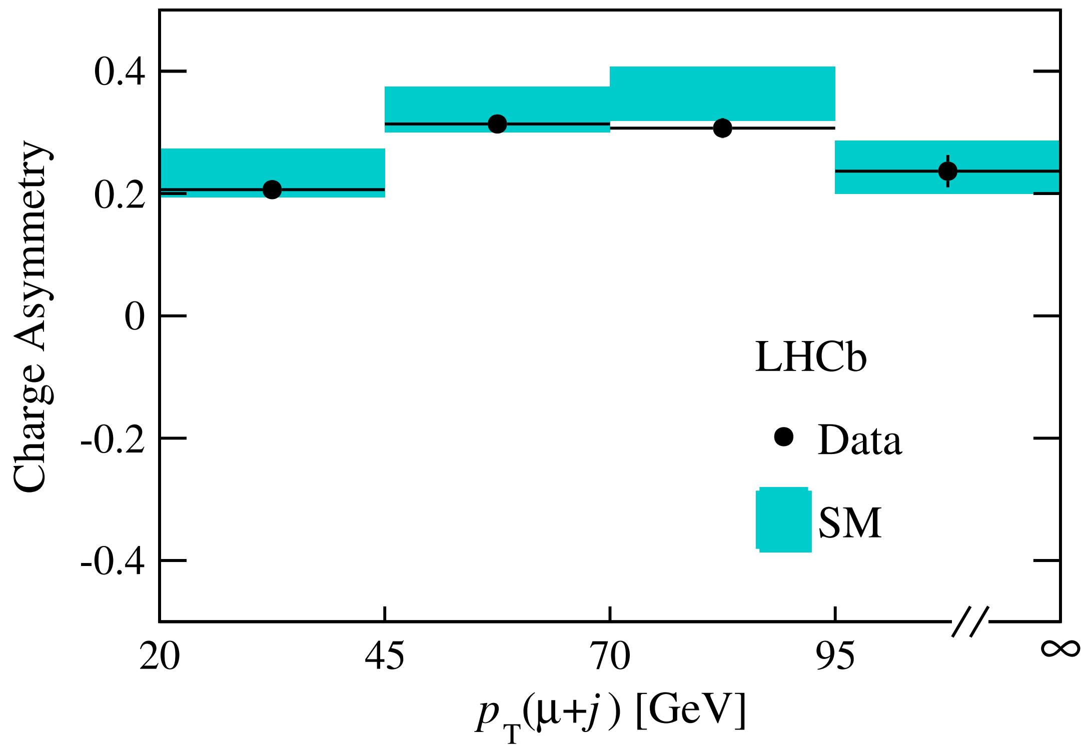
W+Jet

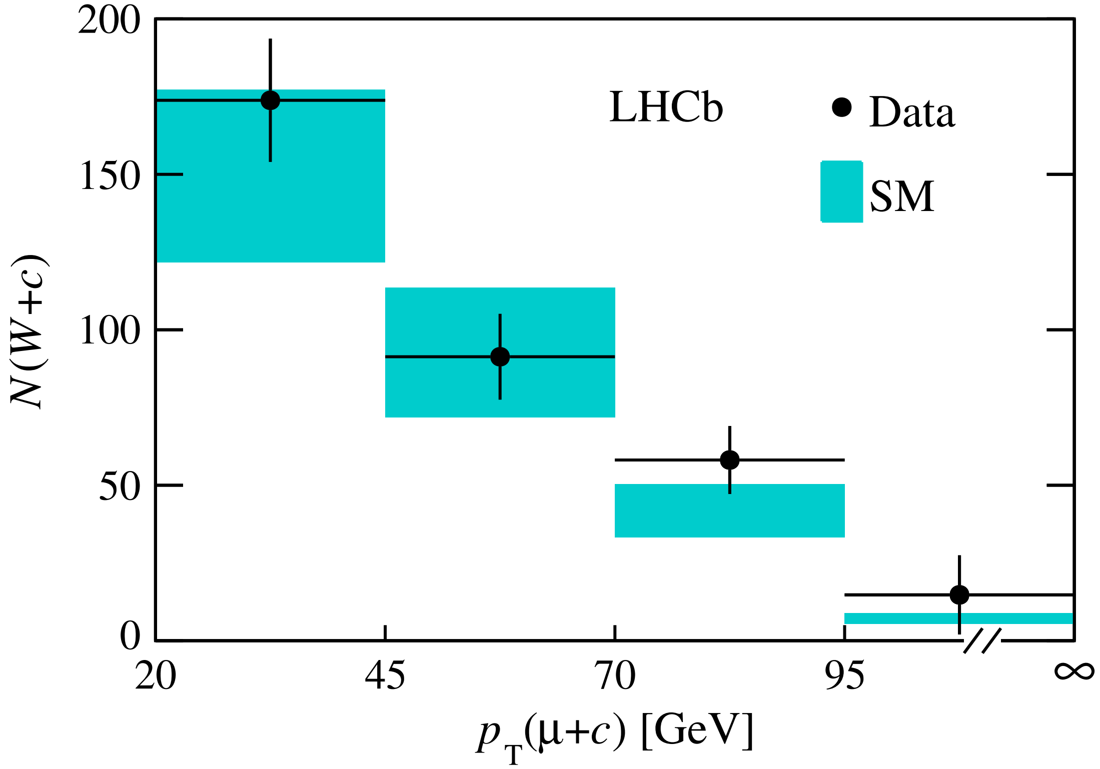
	Results		SM prediction	
	7 TeV	8 TeV	7 TeV	8 TeV
$\frac{\sigma(Wb)}{\sigma(Wj)} \times 10^2$	$0.66 \pm 0.13 \pm 0.13$	$0.78 \pm 0.08 \pm 0.16$	$0.74^{+0.17}_{-0.13}$	$0.77^{+0.18}_{-0.13}$
$\frac{\sigma(Wc)}{\sigma(Wj)} \times 10^2$	$5.80 \pm 0.44 \pm 0.75$	$5.62 \pm 0.28 \pm 0.73$	$5.02^{+0.80}_{-0.69}$	$5.31^{+0.87}_{-0.52}$
$\mathcal{A}(Wb)$	$0.51 \pm 0.20 \pm 0.09$	$0.27 \pm 0.13 \pm 0.09$	$0.27^{+0.03}_{-0.03}$	$0.28^{+0.03}_{-0.03}$
$\mathcal{A}(Wc)$	$-0.09 \pm 0.08 \pm 0.04$	$-0.01 \pm 0.05 \pm 0.04$	$-0.15^{+0.02}_{-0.04}$	$-0.14^{+0.02}_{-0.03}$
$\frac{\sigma(W^+j)}{\sigma(Zj)}$	$10.49 \pm 0.28 \pm 0.53$	$9.44 \pm 0.19 \pm 0.47$	$9.90^{+0.28}_{-0.24}$	$9.48^{+0.16}_{-0.33}$
$\frac{\sigma(W^-j)}{\sigma(Zj)}$	$6.61 \pm 0.19 \pm 0.33$	$6.02 \pm 0.13 \pm 0.30$	$5.79^{+0.21}_{-0.18}$	$5.52^{+0.13}_{-0.25}$

Top

Inclusive W+jet agrees with NLO SM from MCFM.





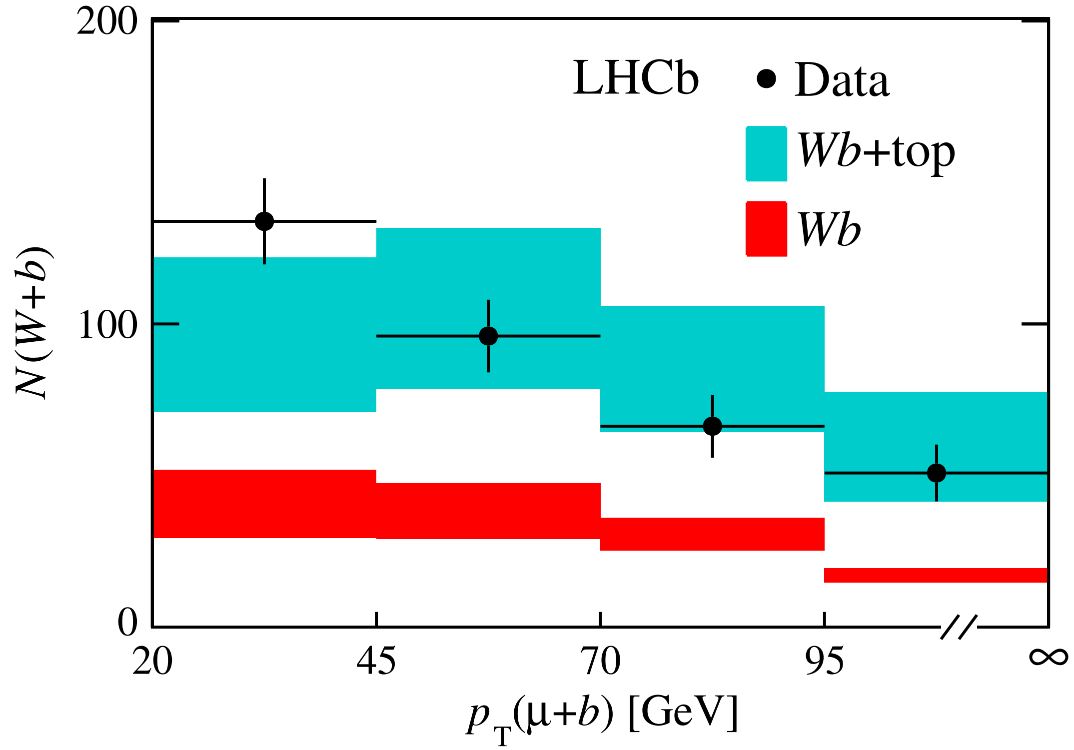


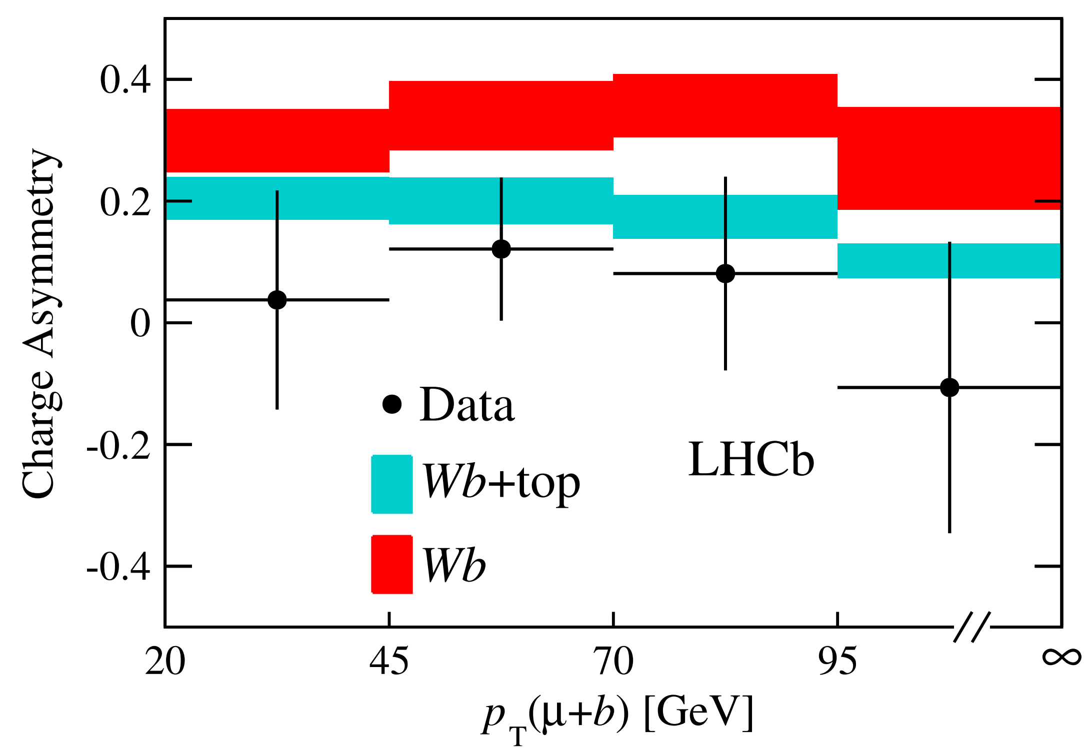
Same for W+c.

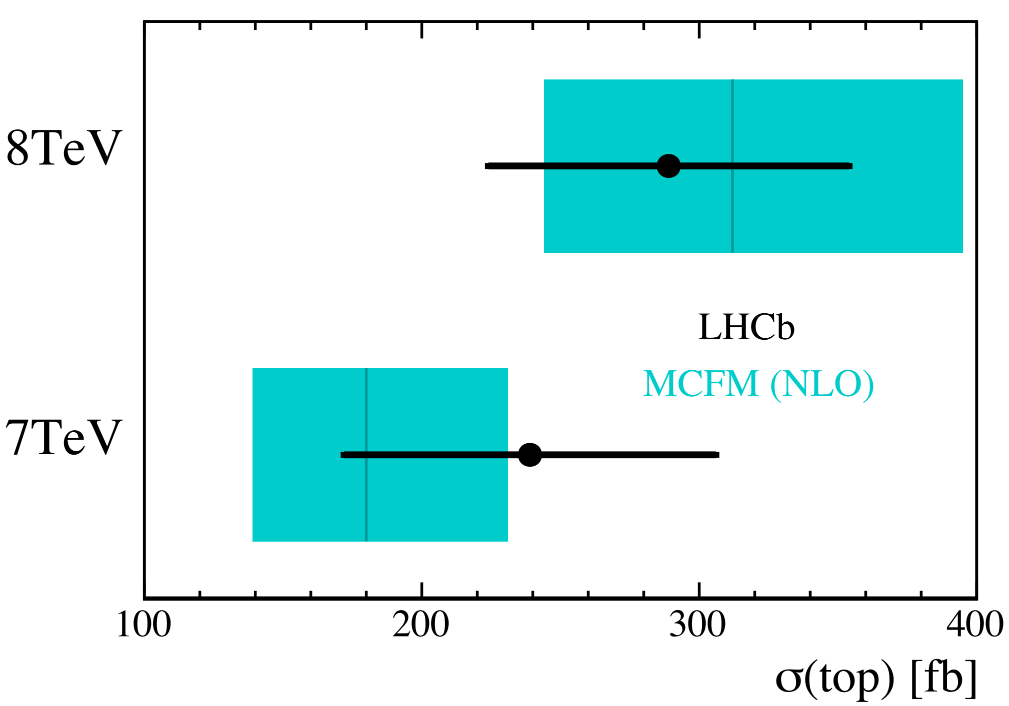
Top

PRL 115 (2015) 112001
LHCb-PAPER-2015-022

Data requires a top contribution (Wb validated in sidebands):





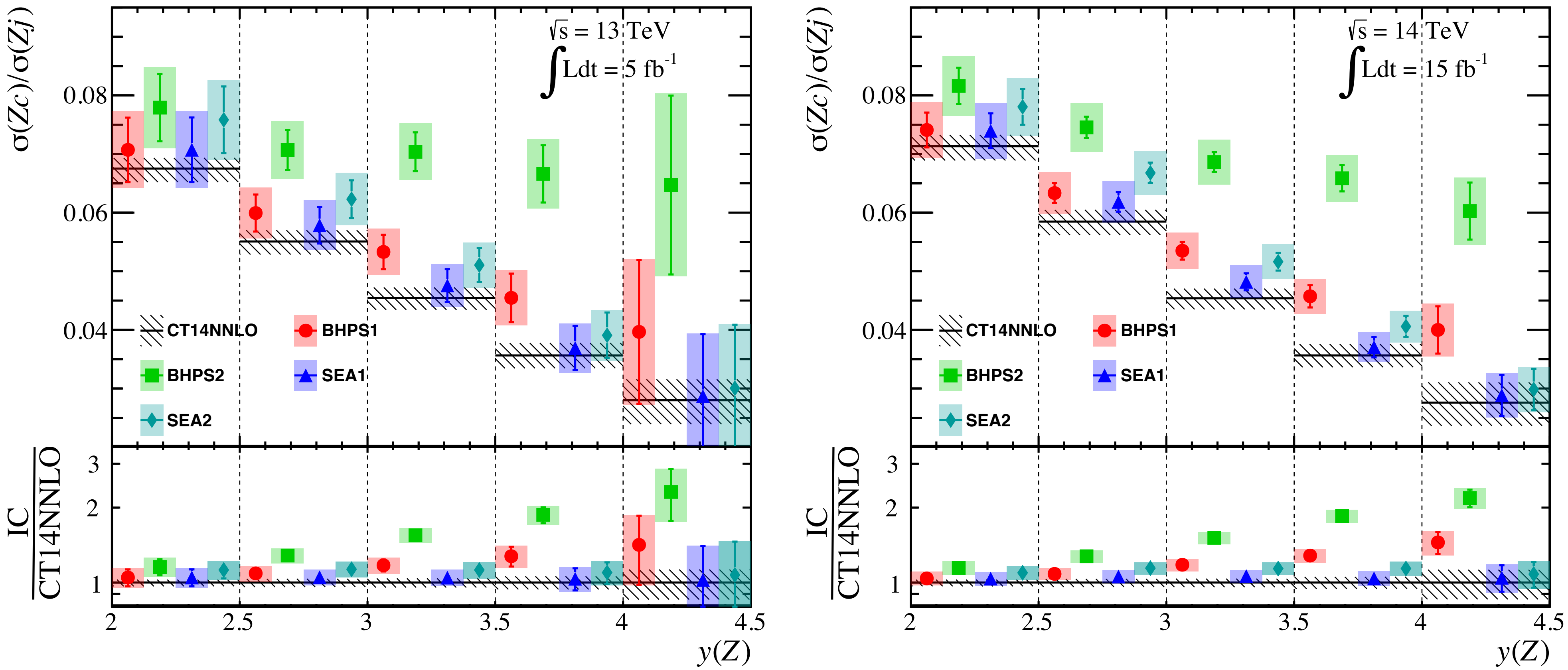


Results for $\sigma(t\bar{t}+t+\bar{t})$:

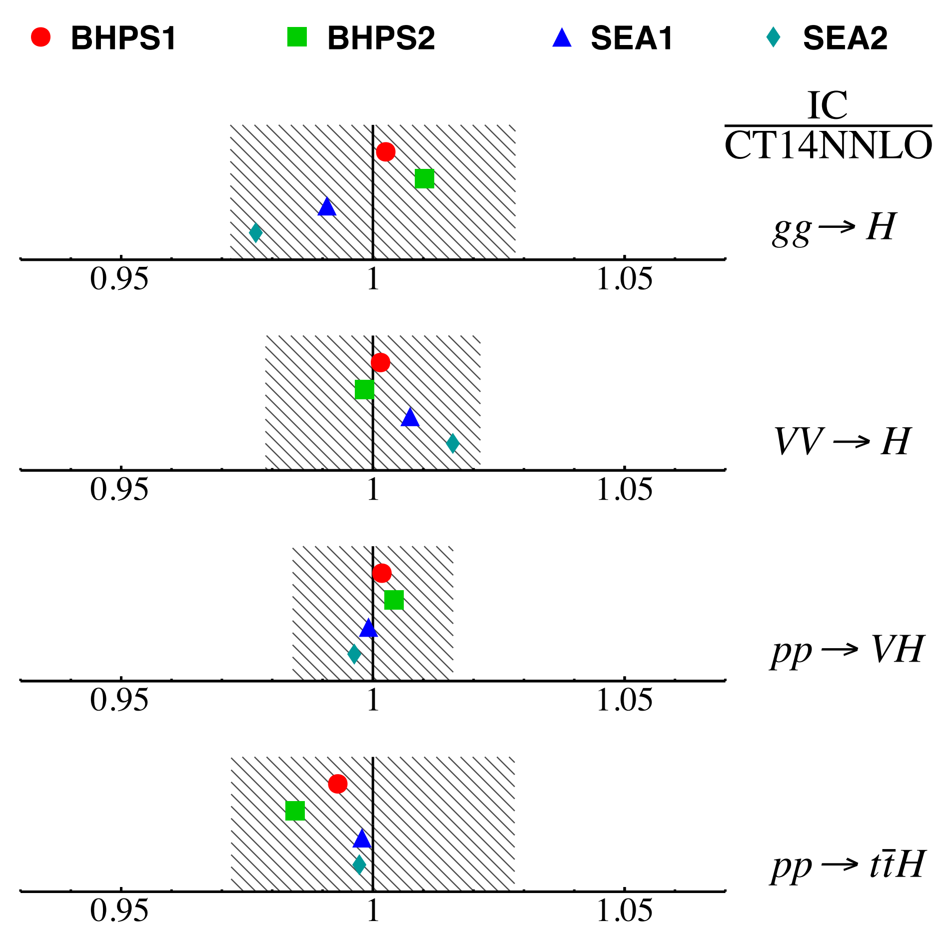
$$\sigma(\text{top})[7\text{ TeV}] = 239 \pm 53\,(\text{stat}) \pm 33\,(\text{syst}) \pm 24\,(\text{theory})\text{ fb}\,,$$

$$\sigma(\text{top})[8\text{ TeV}] = 289 \pm 43\,(\text{stat}) \pm 40\,(\text{syst}) \pm 29\,(\text{theory})\text{ fb}\,.$$

Intrinsic Charm



Predicted Zc/Zj results shown above for LHCb for Runs (left) 2 and (right) 3.



Potential impact on Higgs production in CMS/ATLAS show at right. For H+c (not shown), the effect of intrinsic charm is comparable to that of the SM charm Yukawa coupling!