



*QCD and EW measurements with LHCb*

*Dmytro Volyanskyy*

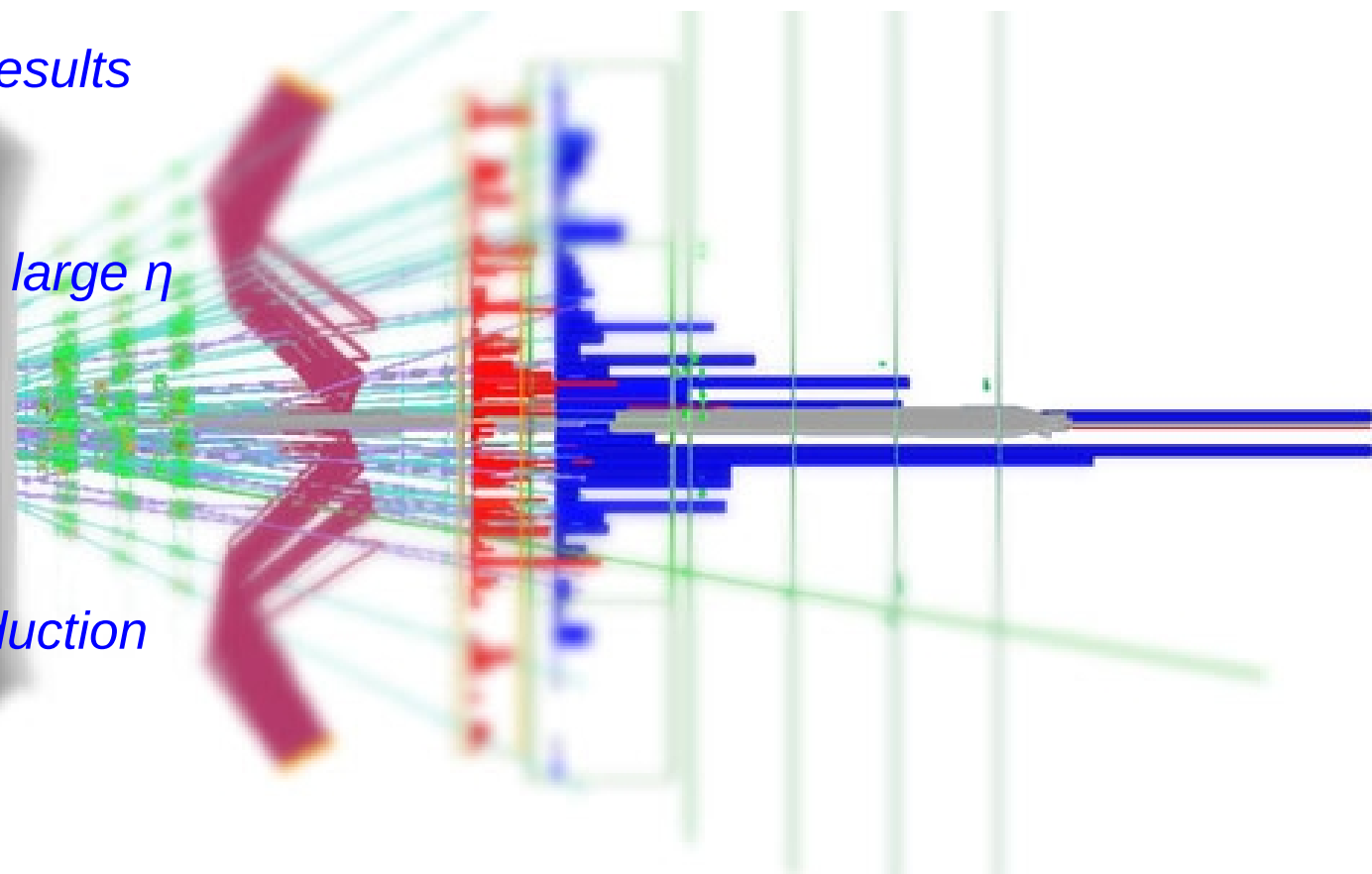
*Max-Planck-Institut für Kernphysik (Heidelberg, Germany)*

*on behalf of the LHCb collaboration*

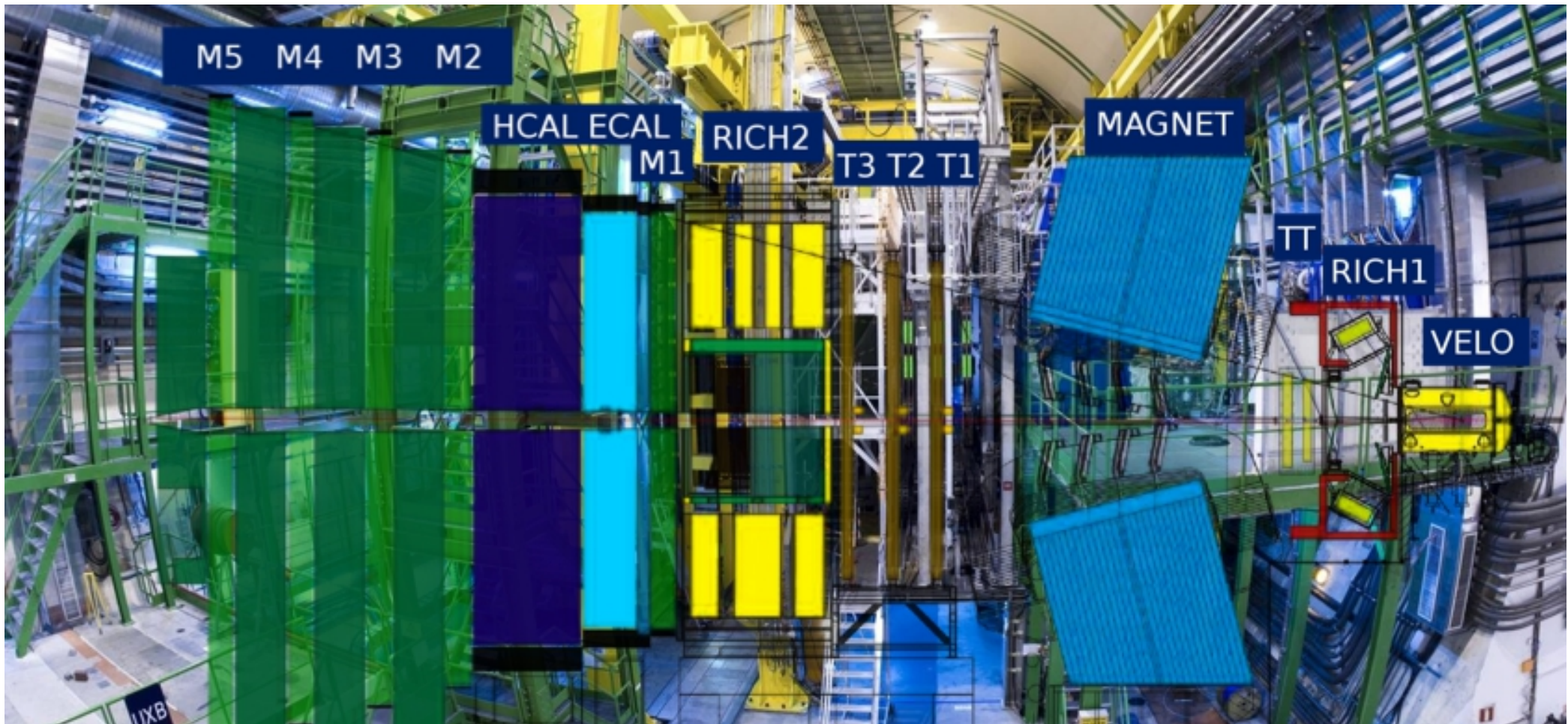
*25<sup>th</sup> Rencontres de Blois "Particle Physics and Cosmology" International Conference*

*May 26-31, 2013, Blois, France*

- *The LHCb experiment*
- *LHCb EW and QCD published results*
- *Recent EW measurements:*
  - *Limits on Higgs production at large  $\eta$*
  - *W and Z boson production*
- *Recent QCD measurements:*
  - *Forward energy flow*
  - *Exclusive  $J/\psi$  and  $\psi(2S)$  production*
- *Summary*

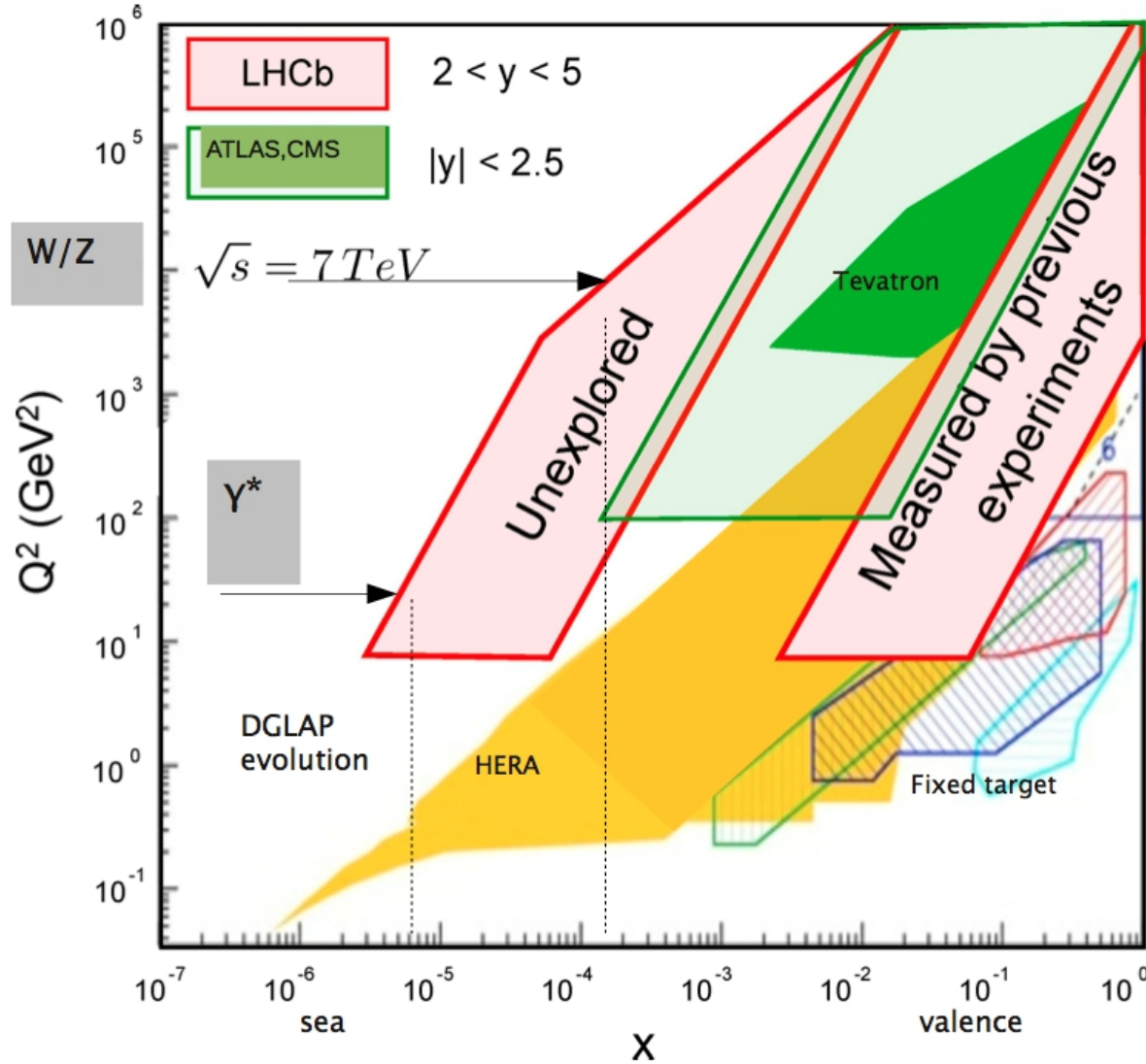


# The LHCb experiment



- *Forward spectrometer with planar detectors*
- *Excellent tracking performance*
- *High quality particle identification*
- *Selective and flexible trigger system*

JINST 3 (2008) S08005



- *LHCb explores particle production in a unique kinematic range:*
  - probes of PDFs at low and at high Bjorken  $x$  and low  $Q^2$  (NNLO calculations are available)
  - PDF uncertainty increases towards large  $\eta$
  - low-mass Drell-Yan &  $W/Z$  cross-section measurements:  $x$  values down to  $\sim 8 \times 10^{-6}$  &  $10^{-4}$

- *Ability to study low- $p_T$  region ( $< 0.5$  GeV/c) at large  $\eta$  ( $> 4$ )*
  - the only LHC experiment that can investigate this region of the phase space
  - great potential to study soft QCD processes

# QCD and EW published results



- *Underlying Event and Diffractive Physics in pp collisions:*
  - ◆ Measurement of the forward energy flow at 7 TeV : Eur. Phys. J. C 73 (2013) 2421
  - ◆ Measurement of charged particle multiplicities at 7 TeV : Eur. Phys. J. C 72 (2012) 1947
  - ◆ Measurement of prompt hadron production ratios at 0.9 and 7 TeV: Eur. Phys. J. C 72 (2012) 2168
  - ◆ Exclusive  $J/\psi$  and  $\psi(2S)$  production at 7 TeV : J. Phys. G: Nucl. Part. Phys. 40 045001
- *Strangeness production in pp collisions:*
  - ◆ Measurement of the inclusive  $\phi$  cross-section at 7 TeV : Phys. Lett. B 703 (2011) 267-273
  - ◆ Measurement of  $V_0$  production ratios at 0.9 and 7 TeV : JHEP 08 (2011) 034
  - ◆ Prompt  $K_s$  production at 0.9 TeV : Phys. Lett. B 693 (2010) 69-80
- *Heavy flavor production in pp collisions:*
  - ◆ Prompt charm production at 7 TeV : Nucl. Phys. B871 (2013) 1-20
  - ◆ Measurement of the  $B^\pm$  production cross-section 7 TeV : JHEP 04 (2012) 093
  - ◆ Measurement of  $\sigma(pp \rightarrow bbX)$  at 7 TeV in the forward region : Phys. Lett. B 694 (2010) 209-216
- *Electroweak boson production in pp collisions:*
  - ◆ Measurement cross-section for  $Z \rightarrow ee$  production at 7 TeV : JHEP02 (2013) 106
  - ◆ Z production cross-section at 7 TeV using tau final states : JHEP 01 (2013) 111
  - ◆ Inclusive W and Z production in the forward region at 7 TeV : JHEP 06 (2012) 058
- *Exotica searches in pp collisions:* :
  - ◆ Limits on neutral Higgs production in the forward region at 7 TeV : arXiv:1304.2591 (submitted to JHEP)

→ underlined results are briefly presented in this talk along with some preliminary measurements

# Higgs Production Studies

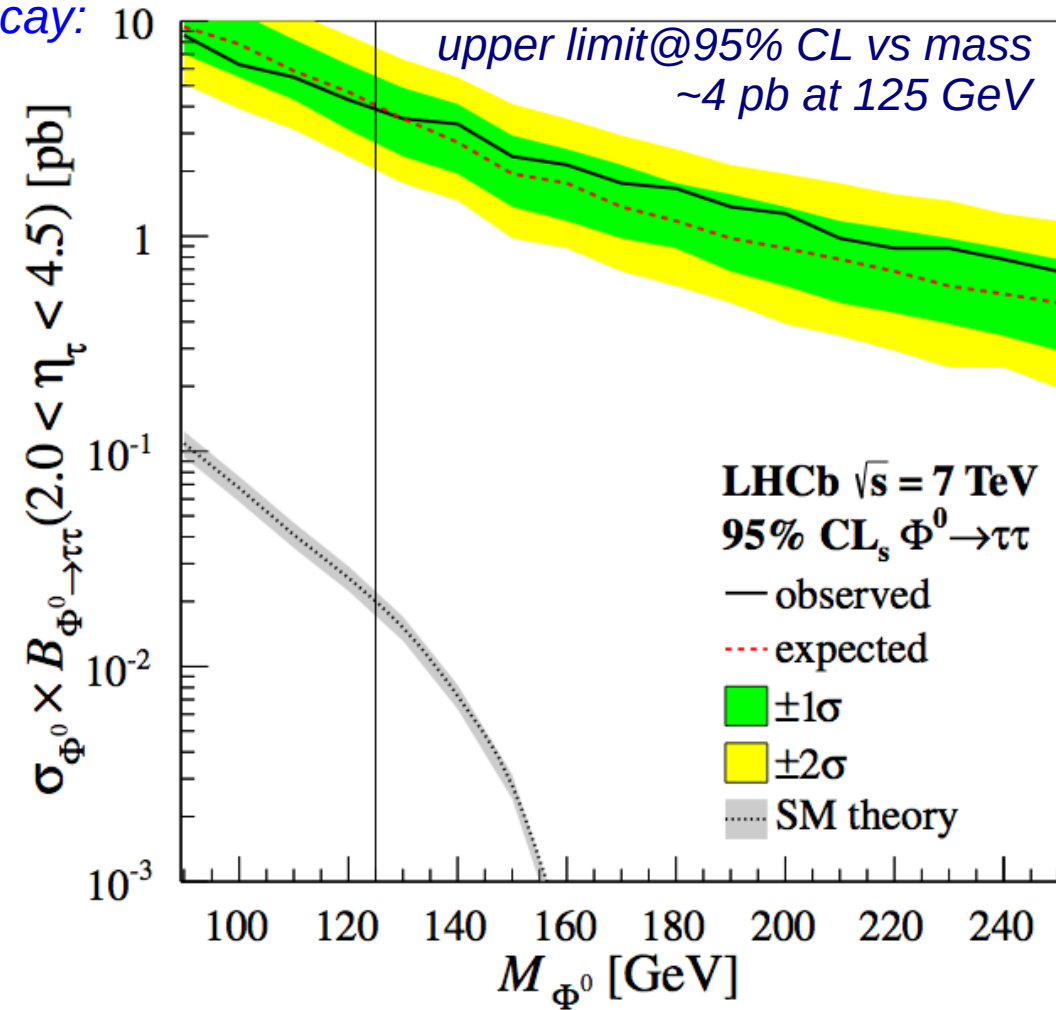
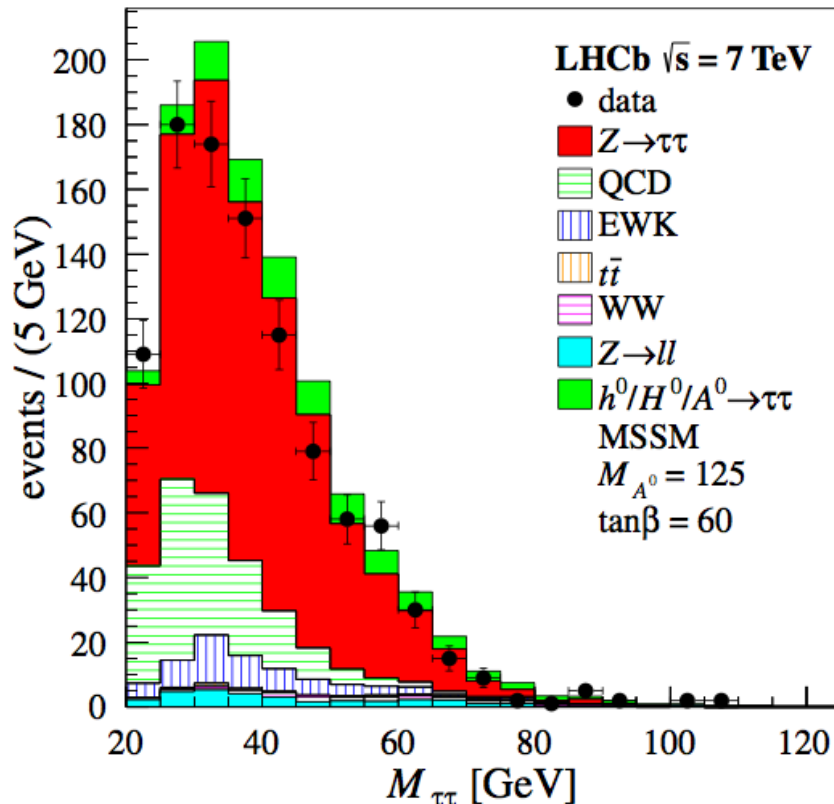
- Model independent search for the general Higgs decay:

$$\Phi^0 \rightarrow \tau\tau \quad (\tau \rightarrow l\nu\nu, 2.0 < \eta_l < 4.5)$$

→ performed with  $1 \text{ fb}^{-1}$  at 7 TeV

→ extension to  $Z \rightarrow \tau\tau$  analysis (arXiv:1210.6289), treated as one of the background sources here

→ no signal excess, no events with  $M > 120 \text{ GeV}$  are observed



constraints on MSSM parameters and models where forward(diffractive) Higgs production is favored

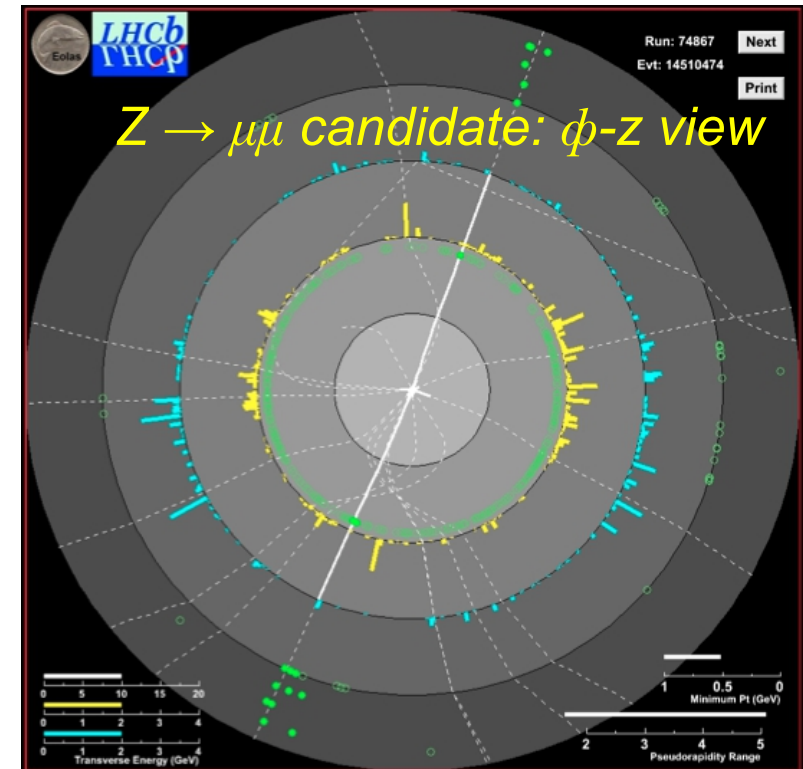
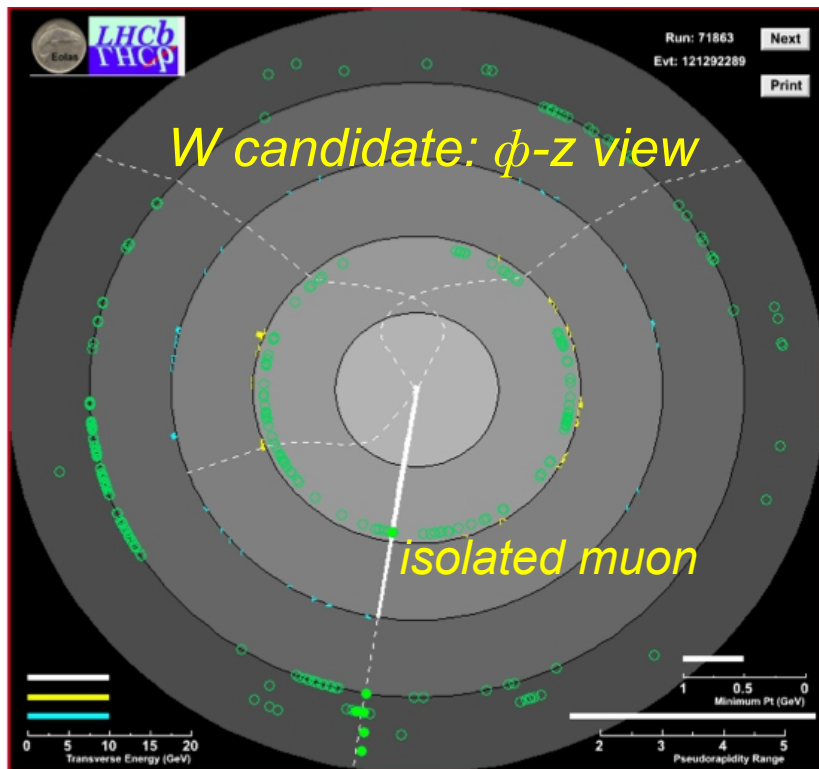
arXiv:1304.2591

# Electroweak Boson Production (I)

•  $Z$  production studied with 3 decay modes:

- ◆  $Z \rightarrow \mu\mu$
- ◆  $Z \rightarrow ee$
- ◆  $Z \rightarrow \tau\tau$

→  $Z$  selection: high  $p_T$  final state particles

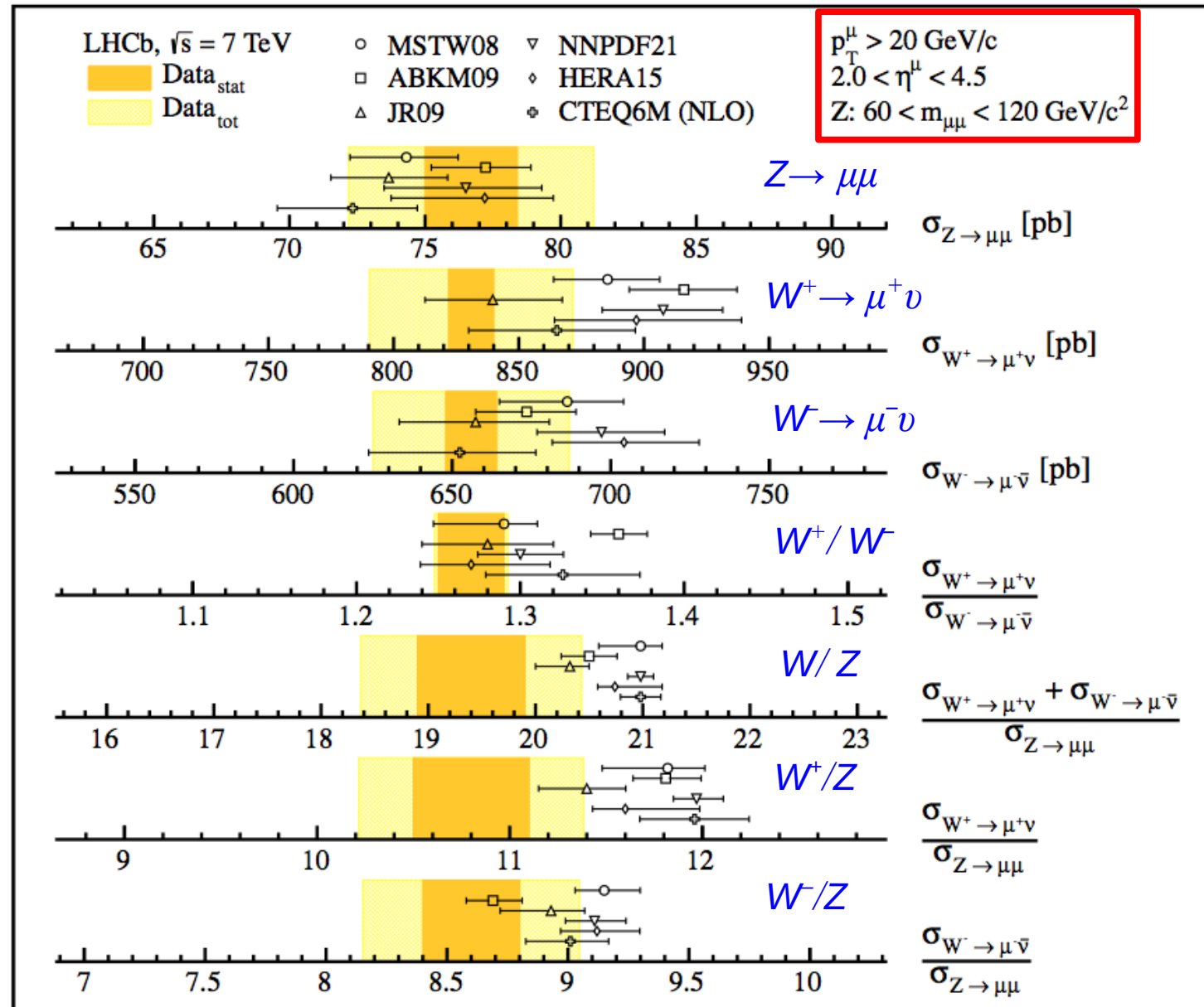


- $W^\pm \rightarrow \mu^\pm \nu$  selection: high  $p_T$  and isolated muons
- $W, Z$  selection efficiencies derived from data; dominant systematic uncertainty besides luminosity
- All results corrected for final state radiation
- Lepton charge asymmetries are investigated

JHEP 06 (2012) 058

# Electroweak Boson Production (II)

- results for muonic final states with  $37 \text{ pb}^{-1}$  7 TeV data



- general agreement with theory predictions, though some PDFs overestimate the ratios of the cross-sections
- theory errors include PDF and scale uncertainties
- for  $W^+ / W^-$  systematic cancels: results are more accurate than predictions
- accuracy of the results will be improved with more data

MSTW08 arXiv:0901.0002  
 ABKM09 arXiv:0908.2766  
 JR09 arXiv:0810.4274  
 NNPDF arXiv:1002.4407  
 HERA15 arXiv:0911.0884  
 CTEQ6M arXiv:0802.0007

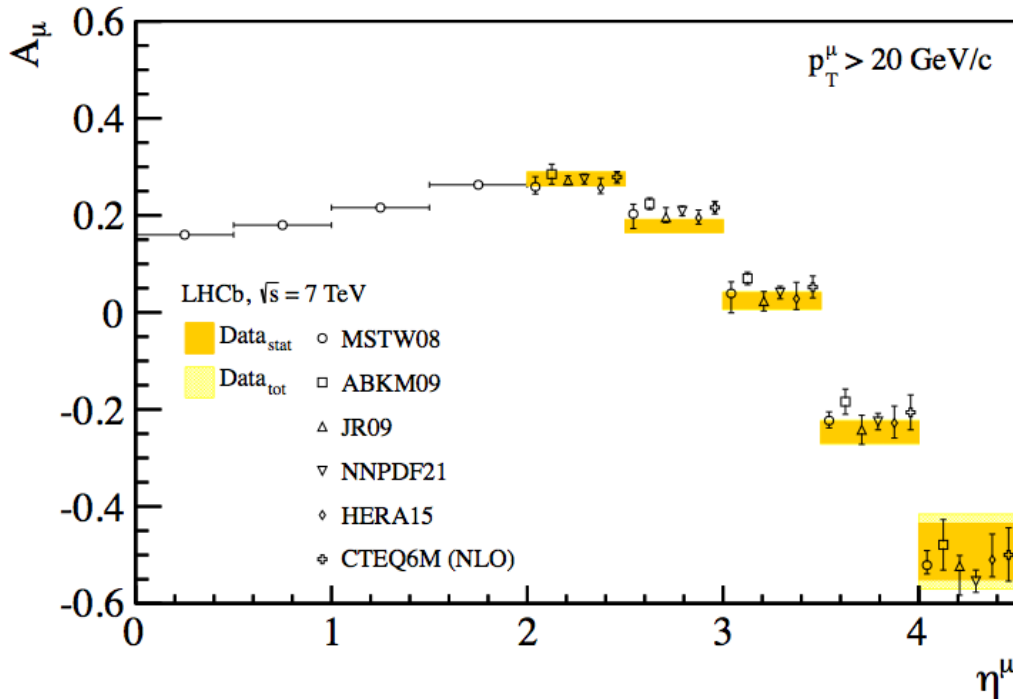


# Electroweak Boson Production (III)

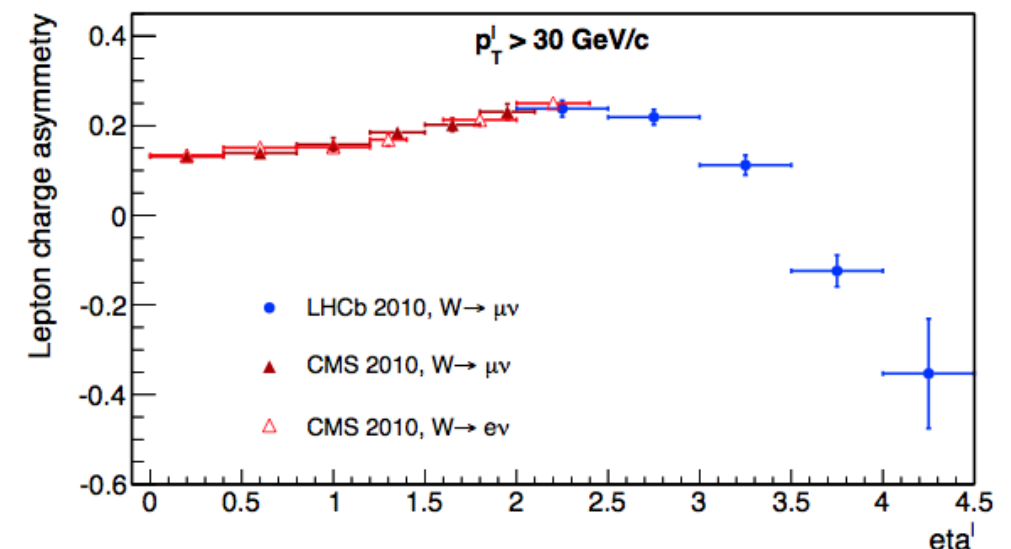
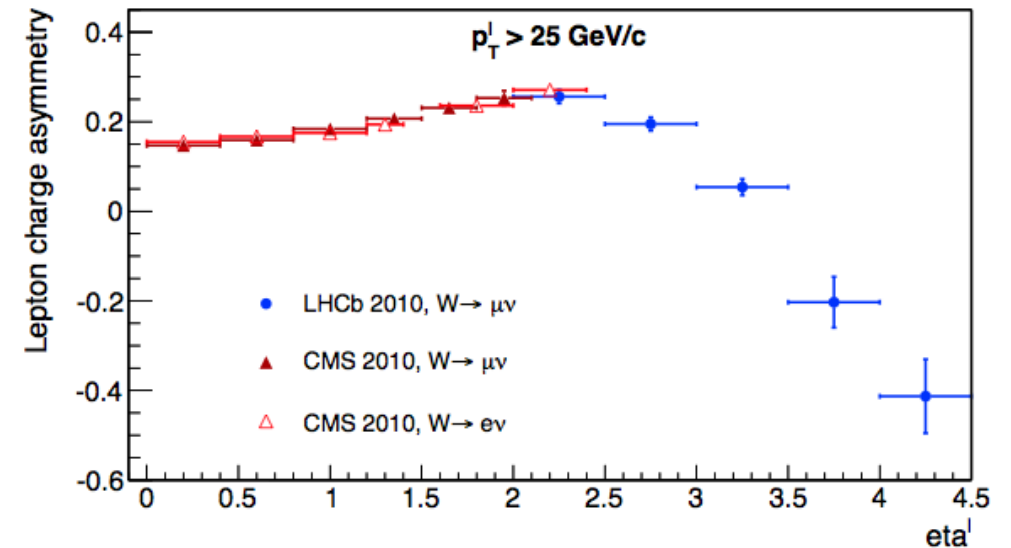
- Lepton charge asymmetry vs muon pseudorapidity:

$$A_\mu = (\sigma_{W^+ \rightarrow \mu^+ \nu} - \sigma_{W^- \rightarrow \mu^- \bar{\nu}}) / (\sigma_{W^+ \rightarrow \mu^+ \nu} + \sigma_{W^- \rightarrow \mu^- \bar{\nu}})$$

→ studied for different  $p_T$  thresholds



MSTW08 arXiv:0901.0002  
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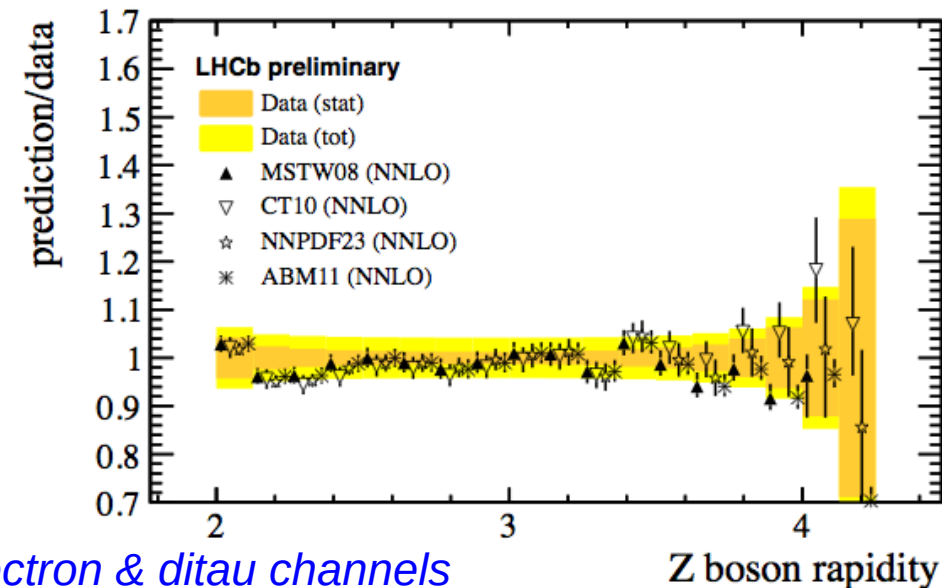
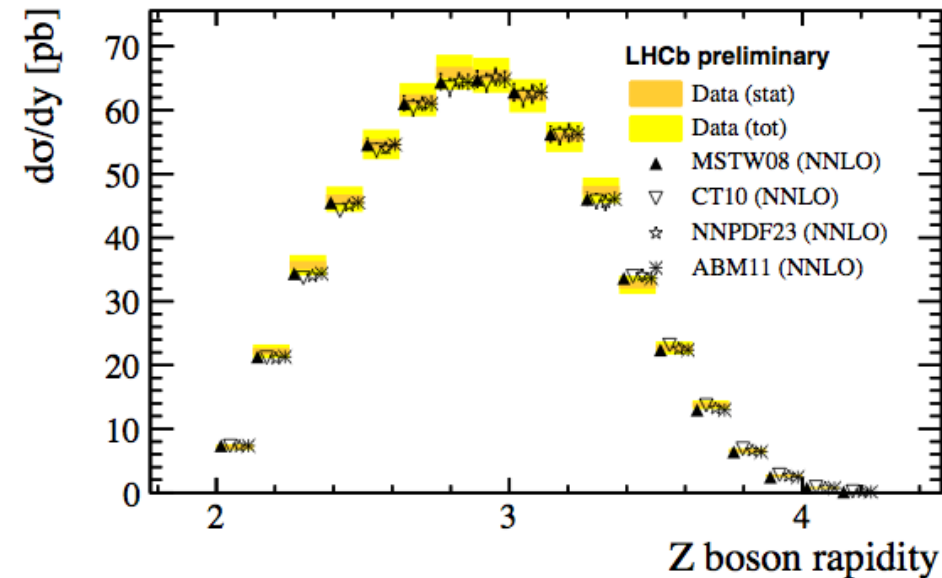
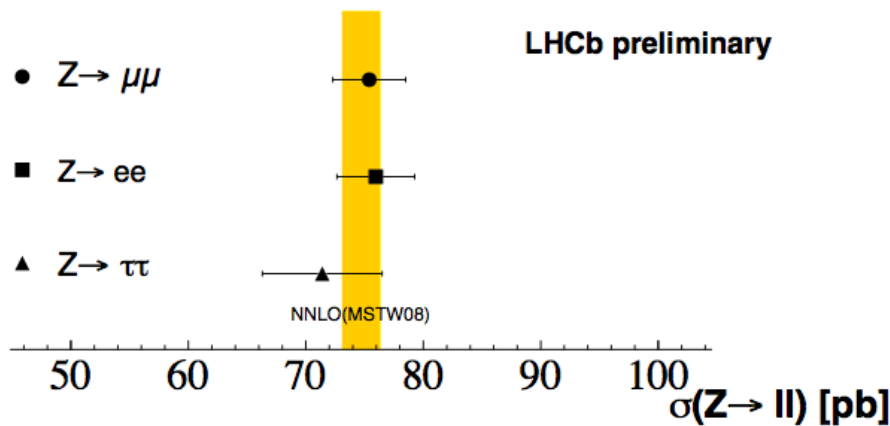
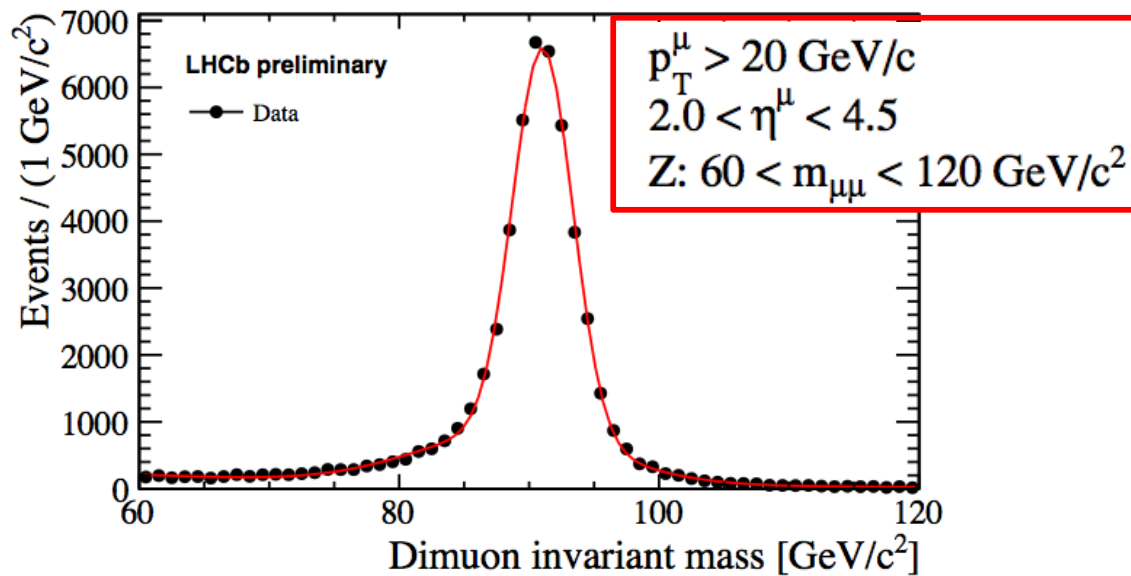


JHEP 06 (2012) 058

- good agreement with theory predictions & CMS (and ATLAS for  $p_T > 20$  GeV not shown here)

# Electroweak Boson Production (IV)

- Recent preliminary results for  $Z \rightarrow \mu\mu$  with  $1 \text{ fb}^{-1}$  of 7 TeV data
  - efficiencies are estimated from data using tag and probe methods
  - signal purity: >99%



- excellent agreement with NNLO pQCD calculations and dielectron & ditau channels

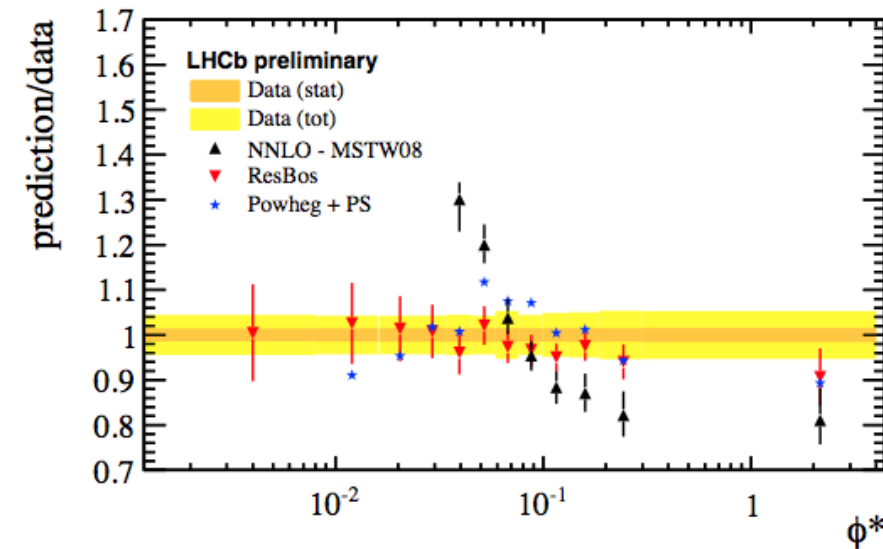
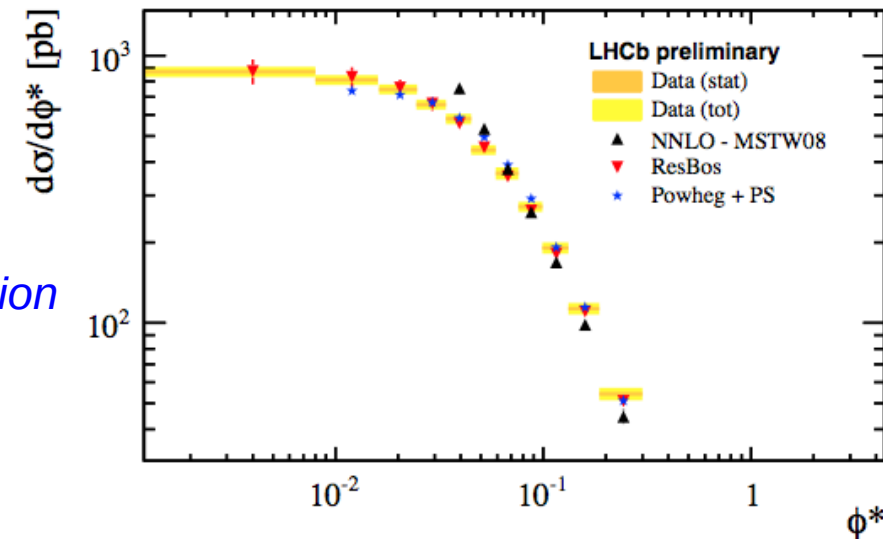
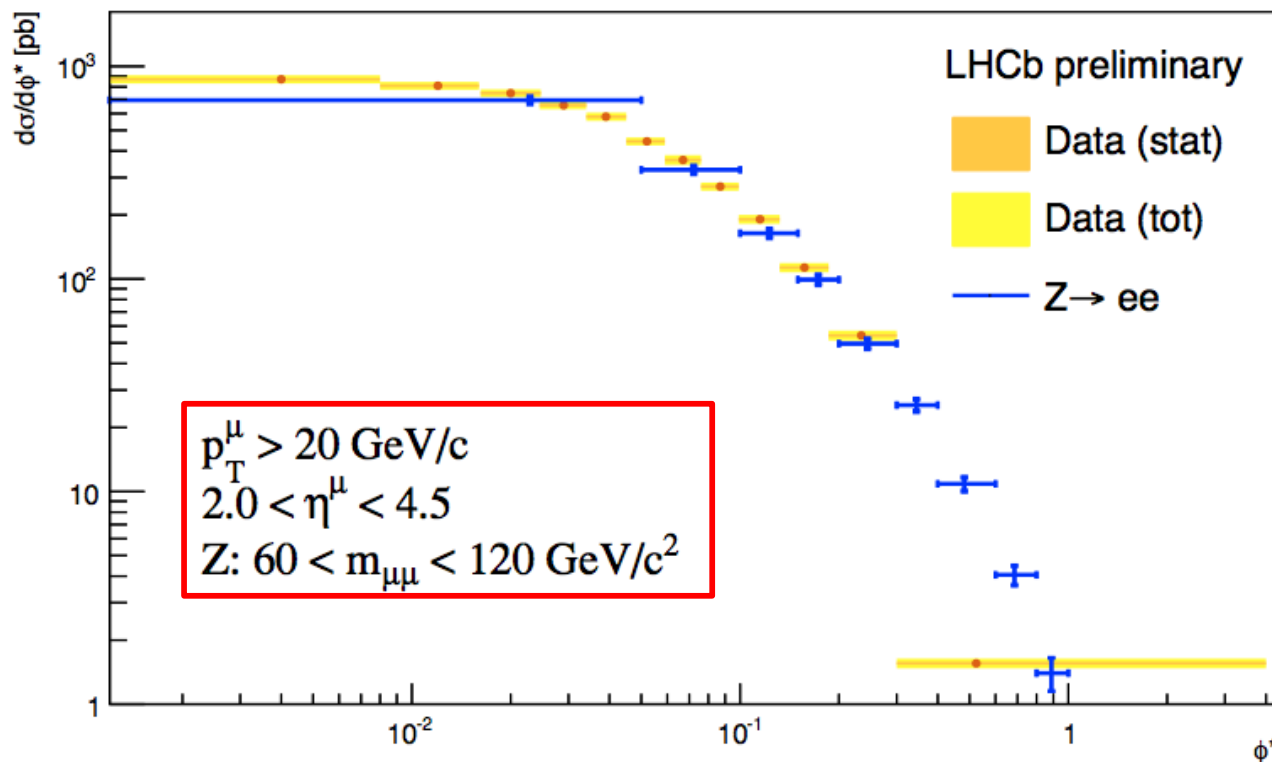
# Electroweak Boson Production (V)

- $Z \rightarrow \mu\mu$  production as a function of:

$$\phi^* = \tan(\phi_{\text{acop}}/2) / \cosh(\Delta\eta/2) \quad \phi_{\text{acop}} = \pi - |\Delta\phi|$$

→ proportional to  $p_T(Z)$  but better determined:  
angles are more precisely measured than  $p(Z)$

- Good agreement between  $Z \rightarrow \mu\mu$  and  $Z \rightarrow ee$  results;  
NNLO fails to describe the shape; ResBos gives better description

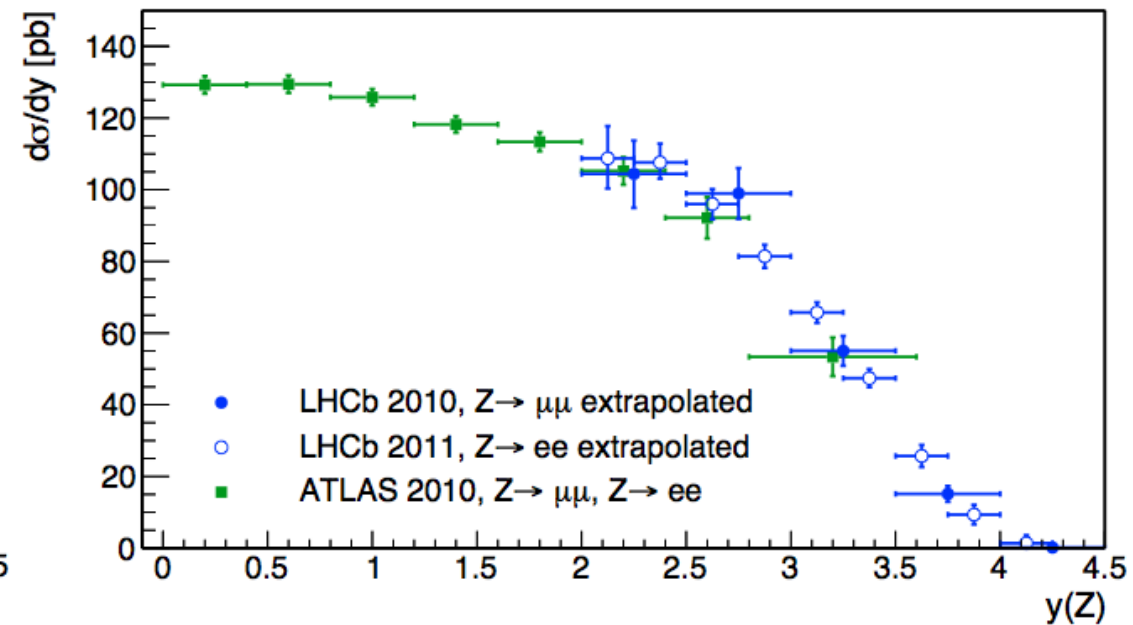
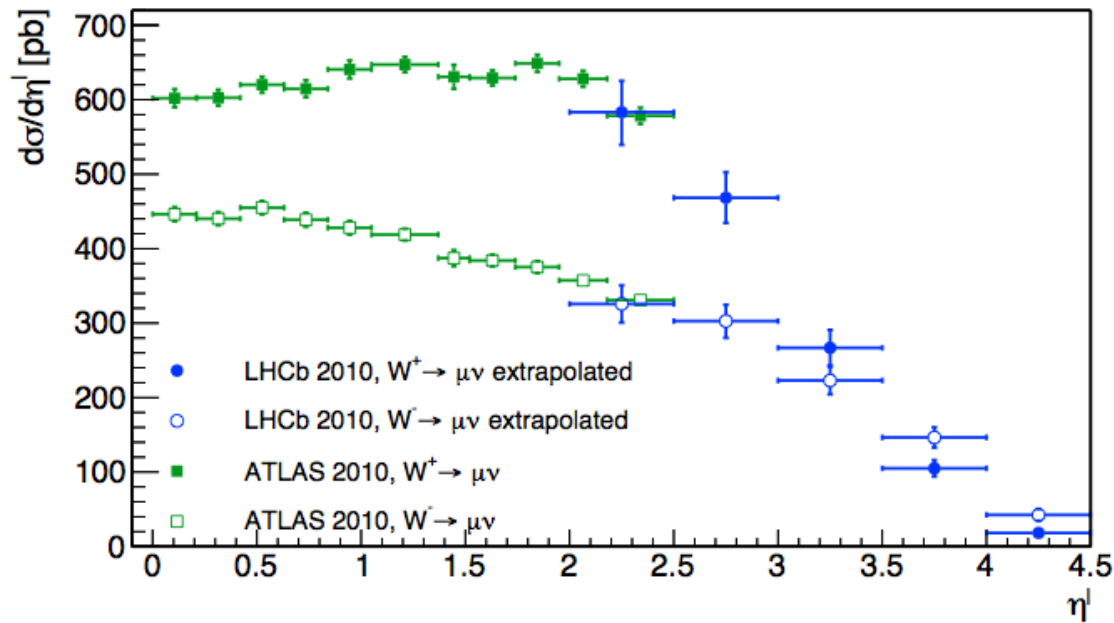


# Electroweak Boson Production (VI)

- Comparison of  $W$  &  $Z$  measurements with ATLAS:

- LHCb results are extrapolated as a function of (pseudo)rapidity to account for different acceptances of the experiments

- extrapolation uncertainty is dominated by PDF uncertainty at high  $\eta$  and scale variation at low  $\eta$



- excellent agreement with ATLAS results extending the measurements into previously unexplored kinematic region: great input for PDF constraining

- *Energy Flow (EF)* :  
→ average energy created in a particular  $\eta$  interval per inelastic  $pp$  interaction

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

- *EF is sensitive to the amount of parton radiation and multi-parton interactions (MPI)*  
→ strongly needed for a precise description of the UE  
→ possibility to discriminate between MPI models  
→ great input for MC tuning
- *improve the existing constraints on ultra high energy cosmic-ray interaction models:*  
→ LHC provides first possibility to compare cosmic-ray showering models at  $E_{\text{lab}}$  of up to  $\sim 10^{17}$  eV

- *EF is measured for the following event classes:*  
→ *inclusive MB*: at least 1 track in  $1.9 < \eta < 4.9$  with  $p > 2$  GeV  
→ *hard scattering*: at least 1 track in  $1.9 < \eta < 4.9$  with  $p_{\text{T}} > 3$  GeV  
→ *diffractive enriched*: inclusive MB with no backward tracks in  $-3.5 < \eta < -1.5$   
→ *non-diffractive enriched*: inclusive MB with at least 1 backward track in  $-3.5 < \eta < -1.5$
- *Charged EF*: tracks traversing the full setup  
*Neutral EF*: data-constrained MC estimate
- *Data corrected for detector effects & compared to PYTHIA-based+cosmic-ray models*

*Eur. Phys. J. C 73 (2013) 2421*

# Forward Energy Flow (II)

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

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

- Systematic effects decrease towards large  $\eta$

- PYTHIA6-based models underestimate  $EF$  at large  $\eta$  and overestimate it at low  $\eta$  in case of all event classes

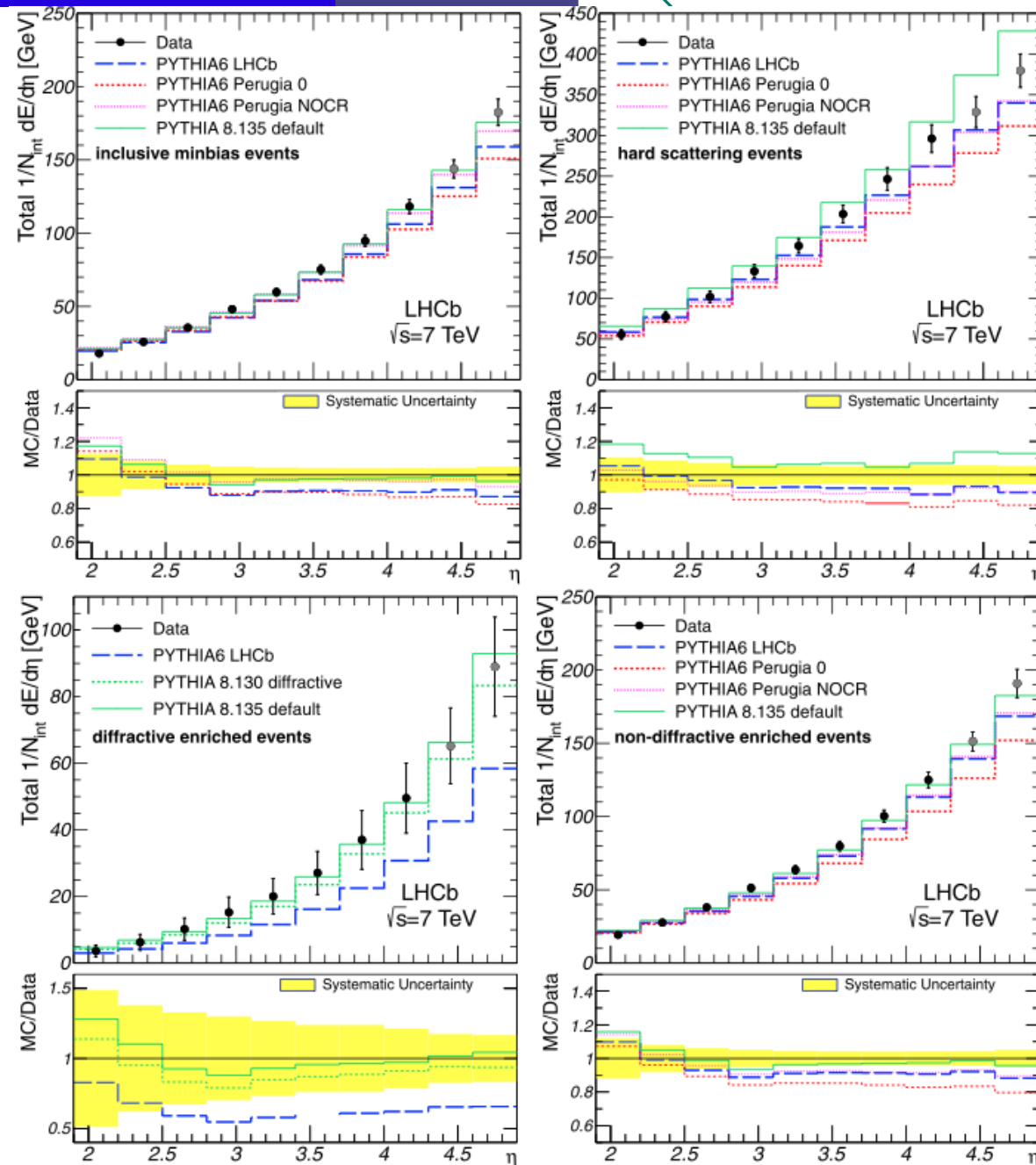
- PYTHIA8 with default parameters gives excellent description of the measurements at large  $\eta$  except for hard scattering events

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

*Eur. Phys. J. C 73 (2013) 2421*



# Forward Energy Flow (III)

- EPOS 1.99, SYBILL 2.1, QGSJET01, QGSJETII 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

thanks to Ralf Ulrich and Colin Baus from KIT for providing these predictions

Astropart. Phys. 35 (2011) 98

J. Phys. : Conf. Ser. 60 (2007) 167

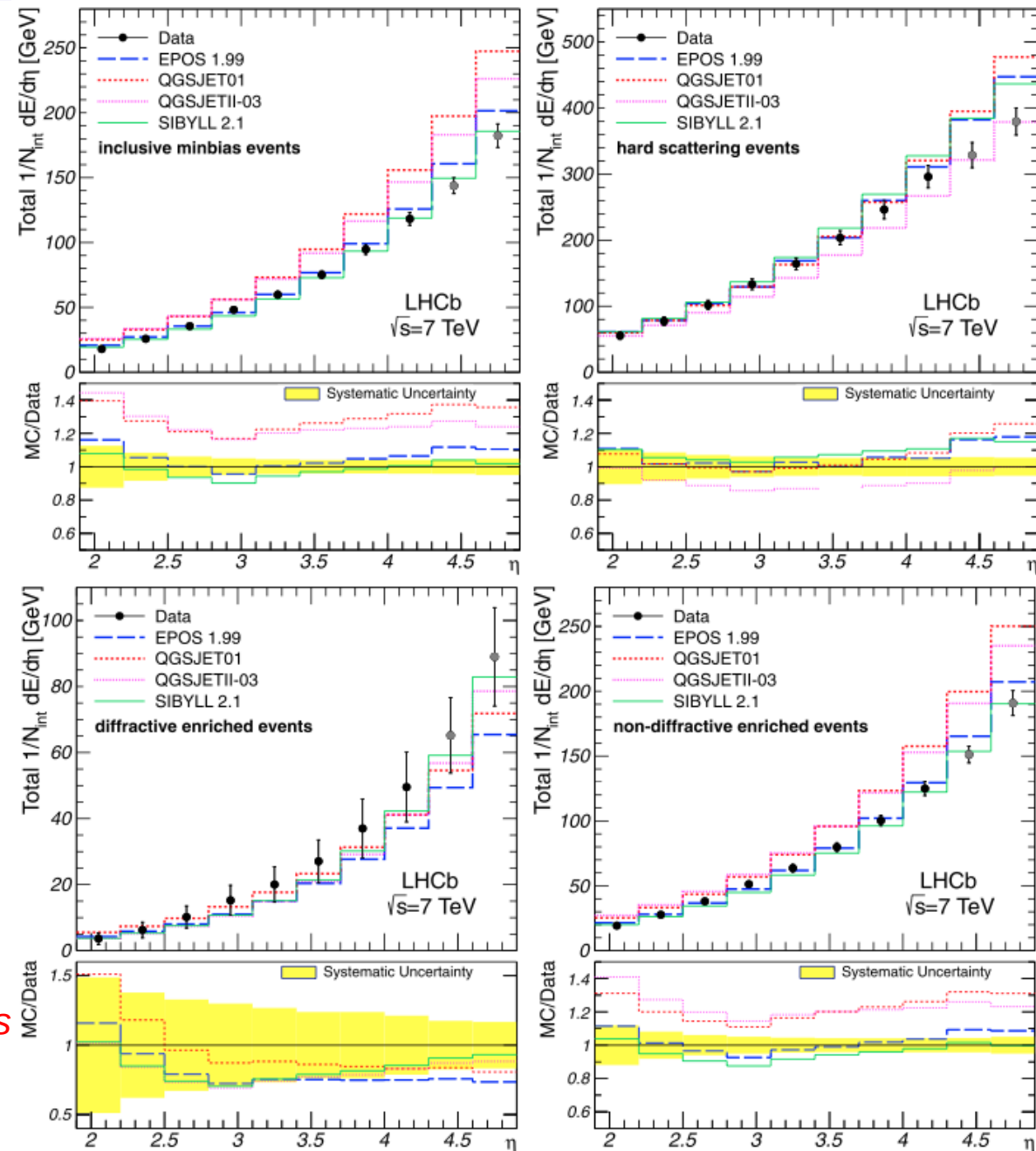
AIP Conf. Proc. 928 (2007) 118.

Nucl. Phys.Proc. Suppl. 196 (2009) 102

Phys. Rev.D80 (2009) 094003

- SYBILL 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

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

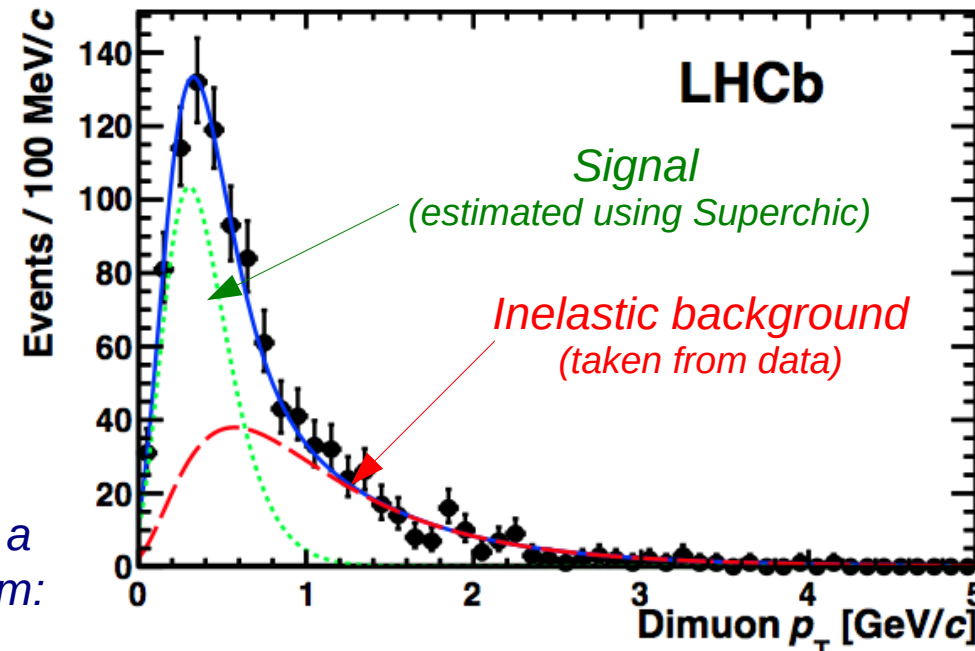
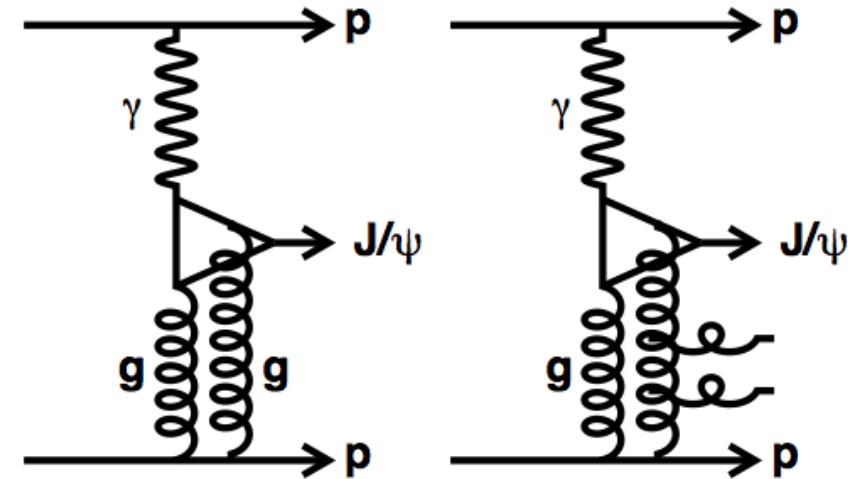


# Exclusive Production (I)

- Exclusive  $J/\psi$ ,  $\psi(2S)$  production with  $36 \text{ pb}^{-1}$  7 TeV data:

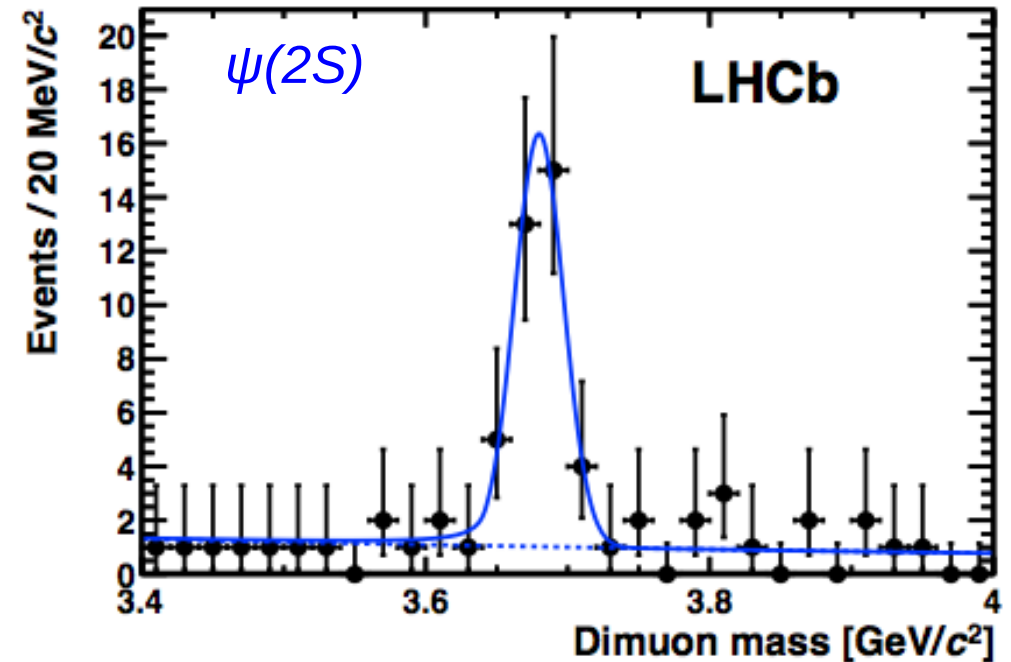
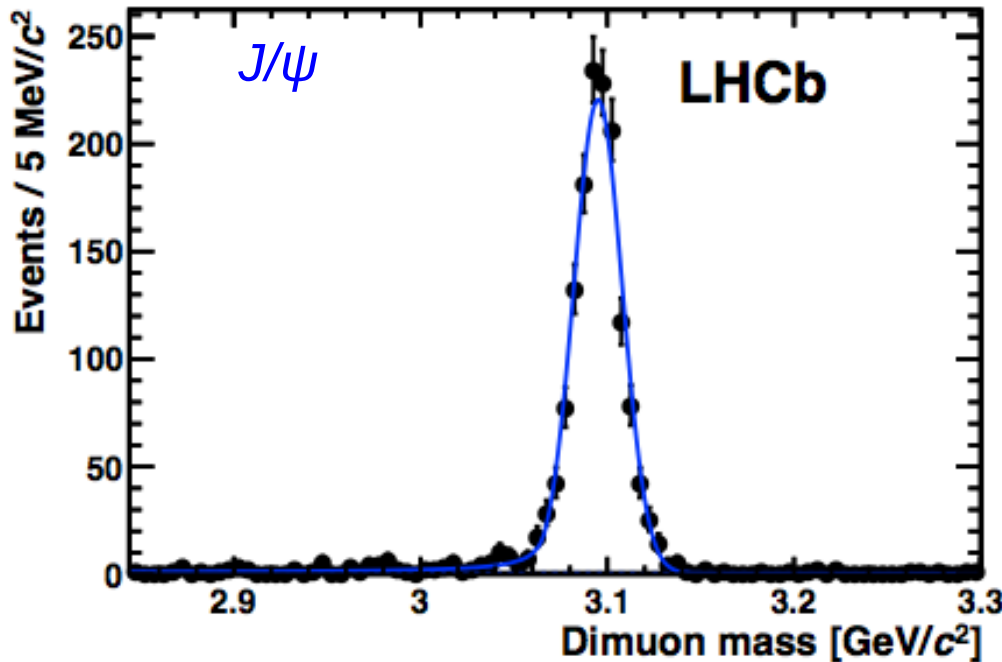
$$p p \rightarrow p p J/\psi (\psi(2S))$$

- occurring via photoproduction  $\gamma p \rightarrow V p$   
cross-sections are calculable within pQCD with large uncertainties; possibility to constrain gluon PDF
- experimental signature: completely empty event except for two muons in the final state (protons escape through the beam pipe)
- selection: no backward tracks, no photons, exactly 2 tracks with  $2.0 < \eta < 4.5$  and  $p_T(\mu\mu) < 0.9 \text{ GeV}$
- contamination from inelastic events, exclusive feed-down  $\chi_c \rightarrow J/\psi \gamma$ ,  $\psi(2S) \rightarrow J/\psi X$
- largest systematic from the fitted signal & background  $p_T(\mu\mu)$  shape
- $J/\psi$  photoproduction cross-section is also measured as a function of the c.o.m. energy of the photon-proton system: good agreement with HERA results





# Exclusive Production (II)



Predictions	$\sigma_{pp \rightarrow J/\psi} (\rightarrow \mu^+ \mu^-)$	$\sigma_{pp \rightarrow \psi(2S)} (\rightarrow \mu^+ \mu^-)$
Gonçalves and Machado	275	
STARLIGHT	292	6.1
Motyka and Watt	334	
SUPERCHIC	396	
Schäfer and Szczurek	710	17
LHCb measured value	$307 \pm 21 \pm 36$	$7.8 \pm 1.3 \pm 1.0$

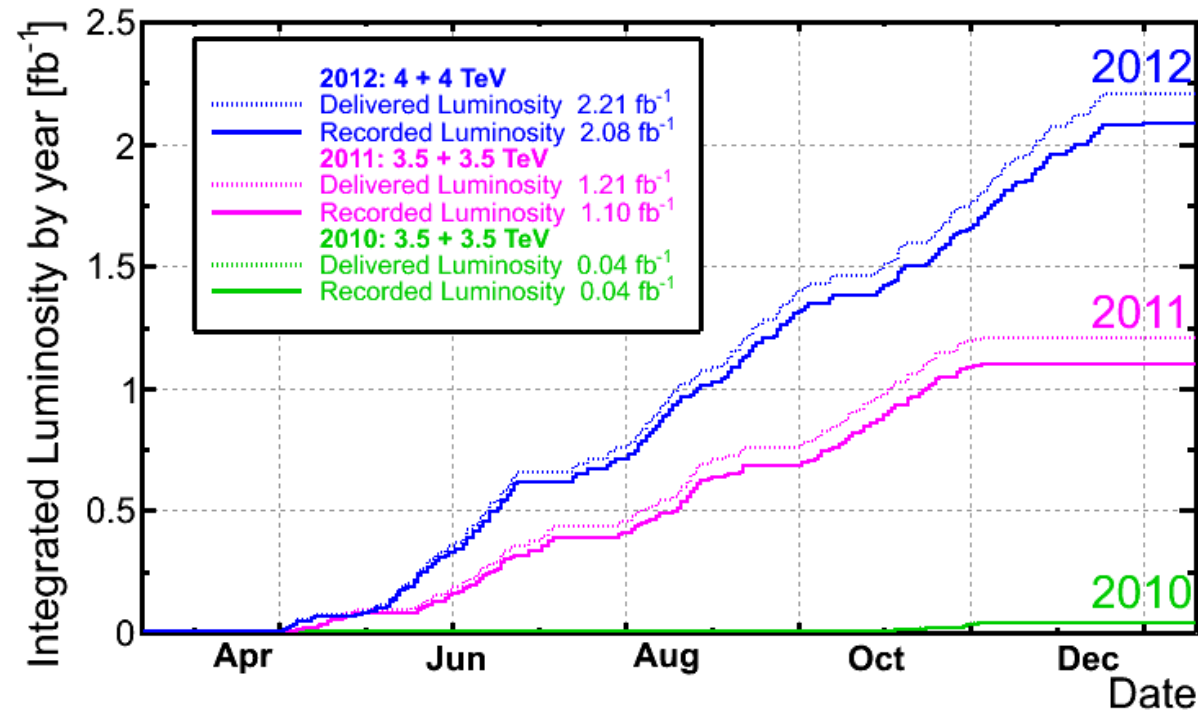
- Phys. Rev. C84 (2011) 011902
- Phys. Rev. Lett. 92 (2004) 142003
- Phys. Rev. D78 (2008) 014023
- Eur. Phys. J. C65 (2010) 433
- Phys. Rev. D76 (2007) 094014

- *LHCb instrumentation permits high-precision studies of QCD and EW processes in a unique, previously unexplored kinematic range:*
  - *smooth running of the detector over 2009-2013*
  - *3 fb<sup>-1</sup> of high quality data is accumulated*
  - *possibility to perform analyses using pp collisions at 0.9, 2.76, 7.0, 8.0 TeV and in pPb and Ppb interactions at 5.02 TeV*
    - unprecedented and unique input to theory !*
- *Great harvest is performed at 7 TeV – analyses at other collision energies are currently ongoing*
- *Different QCD and EW measurements are performed:*
  - *Electroweak boson production: results are in reasonable agreement with theoretical predictions and ATLAS/CMS measurements providing good input for PDF constraining*
  - *Soft QCD: none of the models used are able to describe fully our results*
  - *First Higgs search is performed: upper limit imposes constraints on MSSM models*

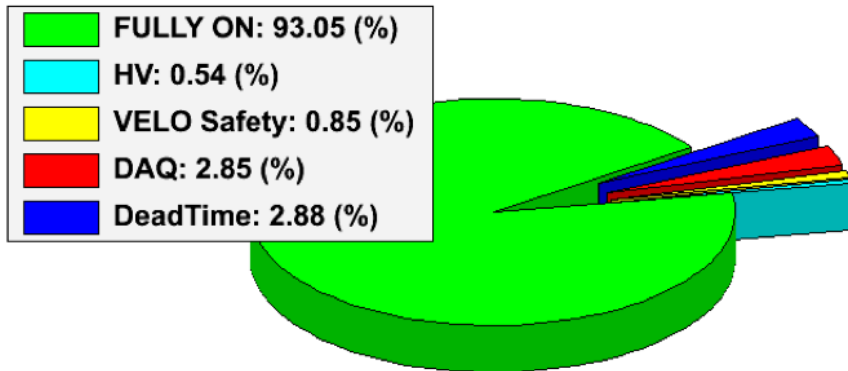
*Stay tuned for further results !*

# Backup: Data taking

year	luminosity	energy (TeV)
2009	6.8 $\mu\text{b}^{-1}$	0.9
2010	0.3 $\text{nb}^{-1}$	0.9
2010	37 $\text{pb}^{-1}$	7
2011	0.1 $\text{pb}^{-1}$	2.76
2011	1.0 $\text{fb}^{-1}$	7
2012	2.0 $\text{fb}^{-1}$	8
2013	3.7 $\text{pb}^{-1}$	2.76
2013	2.0 $\text{nb}^{-1}$	5.02(pPb/Pbp)



LHCb Efficiency breakdown pp collisions 2010-2012



- ~93 % data taking efficiency
- ~99% r/o channels operational
- ~99% of accumulated data are useful for physics analyses
- Luminosity leveling to moderate interaction rate
- In 2011&2012, high luminosity (up to  $4.0 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ ) running
- LHCb design luminosity:  $2.0 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- Smooth data taking by LHCb despite strong challenge for the trigger and offline data processing