Measurement of Beauty-Hadron Decay Electrons in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE

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for the ALICE Collaboration

Hot Quarks 2014

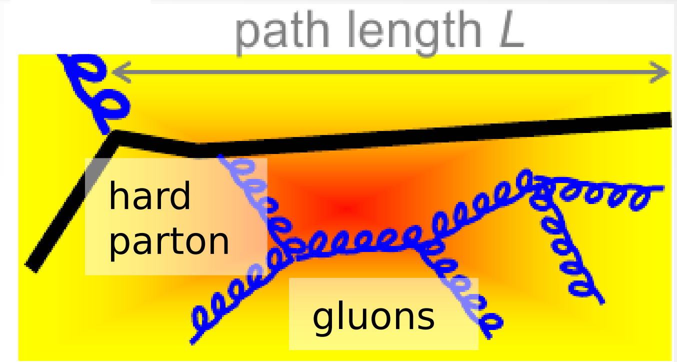
Heavy Quarks in Heavy-Ion Collisions

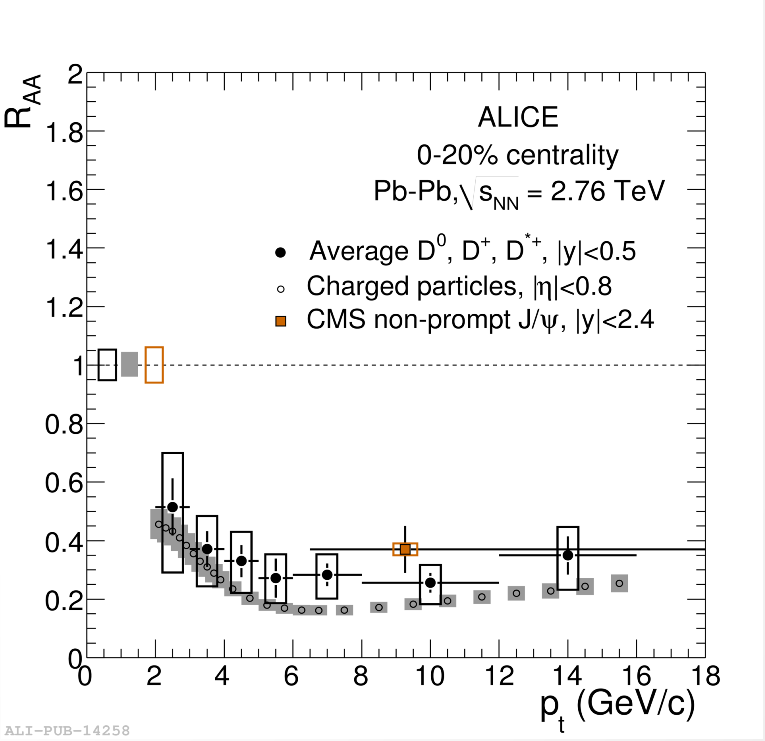
- Heavy Quarks: hard probes
- Creation in initial hard scatterings, calculable with pQCD in pp collisions
- Study in-medium energy loss and collective effects in Pb-Pb collisions
- Expected energy-loss hierarchy

$$\Delta E_b < \Delta E_c < \Delta E_{u,d,s} < \Delta E_{gluon}$$

- In-medium parton energy loss causes a modification of the momentum distribution of heavy-flavor hadrons in Pb-Pb compared to pp collisions
  - Experimental observable: nuclear modification factor - compare change in spectrum from pp to Pb-Pb collisions with a binary-scaling hypothesis:

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{d\sigma_{AA}/dp_T}{d\sigma_{pp}/dp_T} = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

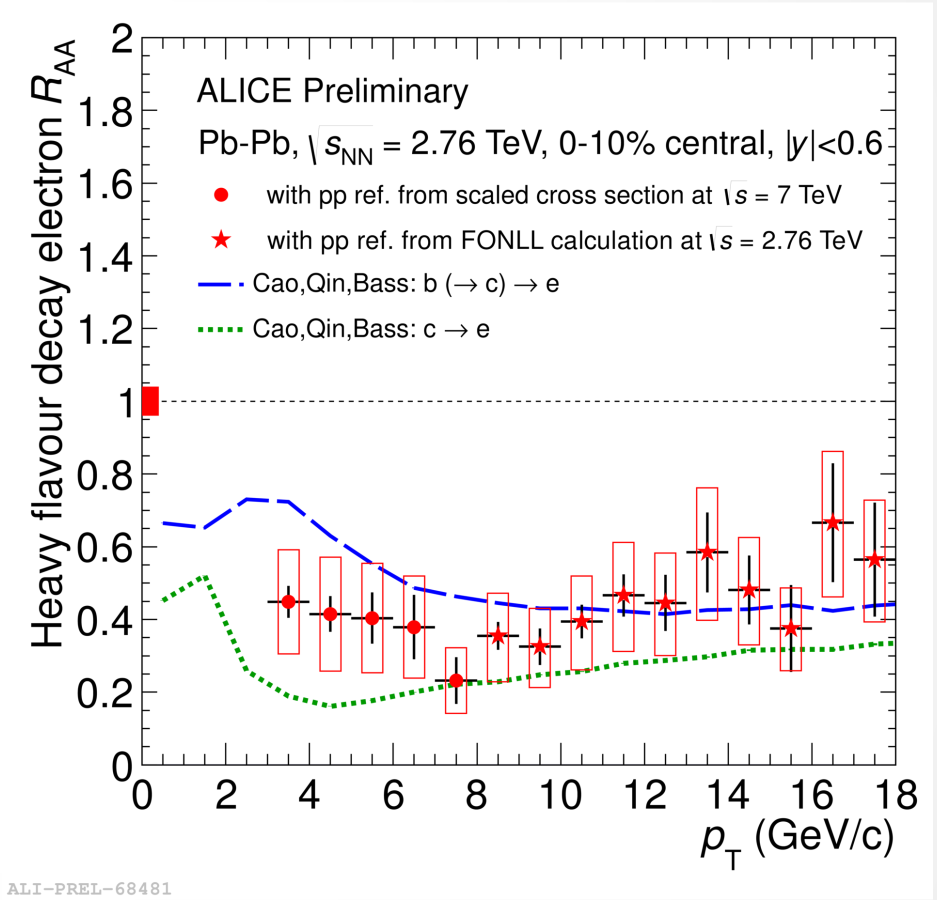




ALICE Collaboration, JHEP 09 (2012) 112
DOI: 10.1007/JHEP09(2012)112

Heavy Flavors in the Electron Channel

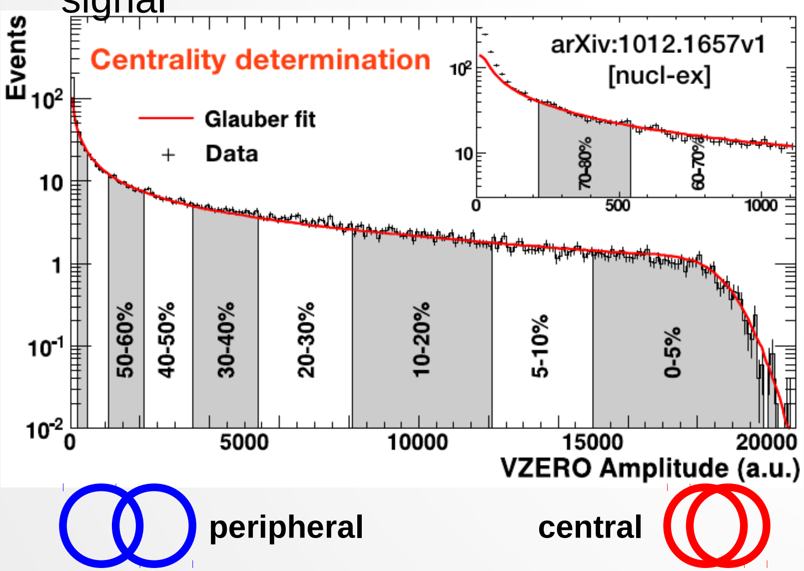
- Charm hadrons reconstructed via hadronic decay channels
- Need measurement for beauty
- Heavy flavor (charm+beauty) measured in the semi-electronic decay channel
  - B.R. of open heavy-flavor hadrons to electrons (B → e + X, D → e + X) ≈10%
- Disentangle beauty and charm contributions in the heavy-flavor electron yield from inclusive measurement → does the expected ordering of the energy loss appear in the R_{AA}?

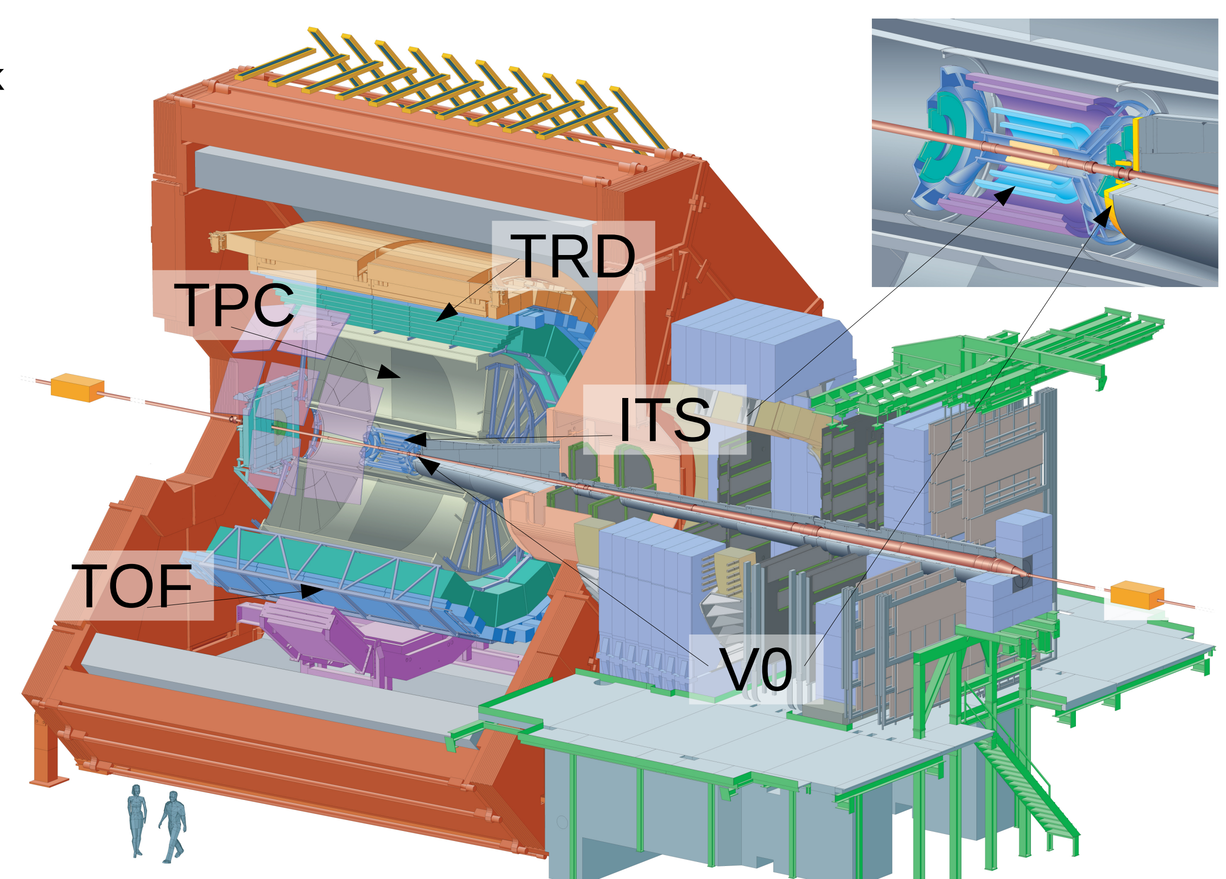


The ALICE-Experiment

- **I**nner **T**racking **S**ystem: Tracking and reconstruction of primary vertex and track impact parameter (resolution better than $50\mu m$ for $p_T > 1.5 GeV/c$)
- **T**ime **P**rojection **C**hamber: Tracking and particle identification via dE/dx
- **T**ime **O**f **F**light Detector: Particle identification
- **V0**: Multiplicity estimation, triggering

Centrality classes based on V0 detector signal



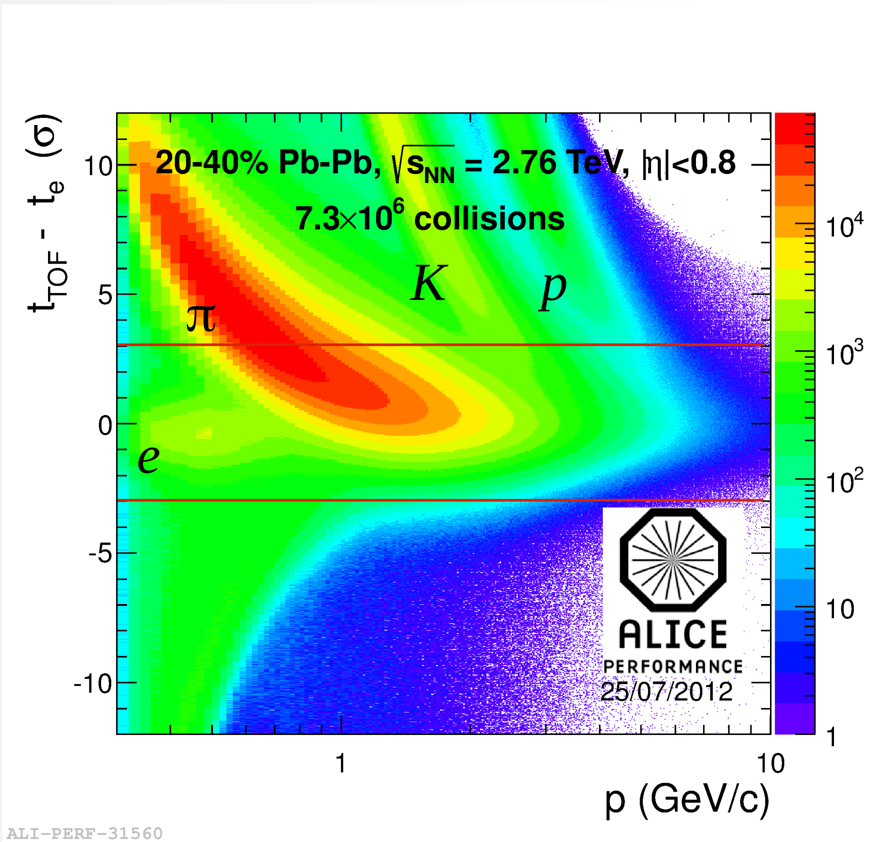


Min. Bias

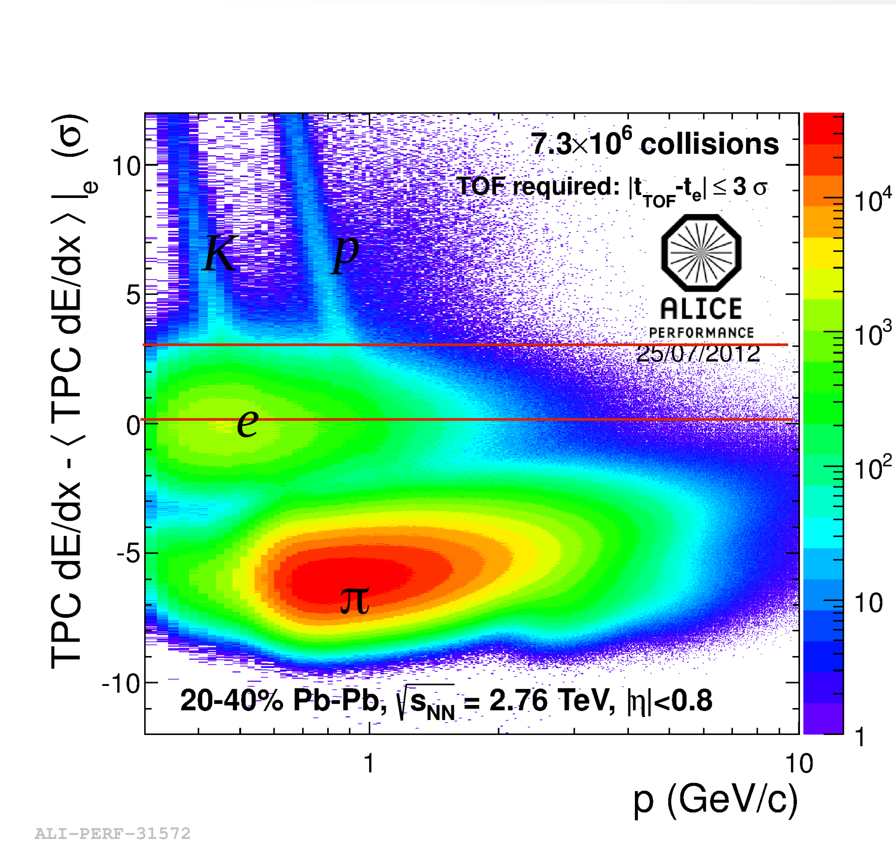
System $\sqrt{s_{NN}}$ (TeV)	pp 7	Pb-Pb 2.76
Time	Apr-Aug 2010	Nov 2010
Events	180 M	17 M

Electron Identification

TOF



TPC



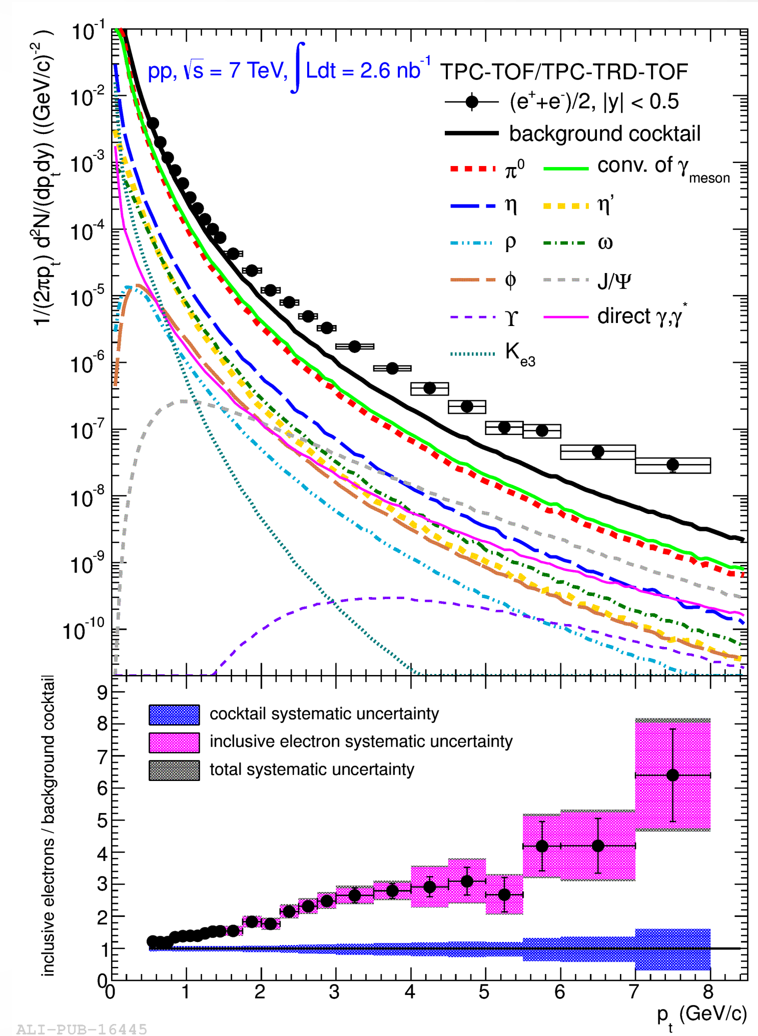
3σ cut on TOF signal

$0<n_\sigma<3$ cut on TPC signal

- Remaining hadron contamination negligible

Background Electron Sources

- Electron candidates from heavy-flavor + background sources
- Largest background from
  - $\pi^0 \rightarrow e^+ e^- \gamma$
  - $\pi^0 \rightarrow \gamma\gamma, \quad \gamma \rightarrow e^+ e^-$
- Independent measurements exist for some of the background sources
- Cocktail approach: Calculate expected yield of background electrons from these measurements and subtract from inclusive electron yield
- Large uncertainties on heavy-flavor yield at low p_T due to low signal-to-background ratio
- Even larger uncertainties in the extraction of the beauty contribution after subtracting the charm-decay electron yield based on the measured D-meson cross section
  - more information needed for improvement



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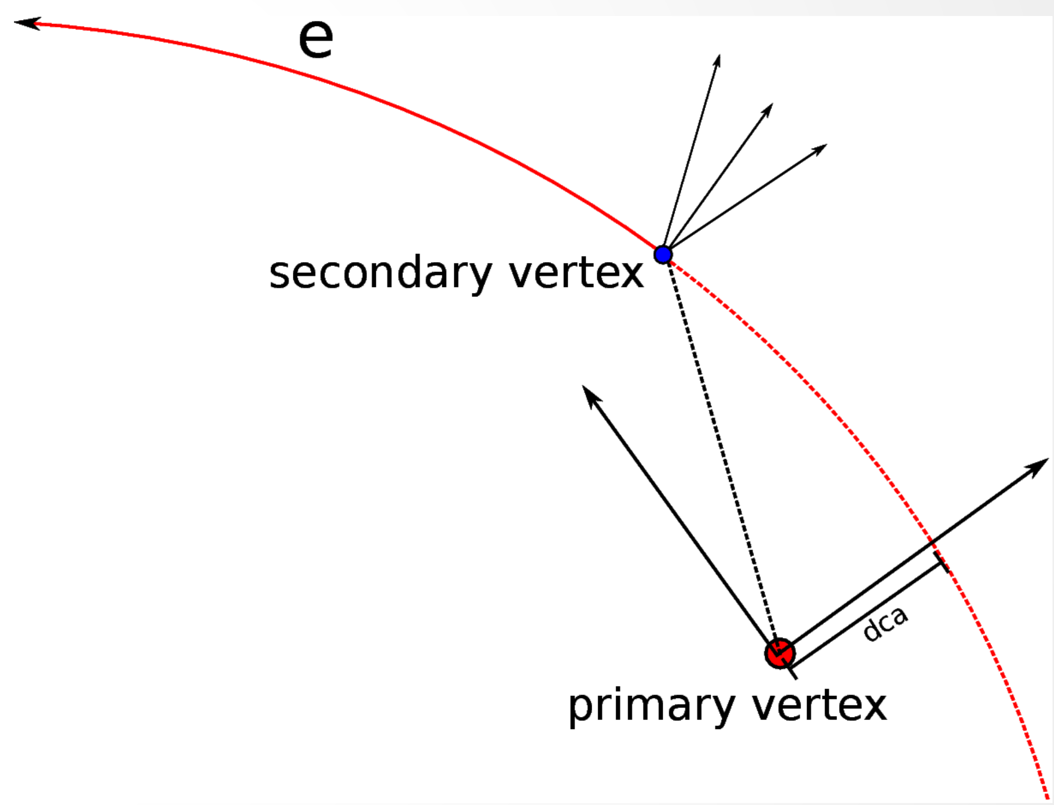
DOI: http://dx.doi.org/10.1103/PhysRevD.86.112007

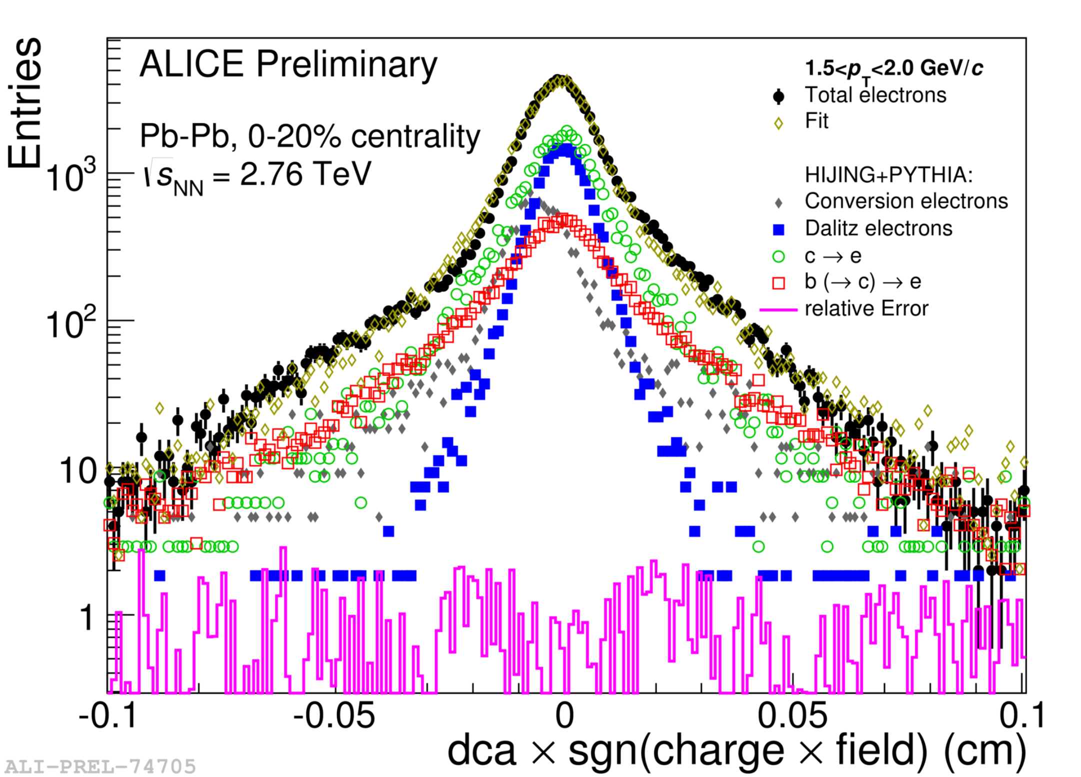
The Impact Parameter

- Idea: beauty-hadron decay length ($c\tau \approx 500 \mu m$) larger than for most background sources
- No determination of decay vertex from single electron track – use impact parameter as proxy for decay length:
  - Impact parameter: Distance of closest approach of reconstructed track to primary vertex
  - Projection of impact parameter on transverse plane used in the analysis
  - Positive or negative sign depending on position (left or right) relative to the interaction vertex
- Value depends on decay vertex displacement, direction of daughter and magnetic field
- Use as additional information for separation of electrons from beauty-hadron decays
- Two alternative strategies: Cut on IP or fit of distributions



Impact-Parameter Distributions of Different Electron Sources

- Electrons from beauty-hadron decays
  - e.g. $B \rightarrow e + X$
  - Widest distribution due to large decay length
- Electrons from charm-hadron decays
  - e.g. $D \rightarrow e + X$
  - Narrower IP distribution due to smaller decay length ($c\tau \approx 100 - 300\,\mu m$)
- Electrons from photon conversions in the detector material
- Electrons produced very close to the primary vertex (mostly $\pi^0 \rightarrow e^+ e^- \gamma$, thus called Dalitz electrons)
  - Width of distribution represents detector resolution



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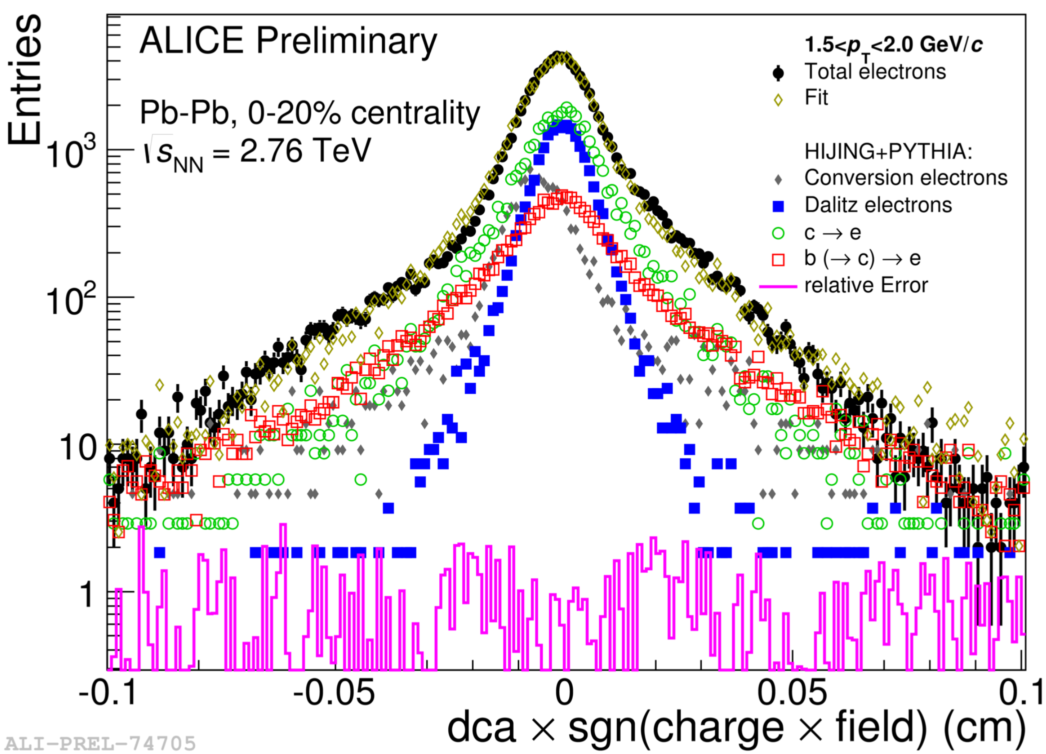

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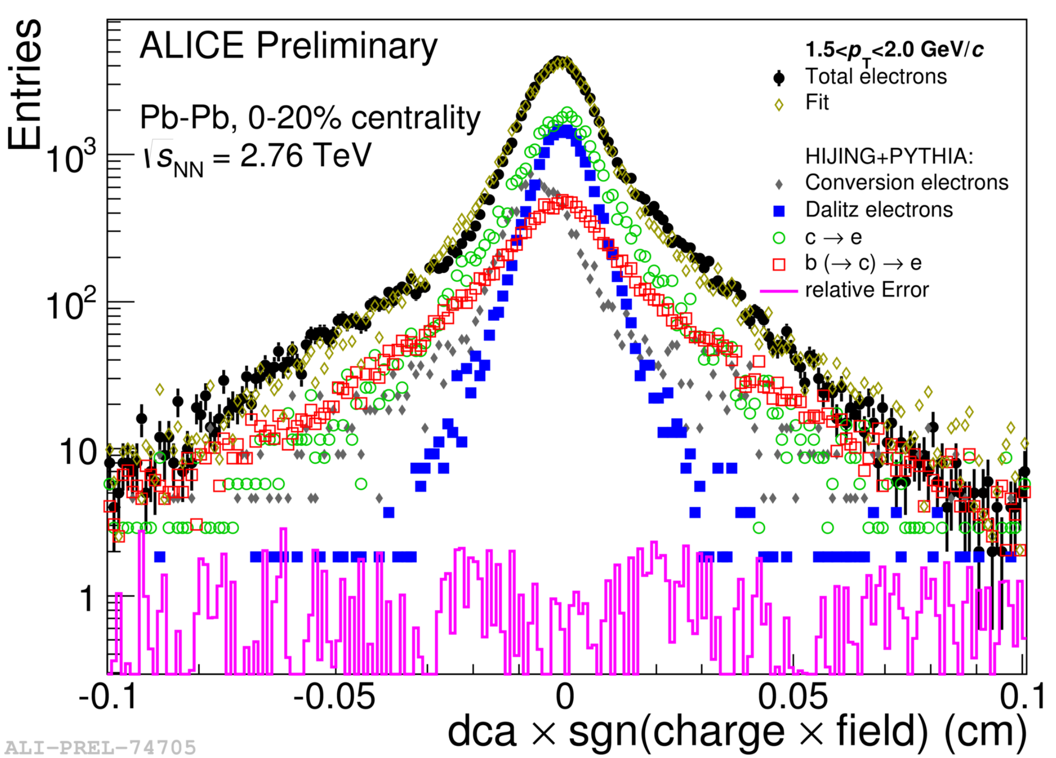
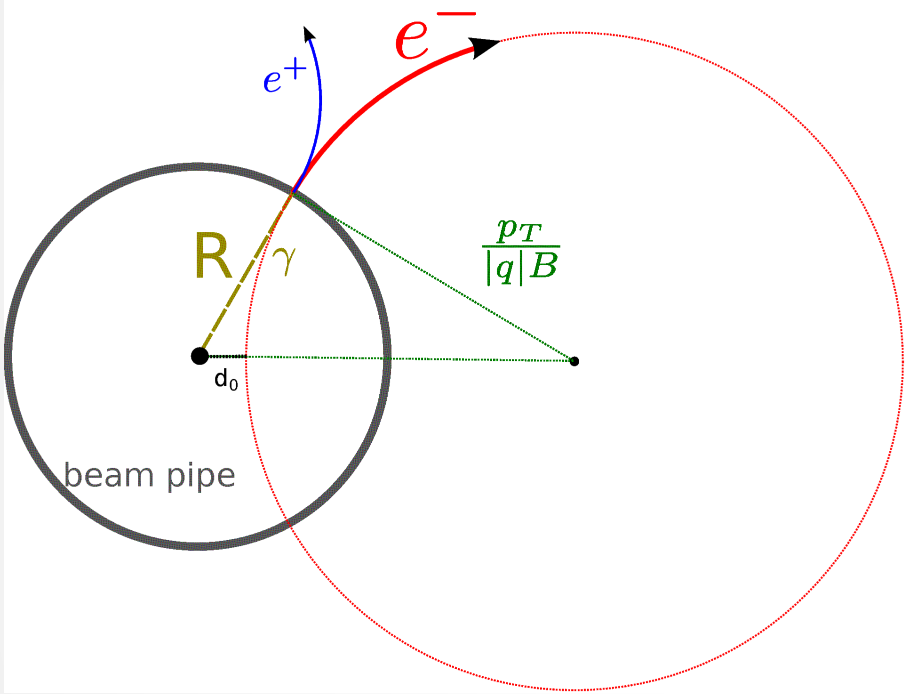
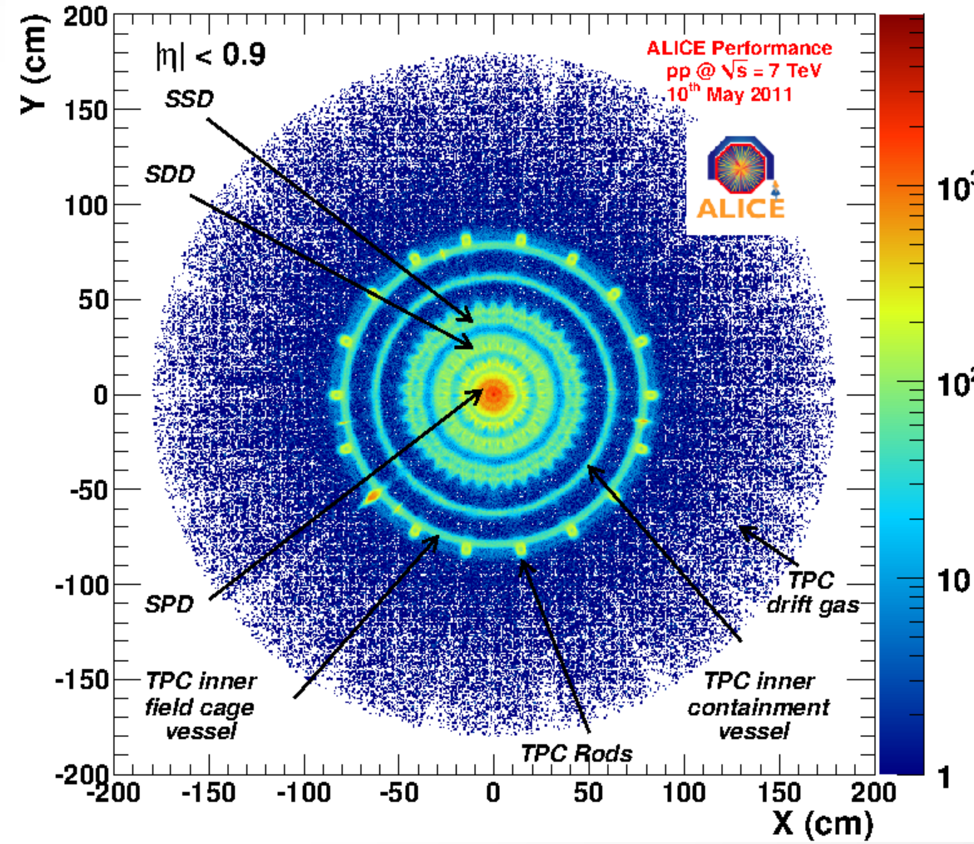


Electrons from Photon Conversions

$$d_0 \approx \frac{R^2|q|B}{2p_T}$$

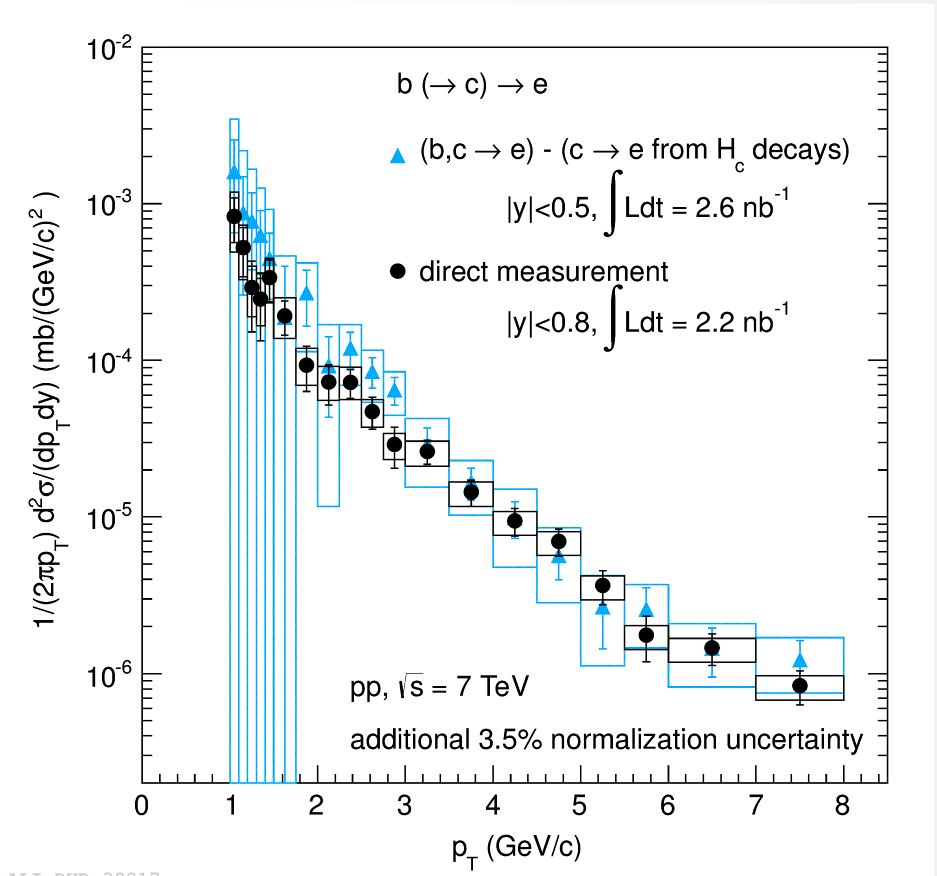




- Electrons from photon conversion have finite impact parameter only due to magnetic field
- Hits in inner layers of ITS required for optimal resolution of impact parameter
- This requirement also decreases the number of electrons from photon conversions produced in the outer layers of the detector
  - Remaining contribution reproduced well by simulations → Correctly taken into account when using simulated IP distributions

The Impact Parameter Cut Method

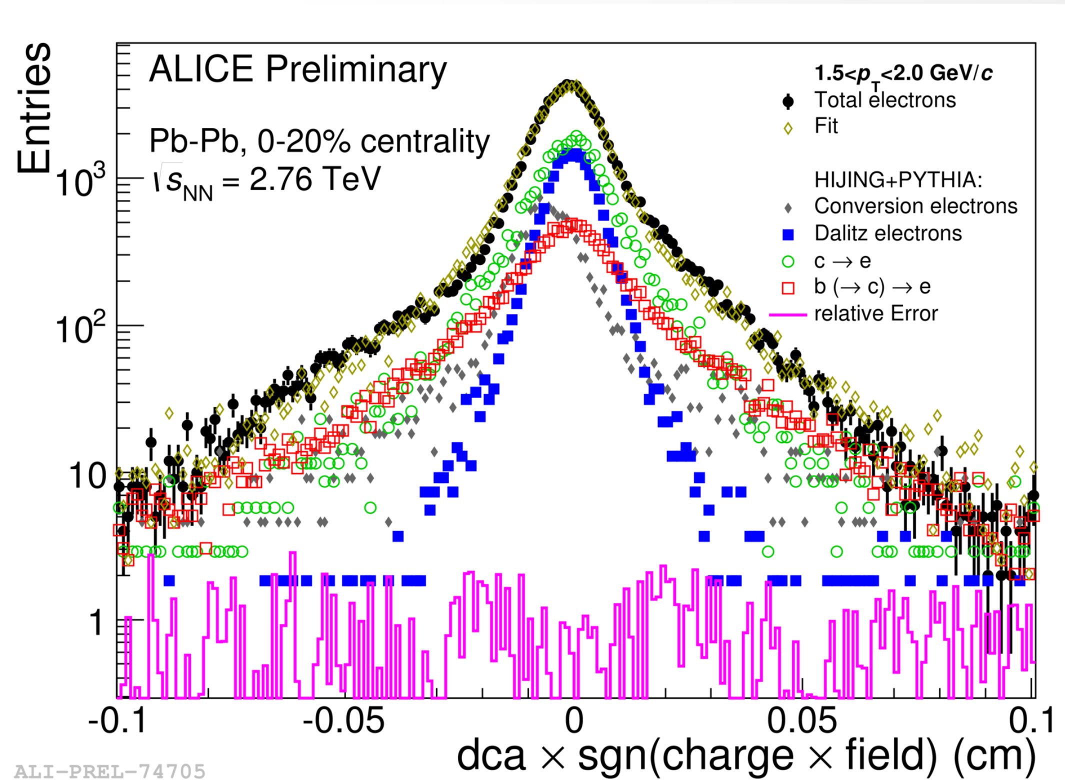
- Estimation of beauty-hadron decay electron yield difficult with cocktail method due to low signal-to-background ratio
- Impact parameter cut method: A cut on the track impact parameter increases signal-to-background due larger decay length of beauty hadrons
- Uncertainties after background subtraction reduced strongly
- Method was used to estimate the p_T-differential invariant cross section of electrons from beauty-hadron decays in pp collisions
- This was used as a reference for the R_{AA} calculation
- For R_{AA} calculation energy scaling (from $\sqrt{s}=7\,TeV$ to $\sqrt{s}=2.76\,TeV$) was done using FONLL predictions



ALICE Collaboration, PLB721(2013)13-23
http://dx.doi.org/10.1016/j.physletb.2013.01.069.

The Impact Parameter Fit Method

- No obvious analytical description of distributions → use templates from Monte Carlo simulations
- Fit likelihood has to take into account fluctuations in both the data and the templates
- Use “binned” method: impact parameter distributions given in histograms
- Perform fits within different p_T-intervals



Template Fit Likelihood

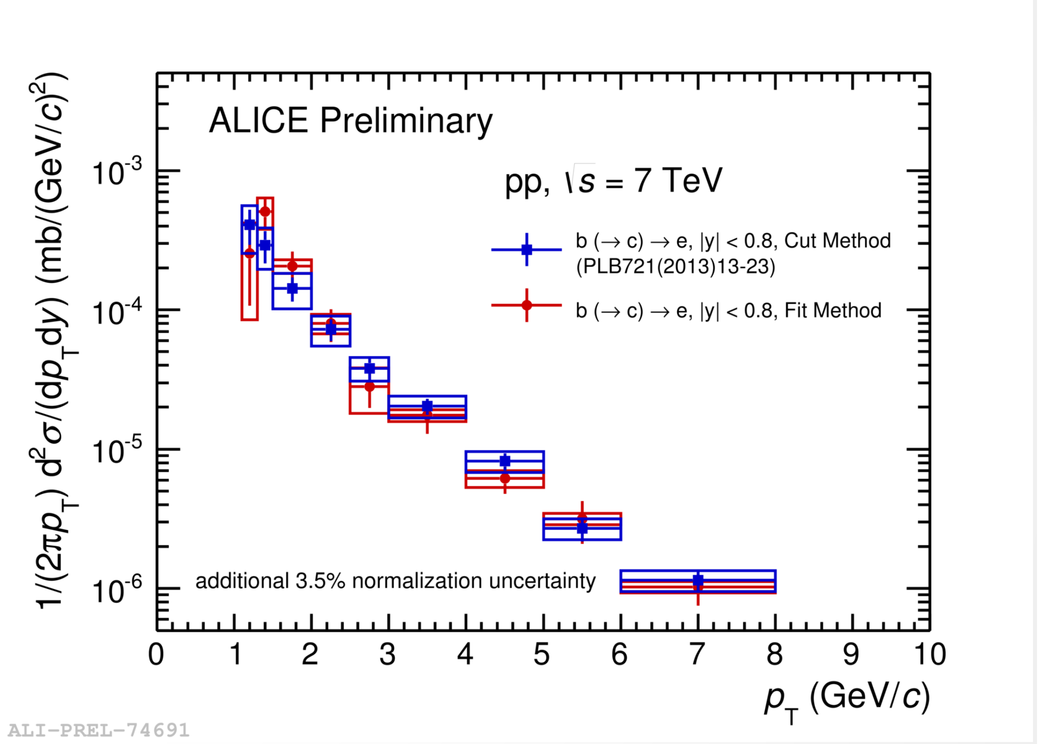
- In each impact-parameter bin, data entries and template entries fluctuate
- The underlying probability distribution is Poissonian
- Idea of template fits:
  - Expectation value of data entries unknown
  - Expectation value of template entries also unknown
  - Expectation values of template entries are free parameters of the fit
  - Expectation value of data entries is weighted sum of template expectation values
- Several hundred free parameters
- Barlow, Beeston (Computer Physics Communications 77(2):219-228, 1993) showed method for maximizing likelihood efficiently – leaves only amplitudes as free parameters
- Fit uncertainties estimated via toy model

$$\log L = \sum_{bin} data(bin) \cdot \log fit(bin) - fit(bin) + \sum_{bin} \sum_{source} N_{source}(bin) \cdot \log A_{source}(bin) - A_{source}(bin)$$

$$fit(bin) = \sum_{source} p_{source} \cdot A_{source}(bin)$$

Validation of Method in pp

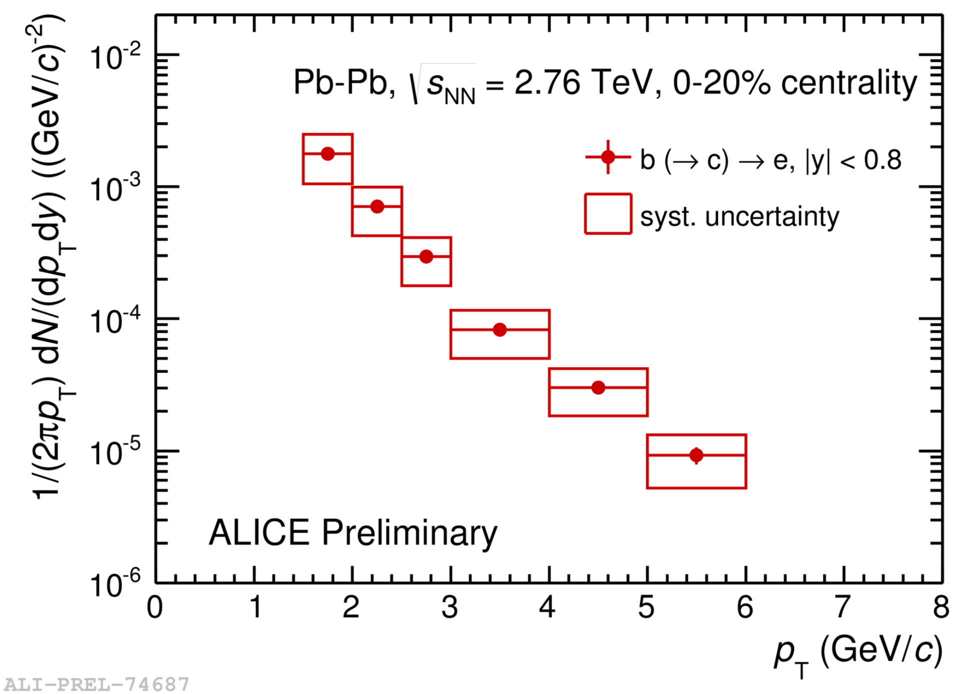
- Impact parameter cut method gives cross check for method in pp
- Methods partially correlated but use information differently
- Good agreement over measured range



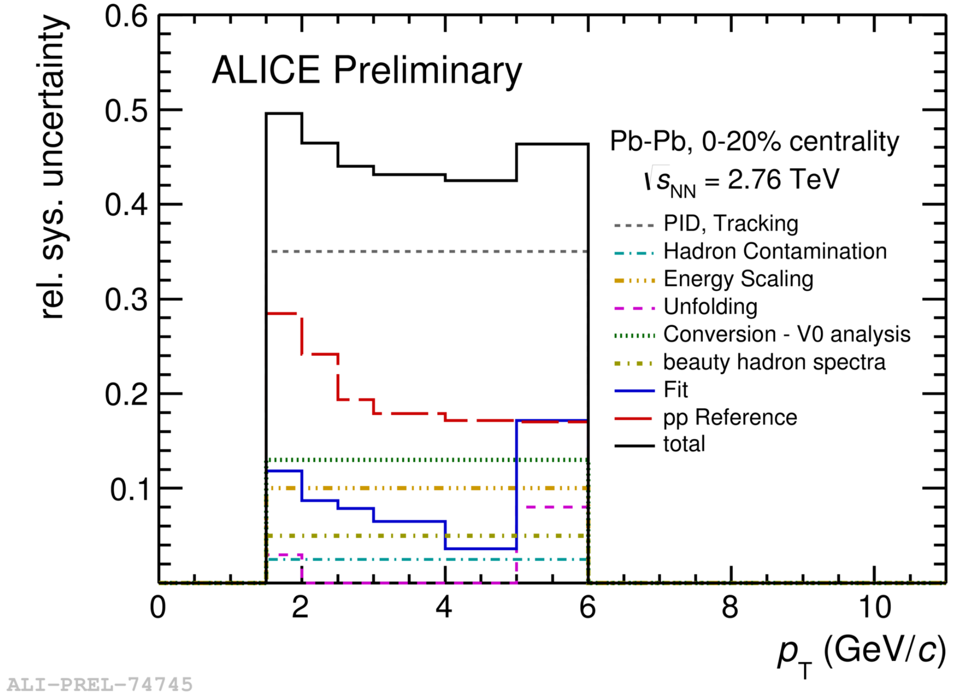
p_T-differential invariant cross section in pp collisions

Yield in Pb-Pb Collisions

Invariant Yield of Electrons from Beauty Hadron Decays in 20% Most Central Pb-Pb Collisions

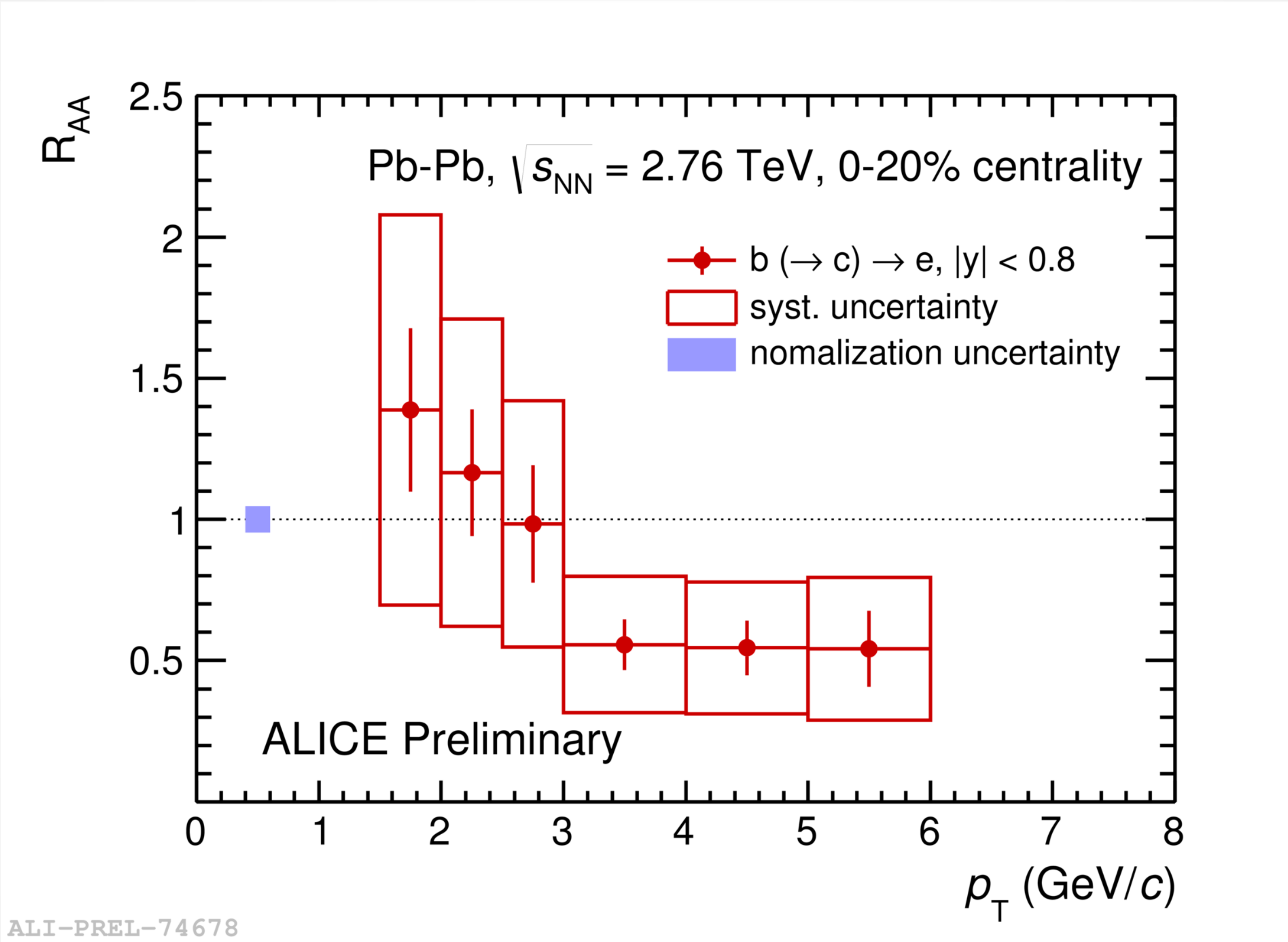


Systematic Uncertainty Contributions



- Systematics currently dominated by TPC-PID uncertainty
- Systematic uncertainties much larger than statistical uncertainties in current p_T range

R_{AA} of Electrons from Beauty-Hadron Decays in Central Pb-Pb Collisions



- Hint of suppression for $p_T > 3\,\mathrm{GeV}/c$

Summary

- First measurement of beauty-hadron decay electrons in central Pb-Pb collisions at $\sqrt{s_{NN}}=2.76\,\mathrm{TeV}$
- Method based on fit with templates from simulations
- Fit uncertainties estimated via toy model
- No background-cocktail subtraction necessary
- Hint of suppression in R_{AA} for $p_{\mathrm{T}}>3\,\mathrm{GeV}/c$

Additional Slides

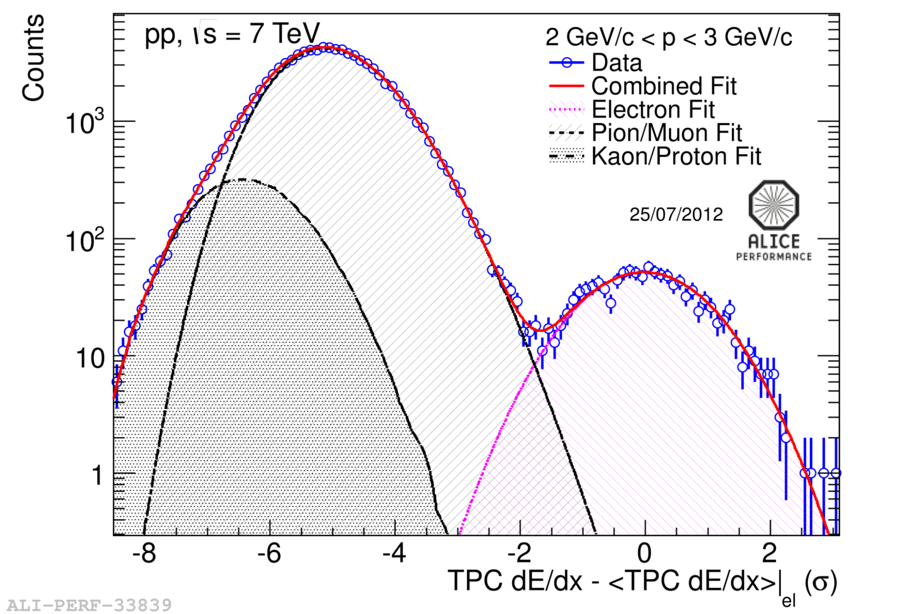
Uncertainty Estimation

- Steps:
  - By sampling create new MC templates from the old MC templates
  - Add the templates according to the assumed truth
  - Sample this sum, to create toy data (statistics as in actual measurement)
  - Apply the fit to the toy MC and data distributions
  - Compare known “true” value and measurement for this model
  - Repeat many times and look at distribution of the difference
- The width of this distribution for a given parameter (or function thereof) is the statistical error of the measurement of this parameter
- The shift in mean of the distribution relative to the “true” value is the bias of the fit in this bin and will go into the systematic error in the end
- Important point: Estimation assumes truth is similar to measured value, so it is a “first order approximation” of the error

Maximum Likelihood Fits

- Generic problem:
  - Histogram with distribution of some quantity in data d_{bin}
  - Functional description of distribution $f_{bin}(\vec{\alpha})$, but unknown parameters $\vec{\alpha}$
  - Within individual bins: Poissonian fluctuations (counts)
- Likelihood (L): Probability of data for given set of parameters interpreted as function of parameters
  - For one bin: $L_{bin} = \frac{f_{bin}(\vec{\alpha})^{d_{bin}} \cdot \exp(-f_{bin}(\vec{\alpha}))}{d_{bin}!}$
- Maximum Likelihood method:
  - Total likelihood is product of contributions in bins:
  - Find maximum w.r.t. unknown parameters
- Useful: log of likelihood for simpler calculation

$$L(\vec{\alpha}) = \prod_{bin} \frac{f_{bin}(\vec{\alpha})^{d_{bin}} \cdot \exp(-f_{bin}(\vec{\alpha}))}{d_{bin}!} \Rightarrow \log L = \sum_{bin} d_{bin} \log f_{bin}(\vec{\alpha}) - f_{bin}(\vec{\alpha})$$



Fit of the TPC signal in pp collisions for illustration purposes

Fit Likelihood – Two Contributions

$$\log L = \sum_{bin} data(bin) \cdot \log fit(bin) - fit(bin) + \sum_{bin} \sum_{source} N_{source}(bin) \cdot \log A_{source}(bin) - A_{source}(bin)$$

$$fit(bin) = \sum_{source} p_{source} \cdot A_{source}(bin)$$

Likelihood for weighted sum of expectation values to correspond to data

Likelihood for Expectation values to correspond to MC templates

- For 200 bins per source – 804 free parameters
- Barlow, Beeston: Maximization wrt. $A_{source}(bin)$ can be done in iterative process
- Only 4 free parameters remain for TMinuit (p_{source})