Particle Production at the LHC

Andrew Powell

University of Oxford

SM@LHC, Durham IPPP

11th – 14th April 2011

Motivation

- The following statement sums it up:

  "The 'underlying event' (UE) is an unavoidable background to most collider observables and having good understanding of it leads to more precise collider measurements" – Rick Field (2006)

- All LHC experiments dependent on generators to provide required understanding of soft QCD processes contributing to the UE
- Min. Bias results from LHC 1st data can:
  - Allow comparisons with different generators
  - Assist in their constraining (tuning)
- Interesting physics in its own right
  - New energy frontier
  - New Physics?

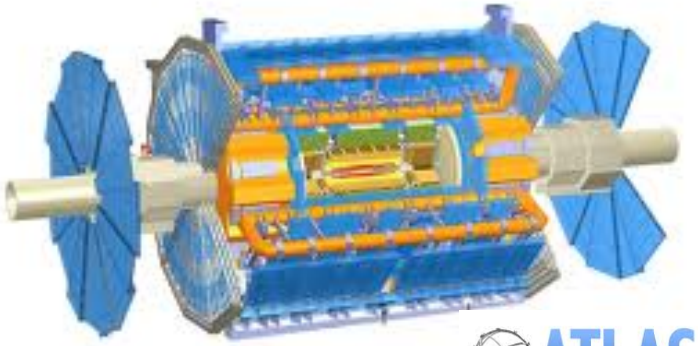
Relevant Min. Bias Measurements

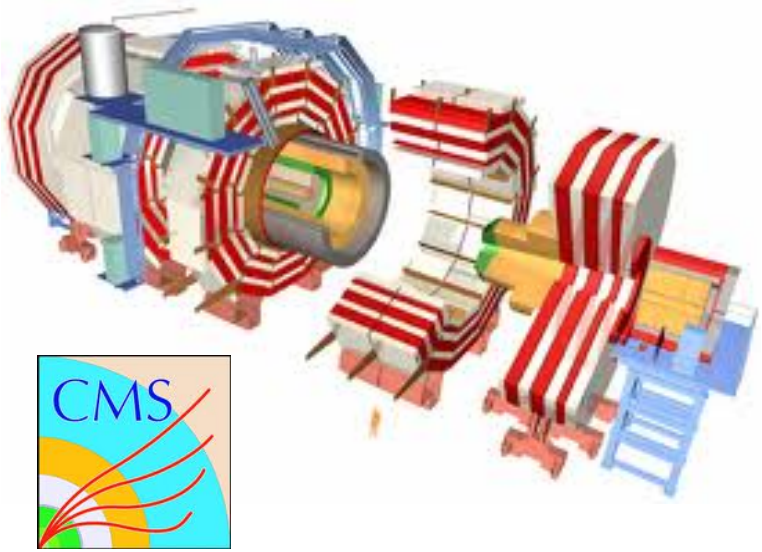
- Particle Multiplicities & Correlations
  - See talks by Andy Buckley and Luca Perrozzi
- Particle Production
  - What are the spectra of specific particle species?
  - How do they compare with theoretical models and previous experiments?
  - Main experimental hurdles:
    - Means of identifying and distinguishing particle species
    - Ability to access production at low pT

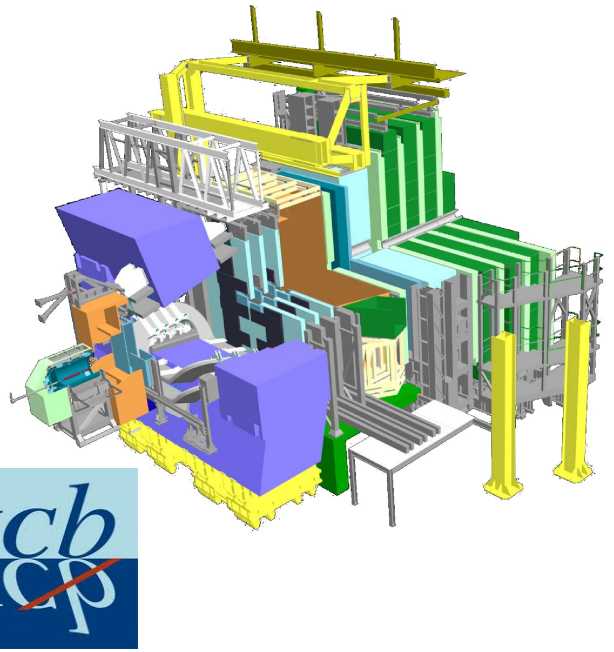
Particle Production

- Several areas of experimental study:
  - Identified Final-State Particle ($K^{\pm}$, $\pi^{\pm}$, p) Spectra
    - Requires good Particle Identification (PID)
      - Particularly suited to the qualities of ALICE & LHCb
  - Strange Resonance (K^0, Λ, ϕ, Ξ, Ω) Spectra
    - PID not necessary
      - Decays well separated from Primary Vertex (except strongly decaying ϕ)
      - Invariant mass sufficient as a discriminating variable (except for ϕ)
      - Accessible by all LHC experiments
  - Cross-Sections of above Processes
    - Requires good knowledge of $\mathcal{L}_{INT}$

The Detectors

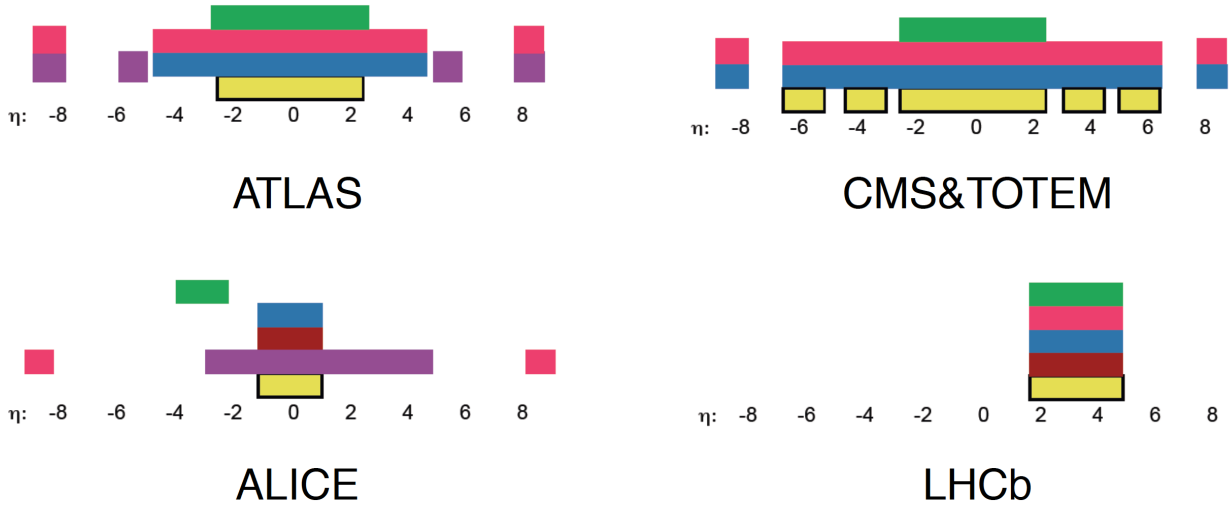






The Detectors

- What about in a more appropriate variable? (η)



Tracking, ECAL, HCAL, lumi Counters, MUONS, Hadron PID

- Complementary detector acceptances
- Potential to compare data/models over extensive η range
- Furthermore, data at different energies: $\sqrt{s}$ = 0.9, 2.76* & 7.0 TeV

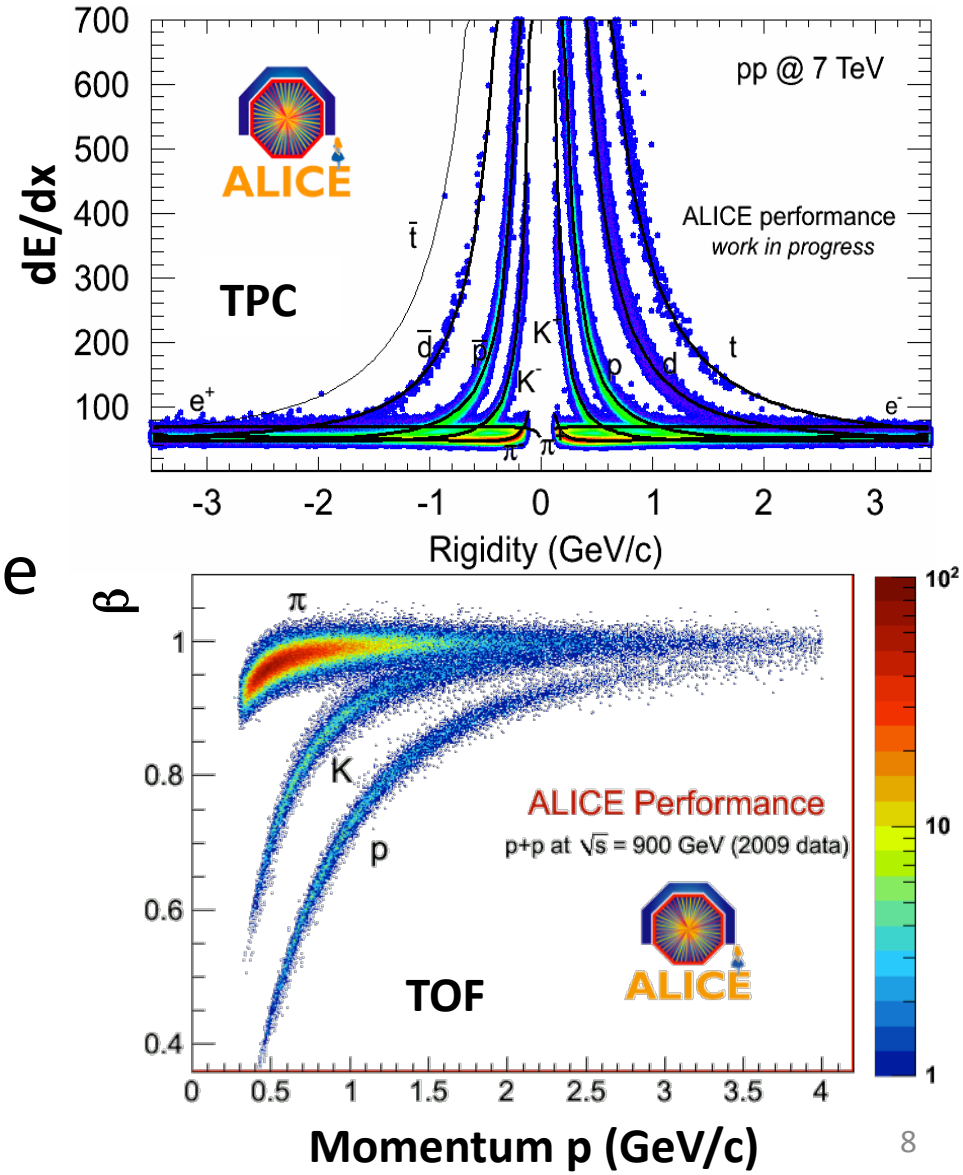
Identified Particle ($K^{\pm}$, $\pi^{\pm}$, p) Spectra

- Possible at ALICE & LHCb due to dedicated PID systems
- Impressive array of results from ALICE
- New and updated LHCb results imminent

Measurement	ALICE		LHCb	
	0.9 TeV	7 TeV	0.9 TeV	7 TeV
Particle pT Spectra	arXiv:1101.4110v2		[IN PREP]	
Anti-p/p	arXiv:1006.5432		LHCb-CONF-2010-009	
$(K^+ + K^-)/(\pi^+ + \pi^-)$	arXiv:1101.4110v2		[IN PREP]	
$(p + \text{Anti-p})/(\pi^+ + \pi^-)$	arXiv:1101.4110v2		[IN PREP]	

ALICE Hadronic PID

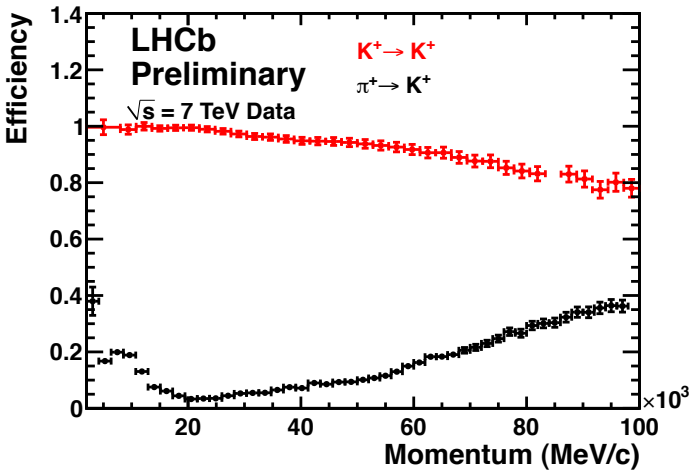
- Provided via several systems:
  - Inner Tracker (ITS)
  - Time Projection (TPC)
  - Time-of_Flight (TOF)
- Combined PID over range 0.1<pT<2.5 GeV
- Kaons also identified via their ‘kinked’ tracks in TPC (weak decays)

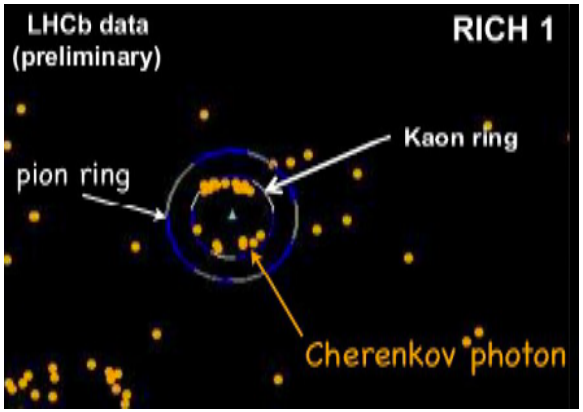


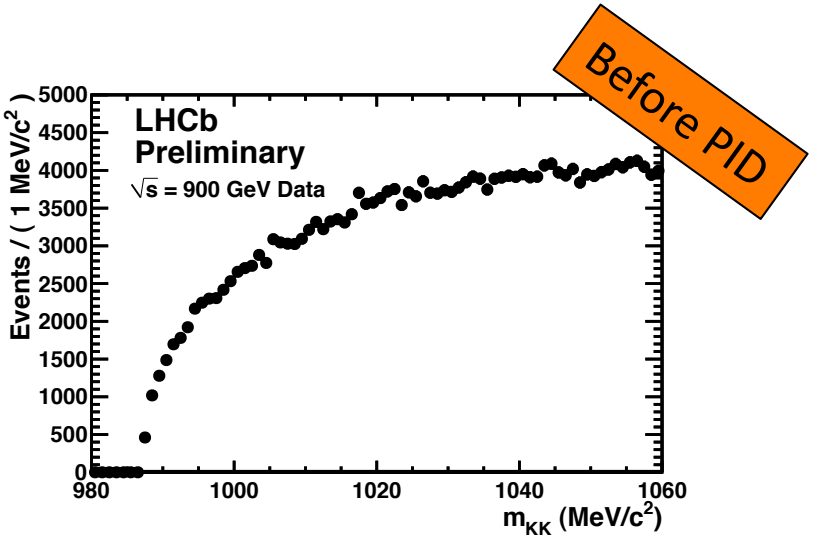
LHCb Hadronic PID

- Provided via two Ring Imaging Cherenkov (RICH) Detectors:
  - RICH-1 : 2<p<60 GeV
  - RICH-2 : 30<p<100+ GeV

$\Delta\log\mathcal{L}(\mathrm{K}-\pi) > 0$



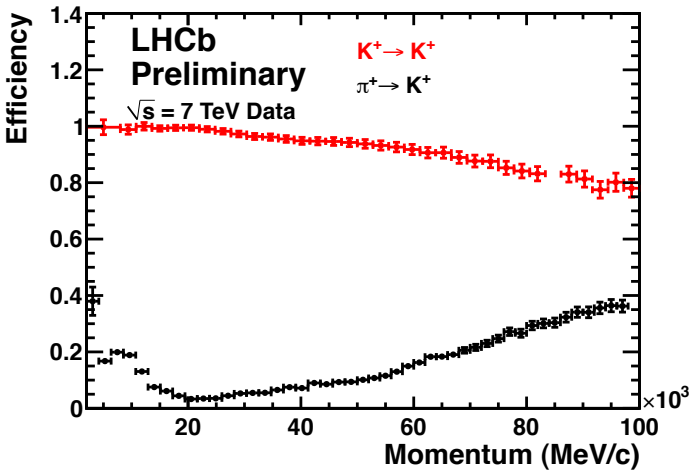


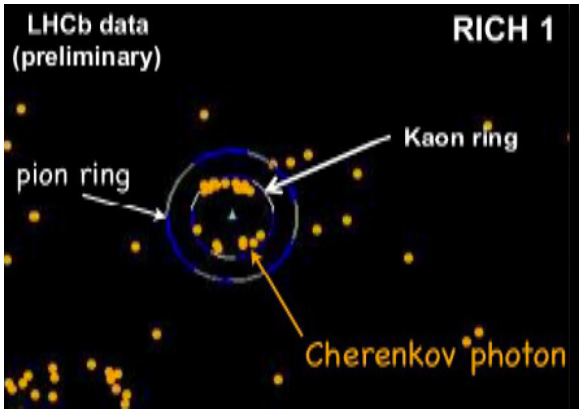


LHCb Hadronic PID

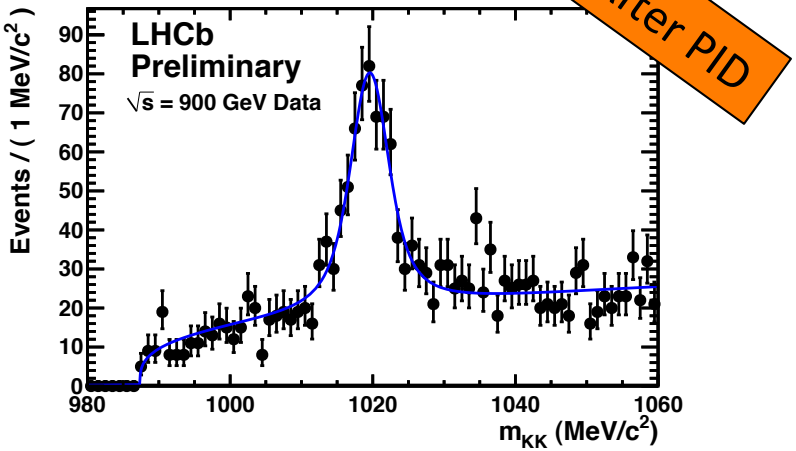
- Provided via two Ring Imaging Cherenkov (RICH) Detectors:
  - RICH-1 : 2<p<60 GeV
  - RICH-2 : 30<p<100+ GeV

$$\Delta\log\mathcal{L}(\mathrm{K}-\pi) > 0$$





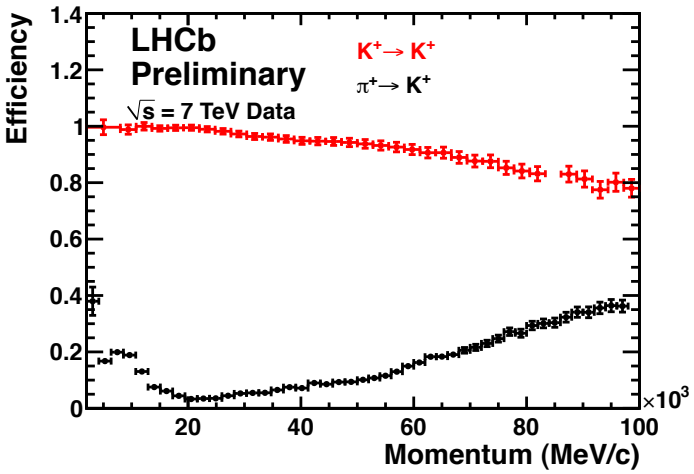
After PID

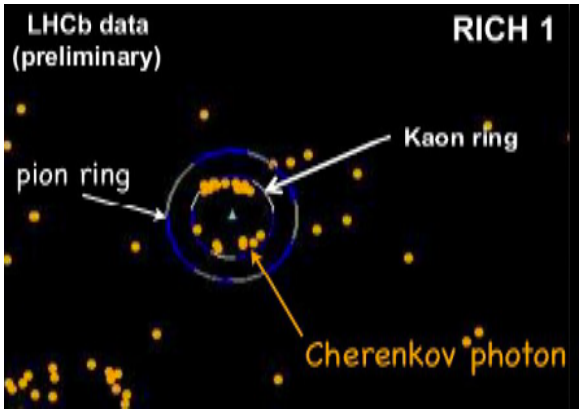


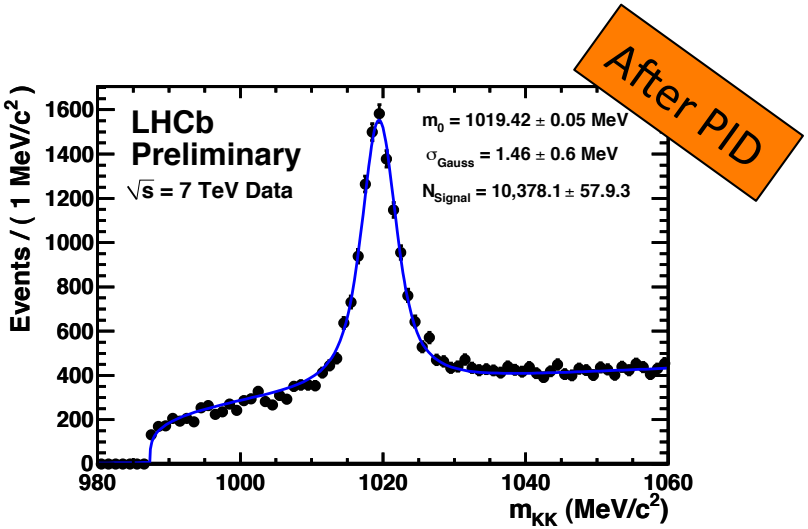
LHCb Hadronic PID

- Provided via two Ring Imaging Cherenkov (RICH) Detectors:
  - RICH-1 : 2<p<60 GeV
  - RICH-2 : 30<p<100+ GeV

$\Delta \log \mathcal{L}(K - \pi) > 0$







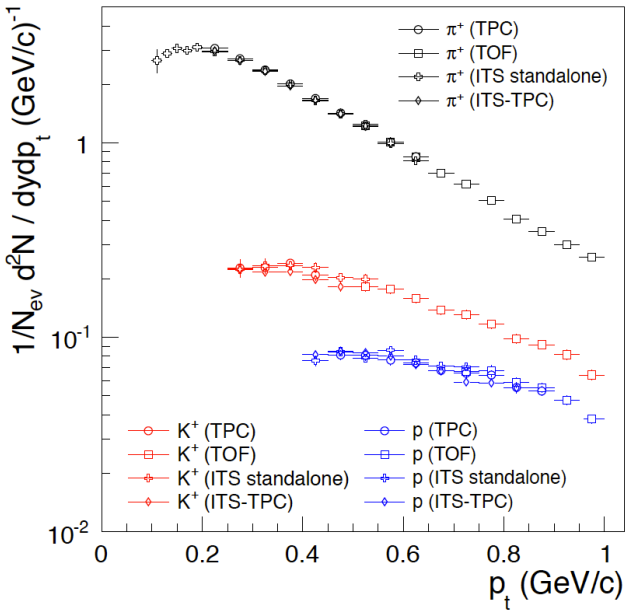
arXiv:1101.4110v2

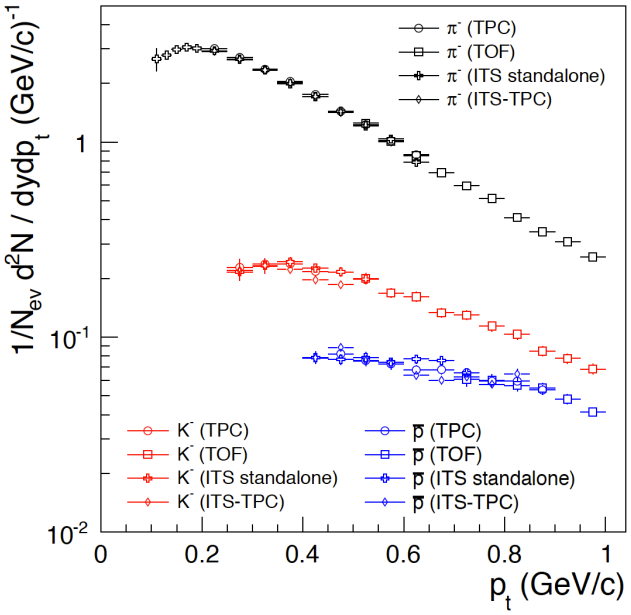
Particle ($K^{\pm}$,$\pi^{\pm}$,p) pT Spectra

- Spectra normalised to inelastic pp collisions (N_{ev})

$|y| < 0.5$

$\sqrt{s} = 0.9$ TeV





- Spectra using the different ALICE PID techniques shown
  - Excellent agreement!
  - Confirms reconstruction efficiencies well reproduced by simulation
- Results from the different analyses are combined to cover full momentum range (0.1<pT<1 GeV)

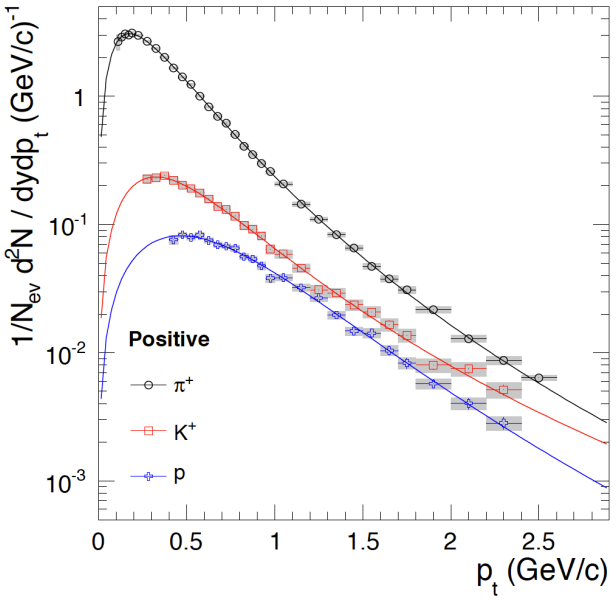
arXiv:1101.4110v2

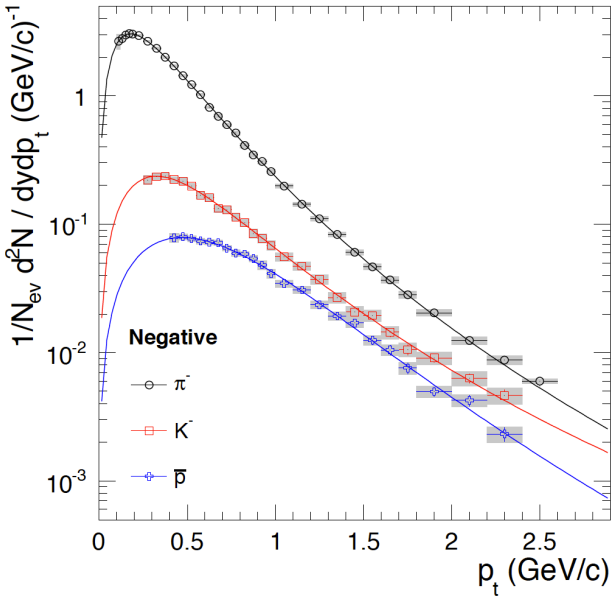
Particle ($K^{\pm}$,$\pi^{\pm}$,p) pT Spectra

- Perform fit to spectra to extract yields and <pT>
  - Use Lévy (Tsallis) function

$|y| < 0.5$

$\sqrt{s} = 0.9$ TeV





Particle	dN/dy	$\langle p_t \rangle$ (GeV/c)	Lowest p_t (GeV/c)	Extrapolation	χ^2/ndf
π^+	$1.493 \pm 0.004 \pm 0.074$	$0.404 \pm 0.001 \pm 0.02$	0.10	10%	14.23/30
π^-	$1.485 \pm 0.004 \pm 0.074$	$0.404 \pm 0.001 \pm 0.02$	0.10	10%	12.46/30
K^+	$0.184 \pm 0.004 \pm 0.015$	$0.657 \pm 0.006 \pm 0.05$	0.25	19%	12.59/23
K^-	$0.183 \pm 0.004 \pm 0.015$	$0.641 \pm 0.006 \pm 0.05$	0.25	19%	6.49/23
p	$0.080 \pm 0.002 \pm 0.006$	$0.775 \pm 0.008 \pm 0.06$	0.40	25%	12.59/20
$\bar{p}$	$0.077 \pm 0.002 \pm 0.006$	$0.767 \pm 0.008 \pm 0.06$	0.40	25%	9.09/20

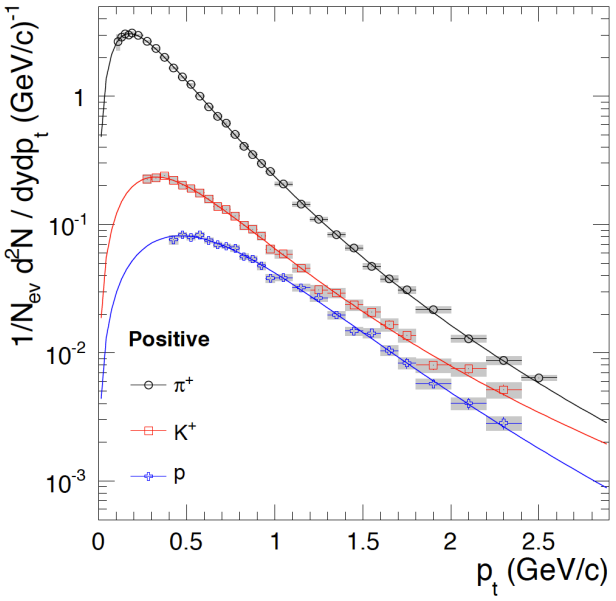
arXiv:1101.4110v2

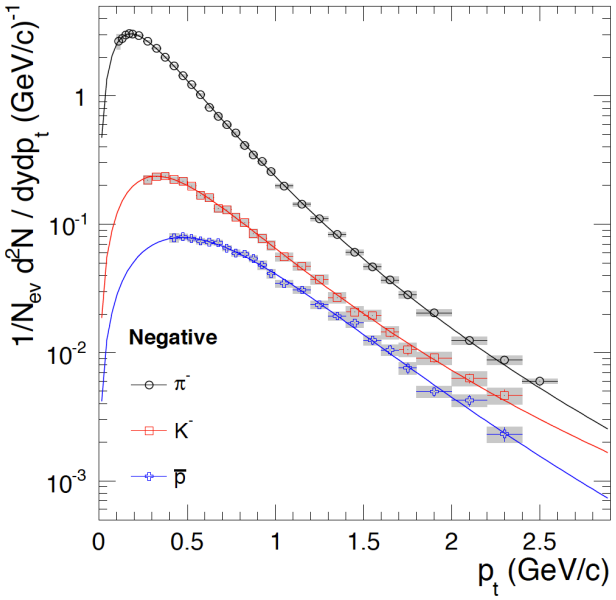
Particle ($K^{\pm}$,$\pi^{\pm}$,p) pT Spectra

- Perform fit to spectra to extract yields and <pT>
  - Use Lévy (Tsallis) function

$|y| < 0.5$

$\sqrt{s} = 0.9$ TeV





Particle	dN/dy	$\langle p_t \rangle$ (GeV/c)	Lowest p_t (GeV/c)	Extrapolation	χ^2/ndf
π^+	$1.493 \pm 0.004 \pm 0.074$	$0.404 \pm 0.001 \pm 0.02$	0.10	10%	14.23/30
π^-	$1.485 \pm 0.004 \pm 0.074$	$0.404 \pm 0.001 \pm 0.02$	0.10	10%	12.46/30
K^+	$0.184 \pm 0.004 \pm 0.015$	$0.657 \pm 0.006 \pm 0.05$	0.25	19%	12.59/23
K^-	$0.183 \pm 0.004 \pm 0.015$	$0.641 \pm 0.006 \pm 0.05$	0.25	19%	6.49/23
p	$0.080 \pm 0.002 \pm 0.006$	$0.775 \pm 0.008 \pm 0.06$	0.40	25%	12.59/20
$\bar{p}$	$0.077 \pm 0.002 \pm 0.006$	$0.767 \pm 0.008 \pm 0.06$	0.40	25%	9.09/20

Consistent!

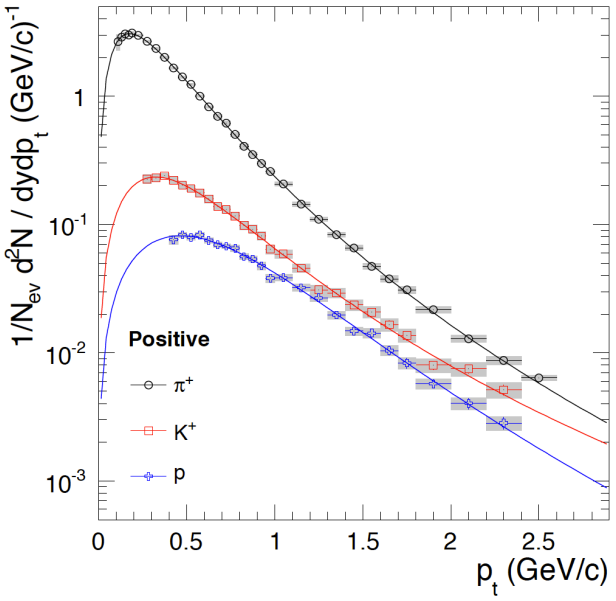
arXiv:1101.4110v2

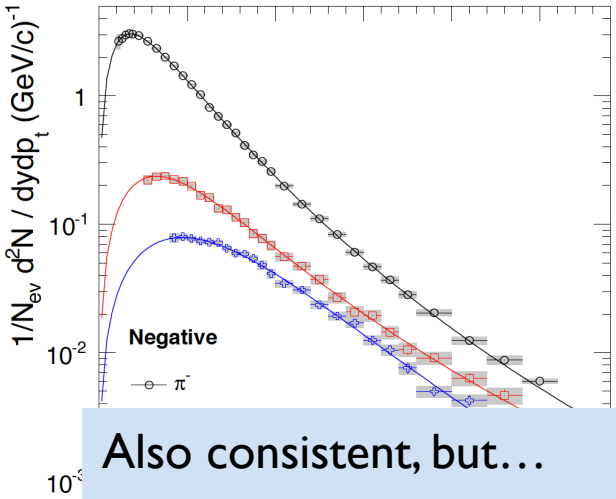
Particle ($K^{\pm}$,$\pi^{\pm}$,p) pT Spectra

- Perform fit to spectra to extract yields and <pT>
  - Use Lévy (Tsallis) function

$|y| < 0.5$

$\sqrt{s} = 0.9$ TeV





Particle	dN/dy	$\langle p_t \rangle$ (GeV/c)	Lowes
π^+	$1.493 \pm 0.004 \pm 0.074$	$0.404 \pm 0.001 \pm 0.02$	
π^-	$1.485 \pm 0.004 \pm 0.074$	$0.404 \pm 0.001 \pm 0.02$	
K^+	$0.184 \pm 0.004 \pm 0.015$	$0.657 \pm 0.006 \pm 0.05$	
K^-	$0.183 \pm 0.004 \pm 0.015$	$0.641 \pm 0.006 \pm 0.05$	
p	$0.080 \pm 0.002 \pm 0.006$	$0.775 \pm 0.008 \pm 0.06$	
$\bar{p}$	$0.077 \pm 0.002 \pm 0.006$	$0.767 \pm 0.008 \pm 0.06$	

Also consistent, but…

High precision anti-p/p ratio studied earlier found mean value of 0.957 ± 0.006 ± 0.014 and pT INDEPENDENT (more on this later)

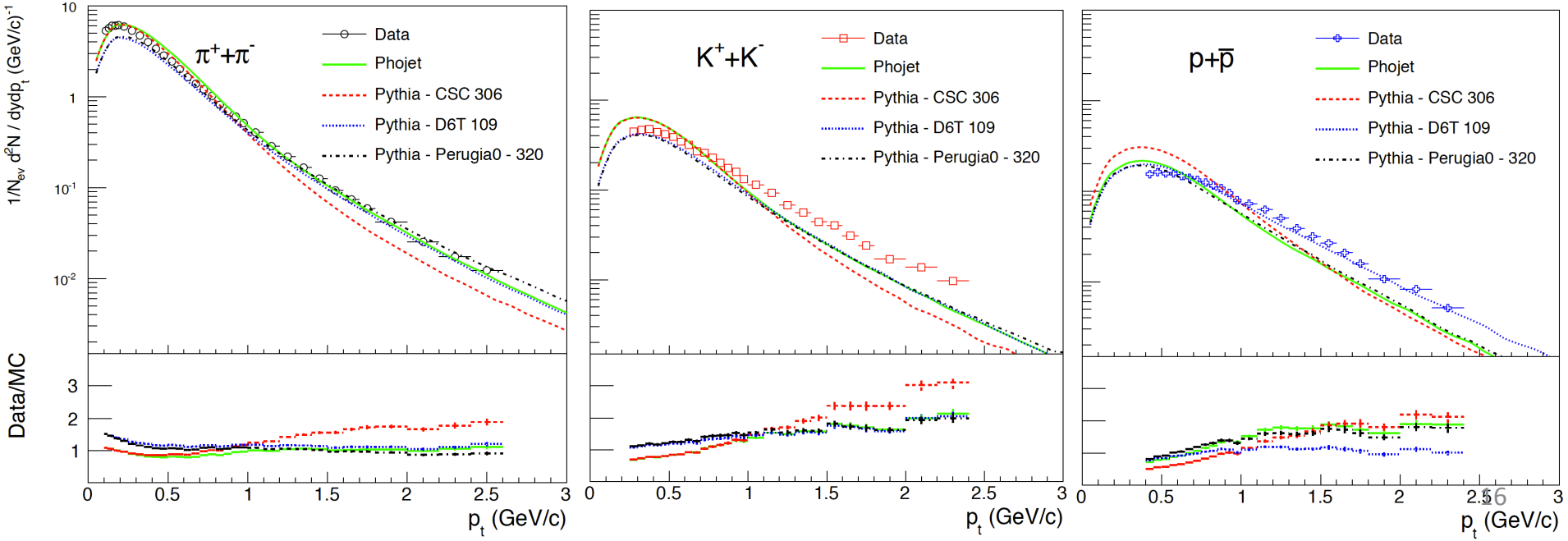
arXiv:1006.5432v1

arXiv:1101.4110v2

Hadron Yields

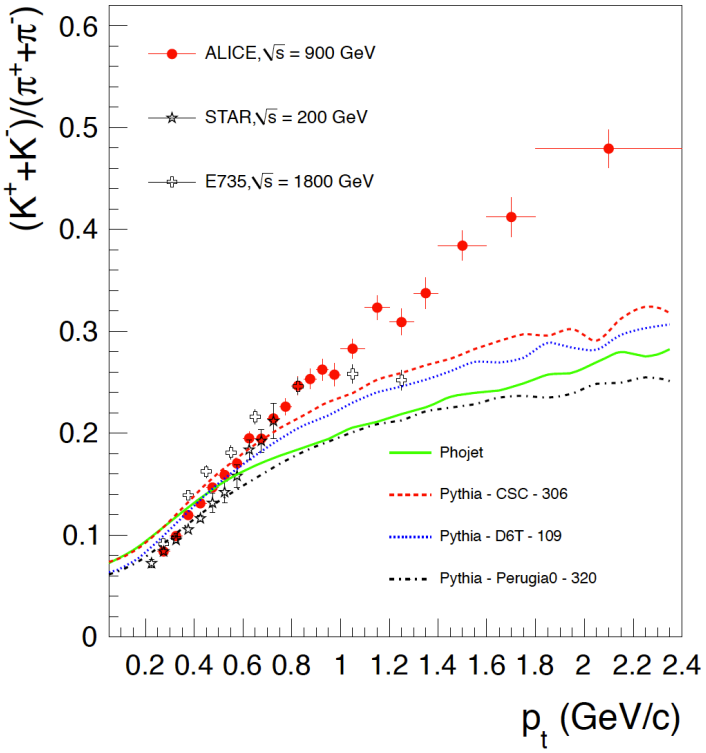
- Comparison of charge summed distributions with models

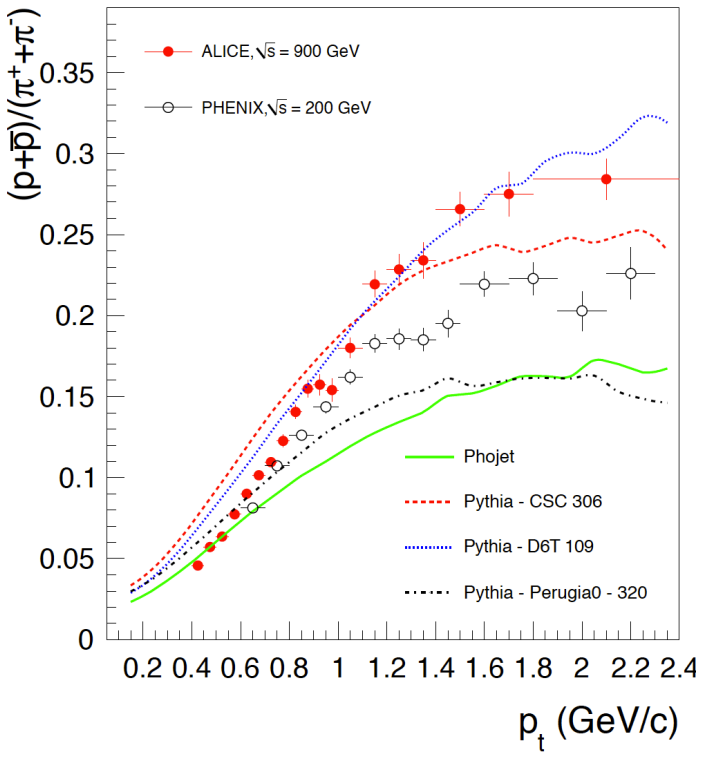
- **Pions**
  - Reasonably described by Phojet, Pythia D6T, Perugia-0
- **Kaons**
  - Underestimated above pT of 1 GeV
- **Protons**
  - Underestimated also, except by Pythia D6T



arXiv:1101.4110v2

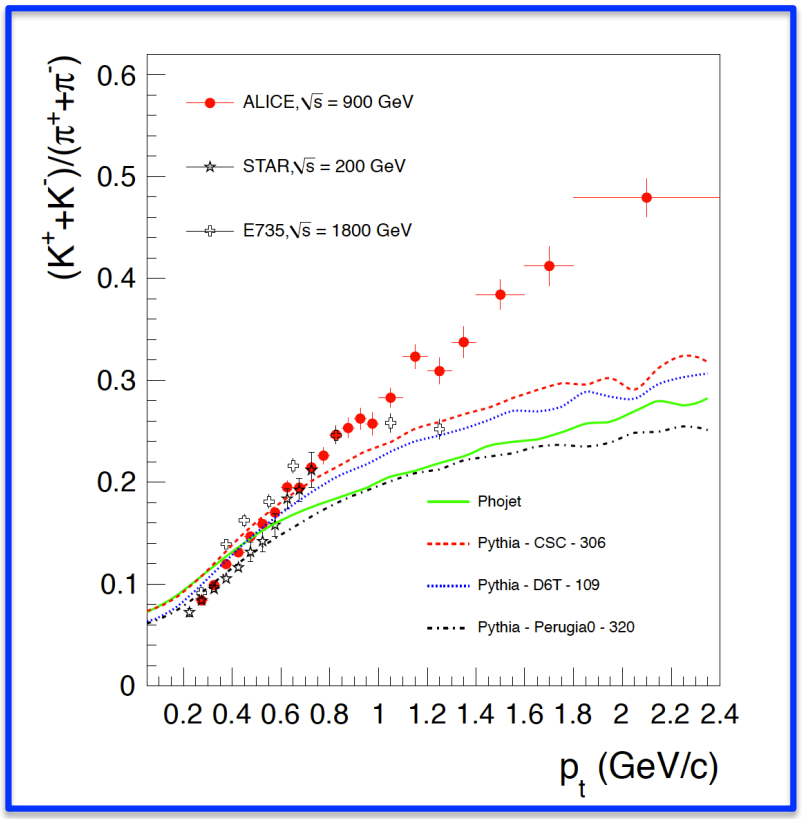
Hadron Yield Ratios

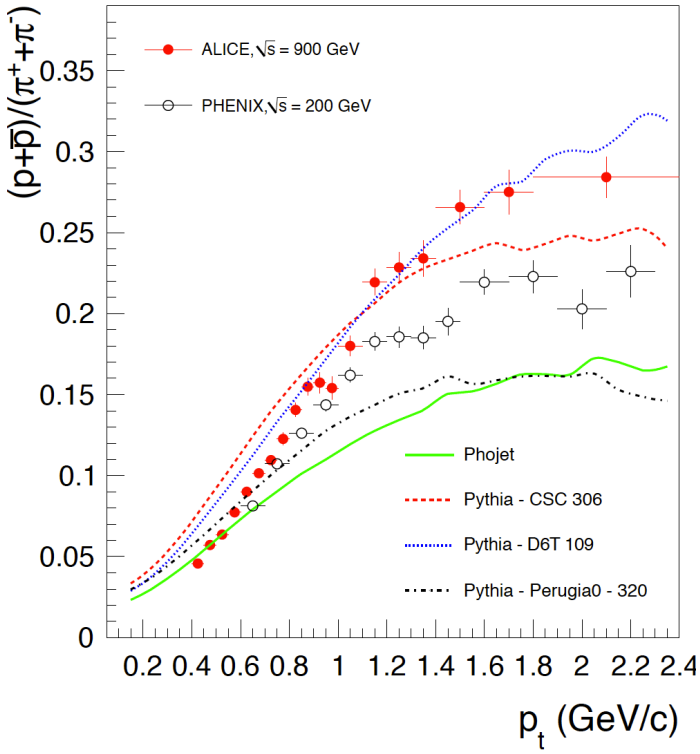




arXiv:1101.4110v2

Hadron Yield Ratios

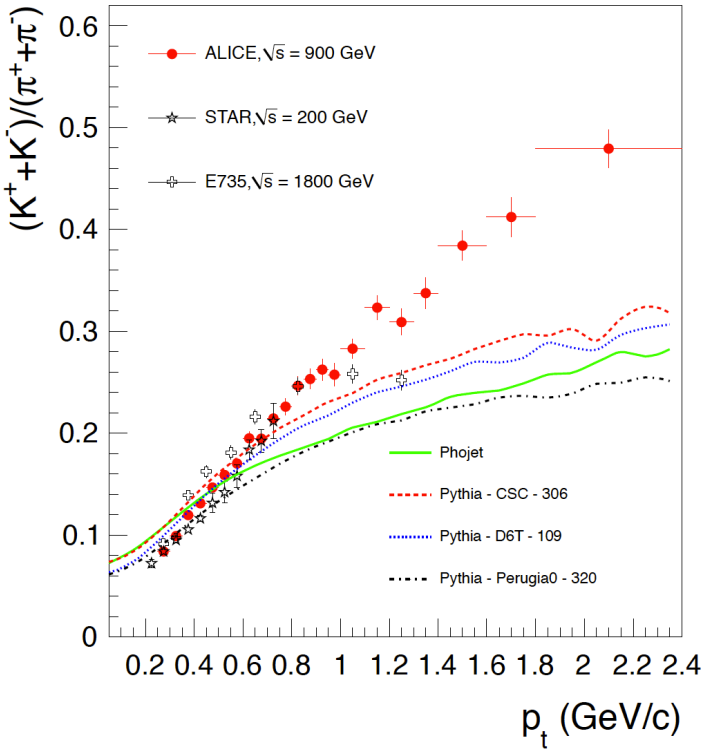


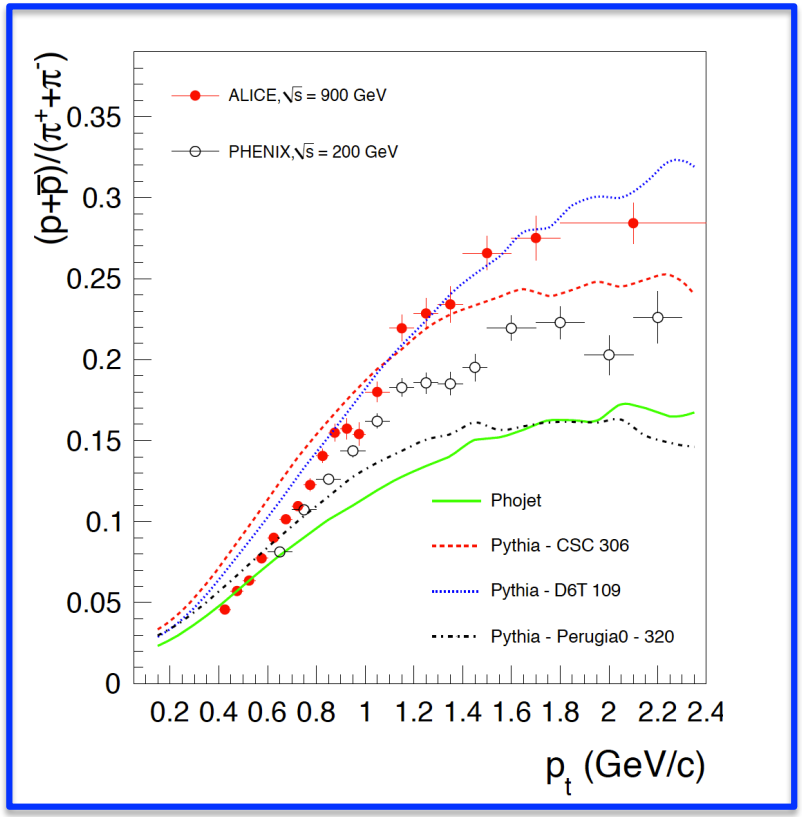


- A lot more strange mesons produced at larger pT than predicted by any model!
- Shape of curve very different from models
- Ratio appears to be independent of √s energy

arXiv:1101.4110v2

Hadron Yield Ratios





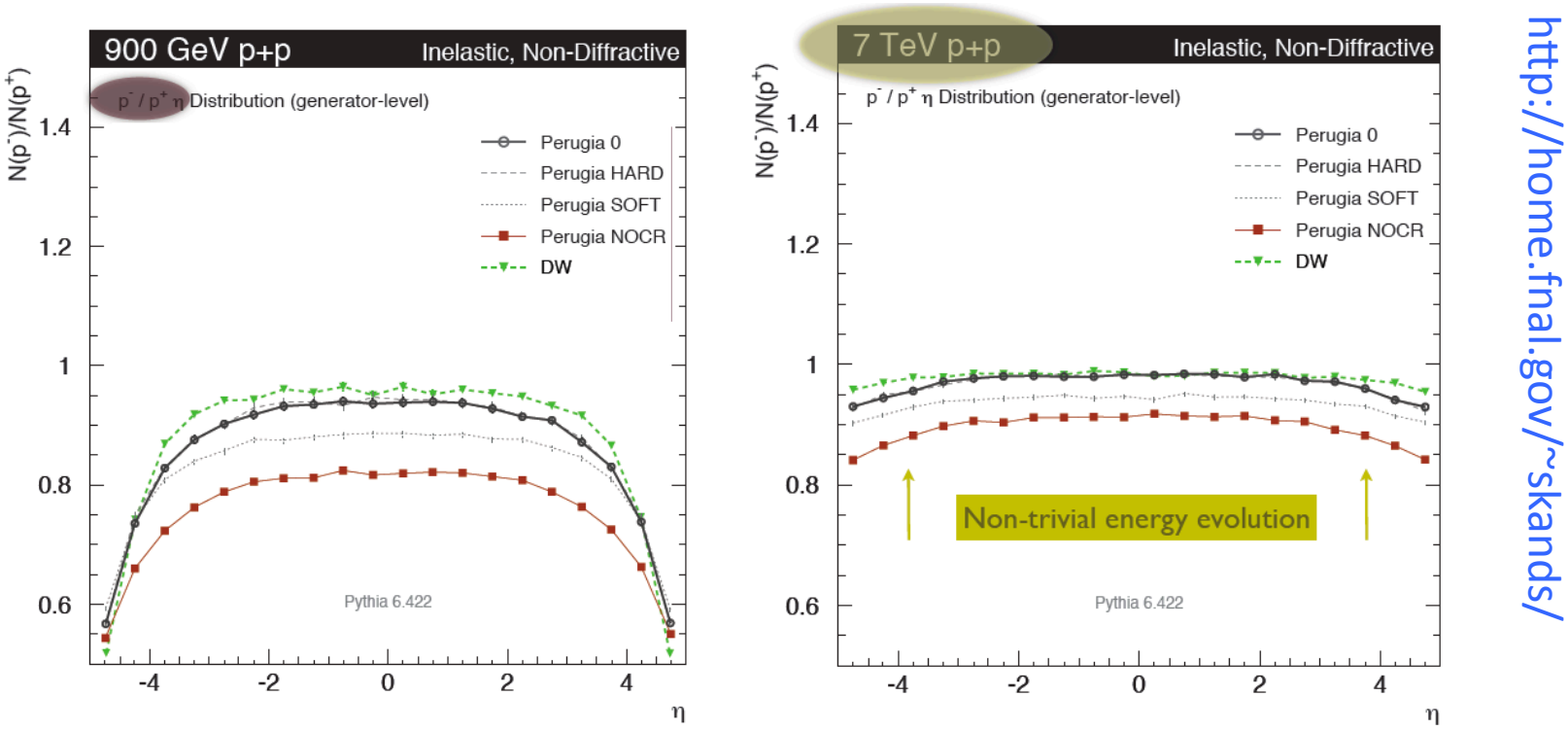
- A lot more baryon production than predicted by Phojet and Perugia0
  - Pythia CSC and D6T have reasonable agreement
- Ratio appears to be independent of √s energy at only low pT
  - Both datasets feed-down corrected.

Phys. Rev. D, 82(7):074018 (2010)

Baryon Transport (Anti-p/p Ratio)

- Conservation of baryon number associated with beam particles
- Model predictions at LHC vary greatly

Peter Skands



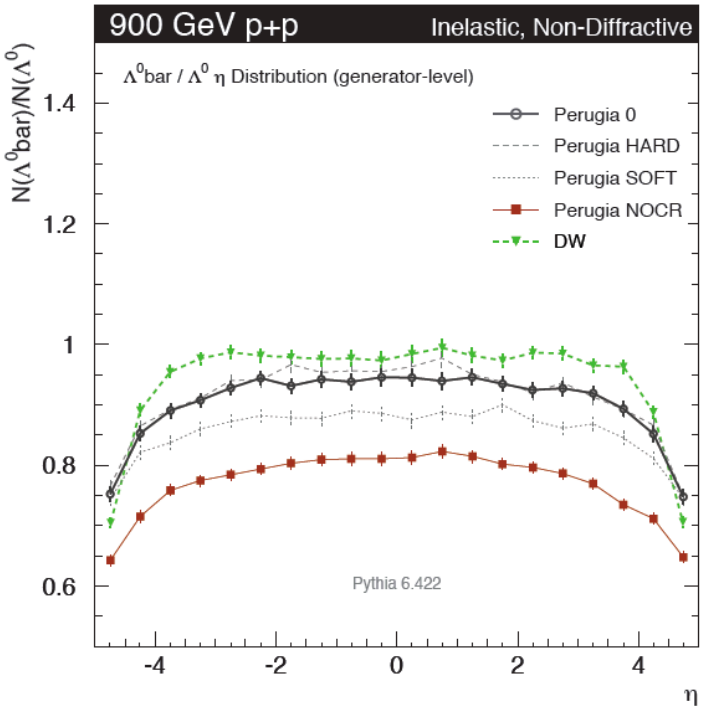
http://home.fnal.gov/~skands/

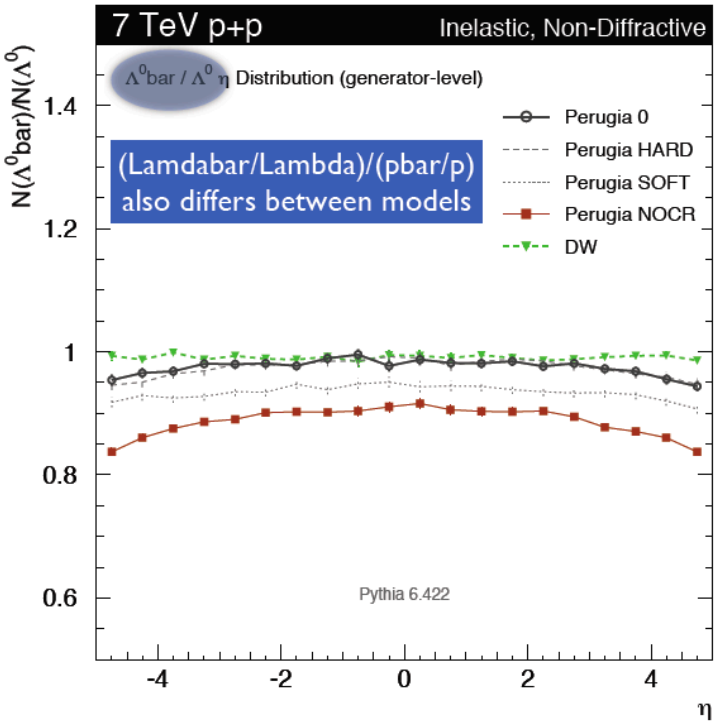
Phys. Rev. D, 82(7):074018 (2010)

Baryon Transport (Anti-p/p Ratio)

- Conservation of baryon number associated with beam particles
- Model predictions at LHC vary greatly

Peter Skands





http://home.fnal.gov/~skands/

Phys Rev Lett Vol.105, No.7, (2010)

LHCb-CONF-2010-003

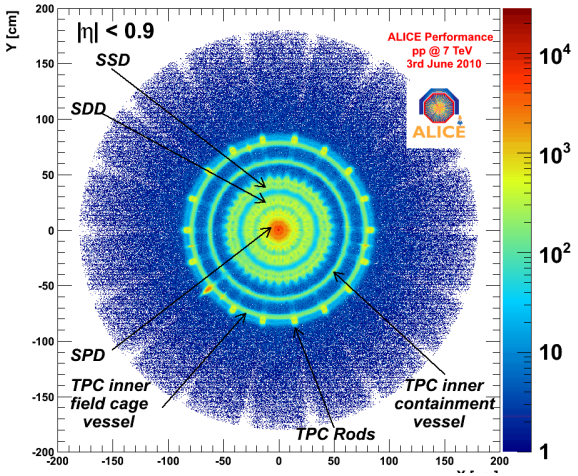
Anti-p/p Ratio

- Experimentally challenging measurement
  - Require <1% precision to distinguish models
- But ratio means:
  - $\mathcal{L}_{INT}$ not required!
  - Systematics cancel to 1st order, but…
- Several areas for potential biases/systematics:
  - Differing material interaction σ for anti-p and p
    - Significantly different at low momentum
    - Accurate description of detector material budget
  - Pollution from 2nd'ary protons
    - Via weak decays and material interactions
  - Contamination from K/π

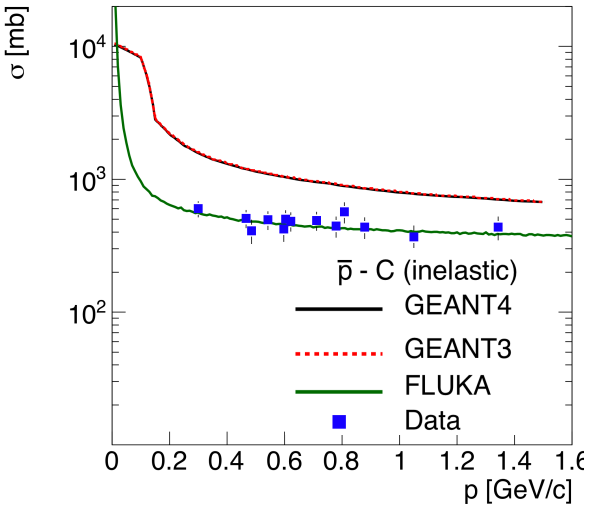
Phys Rev Lett Vol.105, No.7, (2010)

ALICE anti-p/p Strategy

- Performed in a restrictive region of kinematic space
  - |y|<0.5,
    - Low material budget
  - 0.45<p<1.05 GeV
    - Excellent PID via TPC (no misID)

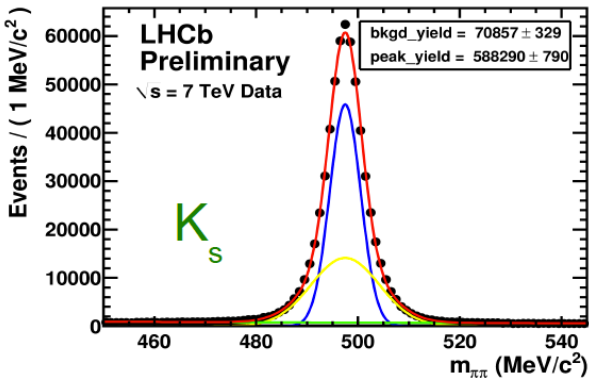


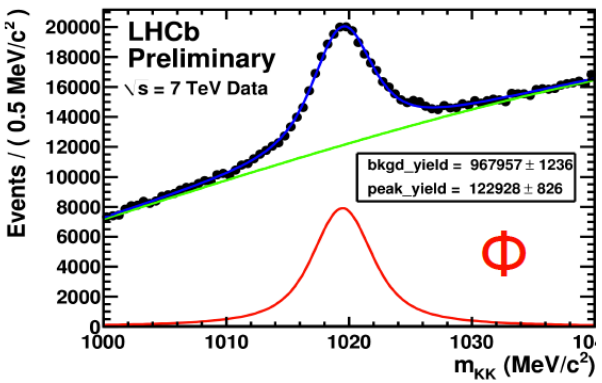
- Detector simulation package chosen that agrees best with external data:
  - FLUKA

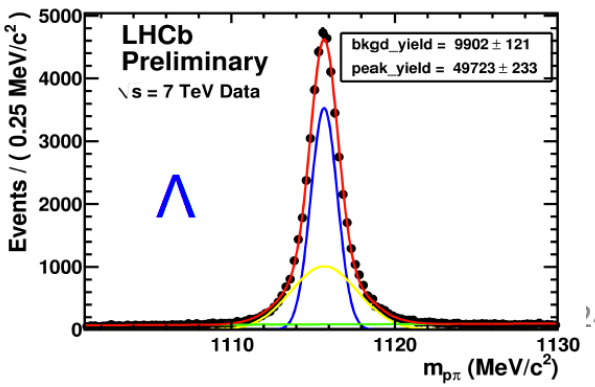


LHCb anti-p/p Strategy

- Performed over all accessible rapidity
  - Minimum momentum limit of 5.0 GeV
    - Limits systematic due to anti-p, p material interaction σ
- Use RICH PID to isolate signal
  - Corrections for hadron cross-contamination considered through calibration samples
    - Requires selecting pure samples of K, π and anti-p, p!

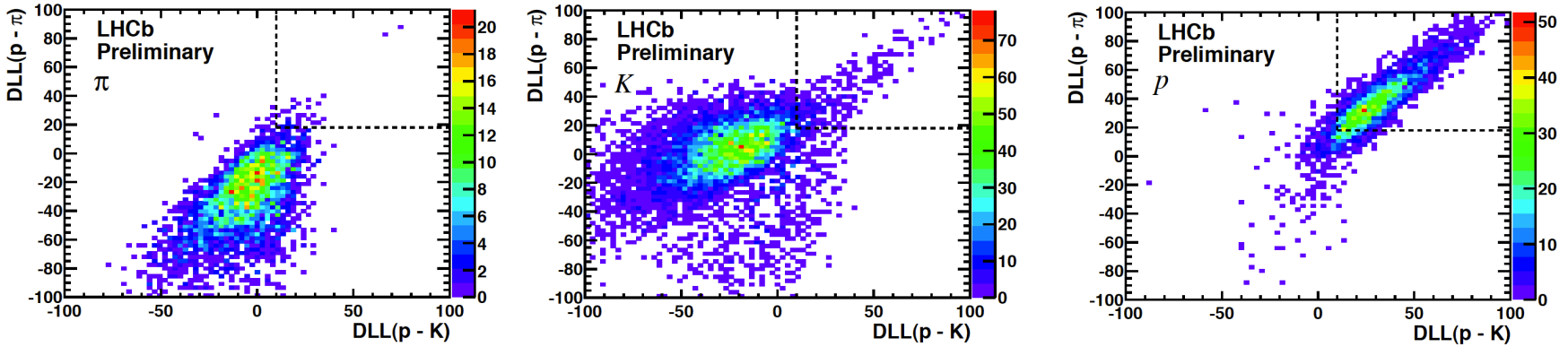






LHCb anti-p/p Strategy

- Performed over all accessible rapidity
  - Minimum momentum limit of 5.0 GeV
    - Limits systematic due to anti-p, p material interaction σ
- Use RICH PID to isolate signal
  - Corrections for hadron cross-contamination considered through calibration samples
    - Requires selecting pure samples of K, π and anti-p, p!



LHCb anti-p/p Strategy

- Analysis becomes a comprehensive particle study:

From data

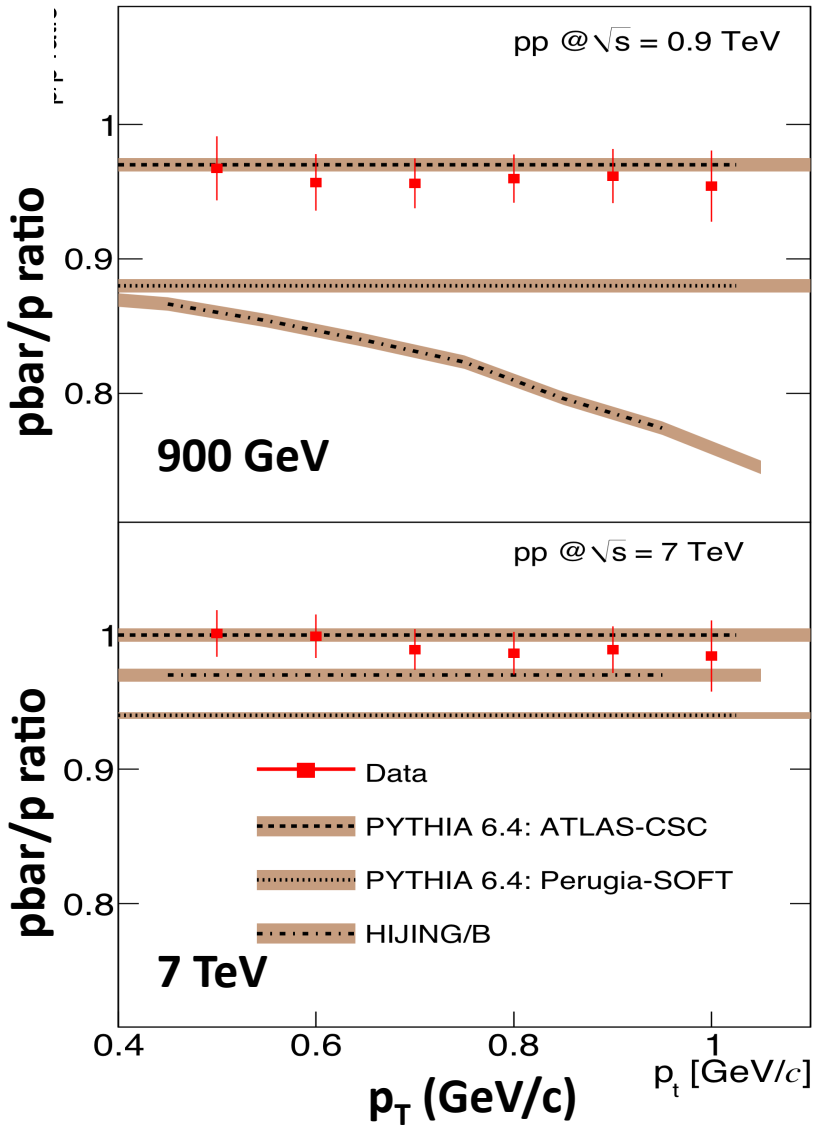
$$\begin{pmatrix} p_{Sel} \\ K_{Sel} \\ \pi_{Sel} \end{pmatrix} = \begin{pmatrix} p \to p & K \to p & \pi \to p \\ p \to K & K \to K & p \to K \\ p \to \pi & K \to p & \pi \to \pi \end{pmatrix} \begin{pmatrix} p_{True} \\ K_{True} \\ \pi_{True} \end{pmatrix}$$

$$\begin{pmatrix} p_{True} \\ K_{True} \\ \pi_{True} \end{pmatrix} = \begin{pmatrix} p \to p & K \to p & \pi \to p \\ p \to K & K \to K & p \to K \\ p \to \pi & K \to p & \pi \to \pi \end{pmatrix}^{-1} \begin{pmatrix} p_{Sel} \\ K_{Sel} \\ \pi_{Sel} \end{pmatrix}$$

- Basis for K/π, p/π and anti-p/p ratio results
  - Publication imminent
  - Only anti-p/p preliminary results to date

Phys Rev Lett Vol.105, No.7, (2010)

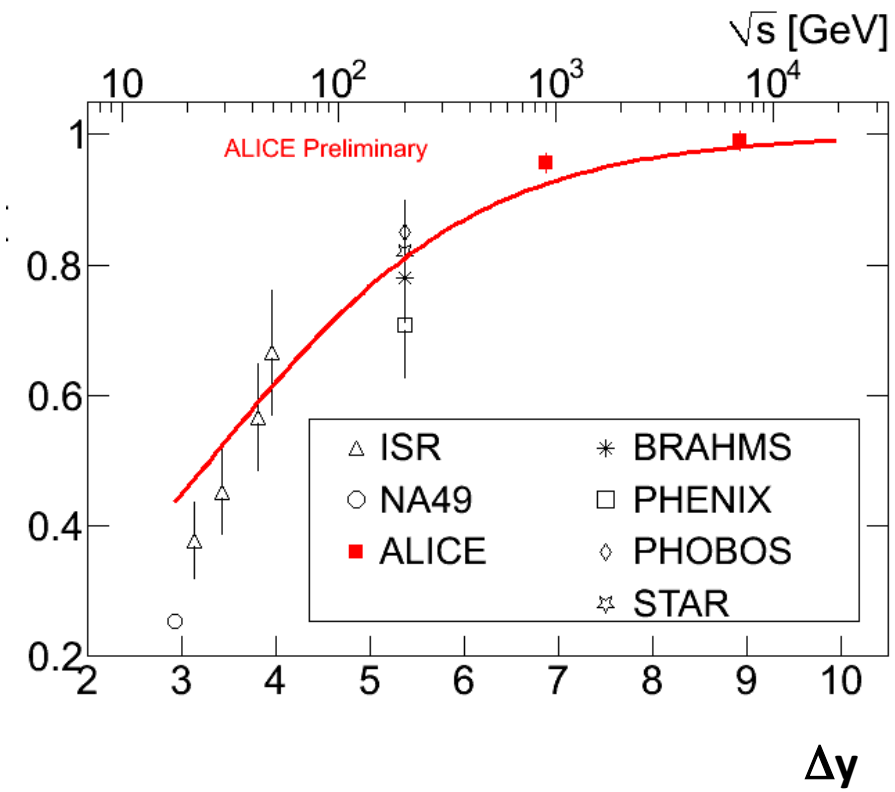
ALICE anti-p/p Results



- No pT dependance
  - Either @ √s = 0.9 or 7 TeV
- Predictions also flat
  - Except HIJING/B @ 0.9 TeV
  - Pythia6.4 best performer
- Result at each energy averaged (vs $\Delta y = y_{beam} - y$)

Phys Rev Lett Vol.105, No.7, (2010)

ALICE anti-p/p Results



- No pT dependance
  - Either @ √s = 0.9 or 7 TeV
- Predictions also flat
  - Except HIJING/B @ 0.9 TeV
  - Pythia6.4 best performer
- Result at each energy averaged (vs $\Delta y = y_{beam} - y$)

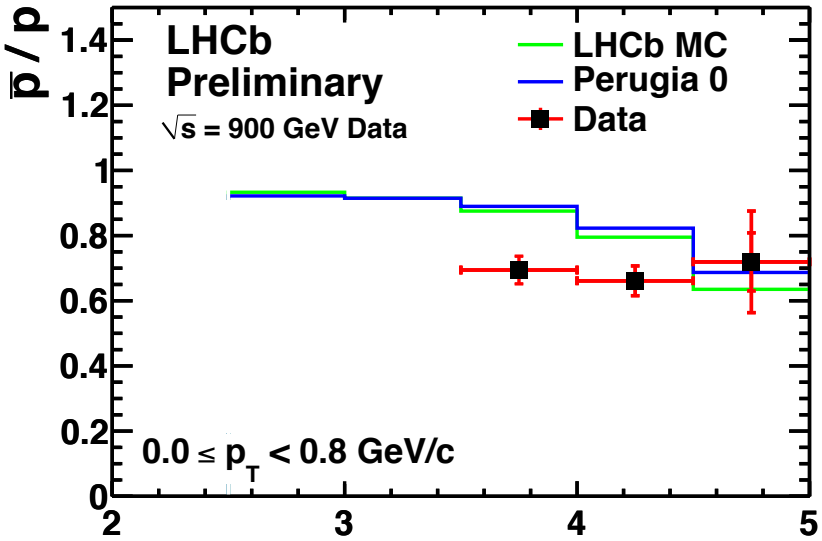
$$\sqrt{s} = 0.9 \text{ TeV} \quad R_{|y|<0.5} = 0.957 \pm 0.006 \pm 0.014$$

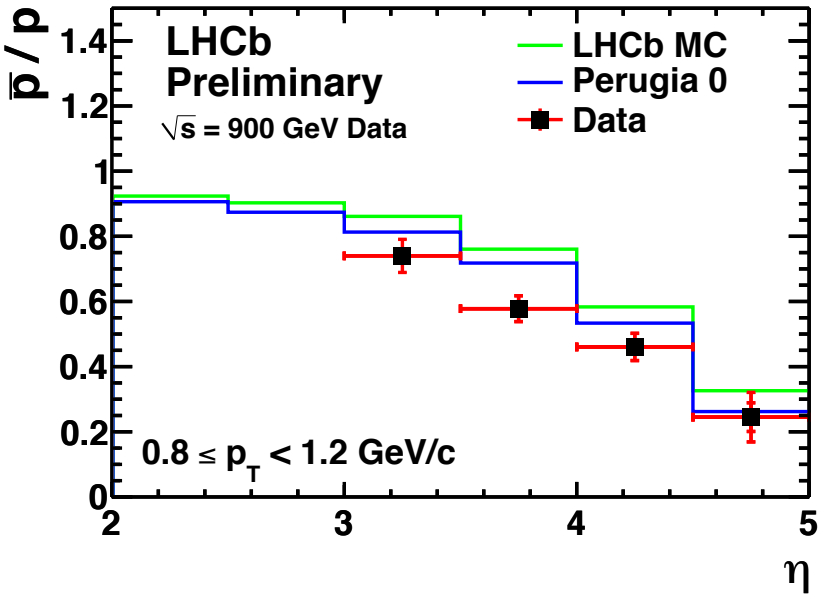
$$\sqrt{s} = 7 \text{ TeV} \quad R_{|y|<0.5} = 0.991 \pm 0.005 \pm 0.014$$

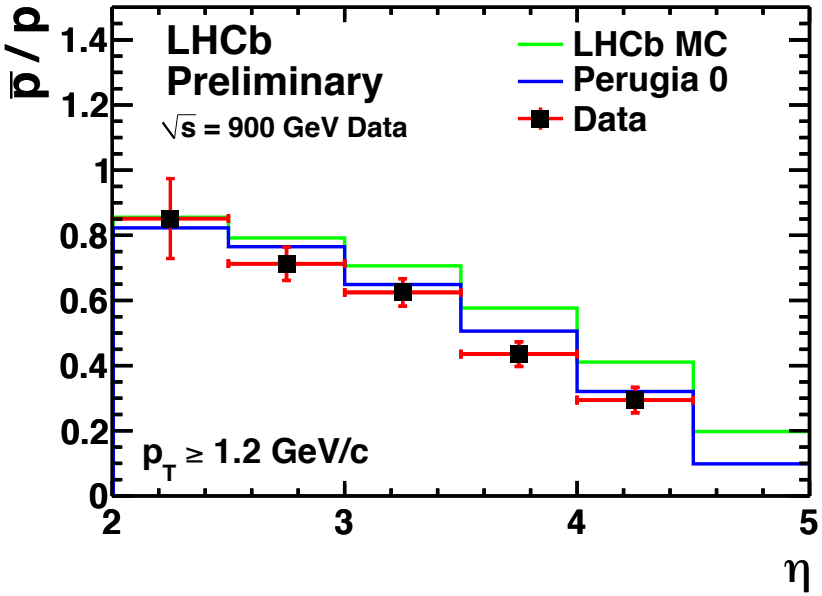
LHCb anti-p/p Results

$\sqrt{s} = 0.9$ TeV

- Ratio considered as a fnc. of η within bins of pT:
  - 0<pT<0.8 GeV
  - 0.8<pT<1.2 GeV
  - pT>1.2





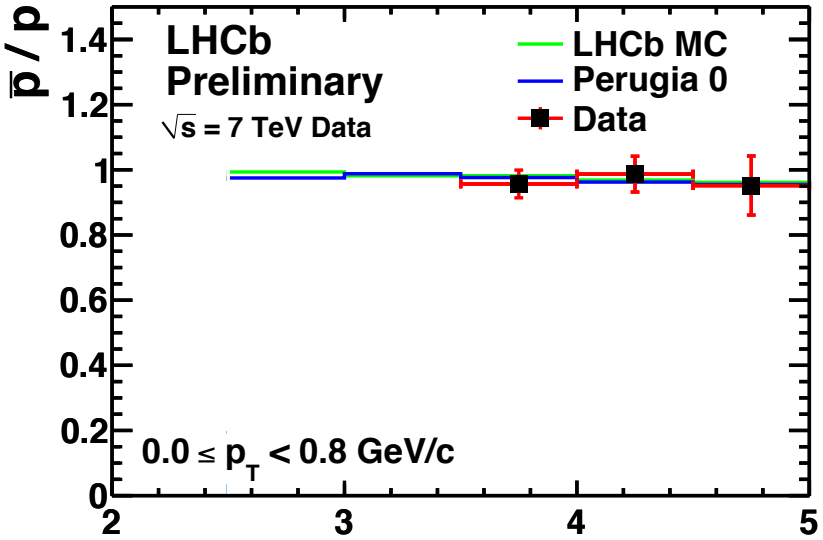


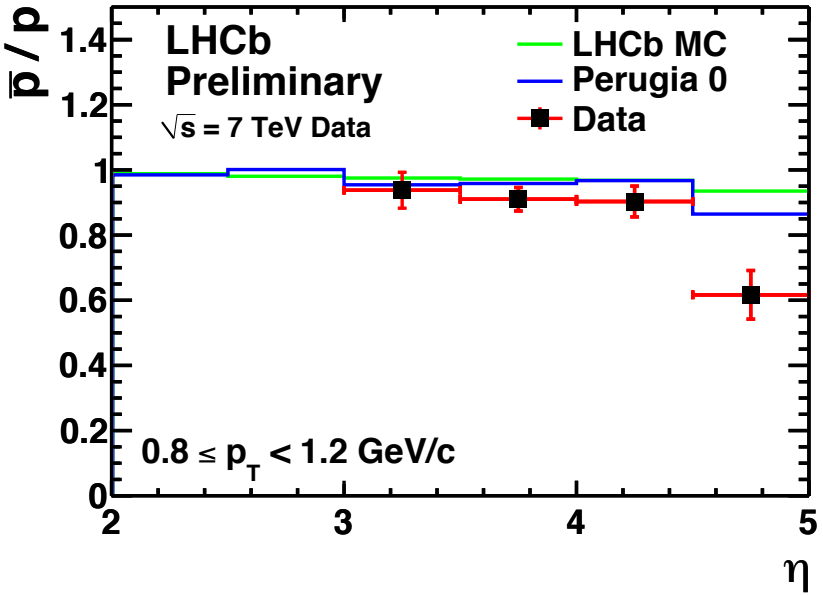
LHCb-CONF-2010-003

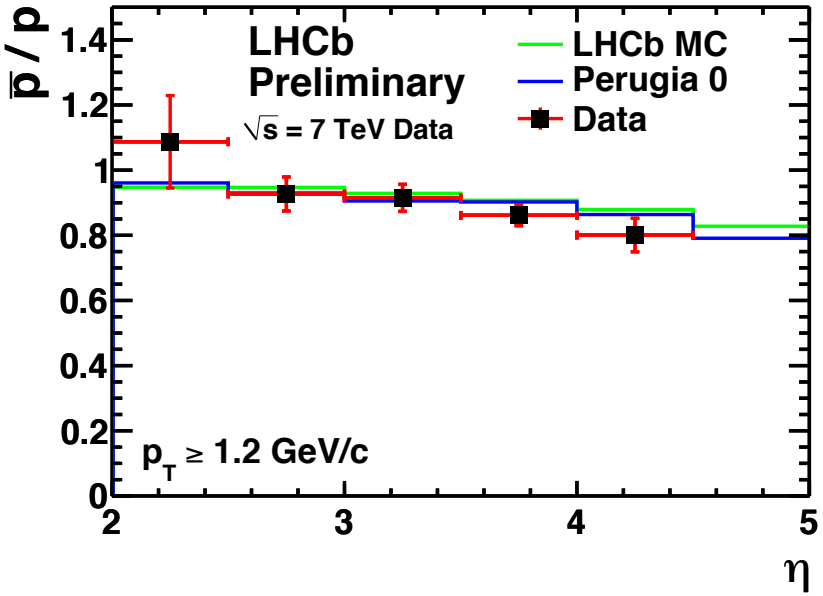
LHCb anti-p/p Results

$\sqrt{s} = 7$ TeV

- Ratio considered as a fnc. of η within bins of pT:
  - 0<pT<0.8 GeV
  - 0.8<pT<1.2 GeV
  - pT>1.2

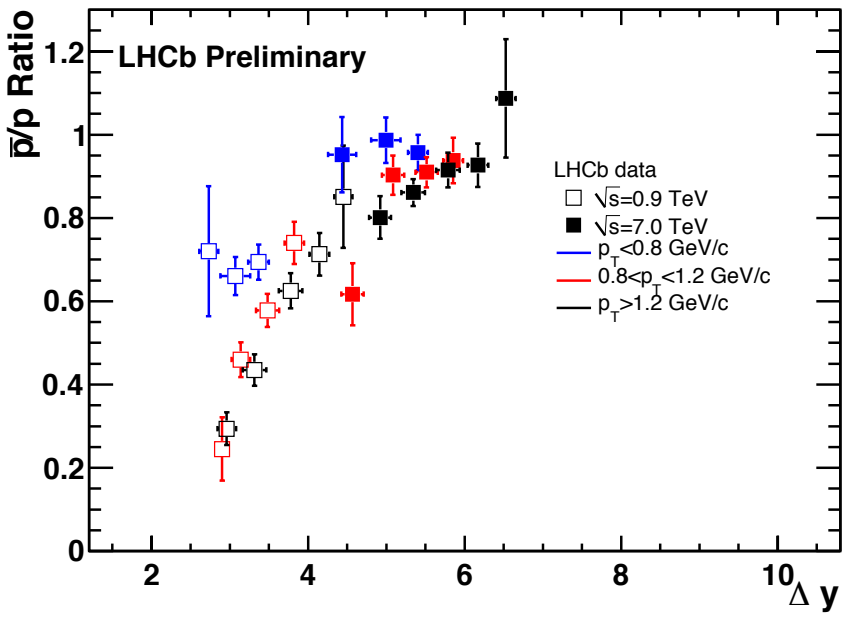






LHCb-CONF-2010-003

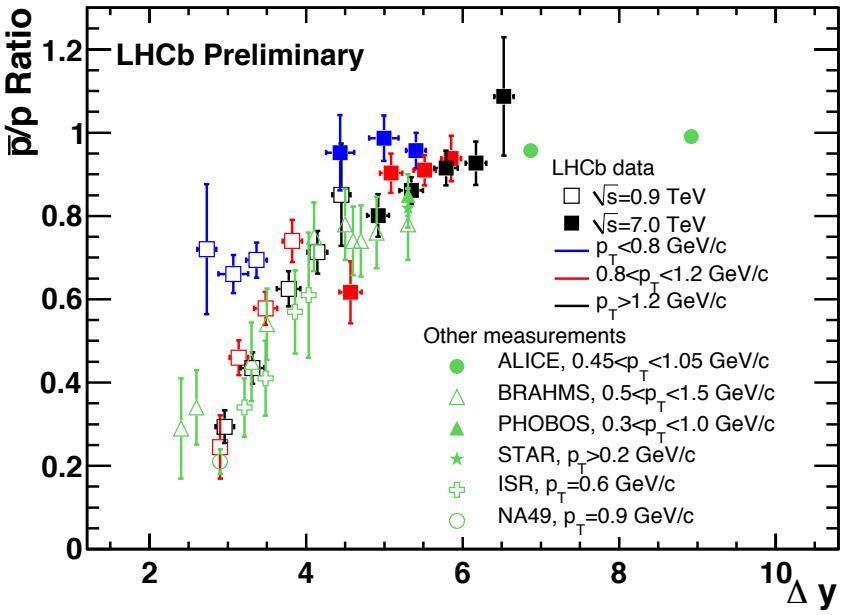
LHCb anti-p/p Results



- Cast ratio as fnc. of Δy, as done by ALICE
  - Span almost 4 units
- Results not averaged over pT
  - Possible pT dependence
- Comparison with other experimental measurements

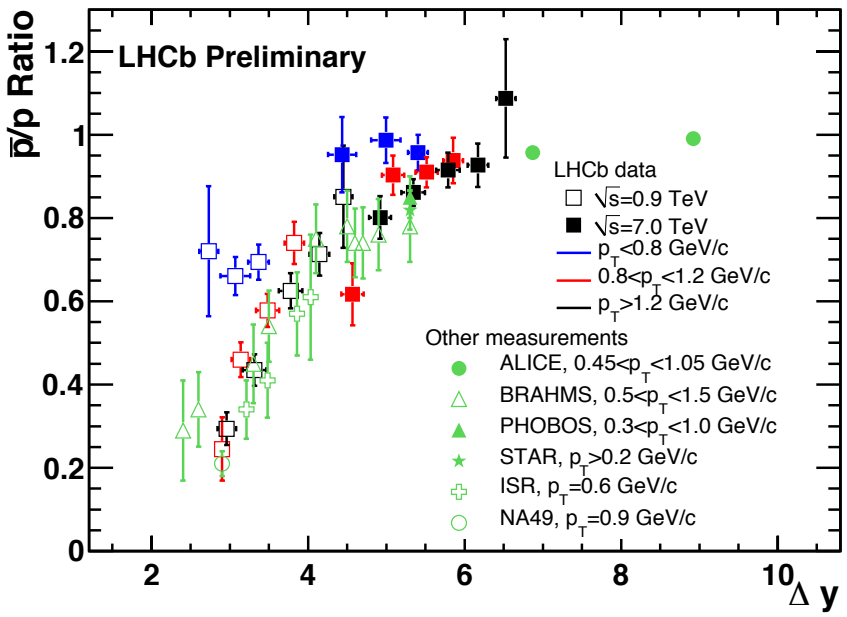
LHCb-CONF-2010-003

LHCb anti-p/p Results



- Cast ratio as fnc. of Δy, as done by ALICE
  - Span almost 4 units
- Results not averaged over pT
  - Possible pT dependence
- Comparison with other experimental measurements
  - Reasonable agreement

LHCb anti-p/p Results



To come:
- Updated anti-p/p
- K/π, p/π ratios
- K,π,p pT spectra

- Cast ratio as fnc. of Δy, as done by ALICE
  - Span almost 4 units
- Results not averaged over pT
  - Possible pT dependence
- Comparison with other experimental measurements
  - Reasonable agreement

Strange Resonance Production

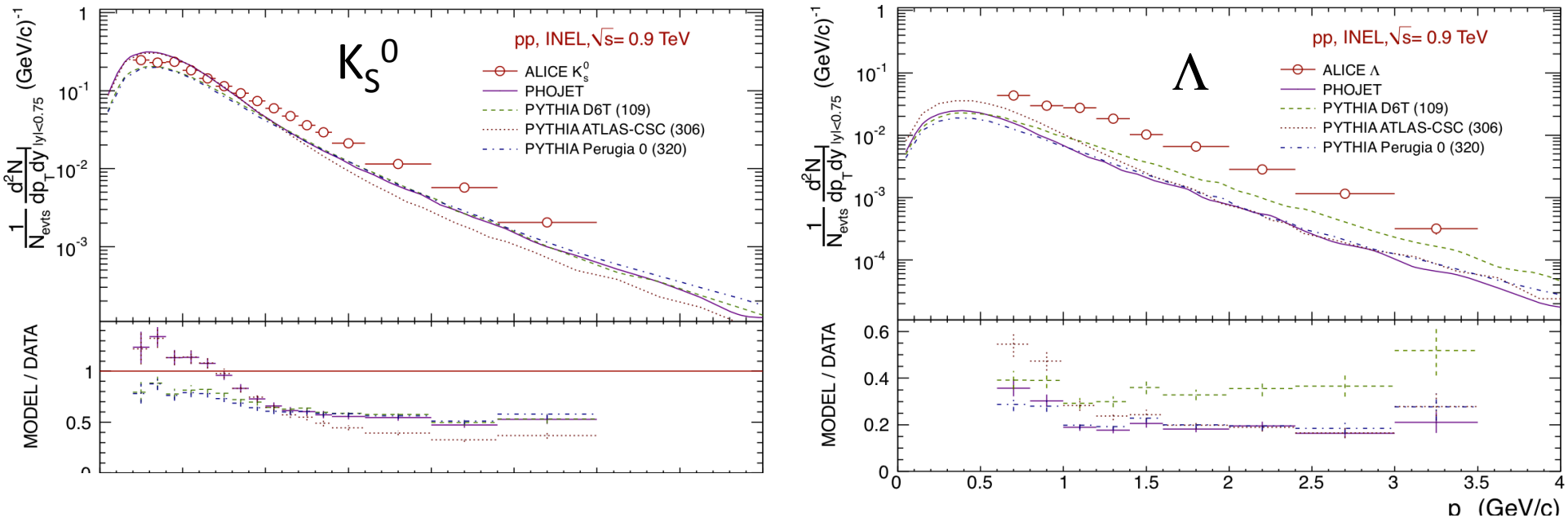
- A probe of fragmentation and hadronisation
- Variety of mesons (K^0, ϕ) and baryons (Λ, Ξ, Ω) accessible by all LHC detectors
  - PID not necessary, invariant mass reconstruction sufficient
- Possible measurements:
  - pT spectra
  - Baryon Transport Ratios (e.g. Λ/Λ)
  - Baryon Suppression Ratios (e.g. Λ/K^0)
  - Cross-sections
    - Requires good knowledge of $\mathcal{L}_{INT}$
    - Achieved at LHCb with novel techniques [Nuc. Instrum. and Methods A 553 (2005) 388]

Strange Production Results

Result	ALICE		LHCb		CMS	
	0.9 TeV	7 TeV	0.9 TeV	7 TeV	0.9 TeV	7 TeV
Resonance pT	✔				✔	✔
Baryon Transport	✔		✔	✔		
Baryon Suppression	✔		✔	✔	✔	✔
KS0 Cross-Section			✔			
ϕ Cross-Section				✔		

Eur. Phys. J. C 71, 1594 (2011)

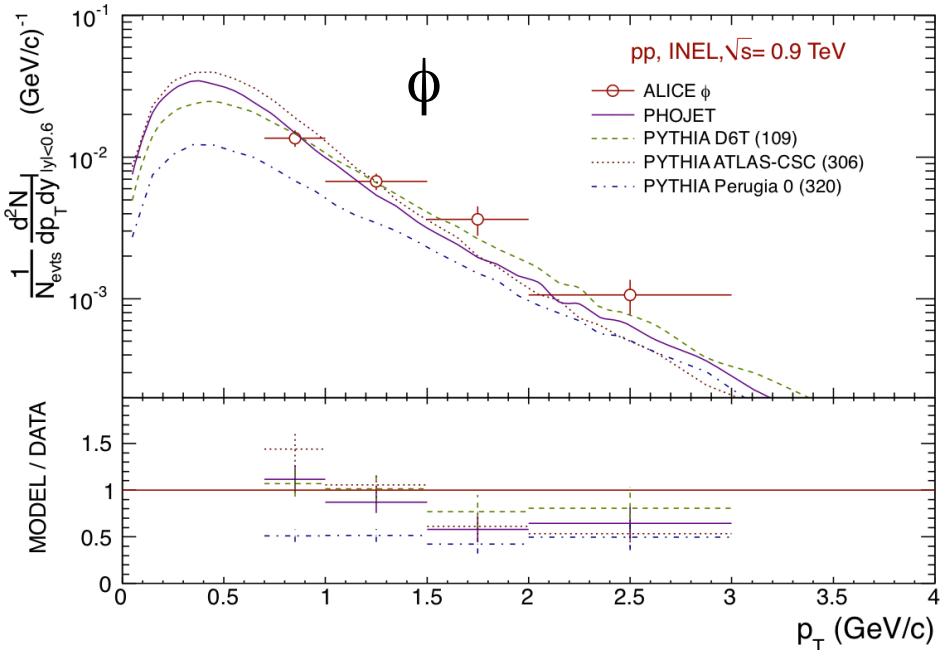
K_S^0 & Λ pT Spectra

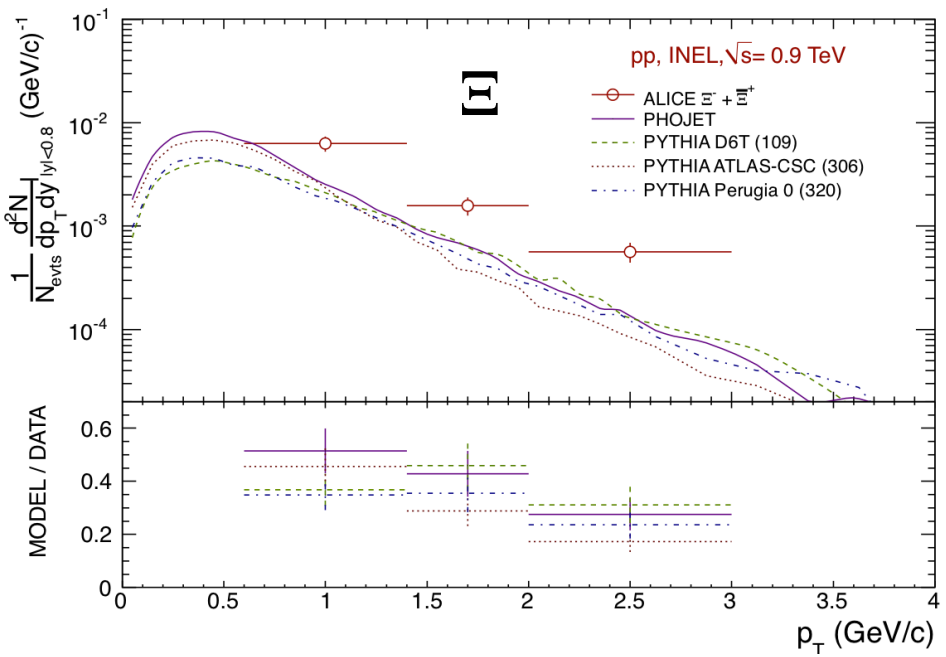


- pT spectra observed to be harder than models predicted
  - pT $\gtrsim$ 1 GeV, particle spectra greatly underestimated by model
  - ~ factor x2 for Kshort

Eur. Phys. J. C 71, 1594 (2011)

ϕ & Ξ pT Spectra

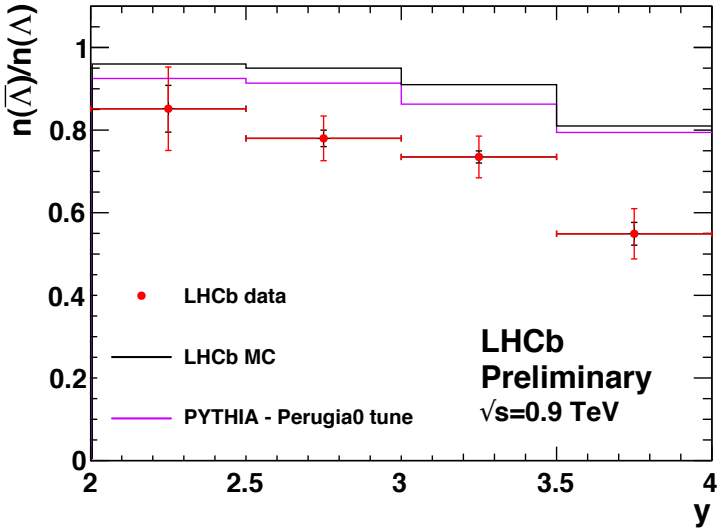


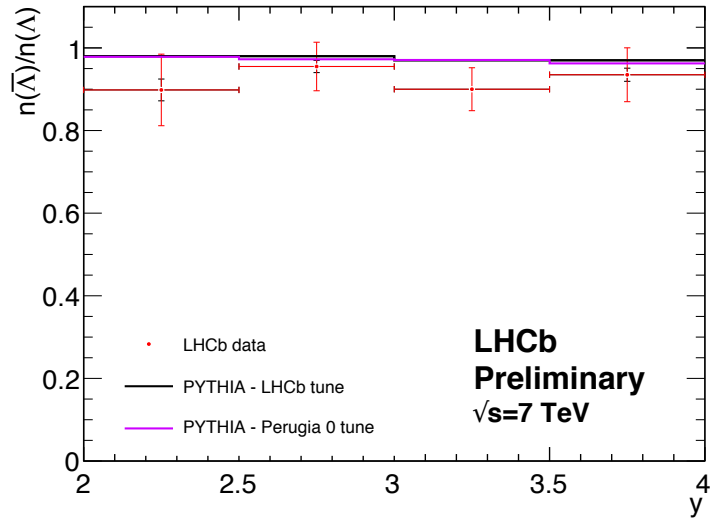


- pT spectra observed to be harder than models predicted
  - ~ factor x 3 for hyperons (discrepancy increases with mass)
  - Discrepancy is smaller for ϕ spectrum
- [Plans at LHCb for similar measurements with Hyperons]

LHCb-CONF-2010-011

Baryon No. Transport ($\bar{\Lambda}/\Lambda$)

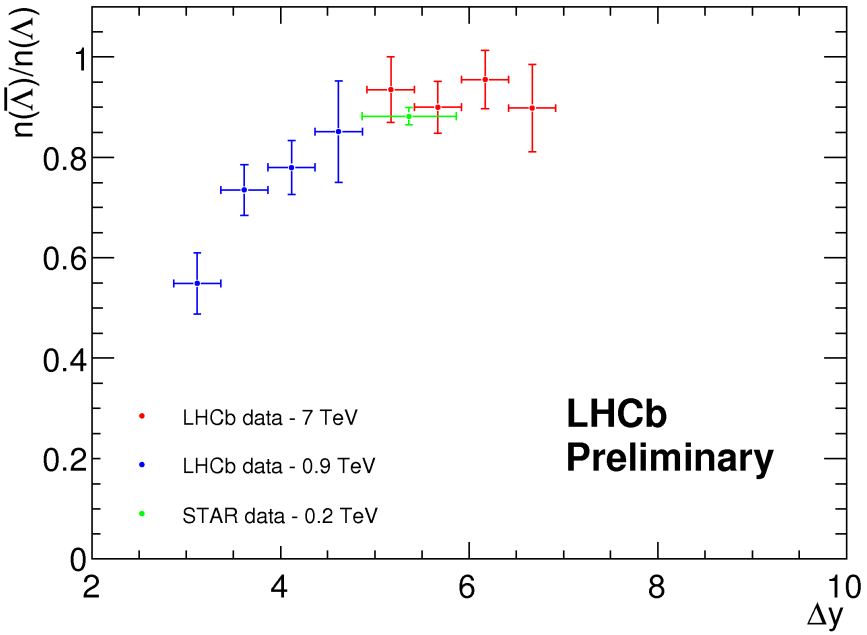




- Ratio considered as a fnc. of y
  - Unique η range of LHCb
  - Clear √s dependence
- More baryon transport than predicted
  - Ratio overestimated at √s = 0.9 TeV
  - More consistent at √s = 7 TeV

LHCb-CONF-2010-011

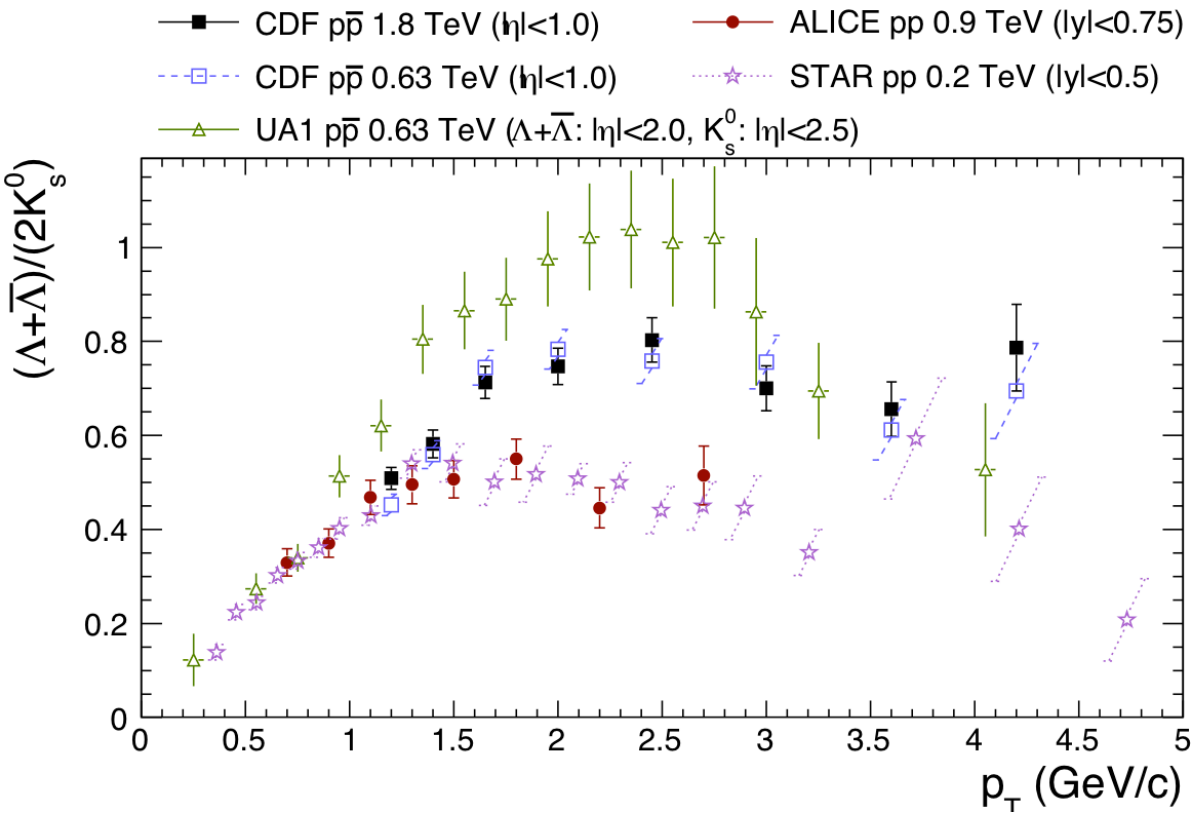
Baryon No. Transport ($\bar{\Lambda}/\Lambda$)



- Ratio vs Δy
  - Consistency between
    - $\sqrt{s}$ = 0.9 TeV
    - $\sqrt{s}$ = 7 TeV
    - STAR data

Eur. Phys. J. C 71, 1594 (2011)

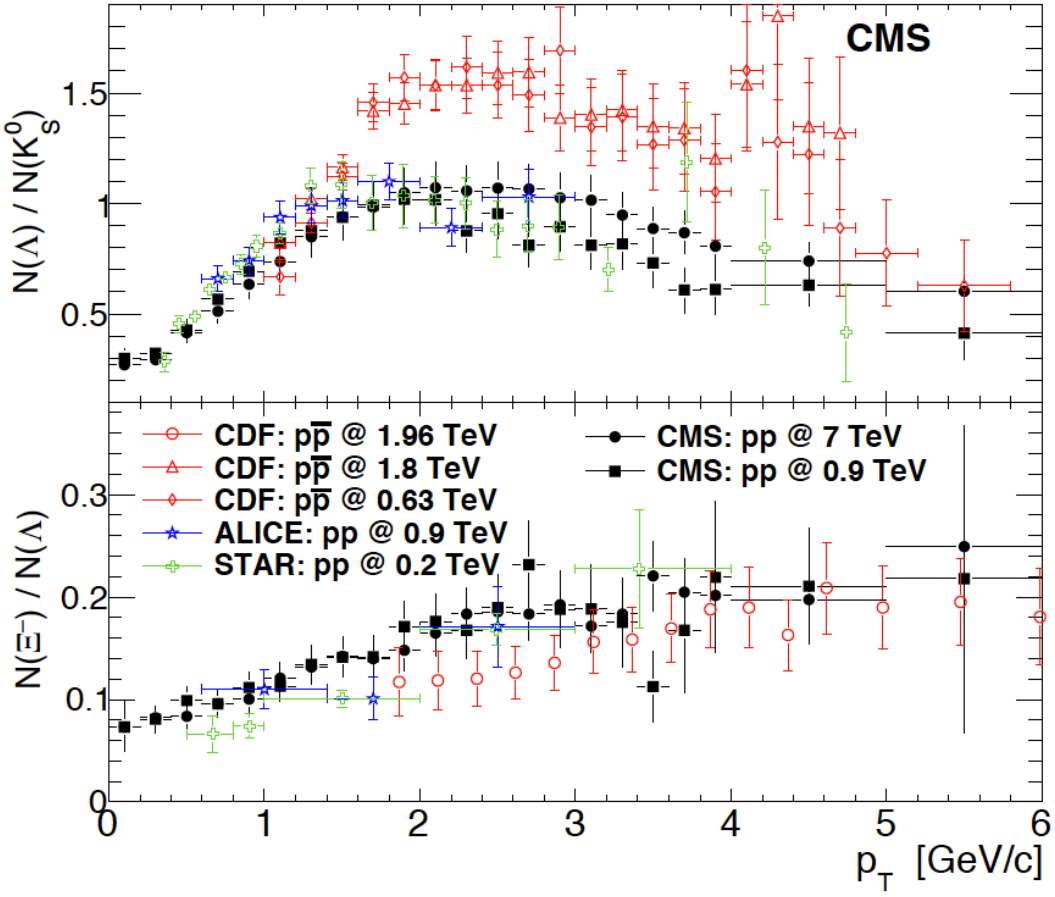
Baryon No. Suppression (Λ/K^0)



- Good agreement between ALICE results and STAR ($\sqrt{s}$ = 0.2 TeV)
  - Implies little or no energy dependence
- UA1 & CDF distributions not 'feed-down' corrected

arXiv:1102.4282v1

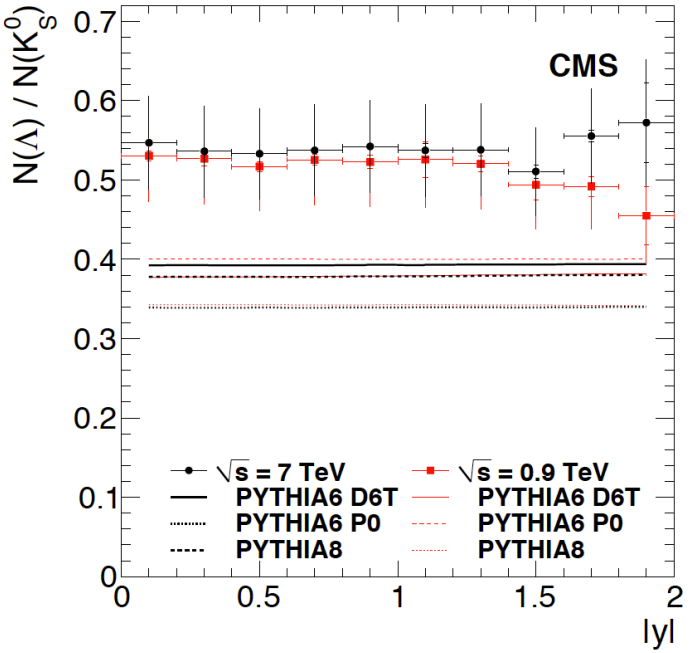
Baryon No. Suppression (Λ/K^0)

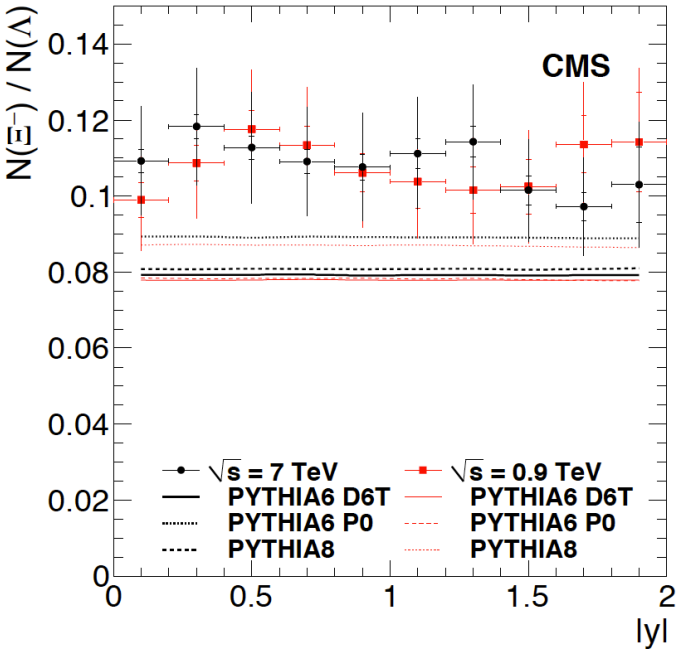


- Very similar results obtained by CMS (plot contains ALICE points)
- Furthermore, Ξ/Λ ratio results obtained (look consistent)

arXiv:1102.4282v1

Baryon No. Suppression (Λ/K^0)

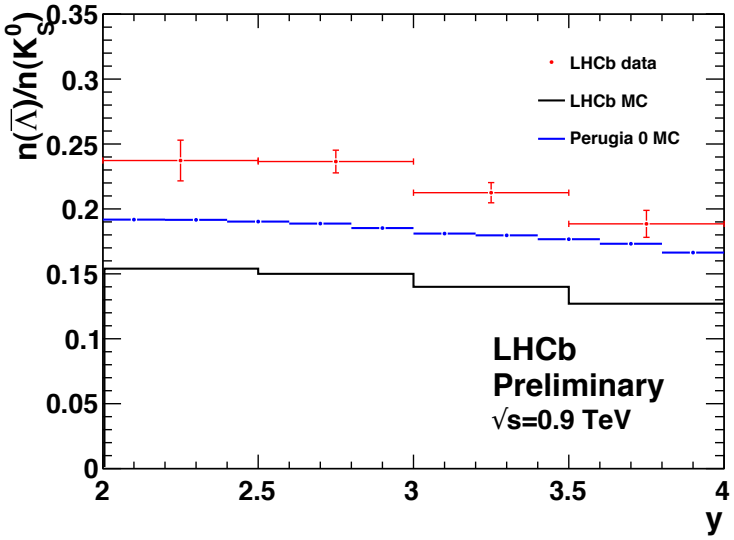


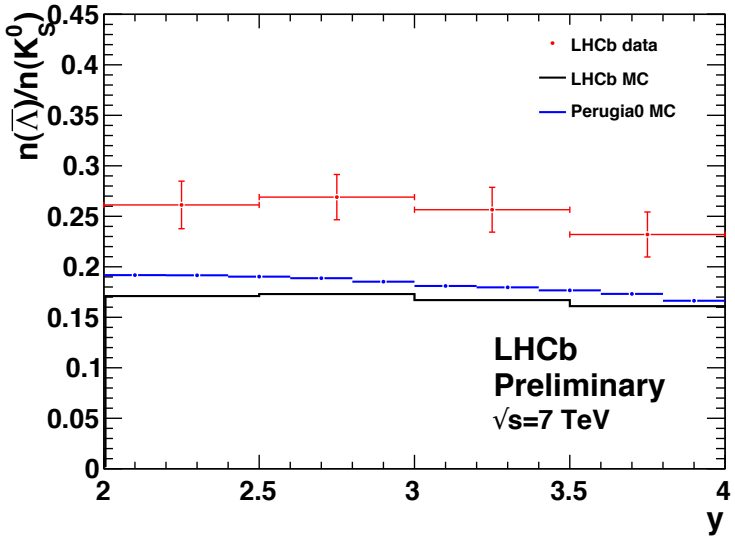


- CMS results vs |y|
- No apparent energy dependence

LHCb-CONF-2010-011

Baryon No. Suppression ($\bar{\Lambda}/K^0$)

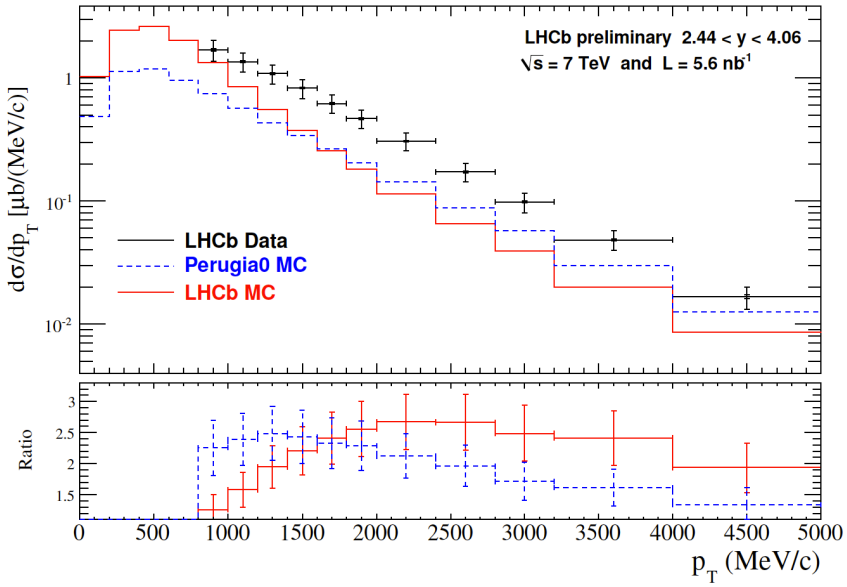


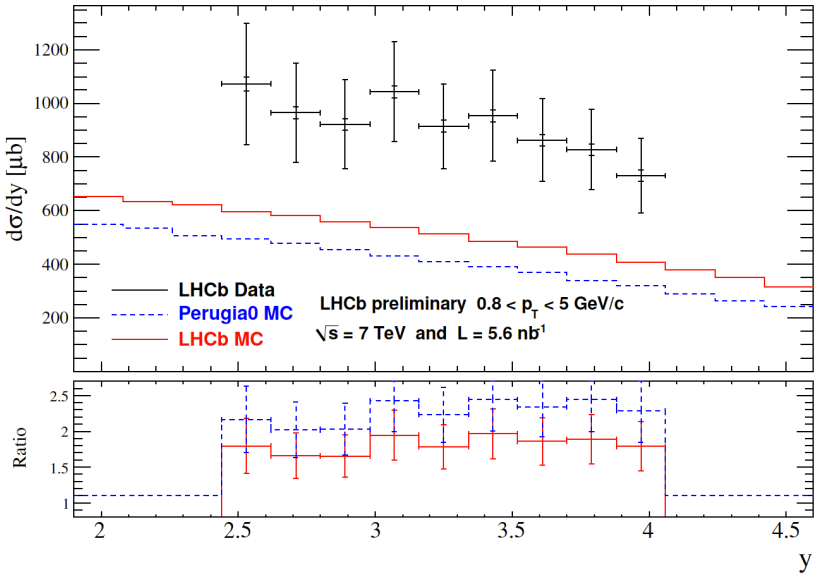


- Ratio larger than expectations
  - At both energies

LHCb-CONF-2010-014

ϕ Production X-Section





- X-section via novel $\mathcal{L}_{INT}$ technique (reduced syst. error)
- pT spectra observed to be harder than models predicted
  - As seen in ALICE analysis (slide 36)
- Production underestimated (again!)

LHCb-CONF-2010-014

ϕ Production X-Section

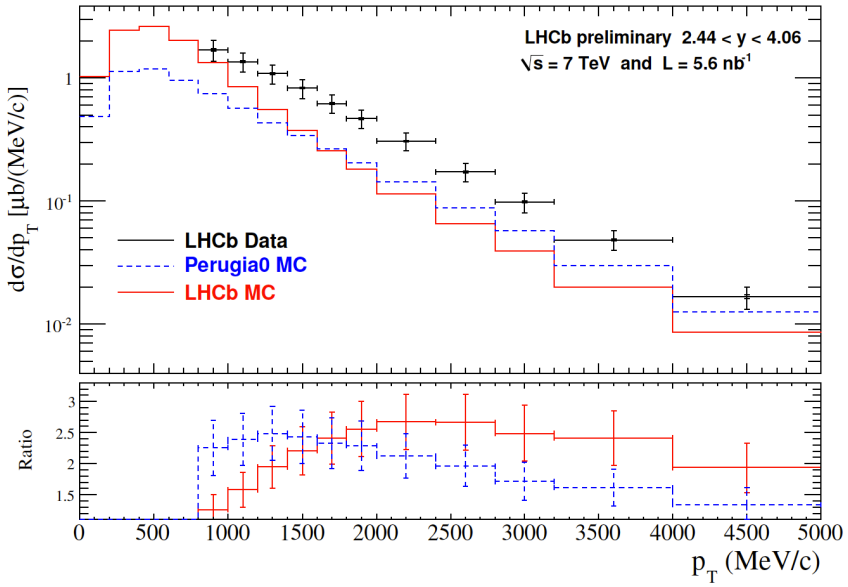
- summed cross section:

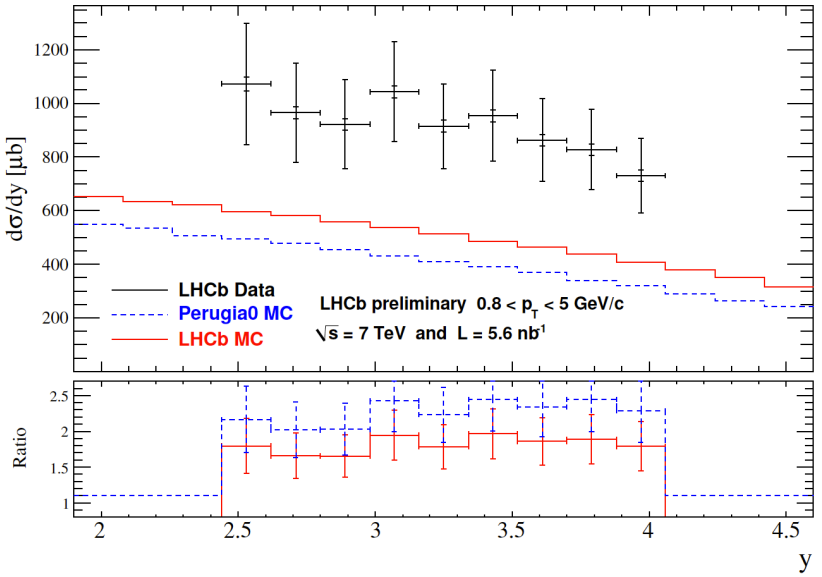
bin-dependent global

$$\sigma(pp \to \phi X) = (1493 \pm 12(\text{stat}) \pm 12(\text{uncorr.syst}) \pm 209(\text{corr.syst}))\ \mu\text{b}$$

$y \in [2.44, 4.06]$

$p_T \in [0.8, 5.0]$ GeV/c





- X-section via novel $\mathcal{L}_{INT}$ technique (reduced syst. error)
- pT spectra observed to be harder than models predicted
  - As seen in ALICE analysis (slide 36)
- Production underestimated (again!)

Summary

- A large number of particle production results
  - Public results from ALICE, CMS & LHCb
  - Results in the pipeline from ATLAS
- Situation from Identified Particle Studies:
  - Models do not produce enough strange particles
  - p/π not correct either
- Situation from Baryon Transport/Suppression Ratios:
  - Models over estimate anti-B/B ratios (LHCb)
  - But underestimate B/meson ratios (CMS,LHCb)
  - Note enough strange produced
- Many more results currently in progress

Thanks Go To…

A big thank you to the following people who assisted me in writing this talk:

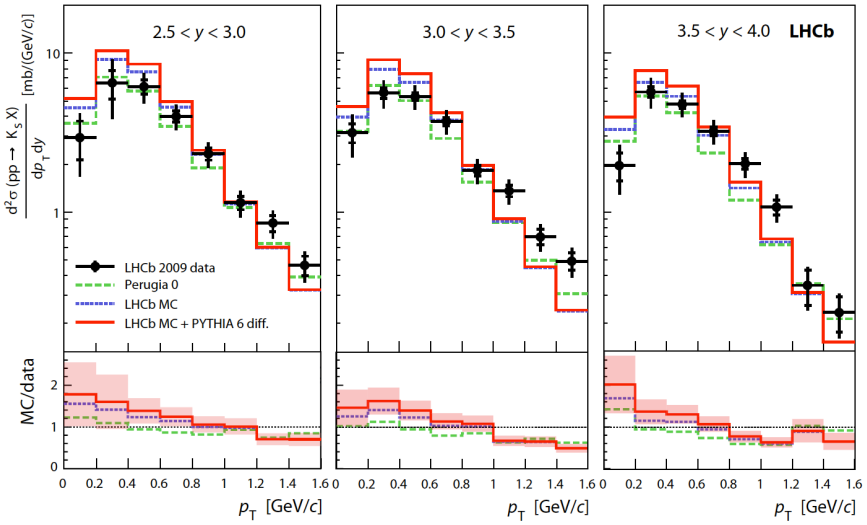
- Raluca Muresan,
- Andrea Contu,
- Guy Wilkinson,
- Emily Nurse,
- Ferenc Sikler,
- Kevin Einsweiler,
- Ermanno Vercelli

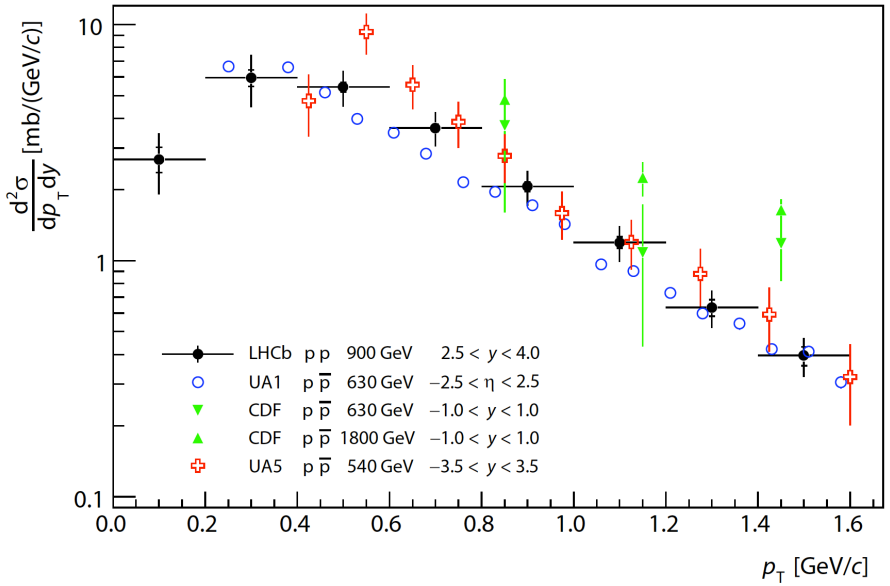
Thank you!

BACKUP

Phys. Lett. B 693 (2010) 69-80

K_S^0 Production X-Section

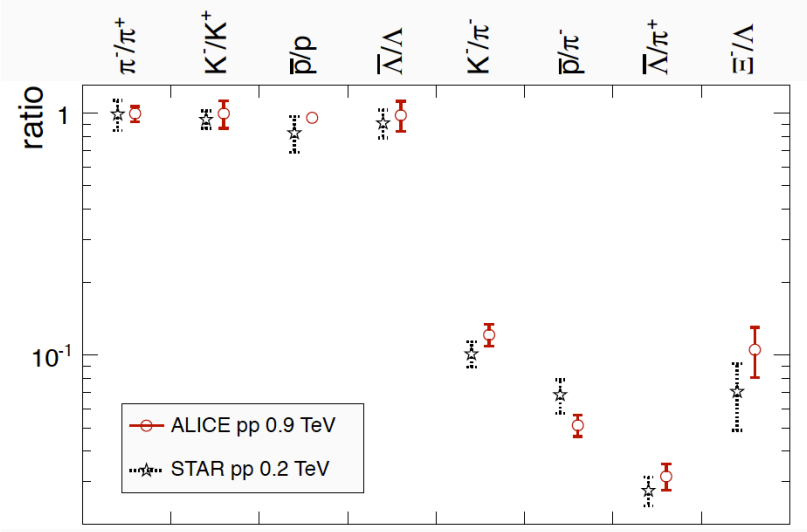


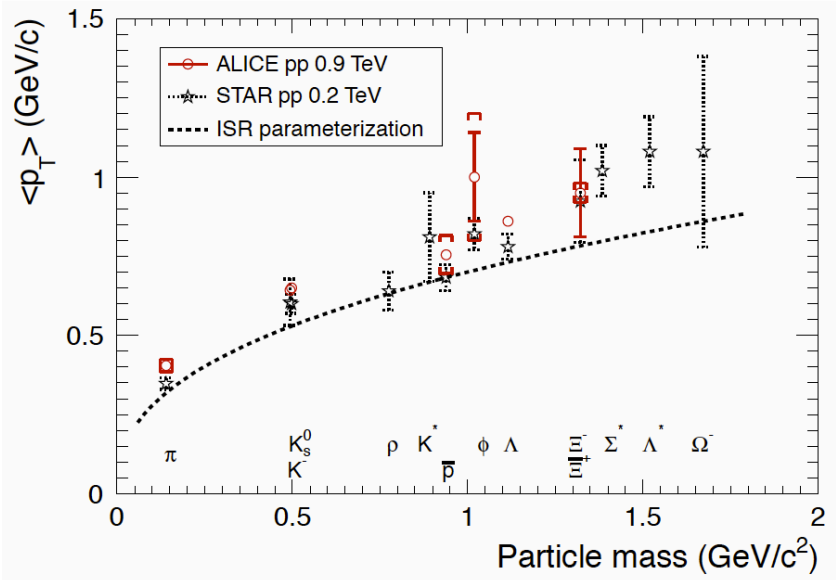


- 1st LHCb result!
- Harder pT spectrum than MC
- Comparison with other experiments
  - Consistent
  - Extends knowledge at low pT

Eur. Phys. J. C 71, 1594 (2011)

Strange Particle Production





Backup MC parameters

- LHCb MC is based on PYTHIA 6.421

parameter	value	parameter	value
CKIN(41)	3.0	PARP(86)	0.66
MSTP(2)	2	PARP(89)	14000
MSTP(33)	3	PARP(90)	0.238
MSTP(81)	21	PARP(91)	1.0
MSTP(82)	3	PARP(149)	0.02
MSTP(52)	2	PARP(150)	0.085
MSTP(51)	10042	PARJ(11)	0.5
MSTP(142)	2	PARJ(12)	0.4
PARP(67)	1	PARJ(13)	0.79
PARP(82)	4.28	PARJ(14)	0.0
PARP(85)	0.33	PARJ(15)	0.018
MSTJ(26)	0	PARJ(16)	0.054
PARJ(33)	0.4	PARJ(17)	0.131

Enabled processes in LHCb MC:

process number	description
11	$f + f' \to f + f'$ (QCD)
12	$f + \bar{f} \to f + \bar{f}'$
13	$f + \bar{f} \to g + g$
28	$f + g \to f + g$
53	$g + g \to f + \bar{f}$
68	$g + g \to g + g$
91	Elastic scattering
92	Single diffractive (AB $\to$ XB)
93	Single diffractive (AB $\to$ AX)
94	Double diffractive
95	Low-pT scattering
421 439	Prompt charmonium
461 479	Prompt bottomonium