Prospects for heavy flavour production cross section measurements in pp collisions at the LHC

A. Sherstnev (University of Cambridge, UK)

- Introduction
- Theory: current status, FONLL and MC@NLO
- Tevatron results and lessons
- ATLAS/ CMS strategy
- LHCb strategy
- Conclusions

Declaimer

- No c-quark/c-hadron physics description. Here heavy flavour means b-quark only. Sorry...
- No HERA information (see. the previous talk)
- Very short information on detectors/triggers at Tevatron and LHC. see corresponding talks of experts:
  - CDF/D0: talks by S. Donati L. Welty
  - ATLAS/CMS: talk by T.Speer
  - LHCb: F.Metlica
  - ALICE: next talk
- Tevatron result description is based on the CDF results only. Certainly D0 makes (or will make) all analyses mentioned later...
-

Motivation: b-physics at the LHC

- New area on $Q^2 \otimes x$ plane (possible BSM deviations...)
- New particles (in BSM scenarios) can decay to c/b-quarks
- CKM matrix and CP-violation phenomenon
- Properties of b-hadrons (B_c, B-barions) with high precision
- Constrains on hadronization models (especially B-hadrons)
- Heavy flavour PDF from experiments

Motivation: σ_{bb} measurements

- Tests of pQCD techniques ($Q \sim m_b >> \Lambda_{QCD}$)
- Background for new physics processes: we need to know the QCD background very precisely
- Compare results in many channels
- Huge statistics will be available very soon (after launch) → it will help to understand our detectors

Theory: introduction

- Current status of theoretical estimations of the bb production process. All code can be divided:
- Cross section calculators:
  - NLO calculations available (done in 90s)
  - Resummation effects (large logarithms – P_T/m_b, S_{hat}/m_b(small-x)): ACOT, BSMN, FONLL, GM-VFNS.
  - Matching xNLO and xLL: NLO+NLL(FONLL)
- MC event generators:
  - LO+LL: PYTHIA, HERWIG, ISAJET (obsolete...), etc.
  - modified LO+LL: PYTHIA low-Pt approximation.
  - NLO+”LL”: MC@NLO.

State of art now: FONLL and MC@NLO

Theory: a general framework

- pQCD calculations have badly converging logarithmic terms if we have 2 highly different energy scales (m_b and S_{hat}, etc.)
- $$\sigma_{full}(m,Q)=\sigma_0\cdot\left(1+\sum_{n=1}\alpha_s^n\sum_{k=0}^{n}c_{nk}\alpha_s^k\left[\ln^k\frac{Q^2}{m^2}+O\left(\frac{m}{Q}\right)\right]\right)$$
- Large terms – LL: $\alpha_s^n\ln^n(Q^2/m^2)$ or NLL: $\alpha_s^n\ln^{n-1}(Q^2/m^2)$ should be re-summed in all orders.
- $$\sigma_{full}(m,Q)\rightarrow\sigma_{full}^{res}(m,Q)=\sigma_0\cdot C(Q,\mu_1)\circ E(\mu_{1,}\mu_0)\circ F(\mu_{0,}\, m)$$
- C is calculated in pQCD, F – PDF/ F_{fragm}, and E is calculated with DGLAP (in LO or NLO approx.)
- Resummation expressions should be matched with FO terms

Spectra: FONLL (1)

- NLO calculations failed to describe Tevatron Run I heavy flavour results.
- Tevatron: the 2nd scale (P_T) appears →large logarithms: $\log(P_T/m_T)$
- They should be re-summed in the whole perturbative expansion (RS) and matched with a Fixed Order (FO) term →FONLL

$$\sigma_{full}^{FONLL}(m,Q)=FO+(RS_{NLL}-FO_{m\rightarrow 0})G(p_T,m)$$

- In order to exclude double counting we substruct massless approximation of FO. Weighting function G defines application area for RS (in the prescription $P_T(b)>5m_b$)

Spectra: FONLL (2)

- The RS expression in FONLL depends on fragmentation functions of light partons to heavy quarks.

$$\sigma_{RS}(m, p_T) = \sum F_i F_j \sigma^{\overline{MS}}_{ij \to k+X}(p_T) D_{k \to Q}$$

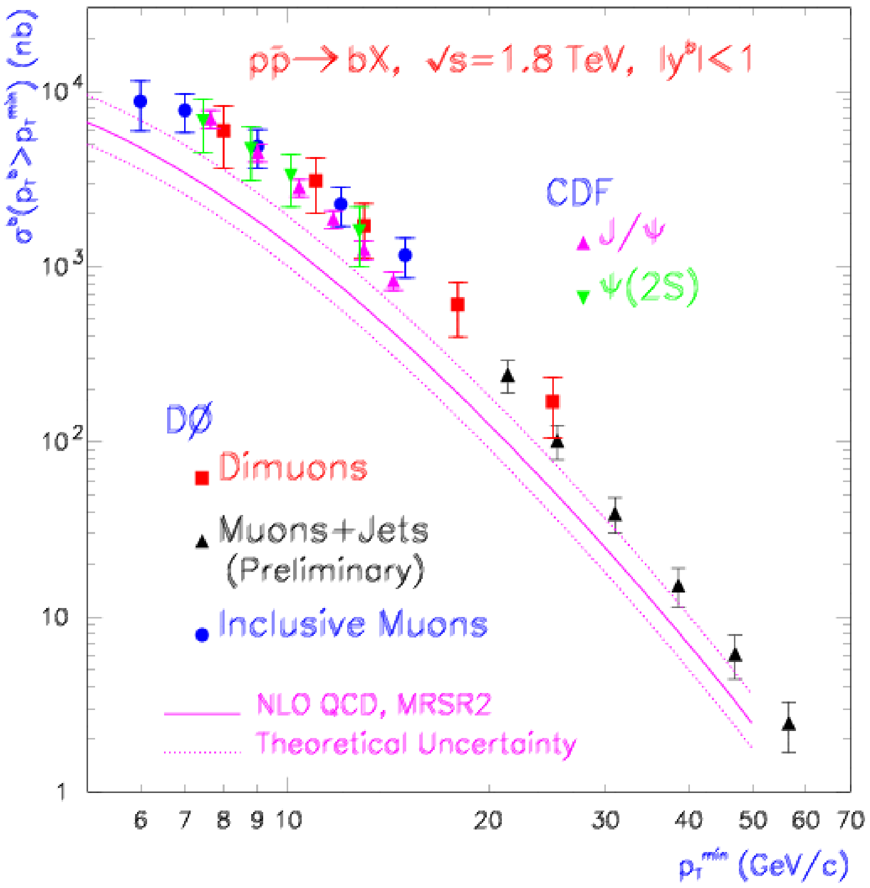
- where $F_{i,j}$ – PDF and D – fragmentation function of light flavour to heavy flavour (by means of DGLAP, no experimental input).
- Weight function is

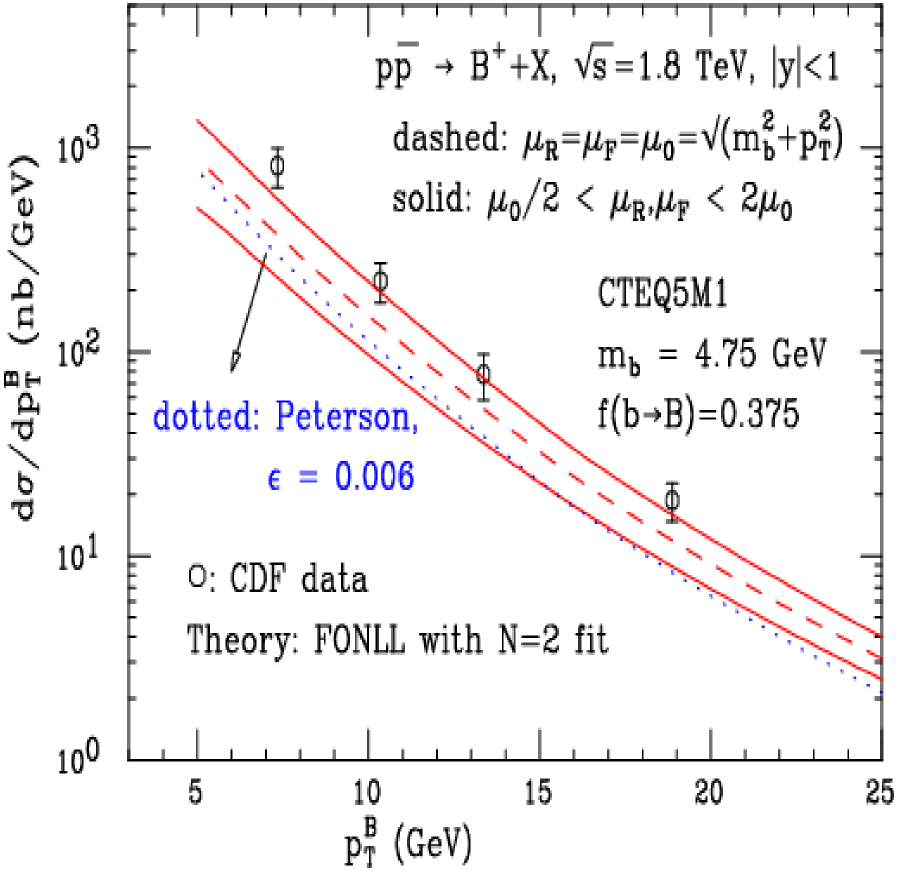
$$G(m_b, p_T) = p_T^2 / (c^2 m_b^2 + p_T^2)$$

- The method can produce full cross sections (with cuts applied) and distributions
- It has been implemented (in codes) for the heavy quark hadroproduction (Tevatron, LHC) and photoproduction (HERA)

Spectra: FONLL (3)

- Tevatron Run I example: NLO fails, FONLL is fine!





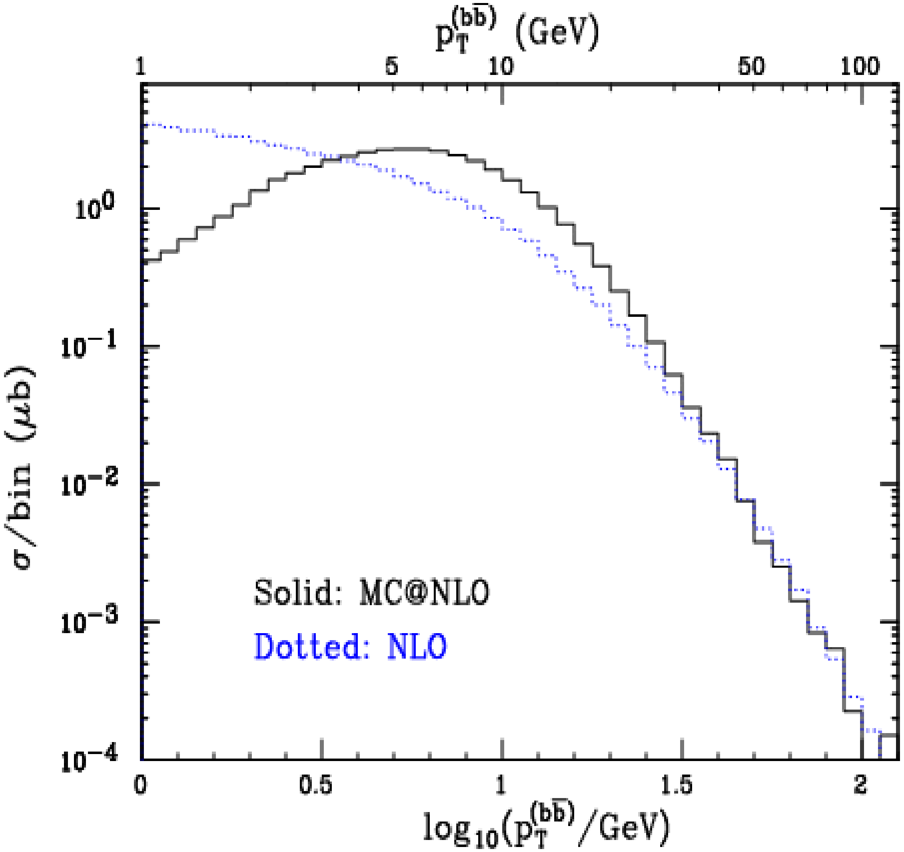
Events: MC@NLO (1)

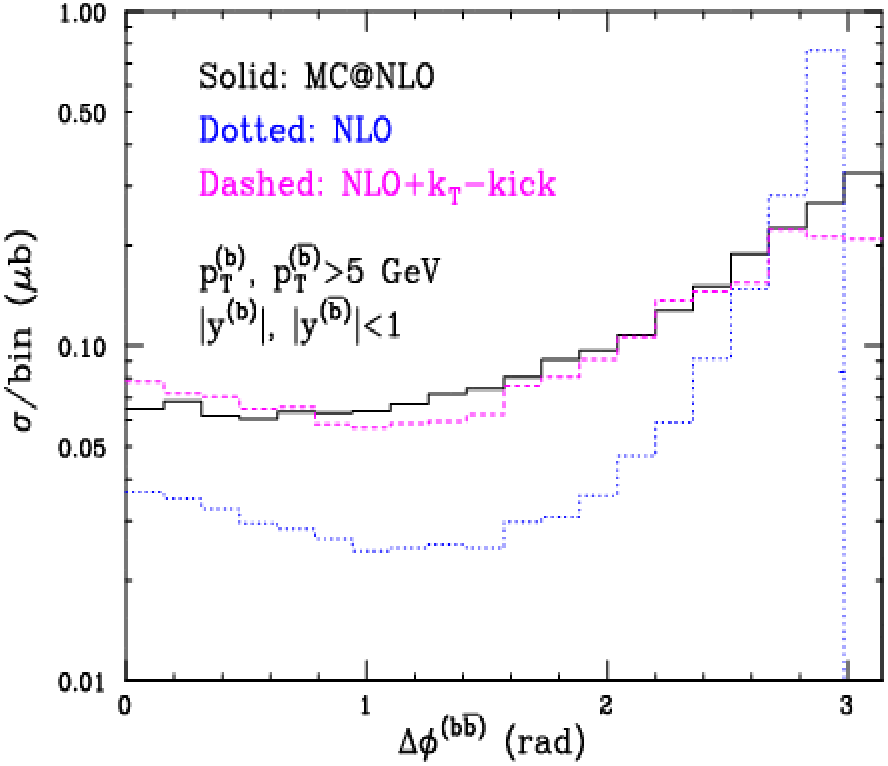
Experiments require events!

- An exact NLO calculator used (LO,virtual/real NLO corr.)
- The program gives exclusive events at NLO (not 0-, 1-, 2-dimentional distributions only!) + showering
- The whole HERWIG showering (with few corrections) and hadronization model.
- Advantages:
  - fast event generation (then at LO!, ~10 times!!);
  - Reliable for the whole P_T(b) region: large QCD scale – sqrt($M_b^2 + P_t^2$)
  - possibility to estimate a NNLO uncertainty (variation of QCD Q_{ren}/Q_{fac} scales)
  - No massive b-quarks in the initial state
- Drawback (just technical):
  - Not ready to (experimental) productions. Fine as a stand-alone program.

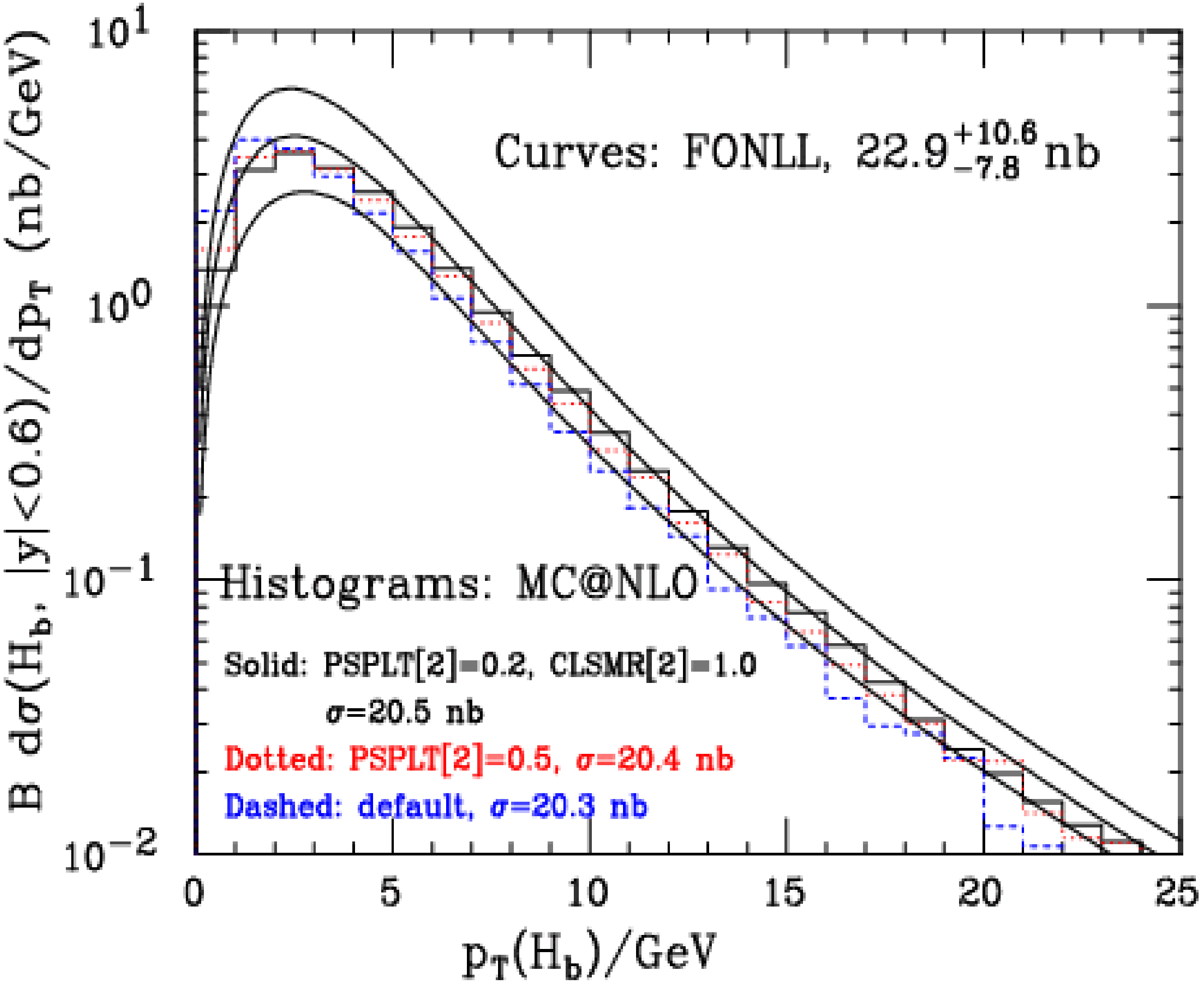
Events: MC@NLO (2)

- Comparison with NLO: MC@NLO vs. pure NLO:





MC@NLO vs. FONLL



Tevatron energy, b-hadron P_T spectrum with no cuts.

MC@NLO: two hadronization model in HERWIG

FONLL: m_b, PDF, fragmentation uncertainties

Theory: future improvements

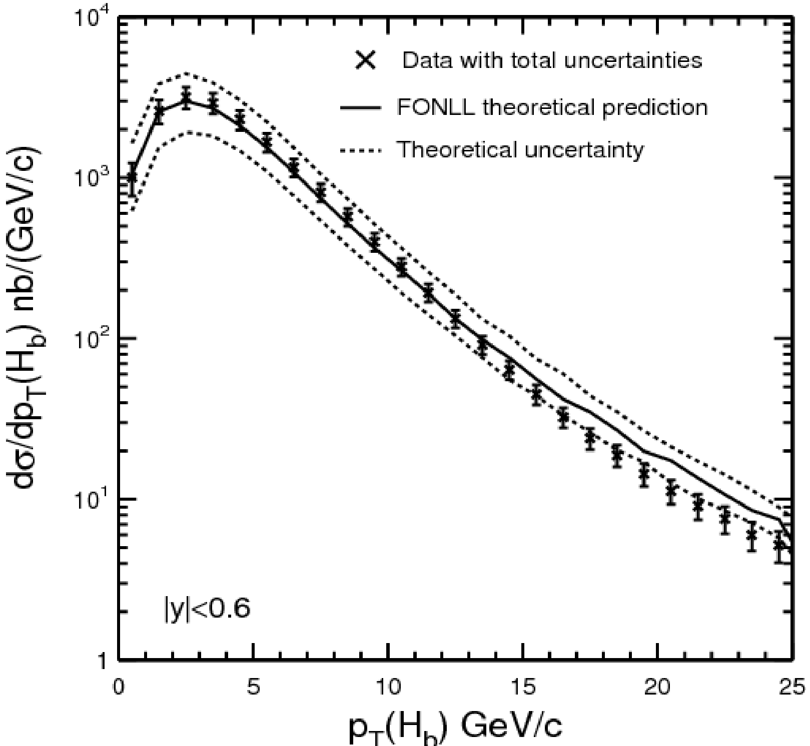
- Theorists and MC code authors have some years till real analyses at the LHC... So, we can try to solve a couple of problems!
- NNLO calculation for the full bb production:
  - QCD scale dependence: variation of $0.5 < Q_{ren} / Q_{fac} < 2$ gives $276 \div 645$ μb (central value – 496 μb) for the full σ_{bb};
  - A great boost in calculations of high radiative corrections has been done in the recent years. The task can be solved!
- Matching FO with NLL and small-x contributions in events:
  - Tevatron experience shows up importance of large logarithms. Experimentalists like events!
  - How to include resummation effects to events? Really complicated problem... No clear ways.

Tevatron II results (1)

- There was a problem with interpretation of the b-hadron production cross section in Run I.
  - first numbers: Data/Theory(NLO) = 2.9 ± 0.2(stat.)± 0.4(syst.)
  - last numbers: Data/Theory(FONLL) = 1.7 ± 0.5(stat.)± 0.5(syst.)
- Run II improvements:
  - better secondary vertex recostruction, more efficient b-hadron ID.
  - much more statistics available.
- Two types of measurements are possible:
  - b-hadrons ($P_T(b) \sim 0 \div 25$ GeV), but huge statistics
  - inclusive b-jet or 2b-jets, no P_T limit, but lower stat.

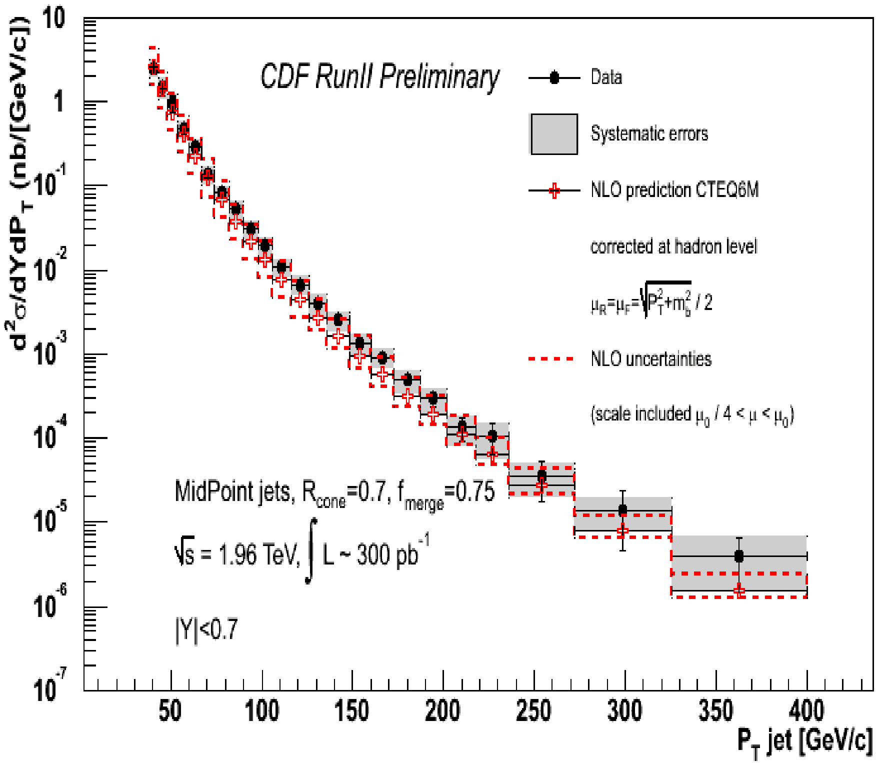
Tevatron II results (2)

- B-hadron production measurements in CDF, rather old (~40 fb^{-1})
- Trigger: Di-muon (L1) + J/ψ selection (HLT: opposite-sign muons and $2.7 < M_{\mu\mu} < 4.0$ GeV).
- Offline: central region ($|\eta(J/\psi)| < 0.6$) and $P_T(\mu) > 1.5$GeV
- $H_b \to J/\psi + X$ selection: pseudo proper decay length (time)
- Systematics: 3%-14%(mainly from Monte-Carlo) hep-ph/0412071
- Comparison with theory (FONLL and MC@NLO approaches) cuts: $P_T(J/\psi) > 1.25$GeV & $|\eta(J/\psi)| < 0.6$
  - Run I: 19.4±0.3(stat.)±0.2(syst.)
  - FONLL: 18.3+8.3/-5.9 nb
  - MC@NLO: 17.2 nb



Tevatron II results (3)

- High-P_T b-tagged jet production measurements in CDF, (~300 fb^{-1} used): hep-ex/0505036, preliminary
- Trigger: inclusive jet events with different P_T thresholds (20, 50, 70, and 100 GeV)
- Jets with $R_{jet}=0.7$ (cone-based MidPoint algorithm) in central region ($|\eta(j)| < 0.7$) used
- $P_T(j)$ range 38÷400 GeV
- b-tagging done by secondary vertex reconstruction
- Comparison with PYTHIA (Tune A) and NLO calculations done

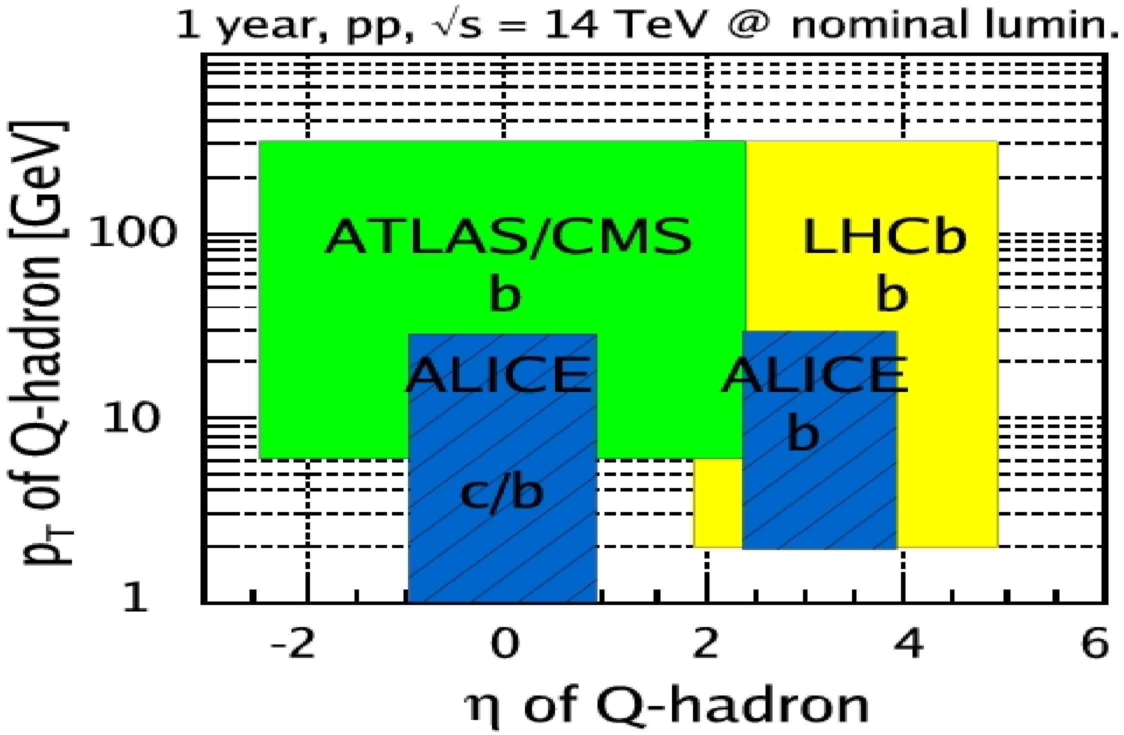


Tevatron lessons

- Two types of complimentary measurements are possible:
- b-hadrons spectra:
  - advantage: low P_T region, huge statistics →rapid measurements
  - advantage: low statistical uncertainty
  - advantage: many channels possible
  - drawback; limited P_T ($P_T(b) \sim 0 \div 25$ GeV only)
- inclusive b-jets (1b or 2b-jets):
  - drawback: low statistics →large stat. uncertainty
  - advantage: almost no P_T limits

LHC

- Huge cross sections of heavy quark production, no problem with statistics (in fact, there is an opposite problem!).
- Main question: triggers (di-muon, single-muon).
- First measurements: inclusive ones. Later, cross sections of selected channels will be available (check of self-consistence)
- LHCb and ATLAS/CMS give complimentary measurements (in different regions)

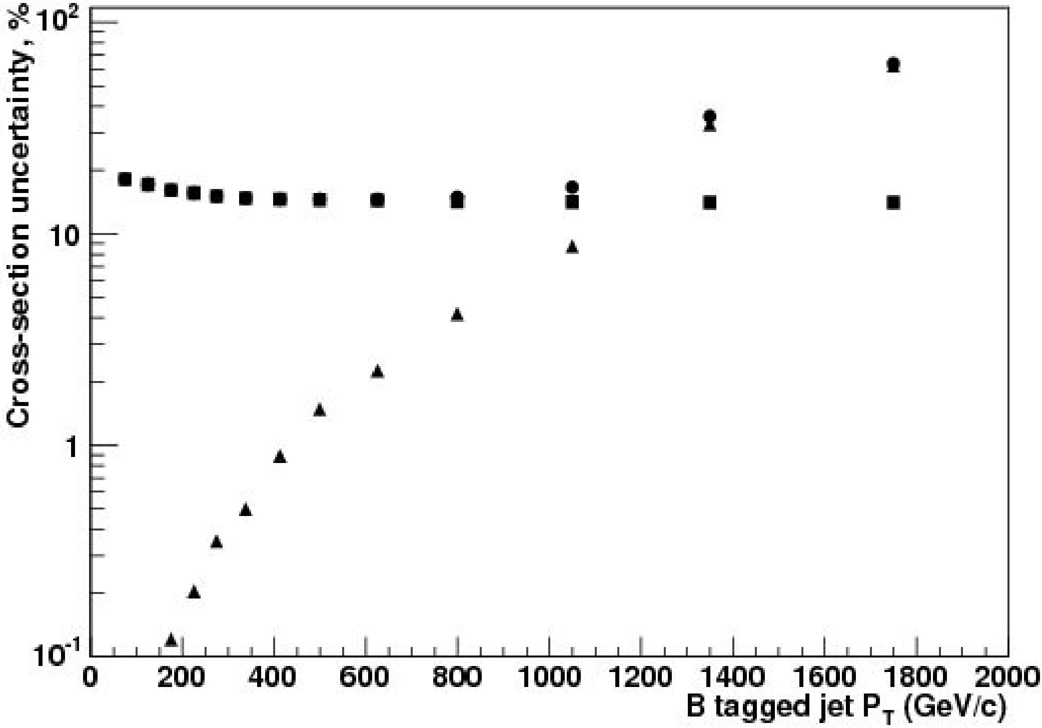


CMS/ ATLAS case

- General purpose detectors.
- Optimized for high-P_T tasks.
- Competition: bandwidth and trigger HLT resources
- Both detectors have precise tracking and vertex subdetectors.
- Triggers: 40MHz $\rightarrow$200(ATLAS)/100(CMS) Hz
- Muon triggers (flexible thresholds for diff. luminosity regimes)
  - ✓ ATLAS di-muon: $P_T(\mu) >$ 3-4 GeV in $|\eta| < 2.7$ (60% efficiency, 10Hz rate for $pp \rightarrow J/\psi + X$ after HLT)
  - ✓ CMS di-muon: $P_T(\mu) >$ 3 GeV in $|\eta| < 2.4$
  - ✓ ATLAS 1-muon: $P_T(\mu) >$ 8 GeV in $|\eta| < 2.7$ (can help to reconstruct hadronic decays, applied for $L < 2 \cdot 10^{32}$ $cm^{-2} \cdot s^{-1}$ only)
  - ✓ CMS 1-muon: $P_T(\mu) >$ 14 GeV in $|\eta| < 2.1$

CMS/ATLAS: σ_{bb} measurements

- Example (CMS, NOTE-2006/120, PTDR-2): Inclusive cross section of the b-jet production in the high-P_T region: (P_T > 50 GeV).
- Event selection: CMS single-muon trigger ($P_T(\mu)$> 14 GeV, $|\eta|$ < 2.1); HLT: muon+b-tagging (secondary vertex).
- Inclusive measurement: cuts -> fitting: $P_T(\mu\text{-}j)$ selection,
- Purity: bb/cc/ll = 66-55%/32-31%/2-15% (low-high P_T range)
- The main systematisc: jet energy scale



LHCb case

- Single arm spectrometer ($\eta \sim 2 \div 5$) optimized for b-physics
- Much lower thresholds of b-hadron reconstruction (up to $P_T \sim 1$-2 GeV)
- Reduced luminosity: 2-$5 \cdot 10^{32}$ cm$^{-2} \cdot$ s^{-1}
- Total rate: 10^{12} bb pairs/year
- Trigger: 40MHz → 2000Hz. The trigger definition is crucial for σ_{bb} measurements.
- HLT trigger: 600Hz for events with J/ψ (trigger efficiency ~75% events with $J/\psi \to \mu\mu$)
- P_T threshold: $P_T(\mu) > 1$ GeV

LHCb: σ_{bb} measurements

- Still no completed strategy/MC analysis for the B-hadron production cross section.
- Ideas are taken from Tevatron experience
  - Main strategy: $pp \to J/\psi + X \to \mu\mu + X$ with secondary vertex reconstruction
  - Events with 3-4 muons ($b \to \mu\nu + c$, $c \to \mu\nu + d$): lower statistics and lower backgrounds
  - D-mesons from secondary vertices (experimentally difficult analysis)
- More complicated problem in comparison with theory: very low P_T(B-hadron) thresholds ~ 1-2 GeV (ATLAS/CMS – 8-10 GeV)

Conclusions

1. The famous problem of the σ_{bb} measurement has disappeared. FNOLL and MC@NLO describes Run II data (almost) properly.
2. In order to measure (and compare with theory!) σ_{HF} we need to decrease theoretical systematics: NNLO and resummation effects in events. A great challenge for theorists...
3. Tevatron ideas (how to measure σ_{HF}) suit the LHC experiments.
4. ATLAS, CMS, LHCb has strategies, published or in preparation, to the task.
5. ATLAS/CMS LHCb will give complementary measurements and the measurements will be available soon...

Other useful slides

PYTHIA

“SemiLO” Model:

- Minimum bias events (LO matrix elements) with b-quarks.
- Soft-Pt singularities are regularized by an extra item ($P_{T,min}$) in the propagators. $P_{T,min}$ value is provided by experimental data.
- PYTHIA showering/hadronization model
- Advantages:
  - The full Pt range simulation
  - better data description (then at LO).
- Drawbacks:
  - It is unknown what it is... (in theory). How to add theoretical corrections and estimate theoretical uncertainty?
  - QCD scale is hard coded

LHCb uses this Monte-Carlo model to produce data in Gauss.