XXVIII CRACOW EPIPHANY CONFERENCE
10-14 JANUARY 2022

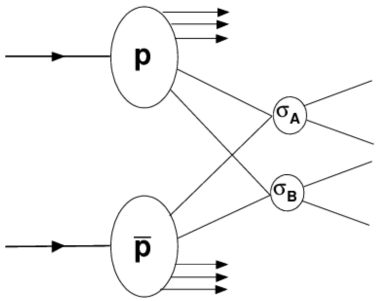
Double-parton Scattering at LHCb and Pythia Tunings

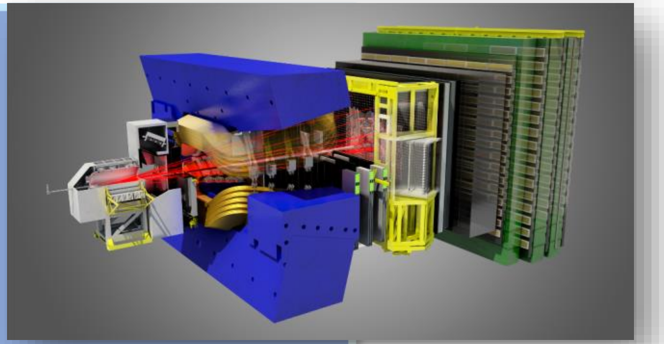
Saliha Bashir

AGH-UST Kraków, Poland

On behalf of LHCb Collaboration

Outline

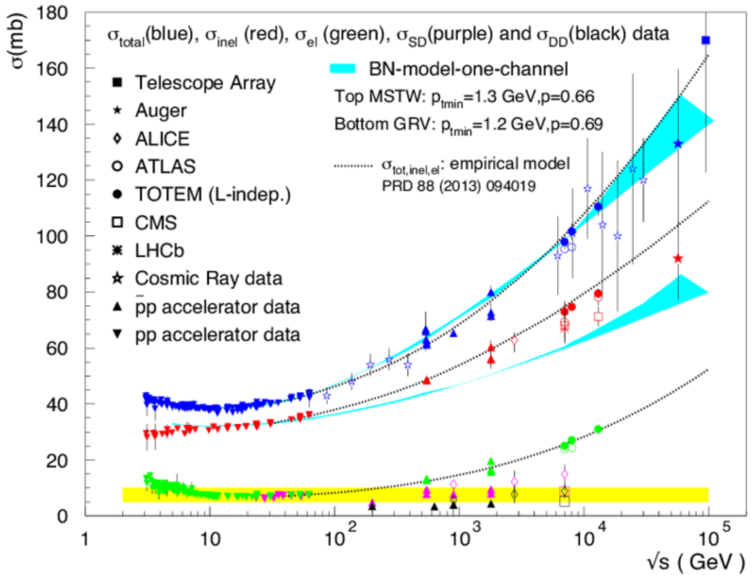




- Motivation
  - Astrophysics
  - Double Parton Scattering (DPS)
  - Soft QCD
- LHCb Experiment
- Recent LHCb Results Aimed to understand DPS
  - Measurement of the J/ψ pair production cross-section in pp collisions at $\sqrt{s_{NN}}$ = 13 TeV JHEP 06 (2017) 047
  - Observation of enhanced double parton scattering in proton-lead collisions at $\sqrt{s_{NN}}$= 8.16 TeV Phys. Rev. Lett.125, 212001(2020)
- Pythia Tunes and Multiplicity Studies

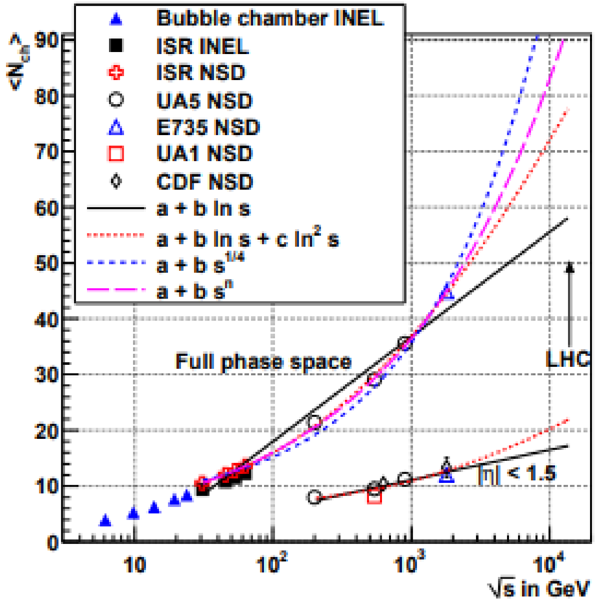
Astrophysics Data and LHC

MC generators go beyond collider Physics: they are also used in cosmic ray Physics to model interactions of cosmic rays with atmosphere



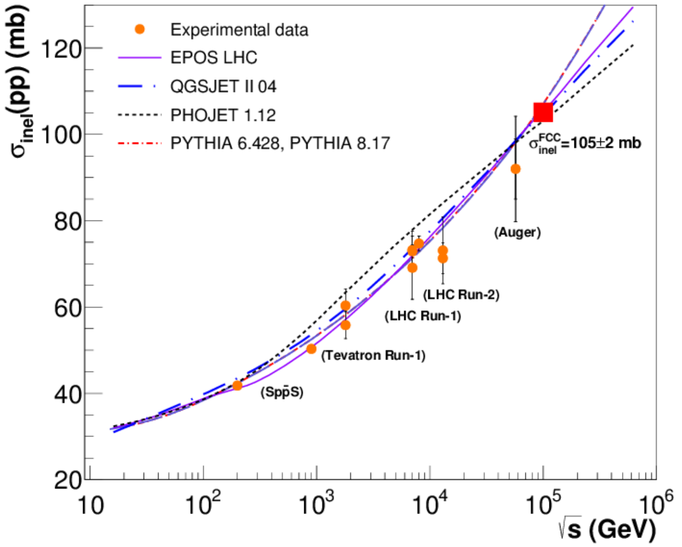
EPJ Web of Conferences 206(3), 06003 (2019)

Total Cross-section as a function of $\sqrt{s}$



J.Phys.G37:083001,2010

Multiplicity as a function of $\sqrt{s}$

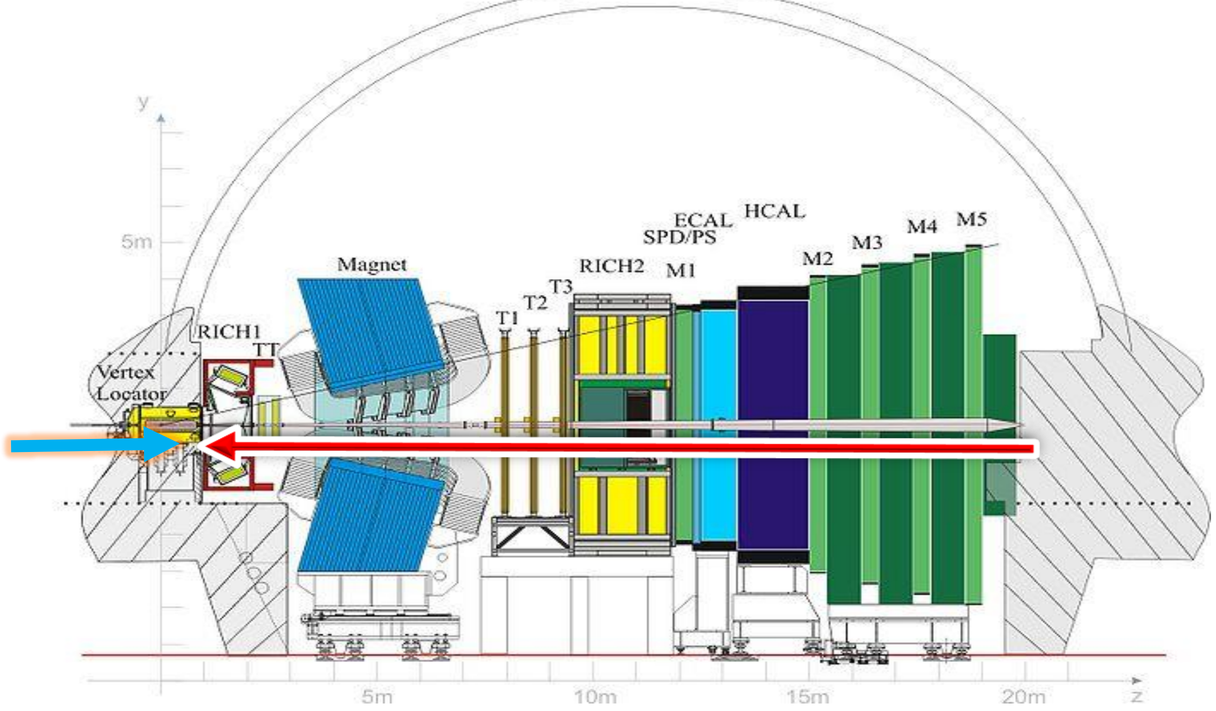


Journal of High Energy Physics 08 (2016) 170

Inelastic cross-section as a function of $\sqrt{s}$

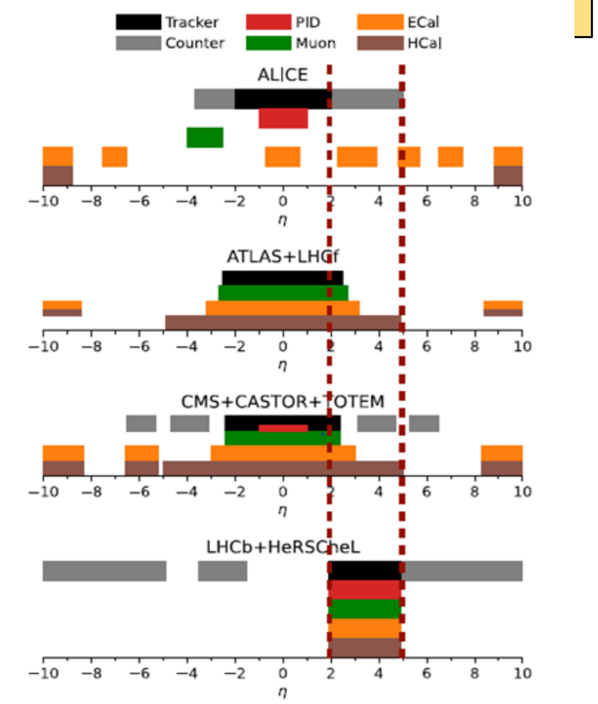
The LHCb Experiment

LHCb JINST 3 (2008) S08005



Physics at LHCb

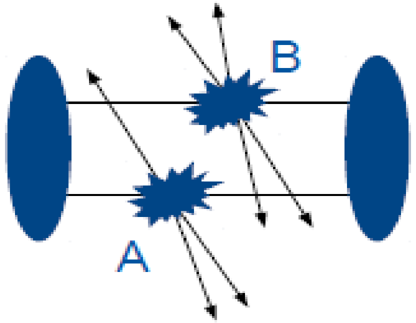
- Matter-antimatter asymmetry
- CP Violation and rare decays of beauty and charm meson
- QCD, electroweak, exotica …



- Rapidity range 2< η < 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
- Calorimeters : ECAL, HCAL, $\Delta E/E$= 1% + 10 / $\sqrt{E[GeV]}$ for ECAL
- High Quality Particle Identification

https://lhcb.web.cern.ch/speakersbureau/html/PerformanceNumbers.html

Double Parton Scattering (DPS)

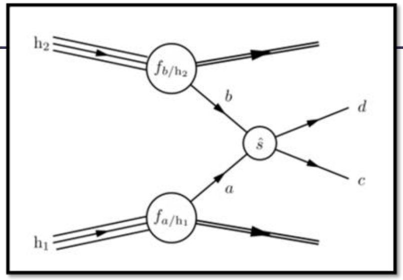


Why do we care?

- To study the mechanism of particle production. (CNM) Important for understanding of QGP
- DPS reveals new structure of protons – particularly correlations between partons in proton

Double Parton Scattering (DPS) – Having two hard interactions in a single pp or pPb collision

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



$f_{a/h_i}(x_i)$: Parton Distribution Function (PDF) (non-perturbative)

$\sigma^{ab \to cd}$: Partonic cross-section (perturbative)

Cross-section expressed as a product of two SPS cross-sections

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

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

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

LHCB-PAPER-2016-057

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

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

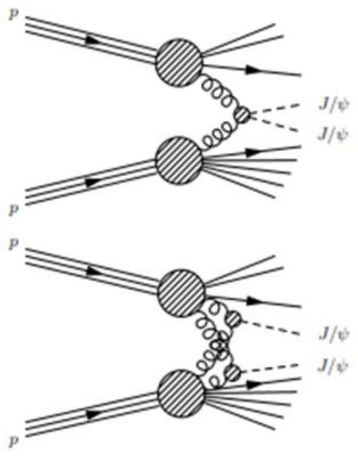
Master Equation to calculate cross-section:

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

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

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



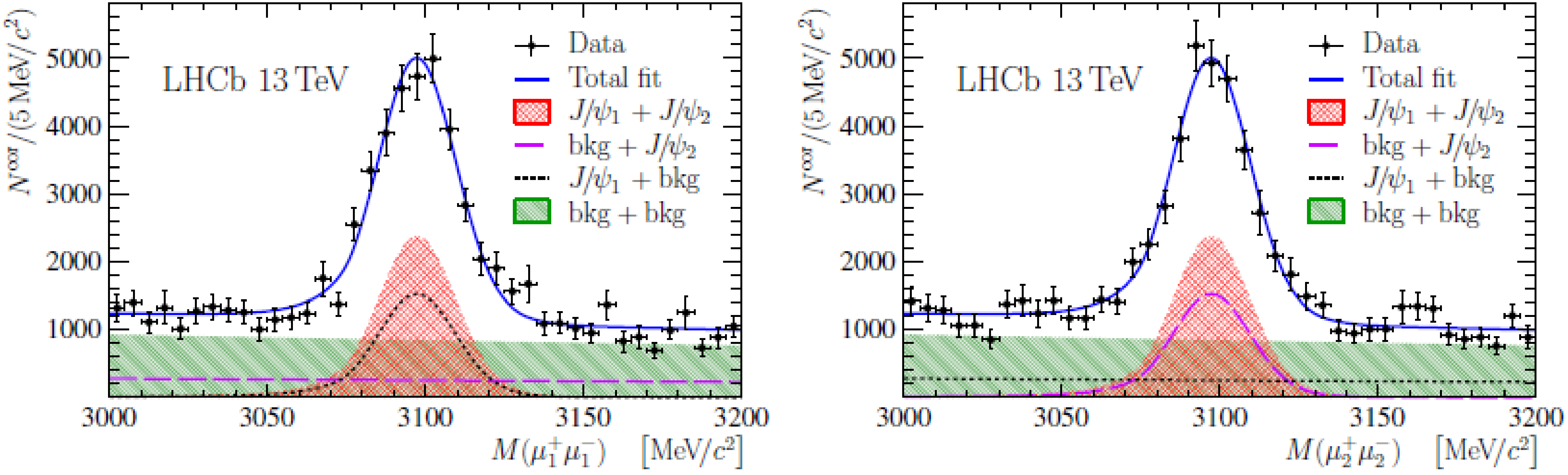
$\boldsymbol{N^{cor}}$ - signal yield after pre-signal efficiency correction

$\boldsymbol{\mathcal{L}}$- Integrated Luminosity

$\boldsymbol{\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)^2}$ - Branching fraction

Cross-section Determination

[JHEP 06 (2017) 047]



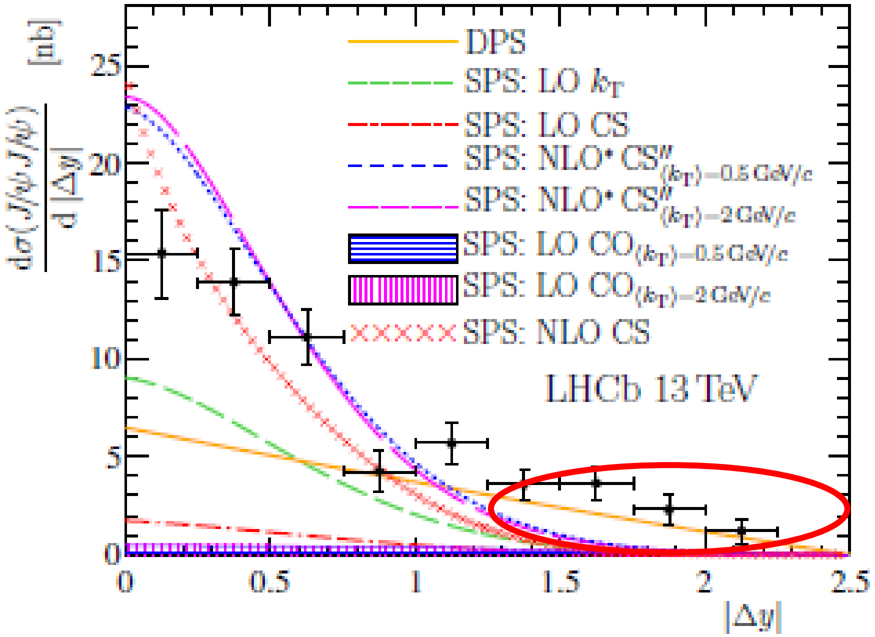
- Signal yield is obtained by fitting to efficiency-corrected 2D mass distribution
- Residual: Residual Contamination from b-hadron decays is determined using simulation
- $\boldsymbol{N^{cor}}$ = (15.8 $\pm$1.1) $\times$ 10^3
- Cross-section : **$\sigma(J/\psi\, J/\psi)$ = 15.2 $\pm$1.0 (stat) ± 0.9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

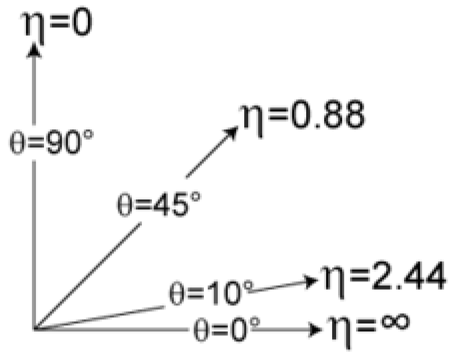
Comparison with Theoretical Predictions

Most significant indication of DPS is from $|\Delta y|$

- For $|\Delta y| > 1.5$ – no SPS contributions (theory)
- DPS contribution is essential

JHEP 06 (2017) 047





$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$

$$y \equiv \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right)$$

The distributions are fit to templates that fix the predicted DPS and SPS shapes

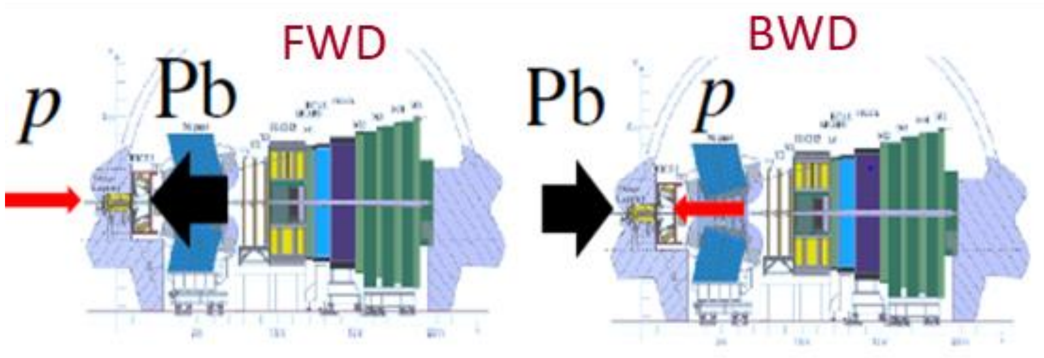
Double Parton Scattering in p-Pb Collisions

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

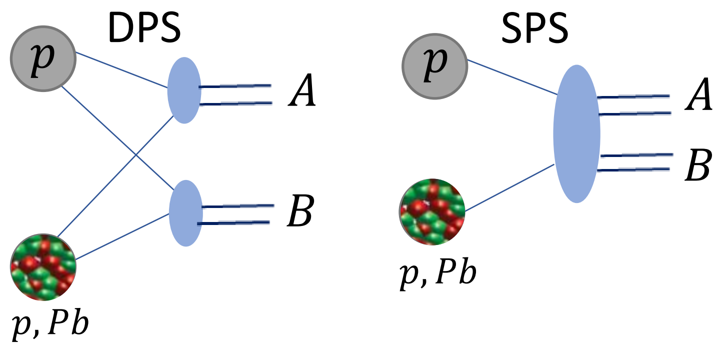
Data Sample:
- pPb collision at 8.16 TeV using 30 nb^{-1}
- FWD and BWD pPb data: 12.2±0.3 nb^{-1} and 18.6±0.5 nb^{-1}
- Pairs (A,B) of Interest: $D^0D^{\pm}, D^0D_s^{\pm}, J/\psi D^{0,\pm}$



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

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

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



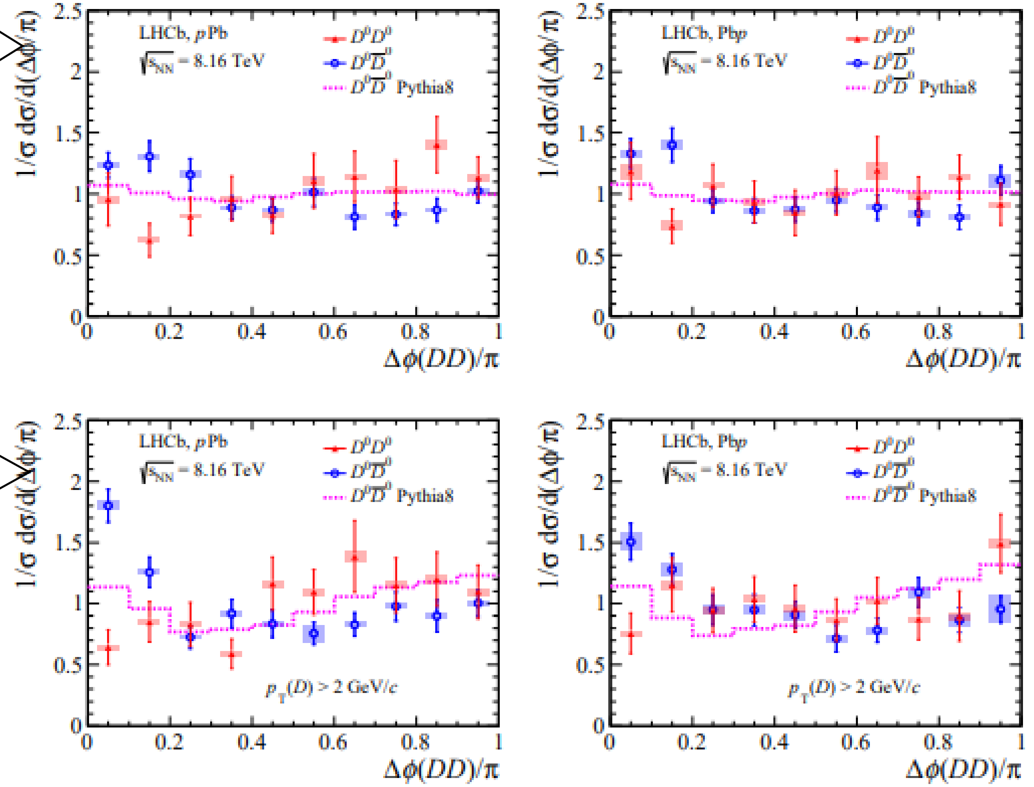
$A, B \equiv D = \{D^0, D^+, D_s^+\}$ and cc

Results

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

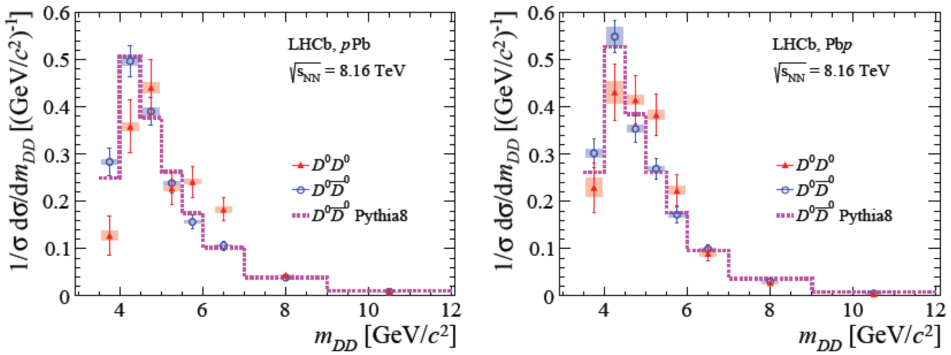
Phys. Rev. Lett.125, 212001(2020)

Without the condition ⇒ uniform for both LS and OS pairs



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

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



- 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

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

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

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)

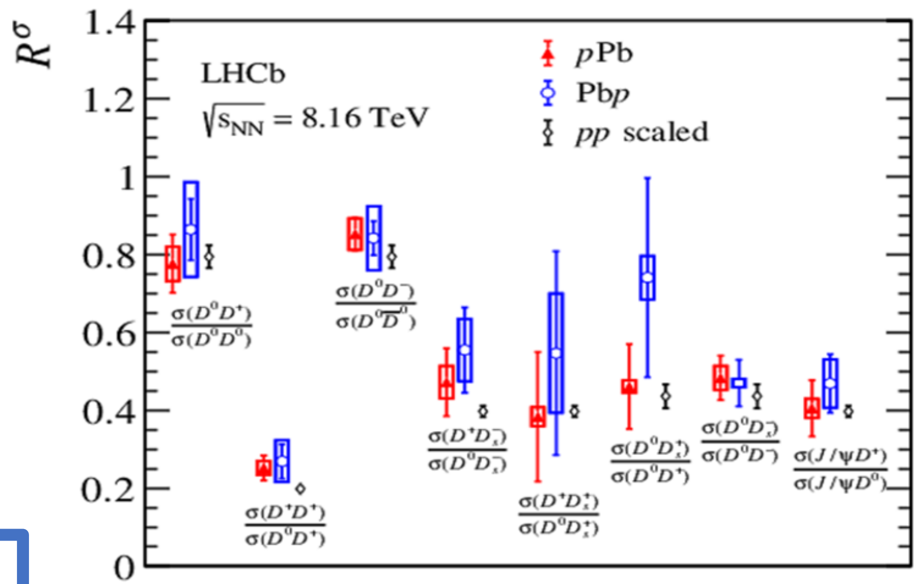
$$R^{D^0D^0} = 1.3 \pm 0.2\ (4.2 \pm 0.8)$$
$$R^{J/\psi D^0} = 1.5 \pm 0.5\ (4.6 \pm 1.3)$$

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)

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

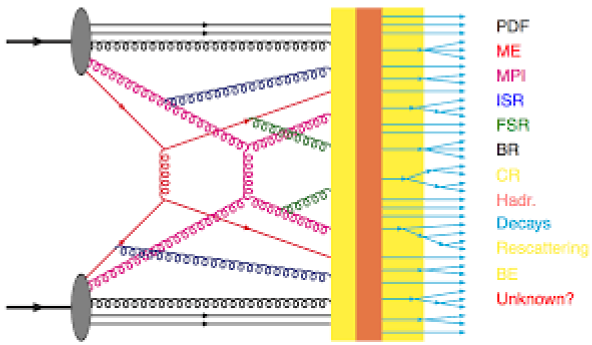
$$\sigma_{eff}(\psi D) = \frac{\sigma_\psi\,\sigma_D}{\sigma_{\psi D}(DPS)}$$



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

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

Pythia Event Generator



- Pythia is a MC event generator of hadron hadron collision based on perturbative QCD which describes scattering over $p_t > 2\ GeV/c$
- Generator keeps on evolving and currently used version is Pythia8.36.
- This version includes tuning from LHC
- An important parameter in Pythia is $\boldsymbol{p_{T0}^{ref}}$, which separates hard and soft QCD
- I am investigating the impact of $\boldsymbol{p_{T0}^{ref}}$ on multiplicity and other parameters as well.
- LHCb might take part in the next Pythia tunes, especially in particle production in forward direction.

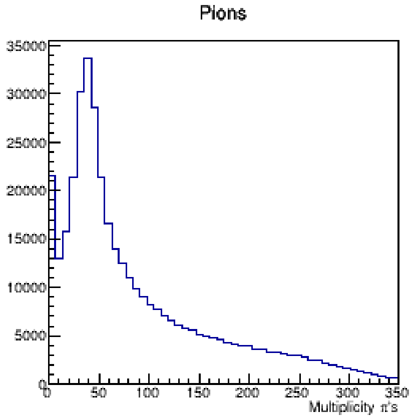
https://pythia.org/manuals/pythia8306/Welcome.html

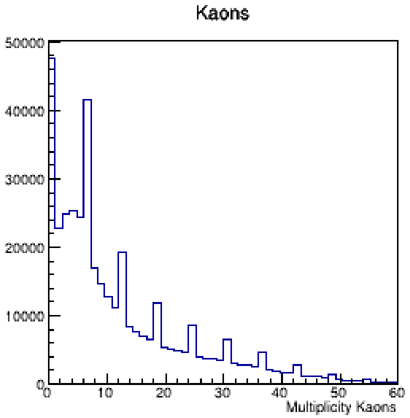
Multiplicity Plots for $p_{T0}^{ref} = 2.0GeV/c$

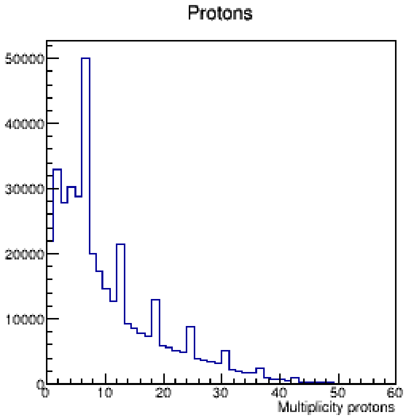
Multiplicity (Average number of hadrons in an event)

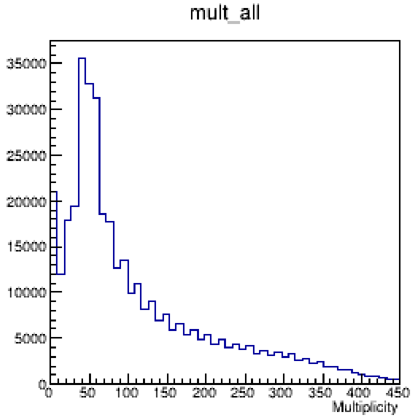
	Particles	Pions	Kaons	Protons	Hadrons
$p_{T0}^{ref} = 2.0\ GeV/c$	All generated events	70.63	9.54	8.79	88.98
	LHCb acceptance	13.64	1.90	1.52	17.06
$p_{T0}^{ref} = 2.74\ GeV/c$	All generated events	52.39	6.95	6.88	66.23
	LHCb acceptance	9.77	1.34	1.09	12.21

- All generated Events



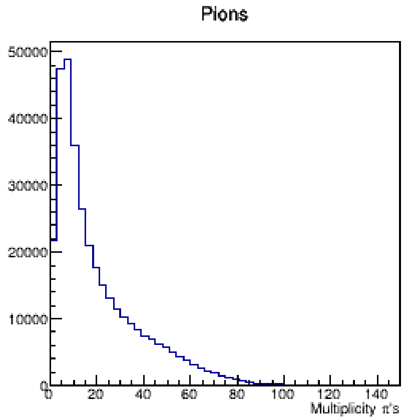


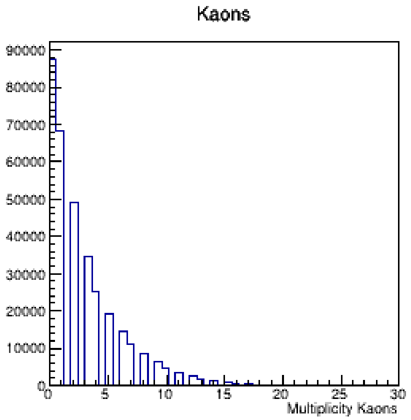


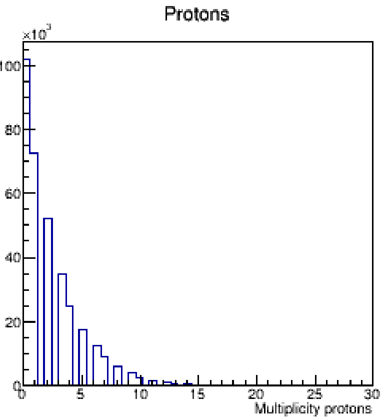


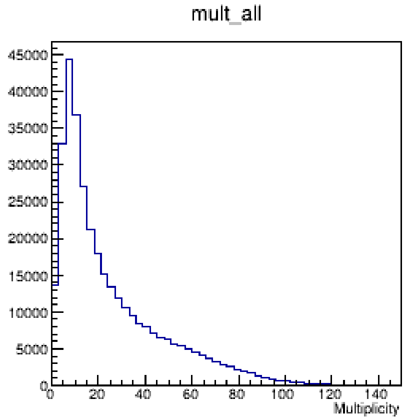
The table shows that p_{T0}^{ref} plays an important role in the multiplicity of hadrons:
Smaller the value of p_{T0}^{ref} larger is the multiplicity

- Within LHCb Acceptance ($2 < \eta < 4.5$)





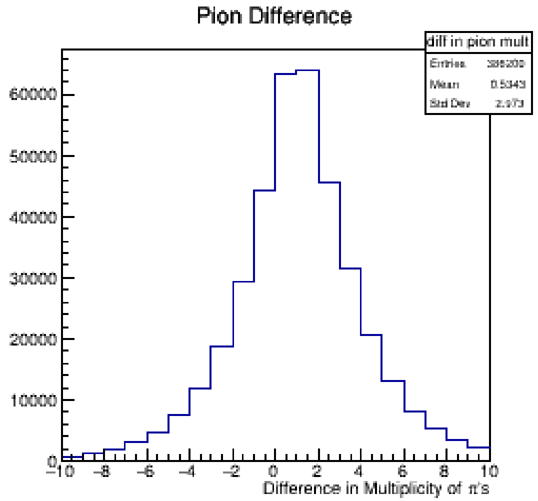


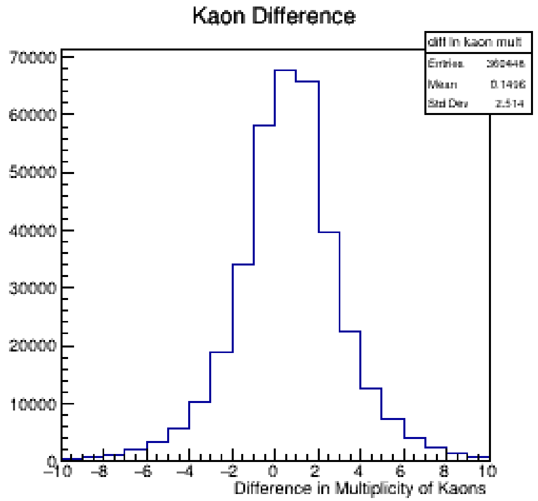


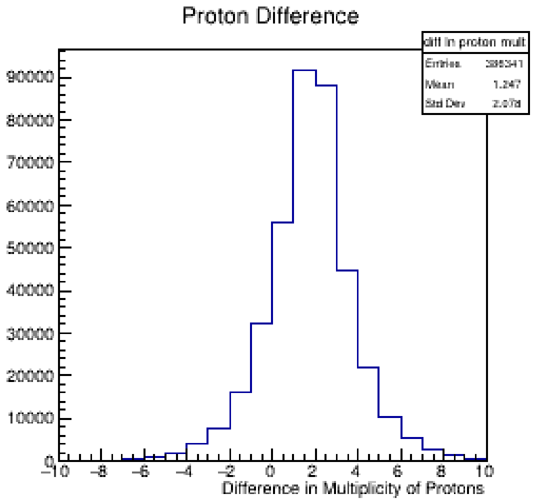
Charge Imbalance in Production (all η)

Average number of particles wrt charge per event						
Particles	π^+	π^-	K^+	K^-	p	$\bar{p}$
$p_{T0}^{ref} = 2.74\ GeV/c$	26.436	25.963	3.5332	3.4207	4.1496	2.7355
$p_{T0}^{ref} = 2.0$ GeV/c	35.551	35.087	4.8338	4.7136	5.1068	3.6903

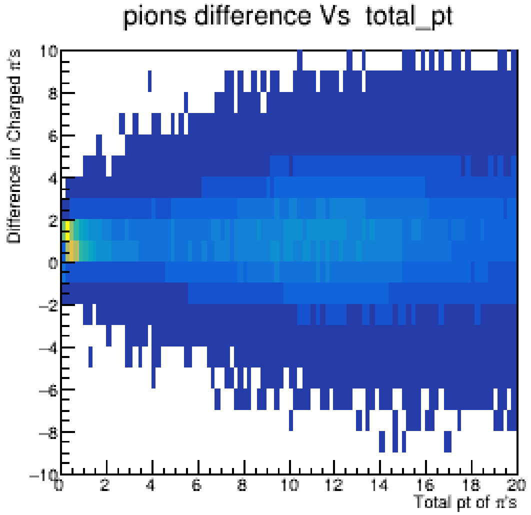
$$p_{T0}^{ref} = 2.0\ GeV/c$$







There is a slight imbalance in positive and negative charged particles generated.



Investigating differences between production of charged hadrons and Pythia production (study is ongoing)

Aim

To predict how many hadrons would hit the silicon sensors

Summary

Soft QCD and DPS are actively studied at LHCb. The contribution of DPS in LHCb are shown in the following papers:

- J/ψD are studied in pPb at $\sqrt{s_{NN}}$= 8.16 TeV
  - Cross-section ratio between LS and OS is 3 times higher as compared to pp data
  - The effective cross-section and Nuclear modification factor are compatible with expected enhancement factor for 3 for DPS over SPS production in ratio of pPb and pp collisions
- Measurement of J/ψ pair production at $\sqrt{s}$= 13 TeV
  - Cross-section calculation shows the DPS contribution to the distribution
- The pythia parameter p_{T0}^{ref} influences the multiplicity of particles. The smaller the value of p_{T0}^{ref} the higher the hadron multiplicities

THANK YOU

This work is partially supported by NCN UMO-2019/35/O/ST2/00546

BACK-UP

Double parton and σ_{eff}

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

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

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

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

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

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

β is impact parameter

p_{T0}^{ref}

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

$$\frac{d\sigma}{dp_T^2} \propto \frac{\alpha_s^2(p_T^2)}{P_T^4}$$

$\sigma \propto \frac{1}{P_T^2}$ (Cross-section diverges at small p_T)

Hard Scattering ~ High p_T (i.e. p_T > 5GeV)

Multi parton Interactions ($p_T \approx 1GeV$)

$$\frac{d\sigma}{dp_T^2} \propto \frac{\alpha_s(p_T+p_{T0})}{(p_T^2+p_{T0}^2)^2} \implies d\sigma \propto \frac{1}{P_T^2+p_{T0}^2}$$

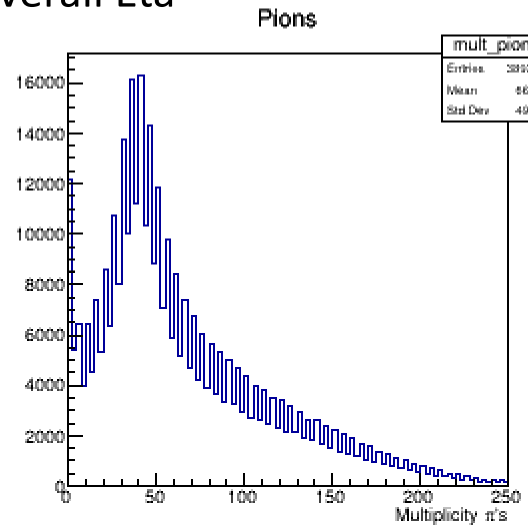
$$p_{T0}(\sqrt{s}) = p_{T0}^{ref}\left(\frac{\sqrt{s}}{\sqrt{s_0}}\right)^{\epsilon}$$

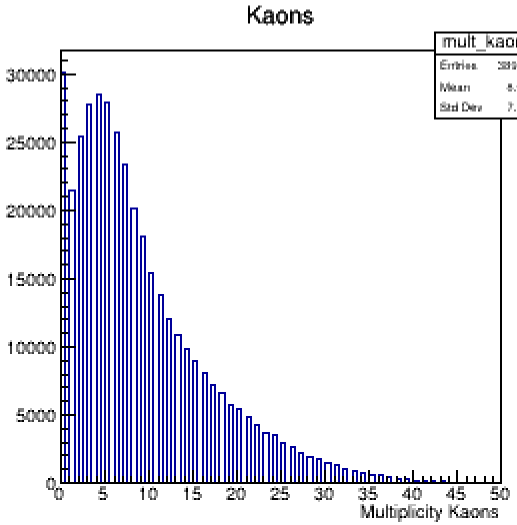
$p_{T0} \implies$ phenomenological parameter determined by data, added to solve the divergence issue

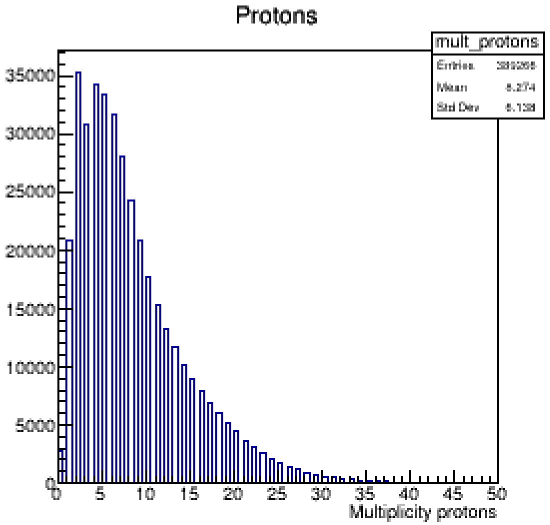
p_{T0}^{ref} is p_{T0} at reference energy $\sqrt{s_0}$
$\epsilon \implies$ energy dependence

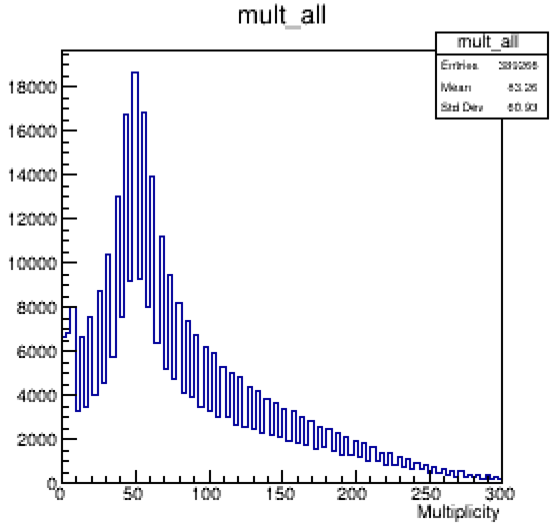
Multiplicity Plots for $p_{T0}^{ref} = 2.74GeV$

Overall Eta

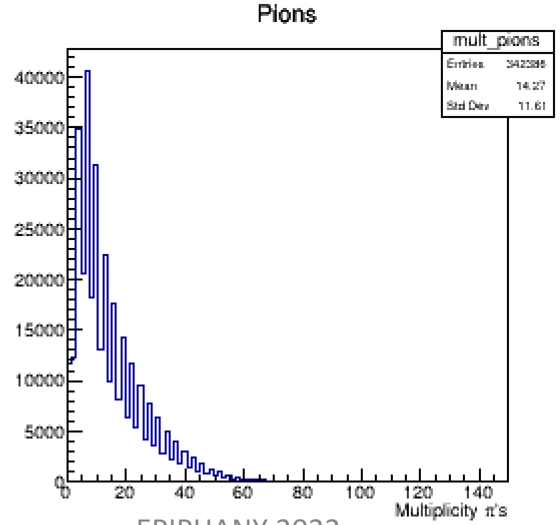


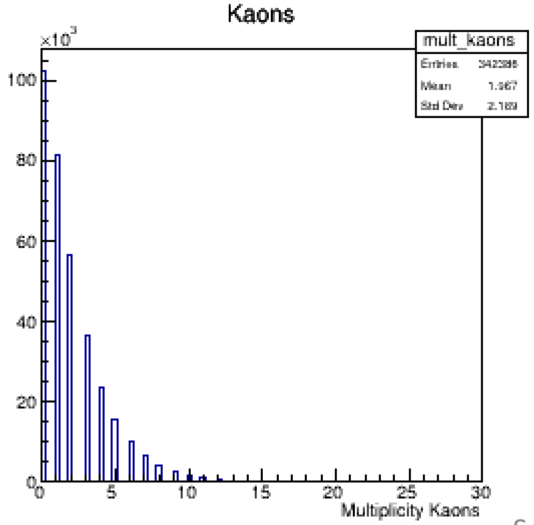


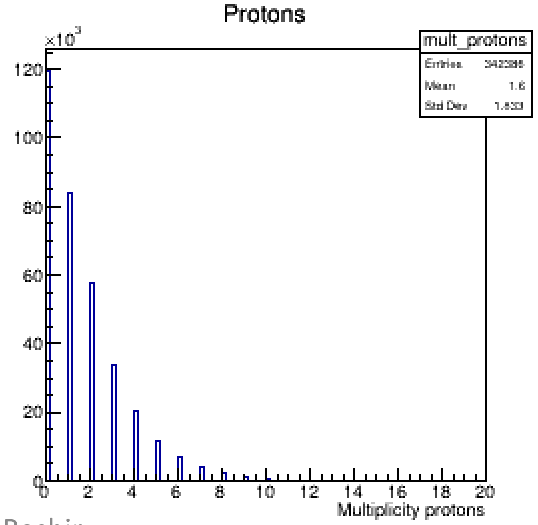


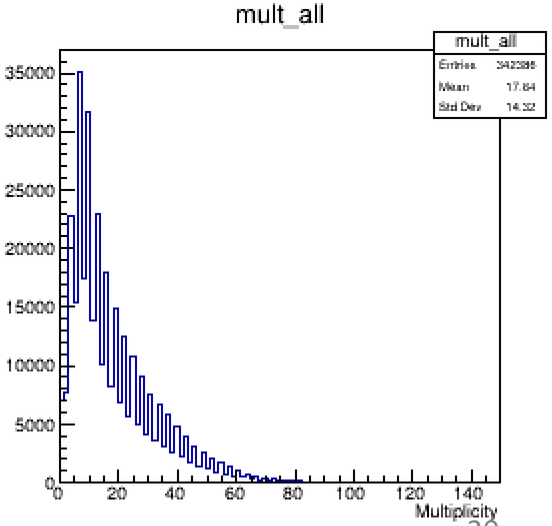


Within LHCb Eta range ($2 < \eta < 4.5$)





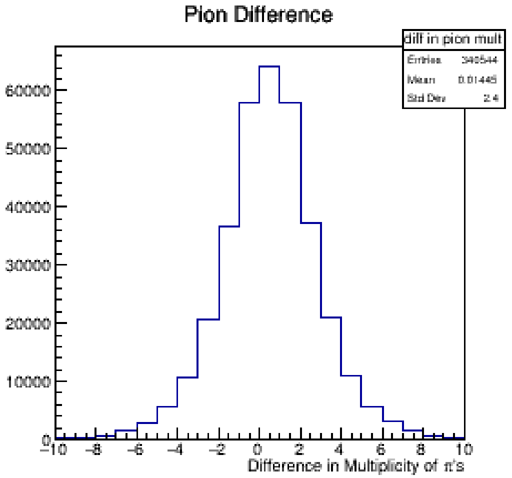


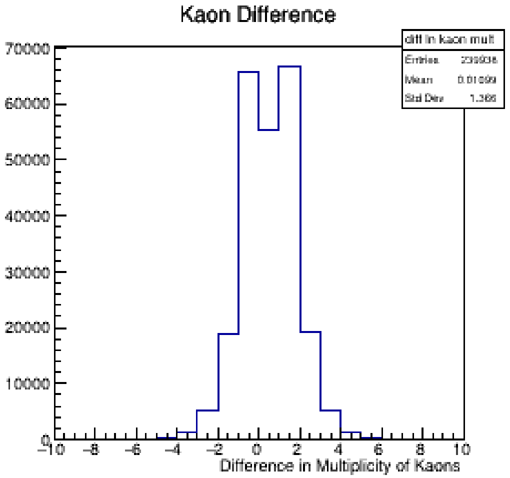


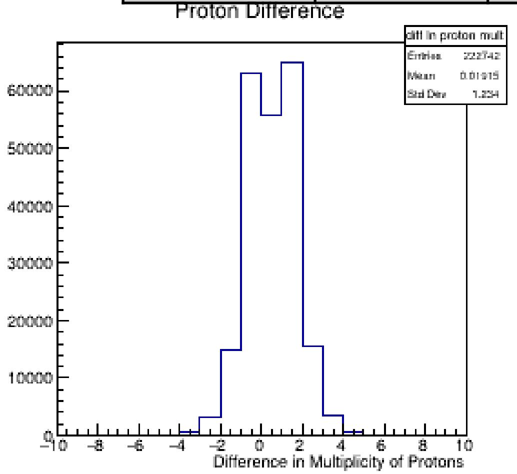
Difference in Multiplicities LHCb η Acceptance

Average number of Particles per event						
Particles	π^+	π^-	K^+	K^-	p^+	p^-
$p_{T0}^{ref} = 2.7$	4.8923	4.8786	0.67629	0.67099	0.55221	0.54368
$p_{T0}^{ref} = 2.0$	6.8259	6.8153	0.9546	0.9490	0.76678	0.75449

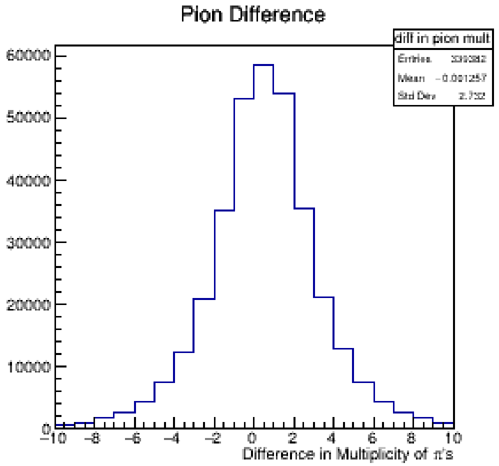
$p_{T0}^{ref} = 2.7$

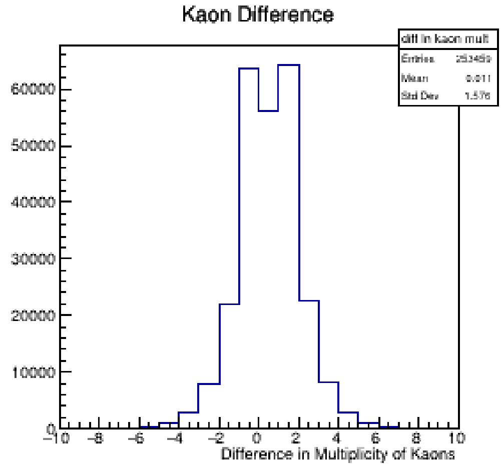


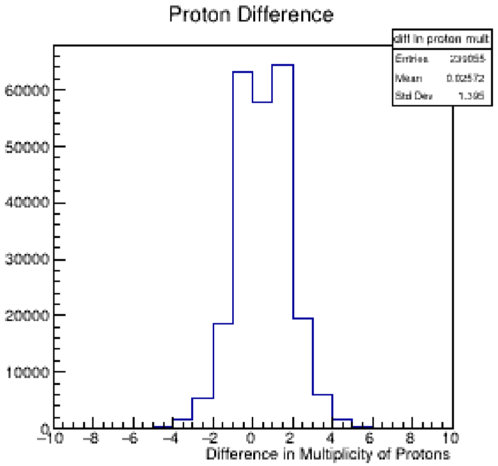




$p_{T0}^{ref} = 2.0$

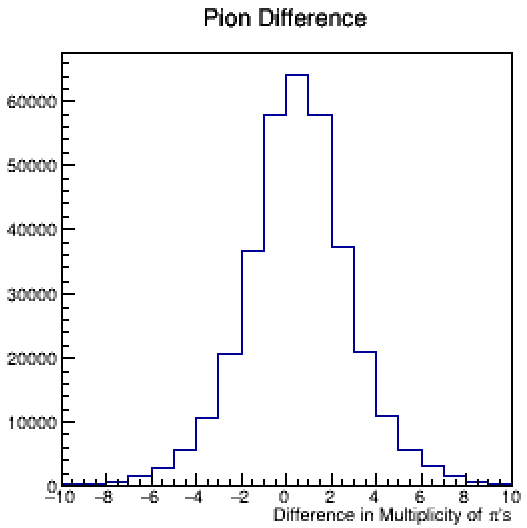


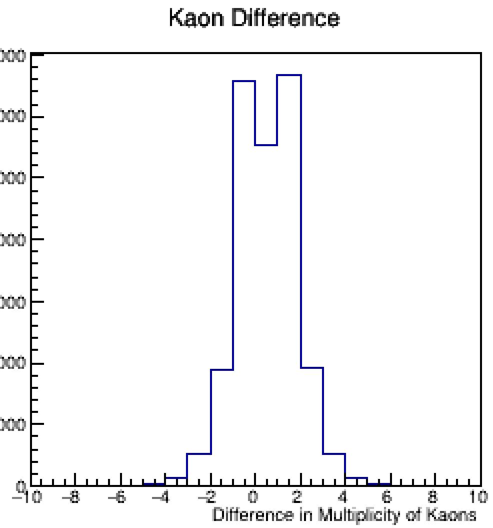


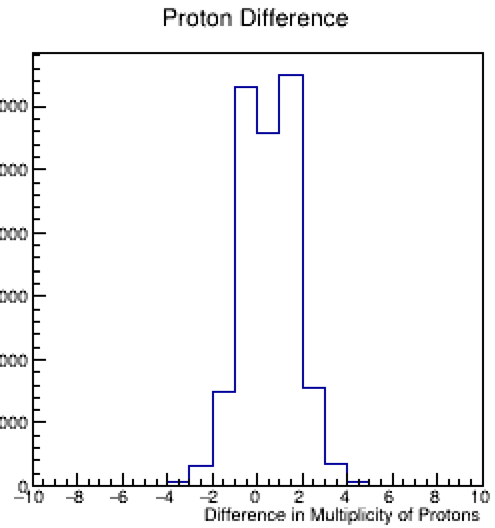


Difference in Multiplicities (LHCb Acceptance)

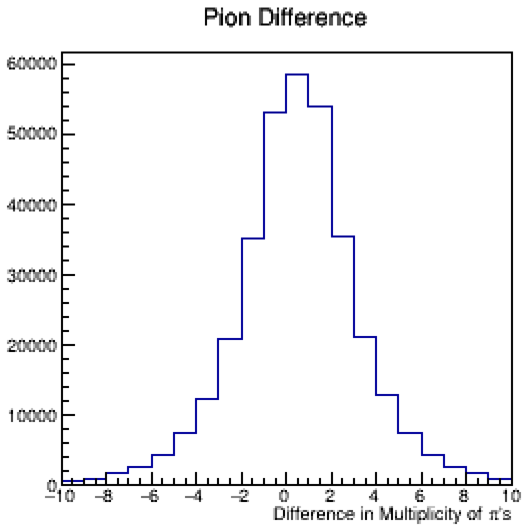
$$p_{T0}^{ref} = 2.74GeV$$

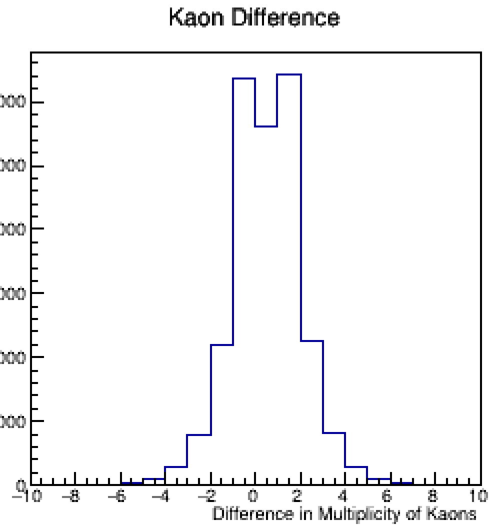


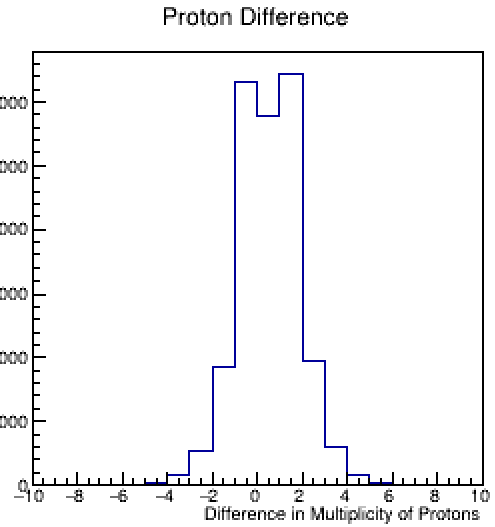




$$p_{T0}^{ref} = 2.0GeV$$



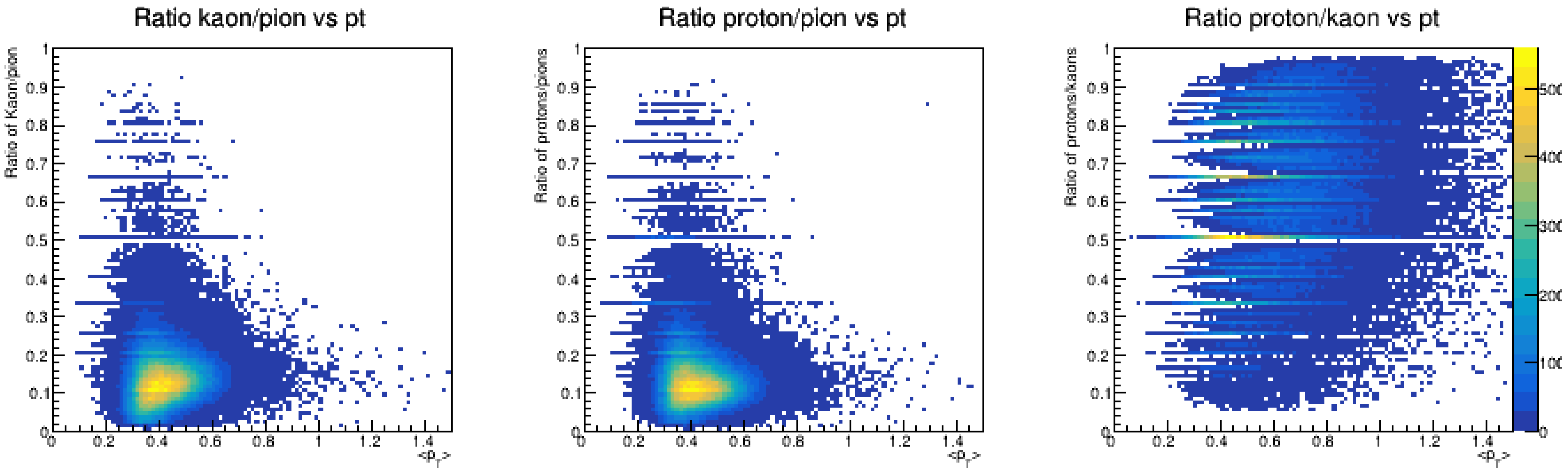




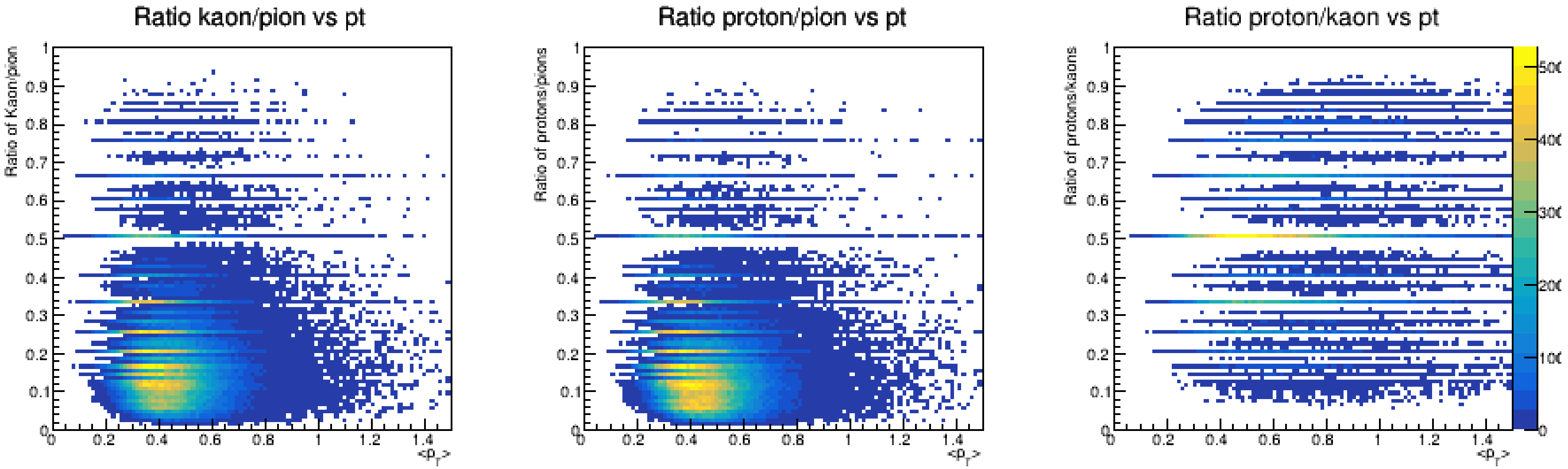
Multiplicity of Differences in Charged Particles Vs Total pt

$p_{T0}^{ref} = 2.74GeV$

All η values



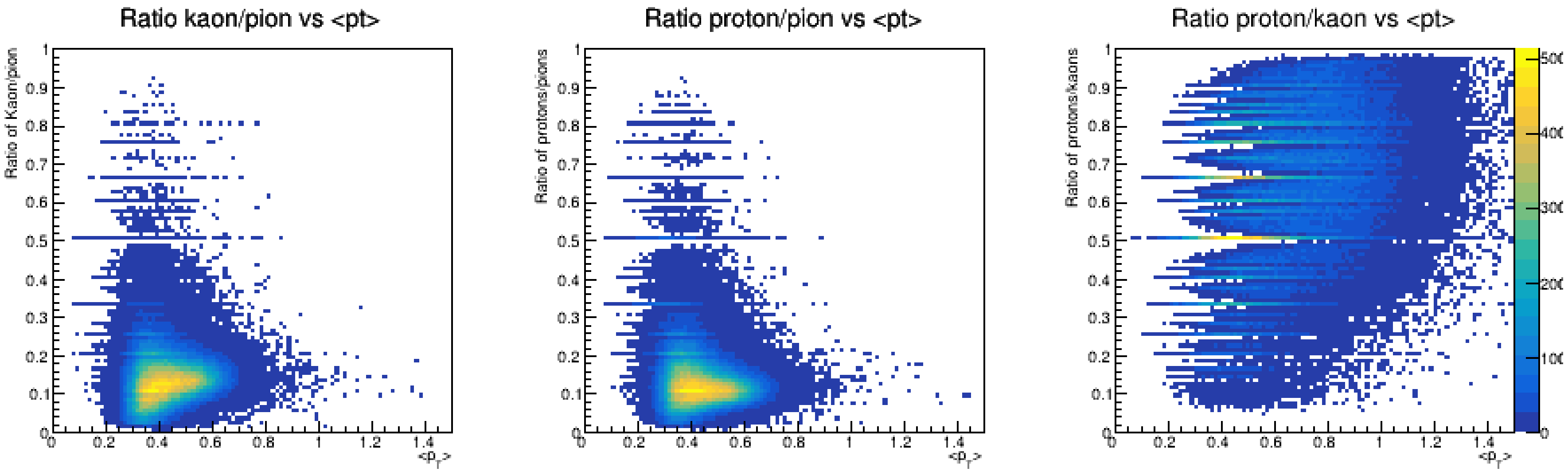
LHCb Acceptance



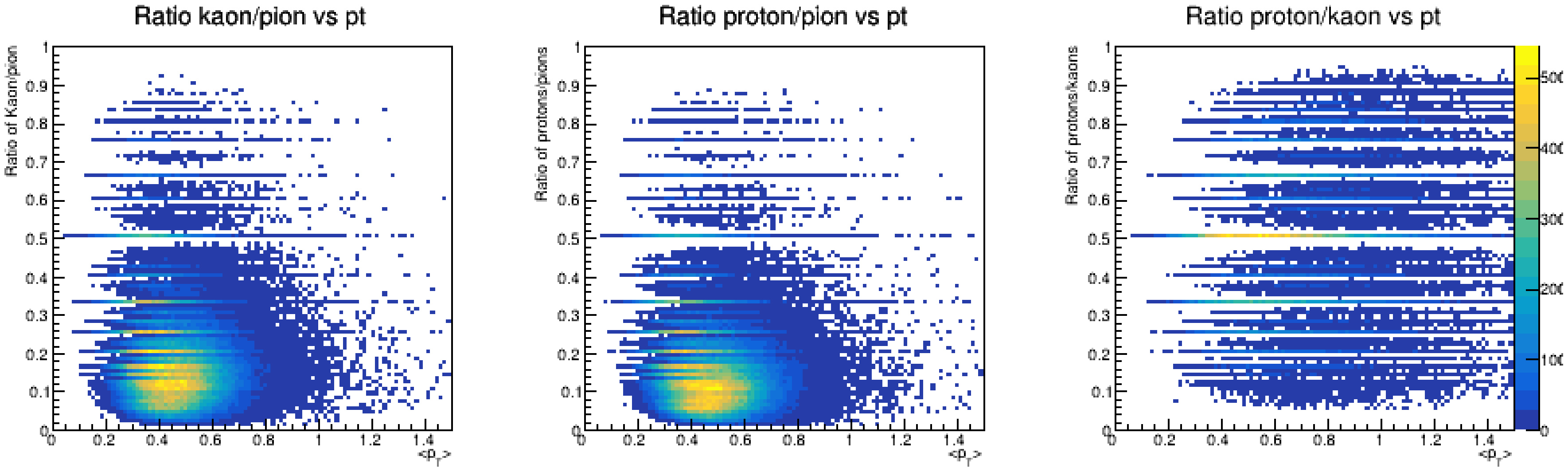
$p_{T0}^{ref} = 2.0$

Multiplicity of Differences in Charged Particles Vs Total pt

All η values



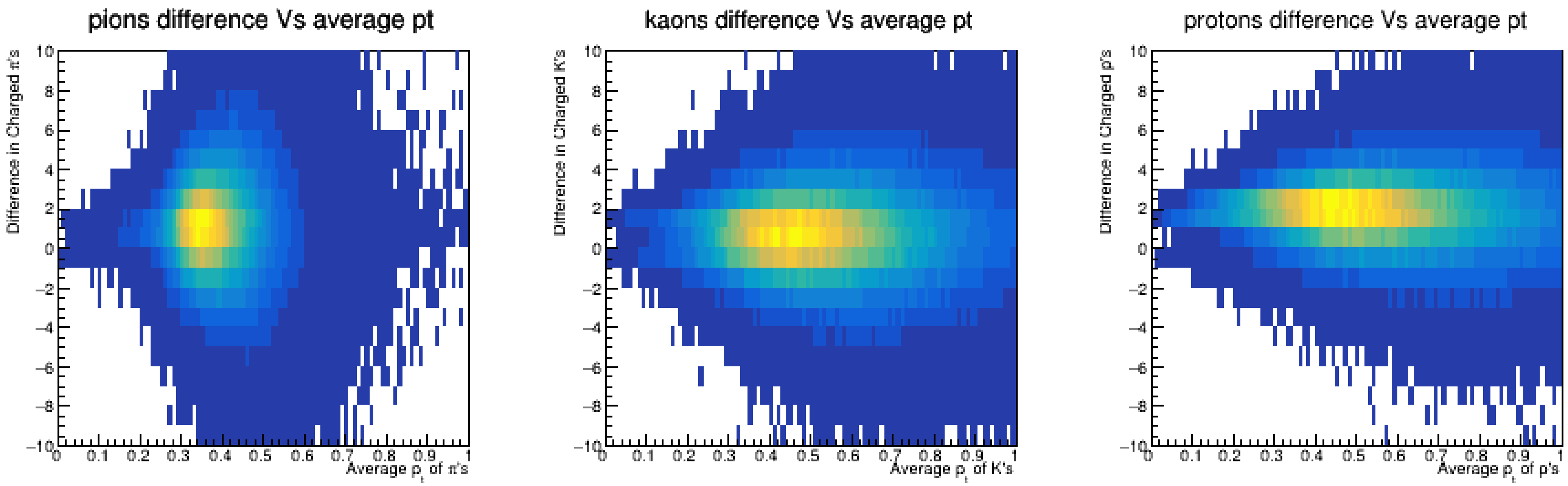
LHCb Acceptance



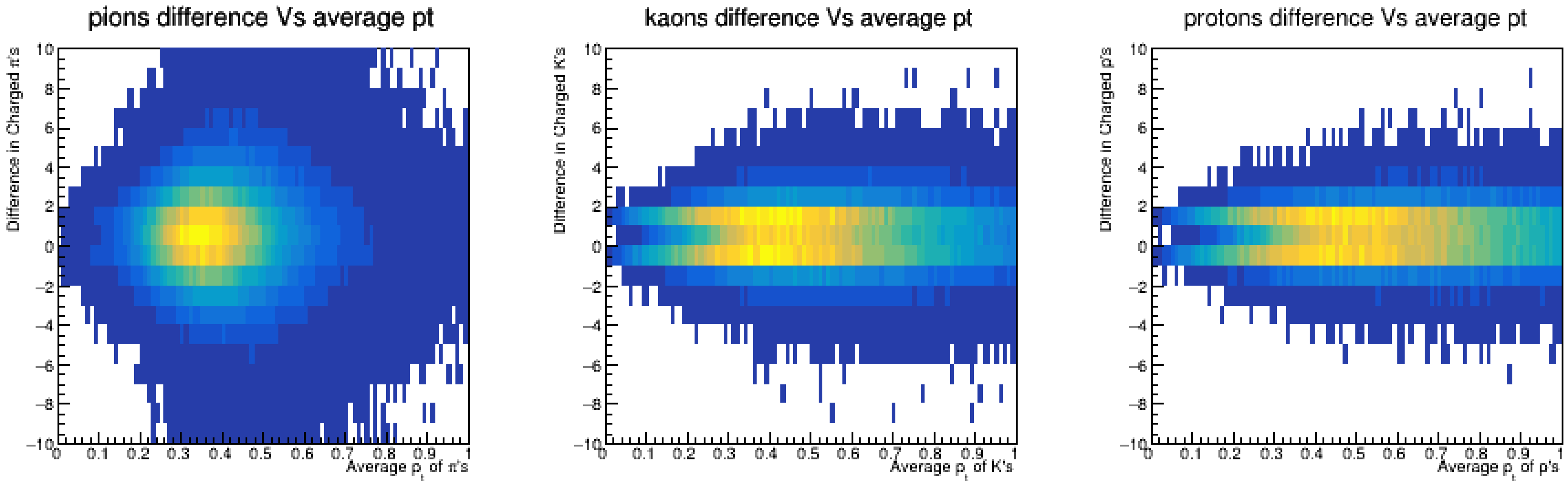
Difference in Multiplicity of Charged Particles Vs <pt>

$$p_{T0}^{ref} = 2.74GeV$$

All η values



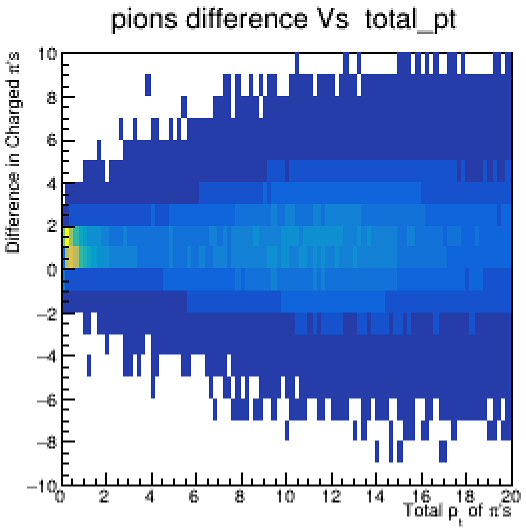
LHCb Acceptance

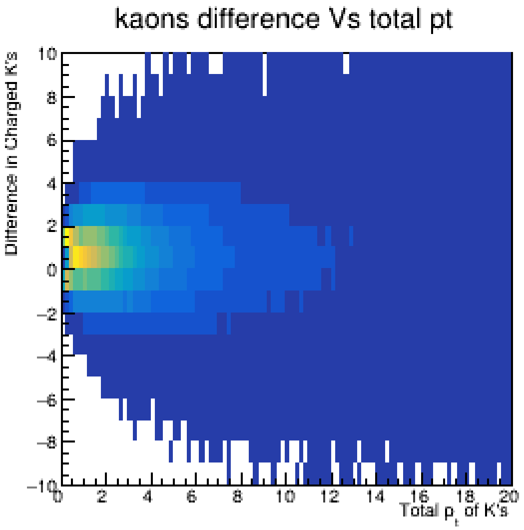


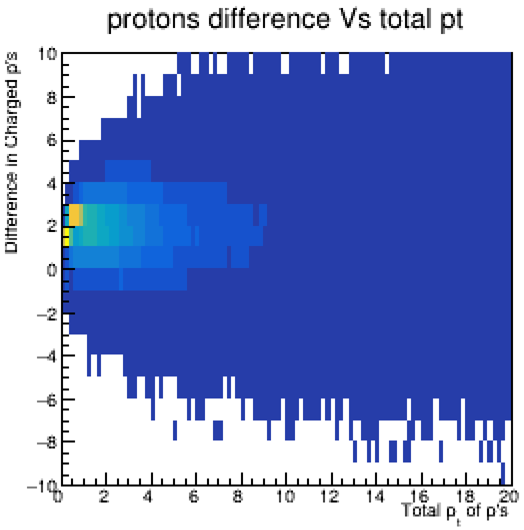
Difference in Multiplicity of Charged Particles Vs <pt>

$p_{T0}^{ref} = 2.0$

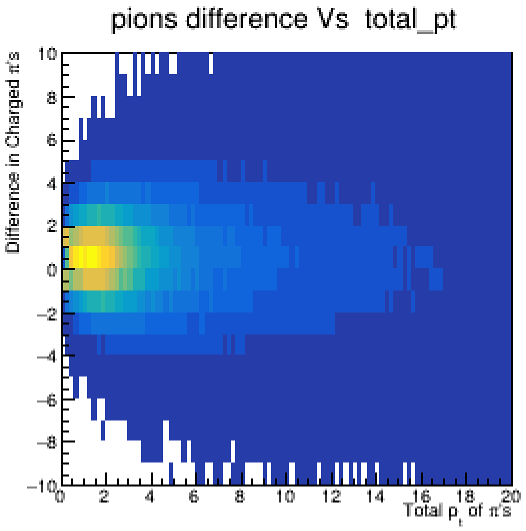
All η values

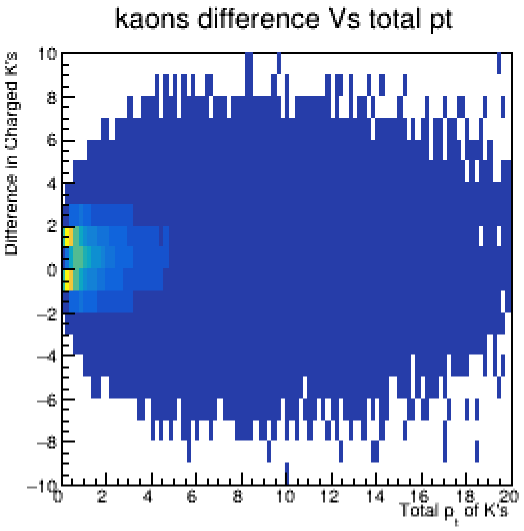


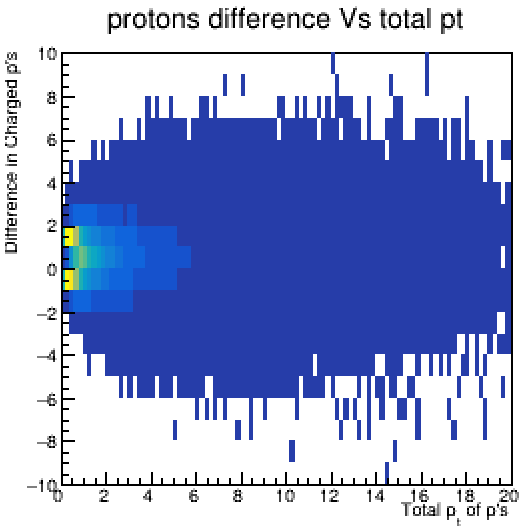




LHCb Acceptance



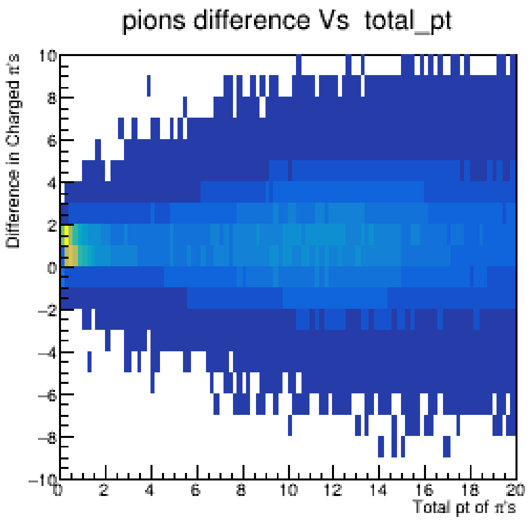


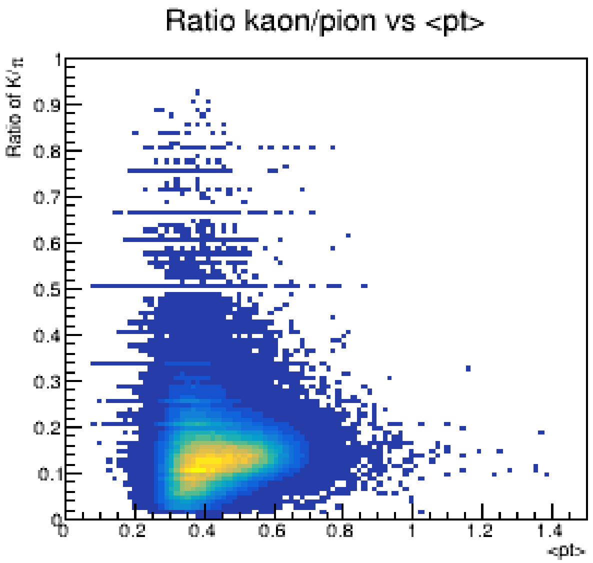


Multiplicity of Differences in Charged Particles and Ratio plots wrt total and <pt>

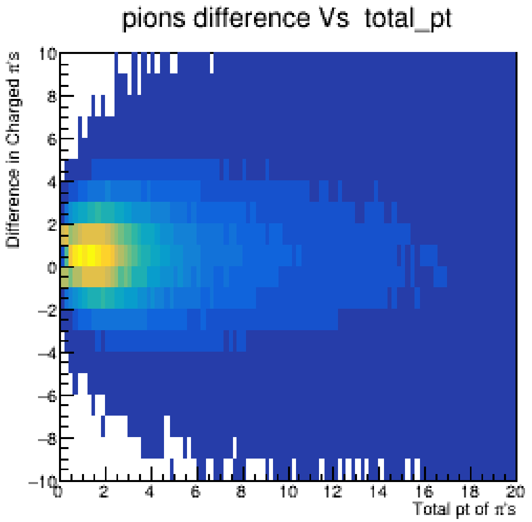
$p_{T0}^{ref} = 2.0\ GeV$

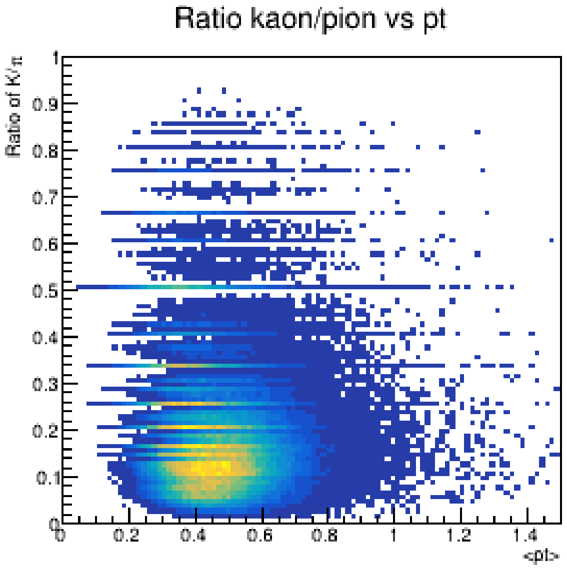
Overall η Range





LHCb Acceptance

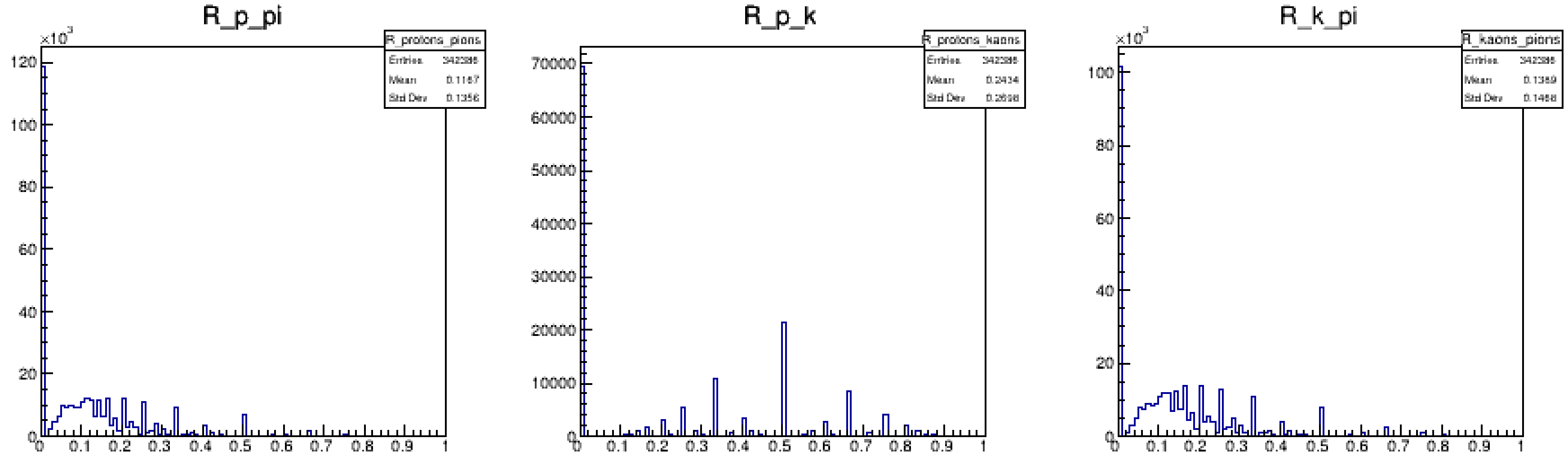




Ratio Plots (LHCb Acceptance)

Average Ratio in an Event			
Particles	p/π	p/K	K/π
p_{T0}^{ref} = 2.74GeV	0.112157	0.813407	0.137886
p_{T0}^{ref} = 2.0GeV	0.111519	0.79909	0.139558

- $p_{T0}^{ref} = 2.74 GeV$



- $p_{T0}^{ref} = 2.0 GeV$