Nuclear and Particle Physics 4b
Physics of the Quark Gluon Plasma

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Lectures and Exercise
Summer Semester 2016
Organization

• Language: English

• Lecture:
  • Wednesday 13:00-15:00
  • Phys 01.402

• Marks / examination → only if required / desired
  • Seminar presentation → schein
  • Oral Exam → grade

• Office hours: tbd on demand
Info: Email and Website

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Hard Processes

- Hard Processes: Factorization
  - High pt hadrons
  - Heavy Flavours
- Collision System
  - pp: pQCD
  - pA: Initial vs Final State effects
  - AA: Energy Loss
Hard Processes (1)

- Hard processes are those processes with high momentum transfer which are calculable with perturbative QCD techniques
  - The QCD coupling constant $\alpha_s$ is small (asymptotic freedom) for processes with high momentum transfer ($Q^2$) $p_T, m > Q_0 \gg \Lambda_{\text{QCD}}$, where $Q_0 = O(1\text{GeV})$ and $\Lambda_{\text{QCD}} \approx 0.2 \text{ GeV}$ is the QCD scale
  - High momentum transfer $\Rightarrow$ short distances $\Rightarrow$ Time Scale short ($\tau_{\text{form}} \approx 1/p_T \ll 1/Q_0 \sim 0.1 \text{ fm/c}$)
- Experimental observables connected to hard processes are:
  - Hadrons with high $p_T \rightarrow$ Jets
  - Mesons and baryons from open heavy flavour (charm and beauty)
  - Quarkonia ($J/\Psi, \Psi', \Upsilon, \Upsilon', \Upsilon''$)
Hard Processes (2)

- In heavy ion collisions high $p_T$ hadrons and heavy flavour are the product of the fragmentation of partons with even higher $p_T$ which:
  - Have been produced on a very short time scale
  - Have crossed all the phases of the fireball evolutions
and therefore can be used as a probe sensitive to the properties of the medium created in the collisions

\[ \tau \sim \frac{1}{p_T} \ll \frac{1}{Q_0} \]
\[ \sim 0.1 \text{ fm/c} \]
Hard Processes (3)

- In the $p_T$ spectra the change from “soft” to “hard” production appears as a change in slope.
  - From the exponential trend, we go to a power-law.
- At RHIC energy, particles with $p_T > 4$ GeV are less than 0.1%.

![Graph showing power-law trend](image)
Factorization and universality

Hard processes in pp collisions are calculable with pQCD techniques using factorization theorem:

\[ \sigma_{hh \rightarrow Hx} = PDF(x_a, Q^2)PDF(x_b, Q^2) \otimes \sigma_{ab \rightarrow q\bar{q}} \otimes D_{q \rightarrow H}(z_q, Q^2) \]

- The partonic cross section \( \sigma_{ab \rightarrow qq} \) is calculable with pQCD.
- The PDF and the fragmentation function instead are non-perturbative:
  - Long distances, long time scales
  - They are not calculable with pQCD techniques

**Assumptions:**
1. The hard cross section and the non-perturbative ingredients (PDF, fragmentation) can be **factorized**
2. Fragmentation functions and parton distribution functions are **universal**
   - can be measured from experimental data (i.e. FF from ee, PDF from ep) and used for pp.
# Partonic cross section

| Process          | $\sum |\mathcal{M}|^2 / g^4$ | $\theta^* = \pi/2$ |
|------------------|-----------------------------|---------------------|
| $q \, q' \to q \, q'$ | $\frac{4}{9} \left( s^2 + \hat{u}^2 \right) + \frac{4}{9} \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}$ | 2.22 |
| $q \, \bar{q}' \to q \, \bar{q}'$ | $\frac{4}{9} \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2}$ | 0.22 |
| $q \, q \to q \, q$ | $\frac{4}{9} \left( s^2 + \hat{u}^2 \right) + \frac{8}{27} \frac{s^2}{\hat{u} \hat{t}}$ | 3.26 |
| $q \, \bar{q} \to q' \, \bar{q}'$ | $\frac{4}{9} \left( \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2} \right) - \frac{8}{27} \frac{\hat{u}^2}{\hat{s} \hat{t}}$ | 2.59 |
| $q \, \bar{q} \to q \, \bar{q}$ | $\frac{32}{27} \frac{\hat{t}^2 + \hat{u}^2}{\hat{u} \hat{t}} - \frac{8}{3} \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2}$ | 1.04 |
| $q \, g \to q \, g$ | $\frac{1}{6} \frac{\hat{t}^2 + \hat{u}^2}{\hat{u} \hat{t}} - \frac{3}{8} \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2}$ | 0.15 |
| $g \, g \to q \, \bar{q}$ | $-\frac{4}{9} \frac{s^2 + \hat{u}^2}{\hat{s} \hat{u}} + \frac{\hat{u}^2 + \hat{s}^2}{\hat{t}^2}$ | 6.11 |
| $g \, g \to g \, g$ | $\frac{9}{2} \left( 3 - \frac{\hat{u} \hat{t}}{\hat{s}^2} - \frac{\hat{s} \hat{u}}{\hat{t}^2} - \frac{\hat{s} \hat{t}}{\hat{u}^2} \right)$ | 30.4 |

Relative importance at equal parton luminosities

Diagram (a) shows the process $q \, q' \to q \, q'$, diagram (b) shows $q \, \bar{q}' \to q \, \bar{q}'$, diagram (c) shows $q \, q \to q \, q$, and diagram (d) shows $q \, \bar{q} \to q' \, \bar{q}'$. Each diagram corresponds to a specific process as described in the table.
Parton Distribution Functions

- PDF are the probability density of finding a parton with a certain fraction $x$ of the proton momentum in a process with momentum transfer $Q^2$.
  - If the proton is made by pointlike particles (quark/parton) the structure functions (and the PDF) should be a function only of $x$ and not of $Q^2$ (Bjorken scaling).
  - In Deep Inelastic Scattering (DIS) we observe that Bjorken scaling is violated, i.e., the structure functions depend on $Q^2$.
  - Gluon radiation causes the evolution of structure functions and the PDF with $Q^2$.

They are extracted from DIS experimental measurements at a certain scale $Q_0^2$.

With DGLAP equations it is possible to calculate how the PDF evolve from a scale $Q_0^2$ to another scale $Q^2$. 

HERA: $e^\pm p$ scattering

H1 and ZEUS

FIT
The fragmentation function $D_{q\rightarrow H}(z,Q^2)$ represents the probability that the quark $q$ produces a hadron $H$ with a fraction $z$ of the quark momentum ($p_H = z p_q$).

- The fragmentation functions are extracted from data in $e^+e^-$ collisions.
- They are then applied in other type of collisions.
- As for the PDF, there is a scaling violation → the fragmentation functions depend on $Q^2$.
- They are measured at a certain scale $Q_0^2$ and evolve with DGLAP equations.
String fragmentation model

- The “string fragmentation model” is used to describe the fragmentation in Monte Carlo models, e.g. PYTHIA

- The $q\bar{q}$ pairs are kept together by a string (color flux tube)

- As soon as the $q$ and $\bar{q}$ move apart, the energy is kept in the string. For a certain distance $r$ we have:

$$V(r) = -\frac{A(r)}{r} + \kappa r$$

$$\kappa = 1 \text{ GeV/fm}$$

- Above a certain distance, it is energetically favorable to break the string creating a new pair $q\bar{q}$ (of light quark) rather than keeping to increase the distance

- The string breaks and a new hadron pair is created
$p_T$ spectrum in $pp$

RHIC 200 GeV

Factorization:
$pQCD + PDF, FF$
(universality) works

CDF 1.8 TeV

LHC 13 TeV

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High $p_T$ hadrons in nucleus-nucleus collisions
Nucleus-Nucleus Collisions

- Rutherford experiment \( \alpha \rightarrow \text{atom} \) discovery of nucleus
  - SLAC electron scattering \( e \rightarrow \text{proton} \) discovery of quarks

- Hard processes occur in nucleon-nucleon (NN) collisions
- Heavy-ion collision: Many NN collisions
  - Hard process is independent of number of NN collisions

- Hard processes in nucleus-nucleus collisions is expected to **scale with the number of** elementary nucleon-nucleon collisions realized in the nucleus-nucleus collision

\[ \sigma_{\text{hard}}^{AB} = \sigma_{\text{hard}}^{pp} \times N_{\text{coll}} \]

- Therefore it is expected that the \( p_T \) spectra measured in nucleus-nucleus collisions can be obtained from those in pp with the simple scaling law (binary scaling)

\[ \frac{dN_{AA}}{dp_T} = N_{\text{coll}} \times \frac{dN_{pp}}{dp_T} \]
Nuclear modification factor $R_{AA}$

• Without QGP, HI collision is superposition of NN collisions with incoherent fragmentation

• The **nuclear modification factor** is defined as:

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

• In case there are no nuclear effects:
  - $R_{AA} < 1$ in the soft physics regime (low $p_T$)
  - $R_{AA} = 1$ at high $p_T$ where hard processes dominate

- For central AA collisions

  - RHIC (200 GeV)
    - $N_{part} \approx 400$
    - $N_{coll} \approx 1200$
    - $(N_{part}/2)/N_{coll} \approx 1/6$
  - LHC (5TeV)
    - $N_{part} \approx 400$
    - $N_{coll} \approx 2000$
    - $(N_{part}/2)/N_{coll} \approx 1/10$
Breaking of binary scaling

The binary scaling in nucleus-nucleus collisions is broken by:

- **Initial state effects → due to variations of PDF and/or of parton momenta in the initial state**
  - Present in pA and AA collisions
    - Cronin effect
    - Modifications of PDF in nuclei wrt those in nucleons
    - Formation of a state of Color Glass Condensate (gluon saturation at low x)

- **Final state effects → variations of fragmentation functions due to the presence of a medium created in the collision**
  - Present only in AA
    - Energy loss / Jet quenching
Initial State Effects
Cronin Effect

- Discovered in the ’70 in proton-nucleus collisions at Fermilab
- For $p_T \approx 2$ GeV/c: $R_{pA} > 1$
- At high $p_T$, the $p_T$ spectrum is translated horizontally towards higher values of $p_T$
  - for a fixed $p_T$ looks like $R_{pA} > 1$ given the falling trend of the spectrum

- When the hard process occurs, the projectile parton already has an “initial $k_T$”, due to elastic collisions already occurred with other nucleons of the target nucleus and give an “extra $k_T$ kick” to the produced parton
  - With increasing $p_T$ this “extra $k_T$ kick” becomes a smaller fraction of the observed $p_T$, therefore the Cronin enhancement should disappear for $p_T \to \infty$. 
The parton density for nucleons inside a nucleus are different from those in free nucleons.

Observed for the first time in 1983 by EMC experiment.

- Ratio between structure functions in Calcium and deuterium:

\[ \frac{F_2(Ca)}{F_2(D)} \]

- PDF in nuclei

- EMC effect

- Fermi motion

- Shadowing

- Anti-shadowing
Color Glass Condensate

Universal form of matter inside ion colliding at very high energy → **COLOR GLASS CONDENSATE**

Lorenz contraction → gluons appear as “gluonic wall” where the gluons themselves are disordered

Parton evolution proceeds via soft collinear gluon emission

At a characteristic momentum scale (**saturation scale**) gluon density is large enough that parton evolution becomes non-linear → parton recombination.

Gluons act as frozen color sources (Color Glass Condensate)

Scale depends on \( x \) and \( A \) → geometric scaling
Final State Effects
Energy Loss

- A parton created on a short time scale after the collision (i.e. a heavy quark and/or with $p_T$) looses energy while escaping from the interaction region with two mechanisms
  - Scattering with the partons of the medium (**collisional energy loss**)
  - **Radiation** of gluons (gluonstrahlung)
- At high energy the dominant mechanism is the radiation
- What we observe
  - It is slowed (=its $p_T$ decreases while crossing the medium)
  - The spectrum at high $p_T$ is suppressed (**quenching**)

Spectrum in $pp$

Quenched spectrum
Radiative energy loss

- Energy Loss (BDMPS : acronym of the authors)
  - Gluon radiation with “multiple soft scatterings”

\[ \langle \Delta E \rangle \propto \alpha_s C_R \hat{q} L^2 \]

- \( \alpha_s \) = QCD coupling constant (running)
- \( C_R \) = Coupling Factor Casimir
  - 4/3 for quark-gluon coupling
  - 3 for gluon-gluon coupling
- \( \hat{q} \) = transport coefficient
  - Connected to characteristics (opacity) of the medium
  - Proportional to the density (and the momenta) of the gluons
- The dependence on \( L^2 \) is due to the fact that the radiated gluons are colored and can therefore also interact with the medium
Transport coefficient

- The transport coefficient is connected to the gluon density and therefore to the energy density of the medium
  \[ \hat{q} \propto \varepsilon^{3/4} \]

- From the measured energy loss one can derive an indirect measurement of the energy density of the system
How much energy is lost?

- Formula BDMPS:

\[
\langle \Delta E \rangle = \frac{1}{4} \alpha_s \, C_R \, \hat{q} \, L^2 \quad \text{analisi dimensionale} \quad \Rightarrow \quad \langle \Delta E \rangle = \frac{\alpha_s \, C_R \, \hat{q} \, L^2}{4 \hbar c}
\]

- Numerical values
  - \( \hat{q} = 5 \text{ GeV}^2/\text{fm} \rightarrow \) typical value to fit RHIC data
  - \( \alpha_s = 0.2 \rightarrow \) value for process with \( Q^2 = 10 \text{ GeV} \)
  - \( C_R = 4/3 \)
  - \( L = 5 \text{ fm} \)

- Therefore:

\[
\langle \Delta E \rangle \approx \frac{0.2 \cdot \frac{4}{3} \cdot 5 \cdot 25}{4 \cdot 0.197} \approx \frac{5 \cdot 25}{3} \approx 40 \text{ GeV}
\]

- Huge value! Only partons with energy > 40 GeV/c can cross 5 fm of fireball and escape with high \( p_T \).
Energy loss and hadronization

- A high $p_T$ parton escapes from the fireball before hadronizing
  - Hadronization by vacuum fragmentation
  - Jet Production as in pp
- If instead the parton looses lots of energy while crossing the deconfined medium and it is slowed down
  - It can eventually reach thermal equilibrium with the medium before hadronizing
  - It can hadronize in the medium (and not in the vacuum)
    - Modification of fragmentation function
    - Possible hadronization for coalescence/recombination
Fragmentation vs. coalescence

- Two hadronization mechanisms:
  - **Fragmentation**: a high $p_T$ parton fragment in hadrons with lower $p_T$ ($p_H = z \cdot p_q$ with $z<1$)
  
  
  - **Recombination/coalescence**: partons with low $p_T$ combine to form a hadron with higher $p_T$

\[ p_h = z \cdot p_q \text{ with } z<1 \]

\[ p_h = p_{q1} + p_{q2} \]
In summary...

Binary scaling in nucleus-nucleus collisions is broken by:

- **Initial state effects → due to variations of PDF and/or parton momenta in the initial state**
  - Present in pA and AA collisions
    - Cronin effect
    - Modifications of PDF in nuclei wrt those in nucleons
    - Formation of a state of Color Glass Condensate (gluon saturation at low x)

- **Final state effects → variations of the fragmentation functions due to the presence of a medium created in the collision**
  - Present only in AA
    - Energy loss / Jet quenching
      - Hadronization in the medium – Fragmentation vs. coalescence/recombination
Hadrons with high $p_T$

Results
$R_{AA}$ for charged hadrons and $\pi^0$

- Suppression by a factor $\approx 5$ for $p_T > 4$ GeV
  - Is it a final state, due to energy loss?
  - Control experiment: RAA in d-Au collisions, RAA for particles not subject to strong interactions (photon)

\[
R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}
\]
Initial or final state effects (1)

- Measurement of $R_{AA}$ (indicated with $R_{dAu}$) in deuteron-Au collisions
  - In these collisions no medium is created and there are no final state effects
  - Initial state effects instead are present
- The results of dAu show the expected Cronin enhancement
- The effect seen in AuAu is not due to initial state
Initial or final state effects (2)

- Direct photons (obtained subtracting the decays of $\pi^0$ and $\eta$) are a “medium-blind probe” (do not feel strong interactions) and scale with $N_{\text{coll}}$ as expected for hard processes.

- The quenching observed for hadron is a final state effect.

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**Figure by D. d’Enterria**
Characterizing the medium

- Low sensitivity of $R_{AA}$ to the value of $\hat{q}$ for $\hat{q} > 4$-5 GeV$^2$/fm
- If the medium is very dense ($q$ large) the hadrons measured at high $p_T$ are those produced in the corona which therefore cross a short distance in the medium and are not slowed down even when the energy density is really large (surface emission)
- The measurement of single particles with high $p_T$ (“leading hadrons”) is not a penetrating probe
Surface emission

- For $qq_{\bar{b}a}$ pairs produced inside the fireball
  - The produced partons are slowed down in the way through and hadronize to lower $p_T$ hadrons
- For $qq_{\bar{b}a}$ pairs produced at the surface of the fireball (corona)
  - The parton with momentum directed towards outside hadronizes in a high $p_T$ hadron (in a jet) which is detected
  - The parton emitted towards inside has to cross the whole fireball, loses energy and hadronizes to low $p_T$ hadrons
- The study of azimuthal angular correlations between two high $p_T$ particles can provide further experimental evidence for this hypothesis
Angular Correlations (1)

- In every event, we consider the hadron with higher $p_T$ (trigger particle, with $p_T >$ some threshold eg. $p_T^{\text{trig}}>4 \text{ GeV}$)
- We build an azimuthal distribution of the other high $p_T$ particles in the event (eg. with $p_T^{\text{assoc}} > 2 \text{ GeV}$)
  - The trigger particle defines the zero of the azimuthal angle
- For LO processes, the hard hadrons are produced in two jets back-to-back and therefore the angle $\Delta \phi$ between the trigger particle and the other high $p_T$ particles has preferential values (peaks) around $0^\circ$ and $180^\circ$
Angular Correlations (2)

- In pp and in peripheral Au-Au collisions the angular distribution of high $p_T$ particles has two peaks at 0° and 180° (back-to-back emission)
- In central Au-Au collisions, the away-side-peak is not observed
  - Suppression of jet back-to-back emission in Au-Au central collisions
Angular Correlations (3)

- In d-Au collisions the same structure (two back-to-back peaks) as in pp collisions is observed.
- The away-side jet (ie 180° peak) suppression is a final state effect.
Charged particles $R_{AA}$ at LHC

- The suppression increases with centrality.
- $R_{AA}$ has a minimum (maximum suppression) for $p_T \sim 6$-7 GeV/c for all centrality classes.
- $R_{AA}$ increases for $p_T > 10$ GeV/c and looks like flattening above 30 GeV/c.
Charged particles $R_{AA}$ at LHC

- **Comparison with $R_{AA}$ at RHIC**
  - In the common pT region, the suppression observed at RHIC and at LHC has a similar shape with a maximum at pT~2 GeV/c
  - The suppression observed at LHC is larger

- **Indications/possible explanations:**
  - Denser medium
    - Note: keep in mind the slope of the spectrum: less steep spectrum (“harder”) $\rightarrow$ higher RAA for the same energy loss
  - Larger / loner lived medium
$R_{AA}$ at RHIC and LHC

Measured $R_{AA}$ is a ratio of yields at a given $p_T$

The physical mechanism is energy loss; shift of yield to lower $p_T$

Oversimplified calculation:
- Fit pp with power law
- Apply energy shift or relative E loss

RHIC: $n \approx 8.2$

$LHC: n \approx 6.4$

$\left(1-0.23\right)^6.2 = 0.20$

$\left(1-0.23\right)^{4.4} = 0.32$

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The reaction plane dependence of RAA constrains the path length dependence of parton energy loss.

The reaction plane dependence of RAA at RHIC poses a problem to perturbative energy loss models (PHENIX, Phys.Rev.Lett.105:142301,2010)
Control experiment at LHC

- Confirm that the suppression in PbPb is a final state effect, for $p_T > 5$ GeV/c $R_{pA} \approx 1$

Electroweak observables

- $\gamma$, PLB 710 (2012) 256
- $W^\pm$, PLB 715 (2012) 66
- $Z^0$, PRL 106 (2011) 212301, CMS-PAS-HIN-13-004

ALICE, arXiv:1210.4520
Onset or RAA

- Three Goals of Beam Energy Scan program at RHIC:
  - Turn-off of QGP signatures
  - Find critical point
  - First order phase transition.

- Transition from enhancement ($R_{AA} > 1$) to suppression ($R_{AA} < 1$) and evolution of $R_{AA}$ with energy

\[ \text{R}_{\text{CP}} \text{ suppression at high } p_T \text{ sets in from } \sqrt{s_{NN}} = 39 \text{ GeV on} \]
Jets

Motivation: understand parton energy loss by tracking the gluon radiation

Qualitatively two scenarios:
1) In-cone radiation: $R_{AA} = 1$, change of fragmentation
2) Out-of-cone radiation: $R_{AA} < 1$

QCD calculations are provided in terms of quarks and gluons in the final state.
After hard scattering, quarks and gluons follow a branching process and then hadronize, leading to a collimated bunch of hadrons as characteristic signal in the detector: a jet.

Jet definition (which particles do you combine? How?)
→ Jet reconstruction

Two categories of jet reconstruction algorithms:

• Sequential recombination
  Successively merge “particles” in order of relative transverse momentum

• Cone
  Sum content of Cone with radius $R$

Robust against emission of soft particles and collinear splitting

JET RADIUS $R$
- underlying event & pileup “noise”: small $R$ better (it captures less)
- multi-hard-parton events: small $R$ better (it resolves partons more effectively)
- Hadronization:
  large $R$ better (less non-perturbative corrections)
- Out-of-cone radiation: large $R$ better (it captures more)
Di-jet imbalance at LHC

Clear peaks: *jets* of fragments from high-energy quarks and gluons
And a lot of uncorrelated ‘soft’ background
Di-jet imbalance at LHC

- Difference in energy between the leading jet (= the one with largest energy in the event) and the sub-leading (the jet with higher energy in the opposite hemisphere): Quantified as:

\[ A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \quad \Delta \phi_{12} > \frac{\pi}{2} \]

Di-jet events should have \( A_J \approx 0 \)

- Small deviation from zero due to gluon radiation outside the jet cone
- Larger deviations from zero expected for energy loss in the QGP

Significant imbalance between energies of the two jets for central events
Heavy Flavours
Heavy flavours in pp

- Because of their large mass \((m_b \sim 4.8 \text{ GeV}, m_c \sim 1.2 \text{ GeV})\), charm and bottom (heavy flavours) quark can be produced only in parton scattering with large momentum transfer \(Q^2\), which happen in the initial phase of the collision.
  - Their production can be described with pQCD
- The measurement in pp collisions allows to:
  - Test the factorization hypothesis and theoretical models based on pQCD
  - Obtain a reference for the measurement of RAA

![Diagram showing processes](image)

- Leading order \(\alpha_s^2\)
- Next to leading order \(\alpha_s^3\)
pQCD vs. experimental data (beauty)

- pQCD with factorization reproduces well the beauty data at Tevatron and at LHC
- Measured from the decay chain $B \rightarrow J/\Psi \rightarrow e^+e^- (\mu^+\mu^-)$
Experimental data on charm mesons at Tevatron are on the upper limit of the predictions from pQCD and factorization.

CDF, $\sqrt{s}=1.96$ TeV, PRL 91:241804 (2003)
pQCD vs. experimental data (charm)

- Same situation at LHC for pp collisions at 7 TeV
Heavy flavours in AA

• The measurement in AA collisions allows to:
  • Test the energy loss models which predict a different energy loss for hadrons with charm and beauty wrt the light hadrons because:
    ✓ Heavy flavour come from a quark fragmentation, light hadrons (especially at LHC) come mostly from gluons
    ✓ Dead cone effect: suppression of radiation at small angles for quarks with large mass
  • Energy loss in the limit BDMPS (acronym of the authors of the model)
    \[
    \langle \Delta E \rangle \propto \alpha_s C_R \hat{q} L^2
    \]
    • For heavy quarks it is expected a smaller energy loss because of:
      • Casimir Factor
        – Light hadrons at high $p_T$ mostly come from gluon jets, while heavy hadrons come from jets of heavy quarks
      • Dead-cone effect
        – The radiation of gluons is expected to be suppressed at angles $\theta < M_q/E_Q$
Radiative energy loss and $R_{AA}$

- Increasing the transport coefficient $q$
  - Energy loss increases
  - $R_{AA}$ decreases

- Effect of the charm quark mass
  - Less energy loss (dead cone)

- Effect of the beauty quark mass
  - $m_b > m_c$, dead cone effect larger
In Summary

- Based on models of radiative energy loss, it is expected to measure a hierarchy in the nuclear modification factor:

\[ \Delta E_g > \Delta E_{\text{charm}} > \Delta E_{\text{beauty}} \]

\[ R_{AA} (\text{light hadrons}) < R_{AA} (D) < R_{AA} (B) \]

Illustration (graph) showing the modification factors for different hadrons with a reference to Wicks, Gyulassy, “Last Call for LHC Predictions” workshop, 2007.
Heavy Flavours: experimental techniques
### open charm and beauty states

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<th>Hadron</th>
<th>Mass (MeV)</th>
<th>$c\tau$ (μm)</th>
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<tr>
<td>$D^+(c\bar{d})$</td>
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<td>312</td>
</tr>
<tr>
<td>$D^0(c\bar{u})$</td>
<td>1865</td>
<td>123</td>
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<td>$D_s^+(c\bar{s})$</td>
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<td>147</td>
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<td>$\Lambda^+_c(ucd)$</td>
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<td>$\Xi^+_c(usc)$</td>
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<td>$\Xi^0_c(dsc)$</td>
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<td>$\Omega^0_c(ssc)$</td>
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<td>460</td>
</tr>
<tr>
<td>$B^0_s(sb)$</td>
<td>5370</td>
<td>438</td>
</tr>
<tr>
<td>$B^0_c(cb)$</td>
<td>$\approx$ 6400</td>
<td>100 – 200</td>
</tr>
<tr>
<td>$\Lambda^0_b(ubd)$</td>
<td>5624</td>
<td>368</td>
</tr>
</tbody>
</table>

- **Life time** ≈ 0.5-2 ps (weak decay)
  - heavy quarks are produced in the first instants of the collision and live for all the evolution of the fireball
- $c\tau$ ≈ 100-500 micron
  - **Decay Vertex (secondary) of hadrons with open heavy flavour away from** ≈ 100 micrometers from the vertex (primary) where the pp or AA interaction occurred
Heavy Flavours with ALICE

- **Open charm from hadronic decays at central rapidity**
  - \( D^0 \rightarrow K^-\pi^+ \)
  - \( D^+ \rightarrow K^-\pi^+\pi^+ \)
  - \( D^{*+} \rightarrow D^0\pi^+ \)
  - \( D^0 \rightarrow K^-\pi^+\pi^+\pi^- \)
  - \( D_s \rightarrow K^-K^+\pi^+ \)
  - \( \Lambda_c^+ \rightarrow pK^-\pi^+ \)

- **Open charm and open beauty from semileptonic decays**
  - \( D, B \rightarrow e^\pm + X \) (central rapidity)
  - \( D, B \rightarrow \mu^\pm + X \) (forward rapidity)

- **Open beauty from non-prompt \( J/\psi \) at central rapidity**
  - \( B \rightarrow J/\psi \rightarrow e^+e^- \)

**Detector Technologies**

- **ITS**: vertexing + tracking
- **TPC**: tracking + PID (\( \pi, K, e \))
- **TOF**: PID (\( \pi, K, p \))
- **TRD**: PID (\( \pi, e \))
- **EMCAL**: PID (\( e \))
- **MUON**: \( \mu \) tracking + PID

Electronic/hadronic: \( |\eta| < 0.9 \)  Muonc: -4< \( \eta < 2.5 \)
Experimental techniques (1)

- **Non-photonic electrons**
  - We build $p_T$ spectra of identified electrons
    - Identification: $dE/dx$ (STAR), $p/E$ in Electromagnetic Calorimeters, RICH (PHENIX), TRD,EMCAL (ALICE)
  - We subtract electrons which do not come from heavy flavour decay
    - Main source of background electrons: photon conversion $\gamma \rightarrow e^+e^-$
    - Dalitz decay of $\pi^0$, $\eta$, $\eta'$
    - Decay of $\rho$, $\phi$, ...
  - The background is subtracted based on:
    - Monte Carlo Simulations (STAR)
    - Measurements with different conversion material (PHENIX)
    - Vertex detectors which allow to measure the distance of closes approach of the tracks to the primary vertex (ALICE and also STAR and PHENIX with the upgrade)
Experimental techniques (2/1)

- Exclusive reconstruction of charm mesons and baryons from hadronic decays

<table>
<thead>
<tr>
<th>Meson</th>
<th>Final state</th>
<th># charged bodies</th>
<th>Branching ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0$</td>
<td>$\rightarrow K^-\pi^+$</td>
<td>2</td>
<td>3.8%</td>
</tr>
<tr>
<td></td>
<td>$\rightarrow K^-\pi^+\pi^+\pi^-$</td>
<td>4</td>
<td>Total 7.48%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non resonant 1.74%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$D^0 \rightarrow K^-\pi^+\rho^0 \rightarrow K^-\pi^+\pi^+\pi^-$ 6.2%</td>
</tr>
<tr>
<td>$D^+$</td>
<td>$\rightarrow K^-\pi^+\pi^+\pi^+$</td>
<td>3</td>
<td>Total 9.13%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Non resonant 8.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$D^+ \rightarrow K^{\text{bar}}\rho^0(1430)\pi^+ \rightarrow K^-\pi^+\pi^+$ 2.33%</td>
</tr>
<tr>
<td>$D_{s}^+$</td>
<td>$\rightarrow K^+K^-\pi^+$</td>
<td>3</td>
<td>Total 4.3%</td>
</tr>
<tr>
<td></td>
<td>$D_{s}^+ \rightarrow K^+K^{\text{bar}}\rho^0 \rightarrow K^+K^-\pi^+$ 2.0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$D_{s}^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$ 1.8%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Experimental techniques (2/2)

- Exclusive reconstruction of charm mesons and baryons from hadronic decays

- We build all the pairs/triplets/quadruplets of tracks with the right charge combination
  - Huge number of combinations !!!
  - A method of particle identification (dE/dx or TOF) can reduce the combinatorics

- Reconstruction of vertex (secondary) of the group of “candidate” tracks
  - Selection of candidates based on the distance primary-secondary …
More details on $D \to$ hadrons

- Pair of opposite sign charged tracks / Triplet of charged tracks
  - large and opposite sign (pair) impact parameter
  - Good pointing of reconstructed $D$ momentum to primary vertex
  - Large distance between primary and secondary vertex ($c\tau = 310$ mm)
  - Good pointing of the reconstructed $D$ momentum to the primary vertex

- $D_s (\to K+K-\pi+)$ has shorter lifetime than $D^+$
  - Looser topological cuts
  - PID cuts more background (2 tracks should be compatible with Kaon hypothesis)
  - Exploit resonant intermediate state: $M(KK)$ compatible with phi mass

- $D^{*+} \to D^0\pi^+$ (Strong decay)
  - Attach a Low-pT pion to $D^0$ candidates
  - Exploit narrow signal in $\Delta M = M(K\pi\pi) - M(K\pi)$
Invariant mass spectra in pp

D0

Down to pt=1 GeV/c

D+

D*++
Invariant mass in PbPb

D0

D+

D*+
From signals to cross-sections

\[ \frac{d\sigma^{D^+}}{dp_t} \bigg|_{|y|<0.5} = \frac{1}{2 \Delta y \Delta p_t} \frac{f_{\text{prompt}}(p_t) \cdot N^{D^\pm \text{raw}}(p_t) \bigg|_{|y|<y_{\text{fid}}}}{(\text{Acc} \times \varepsilon)_{\text{prompt}}(p_t) \cdot \text{BR} \cdot L_{\text{int}}} \]

Correction for B\(\to\)D feeddown:
- From FONLL predictions + selection efficiencies from MC
- Check with data driven method based on fit to D meson impact parameter distribution

Correction for reconstruction and selection efficiency:
- From MC simulations

From fits to invariant mass spectra
B feed-down subtraction: why

Different efficiency for prompt and secondary D mesons

- D from B feed-down are more displaced from primary vertex → higher efficiency of topological cuts
B feed-down subtraction: how

Contribution to yield from feed-down B using FONLL prediction for B mesons, decayed to D mesons, multiplied by the reconstruction efficiency for feed-down D mesons

\[ f_{\text{prompt}} = 1 - \left( \frac{N^{D^\pm}_{\text{from B raw}}}{N^{D^\pm}_{\text{raw}}} \right) \]

\[ N^{D^\pm}_{\text{from B raw}} \bigg|_{|y|<y_{\text{fid}}} = 2 \frac{d\sigma^{D^+}_{\text{FONLL}}}{dp_t} \bigg|_{|y|<0.5} \cdot \Delta y \Delta p_t \cdot (\text{Acc} \times \varepsilon)_{\text{feed-down}} \cdot \text{BR} \cdot L_{\text{int}} \]

**Graphs and Data**

- **Graph 1:**
  - Title: \( D^0 \to K^- \pi^+ \)
  - Conditions: \( pp, \sqrt{s} = 7 \text{ TeV}, L_{\text{int}} = 5.0 \text{ nb}^{-1} \)
  - Plot: Prompt fraction of raw yield, \( f \) vs. \( p_t \) (GeV/c).
  - Data points and error bars.
  - Legend: FONLL-based methods, \( D \) impact parameter fit (with total uncertainty).

- **Graph 2:**
  - Title: \( D^0 \to K^- \pi^+ \)
  - Conditions: \( pp, \sqrt{s} = 7 \text{ TeV}, L_{\text{int}} = 5.0 \text{ nb}^{-1} \) for \( 2 < p_t < 3 \text{ GeV/c} \)
  - Plot: Entries (background subtracted) vs. \( p_{t} \) (GeV/c).
  - Data points and error bars.
  - Legend: Prompt, from B, sum.

- **Inset:**
  - Title: \( D^0 \to K^- \pi^+ \) impact parameter distribution.
  - Data points and error bars.
  - Legend: Prompt, from B, sum.

- **Values:**
  - \( f_{\text{prompt}} = 0.88 \pm 0.04 \)
  - \( \sigma_{\text{prompt}} = 60 \pm 2 \mu m \)
  - \( \chi^2/\text{ndf} = 52/41 \)
Hypothesis on RAA of D mesons from B decays needed

- B decays outside the medium: in case of D mesons from B feed-down, the quark crossing the medium is the b quark.
- Energy loss of beauty expected different from that of charm.

\[ f_{\text{prompt}} = 1 - \left( \frac{N^D_{\text{feed-down raw}}}{N^D_{\text{raw}}} \right) = 1 - \langle T_{AA} \rangle \cdot \left( \frac{d^2 \sigma}{dy dp_t} \right)^{\text{FONLL}}_{\text{feed-down}} \cdot R_{\text{AA}}^{\text{feed-down}} \cdot \frac{(\text{Acc} \times \varepsilon)_{\text{feed-down}} \cdot \Delta y \Delta p_t \cdot \text{BR} \cdot N_{\text{evt}}}{N^D_{\text{raw}}/2} \]
Heavy Flavours: results
The $R_{AA}$ values show a good agreement between STAR and PHENIX

- $R_{AA}$ at RHIC (non-photonic electrons)
The values of $R_{AA}$ for non-photonic electrons challenge all the models of energy loss. High values of $\hat{q}$ and no electrons from beauty decays reproduce the data best.
$R_{AA}$ at RHIC – theoretical models (2)

- The values of $R_{AA}$ for non-photonic electrons challenge all the models of energy loss.

An alternative model based on the formation of resonances $Qq$ (heavy quark and light quark) in the plasma explains better the data.
What can we learn at the LHC

Higher c and b cross sections:

- More abundant heavy flavour production
- Better precision (reduced errors)
  \[ \sigma_{LHC}^{c\bar{c}} \approx 10 \cdot \sigma_{RHIC}^{c\bar{c}} \]
  \[ \sigma_{LHC}^{b\bar{b}} \approx 100 \cdot \sigma_{RHIC}^{b\bar{b}} \]

High precision vertex detectors

- Background removal
- Separate c and b
Prompt D meson RAA

Suppression of prompt D mesons in central (0-20%) PbPb collisions by a factor 4-5 for pT>5 GeV/c

- Similar suppression for all D mesons
- Smaller suppression for peripheral events
$R_{pA}$ of charm at LHC

PbPb vs pPb

- Suppression of D mesons in central (0-20%) PbPb collisions by a factor 4-5 for $p_T>5$ GeV/c
  - The effect of shadowing is small at high $p_T$ → the suppression is a final state effect
Hierarchy

- Suppression of D mesons in central PbPb collisions
  - At high $p_T$: the suppression for D mesons and pions is similar (as at RHIC)
  - Maybe there are indications of $R_{AA}^D > R_{AA}^\pi$ at low $p_T$
  - Comparison between D and secondary $J/\psi$ (from B decays)
  - $R_{AA}^{\text{charm}} < R_{AA}^{\text{beauty}}$, as expected for central collisions
D0 elliptic flow

First direct measurement of D flow in heavy-ion collisions

Yield extracted from invariant mass spectra of $K\pi$ candidates in 2 bins of azimuthal angle relative to the event plane

$$v_2 = \frac{\pi}{4} \frac{N_{IN} - N_{OUT}}{N_{IN} + N_{OUT}}$$
Conclusions

- The results of measurements of high $p_T$ hadrons at RHIC and LHC
  - $R_{AA}$ for pions
  - Angular correlations for pairs of particles / jet can be explained by a strong energy loss (radiative) in a medium with high energy density, larger than the critical energy for QGP formation.

- The results of the measurements of open heavy flavour
  - Strong suppression of electrons from charm and beauty
    - To conclude, we need to separate charm and beauty (-> vertex detectors)
  - First results from LHC: first indications that $R_{AA}^{\text{charm}} < R_{AA}^{\text{beauty}}$, as expected. We need more statistics to conclude on a possible difference between charm and light flavours.
Homework

Backup
Cronin Effect (1)

- Discovered in the ’70 in proton-nucleus collisions at Fermilab.
- For $p_T \approx 2$ GeV/c the ratio $R_{pA}$ (equivalent to $R_{AA}$ for pA collisions) is larger than 1.

**Graph:**
- $R_{pA} > 1$
- $R_{pA} = 1$
- "soft" segment
- "hard" segment
- Cronin enhancement
Cronin Effect (2)

- At high $p_T$, the $p_T$ spectrum of hadrons produced in pA collisions is:
  - Translated upwards by a normalization factor $N_{\text{coll}} \approx A$
    - As should be for a hard process
  - Translated horizontally towards higher values of $p_T$
    - Which for a certain fixed $p_T$ looks like $R_{\text{pA}} > 1$ given the falling trend of the spectrum
The horizontal translation to higher $p_T$ values comes from the fact that partons inside the projectile have already undergone some elastic collisions with other nucleons of the target nucleus before the hard scattering where the high $p_T$ is produced.

In this way the partons of the target acquire a transverse momentum $k_T$ which increases with the square root of the number of elastic collisions (random walk).
Cronin Effect (4)

- When the hard process occurs, the projectile parton already has an “initial $k_T$” and give an “extra $k_T$ kick” to the produced parton.
  - With increasing $p_T$ of the produced particle, this “extra $k_T$ kick” becomes a smaller fraction of the observed $p_T$, therefore the Cronin enhancement should disappear for $p_T \to \infty$.
  - With increasing $p_T$, $R_{AA}$ should go to 1, but not from below as expected from a soft scaling at low $p_T$, but from above due to Cronin enhancement at high $p_T$.

![Graph showing Cronin effect](image)
Charged particles $R_{AA}$ at LHC

- The increase of $R_{AA}$ at high $p_T$ allows to discriminate between theoretical models
Fragmentation function

Fragmentation function $D q \rightarrow H(z,Q^2)$ gives the probability that a quark $q$ produces an hadron $H$ carrying a fraction $z$ of the quark momentum ($p_H = z p_q$)

- Usually extracted from $e^+ e^-$ data and used in other collision systems

In case of heavy quark fragmentation, the D/B meson takes a large fraction $z$ of the quark momentum

- Fragmentation function shows a peak for $z$ close to 1 (-> hard fragmentation function)
- Example of parameterizations:

$$D_{D/c}(z) \propto \frac{1}{z[1-1/(z-\varepsilon/(1-z))]^{2}}$$

- **Peterson** ($\varepsilon = 0.015$)

$$D_{D/c}(z) \propto (1-z)^{\alpha} z^{\beta}$$

- **Colangelo-Nason** ($\alpha = 0.9$, $\beta = 6.4$)

Parameters from fits to charm production at LEP
Partonic cross-section

- Perturbative expansion in powers of $\alpha S$

State of the art: FONLL = Fixed Order calculation (at NLO) + resummation of next to leading logs

- **Leading order diagrams ($\propto \alpha S^2$)**
  - $q$-$\bar{q}$ annihilation
  - Gluon fusion

- **Next to leading order additional diagrams ($\propto \alpha S^3$)**
  - Higher order terms in pair creation
  - Flavour excitation
  - Gluon splitting
Heavy quarks: energy loss

- Energy loss in the limit BDMPS (acronym of the authors of the model)
  - Approximation where the gluon becomes de-coherent from the parton from which it was emitted with “multiple soft scatterings”

\[
\langle \Delta E \rangle \propto \alpha_s C_R \hat{q} L^2
\]

- For heavy quarks it is expected a smaller energy loss because of:
  - Casimir Factor
    - Light hadrons at high \( p_T \) mostly come from gluon jets, while heavy hadrons come from jets of heavy quarks
  - Dead-cone effect
    - The radiation of gluons is expected to be suppressed at angles \( \theta < M_Q/E_Q \)
Radiative energy loss and $R_{AA} (1)$

- Increasing the transport coefficient $q$
  - energy loss increases
  - $R_{AA}$ decreases

- Effect of the charm quark mass
  - Less energy loss (dead cone)
Radiative energy loss and $R_{AA}$ (2)

- Effect of the charm quark mass
  - Less energy loss (dead cone)

- Effect of the beauty quark mass
  - $m_b > m_c$, dead cone effect larger
Heavy flavours in ALICE

**ALICE channels:**
- electronic (|η|<0.9)
- muonic (-4<η<-2.5)
- hadronic (|η|<0.9)

**ALICE specific features:**
- low-\(p_T\) region
- central and forward rapidity regions
- Both c and b
- Precise vertexing in the central region to identify D (\(c\tau \sim 100-300\ \mu m\)) and B (\(c\tau \sim 500\ \mu m\)) decays

1 year pp 14 TeV @ nominal lumin.
pt differential cross sections

From an integrated luminosity of 5 nb-1

- 300M MB triggers from 2010 data sample
Looking at these ratios in PbPb can provide information on hadronization mechanism and strangeness enhancement. 

Ds expected to be enhanced in PbPb in case of hadronization via recombination.

Δc under study: would allow to study baryon/mesons in the charm sector.
**Comparison to pQCD**

Data compatible with pQCD prediction within uncertainties

- As observed at lower energies, data are on the upper edge of FONLL uncertainty band
Towards RAA: pp reference

- pp data sample at $\sqrt{s}=2.76$ TeV: too small statistics for measuring D meson cross section with enough precision in the same pt intervals used in PbPb

Solution: scale the pt differential cross section measured at $\sqrt{s}=7$ TeV

- Scaling factor defined for each D meson species from the ratio of the cross-sections from FONLL at 2.76 and 7 TeV
- Validated scaling to $\sqrt{s}=1.96$ TeV and comparing with CDF data
- Checked against ALICE measurement at 2.76 TeV
Suppression of prompt D mesons in central (0-20%) PbPb collisions by a factor 4-5 for pT>5 GeV/c
Tools: primary vertex reconstruction

3D reconstruction from tracks of primary (interaction) vertex position with full error-matrix treatment

- Resolution on vertex position depends on multiplicity.
- Important for
  - Impact parameter resolution (in p-p low multiplicity events)
  - Separation of secondary vertices from the primary
  - Determination of the pointing angle

![Graph showing vertex resolution vs. tracklets for 14 TeV, with and without constraint]
Tools: primary vertex reconstruction

**Estimate resolution on data using half events**
- Split tracks in 2 sub-samples and build residuals between reconstructed coordinates from the 2 half-events
Precise determination of secondary vertices is the crucial ingredient for open charm analyses based on the reconstruction of displaced (by ~100 μm) decay topologies.
Tools: impact parameter

Track impact parameter = distance of closest approach of a track to the interaction (primary vertex)

- High resolution provided by the Inner Tracking system (ITS) and in particular by the SPD points (high precision and close to the beam axis)
- Resolution determined by:
  - Resolution on primary vertex (worse in pp)
  - Resolution on particle trajectory, which has two components: detector spatial resolution and $pT$ ($\beta$) dependent multiple scattering.

For $p_T > 1$ GeV/c, $< 60 \mu m (r_\phi)$ in central Pb-Pb.
Charm vs. beauty

A significant fraction (~10-20%) of the measured yield of heavy flavour leptons (electrons or muons) and D mesons comes from B decays (feed-down)

Due to large B lifetime, leptons, D mesons and J/ψ's from B decays are more displaced from the primary vertex
- Wider impact parameter distribution

Can use this feature to separate charm and beauty:
- By cutting on impact parameter to enhance beauty
- By fitting the impact parameter distribution to extract prompt (charm) and displaced (beauty) contributions
Tools: PID

Proton, kaon and pion separation using dE/dx in TPC and TOF information
Tools: electron identification

Strategy based on TOF and TPC
- TOF resolves momentum regions where electron \(\frac{dE}{dx}\) in TPC crosses kaon and proton curves
- Effective for \(p_{t}<4\) GeV/c
- TOF rejects kaons for \(p<1.5\) GeV/c and protons for \(p<3\) GeV/c
- Further hadron rejection with TPC
  - \(n\). sigma cut with respect to electron expected \(\frac{dE}{dx}\)
  - Remaining hadron contamination estimated from data and subtracted
Tools: electron identification

**TRD**
- Extend measurement to higher pt
- Energy deposit (dE/dx) + absorption of Transition Radiation photons
- Cut at 80% of electron efficiency

**EMCAL**
- dE/dx from TPC, momentum (p) from track fit
- Energy (E) from the EMCal cluster matched to the track
- Compatibility of dE/dx with electron energy loss (→ remove hadrons)
- Cut on E/p, e/g/ 0.8<E/p<1.3
More details on $D \rightarrow$ hadrons
D meson reconstruction

STRATEGY: invariant-mass analysis of fully-reconstructed topologies originating from displaced vertices

- build pairs/triplets/quadruplets of tracks with correct combination of charge signs and large impact parameters
- particle identification from TPC and TOF to reject background (at low pt)
- calculate the vertex (DCA point) of the tracks
- require good pointing of reconstructed D momentum to the primary vertex
D0 → K-π+ : selection

Pair of opposite sign charged tracks
- Large and opposite sign impact parameter
- Good pointing of reconstructed D momentum to primary vertex

\[ D_0 \rightarrow K^- \pi^+ \]
D$^+ \rightarrow K^-\pi^+\pi^+$ : selection

**Triplet of charged tracks**

- Large distance between primary and secondary vertex ($c\tau = 310$ mm)
- Good pointing of the reconstructed D momentum to the primary vertex
Ds+ → K-K+π+ selection

Ds has shorter lifetime than D+
- Looser topological cuts
- PID cuts more background (2 tracks should be compatible with Kaon hypothesis)
- Exploit resonant intermediate state: M(KK) compatible with phi mass
The power of PID

**PID strategy:**
- Conservative PID: 3σ cuts on TPC dE/dx and TOF signal
- Preserve close to 100% of the signal and remove background

\[ \text{D}^+ \rightarrow \text{K}^- \pi^+ \pi^+ \]
\[ \text{pp} \sqrt{s} = 7 \text{ TeV} \]

\[ \text{pp} \sqrt{s} = 7 \text{ TeV} \]

**Graphs:**
- **With PID**
  - Mean = 1.869 ± 0.001
  - Sigma = 0.014 ± 0.001
  - Significance (3σ) 23.8 ± 1.1
- **Without PID**
  - Mean = 1.864 ± 0.001
  - Sigma = 0.016 ± 0.002
  - Significance (3σ) 19.1 ± 1.1
\[ D^*+ \rightarrow D^0\pi+ \rightarrow K-\pi+\pi+ \] selection

\[ D^{*\pm} \rightarrow D^0 \pi^\pm \quad (BR = 67.7\%) \]

\[ D^0 \rightarrow K\pi \quad (BR = 3.89\%) \]

- **Strong decay**
  - Topological selection of D0 daughters
  - Attach a pion to D0 candidates
    - *Low momentum (soft) pion*
  - Exploit narrow signal in
    \[ \Delta M = M(K\pi\pi) - M(K\pi) \]
    at the edge of phase space
    - *High S/B*