Central Exclusive Production (CEP) at LHCb

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

Meson 2018

12 June 2018, Krakow.

Overview

1. Central Exclusive Physics (CEP)

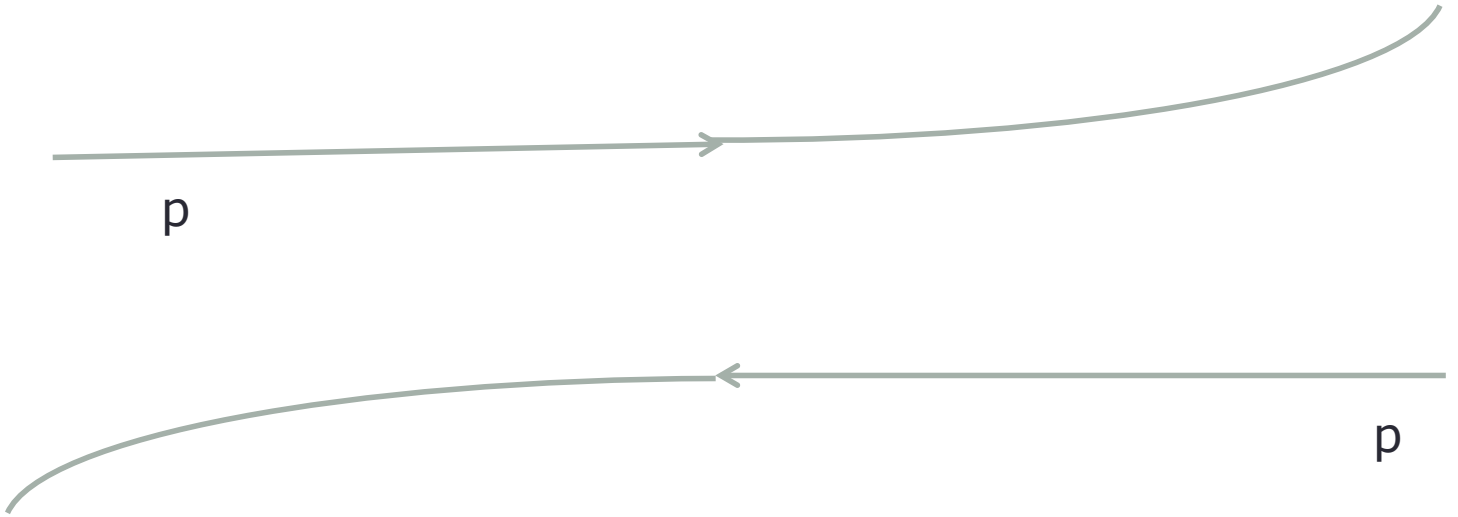
2. LHCb and HeRSCheL Detector

3. Analyses:
   - pp at 13 TeV
   - PbPb at $\sqrt{s_{NN}}$ = 5 TeV
   - pPb and Pb-p at 8 TeV

NEW

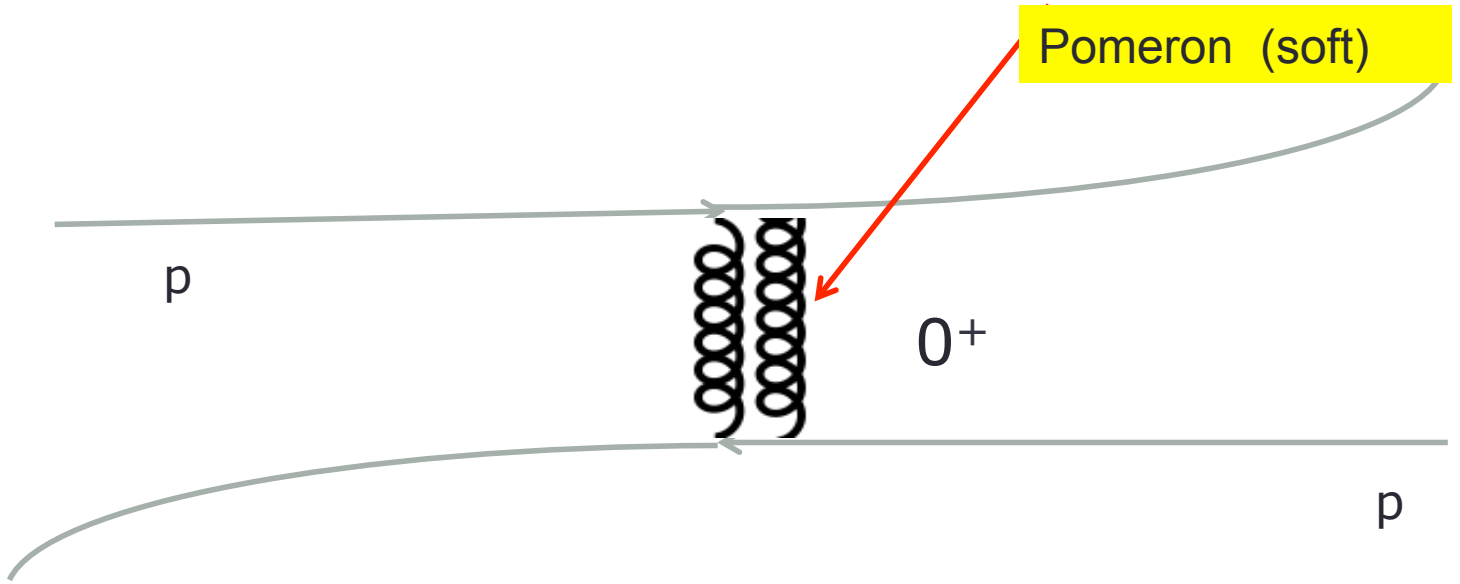
4. Physics reach for CEP

Elastic scattering



$\sigma_{elastic}$ ≈ 35%
$\sigma_{diffractive}$ ≈ 10%
$\sigma_{inelastic}$ ≈ 55%

Elastic scattering



It's QCD – but not as we normally see it. It's colour-free

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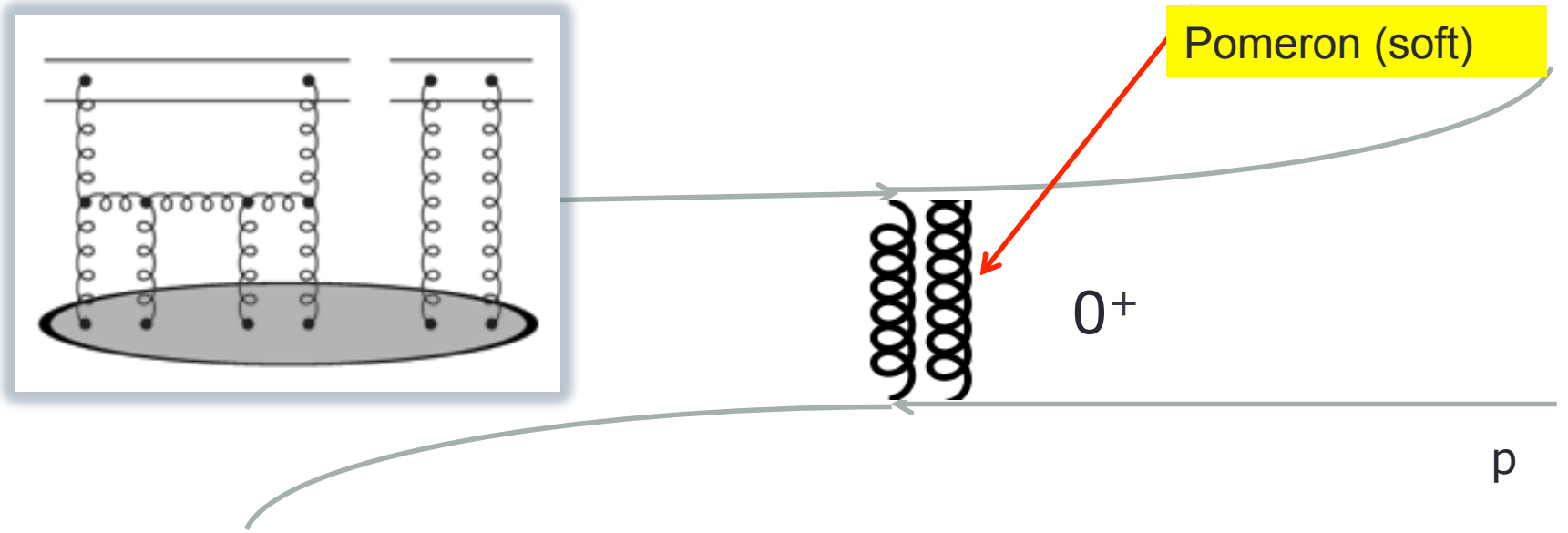
Elastic scattering



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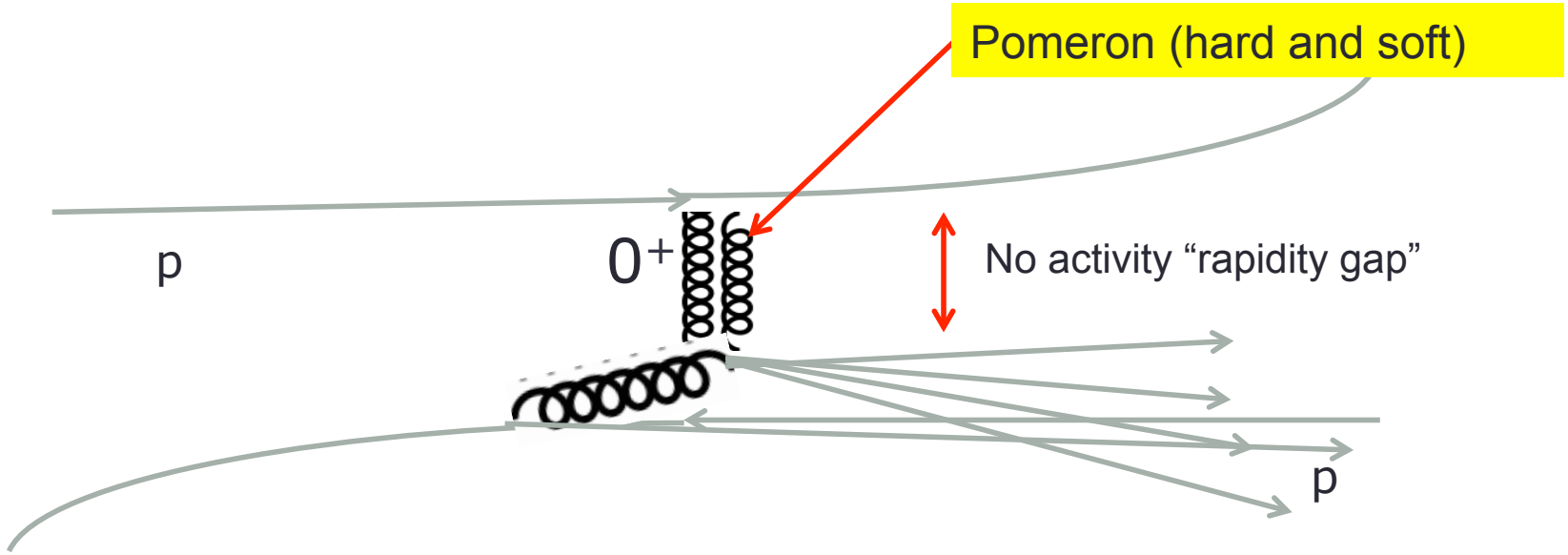
Diffraction



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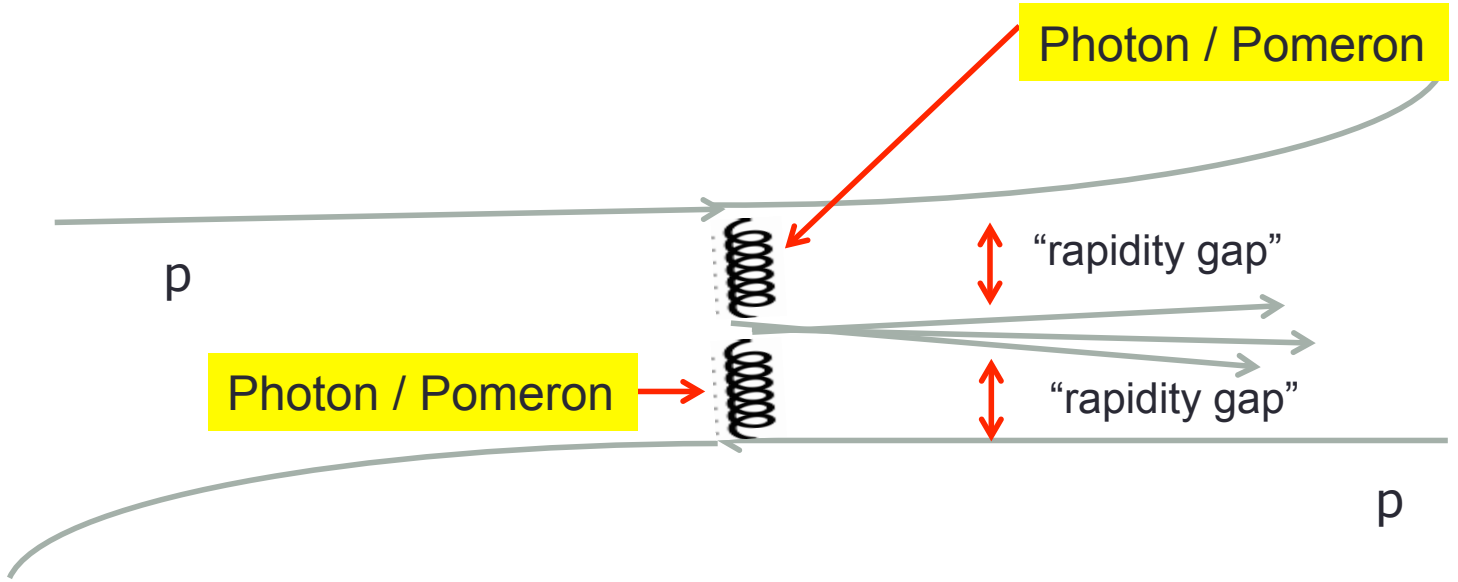
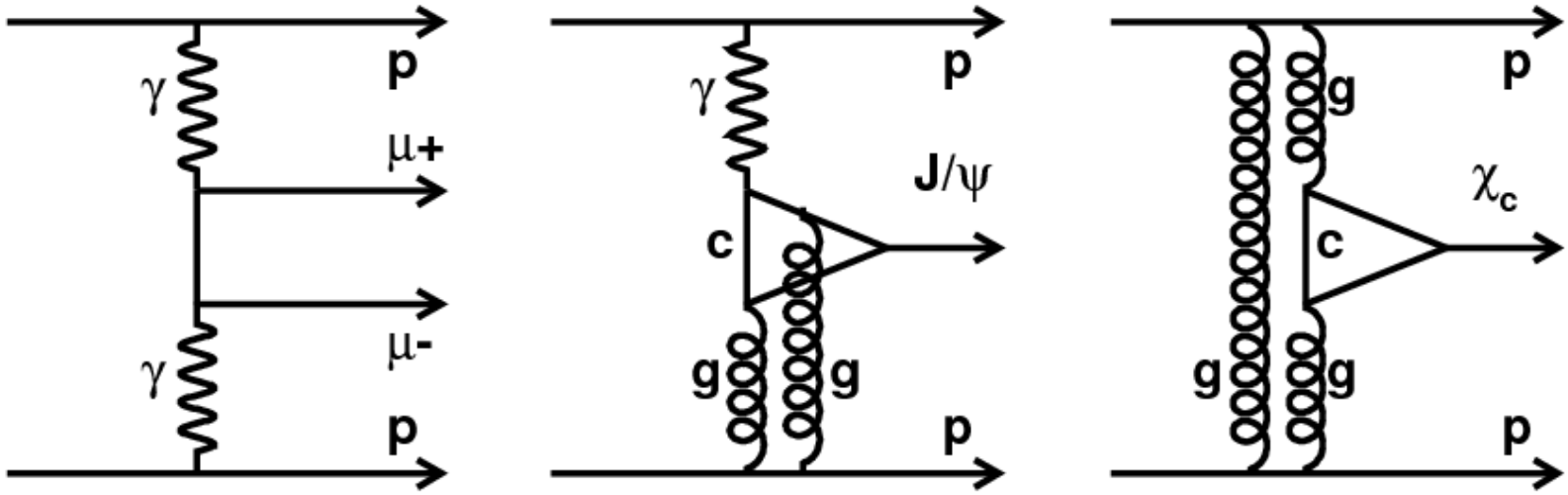
Central Exclusive Production (CEP)



Elastic diffractive:
clean environment to study vacuum, and to produce mesons.

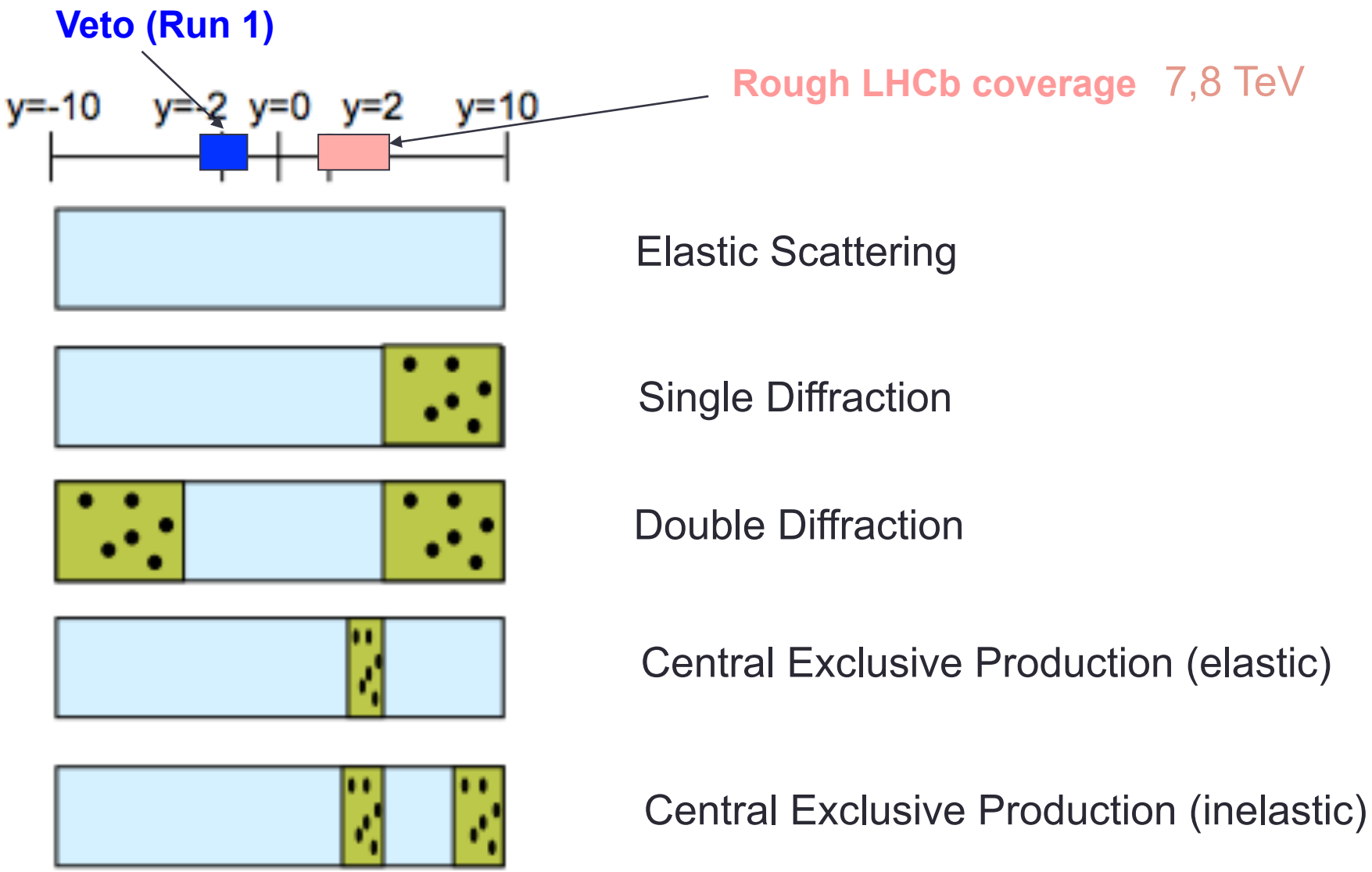
$\sigma_{elastic}$ ≈ 35%
$\sigma_{diffractive}$ ≈ 10%
$\sigma_{inelastic}$ ≈ 55%

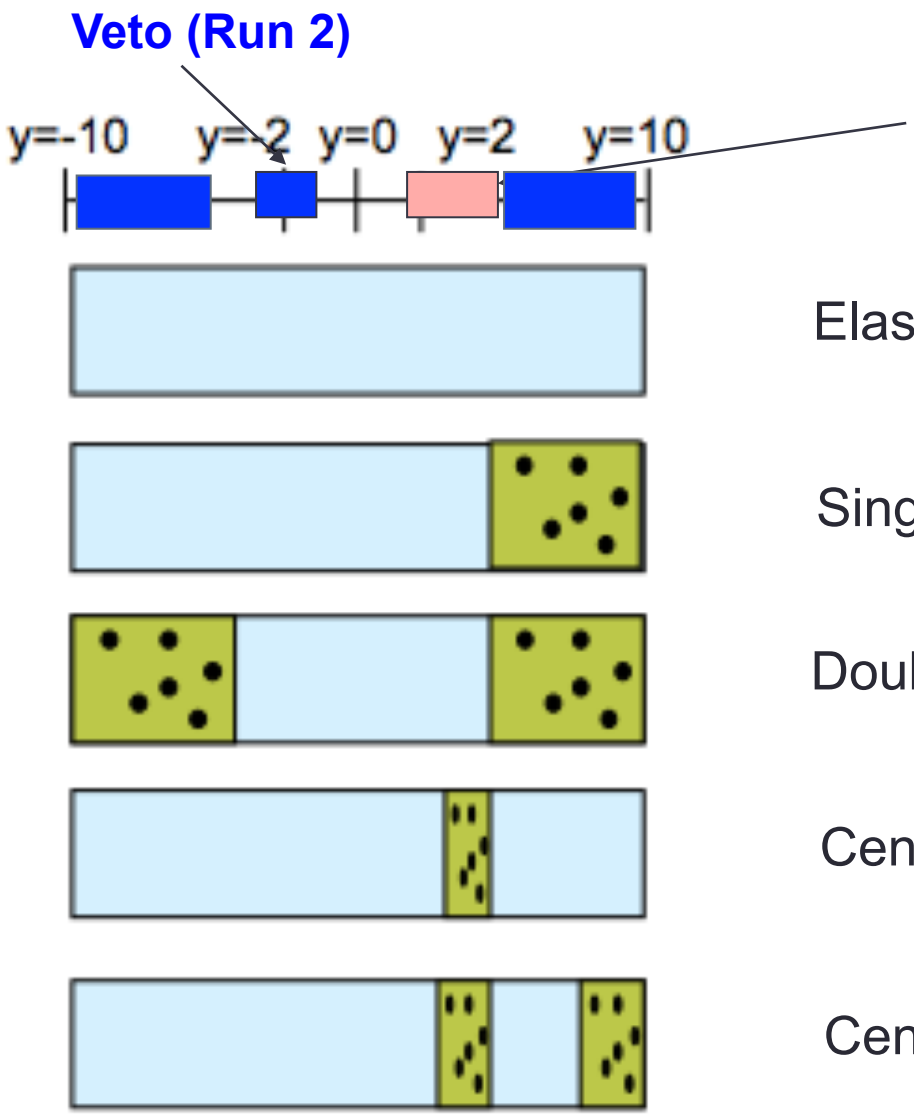
Central Exclusive Production (CEP)



Laboratory to study
- physics of the vacuum
- soft/hard QCD
- saturation
- exotics (tetraquarks, glueballs, hybrids)

Experimentally: Reconstruct central system and identify rapidity gaps


Veto (Run 1)
y=-10
y=-2
y=0
y=2
y=10
Rough LHCb coverage 7,8 TeV
Elastic Scattering
Single Diffraction
Double Diffraction
Central Exclusive Production (elastic)
Central Exclusive Production (inelastic)


Veto (Run 2)
y=-10
y=-2
y=0
y=2
y=10
Rough LHCb coverage 13 TeV
Elastic Scattering
Single Diffraction
Double Diffraction
Central Exclusive Production (elastic)
Central Exclusive Production (inelastic)

Overview

1. Central Exclusive Physics

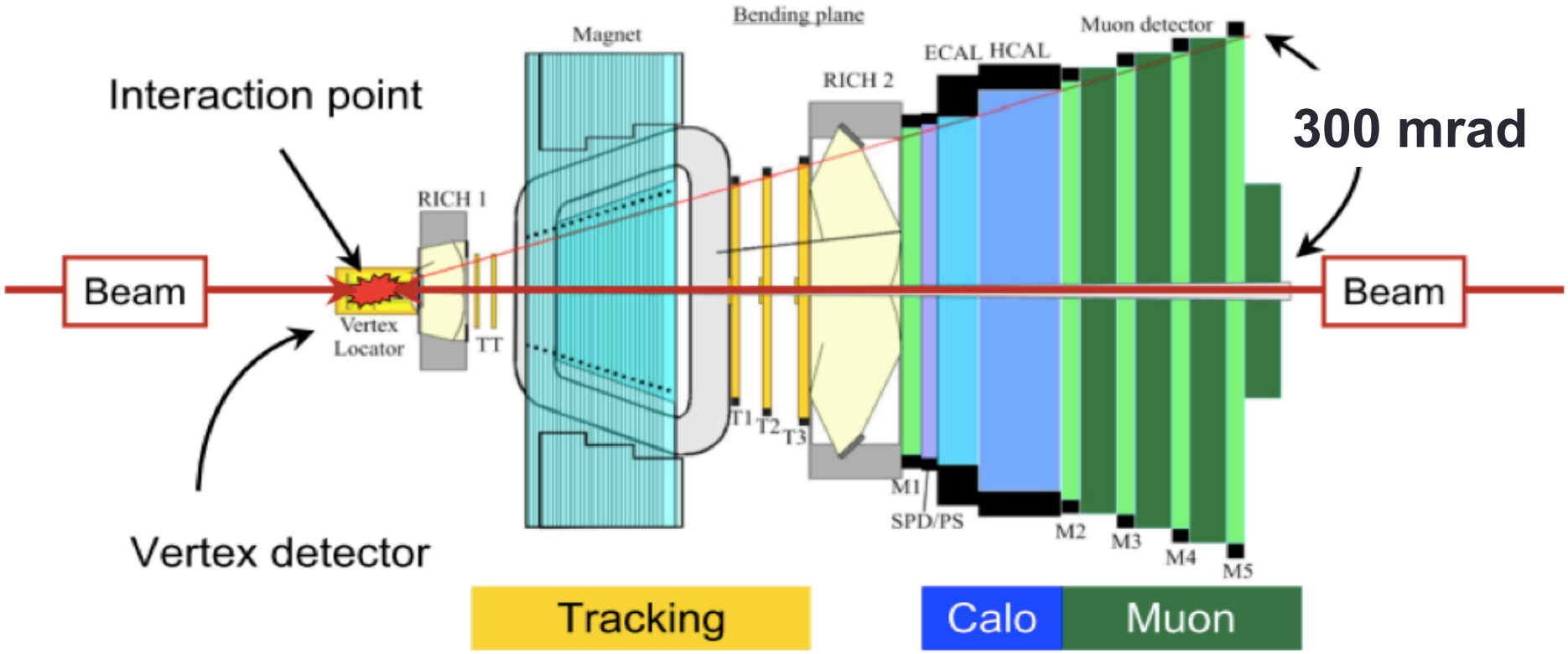
2. LHCb and HeRSCheL Detector

3. Analyses:
   - pp at 13 TeV
   - pPb and Pb-p at 8 TeV
   - PbPb at $\sqrt{s_{NN}}$ = 5 TeV

4. Physics reach for CEP

The LHCb detector

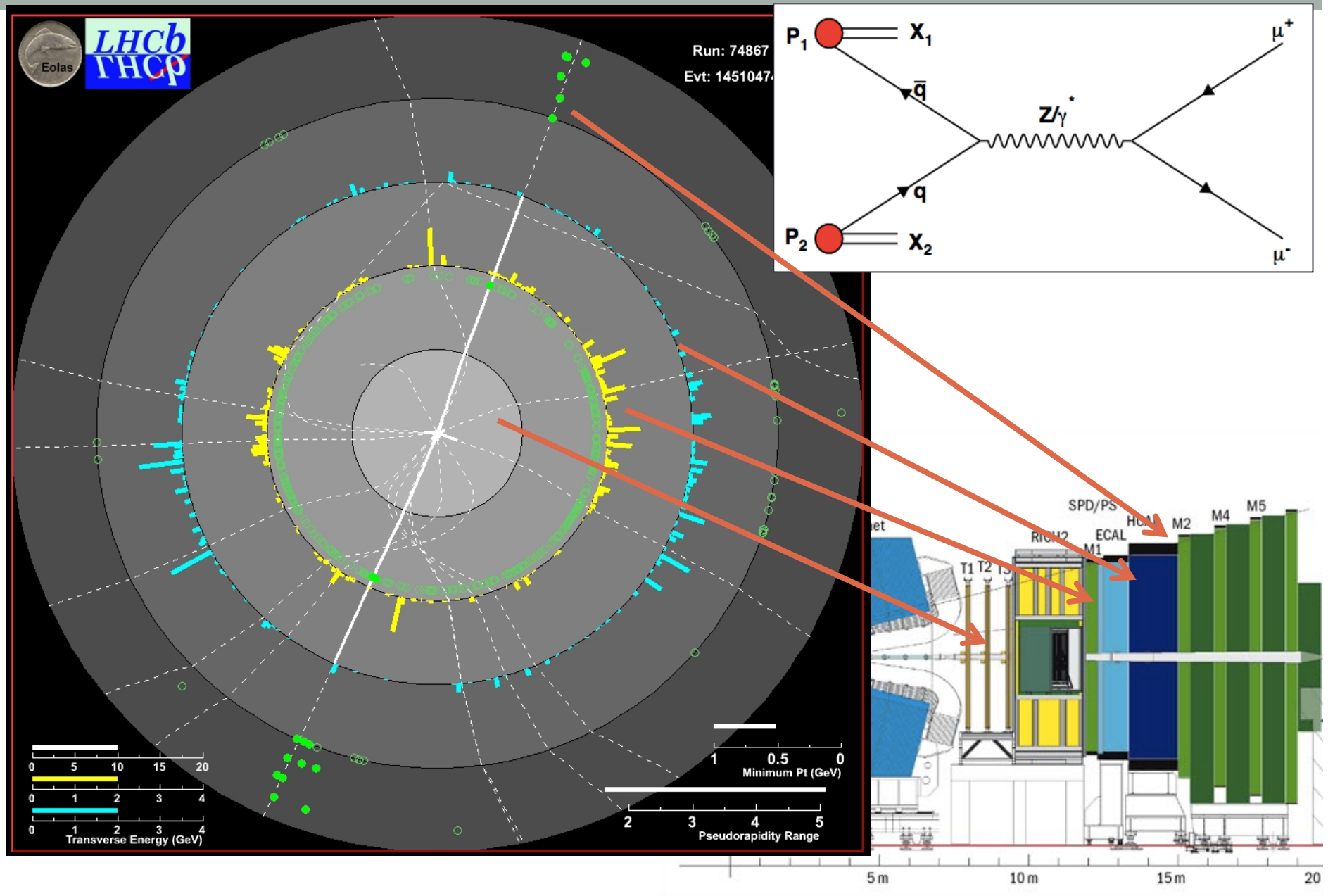
Int. J. Mod. Phys. A 30 (2015) 1530022

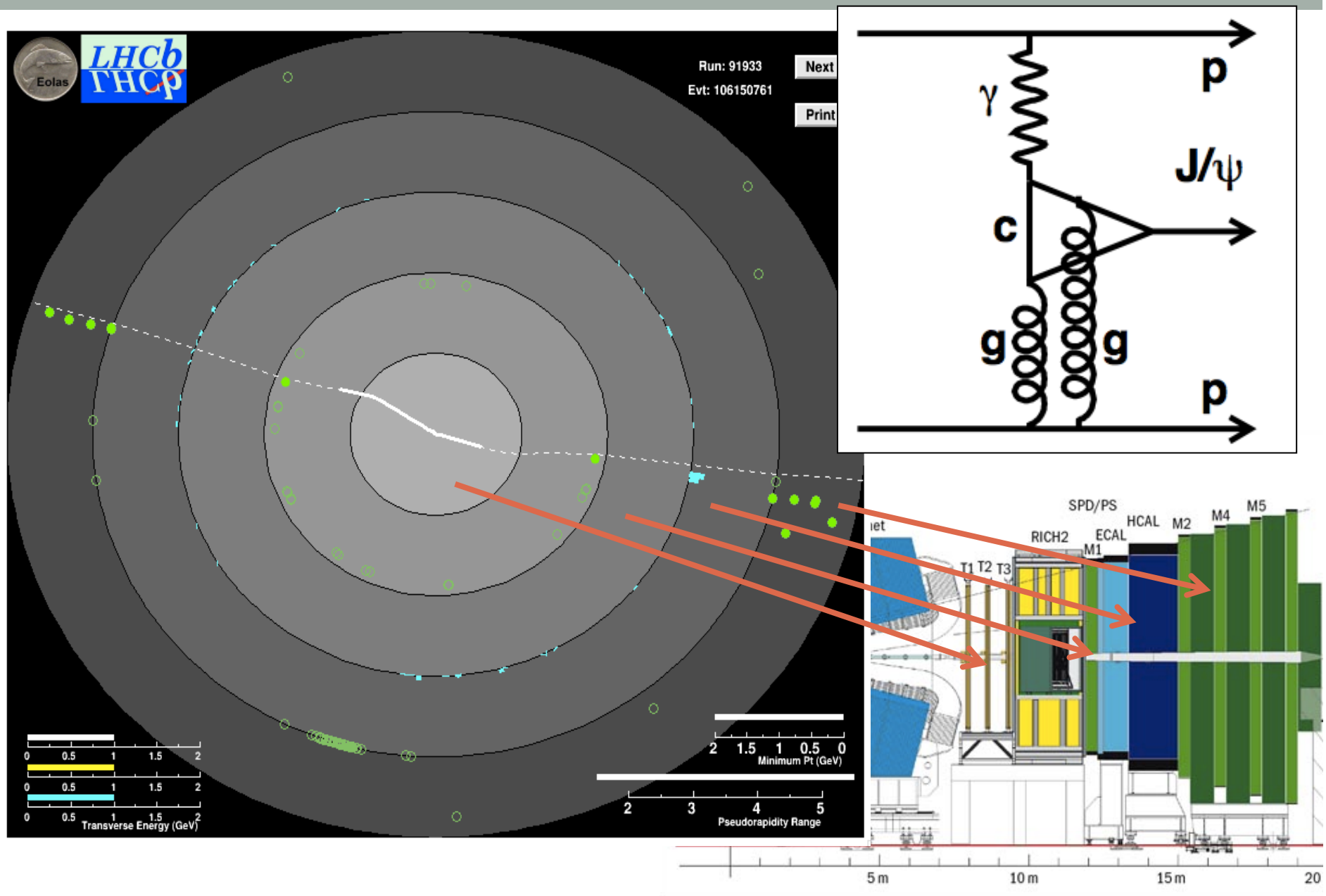


Fully instrumented: $2 < \eta < 5$

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

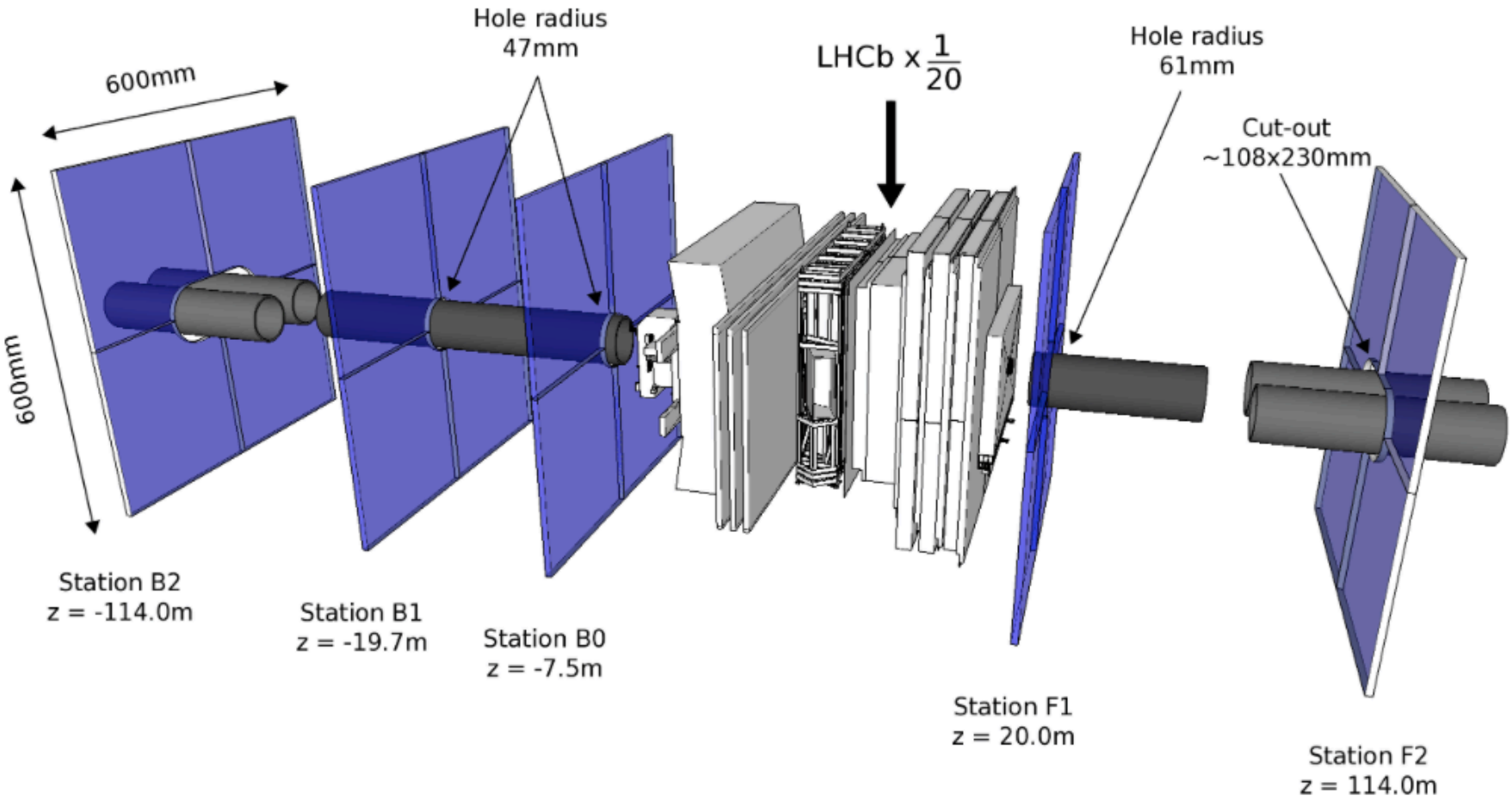
Veto region (Run 2): $-10 < \eta < -5,\ 5 < \eta < 10$

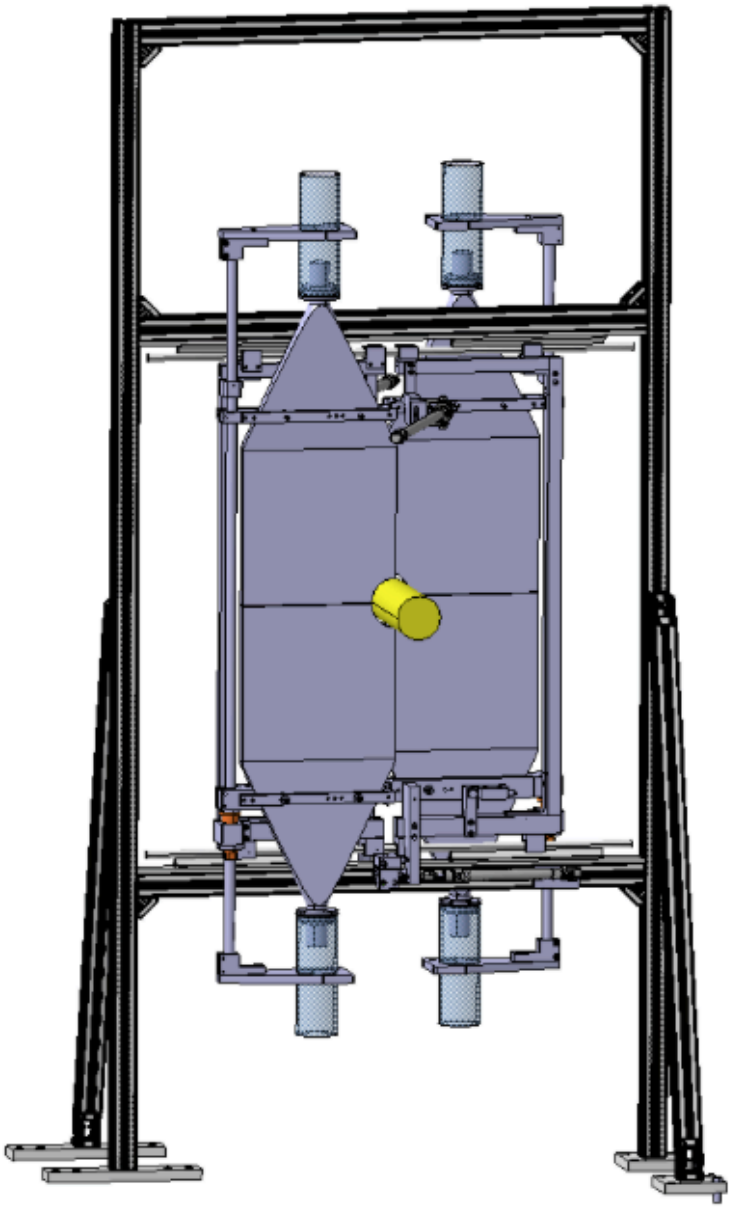

Eolas
LHCb
Run: 74867
Evt: 1451047
0 5 10 15 20
0 1 2 3 4
0 1 2 3 4
Transverse Energy (GeV)
1 0.5 0
Minimum Pt (GeV)
2 3 4 5
Pseudorapidity Range
P1
X1
q̄
Z/γ*
q
P2
X2
μ+
μ-
SPD/PS
M2
M4
M5
ECAL
M1
T1 T2
5 m
10 m
15 m
20

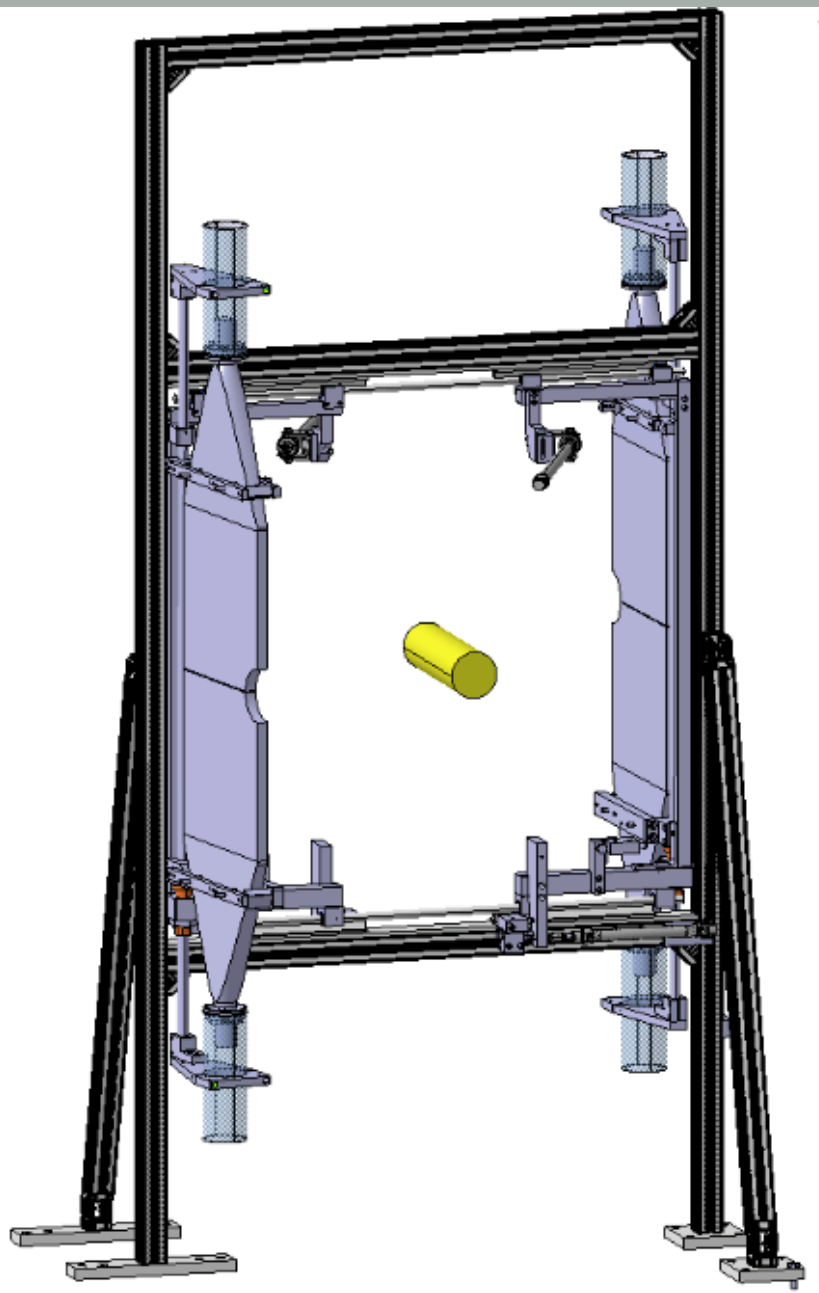

Eolas
LHCb
Run: 91933
Evt: 106150761
Next
Print
Transverse Energy (GeV)
Minimum Pt (GeV)
Pseudorapidity Range
γ
p
J/ψ
c
g
g
p
SPD/PS
HCAL
M2
M4
M5
RICH2
ECAL
M1
T1 T2 T3
5 m
10 m
15 m

High Rapidity Shower Counters at LHCb (HeRSCheL)

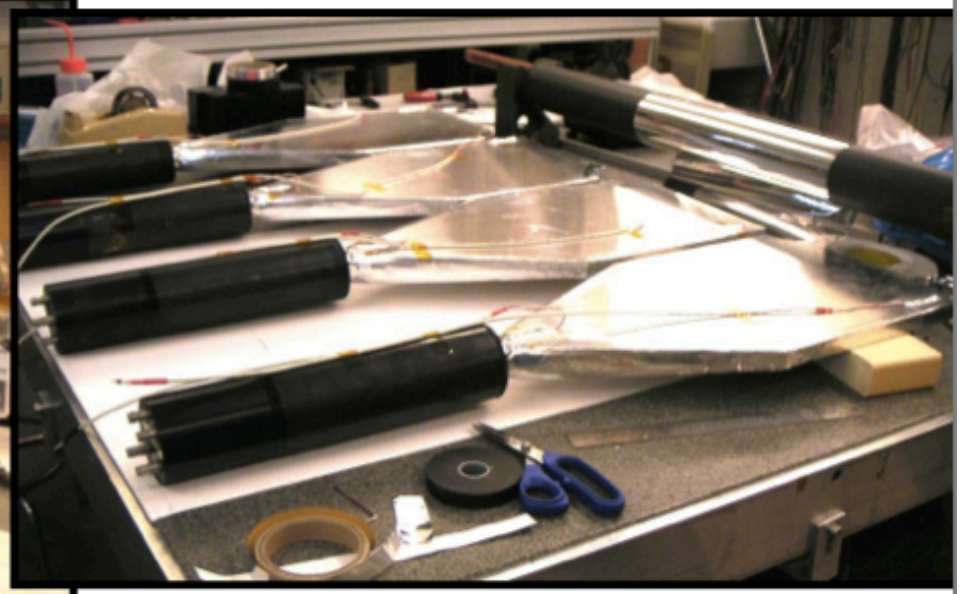
JINST **13** (2018) P04017







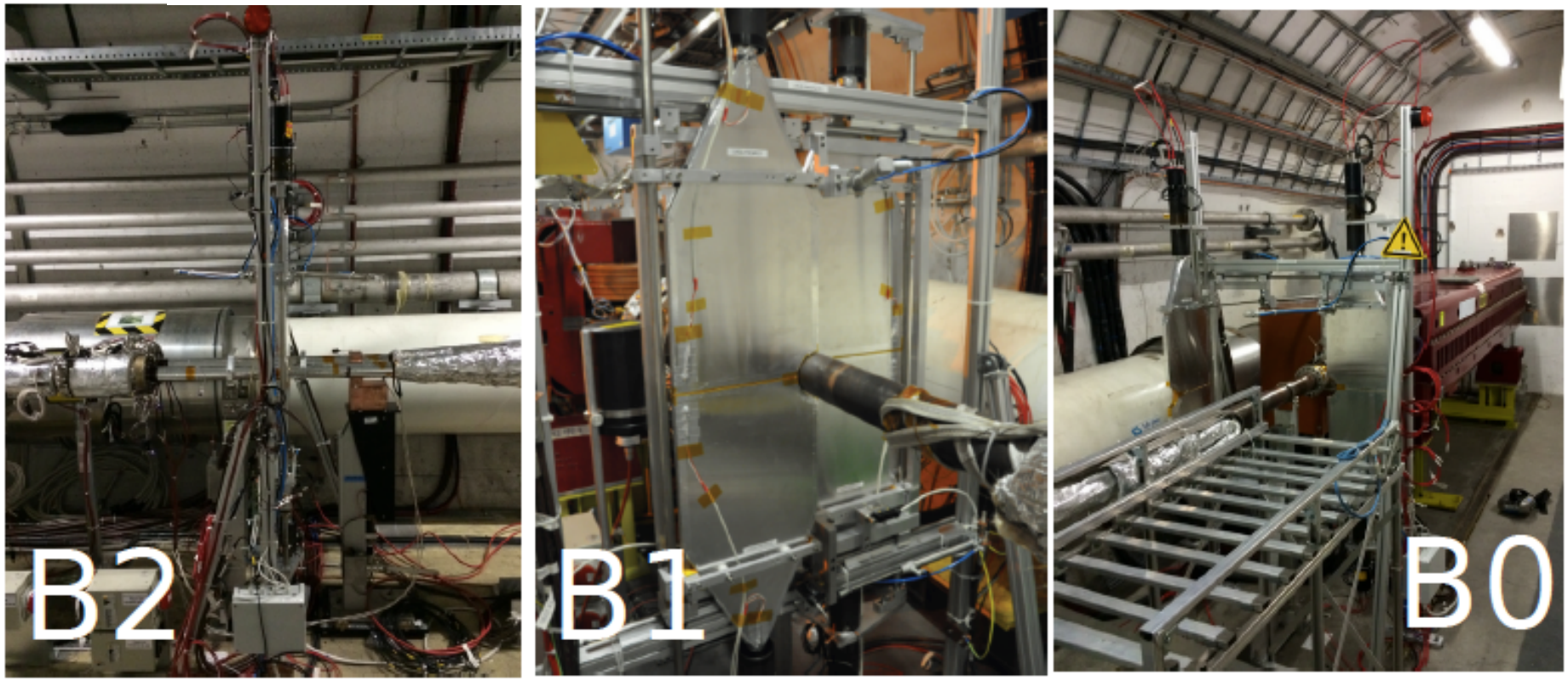
Scintillators, light-guides and PMTs



Backward stations

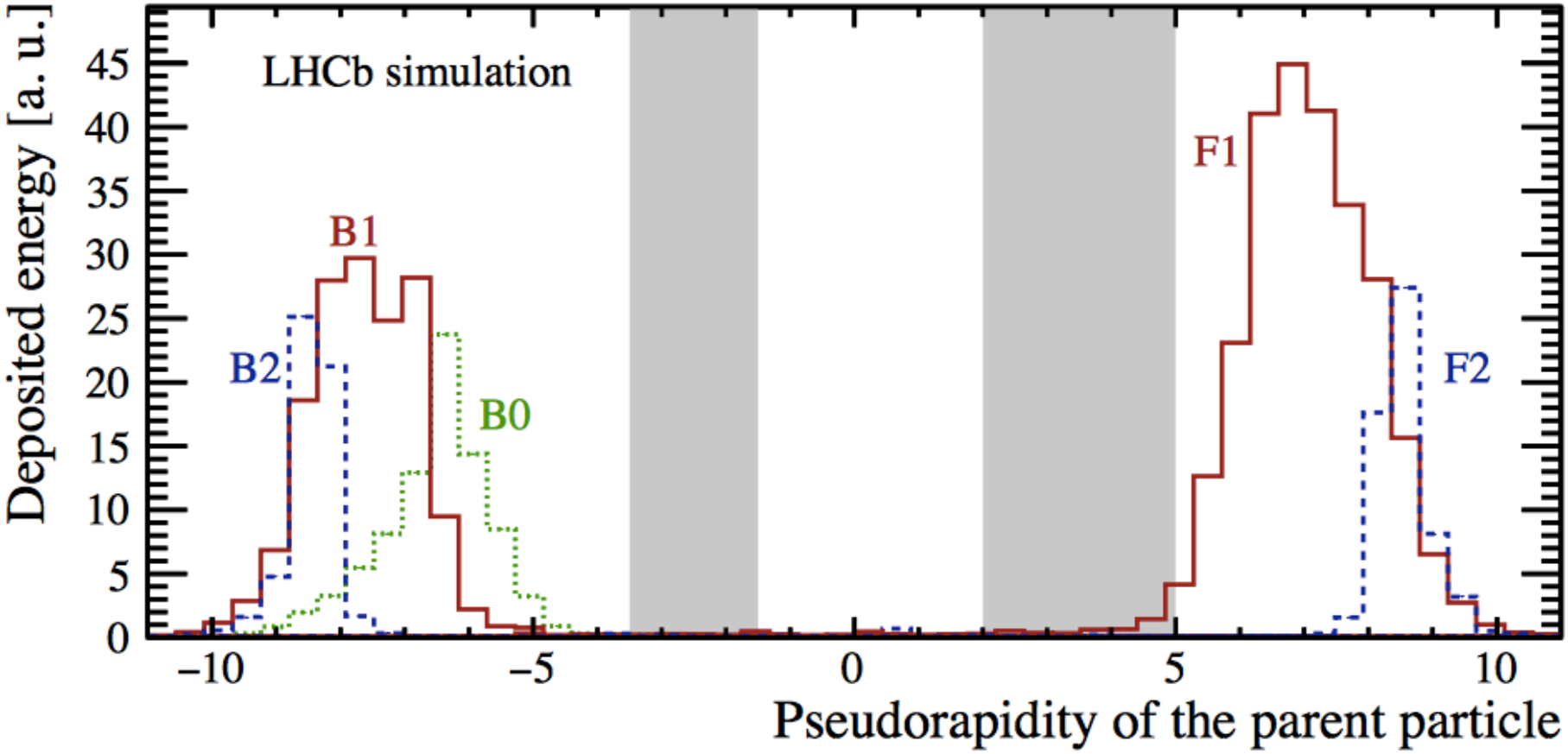
Installation finished in 2014

-114 m **-19.7 m** **-7.5 m**



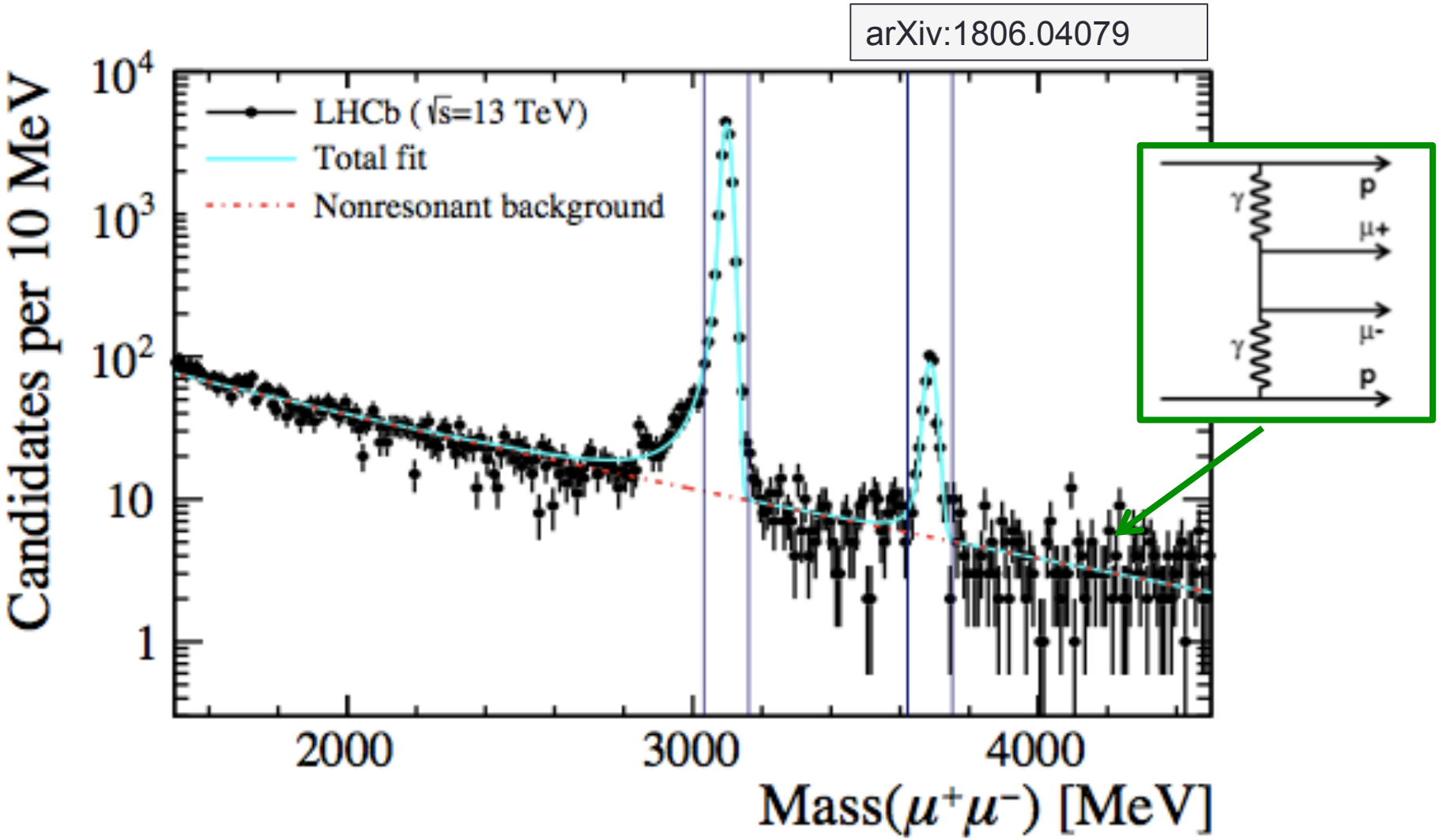
Acceptance

JINST **13** (2018) P04017



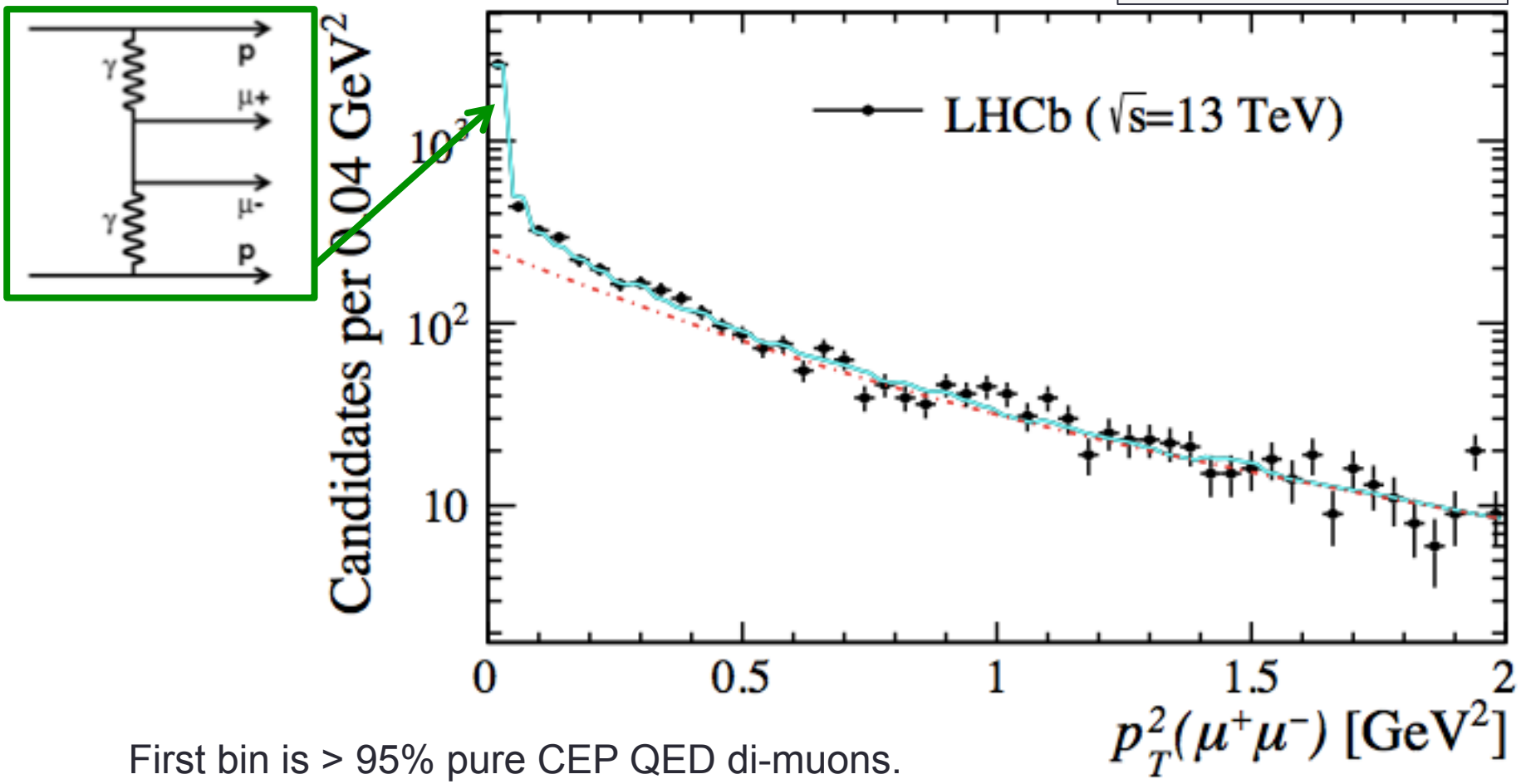
Showers induced by high-rapidity particles interacting with machine elements
Ideally wish to veto on any activity: threshold depends on signal and noise.

Sample 1: Response to CEP events (QED μμ)



Sample 1: Response to CEP events

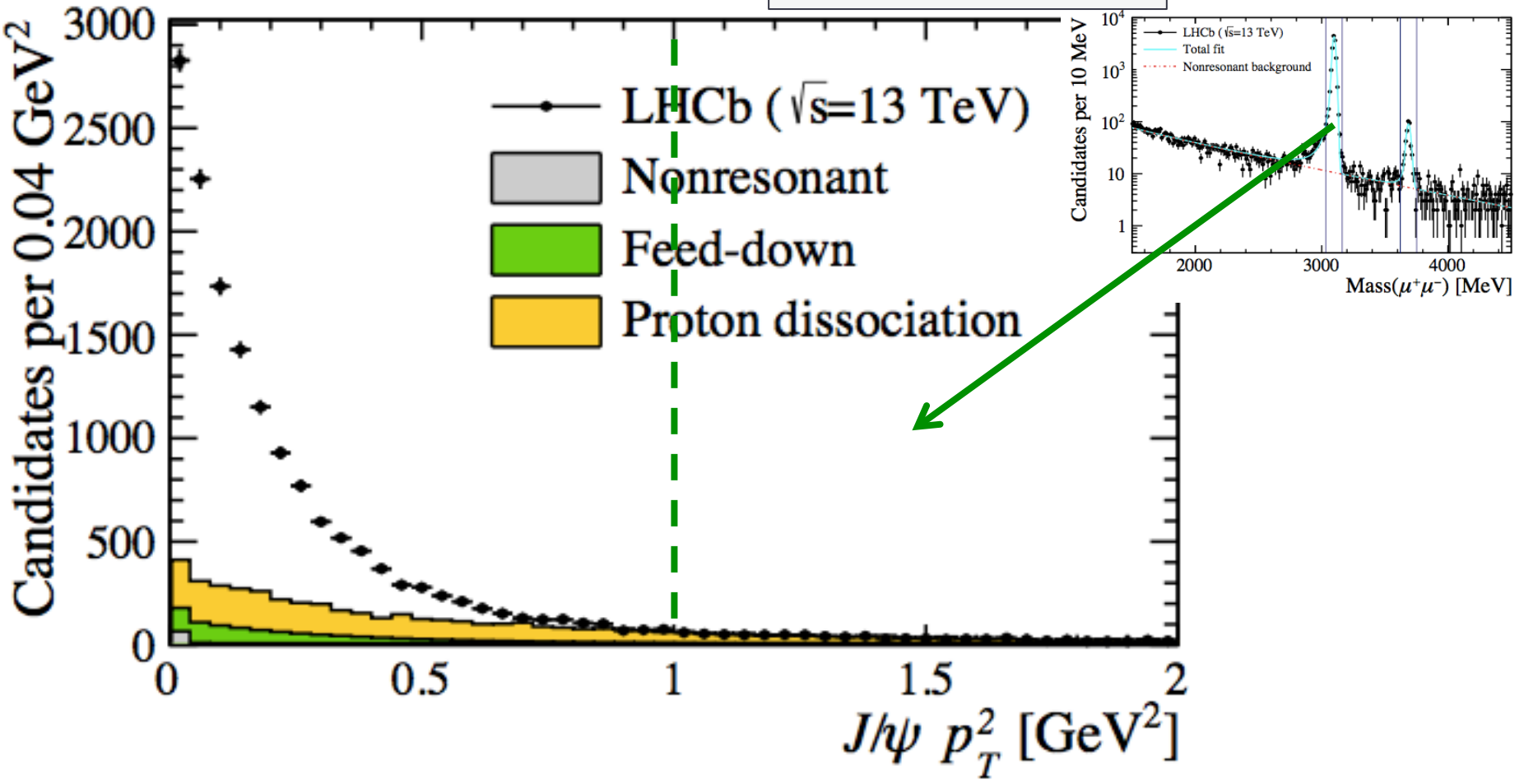
arXiv:1806.04079



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

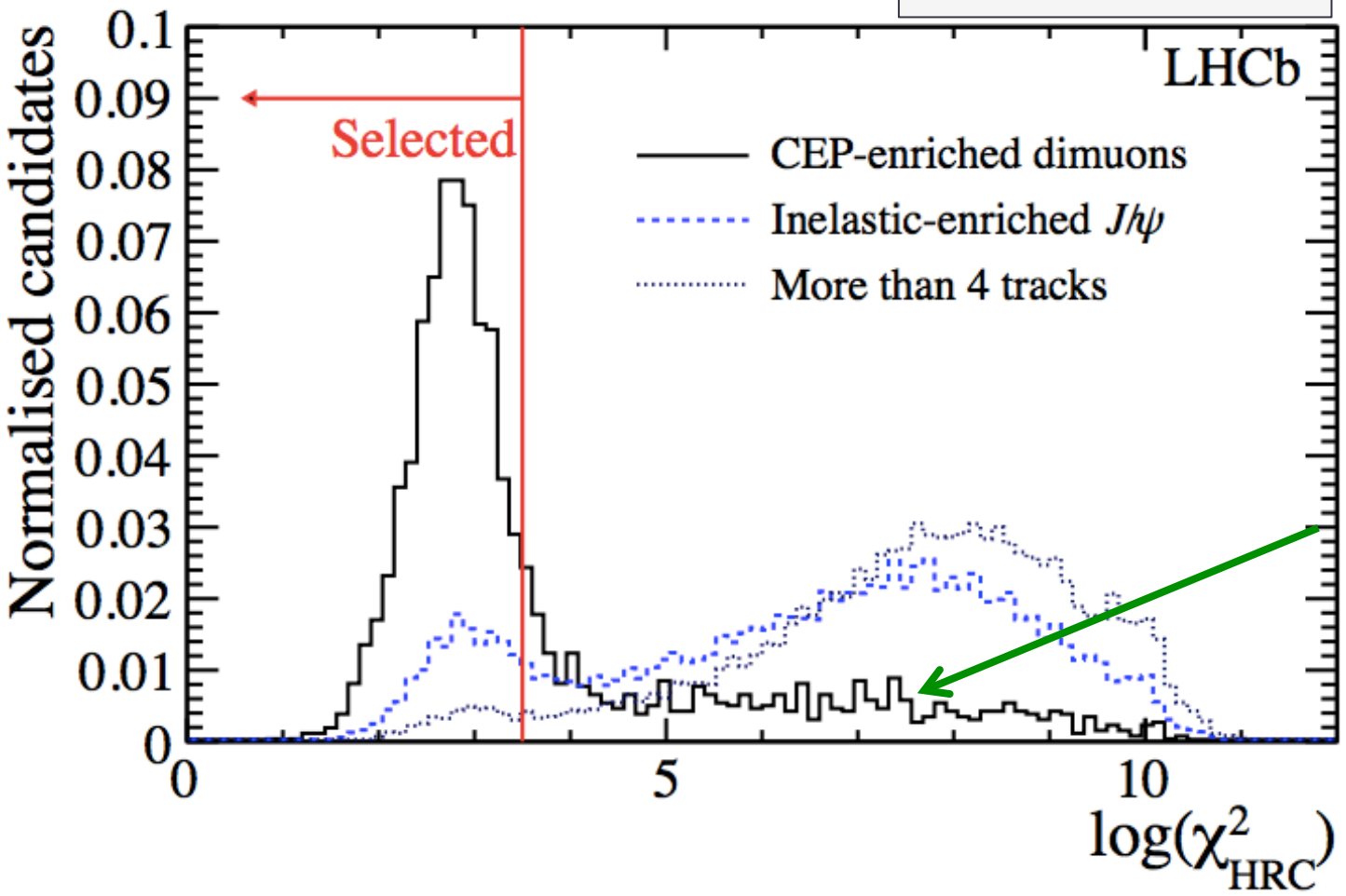
Sample 2: Non-CEP events (J/ψ dissociation)

arXiv:1806.04079



HeRSCheL discriminant for physics signals

arXiv:1806.04079



CEP QED looks like empty-empty events

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

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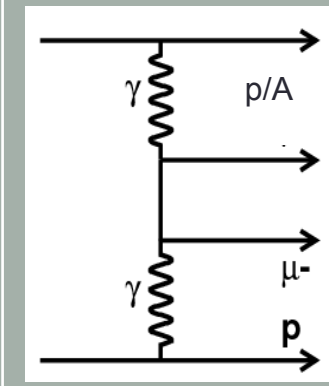
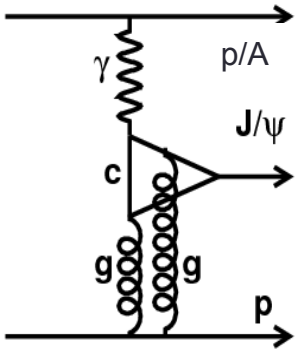
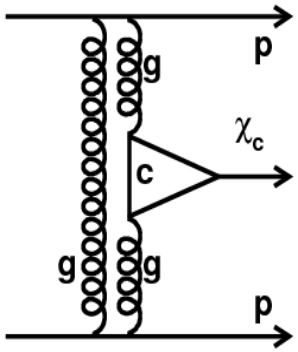
4. Physics reach for CEP

pp / p-Pb / Pb-p / PbPb data-taking

	γγ	γP	PP
			
p-p			Dominant
p-Pb		Enhanced	Supressed
Pb-Pb	Strongly enhanced	Enhanced	Supressed

Vector meson production in pp collisions

	Data-taking year	Energy	Integrated Luminosity	Paper
J/ψ ψ(2S)	2010	7 TeV	37 pb^{-1}	JPG 40 (2013) 045001
	2011	7 TeV	930 pb^{-1}	JPG 41 (2014) 055002
NEW	2015	13 TeV	204 pb^{-1}	arXiv:1806.04079
Υ	2011	7 TeV	945 pb^{-1}	JHEP 09 (2015) 084
	2012	8 TeV	1985 pb^{-1}	
J/ψ+J/ψ	2011	7 TeV	945 pb^{-1}	JPG 41 (2014) 115002
J/ψ+ψ(2S)	2012	8 TeV	1985 pb^{-1}	

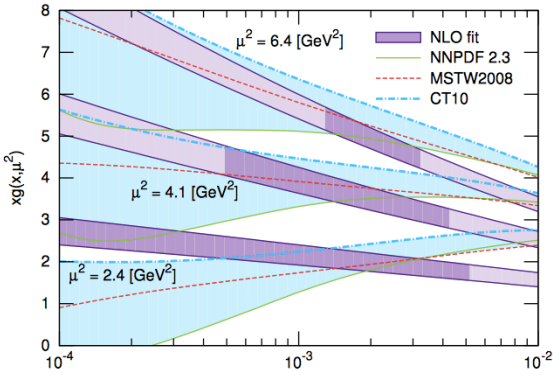
Photo-production

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

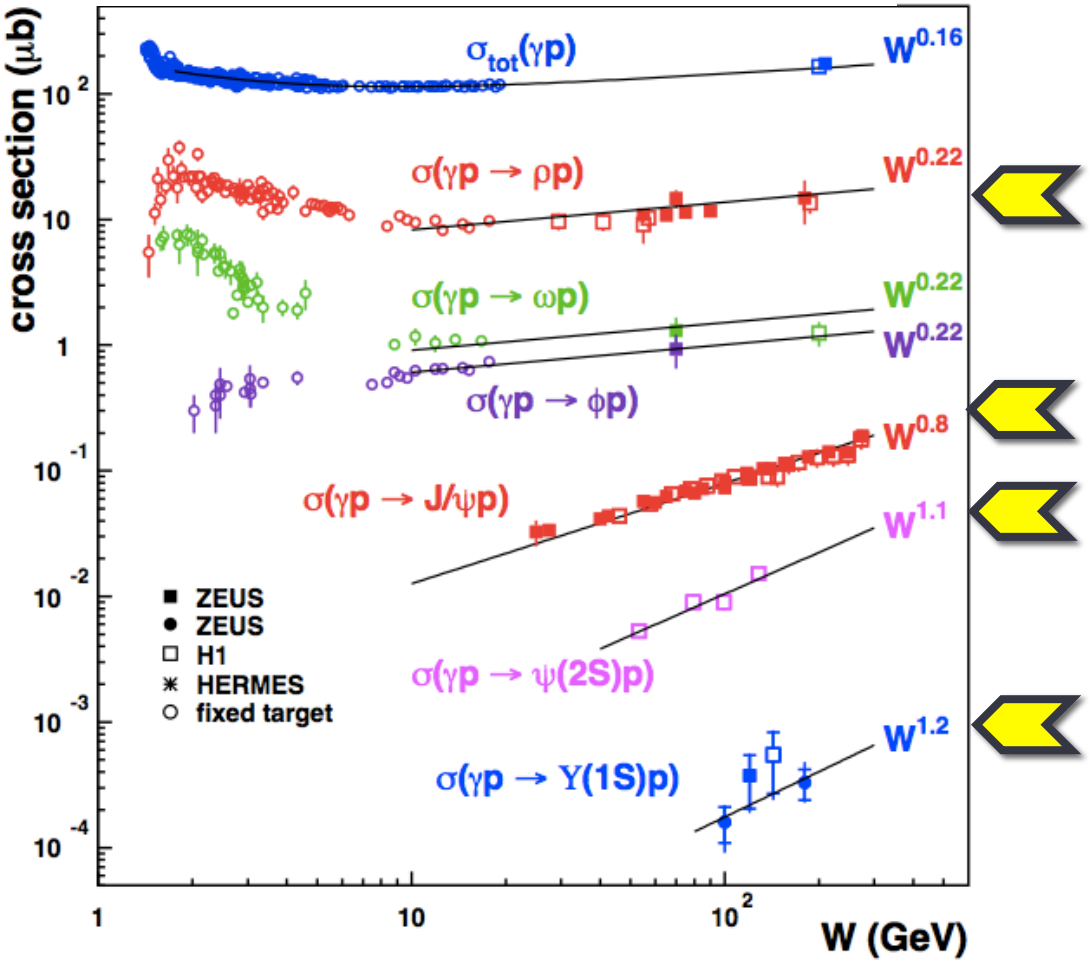
Note:

- soft/hard transition
- $\sigma \sim x^{\lambda}$
- $g(x,Q^2)$

  (down to x=2E-6)



JHEP 11 (2013) 085



10.3204/DESY-PROC-2012-03/58

Cross-section measurement J/ψ / ψ(2S)

Purity: (found from data)
1. non-resonant bkg (1% / 16%)
2. Feeddown (5% / 0%)
3. Inelastic J/ψ / ψ(2S) production (18% / 11%)

Number of events observed

$$\frac{d\sigma}{dy} = \frac{pN}{A\varepsilon L \Delta y}$$

Luminosity

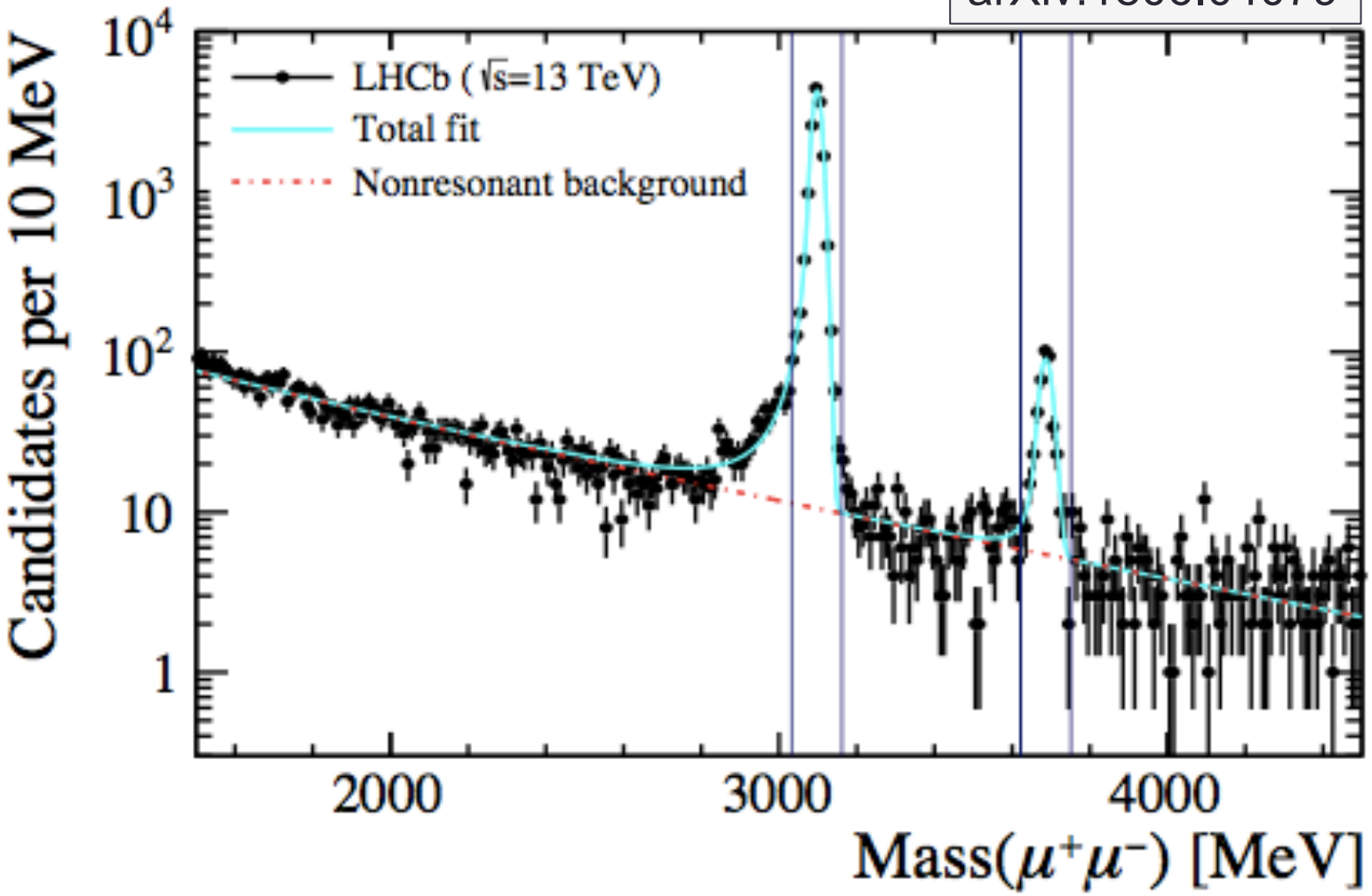
Acceptance (MC)

Efficiency: (found from data)
1. Trigger
2. Tracking & muon id.
3. Single interaction beam-crossing

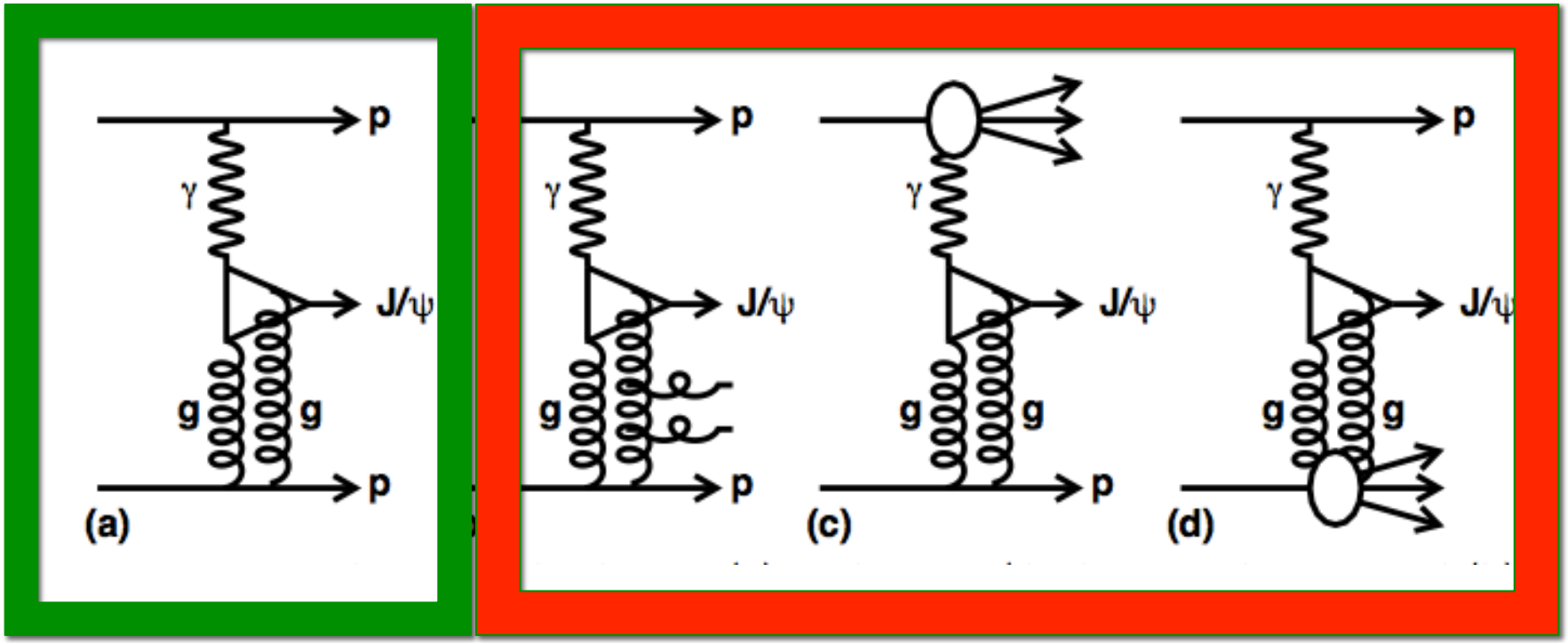
$$P(n) = \mu^n e^{-\mu} / n!$$

Sample: events with two muons and no other charged or neutral activity.

arXiv:1806.04079



Inelastic background



Signal

Background

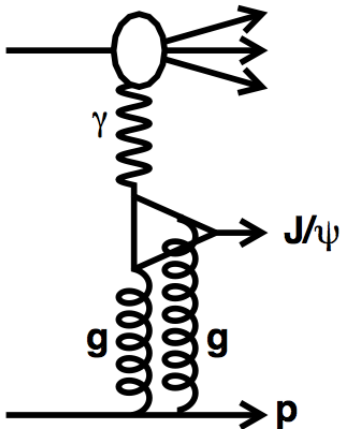
Regge theory: $\frac{d\sigma}{dt} \sim \exp(b_{sig} t)$

$\frac{d\sigma}{dt} \sim \exp(b_{bkg} t)$

$b_{sig} \sim 6\ \mathrm{GeV}^{-2}$

$b_{bkg} \sim 1\ \mathrm{GeV}^{-2}$

Inelastic background J/ψ



Regge theory: $\frac{d\sigma}{dt} \sim e^{bt}$

b-slope of signal is same with/without HeRSCheL
b-slope of bkg changes (because you veto higher-p_T events)

New Technique:

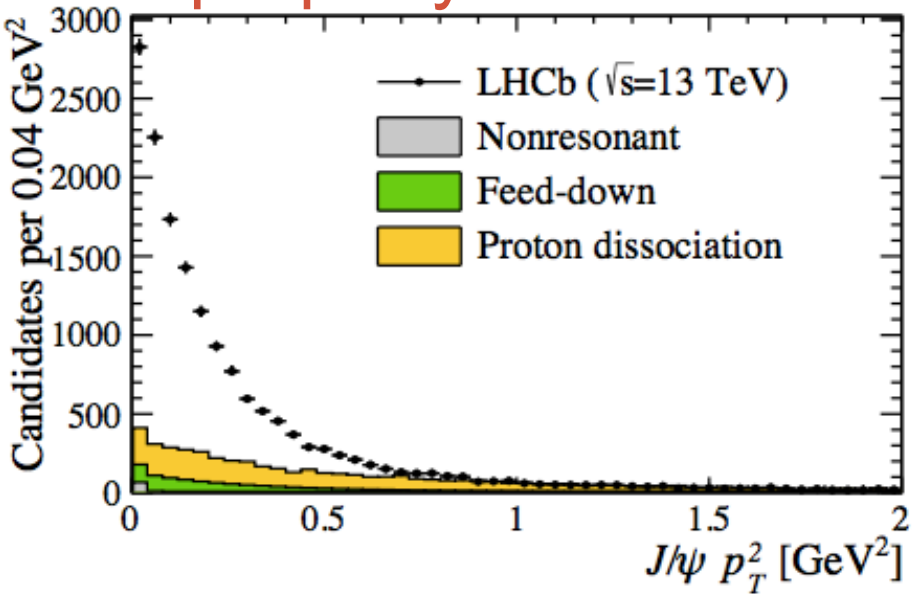
$N_{HRC} = \varepsilon N_{sig} + \beta(p_T) N_{bkg}$

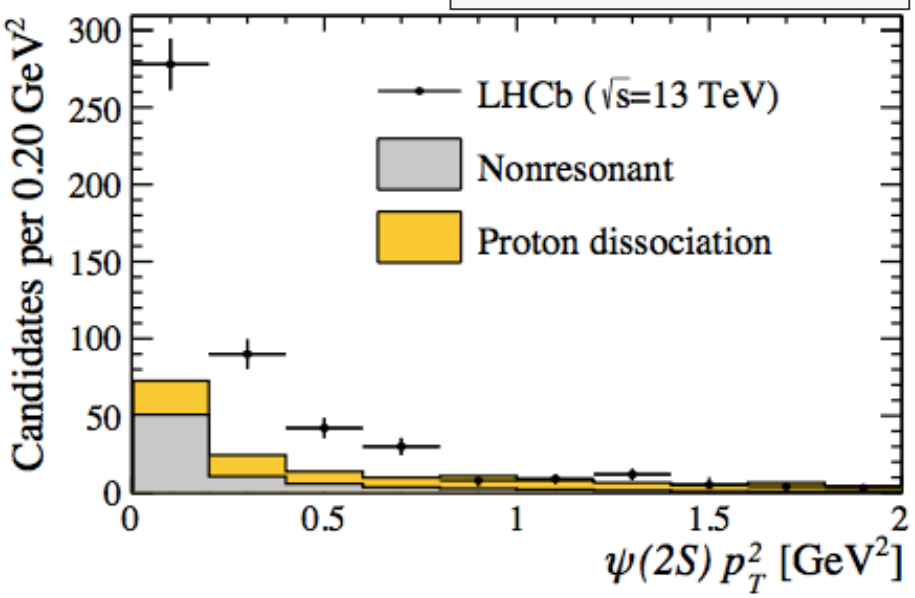
$N_{anti\text{-}HRC} = [1-\varepsilon] N_{sig} + [1-\beta(p_T)]\, N_{bkg}$

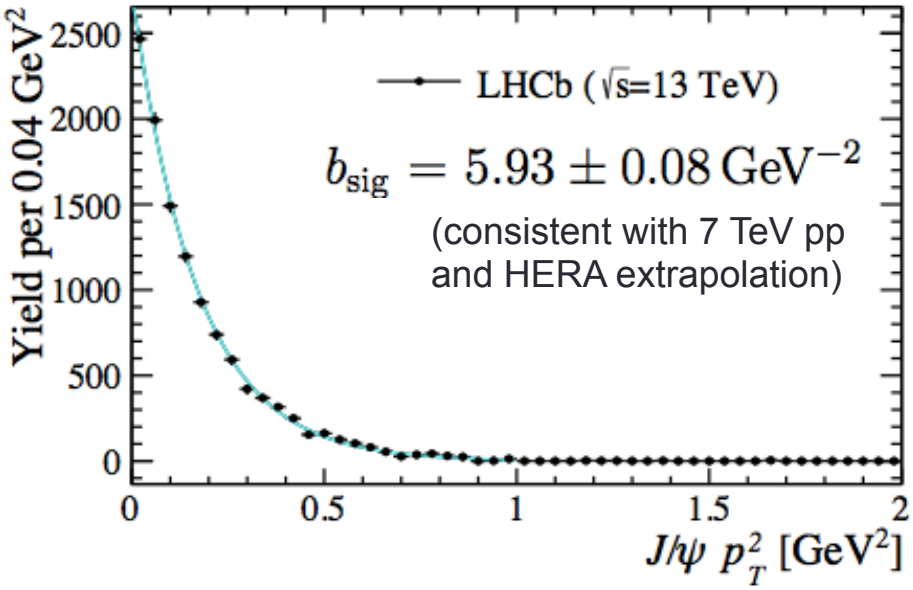
ε known from QED sample
Pure bkg sample obtained
Subtract bkg from total => Signal derived

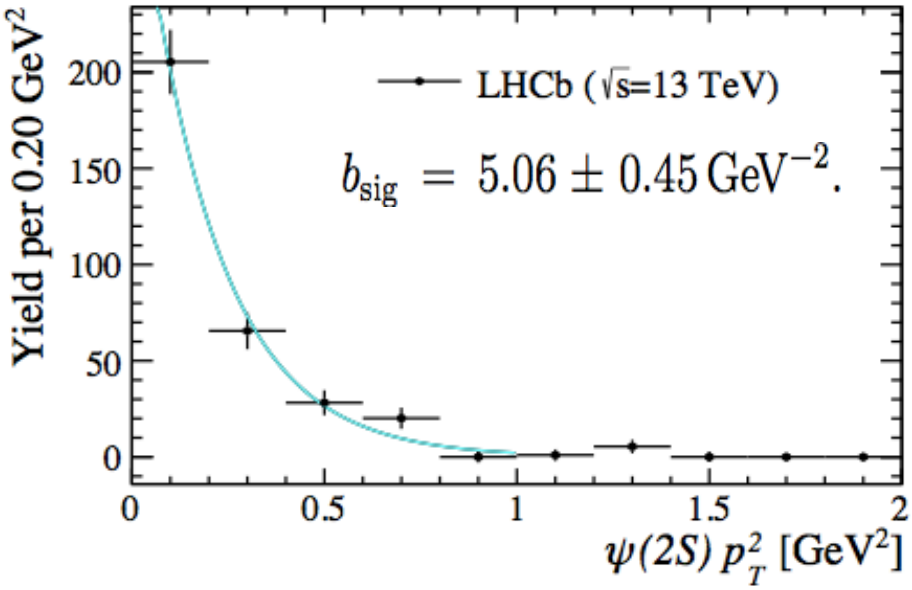
Sample purity

arXiv:1806.04079









Cross-section measured in LHCb acceptance

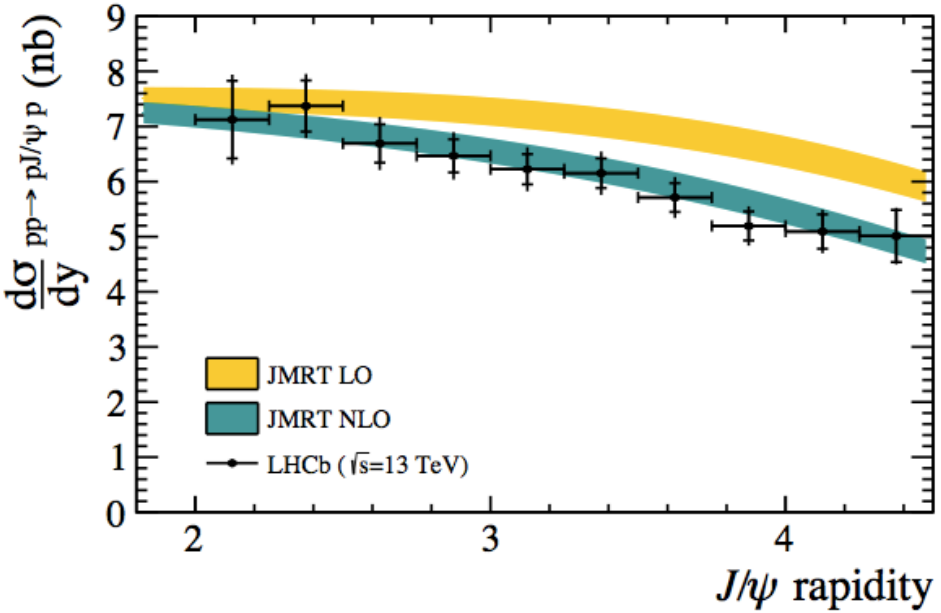
$$\sigma_{J/\psi\to\mu^+\mu^-}(2<\eta<4.5) = 399\pm16\pm10\pm16\ \text{pb},$$
$$\sigma_{\psi(2S)\to\mu^+\mu^-}(2<\eta<4.5) = 10.2\pm1.0\pm0.3\pm0.4\ \text{pb}.$$

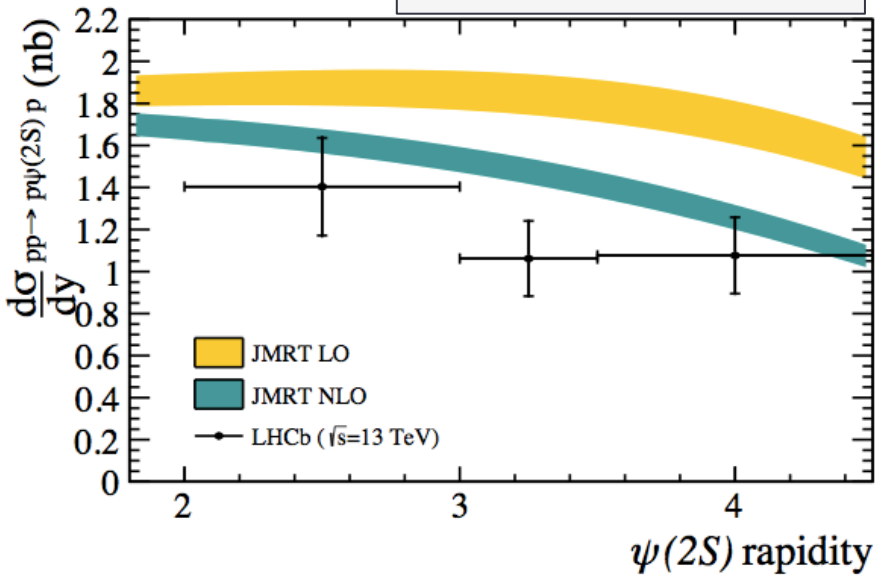
Systematic uncertainties factor two smaller than previous analysis

Source	J/ψ analysis (%)	$\psi(2S)$ analysis (%)
HERSCHEL veto	1.7	1.7
2 VELO track	0.2	0.2
0 photon veto	0.2	0.2
Mass window	0.6	0.6
p_T^2 veto	0.3	0.3
Proton dissociation	0.7	0.7
Feed-down	0.7	-
Nonresonant	0.1	1.5
Tracking efficiency	0.7	0.7
Muon ID efficiency	0.4	0.4
Trigger efficiency	0.2	0.2
Total excluding luminosity	2.5	2.7
Luminosity	3.9	3.9

Differential cross-sections J/ψ and ψ(2S)

arXiv:1806.04079



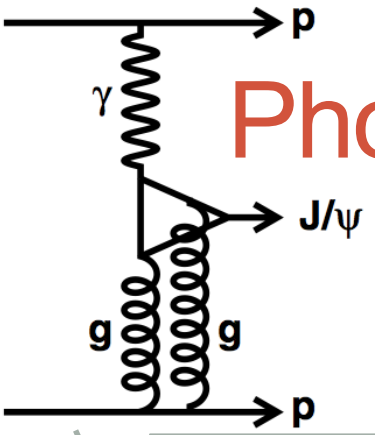


NLO agrees better than LO

S. Jones, A. Martin, M. Ryskin, and T. Teubner, *Probes of the small x gluon via exclusive J/ψ and Υ production at HERA and the LHC*, JHEP **1311** (2013) 085, arXiv:1307.7099.

S. P. Jones, A. D. Martin, M. G. Ryskin, and T. Teubner, *Predictions of exclusive $\psi(2S)$ production at the LHC*, J. Phys. **G41** (2014) 055009, arXiv:1312.6795.

Photo-production cross-section



LHCb measure

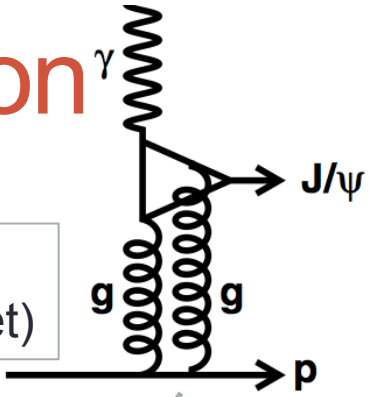


Photo-production
(HERA / fixed target)

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

Gap Survival

Photon Flux

HERA measured power-law: $\sigma_{\gamma p\to J/\psi p}(W) = 81(W/90\,\mathrm{GeV})^{0.67}\,\mathrm{nb}$

Use this for W- solution (in previously measured region). LHCb measures W+

Photo-production cross-section

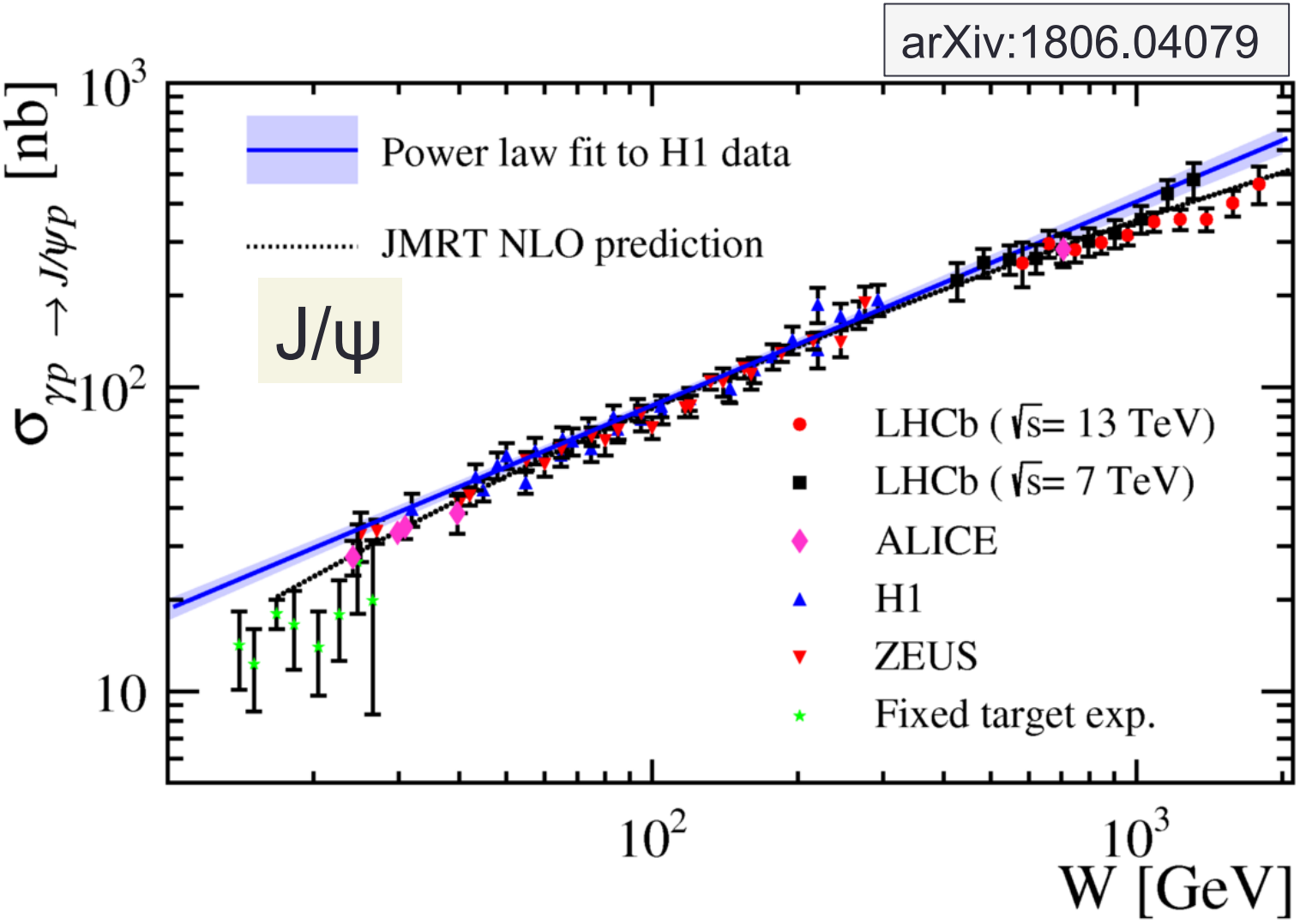
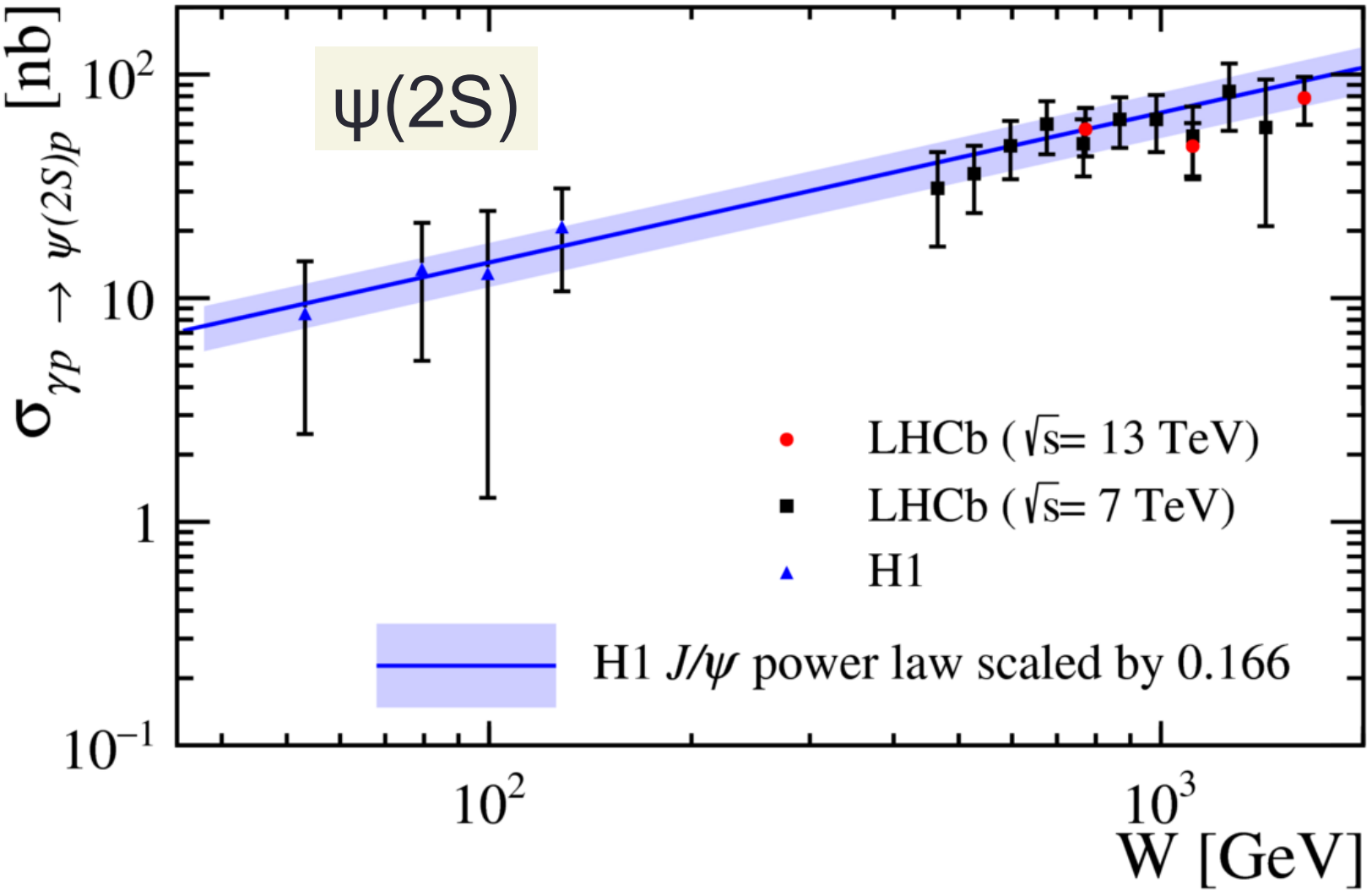


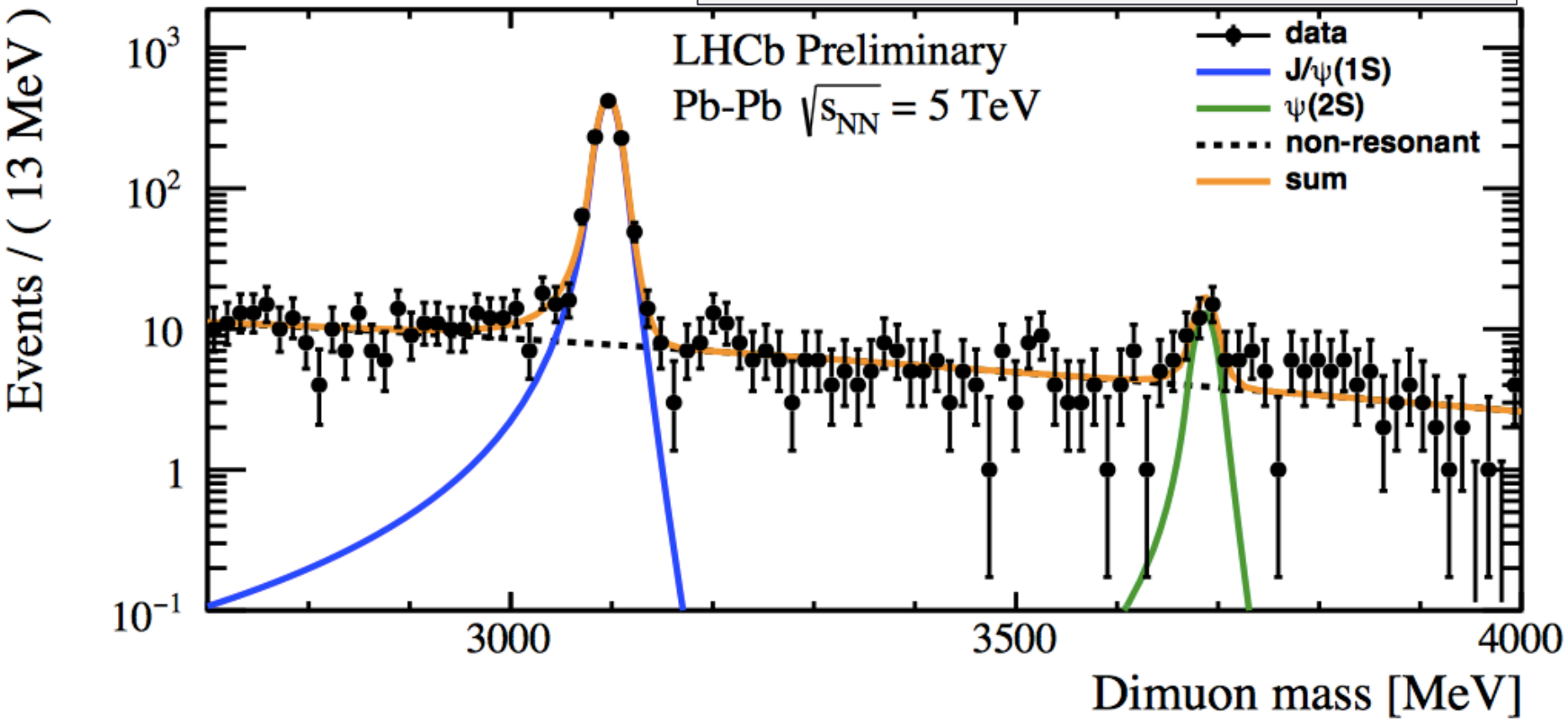
Photo-production cross-section

arXiv:1806.04079:



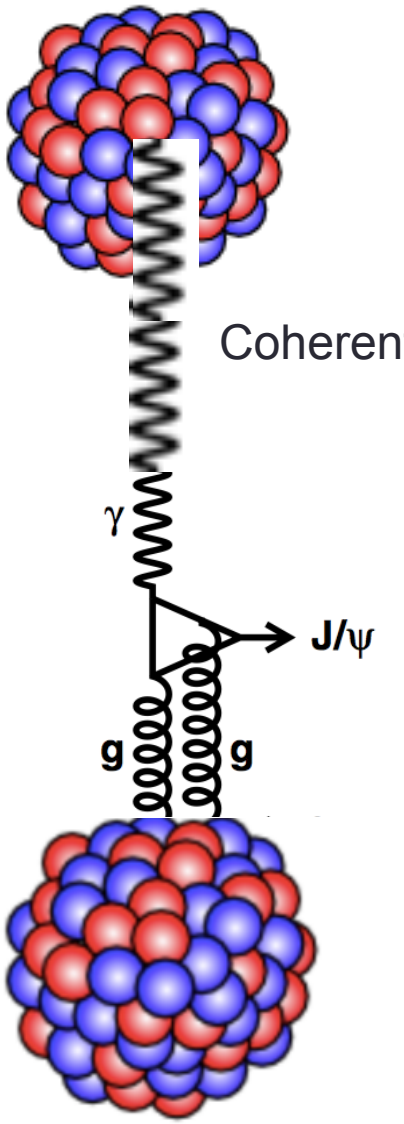
Pb-Pb collisions

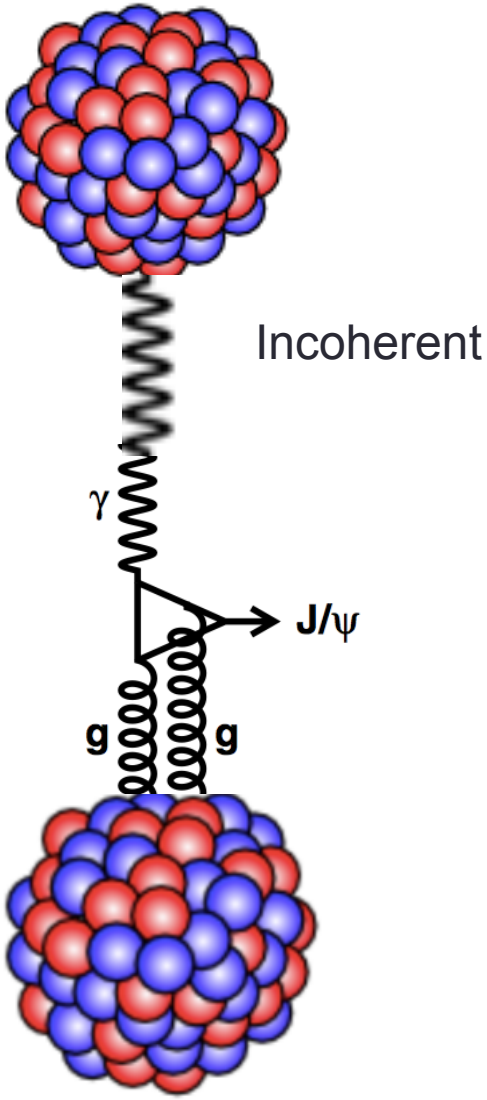
LHCb-CONF-2018-003 (in preparation)



Pb-Pb collisions

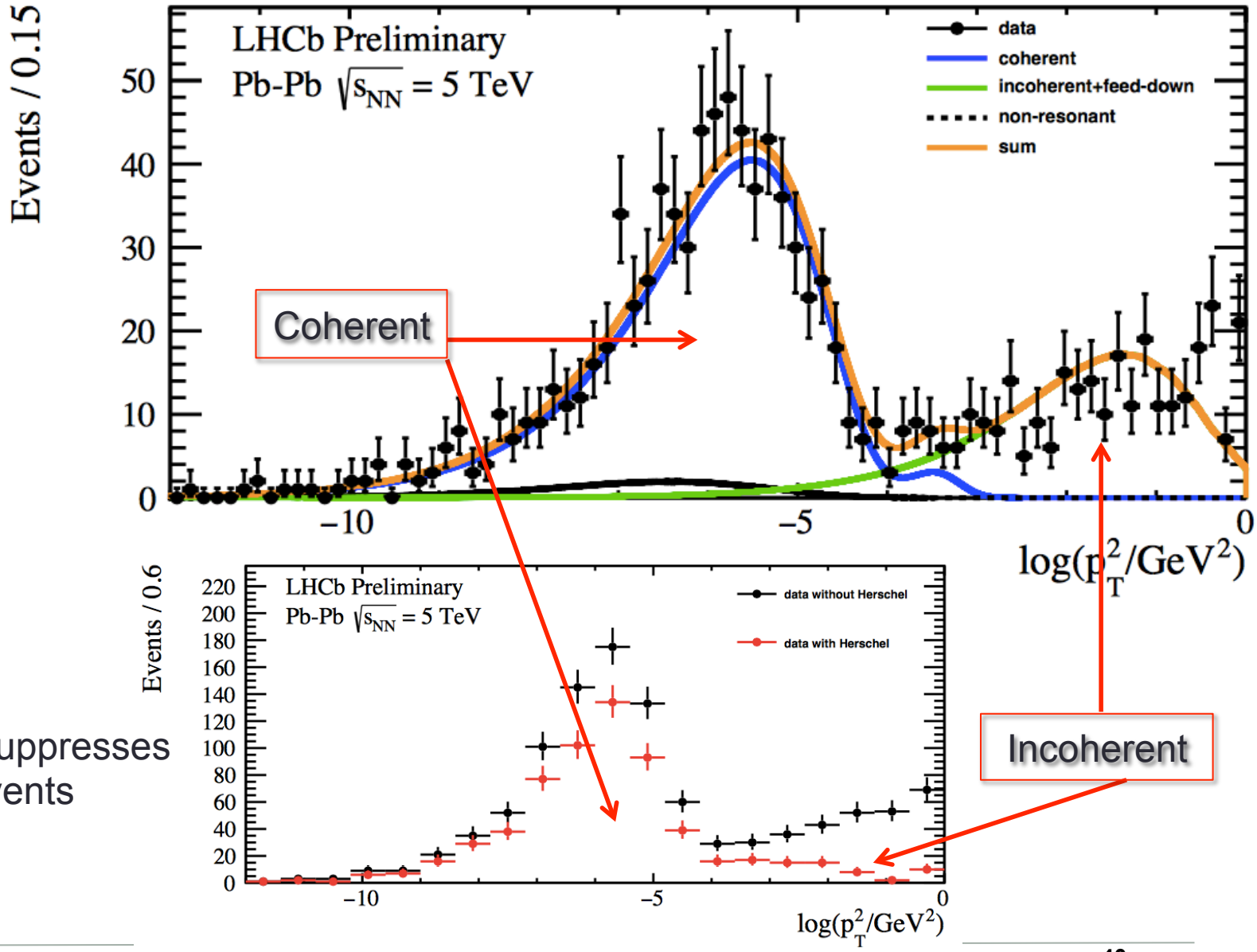
(sensitive to nPDF and saturation)





Pb-Pb collisions

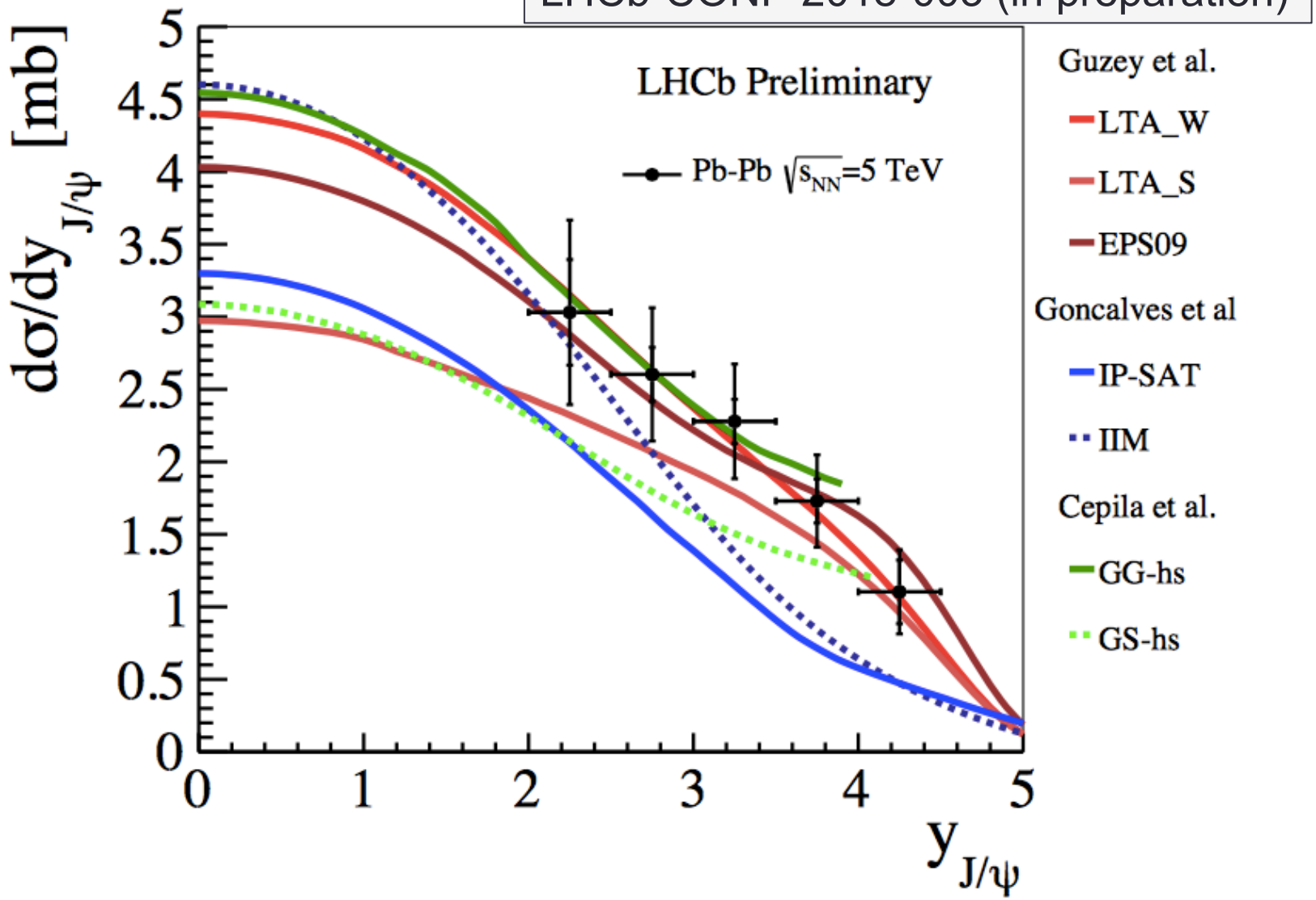
LHCb-CONF-2018-003 (in preparation)



HeRSCheL suppresses incoherent events

Pb-Pb collisions

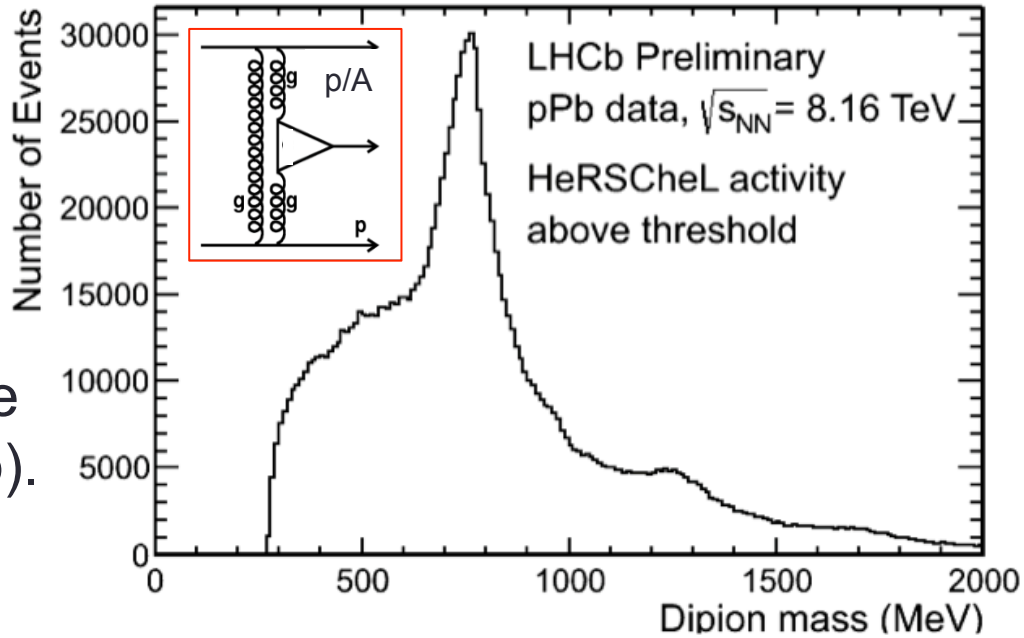
LHCb-CONF-2018-003 (in preparation)

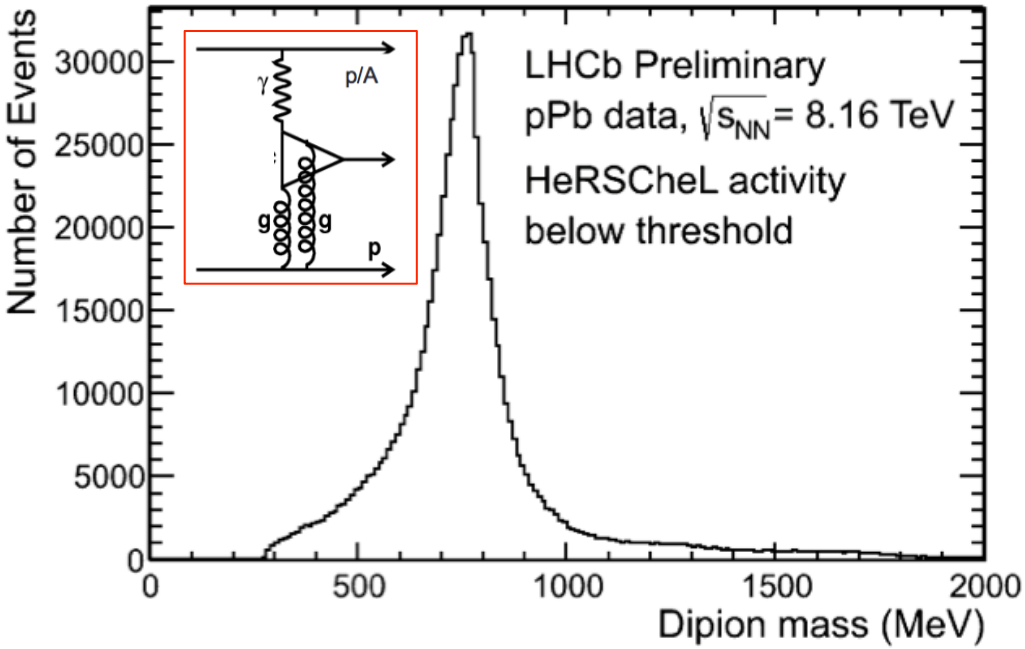


Dipions in pA/Ap

- pp->p(ππ)p has contributions from double-Pomeron-exchange (f0, f2 etc) & photoproduction (ρ).
- Difficult to disentangle (e.g. f0 appearing as shoulder on ρ)
- Difficult to separate exclusive from dissociation

- pA->p(ππ)A has enhanced photoproduction
- Remarkably clean resonance
- *x* down to 10^{-6}, *W* up to 1 TeV





Overview

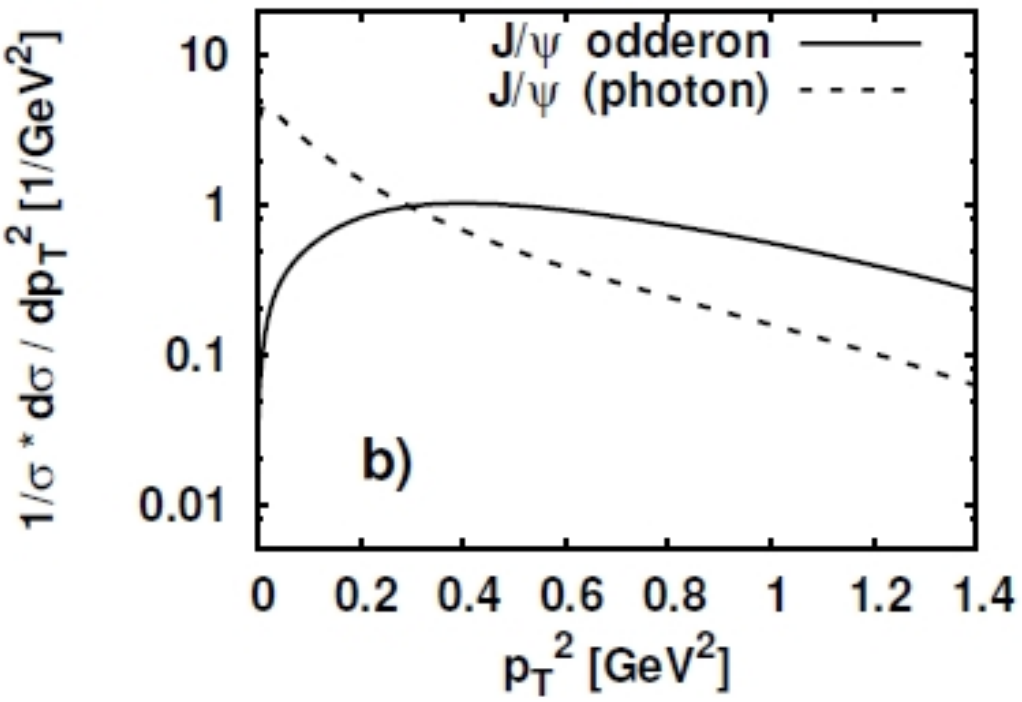
1. Central Exclusive Physics

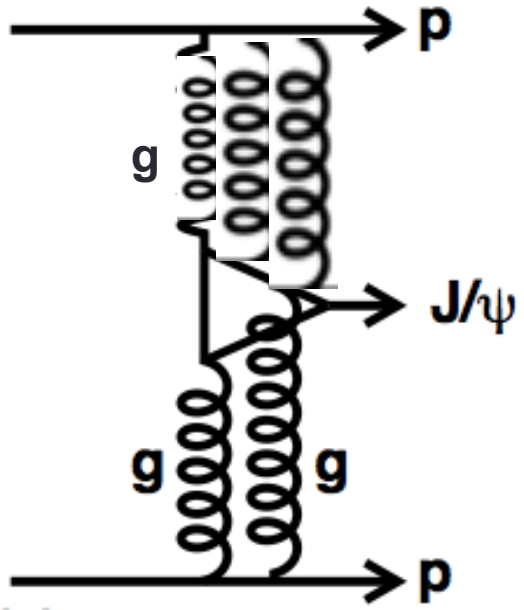
2. LHCb and Herschel Detector

3. Analyses:
   - pp at 13 TeV
   - PbPb at $\sqrt{s_{NN}}$ = 5 TeV
   - pPb and Pb-p at 8 TeV

4. Physics reach for CEP

Odderon





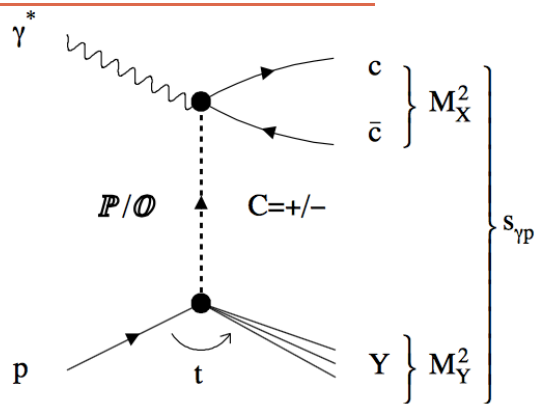
Bzdak, Motyka, Szymanowski, Cudell
PRD 75 (2007) 094023
arXiv:0808.2216

Predictions in pessimistic-central-optimistic scenarios

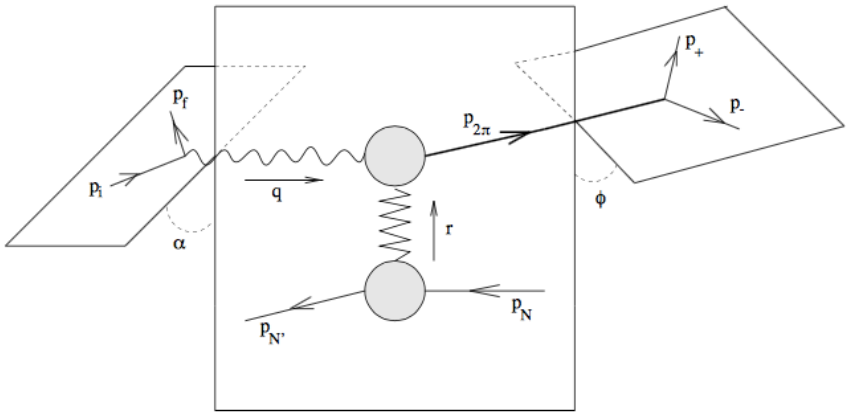
$d\sigma^{\rm corr}/dy$	J/ψ		Υ	
	odderon	photon	odderon	photon
Tevatron	0.3–1.3–5 nb	0.8–5–9 nb	0.7–4–15 pb	0.8–5–9 pb
LHC	0.3–0.9–4 nb	2.4–15–27 nb	1.7–5–21 pb	5–31–55 pb

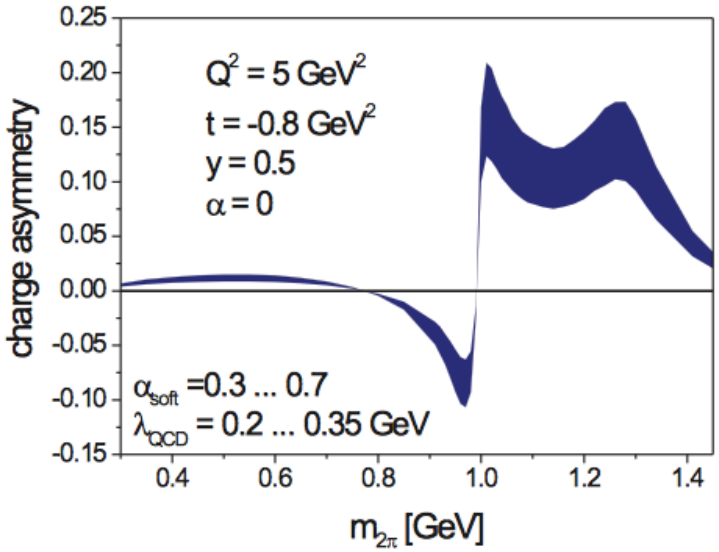
Odderon-Pomeron Interference

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

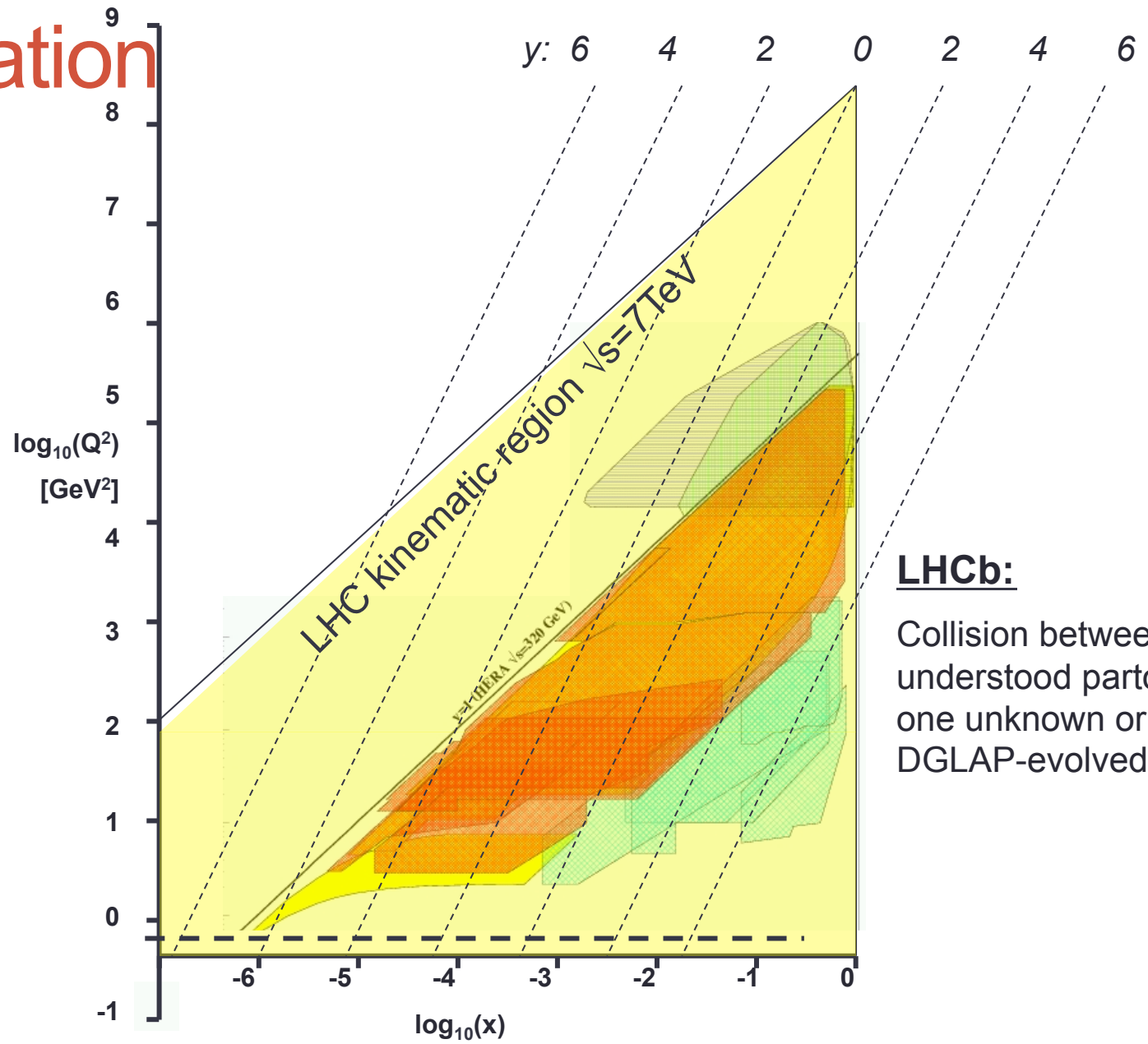


$$A(Q^2, t, m_{2\pi}^2, y, \alpha) = \frac{\sum_{\lambda=+,-} \int \cos\theta \, d\sigma(s, Q^2, t, m_{2\pi}^2, y, \alpha, \theta, \lambda)}{\sum_{\lambda=+,-} \int d\sigma(s, Q^2, t, m_{2\pi}^2, y, \alpha, \theta, \lambda)} = \frac{\int d\cos\theta \cos\theta \; N_{charge}}{\int d\cos\theta \; D}$$





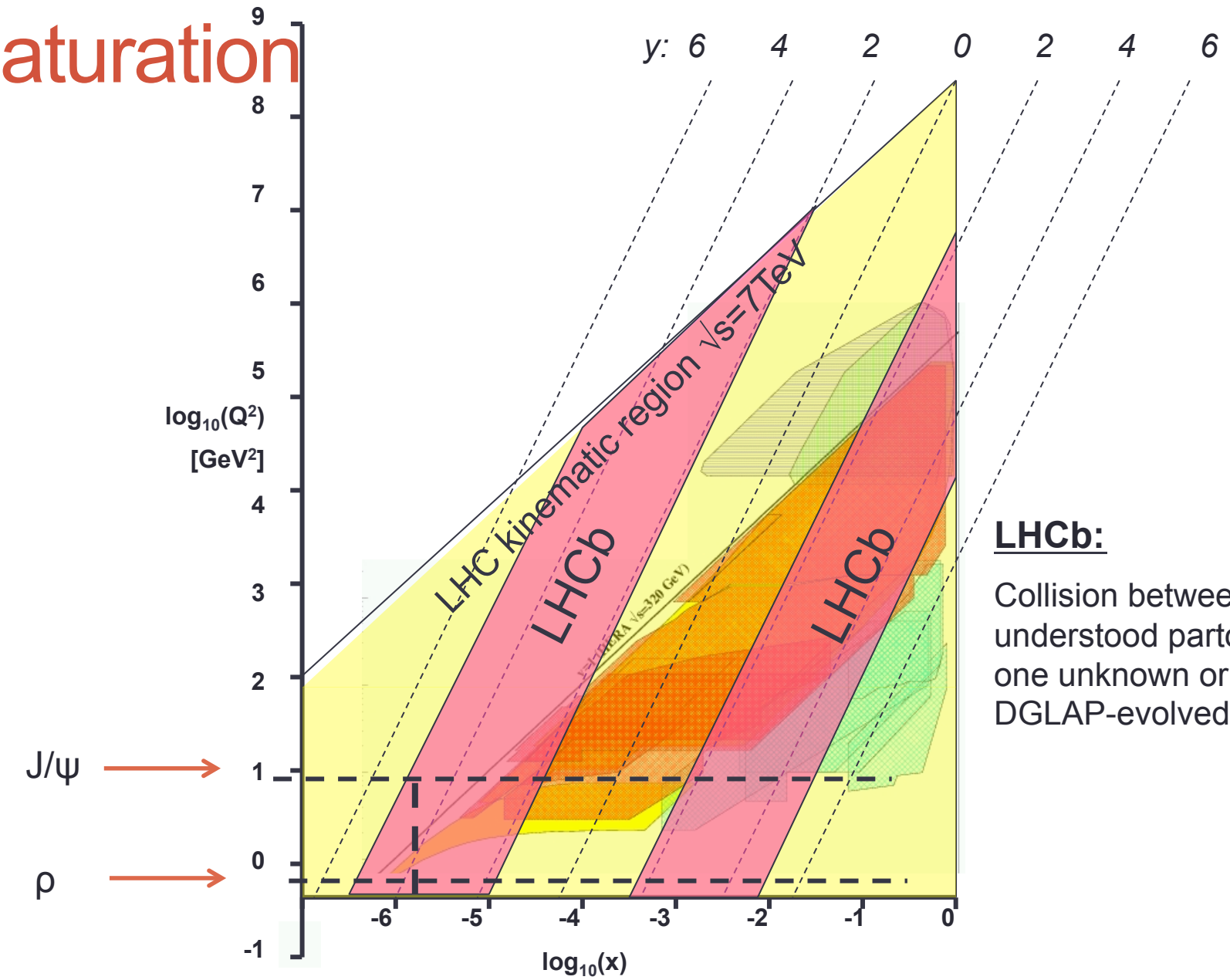
Saturation



LHCb:

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

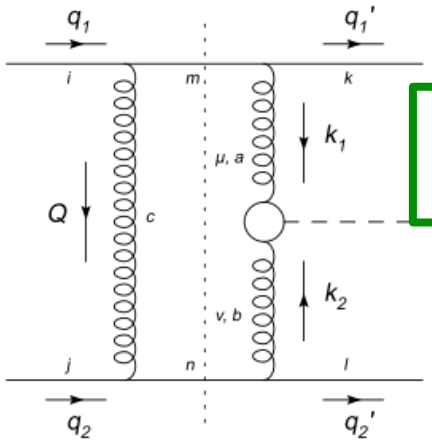
Saturation



LHCb:

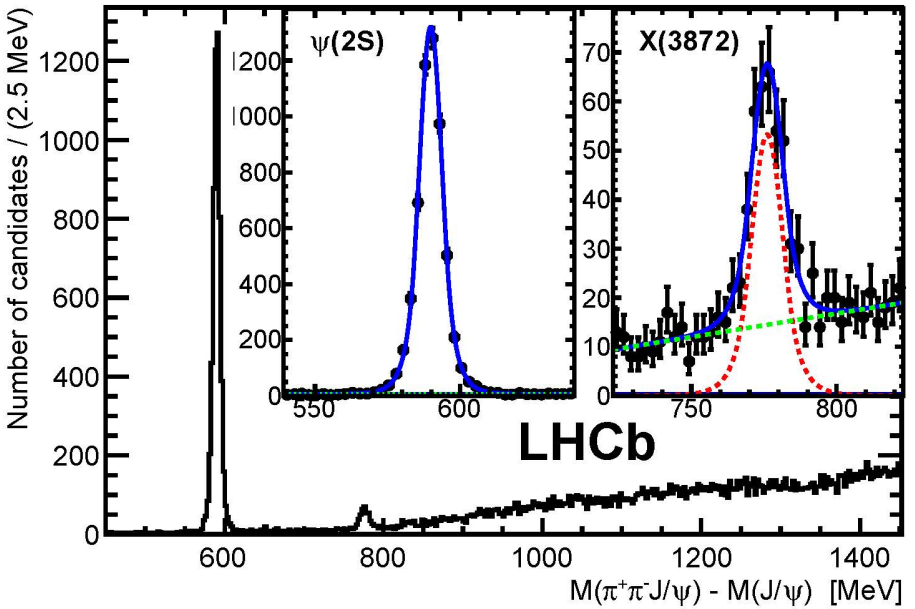
Collision between one well understood parton and one unknown or large DGLAP-evolved parton.

Exotics:
Glueballs, Hybrids, Tetraquarks etc.



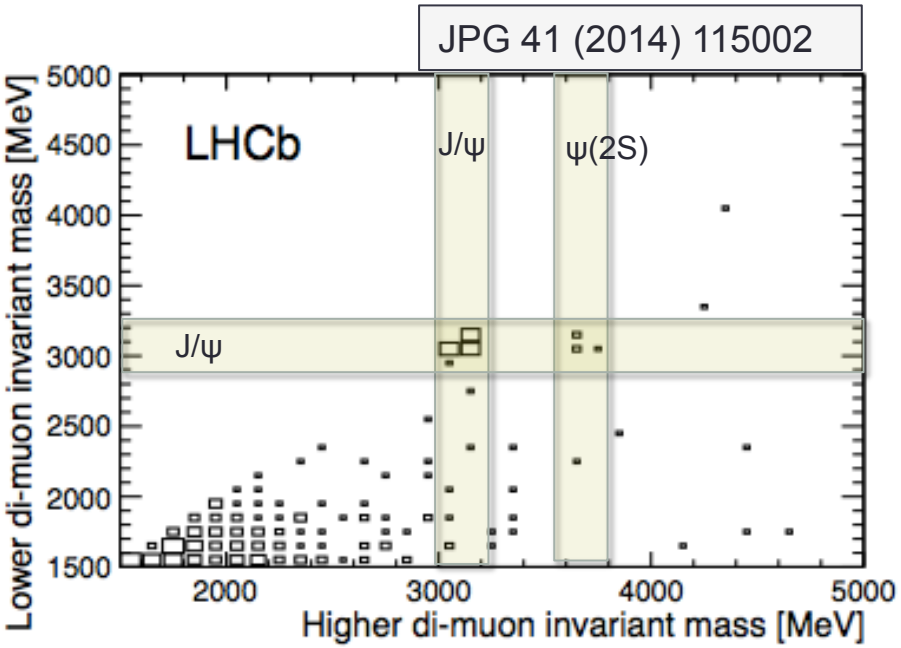
Double-pomeron-exchange processes
Glue Laboratory

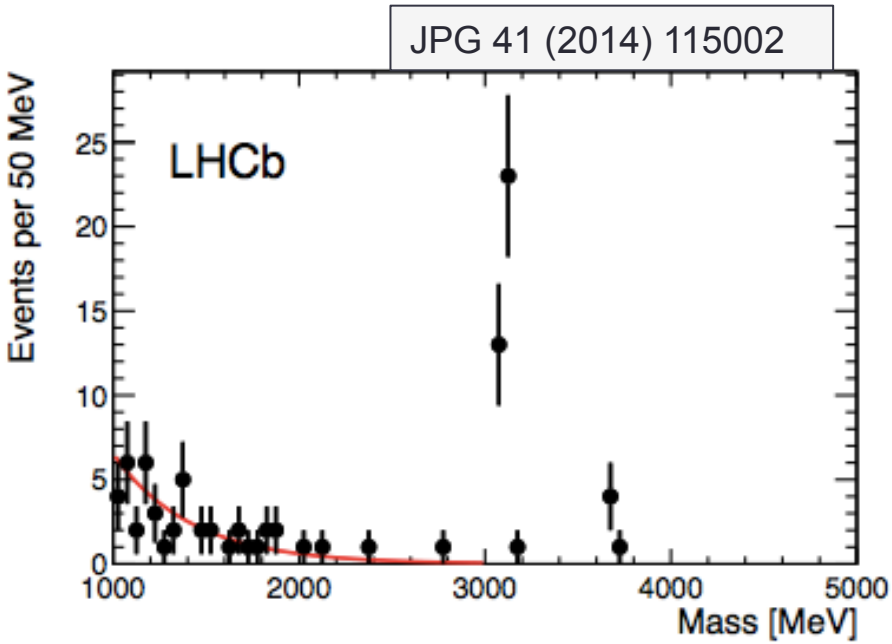
Inclusive X(3872)
Eur.Phys.J. C72 (2012) 1972



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

e.g. Select 4-muon exclusive events

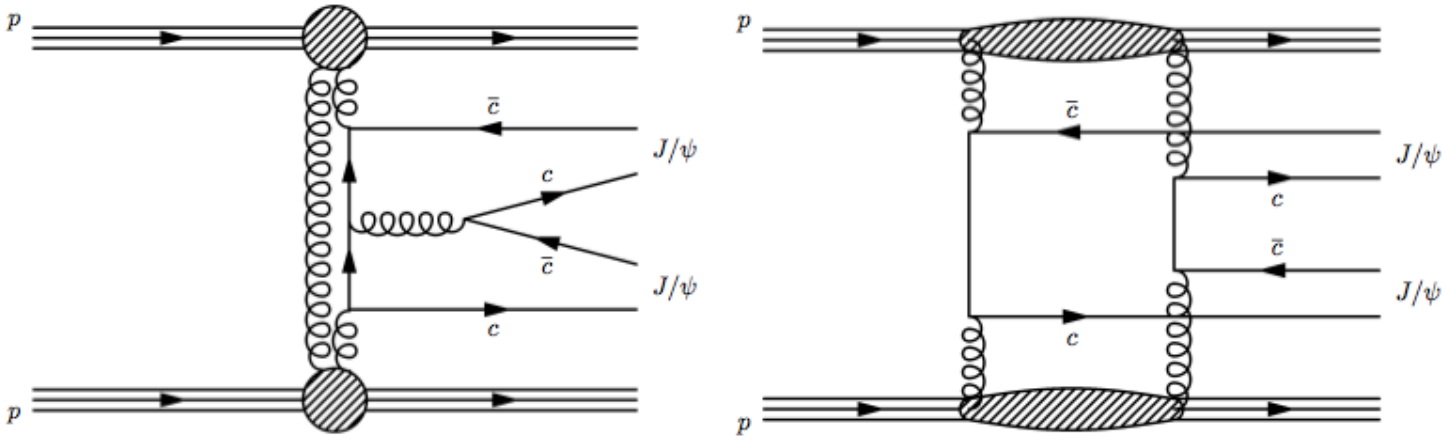




Dimuon spectrum having required other two muons have J/ψ mass

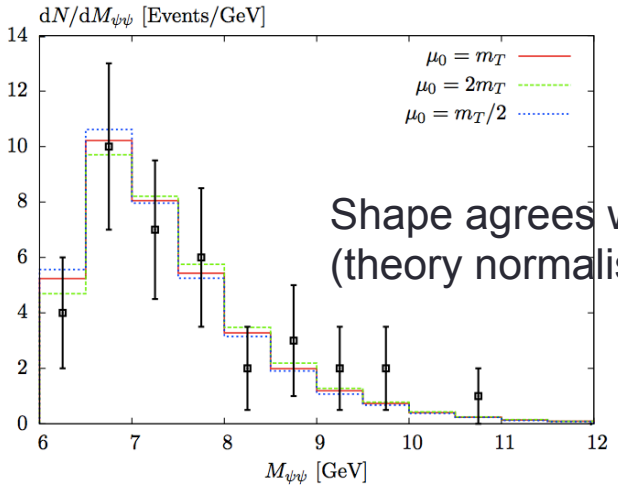
Selection requirement:
Require precisely 4 tracks, at least three identified as muons

Double J/ψ production



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

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



Shape agrees well (theory normalised to data).

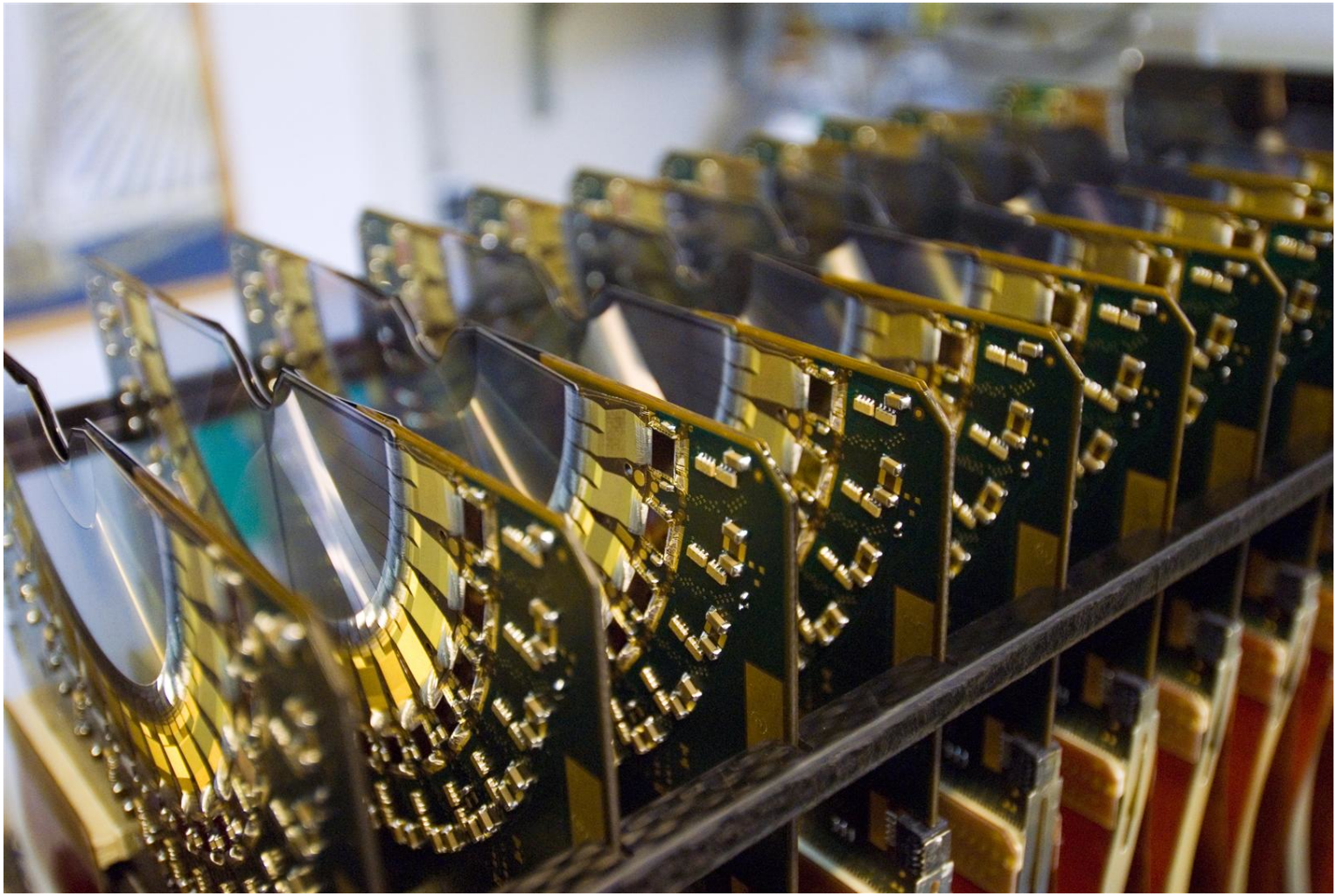
Summary

- Several CEP pp measurements at 7, 8 and (new) 13 TeV using muons.
- New Herschel detector extends detection of rapidity gap and reduces experimental uncertainty.
- Measurements underway in proton-lead and lead-lead collisions

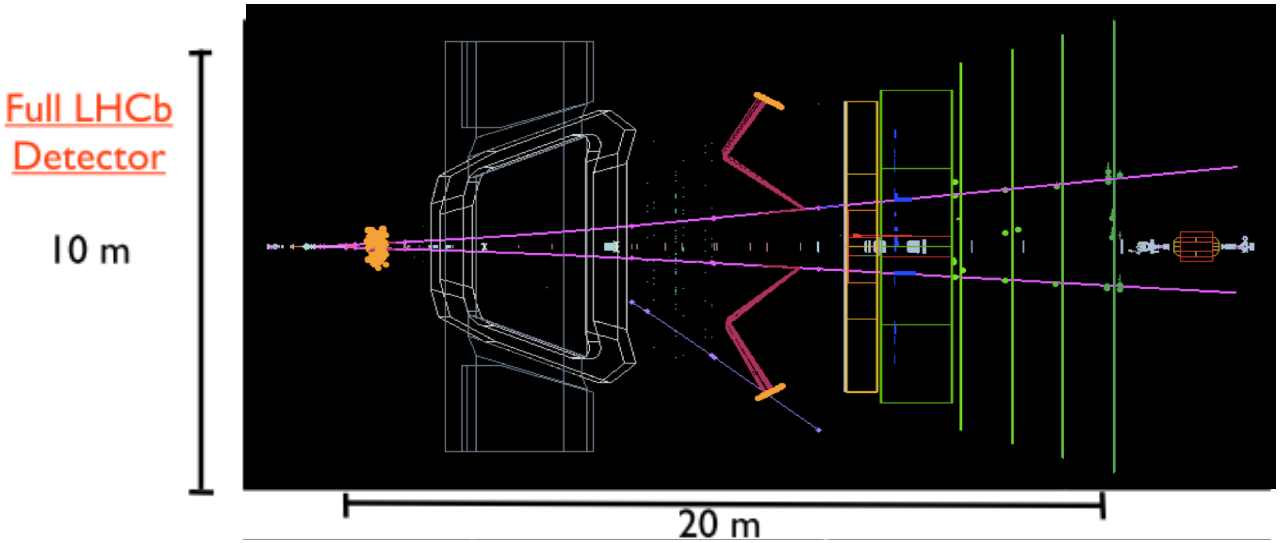
- Excellent laboratory for producing mesons cleanly: large physics reach.

BACKUP

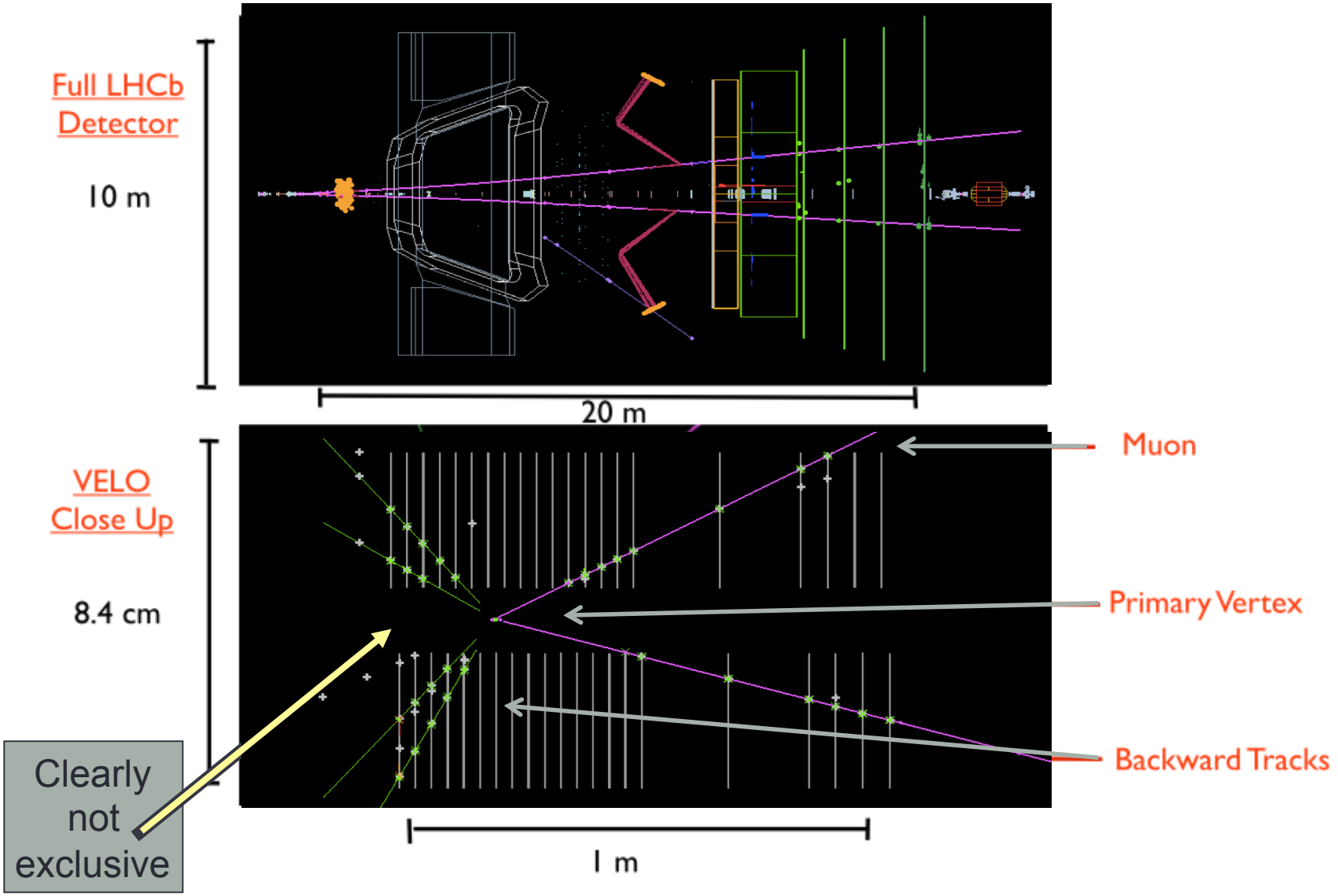
VELO sub-detector



Use of backwards tracks

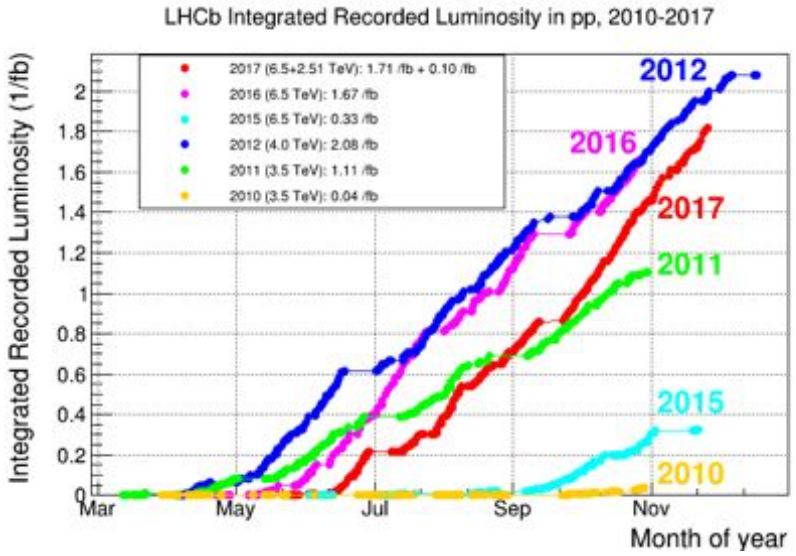


Use of backwards tracks



Collisions

pp Collider



Ion Collider

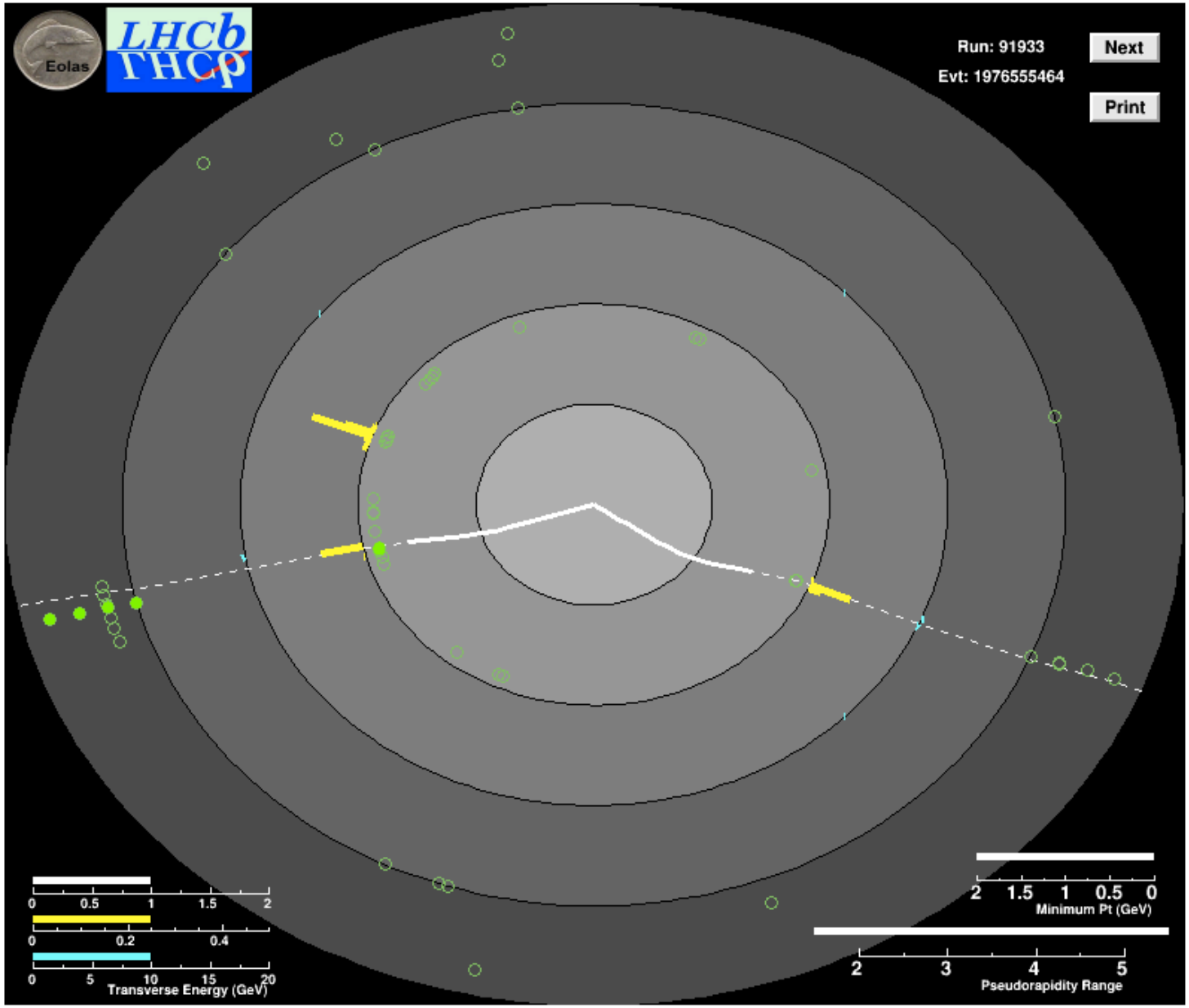
- pA/Ap beam-beam collisions
  - 2013 p-Pb /Pb-p run @ 5 TeV (~1nb^{-1})
  - 2016 p-Pb /Pb-p run @ 5 and 8 TeV (~30nb^{-1})
- A-A collisions
  - 2015 Pb-Pb run @ 5 TeV (~4ub^{-1})
  - 2017 Xe-Xe run @ 5.4 TeV (~0.4ub^{-1})

Ion fixed target

Type	√s	Lumi (μb^{-1})
p-Ne	86.6 GeV	
Pb-Ne	54.5 GeV	0.05
p-Ne	110 GeV	0.5
p-He	110 GeV	0.5
p-Ar	110 GeV	~3
p-Ar	68.6 GeV	~0.05
Pb-Ar	68.6 GeV	~0.05
p-He	110 GeV	1.7
p-He	86.6 GeV	~17
p-He	110 GeV	0.07
p-Ne	110 GeV	~1.0
p-Ne	68.6 GeV	~200

(indicative luminosities)

Candidate for χ_c decay to J/ψ+γ



Selected $\chi_{c0,1,2}$ candidates