Measurement of electrons from beauty-hadron decays in pp collisions at $\sqrt{s}$ = 2.76 TeV to 13 TeV with ALICE

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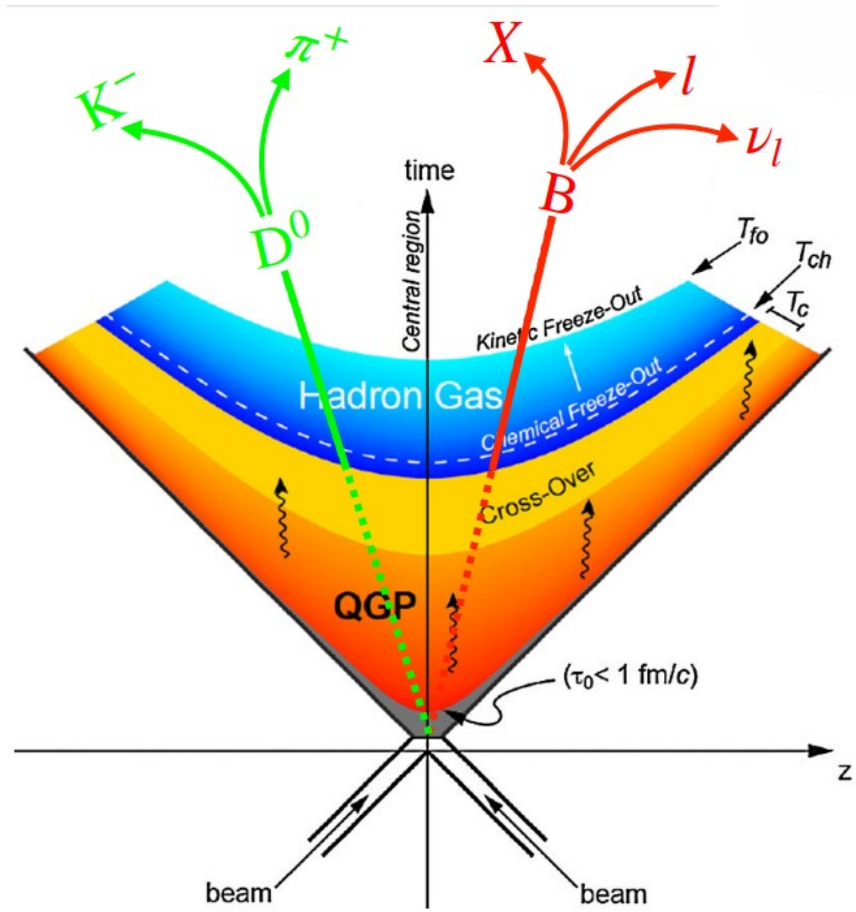
Motivations

Charm and beauty quarks (heavy quarks)

- **Due to their large masses, are produced in the initial hard scattering processes at the early stage of the collisions**
- **They witness the full evolution of the produced medium (quark-gluon plasma) in ultra-relativistic heavy-ion collisions**
- **Traverse in the medium undergoing elastic and inelastic collisions with the constituents of the medium leading to energy loss**
- **Excellent probes to investigate quark-gluon plasma (QGP)**



Nuclear Physics A (987) 144-201

Open heavy-flavour production

- $M_{c,b}$ (1.3, 4.2 GeV/c^2) >> QCD scale parameter ($\Lambda_{QCD} \approx$ 0.2 GeV)
- Production cross-section is calculable perturbatively down to low p_T based on factorization approach

$$d\sigma^{hard}_{AB\to C} = \sum_{a,b} f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes d\sigma^{hard}_{ab\to c}(x_a, x_b, q^2) \otimes D_{c\to C}(z, Q^2)$$

Parton Distribution Function (PDF) | Partonic hard scattering cross-section | Fragmentation function

pp collisions

- Heavy-quark production cross sections are important to test pQCD calculations
- Baseline for measuring nuclear modification in p-A, A-A collisions

p—Pb collisions

- Studies provide access to cold nuclear matter effects

Pb—Pb collisions

- Studies allow us to investigate the QGP effects on heavy-quarks traversing the medium

Presentation in detail by *Ravindra Singh & Renu Bala*

Beauty-electron identification technique

$B,D \longrightarrow e + \nu_e + X$

Heavy Flavour decay electrons (HFe) = Inclusive electrons – Non HF electrons

Data Sample

Identify electrons

$b \longrightarrow e$

$b \longrightarrow (c) \longrightarrow e$

$c \longrightarrow e$

Separate $(c \longrightarrow e)$ contribution

Beauty decay electrons

Background electron sources

- Dalitz & di-electron decays of neutral mesons
- Photon conversions in detector material
- Di-electron decays of quarkonia
- Semi-leptonic decays of charm hadrons

A Large Ion Collider Experiment (ALICE)

Inner Tracking System(ITS)

- **Track reconstruction**
- **Vertex determination**

Time Projection Chamber (TPC)

- **Track reconstruction**
- **Particle identification (PID) via specific energy loss d*E*/dx**

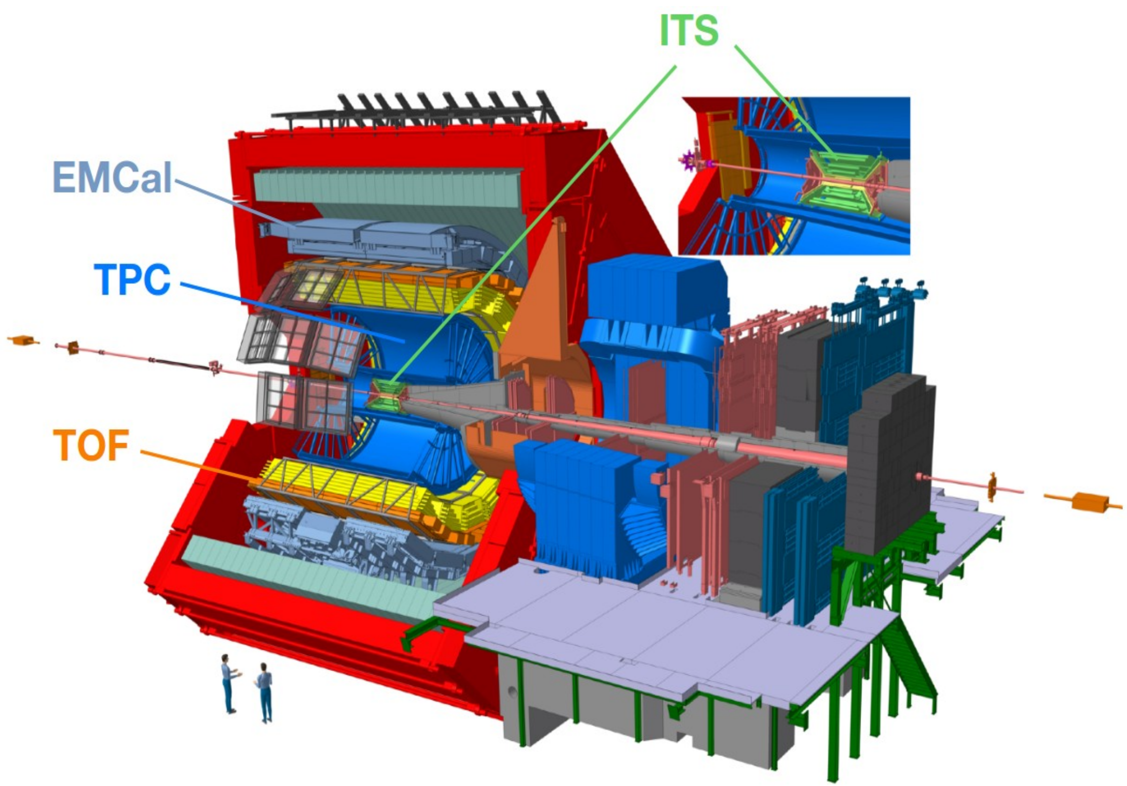
Time-of-Flight (TOF) detector

- **PID via time of flight**

Electro Magnetic Calorimeter(EMCal)

- **Trigger**
- **PID via energy deposited in the EMCal per track momentum, E/*p***

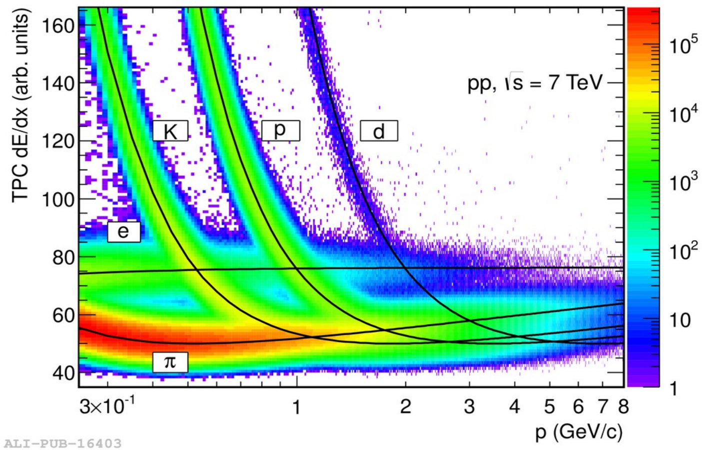
Central barrel coverage : $|\eta| < 0.9$



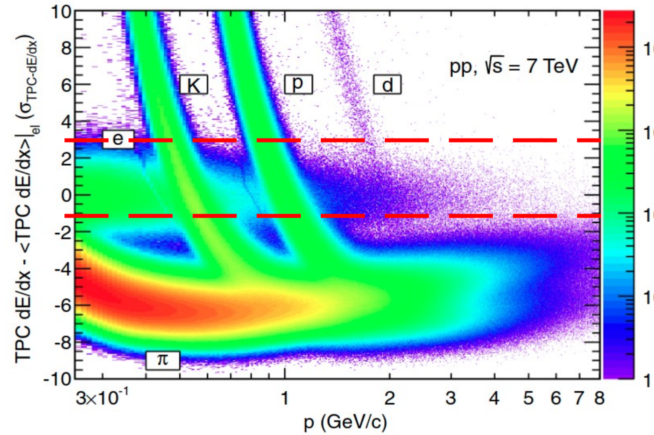
V0 Detector

- **Triggering and multiplicity measurement**

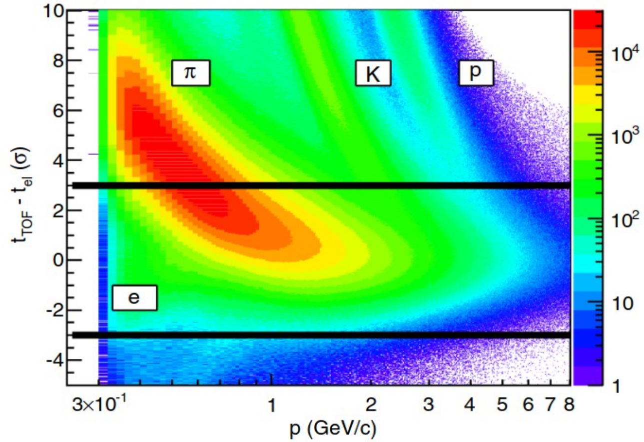
Electron identification in TPC, TOF and EMCal



TPC dE/dx



TPC $n_{\sigma,e}$



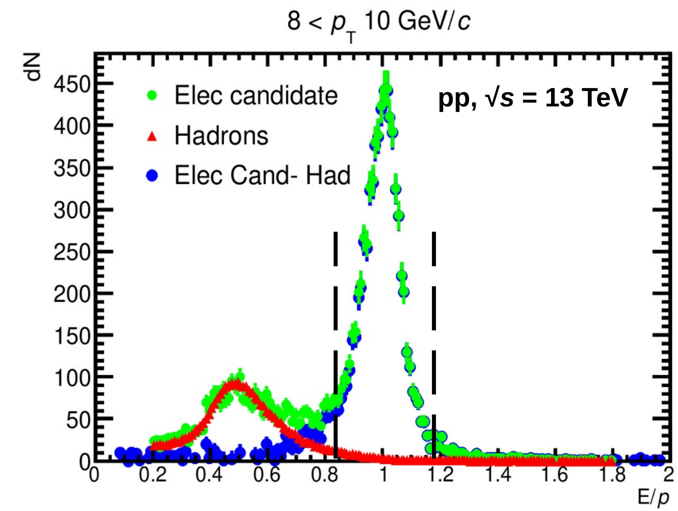
Phys. Rev. D 86, 112007

TOF $n_{\sigma,e}$

- **Electron identification using TPC + TOF at low p_T**
  - TPC : $-1 < n_{\sigma,e} < 3$
  - TOF : $-3 < n_{\sigma,e} < 3$

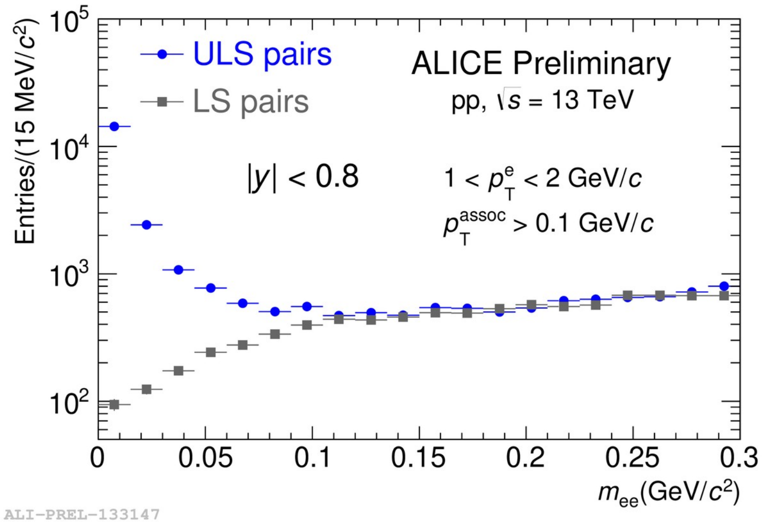
$$n_{\sigma,e} = \frac{(\mathrm{d}E/\mathrm{dx})_{\mathrm{measured}} - (\mathrm{d}E/\mathrm{dx})_{\mathrm{expected}}}{\sigma}$$

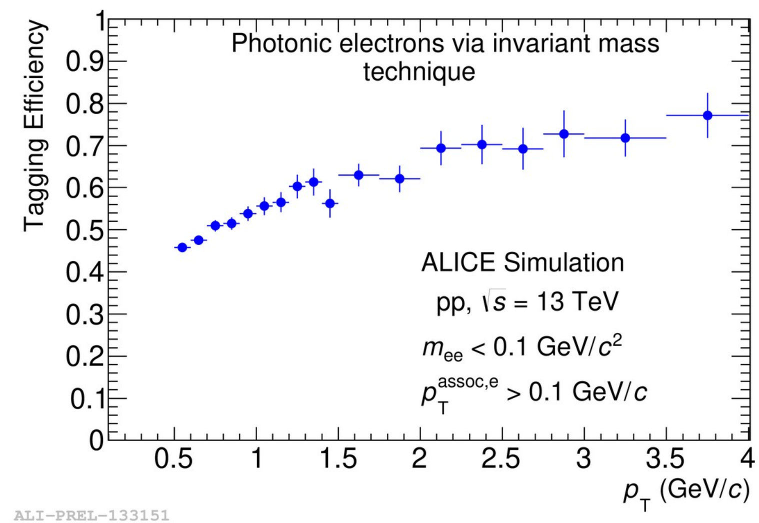
- **Electron identification using TPC + EMCal at high p_T**
  - Energy deposited in the EMCal per track momentum
  - **$0.85 < E/p < 1.2$**
  - Hadrons are selected with **$n_{\sigma,e} < -4$** and scaled based on E/p distribution to estimate hadron contamination
  - Cut on the long-axis of the particle shower



arXiv:2209.04216v1

Photonic electron estimation (Non-HFe)





- Majority of the non-HF electron background is from photonic electron sources
  - **Dalitz decay of light neutral mesons π^0 and η**
  - **Photon conversion : most γ from π^0 convert into the detector material $\gamma \rightarrow e^- e^+$**

- Unlike-Sign Pairs (N_{ULS}) [(e^-, e^+)] → Correlated pairs (from actual decay) + Uncorrelated pairs

- Like-Sign Pairs(N_{LS}) [(e^-, e^-),(e^+, e^+)] → Uncorrelated pairs

$$N_{photonic} = \frac{N_{ULS} - N_{LS}}{\epsilon_{tagg}}$$

$$\epsilon_{tagg} = \frac{N^{found}_{pairs from same mother}}{N_{photonic}}$$

Non-HFe tagging efficiency estimated using MC simulations

Electrons from beauty-hadron decays

- **The distance of closest approach in the transverse plane of reconstructed track to primary vertex is called the impact parameter d_0**

- **Beauty hadrons have a longer lifetime than other electron sources**
  - large decay length → wider d_0 distribution
  - beauty : cτ ~ 500 μm   charm : cτ ~ 60-300 μm

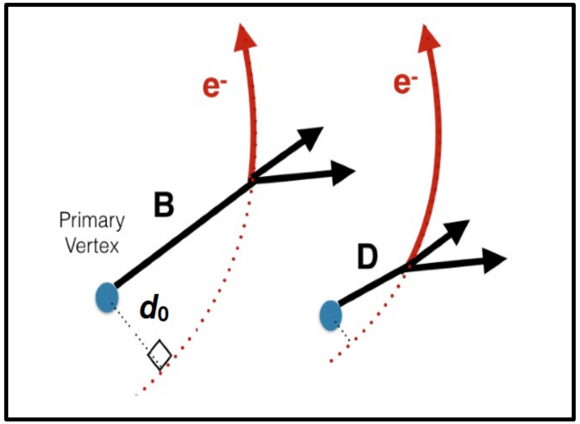
- **d_0 templates produced with Monte Carlo simulations and corrected to include realistic hadron fractions, p_T shapes and detector effects**

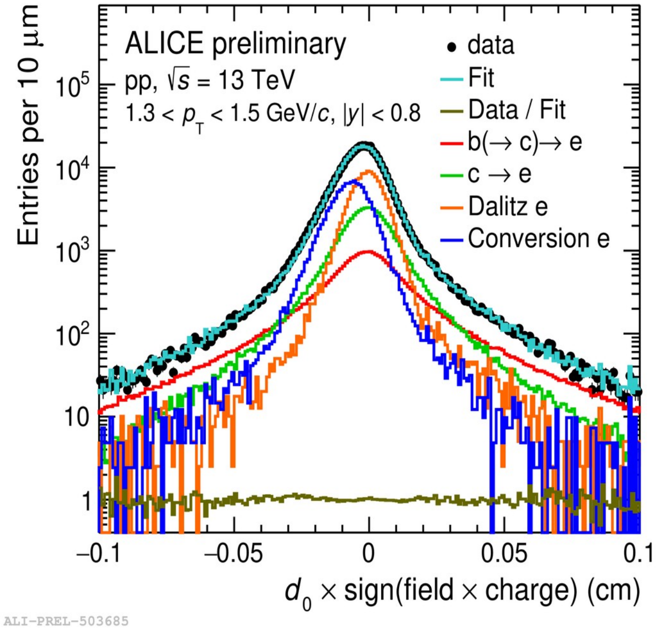
- **Stochastic extraction of raw yield using the impact parameter fit with maximum likelihood approach** *Comp. Phys. Comm. 77, 2 (1993) 219-228*

- $\textit{Fit} = p_0\, d_0^{\mathrm{b\to(c\to)e}} + p_1\, d_0^{\mathrm{c\to e}} + p_2\, d_0^{\mathrm{Dalitz\ e}} + p_3\, d_0^{\mathrm{Conversion\ e}}$

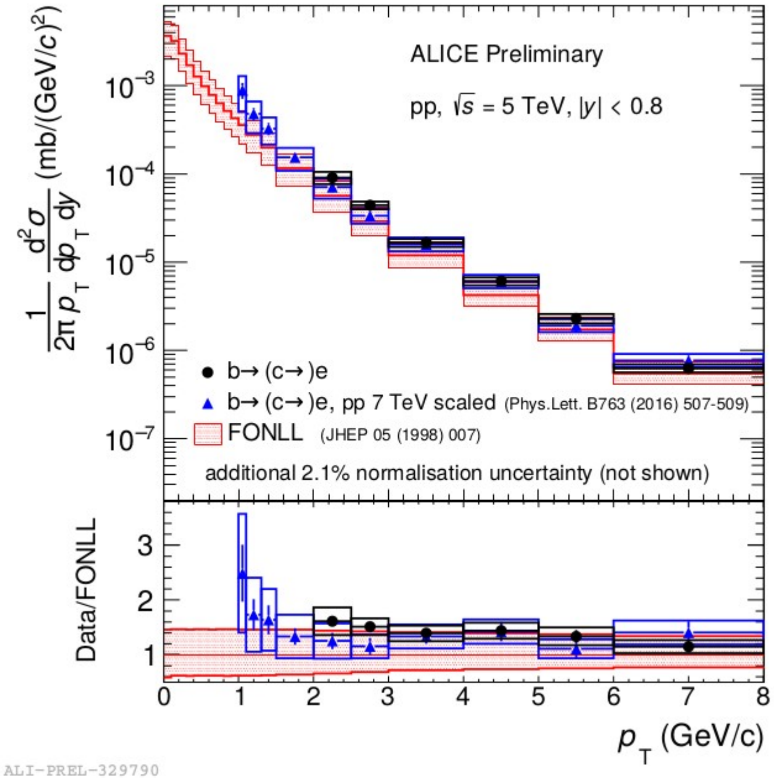
- **The amplitudes p_0, p_1, p_2 and p_3 are free parameters**

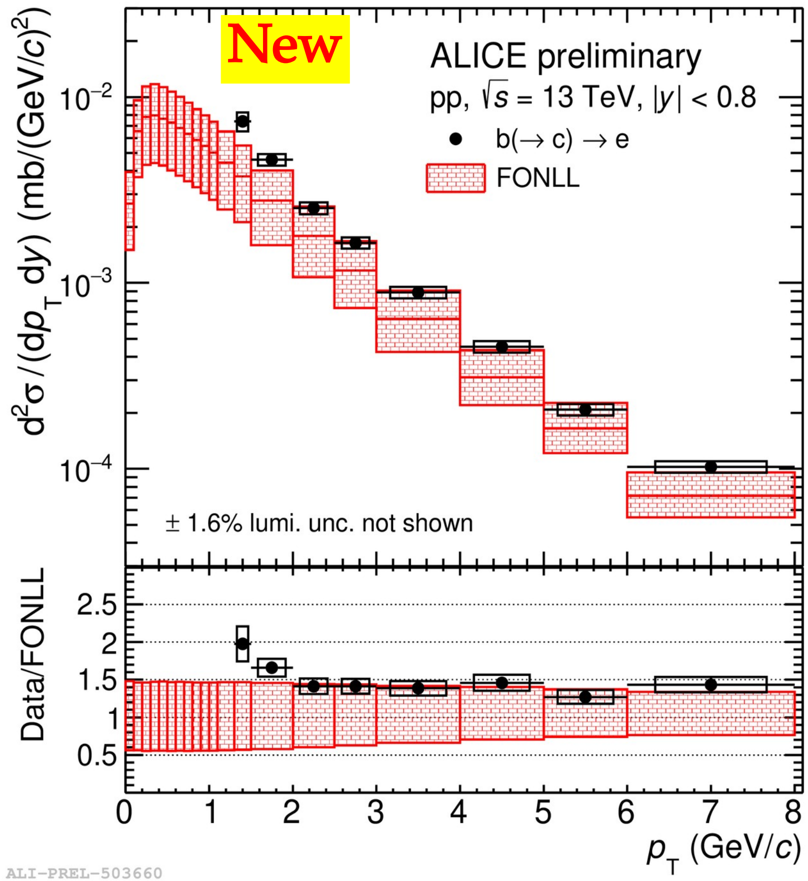
- **The fit takes into account the statistical fluctuations in data and the templates**





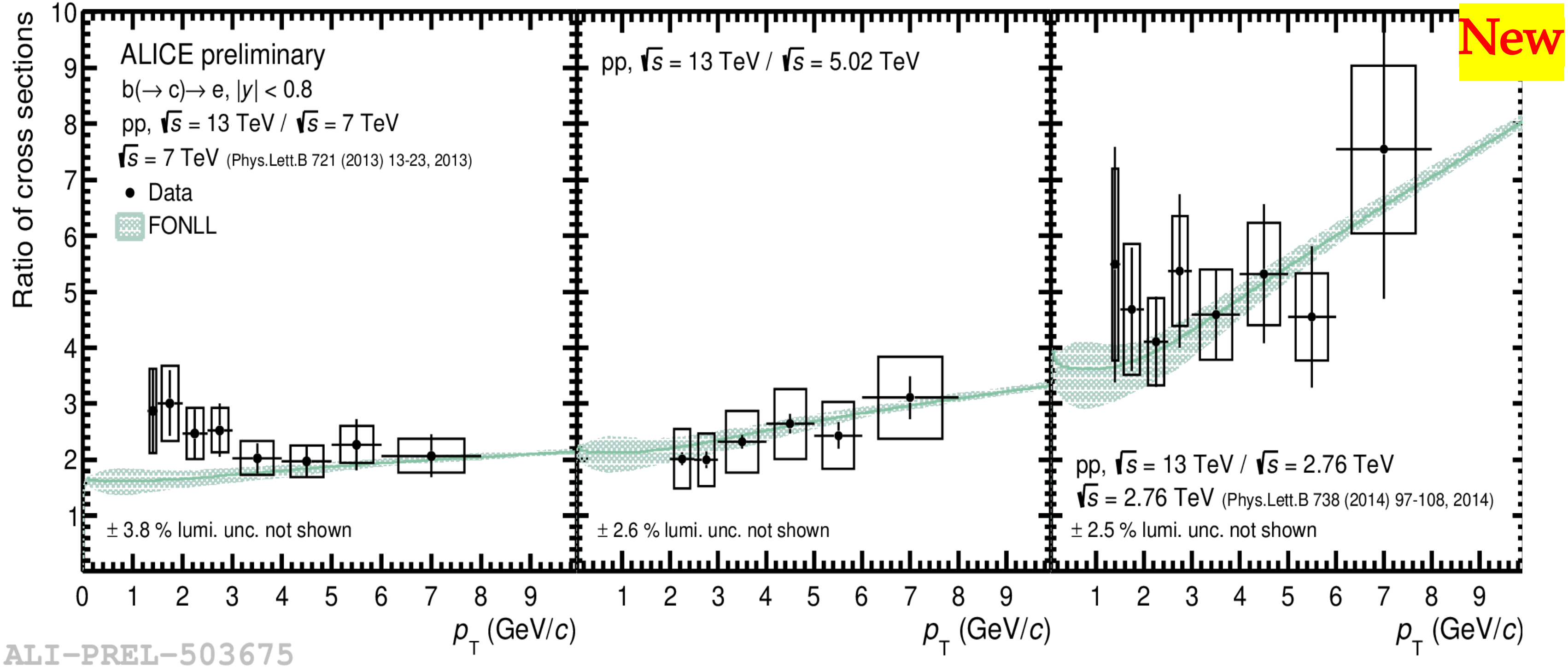
b → e cross sections in pp collisions





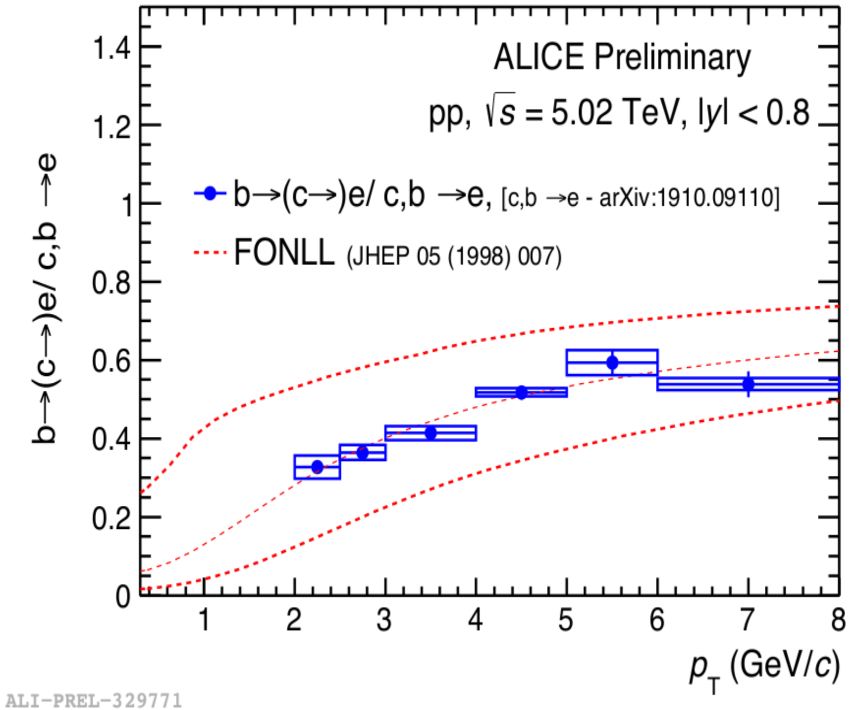
- **Production cross section compared with FONLL**
  - **5 TeV :** lying on the upper edge of the FONLL
  - **13 TeV :** compatible within FONLL uncertainties p_T > 2 GeV/c
  - Smaller uncertainty than FONLL
    - FONLL uncertainties dominated by factorization and renormalization scales
- **Data can constraint the pQCD models**

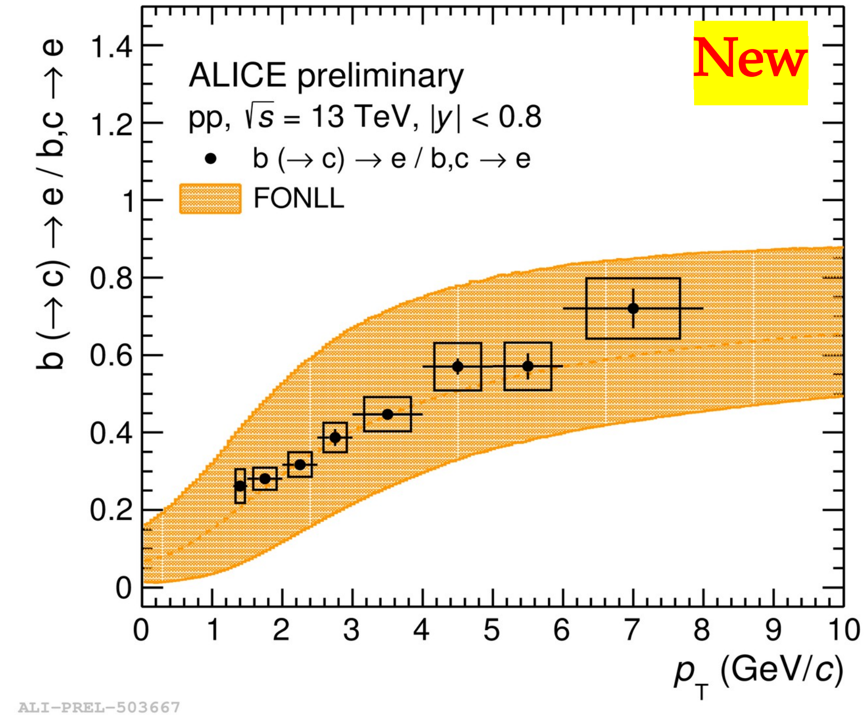
Cross section ratios between different energies



- **Production cross section ratios in pp**
  - Agreement with FONLL within uncertainties
  - Correlated FONLL uncertainties are canceled out
  - Precise measurements at different energies can provide further constraints

Beauty production rate in pp collisions





- **Fraction of beauty-decay electrons to heavy-flavour decay electrons**
  - Measured data in agreement with FONLL
  - Beauty contribution is dominant with increasing p_T

Summary & Outlook

Summary

- **Production cross sections of beauty-decay electrons are described by FONLL**
  - **Smaller uncertainties w.r.t model calculations**
  - **Data can constrain the pQCD models**

- **The ratio of production cross sections at different energies are in agreement with pQCD calculations**

- **The comparison of beauty-decay electron to heavy-flavour decay electron cross sections shows that beauty contribution is dominant at high p_T**

Outlook

- **Extend the pp 13 TeV measurement to high p_T (~ 35 GeV/c) with EMCal detector**
  [work in progress]

Thanks for attention

Backup

Additional Slides

Production time scale

$\tau_{HF} \approx 0.05 - 0.1$ fm/c

$\tau_{QGP\ form}$ (LHC) ≈ 0.3 fm/c

Ref: Fu-Ming Liu and Sheng-Xu Liu, PRC 89 (2014) 034906

QCD Scale parameter & coupling constant

$$\boxed{\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\log(Q^2/\Lambda^2)}.}$$

Ref: Halzen & Martin Sec 7.10 , Phys. 70 (2013) 159-209

Properties of selected open heavy flavour hadrons

Particle	Quark content	$I(J^P)$	Mass (GeV/c^2)	Decay mode	B.R. (%)	$c\tau$ (μm)
D^+	$c\bar{d}$	$\frac{1}{2}(0^-)$	1.8696 ± 0.0002	$K^-\pi^+\pi^+$	9.13 ± 0.19	312 ± 2
				e^+ anything	16.07 ± 0.30	
				μ^+ anything	17.6 ± 3.2	
D^0	$c\bar{u}$	$\frac{1}{2}(0^-)$	1.8648 ± 0.0001	$K^-\pi^+$	3.87 ± 0.05	123 ± 1
				e^+ anything	6.49 ± 0.11	
				μ^+ anything	6.7 ± 0.6	
D_s^+	$c\bar{s}$	$0(0^-)$	1.9685 ± 0.0003	$\phi\pi^+$	4.5 ± 0.4	150 ± 2
				e^+ anything	6.5 ± 0.4	
D^{*+}	$c\bar{d}$	$\frac{1}{2}(0^-)$	2.0102 ± 0.0001	$D^0\ \pi^+$	67.7 ± 0.5	$(2.1 \pm 0.5) \times 10^{-6}$
Λ_c	udc	$0(\frac{1}{2}^+)$	2.2865 ± 0.0001	$pK^-\pi^+$	5.0 ± 1.3	60 ± 2
B^+	$u\bar{b}$	$\frac{1}{2}(0^-)$	5.2792 ± 0.0003	$J/\psi K^+$	0.1013 ± 0.0034	492 ± 2
				$l^+\nu_l$ anything	10.99 ± 0.28	
B^0	$d\bar{b}$	$\frac{1}{2}(0^-)$	5.2795 ± 0.0003	$J/\psi K_S^0$	0.0436 ± 0.0016	455 ± 2
				$l^+\nu_l$ anything	10.33 ± 0.28	
B_s^0	$s\bar{b}$	$0(0^-)$	5.3663 ± 0.0006	$J/\psi\phi$	0.14 ± 0.05	441 ± 8
b hadrons				J/ψ anything	1.16 ± 0.10	

FONLL

- At leading order (LO), the only processes contributing to heavy-flavor production are gluon fusion and quark anti-quark annihilation.

- At next-to-leading order (NLO) processes such as gluon splitting or flavor excitation have to be considered in addition.

State of the art perturbative calculations of heavy-flavor production go even further in the sense that they calculate cross sections at fixed order with a next-to-leading-log resummation of higher orders in α_s .

Heavy flavour decay modes

- Due to short life time ($t \sim 10^{-12}$ s) of D, B mesons, they decay before reaching the detector, hence they have to be studied from their decay products.

Hadronic modes

- Full reconstruction of heavy-flavour hadrons via hadronic decay channels
- Invariant-mass analysis is done to obtain the raw yield

$$D^0 \to K^+ \pi^- \text{ , } D^+ \to K^- \pi^+ \pi^+$$

$$\Lambda_c^+ \to p\, K^- \pi^+ \text{ , } \Lambda_c^+ \to p\, \pi^+ \pi^-$$

$$D_s^+ \to \pi^+ \varphi \to \pi^+ K^- K^+ \text{ , } \Sigma_c^{0,++} \to \Lambda_c^+ \pi^{-,+}$$

$$\Xi_c^0 \to \Xi^- \pi^+ \text{ , } \Xi_c^+ \to \Xi^- \pi^+ \pi^+ \text{ , } \Omega_c^0 \to \Omega^- \pi^+$$

Semi-leptonic modes

- Substantial branching ratio : ~ 10%
- High-p_T leptons can be exploited for defining triggers using information from the ALICE EM calorimeter

$$D, B \longrightarrow \ell(e,\mu)\, \nu_\ell\, X$$

Reference : P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020), arXiv:2209.04216v1

Sources of non-heavy flavour electrons

Dominant source of background electrons

- **Photonic electrons :** $\pi^0 \rightarrow e^- e^+ \gamma$, $\pi^0 \rightarrow \gamma\gamma$, $\gamma \rightarrow e^- e^+$
  - Electrons from decay of light neutral mesons (π^0, η) and γ conversion
  - Subtracted from inclusive electron sample using photonic electron subtraction method

- **Electrons from $W^{\pm}$ and Z^0 boson decay :** $W^{\pm} \rightarrow e^- \nu_e^{(-)}$ and $Z^0 \rightarrow e^- e^+$
  - Significant at high p_T ($p_T \geq 20$)
  - Calculated with the POWHEG event generator and subtracted from the fully corrected cross section.

Negligible contributions

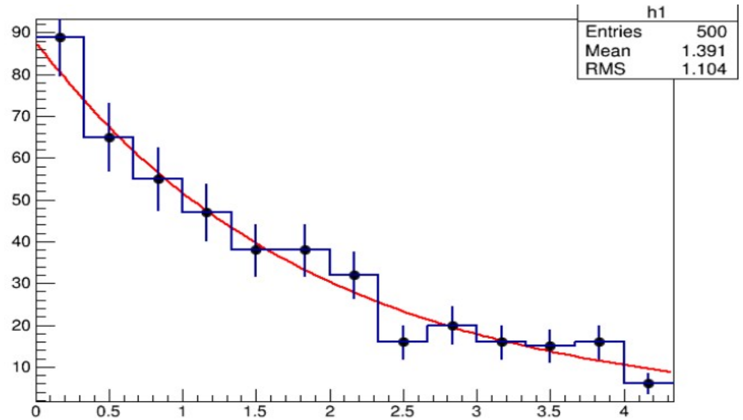
- **Di-electron decays of light vector mesons** (ρ, φ, ω) *JHEP 10 (2018) 061*

- **Di-electron decays of quarkonia** $(J/\psi, \Upsilon)$ *PLB 754 (2016) 81-93* , *JHEP 10 (2018) 061*

- **Electrons from weak decays of $K^{0/\pm}$** : $K^0 \rightarrow \pi^{\pm} e^{\mp} \nu_e^{(-)}$ $K^{\pm} \rightarrow \pi^{\pm} e^{\pm} \nu_e^{(-)}$ ($K^{\pm}_{e3}$ **decay**)
  PLB 754 (2016) 81-93 , *JHEP 10 (2018) 061*

Maximum likelihood and Least Square Fit methods

Maximum Likelihood Fit



- The parameters are estimated by finding the maximum of the likelihood function.

- Likelihood : $L = {}_i\Pi^N P_i(n_i / f_i)$
  n_i : observed counts in the i^{th} bin
  f_i : value of the fit function at i^{th} bin (expected counts)

- The Likelihood for a histogram is obtained by assuming a Poisson distribution in every bin.

- The probability of a particle landing in i^{th} bin can be written as $p_i = f_i^{n_i} exp(-f_i) / n_i!$.

- The total probabilities for all bins will be product of probabilities of the individual bins which is nothing but L.

- To maximize L we take log of likelihood i.e $log(L) = {}_i\Sigma^N n_i log(f_i) - f_i$

- Function f has the parameters say $\alpha_1, \alpha_2, \ldots, \alpha_n$ and root checks for what combinations of these α's the log of the likelihood is maximum. That is what a log-likelihood fit does.

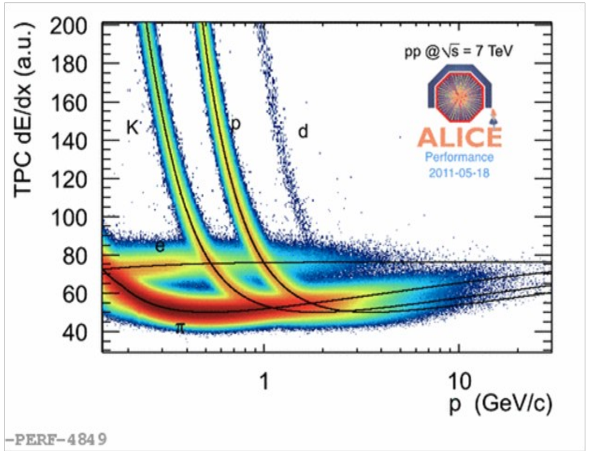
Least Square Fit

- if we start with bins having Gaussian distribution i.e $p_i = C exp(n_i - f_i)^2 / 2\sigma_i^2$ instead of Poisson then we will end up with $log(L) = {}_i\Sigma^N (n_i - f_i)^2 / \sigma_i^2 = \chi^2$, a default root fit option.

The Bethe-Bloch Equation

- Describes the average energy loss of charged particles when travelling through matter.

$$-\frac{dE}{dx} = \frac{4\pi e^4}{m_0}\frac{z^2}{v^2}NZ\left\{ ln\left(\frac{2m_0v^2\gamma^2}{I}\right) - \beta^2 - \delta^2 - \frac{2C}{Z}\right\}$$



z = Charge of primary particle   v = Velocity of charged particle

N = Number density of absorber   Z = Atomic Number of absorber

m_0 = Rest mass of electron $\beta = v/c, \gamma = 1/(1-\beta)$

δ =Density Correction factor   C=Shell Correction factor

- $n\sigma^{TPC} = (dE/dx)_{theo} - (dE/dx)_{measured}$ in terms of σ_{det} (TPC dE/dx resolution)

- TPC space point resolution : rφ = 300 μm.

- TPC Momentum resolution : ~ 10% @ 50 GeV/c.

- dE/dx resolution : 5.5 @ low multiplicity and 8.6 @ high multiplicity.

- dE/dx only depends on β and independent of m

- $\langle dE/dx\rangle_{measured} = \langle dE/dx\rangle_{collisional} + \langle dE/dx\rangle_{radiative}$ (at few MeV rad > coll. loss)