FORWARD PRODUCTION MEASUREMENTS WITH LHCb

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Istituto Nazionale di Fisica Nucleare, Cagliari

The 2nd International Conference on the Initial Stages in High-Energy Nuclear Collisions

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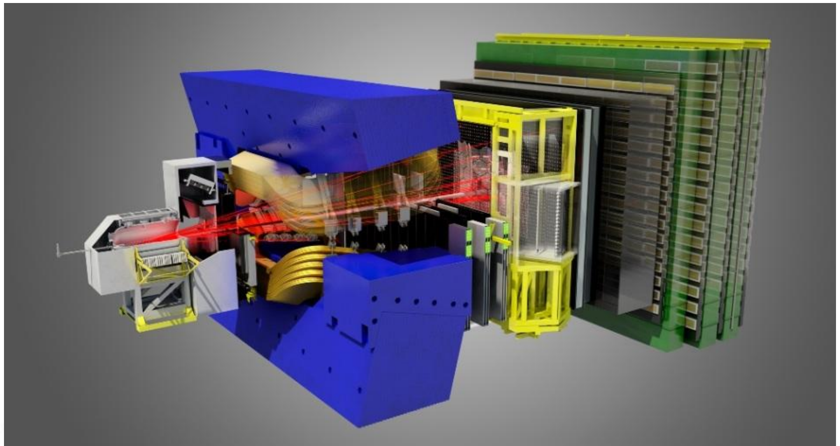
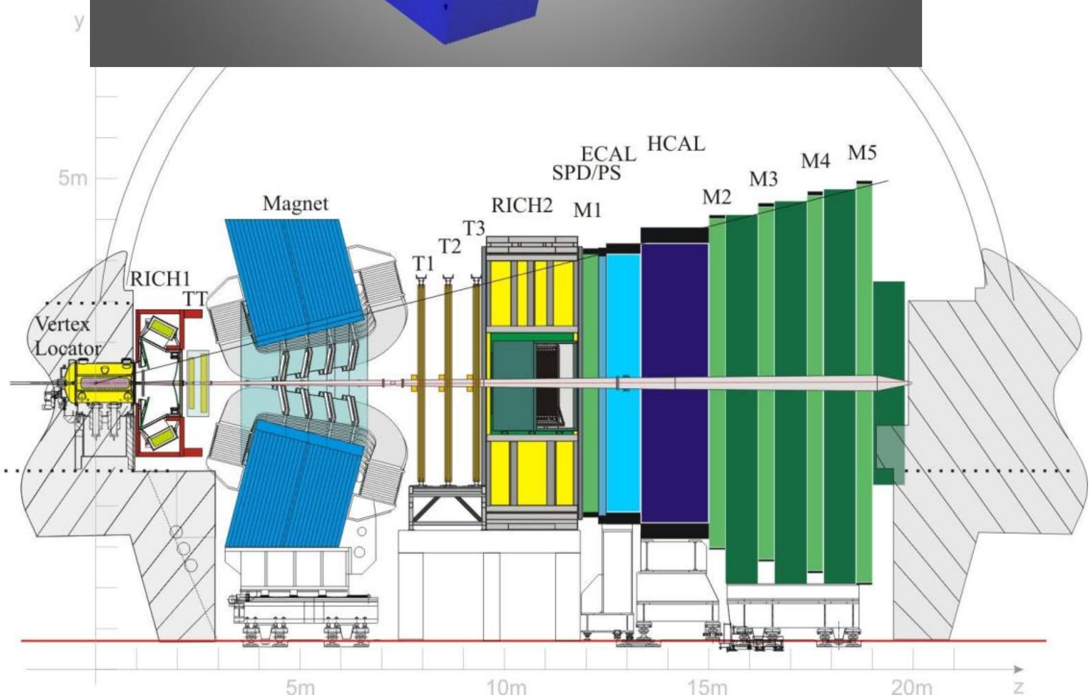
Outline

- **LHCb detector**
- **Forward production measurements**
  - Forward energy flow — **EPJC73 (2013) 2421**
  - Central exclusive production (CEP)
    - CEP of J/ψ and $\psi(2S)$ — **J. P. G 40 (2013) 045001**, **J. P. G 41 (2014) 055002**
    - CEP of charmonium pairs — **J. P. G 41 (2014) 115002**
  - Production ratios of identified particles — **EPJC 72 (2012) 2168**
- **Summary**

LHCb detector





Backward ⟵ ⟶ Forward

- Single arm spectrometer $2 < \eta < 5$
- Stations:
  - **Vertex locator (VELO)**

    Both forward and backward

    20 μm IP resolution for p_T > 2 GeV/c
  - **4 tracker stations & 4 Tm integrated field**

    0.4%-0.6% momentum resolution
  - **Calorimeters**
  - **RICH detectors**

    ε(K→K)~95% for (π→K)~5%
  - **Muon system**

    Muon Identification ε~97% MisID~2%

JINST 3 (2008) S08005

Forward Energy Flow

- **Motivation**
  - **Energy Flow (EF): Average energy per event in a given *η* interval**

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

  - **Sensitive to parton radiation and multiple parton interaction**
  - **Tests of event generators – collider and cosmic ray models**

- **Data sample**
  - **0.1 nb^{-1} low pile-up data collected at 7 TeV**
  - **At least one VELO track required in the trigger**

EPJC73 (2013) 2421

Forward Energy Flow

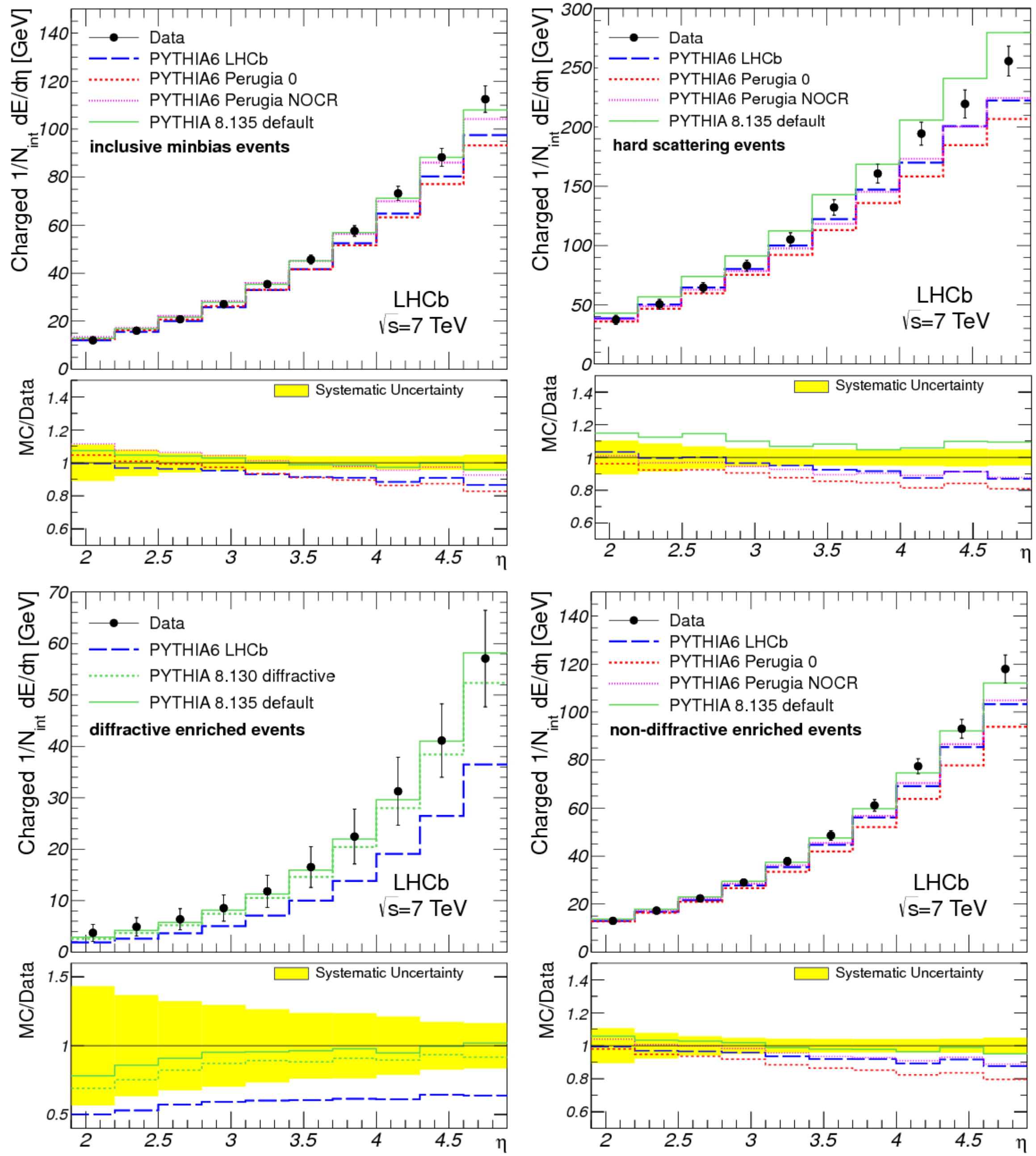
- **Analysis Strategy**
  - **Measurement with tracks 2 GeV/*c* < *p* < 1 TeV/*c***
  - **Four different event classes**
    - **Inclusive minimum bias –** at least one track with $p > 2$ GeV/c
    - **Hard-scattering –** at least one track with $p_T > 3$ GeV/c
    - **Diffractive enriched –** no backward tracks
    - **Non-diffractive enriched –** at least one backward track
  - **Corrected to particle level**
    - **Charged energy flow –** only tracking information (no PID; $E \approx p$).
    - **Total energy flow –** data-constrained MC estimate of neutral component (Calorimeter information)
  - **Systematics dominated by model uncertainty and selection cuts**

EPJC73 (2013) 2421

Charged Energy Flow vs. PYTHIA

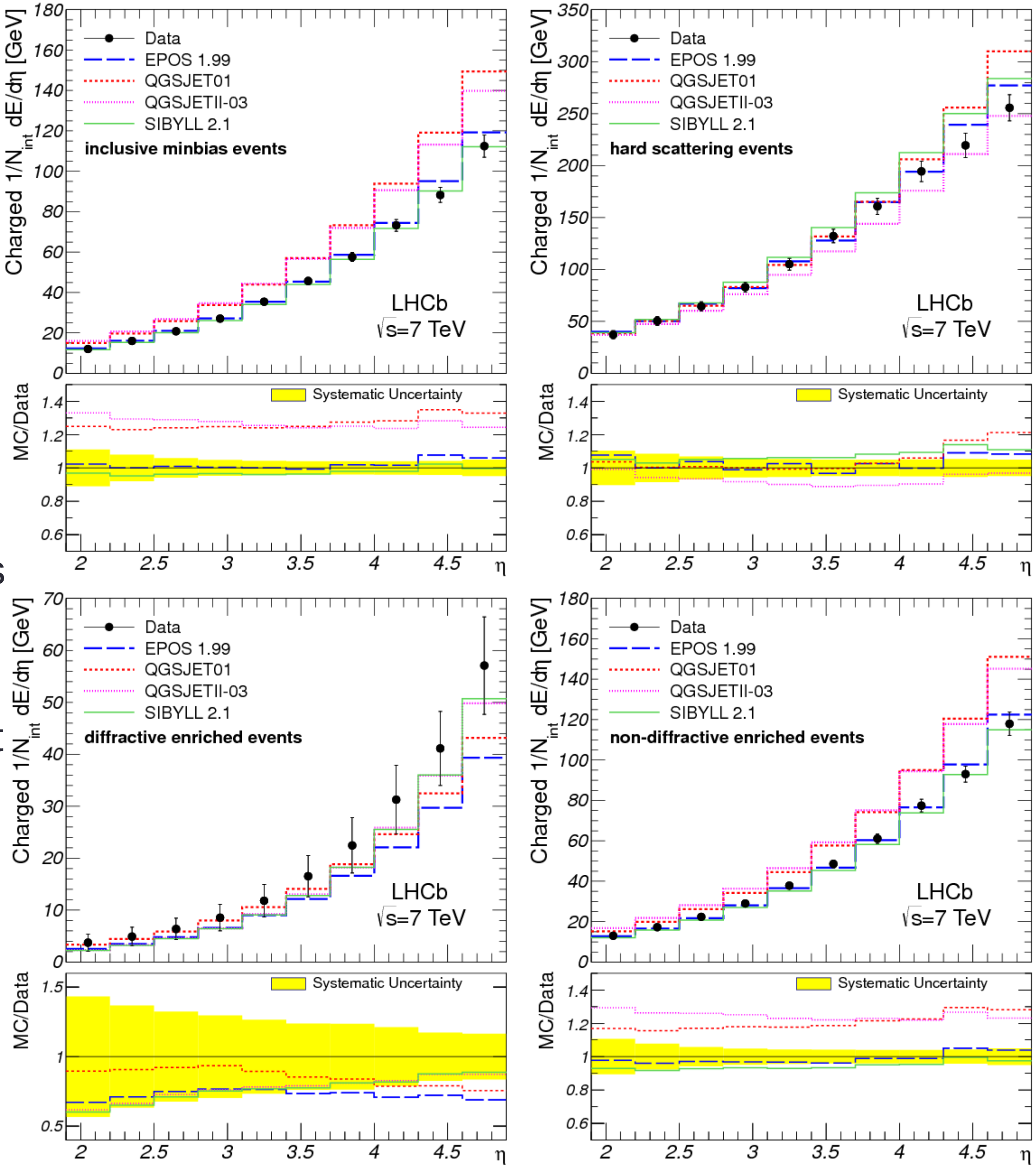
- Energy Flow increases with momentum transfer
  $EF_{diff} < EF_{incl} < EF_{ndiff} < EF_{hard}$
- PYTHIA6 underestimates charged EF for all event classes at high η
- PYTHIA8 – best agreement for diffractive enriched events, yet it overestimates EF in hard scattering ones
- Same conclusions apply for the total EF (backups)

EPJC73 (2013) 2421



Charged Energy Flow vs. cosmic ray models

- Cosmic-ray interaction models tend to overestimate the EF
- SYBILL and EPOS give the best description for MB inclusive events
- SYBILL gives good agreement in all 4 LHCb event classes except at high η for hard scattering events
- Total energy flow given in backups



EPJC73 (2013) 2421

Central exclusive production

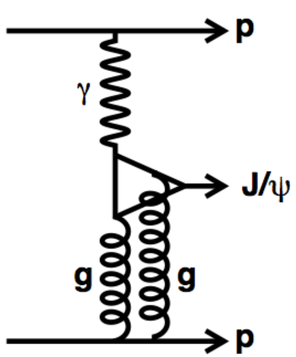
- **CEP: protons remain intact**

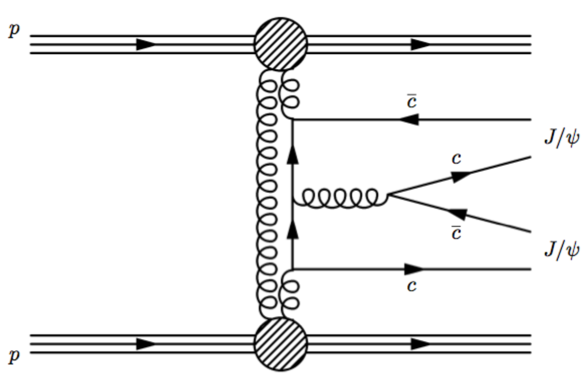
$$h_1(p_1) + h_2(p_2) \rightarrow h_1(p_1') + X + h_2(p_2')$$

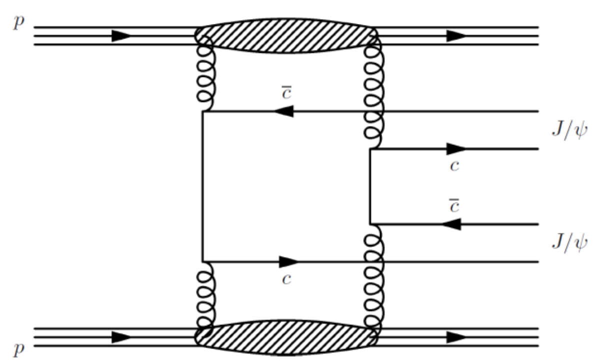
Observed

- **Physics motivation**: tests of QCD
  - Pomeron – γ interactions
  - Double pomeron exchange (pomeron-pomeron fusion)
- **CEP at LHCb**
  - Elastic scattering with intact and un-tagged protons

Fractional momentum of the parton $x \sim 5*10^{-6}$



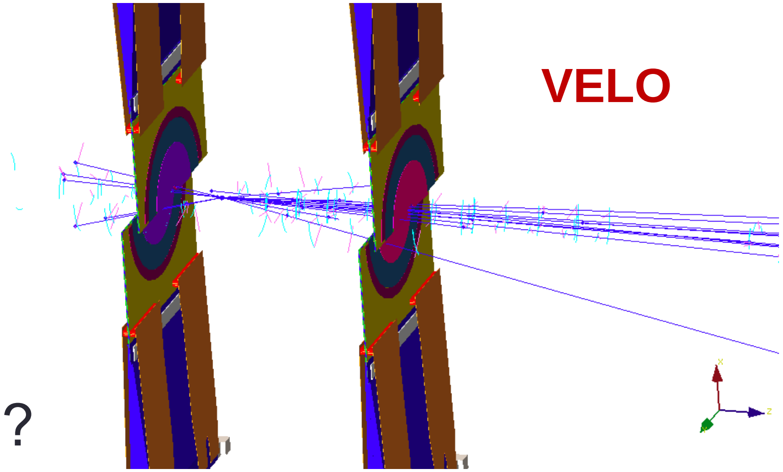


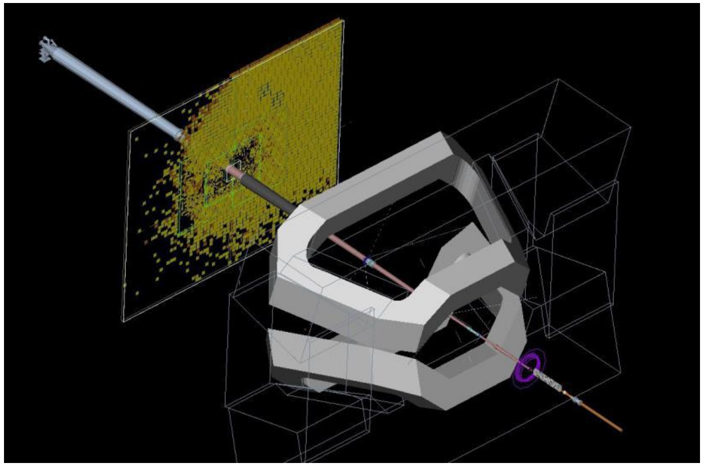


CEP study at LHCb

- Two key subsystems for CEP study at LHCb
- **Vertex locator**
  - Precise track and vertex reconstruction
  - LHCb is “forward spectrometer”?

    VELO also has coverage for backward track reconstruction
- **Scintillator Pad Detector (SPD)**
  - Provides input to hardware trigger
  - Used primarily as multiplicity detector

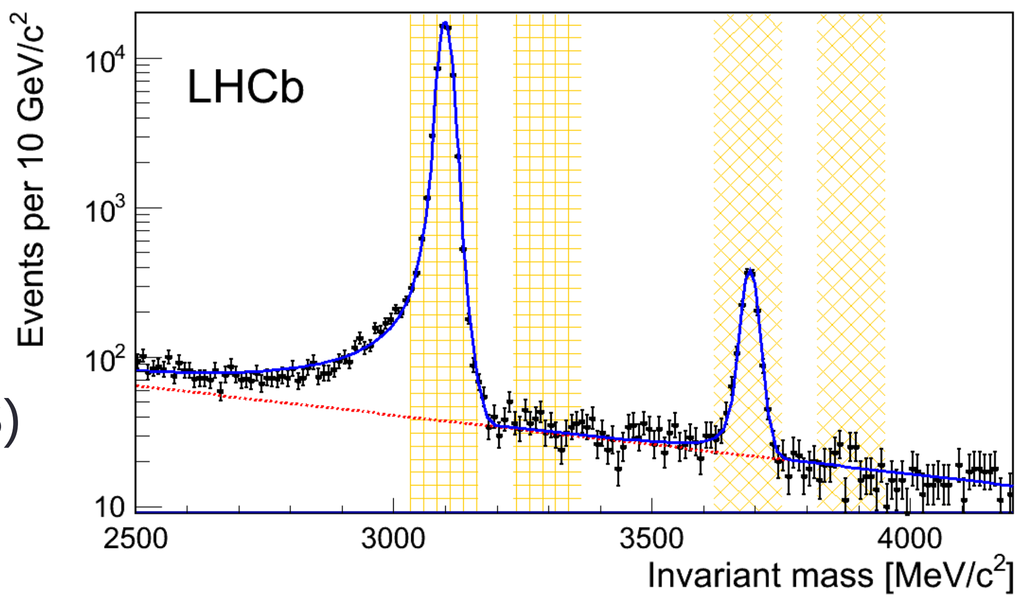




CEP of J/ψ and $\psi(2S)$

J. P. G 41 (2014) 055002

- **Data sample**
  - 930 pb^{-1} collected at 7 TeV
  - Events with less than 10 SPD hits triggered
- **Selection**
  - Exact one primary interaction (24% of total sample)
  - No backward tracks
  - No photons
- **Mass fit**
  - Signal – Crystal Ball
  - Background - Exponential
  - 55895 J/ψ and 1565 $\psi(2S)$

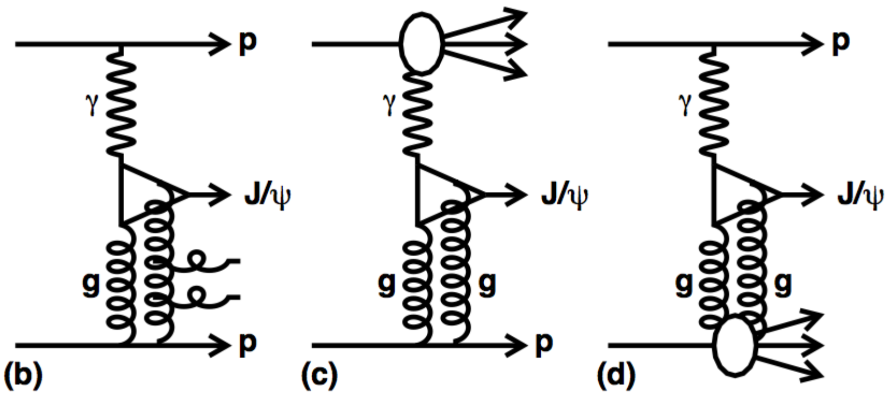


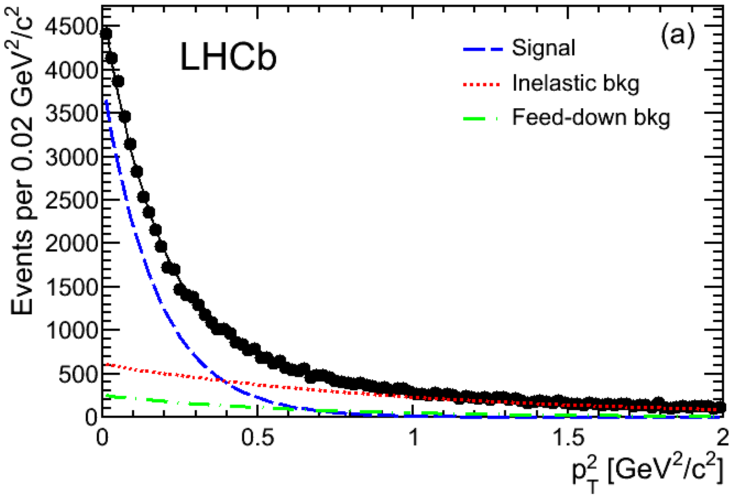
CEP of *J/ψ* and *ψ*(2S)

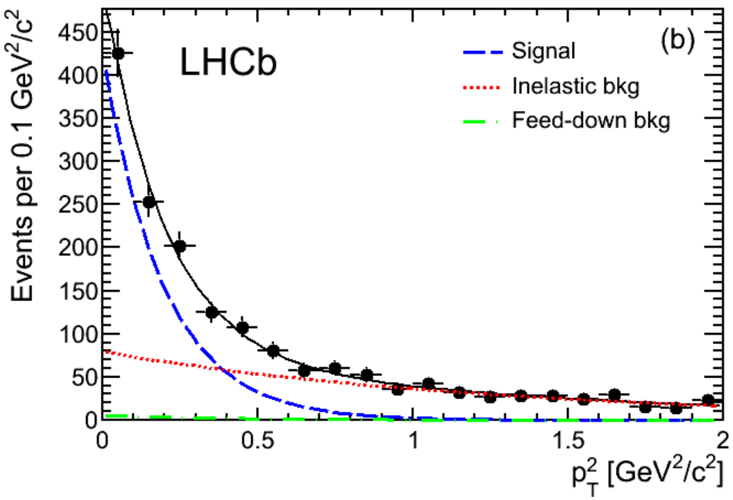
J. P. G 41 (2014) 055002

- Background
  - Feed-down
    - Estimated using other exclusive productions and simulation
  - Inelastic (dominant)
    - Estimated using collision data
    - Fit to p_T^2

Regge theory







CEP of *J/ψ* and *ψ*(2S)

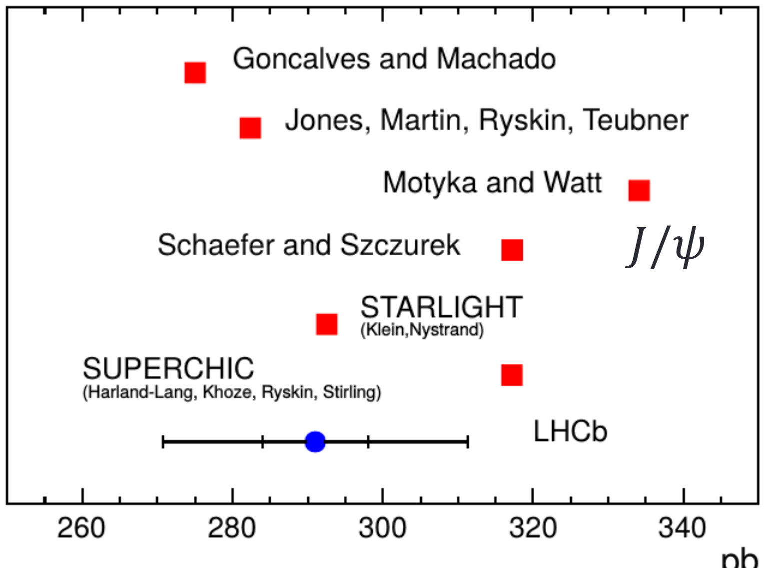
J. P. G 41 (2014) 055002

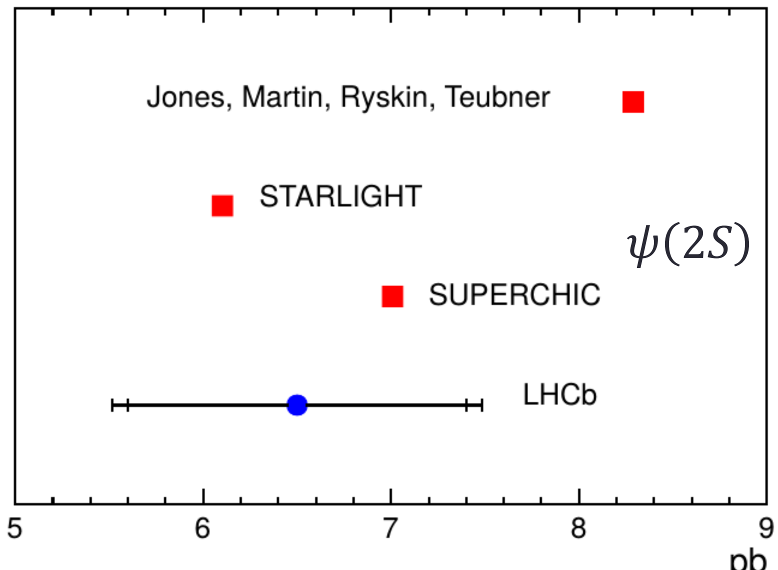
- Integrated cross-sections

$$\sigma_{pp\to J/\psi\to\mu^+\mu^-}(2.0<\eta_{\mu^\pm}<4.5)=291\pm7(\text{stat.})\pm19(\text{sys.})\ \text{pb}$$

$$\sigma_{pp\to\psi(2S)\to\mu^+\mu^-}(2.0<\eta_{\mu^\pm}<4.5)=6.5\pm0.9(\text{stat.})\pm0.4(\text{sys.})\ \text{pb}$$

- Comparison with theoretical predictions: good agreement





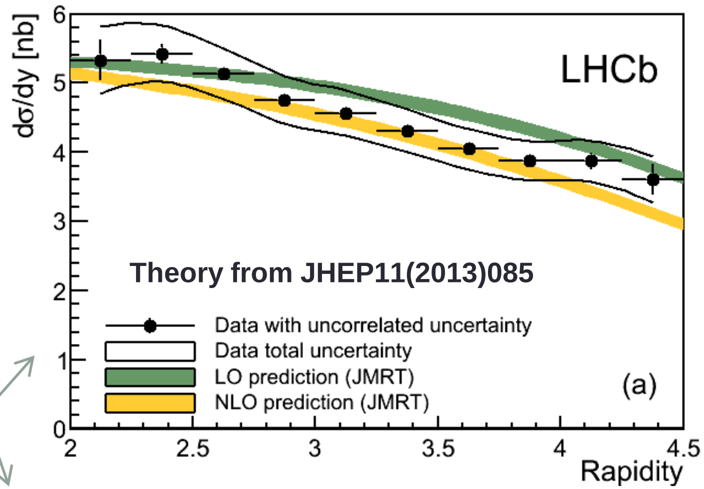
Phys. Rev. C84 (2011) 011902 , JHEP **1311** (2013) 085
Phys. Rev. D78 (2008) 014023, Phys. Rev. **D76** (2007) 094014
Phys. Rev. Lett. 92 (2004) 142003, Eur. Phys. J. **C65** (2010) 433

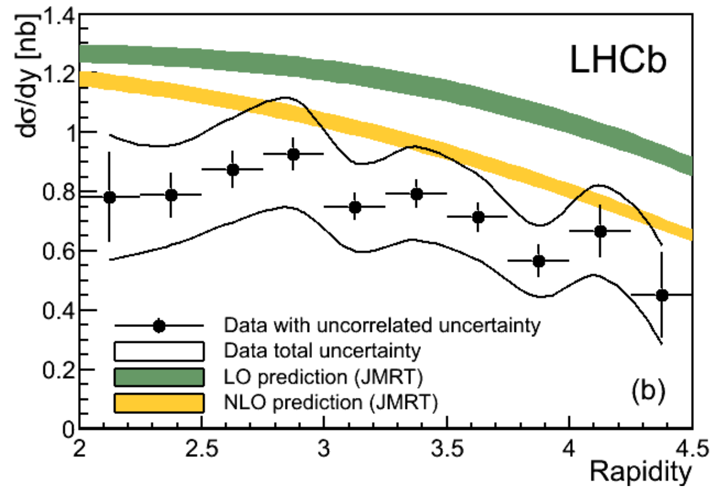
CEP of J/ψ and $\psi(2S)$

J. P. G 41 (2014) 055002

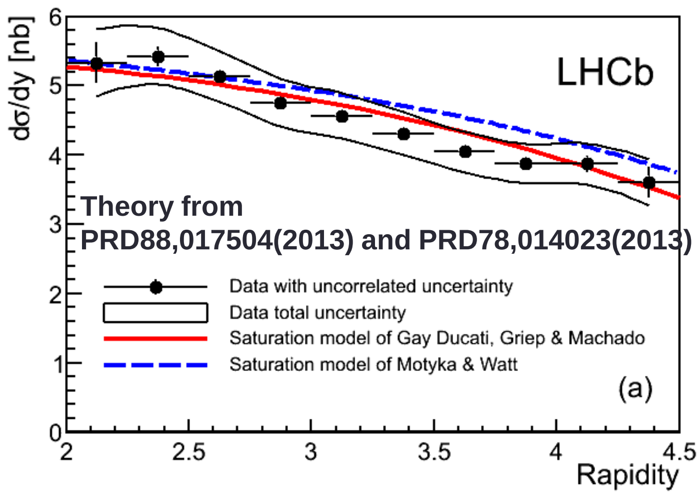
- Differential cross-sections

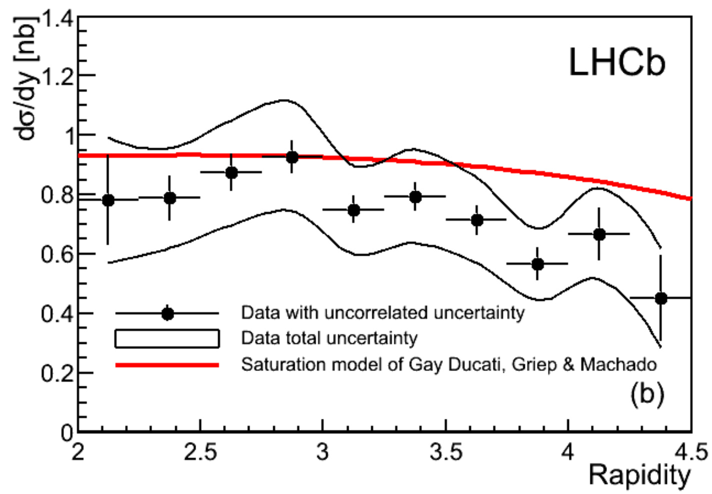
J/ψ





$\psi(2S)$





CEP of *J/ψ* and *ψ*(2S)

J. P. G 41 (2014) 055002

- Exclusive production in *pp* collisions is related to photoproduction

photon fluxes

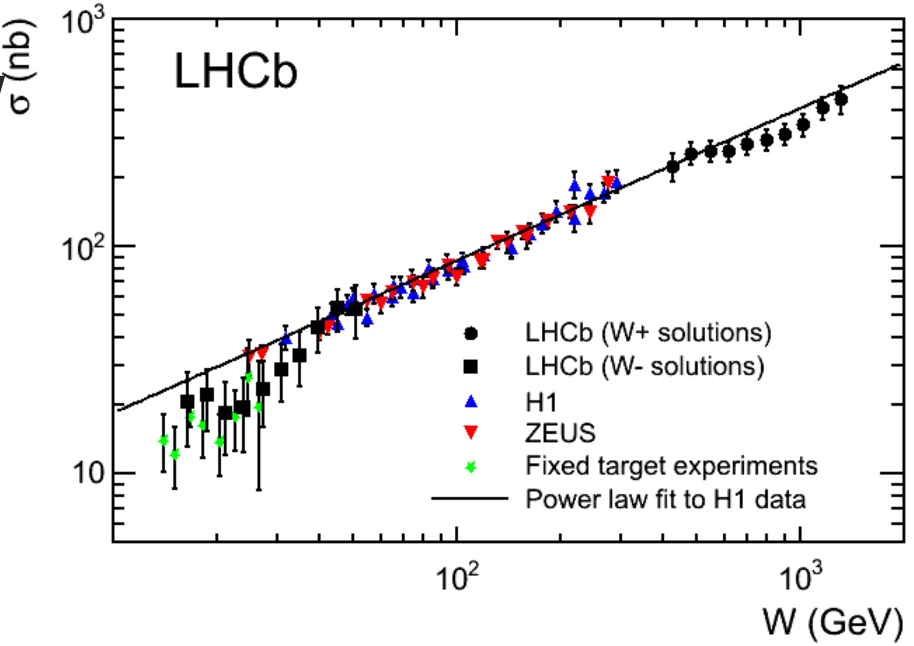
absorptive corrections

$$\left.\frac{d\sigma}{dy}\right|_{pp\to pJ/\psi\, p} = r_+ k_+ \frac{dn}{dk_+}\sigma_{\gamma p\to J/\psi\, p}(W_+) + r_- k_- \frac{dn}{dk_-}\sigma_{\gamma p\to J/\psi\, p}(W_-)$$

JHEP11(2013)085

- Derive $\sigma_{\gamma p\to j/\psi p}(W_\pm)$ from the results using a power-law relationship determined by the H1 collaboration

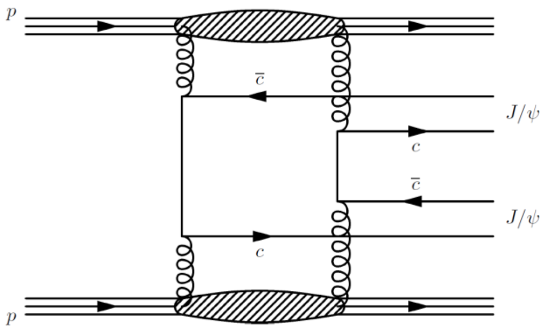
$$\sigma_{\gamma p\to J/\psi\, p}(W) = 81(W/90\ \mathrm{GeV})^{0.67}\mathrm{nb}$$



Good agreement

J. P. G 41 (2014) 115002

CEP of charmonium pairs



- Motivation
  - Production via exchange of two pomerons
  - Help to understand charmonium pair production
- Data sample
  - 3 fb^{-1} collected at both 7 and 8 TeV, average energy 7.6 TeV
- Selection
  - Exactly four forward tracks
  - At least three identified muons
  - J/ψ and $\psi(2S)$ within [-200, 65] MeV from nominal mass

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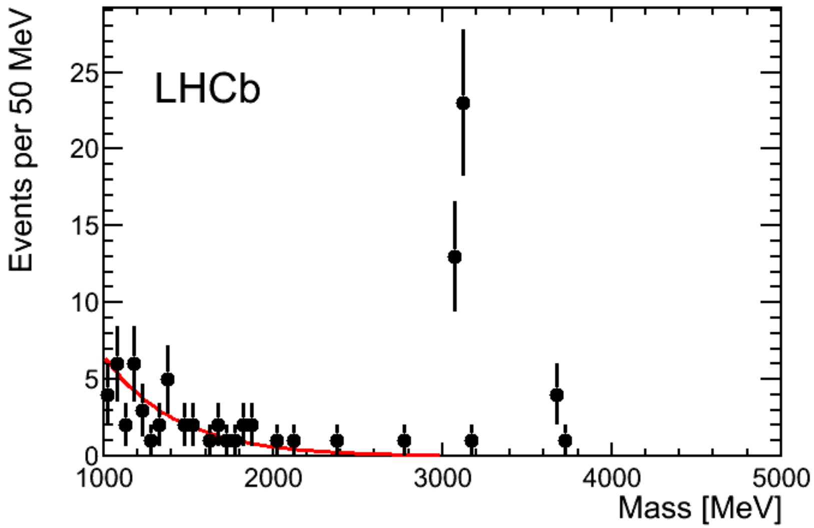
CEP of charmonium pairs

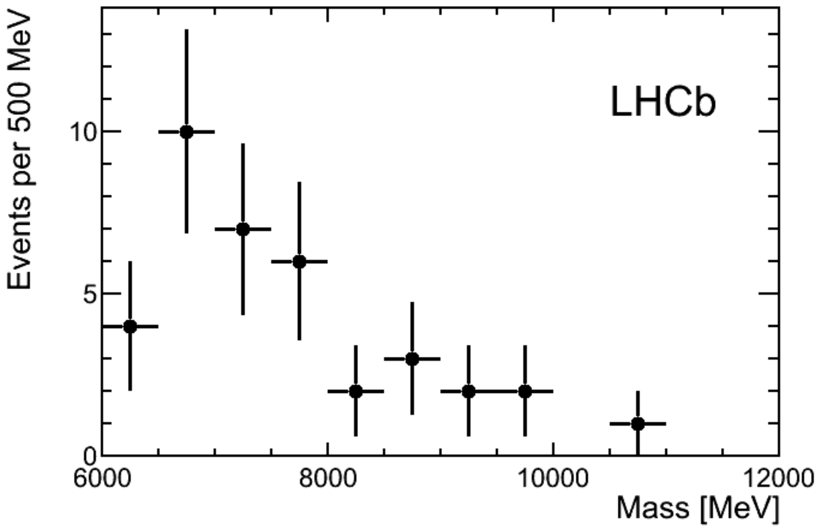
- Invariant mass

Di-muon



J/ψ J/ψ

Four muon



J/ψ ψ(2S) in backup

- Result
  - 37 *J/ψ J/ψ* and 5 *J/ψ ψ*(2S) candidates found

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CEP of charmonium pairs

- Results

$$\sigma^{J/\psi J/\psi} = 58 \pm 10(\text{stat}) \pm 6(\text{syst})\ \text{pb},$$
$$\sigma^{J/\psi\psi(2S)} = 63^{+27}_{-18}(\text{stat}) \pm 10(\text{syst})\ \text{pb},$$
$$\sigma^{\psi(2S)\psi(2S)} < 237\ \text{pb},$$
$$\sigma^{\chi_{c0}\chi_{c0}} < 69\ \text{nb},$$
$$\sigma^{\chi_{c1}\chi_{c1}} < 45\ \text{pb},$$
$$\sigma^{\chi_{c2}\chi_{c2}} < 141\ \text{pb}$$

First observed

Inelastic included

90% CL

- Comparison between inclusive and exclusive

$$\sigma^{J/\psi J/\psi}/\sigma^{J/\psi}|_{\text{inclusive}} = \left(5.1 \pm 1.0 \pm 0.6^{+1.2}_{-1.0}\right) \times 10^{-4}$$
$$\sigma^{J/\psi J/\psi}/\sigma^{J/\psi}|_{\text{exclusive}} = (2.1 \pm 0.8) \times 10^{-3}$$

- Comparison with theory

CEP: $24 \pm 9\text{pb}$
Theory: $8 - 36\text{pb}$

Eur. Phys. J. C 71 1714
and private communication

$$\frac{\sigma(J/\psi\psi(2S))}{\sigma(J/\psi J/\psi)} = 1.1^{+0.5}_{-0.4}$$

Theory: 0.5 Phys. Rev. D 84 094023

Production ratios of identified particles

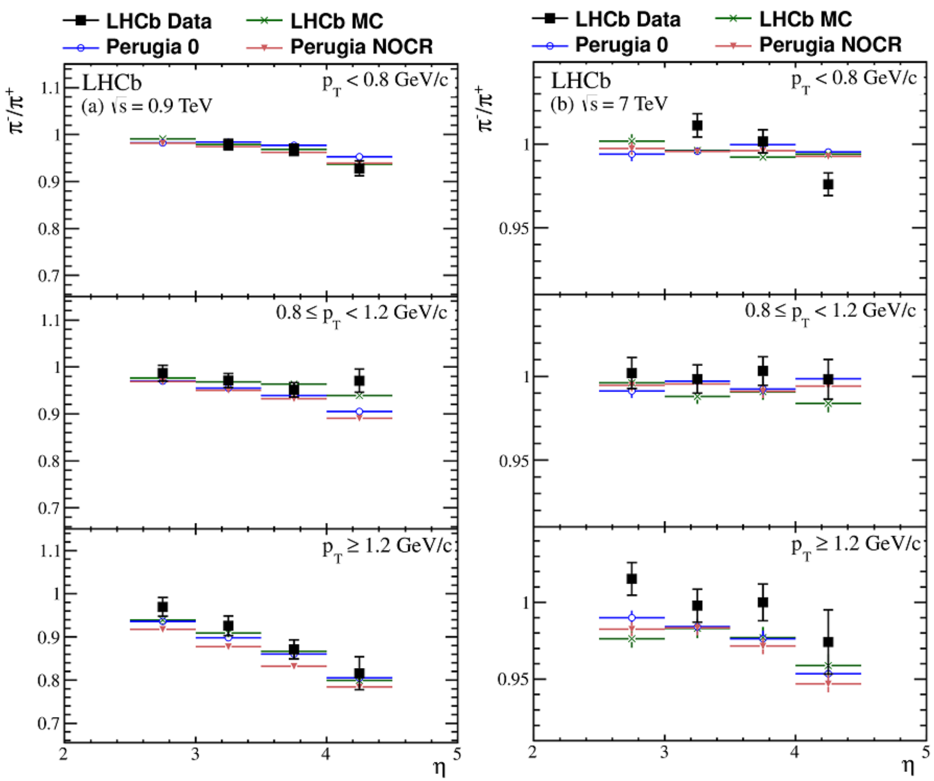
Eur. Phys. J. C 72 (2012) 2168

- Antiparticle/particle ratios

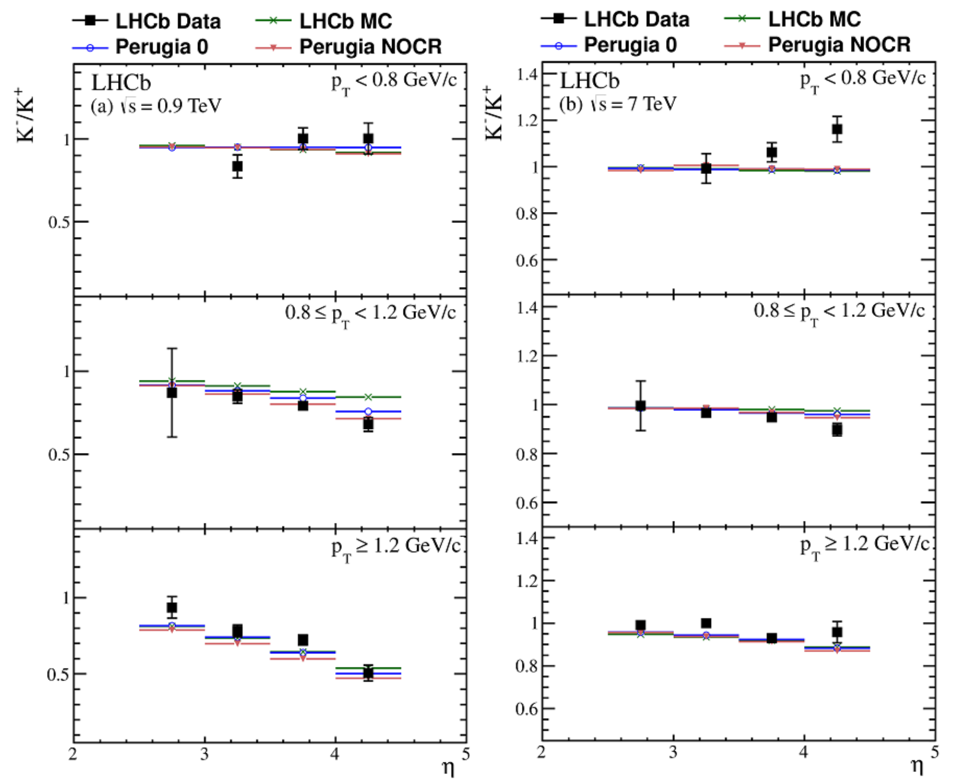
Measured at 0.9 and 7 TeV

  - Ratio drops at large rapidity, especially at higher p_T
  - Reasonable agreement with all considered MC tunes

π^-/π^+



K^-/K^+

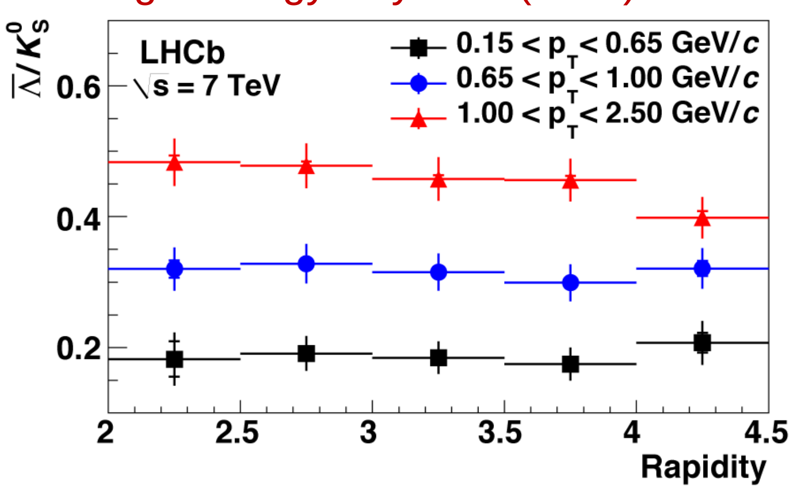


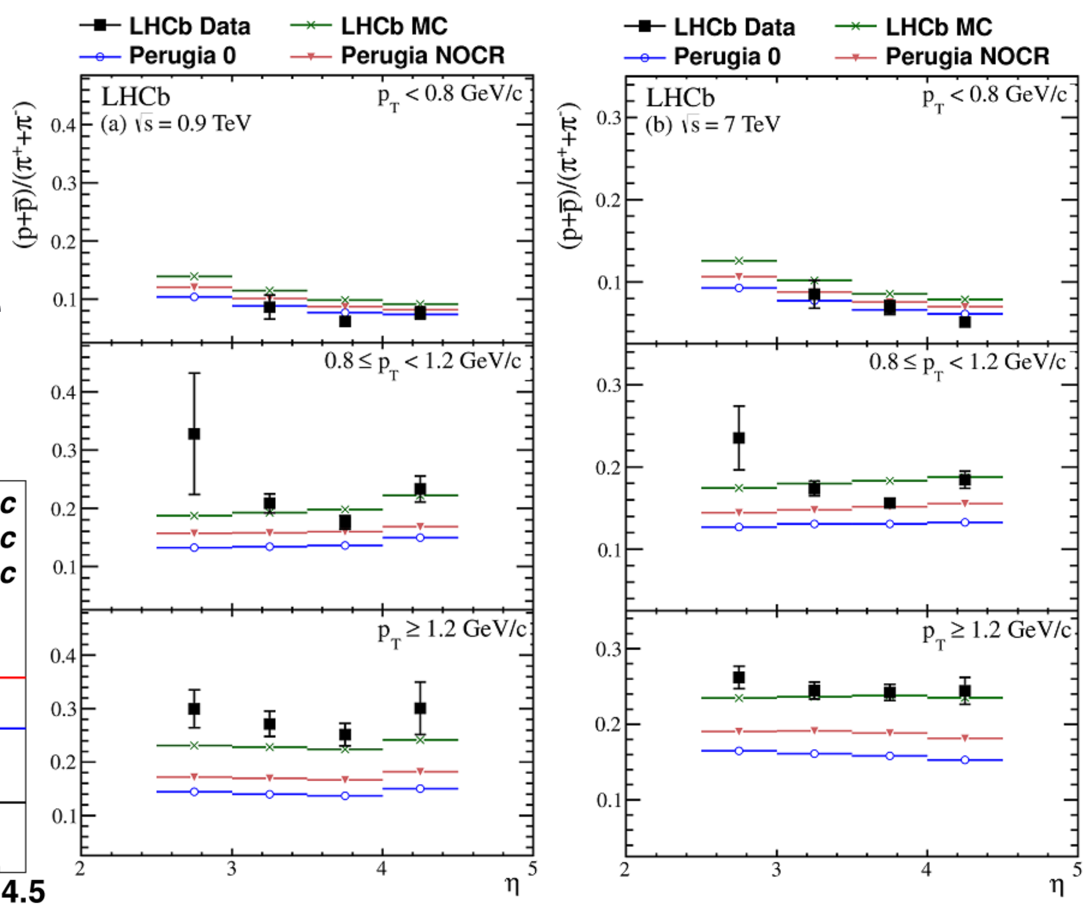
Production ratios of identified particles

Eur. Phys. J. C 72 (2012) 2168

- Baryon to Meson Ratio and Light Baryon Suppression
  - LHCb MC agrees better
  - PYTHIA6 Perugia tunes underestimate the ratio
  - Smaller baryon suppression in high p_T. Similar qualitative trend in $\bar{\Lambda}/K_s^0$ measurement

J. High Energy Phys. 08 (2011) 034





Production ratios of identified particles

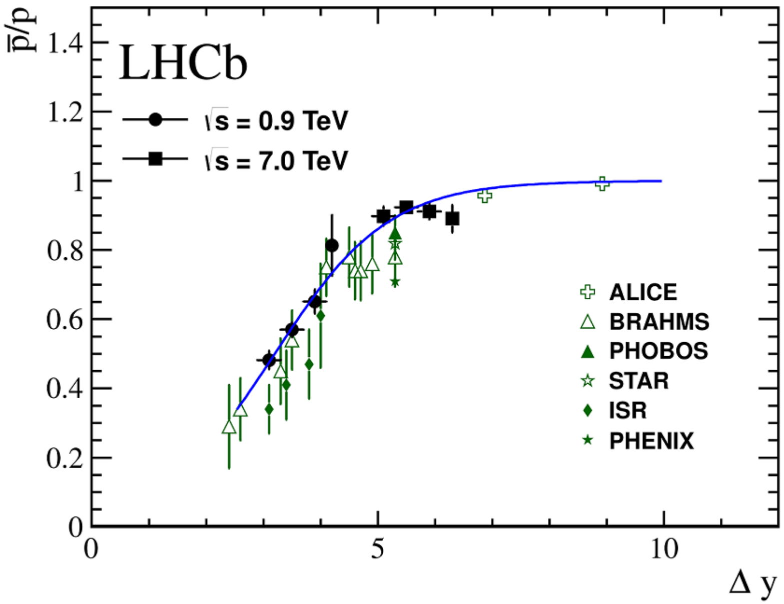
Eur. Phys. J. C 72 (2012) 2168

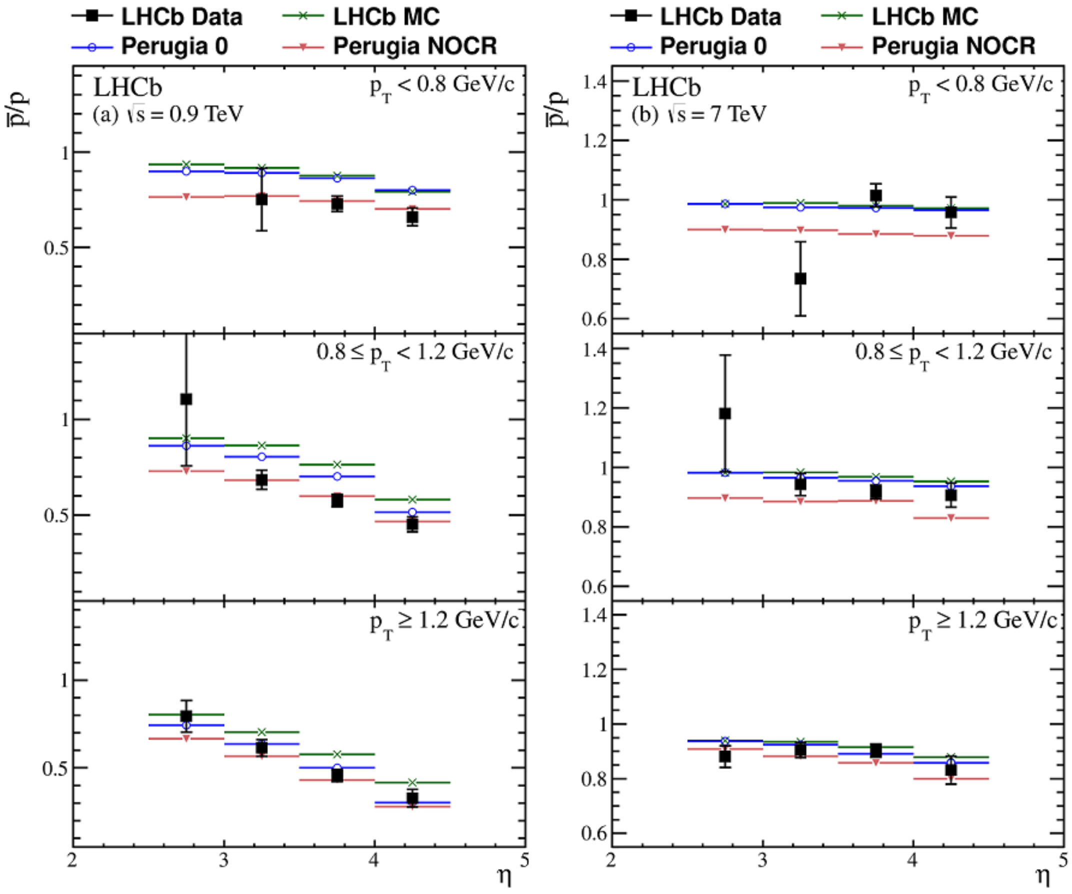
- Baryon number transport

Agree with Perugia NOCR better

Measured at 0.9 and 7 TeV
Rapidity loss $\Delta y = y_{beam} - y_{particle}$
First measured in this Δy range
Complementary to ALICE data

Eur. Phys. J. C 72 (2012) 2168





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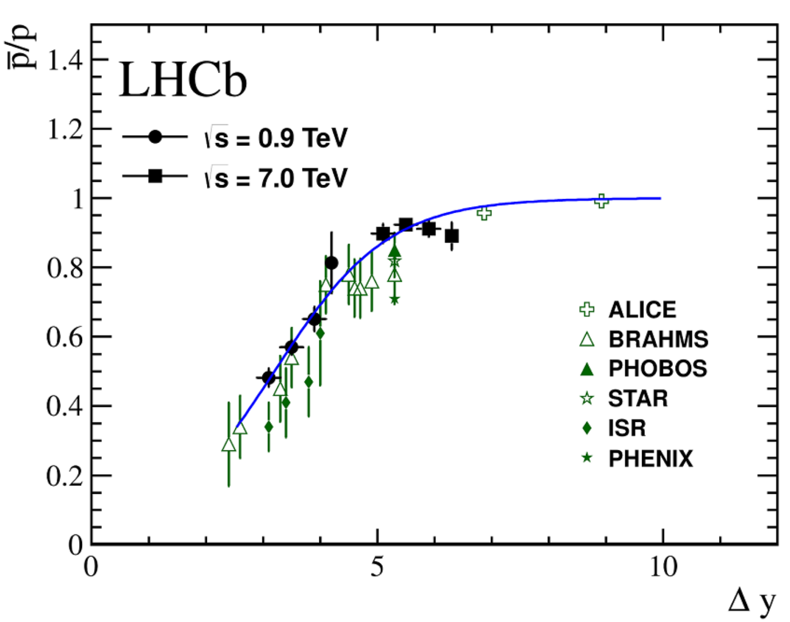
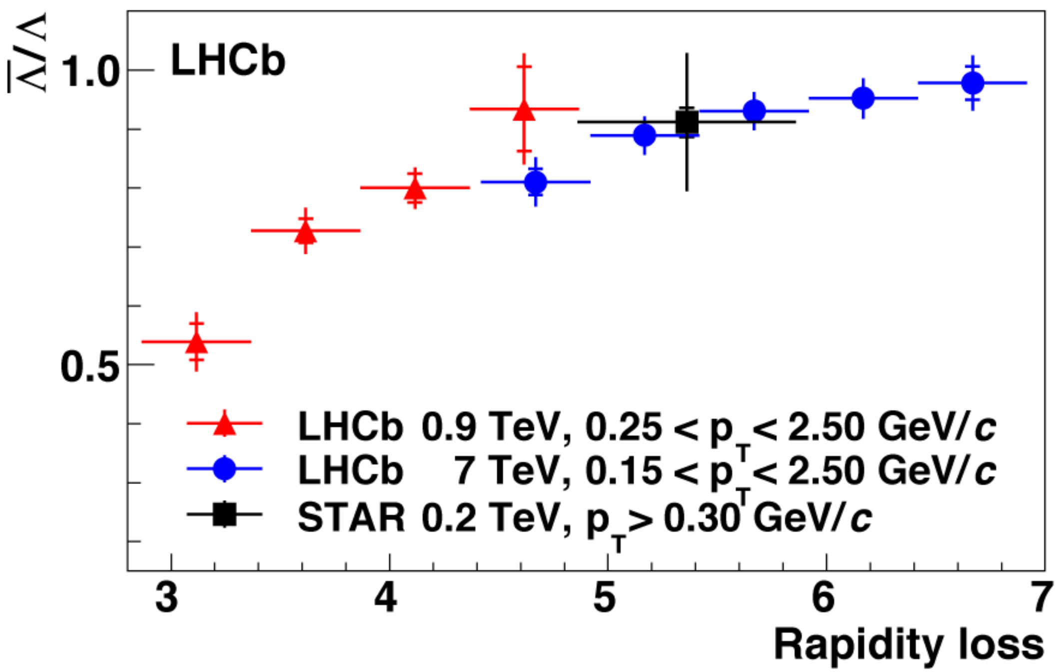


Similar dependence seen in strange baryon production
Behavior as a function of Δy is independent of $\sqrt{s}$

J. High Energy Phys. 08 (2011) 034



Summary

- **Forward energy flow** has been measured. PYTHIA8 provides better description. Cosmic ray shower models describe minimum bias data well.
- **Exclusive J/ψ and $\psi(2S)$** cross-sections have been measured at LHCb. Results are **consistent** with theory and photo-production results from HERA.
- **First observation** of CEP with pairs of S-wave charmonium at LHCb. Upper limits calculated for pairs of P-wave charmonium
- Production ratio for identified particles have been measured. Baryon number transport and baryon suppression are **not well described** by PYTHIA tunes.

Total EF estimate

For each $\Delta\eta$, main assumption:

$$\Delta EF_{Neutral,PV} \propto \Delta EF_{Charged,PV}$$

at collision's primary vertex (PV), hence after unfolding with detection efficiency and acceptance.

$$\Delta EF_{Neutral,PV} = \Delta EF_{Charged,PV} \times \frac{\Delta EF_{Neutral,gen}}{\Delta EF_{Charged,gen}}$$

where $\Delta EF_{Neutral,gen}$, and $\Delta EF_{Charged,gen}$ are the generator results for these quantities in corresponding $\Delta\eta$.

Extra correction:

$$\Delta EF_{Neutral,PV} = \Delta EF_{Charged,PV} \times \frac{\Delta EF_{Neutral,gen}}{\Delta EF_{Charged,gen}} \times \frac{1 + R_{data,RECO}}{1 + R_{MC,RECO}}$$

where

$$R_{data,RECO} = \frac{\Delta EF_{calorimeter,data}}{\Delta EF_{Charged\ raw,data}}$$

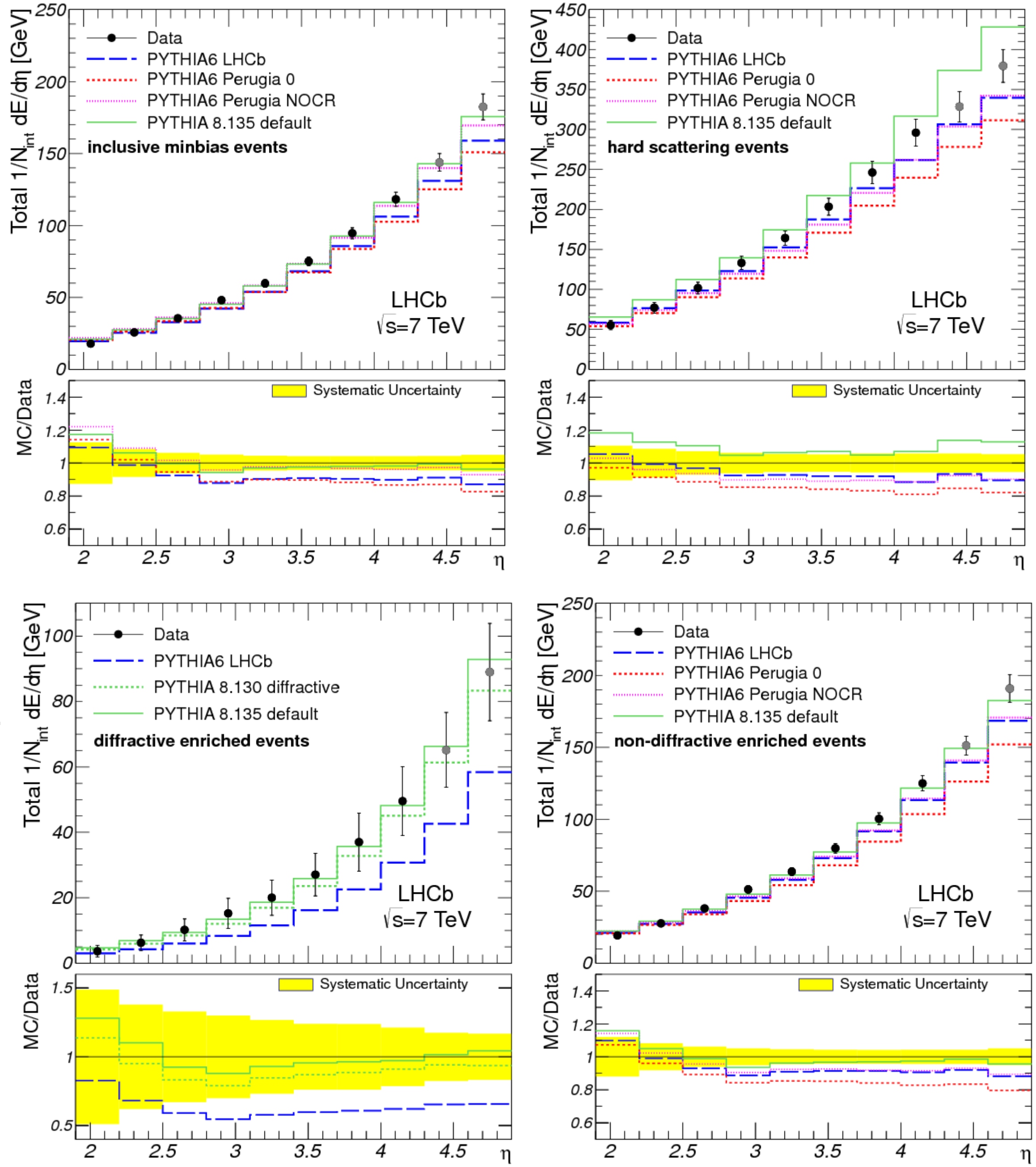
and

$$R_{MC,RECO} = \frac{\Delta EF_{calorimeter,simulated}}{\Delta EF_{Charged\ raw,simulated}}$$

- $EF_{calorimeter,data}$ - measured energy flow through calorimeter in data;
- $EF_{calorimeter,simulated}$ - reconstructed energy flow through calorimeter in simulation;
- $EF_{Charged\ raw,data}$ - raw estimate of charge energy flow in data, before unfolding to PV.
- $EF_{Charged\ raw,simulated}$ - reconstructed energy flow for charged particles in simulation.

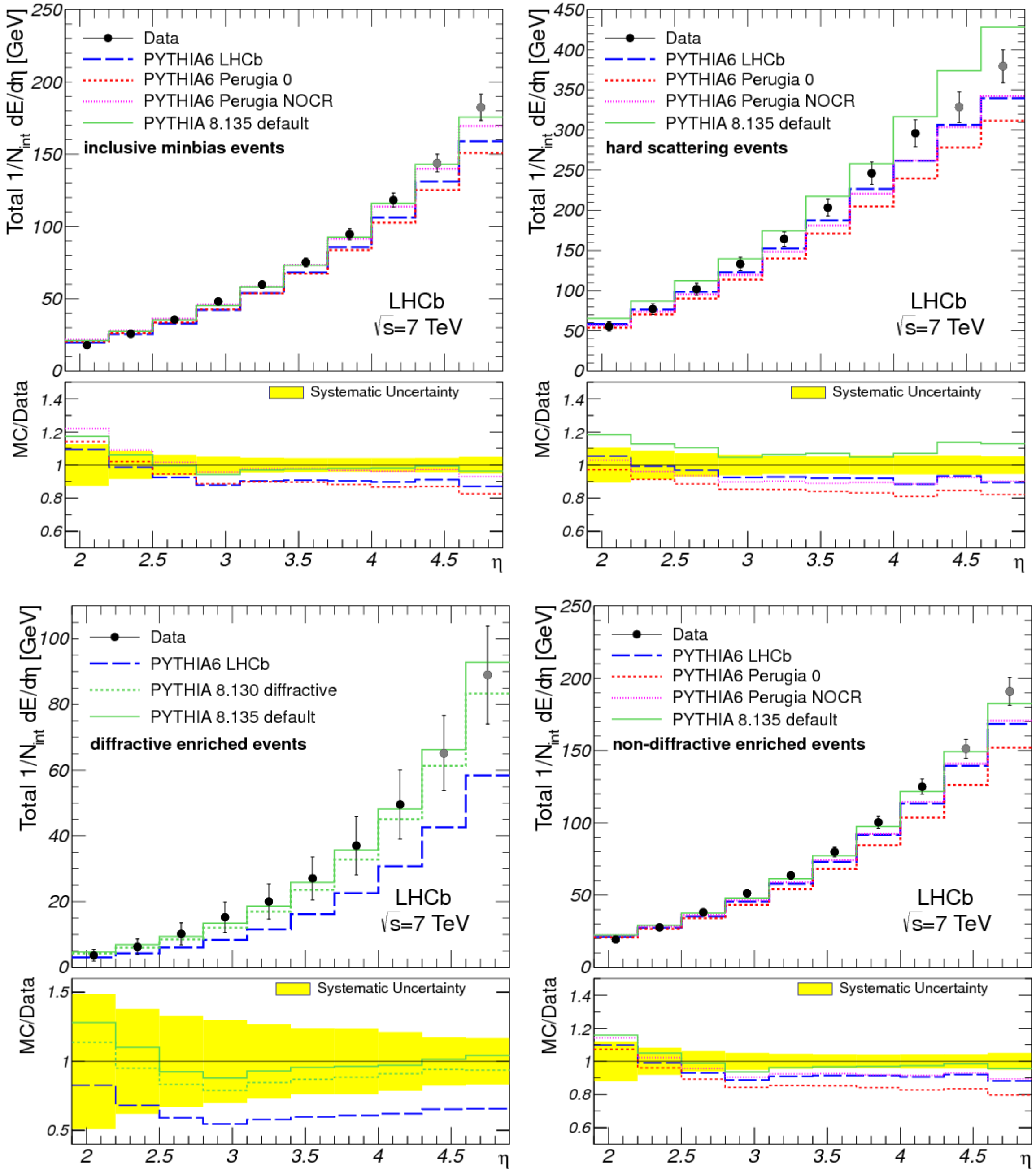
Total EF vs.. PYTHIA

- Total energy flow for all 4 event classes; LHCb data vs. PYTHIA tunes results;
- PYTHIA8 agrees with diffractive events, but not with the hard p_T events, where it overestimates the energy flow;
- PYTHIA6 underestimates the energy flow at high-η for all cases.
- No PYTHIA tune describes all 4 components;
- PYTHIA8 give best agreement in general.



Total EF vs.. cosmic ray model

- Total energy flow for all 4 event classes; LHCb data vs. cosmic ray model;
- QGSJET models overestimates the soft p_T component in MB inclusive and non-diffractive;
- SYBILL reproduces the best all 4 cases, this time there is a more pronounced disagreement in last 2 high-η bins for the hard component.



CEP of charmonium: *J/ψ ψ*(2S) mass