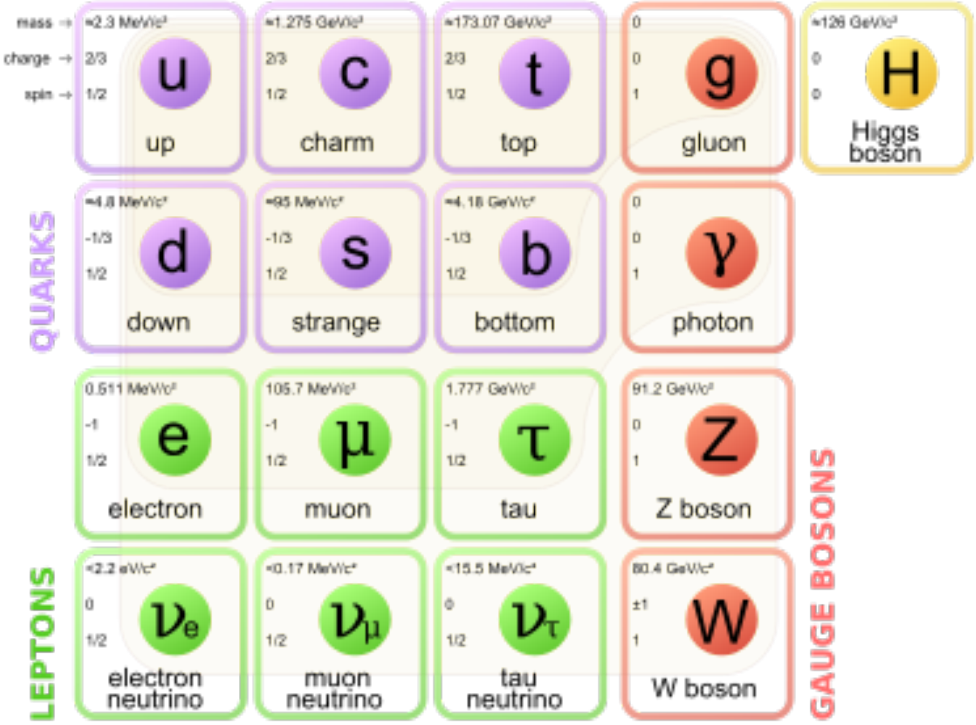
Heavy quarks



- There are three generations of quarks and a very wide range of quark couplings and masses.

- We observe hadrons, not quarks.

- The top quark is so massive that it decays on timescales shorter than the typical hadronization time.

- Bottom and charm quarks are the most massive quarks that can comprise observable particles.

- These are termed the “heavy flavor” hadrons.

Why study heavy-flavor

High energy physics experiment

- Their large mass allows relatively precise theoretical predictions via pQCD calculations.
- We can learn a great deal in the area of strong interactions.
- The production of heavy flavor hadrons tests QCD theory, and spectroscopy explores the interactions and dynamics of quarks inside of hadrons.

Why study heavy-flavor

High energy physics experiment

- CP violation :
  - Lifetimes and branching fractions are at the boundary of weak decays and hadronic physics effects.
  - The 3x3 CKM matrix allows for a CP-violating phase, and with enough independent measurements, it is possible to test SM predictions for CP violation.
  - Standard model prediction of CP violation is not sufficient to explain the current matter-antimatter asymmetry of the universe.
  - So continually searching for additional sources of CP violation due to physics beyond the standard model.
  - Heavy meson mixing and oscillations is another avenue to test CP violation as well as provide powerful constraints on CKM matrix elements.

- New physics :
  - Look for rare decays of heavy hadrons that in turn provide exquisitely sensitive probes for new physics.

- **Heavy-ion physics**
  - Heavy flavor hadrons are unique probes to understand the properties of quark gluon plasma.

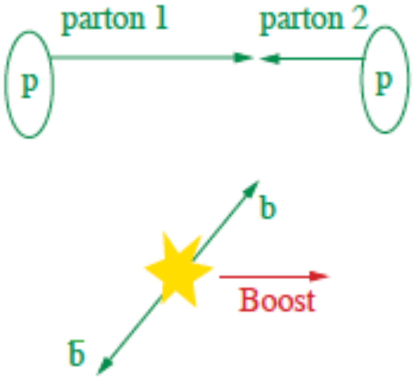
Heavy flavor in $e^+ e^-$ collider

Point particles

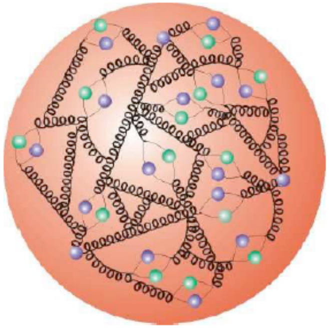
- PEP II at SLAC (9 GeV) and KEKB at KEK (8 GeV).
- Cleanest way to produce B hadrons.
  $e^+ + e^- \rightarrow \Upsilon(4S) \rightarrow B$
- Only produce B^0 and B^{+-} mesons.
- Beam energy is precisely known
  - Constrain on B kinematics.

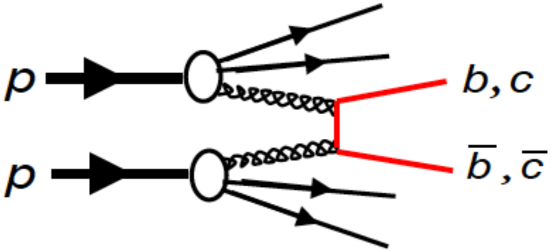
Heavy flavor in pp collider

- Energy of particular collision unknown but distributions are known
  - Scan wide variety of energy range
  - At LHC : dominant source is gluon fussion
- B kinematics
  - Asymmetric x values
  - Strongly boosted



- Protons are complicated objects
  - Valence quarks and sea quarks, gluons
- Available energy of proton collisions depends on partons
  $s' = x_1 . x_2 . s$ (x is fraction of proton momentum carried by partons)



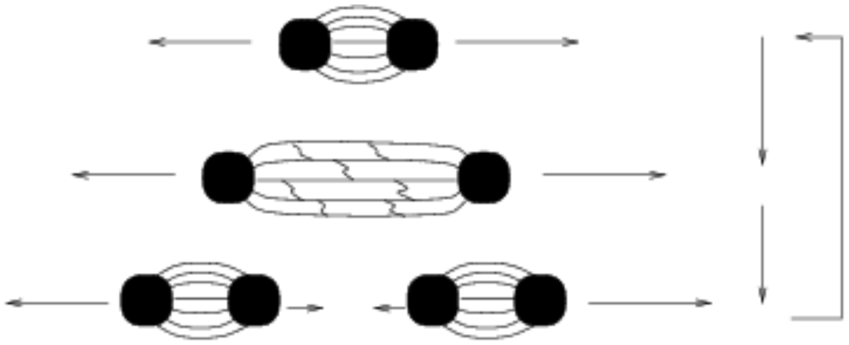


Fragmentation and hadronization

- The physics mechanisms we study in theory deal at partonic level, but experimentally we observe hadrons.
- In between exists a very important hadronization phase, where all the outgoing partons end up confined inside hadrons.
- Cannot be described by first principles, but needs some modeling.
- This is no surprise : because of hundreds of known hadron species each with its mass, width, couplings, decay patterns etc etc → some of which we don't know.
- Main approach of the models : string fragmentation and cluster fragmentation

Fragmentation and hadronization

Example model : string fragmentations



- As q and qbar move apart, the potential energy stored in the string increases.
- The string break by producing new qqbar pairs.
- In the invariant mass of the either of these string pieces is large enough, further breaks occur.
- Both models are not obtained from first principles and need many parameters

Fragmentation fraction of c and b quark

- Heavy quarks produced in pp collisions are accompanied by qqbar pairs created in the fragmentation process.
- Heavy quarks combine with other quarks to form mesons (Qq_1) or baryons (Qq_1q_2).
- Probabilities for c/b quark to hadronise as a particular charmed/bottom hadron, f ($c \rightarrow H_c$)/f ($b \rightarrow H_b$) is given by fragmentation fraction.
- The fragmentation fractions cannot be predicted by Quantum Chromodynamics (QCD) and have to be measured.
- It is usually assumed that they are universal, i.e. the same for quarks produced in e^+e^-, ep and also in pp or other hadronic collisions.

Charm quark

Meson	**Frag Fraction**	**Mass** (GeV/c^2**)**
D^0 (c ubar)	55.3 +- 5 %	1.864
D^+ (c dbar)	23.4 +- 2 %	1.869
D_s (c sbar)	9.1 +- 2 %	1.968
Λ_c^+ (cud)	5.8 +- 0.9 %	2.286
D^{*+} (c dbar)	24.1 +- 1.5 %	2.010
D^{*0} (c ubar)	~ 24 %	2.006

Beauty quark

Meson	**Frag Fraction**	**Mass** (GeV/c^2**)**
B^+ (u bbar)	37.5 +- 1.5 %	5.27915
B^0 (d bbar)	37.5 +- 1.5 %	5.27953
B^0_s (s bbar)	16.0 +- 2.5 %	5.3663
Λ_b^0 (bud)	9.0 +- 2.8 %	5.62

Quarkonia (c cbar), (b bbar) : very small

Branching ratios

- Branching ratios are also experimentally determined.
- Listing large branching ratios

Charm

D0:
- e+ anything : 6.49 %
- μ+ anything : 6.7 %
- $K^- \pi^+$: 3.88 %
- $K_s^0 \pi^0$: 1.19 %

D^+ :
- e+ anything : 16.07 %
- μ+ anything : 17.6 %
- K^{0bar} $e^+ \nu_e$: 8.83 %
- K- $\pi^+ \pi^+$: 7.32 %
- $K^0 \pi^+$: 1.46 %

D_s :
- e+ anything : 6.5 %
- $K^+ k^0_s$: 1.49 %
- $K^+ k^{0bar}$: 2.29%
- $K^+ K^- \pi^+$: 5.39 %

Λ_c^+ :
- p K^{0bar} : 2.3 %
- p $K^- \pi^+$: 5.0 %

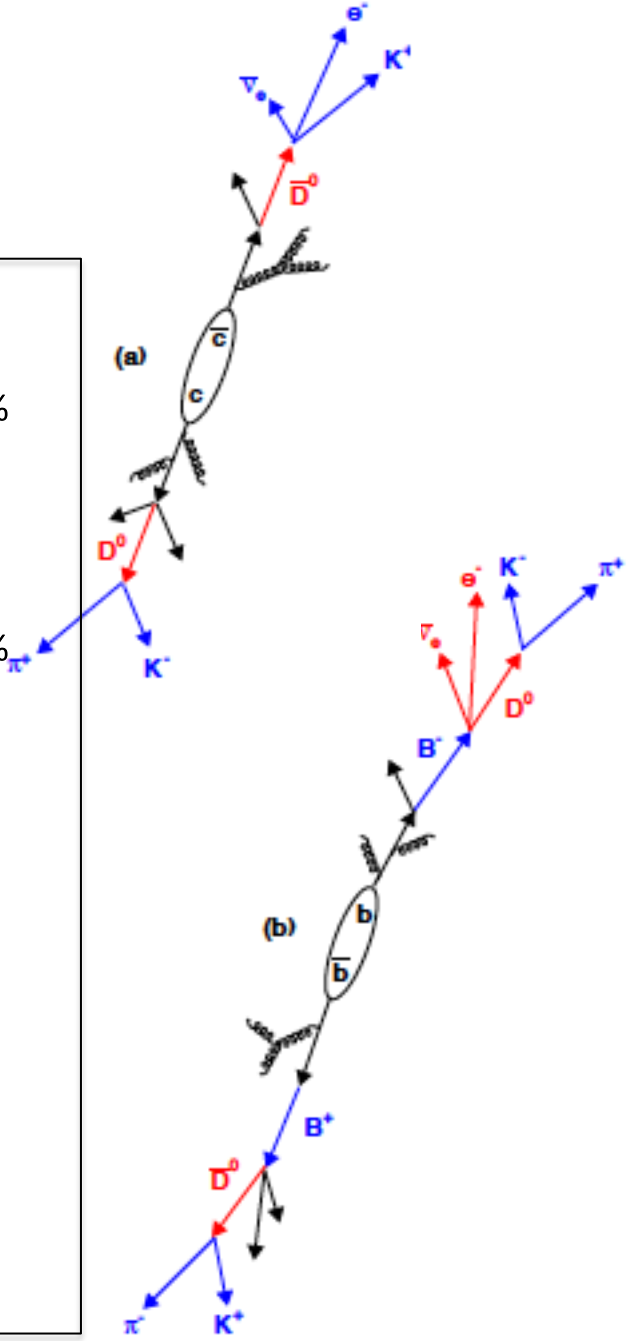
Bottom

B^+:
- e/μ+ anything : 10.00 %
- $D^{0bar} \pi^+$: 0.481 %
- $\eta_c K^+$: 0.096 %
- J/Ψ K^+ : 0.1 %

B^0 :
- e/μ+ anything : 10.33 %
- $D^- \pi^+$: 0.268 %
- $\eta_c K^0$: 0.079 %
- J/Ψ K^0 : 0.0873 %
- J/Ψ $K^+ \pi^-$: 0.12 %

$B^0{}_s$:
- e/μ+ anything : 10%
- D_s^- l ν_l : 7.9%
- $D_s^- \pi^+$: 0.3%

$\Lambda_b{}^0$:
- $\Lambda_c{}^+ \pi^-$: 0.57 %
- $\Lambda_c{}^+$ $l^- \nu_l$: 6.5 %



Heavy flavor production

- pp collisions have large production rates for heavy quarks.

- But how many are produced compared to other junk of background processes?

- For Tevatron:
  - Hadronic interactions : 50mb
  - c and b quarks in the central region : 10 µb

- At LHC:
  - Next-to-leading order perturbative QCD calculations predict values of about 10 mb for charm and 0.5 mb for beauty at 14 TeV.
  - Non-heavy flavour inelastic interactions cross section is about 70 mb (background).
  - Lets take the designed instantaneous luminosity for all LHC experiments in pp collisions.
    - ATLAS and CMS : 10^{34} cm^{-2}s^{-1}
    - LHCb : 10^{32} cm^{-2}s^{-1}
    - ALICE : 10^{30} cm^{-2}s^{-1}
  - N heavy quarks

1 barn = 10^{-24} cm^2

N = $dL/dt * \sigma$

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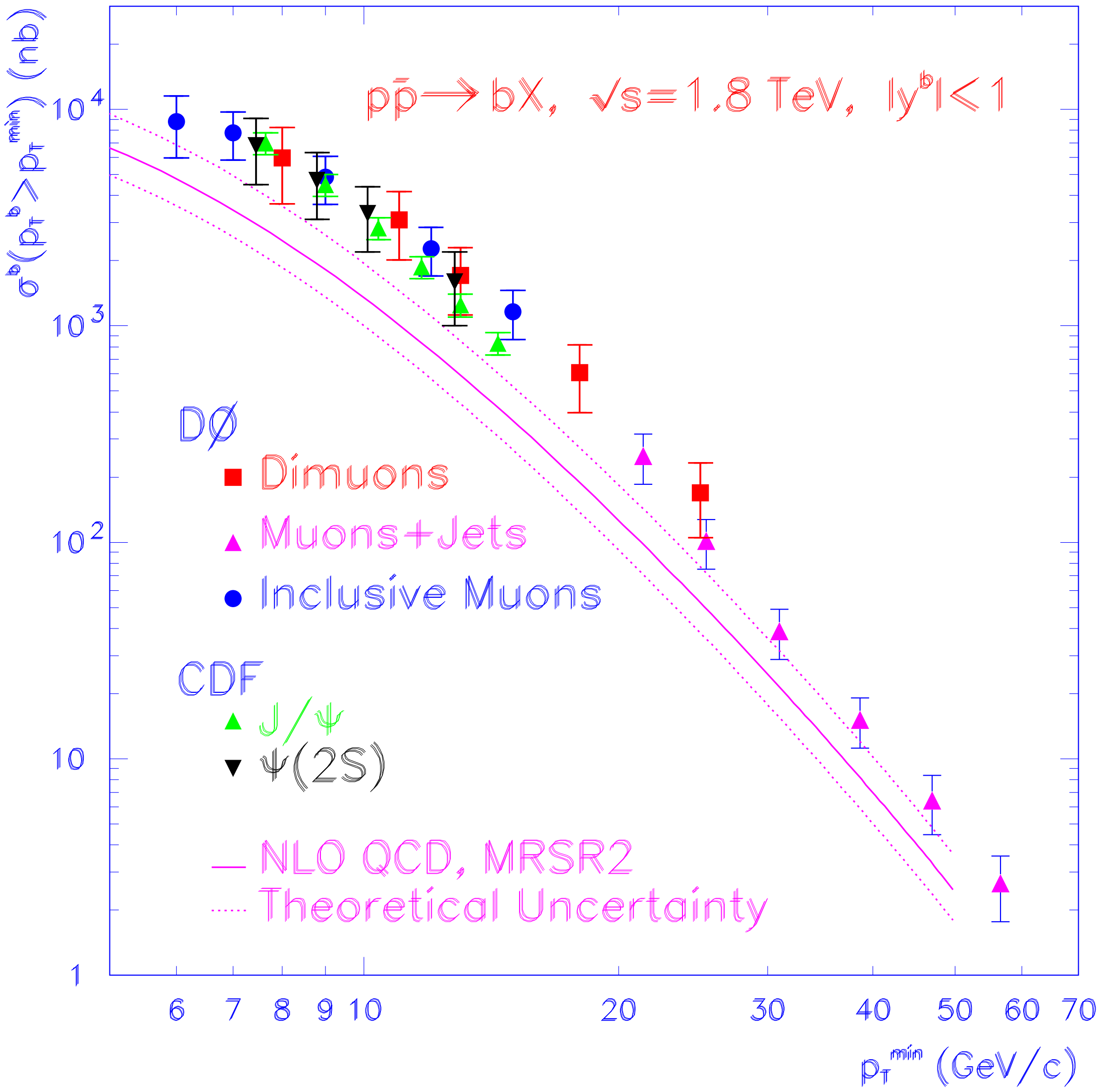
	charm	beauty	Background
ATLAS	10^{8} s^{-1}	5×10^{6} s^{-1}	7×10^{8} s^{-1}
LHCb	10^{6} s^{-1}	5×10^{4} s^{-1}	7×10^{6} s^{-1}
ALICE	10^{4} s^{-1}	5×10^{2} s^{-1}	7×10^{4} s^{-1}

At Tevatron



Cross-section of hadronic interactions at the Tevatron is about 50mb

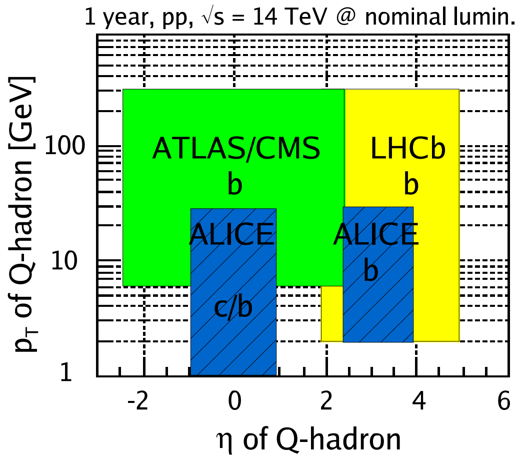
For the production of b and c quarks in the central region where the experiments have sensitivity, it is only about 10 μb.

Example of b-bbar production in different experiments

	BaBar / Belle (ee)	**CDF / D0 (pp)**	**ATLAS / CMS (pp)**	**LHCb (pp)**
$\sqrt{s}$ [GeV]	10.58 (Y(4S))	1980	7000 / 8000	7000 / 8000
BB production	coherent BB state	Incoherent BB state		
σ_{bb} [μb] in acceptance	0.0011	6.3	75	94
L [fb^{-1}]	550 / ~1000	~10	~30	3
bb pairs in acceptance [10^{11}]	0.01	0.6	22	3

How do we measure heavy-flavour hadrons

- So we have many heavy quarks but more background.
- Luminosity conditions in ATLAS, CMS and LHCb allow multiple interactions per bunch crossing
  - requirements of even stronger identification and selection of heavy-flavour events already at trigger level.
- The four detectors at the LHC have different features and design requirements
  - but all of them have good capabilities for heavy-flavour measurements.



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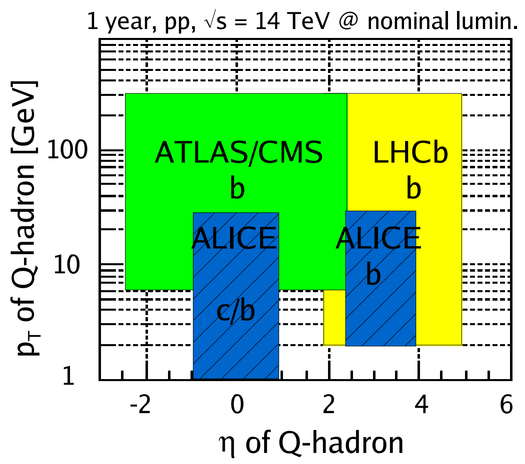
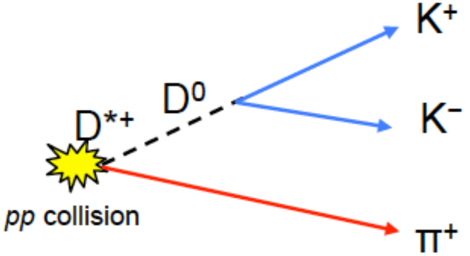
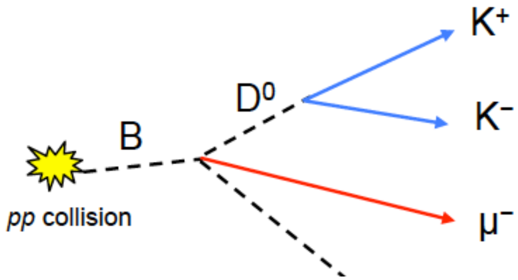


- Experimentally, the key elements for a rich heavy-flavor program are track and vertex reconstruction and particle identification (PID).
- D meson have lifetimes of 125–300 μm and B mesons have around 500 μm.
- So that these boosted hadrons are likely to decay at secondary vertices a significant distance (of the order of a millimeter) from the beam line and interaction point of the pp beams.
- The reconstruction of these secondary vertices or the observation that a charged particle track is inconsistent with pointing back to the beam line is a powerful signature for identifying heavy flavor decays.





How do we measure heavy-flavour hadrons

- Secondly, B and D hadrons have semileptonic branching ratios that are about 10% while it is rare for leptons to be produced in the prompt decays of light hadrons.

- The detector capability to perform these tasks need good transverse impact parameter (d0) resolution.

- All experiments at LHC are equipped with high position-resolution silicon-detector layers, including pixel detector for the innermost layers, for precise tracking and impact parameter measurement.

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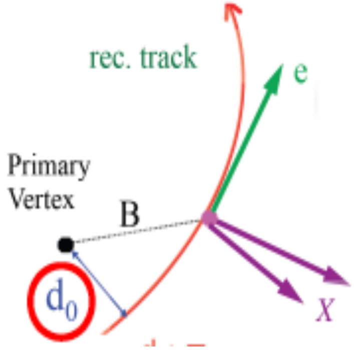
- One of the clean signal of b is the signature provided by B → J/ Ψ X.

- While the product branching fraction B → J/ Ψ(→μμ)K is only 6 → 10^{-4}, these decays provide a distinctive and accurate signature and are a rich source of information about the b → $c\bar{c}s$ transition.

- They also provide triggering and tagging for the study of global properties of b hadrons.

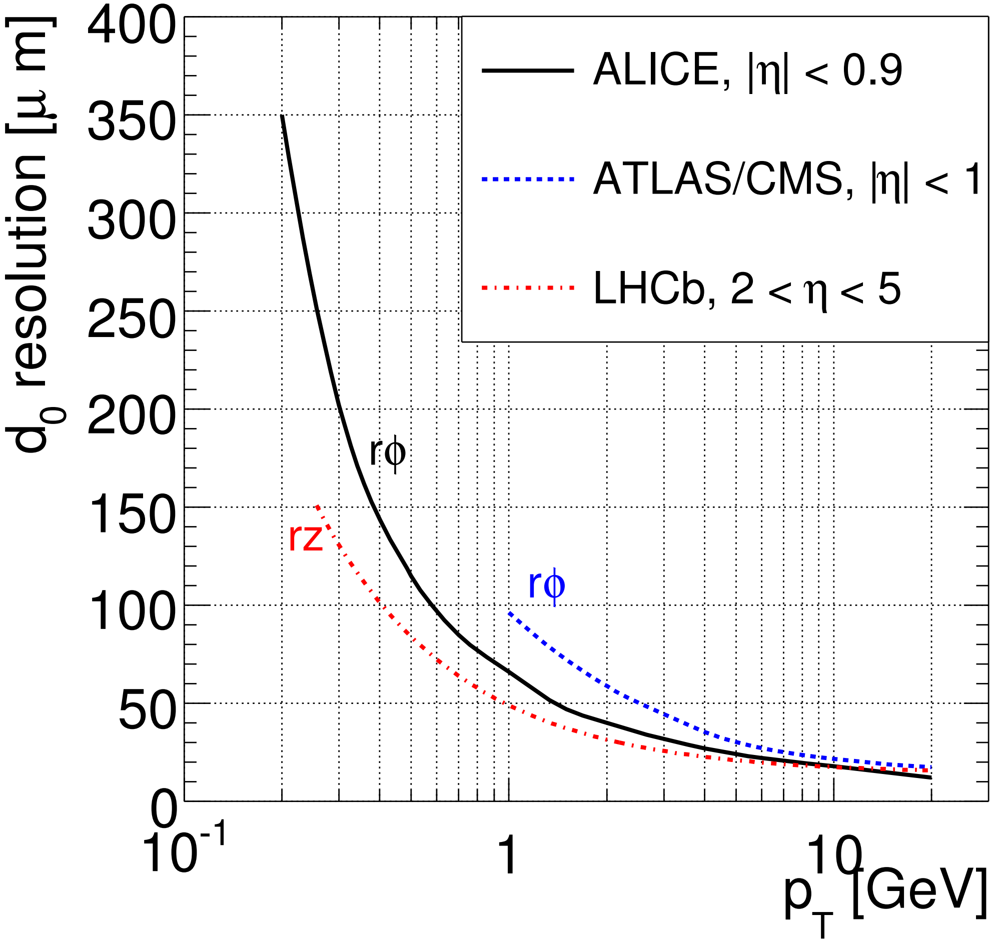


d_0 : transverse impact parameter

Summarize detector capabilities for heavy-flavour physics

- Need good vertex detection, both primary and secondary.
- Good impact parameter resolution.
- Need high resolution electromagnetic calorimeters to identify electrons.
- To reconstruct exclusive hadronic decays, preferable in charm, hadron identification is important.
- Good π/K/p separation via dE/dx or time-of-flight measurements.
- Good trigger to enhance and tag heavy-flavour events.

Back up



d_0 resolution [μ m]
400
350
300
250
200
150
100
50
0
10^{-1}
1
10
p_T [GeV]
ALICE, $|\eta| < 0.9$
ATLAS/CMS, $|\eta| < 1$
LHCb, $2 < \eta < 5$
rϕ
rz
rϕ