Use of MC Tools in LHCb

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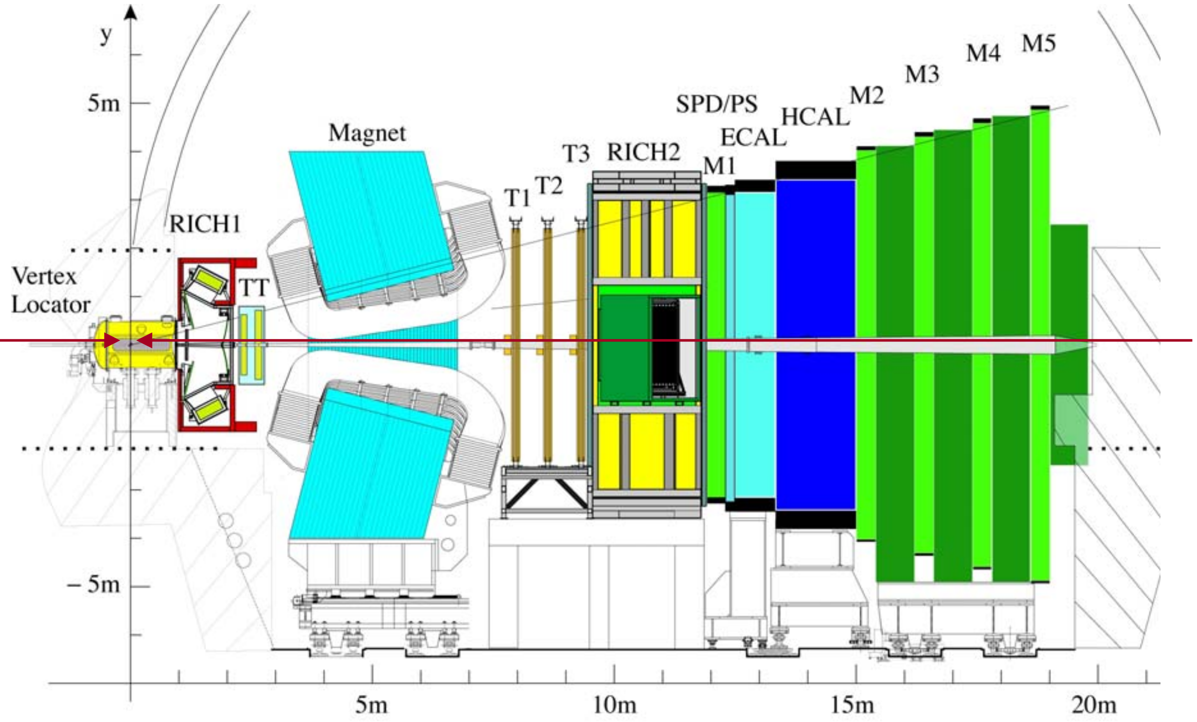
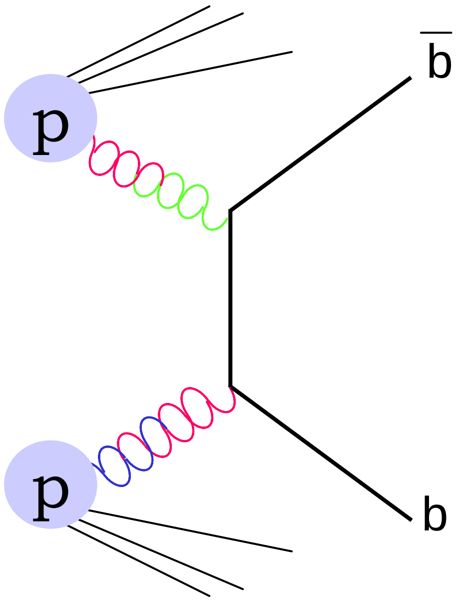
The LHCb Experiment



- Single arm spectrometer with acceptance from 10 to 300 mrad ($2 < \eta < 5$).
- Located at IP8 of LHC: study of ***B* physics with *pp* collisions** at $\sqrt{s}$ = 14 TeV.

B production in pp collisions at $\sqrt{s}$ = 14 TeV

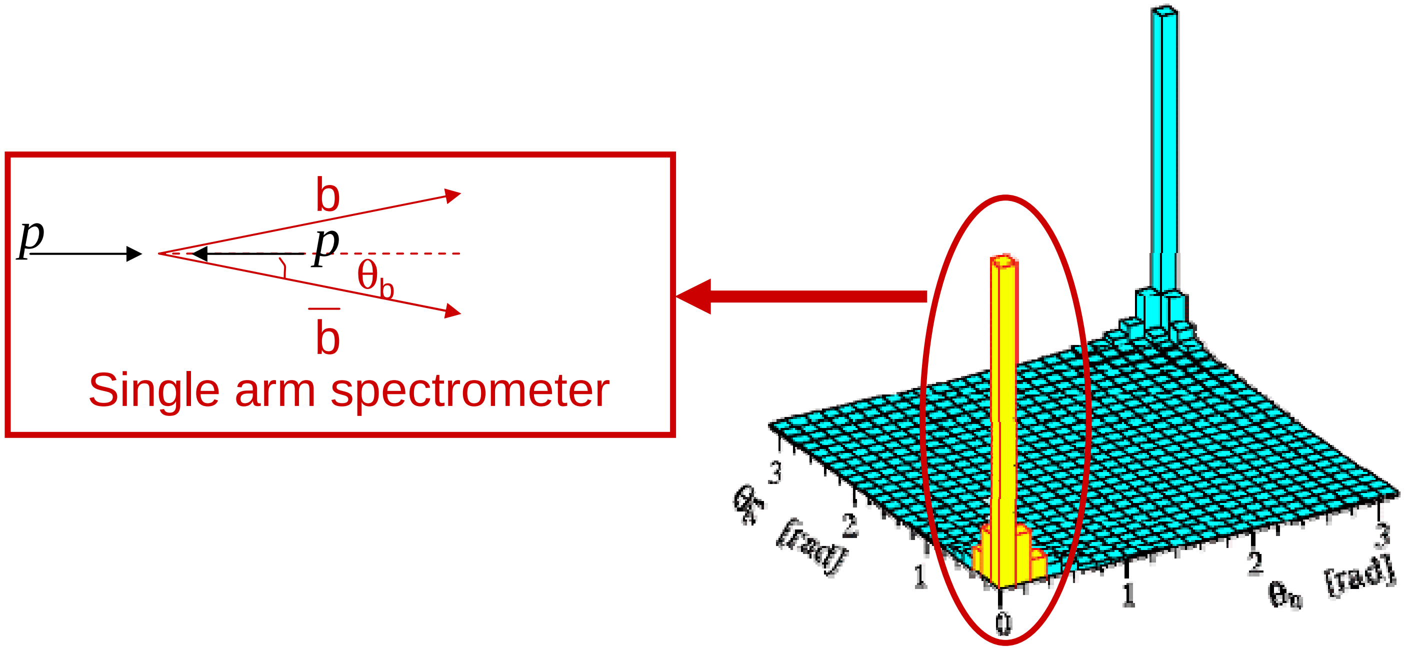


- Production of **all *B* hadron species**: B^0, B^+, B_s^0, and b-baryons (Λ_b, Ξ_b, ...).
- Production of B_c^+, ($b\bar{b}$) states and also large production of charm hadrons (J/ψ for example).

- Presence of *fragmentation tracks*: precise determination of primary vertex.
- Presence of *proton remnants*: possible B/$\bar{B}$ production asymmetries.

$$\frac{\sigma_{b\bar{b}}}{\sigma_{inel}} = \frac{0.5mb}{80mb} \sim 0.006$$

B production in pp collisions at √s = 14 TeV

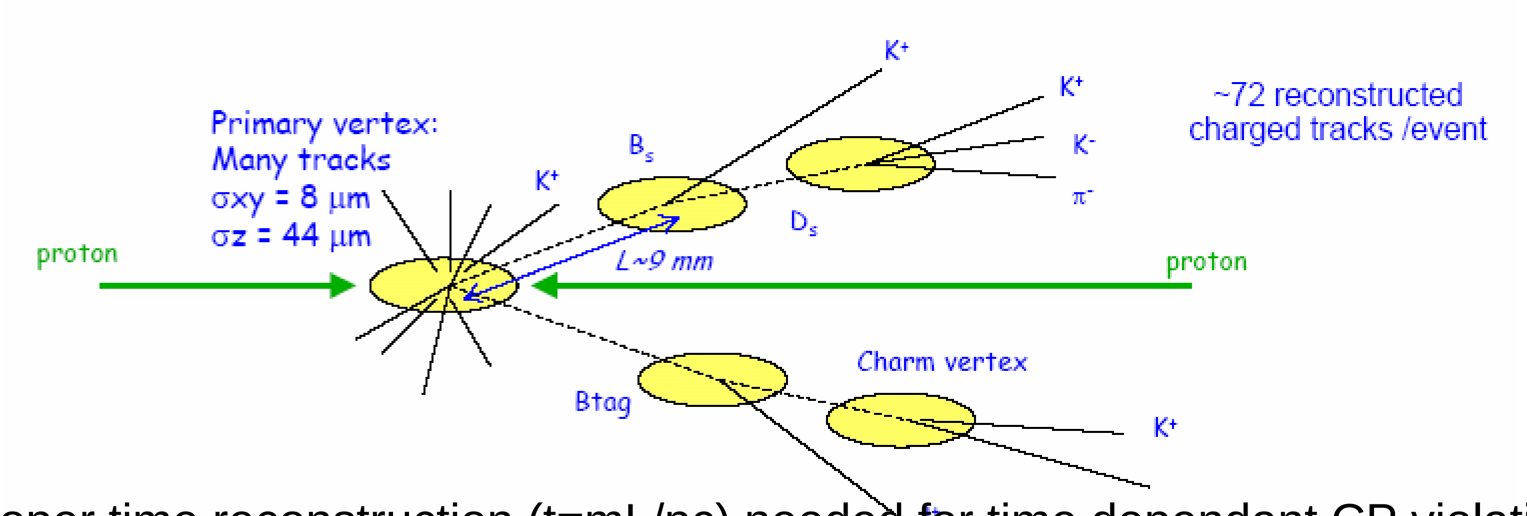


- Both *b* in acceptance: possibility of *B* production *flavour tagging*.
- 15 % of σ_{bb} with both *b* in LHCb acceptance (*bb* correlation).

Physics Program of LHCb

- ***Measurement and study of CP violation*** in the B meson sector:
  - Properties of $B_s^0/\bar{B}_s^0$ oscillations,
  - CP Asymmetries for example in $B^0 \to \pi^+\pi^-\pi^0$ (CKM α angle), $B^0 \to J/\psi\, K_s^0$ (CKM β angle), $B_s^0 \to h^+h^-$ (CKM γ angle)
- Study of rare *B* decays (search for New Physics, eg $B^0 \to K^* \mu\, \mu$)
- Precise determination of *B* physics parameters (Λ_b initial polarizations and asymmetries, B_c^+ mass, width and branching fractions, ...)
- Charm physics, top and Higgs physics.
- ~20000 B^0 and ~5000 B_s^0 per second in LHCb: need for an efficient trigger:
  - Level 0: high p_T objects in calorimeters and muon detectors,
  - High Level Trigger: displaced vertices, dimuon mass and exclusive reconstruction of interesting final states.
  - Reduce rate from 40 MHz to 2 kHz.

Typical ***B*** event in LHCb



Proper time reconstruction (t=mL/pc) needed for time dependant CP violation measurements: need to measure L(~9mm) and p (~1-100 GeV/c) , resolution ~ 40 fs ($B_s \rightarrow D_s^- \pi^+$)

Tag the B production state :

- use the other B
  - charge of lepton
  - charge of kaon (from D decay)
  - inclusive vertex charge
- use same side fragmentation tracks (K for B_s) or excited B states.

Generator Properties for LHCb

- Description of pp collisions at LHC energy:
  - Assess ***trigger rates***,
  - Assess ***reconstruction efficiencies*** of both signal and tag B.
- Description of *B* and *D* decays:
  - Compute ***reconstruction efficiencies***,
  - Compute ***tagging efficiencies***: content of *B* and *D* decays to *K* and leptons,
  - Composition of ***background*** (CP measurement dilutions, rare decays)
  - Mode specific features (angular distributions, asymmetries)
- Description of background in LHCb: beam bas interactions, ...

Generation Software Structure

- Software is based on **Gaudi** and **LHCb common software**:
  - General functionalities provided (*persistency*, *histograms*, ...)
- All generators are "wrapped" into **Gaudi algorithms or tools** to make them "callable and controllable" from the framework:
  - Job *options to control* what to generate and how to generate it
- All generators interfaced with **HepMC**
  - IO Exchange format between generators themselves and with detector simulation
  - "Encapsulated" in LHCb Event model (HepMCEvent)
    - *Transient store access*
    - *Persistency*

    → Access of generator information in analysis applications.

Generation Software Structure (2)

- Structure is ***flexible*** enough to adapt a large variety of generators.
- Production and decay ***steps are separated***. Different generators can be used for both phases. (For example Pythia + EvtGen).
- Pile-up and beam properties are generated separately.
- Particle properties (masses, widths, ...) and random number generator are common between all generators used for consistency and for reproducibility of events.

What to generate

- Need different **types of "events"**
  - *Particle guns* (calibration, test beams, single beam in IP8)
  - Single pp-collisions and bunch crossing at different luminosities (*pile-up*)
  - *Minimum bias*
  - ***"Signal" events***: B^0, $B_s{}^0$ and B^+ forced to decay in many decay modes to study physics performances of LHCb for important CP or mixing analysis, but also b-baryons, open charm, heavy quarkonia, Higgs, Z^0, etc. etc. etc.
  - *Beam gas* in the VELO and beam pipe
  - LHC machine *background* (survivors of beam gas in accelerator)

Generator Packages Used (1)

- **PYTHIA**:
  - Main generator used in LHCb for the production part.
  - We currently use version **6.3**
  - We would like to start studying the use of the C++ Pythia versions.
- **HERWIG**:
  - Recently introduced in LHCb simulation software.
  - Used to generate Minimum Bias events, we will also use it to generate inclusive *B* and signal *B* events (simple exchange with Pythia).
- **EvtGen**:
  - Main generator used in LHCb for the production part.
- **PHOTOS** : used in EvtGen as a universal tool to generate radiative corrections to hadron decays.
- **LHAPDF**: PDF repository called from Pythia.

Generator Packages Used (2)

- **SHERPA**: under investigation for use in LHCb as a production and also as a decay generator.

- **BcVegPy**: B_c^+ generator implemented as a user process in Pythia.

- **HIJING**: used to generate beam-gas events in the Velo.

- **AcerMC**: study of background processes with heavy quarks in the final state (Wbb, Zbb, ttbb)

- **Charybdis:** black hole generator.

Pythia (Main Production Generator)

- LHCb ***Minimum Bias*** definition in Pythia consists in usual *flavour excitation*, *gluon splitting* and *pair creation* processes, *elastic* and *diffractive* processes, and *prompt charmonium* production.
- Pythia p_t^{min} parameter is tuned to reproduce the mean charged track multiplicity observed ***at different lower energies*** (UA5 and CDF data), and then extrapolated at LHC energies.
- Parameters are also adjusted to reproduce *B* hadron fractions and excited states proportions observed at other experiments:

Hadron type	Fraction
B^0	40.5 %
B^+	40.5 %
B_s^0	9.9 %
b-Baryon	9.1 %

State	Fraction
B	21 %
B^*	63 %
B^{**}	16 %

EvtGen (Main Decay Generator)

- Use of BaBar EvtGen version as decay generator to decay all hadrons produced by Pythia.
- Implementation of specificities of hadronic environment:
  - ***Incoherent production*** of B hadrons (B0 and Bs0 oscillations)
  - ***CP violation***
- Add *decay models* for modes under study at LHCb: $B \to D K$, $\Lambda_b \to \Lambda V$, ...
- Use of most recent versions of *BaBar decay table* which is very detailed for B^0/B^+ decays and tuned to reproduce multiplicity measurements.
- Used in LHCb simulation for large data challenge.
- LHCb EvtGen version is the starting point of the LHC EvtGen version.
- EvtGen is interfaced with PHOTOS: important for efficiency and background computations to know the effect of ***radiative corrections*** in a large variety of *B* decay channels.

Signal Samples with Pythia + EvtGen

- Events containing a *B* hadron are ***extracted from Minimum Bias***, all hadrons are declared as stable in Pythia.
- Then all hadrons are decayed using EvtGen.
- One of the *B* hadron is ***forced to decay*** into a “signal decay mode” to obtain a sample with only this mode.
- ***Generator level cuts*** are applied to this *B* hadron (momentum cut, angular acceptance cut, ...): even if *B* hadron production is not so rare, event generation can take longer because of these cuts.
- Interface issues:
  - Particles are transferred from Pythia to EvtGen using the *HepMC* classes.
  - Particle masses, widths, and lifetimes are *identical* in Pythia and EvtGen: tuning needed to be sure that all decay modes are compatible with them.
  - Both generators use the same *random number* generator.

Heavy Quarkonia Production Models

- **Prompt J/ψ signals** are important for the physics at LHCb:
  - Main channels to study *B* physics contain a J/ψ in the final state. Prompt J/ ψ can be a *background* to these analysis.
  - They can be used as *calibration* signals to estimate the proper time resolution of the detector.
  - LHCb will contain a *di-muon trigger*.
- Studying *heavy quarkonia* (J/ψ but also Y) is in itself an important subject:
  - improved knowledge of QCD
  - study of the production mechanisms and comparison with NRQCD, Color Singlet Model (CSM)
- LHCb will allow to record a ***large sample*** of heavy quarkonia and then is participating in the development and the test of production model inside Pythia 6.3.

NRQCD In Pythia (1)

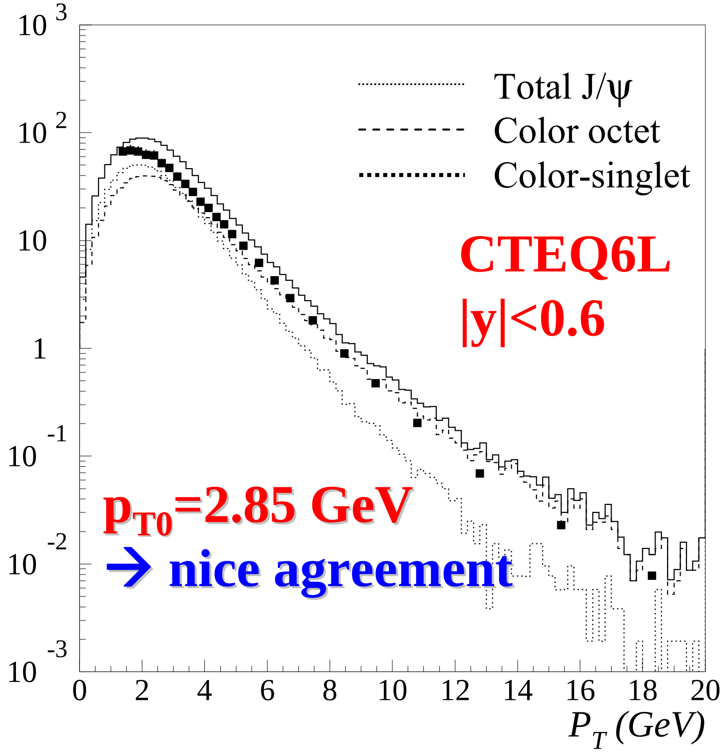
- Production of charm and beauty hidden flavor states in PYTHIA was incomplete:
    - Only color singlet processes (Color Singlet Model).
    - CSM largely fails in shape and normalization.
- Not too flexible
    - Cannot allow simultaneous production of ψ's and Y's, nor Y(1S) and Y(2S), etc.
- Collaboration between Pythia authors, GENSER team and LHCb to introduce, test and validate NRQCD for heavy quarkonia production in PYTHIA.
- Since Pythia 6.324 code is integrated and Pythia can deal with charmonia and bottomonia sectors:
    - Possibility to produce simultaneously J/ψ and Y (introduced as different processes)
    - Still not possible to generate Y' and ψ' simultaneously, but can be implemented in near future

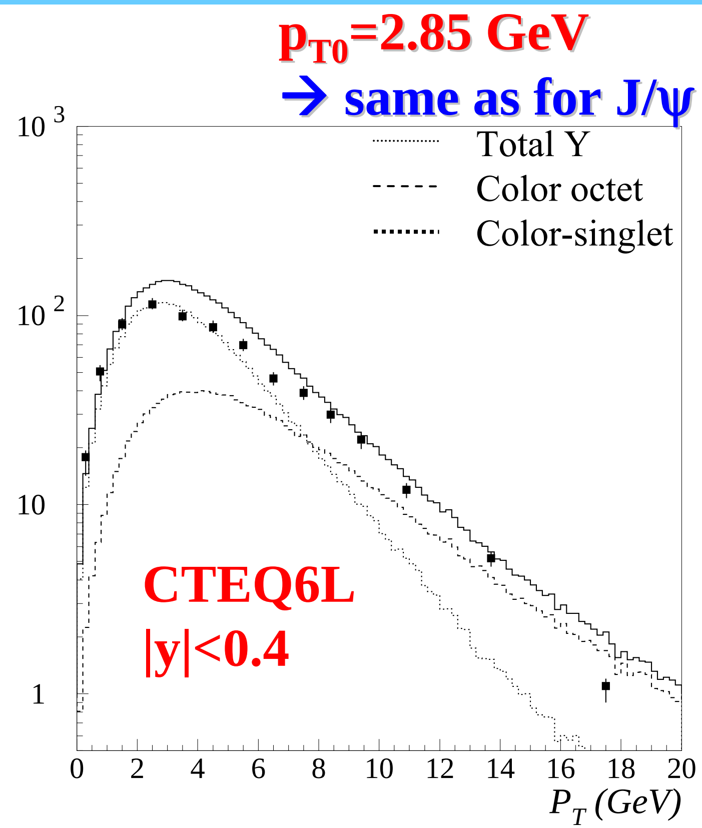
NRQCD In Pythia (2)

- New processes available:
    - $c\bar{c}$ S-wave with color-singlet and color-octet contributions.
    - New modes for χ_c production (not only gluon fusion).
    - Altarelli-Parisi evolution equations: allows the final- state shower evolution both for color-octet charmonia and for bottomonia.
    - Polarization implementation for quarkonia.
    - Production of in P wave charmonia and S and P wave bottomonia.
- See for more details:

http://indico.cern.ch/materialDisplay.py?contribId=3&materialId=slides&confId=3722

NRQCD In Pythia (3)

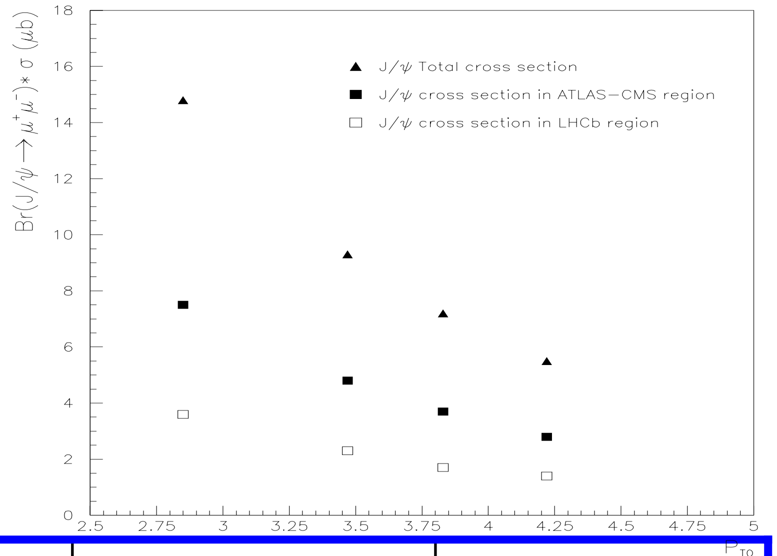




- After tuning of parameters, comparison of prompt J/ψ (not from B) and Y production with Tevatron data.

J/ψ production at LHC

- **Two rapidity regions of interest at LHC:**
  - **-2.5 – 2.5 (ATLAS, CMS)**
  - **1.8 – 4.9 (LHCb)**

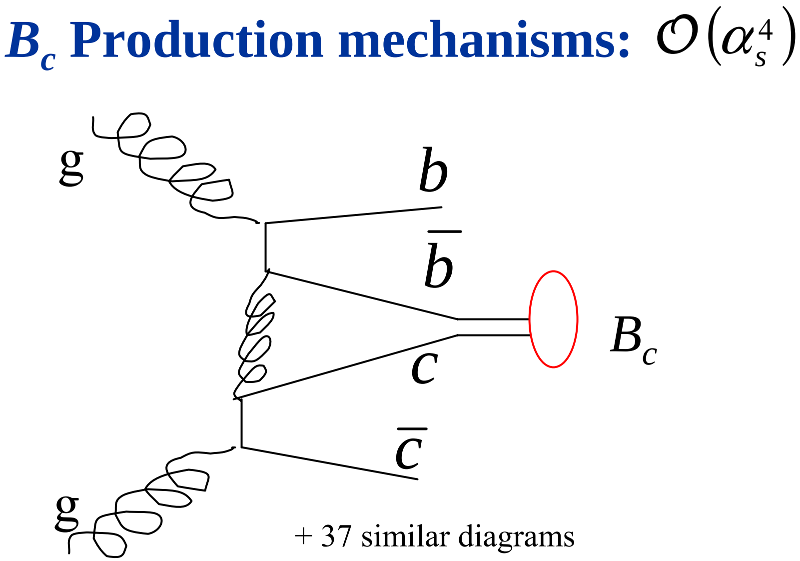


- **Total cross section ranging from 5.5 μb to 15 μb**

ϑ	p_{T0} [GeV]	$BR_{\mu\mu}\cdot\sigma_{tot}$ [μb]	$BR_{\mu\mu}\cdot\sigma_{Atlas,CMS}$ [μb]	$BR_{\mu\mu}\cdot\sigma_{LHCb}$ [μb]
0	2.85	14.8	7.5	3.6
0.1	3.47	9.3	4.8	2.3
0.15	3.83	7.2	3.7	1.7
0.2	4.22	5.5	2.8	1.4

B_c Generator

- B_c^+ production is smaller than other B:



- Need for a specific generator for this process. We use the generator BcVegPy (Comp. Phys. Comm **159**, 192 (2004)) for this purpose.

- Allows to generate specific samples of B_c decays and to study more accurately reconstruction efficiencies, within a low CPU time.

Luminosity Measurements

- Formula for two counter-rotating bunches:
  - Set $v_1 = v_2 = c$ and crossing angle ϕ

$$L = f\, \underline{\underline{N_1\, N_2}}\; 2c\, \cos^2(\underline{\underline{\phi}}/2) \int_{4-\text{fold}} \underline{\underline{\rho_1(\mathbf{x},t)}}\, \underline{\underline{\rho_2(\mathbf{x},t)}}\, d^3x\, dt$$

Measured by AB-BI

Measured by the experiments

Proposed method:

- Inject a tiny bit of gas (if needed at all!) into the vertex detector region
- Reconstruct bunch-gas interaction vertices

  ⇒ get beam angles, profiles & relative positions

  ⇒ overlap integral
- Simultaneously reconstruct bunch-bunch interaction vertices

  ⇒ calibrate 'reference' cross-section

Use Pythia and HIJING generators to simulate beam gas events.

Conclusions

- LHCb Simulation Software is interfaced with a variety of Monte Carlo generators and is flexible enough to use other generators.
- Main requirements for external generators are:
  - Possibility to modify particle properties,
  - Possibility to use an external random number generator,
  - Possibility to interface with HepMC classes.
- Adaptation of EvtGen and implementation of heavy quarkonia production in Pythia could be interesting for other LHC experiments.
- Look forward at C++ generators: expect more possibilities and simpler interface with C++ simulation software.