Probing Soft QCD and Double Parton Scattering (DPS) at LHCb

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Outline

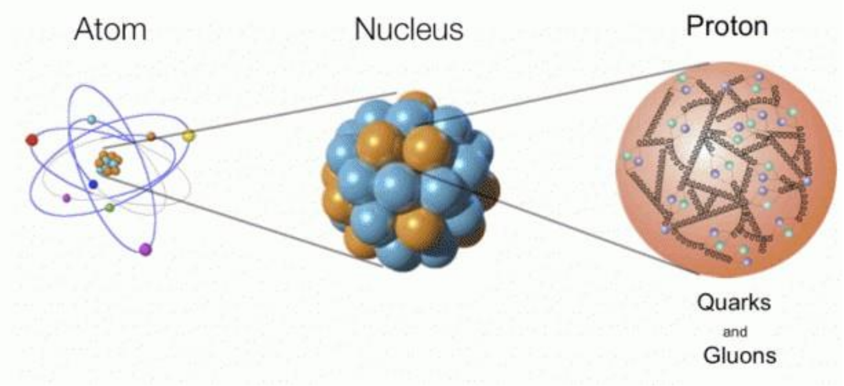
- Introduction to QCD
- LHCb Experiment
- Prompt Charged particles at 13TeV (JHEP 01 (2022) 166)
- Plan: Run3
- Results from LHCb aimed to understand DPS
  - Measurement of the J/ψ pair production cross-section in pp collisions at $\sqrt{s}$ = 13 TeV (JHEP06(2017)047)
  - Measurement of the nuclear modification factor and prompt charged particle production in pPb and pp collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (CERN-EP-2021-130)
- Conclusion

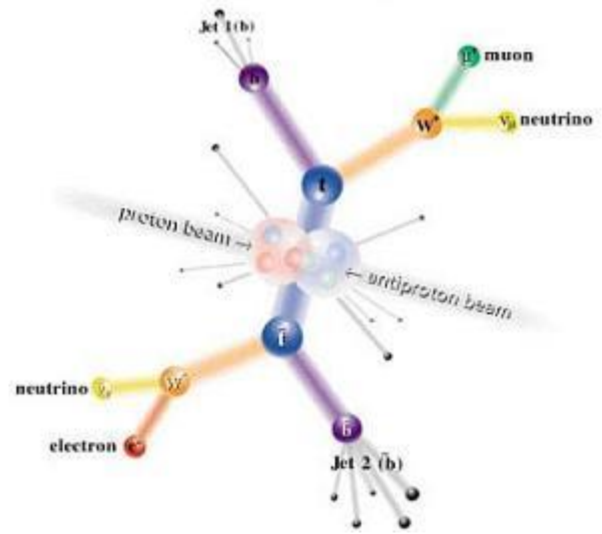
Quantum Chromodynamics (QCD)

Quantum Chromodynamics - the theory of quarks and gluons

- QCD : "nearly perfect" theory that explains nature's strong interactions, is a fundamental quantum theory of quarks and gluon fields
- The dynamics of particles are described by the SM Lagrangian, which is invariant under local gauge transformation group

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$





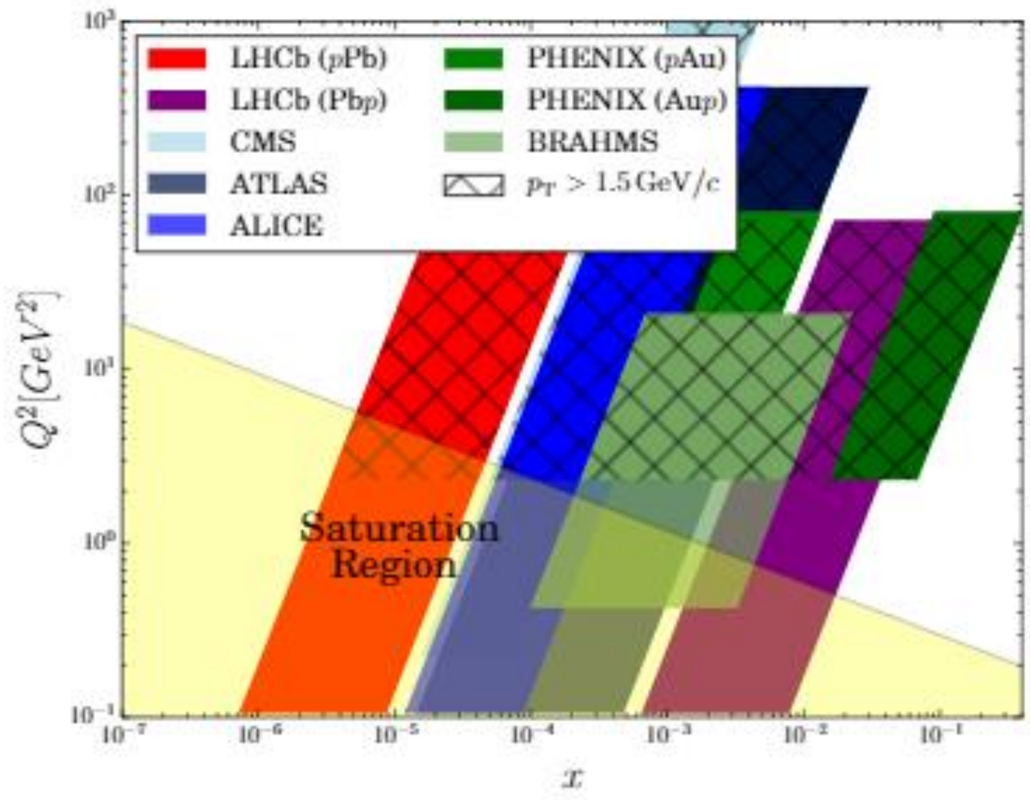
QCD: a practical tool for understanding matter

- at short distances quarks behave as free particles
- weak coupling
  Theory: Perturbation Theory
- at long distance (1fm) quarks confined, strong coupling
  Theory : Non-Perturbative

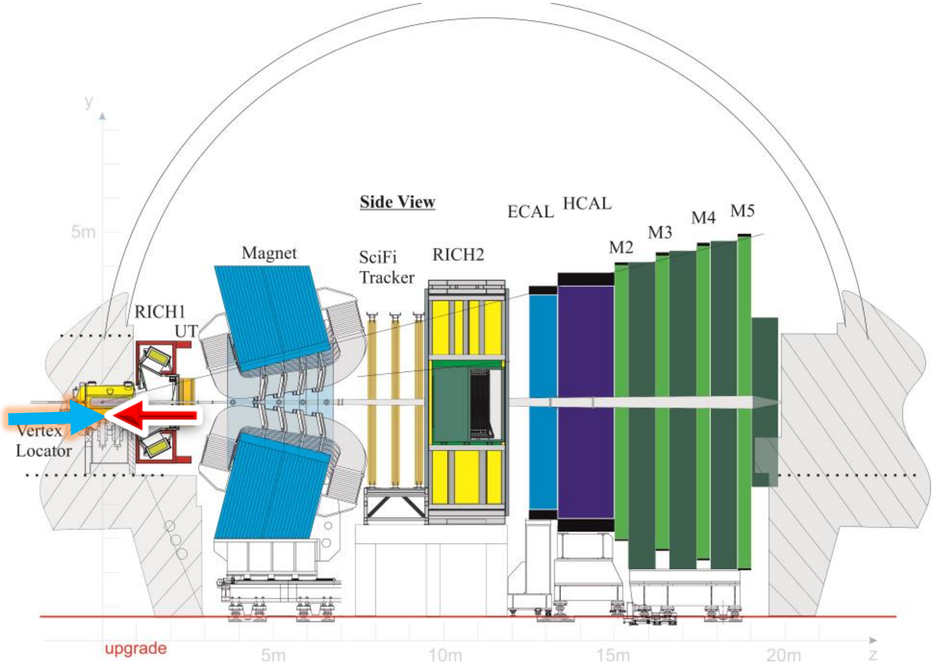
Why do we care about QCD?

- **QCD measurements @LHC**
  - test predictions of QCD phenomena at high(est) energies with large statistical samples

  Experiments at LHC
  - tests pQCD in a new energy regime (totally unexplored kinematic region).
  - provide constraints on PDFs,
  - measure strong coupling constant,
  - study initial and final state radiation fragmentation and parton showering effects.
  - tune MC generators to better describe the data



The LHCb Experiment



LHCb JINST 3 (2008) S08005

Physics at LHCb

- Matter-antimatter asymmetry
- CP Violation and rare decays of beauty and charm meson
- QCD, electroweak, exotica …

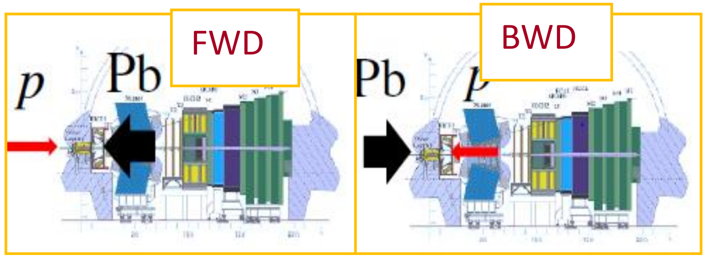
Upgrade:

- Trigger system
- UT
- VELO
- SciFi Tracker

- **Rapidity range 2< η < 4.5 : ~40% of heavy quarks produced hit the detector acceptance**
- **VELO : Decay time resolution ~45 fs**
- **Data Taking Efficiency : 90%**
- **Relative Track Momentum Resolution : 0.5% at low momentum, 1.0% at 200 GeV/c**
- **Track Reconstruction Efficiency : ~ 96 % for long tracks**
- **Selective and flexible Trigger**
- **High Quality Particle Identification**

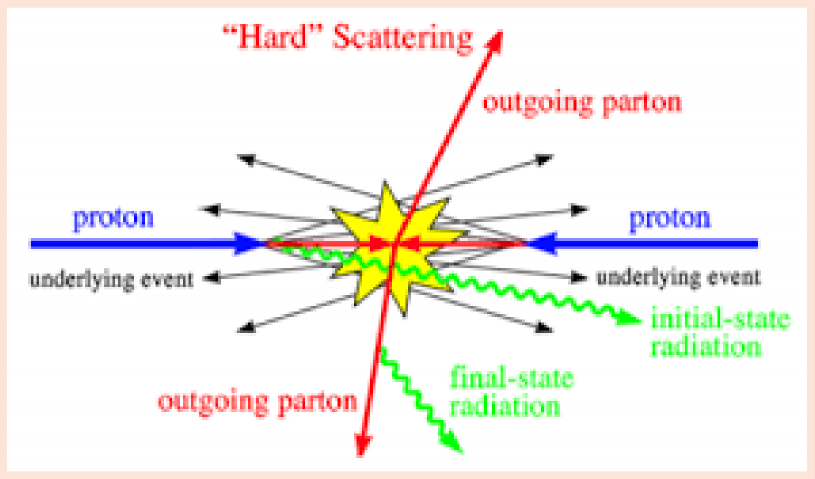
Quantum Chromodynamics at LHCb

- One way to study the innermost structure of hadrons and thus the properties of QCD is to use high energy protons and/or ions from particle accelerators.
- LHCb is a single-arm forward spectrometer designed to efficiently detect particles in $2 < \eta < 4.5$.
- This allows LHCb to make soft QCD measurements such as Parton Distribution Functions (PDFs) and proton structure to be studied in regions not accessible by other LHC experiments
  - At low x values and high Q^2 , **unexplored by other experiments**

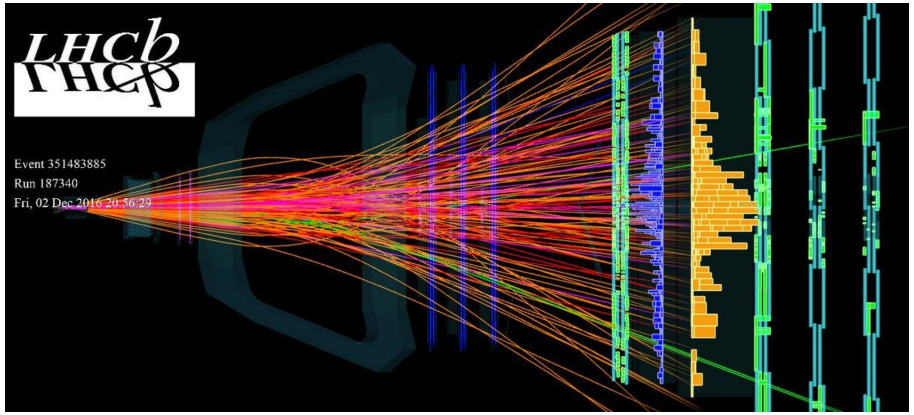


LHCb is also well prepared to study Double Parton Scattering (DPS)

Theoretically



Experimentally



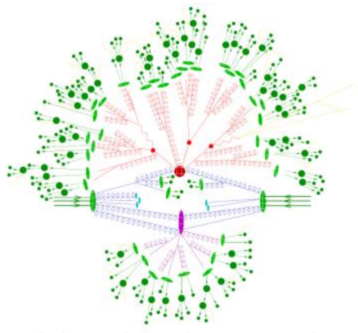
Collisions at LHCb

- Proton-proton (pp)
- Proton-Ion (pA)
- Ion-Ion (AA)

Anatomy of pp Collision

In a pp collision hard and soft processes are superimposed

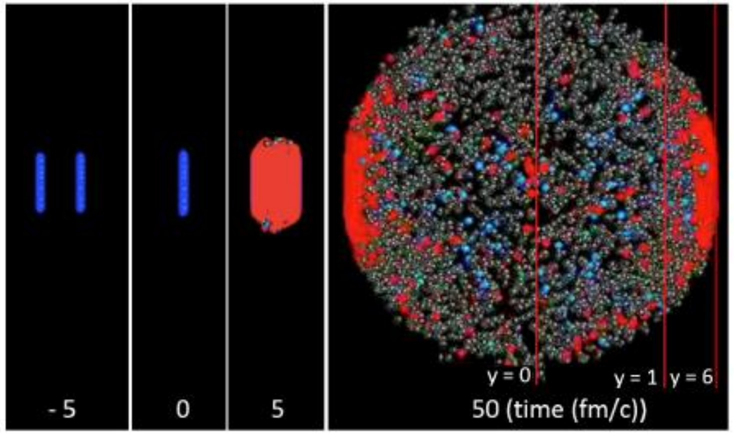
- Hadronization
- Initial State Radiations
- Final State Radiations
- Multiple Parton Interactions
- Double Parton Scattering
- Underlying events



Anatomy of AA Collision

In AA collisions the picture becomes complex.

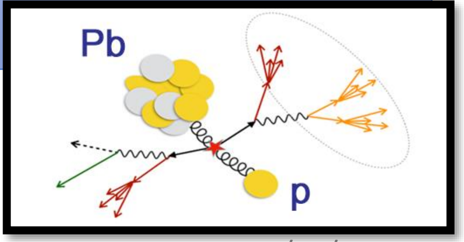
- The coupled quarks and gluons could be described as QGP (at 5fm/c)
- With time QGP expands by strong hydrodynamic pressure and cools down to hadronize into baryons and mesons



Anatomy of pA Collision

The pA collision is a baseline for AA collisions

The energy density is lower than AA, and also the modifications in particle production rate as compared to pp (Cold Nuclear Matter) effects



Measurement of prompt charged-particle production in pp collisions at $\sqrt{s}$ = 13 TeV

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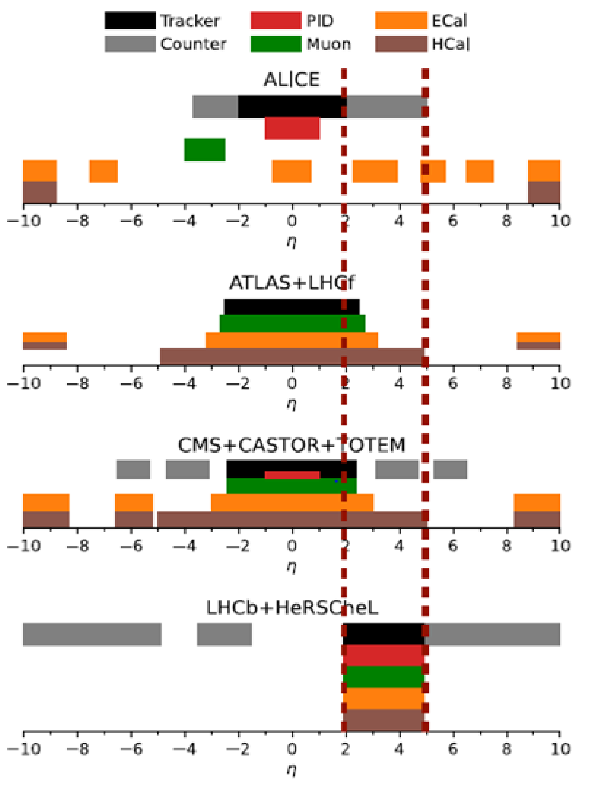
Motivation

- Measurements of hadrons production in high-energy collisions important input to phenomenological interaction models in non-perturbative quantum chromodynamics.
- These types of measurements have also been performed by ALICE, ATLAS & CMS **but** LHCb experiment is one of the unique experiment with the ability to study low-p_T processes at large η , tracking performance for charged particles with 2<p<1000 GeV, high quality particle identification and precise reconstruction which makes these results unique.
- Comparision to Monte Carlo Event Generators (not only for central regions)
- This paper took the longest time to publish because of the detector corrections and hence this is one of the reasons that this type of measurements would be useful for the measurement in RUN3.



Data Sample

- Zero-bias trigger in 2015
- Integrated luminosity of 5.4 nb^{-1}
- pp collisions at $\sqrt{s}$ = 13 TeV
- Models used for simulation are Pythia, EPOS,SIBYLL and QGSJETII

Differential Cross-section is computed as:

$$\frac{d^2\sigma}{d\eta dp_T} \equiv \frac{n}{\mathcal{L}\Delta\eta\Delta p_T}$$

n= number of prompt charged particles produced

Tracks

- Basic Selection

  "Use only tracks traversing the entire tracking system"

$$n_{cand} = \varepsilon n + \sum_i n_i$$

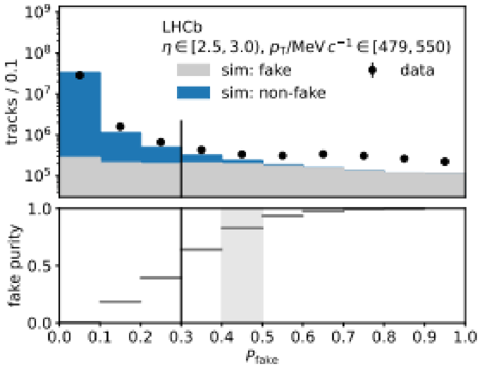
n_{cand} - number of candidate tracks
n – number of signal particles
ε- total efficiency (simulation)
$\sum_i n_i$- number of background tracks from various sources (simulation)

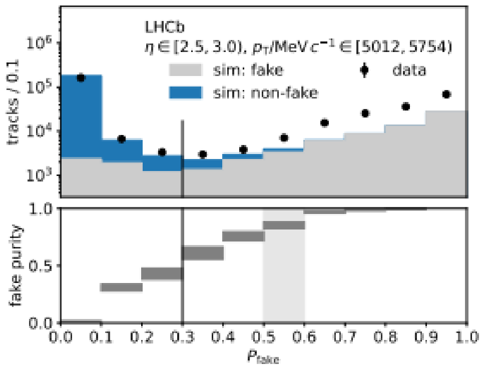
Fake tracks

- Random matches of hits
- They are of two types
  - Fake tracks in isolation
  - Fake tracks nearby a real track
- Require fake-track probability of $P_{\text{fake}} < 0.3$ (fake tracks in isolation) $\sim 40 - 80\%$ *of the fake tracks are rejected*
- It is suppressed by the track reconstruction software (fake tracks nearby a real track)

Proxy for Fake tracks

- In each kinematic bin divide P_{fake} distribution into ten bins





Non-Prompt Tracks

- Source of background
  - Originate from the interaction of particles with the detector material or decays of long-lived particles
  - Contribution from interaction of beam with the residual gas are establish based on control sample

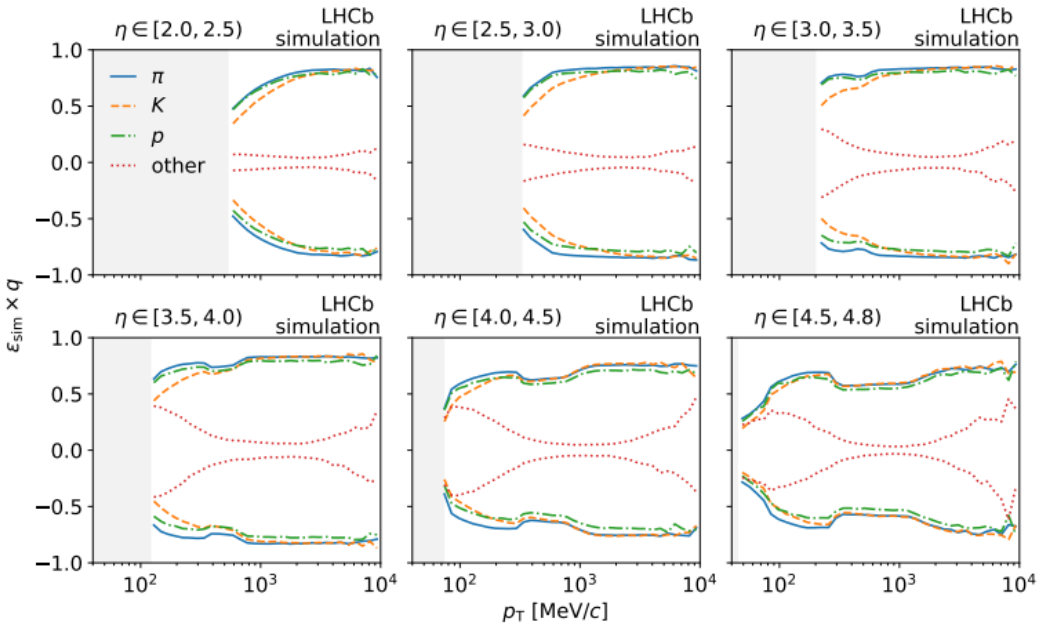
Proxy for Material Interactions

- Number of tracks produced in interactions of charged pions with the detector material form combinations of three tracks hadronic interactions produce 3 or more charged particles)
- Apply further topological and kinematic requirements optimised using simulation

Detector Corrections and Efficiencies

- The total efficiency to observe prompt long-lived charged particles depends on:
  - Geometric acceptance of the detector (simulation)
  - Track-reconstruction efficiency (simulation)
  - Particle loss due to decays or Interactions with the detector material

  Track-reconstruction efficiency is corrected based on results from muon tracks (J/$\psi \rightarrow \mu\mu$)



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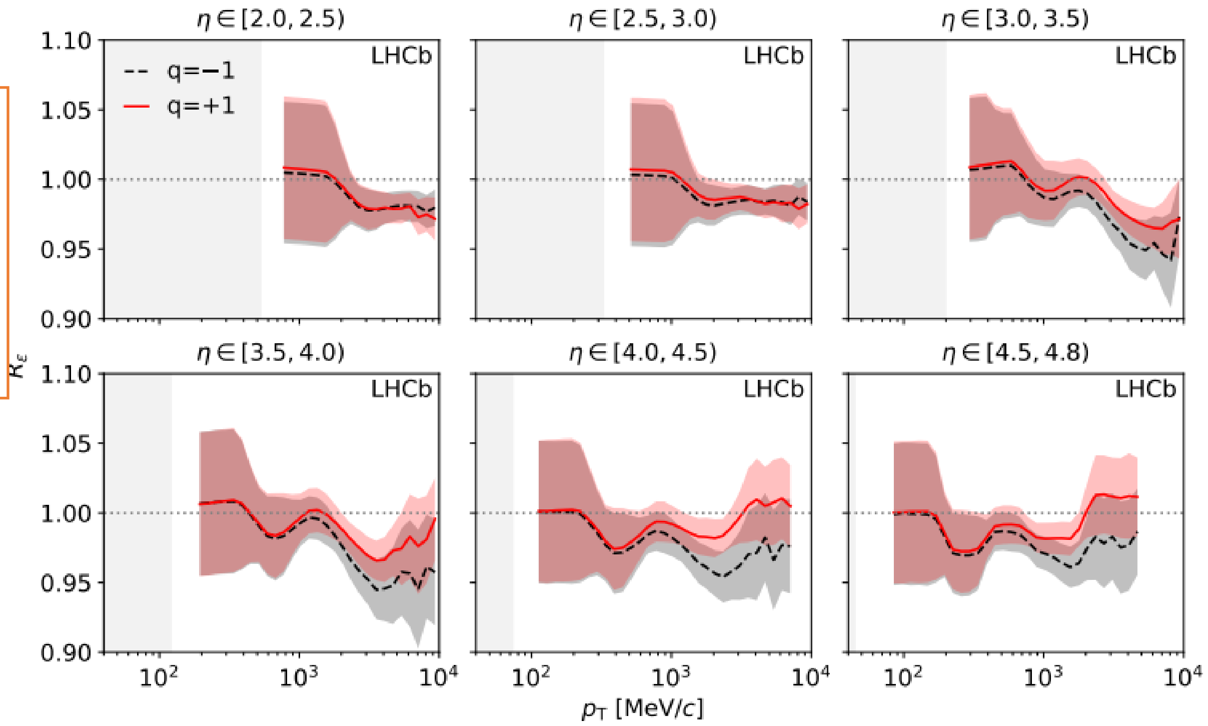
The simulated efficiencies are shown for the charged particles and they are lower for other particles Σ^-, Ξ^- *and* Ω^- because of their shorter lifetimes and higher for e^- *and* μ^-

The simulated efficiency is validated against data

Correction of Simulated Particle Composition

- Simulated particle composition is then corrected by extrapolating LHCb measurements of ratios of prompt hadron production from $\sqrt{s}$ = 0.9 TeV and 7 TeV Eur. Phys. J. C 72, 2168 (2012) to 13 TeV.

- Efficiency corrections, R_ε, for positively and negatively charged particles
- The bands indicate the systematic uncertainty.
- The light-grey areas represent the limit of the kinematic acceptance.



Cross-section Determination and Ratios

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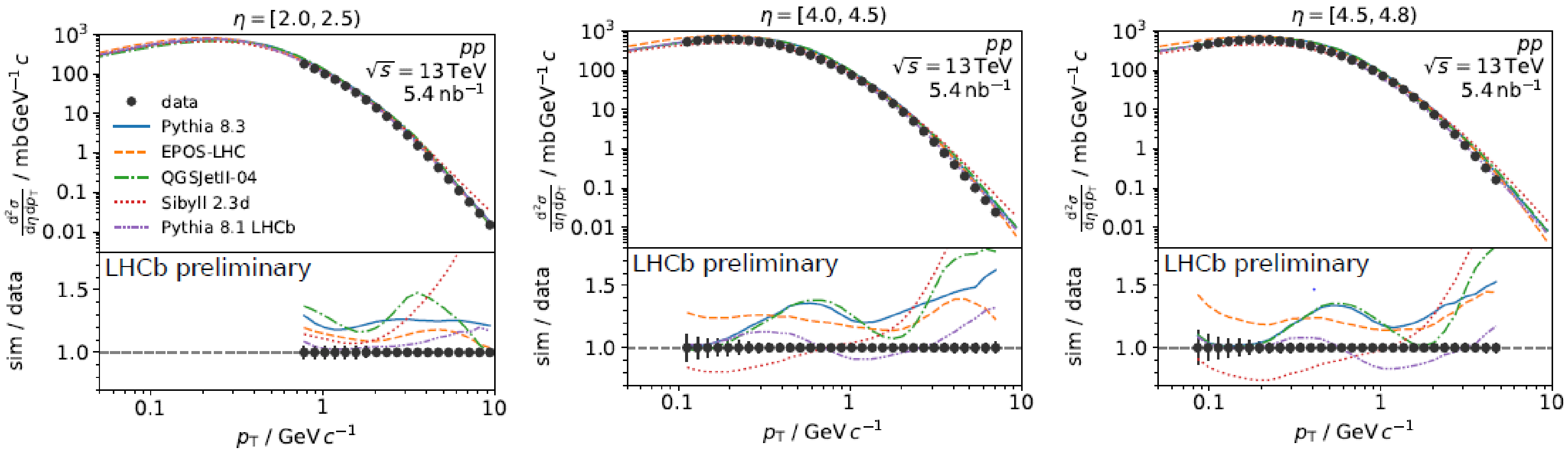
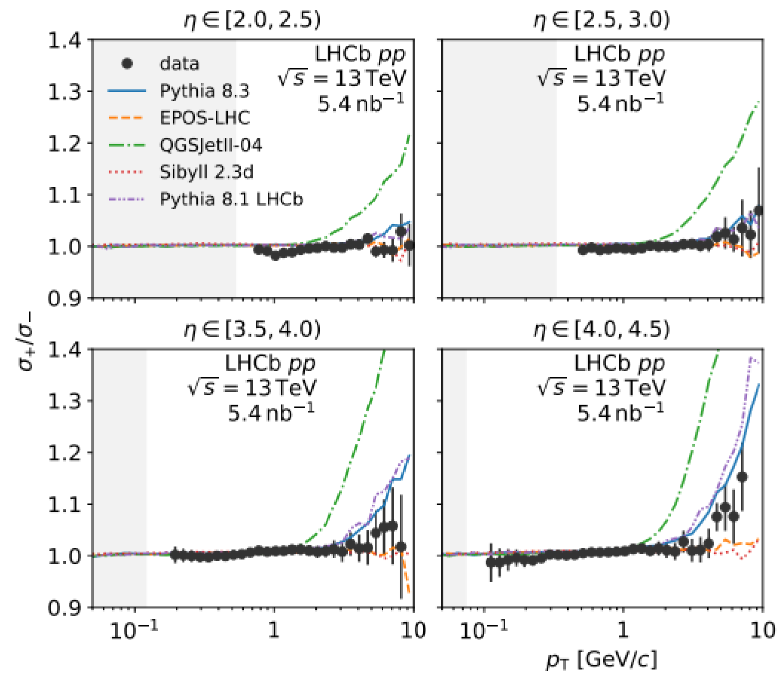




- Differential cross-section is shown as a function of p_T in intervals of η
- Smallest overall deviation observed for EPOS-LHC

- Ratios of the differential cross-sections of positively and negatively charged particles as a function of p_T in intervals of η for the data and models
- Best description is provided by Pythia 8.3

Plan: Run 3

- Measurements of hadron production in new detector with new trigger, new tracking and new data flow
- Comparision with Run 2 and Generators (Pythia 8.3, Herwig+)
- LHCb starting this year with not completely installed VELO, UT and with SciFi
- In 2022 we would be able to measure:
  - Event Multiplicity
  - Energy flow

Analysis Strategy

Multiplicity Distribution of the prompt long-lived charged particles (protons, pions and kaons)

- Minbias sample in pp collision at $\sqrt{s}$ = 13 TeV from RUN3
- Analysis would be done separately for positively and negatively charged particles
- Strange hadron analysis would also be studied
- $\eta \in [2.0, 4.8) \rightarrow$ LHCb Acceptance

J/ψ pair production cross-section in pp collisions

Measurement of the J/ψ pair production cross-section in pp collisions at $\sqrt{s}$ = 13 TeV

JHEP 06 (2017) 047

Motivation:

- Production of J/ψ mesons pairs in pp collision
- DPS can also contribute to quarkonium pair production
- DPS provides information on p_t of partons and their correlation inside proton

$$\sigma^{DPS}_{hh\to ab} = \left(\frac{m}{2}\right)\frac{\sigma^{SPS}_{hh\to a}\,\sigma^{SPS}_{hh\to b}}{\sigma_{eff}}$$

m is the number of "distinguishable partonic subprocesses"
m=1 when a=b
m=2 when a≠b

Data Sample:

- pp collision at 13 TeV using 279$\pm$11 pb^{-1}data.
- Both J/ψ mesons, p_t < 10 GeV/c , 2.0 < y < 4.5

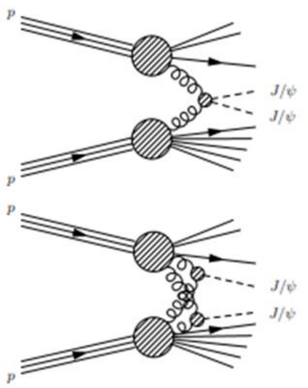
Trigger targeted at selecting high quality muons.

- Good track qualities having:
  p_t > 0.65 GeV/c; 6 < p < 200 GeV/c; 2 < η < 5;
- Four muons to come from the same PV
- Duplicate tracks and multiple candidates removed

Master Equation to calculate cross-section:

$$\boldsymbol{\sigma(J/\psi J/\psi) = \frac{N^{cor}}{\mathcal{L} \times \mathcal{B}(J/\psi \to \mu^+\mu^-)^2}}$$

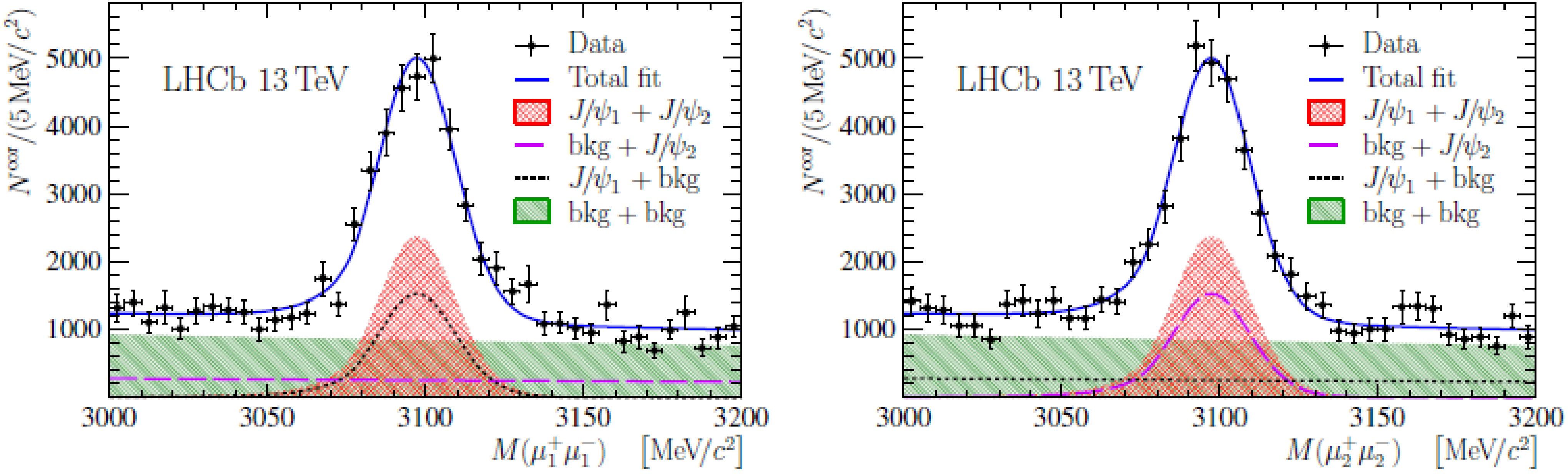
$$\sigma_{DPS}(\mathrm{J}/\psi\mathrm{J}/\psi) = \frac{1}{2}\frac{\sigma(\mathrm{J}/\psi)^2}{\sigma_{eff}}$$



$\boldsymbol{N^{cor}}$ - signal yield after per event efficiency correction
$\boldsymbol{\mathcal{L}}$- Integrated Luminosity
$\boldsymbol{\mathcal{B}(J/\psi \to \mu^+\mu^-)^2}$ - Branching fraction

Cross-section Determination

[JHEP 06 (2017) 047]



- Signal yield is obtained by fitting to efficiency-corrected 2D mass distribution
- Residual: Residual Contamination from b-hadron decays is determined using simulation
- $\boldsymbol{N^{cor}}$ = $(15.8 \pm 1.1) \times 10^3$
- Cross-section : **$\boldsymbol{\sigma(J/\psi\, J/\psi)}$ = 15.2 $\pm$1.0 (stat) $\boldsymbol{\pm 0.9\ (syst)\ nb}$**

Comparison with Theoretical Predictions

Most significant indication of DPS is from $|\Delta y|$ and $m(J/\psi\, J/\psi)$

For $|\Delta y| > 1.5$ – no SPS contributions (theory)

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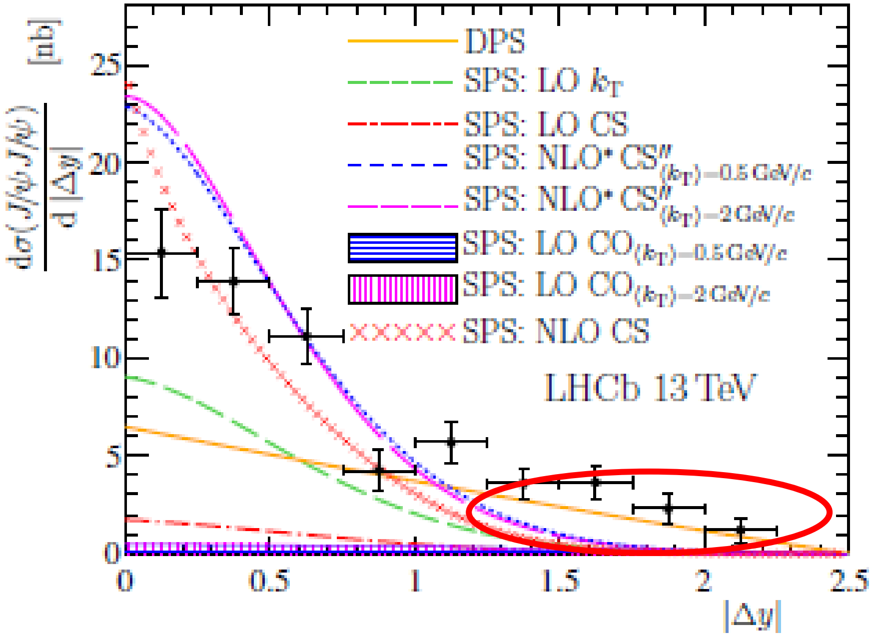

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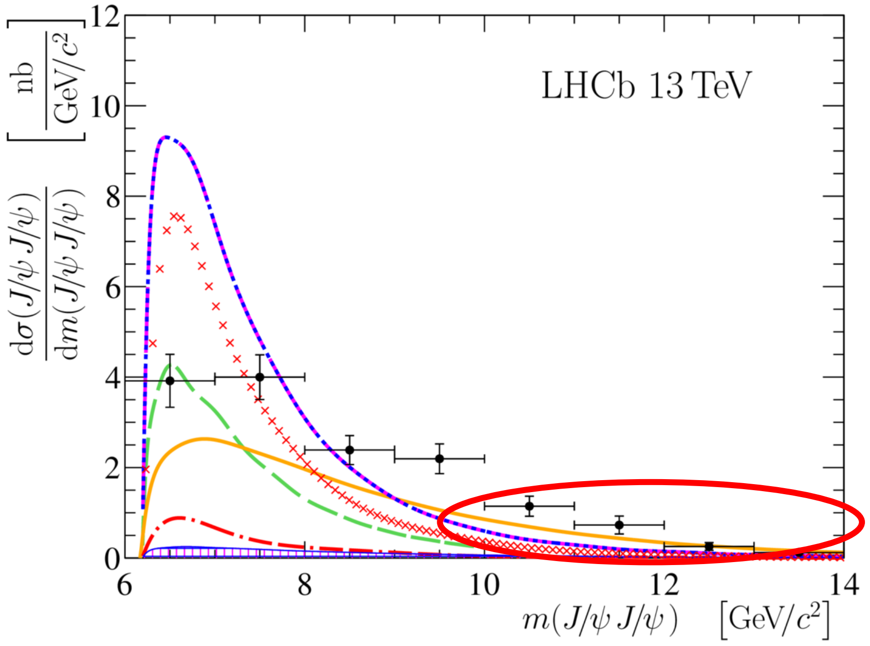
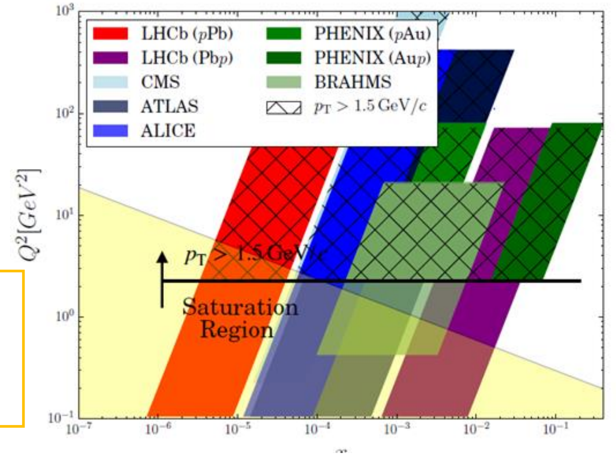


To derive the DPS fraction the distributions are fit to templates that fix the predicted DPS and SPS shapes

Charged particle production in pPb at $\sqrt{s_{NN}}$ = 5.02 TeV

Measurement of the nuclear modification factor and prompt charged particle production in pPb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV (CERN-EP-2021-130)



Motivation

- Collisions of pPb provide study of nuclear effects in initial and final state.
- Dynamics of HI probed in context of Cold Nuclear Matter(CNM) and saturation scale

Background:

- fake tracks ~algorithm
- secondary particles ~Small IP

$$R_{pA} \equiv \frac{\sigma_{pA}}{A\sigma_{pp}}$$

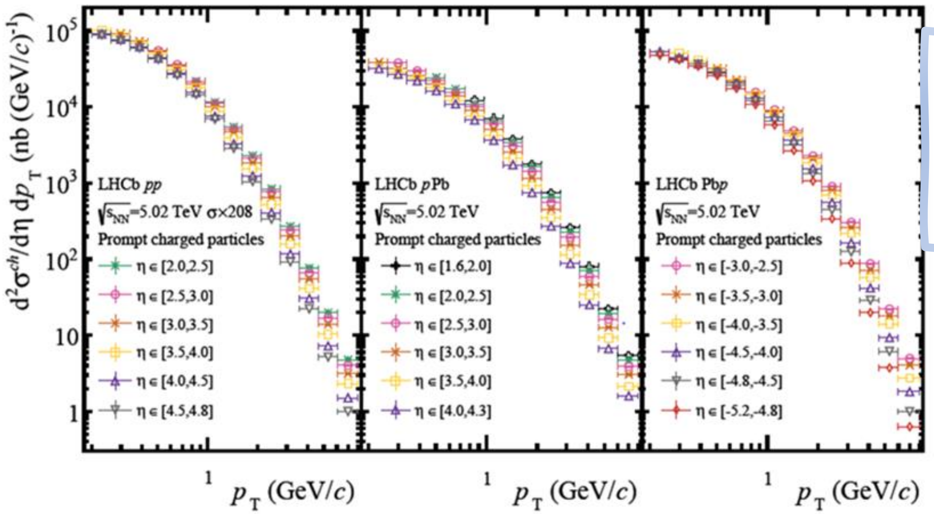
Data Sample

LHCb pPb data from 2013 (81.84 μb^{-1}), pp – 2015 (3.49 nb^{-1}).

- $p > 0.2$ GeV/c, $0.2 < p_T < 8$ GeV/c,
- pp : $2 < \eta < 4.8$
- pPb (FWD): $1.5 < \eta < 4.3$
- pPb (BWD): $-5.3 < \eta < -2.5$.

Selection with min bias trigger (one reconstructed track).

MC models: pPb→EPOS-LHC and pp→Pythia



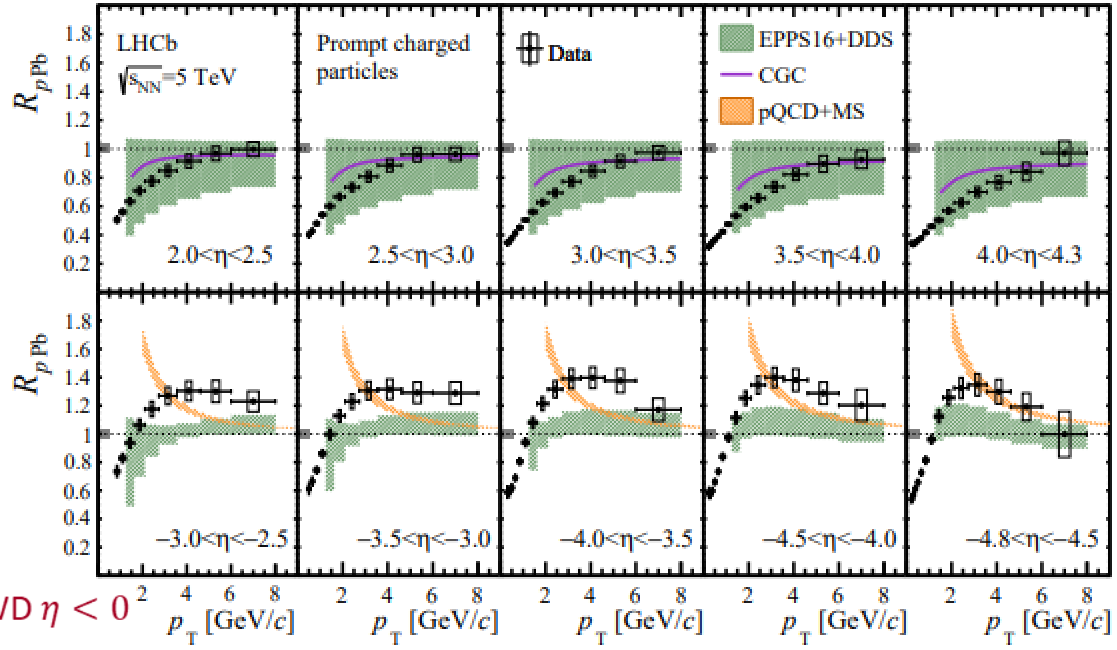
Differential cross-section:

$$\frac{d^2\sigma^{ch}(\eta, p_T)}{d\eta\, dp_T} \equiv \frac{N^{ch}}{\mathcal{L}\, \Delta\eta\, \Delta p_T}$$

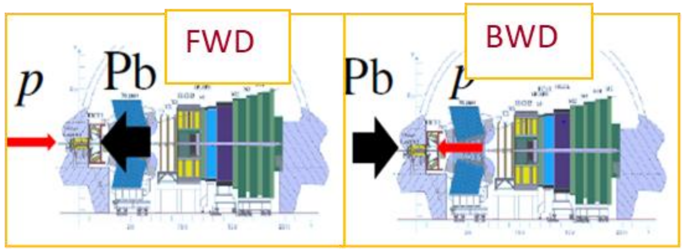
Nuclear Modification Factor

CERN-EP-2021-130

FWD $\eta > 0$



BWD $\eta < 0$



Results:

1. Suppression of charged particle production in pPb wrt pp at forward rapidity reaching $R_{pPb} = 0.3$ for low-p_T and high η.
2. Enhancement at backward rapidity for $p_T > 1.5$ GeV/c. Max $R_{pPb} \sim 1.3$ is reached (depending on η).

Comparison with models for $p_T > 1.5$ GeV/c:

- nPDF set EPPS16 and CT14 reproduces forward data (within large uncertainties),
- CGC in the FWD (saturation region),
- pQCD+Multiple Scattering in the nucleus in agreement with the most backward data, but is unable to reproduce the other regions.

Nuclear Modification Factor

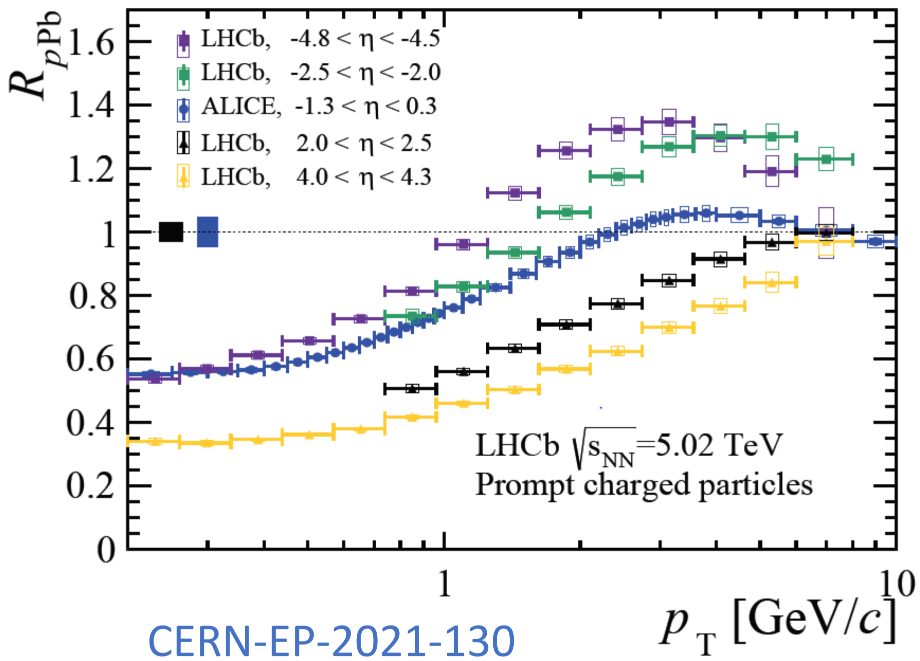
Comparison with other experiments:

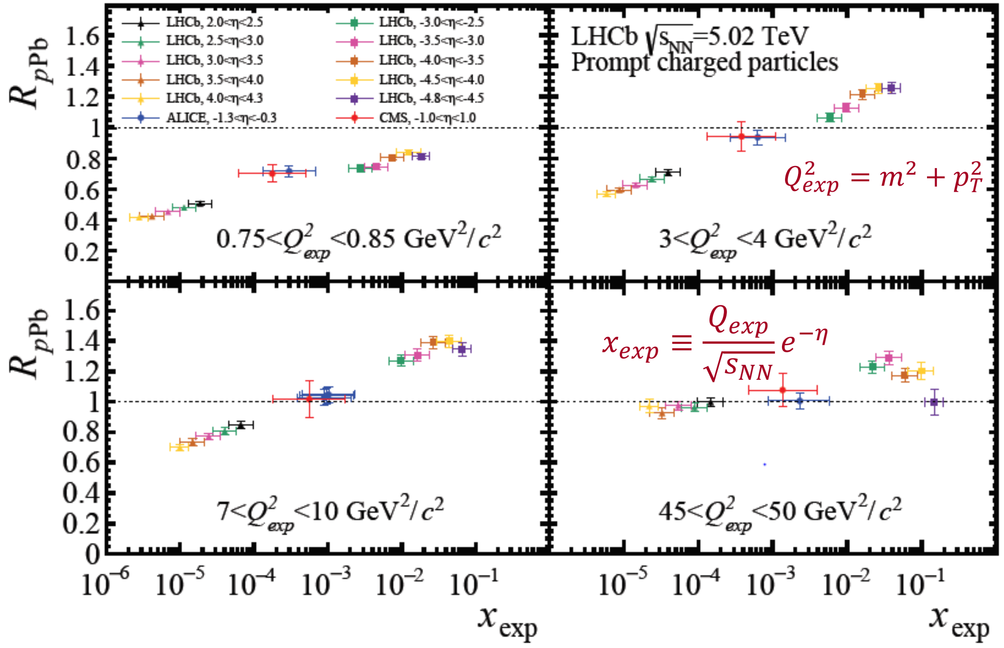
- Most precise measurement of R_{pPb} to date.
- New LHCb result extended R_{pPb} coverage from very backward to very forward rapidity.

Evolution with x and Q^2 (crucial for Cold Nuclear Matter study):

$$Q^2_{exp} = m^2 + p_T^2,\ m = 256\ \text{MeV/c}^2,\ x_{exp} \equiv \frac{Q_{exp}}{\sqrt{s_{NN}}} e^{-\eta}$$

- Agreement in bins of Q^2_{exp}.
- R_{pPb} depends on x_{exp} with start of decreasing at $x_{exp} > 0.1$





[CERN-EP-2021-130](https://cds.cern.ch/record/2021130)

Conclusion

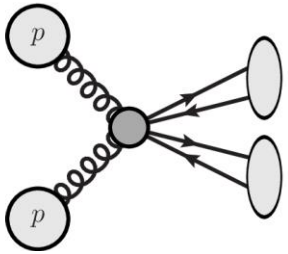
- LHCb detector is a forward general-purpose detector with flexible data acquisition, excellent lifetime resolution and charged particle identification.
- Soft QCD and double parton scattering are actively studied as complementary to other LHC experiments.
- I have presented some of the recent LHCb results on double-parton scattering:
  - Measurement of prompt charged-particle production in pp collisions at $\sqrt{s}$ = 13 TeV (JHEP 01 (2022) 166)
  - Measurement of the J/ψ pair production cross-section in pp collisions at $\sqrt{s}$ = 13 TeV (JHEP06(2017)047)
  - Measurement of the nuclear modification factor and prompt charged particle production in pPb and pp collisions at $\sqrt{s_{NN}}$ =5.02 TeV (CERN-EP-2021-130)
- Production of charged particles in proton-proton and proton-lead collisions with the comparison to various physics models.
- I have also presented the prospects for early QCD measurements in modernised LHCb spectrometer in Run 3.

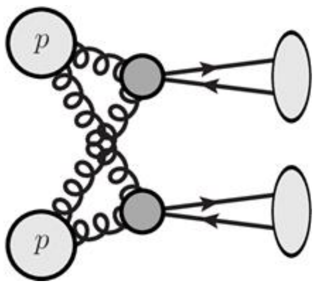
Thank You.. !!

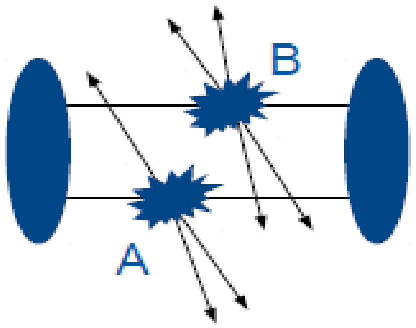
Back-Up

Double Parton Scattering

- Single Parton Scattering
  - One hard parton-parton scatter
  - Probe higher order diagrams
- Double Parton Scattering
  - Two hard scatters within same protons
  - Increasingly important at higher s
  - Partonic correlations







$$\sigma_{hh\to ab}^{DPS} = \left(\frac{m}{2}\right)\frac{\sigma_{hh\to a}^{SPS}\,\sigma_{hh\to b}^{SPS}}{\sigma_{eff}}$$

$$d\sigma^{h_1h_2\to cd} = \int_0^1 dx_1 \int_0^1 dx_2 \sum_{a,b} f_{a/h_1}(x_1,\mu_F^2) f_{b/h_2}(x_2,\mu_F^2)\, d\sigma^{ab\to cd}(Q^2,\mu_F^2)$$

m is the number of “distinguishable partonic subprocesses”
m=1 when a=b
m=2 when a≠b

$f_{a/h_i}(x_i)$: Parton Distribution Function (PDF) (non-perturbative)
$\sigma^{ab\to cd}$: Partonic cross-section (perturbative)

σ_{eff} is effective cross-section, and is related to collision geometry (independent from final state)

Double parton Scattering and σ_{eff}

σ_{eff}

- characterizes size of effective interaction region ,
- gives information on the spatial distribution of partons
- Effective cross section σ_{eff} is directly related with parton spatial density

$$\sigma_{DPS} = \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}}$$

$$\sigma_{\text{eff}} = [\int d^2\beta [F(\beta)]^2]^{-1}$$

$$F(\beta) = \int f(b) f(1-b) d^2 b$$

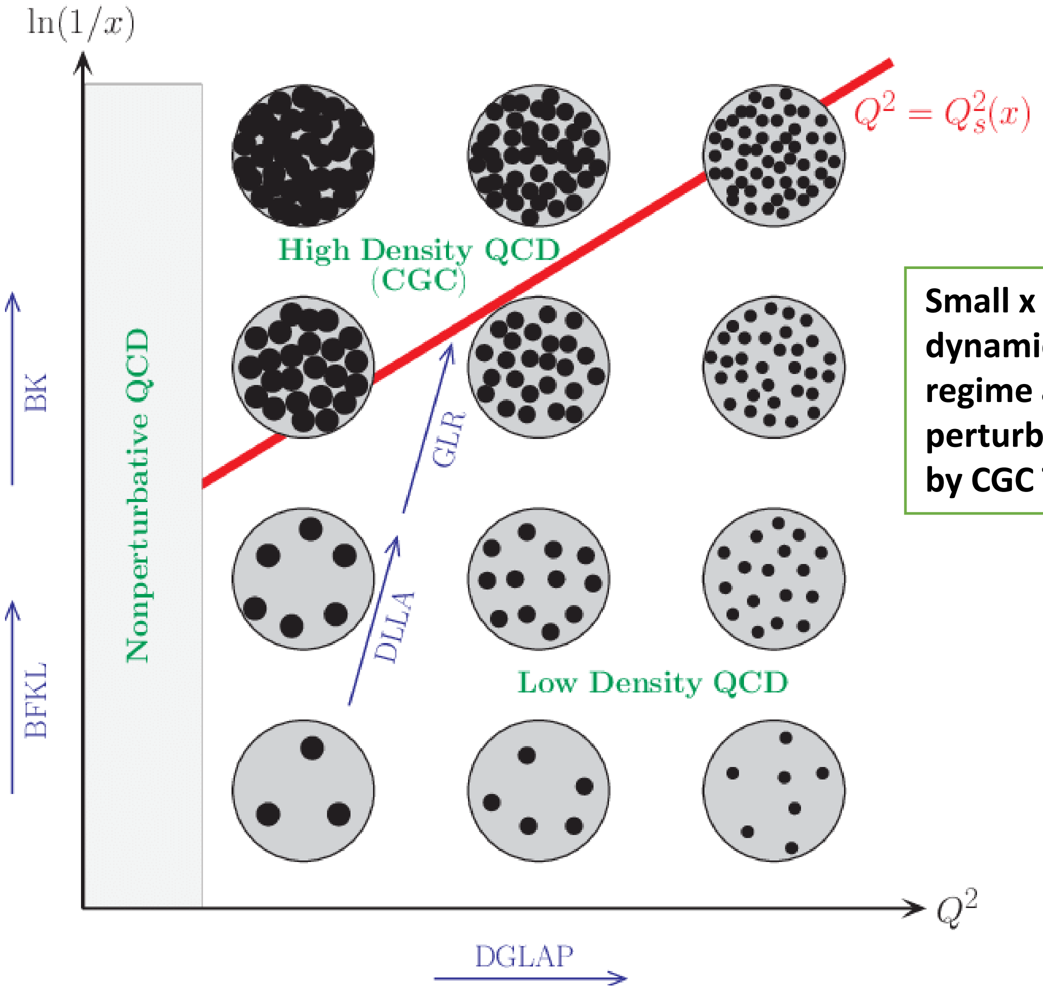
β is impact parameter

where f(b) is the density of partons in transverse space.

=> Having σ_{eff} measured we can estimate f(b)

Color Glass Condensate

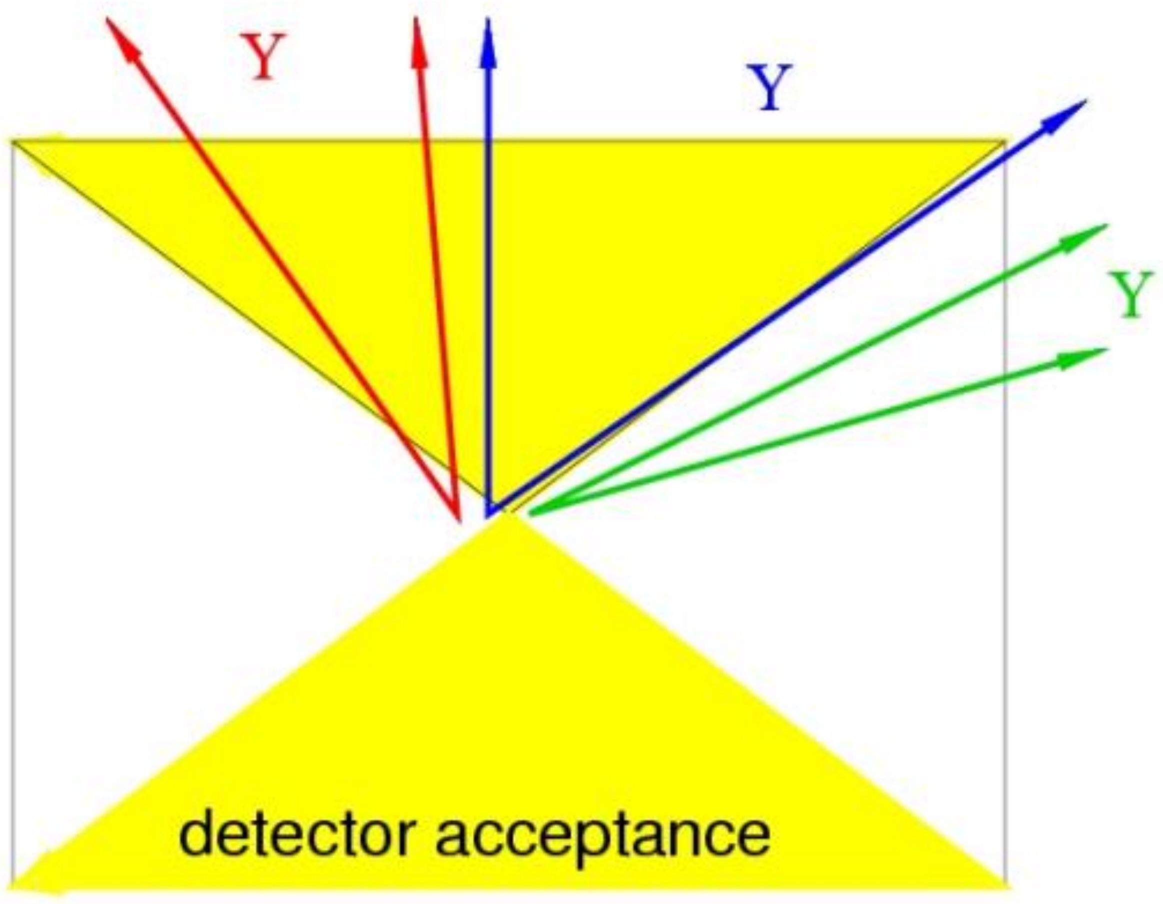
CGC Model



Small x and small Q^2 , the dynamics of QCD in this regime are non linear, non-perturbative and described by CGC Theory.

Geometric Acceptance of the detector

- Acceptance
  - refers to purely geometric fiducial volume of the detector
- Efficiency
  - refers to purely detector effectiveness in finding objects which have passed through the detector



Double Parton Scattering in p-Pb Collisions

Observation of enhanced double parton scattering in proton-lead collisions at $\sqrt{s_{NN}}$= 8.16 TeV

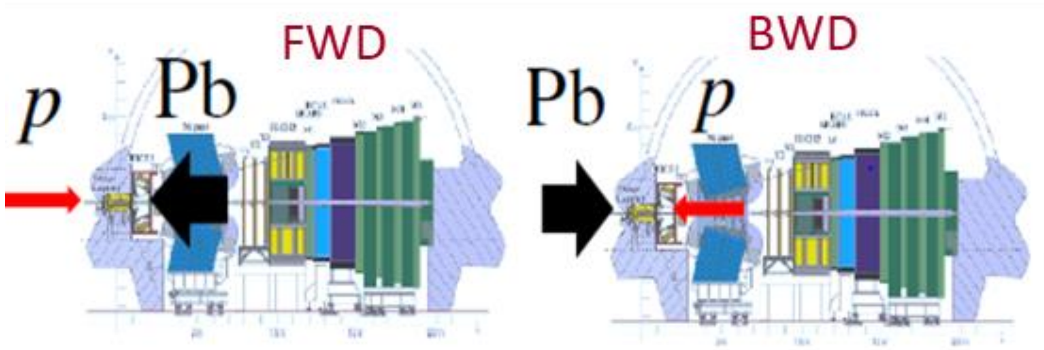
Phys. Rev. Lett.**125**, 212001(2020)

Motivation:

- Ratio of DPS to SPS cross-section in pPb is expected to be about 3 times larger than in pp

Data Sample:

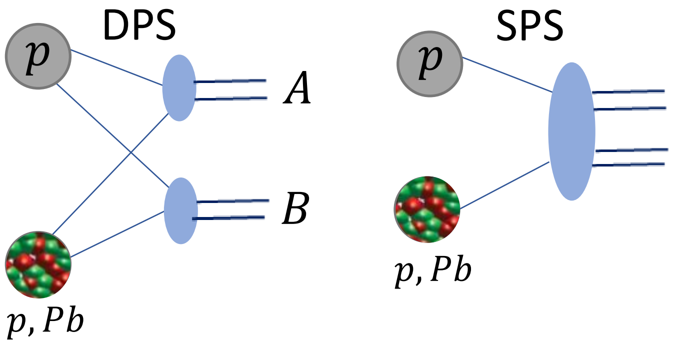
- pPb collision at 8.16 TeV using 30 nb^{-1}
- FWD and BWD pPb data: 12.2±0.3 nb^{-1} and 18.6±0.5 nb^{-1}
- Pairs (A,B) of Interest: $D^0D^{\pm}, D^0D_s^{\pm}, J/\psi D^{0,\pm}$



$$pp(pPb) \to A + B + X$$

$$\sigma_{DPS}^{AB} = \frac{k}{2}\frac{\sigma^A\,\sigma^B}{\sigma_{eff}}$$

$k = 1(2)$ for $A = B(\neq B)$



$A, B \equiv D = \{D^0, D^+, D_s^+\}$ and cc

Results

$\Delta\phi$ Distribution for D^0D^0 and $D^0\overline{D^0}$ with and without $p_t\ (D^0)$ > 2 GeV/c.

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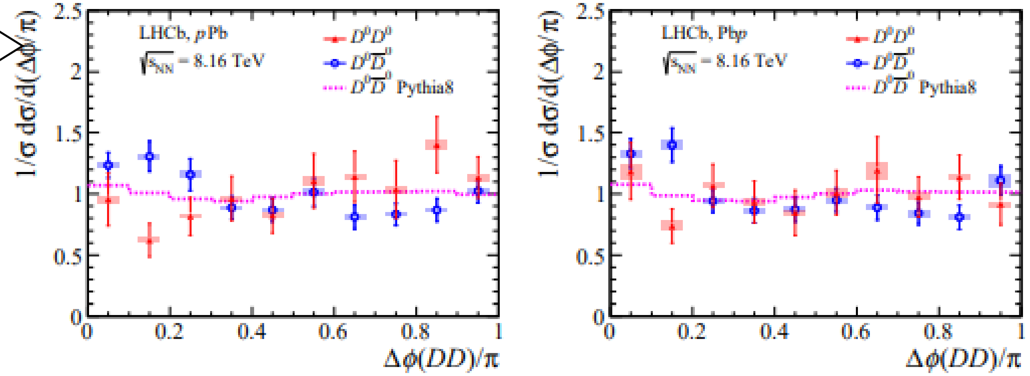
Without the condition ⇒ uniform for both LS and OS pairs



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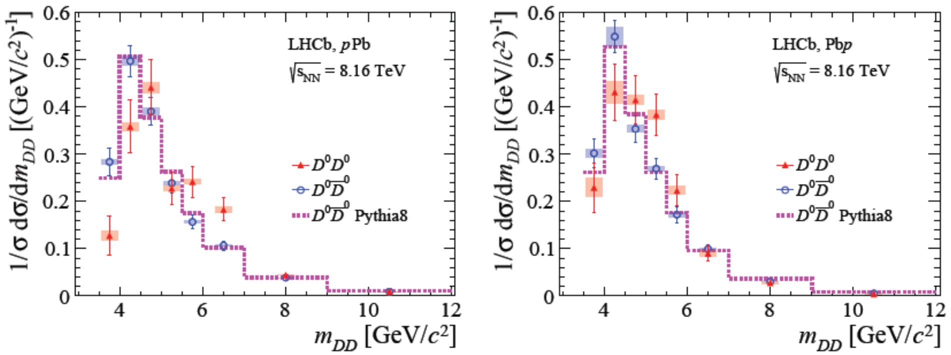
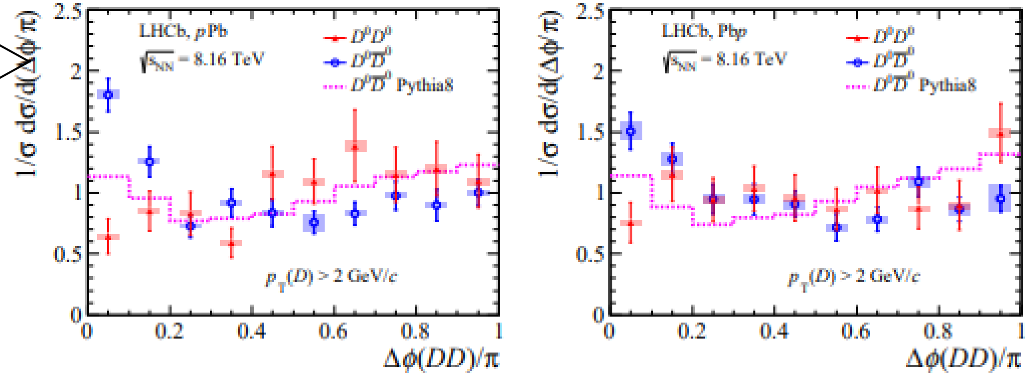


With $p_t\ (D^0)$ > 2 GeV/c



- Distribution for m_{DD} in $D^0\overline{D^0}$ pairs peaks at higher values as compared to D^0D^0.
- $D^0\overline{D^0}$favors $\Delta\phi \sim 0$, compatible with being flat and inconsistent with Pythia8 simulations.
- Uniform D^0D^0 $\Delta\phi$ distributions are consistent with large DPS contribution in LS pair production

σ_{eff} and R

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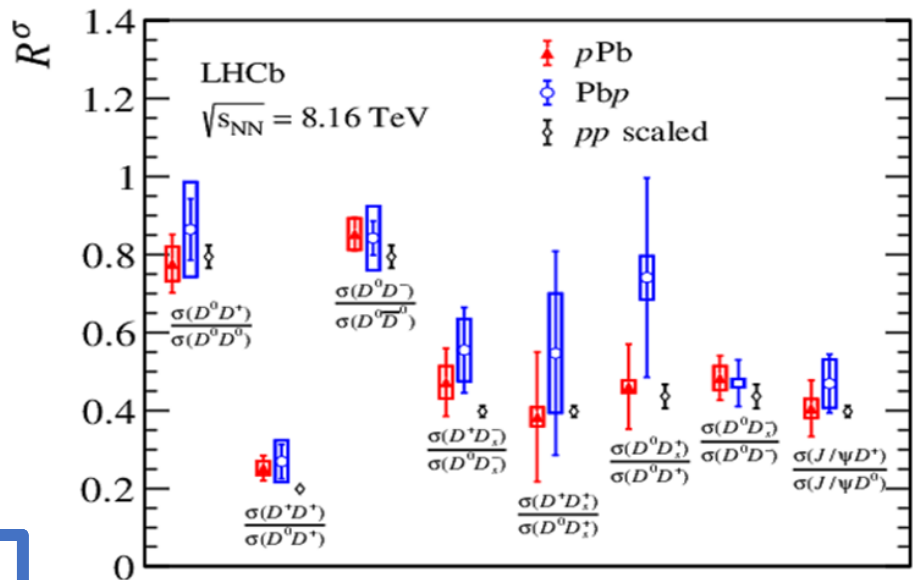
$$R \equiv \frac{\sigma_{pPb}}{208\sigma_{pp}}$$

R is measured for $J/\psi D^0$ and $D^0 D^0$:
σ_{pPb} - cross-section of charm pairs in pPb
σ_{pp}- cross-section of charm pairs in pp

Results:
Nuclear Modification factors for pPb (Pbp)

$$R^{D^0D^0} = 1.3 \pm 0.2 \ (4.2 \pm 0.8)$$
$$R^{J/\psi D^0} = 1.5 \pm 0.5 \ (4.6 \pm 1.3)$$



Pairs	$-5 < y(H_c) < -2.5$	$1.5 < y(H_c) < 4$	pp extrapolation
D^0D^0	$0.99 \pm 0.09 \pm 0.09$	$1.41 \pm 0.11 \pm 0.10$	4.3 ± 0.5
$J/\psi D^0$	$0.64 \pm 0.10 \pm 0.06$	$0.92 \pm 0.22 \pm 0.06$	3.1 ± 0.3

$\sigma_{eff,pp}$ scaled by Pb nucleus (208)

$$\boldsymbol{\sigma} = \frac{\boldsymbol{N^{cor}}}{\boldsymbol{\mathcal{L} \times \mathcal{B}_1 \times \mathcal{B}_2}}$$

$$\sigma_{eff}(DD) = \frac{1}{2}\frac{\sigma_D\,\sigma_D}{\sigma_{DD}(DPS)}$$

$$\sigma_{eff}(\psi D) = \frac{\sigma_\psi\,\sigma_D}{\sigma_{\psi D}(DPS)}$$

The results confirm the expectation that DPS production in pPb collisions is enhanced by factor 3 compared to SPS