

Minimum Bias and MC Tuning at LHCb

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on behalf of the LHCb collaboration

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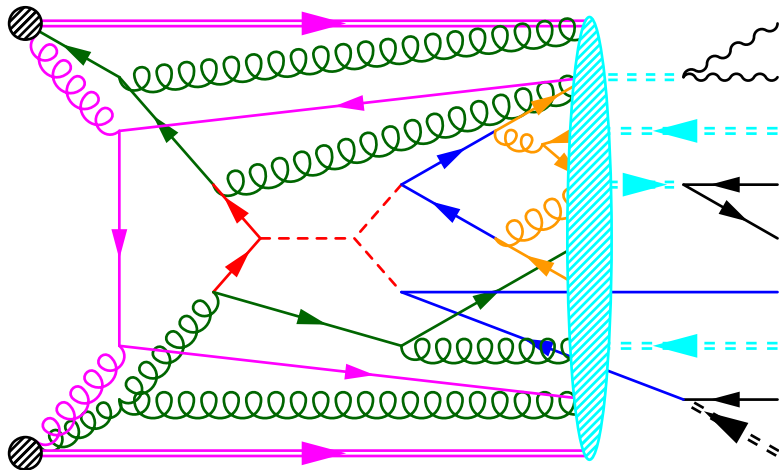


11th INTERNATIONAL WORKSHOP ON MULTIPLE
PARTONIC INTERACTIONS AT THE LHC



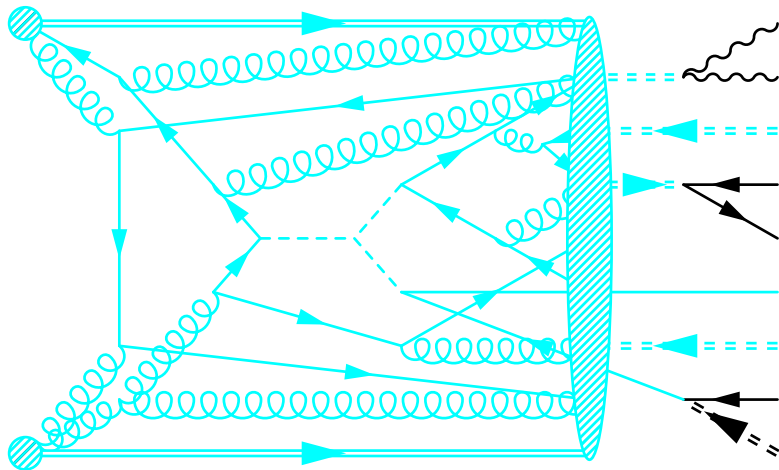
Event Anatomy

- 1) hard process 3) ISR 5) underlying event 7) particle decays
 2) resonance decays 4) FSR 6) hadronization



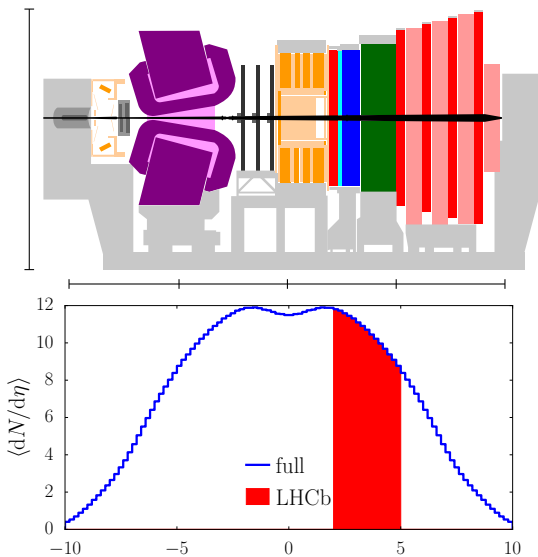
LHCb Event Anatomy

1) production 2) particle decays



LHCb Acceptance

[JINST 3 (2008) S08005]



- **hard process**
 - PDFs, phase space cut-offs (\hat{p}_T , \hat{m}), renormalization scale, factorization scale, SM parameters (CKM, $\alpha_s(M_Z)$, $\sin \theta_W$)
- **parton showers**
 - $\alpha_s(M_Z)$, scales, p_T damping, matching parameters, ordering method
- **underlying event**
 - $\alpha_s(M_Z)$, hard processes, p_T damping, beam profile (shape, impact parameter), color reconnection
- **hadronization**
 - longitudinal momentum sharing, transverse width, flavor composition, vector to pseudo-scalar composition, baryon and meson production ratios



Observables

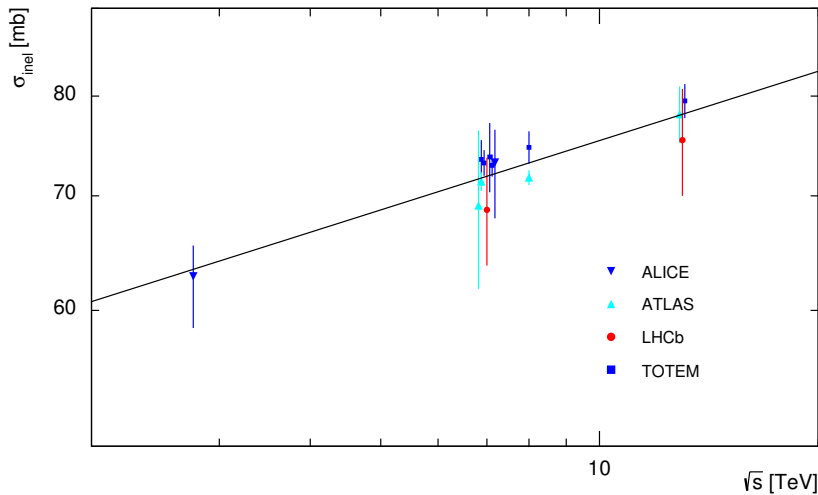
- test non-perturbative regimes of QCD
- tune multi purpose event generators
- look for new effects to refine models
- **hard process**
 - onia **inclusive cross-sections**
 - onia p_T **distributions**
- **ISR**
 - light jet thrust ($\alpha_s(M_Z)$)
 - p_T from $Z \rightarrow \mu\mu$ (primordial k_T)
- **FSR**
 - similar to ISR
- **underlying event**
 - onia measurements
 - IR safe **energy flow**
- **hadronization**
 - final state flavor composition
 - IR sensitive **charge density and multiplicity**
- particle decays
 - branching fractions
 - mass distributions, angular distributions, etc.



LHCb Public RIVET Analyses

analysis	plugin	reference
inelastic cross-section	LHCB_2015_I1333223	JHEP 1502 (2015) 129
charge particle multiplicities and densities	LHCB_2014_I1281685	Eur. Phys. J. C 74 (2014) 2888
energy flow	LHCB_2013_I1208105	Eur. Phys. J. C 73 (2013) 2421
prompt charm cross-sections	LHCB_2013_I1218996	Nucl. Phys. B 871 (2013) 1-20
charged particle ratios	LHCB_2012_I1119400	Eur. Phys. J. C 72 (2012) 2168
V^0 ratios	LHCB_2011_I917009	Eur. Phys. J. C 72 (2012) 2168
inclusive ϕ cross-sections	LHCB_2011_I919315	Phys. Lett. B 703 (2011) 267-273
prompt K_S^0 cross-sections	LHCB_2010_S8758301	Phys. Lett. B 693 (2010) 69-80
inclusive $b\bar{b}$ cross-sections	LHCB_2010_I867355	Phys. Lett. B 694 (2010) 209-216





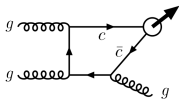
Onia Production



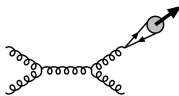
- onia production typically modeled with NRQCD

$$d\sigma(pp \rightarrow H + X) = \sum_{s,L,J} d\hat{\sigma}(pp \rightarrow Q\bar{Q}[{}^{2s+1}L_J] + X) \langle \mathcal{O}^H[{}^{2s+1}L_J] \rangle$$

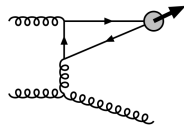
- physical state is expanded as Fock states



$$gg \rightarrow c\bar{c}[{}^3S_1^{(1)}]g$$



$$gg \rightarrow c\bar{c}[{}^3S_1^{(8)}]g$$



$$gg \rightarrow c\bar{c}[{}^1S_0^{(8)}, {}^3P_J^{(8)}]g$$

p_T Damping

- perturbative short-distance matrix elements, $\hat{\sigma}$, diverge at low p_T
 - smoothly re-weight

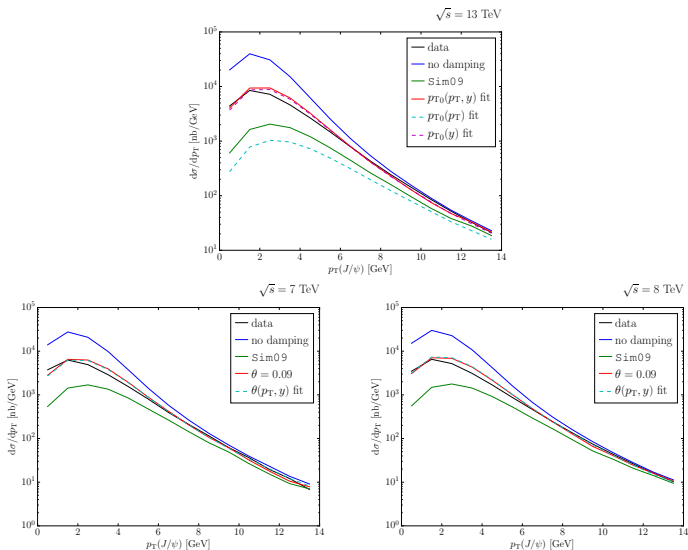
$$\left(\frac{p_T^4}{p_{T0}^2 + p_T^2} \right) \left(\frac{\alpha_s(p_{T0}^2 + p_T^2)^2}{\alpha_s(p_T^2)} \right)$$

- allow p_{T0} to be energy dependent

$$p_{T0}(\sqrt{s}) = p_{T0}(E_0) \left(\frac{\sqrt{s}}{E_0} \right)^\theta$$

- fit LHCb data at various \sqrt{s} to obtain both p_{T0} and θ





Energy Flow



Multi Parton Interaction Models

hard \rightarrow soft model (HEP)soft \rightarrow hard model (air-shower)

- begin with t -channel $2 \rightarrow 2$ QCD

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

- divergent in p_T , cut-off or damp

$$\frac{\alpha_s^2(p_{T0}^2 + p_T^2)}{\alpha_s^2(p_T^2)} \frac{p_T^4}{(p_{T0}^2 + p_T^2)^2}$$

- models color screening and saturation effects
- number of interactions also depends on impact parameter

$$f(x, b) = f(x)g(b)$$

- begin with Regge effective field theory

$$d\sigma \propto \frac{dM^2}{M^2}$$

- M is mass of the diffractive system
- exchange of color-singlet pomeron between hadrons
 - leading structure is $f\bar{f}$ or gg
 - at high energy primarily gg
- include hard structure by resolving pomeron constituents
- requires some smooth transition between the two regimes



- measure charged energy flow
 - veto events with more than 1 primary vertex
 - use tracks with VELO and IT or OT hits
 - $2 < p < 1000$ GeV

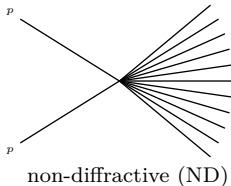
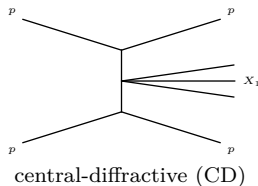
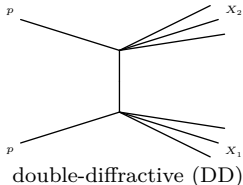
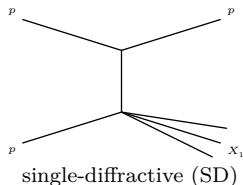
$$\frac{1}{N} \frac{dE}{d\eta} = \frac{1}{\Delta\eta} \left(\frac{1}{N} \sum_{i=1}^{n(\Delta\eta)} E_i \right)$$

- $N \equiv$ number of inelastic pp interactions
 - $n \equiv$ number of tracks within bin of $\Delta\eta$
- 1 unfold detector effects with bin-to-bin corrections
 - estimate systematic uncertainty from model bias using various PYTHIA configurations
 - 2 calculate total energy flow using neutral to charged ratio, R

$$F_{\text{total}} = F_{\text{charged}}(1 + R_{\text{gen}}) \left(\frac{1 + R_{\text{data}}}{1 + R_{\text{MC}}} \right)$$



$$\sigma_{\text{inelastic}} = \sigma_{\text{SD}} + \sigma_{\text{DD}} + \sigma_{\text{CD}} + \sigma_{\text{ND}}$$

**hard**

- $p_T > 3 \text{ GeV}$
- $1.9 < \eta < 4.9$

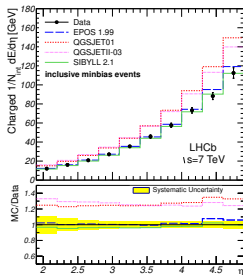
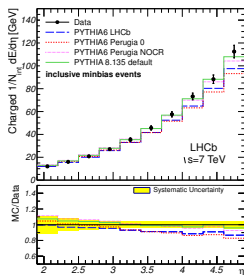
diffractive

- no track with $-3.5 < \eta < -1.5$
- $\approx 70\%$ purity with PYTHIA 6

non-diffractive

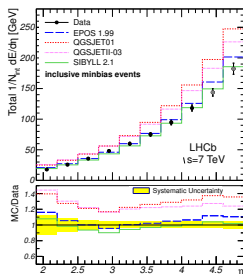
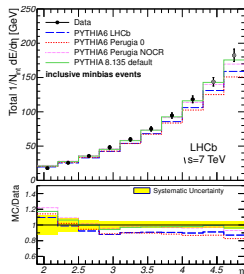
- track with $-3.5 < \eta < -1.5$
- $\approx 90\%$ purity with PYTHIA 6





charged

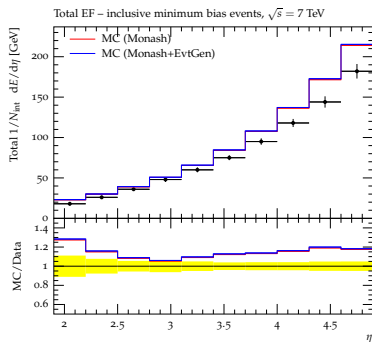
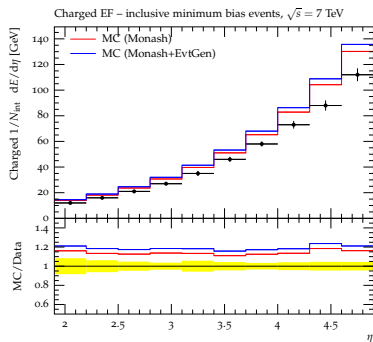
- PYTHIA 8 and 6 with no CR model data well
- PYTHIA 6 under-estimates for large η
- EPOS and SIBYLL model data well
- QGSJET uniformly over-estimates



total

- similar behavior to charged energy flow





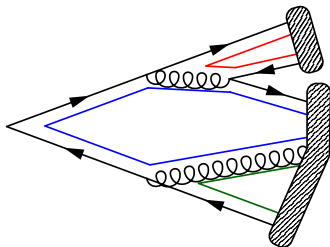
- slight overestimate of energy flow, not dependent on decays

Charge Multiplicity



Hadronization Models

string model (PYTHIA)

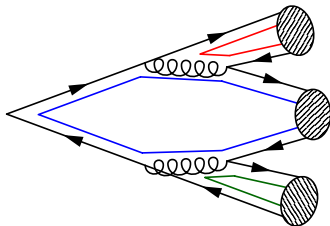


- linear confinement

$$V \approx \kappa r - \frac{4\alpha_s}{3r}$$

- **split strings into hadrons**
- kinematics well modeled
- poor final state flavor description

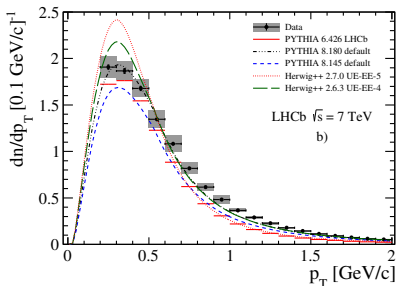
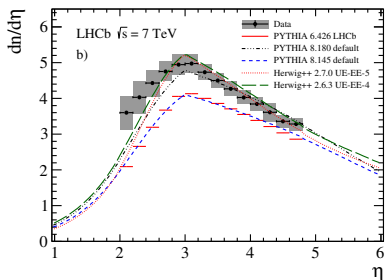
cluster model (HERWIG)



- pre-confinement
 - clusters independent of hard process scale
 - dependent on QCD and shower scale
- **decay clusters into hadrons**
- kinematics not as well modeled
- better final state flavor description

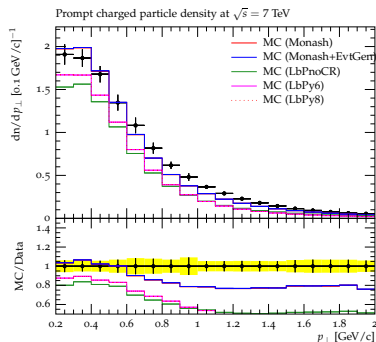
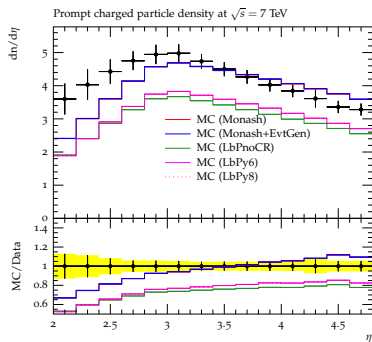
- visible event
 - at least one charged particle
 - $2.0 < \eta < 4.8$
 - $p_T > 0.2 \text{ GeV}$
 - $p > 2 \text{ GeV}$
 - $\tau < 10 \text{ ps}$
 - reconstructed event
 - at least one track
 - must traverse all tracking stations
 - pass within 2 mm of beamline
 - originate from luminous region
- ① correct for sample impurity
 - $\approx 6.5\%$ fakes, $\approx 1\%$ duplicates, $\approx 4.5\%$ non-prompt
 - ② account for visible events with no reconstructed tracks
 - ③ unfold distribution for pile-up effects
 - ④ apply reconstruction efficiencies





- the p requirement causes the falling distribution at low η
- neither PYTHIA 6 nor PYTHIA 8.145 were tuned with LHC data
 - these significantly under-estimate the data
- PYTHIA 8.180 describes the data well
- HERWIG++ does as well, except for $0.2 < p_T < 0.5$

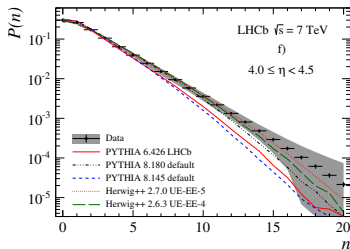
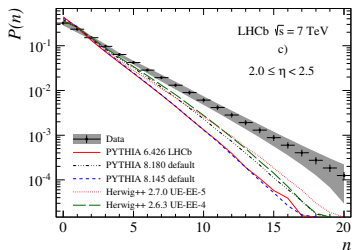




- Monash density in better agreement

Multiplicity Results

[Eur. Phys. J. C 74 (2014) 2888]

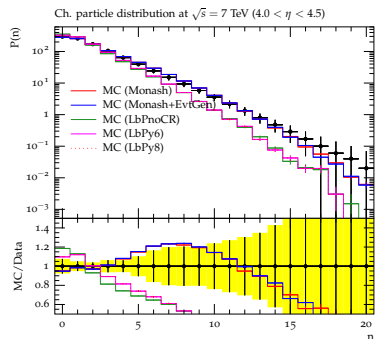
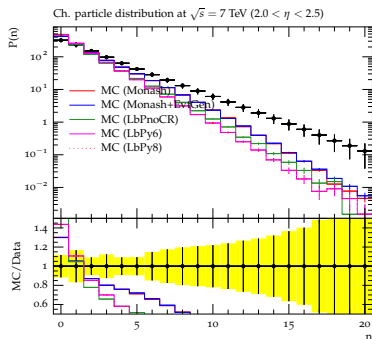


- distributions for $2.0 < \eta < 2.5$ and $4.0 < \eta < 4.5$
 - inclusive, differential p_T , and differential η distributions in appendix
- at low and high η all tunes under-estimate for high multiplicity
 - LHC tunes do slightly better
 - non-LHC tunes typically over-estimate low multiplicity
- inclusively PYTHIA 8.180 describes data well, but under-estimates for high multiplicity
- HERWIG++ 2.6.3 consistently describes inclusive data well
- HERWIG++ 2.7.0 does not model the range $15 < n < 25$ well



Multiplicity Monash

[A. Greco]



- Monash multiplicity in better agreement

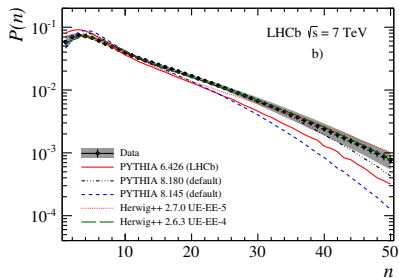
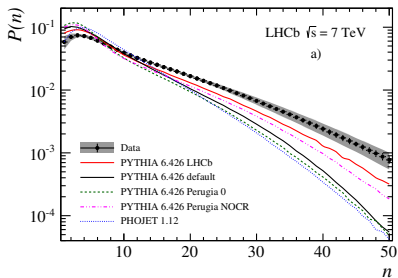


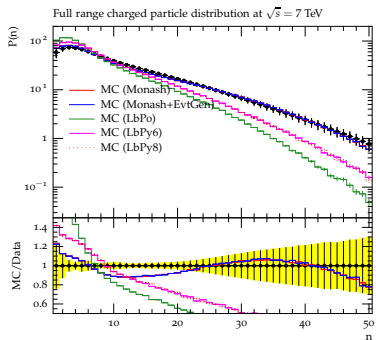
Conclusions

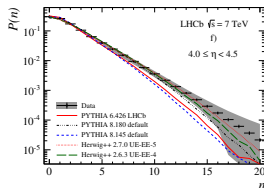
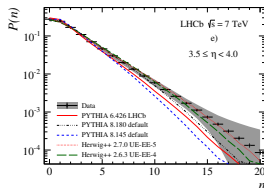
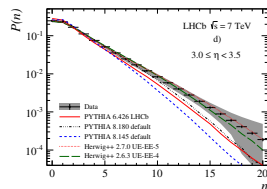
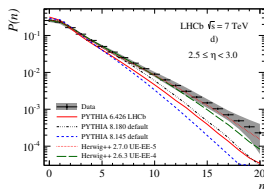
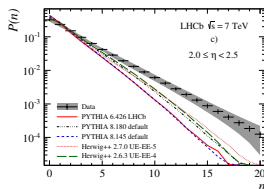
- large potential for tuning from LHCb
 - onia sector
 - forward flavor composition
 - forward soft QCD
- validates consistency of the MPI and hadronization models at LHC energies for forward production
- no unexpected behavior
- non-LHC tunes underestimate forward particle density
- PYTHIA 4C performs well, Monash tune does better
- HERWIG++ UE-EE-4 tune consistently out-performs UE-EE-5
- some more 13 TeV results underway

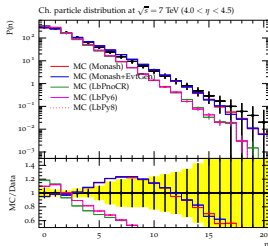
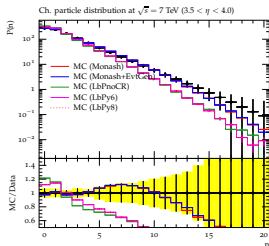
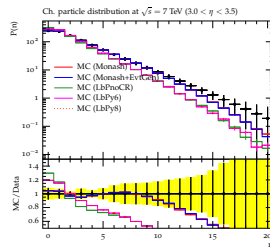
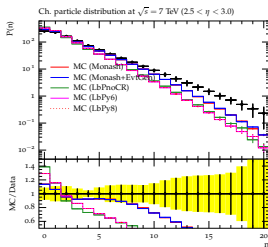
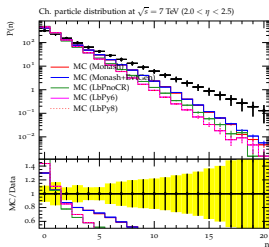


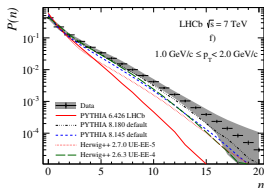
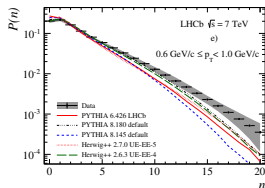
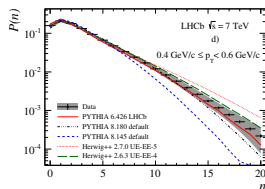
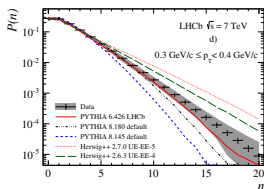
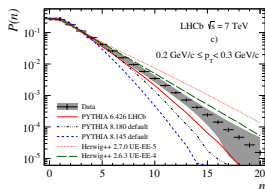
Inclusive Multiplicity Results

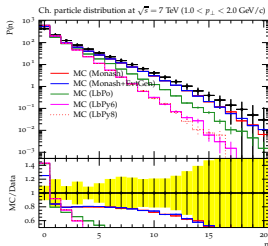
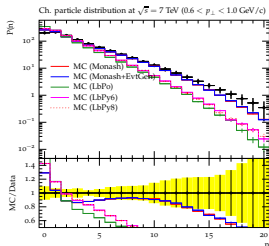
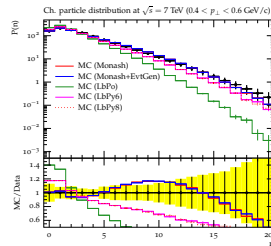
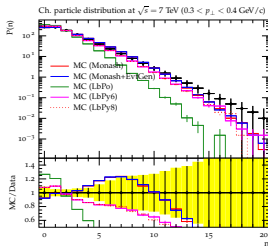
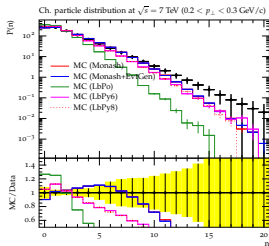




Differential Multiplicity Results (η)

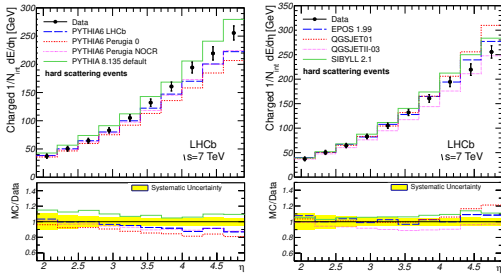


Differential Multiplicity Results (p_T)



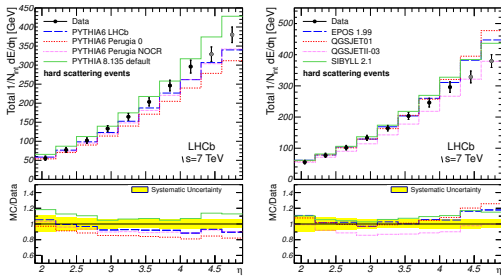
Energy Flow Hard Scatter

[Eur. Phys. J. C 73 (2013) 2421]



charged

- PYTHIA 8 uniformly over-estimates
- PYTHIA 6 under-estimates for large η
- EPOS, QGSJET01, and SIBYLL over-estimate for large η
- QGSJETII-03 under-estimates at middle η



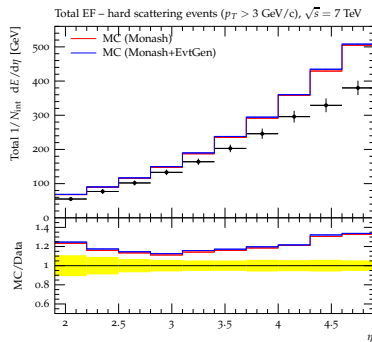
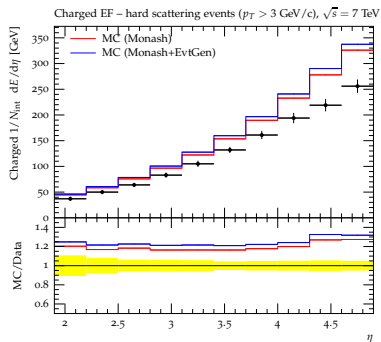
total

- similar behavior to charged energy flow



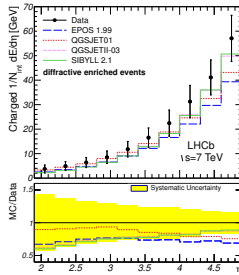
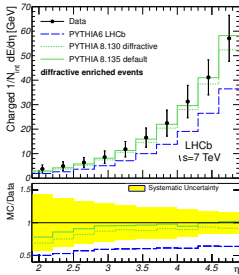
Hard Scatter Monash

[A. Greco]

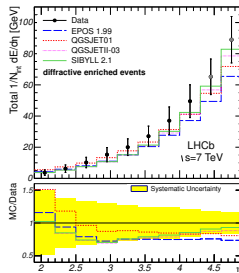
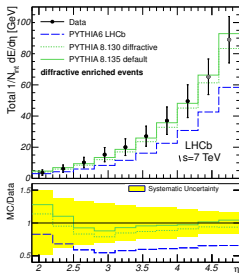


Energy Flow Diffractive

[Eur. Phys. J. C 73 (2013) 2421]

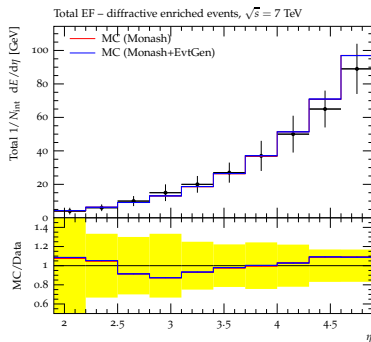
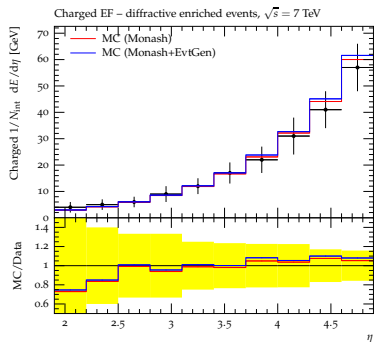
**charged**

- larger systematic from detector effects and magnet polarity
- PYTHIA 8 models data well
- PYTHIA 6 significantly under-estimates
- remaining generators under-estimate

**total**

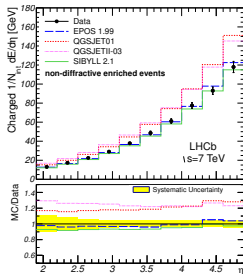
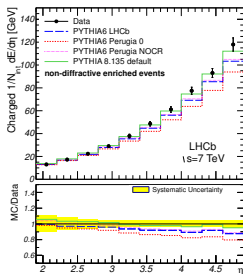
- similar behavior to charged energy flow for PYTHIA
- remaining generators more consistent with data
- EPOS and QGSJET01 under-estimate at high η



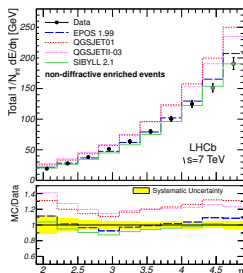
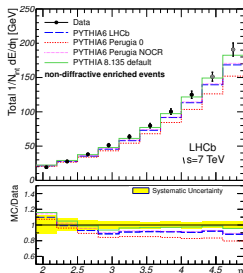


Energy Flow Non-diffractive

[Eur. Phys. J. C 73 (2013) 2421]

**charged**

- similar to inclusive results
- PYTHIA 8 models data well
- EPOS and SIBYLL also model data well

**total**

- similar behavior to charged energy flow



Non-diffractive Monash

[A. Grecu]

