Heavy Flavor Production in Hadronic and Nuclear Collisions at LHCb

Philip Ilten
on behalf of the LHCb Collaboration

Massachusetts Institute of Technology

February 15, 2017

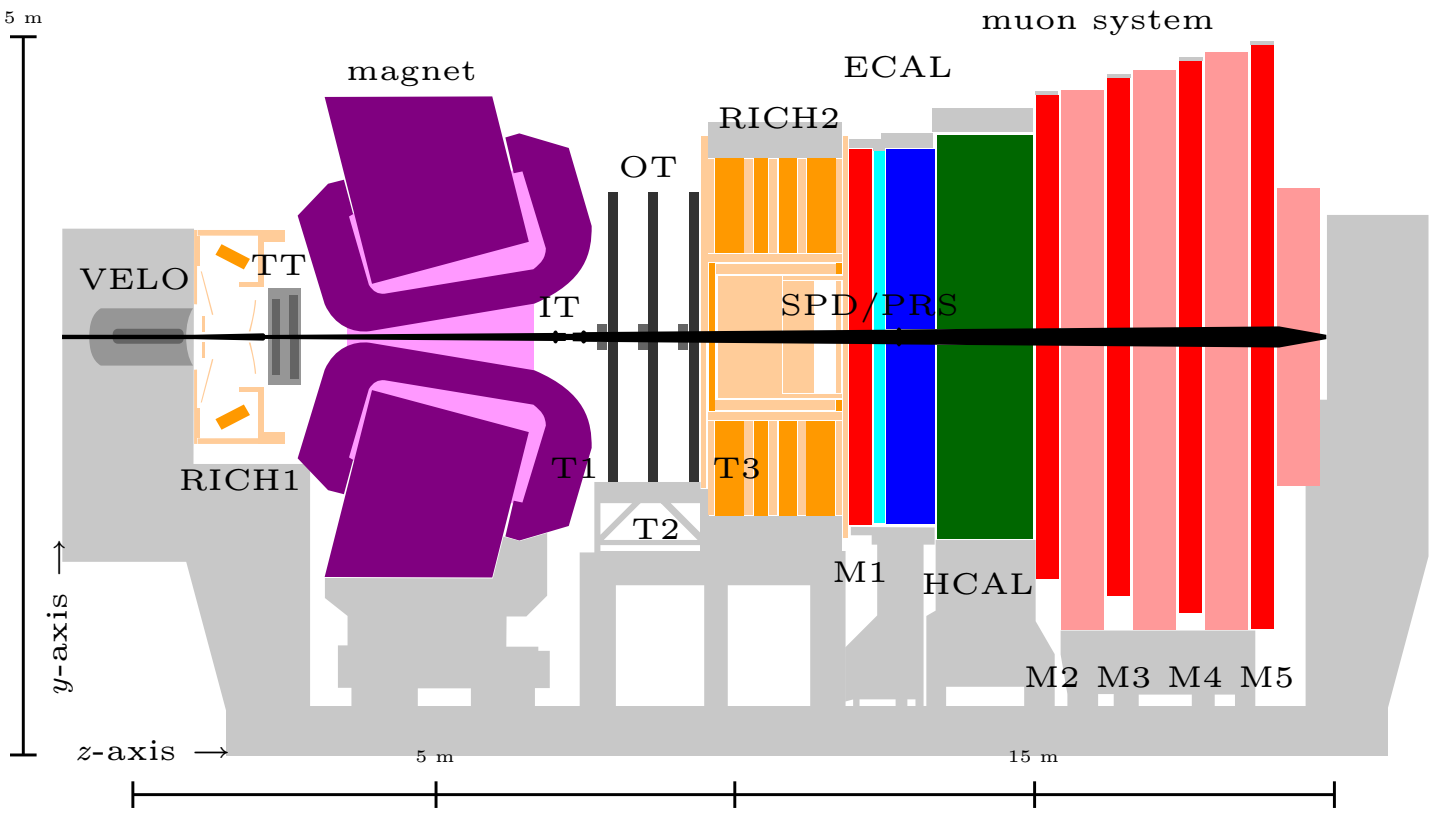
Santa Fe Jets and Heavy Flavor Workshop

Overview

- detector introduction
- inclusive heavy flavor jet tagging
- heavy quarks with $W + \text{jet}$
- intrinsic charm
- J/ψ production in jets

Detector

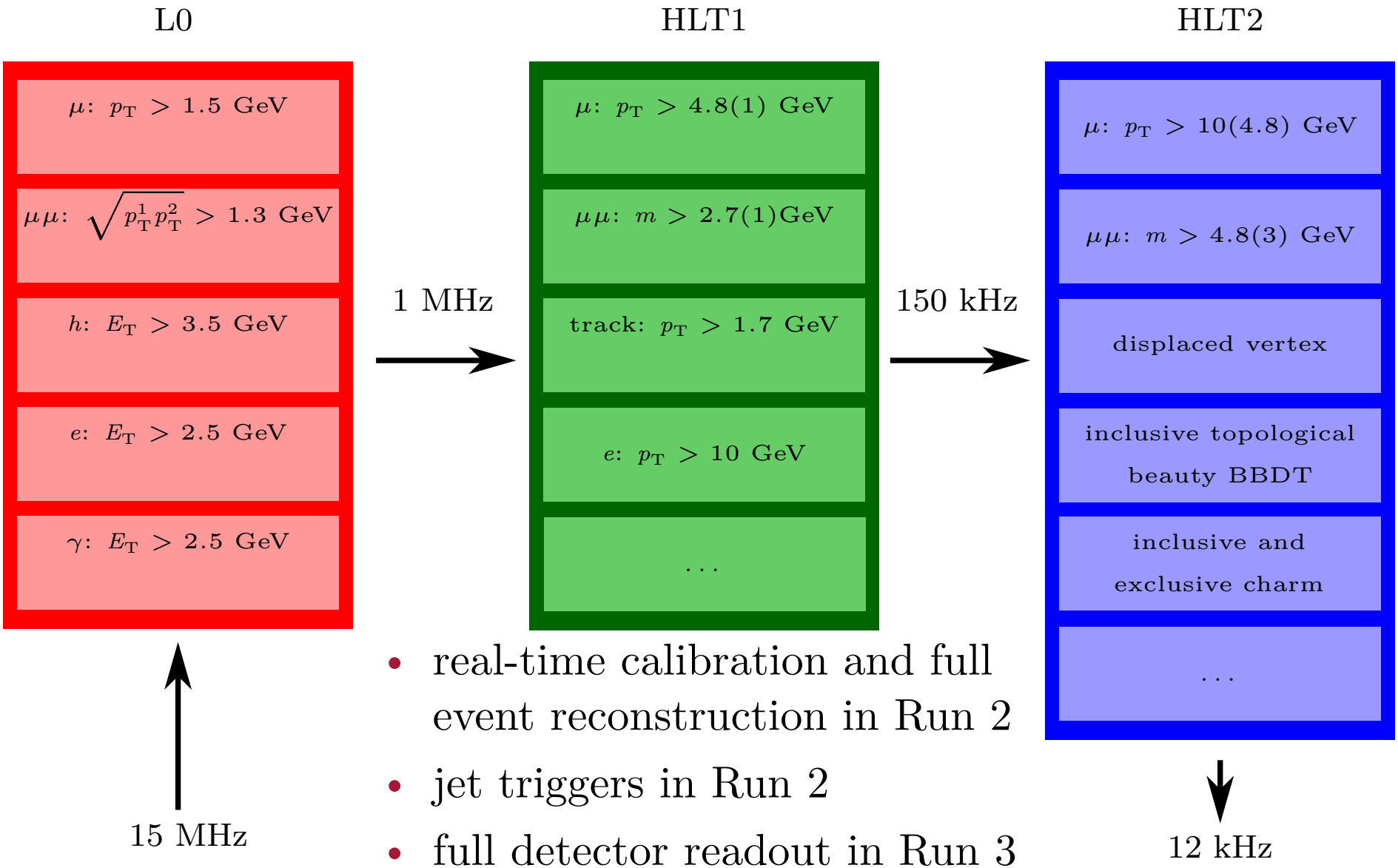
LHCb, IJMPA **30** (2015)



- fully instrumented between $2 < \eta < 5$
- momentum resolution between 0.5% at 5 GeV to 1% at 200 GeV
- impact parameter resolution of $13 - 20$ μm for tracks
- secondary vertex precision of $0.01 - 0.05(0.1 - 0.3)$ mm in $xy(z)$

Trigger

LHCb, JINST 8 (2013) P04022



- real-time calibration and full event reconstruction in Run 2
- jet triggers in Run 2
- full detector readout in Run 3

Datasets

V. Vagnoni (2015) HL-LHC

- projected luminosity per run

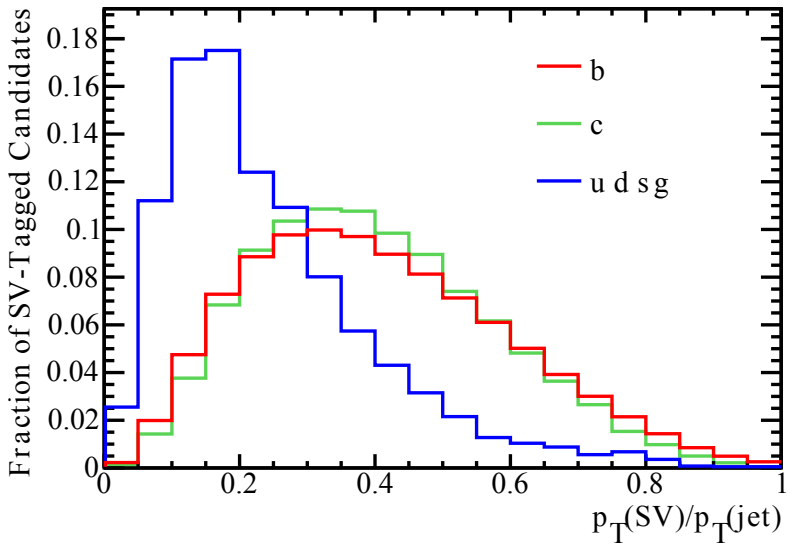
LHC era				HL-LHC era	
Run 1(a) 2011	Run 1(b) 2012	Run 2 2015 - 2019	Run 3 2021 - 2023	Run 4 2027 - 2029	Run 5 2031 - ?
1 fb^{-1}	2 fb^{-1}	5 fb^{-1}	15 fb^{-1}	23 fb^{-1}	300 fb^{-1}?

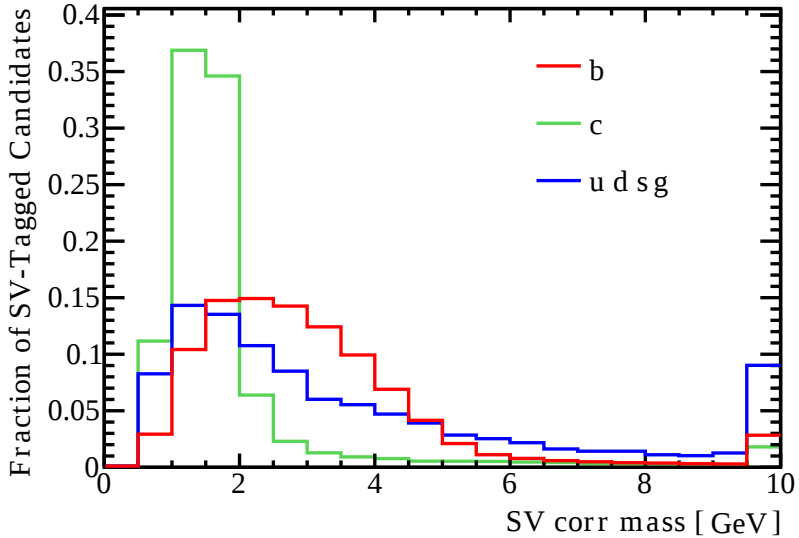
- LHCb upgrade during LS 2
  - LHCb-PUB-2014-040
  - replacement of readouts and photo-detectors for the RICHs
  - replacement of tracking detectors
  - **full software trigger**, see LHCb-TDR-016
    - currently limited by hardware readout at 1 MHz
    - upgrade will read out entire detector at 40 MHz

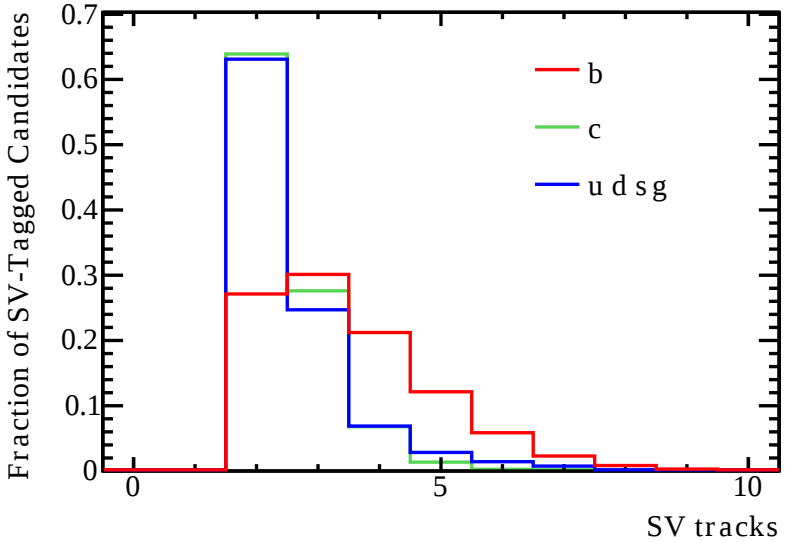
Heavy Flavor Jets

SV Observables

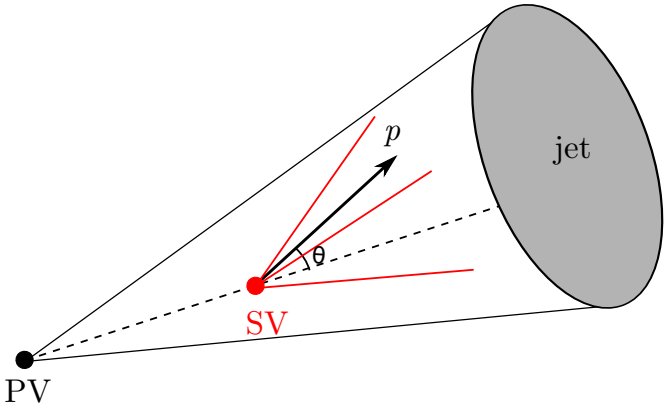
LHCb, JINST **10** (2015)





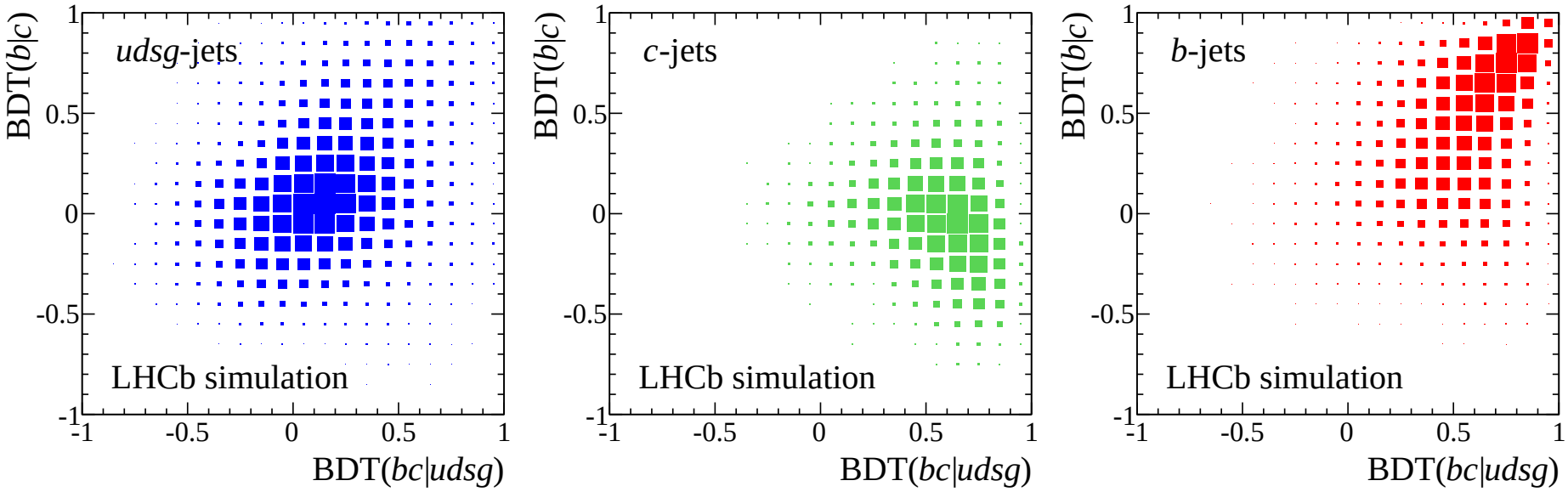


$$M_{\text{cor}} = \sqrt{M^2 + p^2 \sin^2\theta} + p \sin\theta$$



BDT Separation

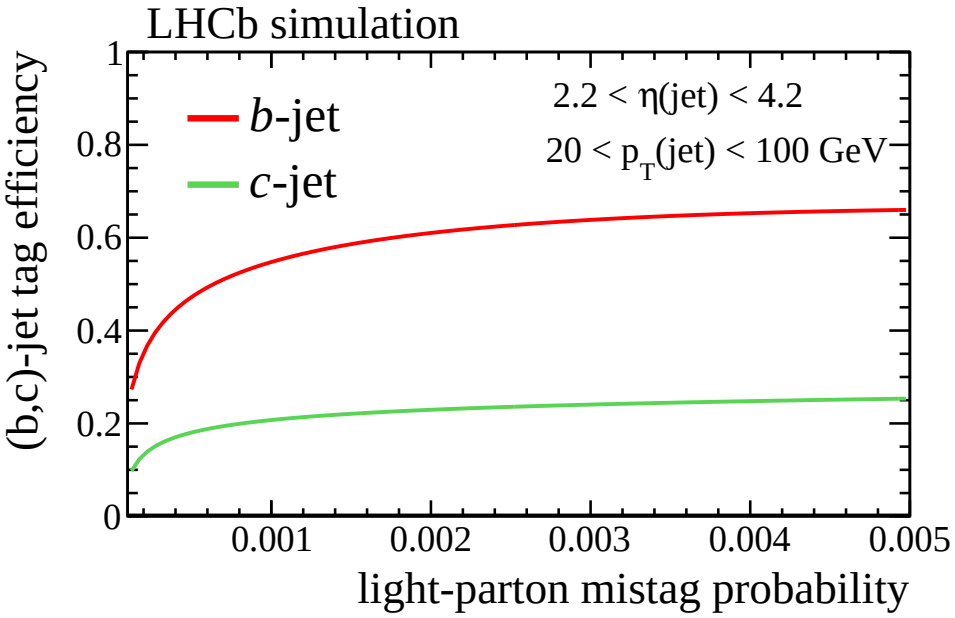
LHCb, JINST **10** (2015)

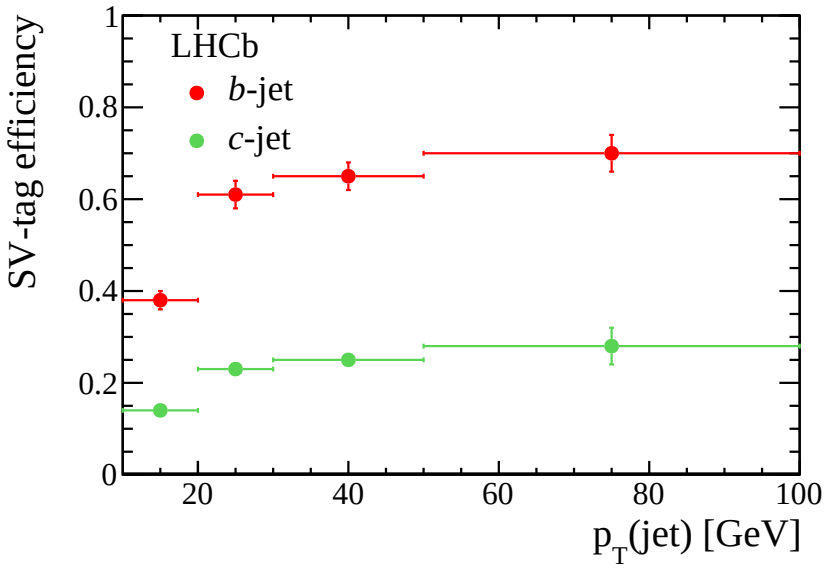


- BDT($bc|udsg$): c and b as signal, $udsg$ as background
- BDT($b|c$): b as signal c as background
- fit 2-dimensional BDT($bc|udsg$) versus BDT($b|c$) distribution

Efficiencies

LHCb, JINST **10** (2015)

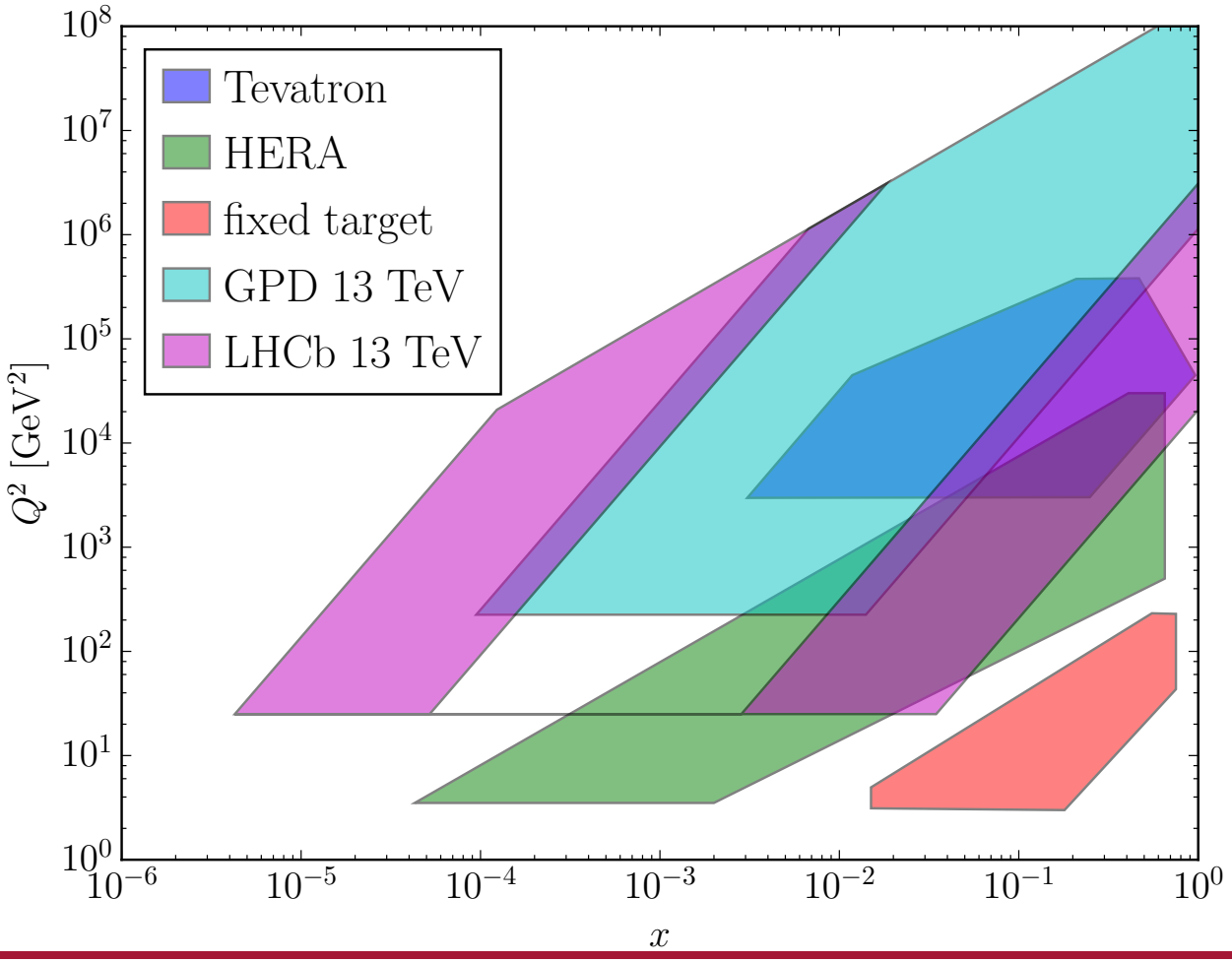




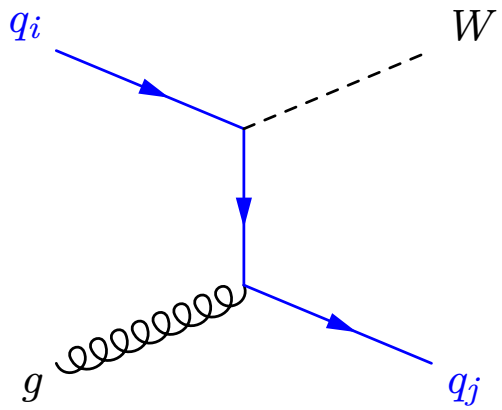
W+jet Measurements

Forward Kinematics

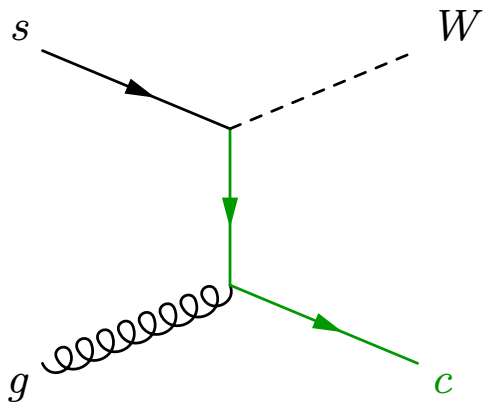
$$\sigma = \int xfx(f_1, x_1, Q^2) xfx(f_2, x_2, Q^2) \hat{\sigma} \, \mathrm{d}x_1 \mathrm{d}x_2, \quad x = \frac{Qe^{\mp y}}{\sqrt{s}}$$



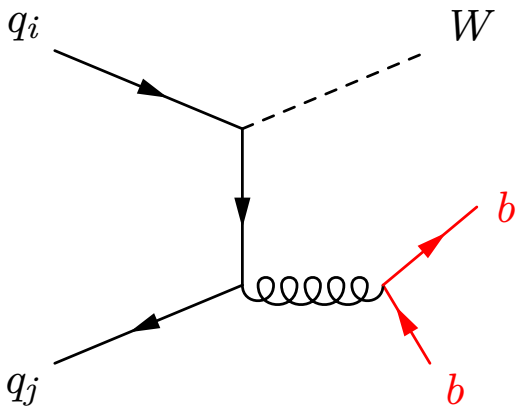
W+jet Production



W + $udsg$-jet

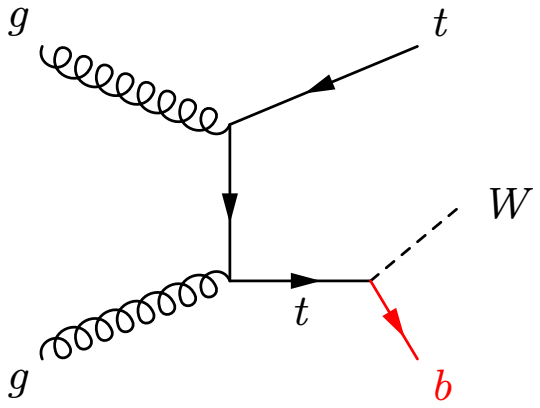


W + c-jet

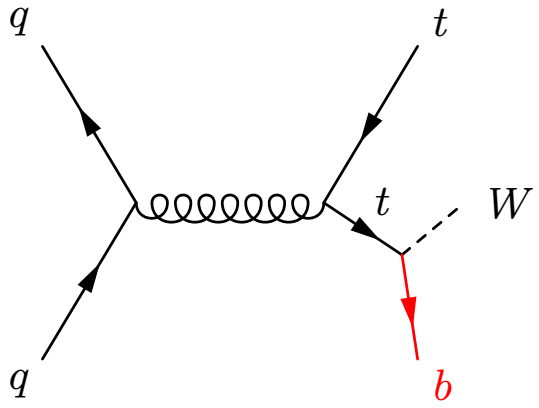


W + b-jet

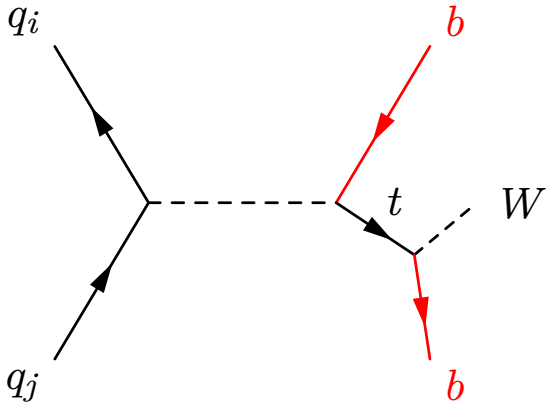
- sensitive to valence PDFs and strange quark asymmetries



gluon fusion



quark fusion

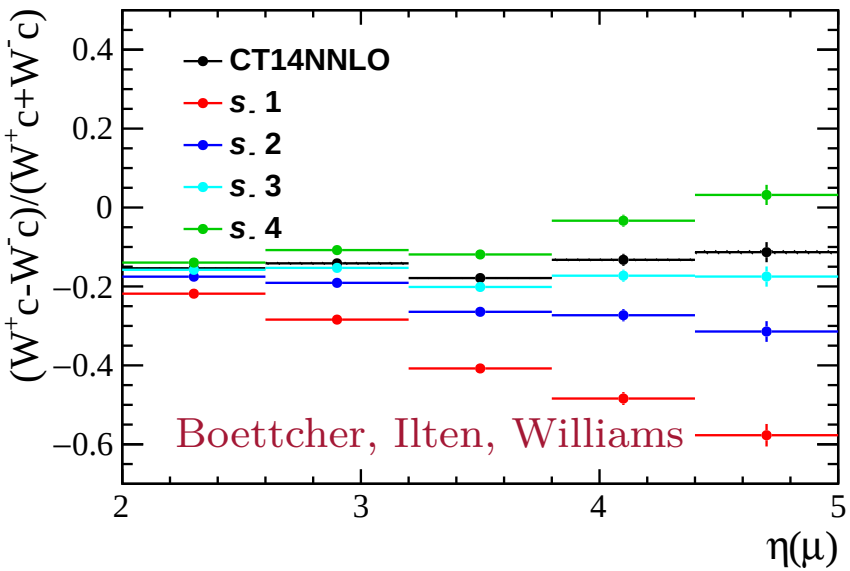


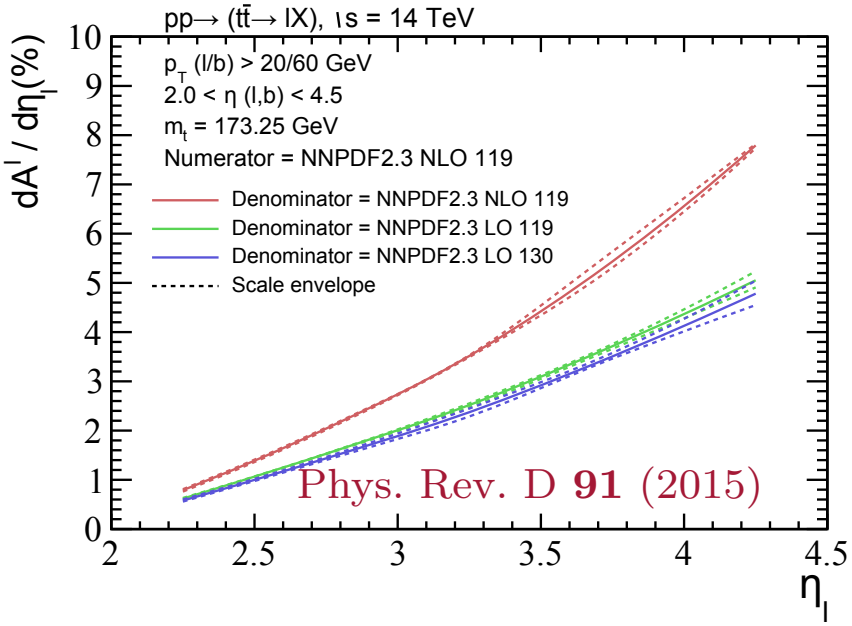
single top

- sensitive to the gluon PDF and top asymmetries

Strange and Top Asymmetries

- expect $\approx 2\%$ uncertainty on $\mathcal{A}(W\,c)$ from Run 2
- roughly 2% top asymmetry with 0.5% uncertainty from Run 3

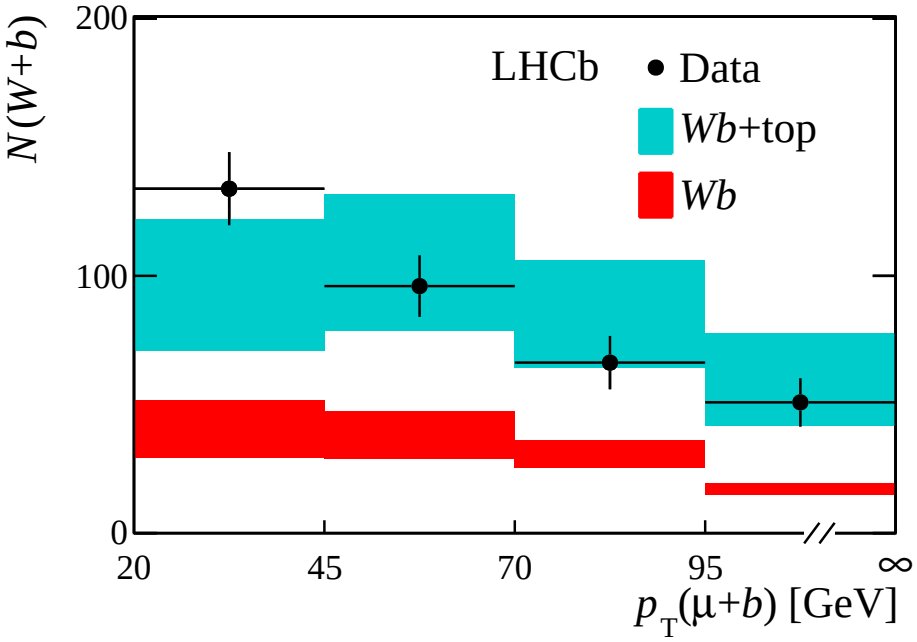


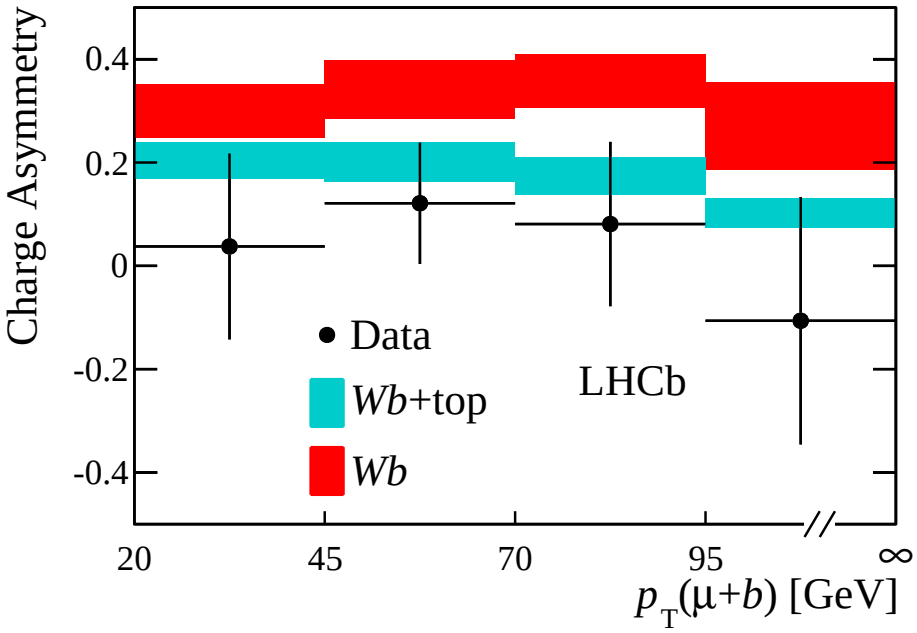


$$A^{\ell} = \frac{N(\ell^+) - N(\ell^-)}{N(\ell^+) + N(\ell^-)}$$

Analyses

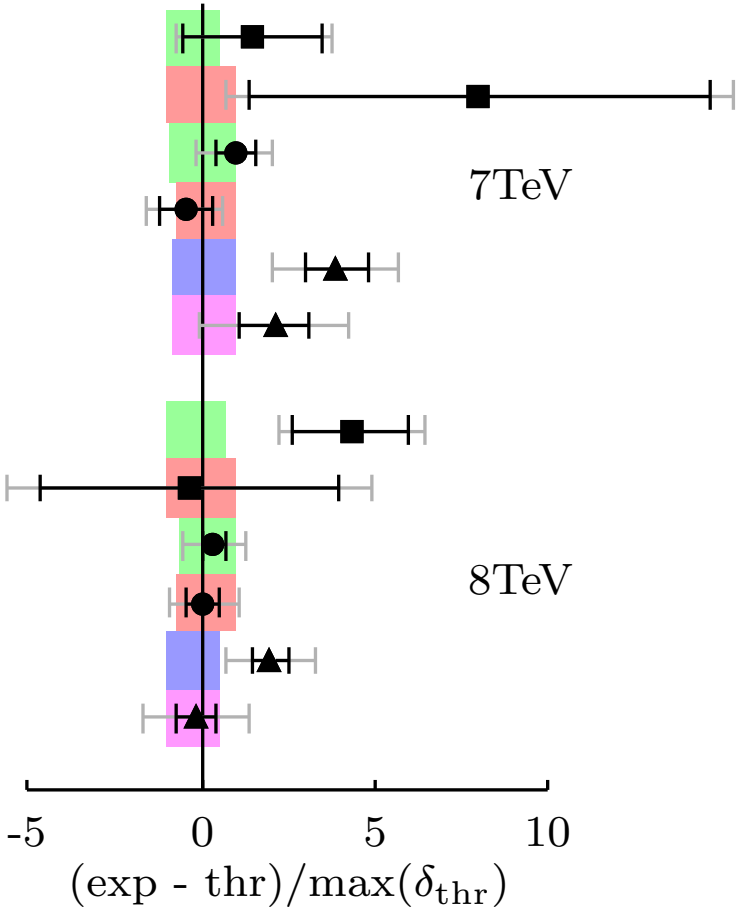
- LHCb, JINST **10** (2015): validation of performance
- LHCb, PRD **92** (2015): $W + c$ and $W + b$ measurement
- LHCb, PRL **115** (2015): first forward top measurement
- LHCb, PLB **767** (2017): $t\bar{t}$, $W + c\bar{c}$, and $W + b\bar{b}$



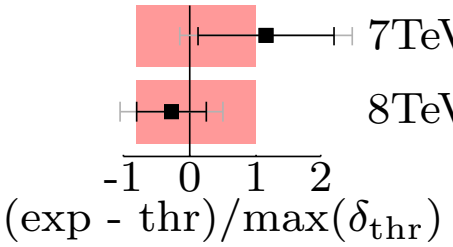


W+jet Results

LHCb, PRD **92** (2015)
LHCb, PRL **115** (2015)



$-0.09 \pm 0.08 \pm 0.04$	$\mathcal{A}(Wc)$
$0.51 \pm 0.20 \pm 0.09$	$\mathcal{A}(Wb)$
$5.80 \pm 0.44 \pm 0.75$	$\sigma(Wc)/\sigma(Wj) \times 10^2$
$0.66 \pm 0.13 \pm 0.13$	$\sigma(Wb)/\sigma(Wj) \times 10^2$
$6.61 \pm 0.19 \pm 0.33$	$\sigma(W^-j)/\sigma(Zj)$
$10.49 \pm 0.28 \pm 0.53$	$\sigma(W^+j)/\sigma(Zj)$
$-0.01 \pm 0.05 \pm 0.04$	$\mathcal{A}(Wc)$
$0.27 \pm 0.13 \pm 0.09$	$\mathcal{A}(Wb)$
$5.62 \pm 0.28 \pm 0.73$	$\sigma(Wc)/\sigma(Wj) \times 10^2$
$0.78 \pm 0.08 \pm 0.16$	$\sigma(Wb)/\sigma(Wj) \times 10^2$
$6.02 \pm 0.13 \pm 0.30$	$\sigma(W^-j)/\sigma(Zj)$
$9.44 \pm 0.19 \pm 0.47$	$\sigma(W^+j)/\sigma(Zj)$

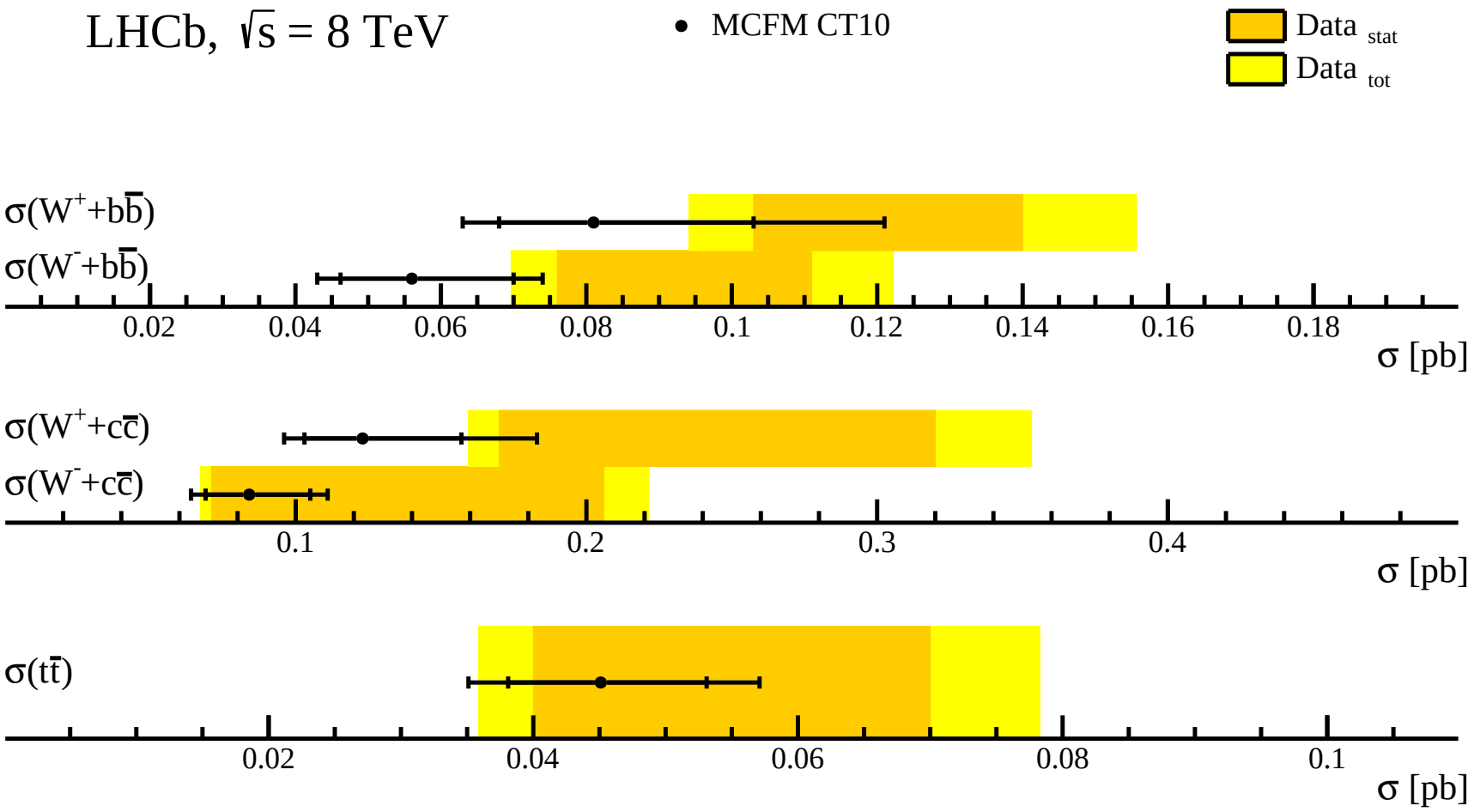


7TeV $239 \pm 53 \pm 41$ [fb]

8TeV $289 \pm 43 \pm 49$ [fb]

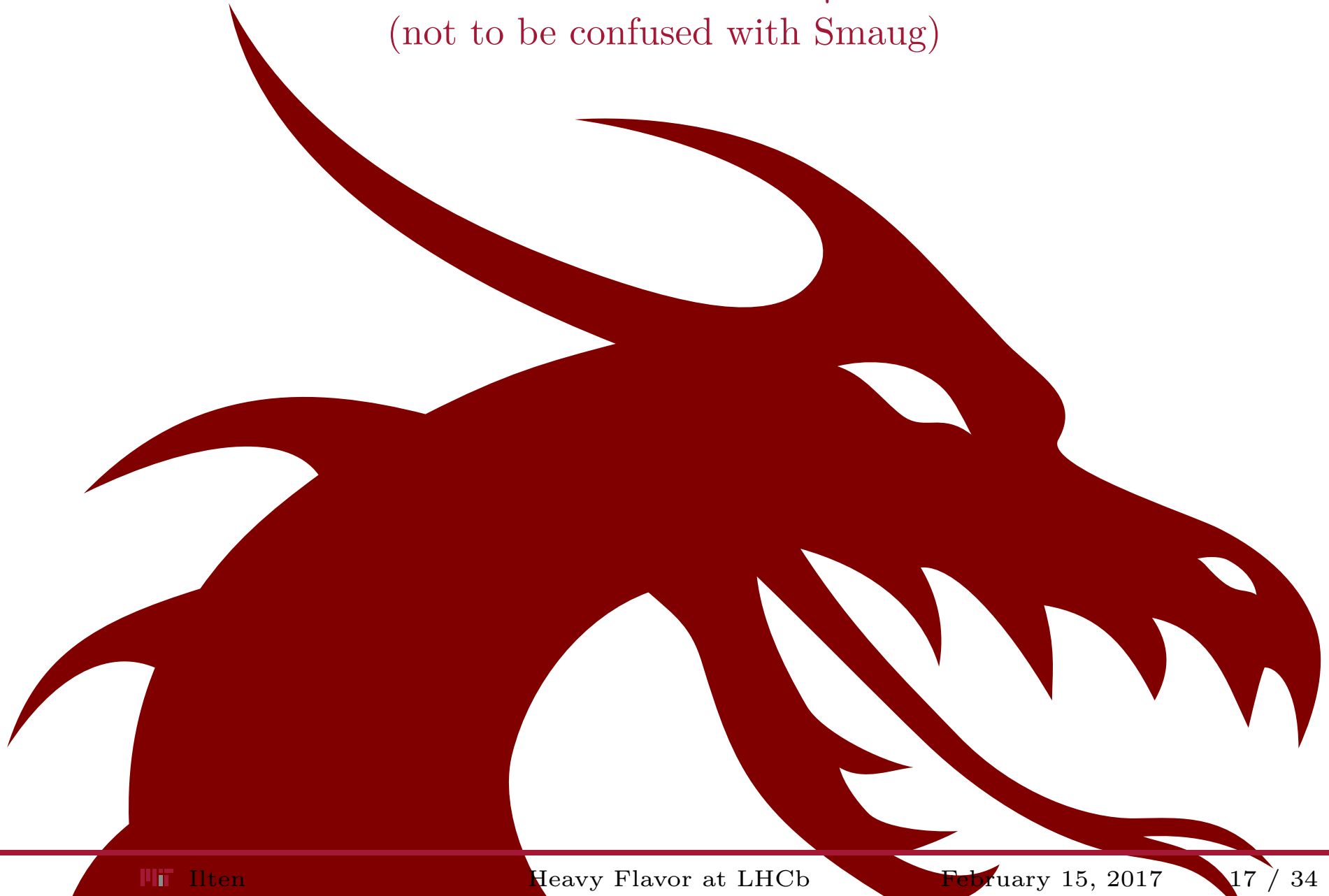
$W + Q\bar{Q}$ Results

LHCb, PLB **767** (2017)



Intrinsic Charm with $Z + c$ and SMOG

(not to be confused with Smaug)



Intrinsic Charm

- *extrinsic* heavy-flavor content from soft gluon splitting

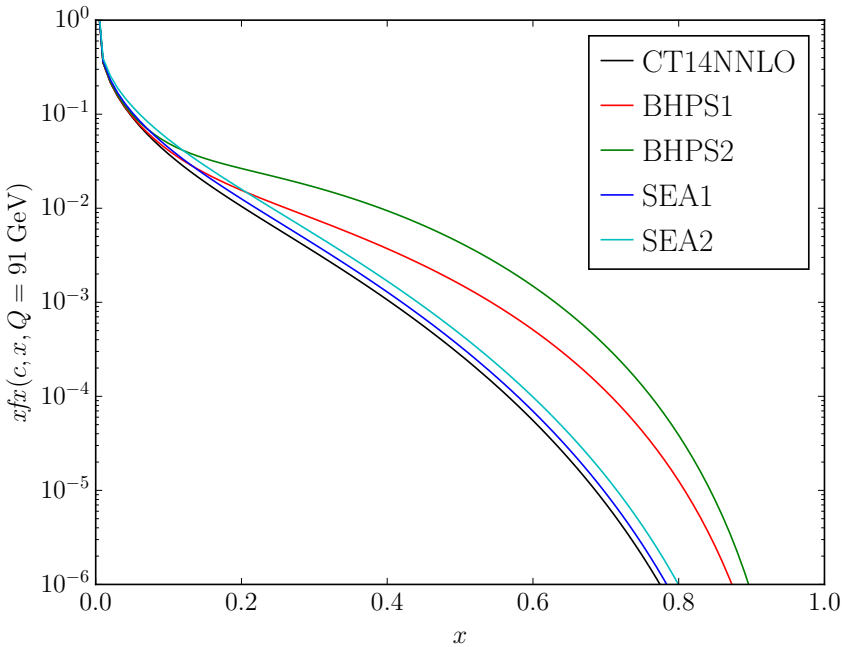
$$xfx(c, x, Q^2) \approx (1 - x)xfx(g, x, Q^2)$$

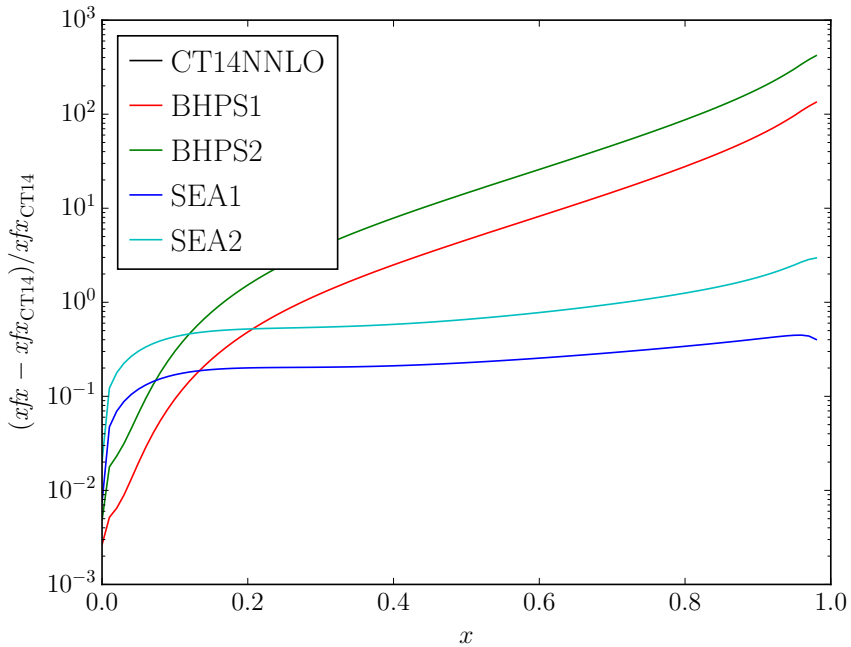
- *intrinsic* content also possible, bound to valence quarks
  - see Adv. High Energy Phys. **2015**, 231547 (2015)
  - percent-level charm content possibly seen in DIS
  - $Q \approx 1 - 10$ GeV, high-x
  - excluded from some global PDF fits

Adv. High Energy Phys. **2015**, 231547 (2015)

Intrinsic Charm PDFs

- consider two models from CT14 (Phys. Rev. D **93**, no. 3, 033006 (2016))
  - BHPS: valence-like via the light-cone picture of nucleon structure
  - SEA: sea-like assuming IC $\propto [\bar{u}(x, Q_0) + \bar{d}(x, Q_0)]$ for $Q_0 < m_c$
- two normalization points, $\langle x \rangle_{\mathrm{IC}} \equiv \int_0^1 x\mathrm{IC}(x, m_c)\mathrm{d}x$
  - 1: $\langle x \rangle_{\mathrm{IC}} = 0.6\%$
  - 2: $\langle x \rangle_{\mathrm{IC}} \approx 2\%$ (maximally allowed from global fit)

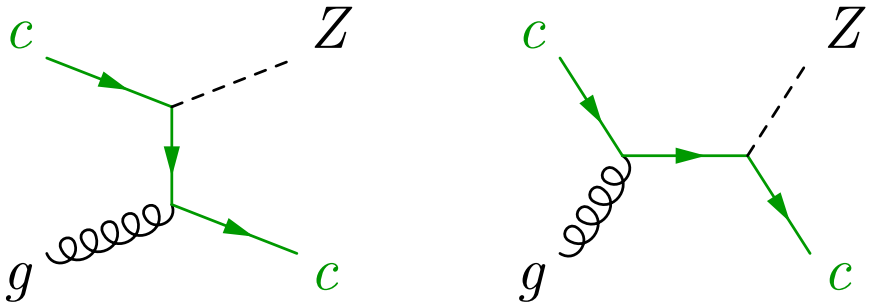




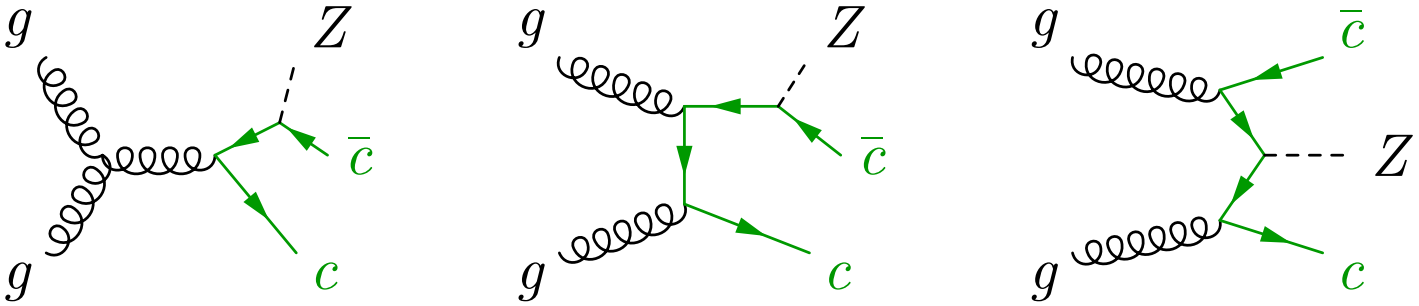
Z Production with Charm

Boettcher, PI, and Williams, PRD **93** (2016)

- measure ratio of $Z + c$-jet to Z+jet



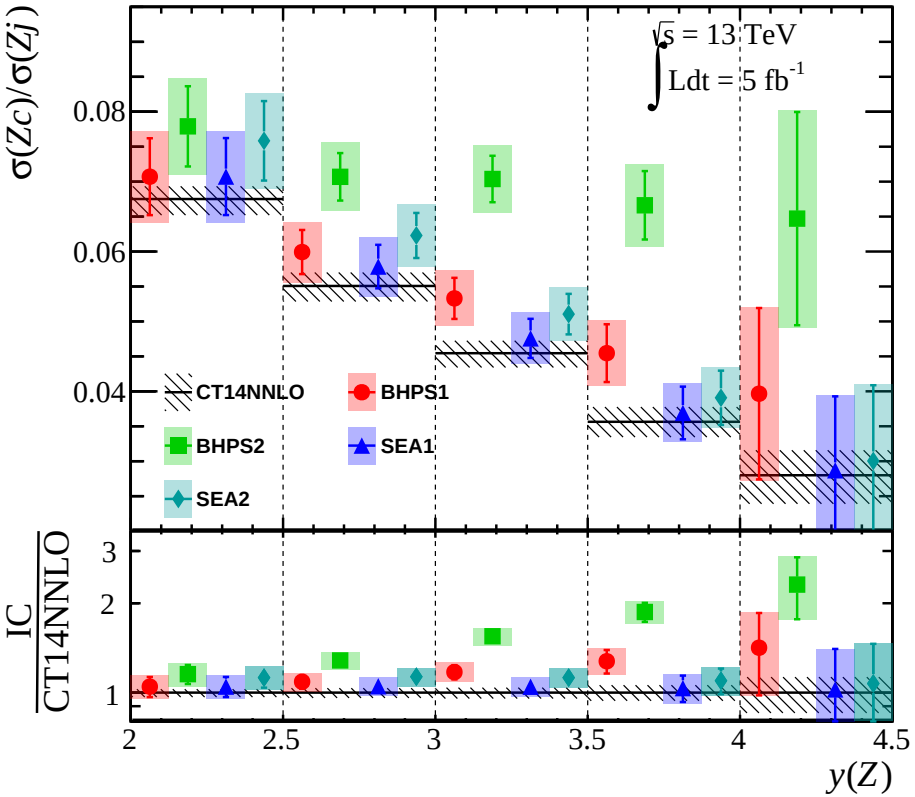
- not all $Z + c$-jet final states from intrinsic charm



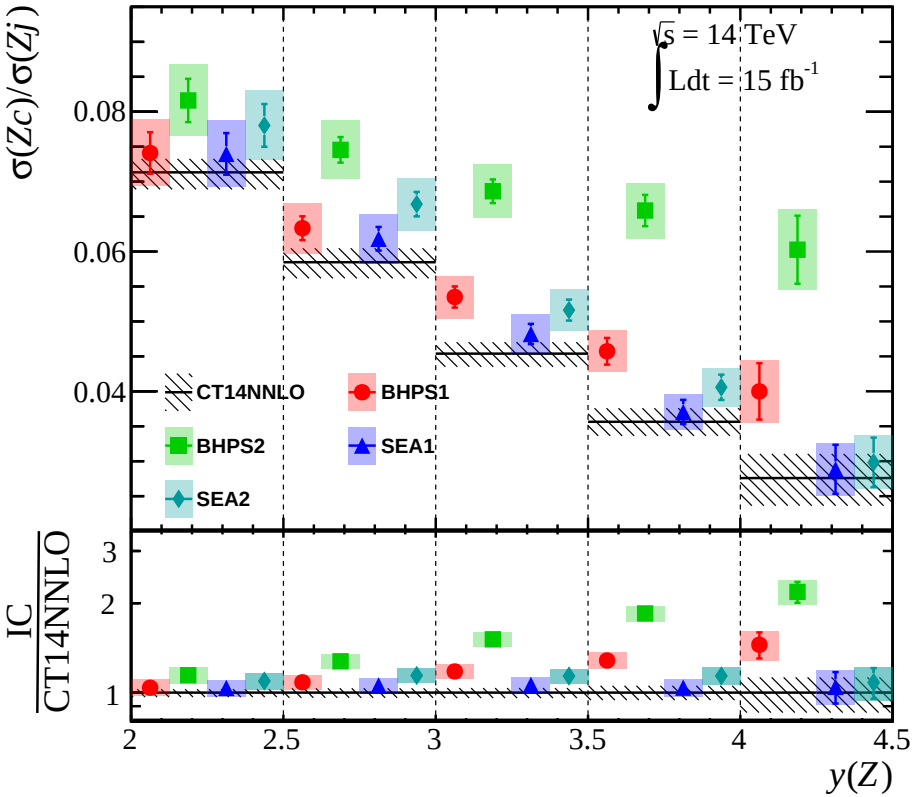
Expected Sensitivity

Boettcher, PI, and Williams, PRD **93** (2016)

LHCb Run 2



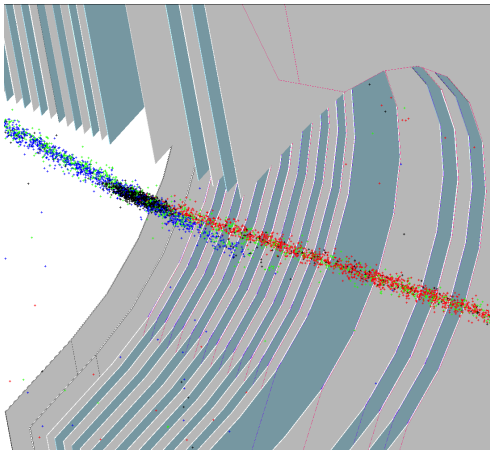
LHCb Run 3



SMOG

LHCb, JINST **9** P12005 (2014)

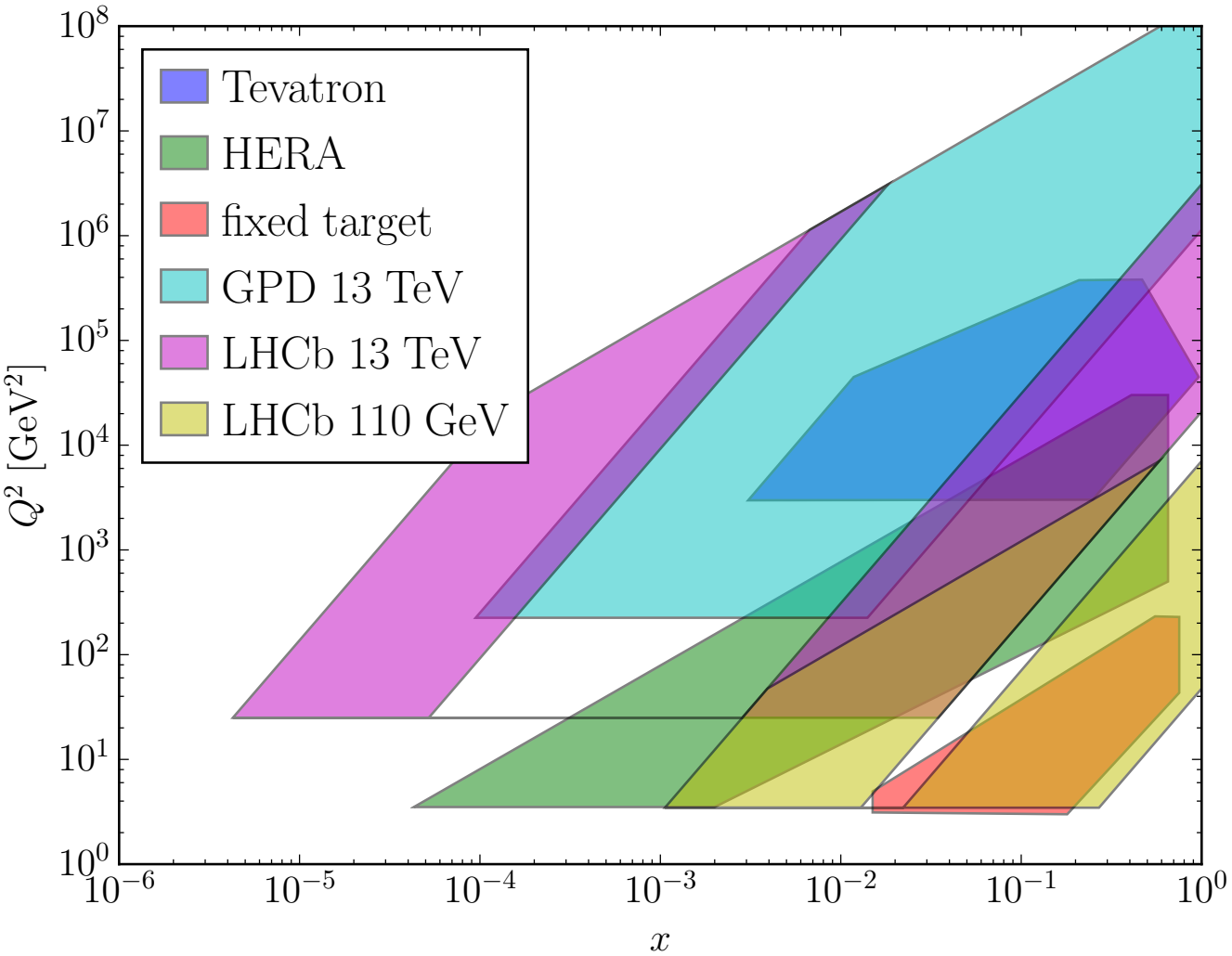
- **S**ystem for **M**easuring **O**verlap with **G**as
- used for precision luminosity measurements using beam gas imaging (uncertainty of 1.16%)
- at $\sqrt{s} = 110$ GeV $y = y_{\text{com}} + 4.77$



type	$\sqrt{s}$ [GeV]	year	time
pNe	87	2012	30m
PbNe	54	2013	30m
pNe	110	2015	12h
pHe	110	2015	7h
pAr	110	2015	20h
pAr	69	2015	11h
PbAr	69	2015	100h
pHe	110	2016	20h
pHe	87	2016	87h

Bjorken-x Coverage

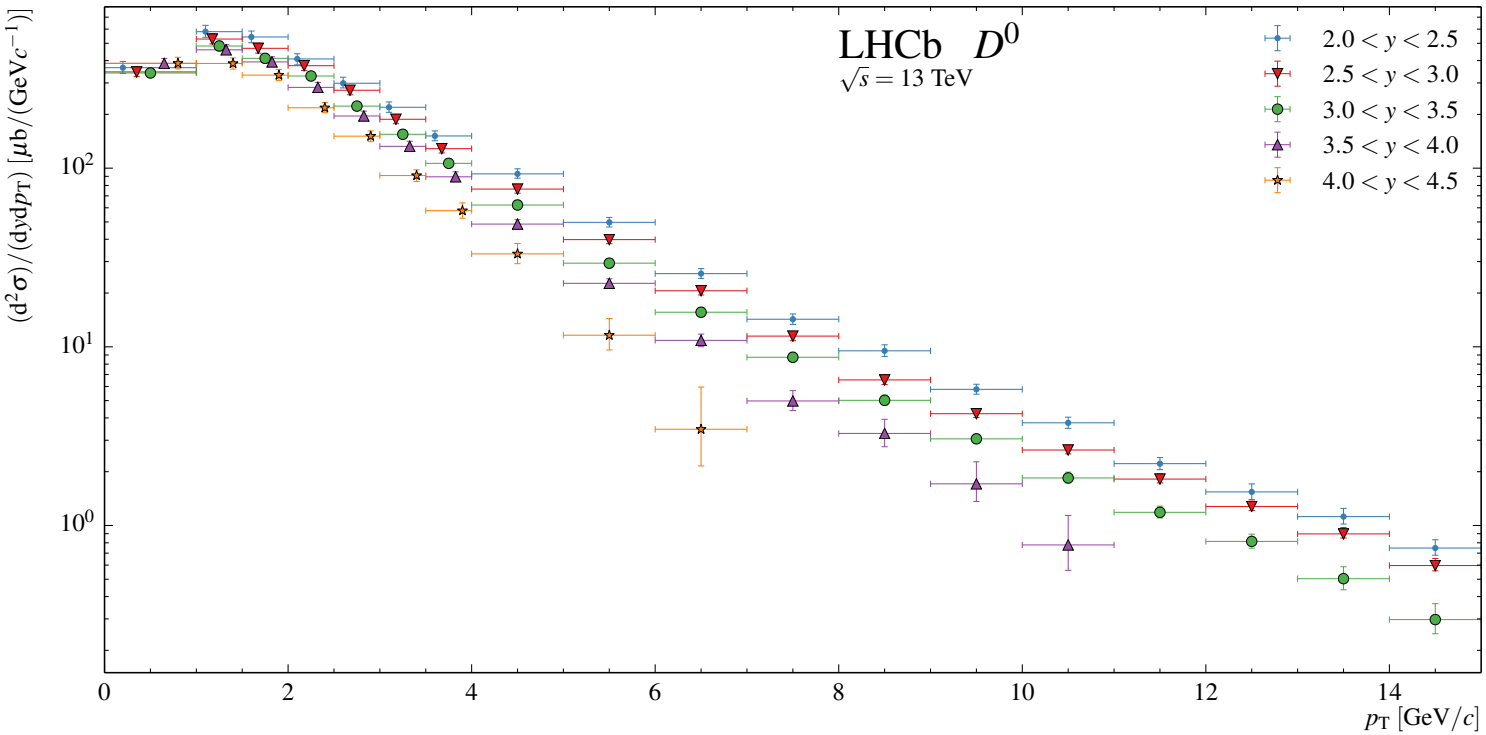
- parton distribution function (PDF) parameter space in Q^2 and x



Measurements

LHCb, JHEP **1603**, 159 (2016)
LHCb, JHEP **1510**, 172 (2015)

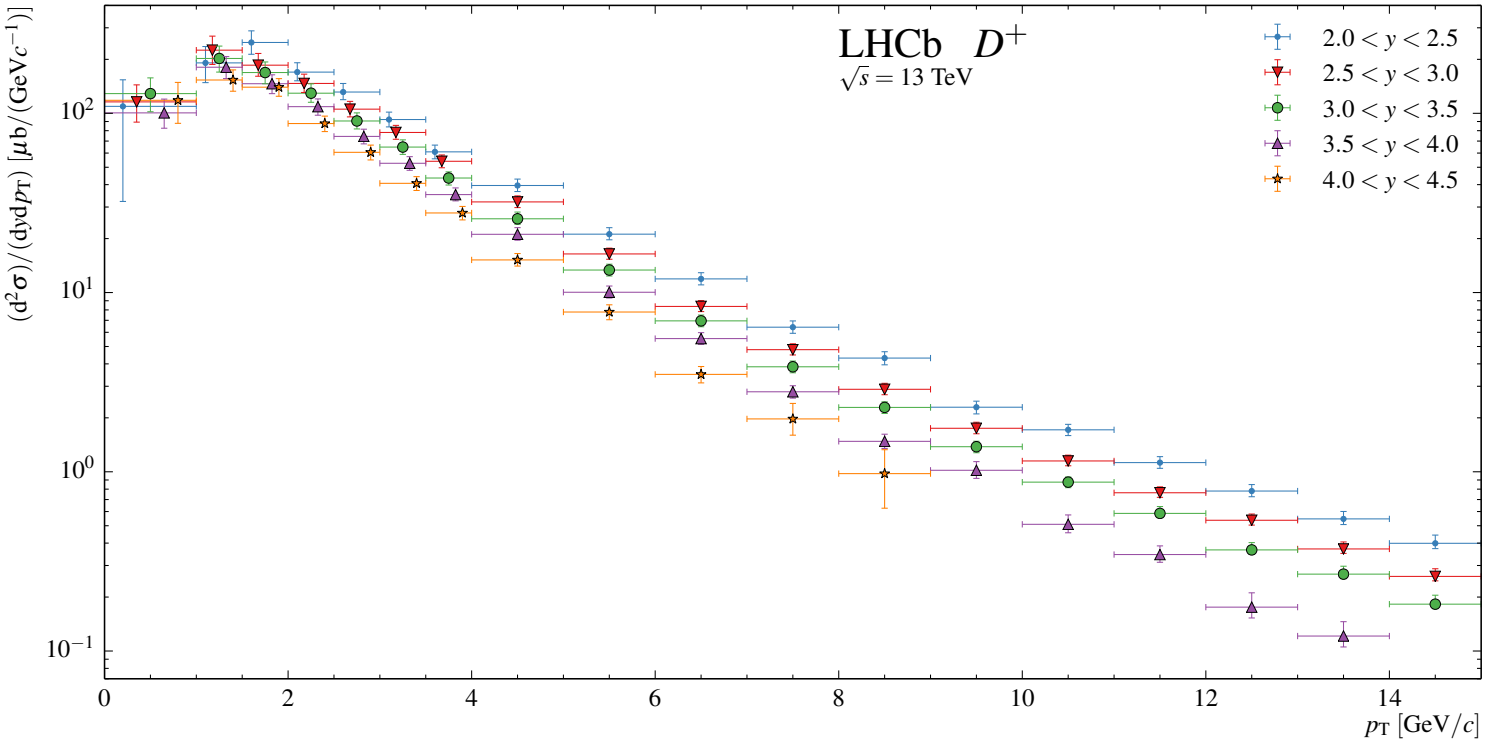
- open and hidden-charm cross-sections with pp data
- use the $J/\psi[\mu\mu]$, $D^0[K^+\pi^-]$, and $D^+[K^+\pi^-\pi^+]$ channels



Measurements

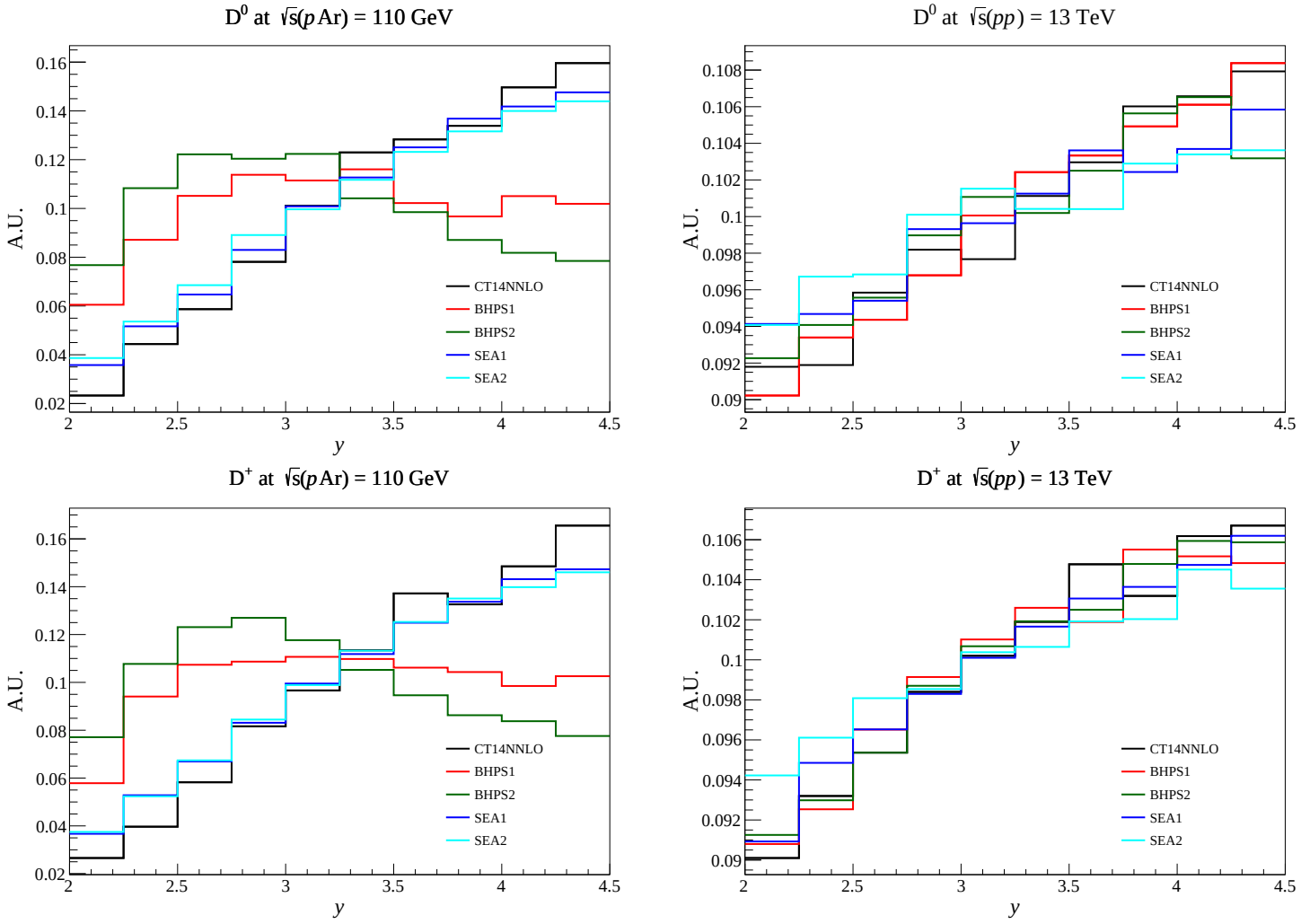
LHCb, JHEP **1603**, 159 (2016)
LHCb, JHEP **1510**, 172 (2015)

- can also reduce low-x gluon uncertainty by up to factor of 4 (arXiv:1610.09373 [hep-ph])



Future Measurements

- same measurements but with pHe and pAr data
- rough predictions in LHCb acceptance from PYTHIA 8

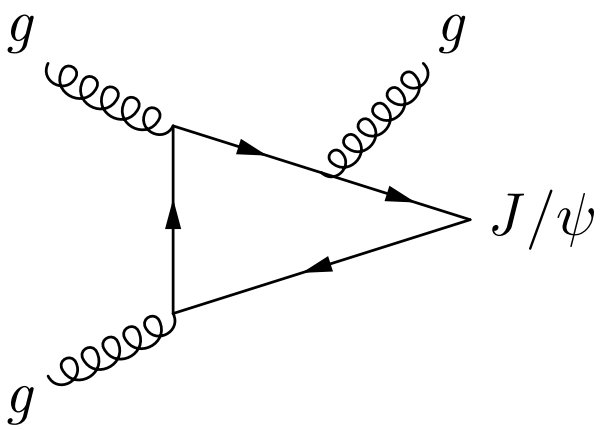


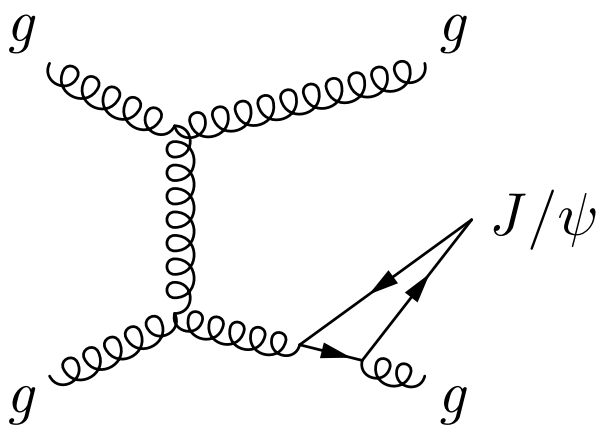
J/ψ Production in Jets

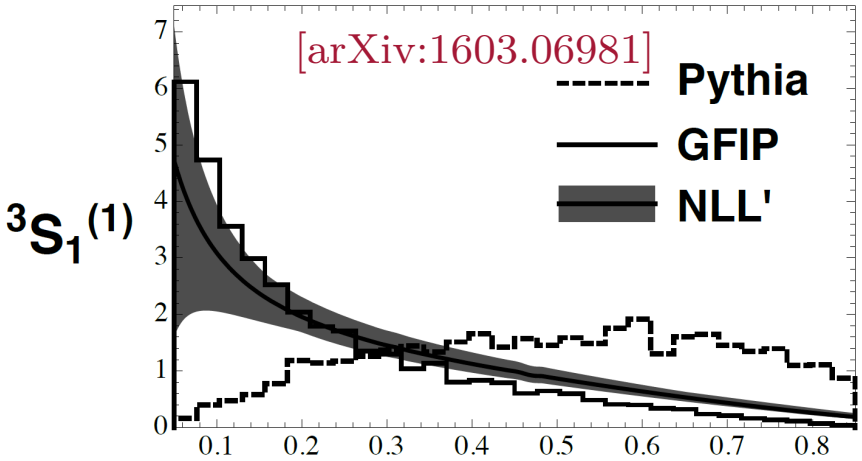
A Tale of Two Pictures

LHCb, arXiv:1701.05116

1. NRQCD hard process, octet states showered with QCD splittings
2. shower with NRQCD splittings, match with hard process







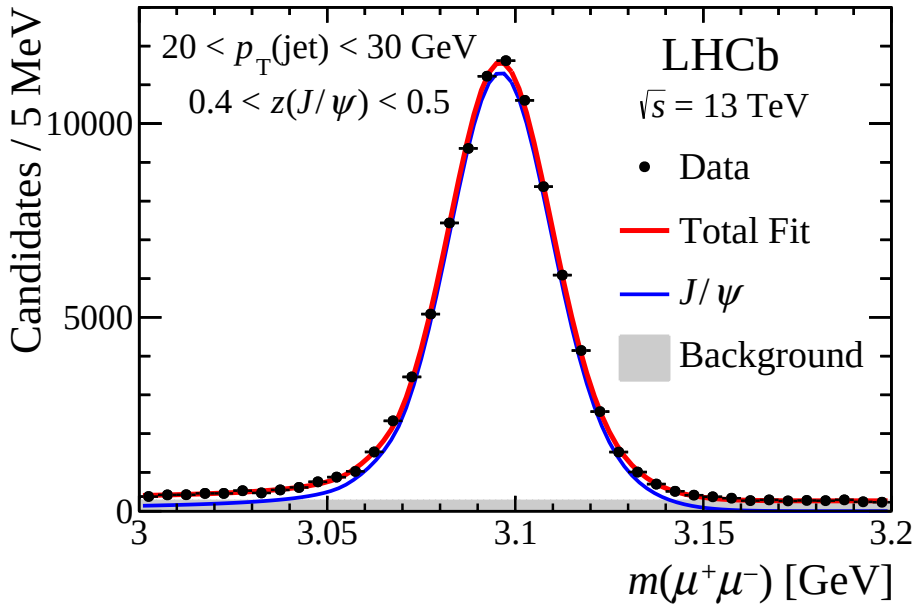
- J/ψ trigger writes out full events
- select jets with J/ψs
- measure $z \equiv p_{\mathrm{T}}(J/\psi)/p_{\mathrm{T}}(\mathrm{jet})$

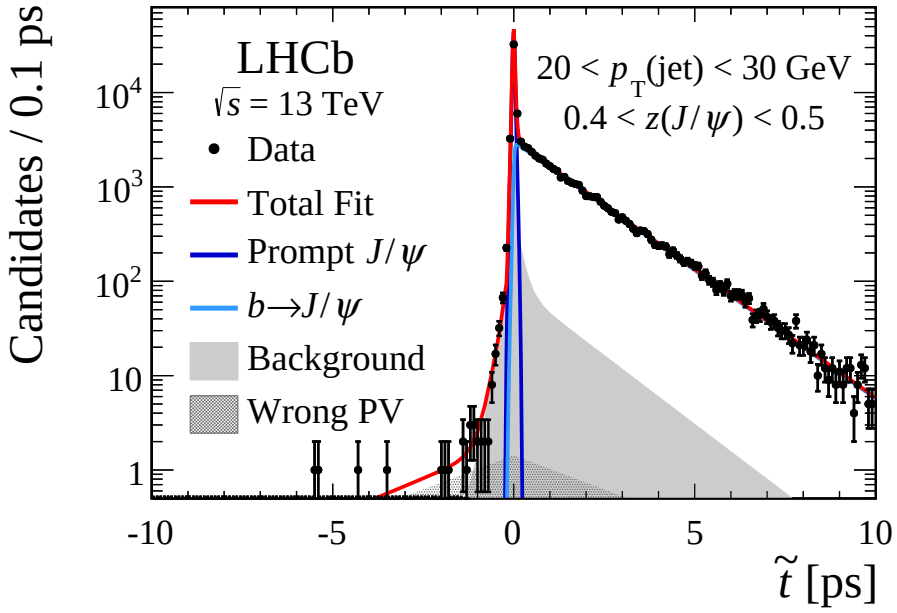
Signal Determination

LHCb, arXiv:1701.05116

- determine J/ψ signal yield with mass fits
- separate prompt from displaced yields with pseudo-lifetime fits

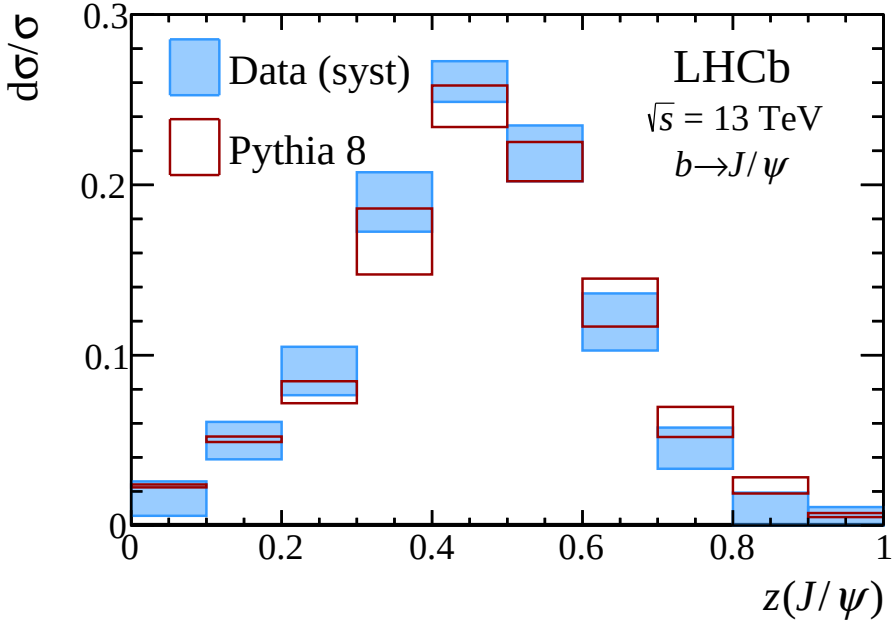
$$\tilde{\tau} \equiv (x_z - x_z(\mathrm{PV}))m/p_z$$

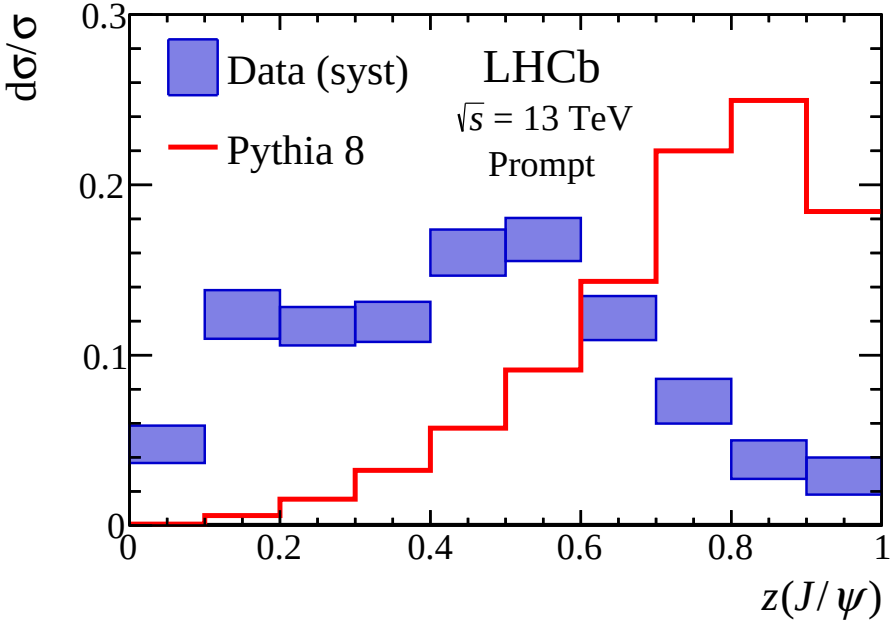




Results

LHCb, arXiv:1701.05116

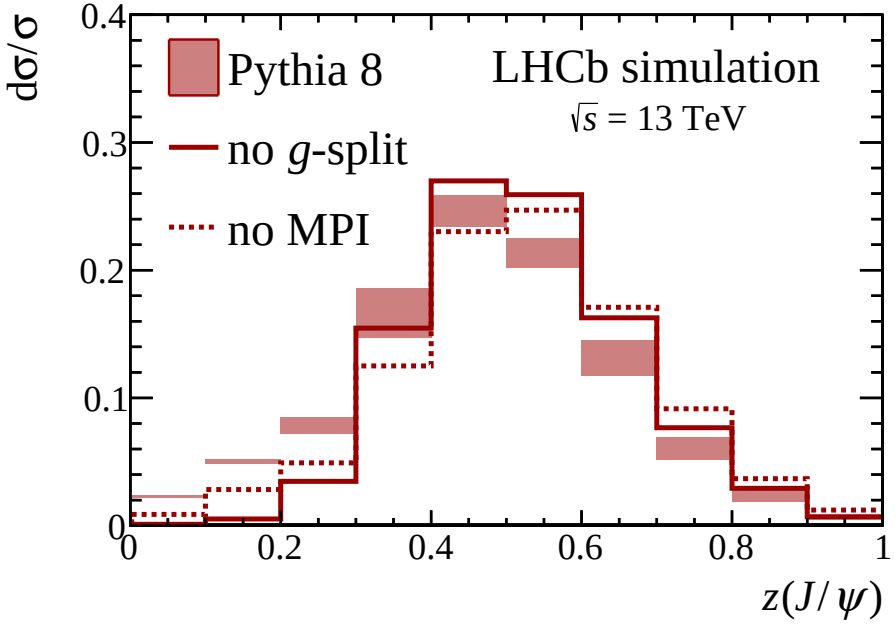




- PYTHIA 8 implements the LO hard process picture
- not the end of the story, need different predictions and more measurements

QCD Splittings

LHCb, arXiv:1701.05116
PI, Rodd, Thaler, and Williams, arXiv:1702.02947

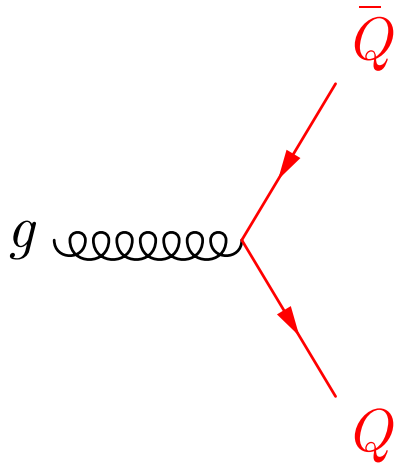


- $g \to Q\bar{Q}$ still not yet fully understood
- major contributor to systematics for top measurements

$$\bar{P}_{q,g} \simeq \frac{1-z}{z} + \frac{z}{1-z} + \frac{1}{2}$$

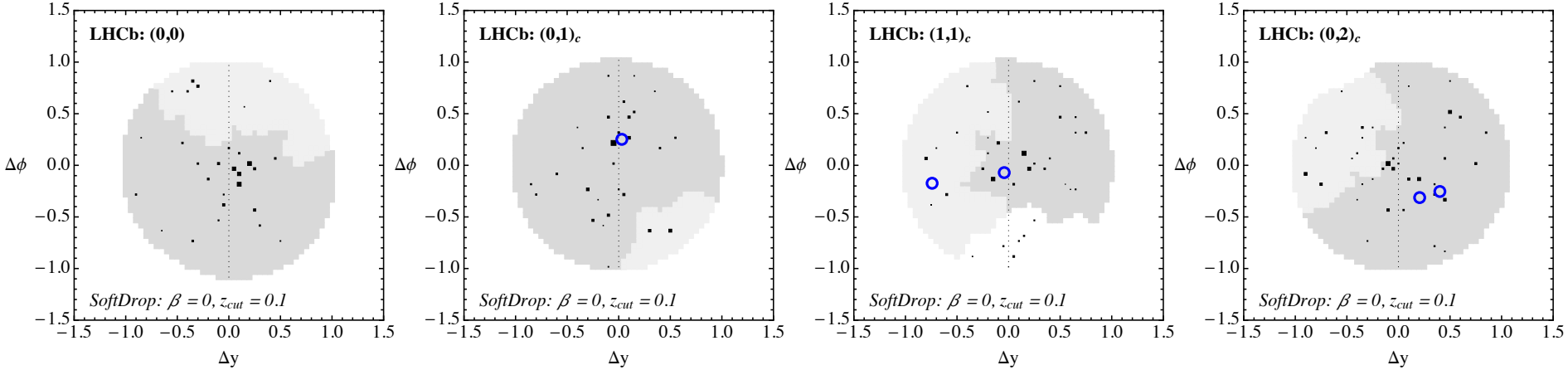
$$P_{g\to Q\bar{Q}} = z^2 + (1-z)^2 + 2\frac{m_Q^2}{m_{Q\bar{Q}}^2}$$

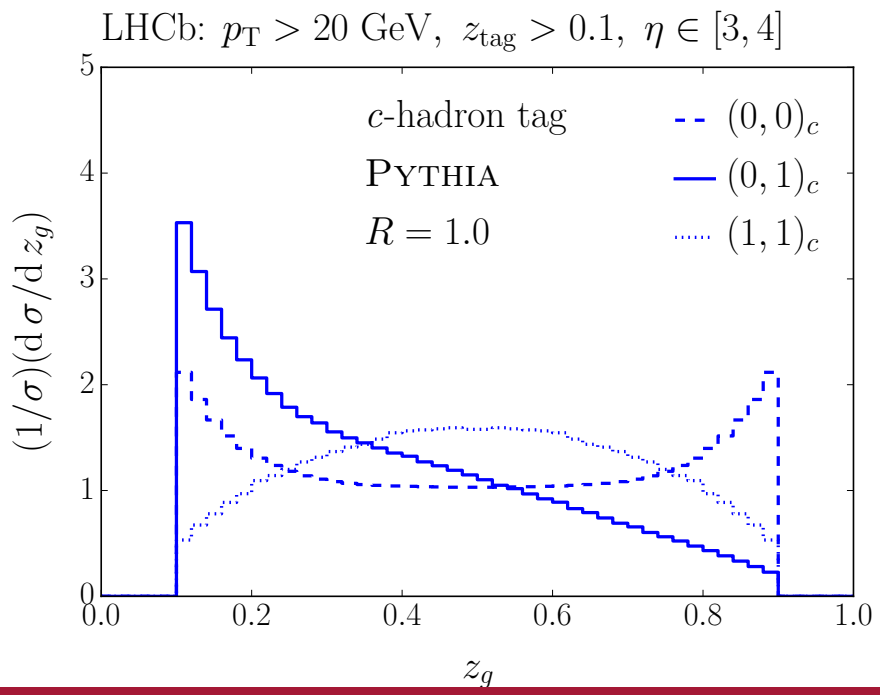
$$P_{Q\to Qg} = \frac{1-z}{z} + \frac{z}{2} - 2\frac{m_Q^2}{m_{Qg}^2 - m_Q^2}$$

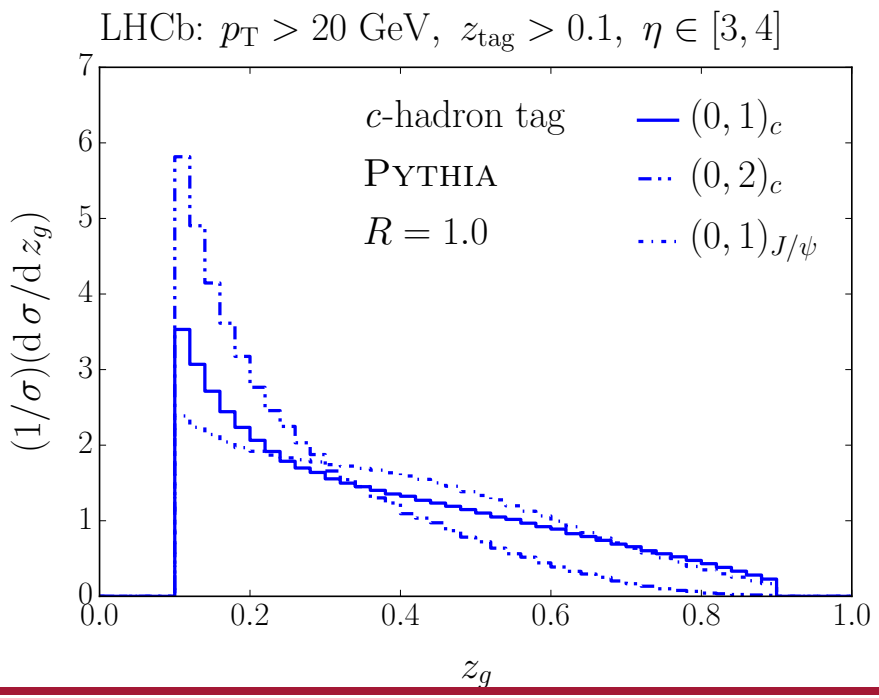


SoftDrop

PI, Rodd, Thaler, and Williams, arXiv:1702.02947







Outlook

Outlook

- robust and efficient $c(b)$-tagging algorithm validated against data
- could see strange asymmetries at end of Run 2
- strong constraints on high-x gluon from top
- top asymmetries should be observable by end of Run 3

- intrinsic charm studies underway both with pp and pAr
- rule out BHSP models at $\langle x \rangle_{\mathrm{IC}} \approx 1\%$ ...or demonstrate IC!

- exciting new quarkonia physics underway
- new methods to directly test heavy flavor splitting

Thank you!