Central Exclusive Production at LHCb: Measurements and Opportunities

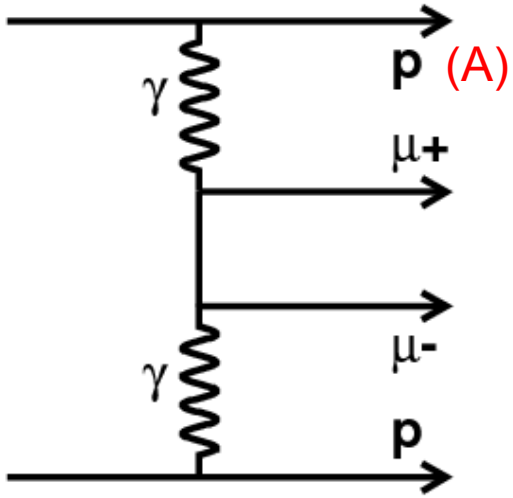
Ronan McNulty (UCD Dublin)
on behalf of the LHCb collaboration

Workshop on QCD and Diffraction - Various Faces of QCD
15-17 November 2018, Krakow.

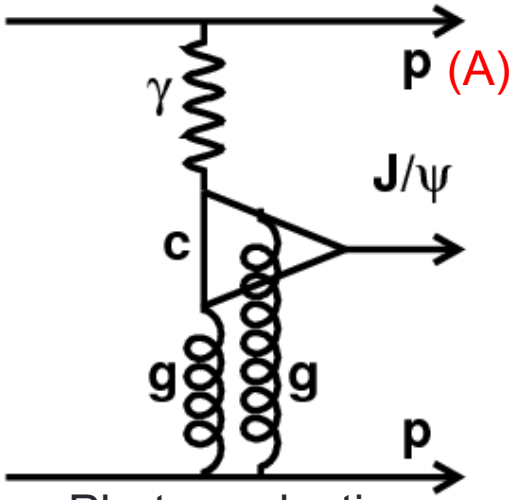
Outline

- **CEP as a probe of QCD**
  - Theoretical and Experimental considerations
- **Tests of QCD**
  - Meson production
  - PDFs
  - Physics of the Vacuum: soft and hard QCD.
- **Open questions in QCD**
  - Saturation
  - Odderon
  - Tetraquarks
  - Glueballs, hybrids.
- **Summary**

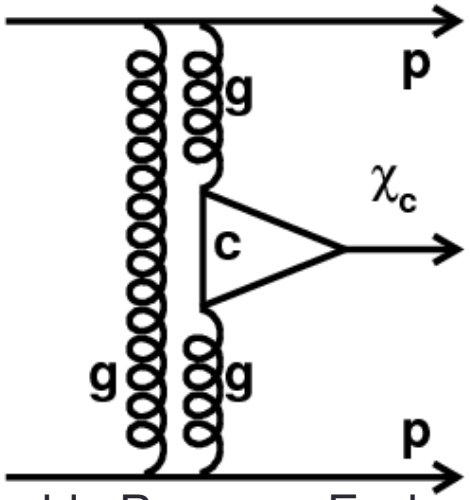
CEP: Colourless propagators



QED



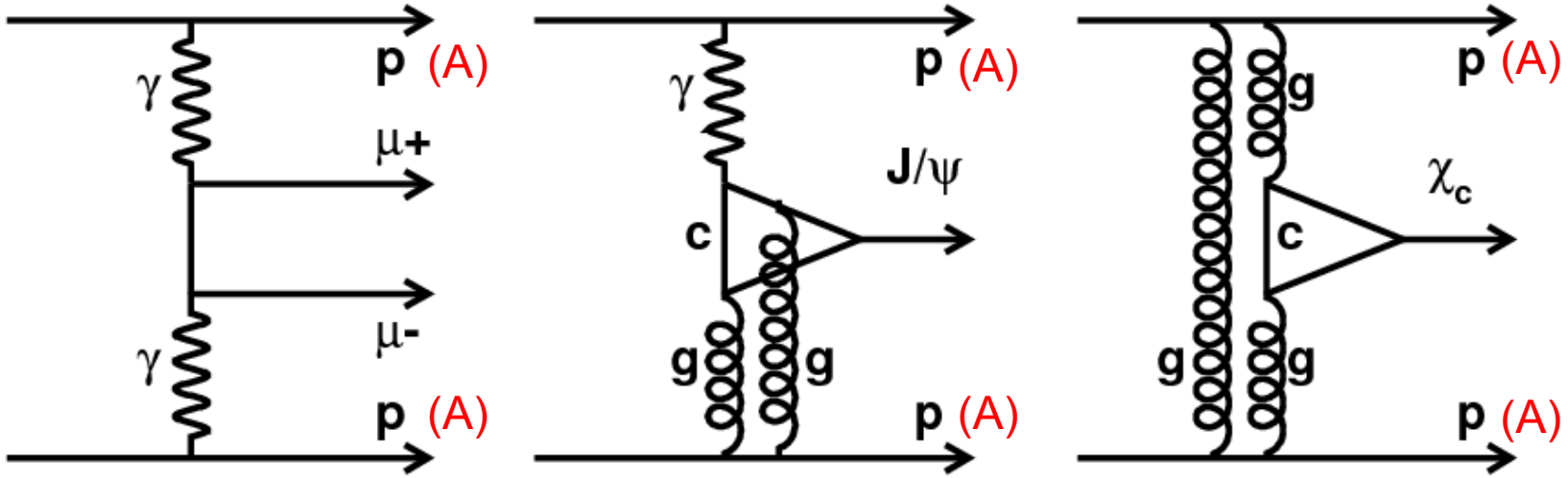
Photoproduction
(Vector Mesons)



Double Pomeron Exchange
(Scalar / Tensor Mesons)

- Signal: central system with rapidity gaps down to proton
- Background: proton dissociation & finite detector acceptance.

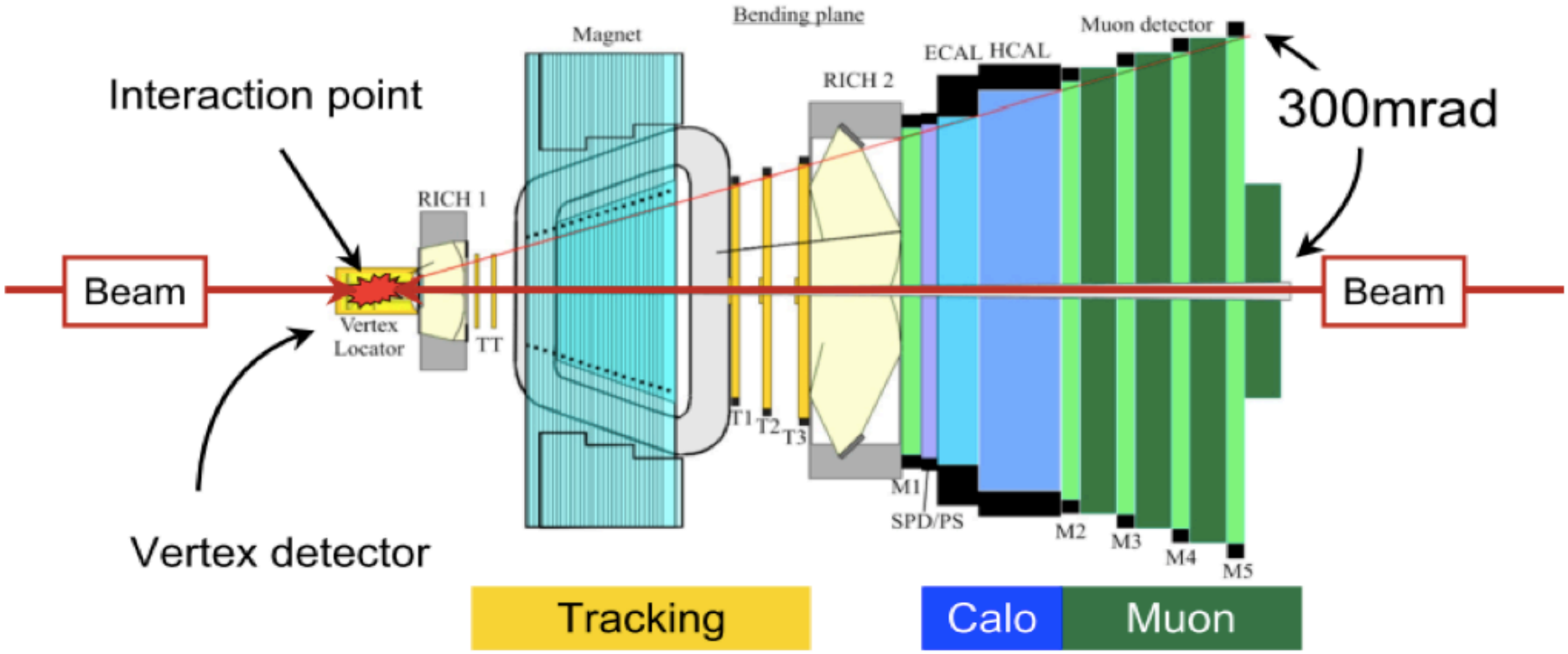
CEP: Complementarity of LHC running



- pp running: generally $\sigma_{PP} > \sigma_{P\gamma} > \sigma_{\gamma\gamma}$
- pA running
  - $\sigma_{P\gamma}$ enhanced by Z^2 in UPC
  - σ_{PP} enhanced by $A^{1/3}$
- AA running
  - $\sigma_{\gamma\gamma}$ enhanced by Z^4 in UPC

The LHCb detector

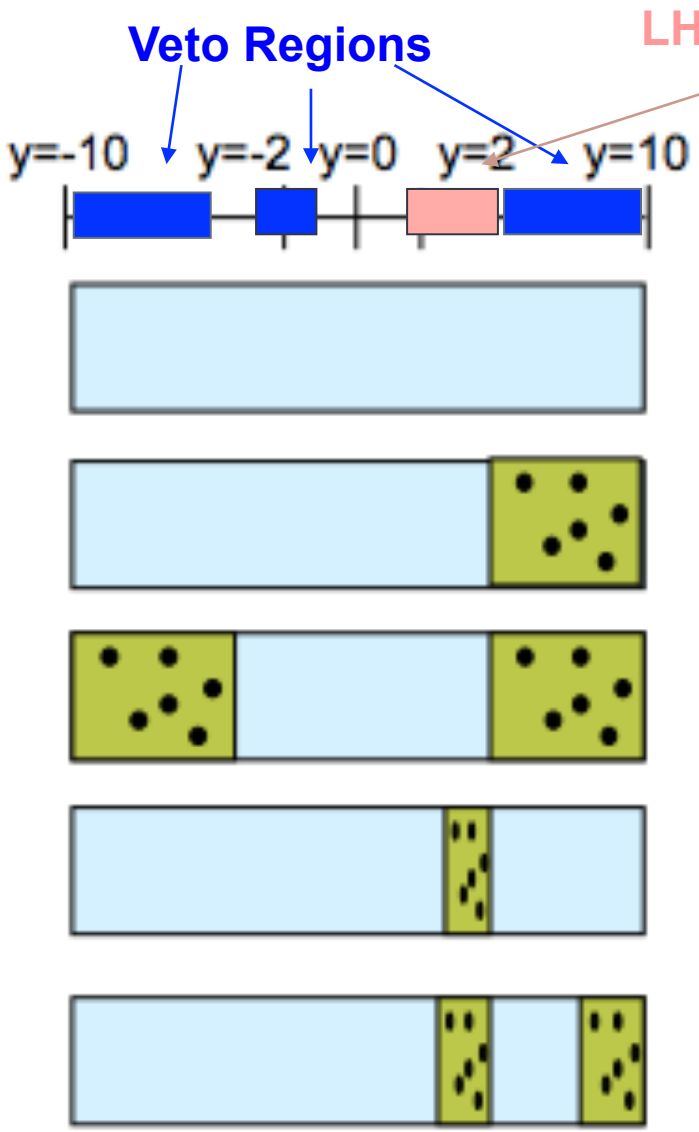
Int. J. Mod. Phys. A 30 (2015) 1530022



Fully instrumented: $2 < \eta < 5$

Veto region (Run 1): $-3.5 < \eta < -1.5$

Veto region (Run 2): $-10 < \eta < -5$, $5 < \eta < 10$



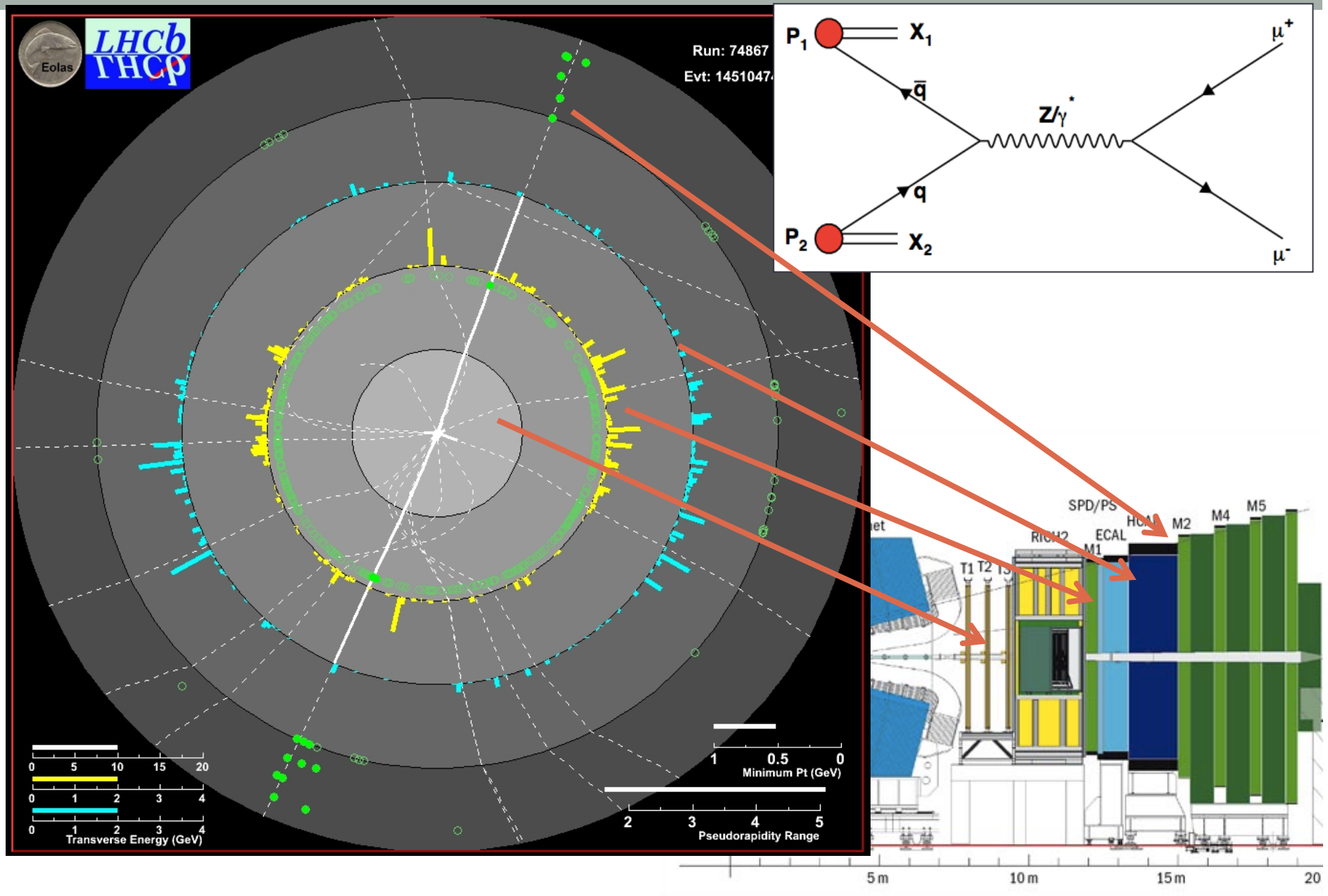
Elastic Scattering

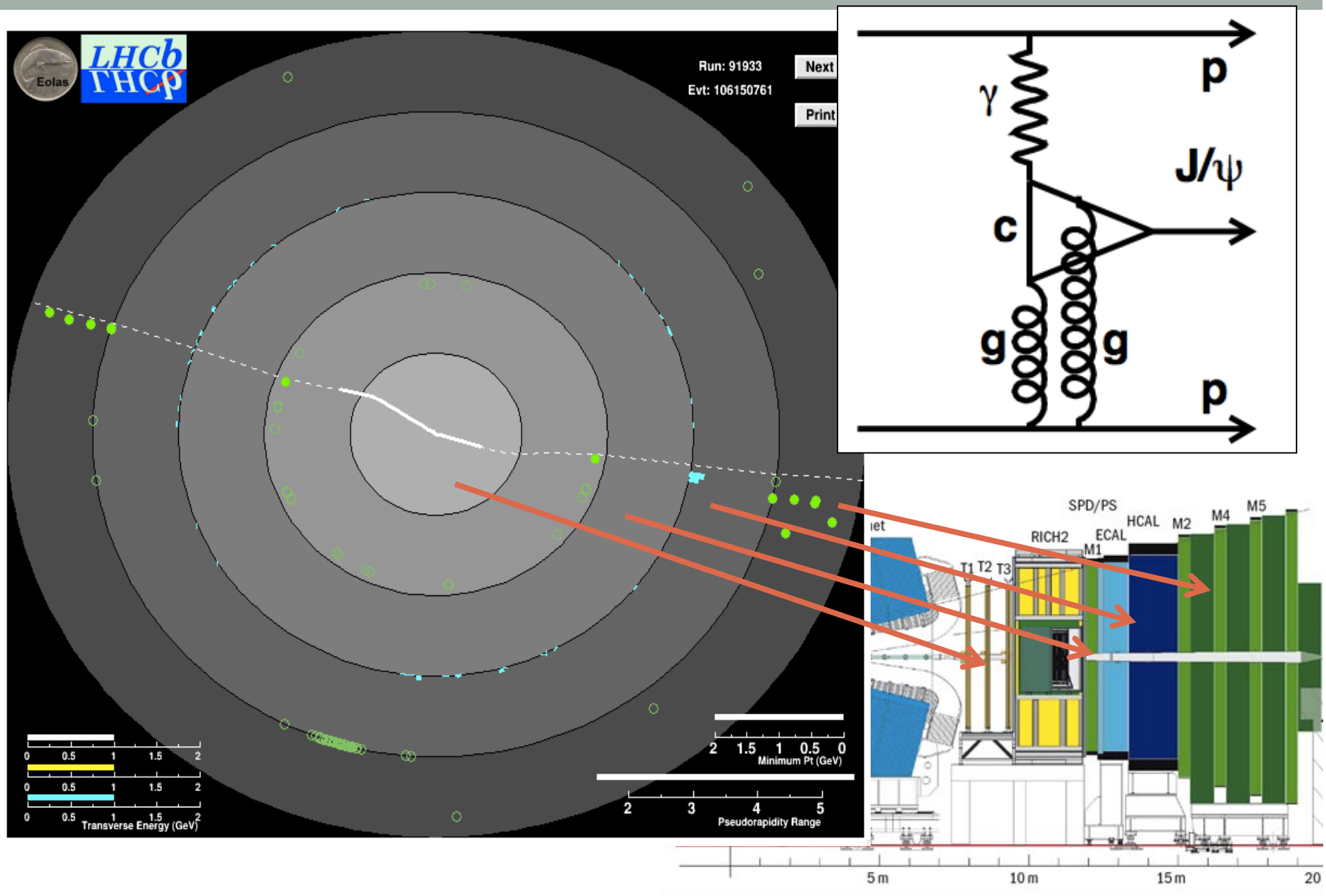
Single Diffraction

Double Diffraction

Central Exclusive Production (elastic)

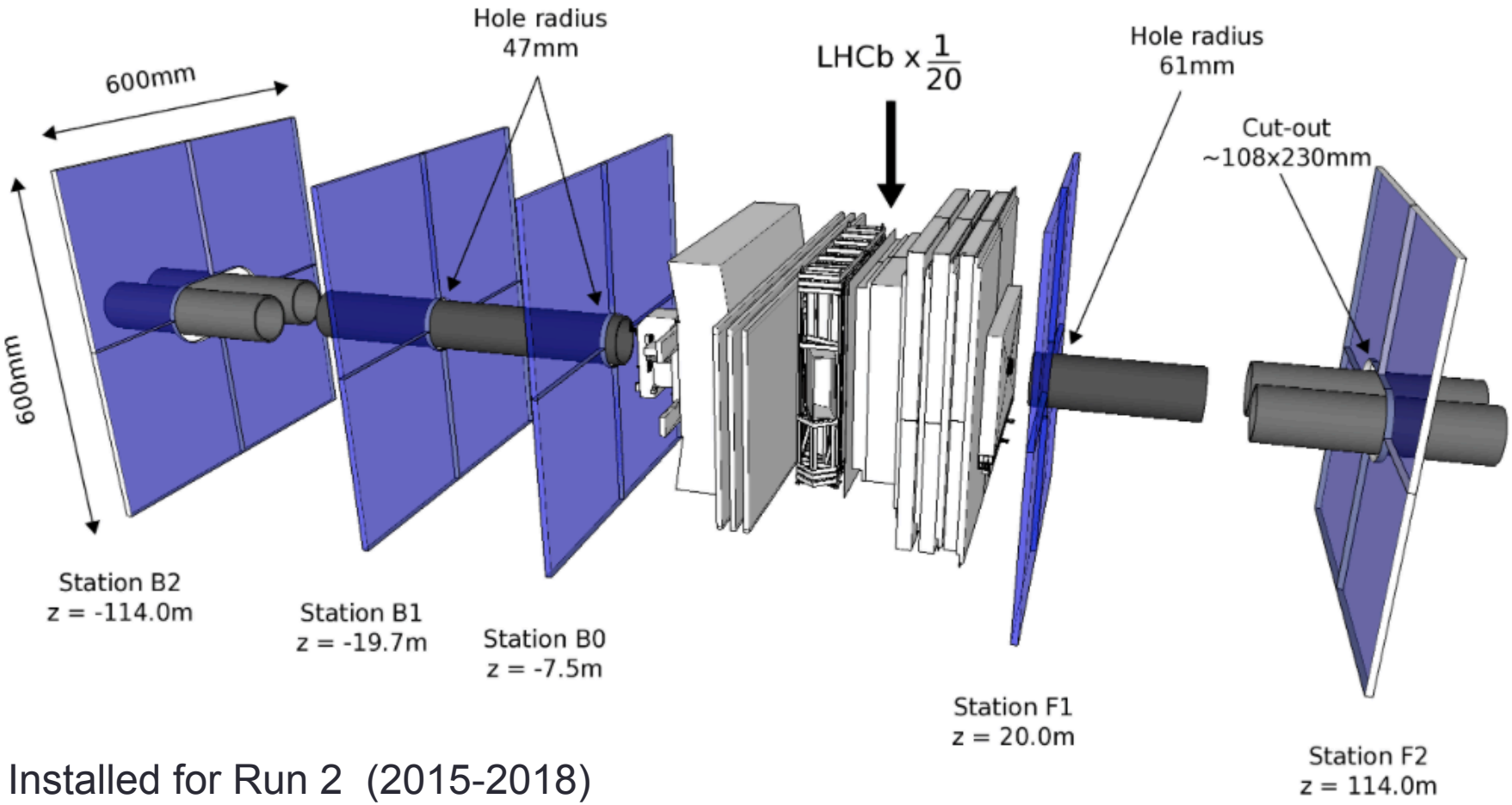
Central Exclusive Production (inelastic)


LHCb
Eolas
Run: 74867
Evt: 1451047
0 5 10 15 20
0 1 2 3 4
0 1 2 3 4
Transverse Energy (GeV)
1 0.5 0
Minimum Pt (GeV)
2 3 4 5
Pseudorapidity Range
P1
X1
q̄
Z/γ*
q
P2
X2
μ+
μ-
SPD/PS
M2
M4
M5
ECAL
M1
T1 T2
5 m
10 m
15 m
20

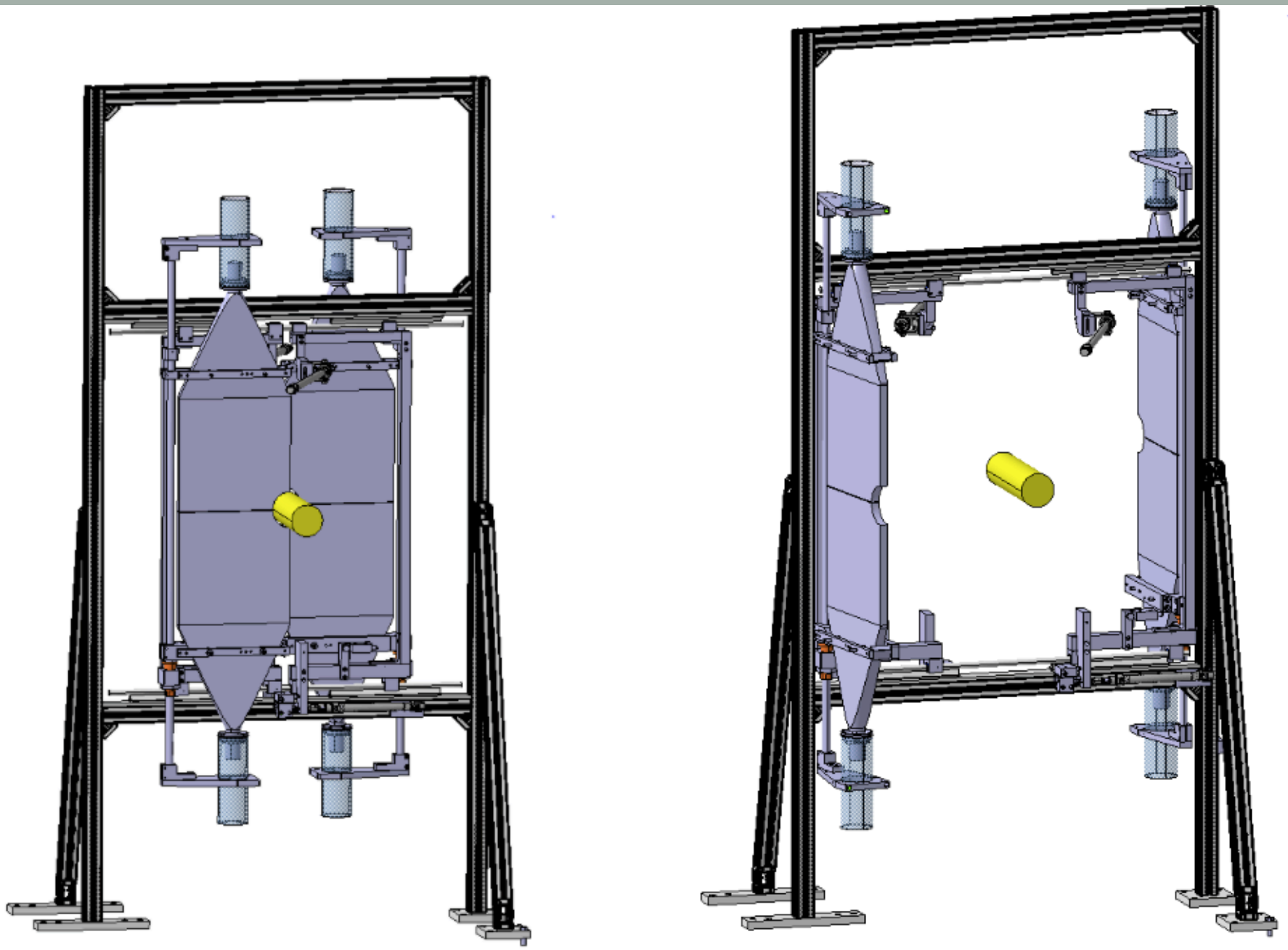

Eolas
LHCb
Run: 91933
Evt: 106150761
Next
Print
Transverse Energy (GeV)
Minimum Pt (GeV)
Pseudorapidity Range
γ
p
J/ψ
c
g
g
p
SPD/PS
HCAL
M2
M4
M5
RICH2
ECAL
M1
T1 T2 T3
5 m
10 m
15 m

High Rapidity Shower Counters at LHCb (HeRSCheL)

JINST **13** (2018) P04017



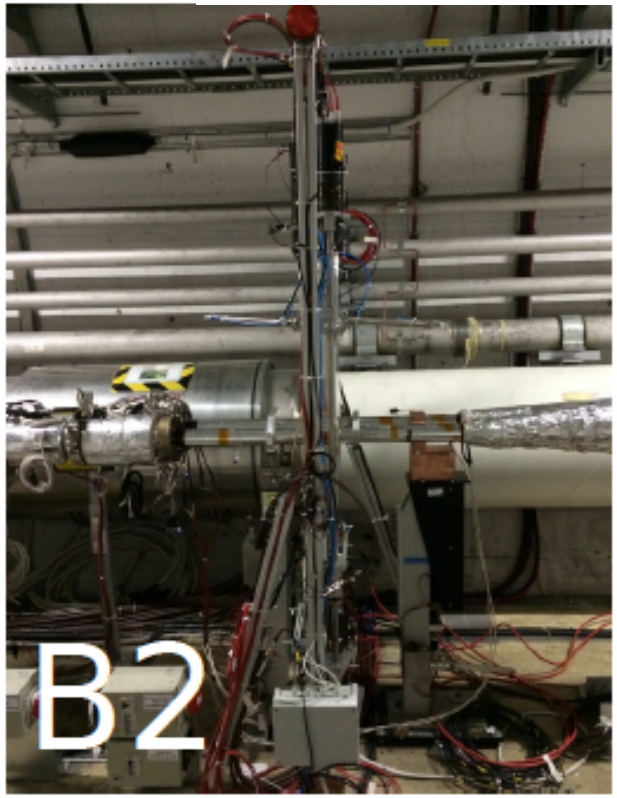
Installed for Run 2 (2015-2018)



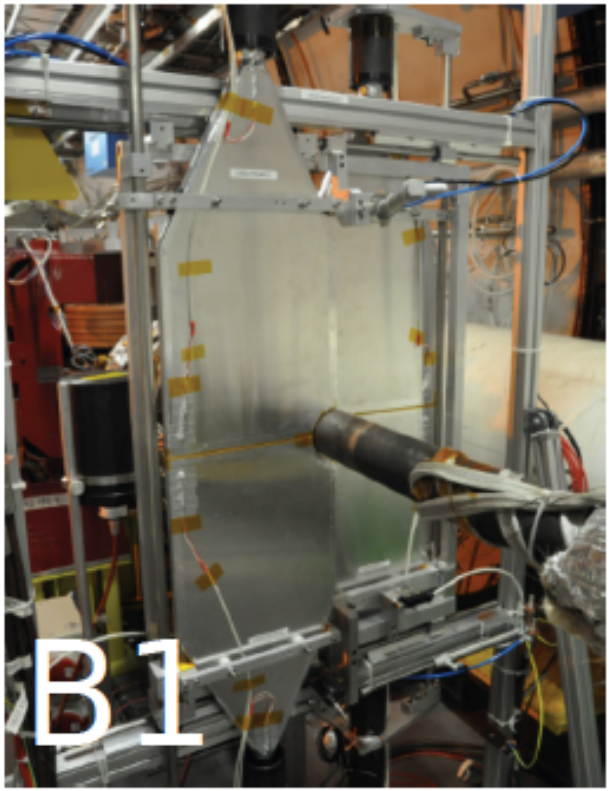
Scintillators, light-guides and PMTs

Backward stations

-114 m



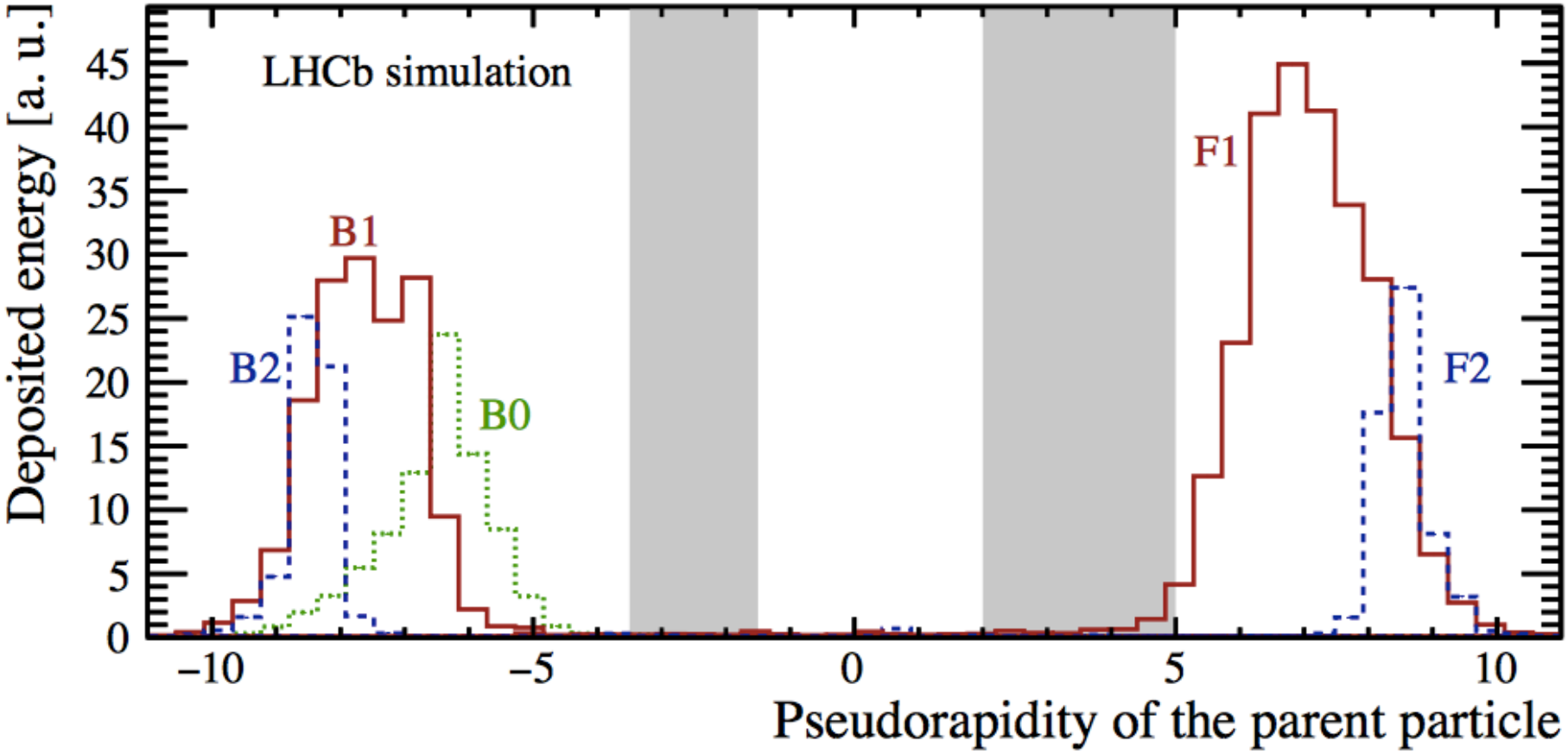
-19.7 m



-7.5 m

Acceptance

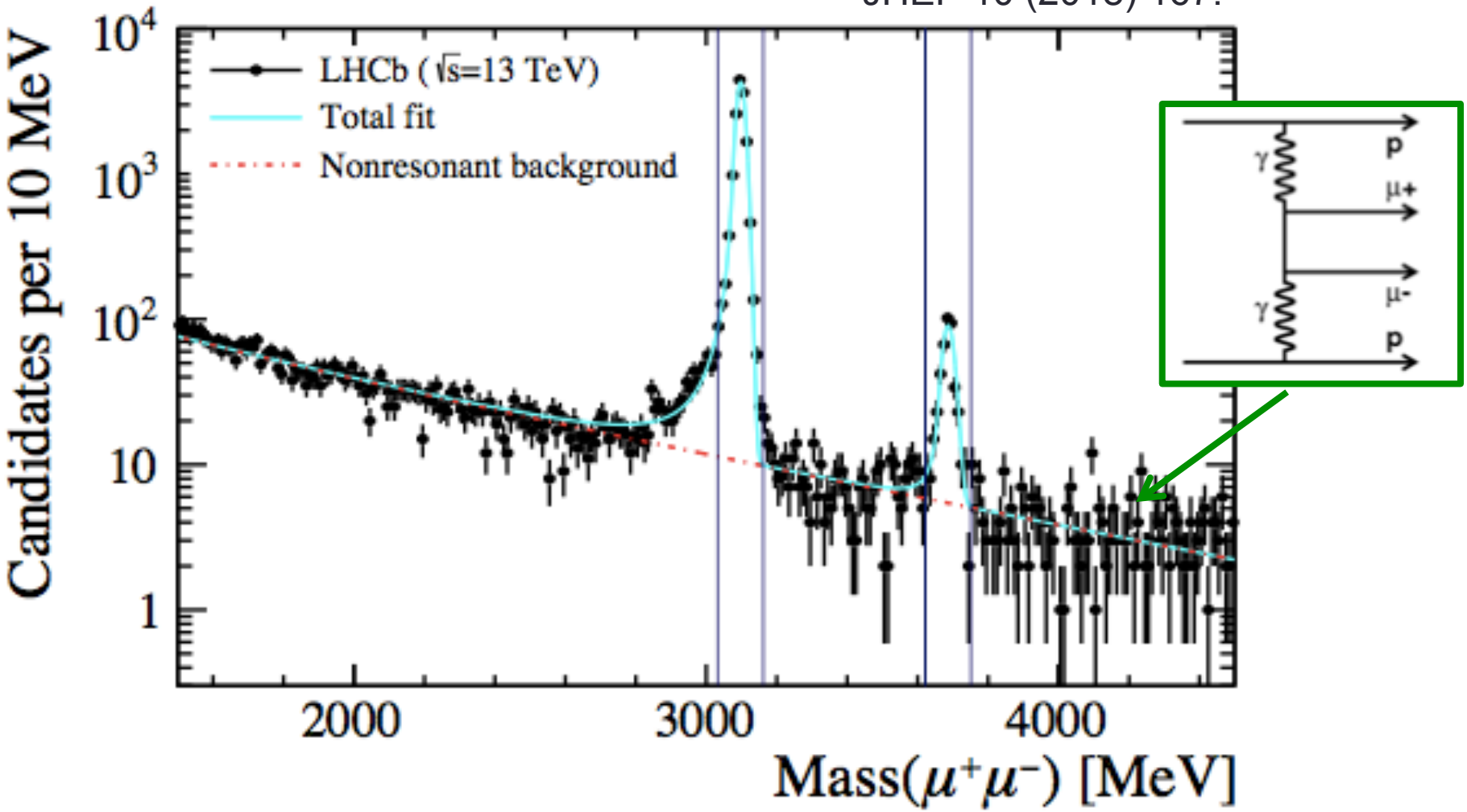
JINST **13** (2018) P04017



Showers induced by high-rapidity particles interacting with machine elements
Ideally wish to veto on any activity: threshold depends on signal and noise.

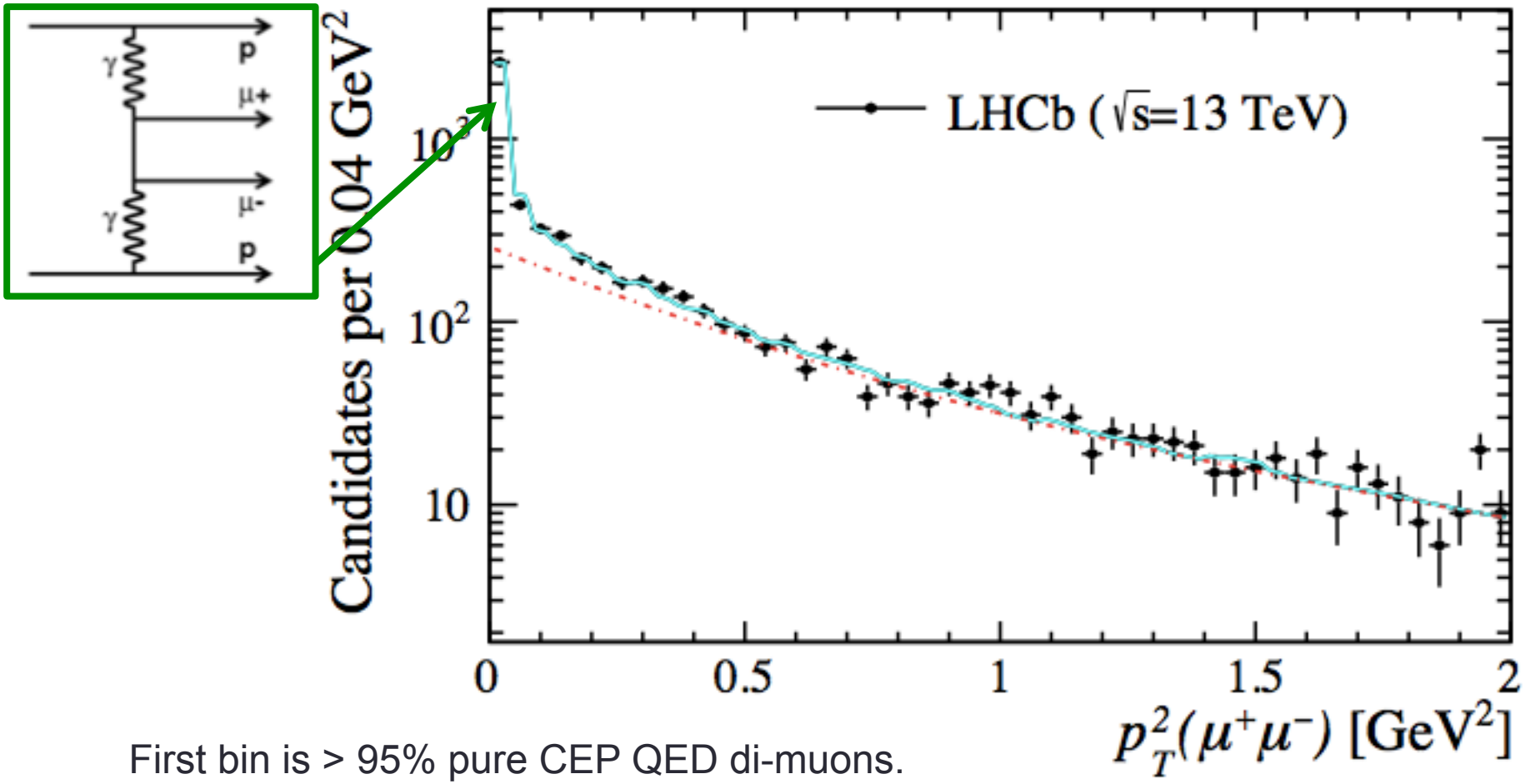
Sample 1: Response to CEP events (QED μμ)

JHEP 10 (2018) 167.



Sample 1: Response to CEP events

JHEP 10 (2018) 167.



First bin is > 95% pure CEP QED di-muons.

Sample 2: Non-CEP events (J/ψ dissociation)

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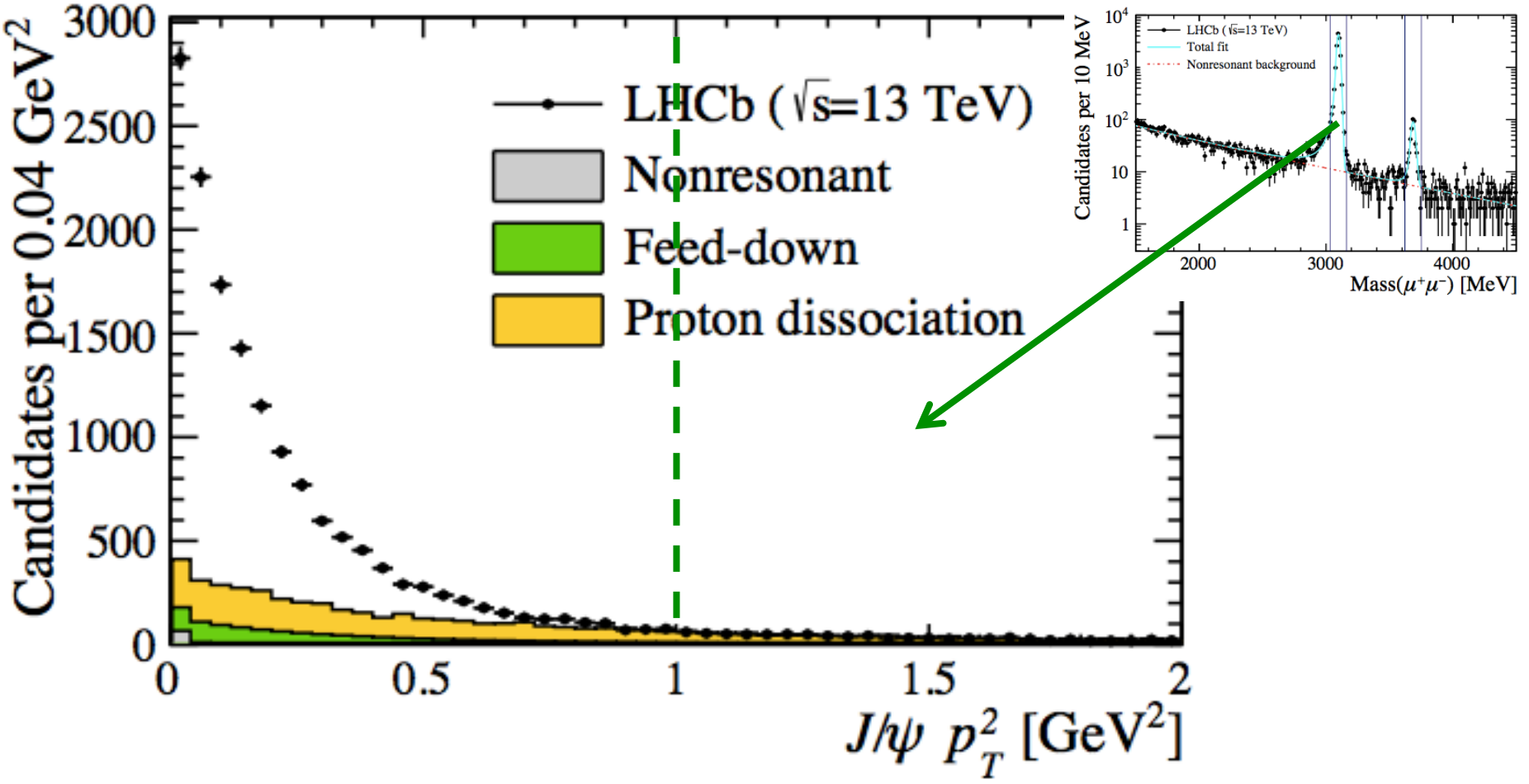
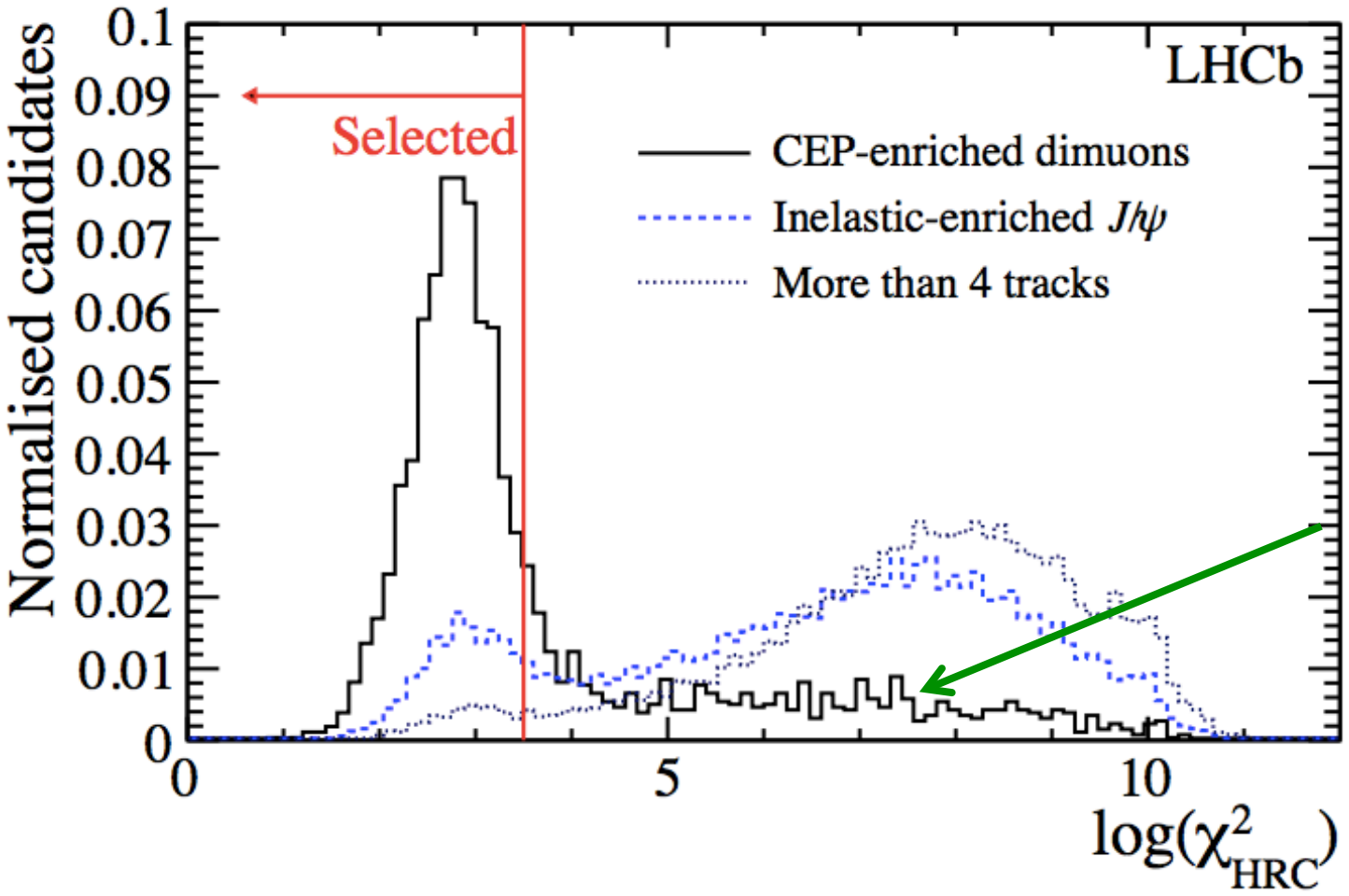


HeRSCheL discriminant for physics signals

JHEP 10 (2018) 167.



CEP QED looks like empty-empty events

Evidence for pile-up (much reduced in p-Pb/Pb-p running)

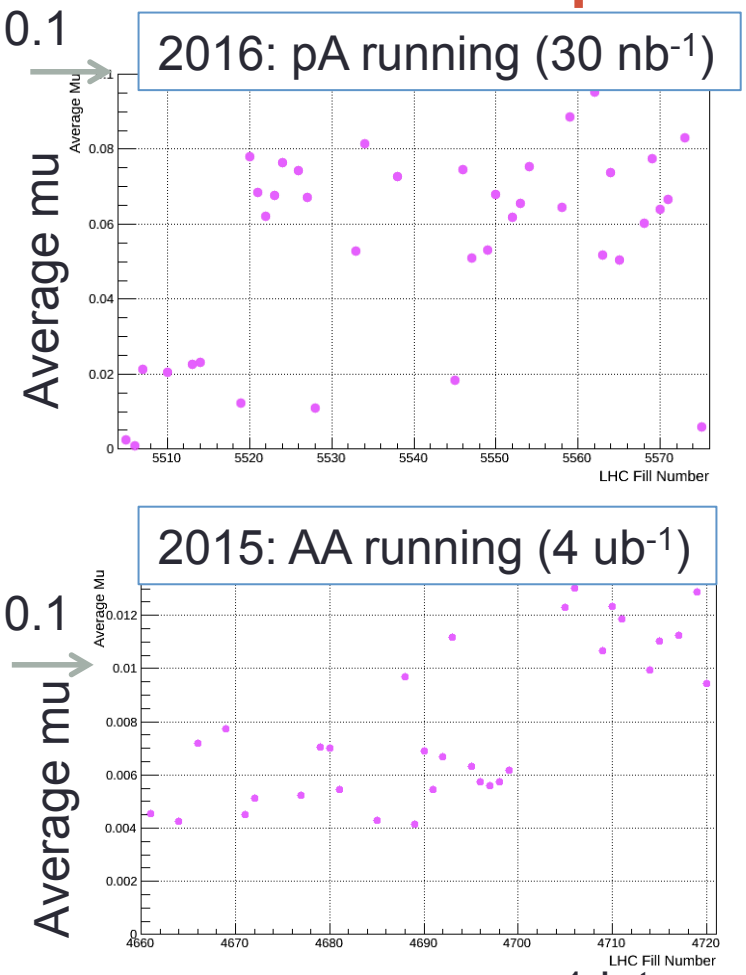
Herschel: considerations for physics

- MIP signal: 2-5 ADC counts. Noise ~5 counts.
- In principle can veto proton remnants (y<10) showering into Herschel.

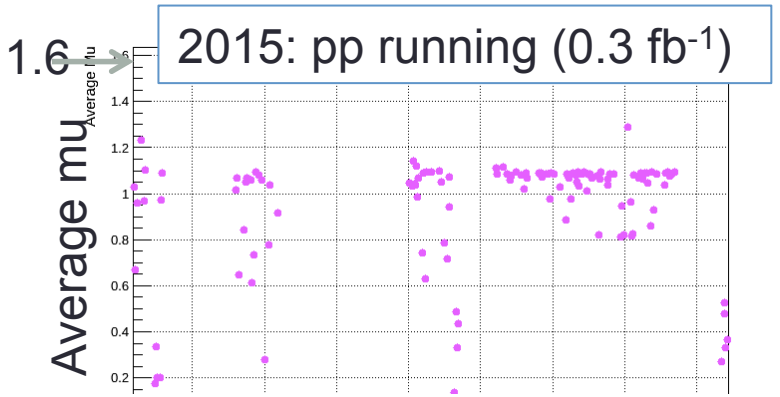
- Complicated by electronic spill-over and machine pile-up (mainly for pp running)

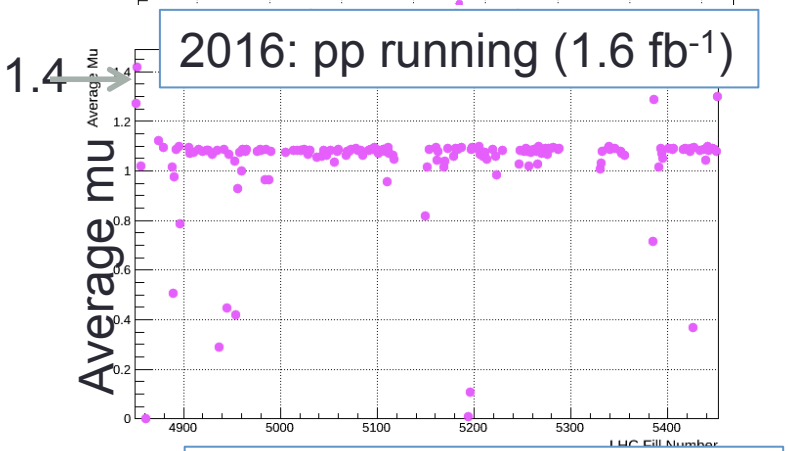
- Note: directionality of break-up.
  - Photoproduction in pA has break-up in p direction
  - Break-up of A gives larger signal than p

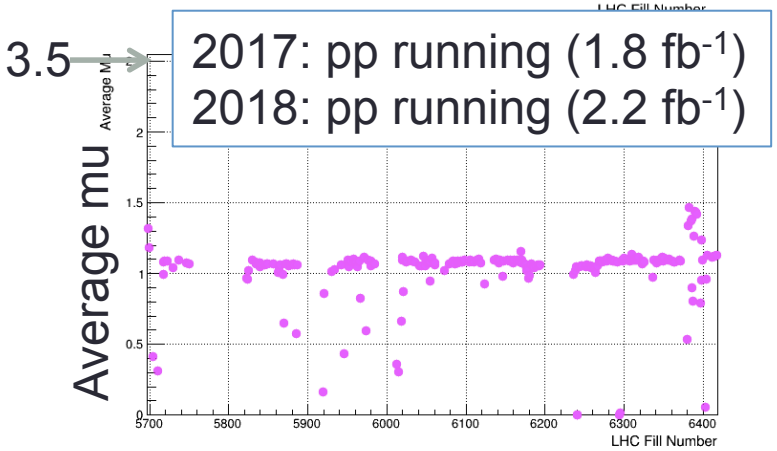
Average number of interactions per crossing



pp: 1 interaction per BCO
pA/AA: 1 in 10 crossings







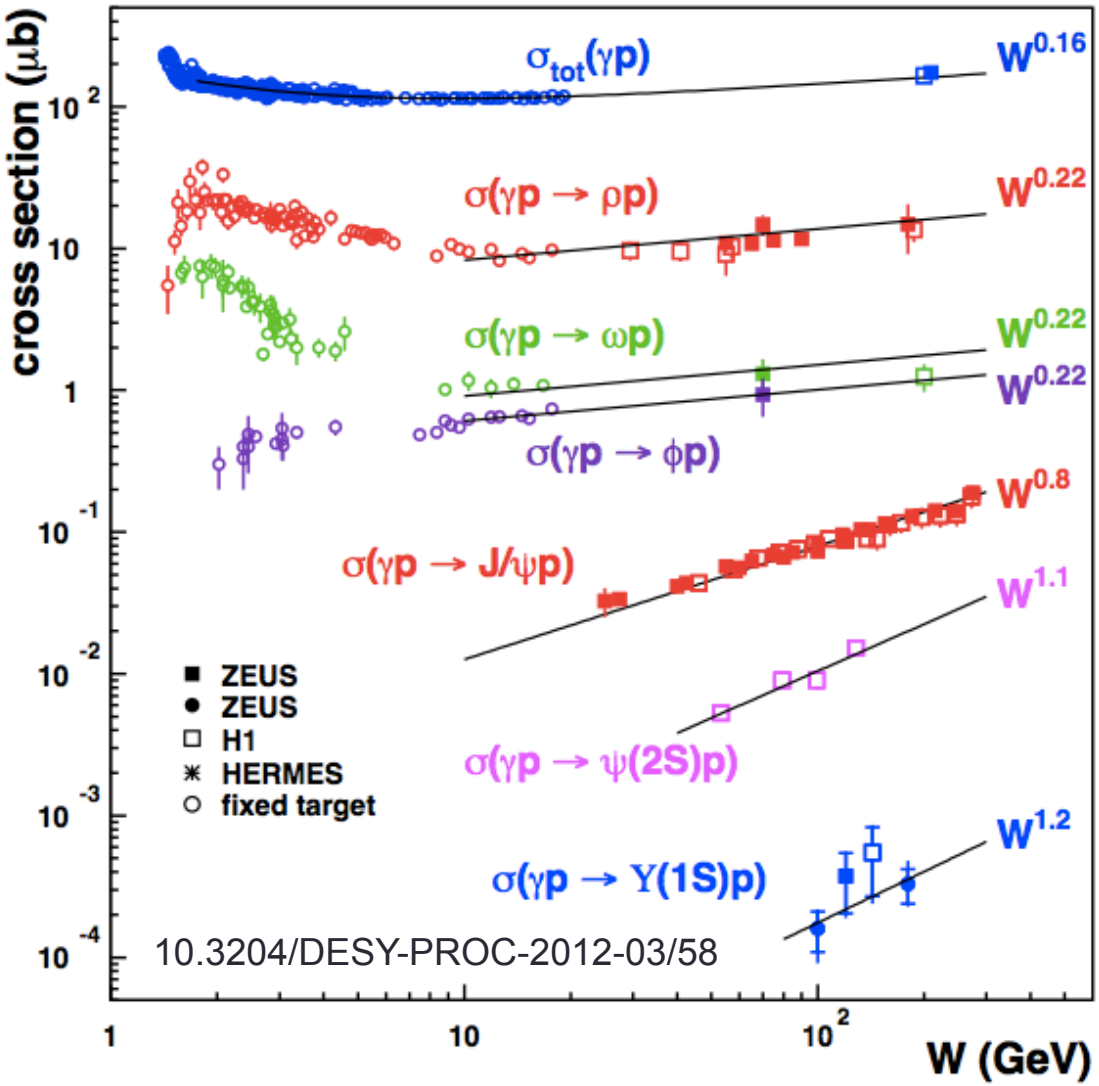
Tests of QCD

Vector mesons

Physics of the Vacuum: soft and hard QCD

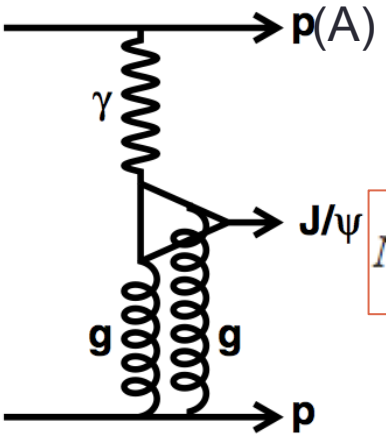
Photo-production of vector mesons

The structure of the proton and nucleus



L.O. prediction in perturbative regime

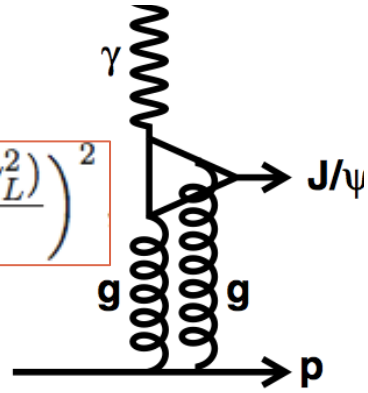
$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}t}\left(\gamma^* p \to J/\psi\, p\right)\right|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} x g(x,\bar{Q}^2)\right]^2 \left(1+\frac{Q^2}{M_{J/\psi}^2}\right)$$

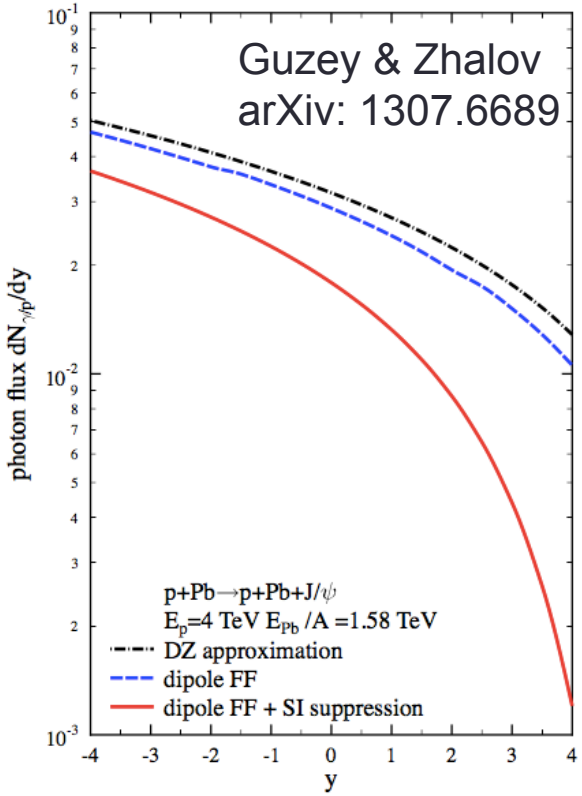


LHC vector meson production related to photo-production through photon flux

$$N_{\gamma/Z}(\omega) \equiv \omega \frac{dN_{\gamma/Z}(\omega)}{d\omega} = \frac{2Z^2\alpha_{\rm em}}{\pi} \int_0^\infty dk_\perp k_\perp^3 \left(\frac{F_Z(k_\perp^2 + \omega^2/\gamma_L^2)}{k_\perp^2 + \omega^2/\gamma_L^2} \right)^2$$

Two-fold ambiguity in pp or AA collisions





Roughly equal cross-sections with rapidity for J/ψ, ψ(2S) ϒ

Strongly peaked to higher rapidities for ρ, ω, ϕ

$x=M^2/W^2 \quad W^2=Me^y\sqrt{s}$

J/ψ: W=[20,2000] GeV, x=[3E-6, 0.02]

ρ: W=[10,1000] GeV, x=[[5E-7, 0.007]

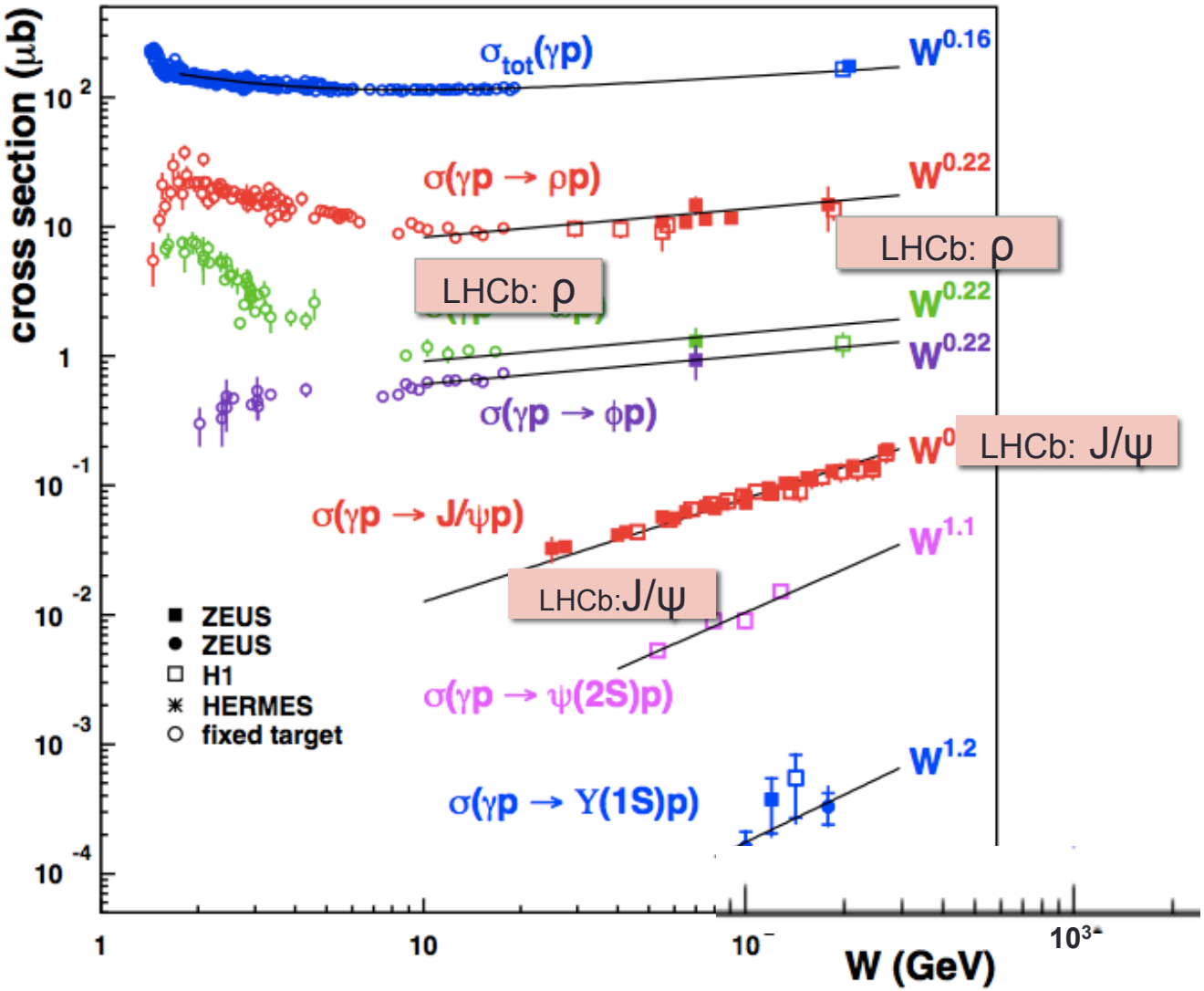
Tests of QCD

J/ψ:

W=[20,2000] GeV,
x=[3E-6, 0.02]

ρ:

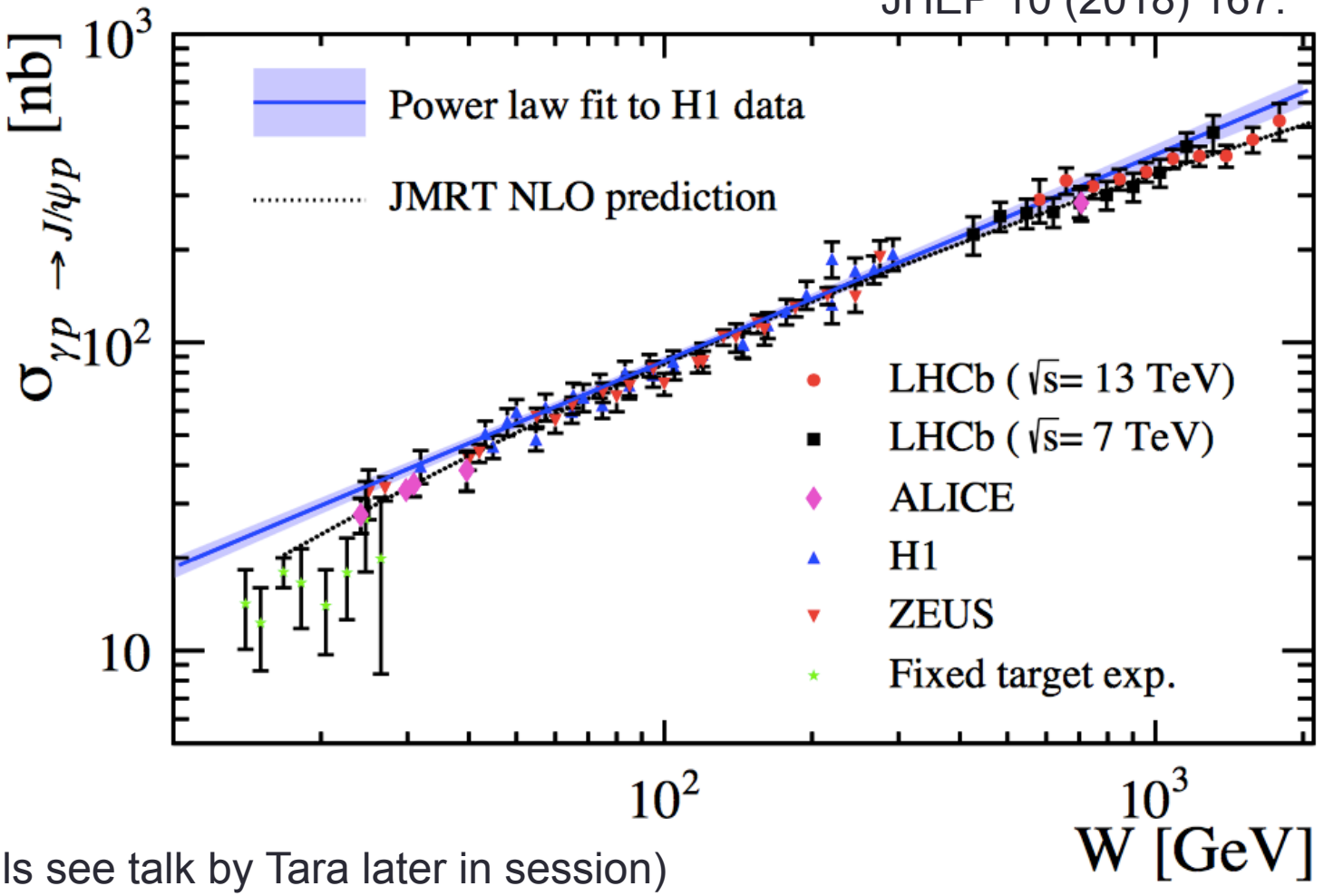
W=[10,1000] GeV,
x=[5E-7, 0.007]



W- solution overlaps HERA results (calibration)
W+ solution is in new energy regime: high W, low x.

LHCb J/ψ compared to lower energies

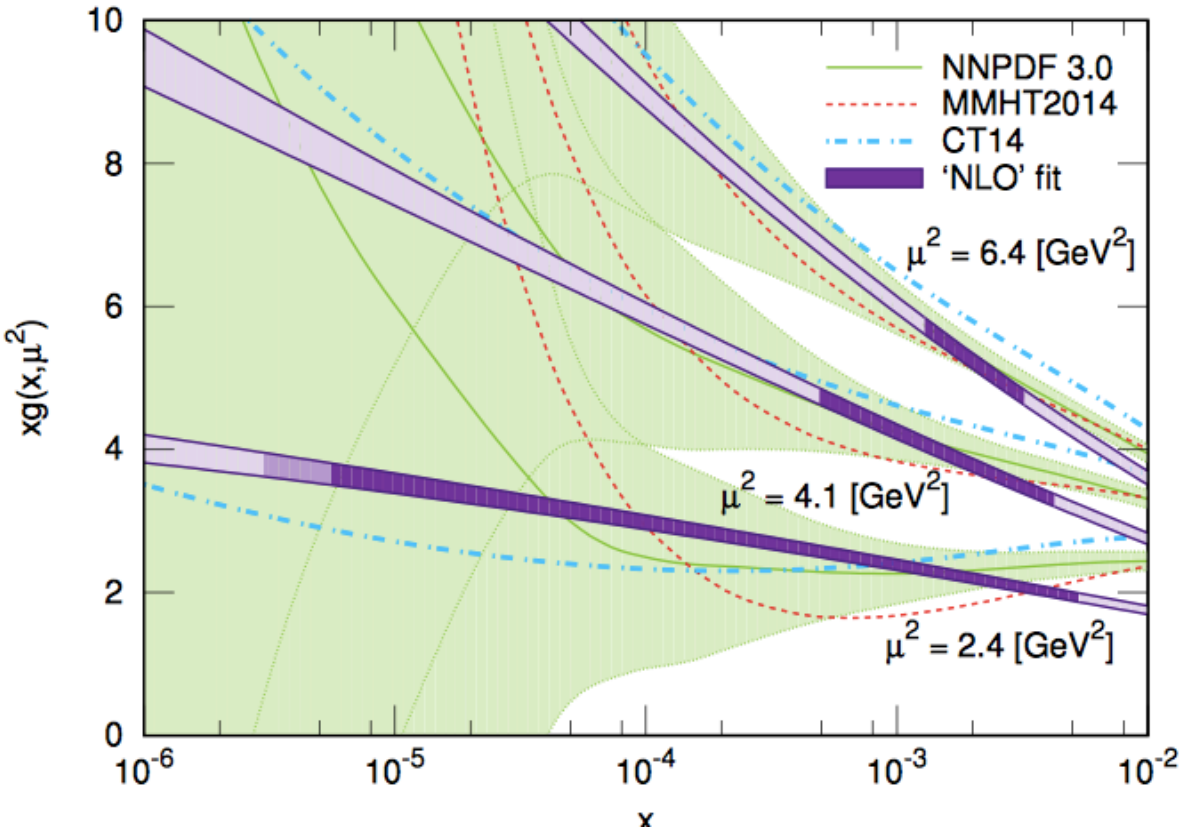
JHEP 10 (2018) 167.



(...for details see talk by Tara later in session)

Gluon PDF determination

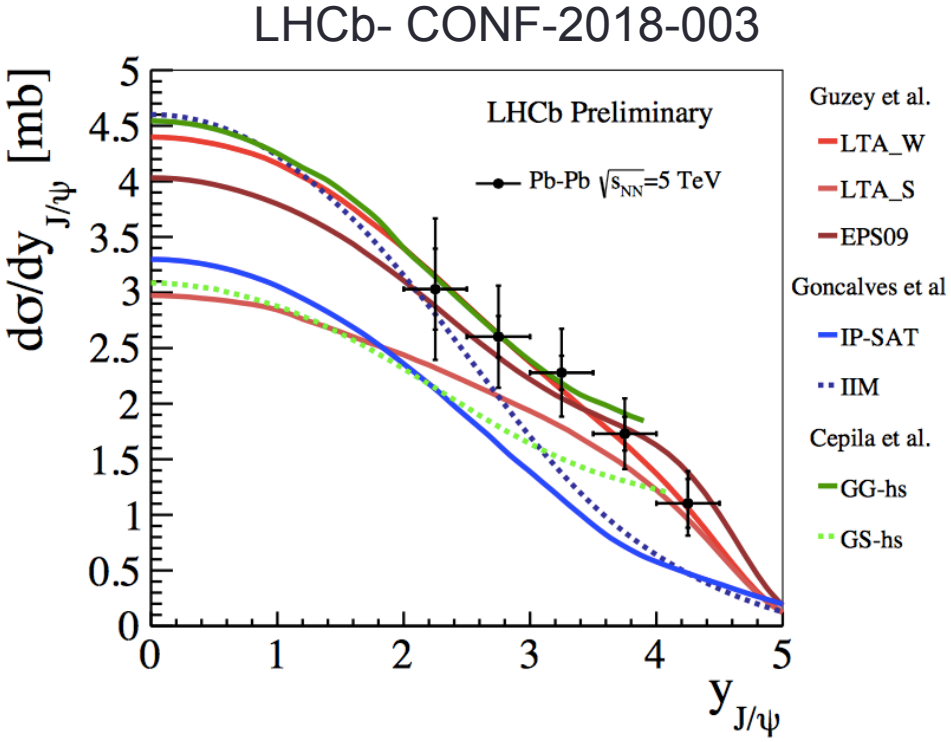
- Major impact on gluon PDF (yet this is not included in default global PDF sets)

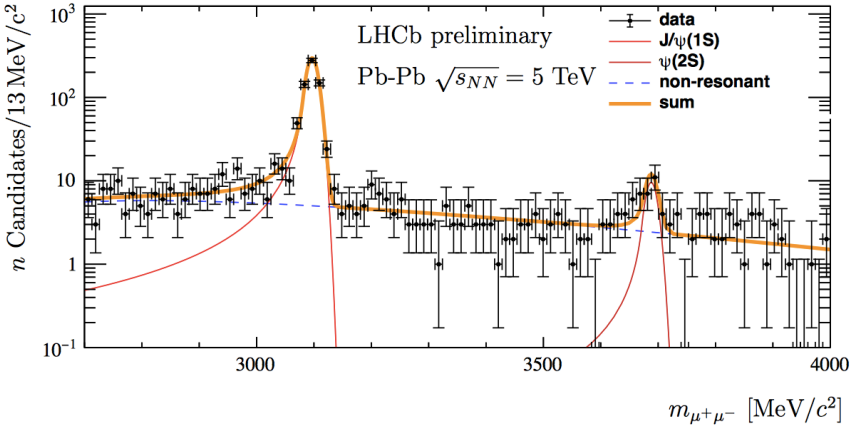


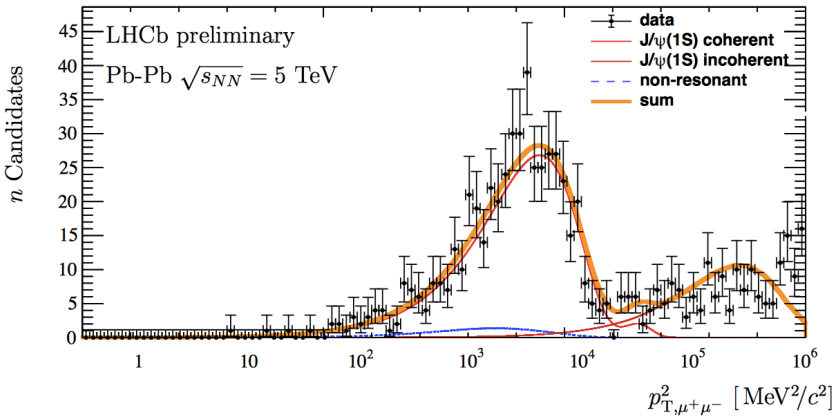
Jones, Martin, Ryskin, Teubner
JHEP 1311 (2013) 085
J.Phys. G44 (2017) no.3, 03LT(

Nuclear PDF determination

- In similar way $\sigma_{\gamma A}$ gives nuclear PDFs (or shadowing)
- LHCb measurement of J/ψ CEP in Lead-lead collisions



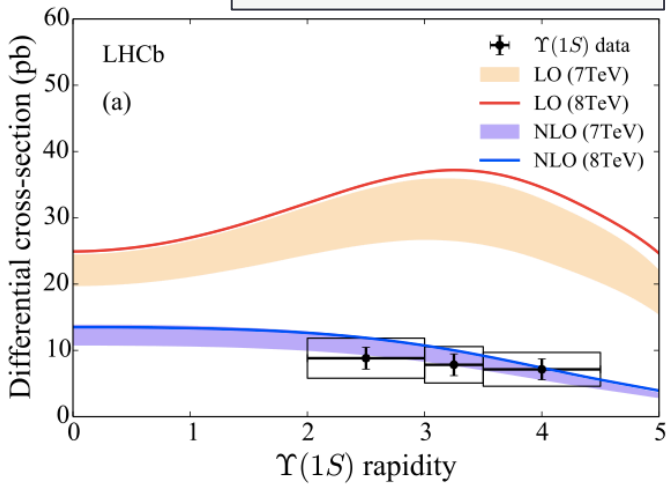


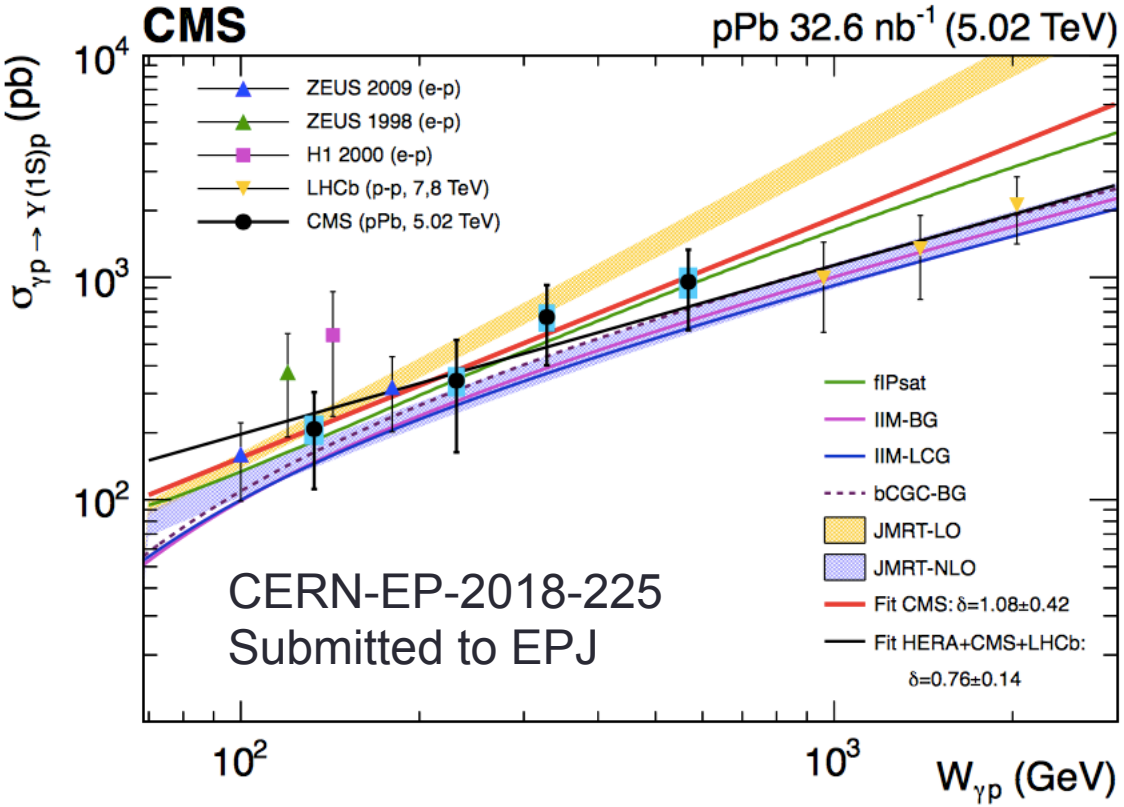


Upsilon photoproduction

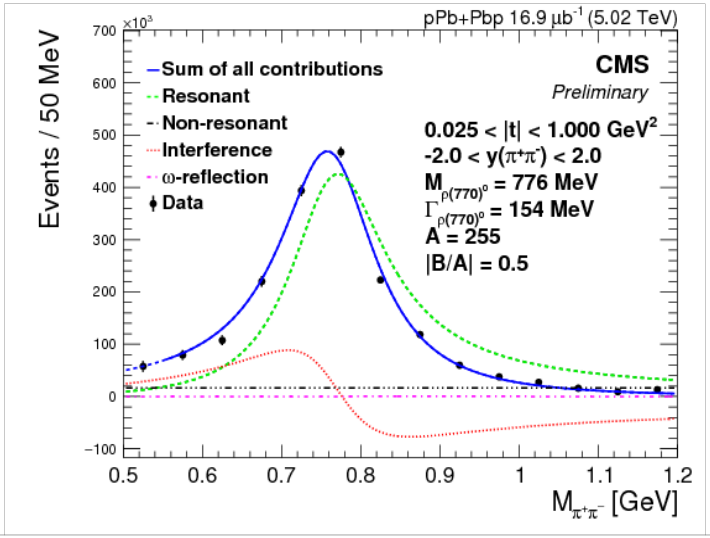
Measurement by LHCb in pp and recent CMS in pPb

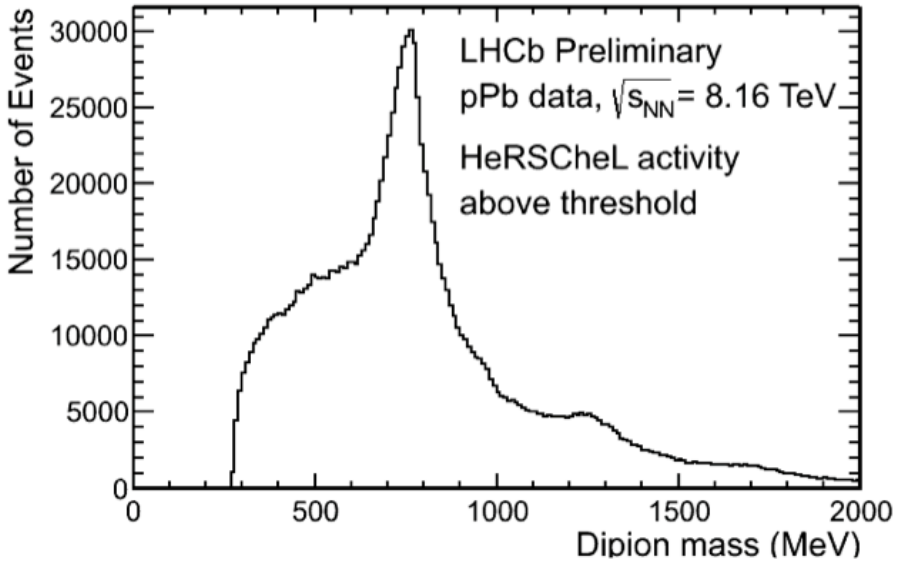
JHEP 1509 (2015) 084

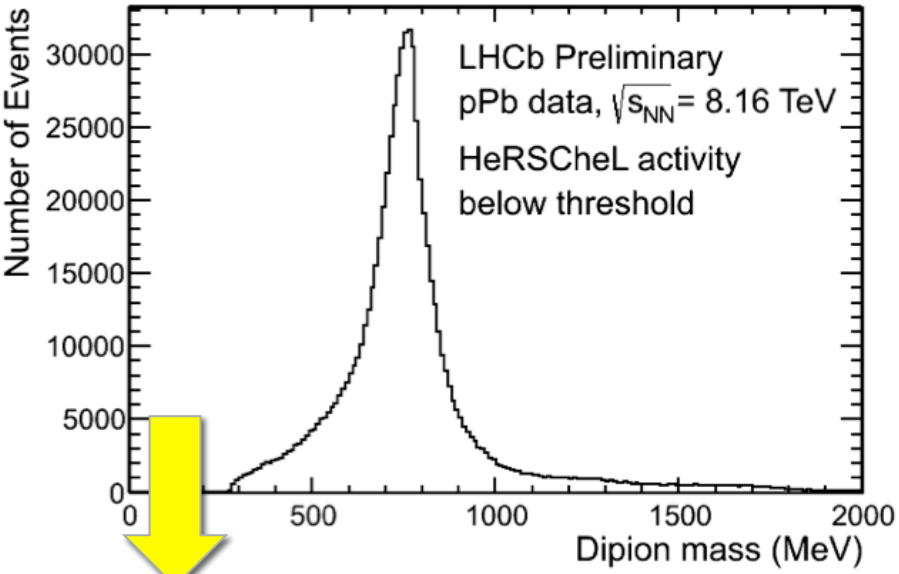


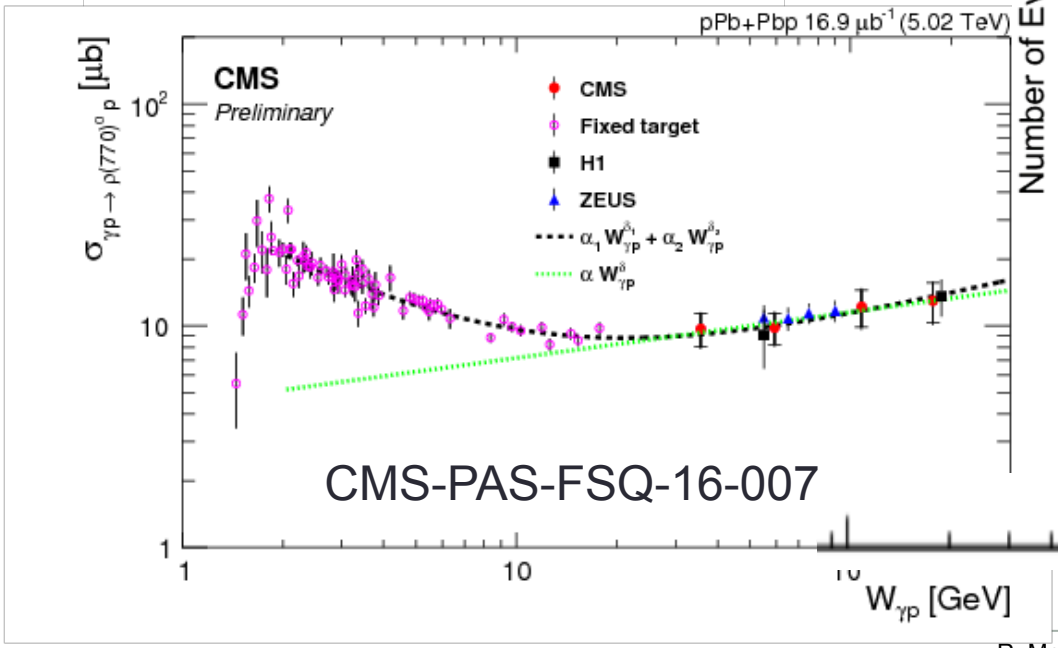


Rho photoproduction



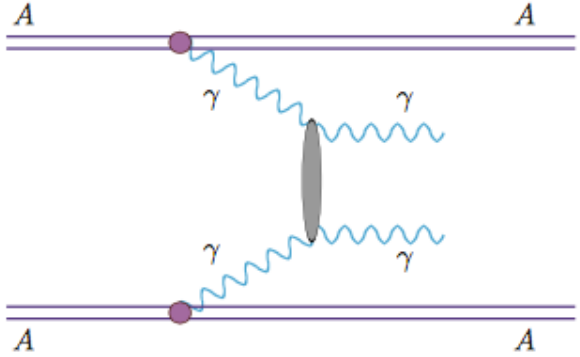




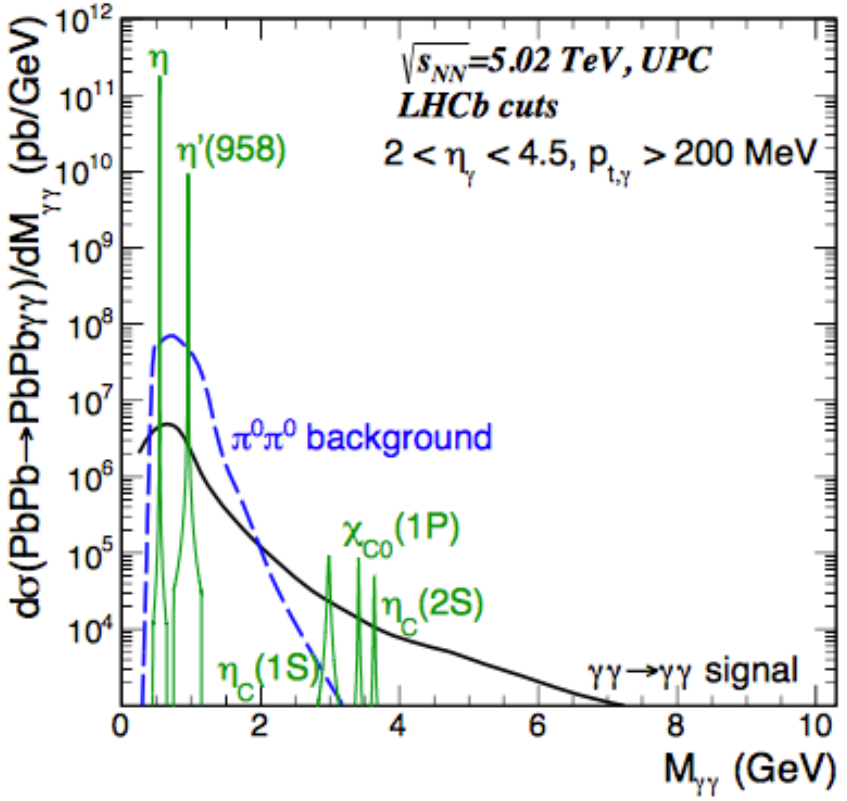


Complementarity of AA running: light-by-light scattering

M. Kłusek-Gawenda, arXiv:1809.03823



ATLAS, Nature Phys. 13 (2017) 852
CMS, CMS-PAS-FSQ-16-012 (2018)
$M_{\gamma\gamma}$>5 GeV

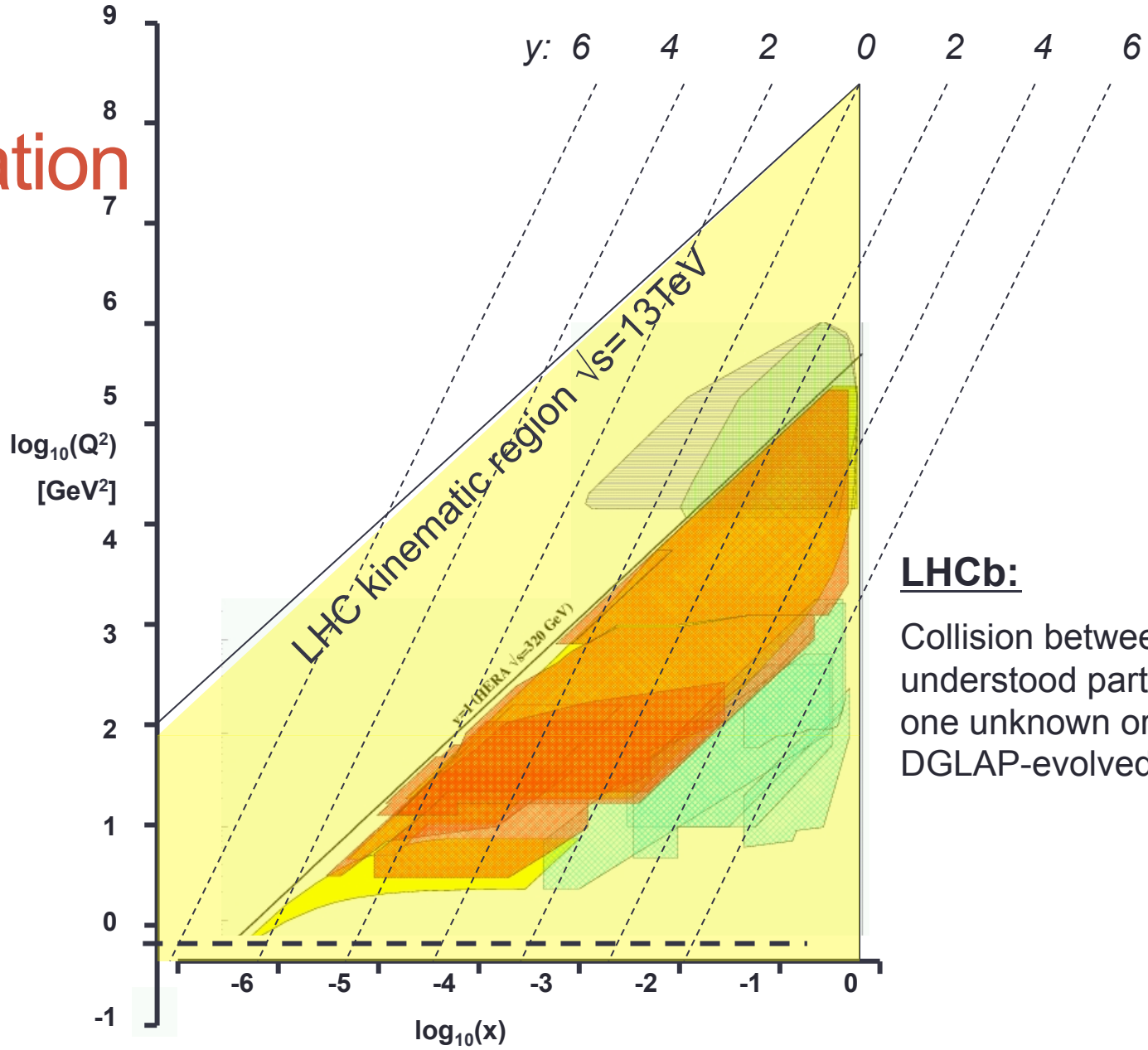


LHCb in principle can go to lower masses
$\pi^0\pi^0$ can be removed through pT spectrum <100 MeV for signal

2018: Aim for 4μb^{-1} of data.
(Sufficient for seeing resonances but not continuum)

Open questions in QCD....

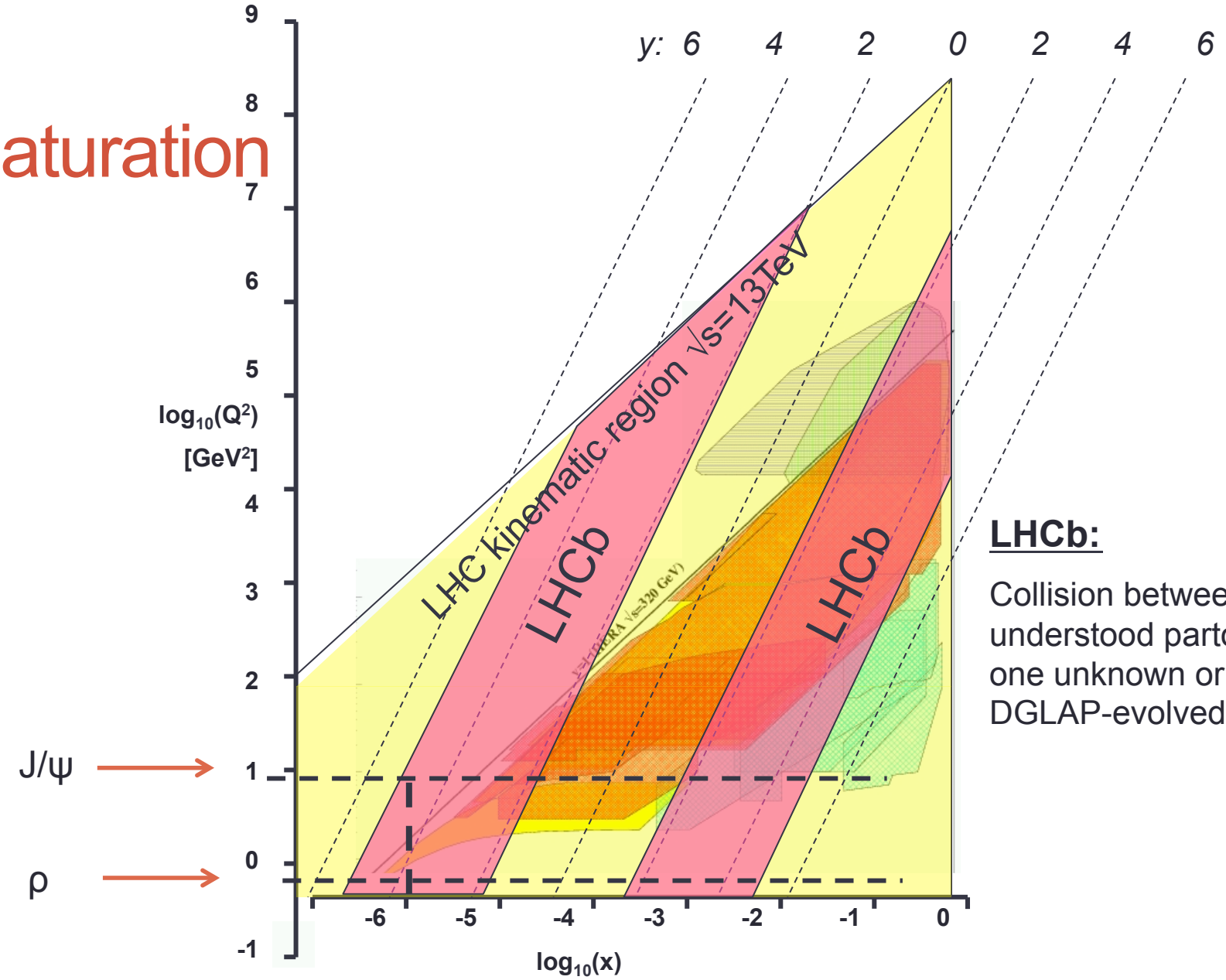
Saturation



LHCb:

Collision between one well understood parton and one unknown or large DGLAP-evolved parton.

Saturation

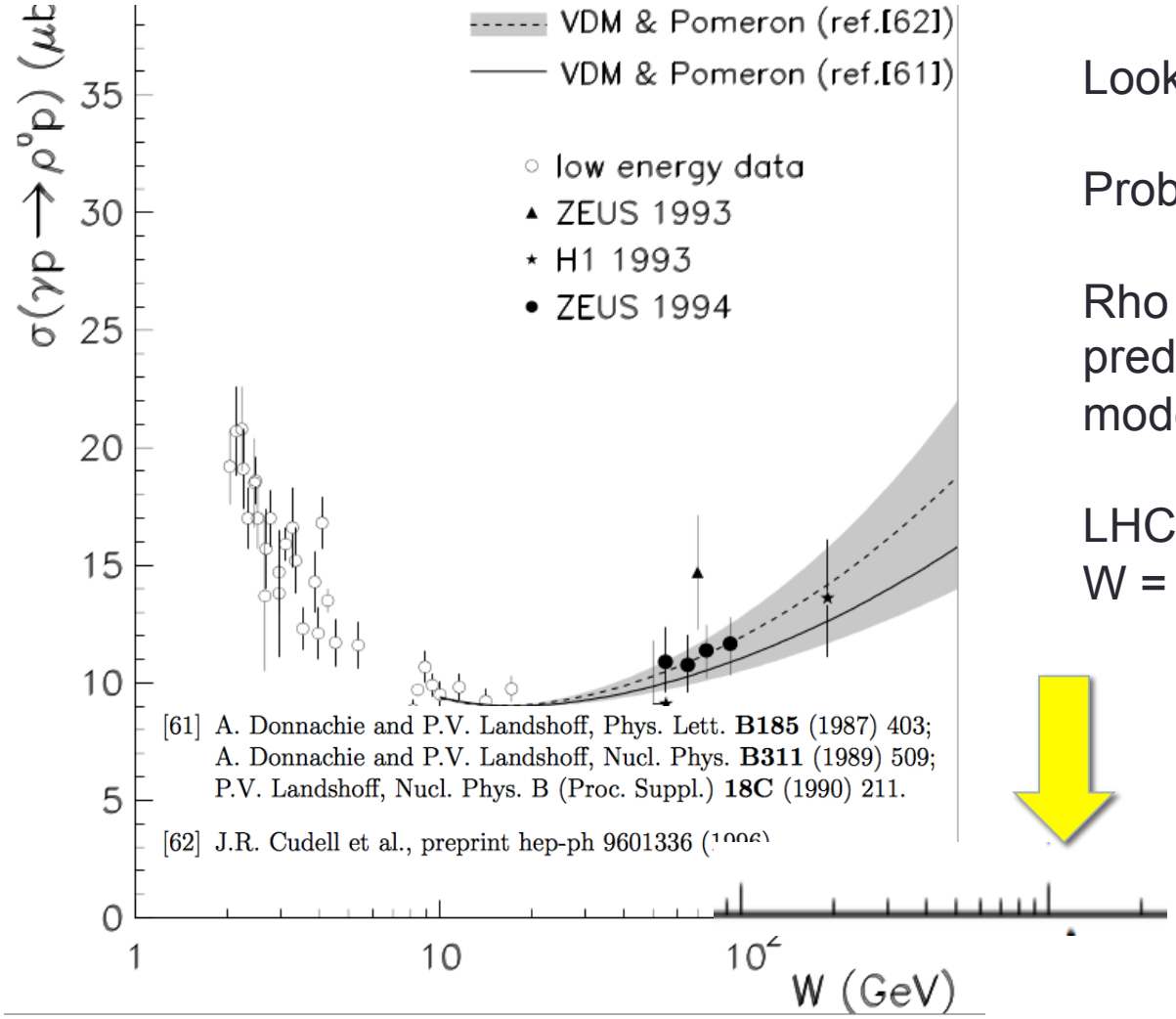


LHCb:

Collision between one well understood parton and one unknown or large DGLAP-evolved parton.

Saturation

Eur.Phys.J.C2:247-267,1998



Look to low-x low-Q^2 region.

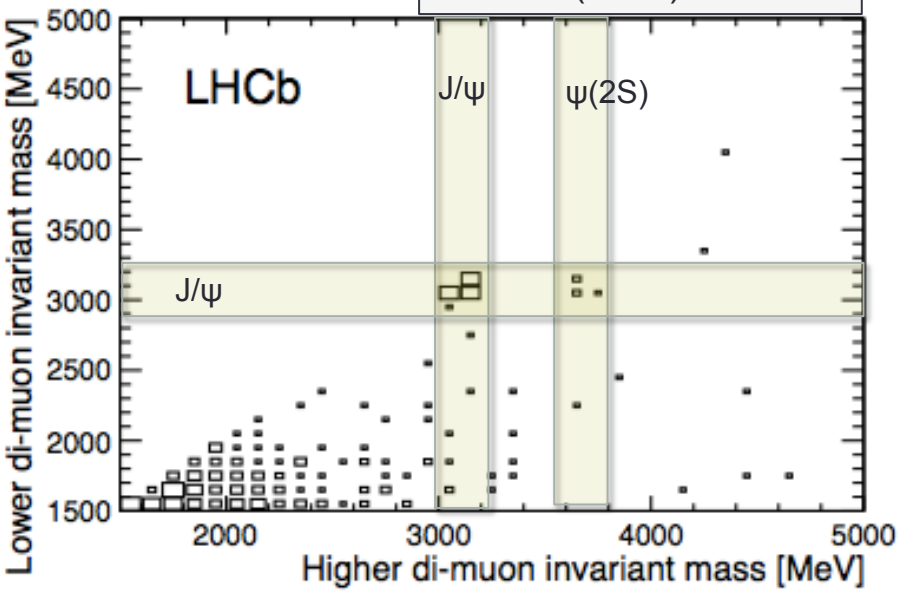
Problem is not perturbative

Rho photo-production predictions depend on modelling of Pomeron

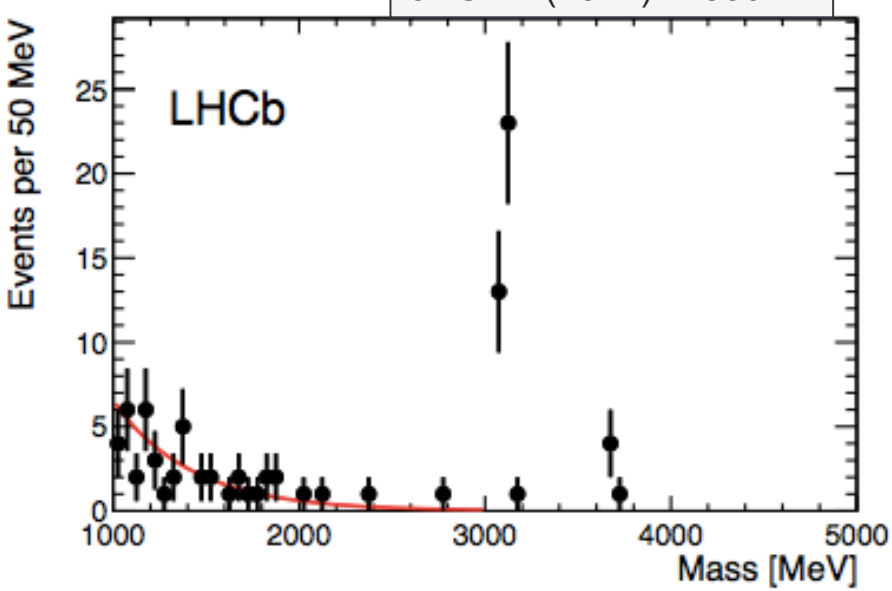
LHCb can measure this at W = 1TeV (x=5E-7)

Open questions in QCD: Exotics

JPG 41 (2014) 115002



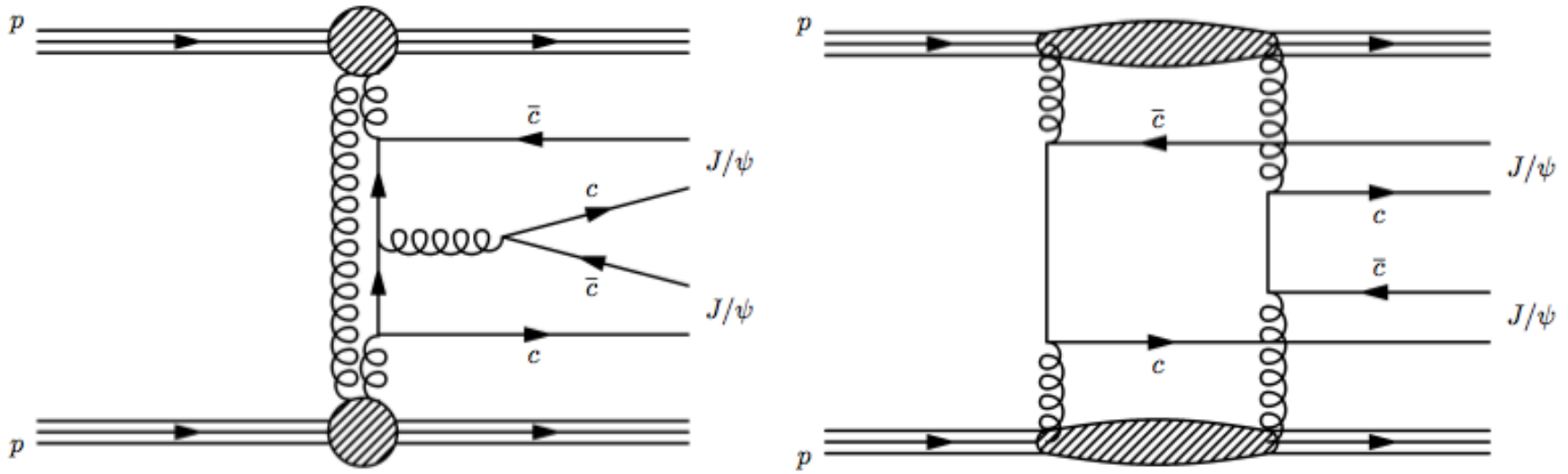
JPG 41 (2014) 115002



Dimuon spectrum having required other two muons have J/ψ mass

Selection requirement:
Require precisely 4 tracks, at least three identified as muons

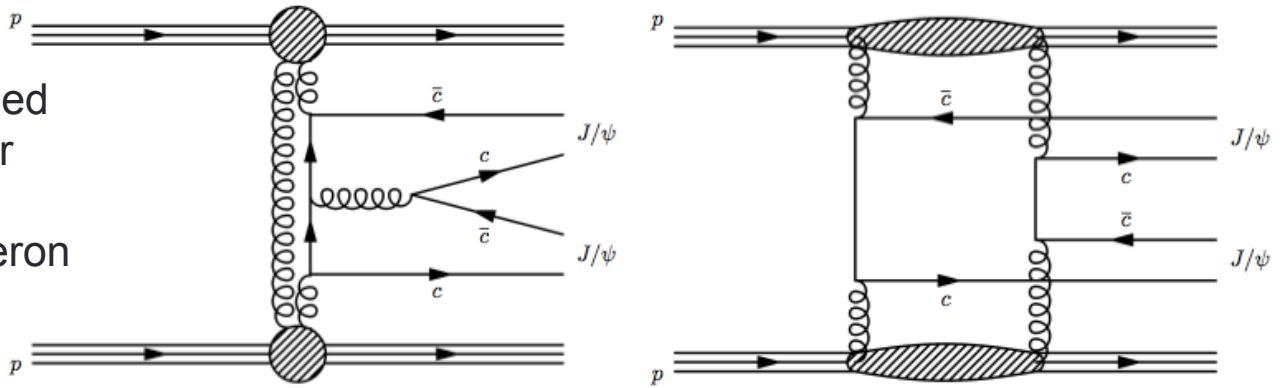
Double J/ψ production



Final state theoretically studied in diphoton production (linear collider) but not through double pomeron exchange (hadron collider)

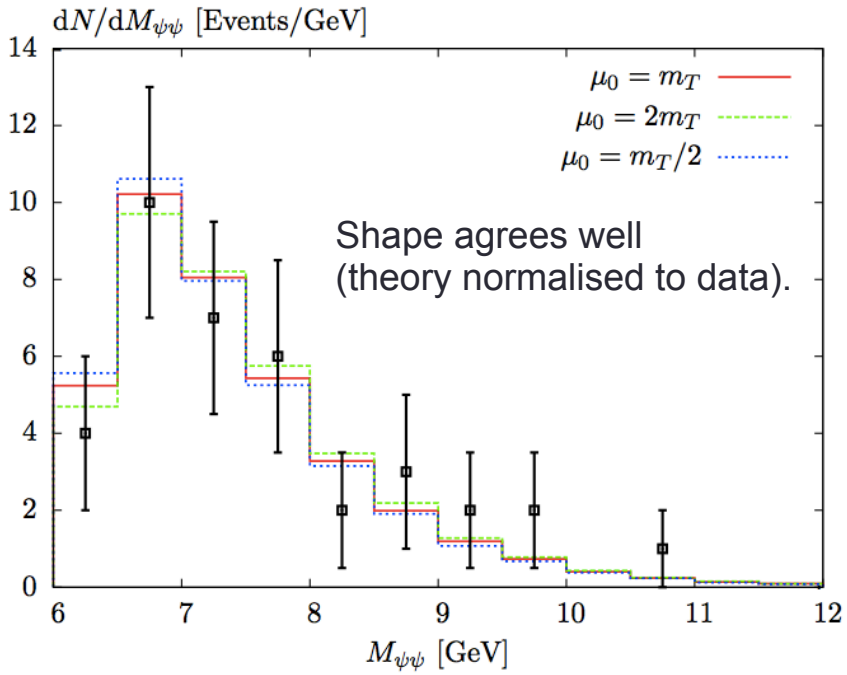
Sensitivity to higher mass states (tetraquarks, η_b)
Inclusive production has attracted much interest (DPS effects)

Double J/ψ production (Tetraquark candidate)



Final state theoretically studied in diphoton production (linear collider)
but not through double pomeron exchange (hadron collider)

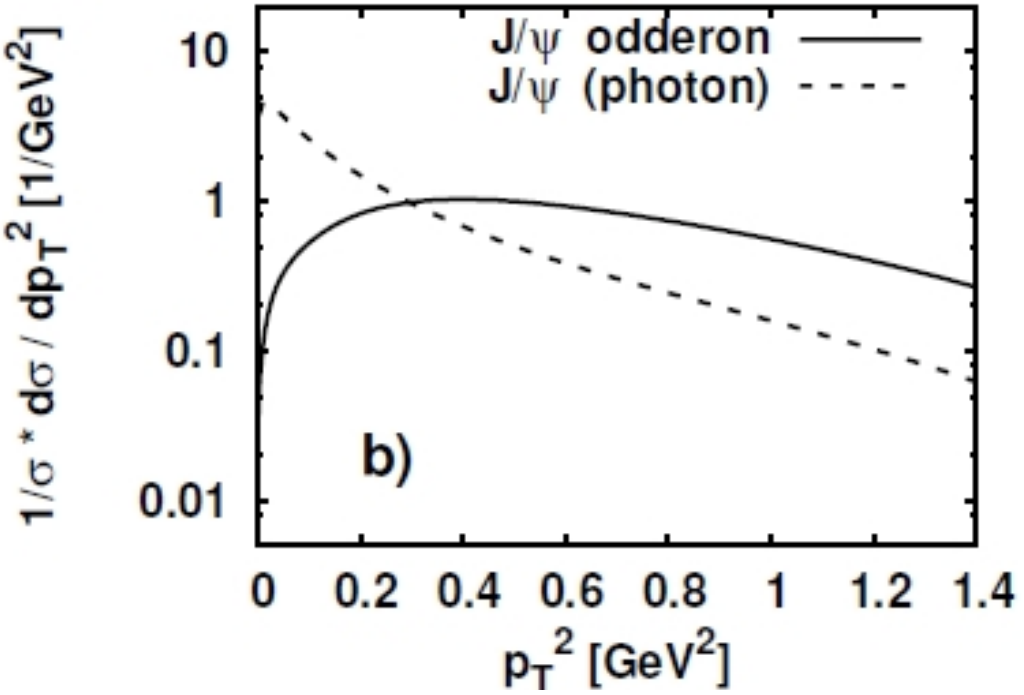
Sensitivity to higher mass states (tetraquarks, η_b)
Inclusive production has attracted much interest (DPS)

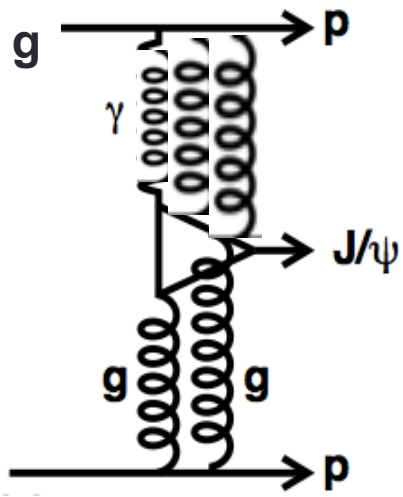


LHCb estimates exclusive cross-section. **24+-9 pb**

Harland-Lang, Khoze, Ryskin:
JPG 42 (2015) 5,055001 **2-7 pb**

Open questions in QCD: The odderon (1)





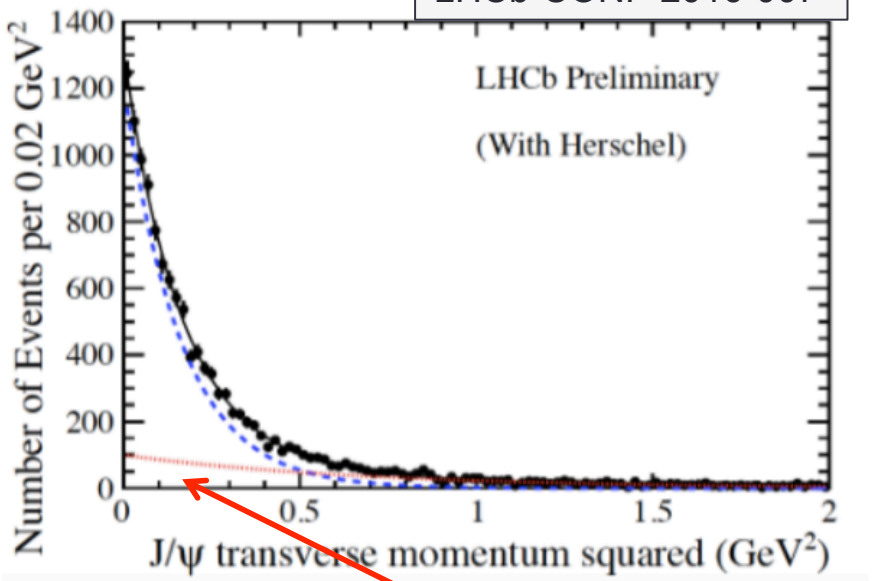
Bzdak, Motyka, Szymanowski, Cudell
PRD 75 (2007) 094023
arXiv:0808.2216

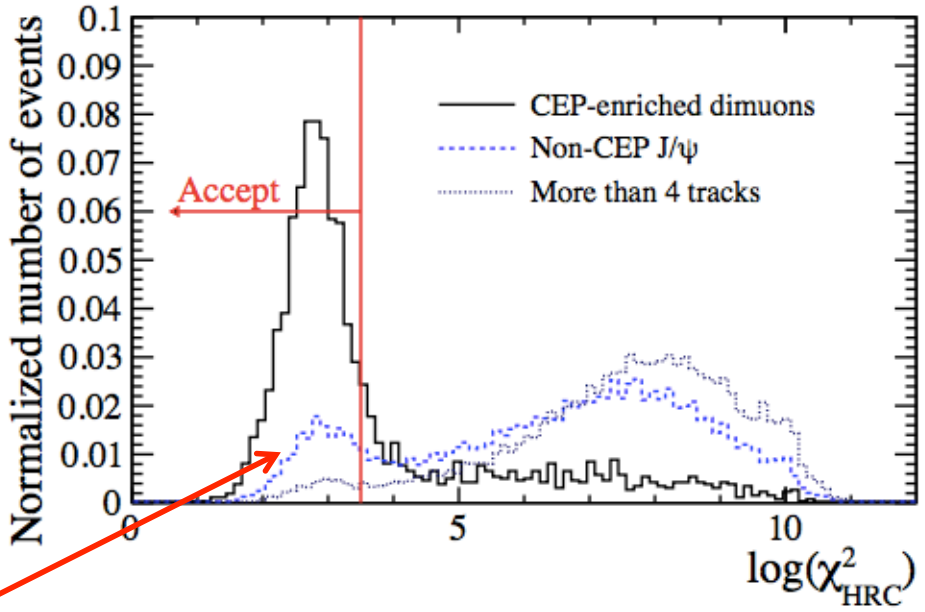
$d\sigma^{\rm corr}/dy$	J/ψ		Υ	
	odderon	photon	odderon	photon
Tevatron	0.3–1.3–5 nb	0.8–5–9 nb	0.7–4–15 pb	0.8–5–9 pb
LHC	0.3–0.9–4 nb	2.4–15–27 nb	1.7–5–21 pb	5–31–55 pb

Requires understanding p_T^2 spectrum for proton dissociation (or rejection of it)

Odderoproduction

LHCb-CONF-2016-007

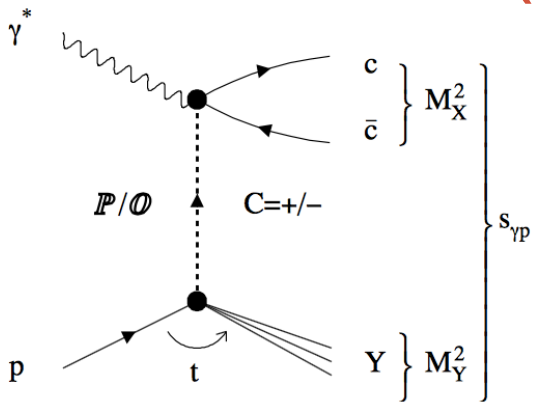




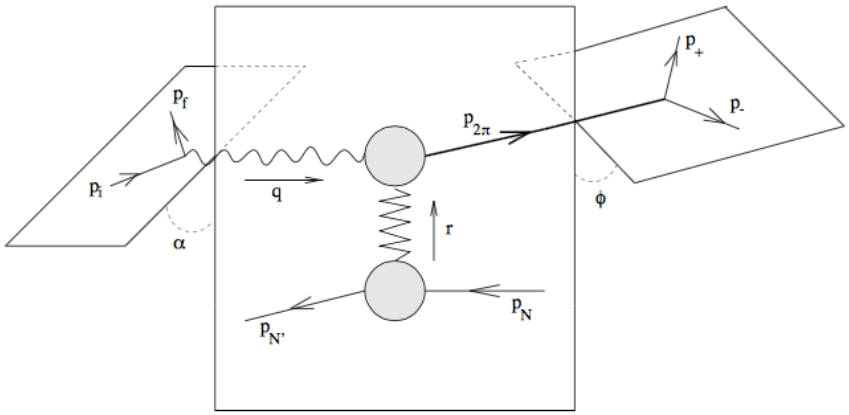
Proton dissociation or Odderoproduction ? !

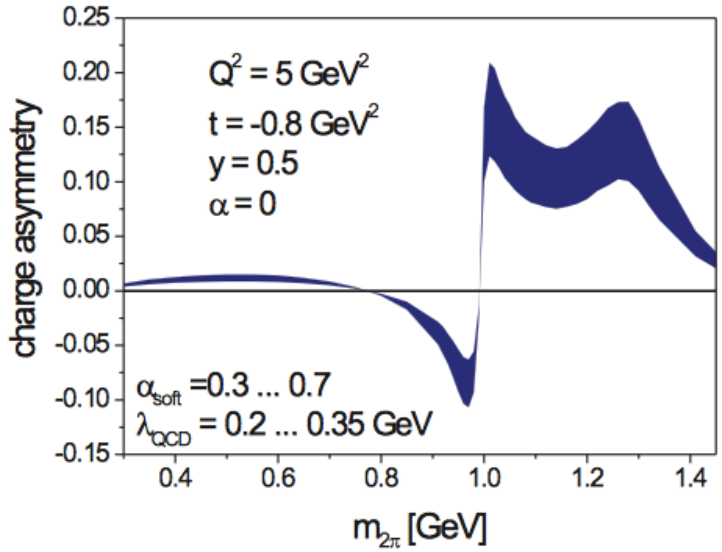
Open questions in QCD: The odderon (2)

Brodsky, Rathsman, Merino,
PLB461 (1998) 114.
Hagler, Pire, Szymanowski, Teryaev,
EPJ26 (2002) 261.
Bolz, Ewerz, Maniatis, Nachtmann, Sauter,
Schoening, JHEP 1501 (2015) 151.



$$A(Q^2, t, m_{2\pi}^2, y, \alpha) = \frac{\sum_{\lambda=+,-} \int \cos\theta \, d\sigma(s, Q^2, t, m_{2\pi}^2, y, \alpha, \theta, \lambda)}{\sum_{\lambda=+,-} \int d\sigma(s, Q^2, t, m_{2\pi}^2, y, \alpha, \theta, \lambda)} = \frac{\int d\cos\theta \cos\theta \; N_{charge}}{\int d\cos\theta \; D}$$

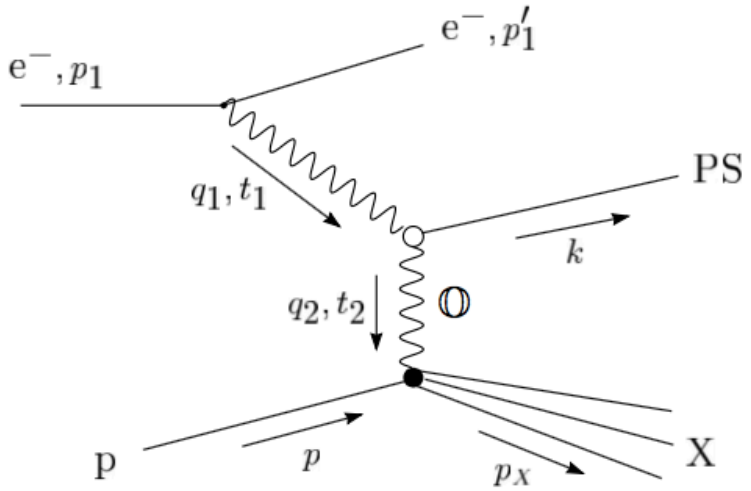


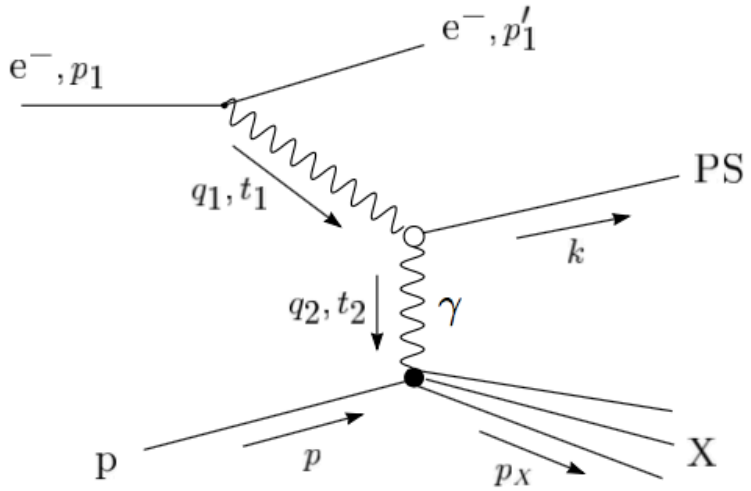


Open questions in QCD: The odderon (3)

Czyzewski et al., PLB398 (1997) 400.
Berger et al., EPJ C9 (1999) 491.
M.G. Ryskin EPJ C2 (1998) 339.
Kilian & Nachtmann, EPJ C5 (1998) 317.

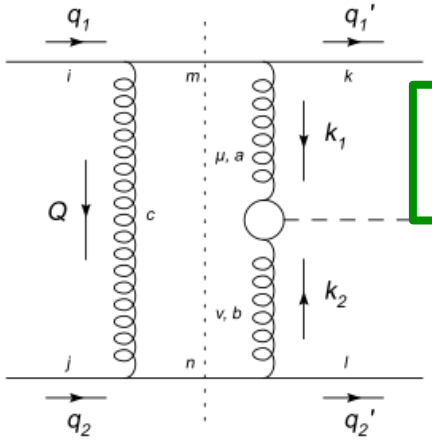
γp->ηp, γp->π^0p, γp->f_2p, γγ->$\pi^0\pi^0$





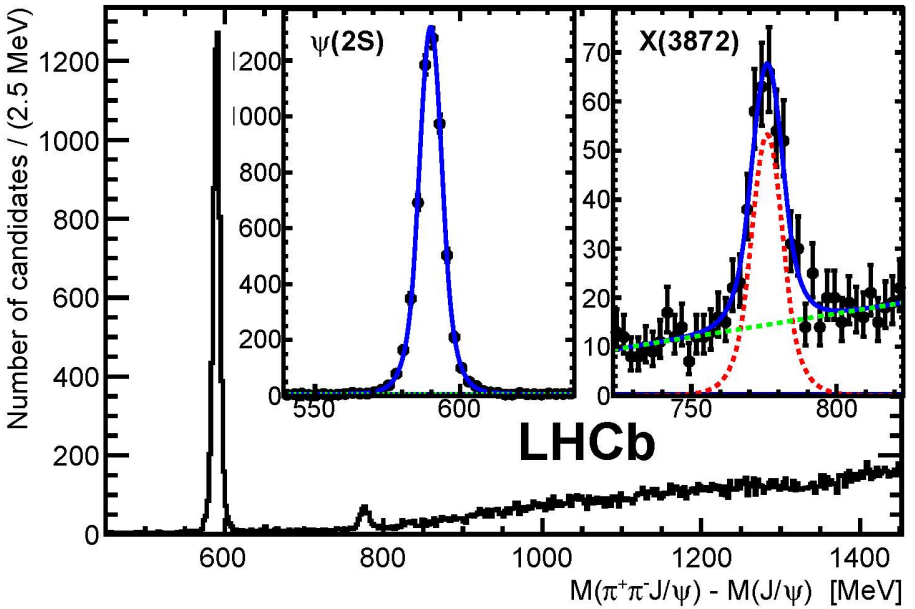
In pp colisions, photon flux small so γγ cross-section small (and calculable)
Photon-Odderon production 'small'/unknown
Pomeron-Pomeron production suppressed, but still constitutes a background.

Open questions in QCD: Glueballs, Hybrids



Double-pomeron-exchange processes
Glue Laboratory

Inclusive X(3872)
Eur.Phys.J. C72 (2012) 1972



Clean environment for
meson production.
Spin and parity analysis possible.

Summary

Central Exclusive Production
is an attractive environment
theoretically and experimentally
to study QCD
and look for new effects.