Measurements of particle production and their correlations at the LHC with the ATLAS detector

Soft QCD results

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Overview

- **The transverse polarization of Λ and $\bar{\Lambda}$ at $\sqrt{s} = 7$ TeV**

  PRD 91 (2015) 032004

- **Two-particle Bose-Einstein correlations at $\sqrt{s} = 0.9$ and 7 TeV**

  arXiv:1502.07947, submitted to EPJC (February 2015)

- **The differential production cross section of the $\phi(1020)$ meson at $\sqrt{s} = 7$ TeV**

  EPJC 74 (2014) 2895

The transverse polarization of Λ and $\bar{\Lambda}$ at $\sqrt{s} = 7$ TeV

The transverse polarization of Λ and $\bar{\Lambda}$ at $\sqrt{s} = 7$ TeV

Motivation:

- Large transverse polarization of Λ hyperons (up to 30%) was observed in inclusive pp and pn collisions by previous experiments, contrary to pQCD predictions of much smaller polarization
- On the other hand, the $\bar{\Lambda}$ polarization was measured to be consistent with zero by all previous experiments
- Some common features of the polarization P_T^{Λ}:
  - increases with p_T^{Λ} until it saturates at ~ 1 GeV
  - decreases as the Feynman variable $|x_F|$★ approaches zero
  - no strong dependence on the center-of-mass energy observed (tested up to $\sqrt{s} \approx 40$ GeV)

No current model adequately describes all observations

Measurement in new kinematic regions could provide additional insight into mechanism responsible

ATLAS extends kinematic reach of past experiments to higher p_T^{Λ} and lower x_F

★ The **Feynman** $x_F = \frac{p_L}{p_L^{max}} = \frac{2p_L}{\sqrt{s}}$ is a scaling variable defined to describe inclusive hadronic interactions, where $\boldsymbol{p_L^{max}}$ is the maximum allowed $\boldsymbol{p_L}$ of a generated particle in the CM frame, based on the collision energy and particles' masses; $\boldsymbol{x_F} \in [-1; 1]$

The transverse polarization of Λ and $\bar{\Lambda}$ at $\sqrt{s} = 7$ TeV

Introduction:

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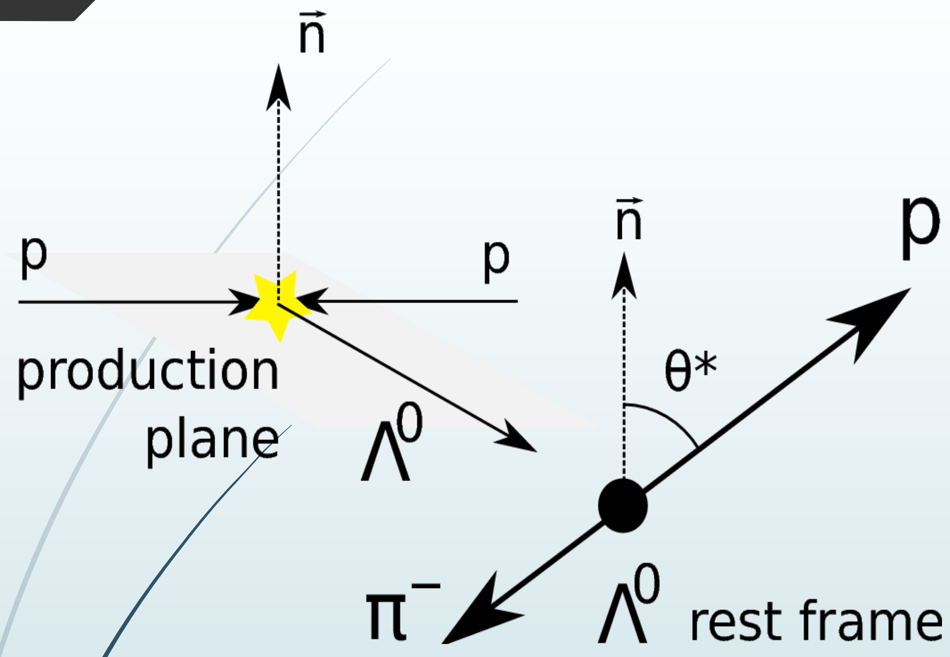

The polarization is measured:

- in the direction **normal** to the Λ production plane:

$$\vec{n} = \hat{p}_{beam} \times \vec{p}$$

Only P_T^{Λ} can be non-zero, $P_L^{\Lambda} = 0$ (PC req.)

- as a function of the p_T^{Λ} and $x_F = p_z^{\Lambda}/p_{beam}$

ATLAS 2010 pp data $\sqrt{s} = 7$ TeV, 760 μb^{-1} (low pile-up conditions)

- $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ decays
- The fiducial phase space:
  - $0.8 < p_T < 15\ GeV$
  - $5 \cdot 10^{-5} < x_F < 0.01$
    (the fixed-target exps: 0.01 – 0.6)
  - $|\eta| < 2.5$
  - The data are corrected for detector effects, etc.

The angular probability distribution is given by:

$$g(t; P_T^{\Lambda}) = \frac{1}{2}(1 + \alpha P_T^{\Lambda} t)$$

where $t \equiv \cos\theta^*$, $\alpha = 0.642 \pm 0.013$ is the world average value of the parity-violating decay asymmetry for the Λ

($-\alpha$ for the $\bar{\Lambda}$)

The transverse polarization of Λ and $\bar{\Lambda}$ at $\sqrt{s} = 7$ TeV

Signal fraction extraction:

- Apply the selection criteria to reduce the combinatorial and physics ($K_s^0 \to \pi^+\pi^-$, $\gamma \to e^+e^-$) backgrounds
- Search for the **long-lived**, **two-prong decays** and construct the $Mass_{inv}$ distribution in the range $1100 < m_{p\pi} < 1135\ MeV$

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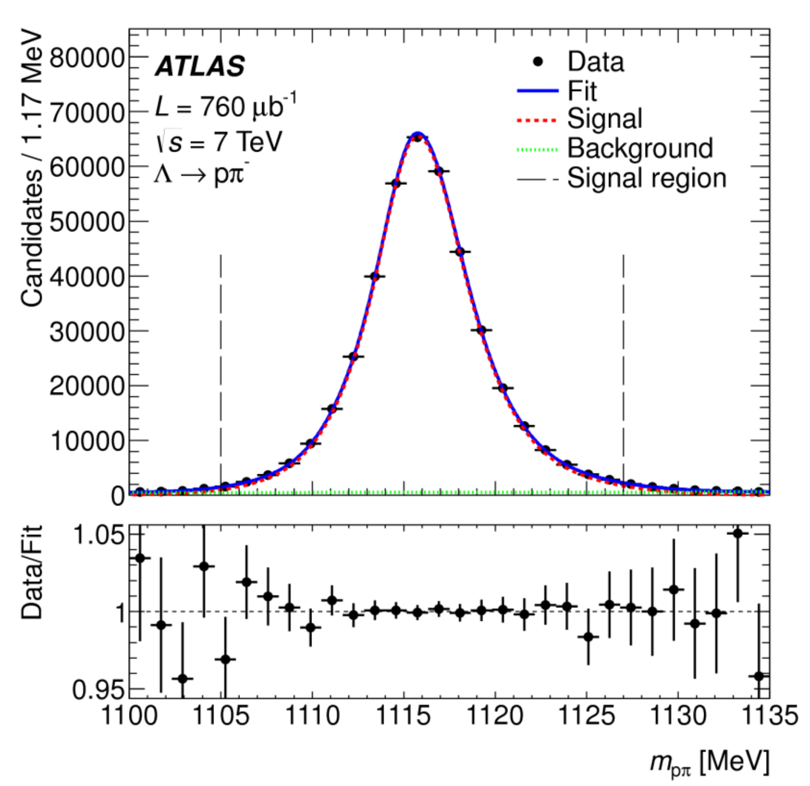

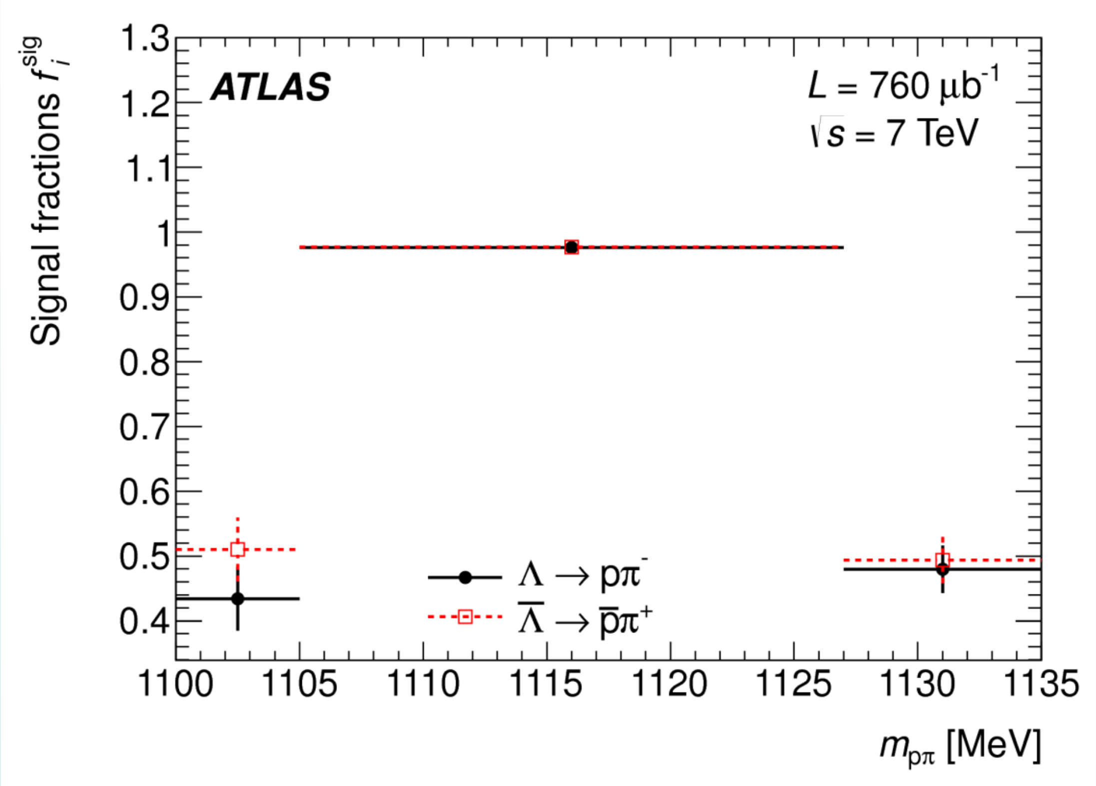

- Divide $Mass_{inv}$ range into the **signal region** ($1105 < m_{p\pi} < 1127\ MeV$) and the 2 **sidebands**
- Multi-parameter fits to extract the signal fraction f_i^{sig} separately in the 3 mass regions ($i = 1, 2, 3$)

The transverse polarization of Λ and $\bar{\Lambda}$ at $\sqrt{s} = 7$ TeV

Polarization extraction:

- The reconstructed decay angle distribution:

$$g_{det}(t'; P_T^{\Lambda}) \propto \frac{1}{2}\int_{-1}^{1} dt\left[\left(1+\alpha P_T^{\Lambda} t\right)\varepsilon(t)\right]R(t', t)$$

where t' – the true value of $\cos\theta^*_{det}$, $\varepsilon(t)$ – the reconstruction efficiency, $R(t', t)$ – the resolution function

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Method of moments *is used to extract the value of* P_T^{Λ}

- It exploits the fact that, for any value of P_T^{Λ}, the first moment (expectation value) of the angular distribution can be expressed as a linear combination of the first moments of angular distributions with $P_T^{\Lambda} = 0$ and $P_T^{\Lambda} = 1$

$$E(P_T^{\Lambda}) = \int_{-1}^{1} dt'\, t'\, g_{det}(t'; P_T^{\Lambda}) = E(0) + [E(1) - E(0)]P_T^{\Lambda}$$

E(0), E(1) estimated using MC simulation as averages of the reconstructed decay angle values for samples with P_T^{Λ} set to 0 and 1

The transverse polarization of Λ and $\bar{\Lambda}$ at $\sqrt{s} = 7$ TeV

Background contribution:

- To correct for the BGD contribution, the first moments are calculated separately in the signal and sideband regions
- The first moment of the BGD angular distribution, $\boldsymbol{E_{bkg}}$ is assumed independent of $m_{p\pi}$ – verified with MC

The expected first moment in each of the 3 regions:

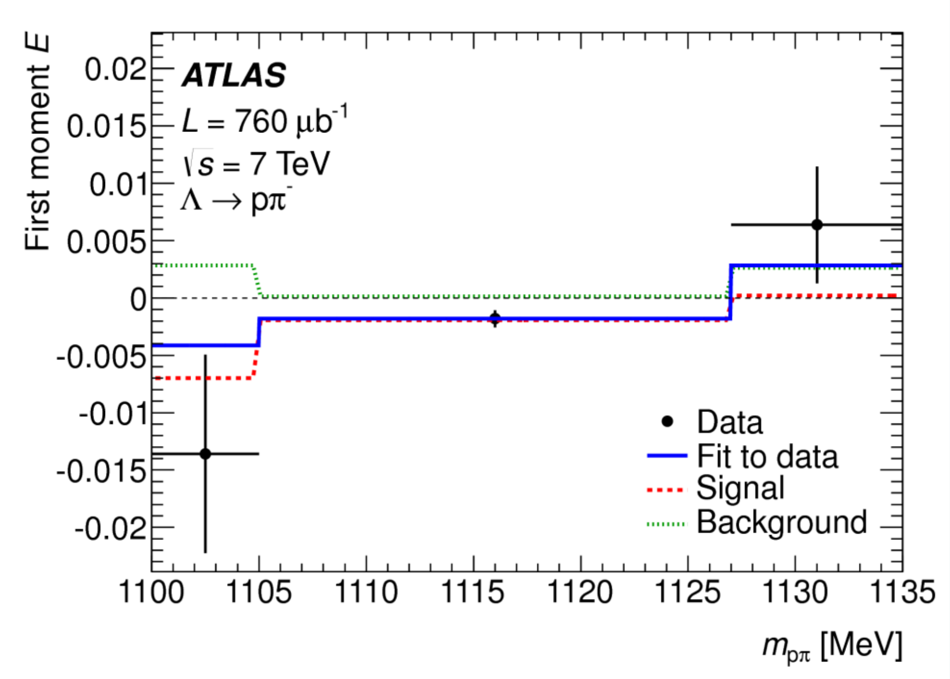
$$E_i^{exp}(P_T^{\Lambda}, E_{bkg}) = f_i^{sig}\{E_i^{MC}(0) + [E_i^{MC}(1) - E_i^{MC}(0)]P_T^{\Lambda}\} + (1 - f_i^{sig})E_{bkg}$$

where $E_i^{MC}(0), E_i^{MC}(1)$ estimated from MC

f_i^{sig} – the signal fractions from fit to $m_{p\pi}$

The values of $\boldsymbol{P_T^{\Lambda}}$ and $\boldsymbol{E_{bkg}}$ are extracted in a least-squares fit:

$$\chi^2(P_T^{\Lambda}, E_{bkg}) = \sum_{i=1}^{3} \frac{[E_i - E_i^{exp}(P_T^{\Lambda}, E_{bkg})]^2}{\sigma_{E_i}^2}$$



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The transverse polarization of Λ and $\bar{\Lambda}$ at $\sqrt{s} = 7$ TeV

Main results:

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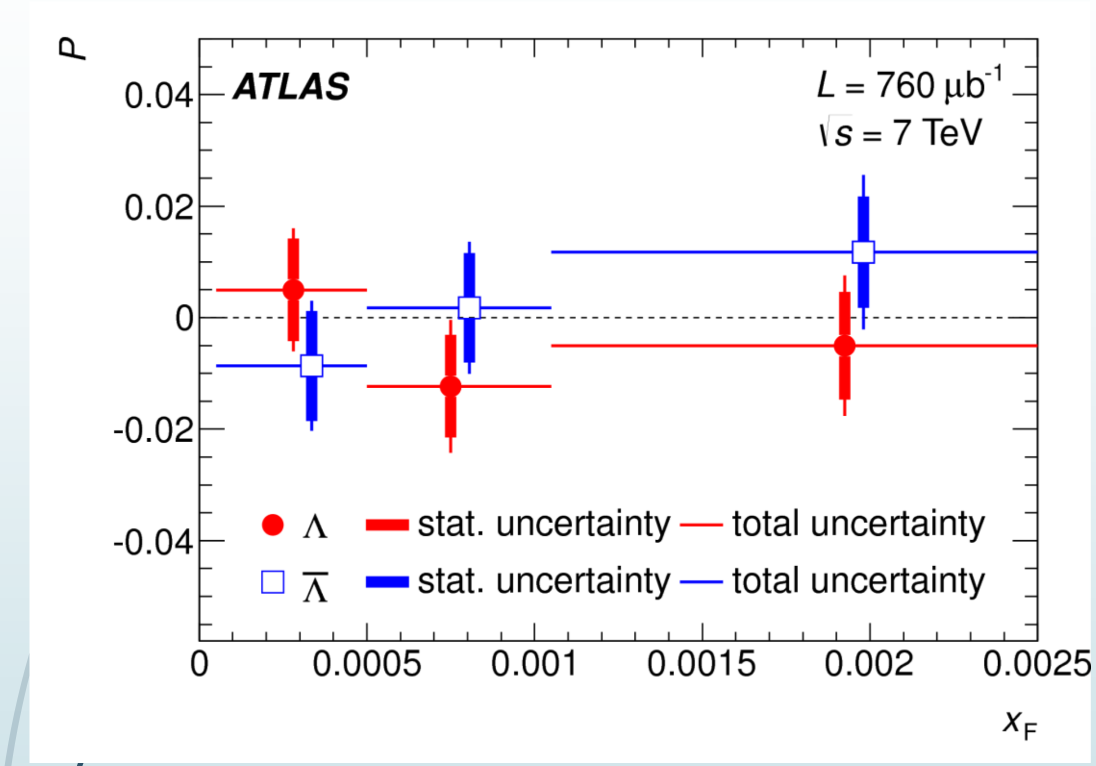
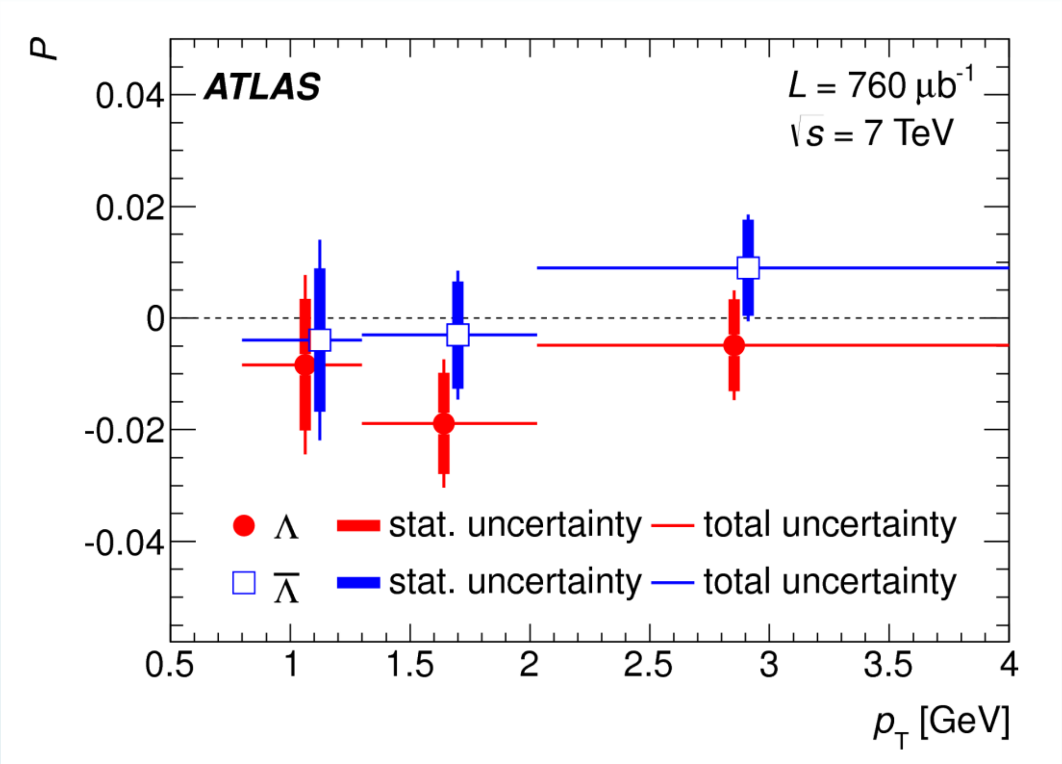




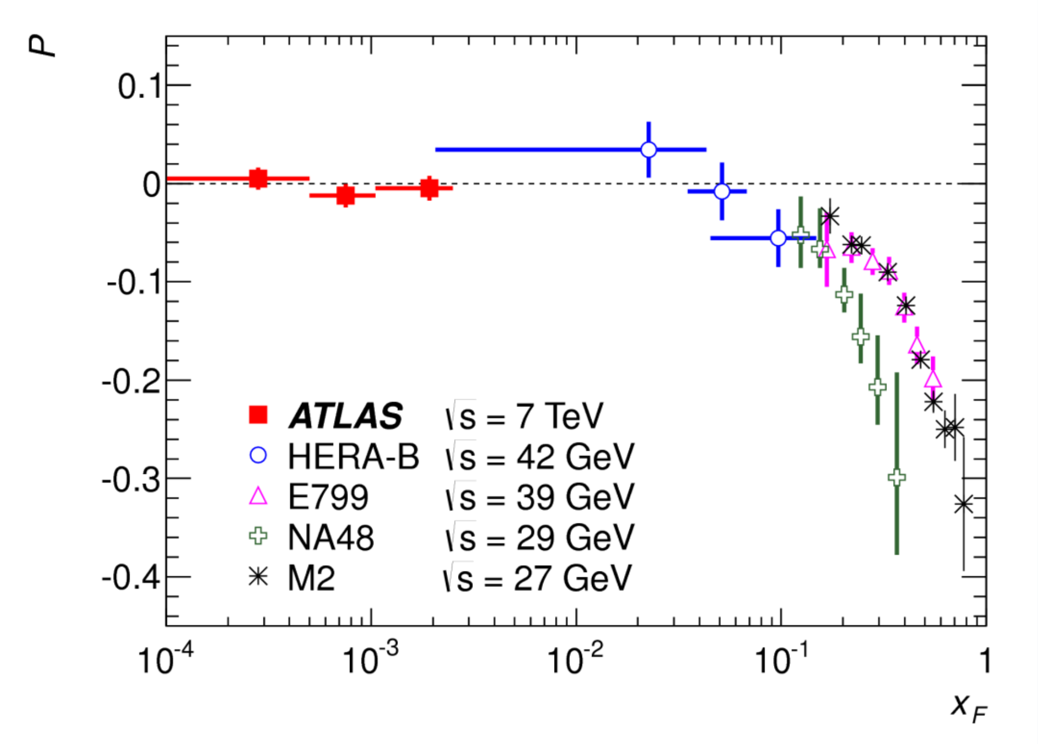
- In p_T and x_F bins, the polarization is found to be < 2% and is consistent with zero in all bins – no significant dependence on p_T or x_F is observed
- The average transverse polarization of $\boldsymbol{\Lambda}$ and $\bar{\boldsymbol{\Lambda}}$ in the full fiducial phase space is consistent with zero:

$$P_T^{\Lambda} = -0.010 \pm 0.005_{stat} \pm 0.004_{syst}$$

$$P_T^{\bar{\Lambda}} = -0.002 \pm 0.006_{stat} \pm 0.004_{syst}$$

The transverse polarization of Λ and $\bar{\Lambda}$ at $\sqrt{s} = 7$ TeV

Comparison with the previous experiments:



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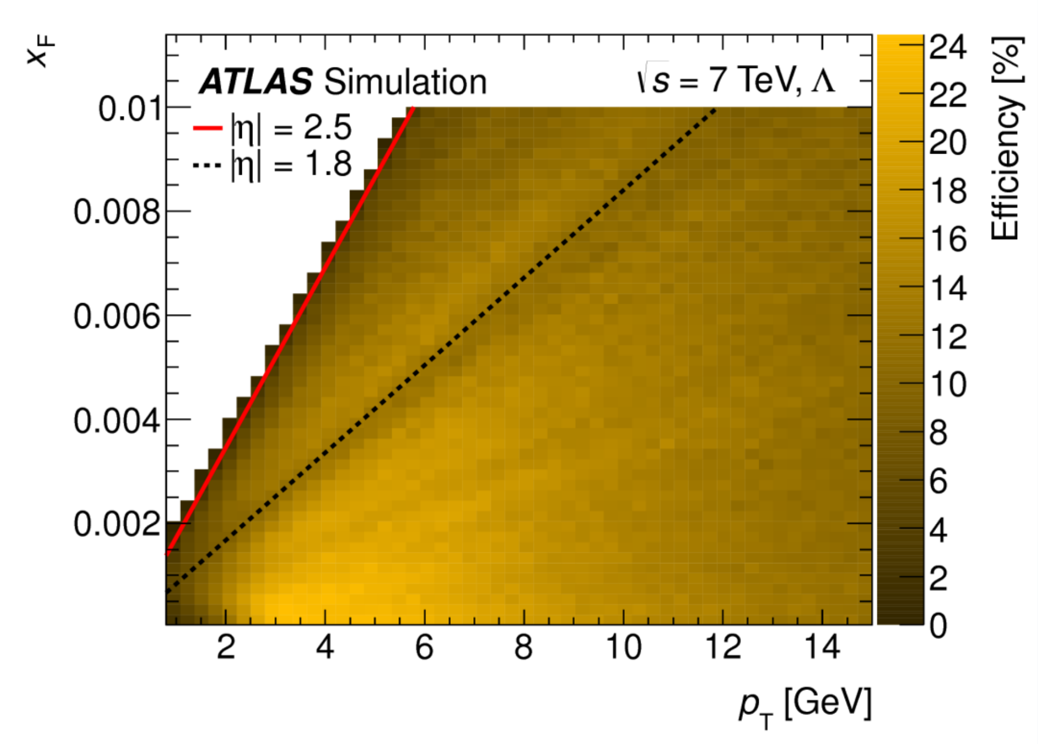


- The ATLAS result for:
  - P_T^{Λ} is consistent with an extrapolation of fits from previous measurements to low x_F, which suggests that the magnitude of the polarization should decrease as x_F approaches zero
  - $P_T^{\bar{\Lambda}}$ is consistent with zero as by all the previous experiments

- The measured P_T^{Λ} values depend on the reconstruction efficiency within the fiducial phase space, $\epsilon(x_F, p_T)$, and on the differential polarization $P_T^{\Lambda}(x_F, p_T)$
- The efficiency maps of reconstructed Λ and $\bar{\Lambda}$ decays are provided in the HEPDATA database for comparisons

Two-particle Bose-Einstein correlations at $\sqrt{s} = 0.9$ and 7 TeV

Bose-Einstein correlations at $\sqrt{s} = 0.9$ and 7 TeV

Motivation:

- **Bose-Einstein correlations (BEC)** – correlations between two identical bosons (consequence of the symmetry of identical bosons wave function)
- **BEC effect** corresponds to an enhancement in two identical boson correlation function when the two particles are near in momentum space
- BEC is a sensitive probe of the space-time geometry of the hadronization region – allows the determination of the size and the shape of the source from which particles are emitted
- Studies of the dependence of BEC on particle multiplicity and transverse momentum are of special interest as help to understand the multiparticle production mechanism

Bose-Einstein correlations at $\sqrt{s} = 0.9$ and 7 TeV

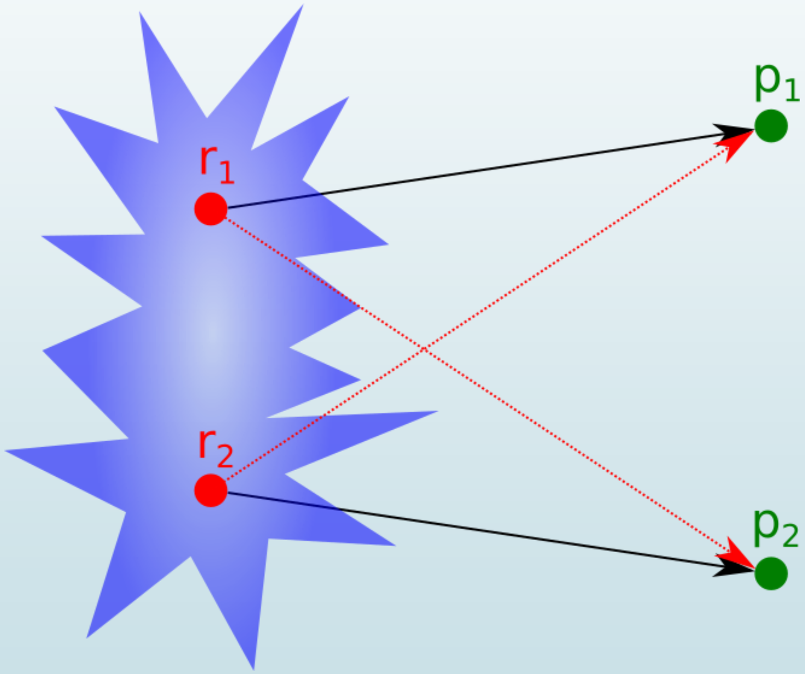
Two-particle correlation function:

➨ $$C_2(q) = \frac{P(p_1, p_2)}{P(p_1)P(p_2)}$$

where $P(p_1, p_2)$ – probability to observe two particles with momenta p_1 and p_2,
$P(p_1)$, $P(p_2)$ – probability to observe one particle with momenta p_1 or p_2

The density function is parameterized in terms of the Lorentz invariant four-momentum difference squared of the particles pair:

$$Q^2 = -(p_1 - p_2)^2$$



➨ BEC effect is described by a function with 2 parameters:

$$C_2(Q) = C_0[1 + \Omega(\lambda, QR)](1 + \varepsilon Q)$$

where C_0 – a normalization factor
ε accounts for the long-range momentum correlations
R – **the effective radius** of the source size
λ – **the strength parameter** (the incoherence or chaoticity factor):

- $\lambda = 0$ ($= 1$) for purely **coherent** (**chaotic**) sources

Bose-Einstein correlations at $\sqrt{s} = 0.9$ and 7 TeV

Constructed correlation functions:

arXiv:1502.07947, subm. to Eur. Phys. J. C

- **The $C_2(Q)$ correlation function** is a ratio of:
  - the like-sign (LS) particle (track) pairs Q distribution – **the signal distribution $N^{ls}(Q)$ with BEC** and
  - the particle (track) pairs Q distribution – **the reference distribution $N^{ref}(Q)$ without BEC**
- **The experimentally constructed:**
  - **The $C_2(Q)$ correlation function:**

$$C_2(Q) = \frac{N^{ls}(Q)}{N^{ref}(Q)}$$

  - **The double ratio $R_2(Q)$ correlation function:**

$$R_2(Q) = \frac{C_2(Q)}{C_2^{MC}(Q)}$$

The "natural choice" for $N^{ref}(Q)$ – **the unlike-sign charged particle pairs of the event (UCP).** The other used reference samples – mixed-event, opposite-hemisphere pairs, rotated track technique.
The $C_2^{MC}(Q)$ is used to correct $N^{ref}(Q)$ to minimize effect of resonances and doesn't include BEC effects.

Parameterizations:

- The Goldhaber spherical source model of a static Gaussian source in the Plane-Wave approach: $\Omega = \lambda e^{-R^2Q^2}$
- The exponential parameterization of a static source – assumes a radial Lorentzian distribution of the source: $\Omega = \lambda e^{-RQ}$
  - *a better description of the data at small Q values*
- The Gaussian and Exponential forms in the Quantum Optics model were studied too.

Bose-Einstein correlations at $\sqrt{s} = 0.9$ and 7 TeV

Double ratio $R_2(Q)$ correlation functions:

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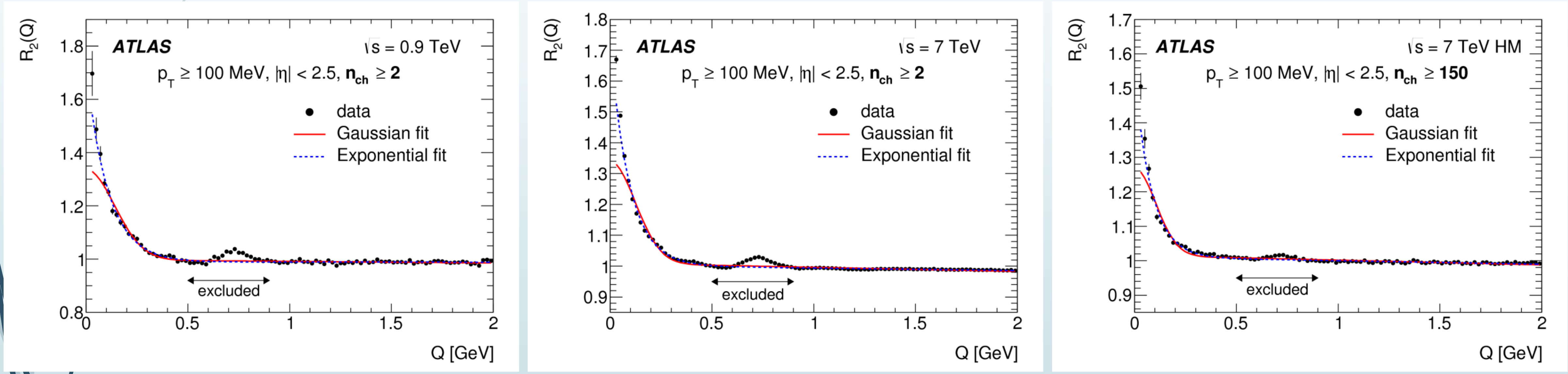
ATLAS pp 2009 data $\sqrt{s} = 0.9$ TeV, 7 μb^{-1}; 2010 data $\sqrt{s} = 7$ TeV and 7 TeV HM, 190 μb^{-1} *and* 12.4 nb^{-1}, *respectively*.

$p_T \geq 100\ MeV$, $|\eta| < 2.5$; 1 PV with ≥ 2 tracks, 7 TeV HM - 1 PV with ≥ 108 tracks

Statistics of selected events: $3.6 \times 10^5, 1 \times 10^7, 1.8 \times 10^4$ at 0.9, 7 TeV and 7 TeV HM, respectively

The data are corrected for detector effects, such as resolution and inefficiencies, coulomb interactions, etc.



- **A clear signal of BEC** is observed in the region of small 4-momentum difference Q
- Q region $0.02 - 2\ GeV$
- The bump at $0.5 \leq Q \leq 0.9$ GeV is due to an overestimation in the MC simulation for ρ-meson (more $\rho \to \pi^+\pi^-$)

Bose-Einstein correlations at $\sqrt{s} = 0.9$ and 7 TeV

Full phase-space results:

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- *The results of BEC parameters for Exponential fits of $R_2(Q)$, the UCP reference sample used (total uncertainties):*

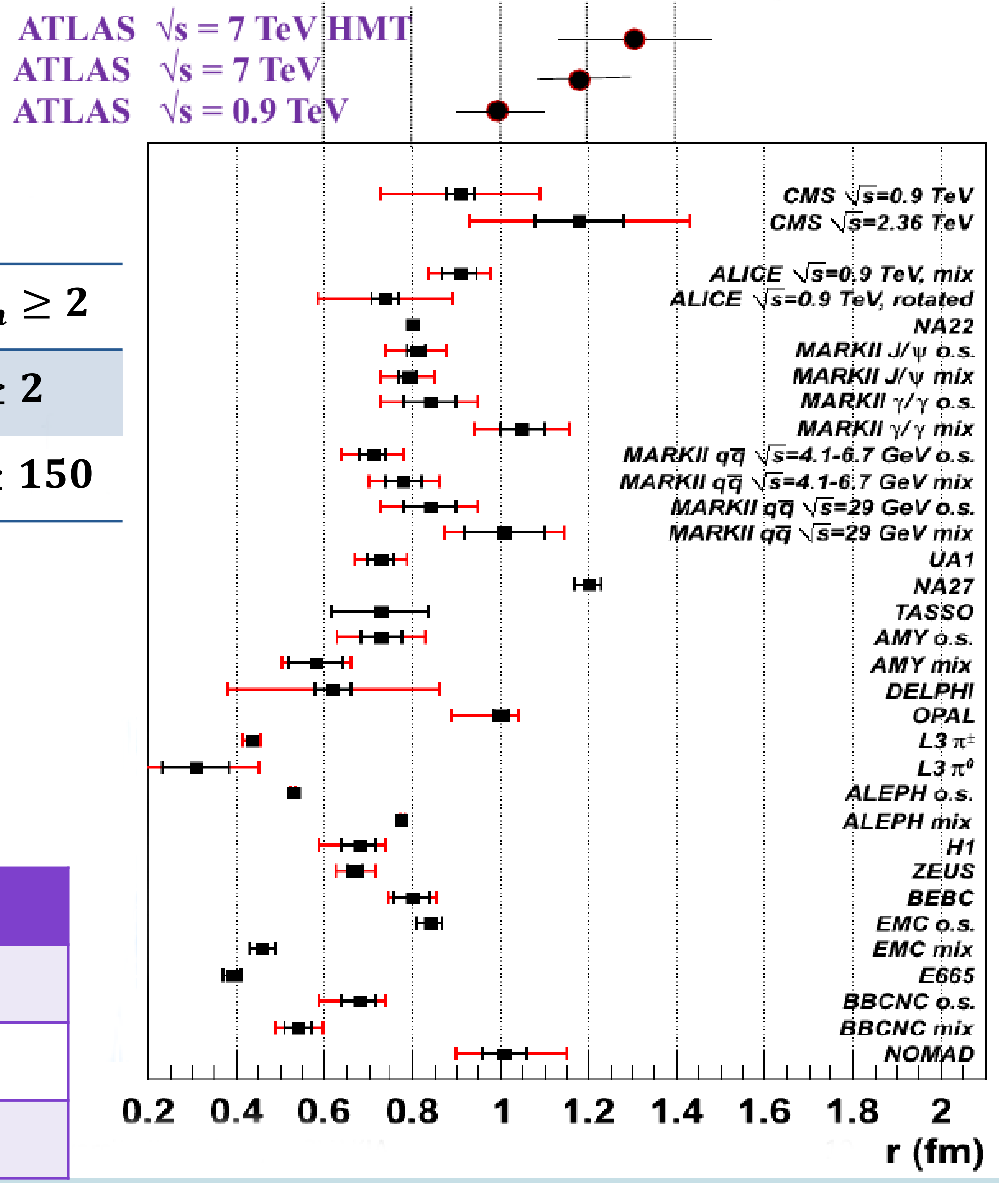
$\lambda = 0.74 \pm 0.1$,	$R = 1.83 \pm 0.25\ fm$	$at\ \sqrt{s} = 0.9\ TeV\ for\ n_{ch} \geq 2$
$\lambda = 0.71 \pm 0.07$,	$R = 2.06 \pm 0.22\ fm$	$at\ \sqrt{s} = 7\ TeV\ for\ n_{ch} \geq 2$
$\lambda = 0.52 \pm 0.06$,	$R = 2.36 \pm 0.30\ fm$	$at\ \sqrt{s} = 7\ TeV\ for\ n_{ch} \geq 150$

Comparison with previous measurements:

- Most of the previous experiments provided R with a Gaussian fit.
- The comparison to the Exponential fit can be done using the scale factor $\sqrt{\pi}$:

$$R^{(G)} = R^{(E)}/\sqrt{\pi}$$

Energy [TeV]	R [fm]
0.9	1.03 ± 0.14
7	1.16 ± 0.12
7 (HM)	1.33 ± 0.17



Bose-Einstein correlations at $\sqrt{s} = 0.9$ and 7 TeV

Parameters λ and R vs. particle multiplicity:

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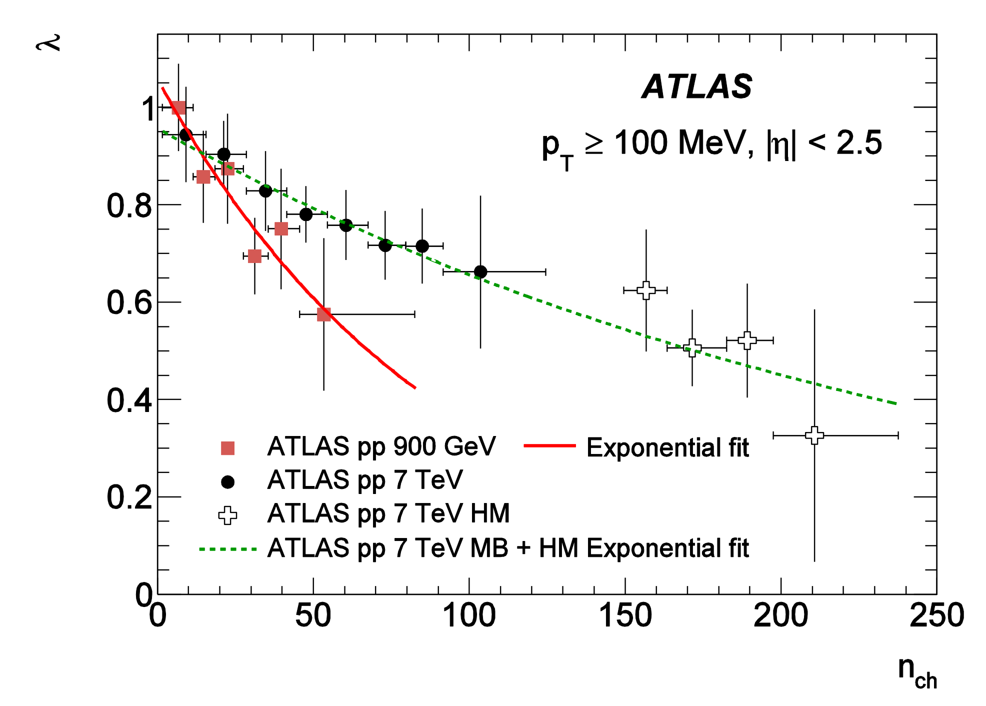
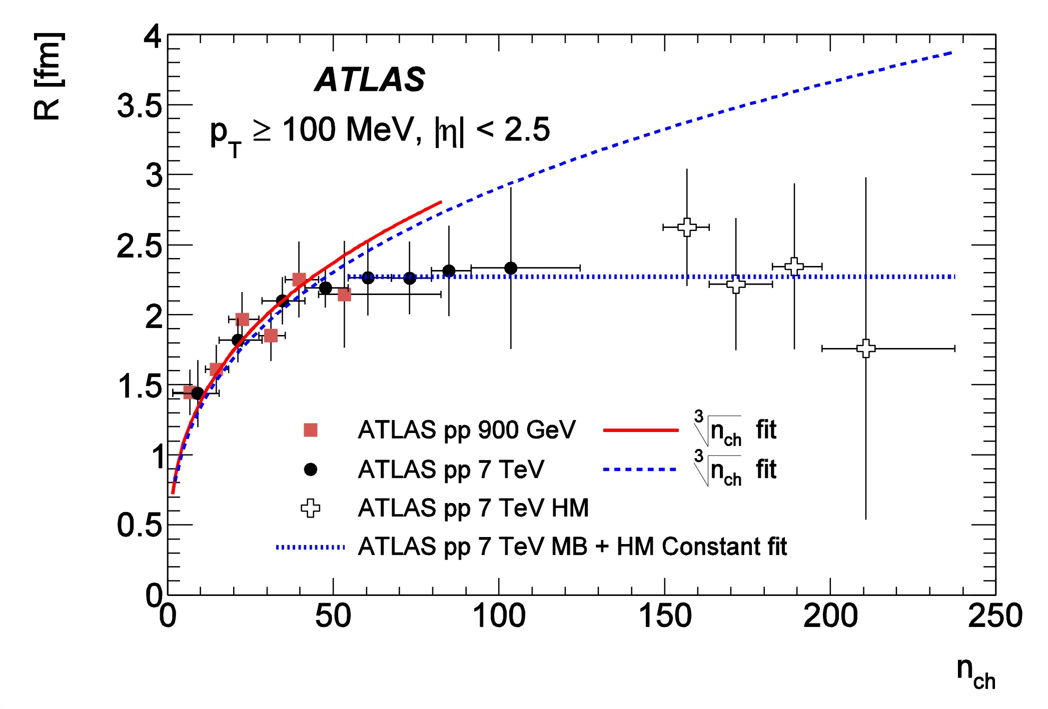




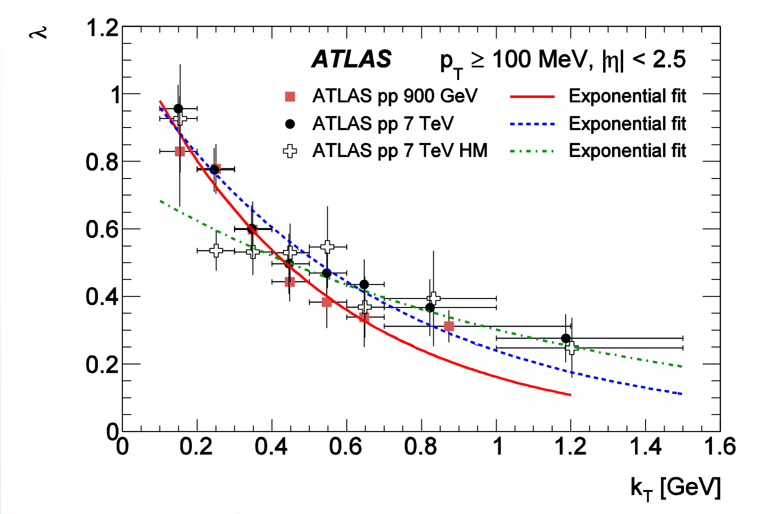
- The error bars – quadratic sum of the statistical and the systematic uncertainties
- The result of the $p_0\sqrt[3]{n_{ch}}$ fit for $n_{ch} \leq 55$:
  - 0.9 TeV: $p_0 = 0.64 \pm 0.07$ [fm]
  - 7 TeV: $p_0 = 0.63 \pm 0.05$ [fm]
- **The result of the Constant for $n_{ch} \geq 55$:**
  - **7 TeV MB + HM: $p_0 = 2.28 \pm 0.32$ [fm]**

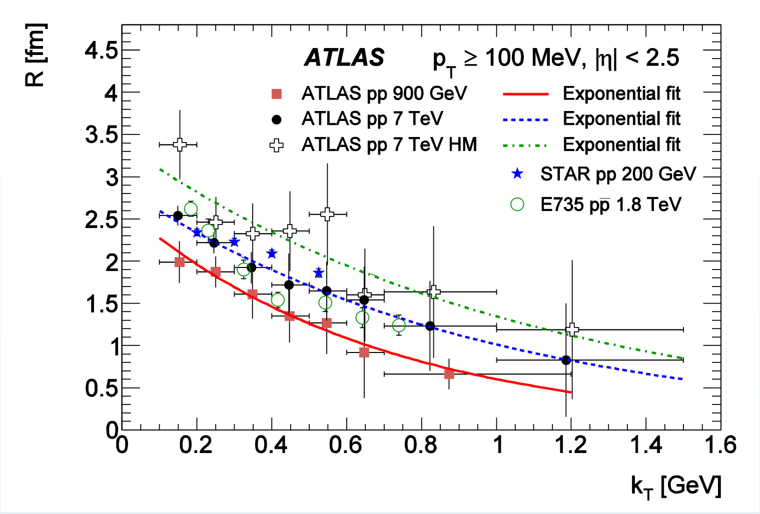
The **saturation of *R*** for high-multiplicity particles (up to ≈ 240) is observed for the first time – predicted by the ***Pomeron-based model*** (due to highly overlapping of colliding protons).

Within the uncertainties **λ** and ***R*** are energy-independent.

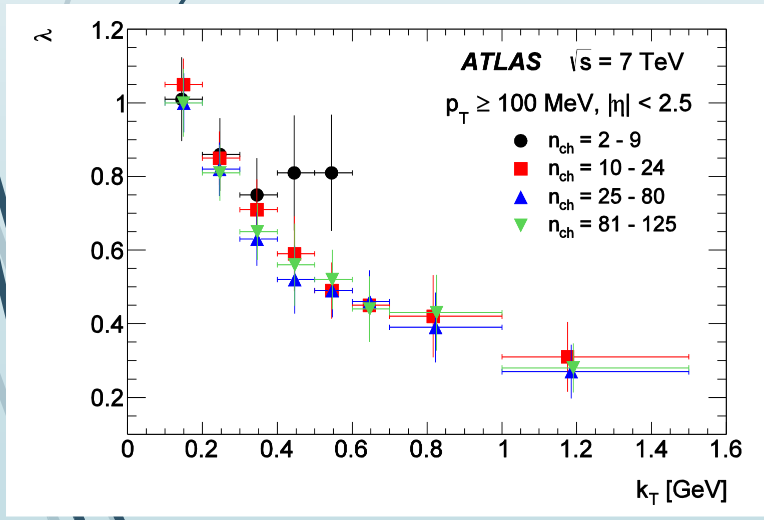
Bose-Einstein correlations at $\sqrt{s} = 0.9$ and 7 TeV

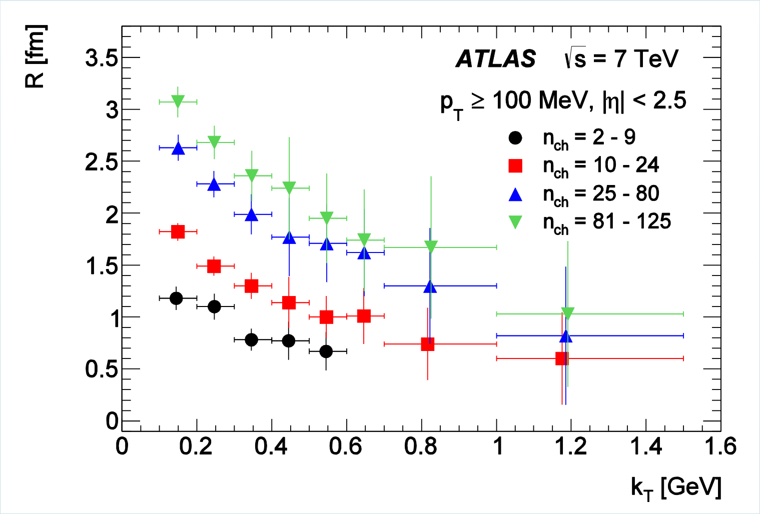
Parameters λ and R vs. track pair k_T:





For different multiplicity regions at $\sqrt{s} = 7$ TeV:





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- The average transverse momentum of the particle pairs:

$$k_T = \frac{|\vec{p}_{T,1} + \vec{p}_{T,2}|}{2}$$

- Within the uncertainties $\boldsymbol{\lambda}$ and $\boldsymbol{R}$ are energy-independent
- Comparison with measurements by the STAR and E735 experiments – in good agreement
- The error bars – quadratic sum of the statistical and the systematic uncertainties
- $\boldsymbol{R}$ decreases with $\boldsymbol{k_T}$ and exhibits an increase with increasing multiplicity

The differential production cross section of the $\phi(1020)$ meson at $\sqrt{s} = 7$ TeV

$\phi(1020)$ differential production cross section at $\sqrt{s} = 7$ TeV

Motivation:

- Measurements of the $\phi(1020)$-meson probe strangeness production at a soft process scale $Q \sim 1\ GeV$, which is sensitive to s-quark and low-x gluon densities
- Also can constrains fragmentation models

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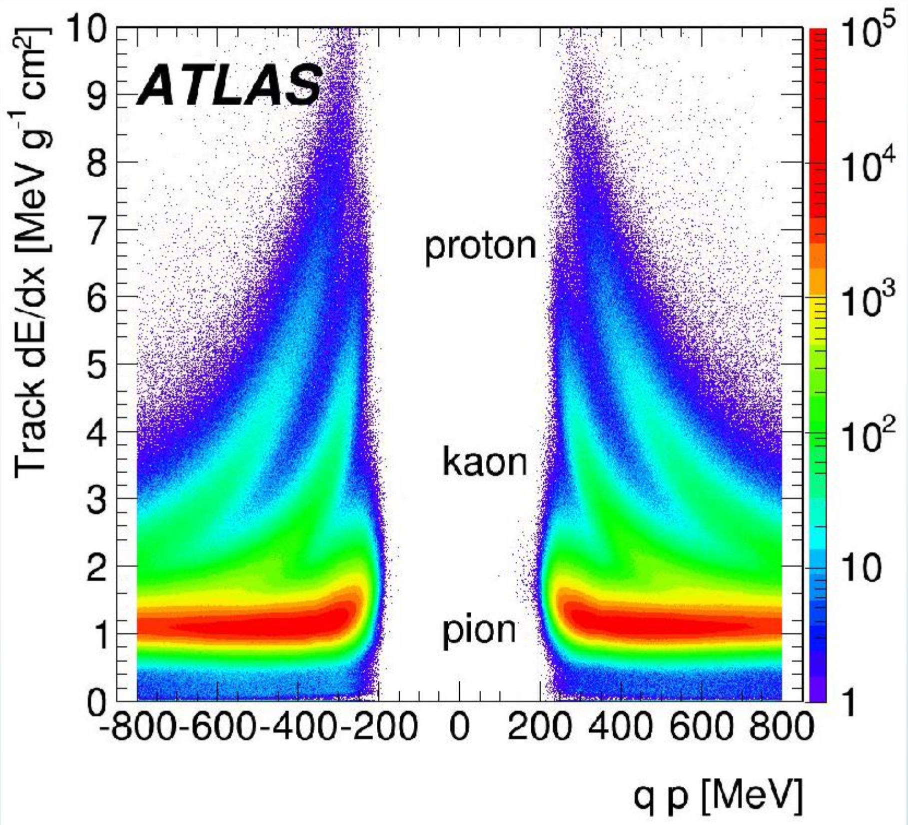
ATLAS 2010 pp data $\sqrt{s} = 7$ TeV, 383 μb^{-1} (low pile-up conditions)

- $\phi \rightarrow K^+K^-$ decays
- $K^\pm$ are identified by $\frac{dE}{dx}$ in the Pixel Detector
- The fiducial phase space:
  - $500 < p_{T,\phi} < 1200\ MeV$
  - $|y_\phi| < 0.8$
  - $p_{T,K^\pm} > 230\ MeV$
  - $p_{K^\pm} < 800\ MeV$
  - The data are corrected for detector effects, etc.

Particle identification:



The truncated mean for the energy loss per track as a function of signed momentum for tracks. The energy lost bands of pions, kaons and protons

$\phi(1020)$ differential production cross section at $\sqrt{s} = 7$ TeV

Signal extraction:

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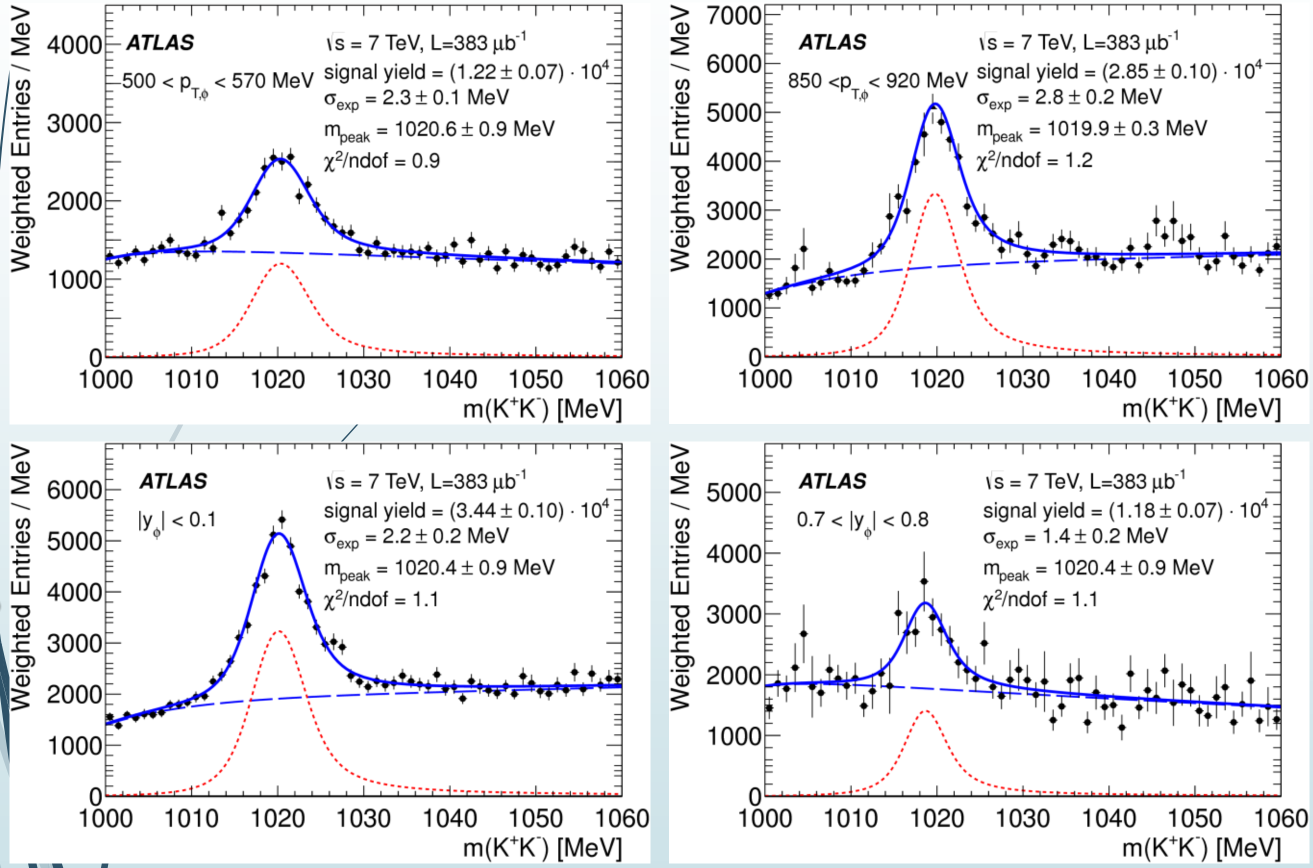


An empirical background description:

$$f_{BKG}(\mathrm{m}) = \left(1 - e^{(2m_K - m)/C}\right) \cdot \left(\frac{m}{2m_K}\right)^A + B\left(\frac{m}{2m_K} - 1\right)$$

where A, B and C determine the background shape

- Apply the selection criteria to reduce the combinatorial background such as:
  - a particle identification (PID) requirement
  - kaon candidates with $P_\pi < 0.1$ and $P_K > 0.84$ conditions
  - $\phi(1020)$ candidates with $1000 < m_{K^+K^-} < 1060\ MeV$, etc.
- The fiducial region is divided into $p_{T,\phi}$ *and* $|y_\phi|$ bins
- **The signal shape is described by a relativistic Breit-Wigner function:**

$$f_{RBW}(m; m_0, \Gamma_0) = \frac{m^2}{(m^2 - m_0^2)^2 + m_0^2 \Gamma^2(m)}$$

where the mass-dependent width:

$$\Gamma(m) = \Gamma_0 \left[\frac{m^2 - 4m_K^2}{m_0^2 - 4m_K^2}\right]^{3/2}$$

where $m_0 = 1019.45\ MeV$ – the fixed $\phi(1020)$ mass
Γ_0 – the natural width of 4.26 MeV
m_K – the charged kaon mass

$\phi(1020)$ differential production cross section at $\sqrt{s} = 7$ TeV

Cross section:

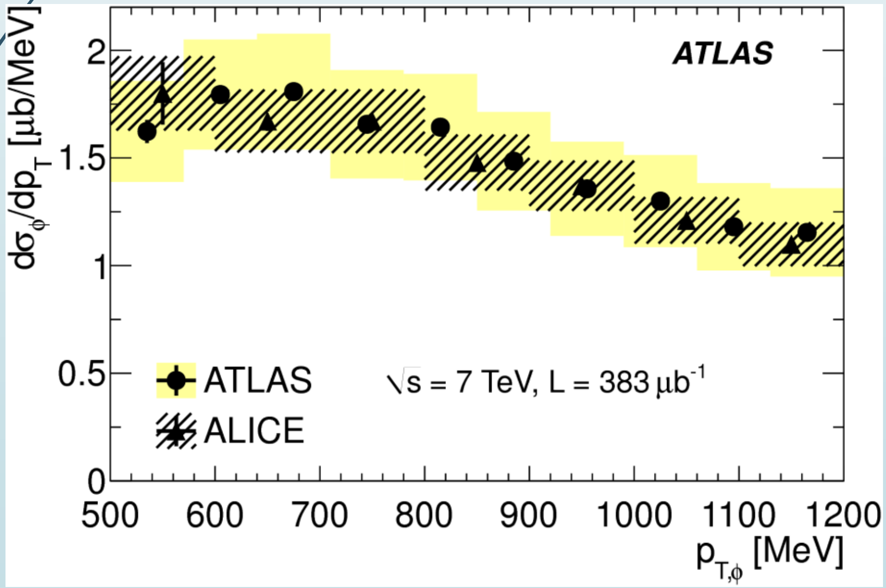
- **The cross section σ^i_{bin} in bin i:** $\sigma^i_{bin} = \frac{N_i}{\mathcal{L}}$

where $\mathcal{L}$ – the integrated luminosity
N_i – the number of efficiency-corrected recons. $\phi \to K^+K^-$ candidates in bin i

The fiducial cross section:

$$\sigma \cdot Br(\phi \to K^+K^-) = 570 \pm 8_{stat} \pm 66_{syst} \pm 20_{lumi}\ \mu b$$

- $\frac{d\sigma}{dp_T}$ extrapolated to the full $|y_\phi| < 0.5$ fiducial volume agrees with **ALICE result** (*to qualitative*):



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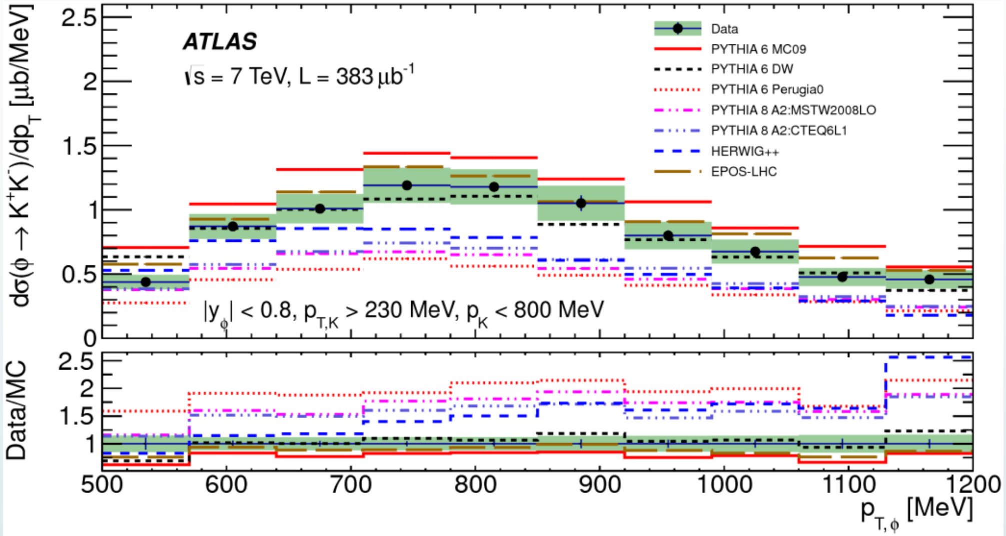
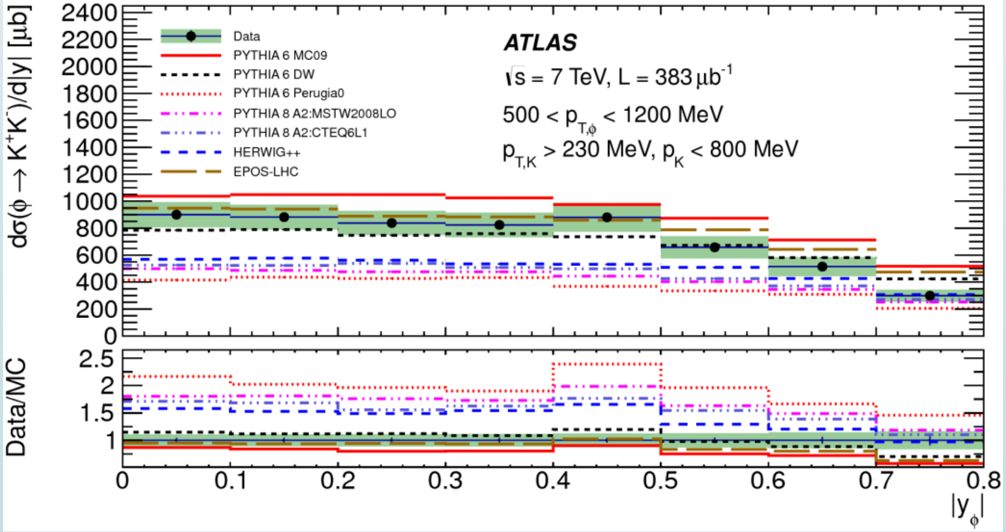
- The **$\phi(1020)$ differential production cross section** as functions of $p_{T,\varphi}$ and $|y_\varphi|$ – large spread of predictions even between different tunes of Pythia6 MC:





Summary

- ***The Λ and $\bar{\Lambda}$ hyperon transverse polarization:***
  - ATLAS measurement of the **Λ** transverse polarization is consistent with zero – in agreement with an extrapolation the previous results to the low Feynman-*x*, which suggest that the polarization should decrease as the Feynman-*x* approaches zero
  - $\bar{\Lambda}$ transverse polarization is also observed to be zero, consistent with previous experiments
- ***Bose-Einstein correlations:***
  - Multiplicity dependence of the BEC was investigated up to very high multiplicities (up to ≈ 240). The saturation effect in multiplicity dependence of the extracted BEC radius was observed at level ***R = 2.28 ± 0.32 fm***
- ***The $\phi(1020)$ differential production cross section:***
  - This measurement can provide useful input for turning and development of phenomenological models in order to improve MC generators

Thank you very much for your attention