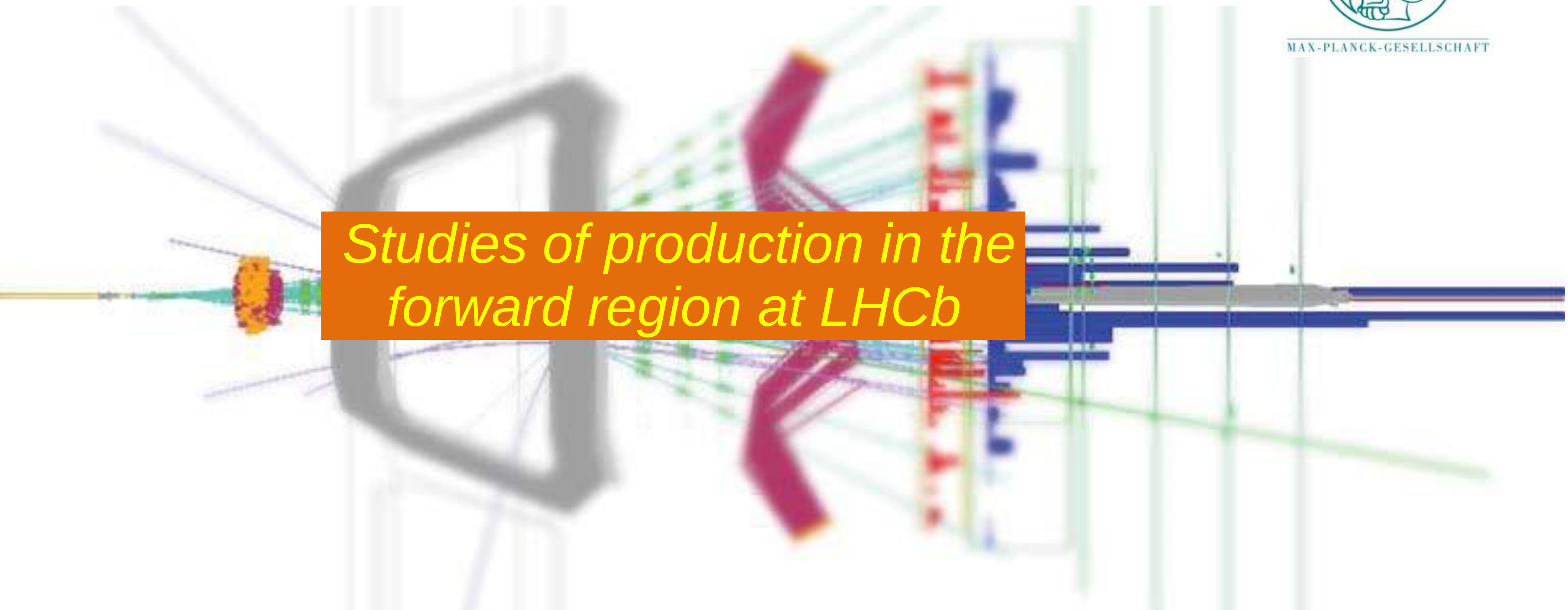
Studies of production in the forward region at LHCb



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on behalf of the LHCb collaboration

International Workshop on Forward Physics at the LHC

November 4-8 Cape Town, South Africa

Outline

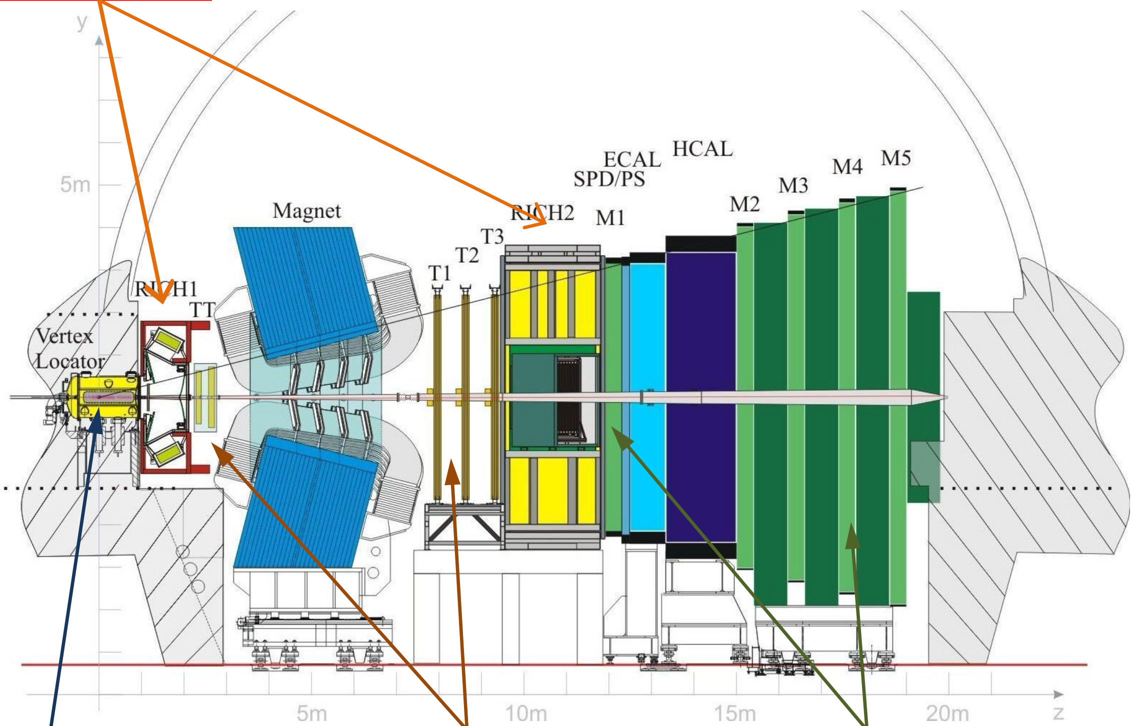
- The LHCb experiment.
- Forward energy flow.
- Charge particle multiplicity.
- Hadron production ratios.
- Charm, double-charm production.
- Summary.

LHCb Experiment.

JINST 3 (2008) S08005

RICH1 & RICH2
$\varepsilon(\mathrm{K}\to\mathrm{K})\approx 95\%$
$\pi\to\mathrm{K}$ mis-id : 5%

Calorimeters
ECAL : $\sigma_E/E \approx 1\% + 10\%/\sqrt{E\,[\mathrm{GeV}]}$



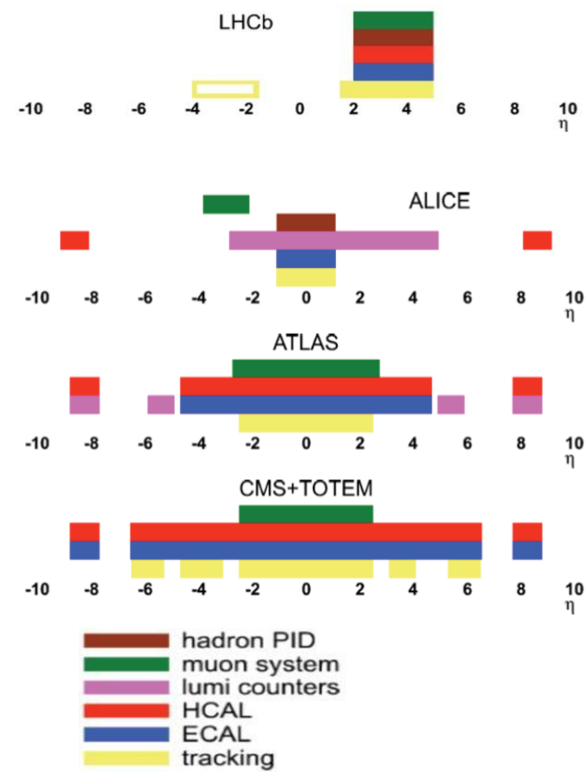
VELO
$\sigma_{IP}\approx 20\mu\mathrm{m}$
for high-p_T tracks
bwd acc. $-4\le\eta\le -1.5$

Traking System
$\Delta p/p = 0.4\%$ @ 5GeV/c
to 0.6% @100GeV/c

Muon System
$\varepsilon(\mu\to\mu)\sim 97\%$
$\pi\to\mu$ mis-id : 1 ~ 3%

Pseudorapidity coverage of the LHC experiments

LHCb Pseudorapidity acceptance
$2 < \eta < 5$



Tracking, RICH, Calorimeters, Muon System covering the full acceptance of the spectrometer.

Forward Energy Flow.

- *Energy Flow (EF) :*

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--- *average energy created in a particular η interval per inelastic pp interaction*

Energy for particle

$$\frac{1}{N_{\text{int}}}\frac{dE_{tot}}{d\eta} = \frac{1}{\Delta\eta}\left(\frac{1}{N_{\text{int}}}\sum_{i=1}^{N_{part,\eta}} E_{i,\eta}\right)$$

Inelastic interactions

Measurement is done for different event classes :

--- *inclusive MB:* at least 1 track in 1.9<η<4.9 with p > 2 GeV

--- *hard scattering:* at least 1 track in 1.9<η<4.9 with pT > 3 GeV

--- *diffractive enriched:* inclusive MB with no backward tracks in -3.5<η<-1.5

--- *non-diffractive enriched:* inclusive MB with at least 1 backward track in -3.5<η<-1.5

"Large" rapidity gap for diffractive process

"No" rapidity gap

Result & Comparison (I).

- *EF increases with the momentum transfer in an underlying pp process:*

$$EF_{\text{hard}} > EF_{\text{non-diffr}} > EF_{\text{incl}} > EF_{\text{diff}}$$

- *PYTHIA6-based models*
  - ➢ *underestimate EF at large η*
  - ➢ *overestimate it at low η*

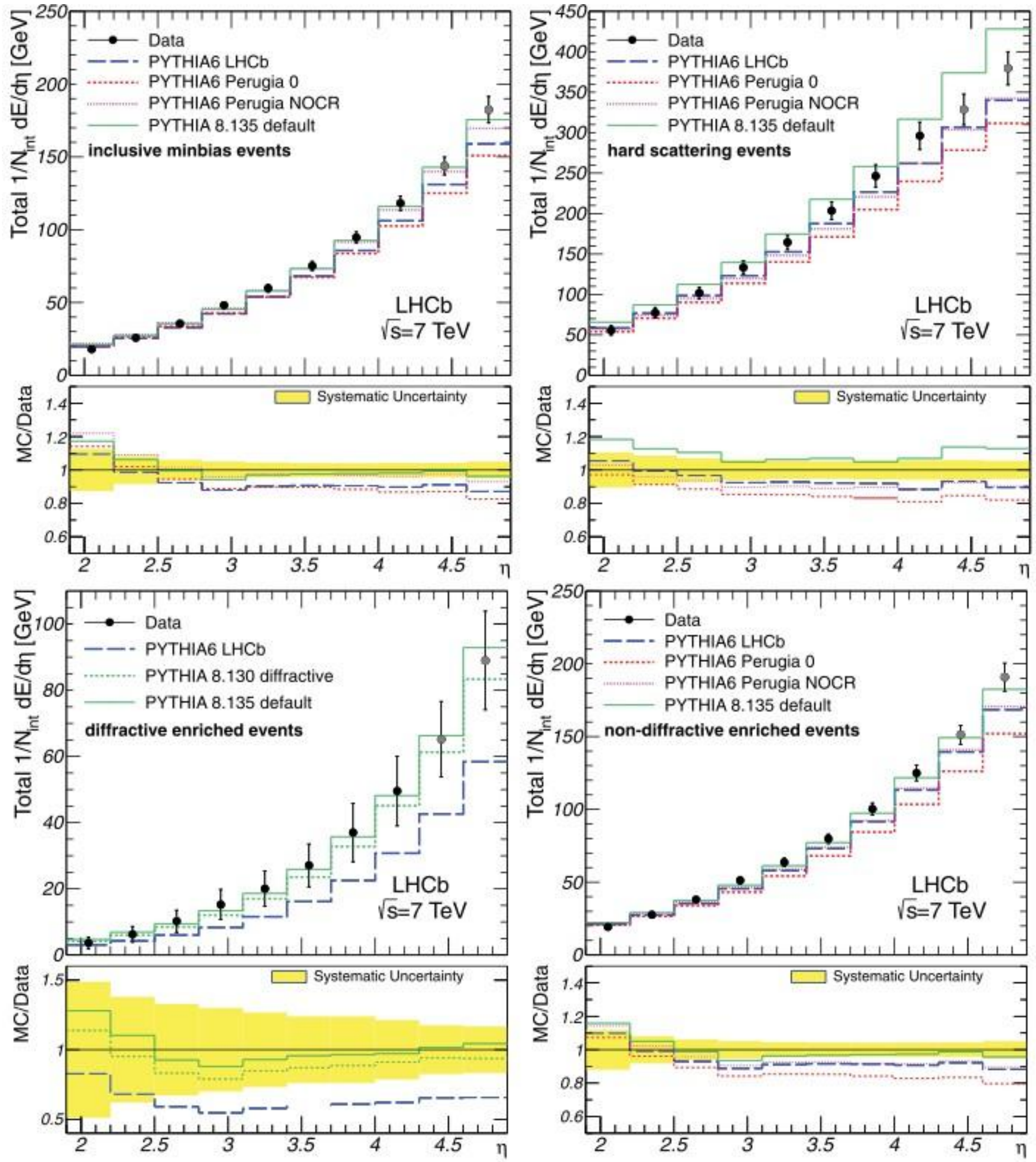
  in case of all event classes

- *PYTHIA8 with default parameters gives excellent description of the measurements at large η except for hard scattering events*

J. of Phys. : Conf. Ser. 331 (2011) 032023.

Phys. Rev. D82 (2010) 074018, arXiv:1005.3457

Comput. Phys. Commun. 178 (2008) 852, arXiv:0710.3820



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Result & Comparison (II).

- *EPOS 1.99, SIBYLL 2.1, QGSJET 01, QGSJET II cosmic-ray interaction models*

  --- soft processes via Pomeron exchanges (Gribov's Reggeon Field Theory)

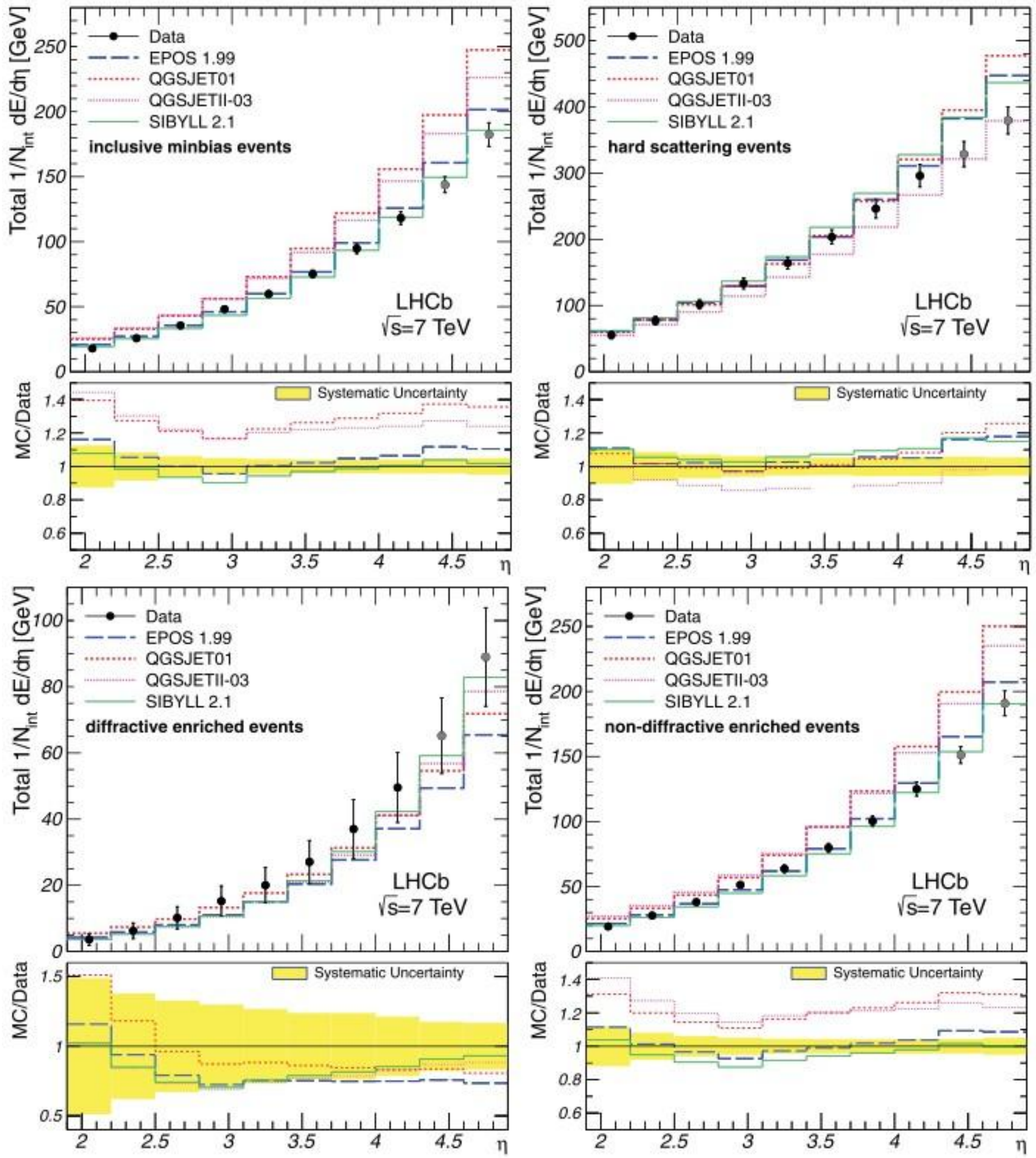
  --- hard processes: pQCD or exchanges of semi-hard Pomerons

  --- models are not tuned to LHC data

- *SIBYLL 2.1 gives the best description of the inclusive and non-diffractive EF*

- *None of the models are able to describe the EF measurements for all event classes:*

  --- valuable input for MC tuning and MPI/UE models



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Charged Particle Mutiplicities.

VELO based measurement: momentum of the track is unknown.

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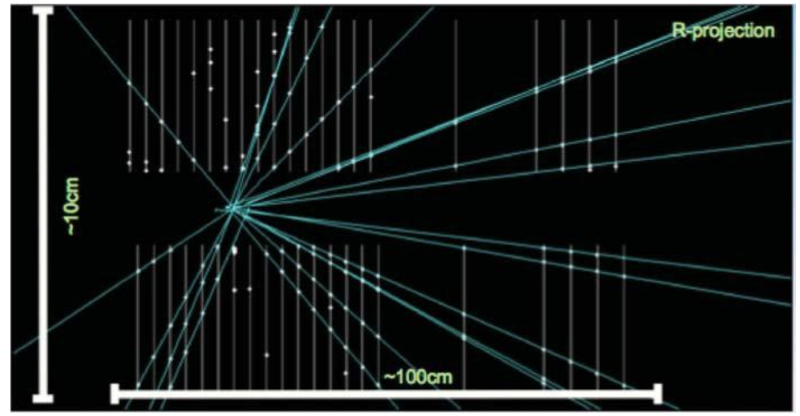
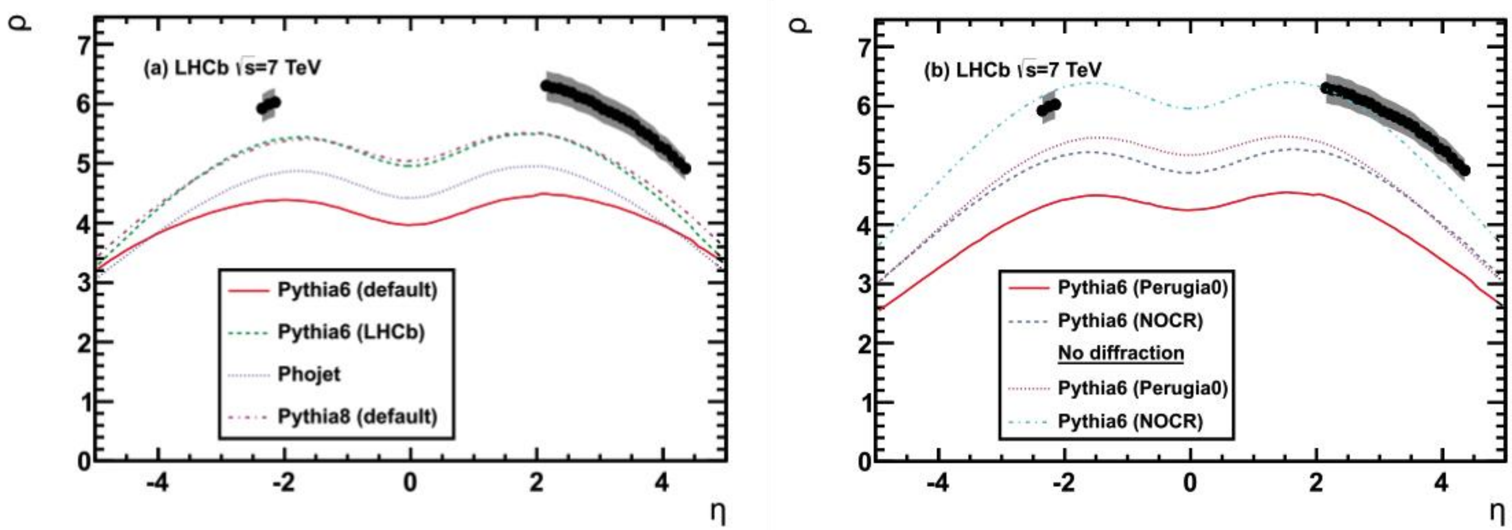
- No magnetic field
  - ➢Only measurement of direction
  - ➢Tracks as a function of η
- Events with ≥ 1 tracks in forward acceptance
  - ➢Inclusive minimum bias interactions
  - ➢Hard interactions with ≥ 1 track with $p_T > 1\,\mathrm{GeV}/c$



Charge particle density per event vs η

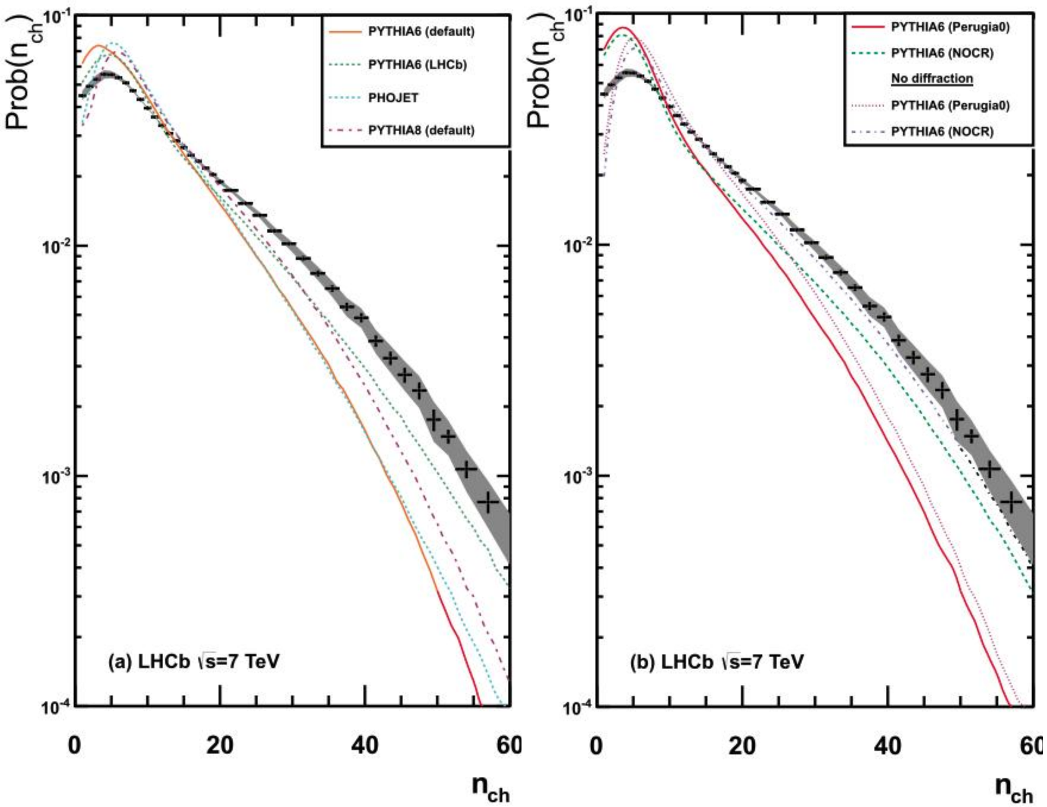


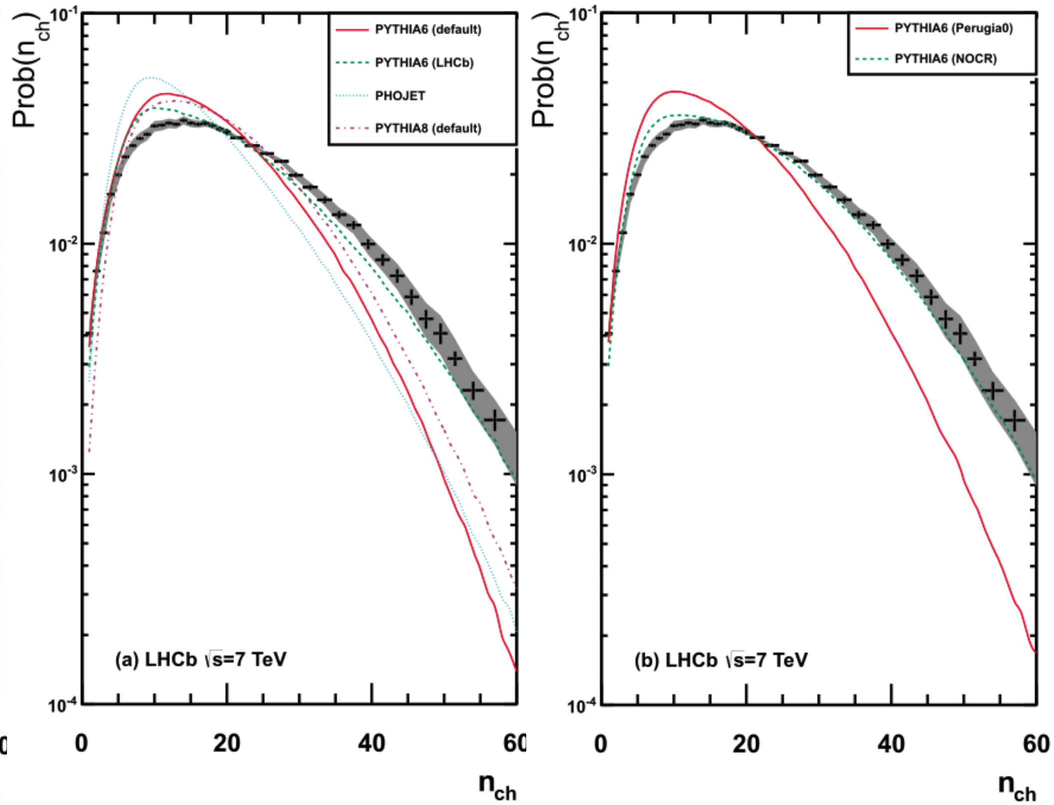
Models underestimate the actual particle densities.

Multiplicity distributions for $2<\eta<4.5$

Inclusive Minimum Bias

Hard Interactions





- ➢None of the model studied is fully able to describe the multiplicities
- ➢Models underestimate multiplicity in the forward region
- ➢Agreement better for hard interactions

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Identified particles.

Particle production ratios as a function of y and p_T

- Antiparticle/particle ratios and ratios of different particle species

$$\frac{\pi^-}{\pi^+},\ \frac{K^-}{K^+},\ \frac{\bar{p}}{p} \quad \text{and} \quad \frac{p+\bar{p}}{\pi^+ + \pi^-},\ \frac{K^+ + K^-}{\pi^+ + \pi^-}$$

- Many systematic uncertainties cancel
- Valuable information about the hadronisation process:
  - Baryon number transport from antiproton/proton
  - Baryon suppression from baryon/meson ratios
  - Strangeness suppression from kaon/pion ratios

Experimental detailes:

- Result based on $0.3\,\mathrm{nb}^{-1}$ at $\sqrt{s} = 0.9\,\mathrm{TeV}$ and $1.8\,\mathrm{nb}^{-1}$ at $\sqrt{s} = 7\,\mathrm{TeV}$
- PID efficiencies from $K_S^0 \to \pi^+\pi^-$, $\Lambda \to p\pi^-$, $\bar{\Lambda} \to \bar{p}$ and $\phi \to K^+K^-$
- Dominant uncertainties from PID due to limited size of calibration sample

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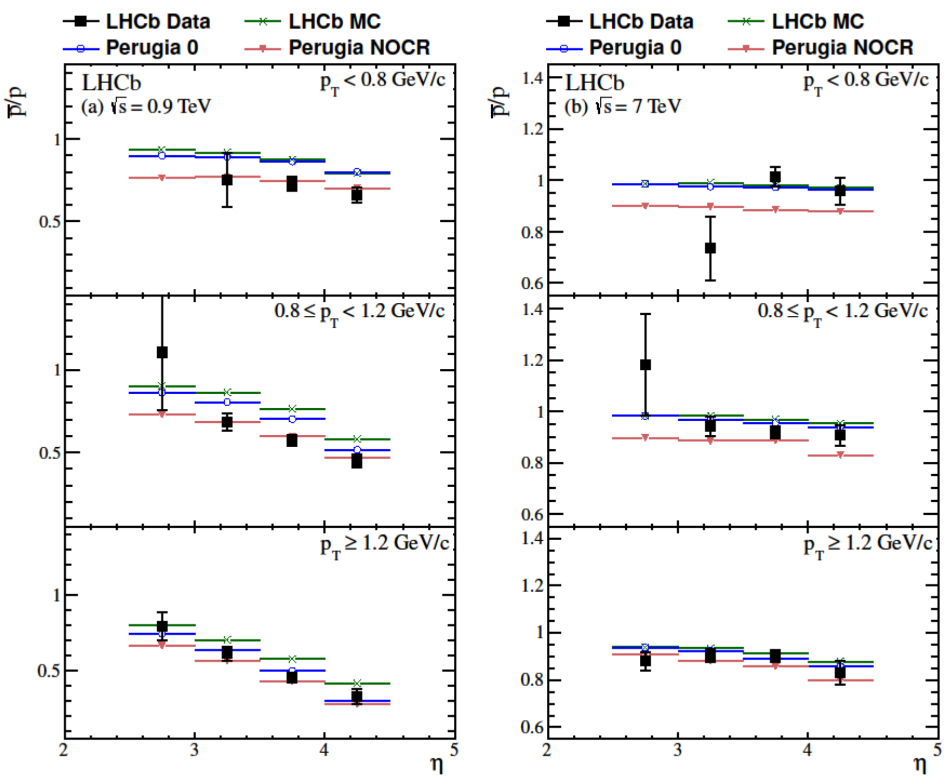
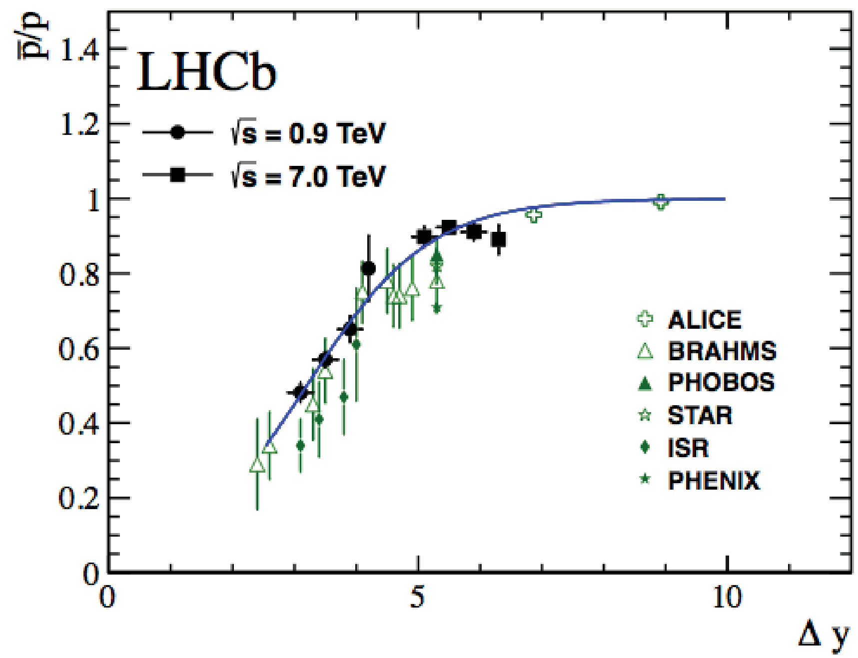
Baryon Number Transport.

$$\bar{p}/p$$

$\sqrt{s} = 0.9\,\mathrm{TeV}$ $\sqrt{s} = 7\,\mathrm{TeV}$



p_T – integrated ratio:



rapidity loss: $\Delta y = y_{beam} - y$

$y_{beam} = 8.9(6.9)$ at $\sqrt{s} = 7(0.9)$ TeV

- Scaling behavior as a function of rapidity loss
- Fit to LHCb&ALICE data based in *Regge–model* of baryon transport

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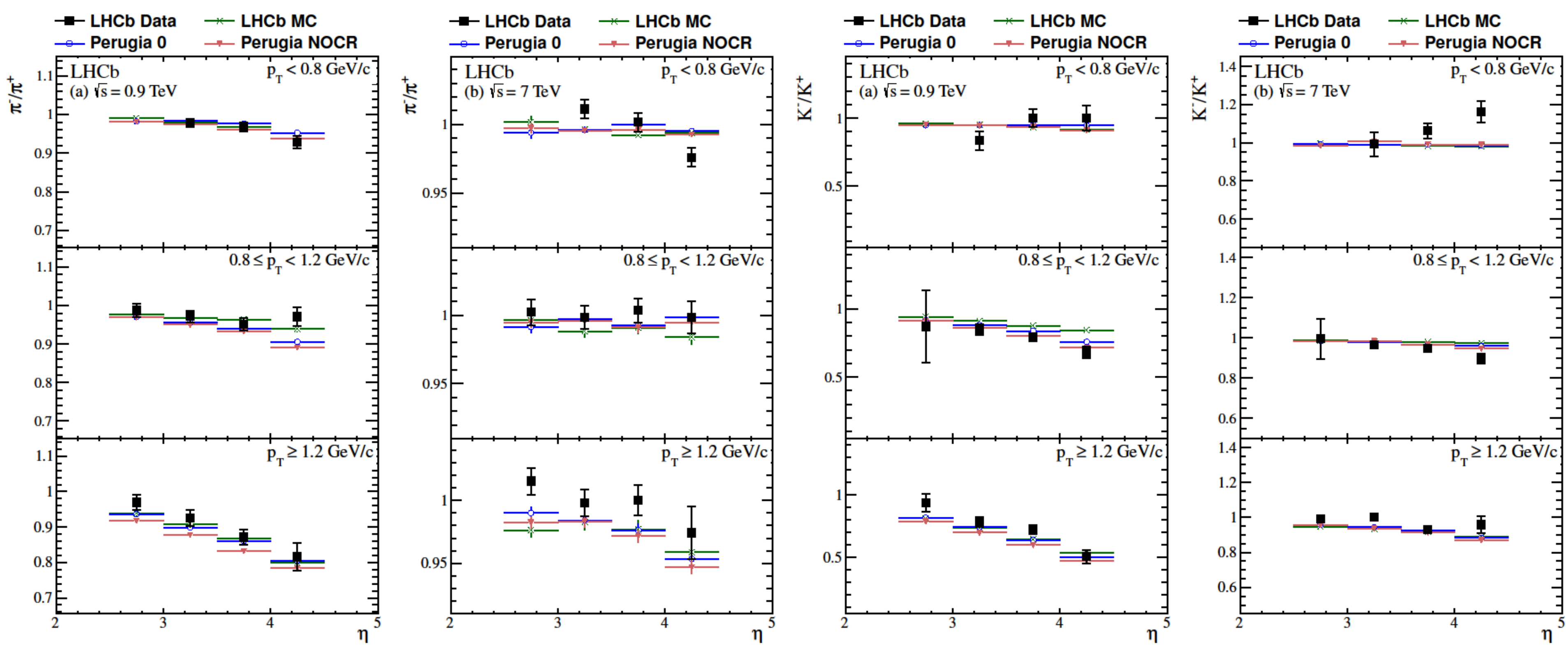
Antiparticle / Particle Ratios.

π^- / π^+ $\qquad$ K^- / K^+

$\sqrt{s} = 0.9\,\mathrm{TeV}$ $\qquad$ $\sqrt{s} = 7\,\mathrm{TeV}$ $\qquad$ $\sqrt{s} = 0.9\,\mathrm{TeV}$ $\qquad$ $\sqrt{s} = 7\,\mathrm{TeV}$



- Charge ratio drops towards lager rapidity (proton beam)
- Effect more pronounced at higher p_T
- General behavior reproduced by PYTHIA tunes

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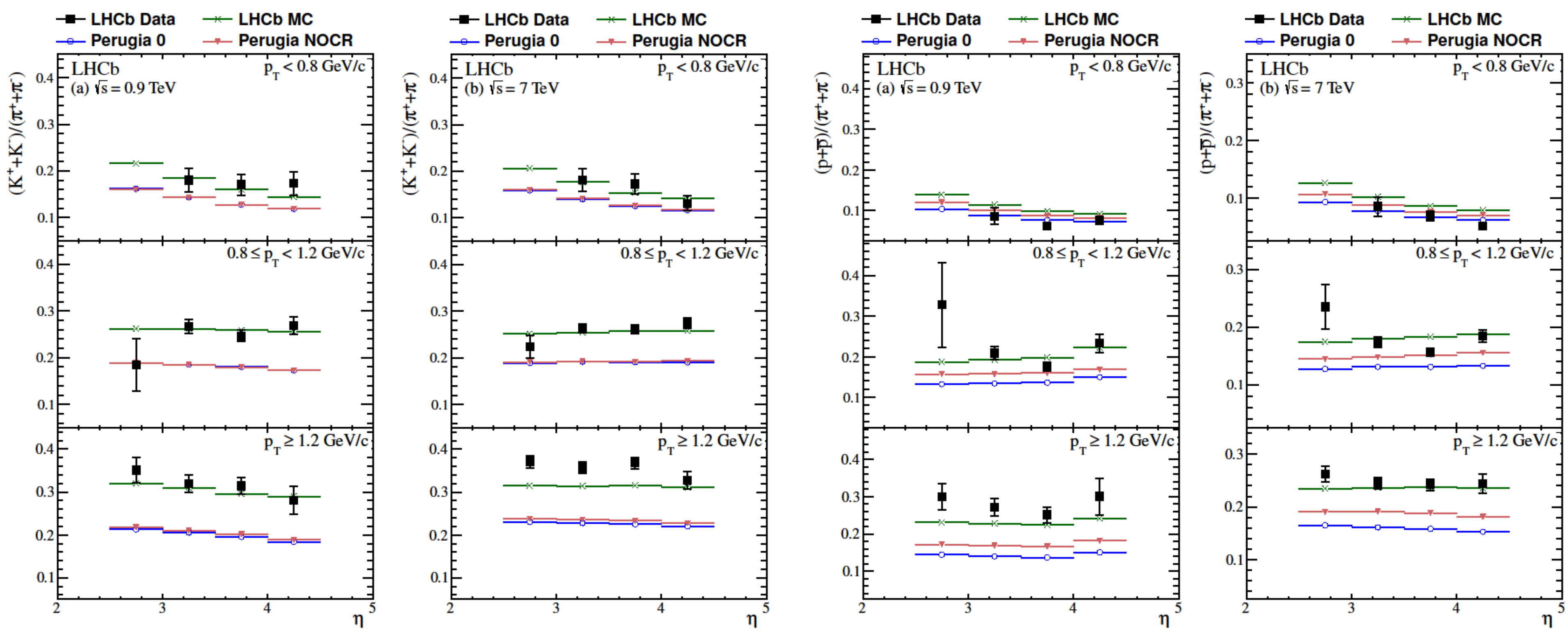
Antiparticle / particle ratios.

$$(K^+ + K^-)/(\pi^+ + \pi^-) \qquad (\bar{p} + p)/(\pi^- + \pi^+)$$

$$\sqrt{s} = 0.9\,\text{TeV} \qquad \sqrt{s} = 7\,\text{TeV} \qquad \sqrt{s} = 0.9\,\text{TeV} \qquad \sqrt{s} = 7\,\text{TeV}$$



- ➢ Strangeness suppression very similar to baryon suppression
- ➢ Less suppression at higher p_T
- ➢ Data best described by LHCb-tune of PYTHIA

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Nucl. Phys. B 871 (2013)

Prompt charm.

Differential production cross sections are measured for prompt charm hadrons:

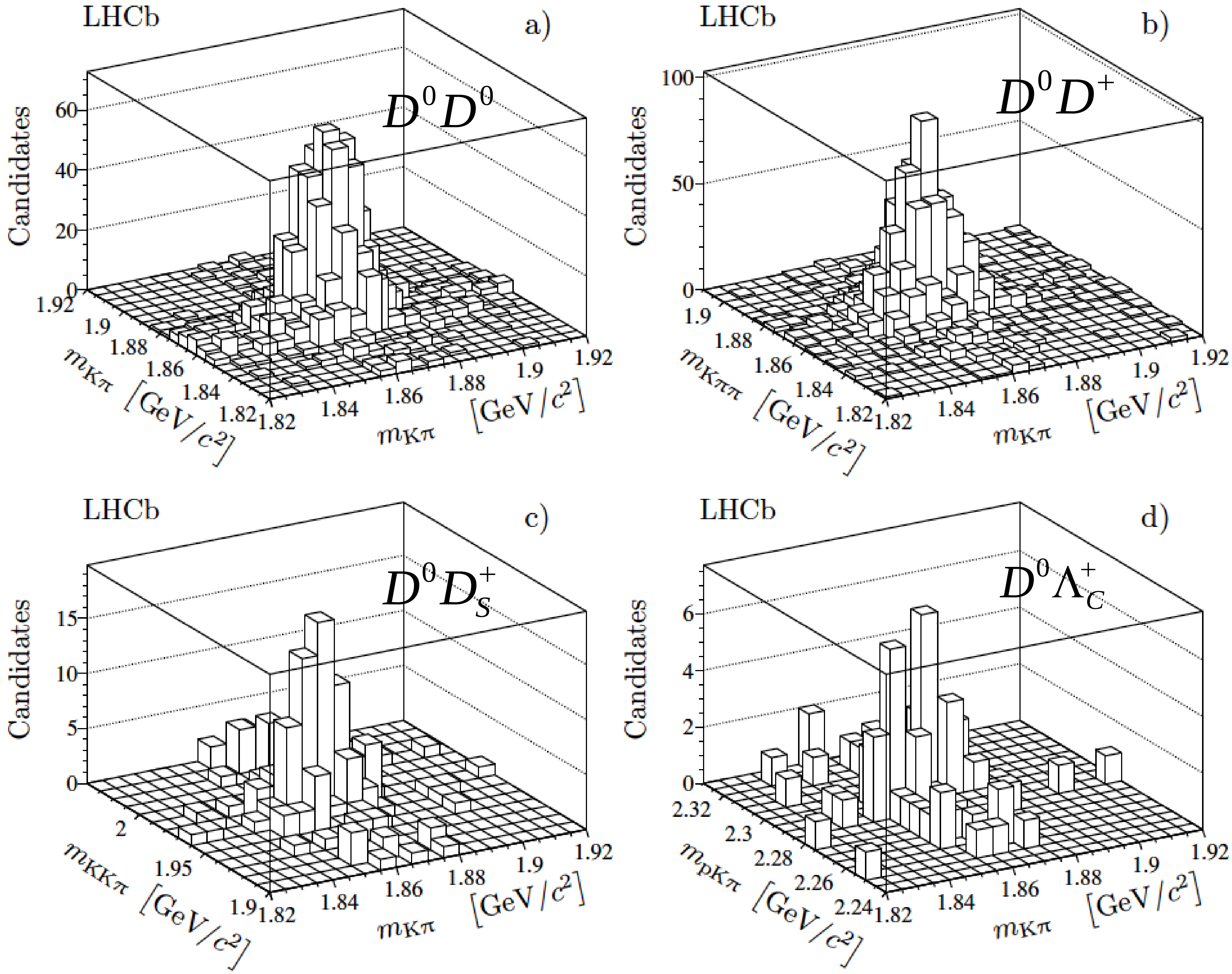
D^0, D^+, D^{*+}, D^+_s and **Λ^+_c**

in fiducial region $2<\eta<4.5$; $0<p_T<8$GeV.

Differential cross-sections compared to theoretical predictions, which reproduce Tevatron & ALICE measurements in central rapidity region.

- Fixed order with next to leading-log resumption **(FONLL) using CTEQ 6.6**
- NLO calculation in the *Generalized Mass Variable Flavour Number Scheme* **(GMVNS)** using **CTEQ 6.5 and CTEQ 6.5c2 (intrinsic charm**)
  - Good agreement with our measurement
  - Effect of intrinsic charm is predicted to be small in this phase space region.

Double Charm Production – Signals.



JHEP06(2012) 141

Double Charm Production - Expectation.

Multi-parton interaction in pp collisions.

Signals observed:

- Double J/ψ production
- J/ψ + open charm
- Open charm
- "CC" production from double parton interactions
- "$C\bar{C}$" production from single- and double parton interactions

Production cross section for double parton interaction:

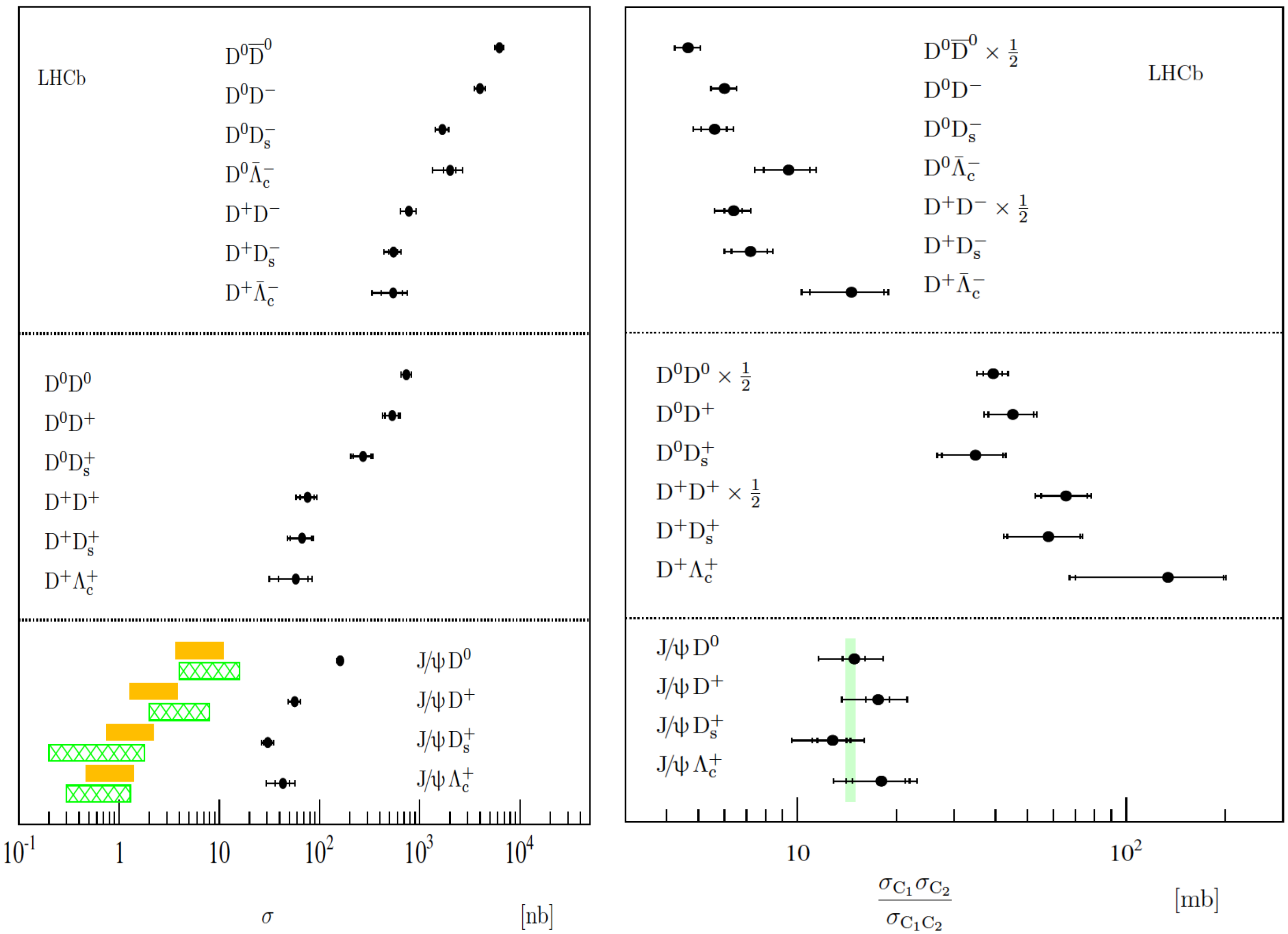
$$\sigma_{DPS}(C_1C_2) = \frac{\sigma(C_1)\times\sigma(C_2)}{k\times\sigma_{eff}}$$

Where:

$k=2$ for $C_1 = C_2$
$k=1$ for $C_1 \neq C_2$

From CDF double-parton-scattering $\sigma_{eff} \sim 15\text{mb}$

Double charm cross-section.



- Theoretical predictions underestimate ***J/ψC*** cross-section
- CDF-DPS cross section fit only to ***J/ψC*** cross-section

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PLB707(2012) 52

Conclusions.

- General event properties.
  - Forward energy flow not well described by PYTHIA6.
  - Charge particle multiplicities not well described by PYTHIA6.
  - PYTHIA8 is more close to the experiment.
  - Cosmic ray models appear to do better.
- Production ratios of identified particles.
  - Antiparticle/particle ratios well described.
  - Scaling of baryon number transport with rapidity difference.
- Double charm production.
  - Double J/ψ production consistent with no multi-parton-interactions.
  - Double charm involving open charm theoretically not understood.

LHCb results.

❖Light quarks in pp collisions

EPJC72(2012) 1947 Measurement of charged particle multiplicities at $\sqrt{s} = 7$ TeV
EPJC73(2013) 2124 Measurement of the forward energy flow at $\sqrt{s} = 7$ TeV
PLB693(2010) 69 Prompt K^0 production in pp collisions at $\sqrt{s} = 0.9$ TeV
PLB703(2011) 267 Measurement of the inclusive ϕ cross-section at $\sqrt{s} = 7$ TeV
JHEP08(2011) 034 Measurement of V^0 production ratios at $\sqrt{s} = 0.9$ and 7 TeV
EPJC72(2012) 2168 Prompt hadron production ratios at $\sqrt{s} = 0.9$ and 7 TeV

❖charm and double charm in pp collisions

NPB871(2013) 1 Prompt charm production in pp collisions at $\sqrt{s} = 7$ TeV
EPJC71(2011) 1645 J/ψ production in pp collisions at $\sqrt{s} = 7$ TeV
JHEP02(2013) 041 J/ψ production in pp collisions at $\sqrt{s} = 2$:76 TeV
JHEP06(2013) 064 Production of J/ψ and mesons in at $\sqrt{s} = 8$ TeV
PLB707(2012) 52 J/ψ pair production in pp collisions at $\sqrt{s} = 7$ TeV
JHEP06(2012) 141 Double charm production with open charm in pp at $\sqrt{s} = 7$ TeV

Backup slides.

PYTHIA tunes.

Non default PYTHIA parameters in the LHCb simulation software

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

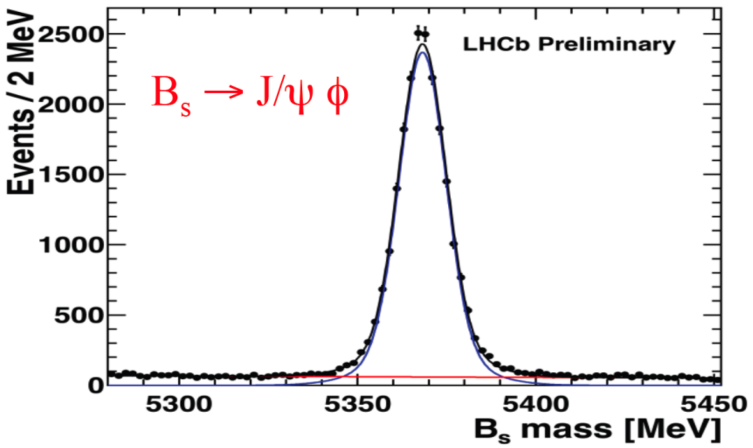
Perugia0 corresponding PYTHIA parameters

Parameter	Value	Parameter	Value
CKIN(41)	12.	PARP(86)	0.95
MSTP(2)	1	PARP(89)	1800
MSTP(33)	0	PARP(90)	0.25
MSTP(81)	11	PARP(91)	2.0
MSTP(82)	4	PARP(149)	0.48
MSTP(52)	1	PARP(150)	0.09
MSTP(51)	7	PARJ(11)	0.5
MSTP(142)	0	PARJ(12)	0.56
PARP(67)	4	PARJ(13)	0.75
PARP(82)	2.0	PARJ(14)	0.0
PARP(85)	0.9	PARJ(15)	0.0
MSTJ(26)	2	PARJ(16)	0.0
PARJ(33)	0.8	PARJ(17)	0.0

PARP(82): UE IR cutoff at reference ecm, Pythia 0: 3.4 Pythia NOCR: 3.19
PARP(89): Reference ecm
PARp(90): UE IR cutoff ecm scaling power

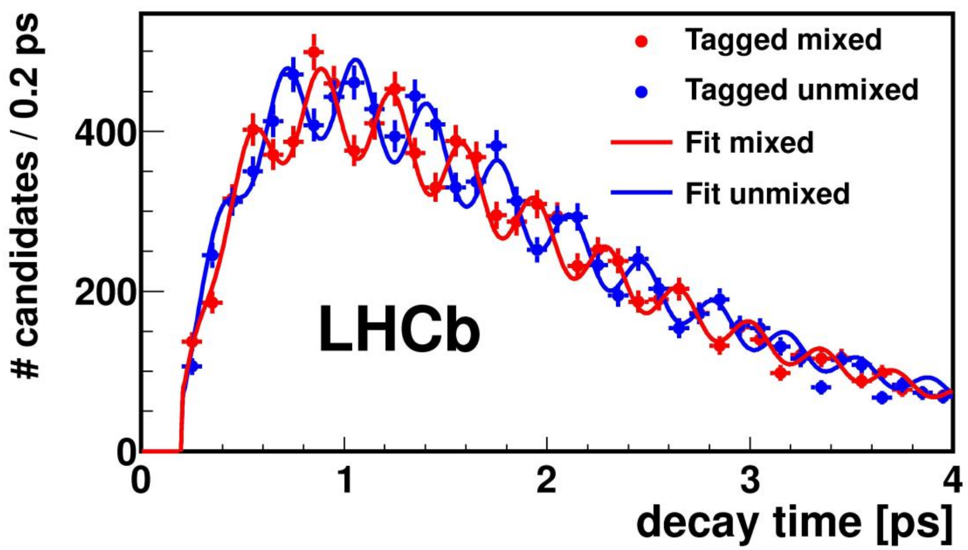
LHCb - Physics.

- Excellent particle-ID and mass resolution for complex decays



B-mass resolution:
$\sigma(m_B) = 8$ MeV/c^2
for Bs → J/ψ X
with J/ψ mass constraint

- Excellent particle-ID, vertex- and proper-time resolution



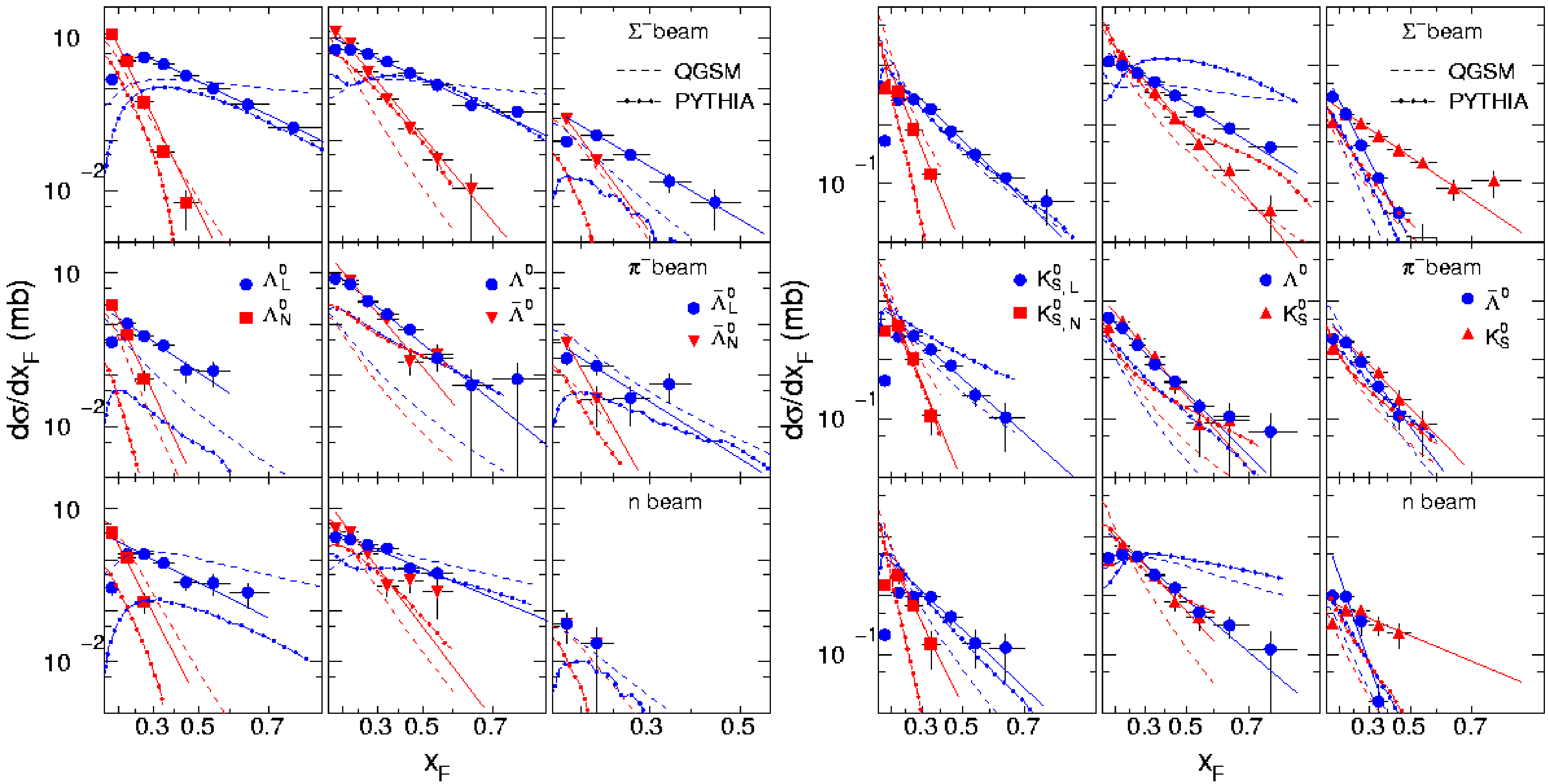
proper time resolution:

$\sigma_t \sim 45$ fs

for B_S - mixing

Pair production of strange particles.

Pair production of strange particles K_S^0, Λ, $\bar{\Lambda}$ with Σ^-, π^- and neutron beams in WA-89.



In general the experimental results can not be described by PYTYIA or quark-gluon string model (QGSM).

Eur. Phys. J C52(2007) 857-874

V^0 production.

V0 is a generic name for long living particles - K_S^0, Λ, $\bar{\Lambda}$ with a strange quark.

Measurement was done at √s = 0.9, 7 TeV

What measurement tell us:

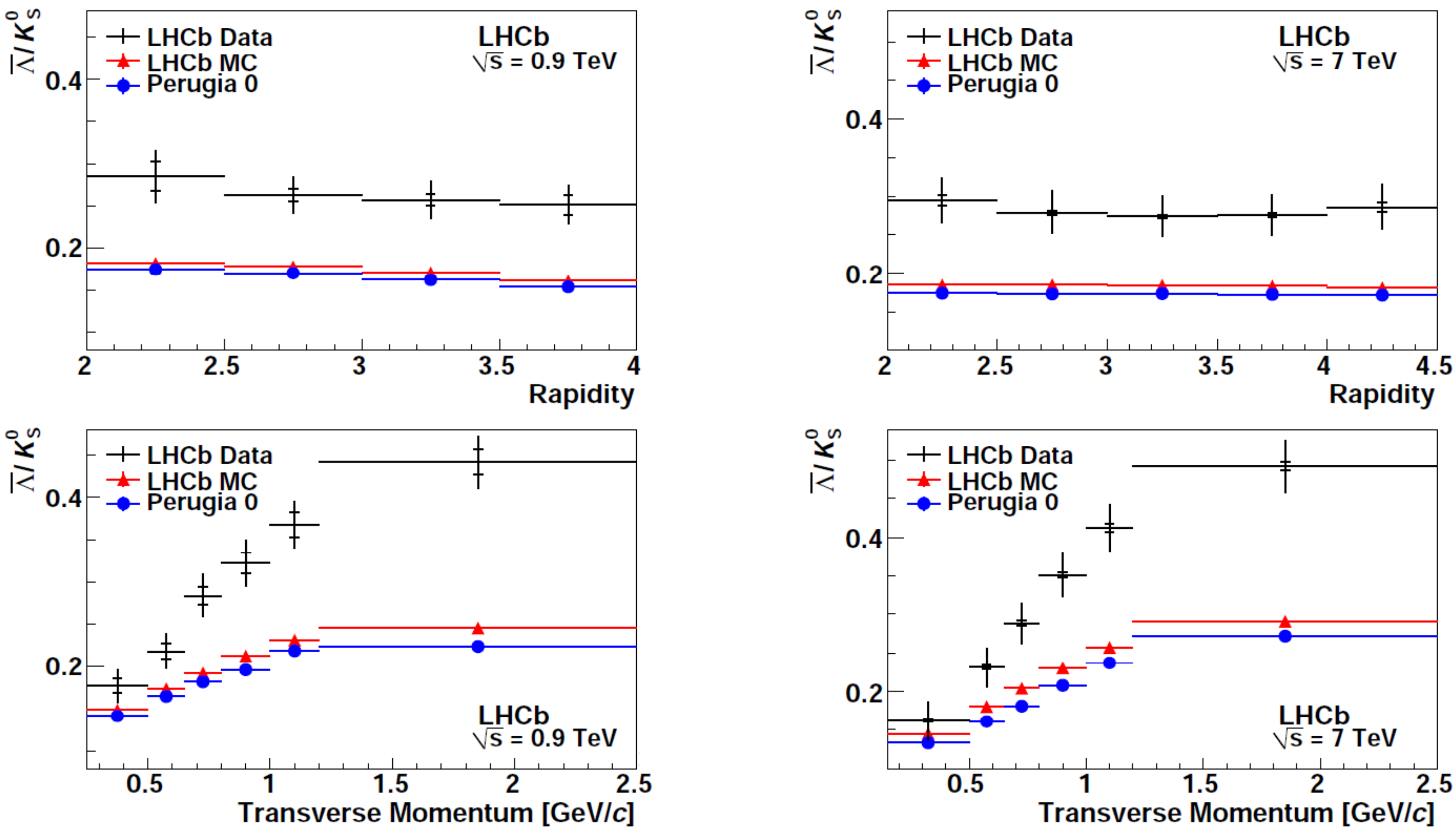
- Quark content of baryons : $p = (ud)u$, $\Lambda = (ud)s$, $\bar{\Lambda} = (\bar{u}\bar{d})\bar{s}$
  - Λ : common quarks with initial state – baryon number transport
  - $\bar{\Lambda}$: no common quarks – particle production in fragmentation

- $\bar{\Lambda}/K_S^0$: measure baryon suppression in fragmentation
- $\bar{\Lambda}/\Lambda$: probe baryon number transport.

Baryon suppression in fragmentation.

√s=0.9TeV

√s=7TeV



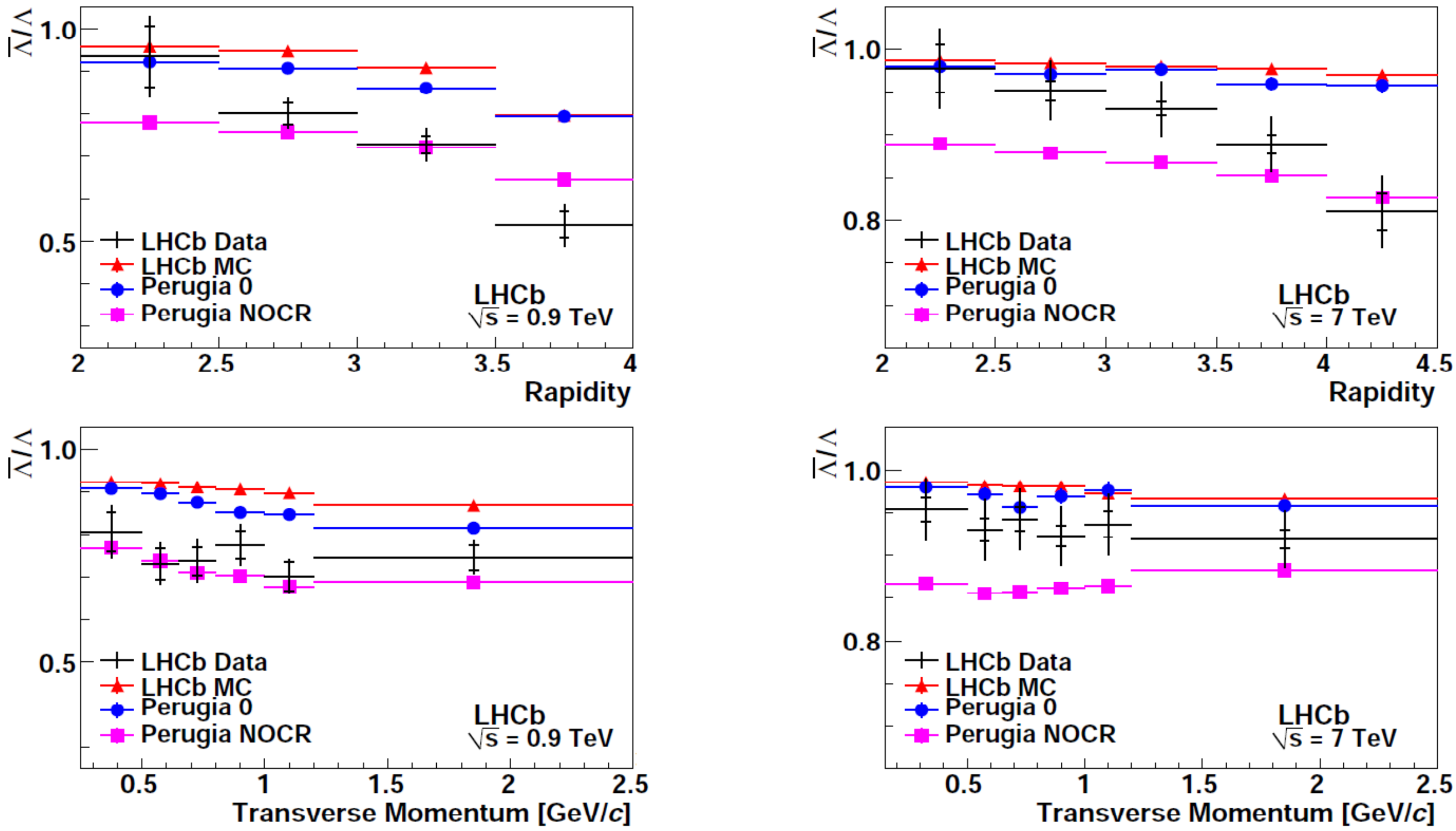
- reduced baryon suppression at large p_T
- models fail to describe the data

JHEP08(2011)034

Baryon number transport.

$\sqrt{s}$=0.9TeV

$\sqrt{s}$=7TeV

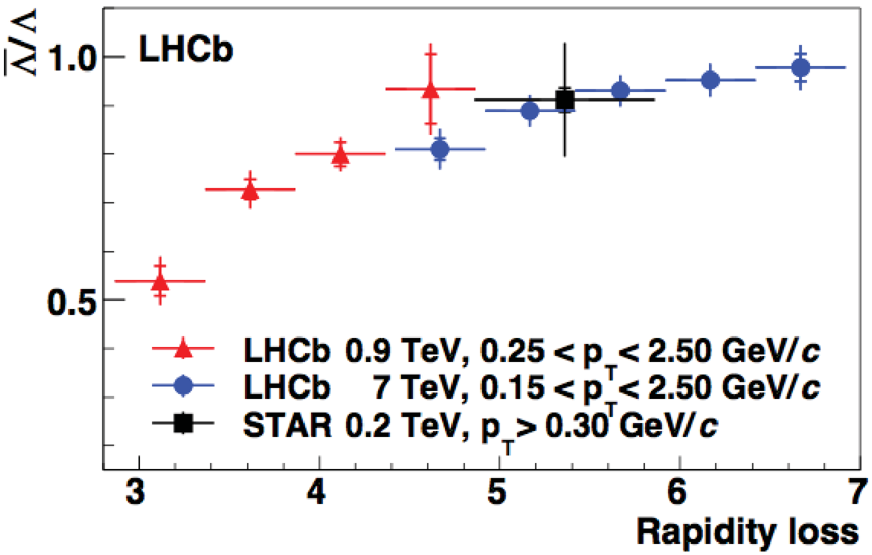


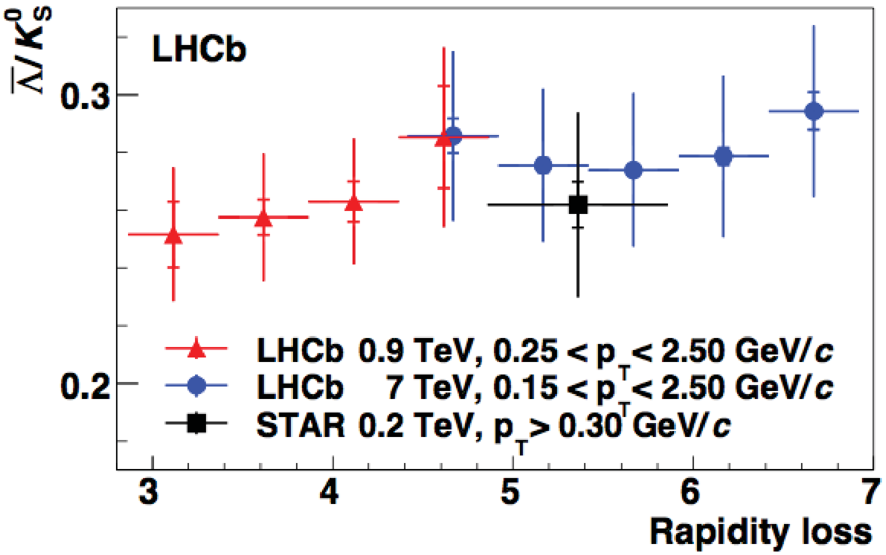
- drop towards large rapidities, stable with p_T
- models fail to describe the data

JHEP08(2011)034

Dependence on rapidity loss

V^0 particle ratios integrated over p_T

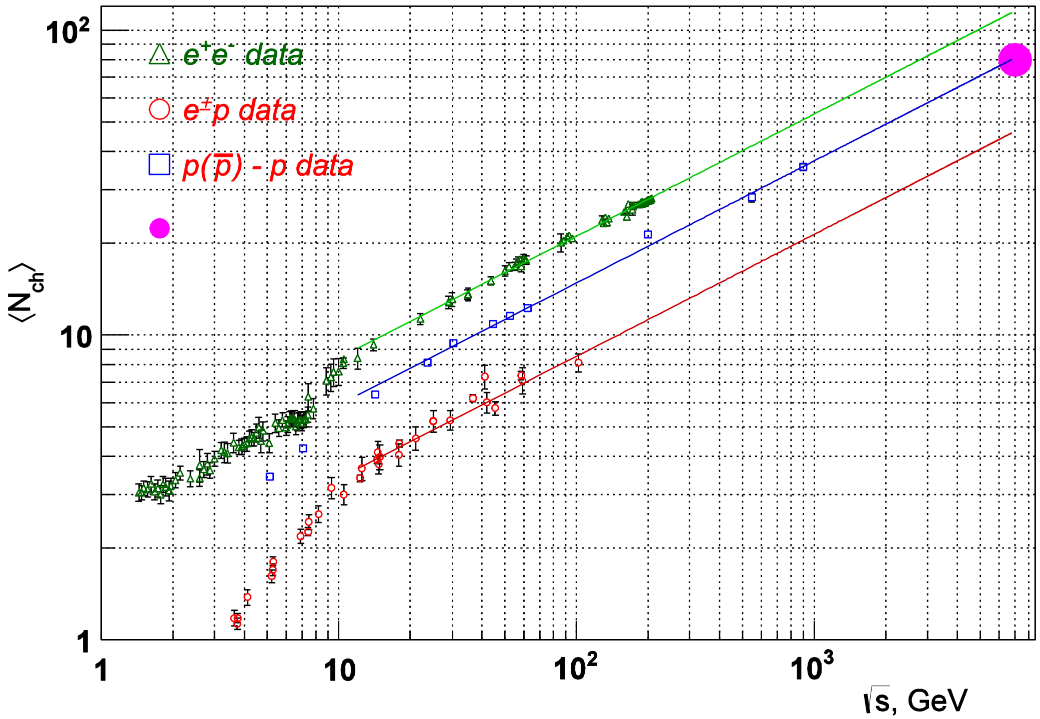




- Scaling behavior for baryon number transport and baryon suppression
- Independent of center-of-mass energy within experimental error
- Weak dependence of fragmentation $\bar{\Lambda}/K_S^0$ as a function of rapidity loss
- Drop in $\bar{\Lambda}/\Lambda$ for $\Delta y \to 0$ dominated by baryon number transport

JHEP08(2011)034

Average multiplicities in the event.



The average charge multiplicities in $e^+e^-, e^\pm p$, $p\bar{p}$ and pp interactions. The data points are taken from PDG 2012. The blue line is the result of the fit of data in $p\bar{p}$ and pp interactions with the power fixed to 1/5, the green and red lines are the offset of fit by ± 1 unit. The magenta dot indicates the expected average charge multiplicities at 7TeV.

The conventional opinion:

$$n_{ch} \sim \log(\sqrt{s})$$

The universal power law for the average multiplicity of charge particles in the event at enegy above 11GeV :

$$n_{ch} = N_0 \times \left(\frac{s}{m_p^2}\right)^{1/5}$$

m_p - proton mass,

$N_0(pp, p\bar{p})$ = 2.32

$N_0(ep)$ = 1.32

$N_0(e^+e^-)$ = 3.32

arXiv:1206.0875