Lepton reconstruction & identification with ALICE & LHCb

A few remarks focused on low-p_T quarkonium

Michael Winn, 25th of April

Context: J/ψ at the LHC

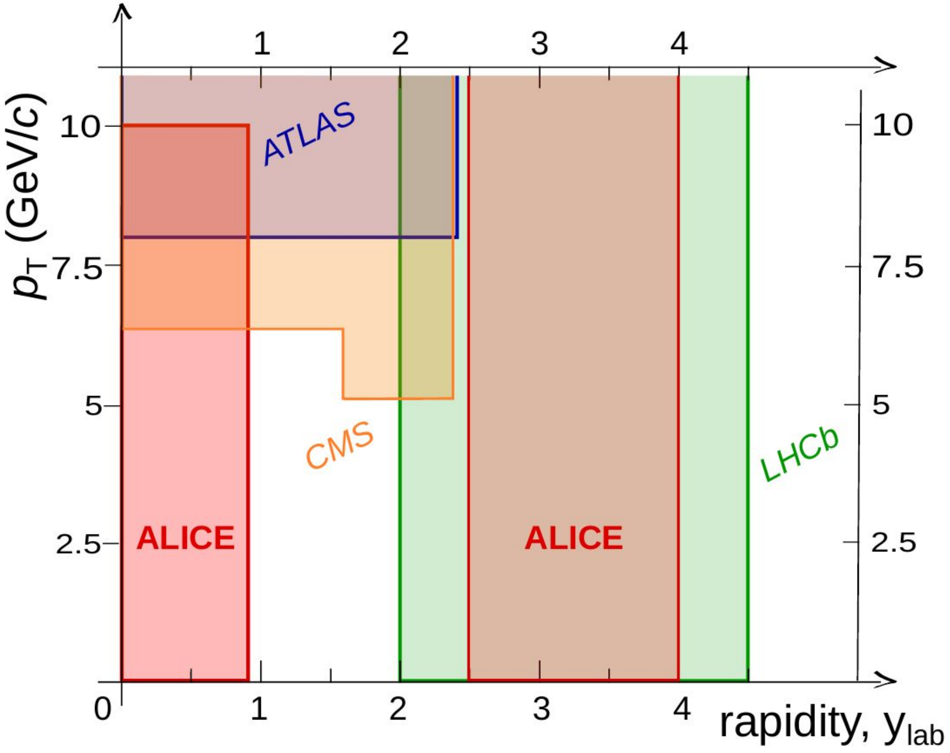


Fig. by A. Maire

Typical acceptances
for J/ψ in pPb in LHC Run 1/2

3 main schemes for ALICE/LHCb
- LHCb dimuons forward
- ALICE dimuons forward
- ALICE dielectrons barrel

Focus on LHCb and ALICE barrel in pp/pPb & UPC

In view of EIC muon-identifier relevanc
in continuous read-out

Goals of the talk

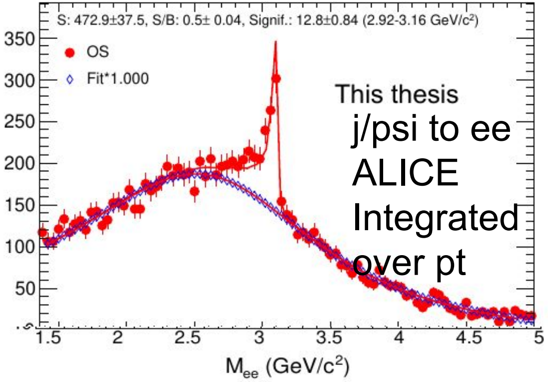
- Comments from analyser´s perspective in view of EIC
  - Not a review of detector technology & operational experiences, performance figures

    You can find those numbers in numerous performance papers

Keep in mind:

- Easy to criticize detector systems with broad scope and limited budget
- Abstraction of speed/lumi difference:

  J/psi rare in ALICE, very abundant in LHCb



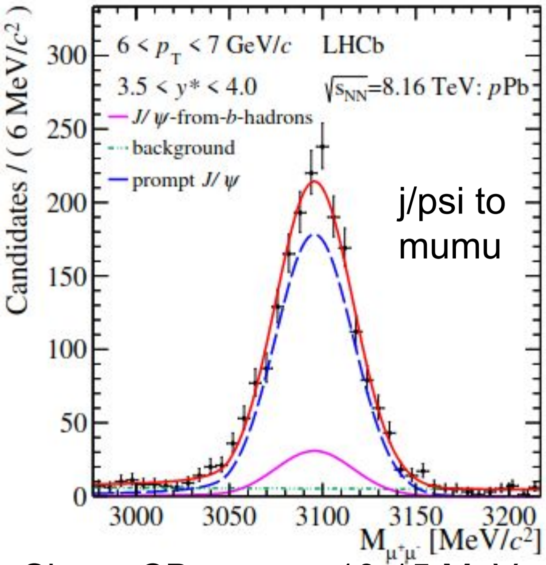
Sigma CB approx. 20-25 MeV at lowest pT

Key points to discuss

Why electrons are used in the barrel of ALICE, why no muon system? When are muons feasible also in the barrel?

Differences between muons and electrons in LHCb

Factors for success beyond detector design



Sigma CB approx. 10-15 MeV at lowest pt (varies with rapidity)

Underlying considerations

Simple starting points

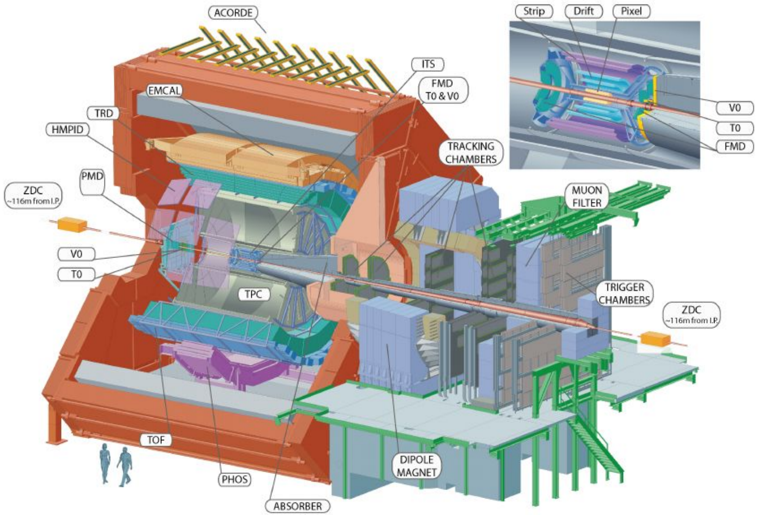
1) Detector physics is a function of **absolute momentum**

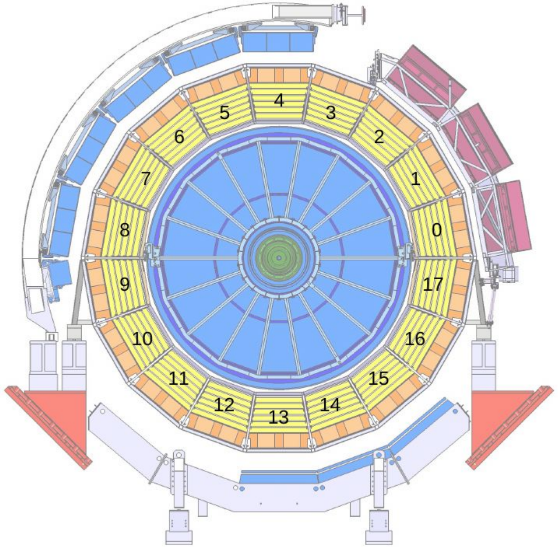
2) **Interplay with tracking/calorimetry:** acceptance of ID detector & capability of system independent of ID-detector

3) Performance **not reducible to resolutions and efficiency/purity only**

4) **Stability and calibration** of detector/PID: limiting factor for PID since simulations often not sufficiently reliable

ALICE central barrel





ITS green
TPC blue
TRD yellow
TOF orange

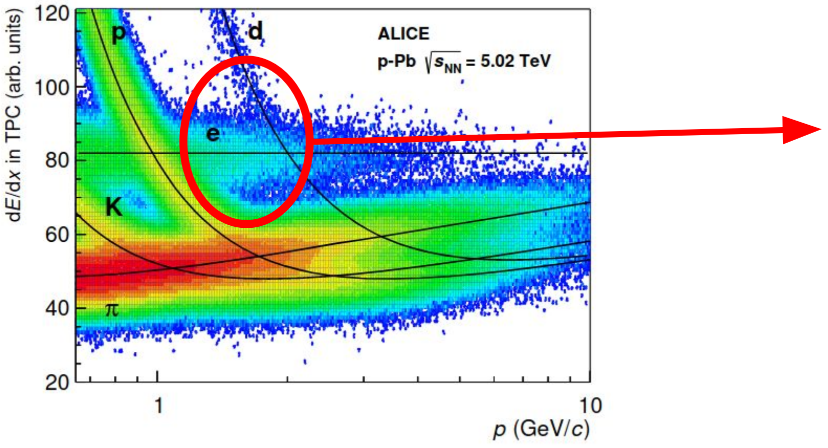
Run 2
configuration

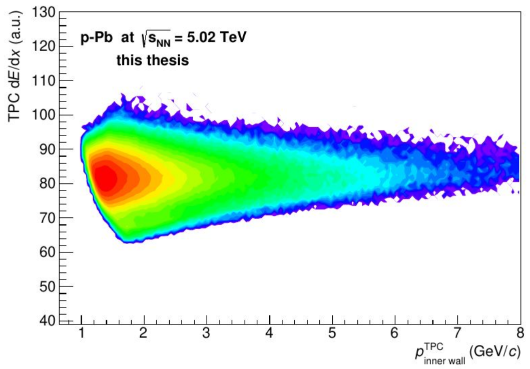
Tracker up to middle of TPC X/X0 about 10 %: very light compared to ATLAS/CMS

- Tracking starting from about 150 MeV for primary tracks with TPC at nominal field (B=0.5 T), outer radius active TPC 2.466 m
  Designed for dN/deta = 8000 and moderate PbPb interaction rates

electron-Identification capability: TPC, EMcal, TRD, TOF

ALICE electron PID for Jpsi





https://arxiv.org/pdf/1503.07179.pdf

TPC at its best and its limits

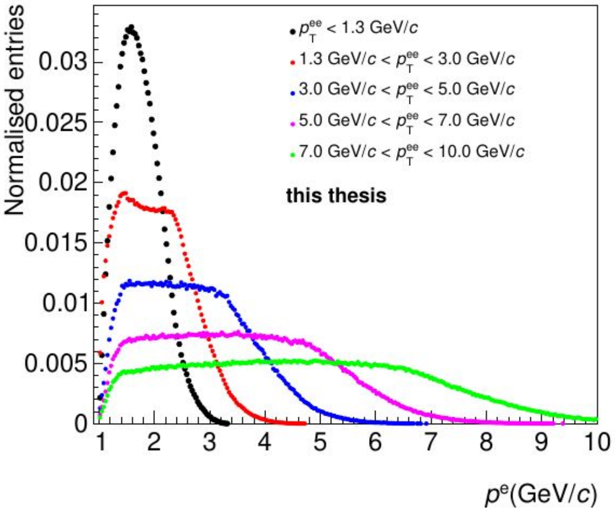
Need to control efficiency in various dimensions:

Momentum, eta, multiplicity, detected track length in detector

Analysis level specific ´post-calibration´ in 3-4 dimensions based on electrons identified by photon conversions

Why not muons? Why only TPC?

Why no muons in ALICE barrel?



J/psi decay daughter kinematics in ALICE eta-range

Absolute momenta for low-pt quarkonia between 1-3 GeV/c in ALICE barrel
N.B.: LHCb muon system specification starts at 3 GeV: https://arxiv.org/pdf/1306.0249.pdf

Main motivation for ALICE: primary leptons in PbPb
- require excellent hadron rejection, dn/deta about 2000 (mostly pions) in PbPb central collisions

A hypothetical ALICE muon system: 4-5 m from interaction point

Considering pi/mu separation good enough for tracks crossing muon-ID system:
Decays in flight become a limitation for background (ctau of muon = 660 m)
- Decays in flight start to dominate mis-ID in LHCb at low p (M1 at 12.1 m from IP, M5 at 18.8 m from IP)

A muon system could have been interesting for Upsilon:
- in any case not competitive with CMS/ATLAS (smaller acceptance)

Electrons with additional motivation for high-purity/lower momentum
- thermal radiation of gamma-conversions/dielectrons, rho spectral functions
- Rho line shape to mumu at low-pt out of scope for muons in a collider at midrapidity in PbPb

Why only TPC?

Detectors	TPC	TRD	TOF	EMCal	ITS
Acceptance					
$\|\eta\|$	< 0.9	< 0.9	< 0.9	< 0.7	< 0.9
ϕ	2π	$0.72 \cdot 2\pi$	2π	$0.3 \cdot 2\pi$	2π
eff. w.r.t ITS-TPC for $p_T \in [1.0, 3.0]$ GeV/c	100%	$\approx$ 80%	70-80%*	$\approx$ 100%**	100%

Table 3.1.: Acceptance and matching efficiencies of central barrel detectors with electron PID capabilities in the 2013 p–Pb data sample. These factors do not take into account the efficiency loss required for a separation from hadrons, which is very different between detectors and as a function of momentum. The acceptances are reported in [206]. The precise values for the matching efficiencies for unidentified tracks can be found in [216] for the TRD and [206] for the TOF. (*) for $|\eta| < 0.8$, (**) for $|\eta| < 0.6$.

Need to multiply ideal curve by 18/13 (detector was not completed): about 80%

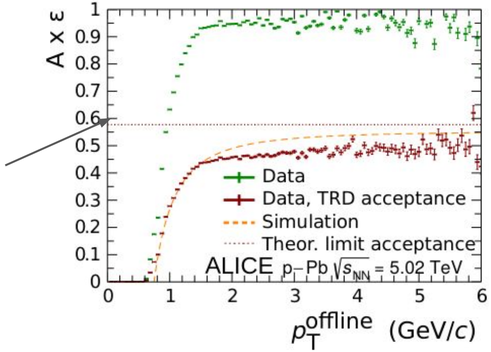


Fig. 51: Acceptance times efficiency of the global online tracking for primary tracks (Data) and tracks in the detector acceptance (Data, TRD acceptance) as function of the transverse momentum of the global offline track (trigger threshold at 2–3 GeV/c). The results of an ideal simulation, not considering non-operational parts of the real detector, are drawn for comparison. The dotted line shows the theoretical limit of the acceptance with 13 out of 18 supermodules installed during the p–Pb data taking period in Run 1.

Main reason: Acceptance x efficiency reduction

Jpsi in ALICE: still rare, statistics is one limiting factor
Calorimeter coverage only partial: not an option in minimum bias collisions
TRD in principle covering full azimuth, see https://arxiv.org/pdf/1709.02743.pdf
However:
Due to boundary effects in geometry to find a TRD tracklet for a TPC track: about 80 %

- about 40 % of candidates lost by requiring both tracks in TRD
- TPC for electrons not anticipated in TDRs: TPC electron-pion separation beyond expectation

With larger statistics in Run 3, electron purity and hence S/B can be further improved for electrons

Comment to EIC: continuous readout, system should have full acceptance, understand the detector capability as a whole including tracker/calo

Muons in ALICE barrel

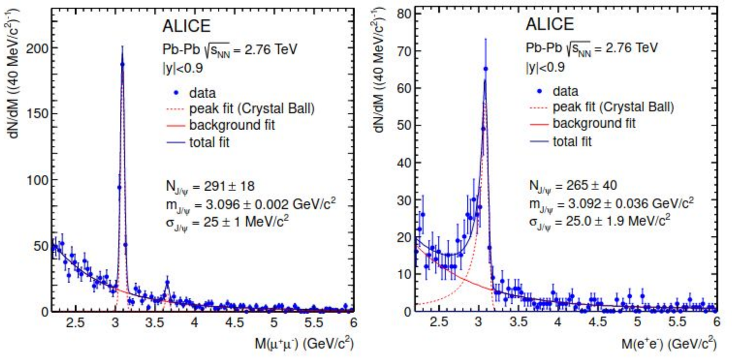
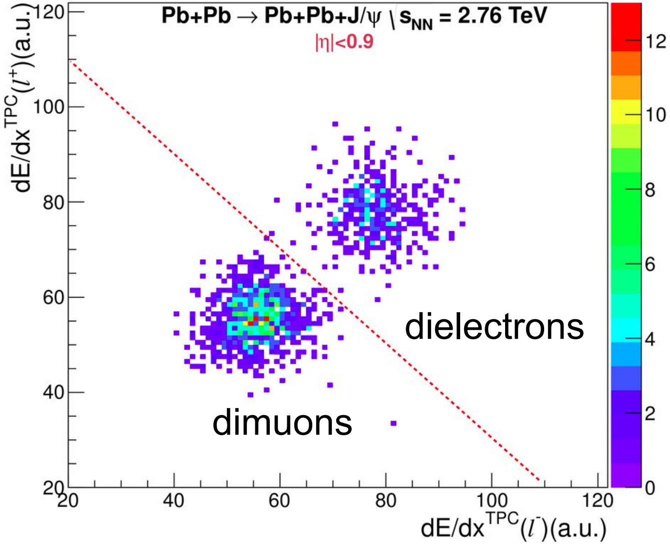


Fig. 24: Invariant mass spectra of $\mu^+\mu^-$ (left) and e^+e^- (right) pairs in ultraperipheral Pb–Pb collisions. The solid and dotted lines represent the background (exponential) and peak (Crystal Ball [50]) fit components, respectively. The bremsstrahlung tail in the e^+e^- spectrum is reproduced in simulation. The mass resolution is better than 1%.

https://arxiv.org/pdf/1402.4476.pdf



https://arxiv.org/abs/1305.1467

UPC collisions: no dedicated mu-ID needed if good e/h separation

My assumption for EIC: no mu-ID system needed to use muons for exclusive reactions

Why ideal muon system better than ideal electron system for J/psi in pp?

Ideal:

- Perfect hadron rejection
- Same resolutions, little impact of Bremsstrahlung

pp 7 TeV jpsitoee Selection set → Sources ↓	*SPDfirst proton band*	*SPDany proton band*	*ITS3any proton band*	*SPDfirst no proton band*	*SPDany no proton band*	*ITS3any no proton band*
γ-conversions	2.0%	10.9%	19.6%	3.8%	10.1%	18.6%
open charm + open charm	19.4%	15.4%	11.9%	18.9%	16.3%	13.4%
open beauty + open beauty	8.2%	4.9%	3.9%	13.2%	8.5%	7.0%
prim. e^+ + sec. e^-	10%	18.2%	21.1%	3.8%	14.7%	18.0%
mis. id. + true $e^\pm$	35.7%	34.8%	30.6%	32.0%	30.2%	26.1%
mis. id. + mis. id.	8.2%	4.9%	3.6%	7.5%	5.4%	4.0%

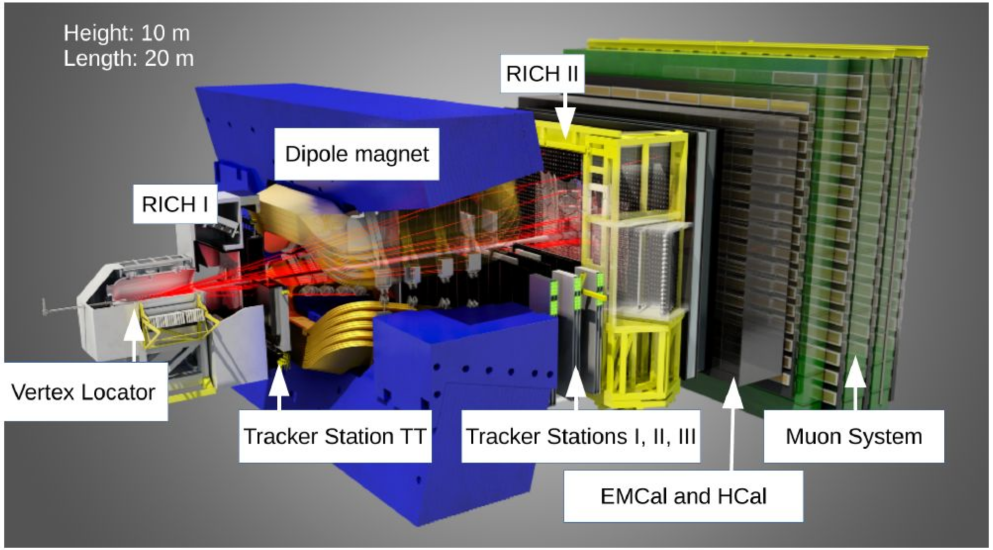
Table III.2: Main contributions to background for different cut sets in Monte Carlo minimum bias PYTHIA 6.4 perugia tune 0 and full GEANT 3 detector simulation.

Muons: no electrons from gamma-conversions originating from pi0 decays in muon sample

No background from pi0 Dalitz decays, largest contribution for muons: eta muonic dalitz decays

- Motivation to do muons for X(3872) with jpsi+2pi in ALICE 3 with muon system instead of electrons
- Naive EIC expectation: negligible importance due to low multiplicity @eA/ep @100 GeV
  For EIC barrel, interesting to look at muon system study for ALICE 3 since aiming at muon-ID above 1 GeV total momentum in similar geometry in terms of distances and B-field

LHCb Detector set-up Run 1/2

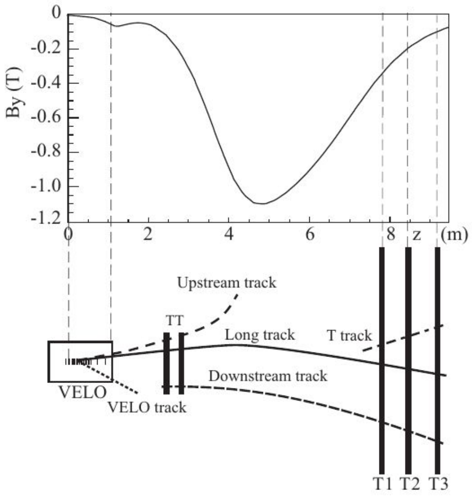


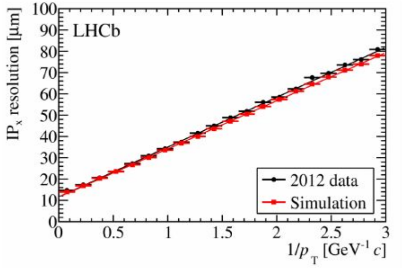
JINST 3 (2008) S08005.

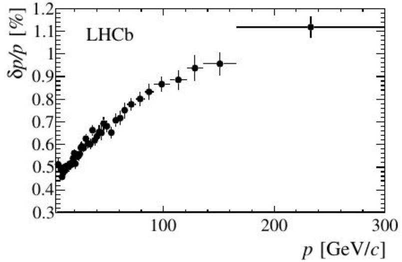
- collect large number of B-hadrons in small angular acceptance: about 27% of b-quarks within acceptance in pp collisions

https://indico.cern.ch/event/614845/contributions/2728917/attachments/1531428/2397092/56_MWinn.pdf

LHCb Tracking





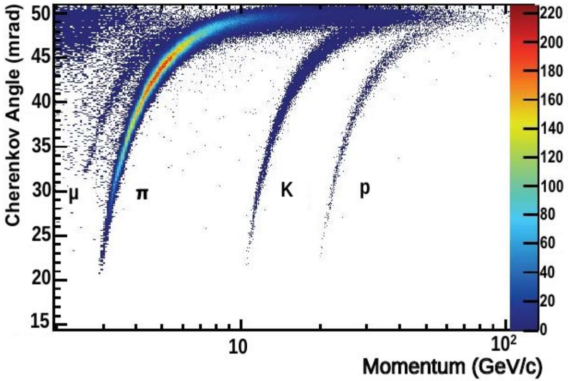


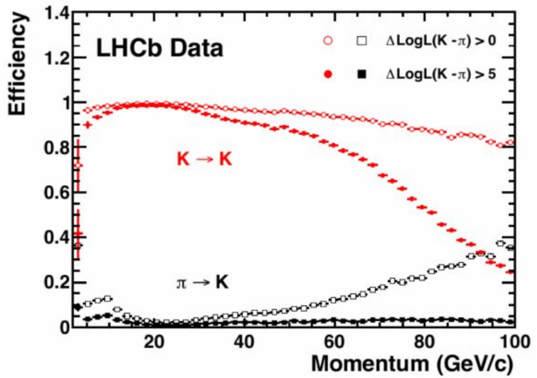
Int. J. Mod. Phys. A 30 1530022.

- VELO: silicon strip telescope down to radial distance to beam $r = 0.8$ cm
- VELO+RICH1+silicon strip+ 4Tm dipole + straw tubes/silicon strips
- tracker with $\approx 30\%$ X_0
- momentum resolution below 1% in wide range
- topological ID of charm and beauty hadrons down to 0 p_T: longitudinal boost

https://indico.cern.ch/event/614845/contributions/2728917/attachments/1531428/2397092/56_MWinn.pdf

LHCb particle identification





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- 2 RICH systems with 2 radiators for charged track PID
- muon-ID behind calorimetry: $\varepsilon_{\mu\to\mu} \approx 97\%$ for $\varepsilon_{\pi\to\mu} \approx$ 1-3 % Mis-ID
- photon measurement & electron/photon-ID with calorimetry and preshower
  $\Delta m(\mu^+\mu^-, \mu^+\mu^-\gamma)$-resolution: 5 MeV/$c^2$ from $\chi_{c1,c2} \to J/\psi + \gamma$-decay with calorimeter

https://indico.cern.ch/event/614845/contributions/2728917/attachments/1531428/2397092/56_MWinn.pdf

Differences between muons and electrons in LHCb

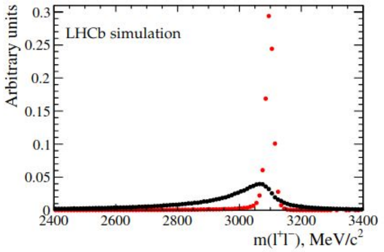


Figure 2.20: Invariant mass of $\ell^+\ell^-$ in the Run I simulation of $\Lambda_b^0 \to pKJ/\psi(\to \ell^+\ell^-)$, where ℓ = (red) μ, or (black) e. Distributions are normalised to the unit area. The dielectron shape is wider and has long tails due to bremsstrahlung.

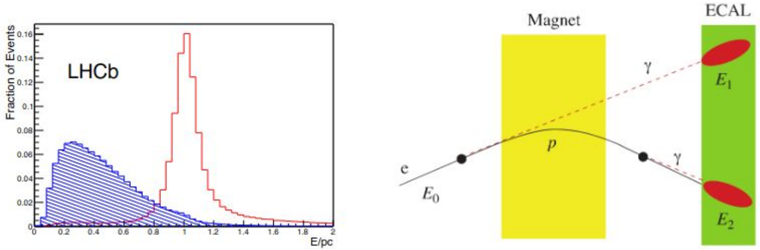


Figure 2.17: Left: Distribution of E/p for electrons (red) and hadrons (blue), as obtained from a part of the 2011 dataset. Taken from [102]. Right: Schematic representation of the bremsstrahlung photons emitted by an electron before and after the magnet. Taken from Ref. [101].

https://tel.archives-ouvertes.fr/tel-02428454/document

Impact of Bremsstrahlung on resolution
Muons resolution: ´perfect´ tracks in a high-resolution set-up
Muon-ID: a 5 stations muon system interspersed with calorimeters and shielding (total 20 lambda_I) https://arxiv.org/abs/1211.1346
Electrons resolution from tracker: strongly impacted by Bremsstrahlung
Electron-ID: electromagnetic calorimeter system with preshower https://arxiv.org/pdf/2008.11556.pdf
Recovery of ´lost´ momentum limited by calorimeter resolution, efficiency/threshold for low-momentum photons

LHCb calorimeter resolution:
focus on b-physics

$$\frac{\sigma(E)}{E} = \frac{(9.0 \pm 0.5)\%}{\sqrt{E}} \oplus (0.8 \pm 0.2)\% \oplus \frac{0.003}{E \sin\theta},$$

Differences between muons and electrons in LHCb

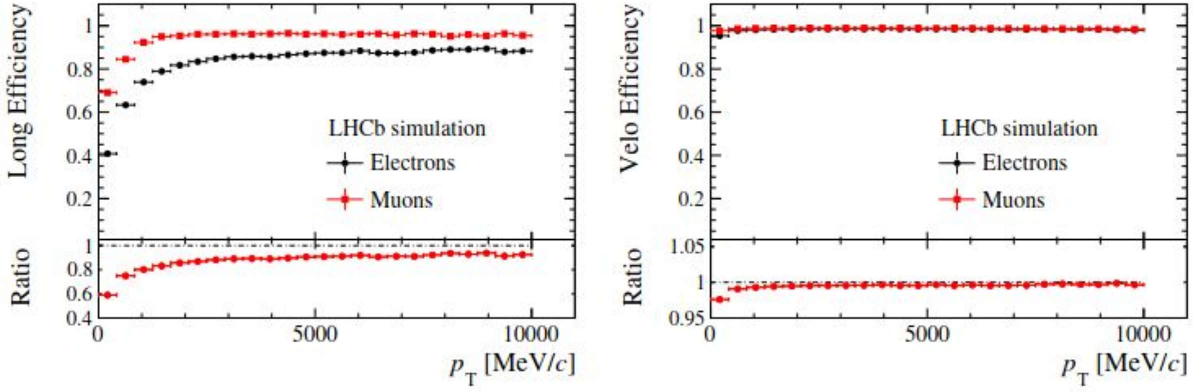


Figure 2: The simulated LHCb (left) long-track and (right) VELO-track reconstruction efficiency for electrons and muons produced in $B^+ \to J/\psi(\to \ell^+\ell^-)K^+$ decays as a function of the lepton's transverse momentum.

https://arxiv.org/pdf/1909.02957.pdf

Sizeable impact of Bremsstrahlung also on efficiency in pattern recognition

Factors for performance beyond detector specification

Good calibration samples & validation crucial for efficiency
Need to be data driven: simulations in particular at low momentum often not reliable

Topological selections and tag & probe with large statistics used by LHCb, V0s by ALICE

LHCb: Hadrons from charm (cross section about O(10) larger than beauty) and muons from non-prompt jpsi

ALICE barrel electrons via gamma conversions:

- only very abundant candle for electron-ID: can be a limitation since not primary
-

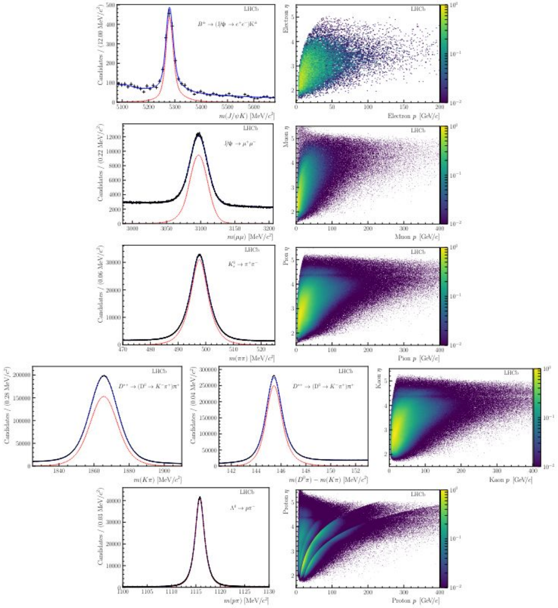
LHCb: muons important for many channels with stringent requirements:

- Bs-> mumu, tau->3mu, Ks->2mu, prompt dark photon search (gammaprime -> mumu)
    - Extensive software for global PID based on **all detectors** developed and used !

EIC: muon validation and calibration to be thought off

Not only a matter of opportunity in terms of channels, but also a matter of capability of cooperation

Detector stability a big factor: may introduce additional dimensions or granularity



https://cds.cern.ch/record/2202412/files/LHCb-PUB-2016-021.pdf
https://arxiv.org/pdf/1803.00824.pdf

Summary

ALICE barrel uses electrons with TPC-only for J/psi analyses

- Very light detector, measurements at small absolute momenta, Bremsstrahlung impact modest and electron-h rejection sufficient with dEdx only keeping large acceptance
- Muons feasible in exclusive environment without ID-detector
- Beyond resolutions/ID: ideal muons better than electrons due to lower physical lepton backgrounds in inelastic hadronic collisions

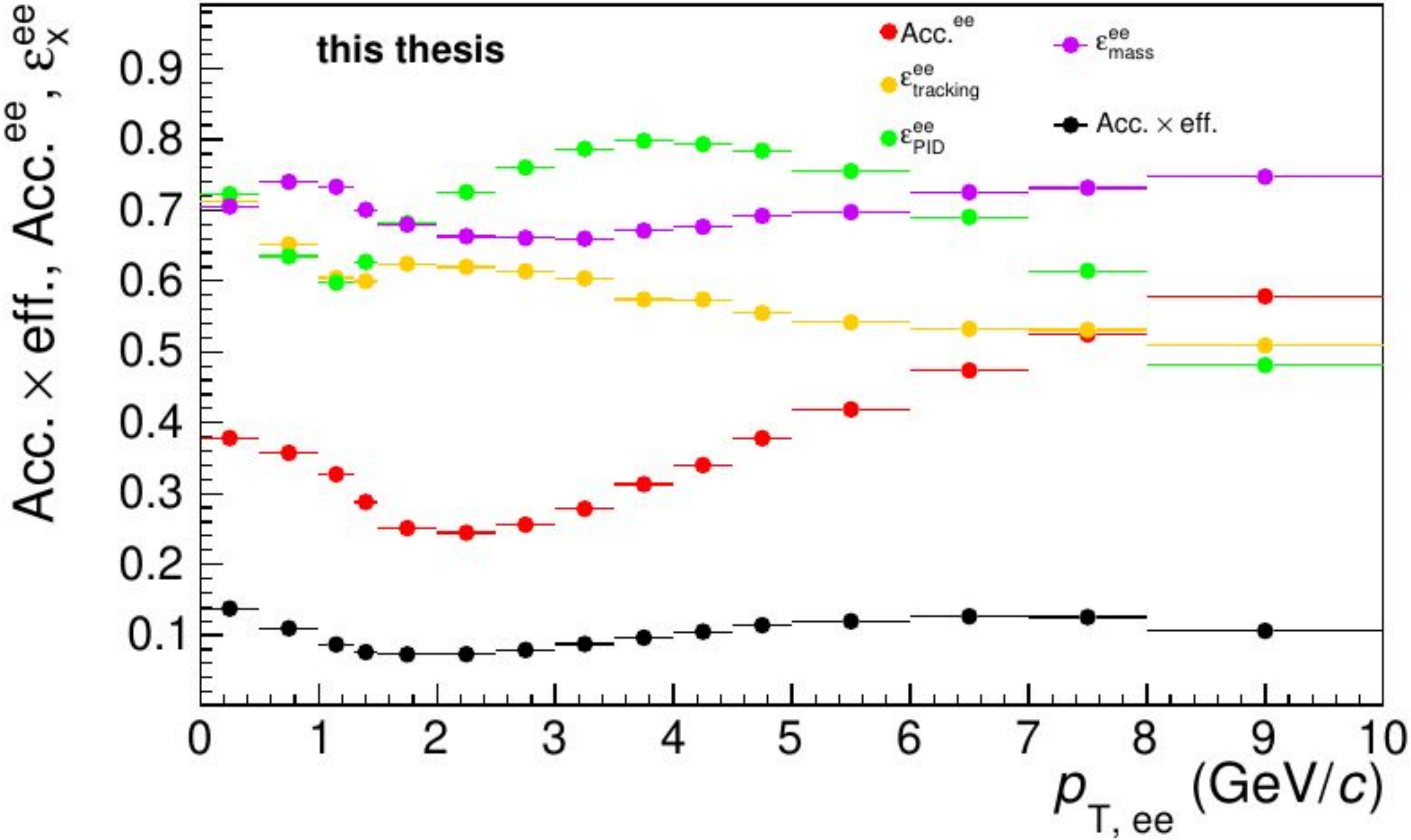
LHCb has electron and muon-identification capability: prompt Quarkonium based on muons

- Electrons: forward geometry, more material budget: higher absolute momenta, more Bremsstrahlung
- Muons: LHCb has an excellent tracker and excellent muon-ID above 3 GeV momentum

Measurement performance not only a matter of detector specification:

- Detector stability, calibration and performance control in real-data often limiting factors of measurement precision
- PID performance ideally not only based on one ID-detector, but take tracker/calo info into account
- Performance control and validation: a collaborative effort

Thank you!



this thesis
$Acc.^{ee}$
ε^{ee}_{mass}
$\varepsilon^{ee}_{tracking}$
ε^{ee}_{PID}
Acc. × eff.
Acc. × eff., $Acc.^{ee}$, ε^{ee}_{X}
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
1
2
3
4
5
6
7
8
9
10
$p_{T, ee}$ (GeV/c)

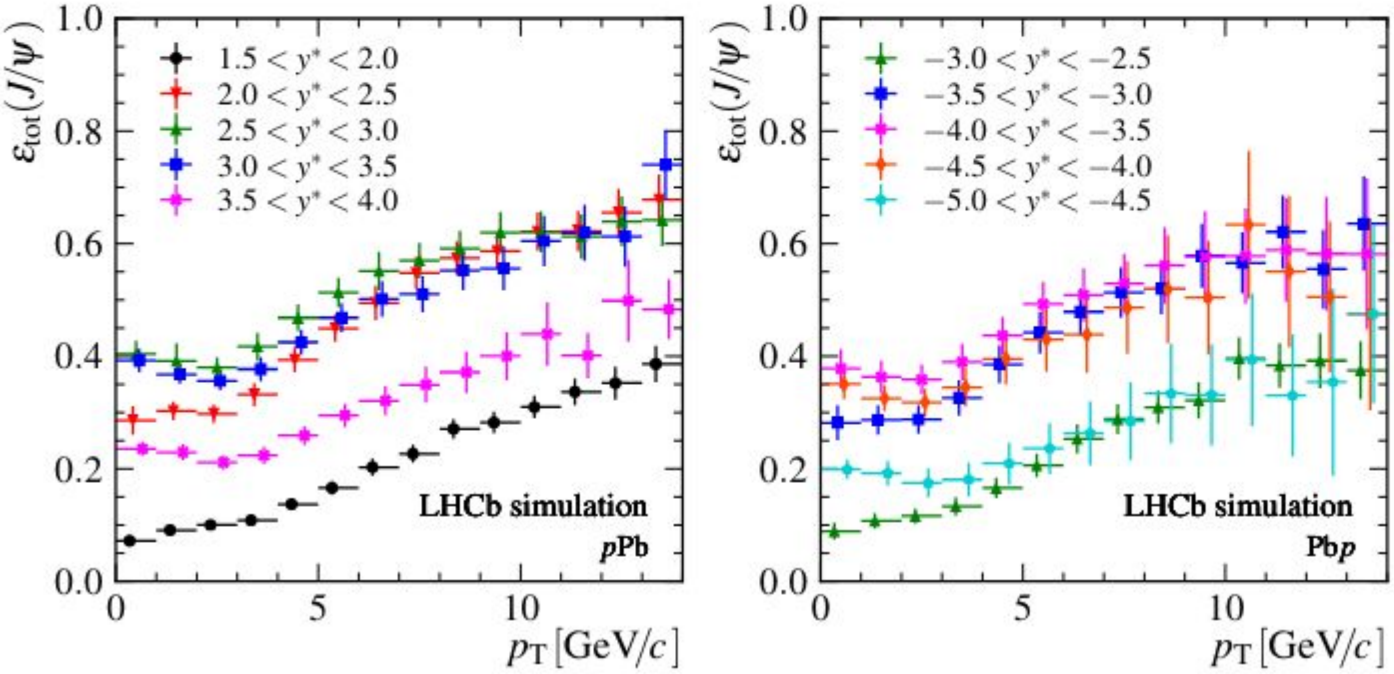
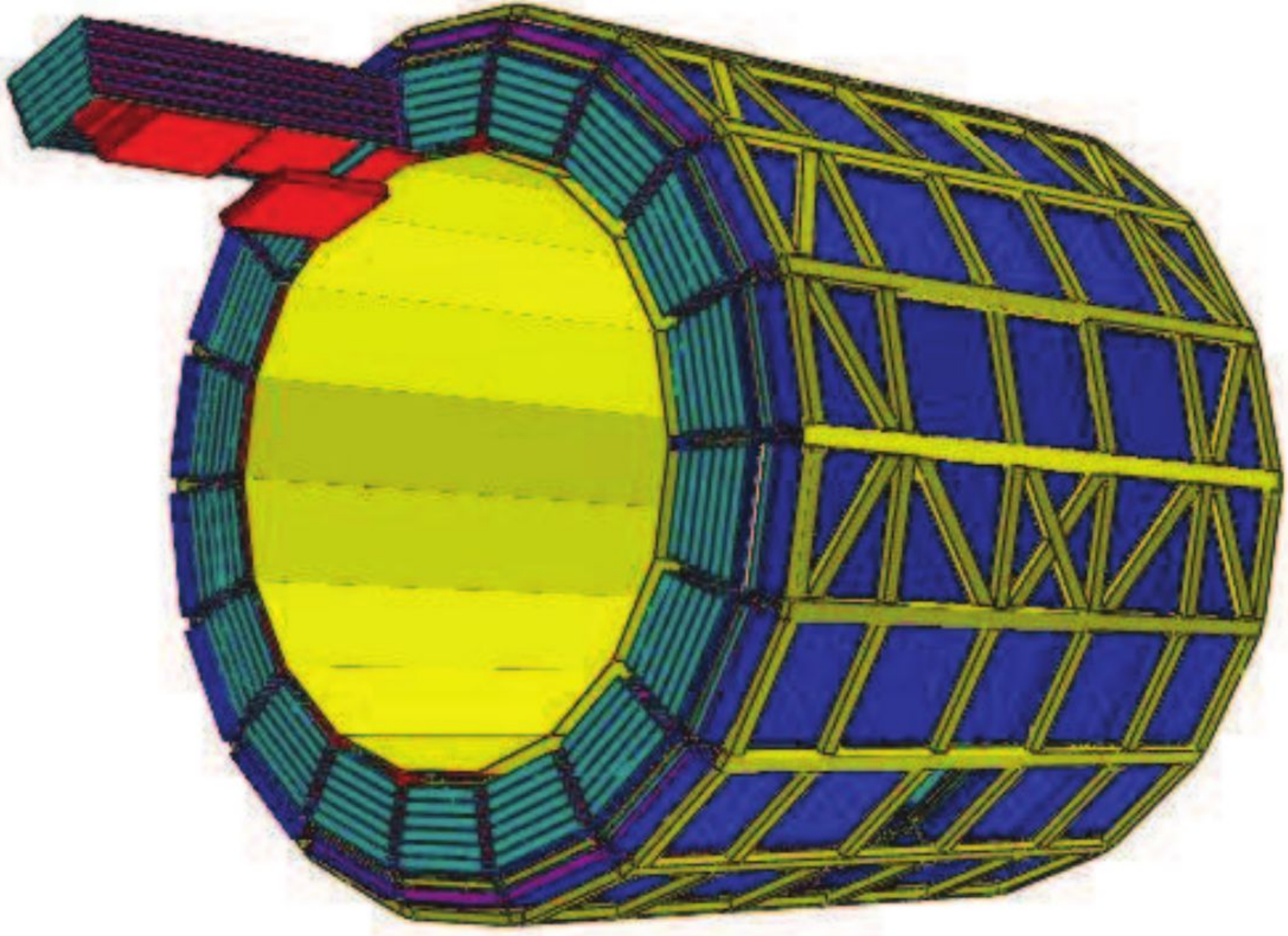


Figure 2: Total J/ψ detection efficiency, $\epsilon_{\rm tot}$, as a function of the J/ψ $p_{\rm T}$ in different y^* bins for (left) pPb and (right) Pbp.



sub-detector	SPD/PS	ECAL	HCAL
number of channels	2×6016	6016	1488
overall lateral dimension in x, y	6.2 m × 7.6 m	6.3 m × 7.8 m	6.8 m × 8.4 m
cell size (mm) Inner	39.7 (SPD), 39,8 (PS)	40.4	131.3
cell size (mm) Middle	59.5 (SPD), 59.76 (PS)	60.6	
cell size (mm) Outer	119 (SPD), 119.5 (PS)	121.2	262.6
depth in z	180 mm, $2.5\ X_0$, $0.1\ \lambda_{int}$	835 mm, $25\ X_0$, $1.1\ \lambda_{int}$	1655 mm, $5.6\ \lambda_{int}$
light yield	~20 p.e./MIP	~3000 p.e./GeV	~105 p.e./GeV
dynamic range	0 - 100 MIP 10 bits (PS), 1 bit (SPD)	0 - 10 GeV E_{T} 12 bits	0 - 20 GeV E_{T} 12 bits

Table 1: Main parameters of the LHCb calorimeter sub-detectors.

https://arxiv.org/pdf/2008.11556.pdf

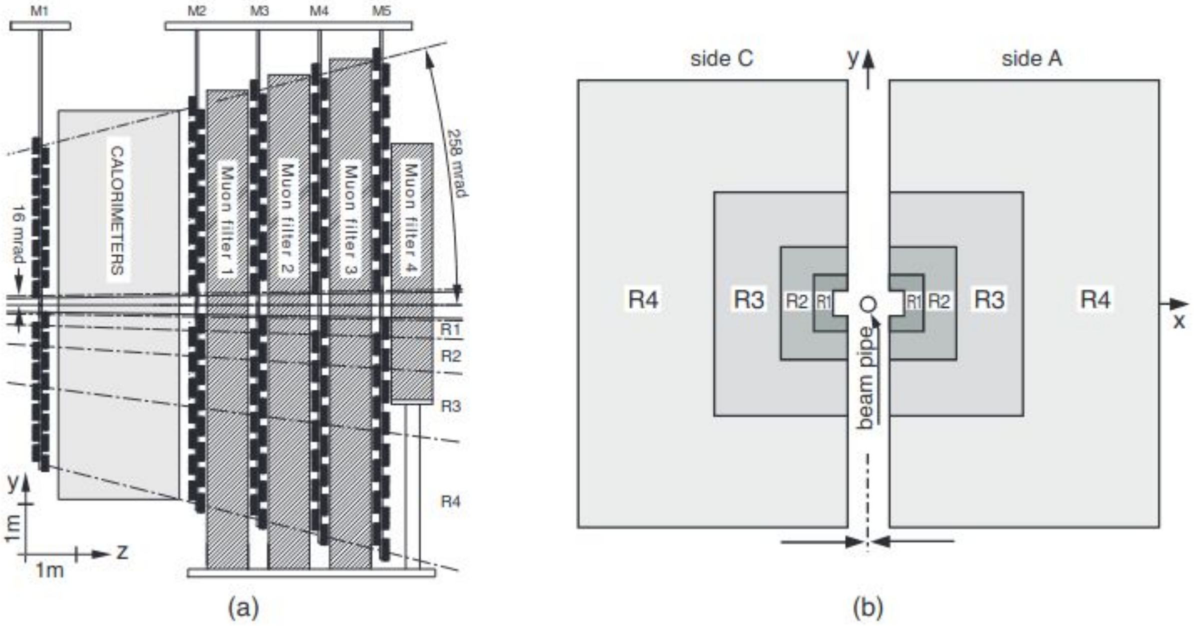


Figure 1: (a) Side view of the LHCb Muon Detector. (b) Station layout with the four regions R1–R4.

https://arxiv.org/pdf/1211.1346.pdf