Production & Spectroscopy of Heavy Hadrons at the LHC

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for the ALICE, ATLAS, CMS, LHCb Collaborations

Hadron2011, 13-17 June, 2011, Munich

Outline

1) **Overview of LHC Experiments**
   - Issues relevant for heavy hadrons

2) **Heavy Flavor Production**
   - Background & Theoretical predictions
   - Charm production
   - Beauty production

3) **Exclusive Final States**
   - Spectroscopy
   - Tool for studying Electro-Weak symmetry breaking

4) **Summary of What We've Learned (so far)**
   - What to look for in the future

~50 Experimental Results from ALICE, ATLAS, CMS, LHCb

What I Won't Cover

Tragically, the organizers ignored my request for more time

- and I only needed 150 extra minutes !

We will have to skip

- nearly interesting experimental details
- many states that have been re-observed at the LHC
- CP-violation and other electro-weak topics
- $B \rightarrow \mu^+ \mu^-$
- top physics (feeble excuse: it doesn't hadronize)

Other LHC Heavy Flavor-related talks at Hadron 2011

- Plenary Sessions
  - Charmonium (Yuanming Gao) & Bottomonium (Nuno Leonardo)
- Parallel Session talks by
  - ALICE: K. Schweda, F. Kramer
  - ATLAS: C. Schiavi
  - CMS: B. Akgun, B. Paolo, H-C Kaestli, C. Grab, J. Wang
  - LHCb: R. Cardinale, G. Sabatino, A. Uklega, B. Liu

Heavy Flavors and LHC Exp's

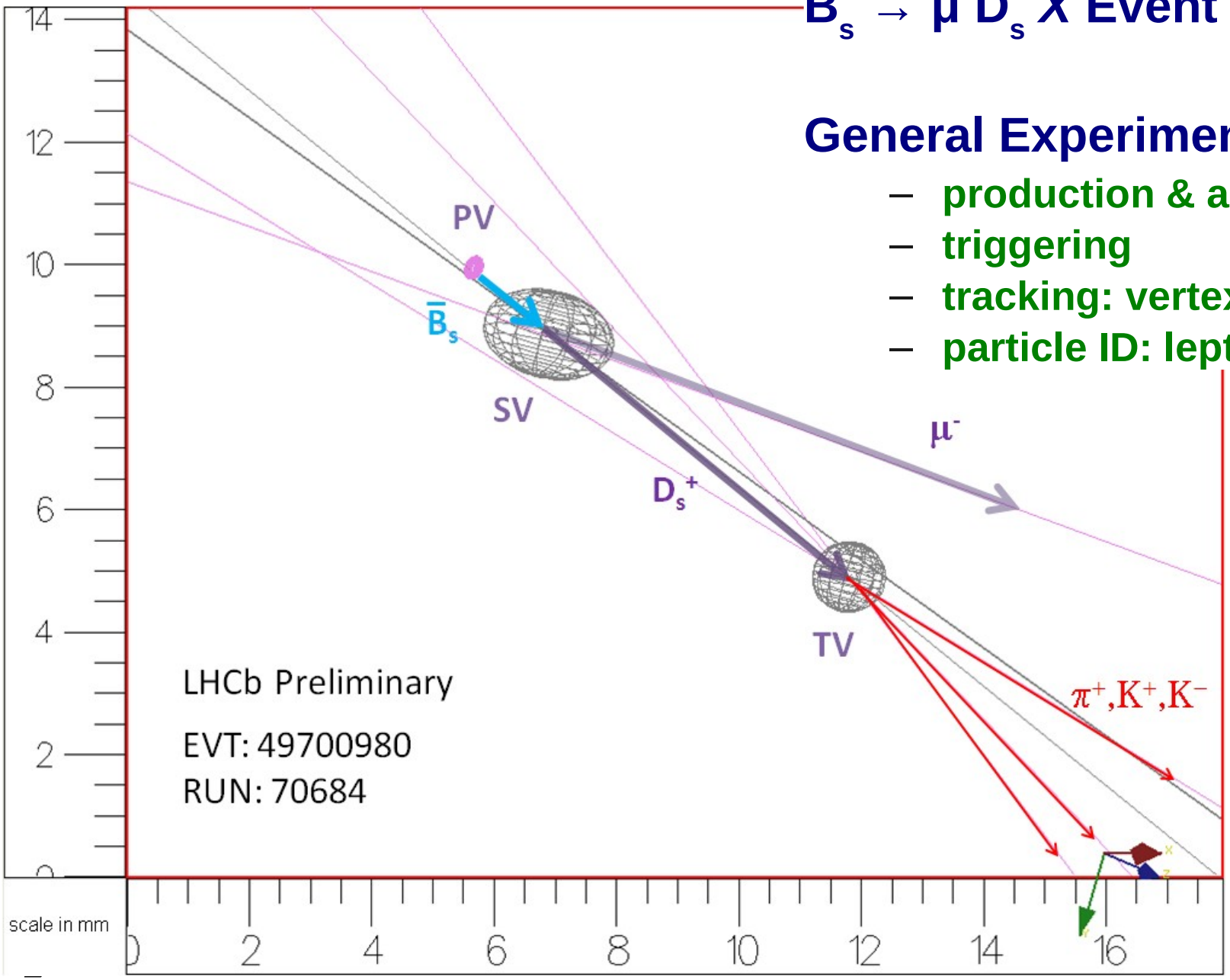
Heavy Flavor Production/Spectroscopy is not the primary focus of any of the LHC experiments

- ATLAS/CMS direct searches for new physics
- LHCb matter-antimatter asymmetry, EW symmetry breaking
- ALICE strongly interacting matter at extreme energy densities

Nevertheless each has good capabilities to make these types of measurements

- unfortunately, no time to go into details of each experiment
- but will highlight a few of the most important issues

Experimental Issues Illustrated



$B_s \rightarrow \mu D_s X$ Event at LHCb

General Experimental Concerns

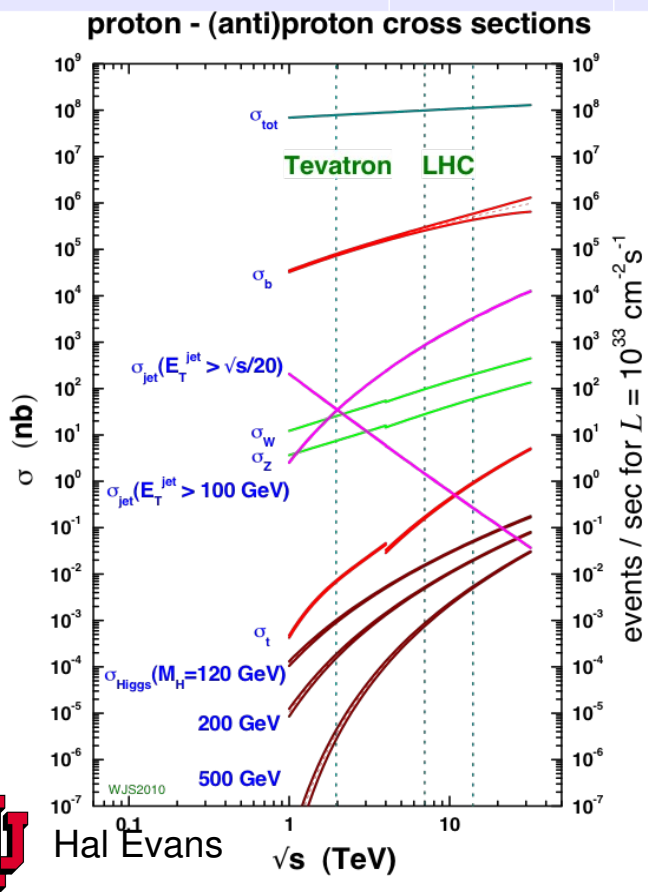
- production & acceptance
- triggering
- tracking: vertexing, mass
- particle ID: leptons, hadrons

Production and Acceptance

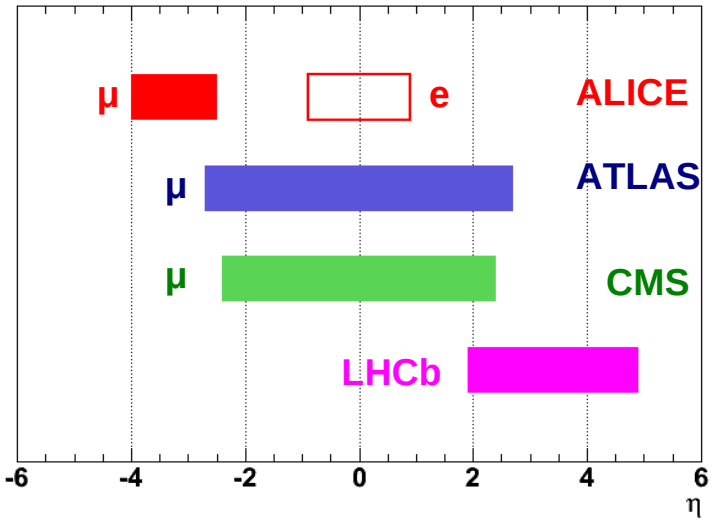
Data Collected

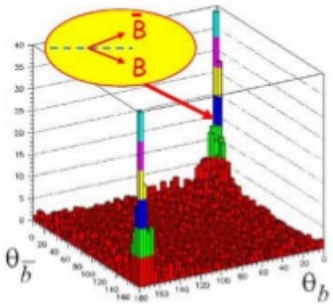
– all exp's efficiency > 90%

pp Luminosity	2010	2011
peak ($cm^{-2}\ s^{-1}$)	$2{\cdot}10^{32}$	$>1{\cdot}10^{33}$
integrated (pb^{-1})	~40	>1000 (>350 LHCb)



Detector Acceptances



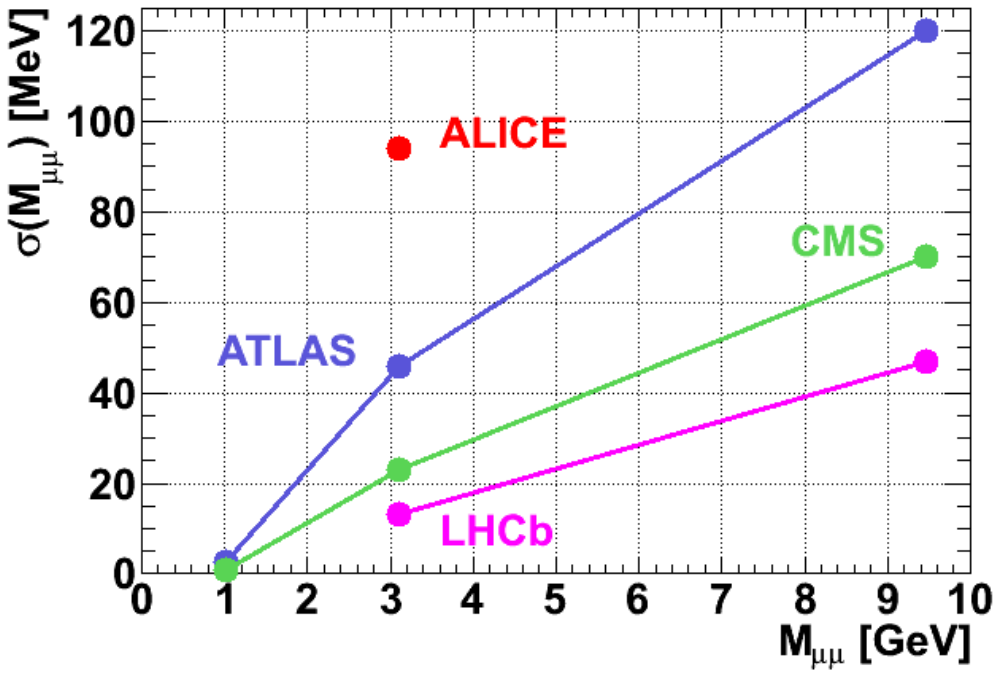


Triggers used in analyses

Trigger	Exp's	Comments
min(micro) bias	all	only earliest data
single muon	all	lowest p_T prescaled
single jet	ATLAS, CMS	lowest p_T prescaled
di-muon	all	unprescaled (so far)
displaced Vtx	LHCb	unprescaled

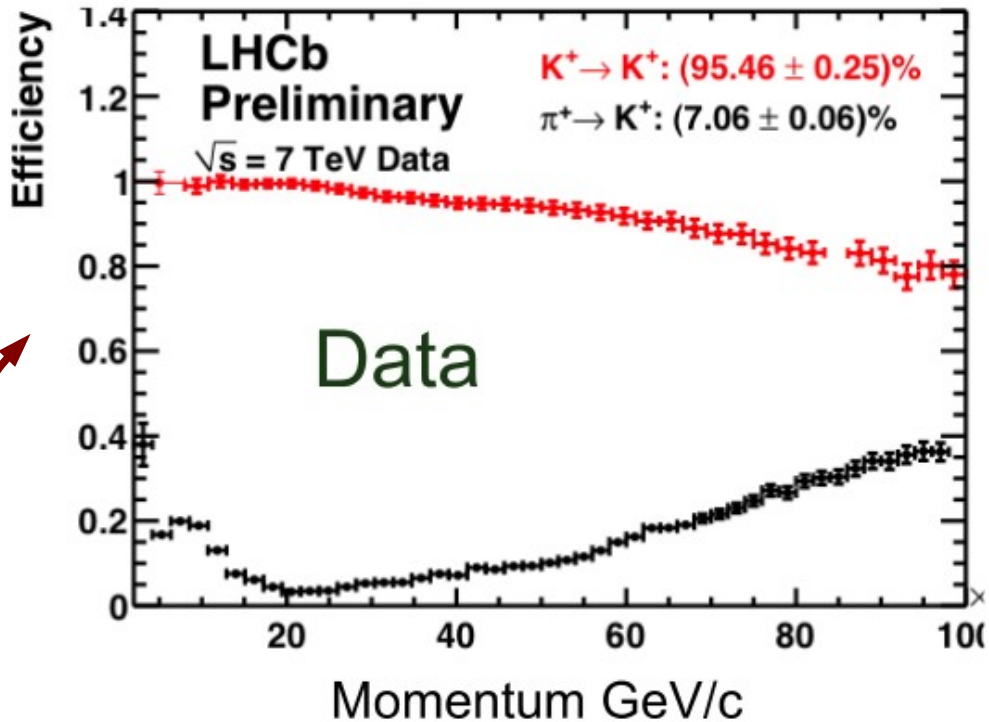
Tracking & Hadron ID

Mass Resolution



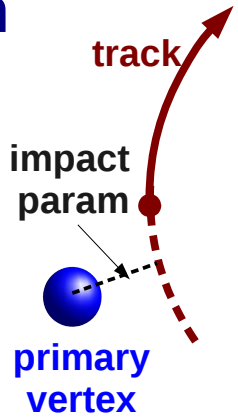
π/K/p Separation

- all exp's have some capabilites
  - > but not used here by ATLAS,CMS,ALICE
- LHCb (RICH) used extensively

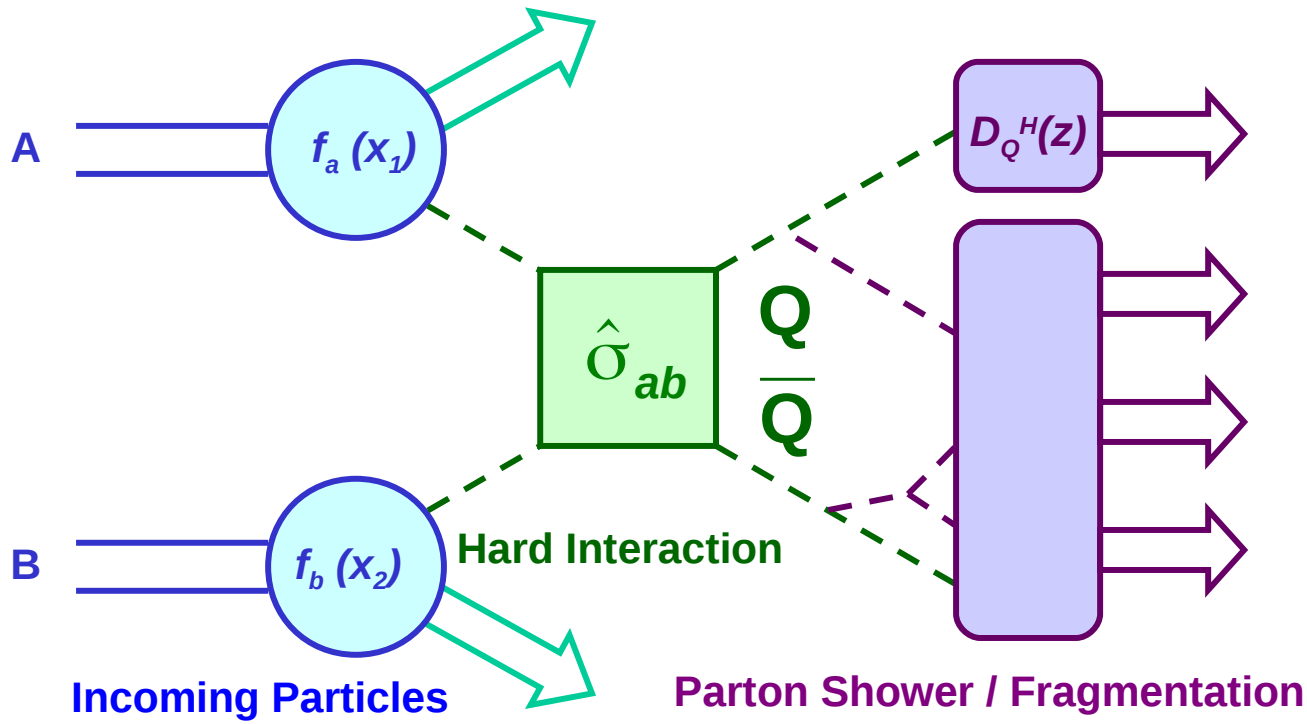


Impact Parameter Resolution

ALICE	~30 μm	p_T = 8 GeV
ATLAS	~30 μm	p_T = 5 GeV
CMS	~30 μm	p_T = 6 GeV
LHCb	~30 μm	high p_T



Heavy Flavor Production

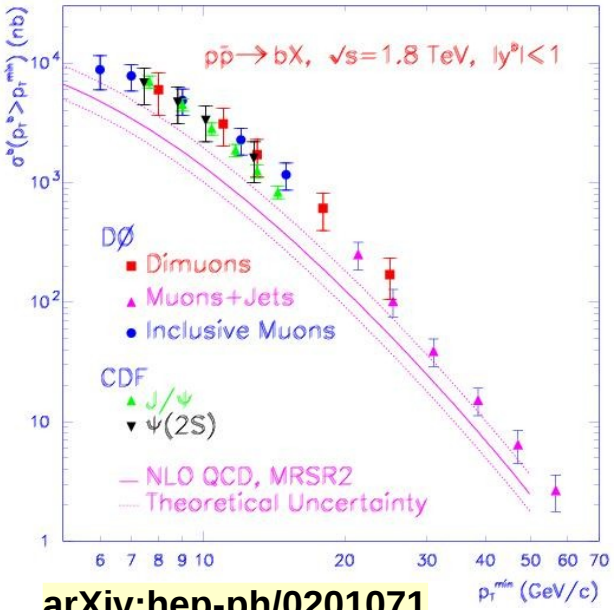


$$\frac{d\sigma(pp\to X)}{d^3p_1\ldots d^3p_n} = \sum_{a,b}\int dx_a\,dx_b\,dz\;\overbrace{f_a(x_1,\mu_F)\,f_b(x_2,\mu_F)}^{\text{PDFs}}$$

$$\times\;\hat{\sigma}_{ab}\underbrace{(p_a,p_b,p_X,\alpha_s}_{\text{Hard Scatter x-sect}}(\mu_R),\underbrace{\mu_R,\mu_F}_{\text{renormalization \& factorization scales}})\;\times\;\overbrace{D_Q^H(z,\mu_F)}^{\text{Fragmentation Function}}$$

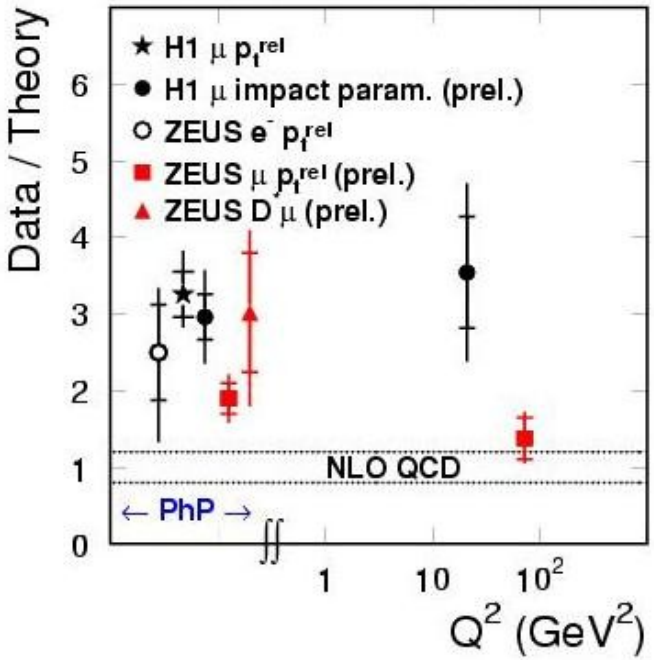
Situation c. 2000

CDF, D0 Run I

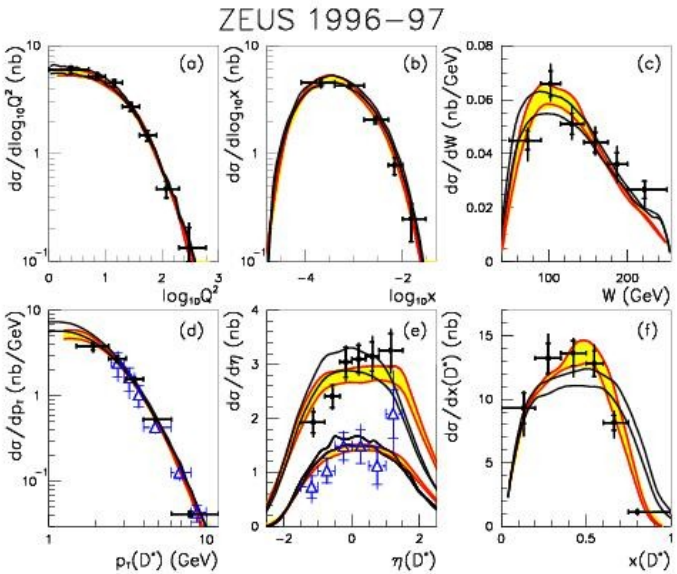


arXiv:hep-ph/0201071

b cross section at HERA



D* production in DIS (ZEUS)



Beauty Production vs NLO predictions

- reasonable agreement in shape, but scale off by factors of 2–3

Charm Production vs NLO Predictions

- agreement generally better, but errors quite large

Could this be New Physics ???

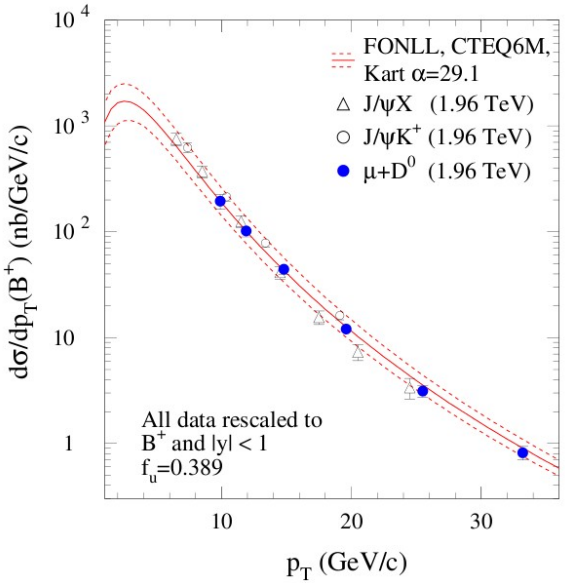
Road to Enlightenment

Experimental Issues: be careful what you report

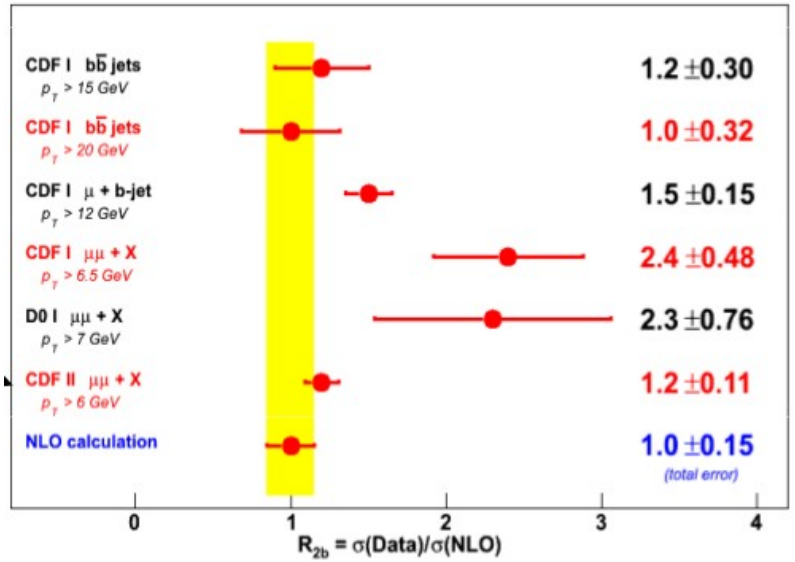
- cross-sections from reconstructed *b*-hadrons ($B^+ \rightarrow J/\psi\ K^+$, ...)
  - careful treatment of fragmentation, updated α_s & PDFs
- cross-sections from *b*-tagged jets

Theory Issues: consistent calculations peripheral to NLO

- Large scale dependence: sizable contributions from beyond NLO
  - low p_T small $x \sim m_b / \sqrt{s}$ effects
  - high p_T large $\log(p_T / m_b)$ (FONLL resummation)
- Consistent (FONLL) treatment of fragmentation functions



CDF: PRD 79 (2009)

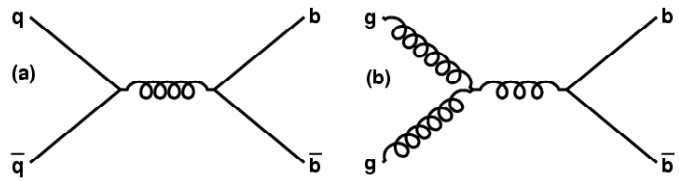


K.Pitts: Beauty09

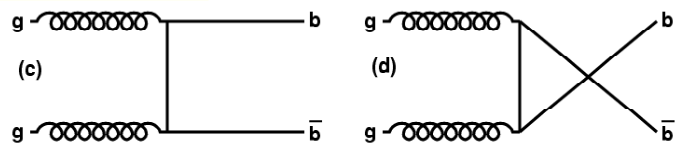
State of the Art

Heavy Flavor Production included in MC generators

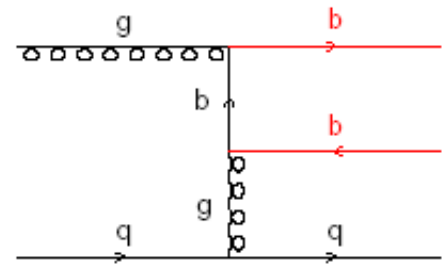
- PYTHIA, HERWIG: **LO with some higher order topologies**



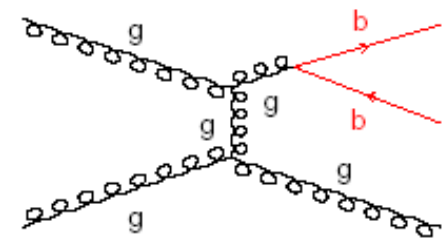
LO: Flavor Creation



NLO: Flavor Excitation



NLO: Gluon Splitting



- MadGraph/MadEvent: **2 → 2,3 Processes**
- CASCADE: **off-shell LO Matrix Elems w/ high-E factorization**
- MC@NLO, POWHEG, FONLL,MCFM: **full NLO calculations**

Experimental Issues

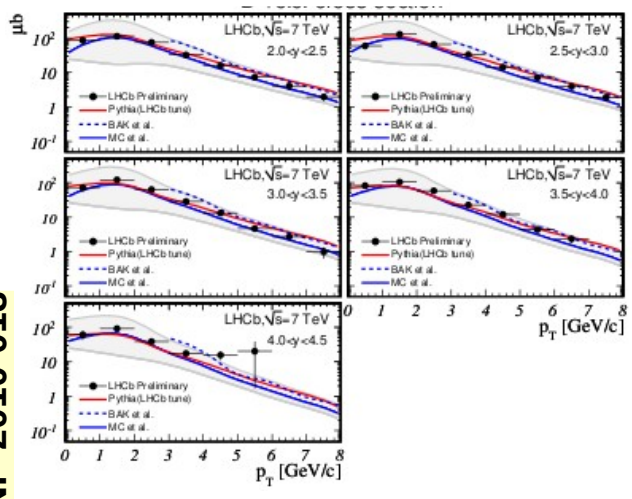
- **Does good data vs NLO agreement extend to new LHC energy regime?**
- **How well do we understand the details of higher order topologies?**
- **Cross-section measurements techniques**
  - > i) inclusive (*b*/*c*-jet, e/μ) ii) partially inclusive (μ D^0 X, J/ψ X,...)
  - > iii) exclusive ($c \rightarrow D^{(*)}$, $B^+ \rightarrow$ J/ψ K^+,...)

Exclusive *c*: LHCb

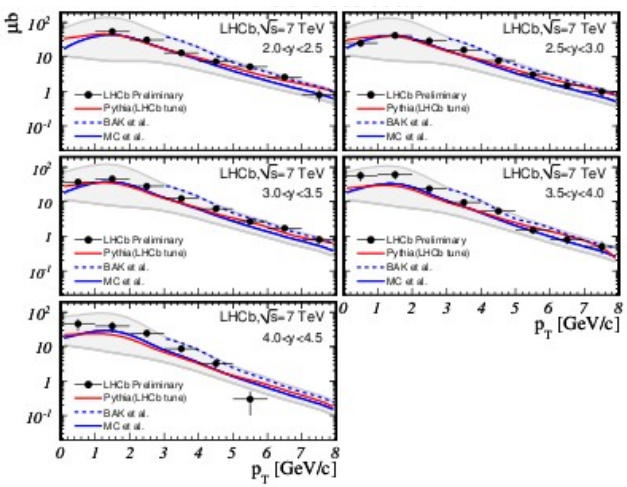
pp → D *X* using micro bias trigger (1.81 nb^{-1} – May, 2010)

– *b*-component extract using fit to D-meson impact parameter distrib.

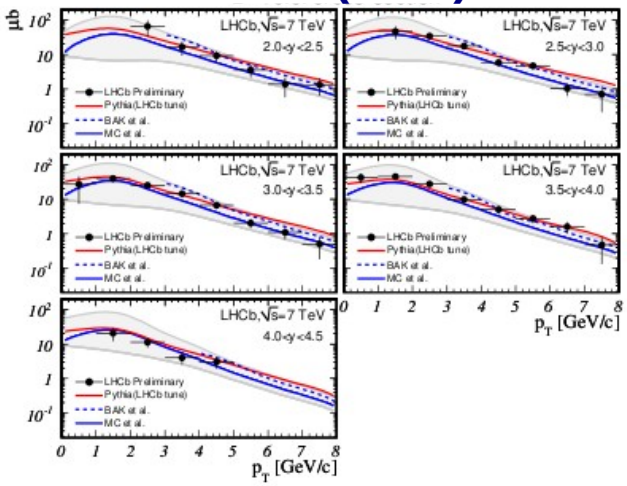
$D^0 \rightarrow K^- \pi^+$



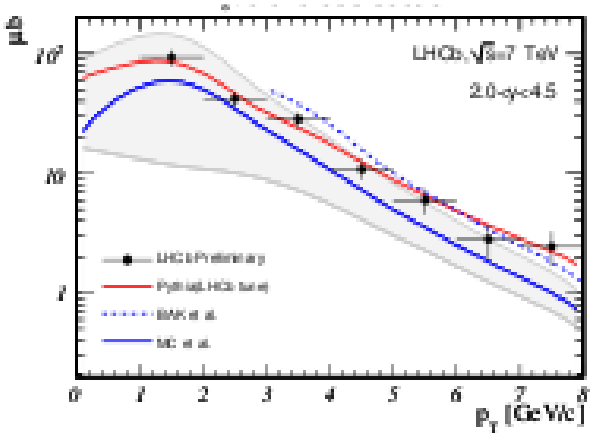
$D^+ \rightarrow K^- \pi^+ \pi^+$



$D^{*+} \rightarrow D^0(K^-\pi^+)\, \pi^+$



$D_s^+ \rightarrow \Phi(K^-K^+)\, \pi^+$



PYTHIA

MC: Cacciari, Frixione, Mangano, Nason, Ridolfi

BAK: Kniehl, Kramer, Schienbein, Spiesberger

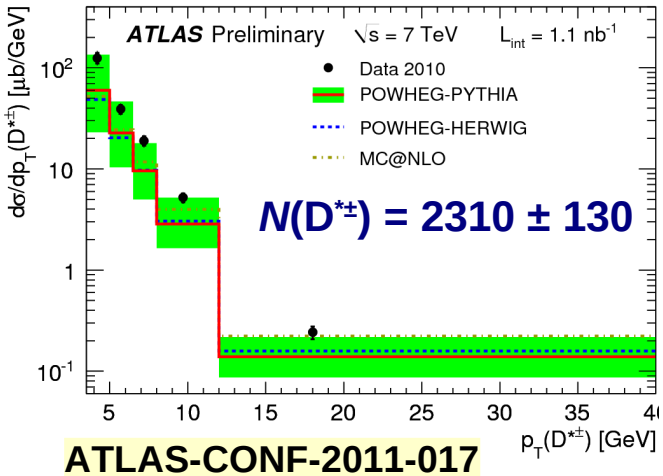
LHCB-CONF-2010-013

Exclusive c: ATLAS

pp → D *X* using minimum bias trigger (1.1 nb^{-1} – Mar-Jul, 2010)

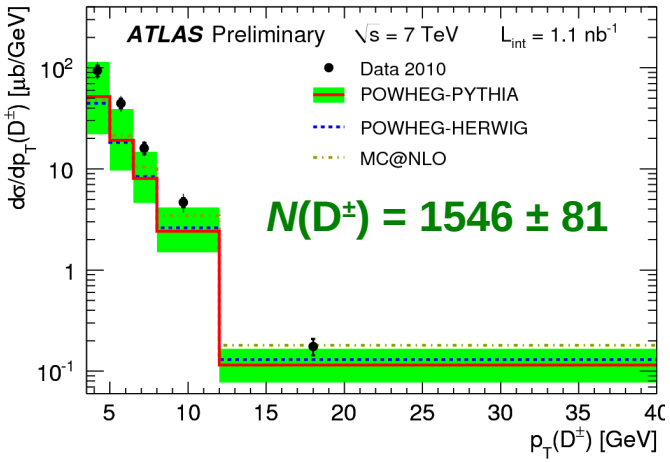
– **contains both *b,c* components (nb: $\sigma_{cc} \sim 20\ \sigma_{bb}$)**

$D^{*+} \rightarrow D^0(K^-\pi^+)\ \pi^+$

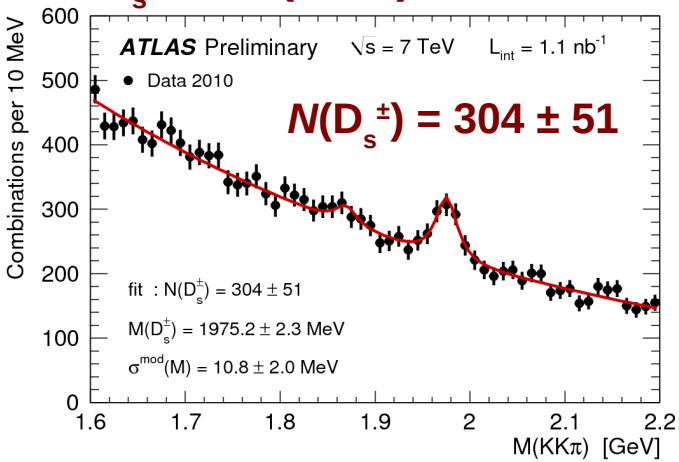


ATLAS-CONF-2011-017

$D^+ \rightarrow K^-\ \pi^+\ \pi^+$



$D_s^+ \rightarrow \Phi(K^-K^+)\ \pi^+$

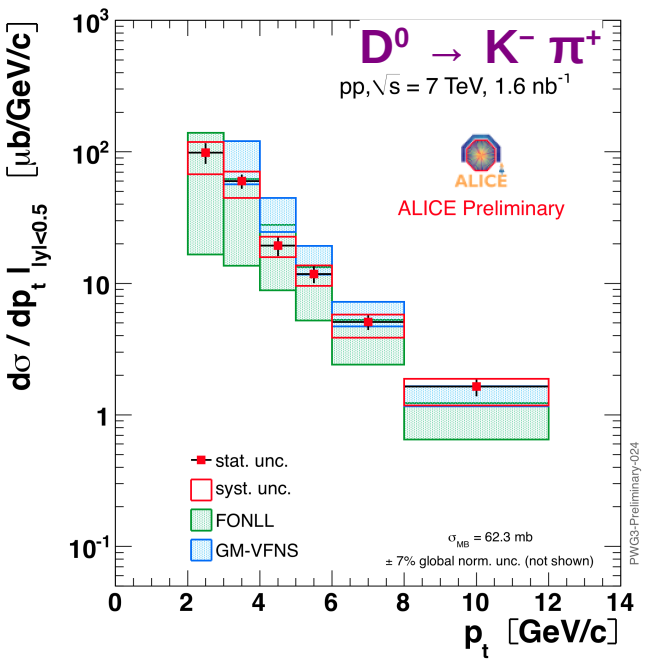


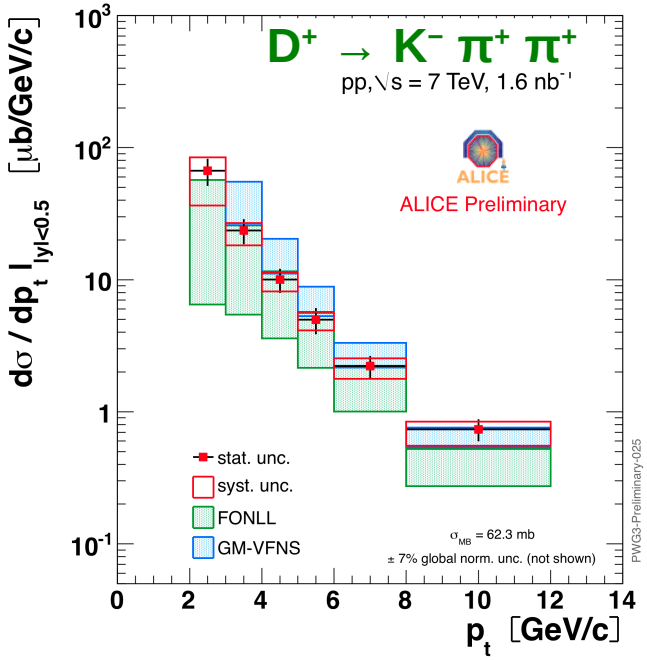
	$\sigma^{vis}[\mu b]$ $(p_T > 3.5$ GeV, $\lvert\eta\rvert < 2.1)$	POWHEG-PYTHIA
$D^{*\pm}$	$285\ \pm 16(\text{stat})\ ^{+32}_{-27}(\text{syst})\ \pm 31(\text{lum})\ \pm 4(\text{br})$	$153\ ^{+169}_{-80}(\text{scale})\ ^{+13}_{-15}(m_Q)\ ^{+24}_{-21}(\text{PDF})\ ^{+20}_{-16}(\text{hadr})$
$D^{\pm}$	$238\ \pm 13(\text{stat})\ ^{+35}_{-23}(\text{syst})\ \pm 26(\text{lum})\ \pm 10(\text{br})$	$132\ ^{+137}_{-65}(\text{scale})\ ^{+11}_{-10}(m_Q)\ ^{+20}_{-18}(\text{PDF})\ ^{+21}_{-11}(\text{hadr})$
$D_s^{\pm}$	$168\ \pm 34(\text{stat})\ ^{+27}_{-25}(\text{syst})\ \pm 18(\text{lum})\ \pm 10(\text{br})$	$59\ ^{+57}_{-28}(\text{scale})\ ^{+4}_{-6}(m_Q)\ ^{+9}_{-8}(\text{PDF})\ ^{+7}_{-8}(\text{hadr})$

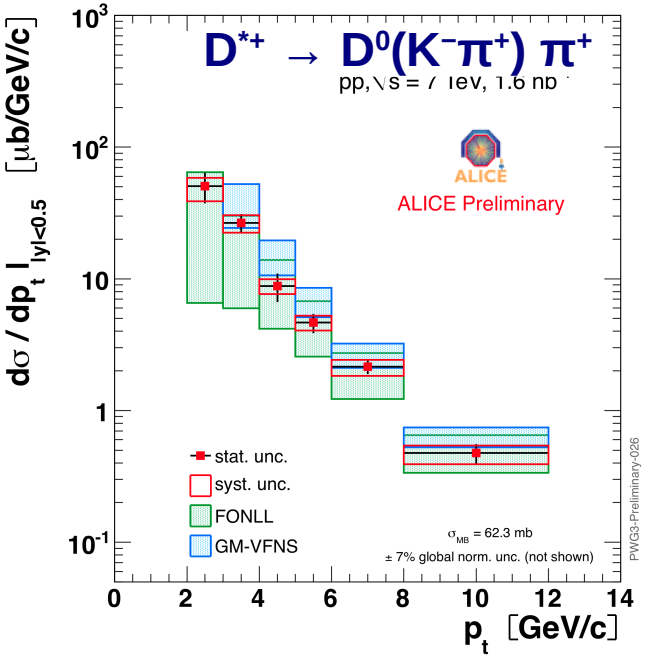
- **data already systematics limited**
- **results agreement with NLO predictions within large uncertainties**

Exclusive *c*: ALICE

pp → D X at √s = 7 TeV: 1.6 nb^{-1} (20% of 2010 data)







FONLL: Cacciari et al.
GM-VFNS: Kniehl et al.

also pp → D X at √s = 2.76 TeV: 1.1 nb^{-1}

– **3 days of data!**

- ***y*** **acceptance is p_T dependent (Δy ~ 1.0 – 1.6)**
- **results scaled to Δy = 0.5**
- **results in good agreement with NLO predictions**

Charm Summary

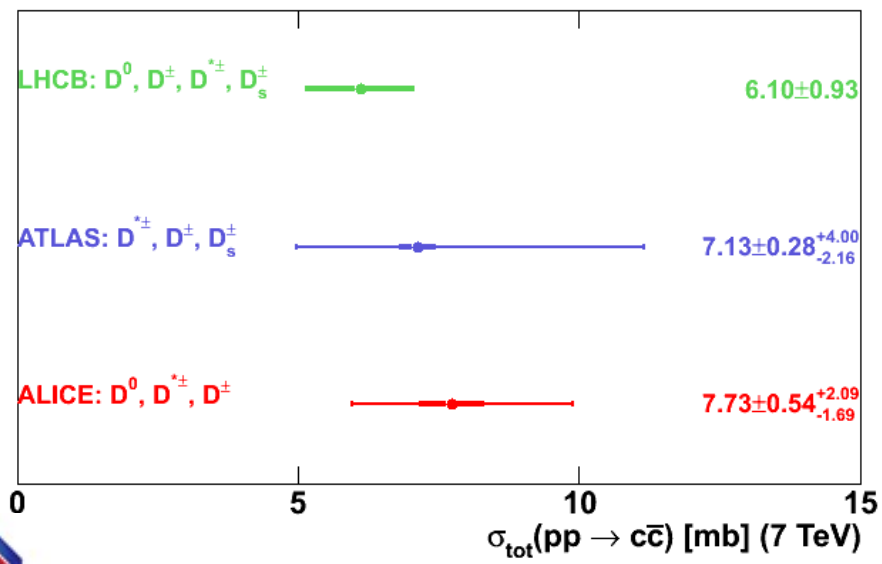
Differential cross-sections within exp acceptances

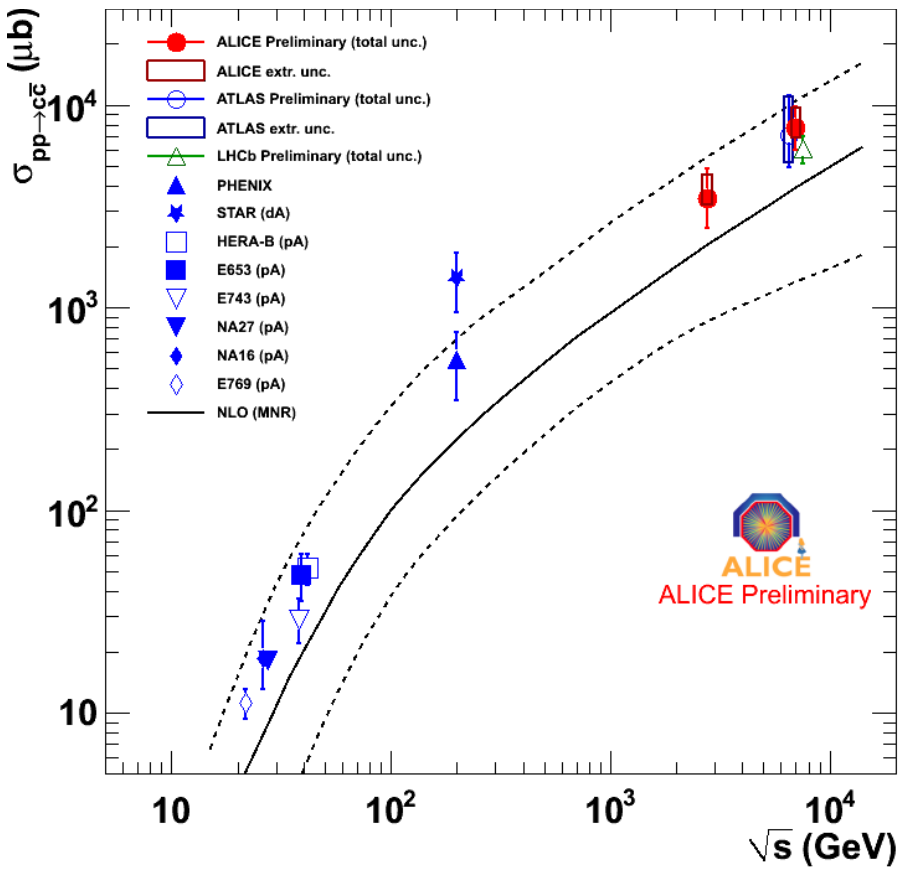
– generally reasonable agreement: data vs NLO – but large uncertainties

Extrapolate individual measurements to full phase space

– theory extrapolation error (ATLAS, ALICE) dominates all others

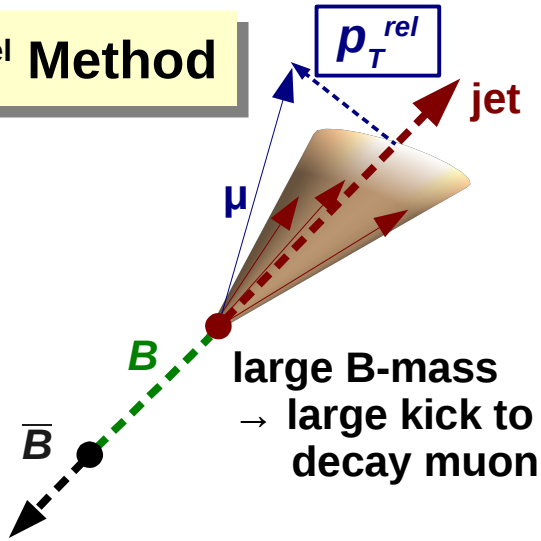
LHCb	PYTHIA
ATLAS	POWHEG-PYTHIA
ALICE	FONLL



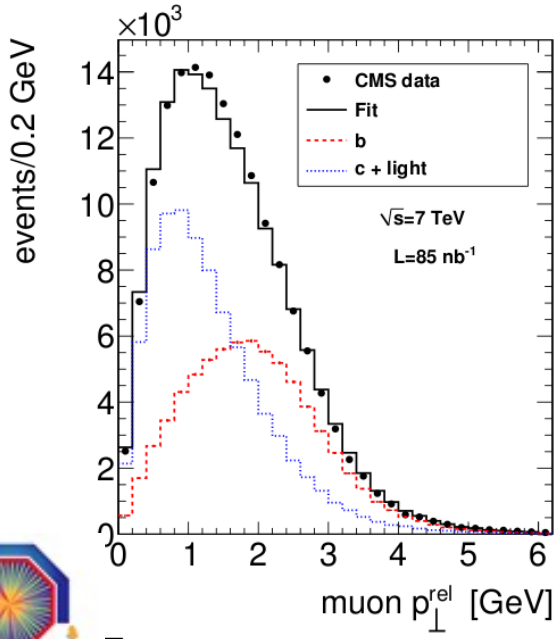


Inclusive *b*: 3 Methods

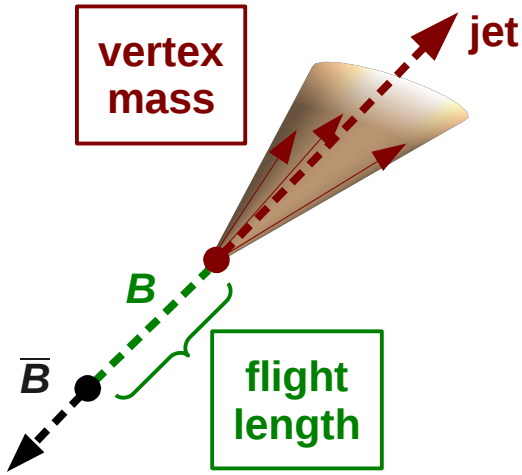
p_T^{rel} Method

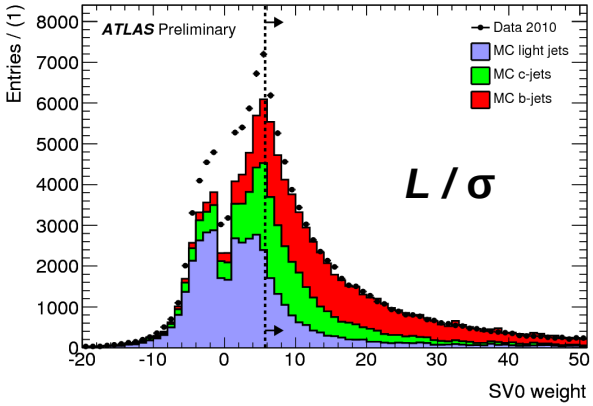


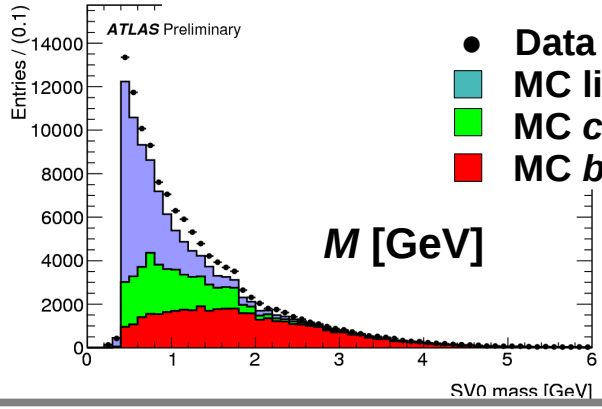
large B-mass
→ large kick to decay muon



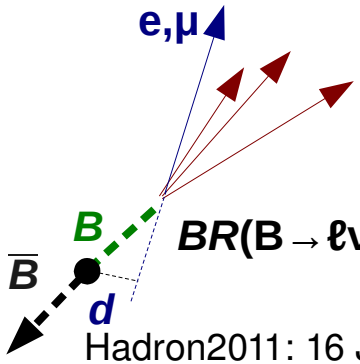
Vertex Method



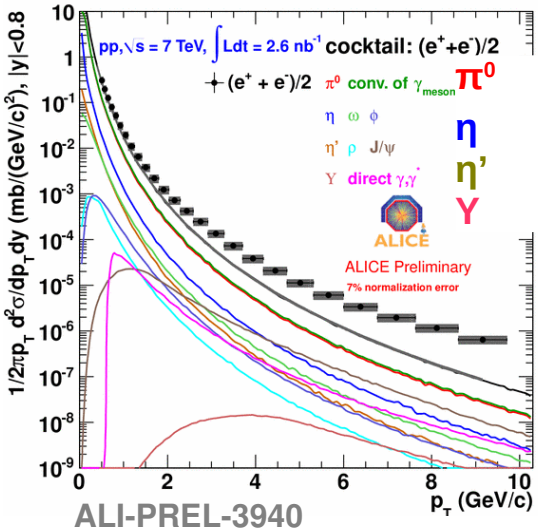




Inclusive Leptons



$BR(B \to \ell\nu X) \sim 11\%$



conv. of γ_{meson}
π^0
η
ω
Φ
η'
ρ
J/ψ
Υ
direct γ,γ*

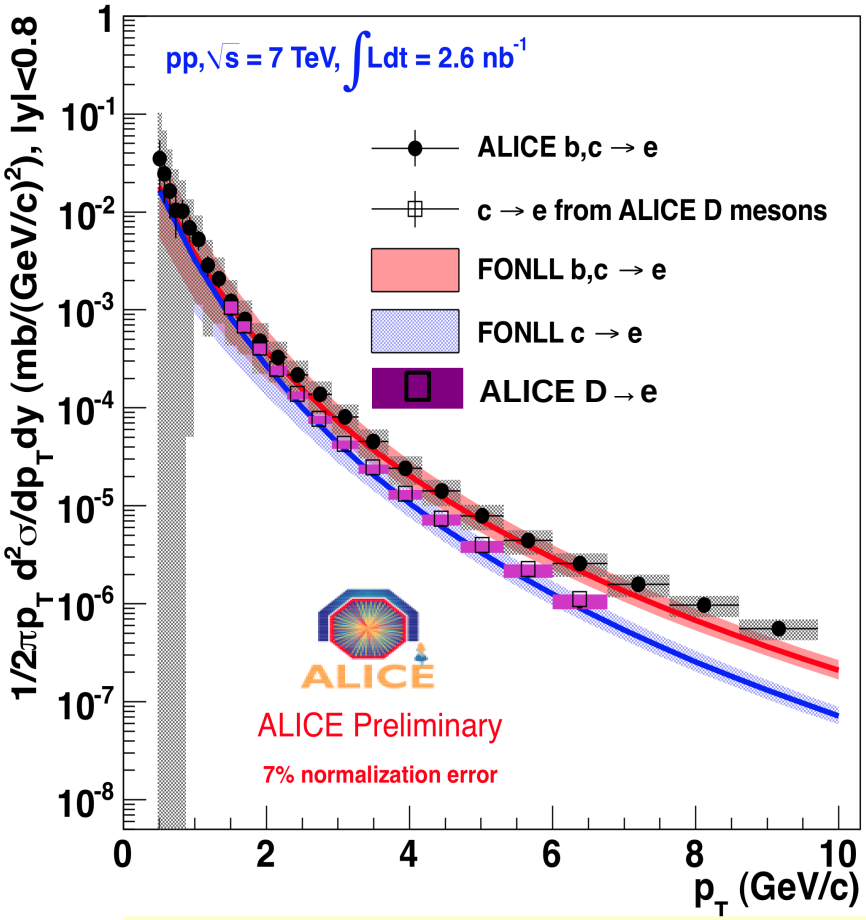
Inclusive HF to Electrons

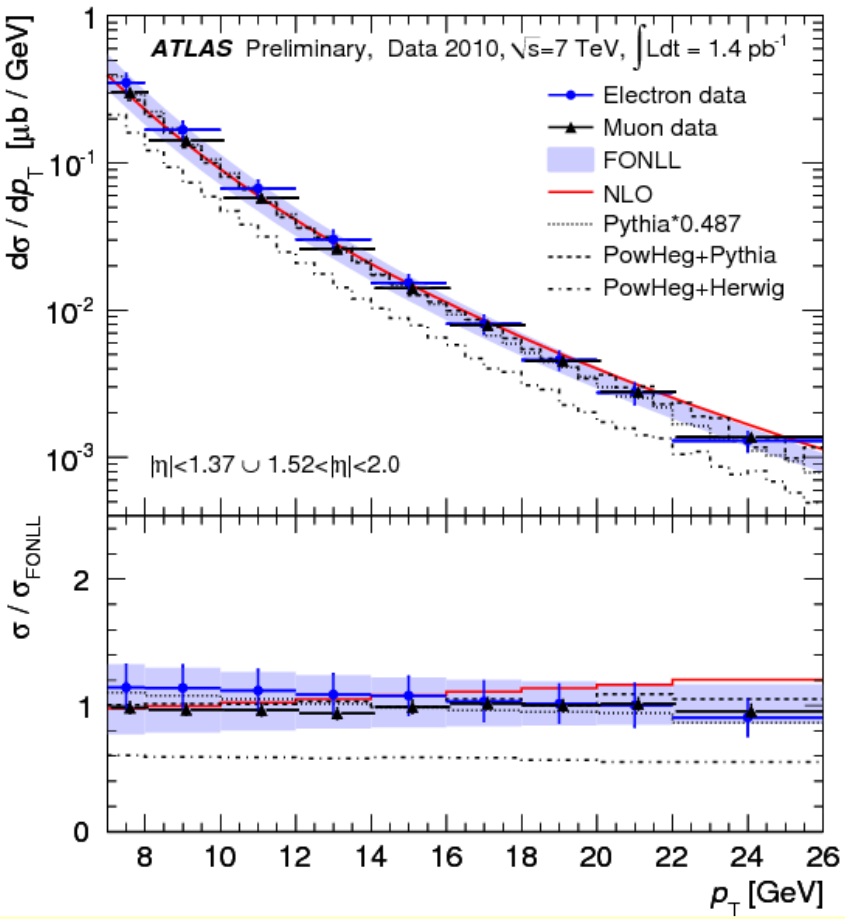
ALICE: 2.6 nb^{-1}

- $\sqrt{s}$ = 7 TeV pp → eX; |y| < 0.8
- "photonic decays" subtr.
  - > using meas π^0 cross-section

ATLAS: 1.3(1.4) pb^{-1} e X (& μ X)

- single e(μ) trig's; |η| < 2.0
- W/Z/γ* subtr. using PYTHIA
  - > norm to NNLO at high mass



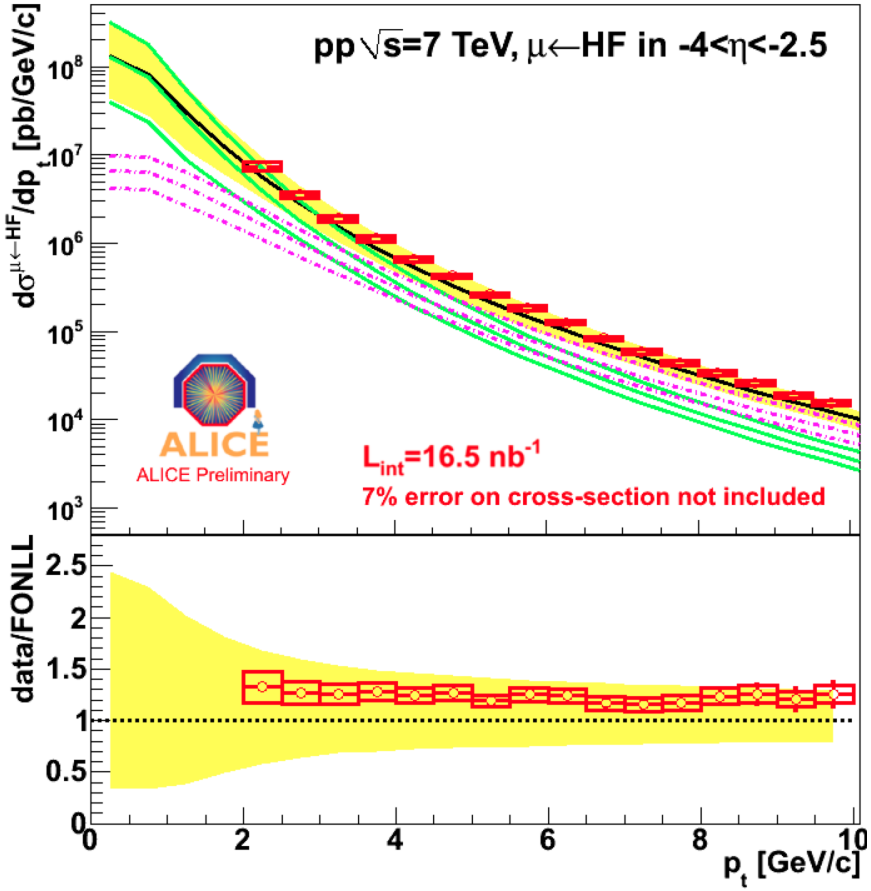


good agreement between HF → e(μ) data and FONLL prediction in low p_T region

Inclusive HF to Muons

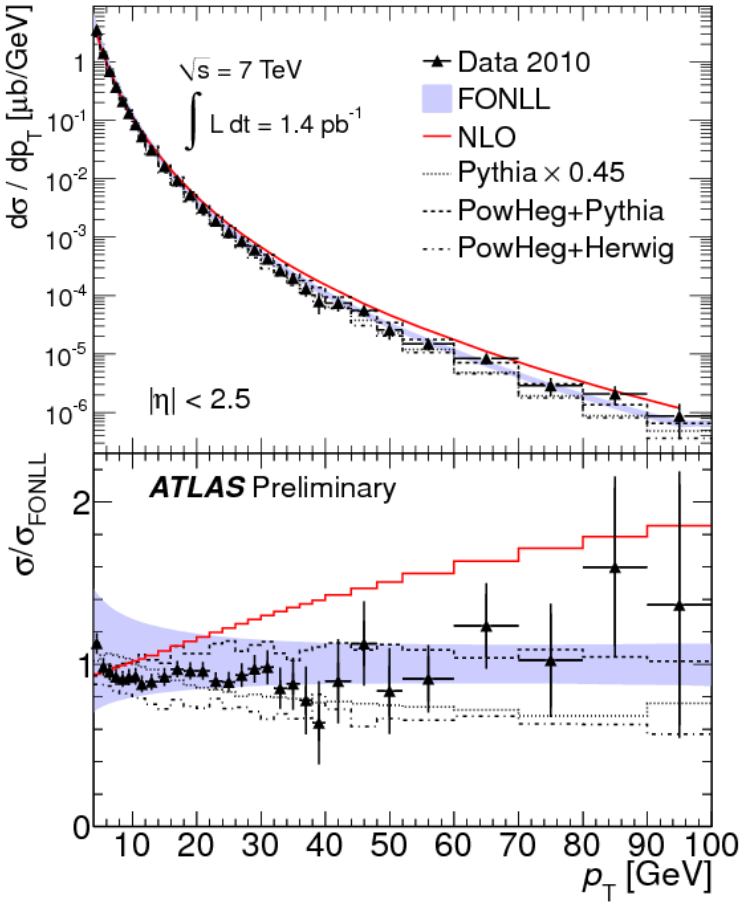
ALICE: 16.5 pb^{-1}

- 7 TeV $pp \rightarrow \mu X$; $-4 < \eta < -2.5$



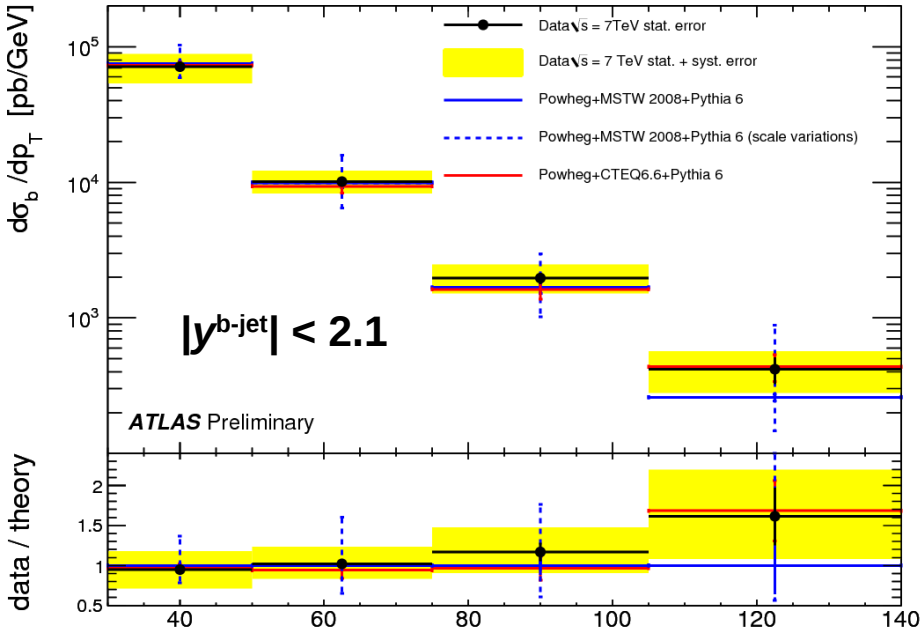
ATLAS: 1.4 pb^{-1}

- single μ trig's; $|\eta| < 2.5$
- D-Y (PYTHIA); W/Z (MC@NLO)
  - > norm to ATLAS W/Z → μ



good agreement between HF → μ data and FONLL prediction in high p_T region

Inclusive *b*: p_T^{rel} Method



ATLAS-CONF-2011-057

ATLAS: 4.8 pb^{-1}

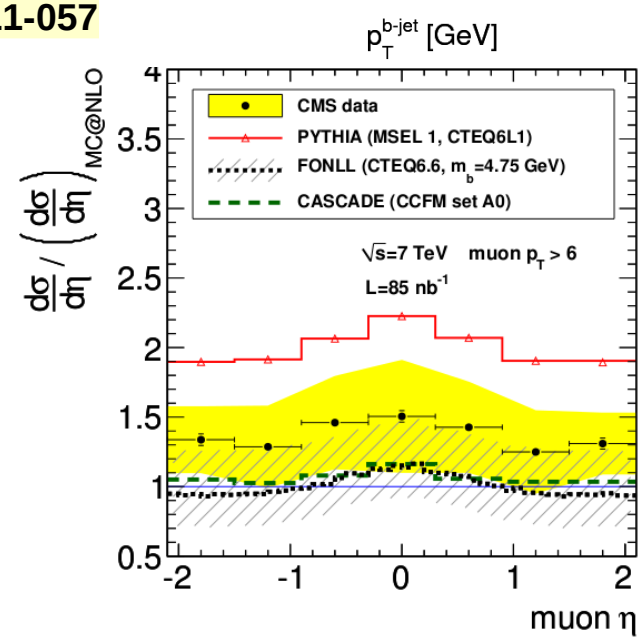
- Muon (>4 GeV) + Jet (>5 GeV) trigger

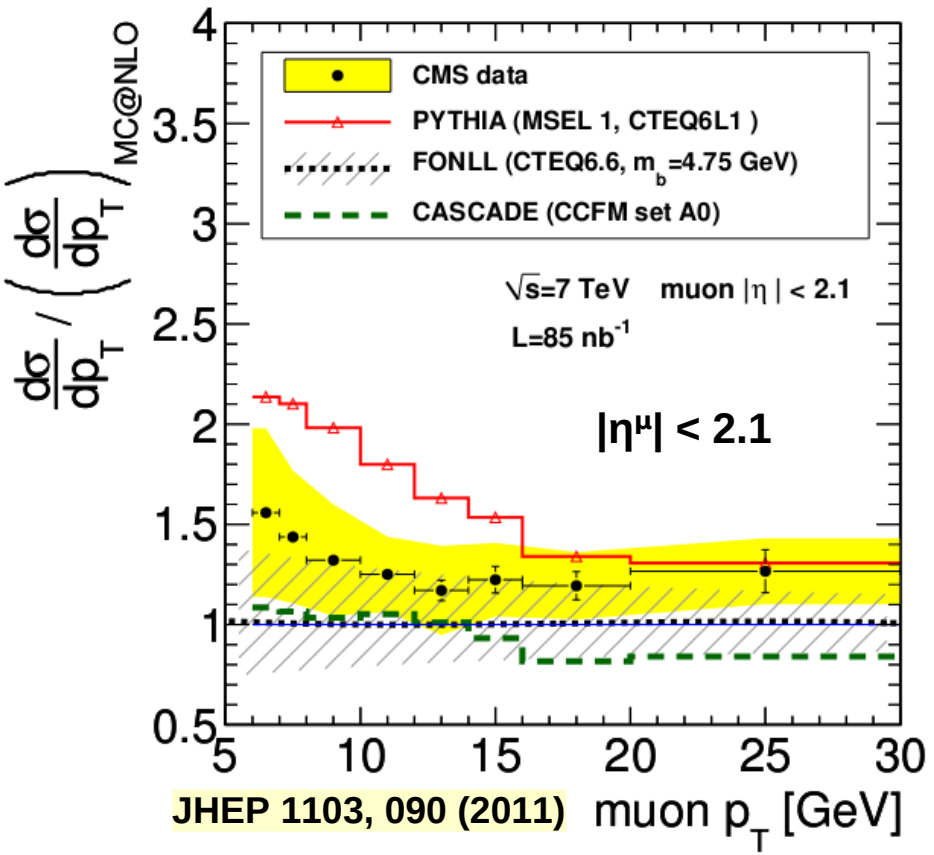
SUMMARY (p_T^{rel} method)

- data already syst limited (p_T^{rel} templates)
- difference from NLO w/in uncertainties

CMS: 85 nb^{-1}

- low pT single muon trigger





JHEP 1103, 090 (2011)

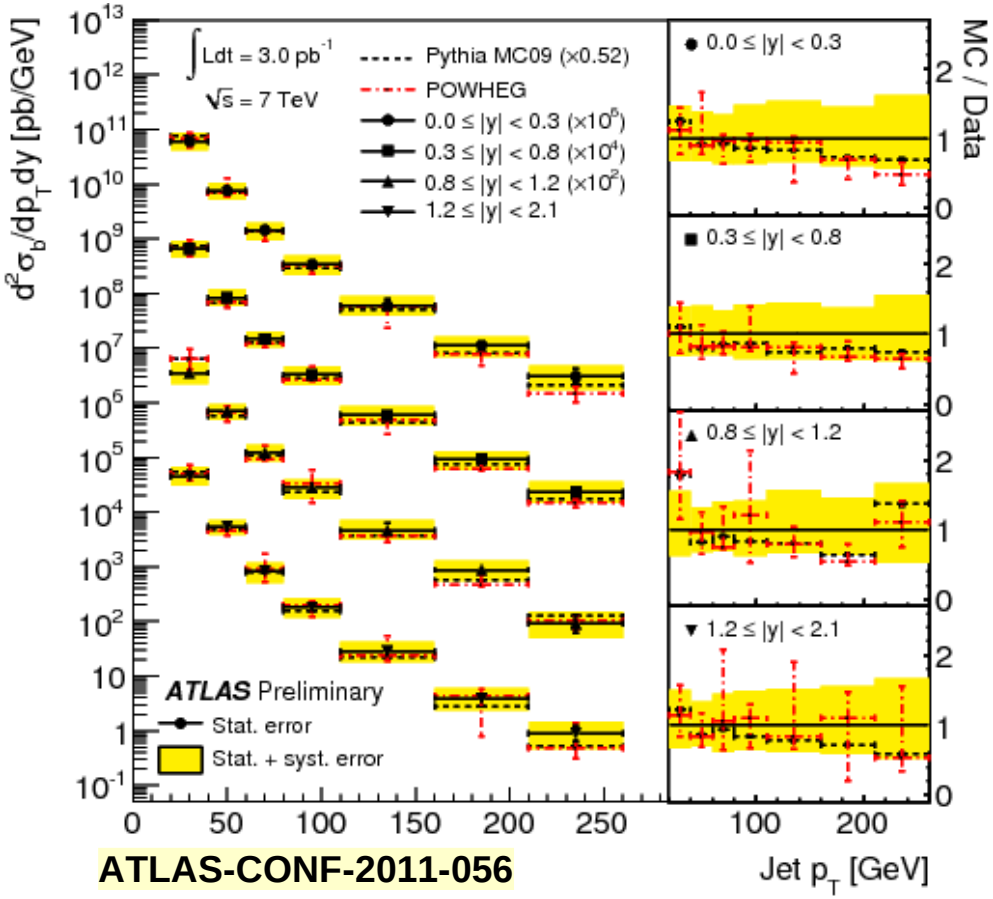
Inclusive *b*: Vertex Method

ATLAS: 3.0 pb^{-1}

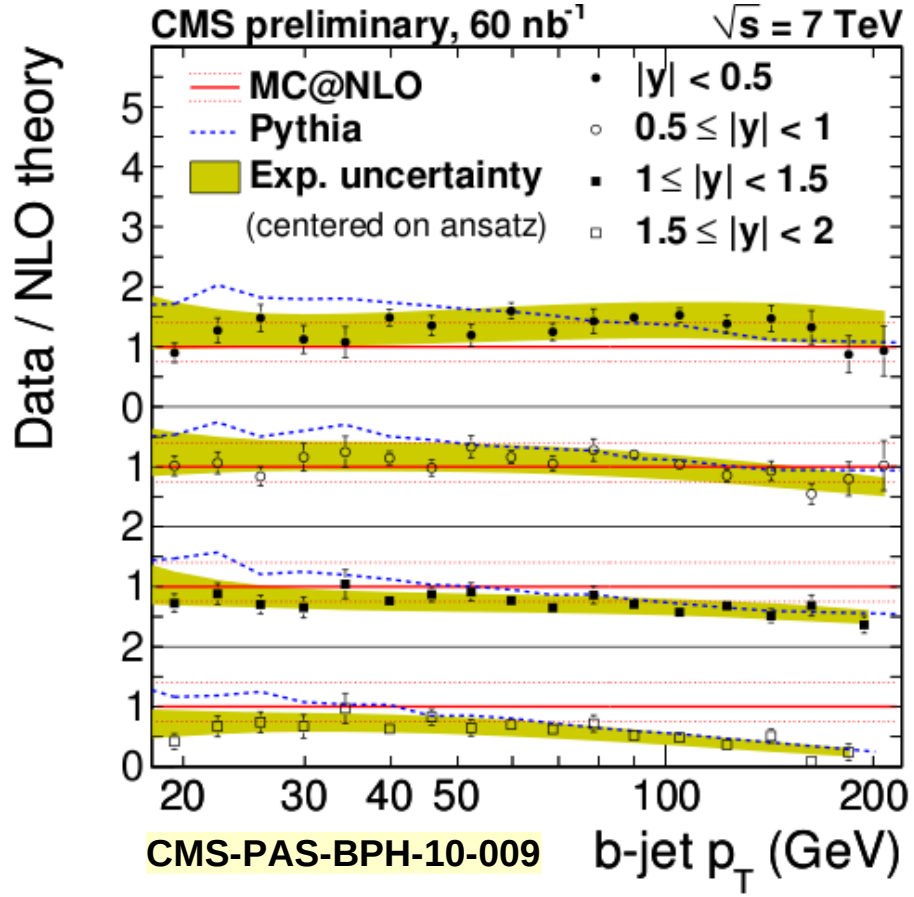
- **Min Bias trigger** **lowest p_T bin**
- **Level-1 jet triggers** **higher p_T bins**

CMS: 60 nb^{-1}

- **Min Bias trigger** **lowest p_T bin**
- **Level-1 jet triggers** **higher p_T bins**

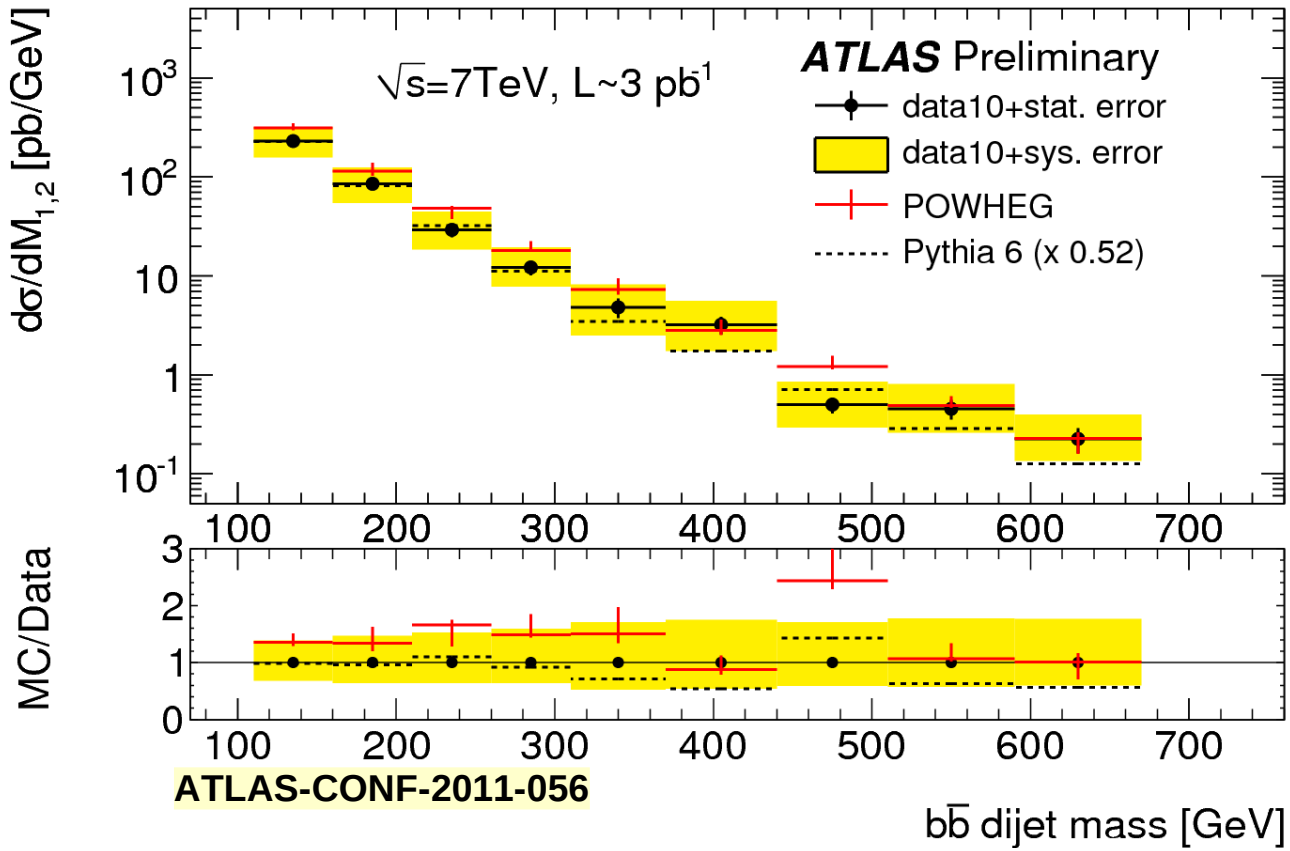


ATLAS-CONF-2011-056



CMS-PAS-BPH-10-009

Inclusive $b\bar{b}$: Vertex Method



ATLAS-CONF-2011-056

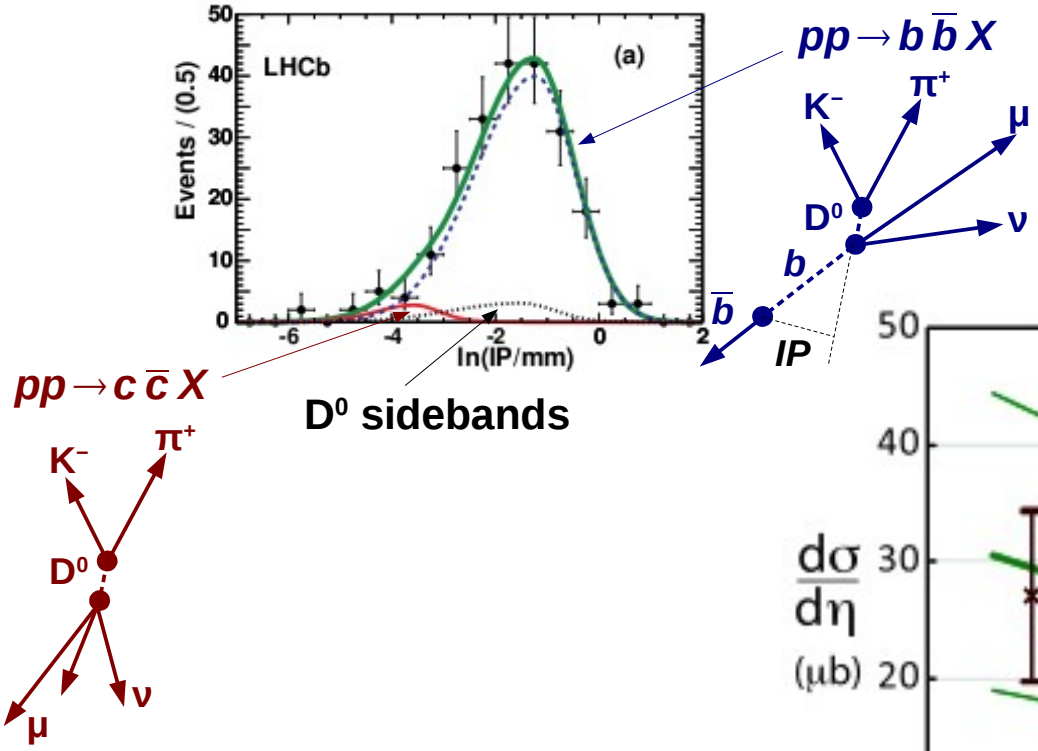
SUMMARY (Vertex Method)

- **data already syst limited (jet E-scale, *b*-tagging)**
- **good agreement with NLO within uncertainties**
- **reasonable agreement with *shape* of PYTHIA prediction**

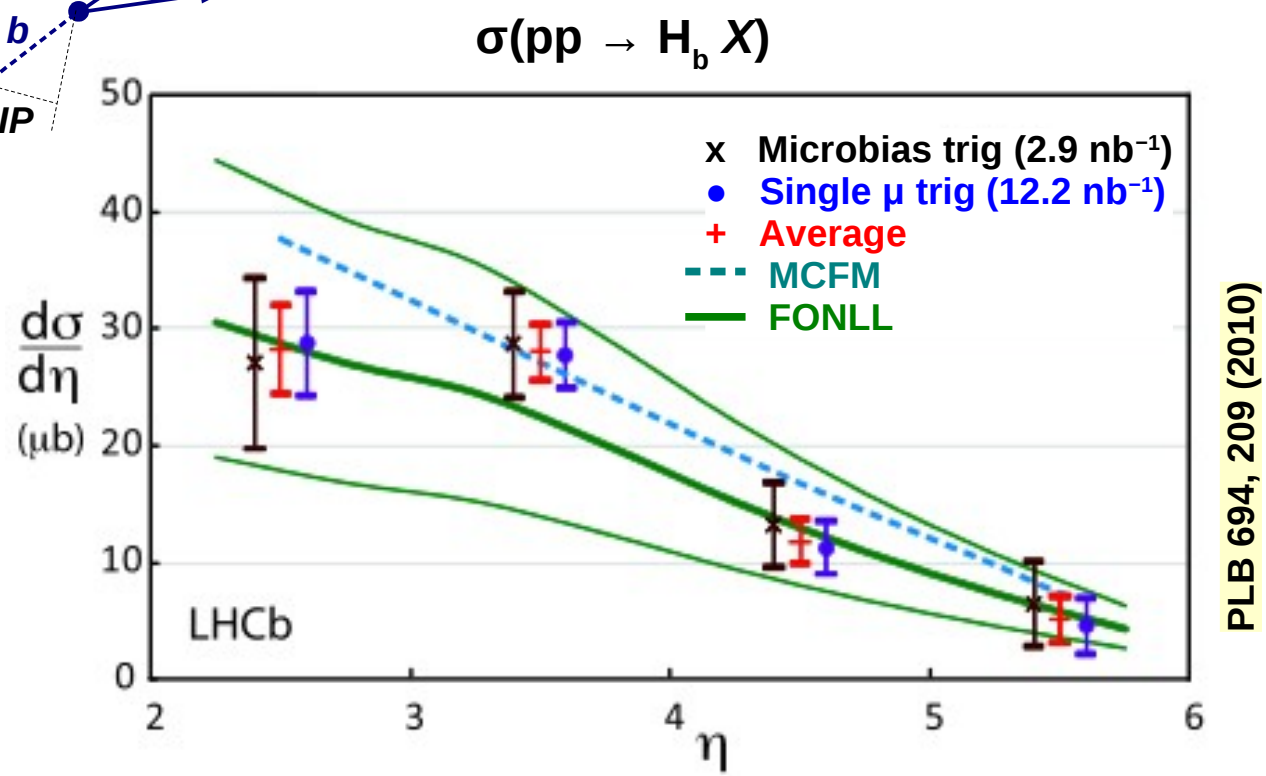
Partially Inclusive: $b \to \mu D^0 X$

$pp \to \mu D^0(K^-\pi^+) X$ (2.9, 12.2 nb^{-1})

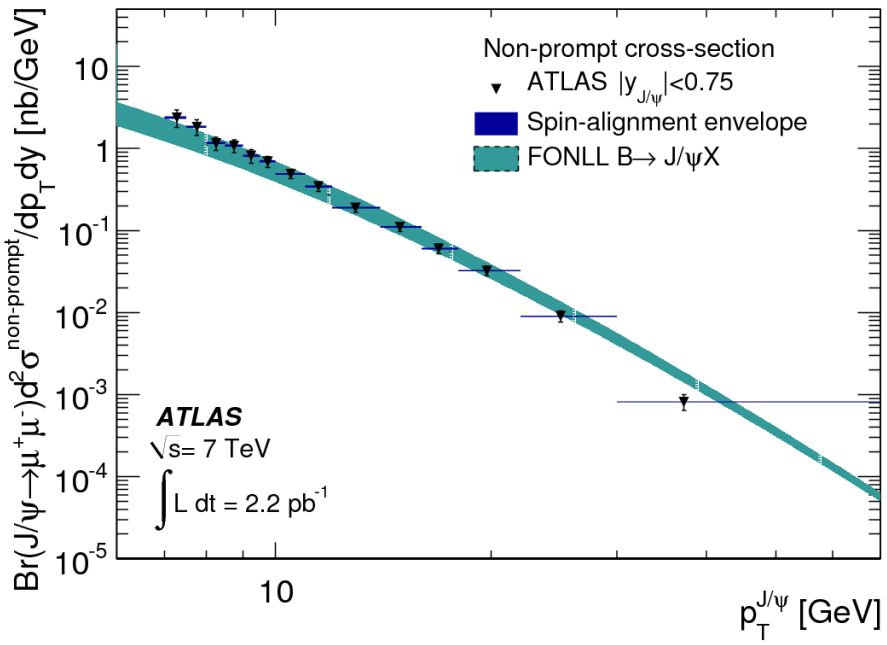
- **Fits to D^0 impact param**



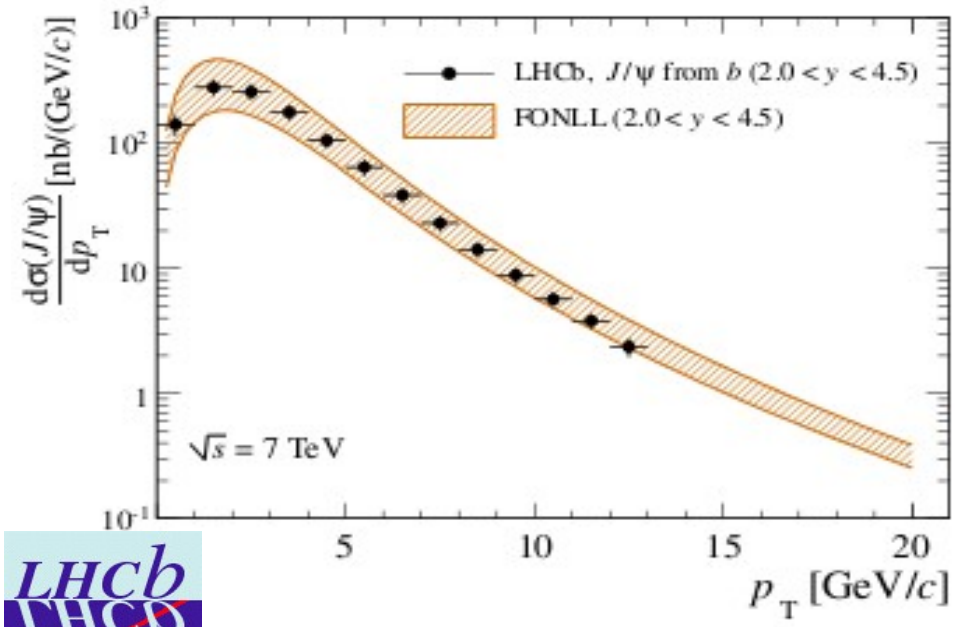
Good agreement data vs FONLL prediction



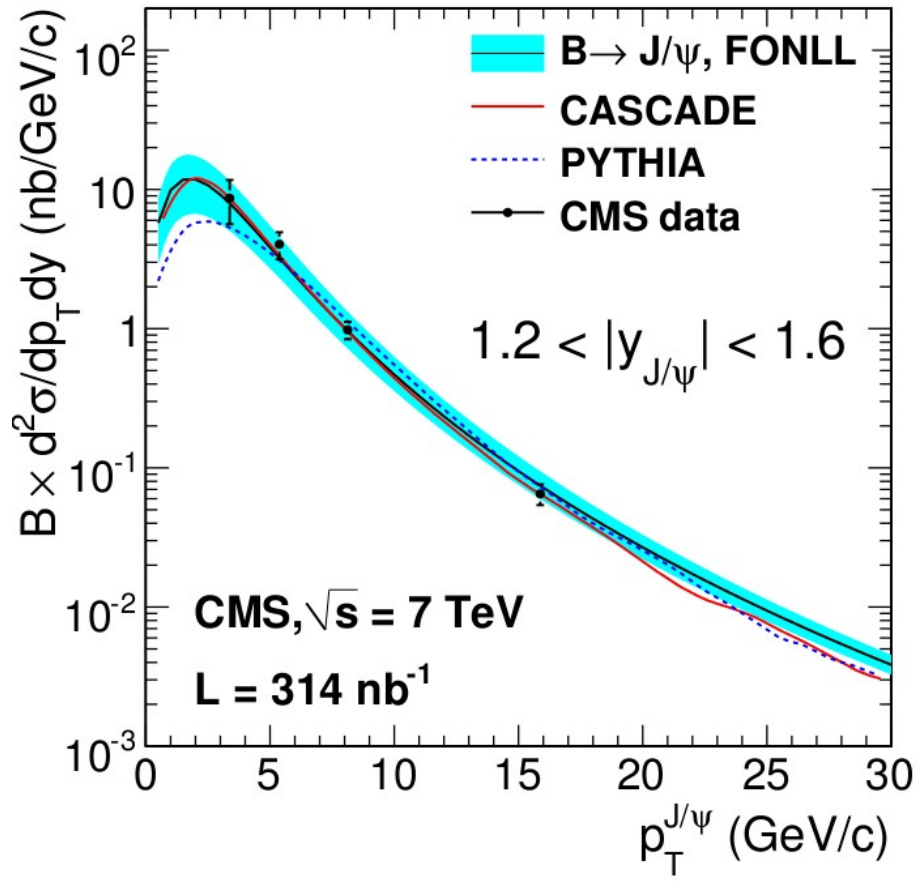
Partially Inclusive: $b \to J/\psi$ X



arXiv:1104.3038



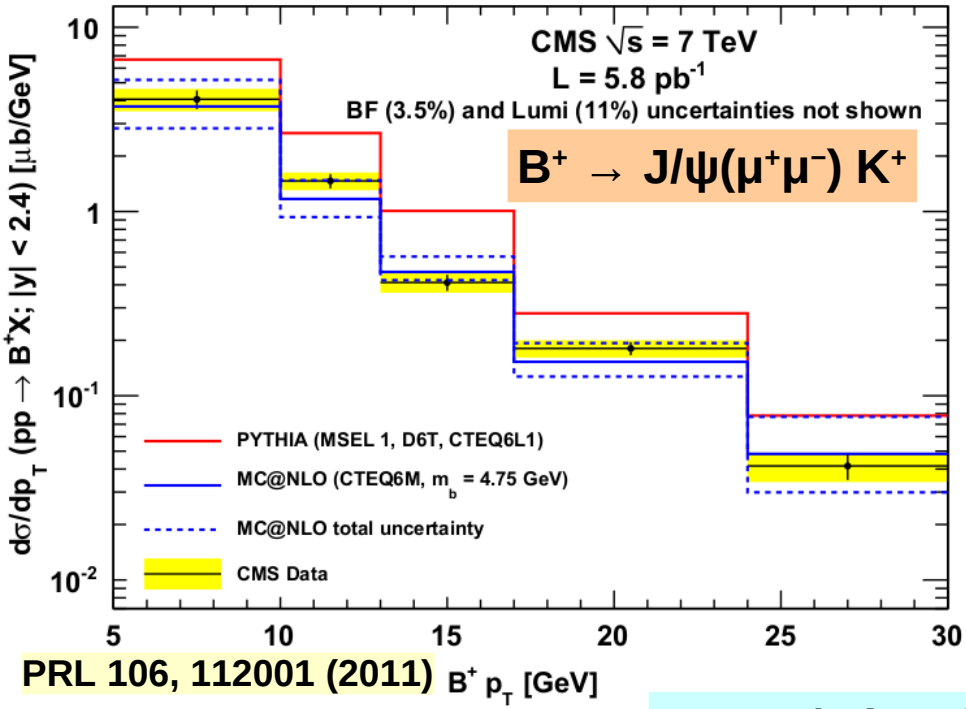
EPJ C71, 1645 (2011)



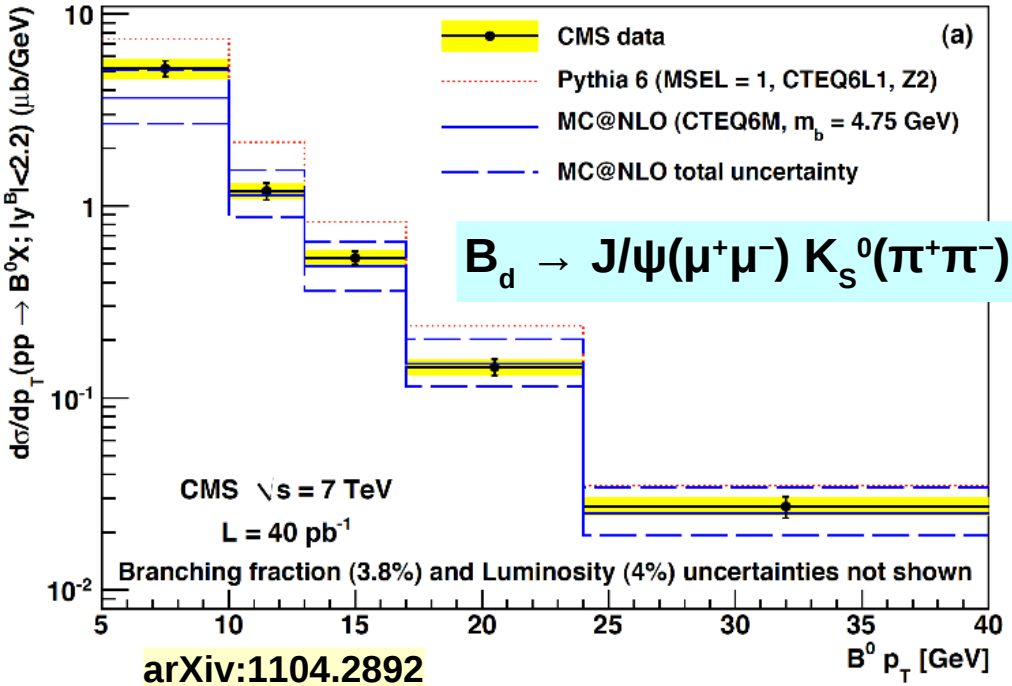
arXiv:1011.4193

Good agreement:
- **data vs FONLL pred (central & forward regions!)**

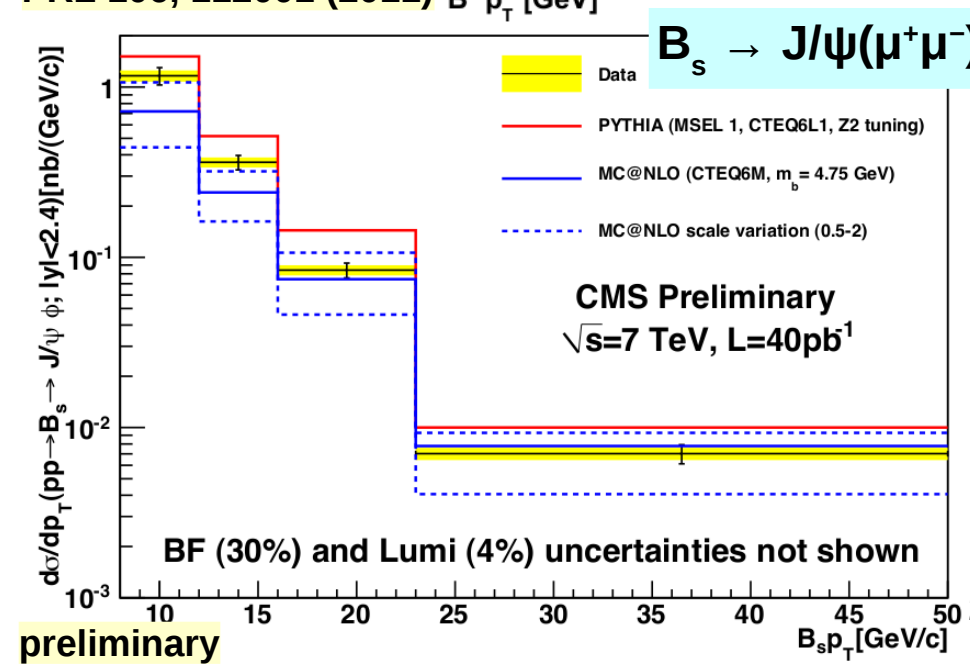
Exclusive Measurements



PRL 106, 112001 (2011)



arXiv:1104.2892

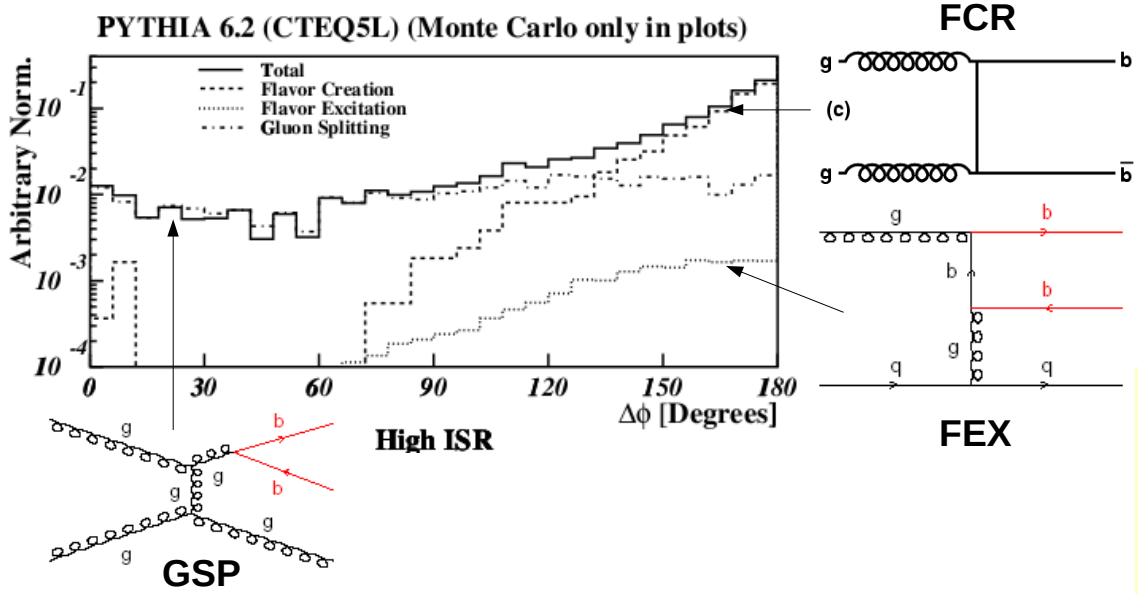


preliminary

- low p_T dimuon trigger
- signal from simultaneous fits to *m*, *ct*
- data lies between NLO and PYTHIA (but consistent with NLO within errors)

$b\bar{b}$ Angular Correlations

CDF: PRD 71 092001 (2005)



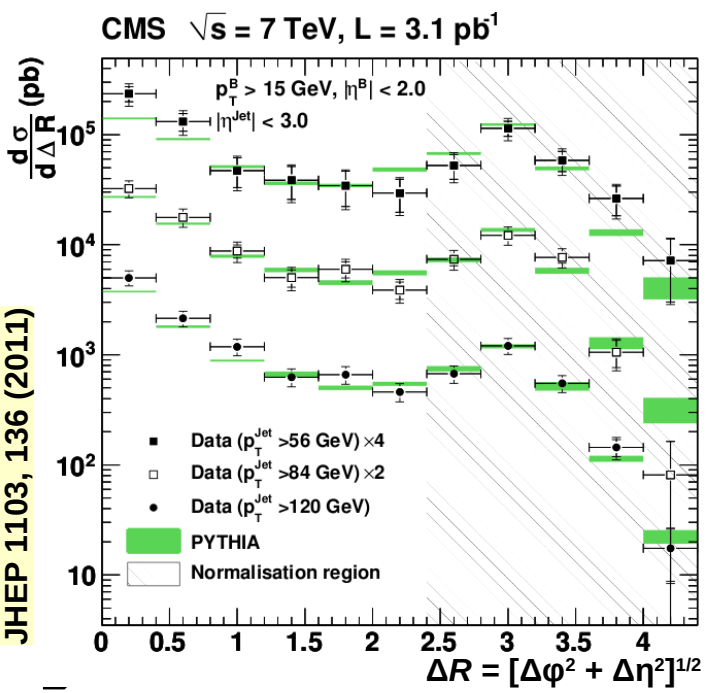
Events with 2 Secondary Vertices

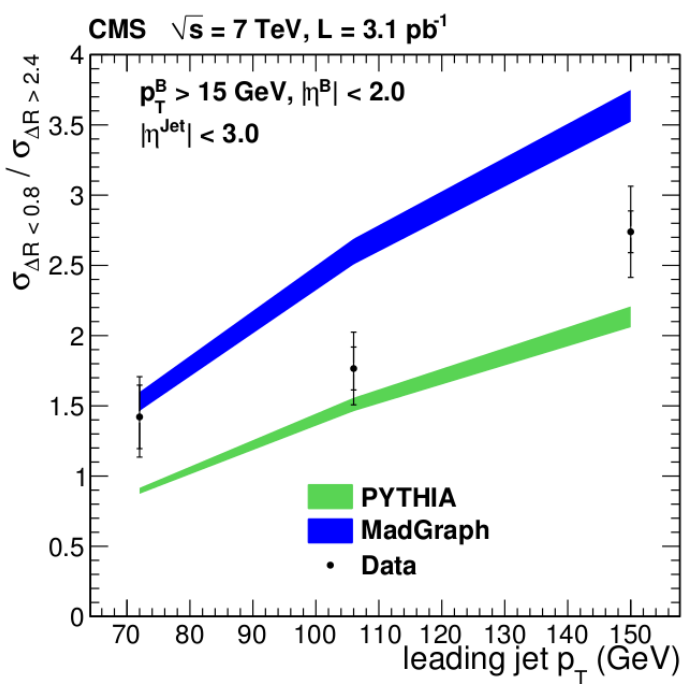
- 3.1 pb^{-1}
- 3 single-jet triggers (56,84,120 GeV)
- using secondary vertices → access to small ΔR (gluon splitting)

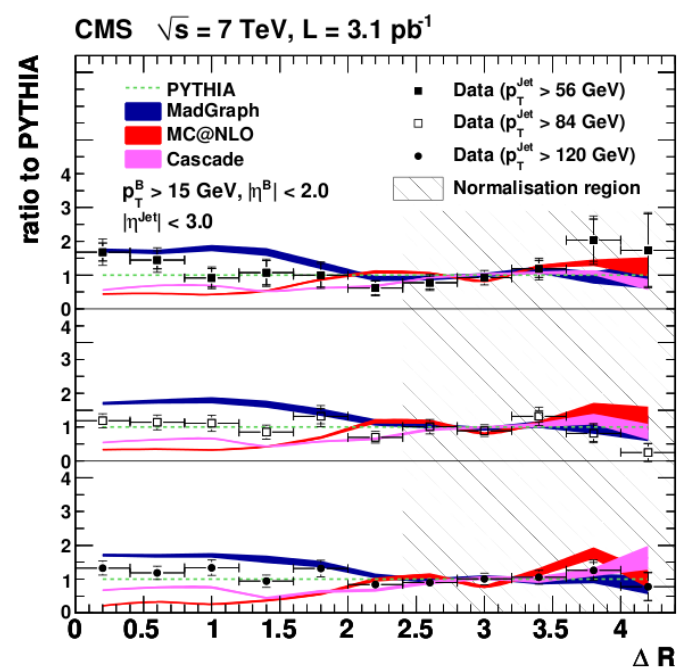
Summary

- data between PYTHIA and MadGraph
- neither MC@NLO nor CASCADE describe Δ*R* shape

JHEP 1103, 136 (2011)







Fragmentation Functions

LHCb

LHCB-CONF-2011-013

- $f_s / (f_u+f_d)$ & $f_{\Lambda b} / (f_u+f_d)$ — 3 pb^{-1}
  - > $b \to \mu\, D^0/D^+/D_s/\Lambda_c X$
- f_s / f_d — 35 pb^{-1}
  - > $B^0 \to D^-\pi^+$, D^-K^+; $B_s \to D_s\pi^+$

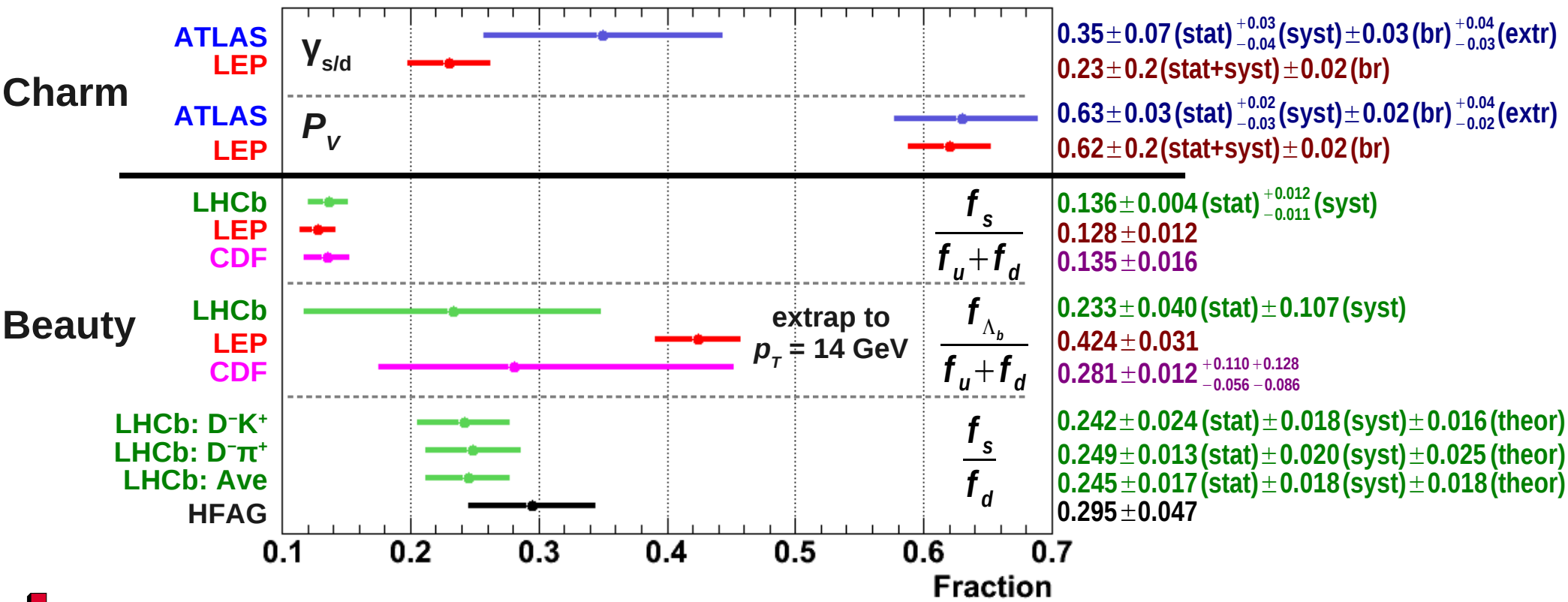
ATLAS

ATLAS-CONF-2011-017

- $\gamma_{s/d} = D_s/D^- + D^{*-}$; $P_V = D^*/D^- + D^{*-}$
  - > D^{*-}, D^-, D_s — 1.1 nb^{-1}

$BR(B_d \to D^- K^+) = (2.02 \pm 0.17 \pm 0.12) \cdot 10^{-4}$

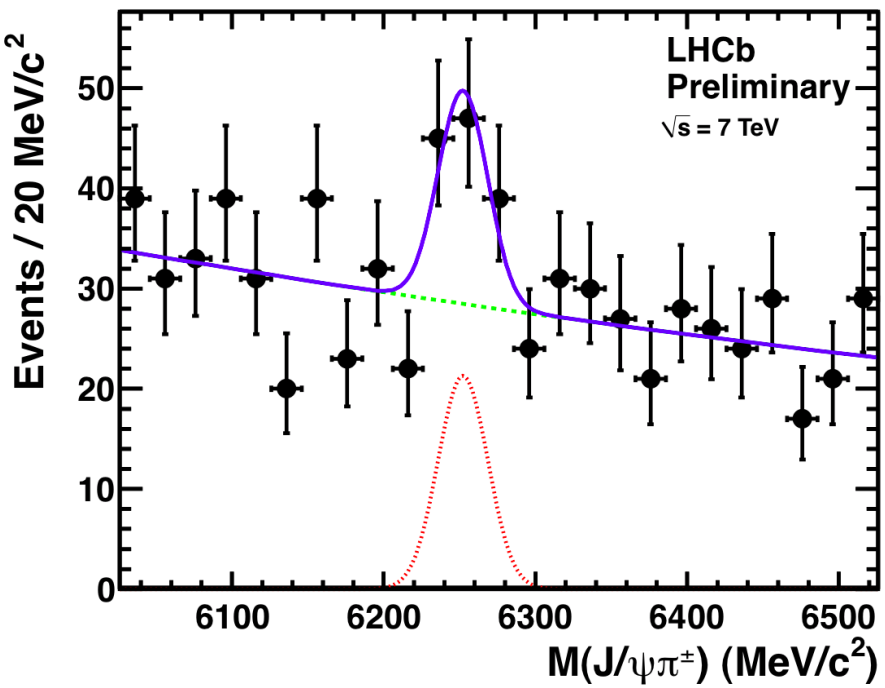
[PDG: $(2.0 \pm 0.6) \cdot 10^{-4}$]



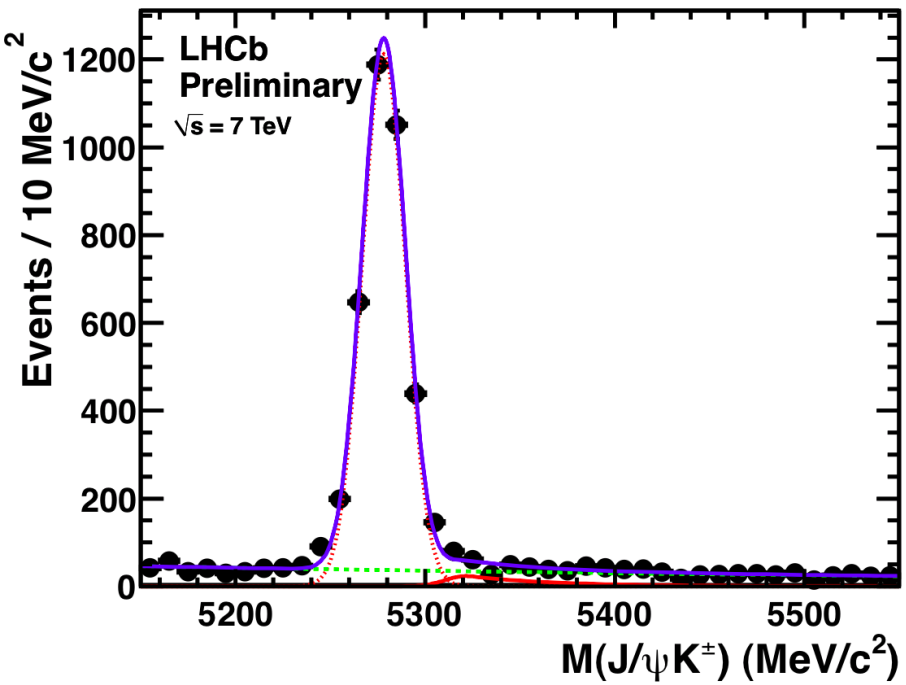
B_c Fraction

Single and Di-Muon Triggers: 32.5 pb^{-1}

$B_c \to J/\psi(\mu^+\mu^-)\ \pi^+$: 43 ± 13 decays



$B^+ \to J/\psi(\mu^+\mu^-)\ K^+$: 3476 ± 62 decays



LHCB-CONF-2011-017

$$\frac{\sigma(B_c^+)\times BR(B_c^+\to J/\psi\,\pi^+)}{\sigma(B^+)\times BR(B^+\to J/\psi\,K^+)} = (2.2 \pm 0.8 \pm 0.2)\%\quad \text{LHCb}$$

$$= (1.4 \pm 0.4 \pm 0.1)\%\quad \text{BcVegPy prediction}$$

Exclusive Decays

All Heavy Flavor Hadrons produced copiously at the LHC

- ALICE, ATLAS, CMS: (re)observed all or most of the low-lying states
- but exclusive reconstruction is an area where LHCb takes the lead

Spectroscopy, etc

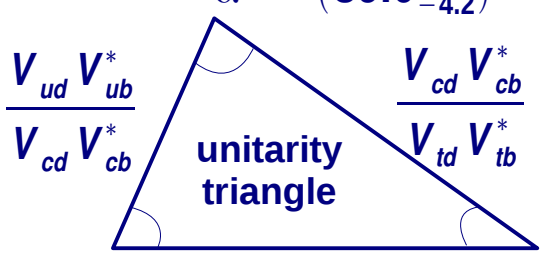
- access to new final states (several firsts already)
- comparison to predictions for masses, BRs, etc

Ingredients for EW studies

- CP violation from a variety of $B_{u,d,s}$ decay channels

$$V_{ub}V_{ud}^{*}+V_{cb}V_{cd}^{*}+V_{tb}V_{td}^{*}=0$$

$$\alpha = \left(89.0^{+4.4}_{-4.2}\right)^{o}$$



$$\gamma = \left(71^{+21}_{-25}\right)^{o} \qquad \beta = \left(21.15^{+0.90}_{-0.88}\right)^{o}$$

CKMFitter: ICHEP 2010

$$V_{us}V_{ub}^{*}+V_{cs}V_{cb}^{*}+V_{ts}V_{tb}^{*}=0$$

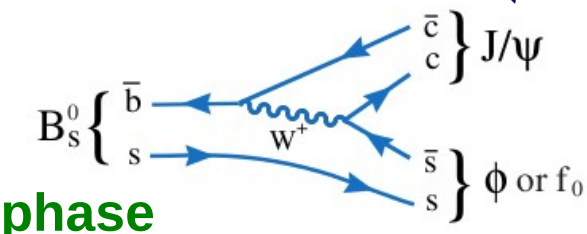
$$\frac{V_{ts}V_{tb}^{*}}{V_{cs}V_{cb}^{*}}$$

$$\beta_s = \left(-18.0^{+1.0}_{-0.8}\right) \times 10^{-3} \quad \text{(SM pred)}$$

Charles, et al, EPJ C41, 1 (2005)

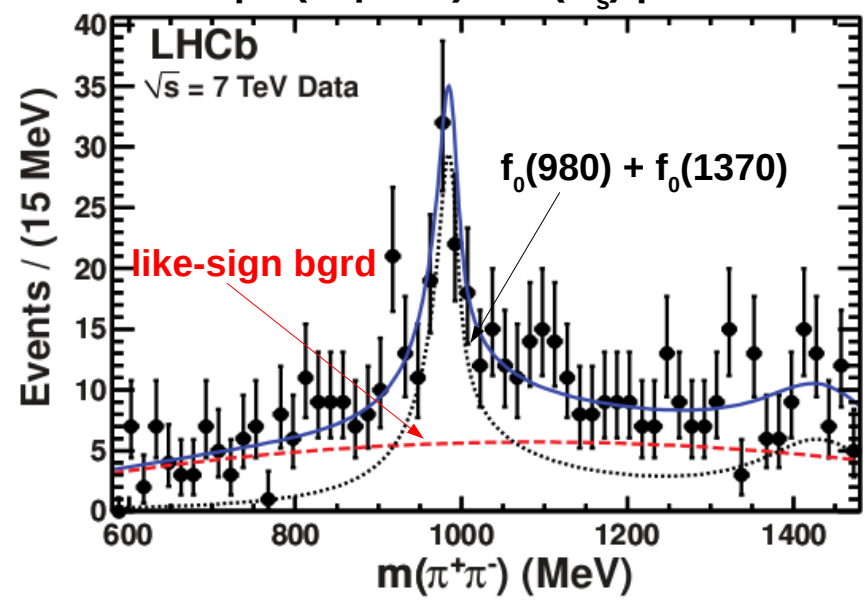
Toward β_s: $B_s \to J/\psi\, f_0(980)$

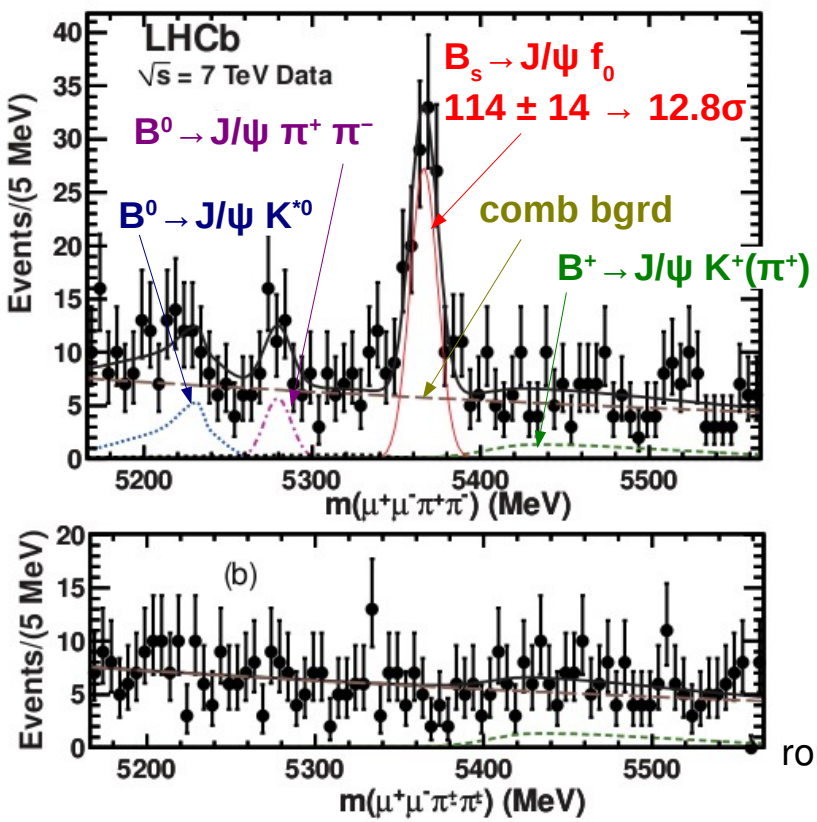
- $B_s \to J/\psi\, f_0(980)$ similar to $B_s \to J/\psi\, \Phi$
  - but consists of a single CP-odd eigenstate
  - angular analysis not needed to extract CPV ($-2\beta_s$) phase



- LHCb analysis: $J/\psi(\mu^+\mu^-)\, f_0(\pi^+\pi^-)$
  - dimuon trigger: 33 pb^{-1}

events with $|\, M(J/\psi\, \pi\pi) - M(B_s)\, | < 30$ MeV





PLB 698, 115 (2011)

$$\frac{\Gamma[B_s^0 \to J/\psi\, f_0(\pi^+\pi^-)]}{\Gamma[B_s^0 \to J/\psi\, \phi(K^+K^-)]} = 0.252\ {}^{+0.046+0.027}_{-0.032-0.033}$$

D0 Note 6152 $(8\ fb^{-1})$ = $0.210 \pm 0.032 \pm 0.036$

predictions = $0.07 - 0.50$

Stone, arXiv:1009.4939

Toward γ: $X_b \to X_c\, 3\pi^{\pm}$, $B_s \to D^0 K^{*0}$

γ Measurements to date rely primarily on: $B^- \to D^{(*)} K^{(*)-}$

- many other modes show good potential, e.g.

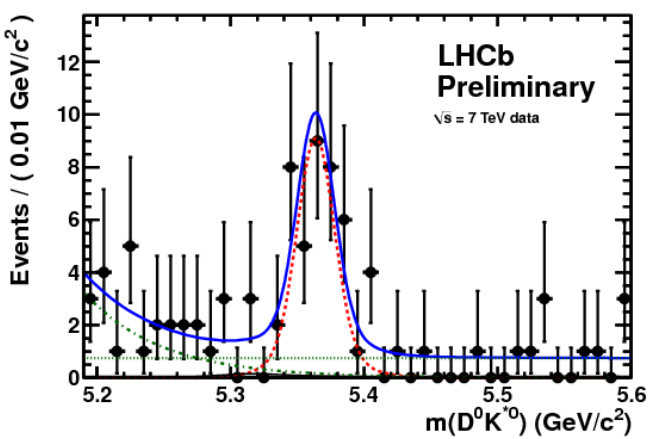
$$B_d^0 \to D^0 K^{*0},\ B^- \to D^0 K^- \pi^+ \pi^-,\ \overline{B}^0 \to D^+ \pi^- \pi + \pi^-,\ B_s^0 \to D_s^+ K^- \pi + \pi^-$$

First step: measure similar/background modes (~36 pb^{-1})

- normalize to higher-stats modes: $B \to D^0 \rho$, $X_b \to X_c\, \pi^-$

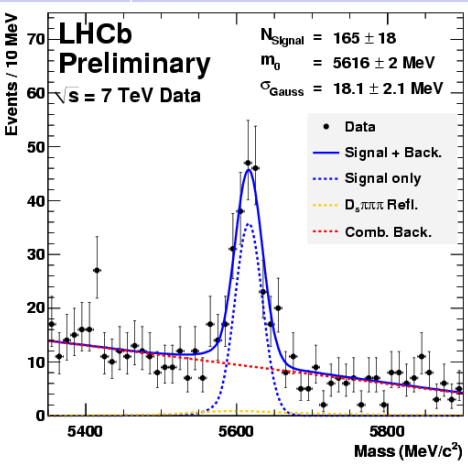
Mode	Events	Branching Ratio (x 10^4)	prev. World Ave
$\overline{B}_s^0 \to D^0 K^{*0}$	34.5 ± 6.9	$4.44 \pm 1.00^{sta} \pm 0.55^{sys} \pm 0.56^{fs/fd} \pm 0.69^{B \to D\rho}$	
$\overline{B}_d^0 \to D^+ \pi^- \pi^+ \pi^-$	1151 ± 45	61.6 ± 2.6 ± 6.9	80 ± 25
$B^- \to D^0 \pi^- \pi^+ \pi^-$	973 ± 45	59.6 ± 2.9 ± 6.1	110 ± 40
$\overline{B}_s^0 \to D_s^+ \pi^- \pi^+ \pi^-$	139 ± 24	62.8 ± 11.0 ± 12.1	84 ± 33
$\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$	165 ± 18	122 ± 14 ± 46	

$\overline{B}_s^0 \to D^0 K^{*0}$



LHCB-CONF-2011-008

$\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^+ \pi^-$

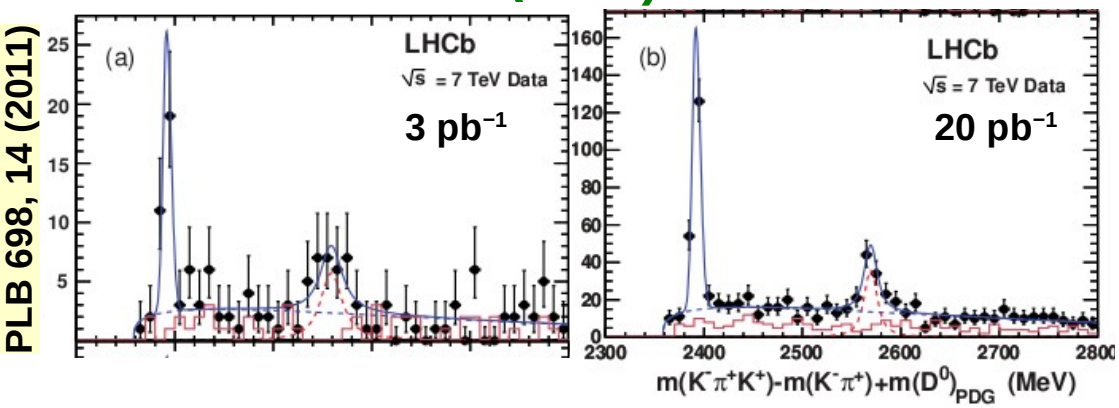


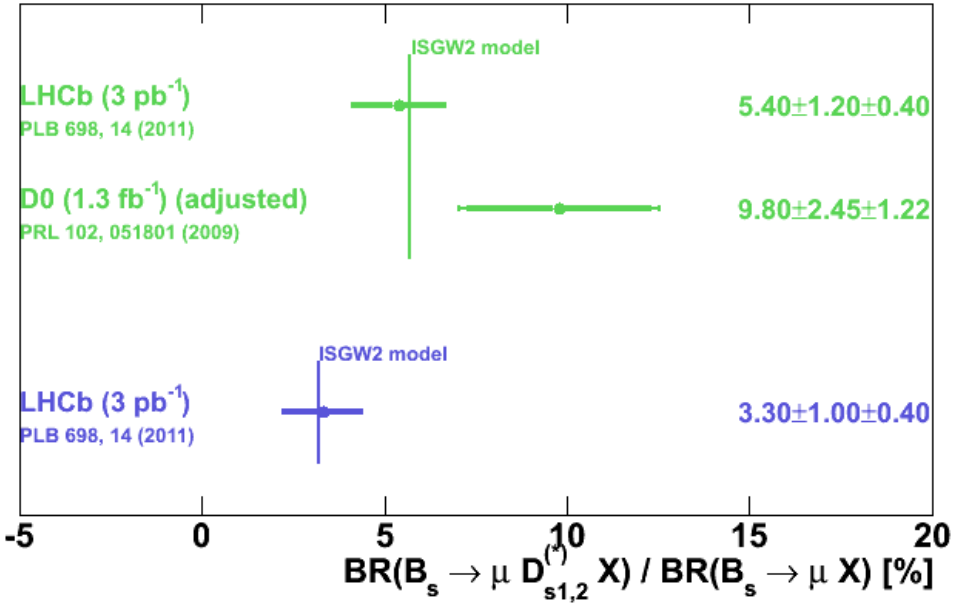
LHCB-CONF-2011-007

B_s Properties: $B_s \to \mu D_{s2}^{*} X$, $K^{*0} \overline{K}^{*0}$

$B_s \to \mu^+ D_{s1}^- X$, $\mu^+ D_{s2}^{*-} X$

- $D_{s1}(2536) \to D^* K$ $J^P = 1^+$
- $D_{s2}^*(2573) \to D K$ $J^P = 2^+$
- search in $D^0(K^-\pi^+) K^+$





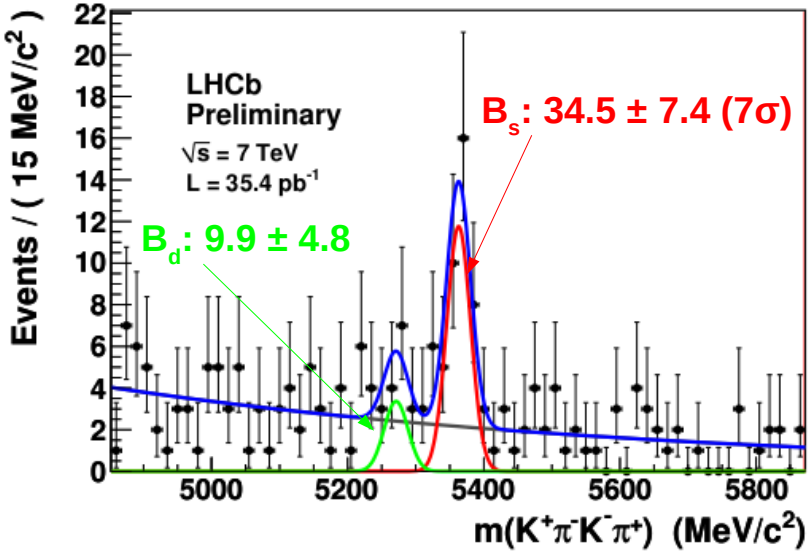
$B_s^0 \to K^{*0} \overline{K}^{*0}$ $(35\ \text{pb}^{-1})$

- normalize to $B^0 \to J/\psi\ K^{*0}$

$$BR(B_s^0 \to K^{*0}\overline{K}^{*0}) = \left[1.95 \pm 0.47(\text{stat}) \pm 0.51(\text{syst}) \pm 0.29(f_d/f_s)\right] \times 10^{-5}$$

$$\text{QCD factorization} = \left[0.79^{+0.43}_{-0.39}\right] \times 10^{-5}$$

Beneke, Rohrer, Yang; NPB 774, 64 (2007)



Where Are We & What's Next?

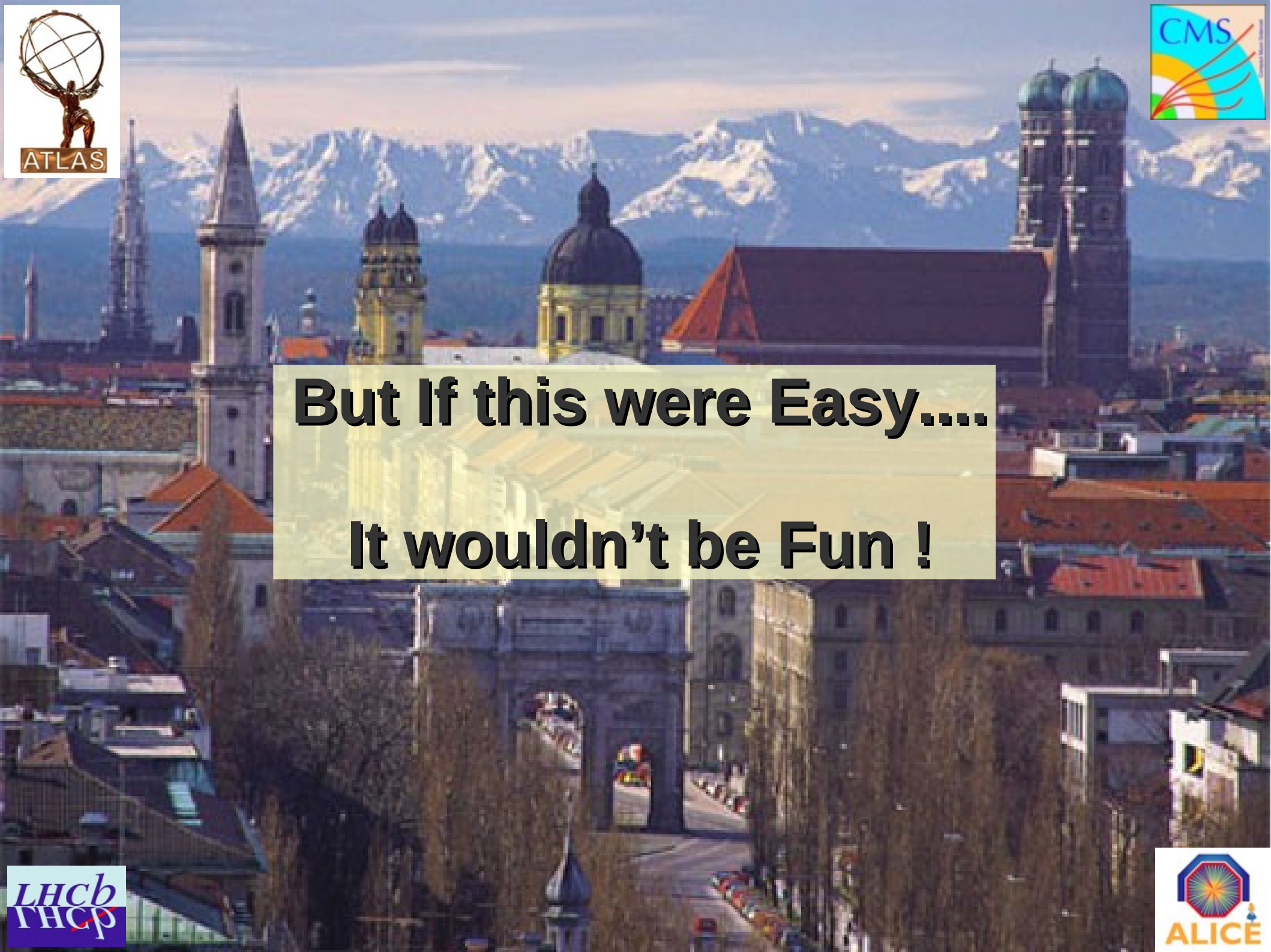
Heavy Flavor Production: data vs predictions

charm	good agreement with NLO (but large uncertainties)
(semi) inclusive *b*	good agreement with NLO, PYTHIA predicts shape well
forward *b*-prod	good agreement with NLO
exclusive *b*	data between NLO & PYTHIA (but w/in uncertainties)
b angular correlations	NLO underestimates / MadGraph overest. gluon splitting

- substantial uncertainties on predictions: scale variations
- measurements now largely systematics limited
- new strategies needed for further studies of H.F. production at the LHC
  - increased luminosity taking away inclusive, low p_T triggers → focus on exclusive states (e.g. CMS $\Lambda_b \to J/\psi\ \Lambda$)

Exclusive Final States & Spectroscopy

- starting to make an impact here (LHCb has several "firsts")
  - LHCb results will accelerate in the future
- Other exp's limited by lack of triggers sensitive to hadronic decays
  - dimuon triggers will be the workhorses

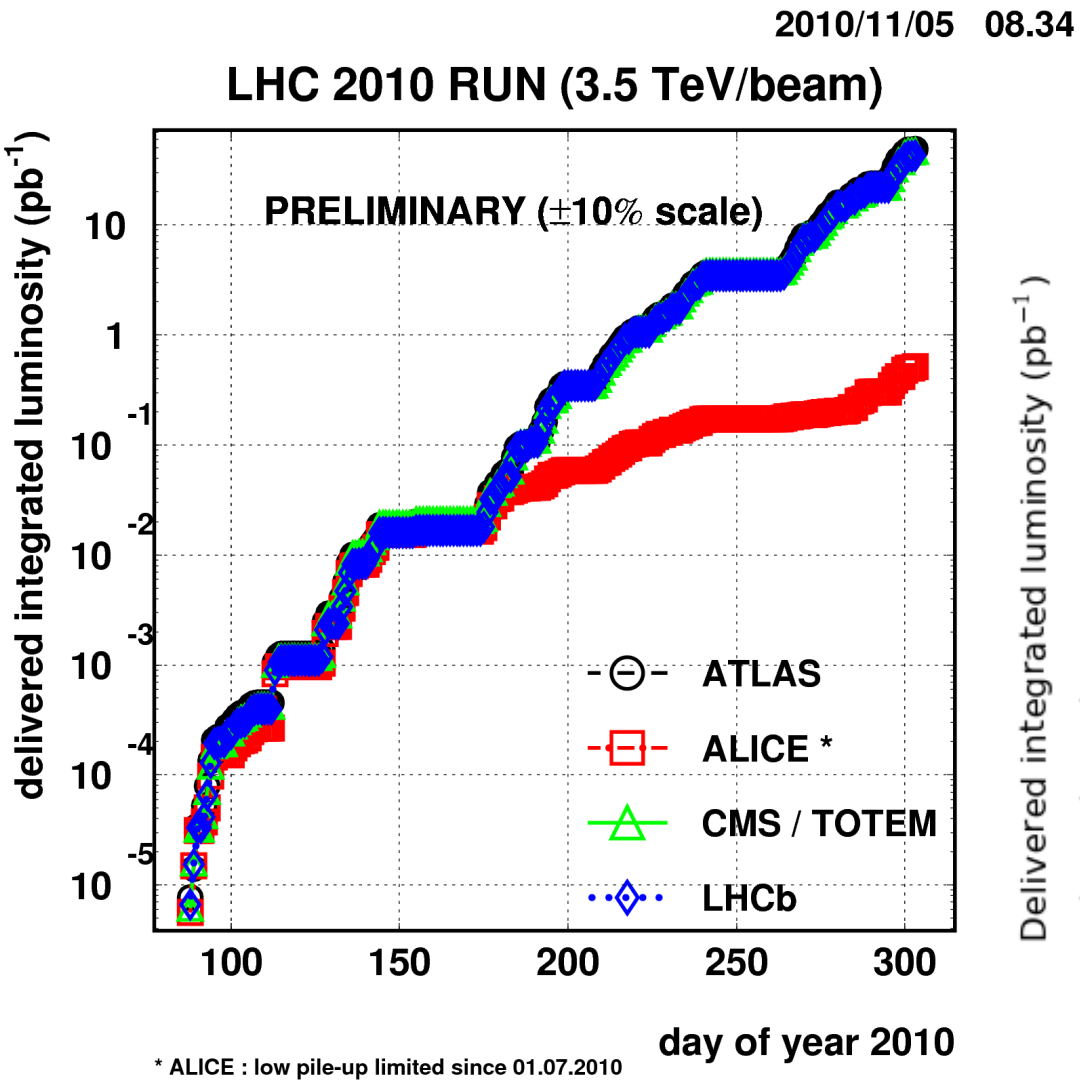


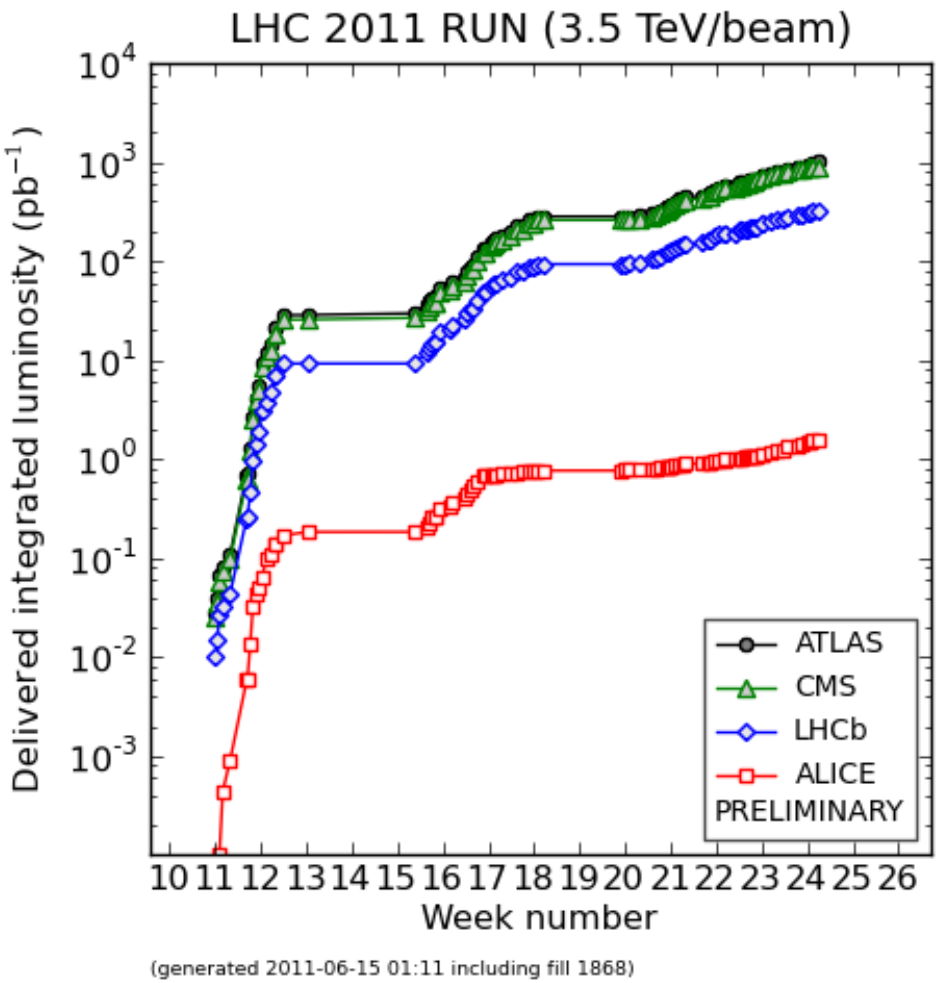
But If this were Easy....

It wouldn't be Fun !

Backup Slides

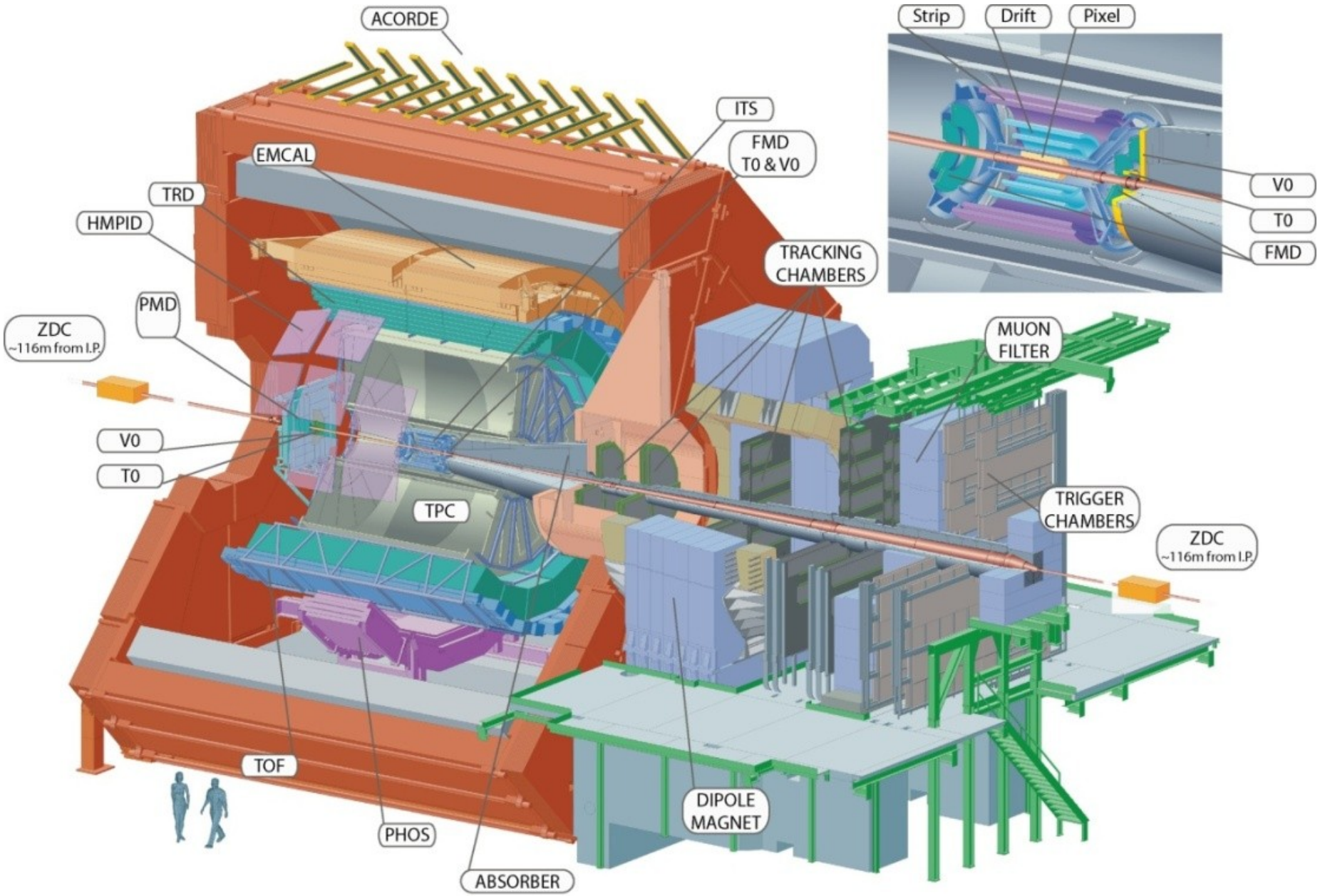
Luminosities



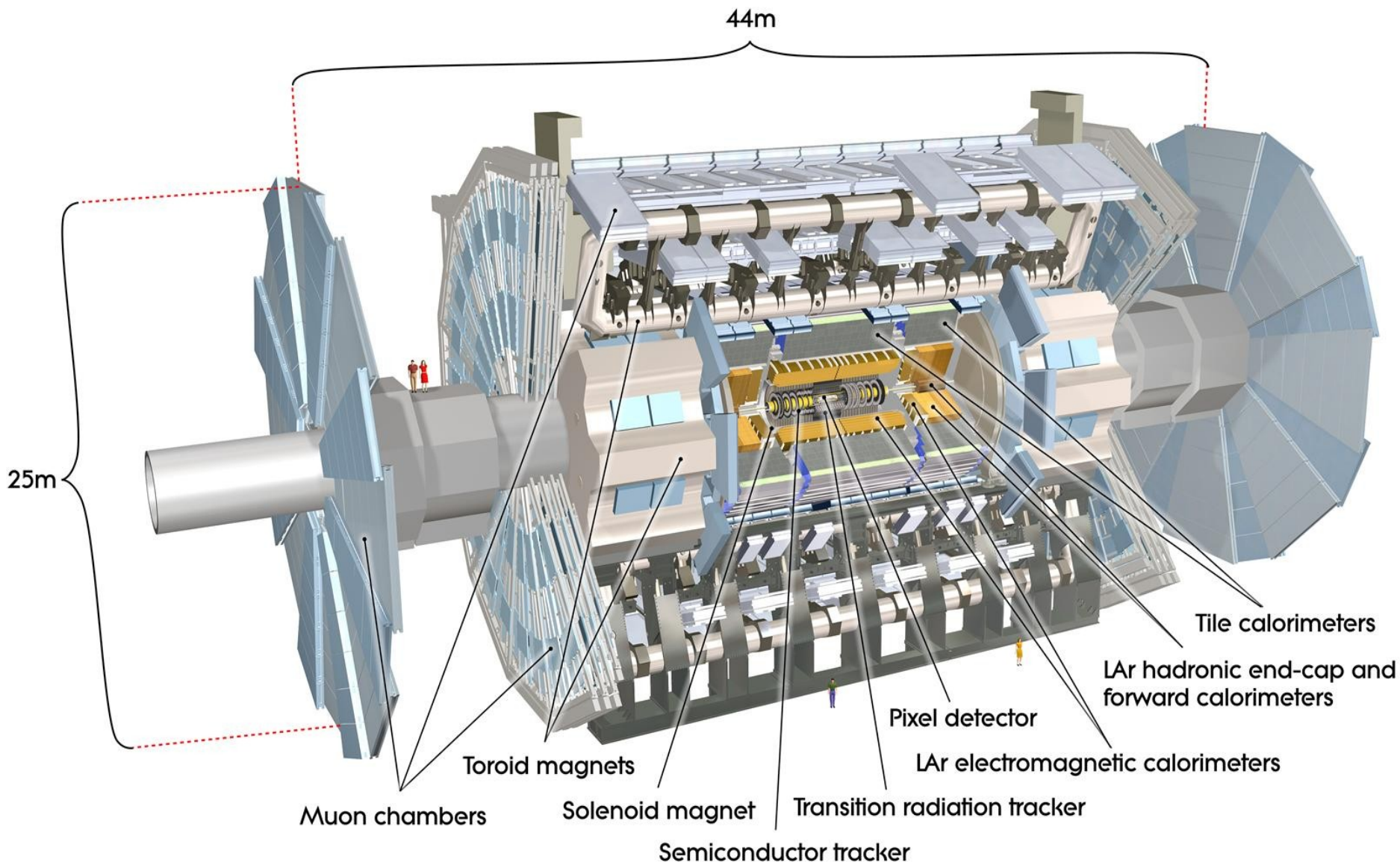


http://lpc.web.cern.ch

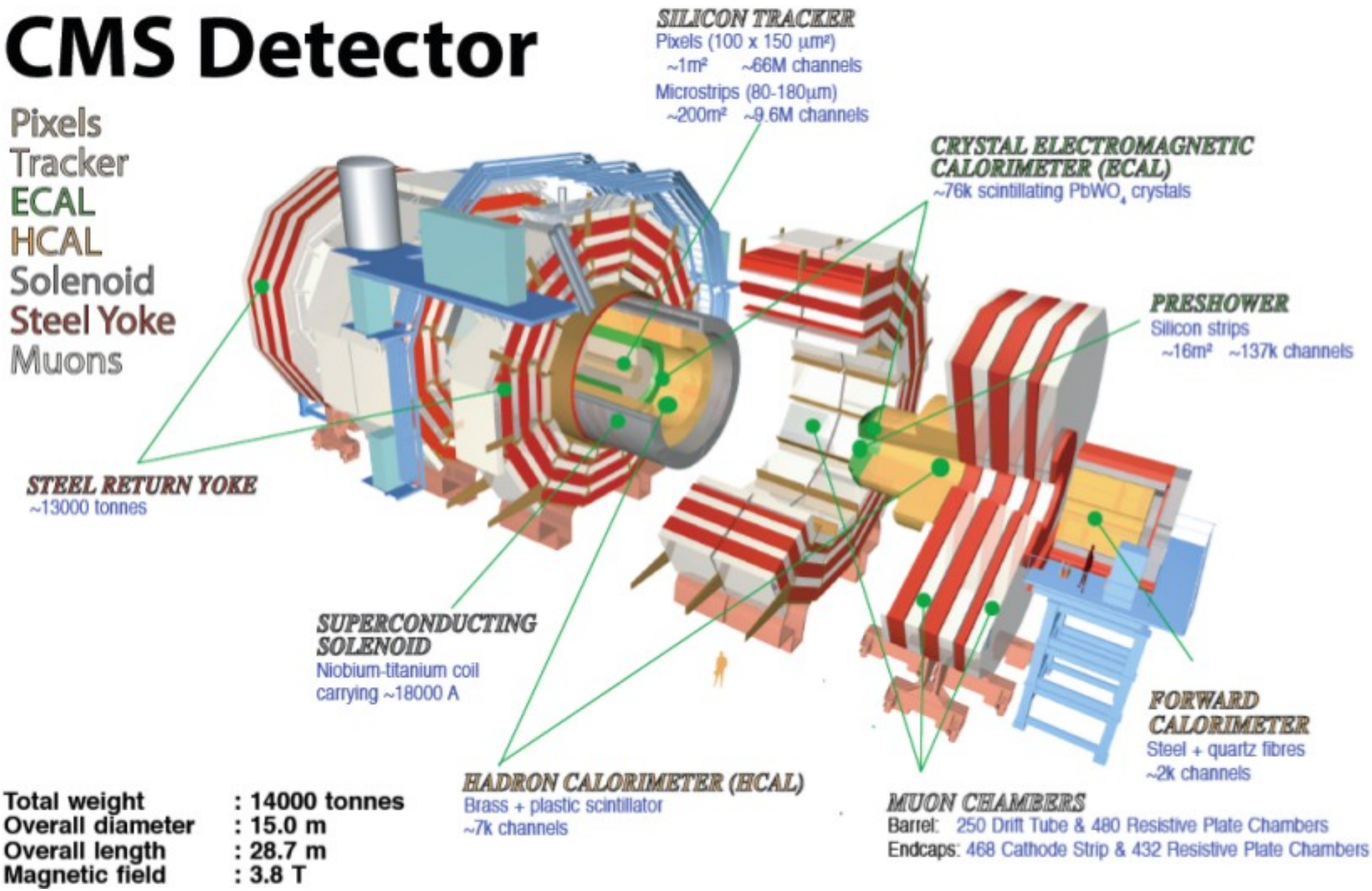
ALICE Detector



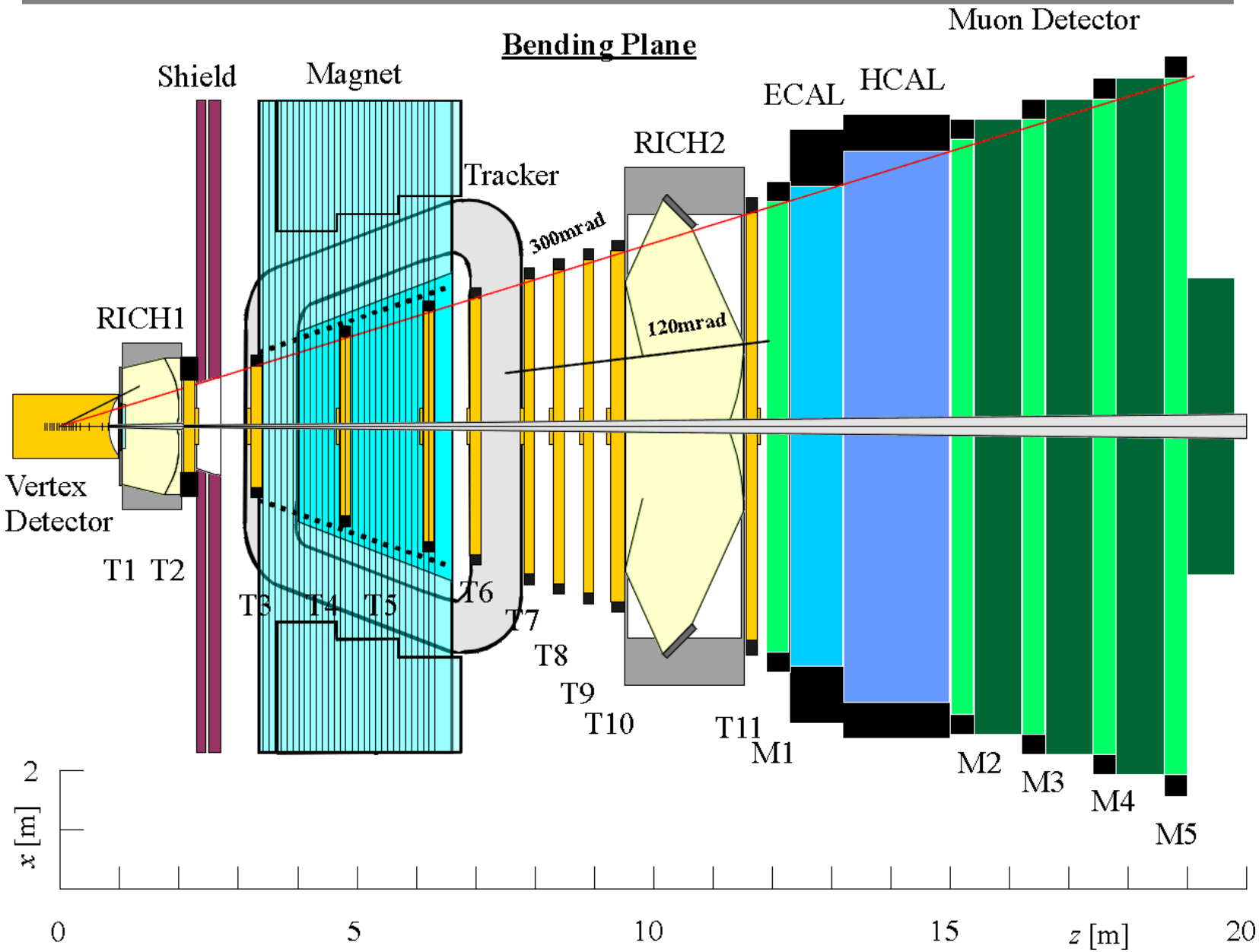
ATLAS Detector



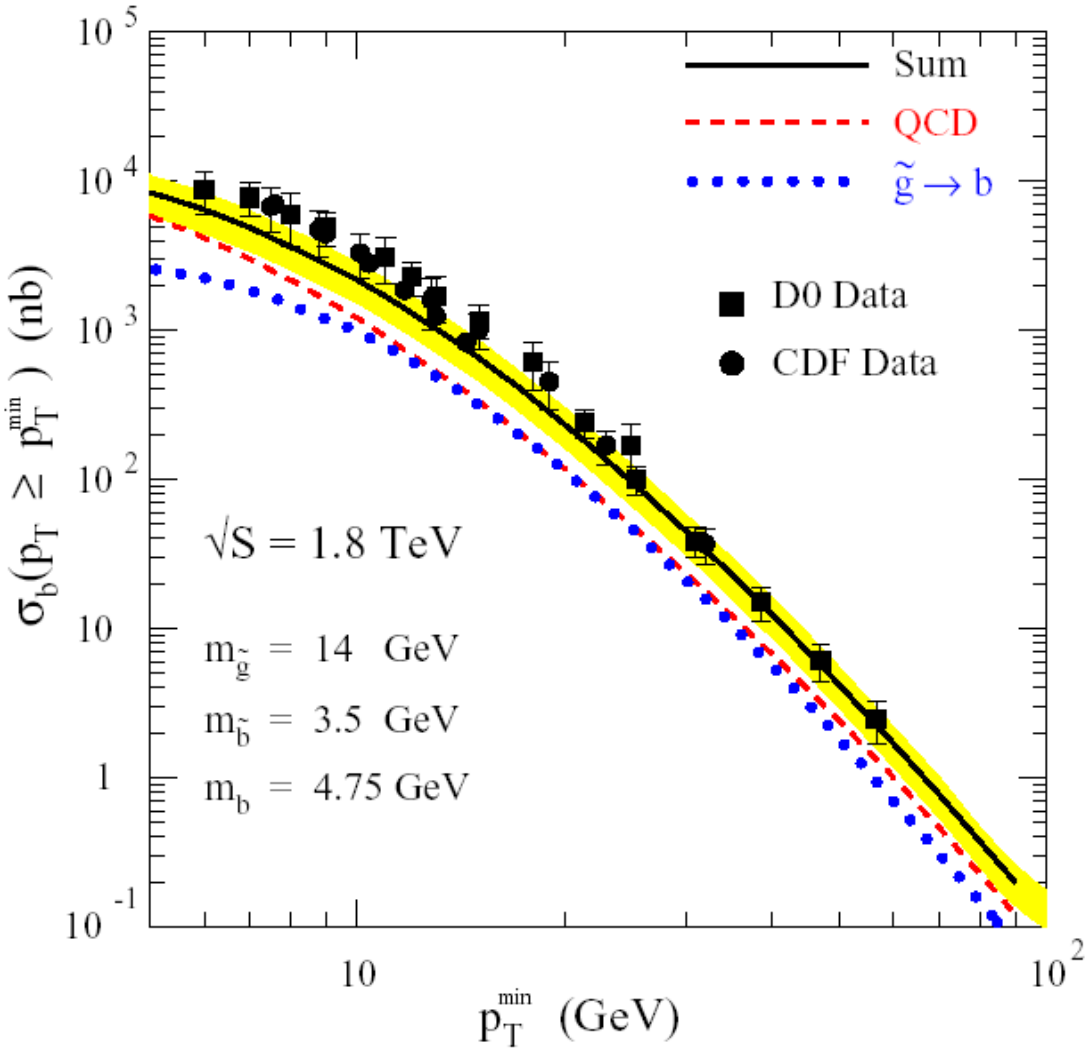
CMS Detector

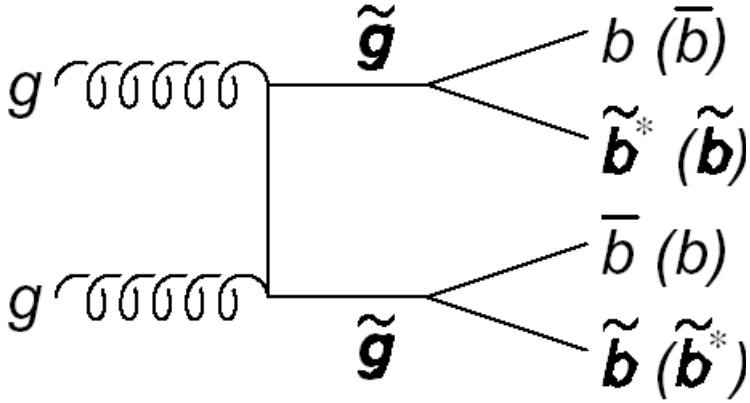


LHCb Detector



New Physics in *b* Production ???

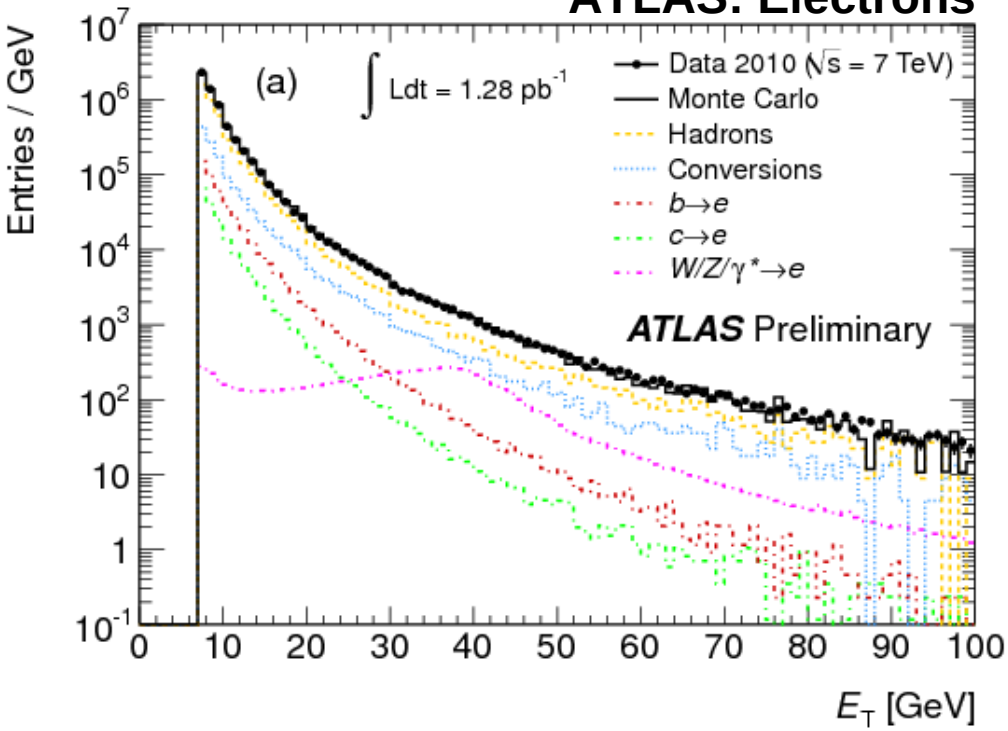




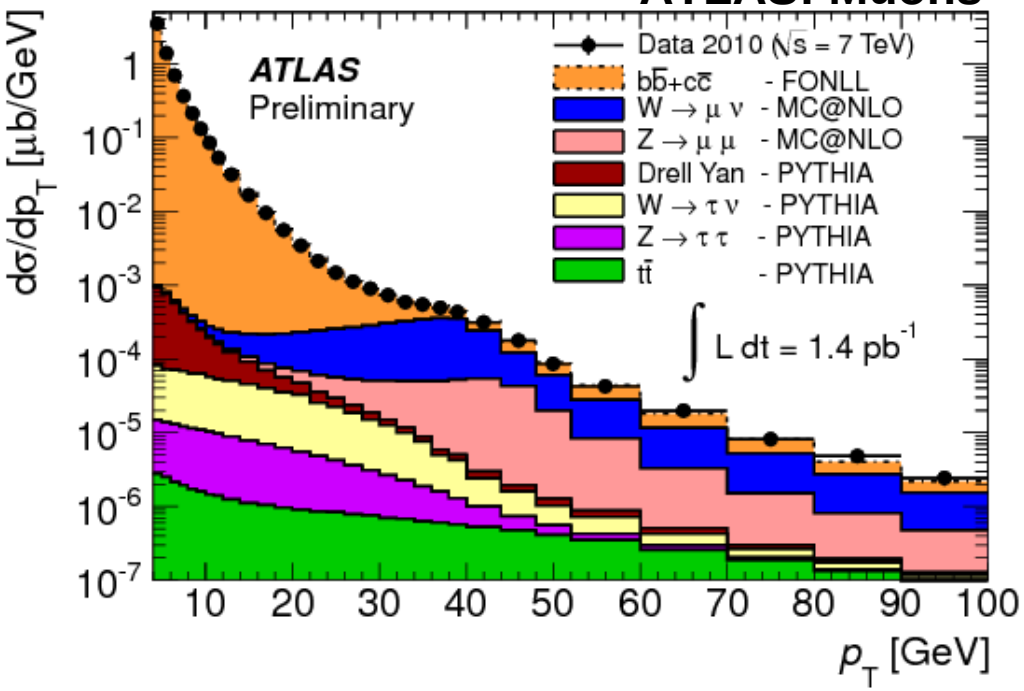
Berger, Harris, Kaplan, Sullivan, Tait, Wagner; PRL 86 (2001)

Incl. HF to Leptons: Composition

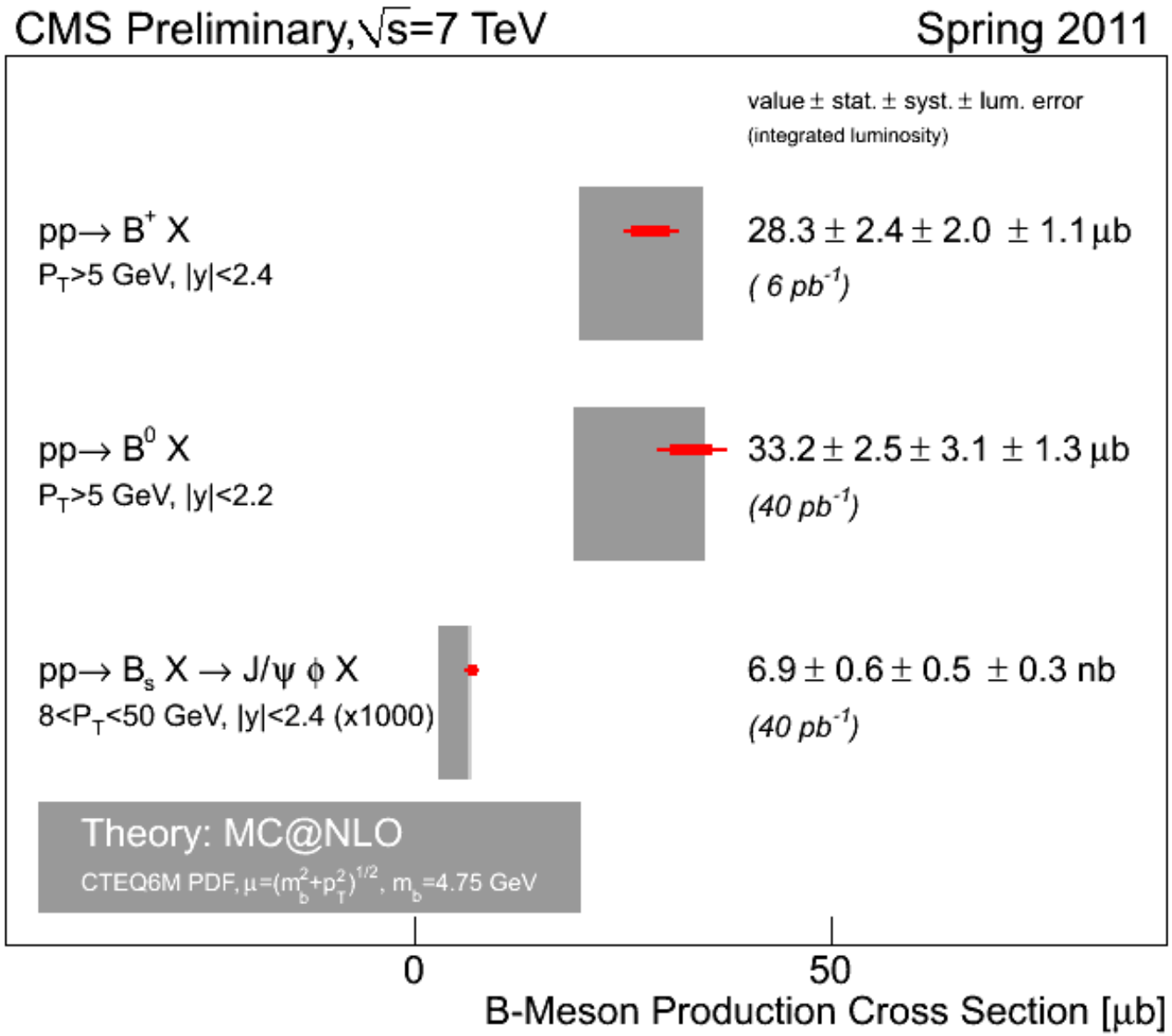
ATLAS: Electrons



ATLAS: Muons



Exclusive *b* Summary

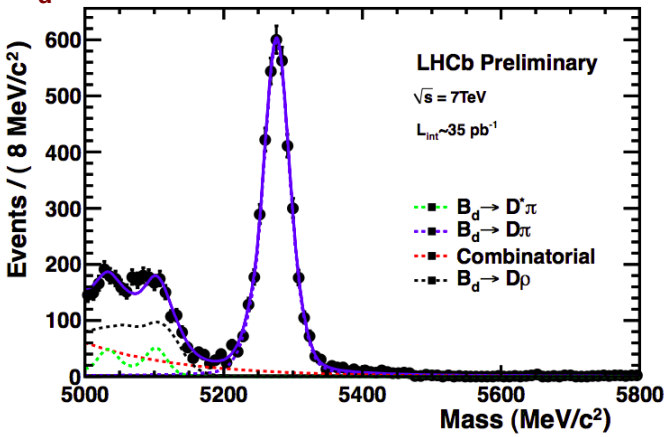


Flavor Fractions: f_s/f_d

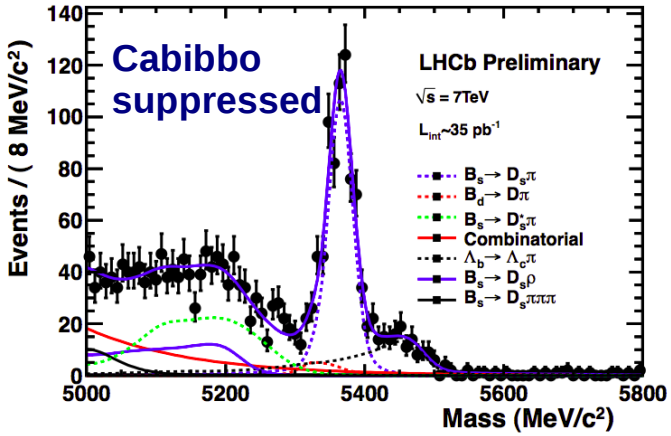
2,3,4 Track Secondary Vertex Trigger: 35 pb^{-1}

– Boosted Decision Tree decay selection

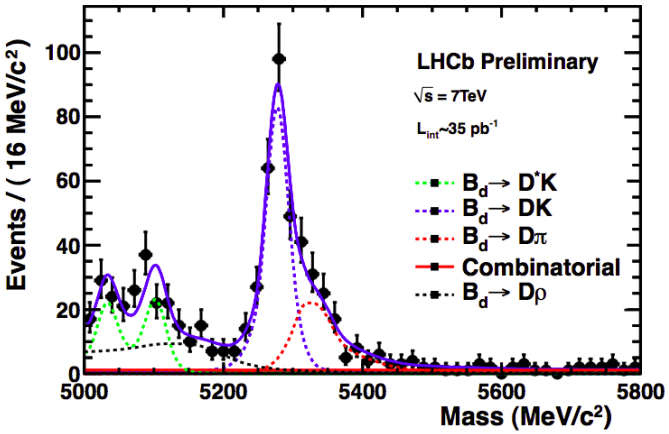
$B_d \to D^- \pi^+$: 4109 ± 75 decays



$B_d \to D^- K^+$: 253 ± 21 decays



$B_s \to D_s^- \pi^+$: 670 ± 34 decays



Mode	f_s / f_d ± stat ± syst ± theor	comments
$B_d \to D^- K^+$	0.242 ± 0.024 ± 0.018 ± 0.016	theoretically clean
$B_d \to D^- \pi^+$	0249 ± 0.013 ± 0.020 ± 0.025	
LHCb ave	0.245 ± 0.017 ± 0.018 ± 0.018	LHCB-CONF-2011-013
HFAG ave	0.295 ± 0.047	arXiv:1010.1589

$BR(B_d \to D^- K^+) = (2.02 \pm 0.17 \pm 0.12) \cdot 10^{-4}$ [PDG: $(2.0 \pm 0.6) \cdot 10^{-4}$]

Adjusting D0 $B_s \to \mu D_{s1} X$

LHCb measurement

- $BR(B_s \to \mu D_{s1} X) / BR(B_s \to \mu X) = (5.4 \pm 1.2 \pm 0.4) \cdot 10^{-2}$

D0 measurement (as quoted by PDG)

- $BR(B_s \to \mu D_{s1} X) \cdot BR(D_{s1} \to D^{*-} K_S^0) = (2.4 \pm 0.6 \pm 0.3) \cdot 10^{-3}$ (meas)
  $BR(B_s \to \mu D_{s1} X) / BR(B_s \to \mu X) = (9.8 \pm 2.5 \pm 1.2) \cdot 10^{-2}$ (adjusted)

D0 measurement adjusted using

- $BR(D_{s1} \to D^* K) = 1$ assumed by LHCb
- $BR(D_{s1} \to D^{*-} K_S^0) = 1/4$
- $BR(B_s \to \mu X) = 9.8\%$ as in LHCb calculation