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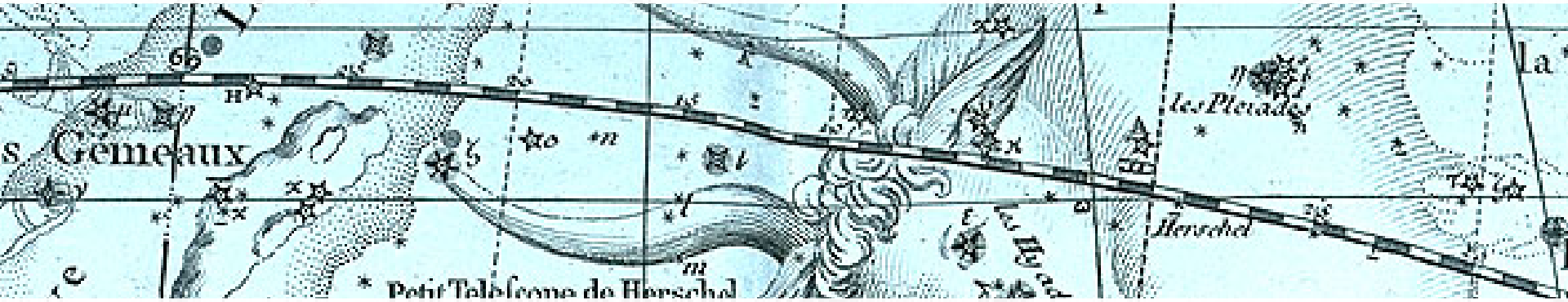



# Central Exclusive Production at LHCb (and other low multiplicity physics)

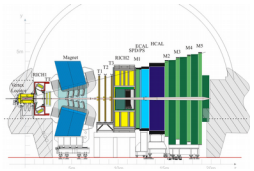
**Paolo Gandini**

*University of Oxford*

Exotic Hadron Workshop @ Edinburgh

27th September 2016

# Outline



*LHCb is in a unique position at the LHC to measure*
*QCD phenomena  at high rapidities and low transverse momenta*

*Perfect to study Central Exclusive Production (CEP) processes at high energy*

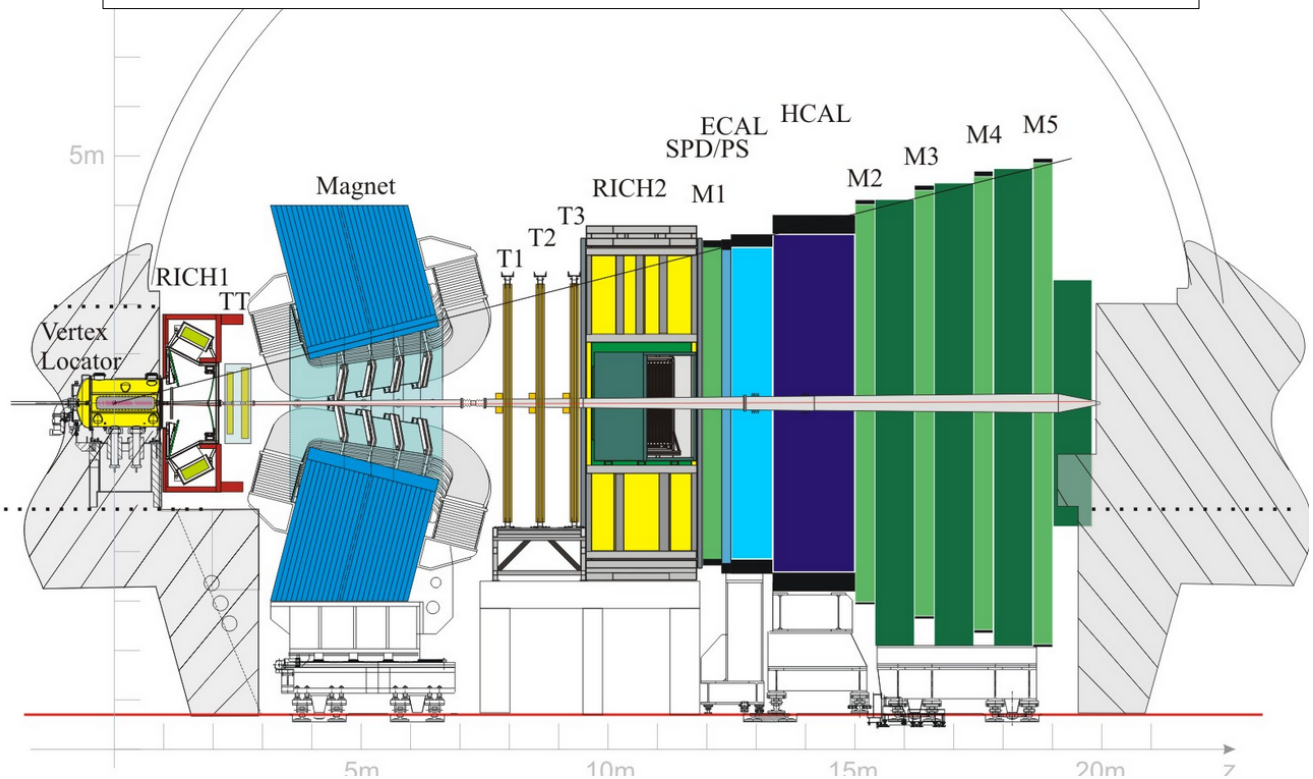
*A **not-so-random** collection of results and ideas → past and future*

*Goal is to to show what we can do/can't do and highlight current activities*

- Theoretical interest & Experimental signatures
- The Herschel detector
- Recent results and examples
- CEP as a production mechanism
- Seaches in production, not in decay

# LHCb Detector

*Please see nice talk by Marco Pappagallo*
*I will highlight the most relevant features for this talk*




Fully instrumented: $2 < \eta < 5$

**Some sensitivity: $-3.5 < \eta < -1.5$**

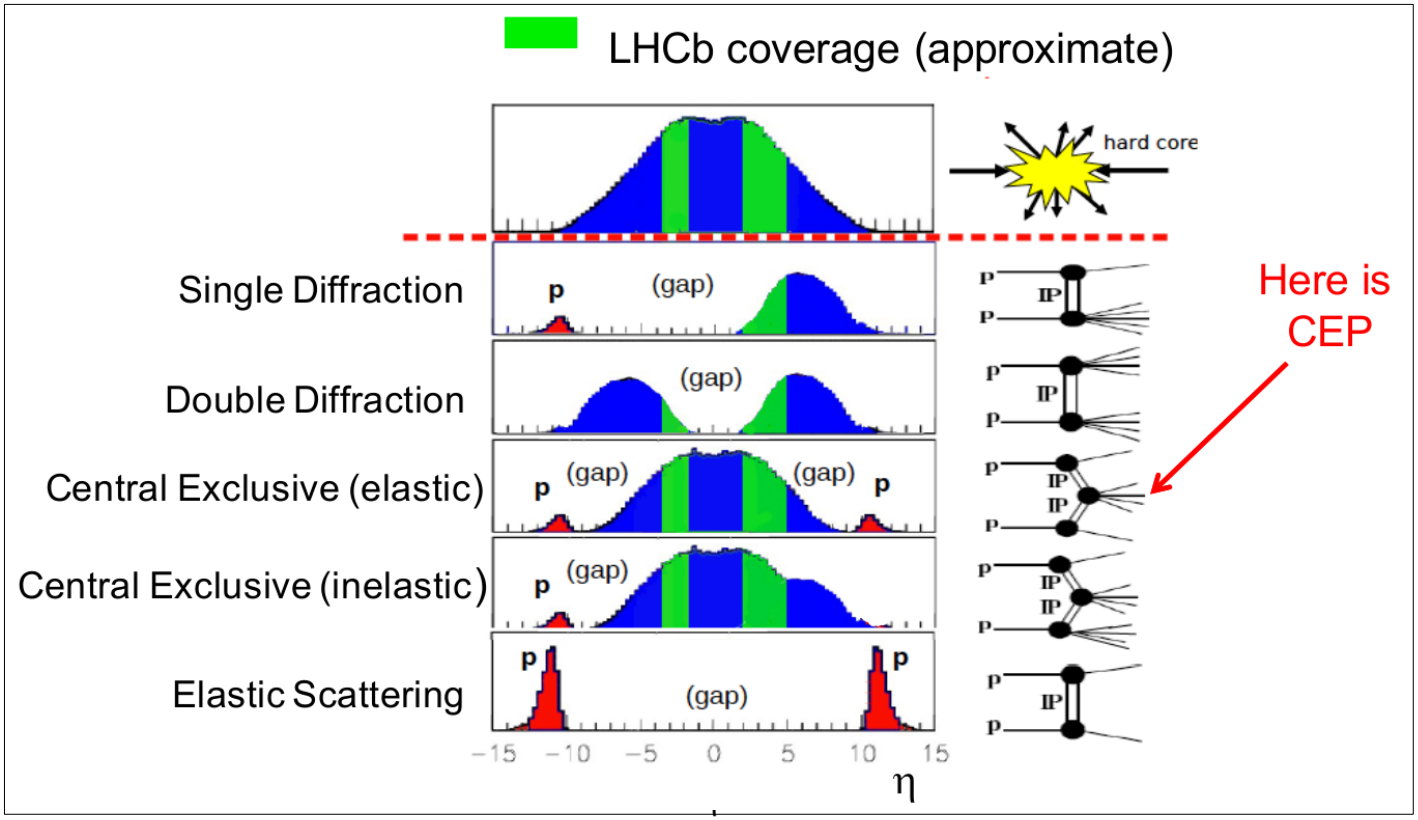
- Forward spectrometer
- Good Vertex measurements
- Precise Tracking
- Excellent PID up to 100GeV
- Versatile Trigger (L0+Hlt)

# CEP – Introduction

- Central Exclusive Production can be done at LHCb → What do we look for?

$$pp \rightarrow p + X + p \text{ (rapidity gaps and protons intact)}$$

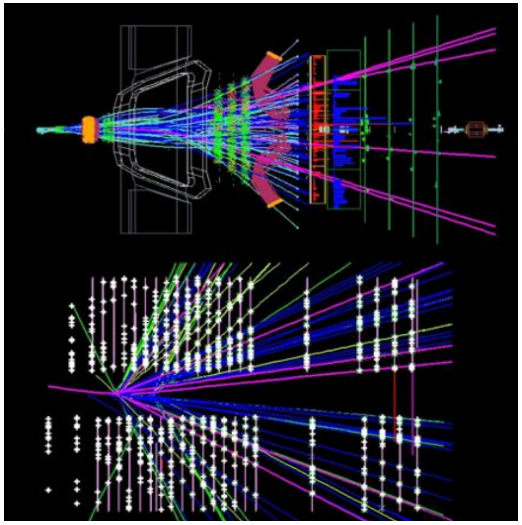
- Colourless objects in QCD, Very low PT objects, Clean experimental environment
- Rich Physics: Photon-Pomeron, Double-Pomeron, Photoproduction, Glueballs, Exotica
- Just to give an idea of "coverage" of various processes:



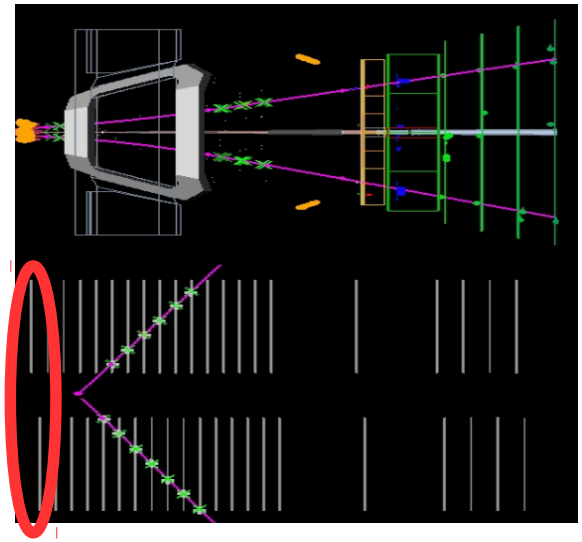
# CEP - Signatures

- How do we select / trigger these events?
- Protons → escape in the beampipe
- Events with low activity in detector
- Look at backwards tracks in the VELO (some η coverage)
- Unique features compared to “standard” LHCb event

Typical Event



CEP-like event: 2muons

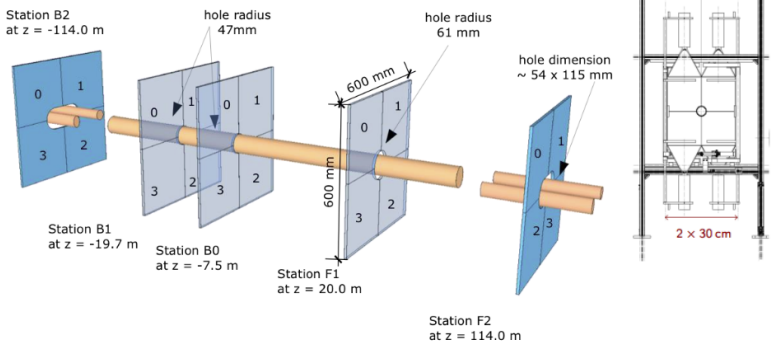


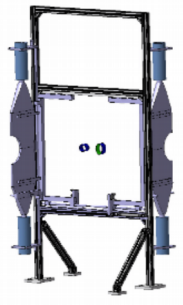
LHCb is forward, but we can detect backward tracks in the VELO (no p information for those)

# Herschel Detector in Run2

- New detector installed for Run2 in 2015. Fully operational
- Start of 2016: new better electronics installed
- Increase η coverage in the forward/backward region
- IDEA is to **veto events with activity at high η**

- Idea: scintillators in the tunnel where beampipe is accessible
- High Rapidity Shower Counters for LHCb: HeRSCheL
- Five planes of scintillators: 4 quadrants, 20mm thick
- Use same electronics of Preshower Detector



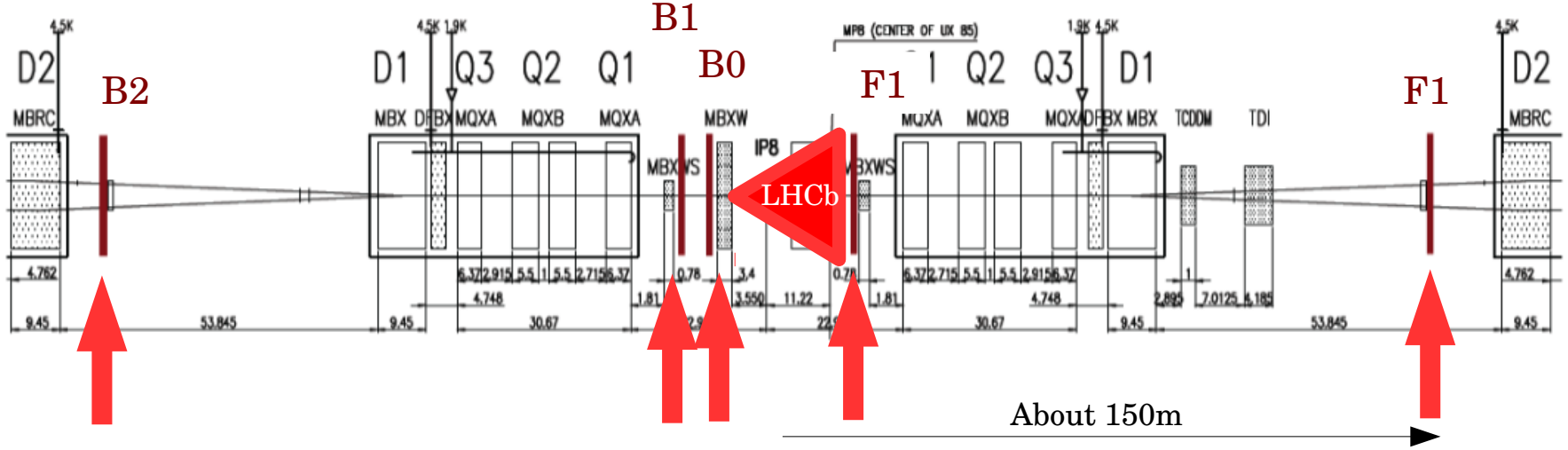



Parking position available

# Herschel Detector in Run2

- New detector installed for Run2 in 2015. Fully operational
- Start of 2016: new better electronics installed
- Increase η coverage in the forward/backward region
- IDEA is to **veto events with activity at high η**

To get an idea on distances




- Fully operational → first analysis using it performed
- Now included in HLT1 to reduce trigger rates
- Work ongoing for the integration in L0 hardware trigger

# Herschel Detector in Run2

Figure 2: Photographs of the backward HERSCHEL stations (left: B0, middle: B1, right: B2)

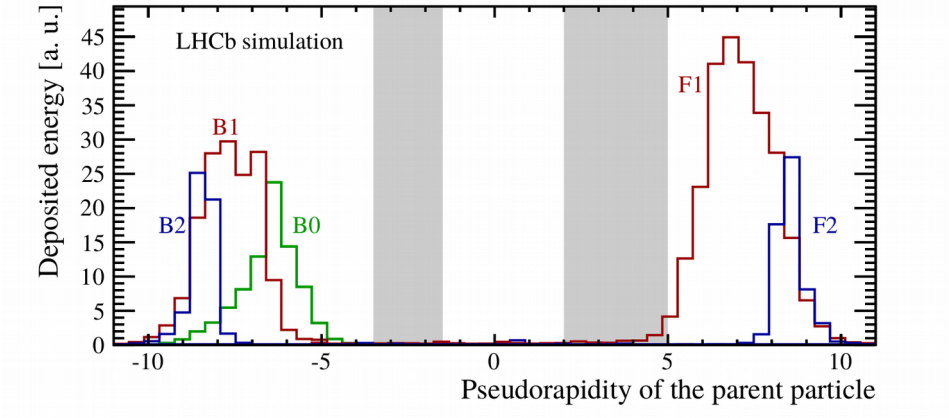
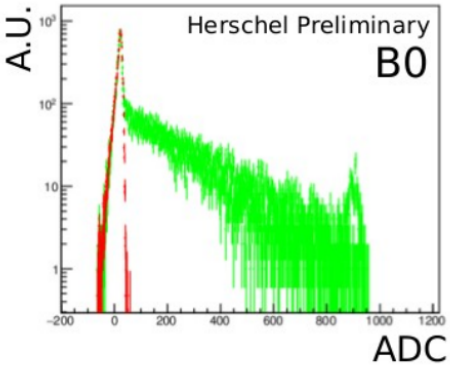
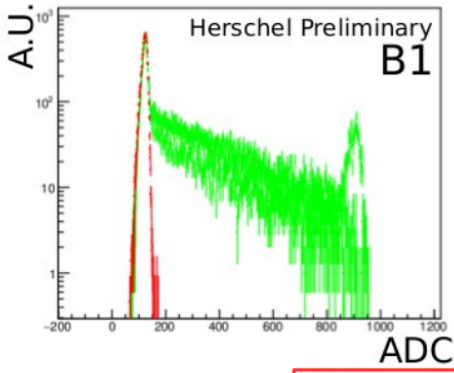


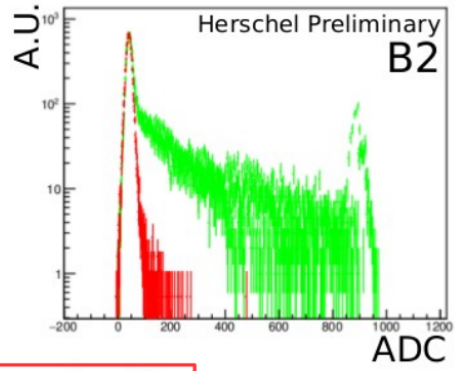

Figure 4: Energy deposit in the scintillators as function of the pseudorapidity of the "parent" particle that caused the shower. The grey area indicates the nominal pseudorapidity coverage of LHCb.

# Herschel Detector in Run2

- Just an example on the ADC distributions observed (2015)
- We can exploit different techniques to evaluate the pedestal
- We can extract the efficiency via data-driven tecniques



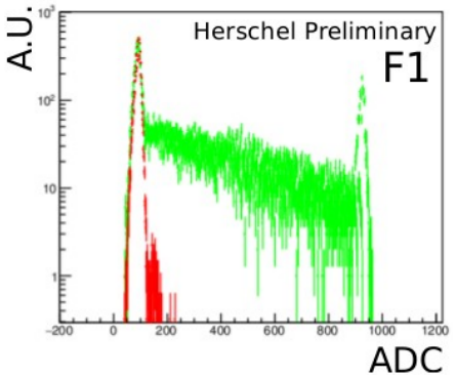



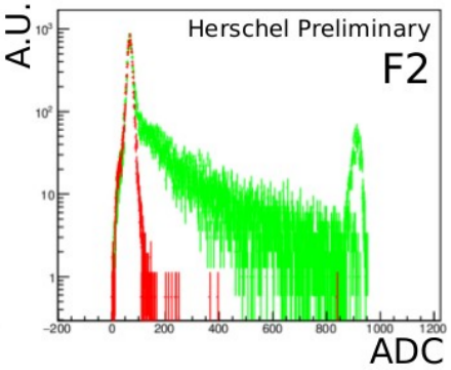




Random trigger on bb crossing

First empty crossing after a bb train

How signal should look like (considering the bunching)



# CEP programme at LHCb

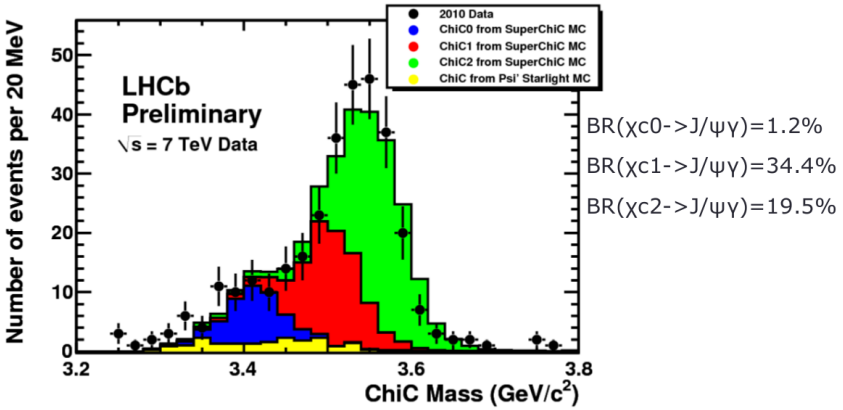
- LHCb has a rich CEP programme → rapidly expanding
- Already published

| | |
|---|---|
| **CEP J/Ψ,Ψ(2S)** | **2014 J. Phys. G. 41 055002** |
| **CEP double J/Ψ** | **2014 J. Phys. G. 41 115002** |
| **CEP ϒ** | **JHEP 1509 (2015) 084** |
| **CEP J/Ψ, Ψ(2S) at 13TeV** | **LHCb-CONF-2016-007** |

- New analyses to come e.g:
  - Other charmonium ($\chi_{0,1,2}$ states)
  - Exotica searches
  - Spectroscopy in CEP
  - (see Marco's talk for details)

- Analyses still ongoing… stay tuned!

Taken for an old CONF note 2010
Should update soon

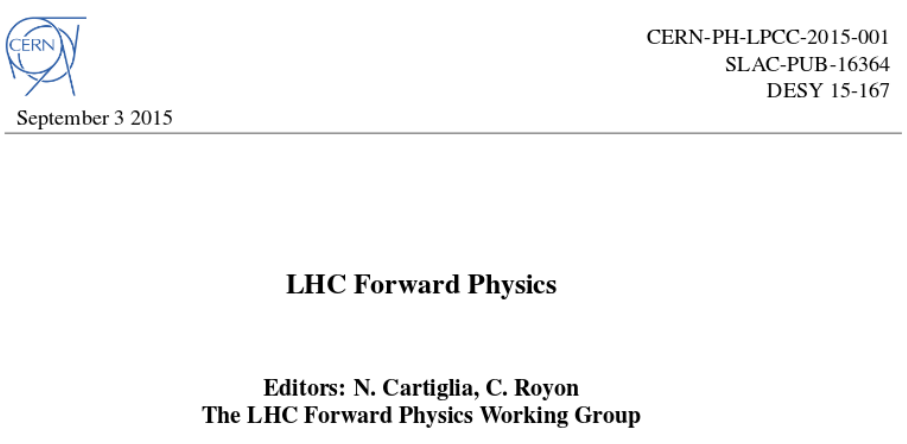



Inelastic contribution appears to be much larger than for J/ψ.
In a first approximation it should be square of bkg in J/ψ process.

# LHC forward physics WG

- LHC wide effort → this is included in forward physics WG
- Yellow pages: http://slac.stanford.edu/pubs/slacpubs/16250/slac-pub-16364.pdf
- A lot of effort both theoretical and experimental communities
- LHCb → Herschel, CMS+TOTEM special runs, ATLAS+ALPHA

- Two methods
  - Tag the protons and momentum balance
  - Veto forward activity and fit the pt2 spectrum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DESY 15-167

September 3 2015

**LHC Forward Physics**

**Editors: N. Cartiglia, C. Royon**
**The LHC Forward Physics Working Group**

**5 Central Exclusive Production** **102**
5.1 Introduction . . . 102
5.2 Analysis techniques and detectors to study exclusive processes at the LHC . . . 104
5.2.1 Analysis techniques . . . 104
5.2.2 Central exclusive production at LHCb and ALICE . . . 104
5.2.3 Central exclusive production at CMS and ATLAS . . . 105
5.3 QCD processes . . . 106
5.3.1 Introduction . . . 106
5.3.2 Forward proton tagging: phenomenological insight and advantages . . . 108
5.3.3 Conventional quarkonium production . . . 110
5.3.4 'Exotic' quarkonium production . . . 113
5.3.5 Photon pair production . . . 114
5.3.6 Light meson pair production . . . 115
5.3.7 Production of low mass resonances and glueballs . . . 118
5.3.8 Quarkonium Pair Production . . . 122

# CEP-type analyses at LHCb

- LHCb can't "reconstruct" the forward/backward intact protons
- Select signal requiring no other activity in the detector
- Extract purity looking at the pt2 distribution (CEP/nonCEP fractions)
- Irreducible backgrounds dominated by inelastic backgrounds
- Undetectable events where the proton breaks up in the forward direction

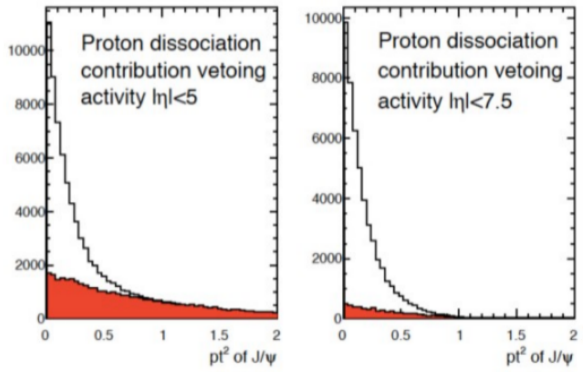
Example of 2013 Jspi paper: NO HERSCHEL

**Updated measurements of exclusive $J/\psi$ and $\psi(2S)$ production cross-sections in $pp$ collisions at $\sqrt{s} = 7$ TeV**

| Correlated uncertainties expressed as a percentage of the final result | |
|---|---|
| $\epsilon_{\rm sel}$ | 1.4% |
| Purity determination ($J/\psi$) | 2.0% |
| Purity determination ($\psi(2S)$) | 13.0% |
| *$\epsilon_{\rm single}$ | 1.0% |
| *Acceptance | 2.0% |
| *Shape of the inelastic background | 5.0% |
| *Luminosity | 3.5% |
| Total correlated statistical uncertainty ($J/\psi$) | 2.4% |
| Total correlated statistical uncertainty ($\psi(2S)$) | 13.0% |
| Total correlated systematic uncertainty | 6.5% |

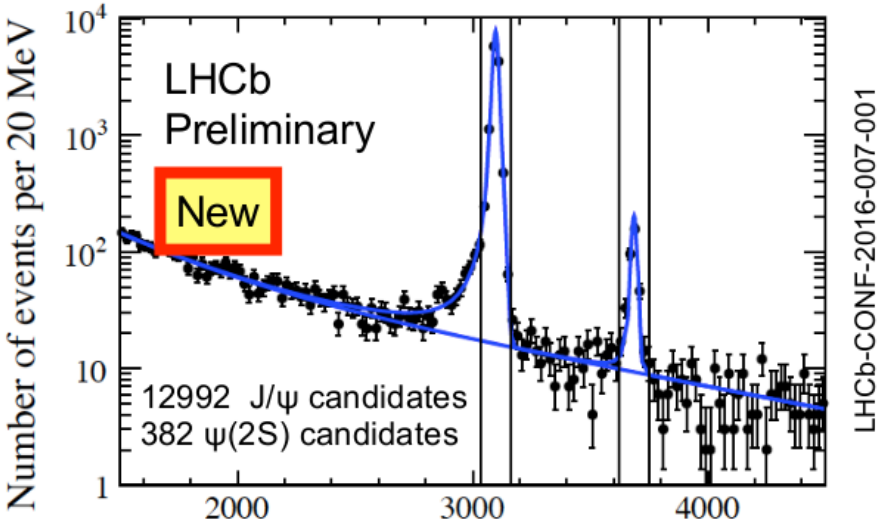
CERN-PH-EP-2013-233
LHCb-PAPER-2013-059

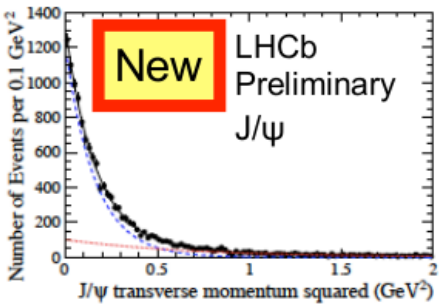
Estimate of potential benefit of vetoing particles up to η<7.5

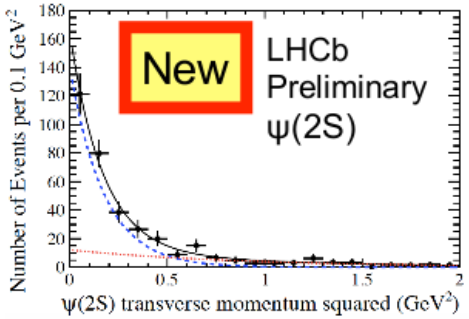


# CEP of J/ψ at 13TeV

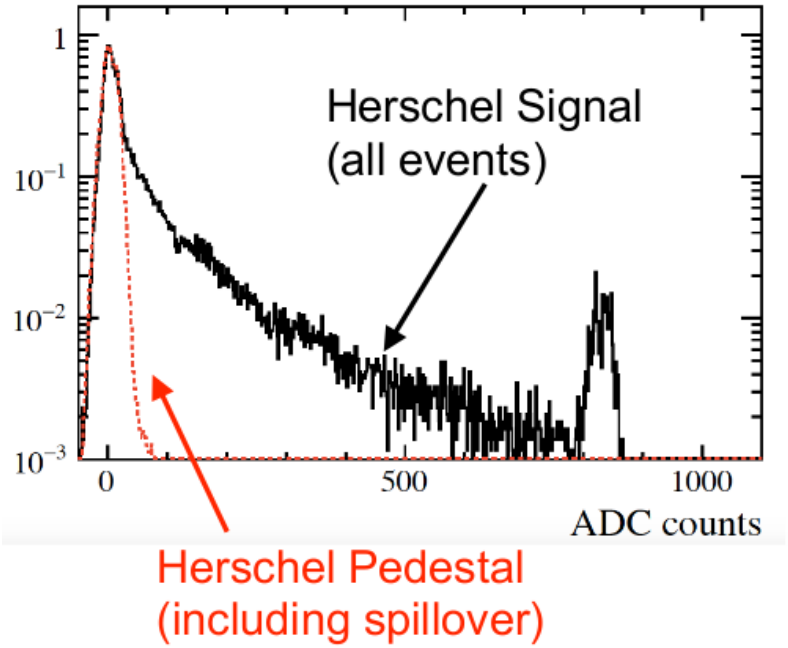
- **Use new 2015 dataset @13TeV (200pb$^{-1}$) + Herschel information**
- Nearly all numbers (efficiencies, etc) come from data driven approaches
- Selection:
  - MuonTriggers for CEP (require low multiplicity on SPD)
  - Two reconstructed muons with $2 < \eta < 4.5$
  - No additional tracks/energy
  - Within 65 MeV/c2 of the J/ψ
  - Herschel VETO applied (and validated with different approaches)
  - Background halved relative to previous analyses

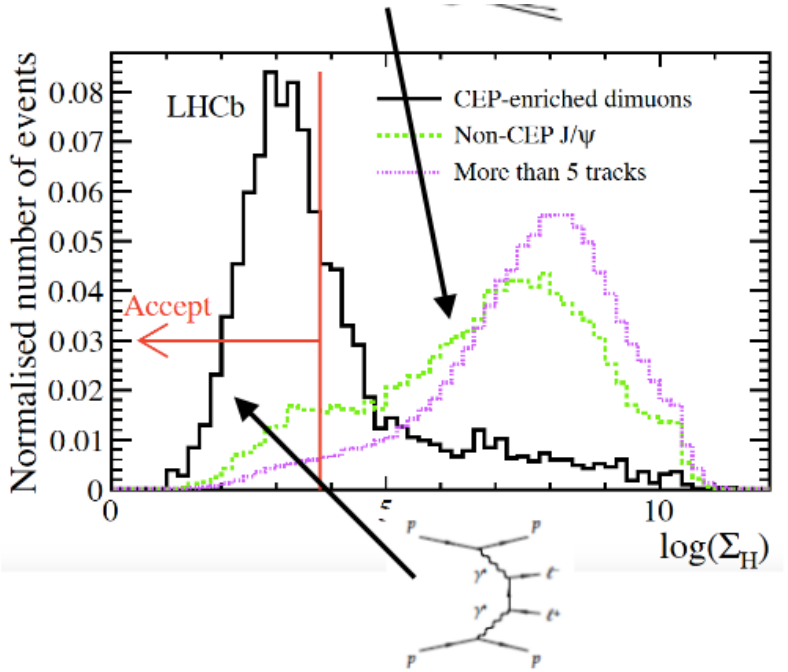


# CEP of J/ψ at 13TeV




- Clean pedestals and complete suppression of pileup
- Pedestals calibrated using non connected channels
- Quadratic sum of normalised signals (ΣH) used to create veto
- Response checked against 3 classes of events
- Clear signal/background enhancement

# CEP of J/ψ at 13TeV

- Results in a CONF note (presented at ICHEP) → now proceeding to a paper

LHCb Preliminary Cross Section

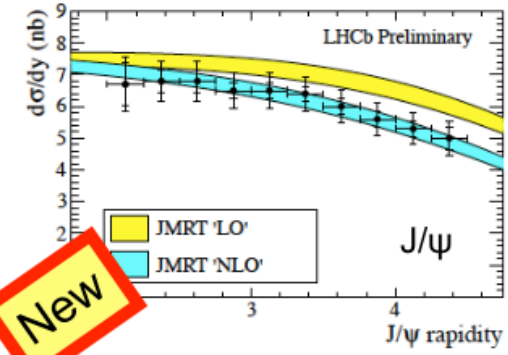
New

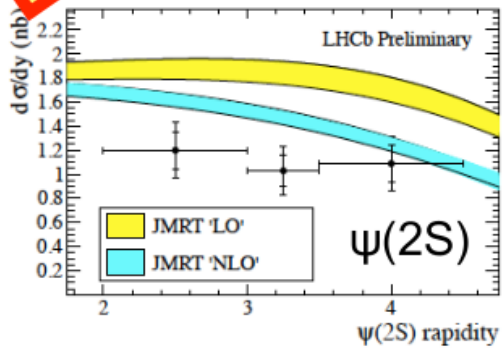
$$\sigma_{J/\psi\to\mu^+\mu^-}(2<\eta_{\mu^+\mu^-}<4.5) = 407\pm8\pm24\pm16\ \text{pb}$$

$$\sigma_{\psi(2S)\to\mu^+\mu^-}(2<\eta_{\mu^+\mu^-}<4.5) = 9.4\pm0.9\pm0.6\pm0.4\ \text{pb}$$

LHCb-CONF-2016-007-001

New



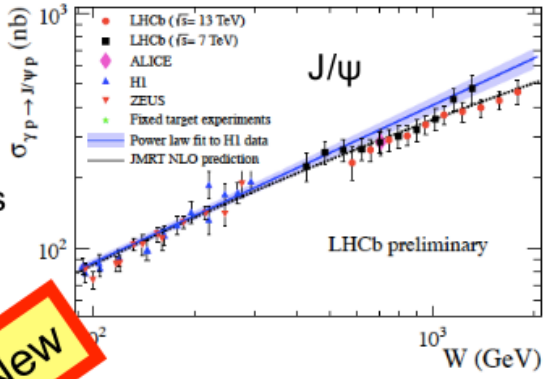



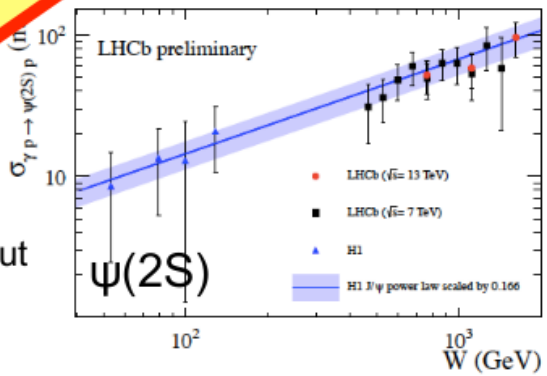

Differential cross section in better agreement with JMRT NLO rather than LO predictions

13 TeV data allows significant extension of the reach in W

Simple power law insufficient but data well described by NLO

New

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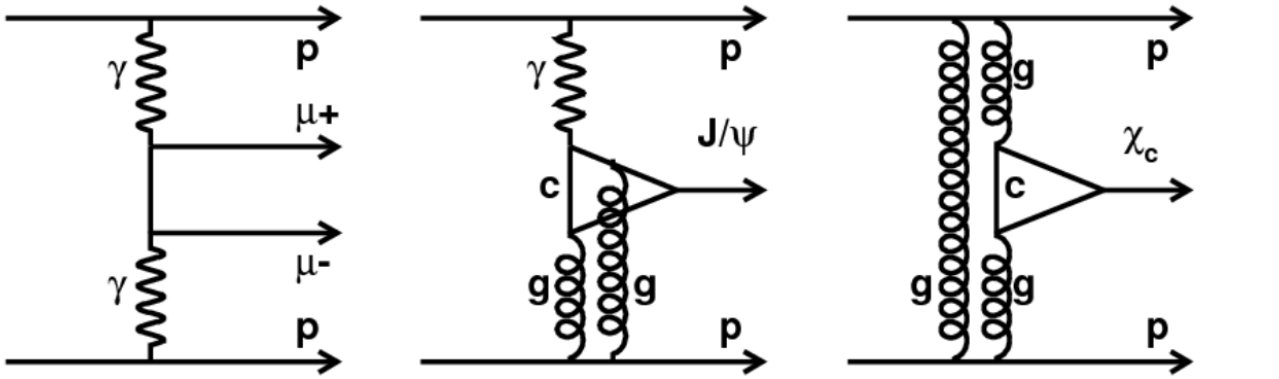
# CEP processes




(Note: $J/\psi \rightarrow \mu\mu$ and $\chi_c \rightarrow J/\psi\gamma$)

Related phenomena where the colourless object creates a particle

- LHC is essentially a gluon collider → cross sections should be high
- But also a gamma collider → photoproduction!
- Provides selection rules for production: e.g pomeron-pomeron $0^{++}$,$2^{++}$
- We could study more exotic quantum number combinations as well
- Reggeon-Reggeon scattering is also possible
- In brief, a very good laboratory for clean direct production

# A few thoughts for the future...

- Taking for the LHC Flavour Physics roadmap → new analyses are possible
- Exploit big dataset both with muon and hadronic channels
- Just two selected examples (not a full list)

- Double Vector
  - η(‘)η(‘) and φφ,φω,ωω
  - Includes final states with pi0
  - Interesting for NonRes-Res production
  - Belle evidence of new resonance

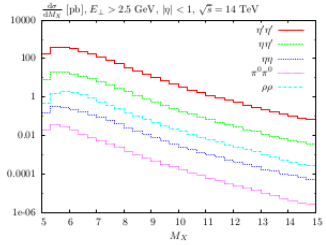



Fig. 5.6: Differential cross section $d\sigma/dM_X$ for the CEP of meson pairs, for meson transverse energy $E_\perp > 2.5$ GeV and pseudorapidity $|\eta| < 1$. Predictions made using `SuperChic` MC [46].

PRL **108,** 232001 (2012) PHYSICAL REVIEW LETTERS week ending 8 JUNE 2012

**Observation of New Resonant Structures in $\gamma\gamma \to \omega\phi$, $\phi\phi$, and $\omega\omega$**

- Gamma Gamma
  - Never observed $\gamma\gamma \to \gamma\gamma$
  - Usually $\gamma\gamma \to X$
  - we can do $X \to \gamma\gamma$
  - Interesting prospects

**Observing light-by-light scattering at the Large Hadron Collider**

David d'Enterria[1] and Gustavo G. Silveira[2]

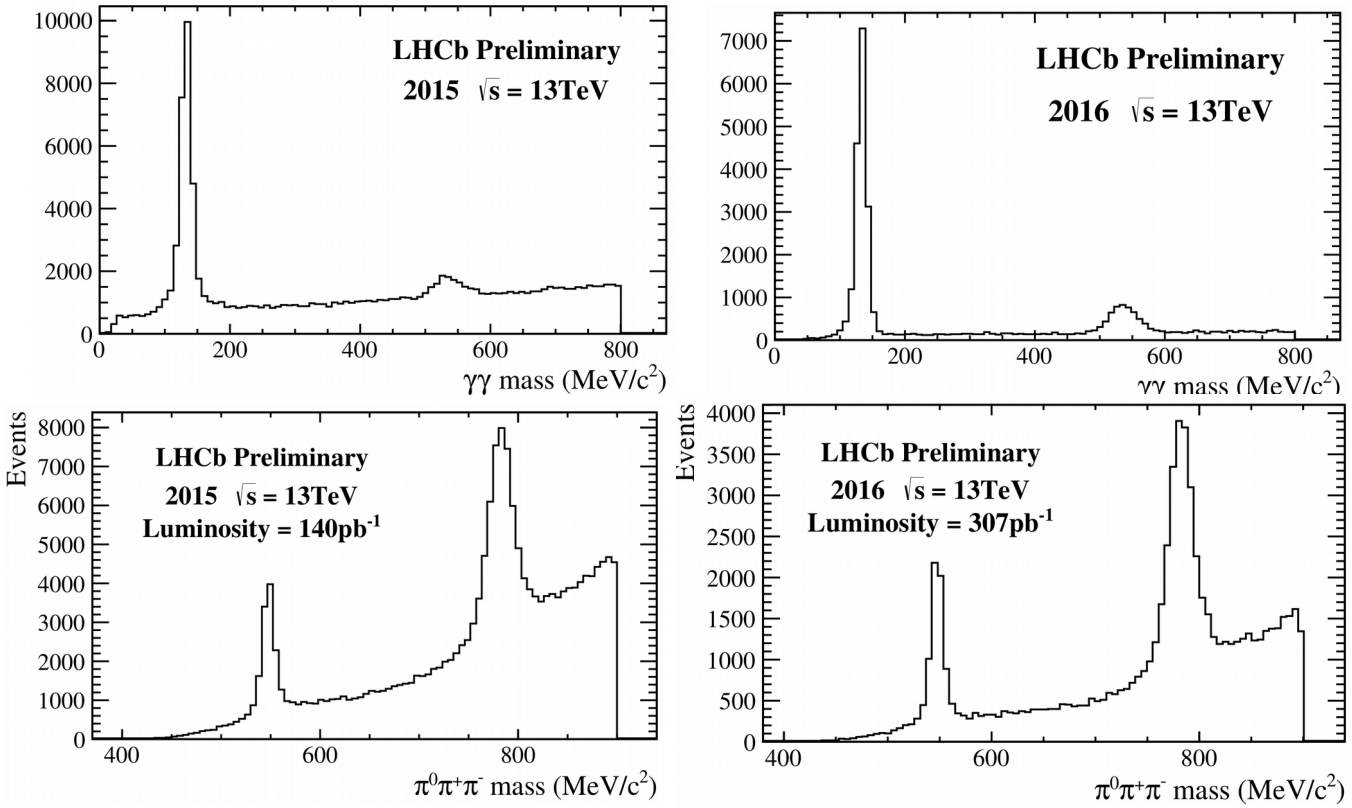
[1] *CERN, PH Department, 1211 Geneva, Switzerland*

[2] *UC Louvain, Center for Particle Physics and Phenomenology (CP3), Louvain-la-Neuve, Belgium*

Elastic light-by-light scattering ($\gamma\gamma \to \gamma\gamma$) is open to study at the Large Hadron Collider thanks to the large quasi-real photon fluxes available in electromagnetic interactions of protons (p) and lead (Pb) ions. The $\gamma\gamma \to \gamma\gamma$ cross sections for diphoton masses $m_{\gamma\gamma} > 5$ GeV amount to 105 fb, 260 pb, and 370 nb in p-p, p-Pb, and Pb-Pb collisions at nucleon-nucleon center-of-mass energies $\sqrt{s_{\rm NN}} = 14$ TeV, 8.8 TeV, and 5.5 TeV respectively. Such a measurement has no substantial backgrounds in Pb-Pb collisions where one expects about 70 signal events per run, after typical detector acceptance and reconstruction efficiency selections.

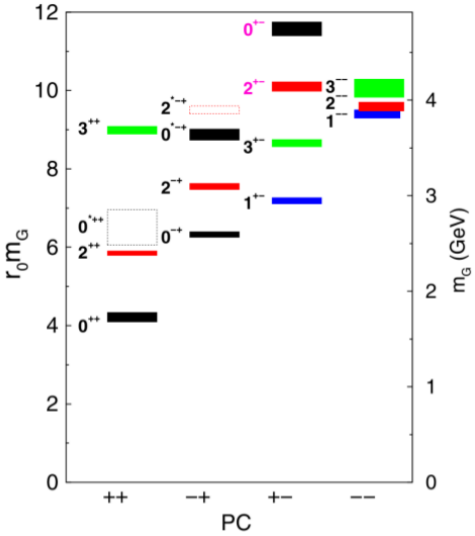
# Using Neutrals

- Benefit from the low multiplicity environment → we can use neutrals
- Performance of LHCb calorimeter depends on occupancy
- In average events, too much activity makes analyses with π0 difficult!
- CEP-like events are much cleaner → different triggers/selections in 2015,2016



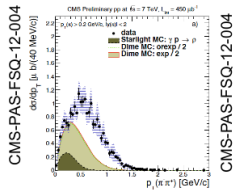
# Gluonic objects

- We can look at hadronic/gluonic objects at low invariant mass
- Standard glueballs, oddballs and hybrids
- E.g DiPion, DiKaon CEP
- Amplitude analysis required, several approaches
- Discussed in this workshop (see Derek Glazier)

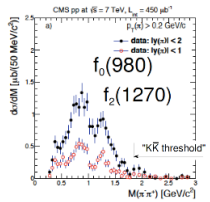



## CEP dipion by CMS

Total cross section: $\sigma_{Vis}$ = 20.5± 0.3(stat.)± 3.1(sys.)± 0.8(lumi) μb




DPE production predictions from IME MC and STARLIGHT (stacked) data enhancement at higher $p_T$)




Differential Cross section,for |y(π)| < 2 and |y(π)| < 1
some evidence of resonant structures

Unfolded cross sections:

$|y(\pi^{\pm})| < 2.0$: $\sigma_{vis} = 20.5 \pm 0.3\ (stat.) \pm 3.1\ (sys.) \pm 0.8\ (lumi)\ \mu b$

$|y(\pi^{\pm})| < 1.0$: $\sigma_{vis} = 8.1 \pm 0.2\ (stat.) \pm 1.2\ (sys.) \pm 0.3\ (lumi)\ \mu b$

Eagerly waiting for new results from all experiments!

- Oddballs:
  - Quantum number $0^{--}$
  - Higher in mass. Don't mix with qqbar
  - Several predictions (lattice) + Holographic models
  - Several decay patterns: f1(1285)γ and f1(1285)ω
  - Fully accessible to LHCb

# Conclusion

- CEP is a very rich field → rapidly expanding programme
- Nice production mechanism & unique experimental conditions
- Quantum number selection rules

- Run2: still 2 years of good data to collect!
- Also we have other dataset to exploit (ions!)
- Any thoughts to add from theory audience?