Diffraction Physics at LHCb

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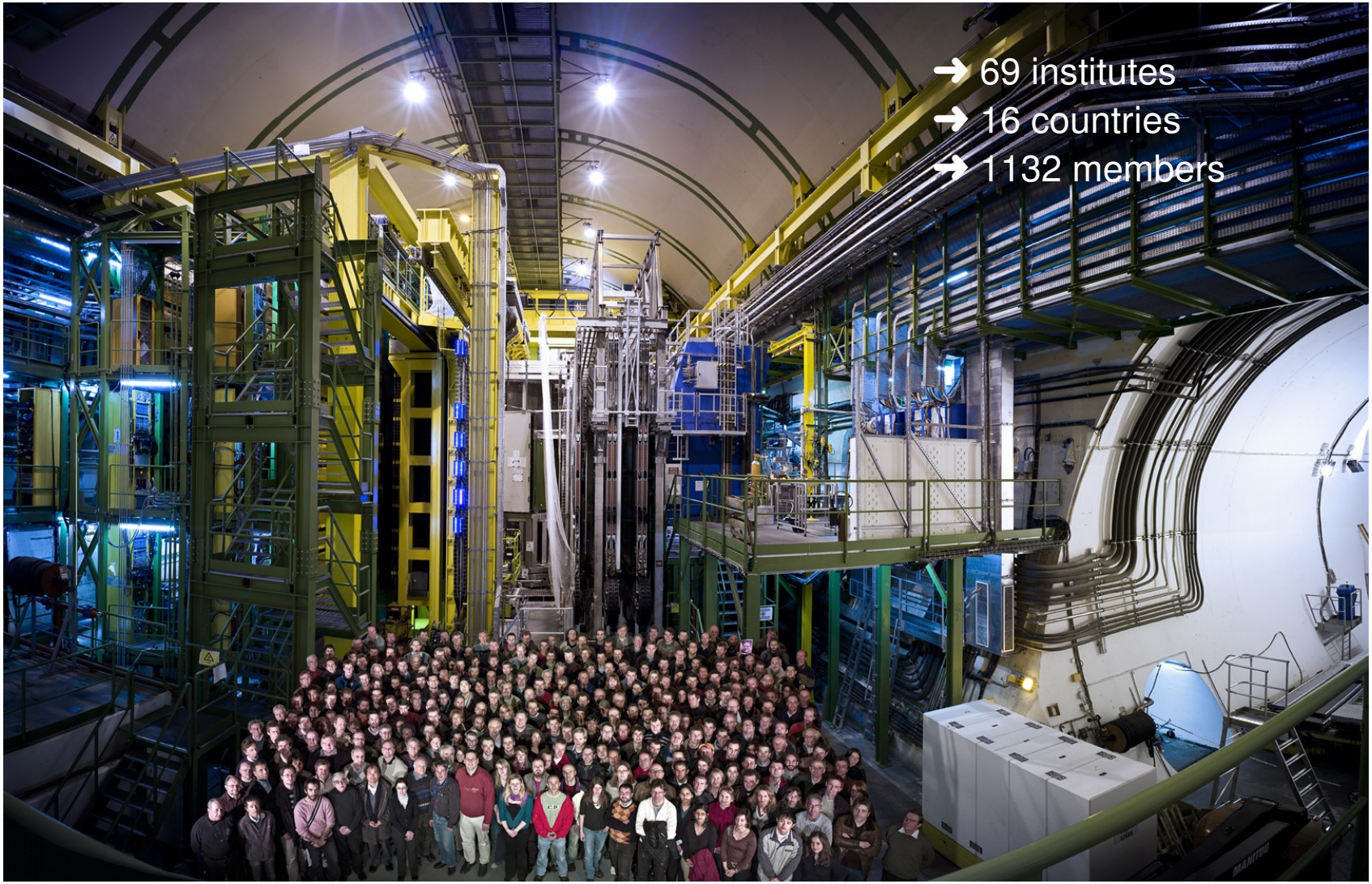
- The LHCb Experiment
- Energy Flow
- Central Exclusive Production
- New Developments
- Summary

1. The LHCb Experiment



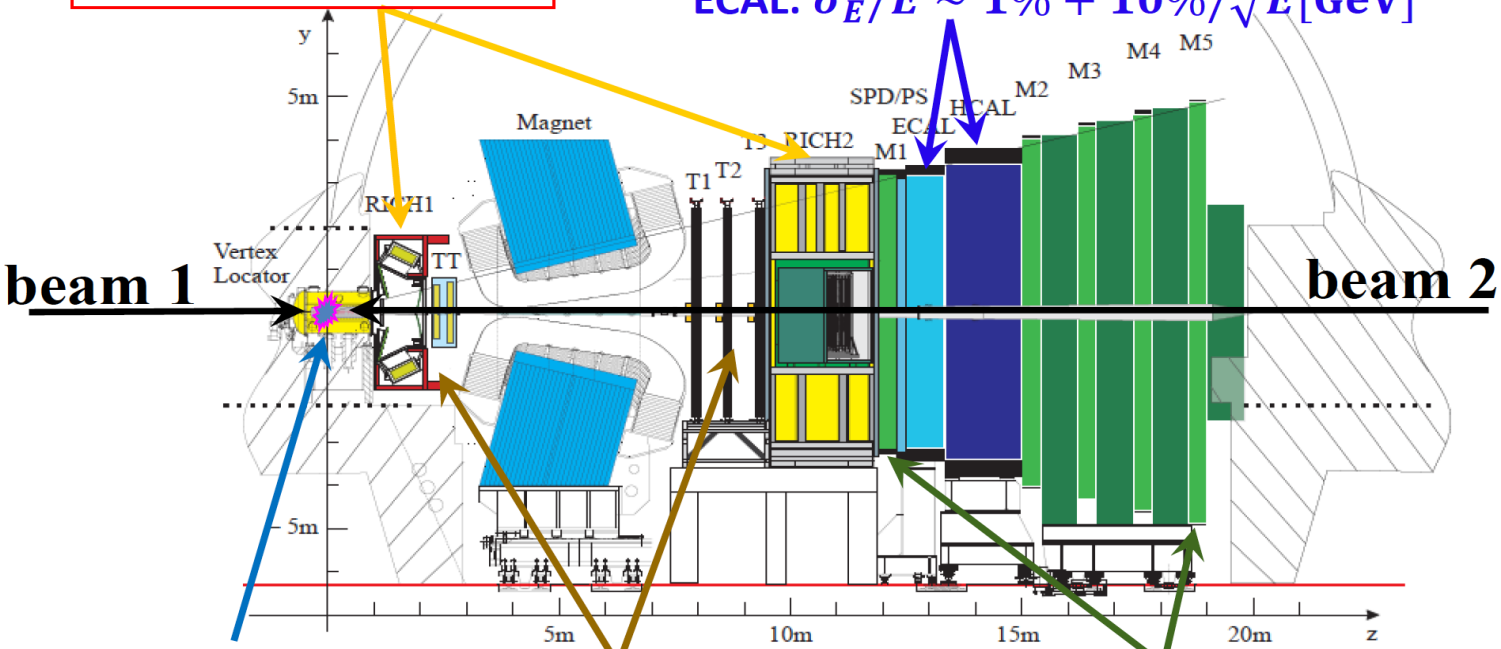
Detector layout and performance

JINST 3 (2008) S08005

Pseudorapidity acceptance
$2 < \eta < 5$

RICH1 & RICH2
$\epsilon(K \to K) \sim 95\%$
$\pi \to K$ mis-id: $\sim 5\%$

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

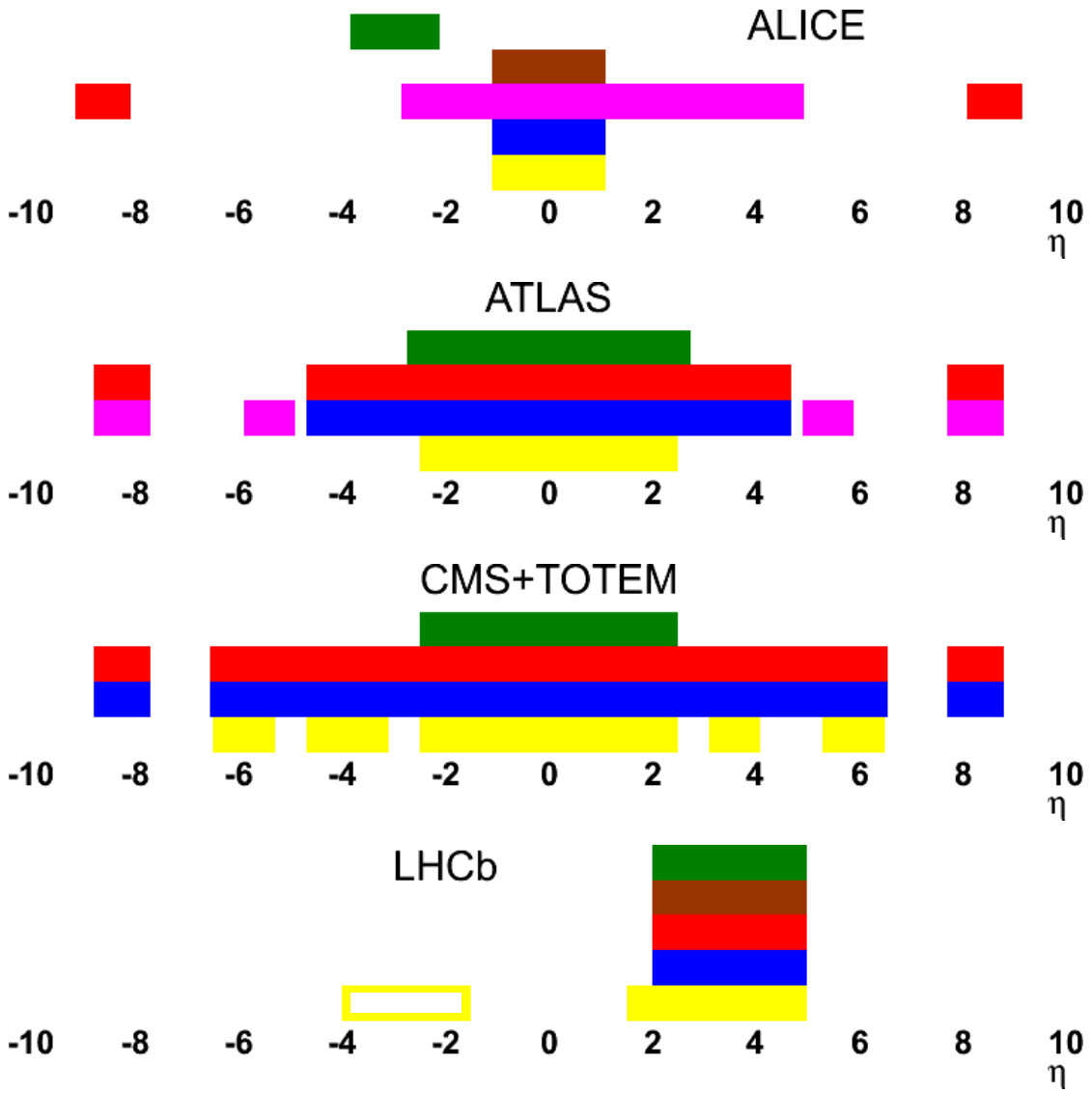


VELO
$\sigma_{IP} \sim 20\ \mu m$
for high-p_T tracks
bwd acc. $-4 < \eta < -1.5$

Tracking System
$\Delta p/p = 0.4\%@5\ \mathrm{GeV}/c$
to $0.6\%@100\ \mathrm{GeV}/c$

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

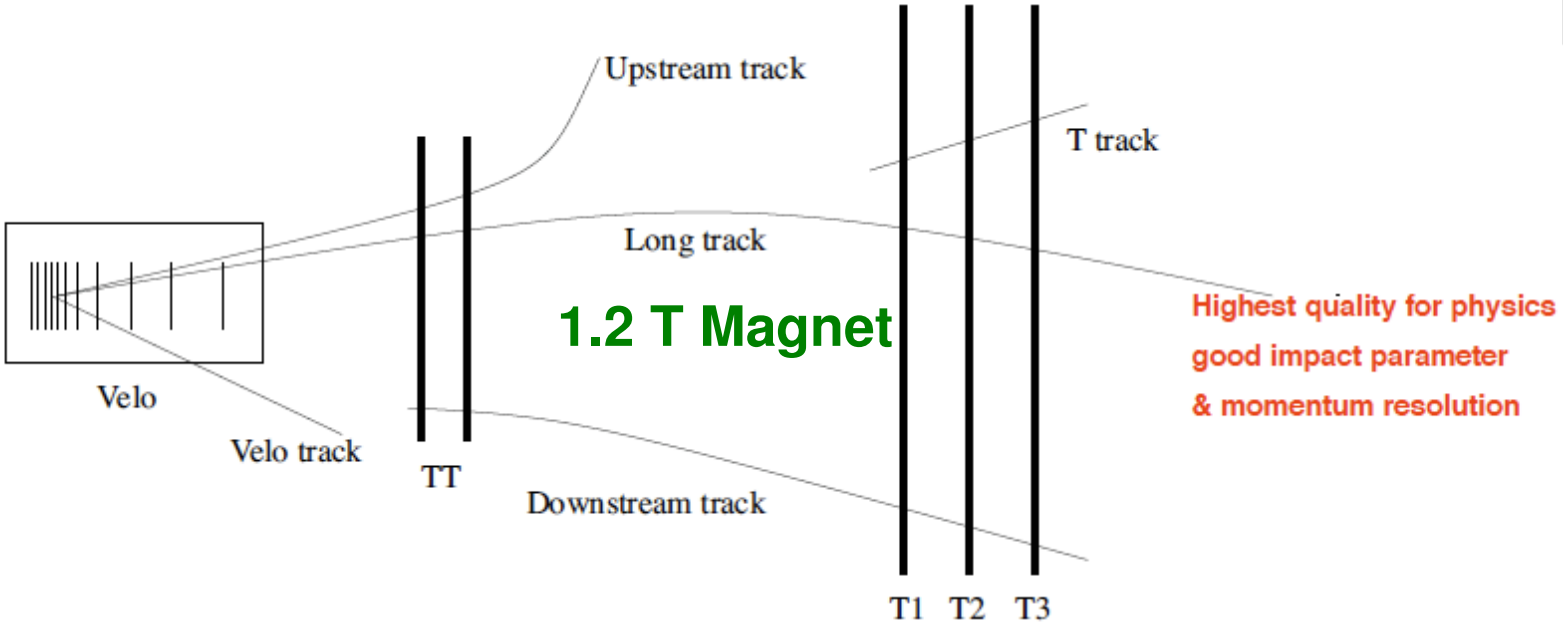
Angular coverage of the LHC experiments



- ALICE
  - central
  - forward muon coverage
- ATLAS & CMS
  - central detectors
- LHCb
  - forward detector
  - tracking, particle-ID and calorimetry in full acceptance

hadron PID
muon system
lumi counters
HCAL
ECAL
tracking

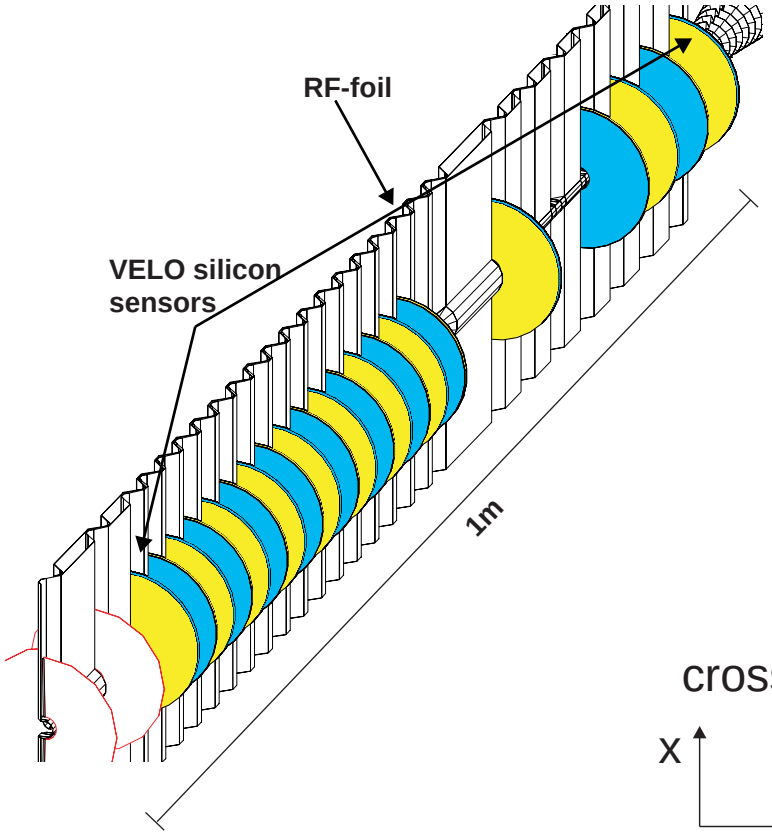
LHCb Tracking



- long and downstream tracks: used for physics measurements
  - ➜ proper momentum measurement (best resolution for long tracks)
- VELO tracks: (primary) vertex reconstruction
  - ➜ large angular acceptance $-4 < \eta < -1.5$ and $1.5 < \eta < 5$
- upstream tracks: subset of VELO tracks with hits in TT
- T-tracks: only found in T-stations (partly from secondary interactions)

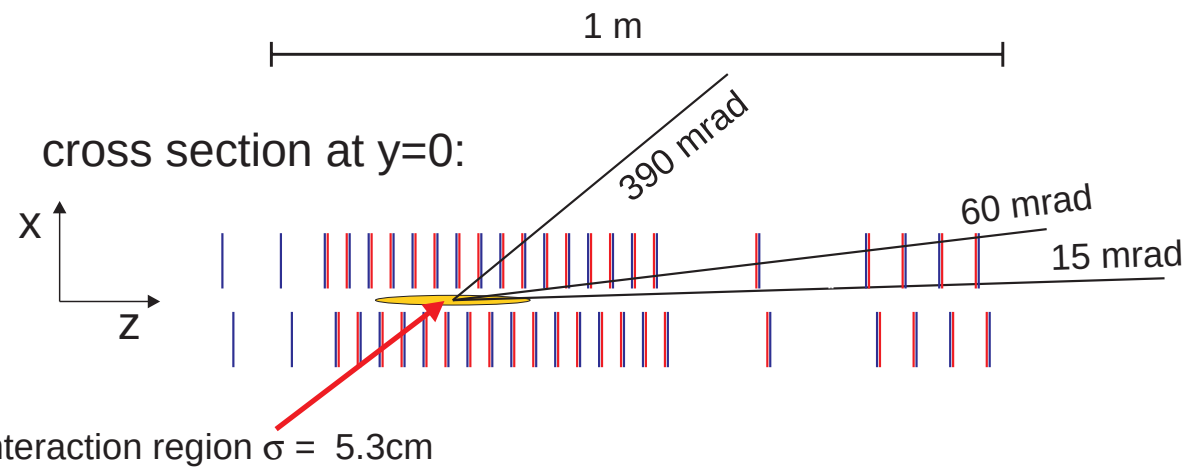
The VErtex LOcator (VELO)

➜ *LHCb subsystem with largest angular coverage*



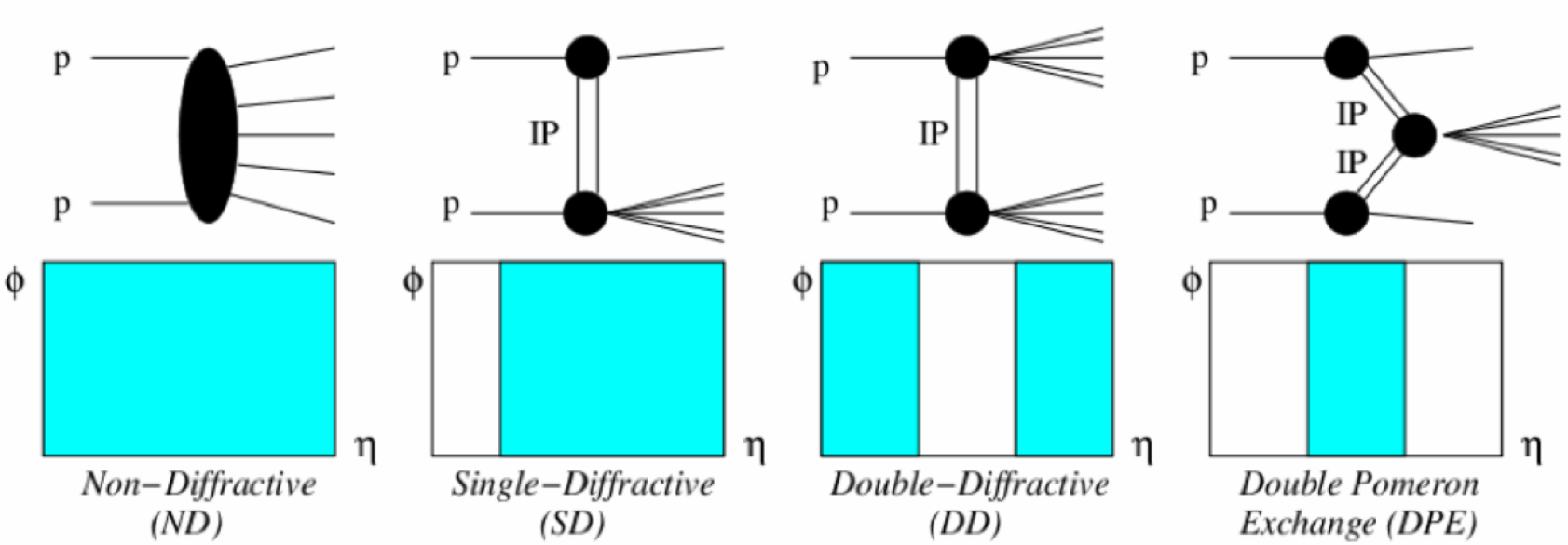
- ➜ 21 $r\phi$ & 2 r-only stations
- ➜ outside of magnetic field
- ➜ no momentum measurement
- ➜ forward and backward coverage
- ➜ blind in central region

cross section at y=0:



Inelastic pp Interactions

➜ *classification of pp-interactions*



❖ Notes:

- differentiation of inelastic cross section according to
  - ➜ color exchange (color octet, gluon): non-diffractive processes
  - ➜ no color exchange (color singlet, pomeron): elastic & diffractive scattering
- no acceptance for elastic scattering with LHCb

Discussion

➜ *inelastic processes are not truly distinguishable*

- example: pp-event with single diffractive signature
  - ➜ one proton is scattered quasi-elastically, OR
  - ➜ both protons are broken up & fragmentation generates a forward proton
- PYTHIA approach: cross sections for different processes

$$\sigma_{inel} = |A_{SD1}|^2 + |A_{SD2}|^2 + |A_{DD}|^2 + |A_{DPE}|^2 + |A_{ND}|^2$$

- alternative view: amplitudes for different processes

$$\sigma_{inel} = |A_{SD1} + A_{SD2} + A_{DD} + A_{DPE} + A_{ND}|^2$$

- comments:
  - ➜ interference terms small in some regions of phase space
  - ➜ experimental cuts allow to probe contributions by certain amplitudes
    - ◆ leading protons, large rapidity gaps: color singlet amplitudes
    - ◆ large multiplicities, large range in η: color octet amplitudes
  - ➜ rigorous separation of diffractive & non-diffractive processes impossible

2. Energy Flow

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

$$EF: \qquad \frac{1}{N_{int}}\frac{dE}{d\eta} = \frac{1}{\Delta\eta}\left(\frac{1}{N_{int}}\sum_{i=1}^{N_{part,\eta}} E_{i,\eta}\right)$$

- ➜ part of underlying event
- ➜ sensitive to multi-parton interactions & parton radiation
- ➜ comparison to PYTHIA 6, PYTHIA 8 and cosmic ray models (generators used to model cosmic ray induced air showers)

❖ analysis for different event classes:

- inclusive minimum bias: ≥ 1 tracks with $\eta \in [1.9, 4.9]$ and $p > 2\,\text{GeV}/c$
- hard scattering: inclusive && ≥ 1 tracks with $p_T > 3\,\text{GeV}/c$
- diffractive enriched: inclusive && 0 tracks with $\eta \in [-3.5, -1.5]$
- non-diffractive enriched: inclusive && ≥ 1 tracks with $\eta \in [-3.5, -1.5]$

Energy Flow: data vs PYTHIA

➜ *(charged+neutral)EF*

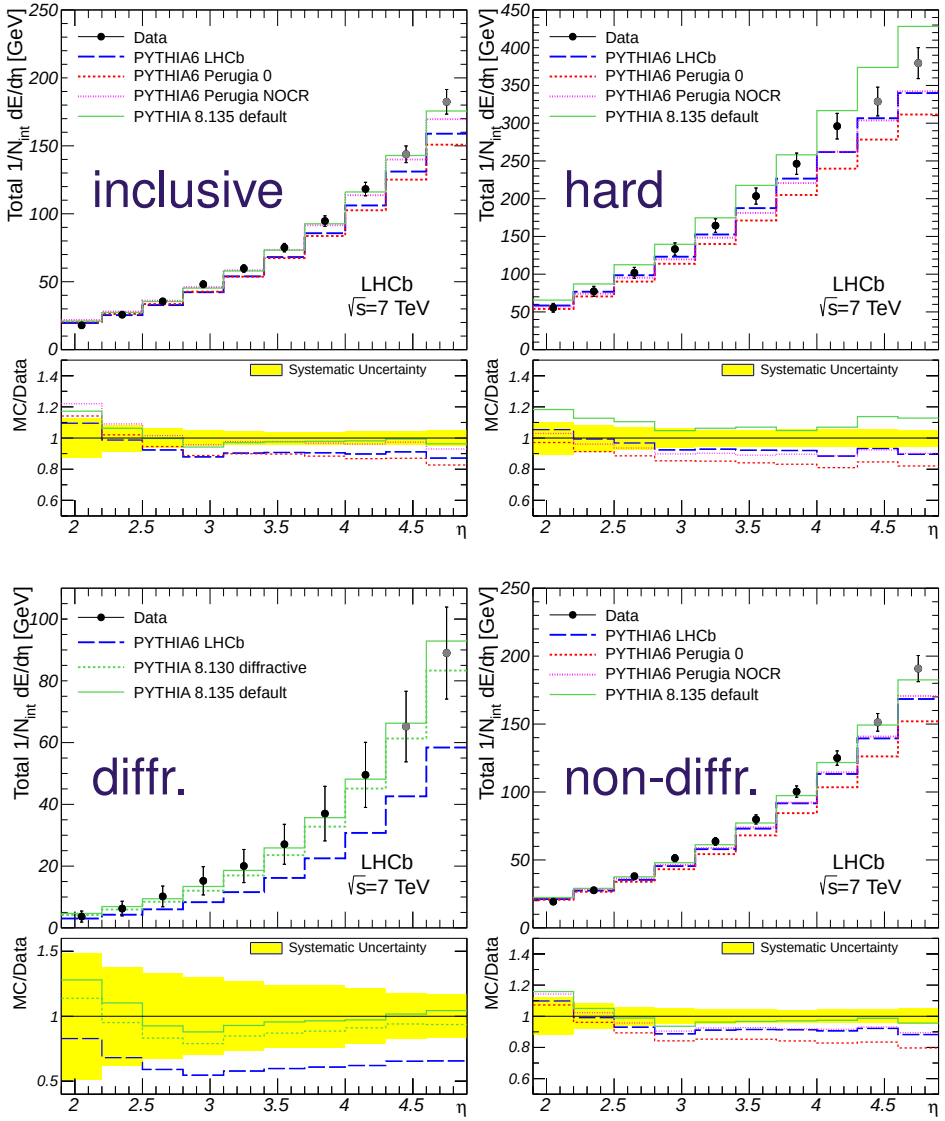
- Energy Flow increases with momentum transfer

  $EF_{diff} < EF_{incl} < EF_{ndiff} < EF_{hard}$

- highest sensitivity at large η
- uncertainties:
  - ➜ dominated by systematics
  - ➜ smallest at large η

PYTHIA 6: Energy Flow is
- ➢ overestimated at small η
- ➢ underestimated at large η

PYTHIA 8.135 default:
- ➢ except for hard scattering the Energy Flow is well described for all samples



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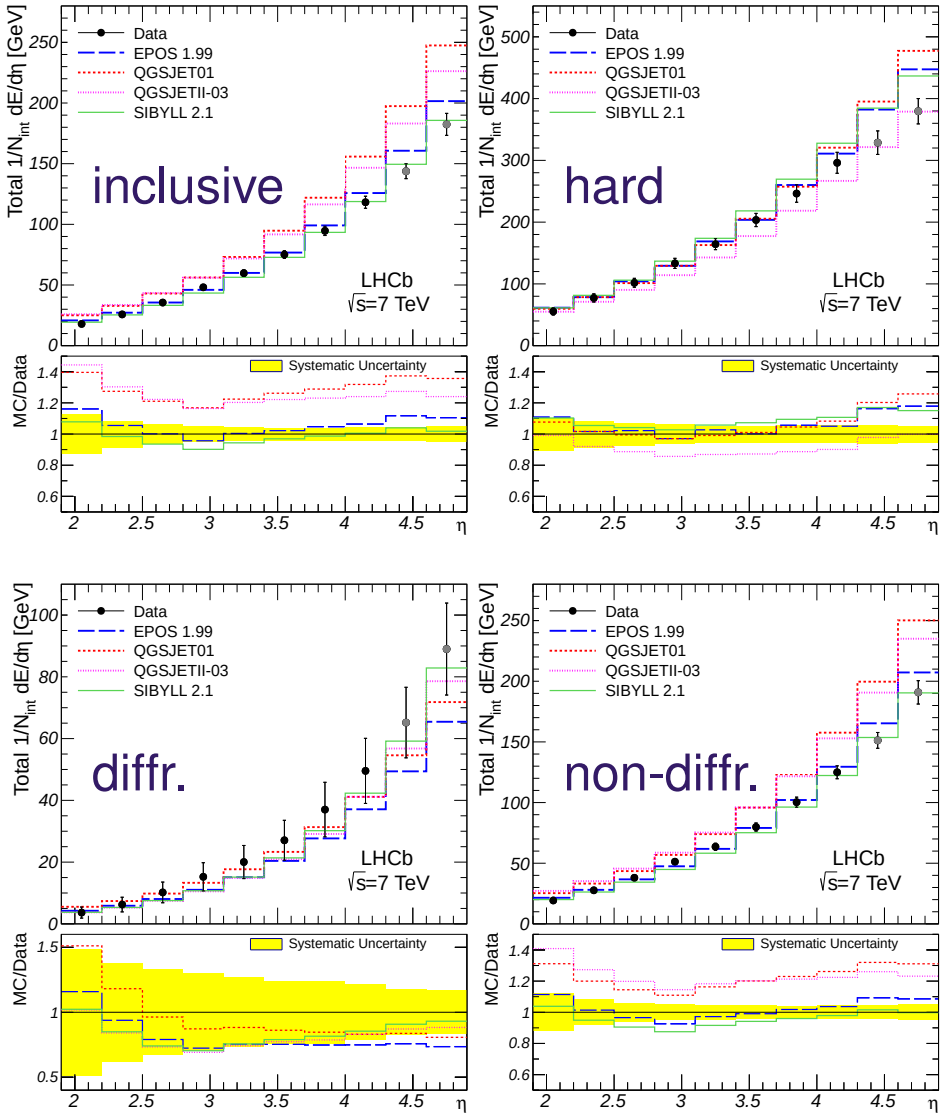
Energy Flow: data vs cosmic ray models

➜ *models not tuned to LHC*

- ➢ EPOS & SIBYLL: good description of EF for inclusive and non-diffractive events
- ➢ QGSJET models: overestimated EF for inclusive and non-diffractive events; good description of hard scattering
- ➢ best description by SIBYLL
- ➢ all models underestimate the EF of diffractive events



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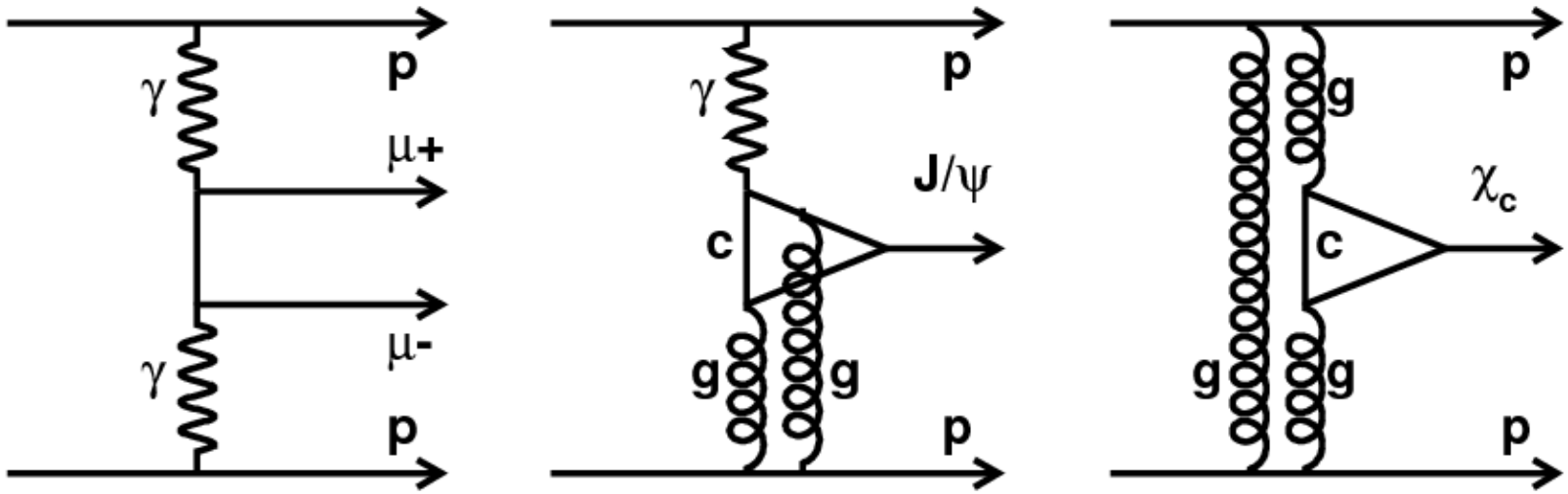
3. Central Exclusive Production

➜ *contributing processes*

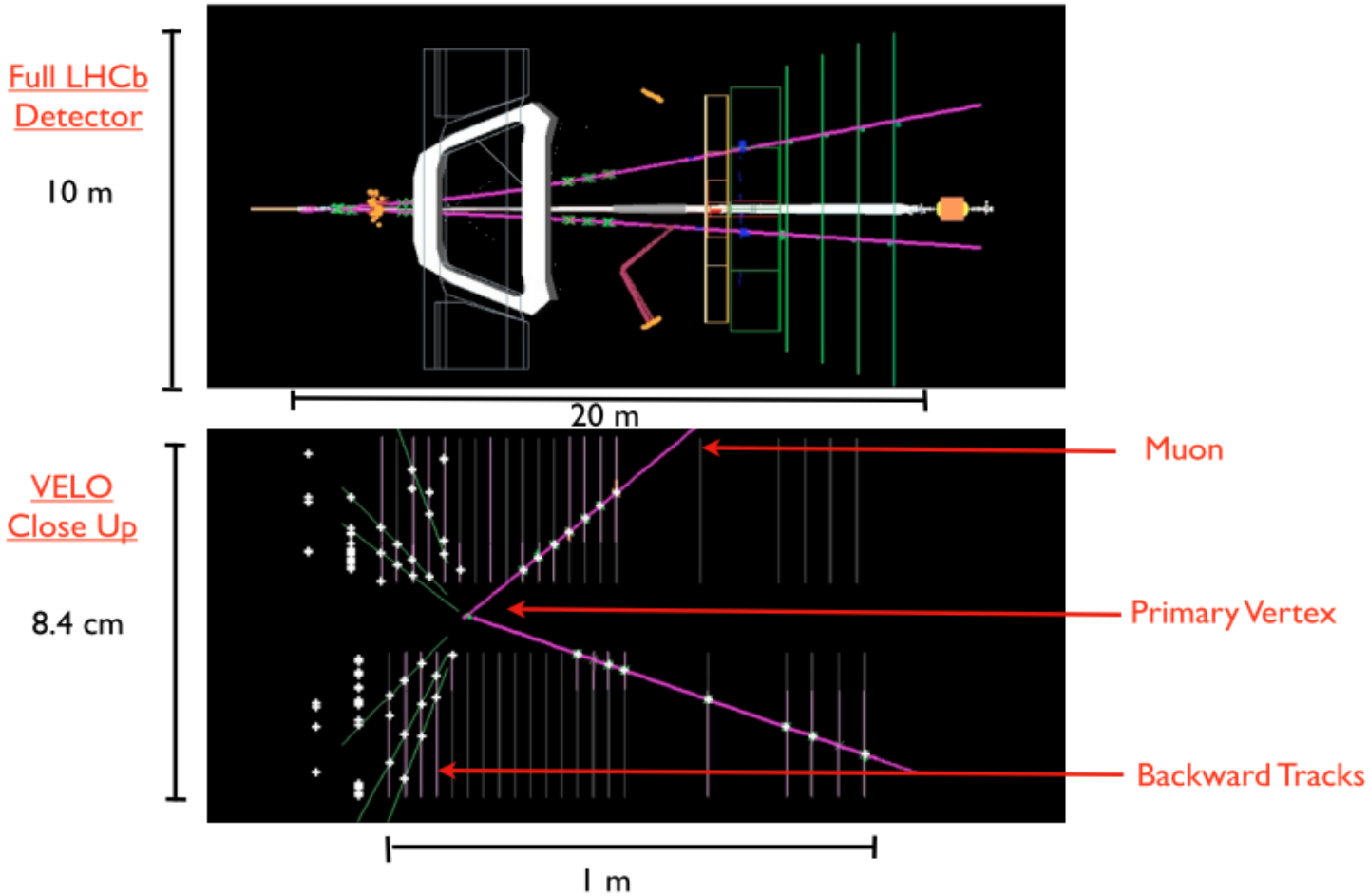


QED **photo production** **double pomeron exchange**

- di-muon or di-muon plus photon final states (for χ_c)
- in the following focus on di-muon final states

Experimental aspects

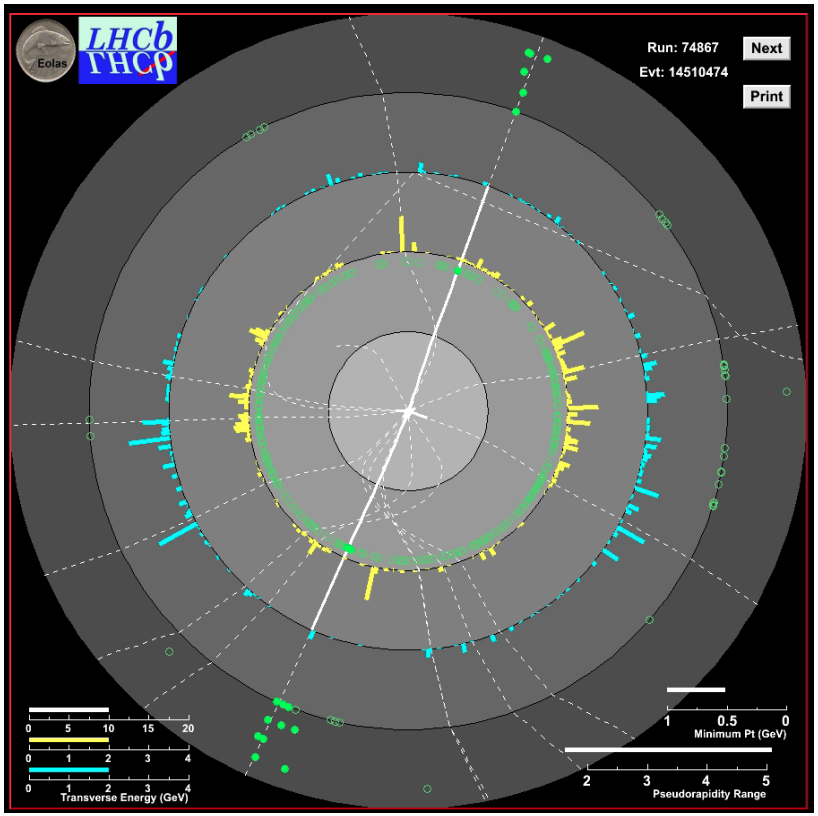
➜ *use VELO to veto non-exclusive processes*

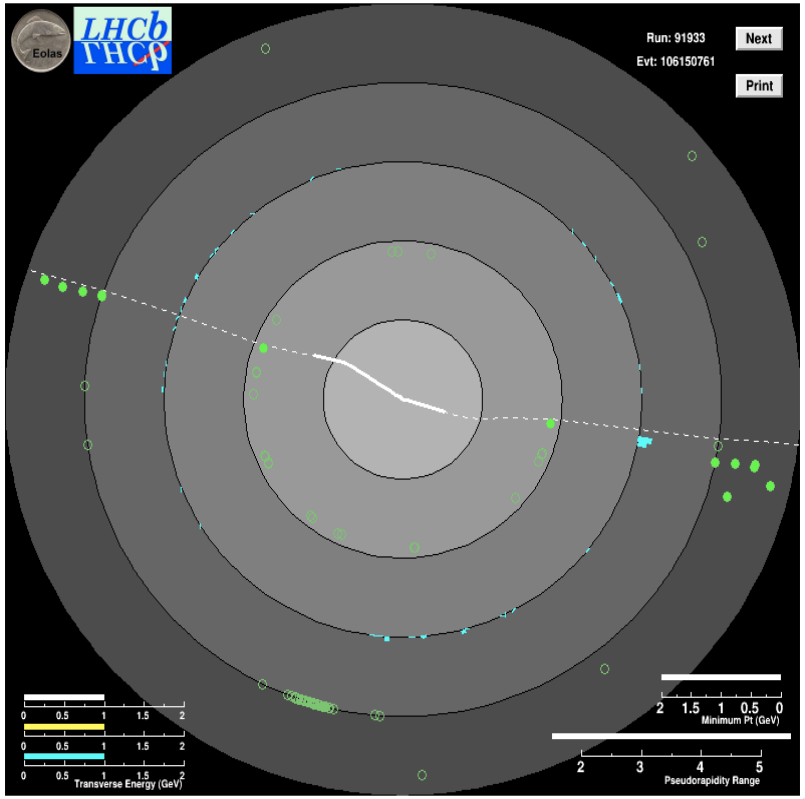


❖ note that some background will remain. . .

Event displays

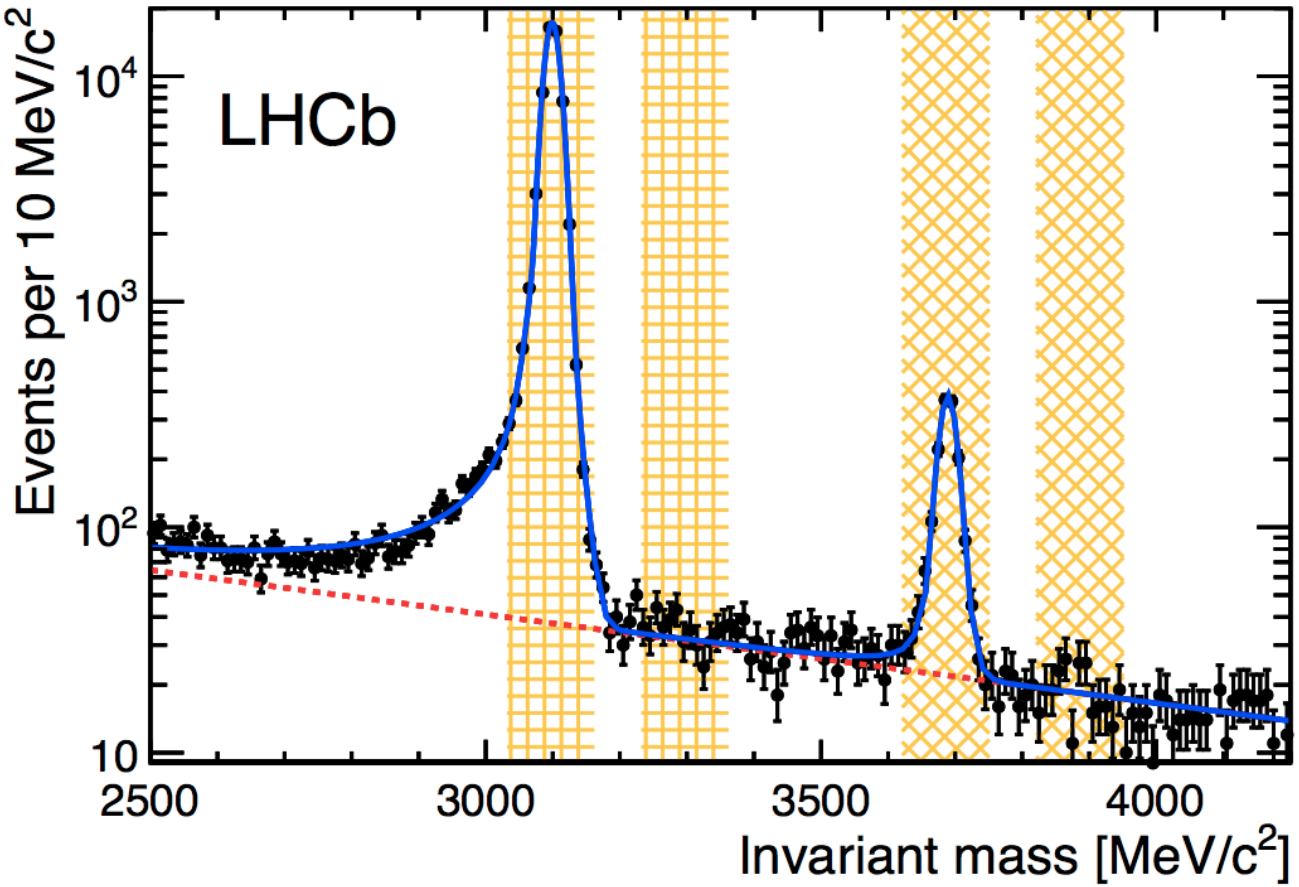
➜ *compare $pp \to Z(\mu\mu)X$ and CEP J/ψ production*





- clean experimental signatures
- very low multiplicities at TeV centre-of-mass energies!

Exclusive di-muon invariant mass spectrum



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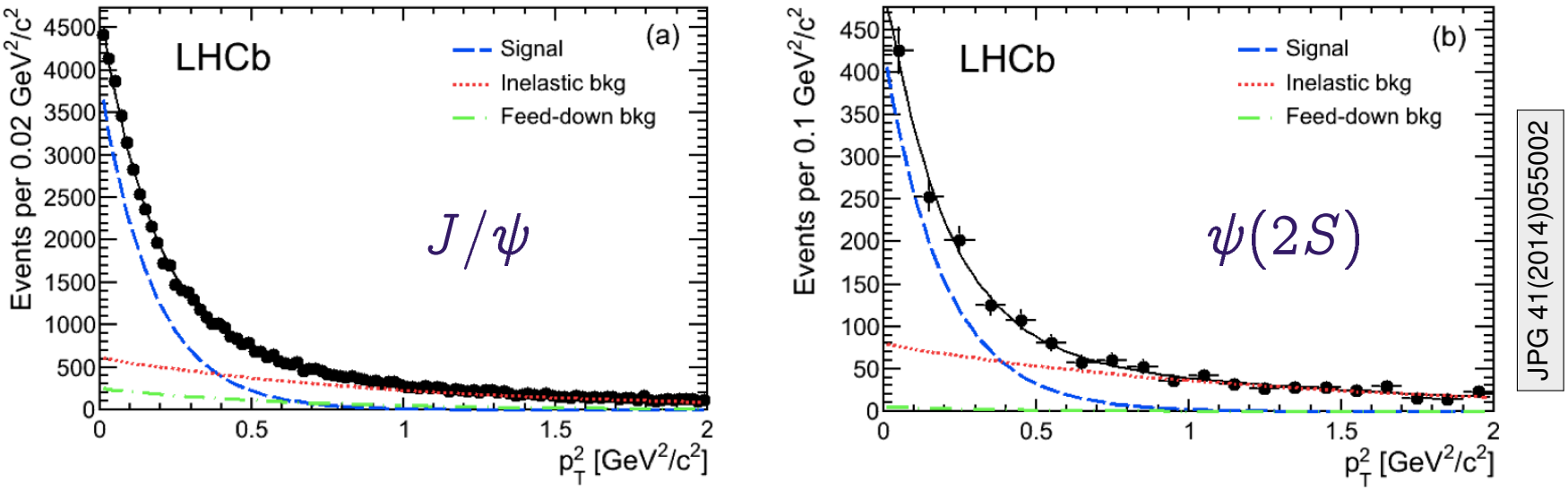
- clear mass peaks of J/ψ and $\psi(2S)$
- exponentially falling QED background

Transverse momentum spectra

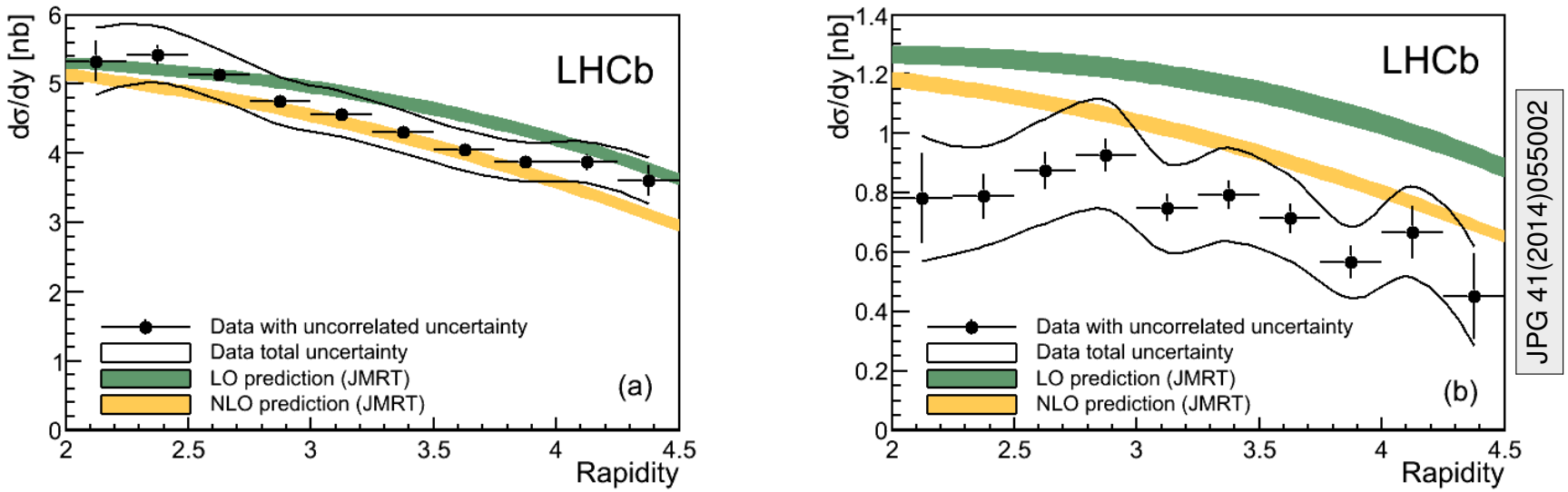
➜ *disentangle exclusive and non-exclusive components*



- superposition of two exponentials - Regge theory inspired $d\sigma/dt \sim e^{bt}$
  - ➜ soft component: CEP
  - ➜ hard component: “normal” QCD
- fitted slopes consistent with expectations extrapolated from HERA
  - ➜ J/ψ: $b_{\mathrm{CEP}} = 5.70 \pm 0.11\,\mathrm{GeV}^{-2}$, $b_{\mathrm{non-excl}} = 0.97 \pm 0.04\,\mathrm{GeV}^{-2}$
  - ➜ $\psi(2S)$: $b_{\mathrm{CEP}} = 5.1 \pm 0.7\,\mathrm{GeV}^{-2}$, $b_{\mathrm{non-excl}} = 0.8 \pm 0.2\,\mathrm{GeV}^{-2}$

Rapidity dependence

➜ *compare data to theoretical predictions*



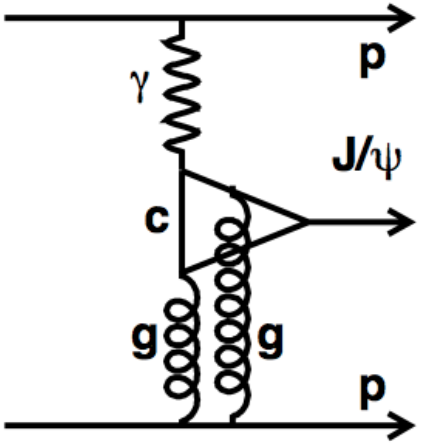
- data and predictions agree within uncertainties
- NLO calculations are preferred

Photo-production cross-section

➜ *theoretical description*

$$\frac{d\sigma}{dy_{pp\to pJ/\psi p}} = r_+ k_+ \frac{dn}{dk_+}\sigma_{\gamma p\to J/\psi p}(W_+) + r_- k_- \frac{dn}{dk_-}\sigma_{\gamma_p\to J/\psi p}(W_-)$$

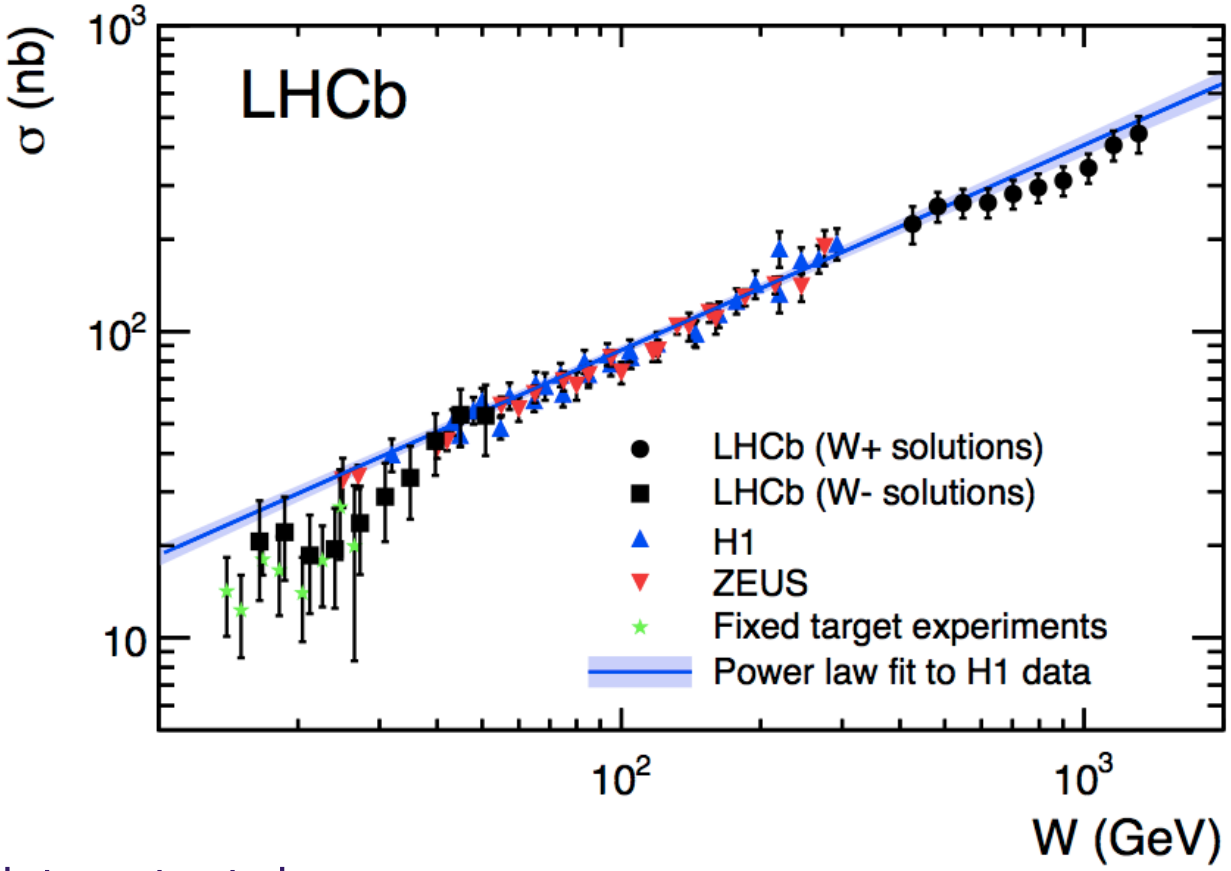
- left-hand side measured by LHCb
- two targets for producing the J/ψ
- LHCb cross-sections proportional to
  - ➜ gap survival probability r
  - ➜ photon flux dn/dk
- sensitivity to gluon PDF $g(x)^2$



HERA measurement: $\sigma_{\gamma p\to J/\psi p}(W) = 81\left(\frac{W}{90\text{GeV}}\right)^{0.67}\text{nb}$

- take $\sigma_{\gamma p\to J/\psi p}(W_\pm)$ from HERA and solve for $\sigma_{\gamma p\to J/\psi p}(W_\mp)$

Comparison to HERA results



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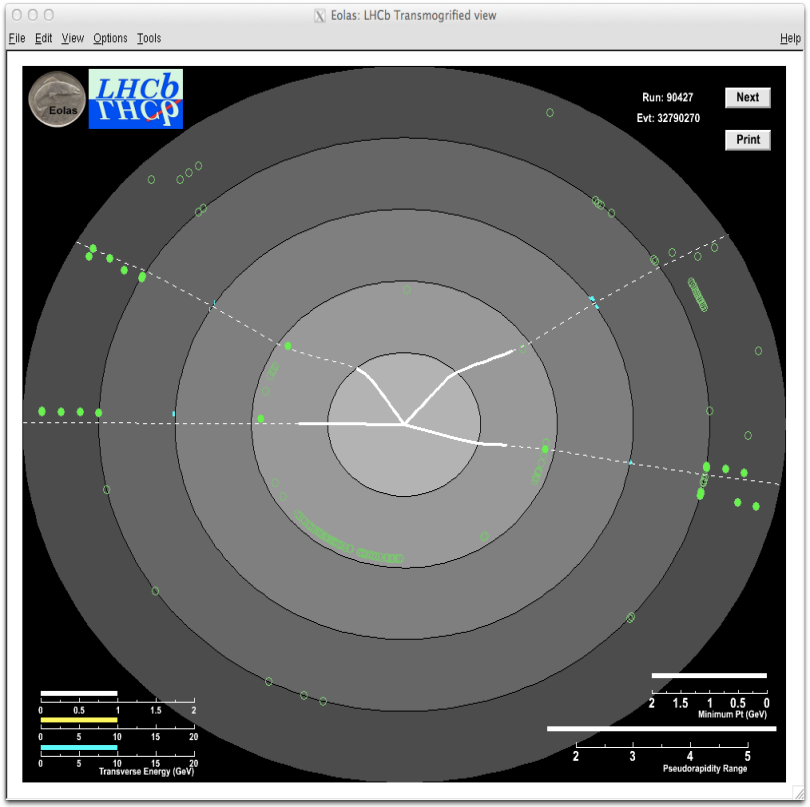
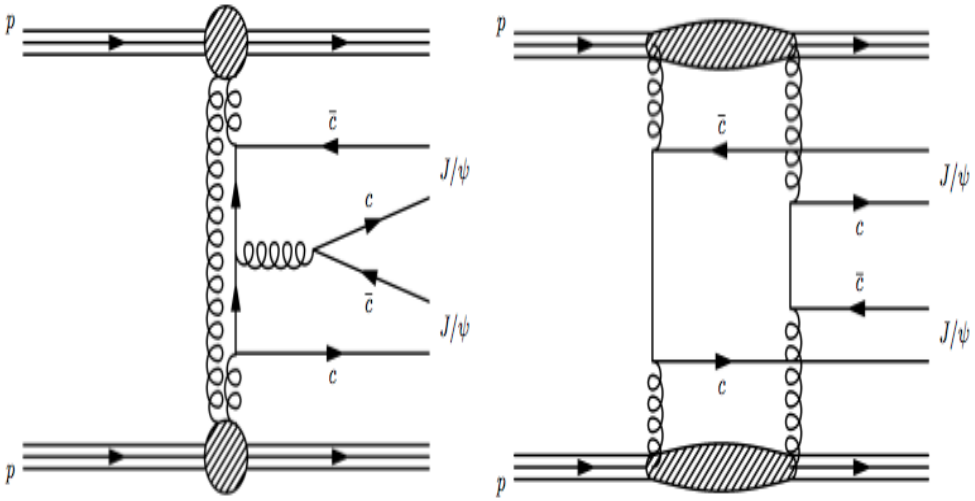
- LHCb data enter twice
- significant extension of kinematic range
- qualitative description by power law works
- evidence for deviation from simple power law ➜ NLO contributions (?)

Double J/ψ production

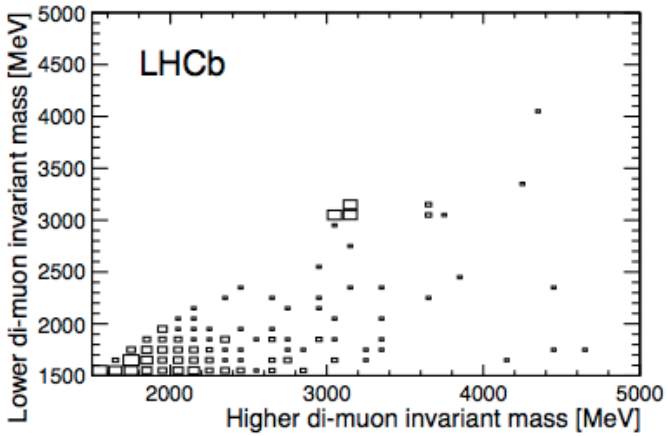
➜ *surprise discovery*

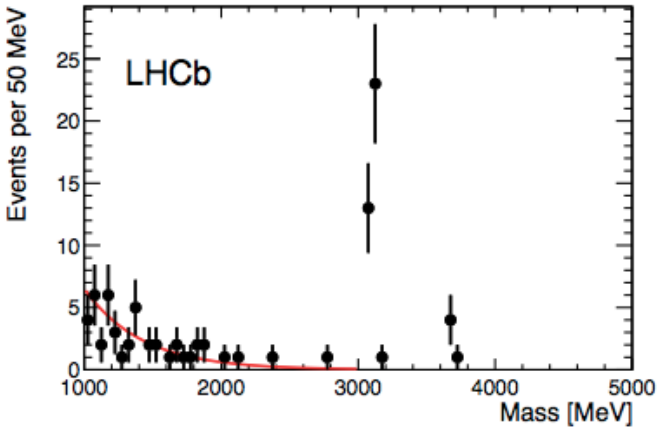




- initially not expected
- a posteriori reasonable well theoretically understood

Double J/ψ mass spectra





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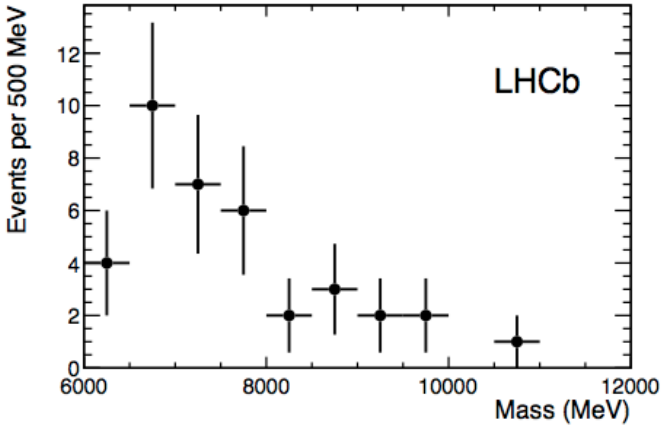

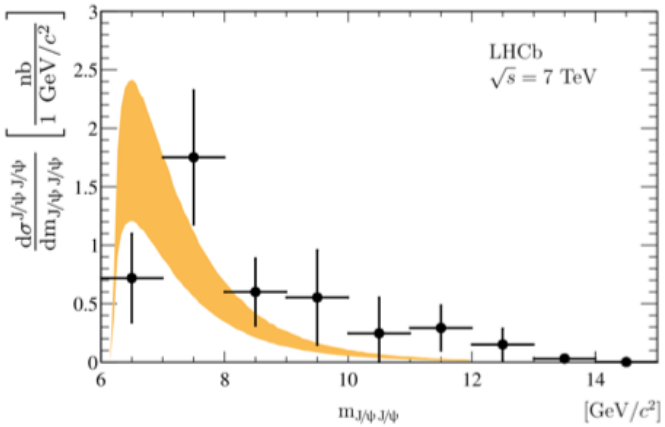

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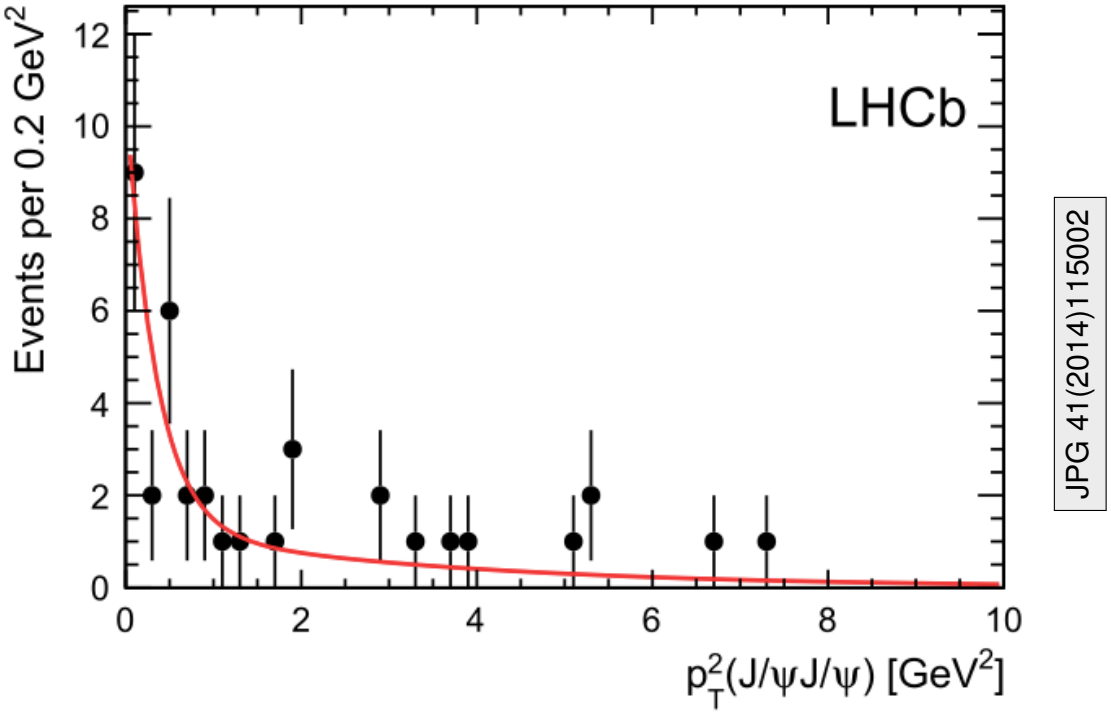
- clean experimental signal
- di-J/ψ mass spectra similar in CEP and inclusive production

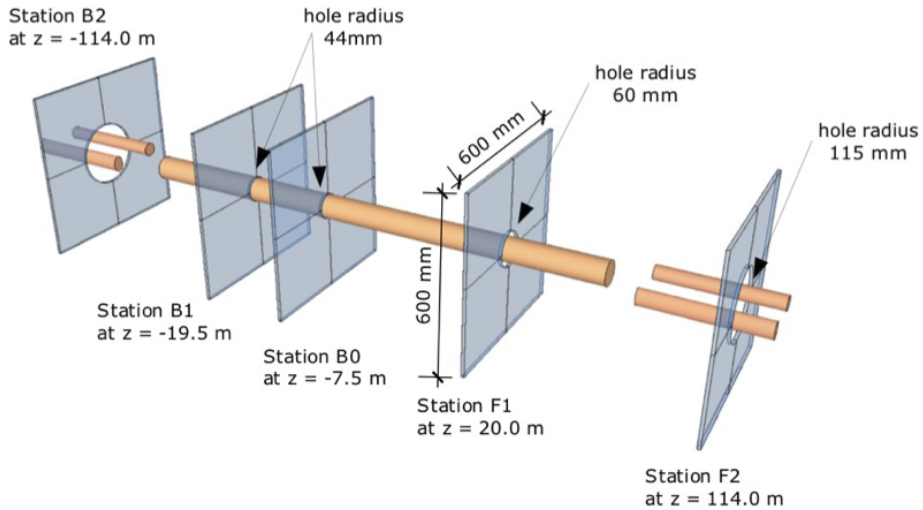
Extraction of the exclusive part

➜ *disentangle components via p_T spectrum*

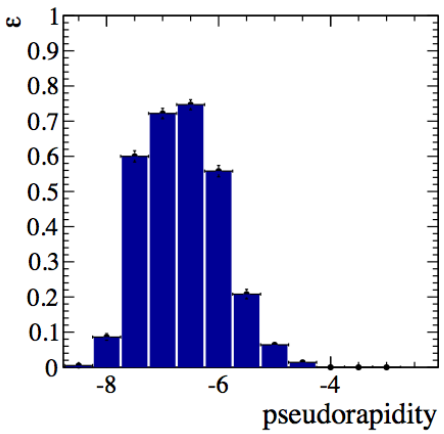


- 42 ± 13% exclusive contribution
- additional large uncertainties from modelling the non-exclusive part

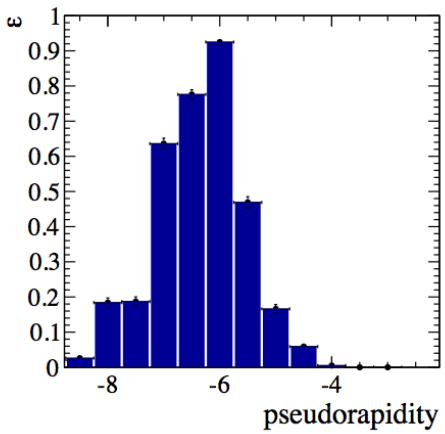
➜ *HeRSCheL: High Rapidity Shower Counters for LHCb*



- forward scintillators for selecting rapidity gaps
- up to ± 114 m from IP
- central region not covered
- gap size $2 < \eta < 8$
  - ➜ huge gain for diffractive physics and central exclusive production (e.g. J/ψ photoproduction on the proton in pA)



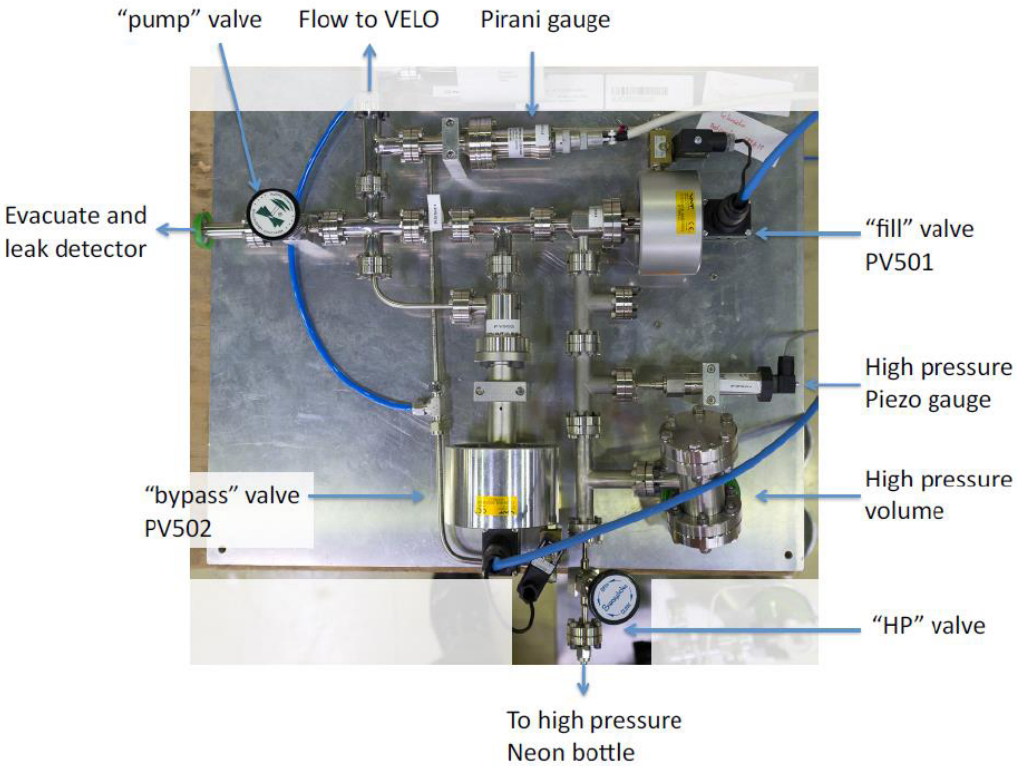
$p_T > 0.5\,\mathrm{GeV}/c$



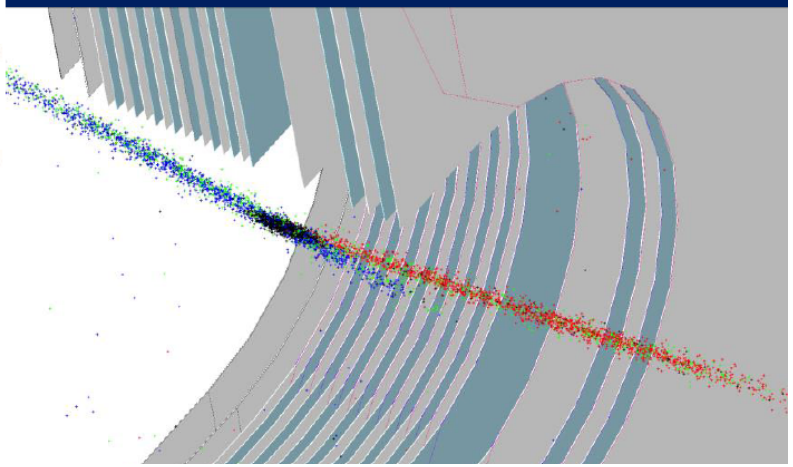
$p_T > 1.5\,\mathrm{GeV}/c$

LHCb simulation results for the efficiency to see charged pions

➜ SMOG: System for Measuring Overlap with Gas



- injection of (Ne) gas into interaction region
- very simple robust system
- used for a precise luminosity determination

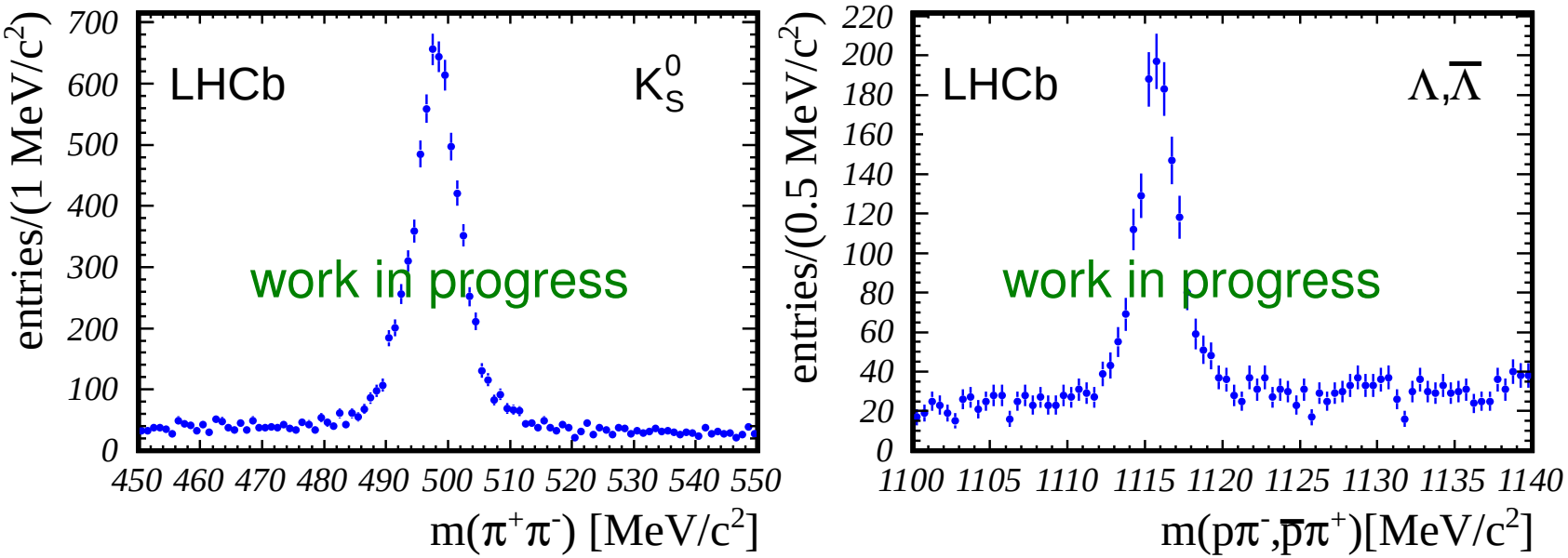


- possibility to inject (noble) gases: Ne or He, Ar, Kr (under discussion)
- fixed target physics in pA and PbA configuration

Nucleus-nucleus interactions

➜ *first look at PbNe collisions using data from O(10) min running*

PbNe-interactions - $\sqrt{s_{NN}}$=54.4 GeV



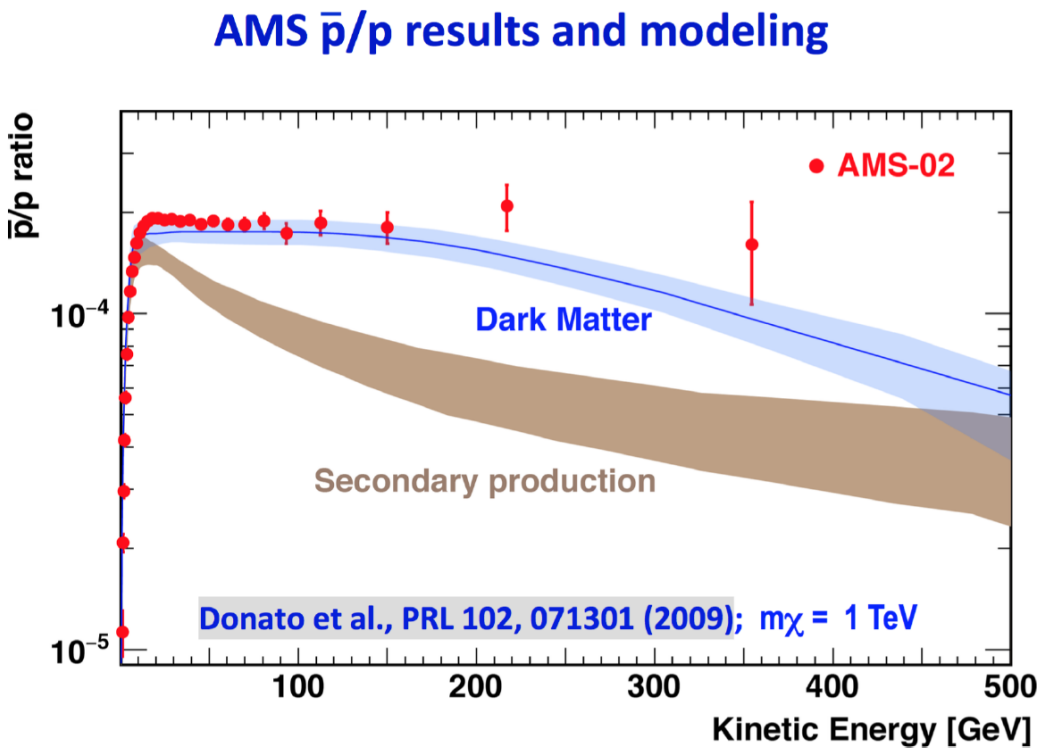
❖ physics potential:

- ➜ explore nuclear structure at large x
- ➜ conditions between SPS and RHIC for QGP studies

Links to other communities

➜ *cosmic ray physics and cosmology*

- understanding of extensive air showers ➜ MC tuning
- understanding the AMS antiproton/proton ratio



❖ use fixed target measurements to clarify: QCD or Dark Matter annihilation

5. Summary

➜ *diffraction physics is an integral part of the LHCb physics portfolio*

- results from RunI
  - ➜ Energy Flow measurements study diffractive particle production
  - ➜ results on single and double charmonium production in CEP
  - ➜ CEP results from p-Pb collisions in the pipeline
- prospects for LHC RunII
  - ➜ improved detector for diffractive physics
  - ➜ more data in pp and p-Pb
  - ➜ new centre-of-mass energies
  - ➜ new developments further enlarge the physics program
    - fixed target physics
    - Pb-Pb collisions