Central Exclusive Production: a window onto quarkonia

Ronan McNulty (UCD Dublin)

New Possibilities in Physics of Quarkonia.
Paris, 24th – 25th September 2015.

Outline

- Theoretical background and motivation
- Experimental signatures

- CEP single charmonium: J/ψ and ψ(2S)
- [Brief mention of CEP μμ and χ_c]
- CEP single bottomonium: Υ(1S) Υ(2S) Υ(3S)
- CEP double charmonium: J/ψJ/ψ, J/ψψ(2S), $\chi_c\chi_c$,

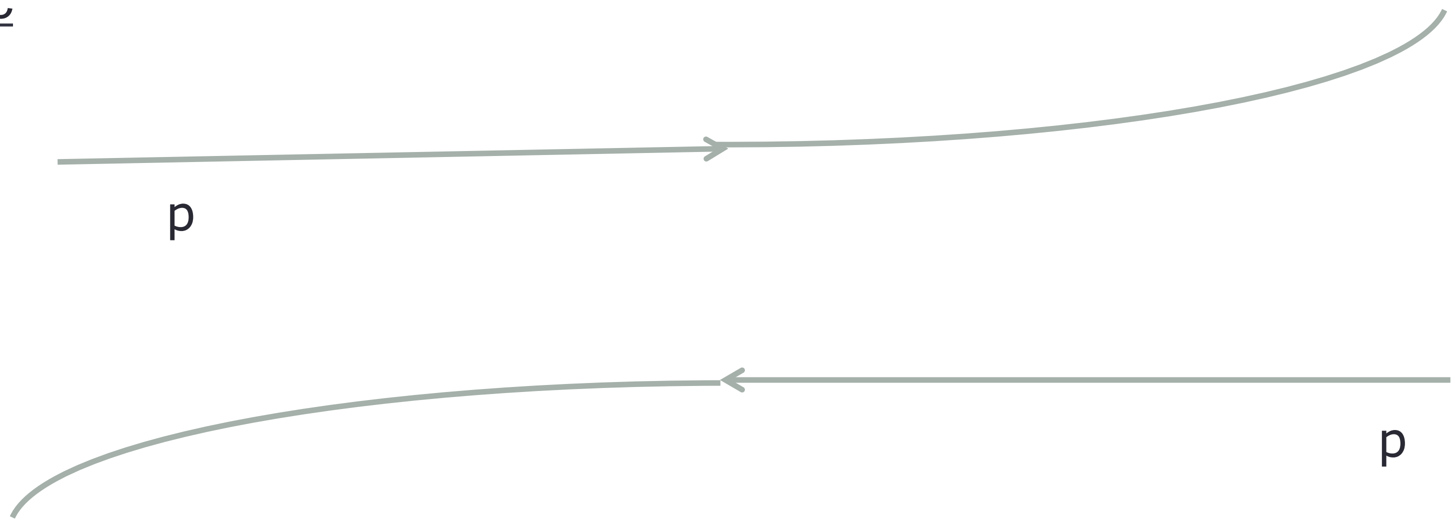
- Questions and challenges.

CEP:
Theoretical background and motivation

- Understanding the vacuum
- **Colourless** objects in QCD (pomeron, reggeon, odderon)
- Search for new phenomena
  - exotics,
  - saturation,
  - glueballs.
- Usually studied through **onia** production
- ***Coloured QCD backgrounds strongly suppressed.***

Physics of the Vacuum

Elastic



It's QCD – but not as we normally see it. It's colourless

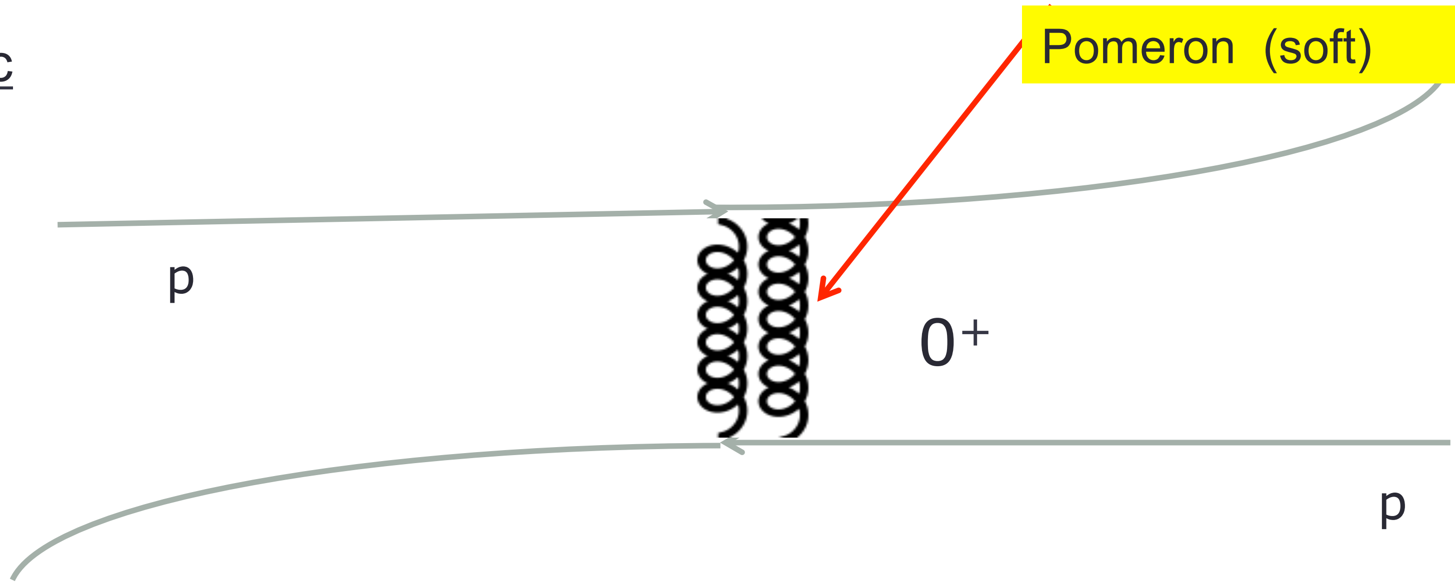
$\sigma_{elastic} \approx 40mb$

$\sigma_{diffractive} \approx 10mb$

$\sigma_{inelastic} \approx 60mb$

Physics of the Vacuum

Elastic



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

$\sigma_{elastic} \approx 40mb$

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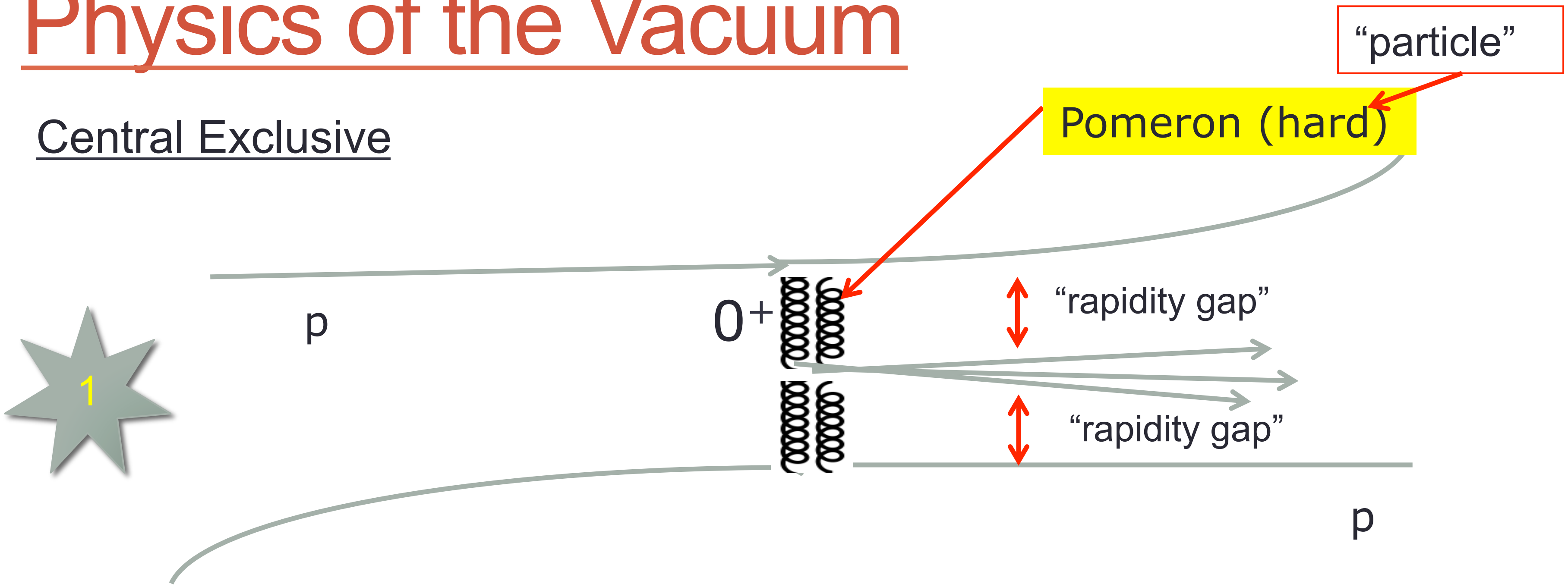
Physics of the Vacuum

Central Exclusive

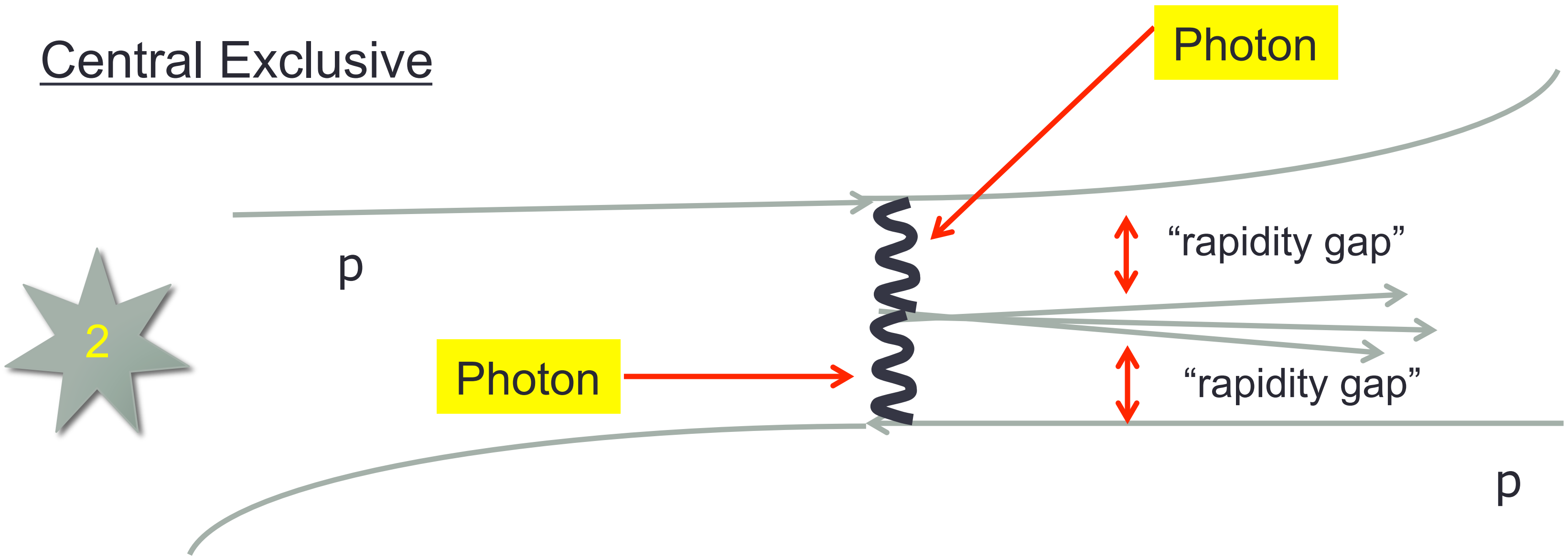


Double Pomeron Exchangle: χ_c,f_0, f_2, ηη, J/ψJ/ψ, H

The onia are produced without the underlying event

Physics of the Vacuum

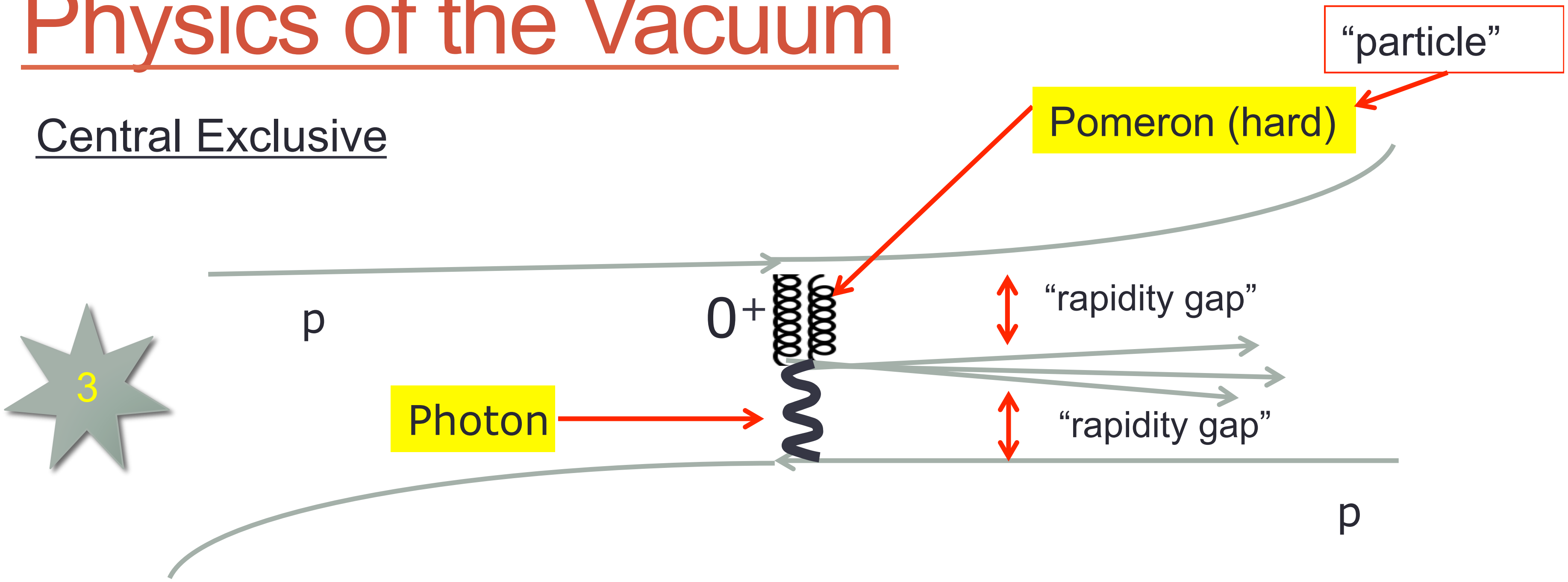
Central Exclusive



QED.

Physics of the Vacuum

Central Exclusive

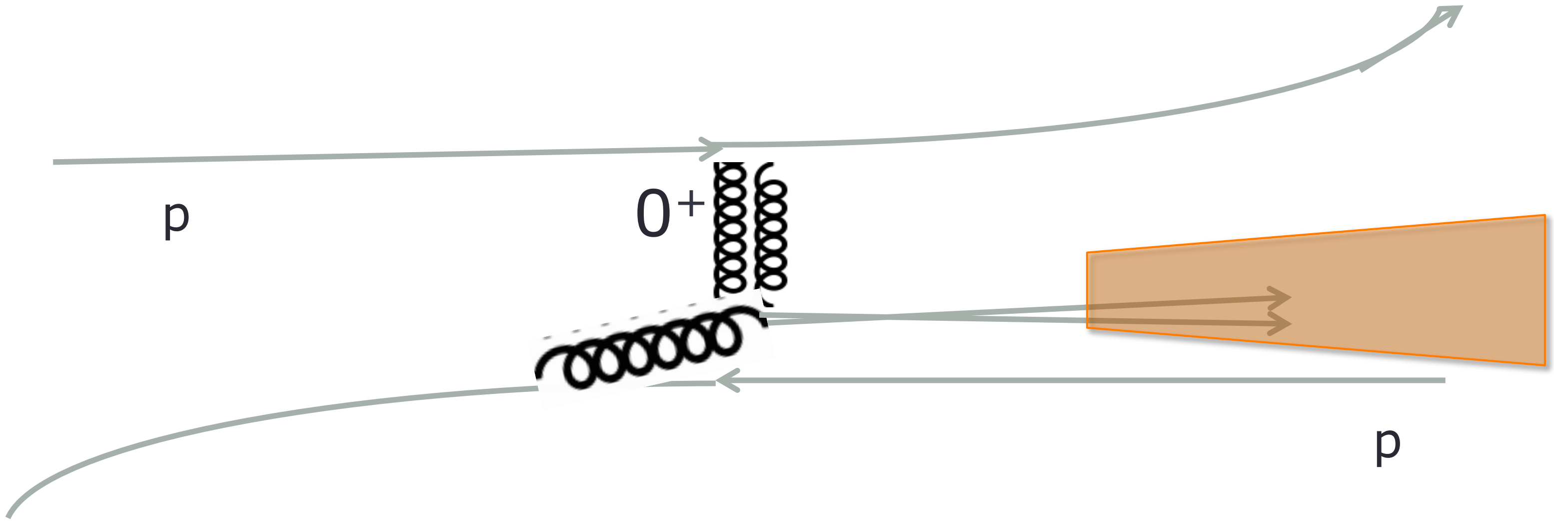


Photoproduction of vector mesons

The onia are produced without the underlying event

Experimental Signatures

Find rapidity gap

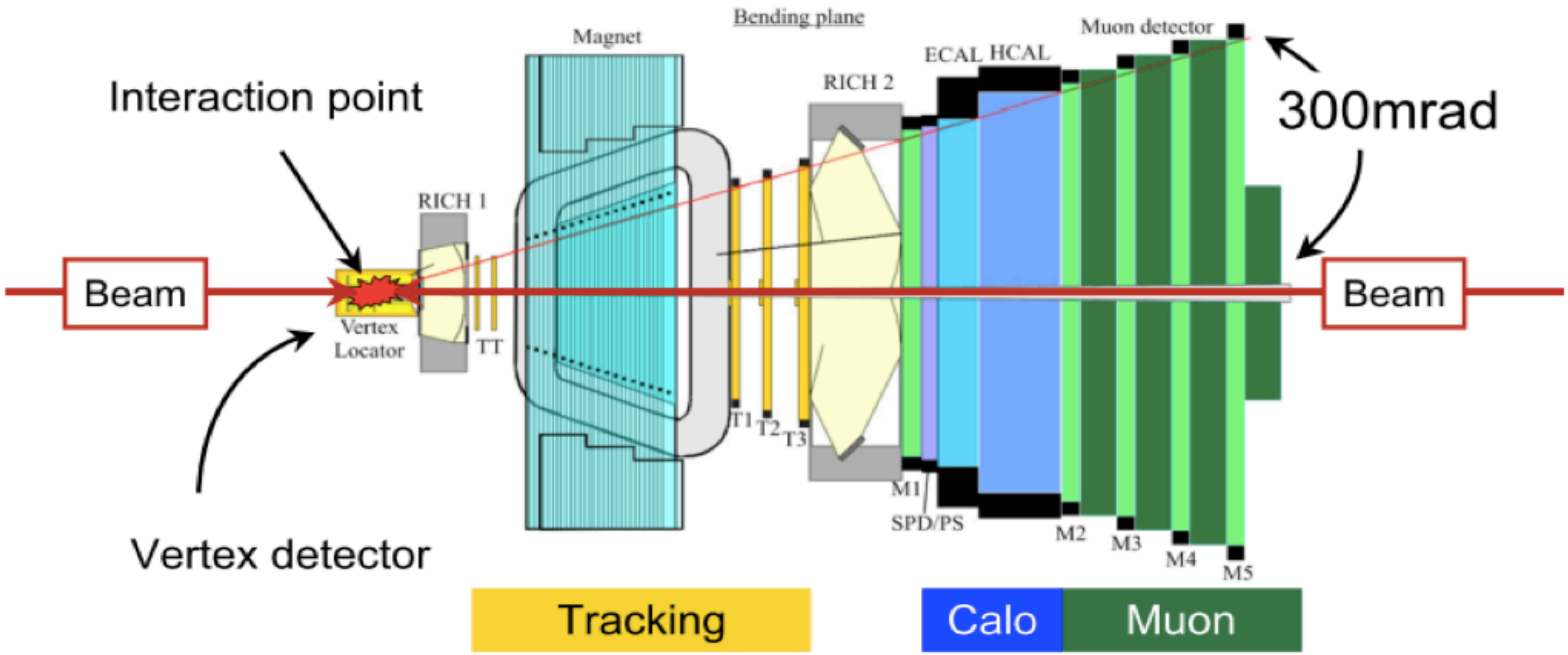


Detect 'central' system including presence of **rapidity gap**

Most pp interactions distribute particles throughout 4π (collimated in jets but also with activity between jets)

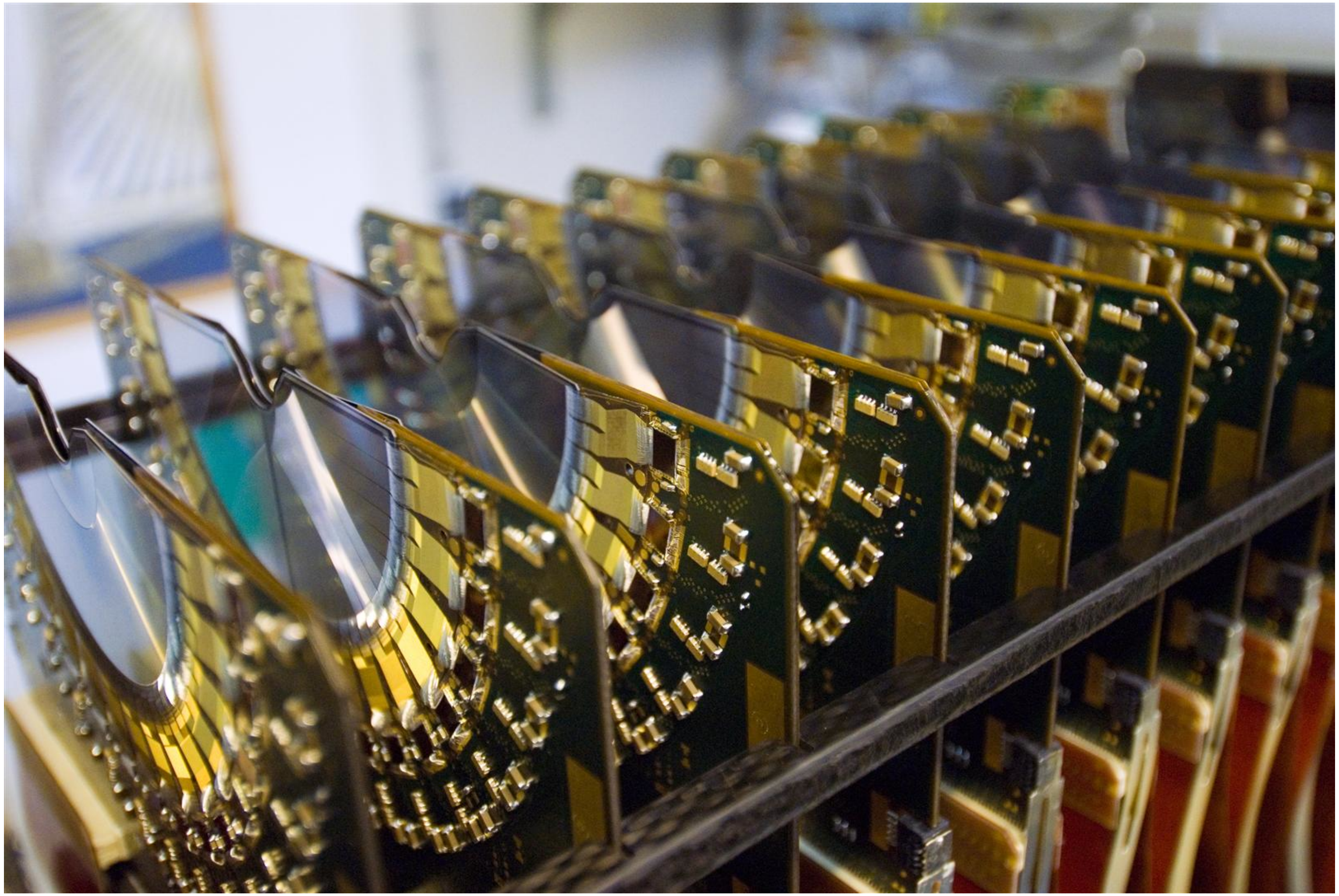
Size of gap you can detect is critical

The LHCb detector



Fully instrumented: $2 < \eta < 5$
Some sensitivity: $-3.5 < \eta < -1.5$

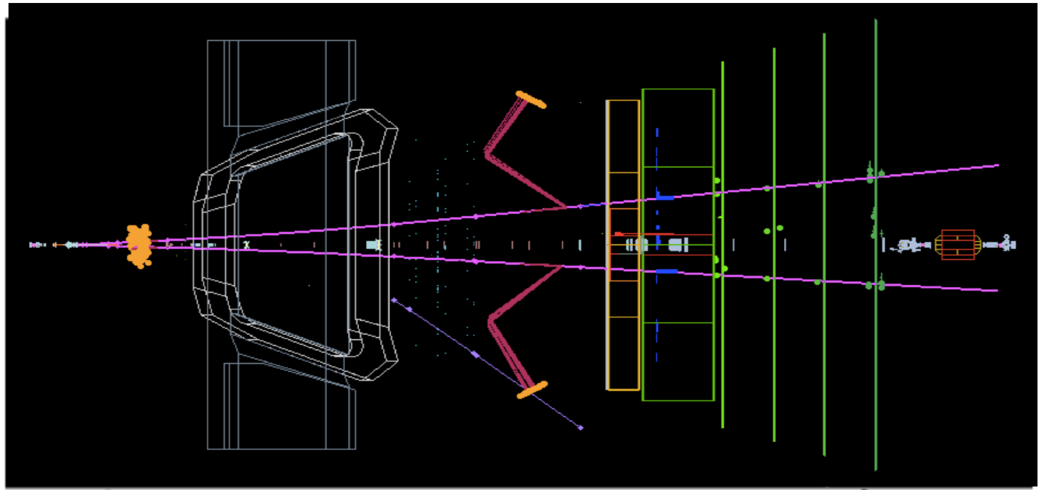
VELO sub-detector



Use of backwards tracks

Full LHCb Detector

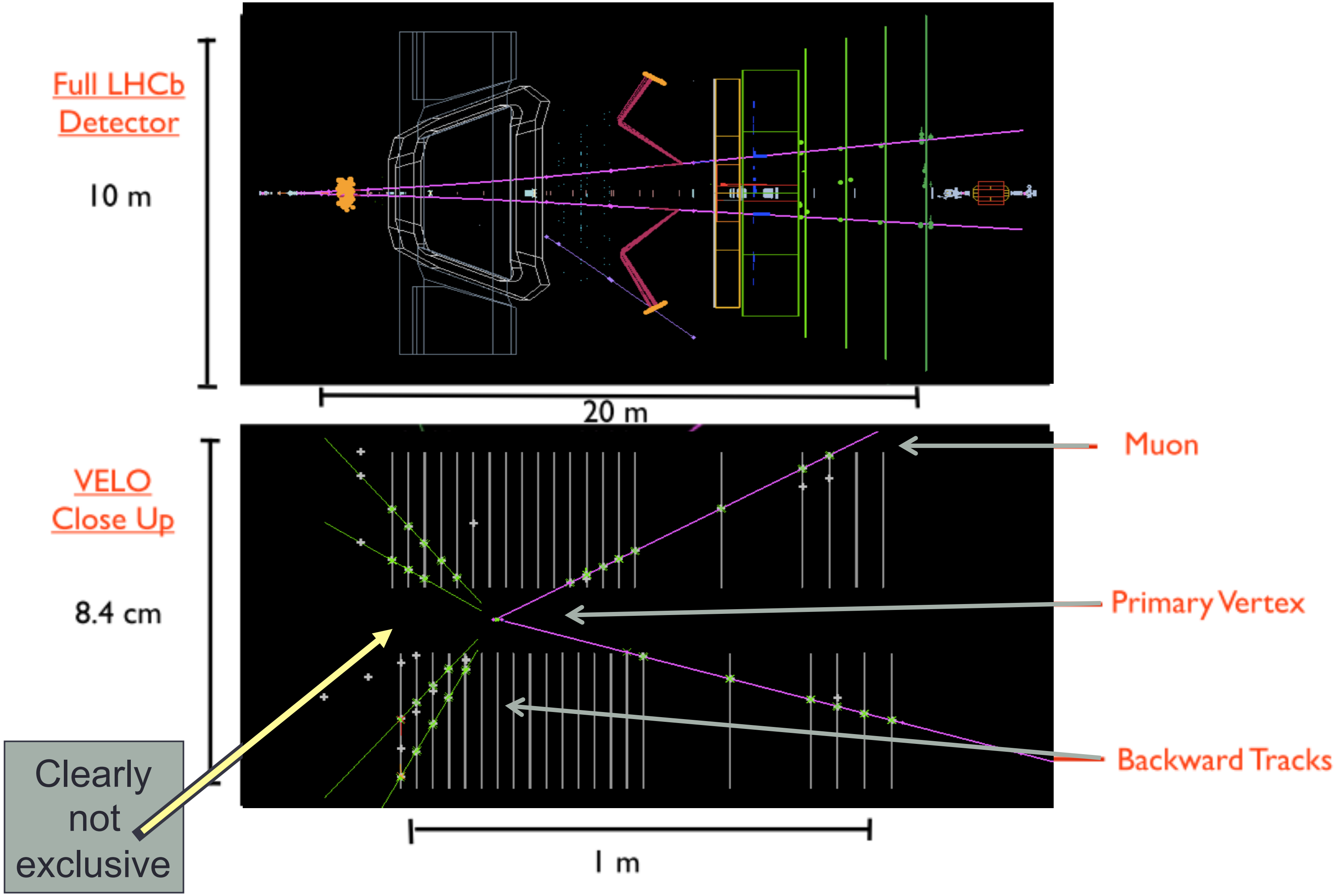
10 m



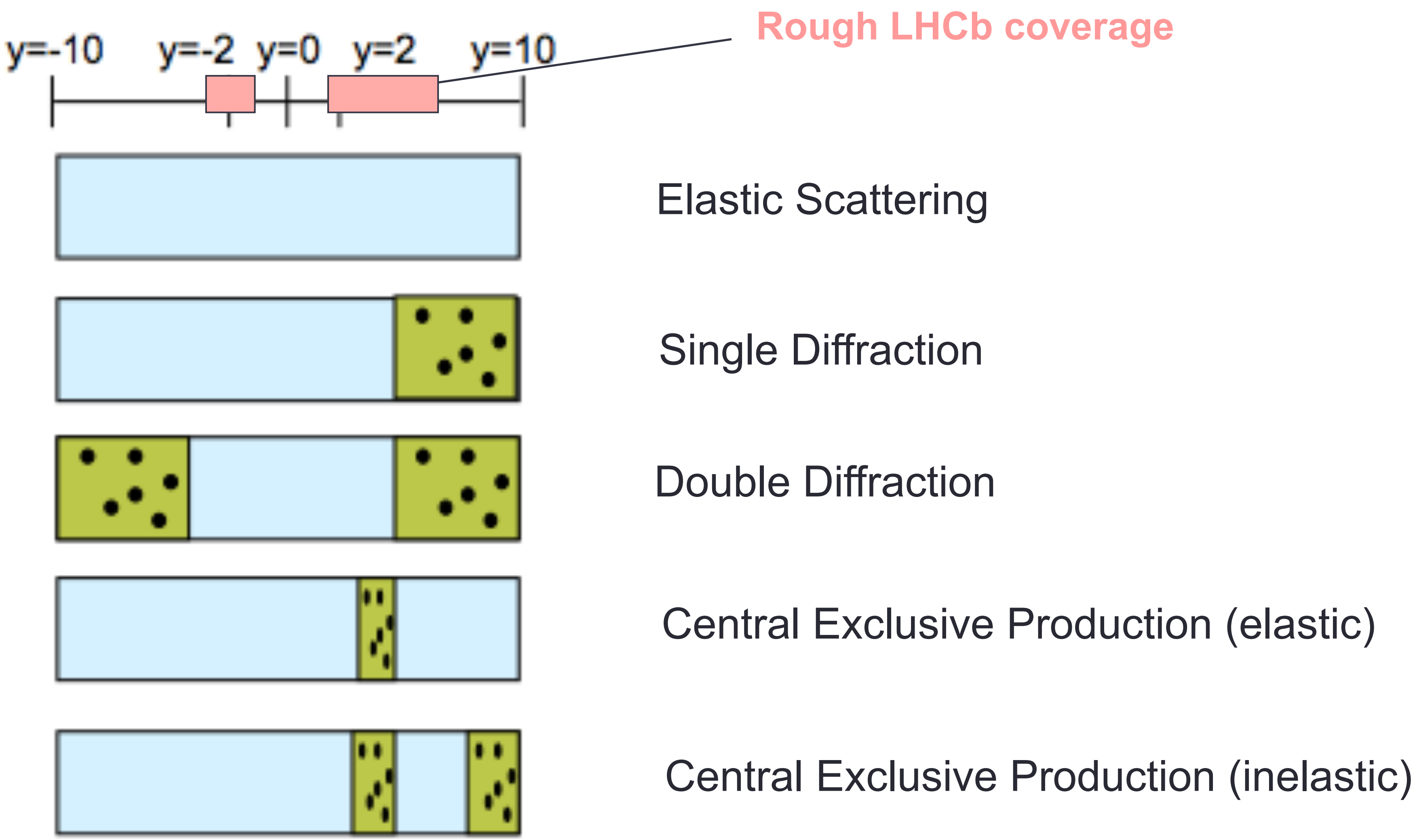
20 m

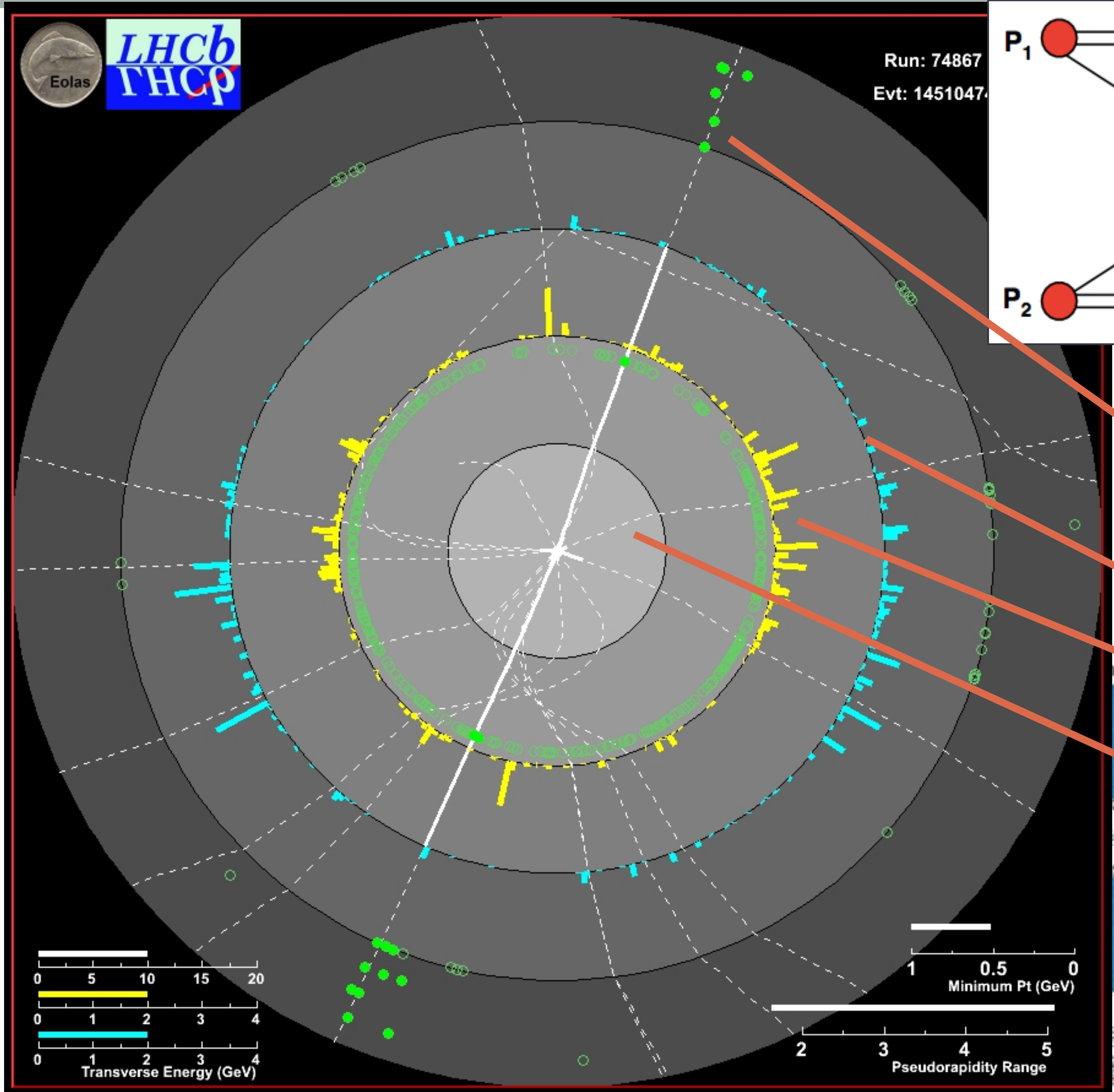
l m

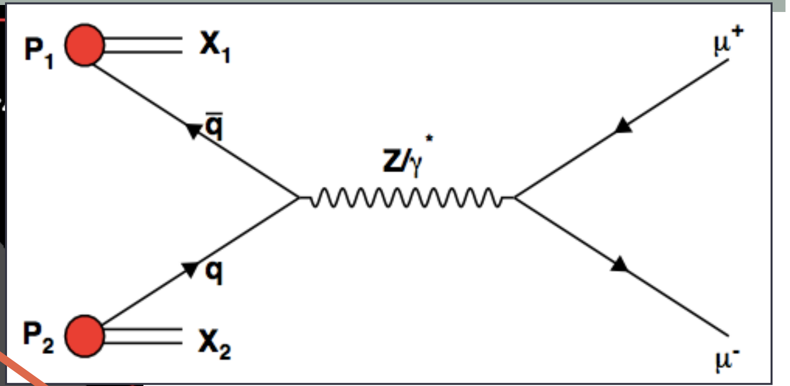
Use of backwards tracks

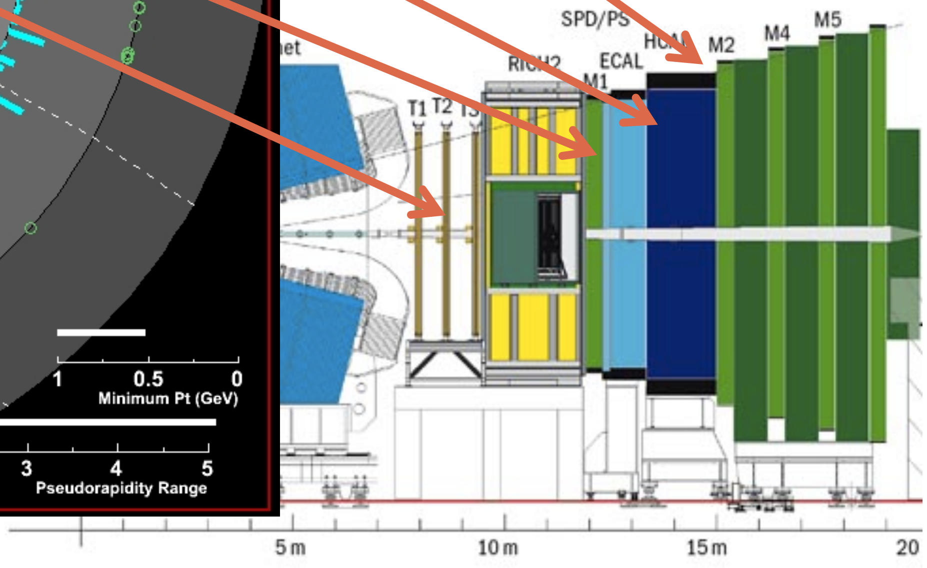


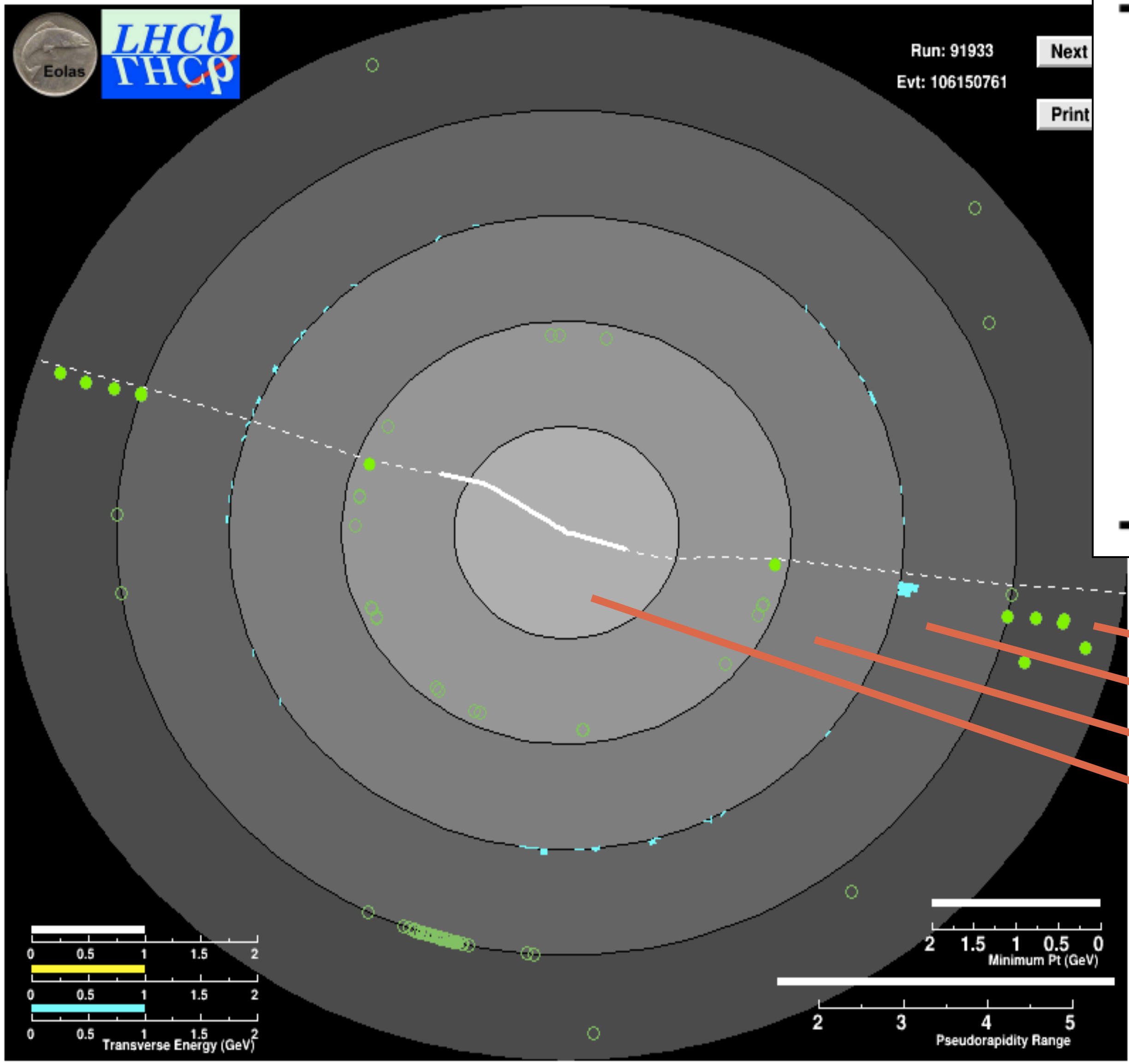
Graphical Representation

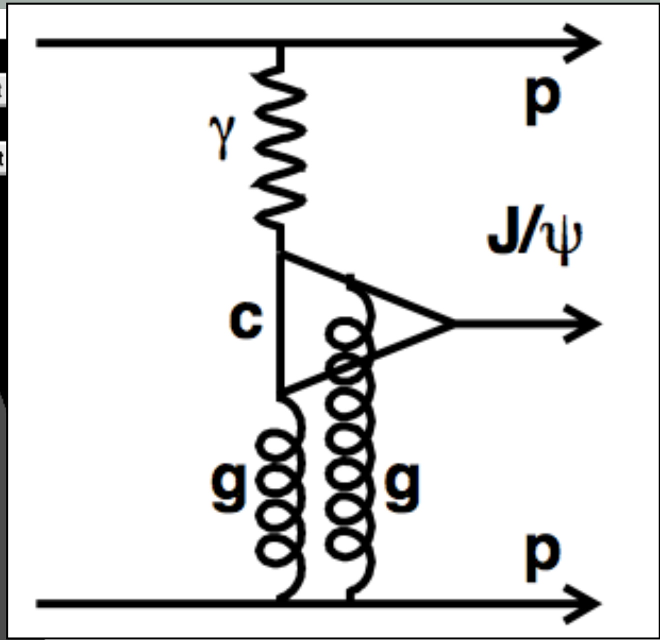


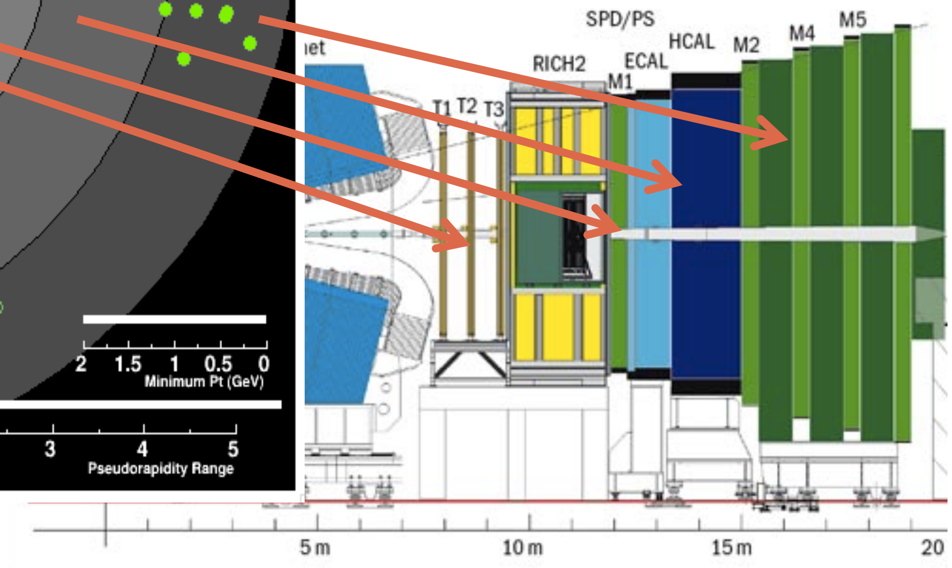

Eolas
LHCb
Run: 74867
Evt: 1451047
0 5 10 15 20
0 1 2 3 4
0 1 2 3 4
Transverse Energy (GeV)
1 0.5 0
Minimum Pt (GeV)
2 3 4 5
Pseudorapidity Range


P1
X1
q̄
Z/γ*
μ+
q
P2
X2
μ-

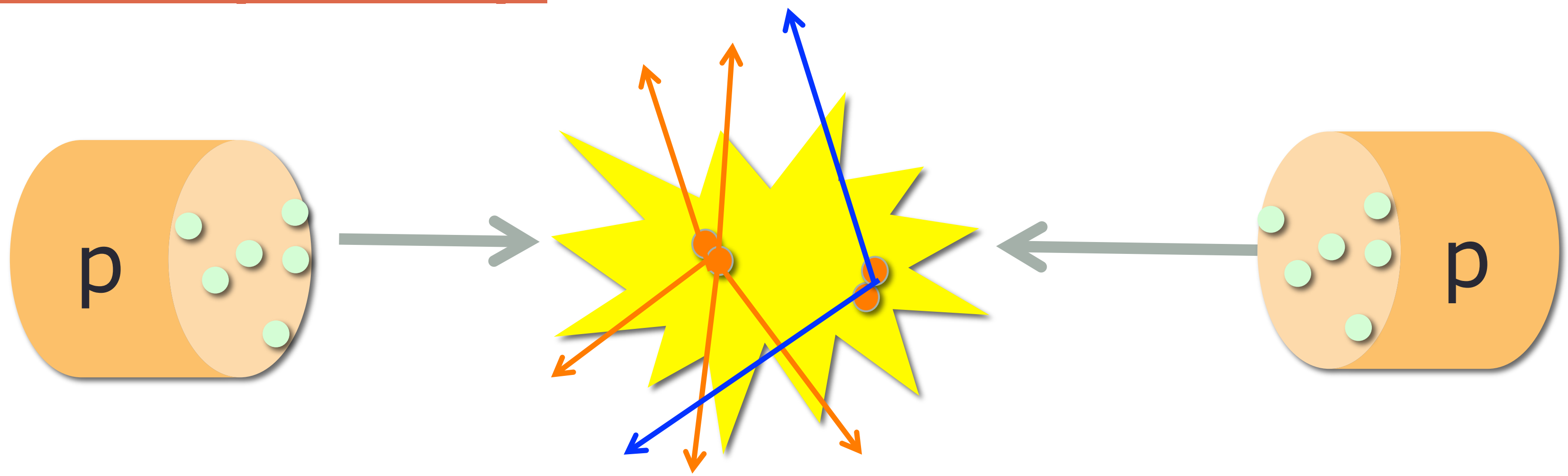

SPD/PS
HCAL
M2
M4
M5
RICH2
ECAL
M1
T1 T2 T3
5 m
10 m
15 m
20


Eolas
LHCb
Run: 91933
Evt: 106150761
Next
Print
0 0.5 1 1.5 2
Transverse Energy (GeV)
2 1.5 1 0.5 0
Minimum Pt (GeV)
2 3 4 5
Pseudorapidity Range

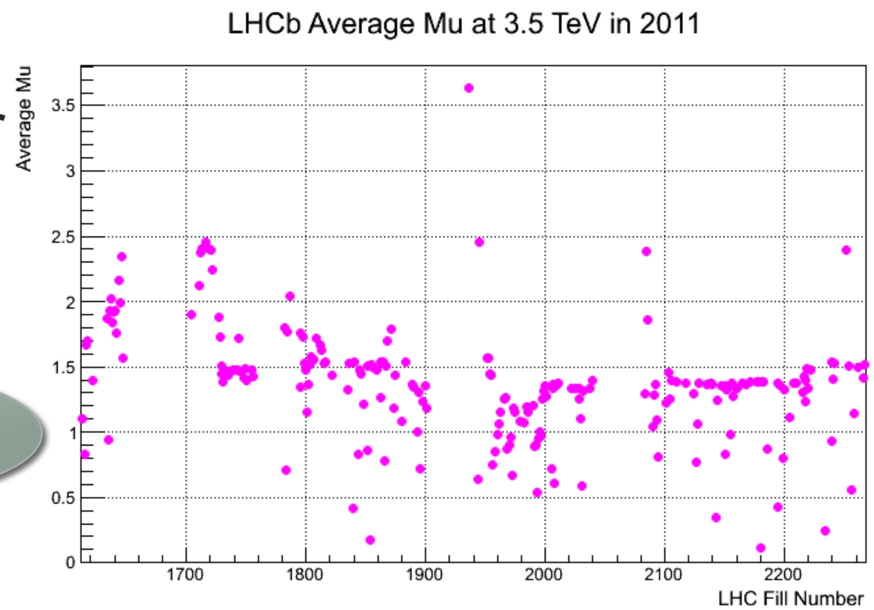

p
γ
J/ψ
c
g
g
p


SPD/PS
HCAL
M2
M4
M5
RICH2
ECAL
M1
T1 T2 T3
5 m
10 m
15 m
20

Beam pile-up



High luminosity requires multiple proton interactions per beam-crossing.



Number of interactions (N) /crossings, distributed

Average #interactions

$$f(N) = \frac{e^{\mu}\mu^{N}}{N!}$$

For LHCb in 2011, $\bar{\mu}$=1.4

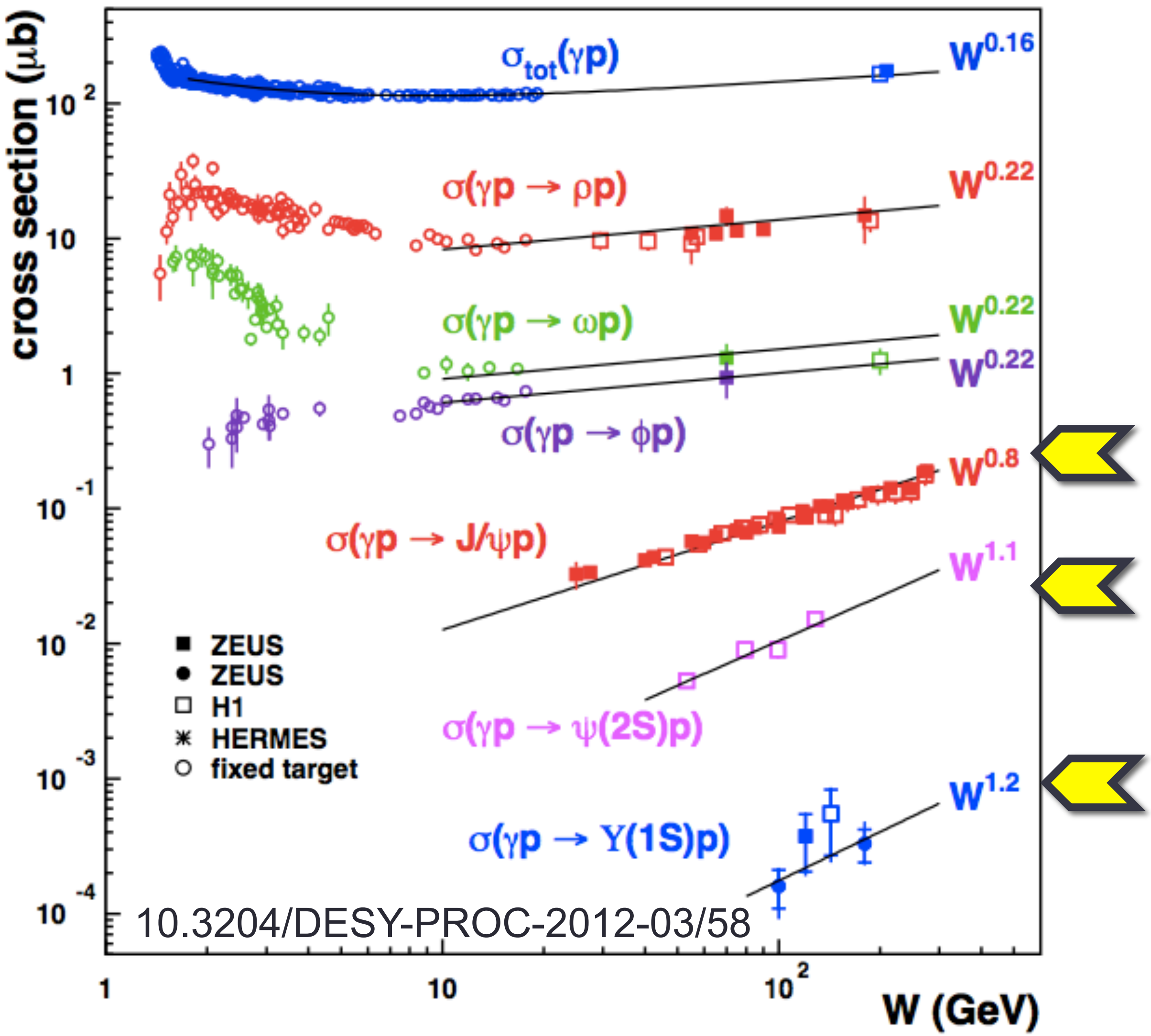
Central Exclusive Production of J/ψ and ψ(2S) mesons

Data-taking year	Energy	Integrated Luminosity	Paper
2010	7 TeV	$37pb^{-1}$	JPG 40 (2013) 045001
2011	7 TeV	$930pb^{-1}$	JPG 41 (2014) 055002

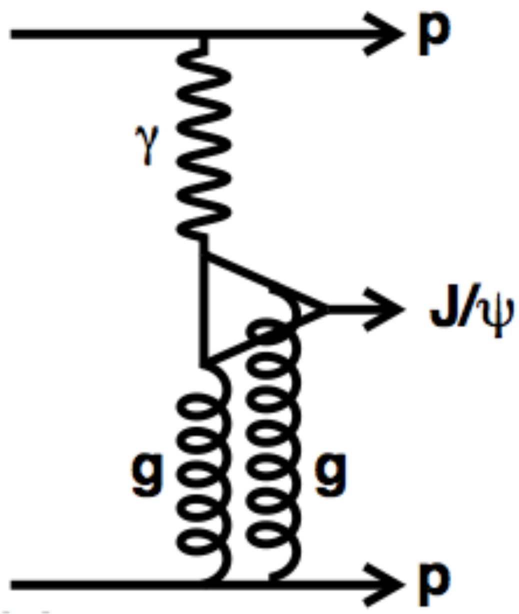
HERA vector meson photo-production results

Note:

- $\sigma \sim x^{\lambda}$
- soft/hard
- $g(x,Q^2)$
  (at x=1E-5)



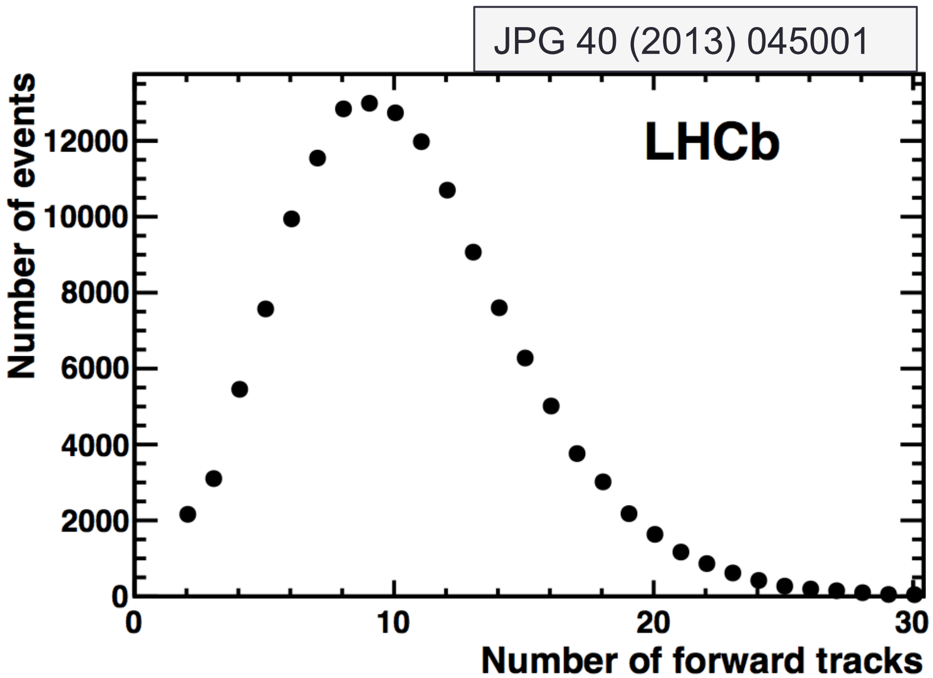
Simple Selection Criteria



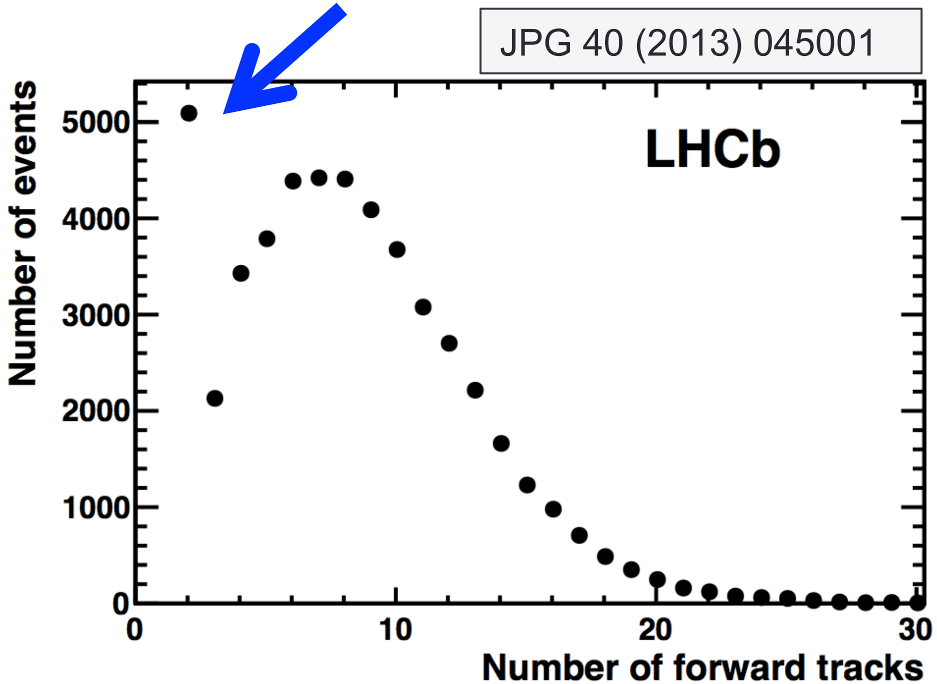
- **Precisely two forward muons**
- **No backward tracks**
- No photons
- p_T^2 of dimuon < 0.8 GeV^2
- Mass of dimuon within 65 MeV of J/ψ or ψ(2S)

2 forward gaps that sum to 3.5 units of rapidity + a backward <gap> of 1.7

Effect of rapidity gap requirement on low multiplicity muon triggered events

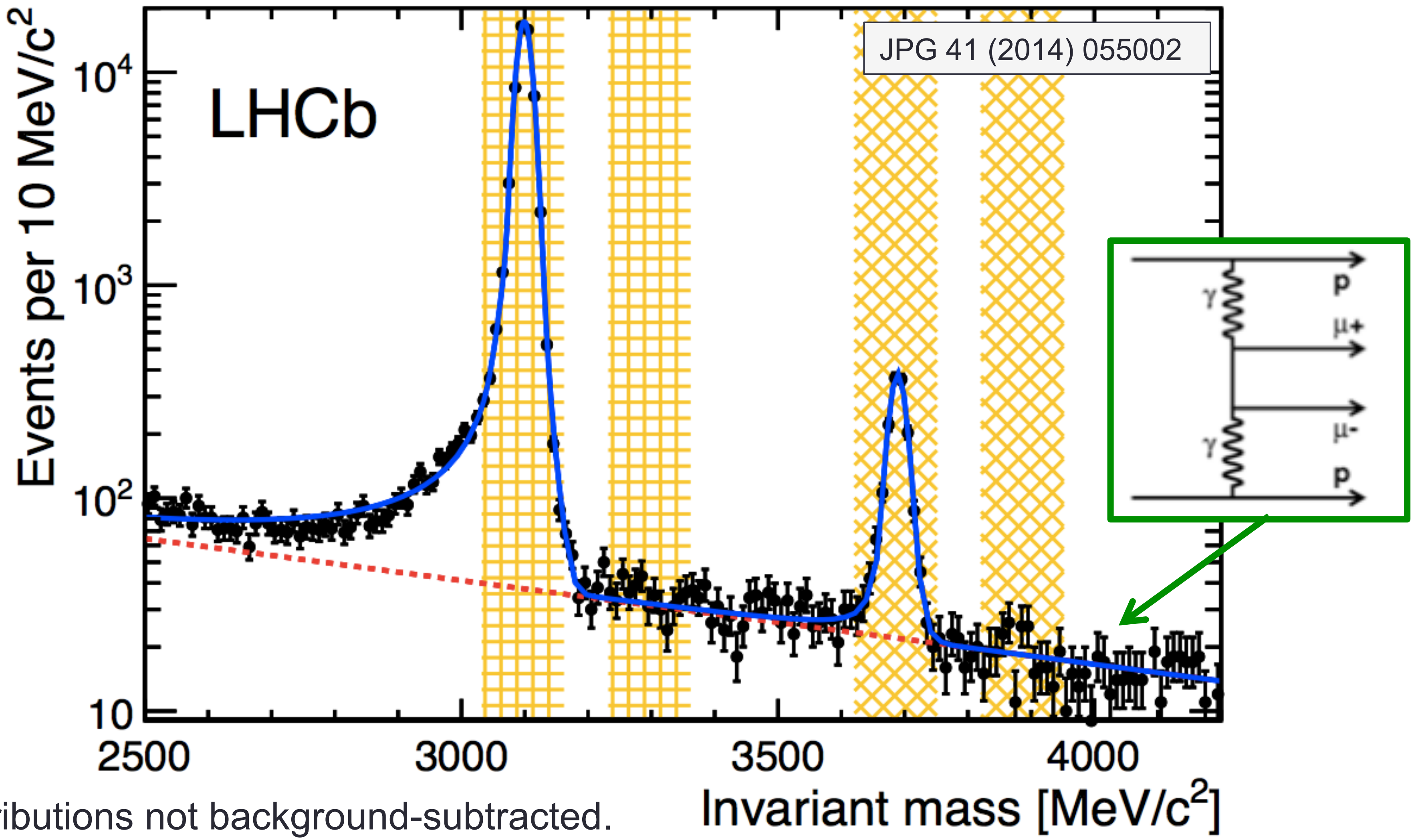


All triggered events



With veto on backward tracks

Non-resonant background very small



Distributions not background-subtracted.
55985 J/ψ and 1565 ψ(2s)

Cross-section measurement J/ψ / ψ(2S)

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

Number of events observed

Luminosity

Acceptance (MC)

Efficiency: (found from data)

1. Trigger
2. Muon identification
3. Single interaction beam-crossing

$$P(1) = \mu^1 e^{-\mu} / 1!$$

Cross-section measurement J/ψ / ψ(2S)

Purity: (found from data)
1. non-resonant bkg (1% / 17%)
2. Feeddown (10% / 2%)
3. Inelastic Jpsi production (40% / 40%)

Number of events observed

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

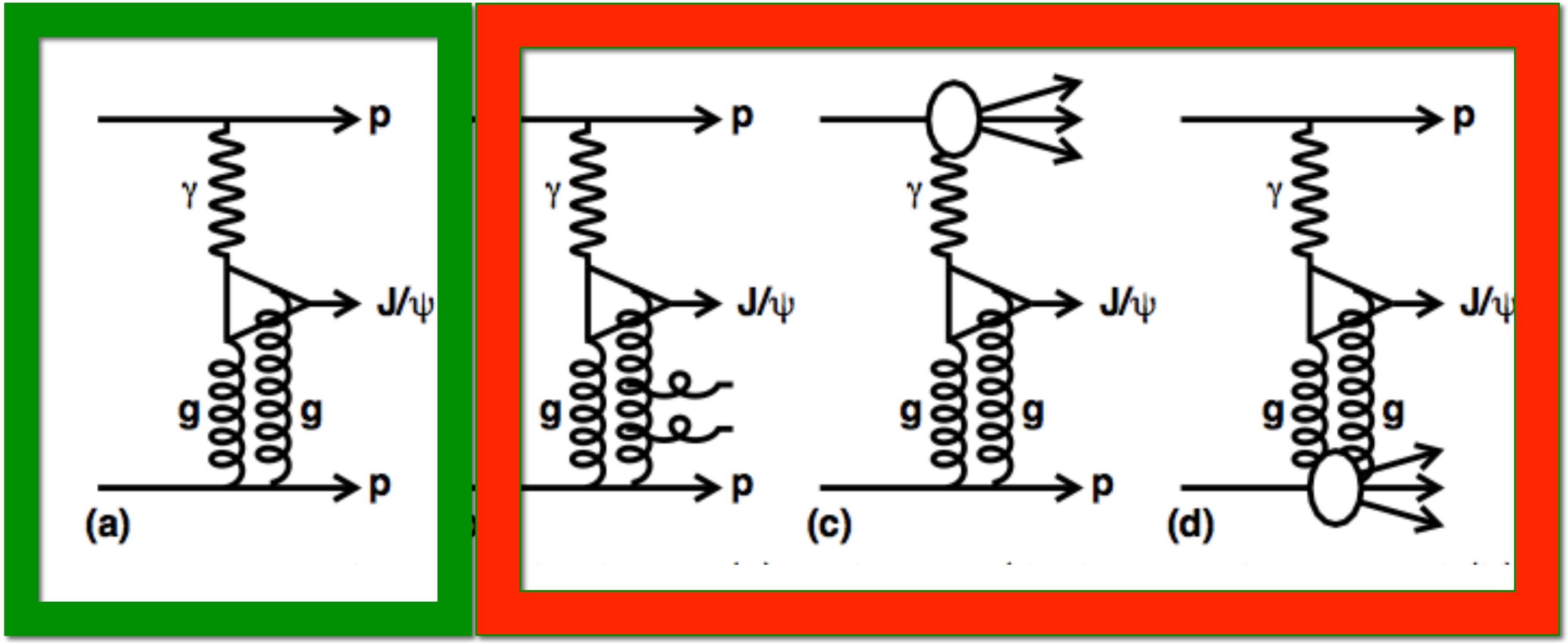
Luminosity

Acceptance (MC)

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

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

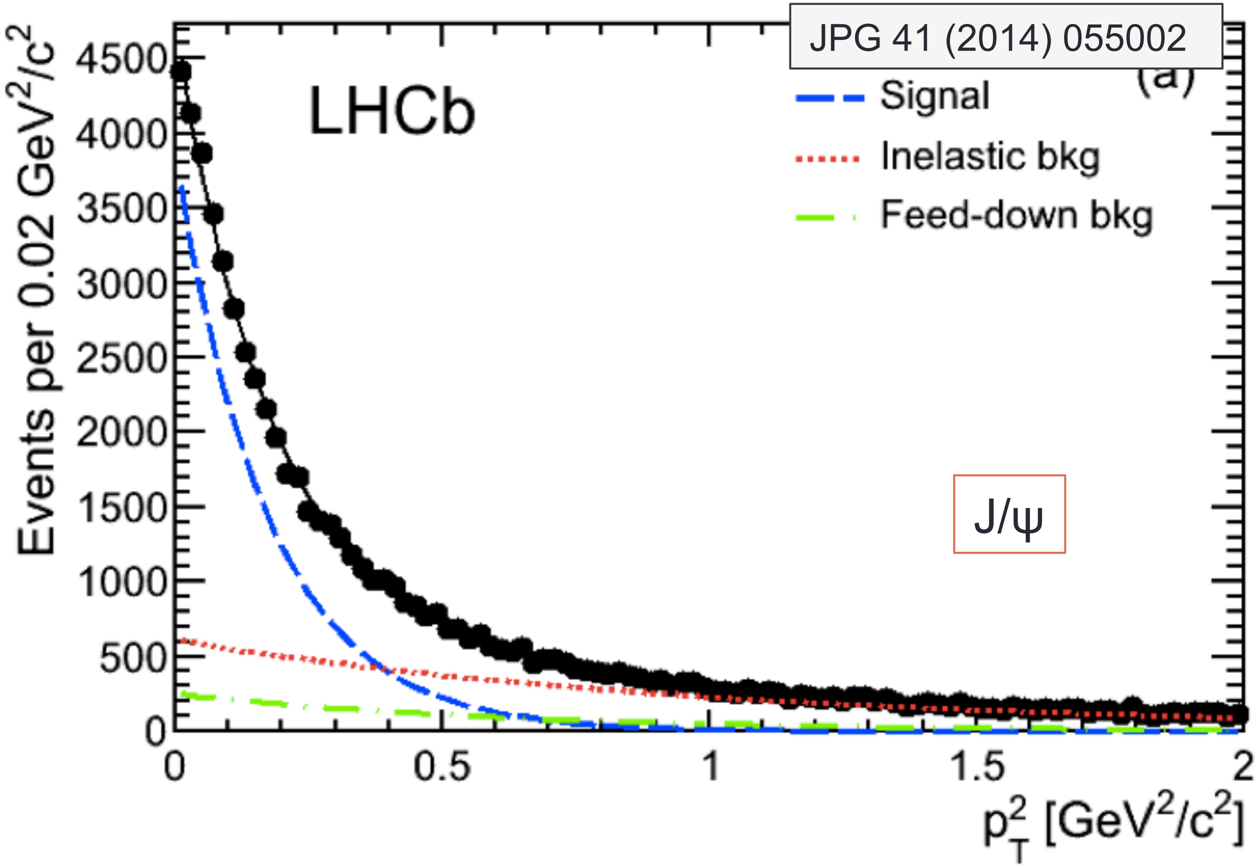
Inelastic background

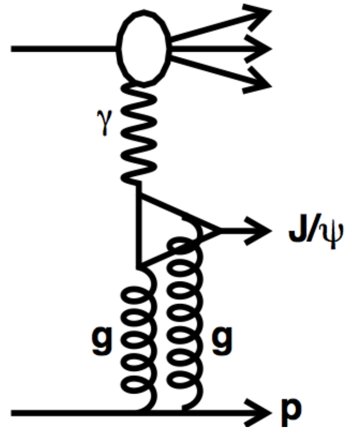


Signal

Background

Inelastic background J/ψ





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

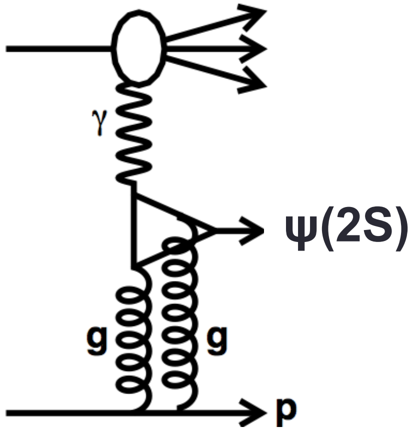
HERA measured:
b_s=4.9 GeV^{-2}
b_{pd}=1.1 GeV^{-2}

LHCb Expect:
b_s ~ 6 GeV^{-2}
b_{pd}~ 1 GeV^{-2}

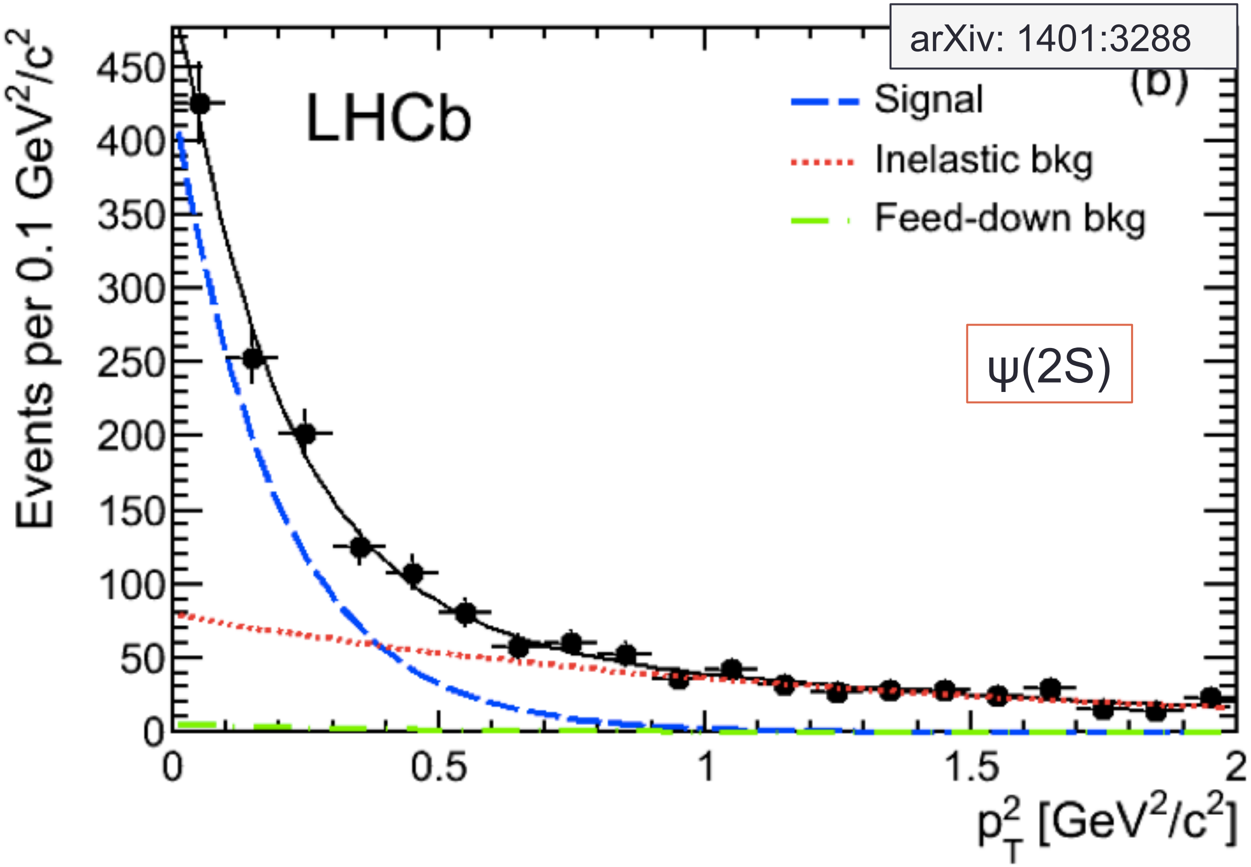
LHCb Fit:
b_s=5.70±0.11 GeV^{-2}
b_{pd}=0.97±0.04 GeV^{-2}

Systematic: Change signal to $(1 + b_{\rm pd} p_{\rm T}^2/n)^{-n}$

Inelastic background ψ(2S)



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



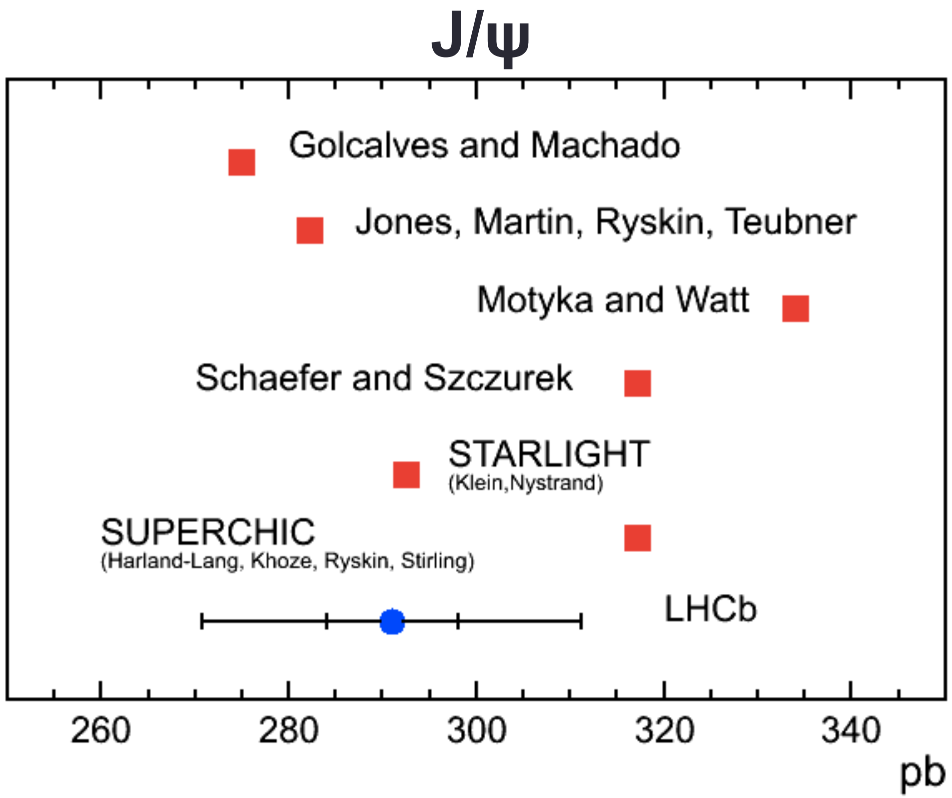
<u>HERA measured:</u>
b_s=4.2 GeV^{-2}
b_{pd}=0.6 GeV^{-2}

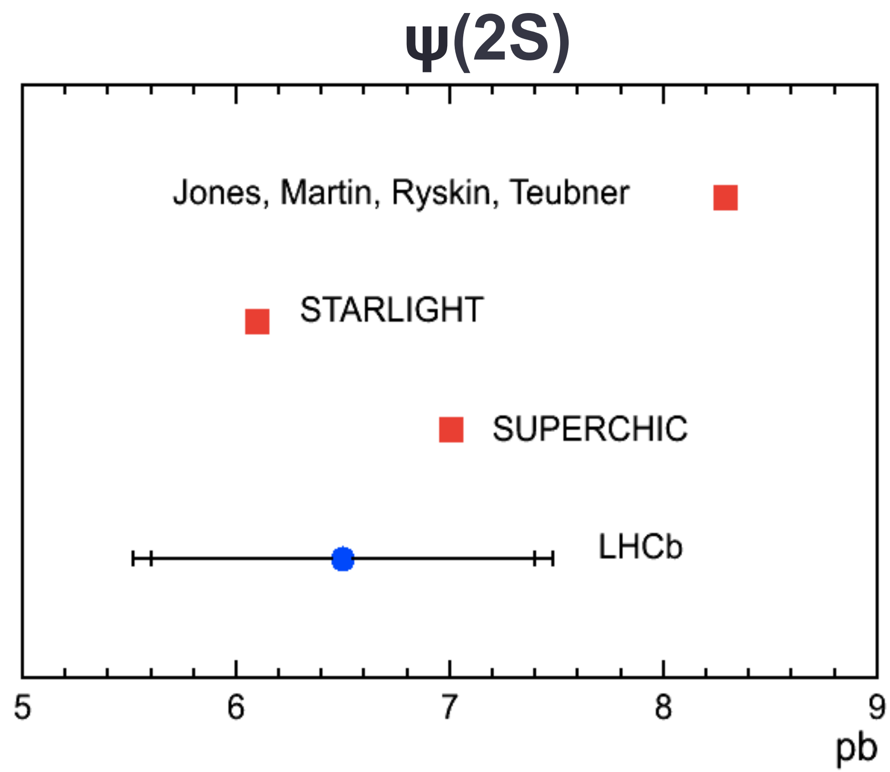
<u>LHCb Expect:</u>
b_s ~ 5.5 GeV^{-2}
b_{pd}~ 0.6 GeV^{-2}

<u>LHCb Fit:</u>
b_s=5.1±0.7 GeV^{-2}
b_{pd}=0.8±0.2 GeV^{-2}

Integrated Cross-sections

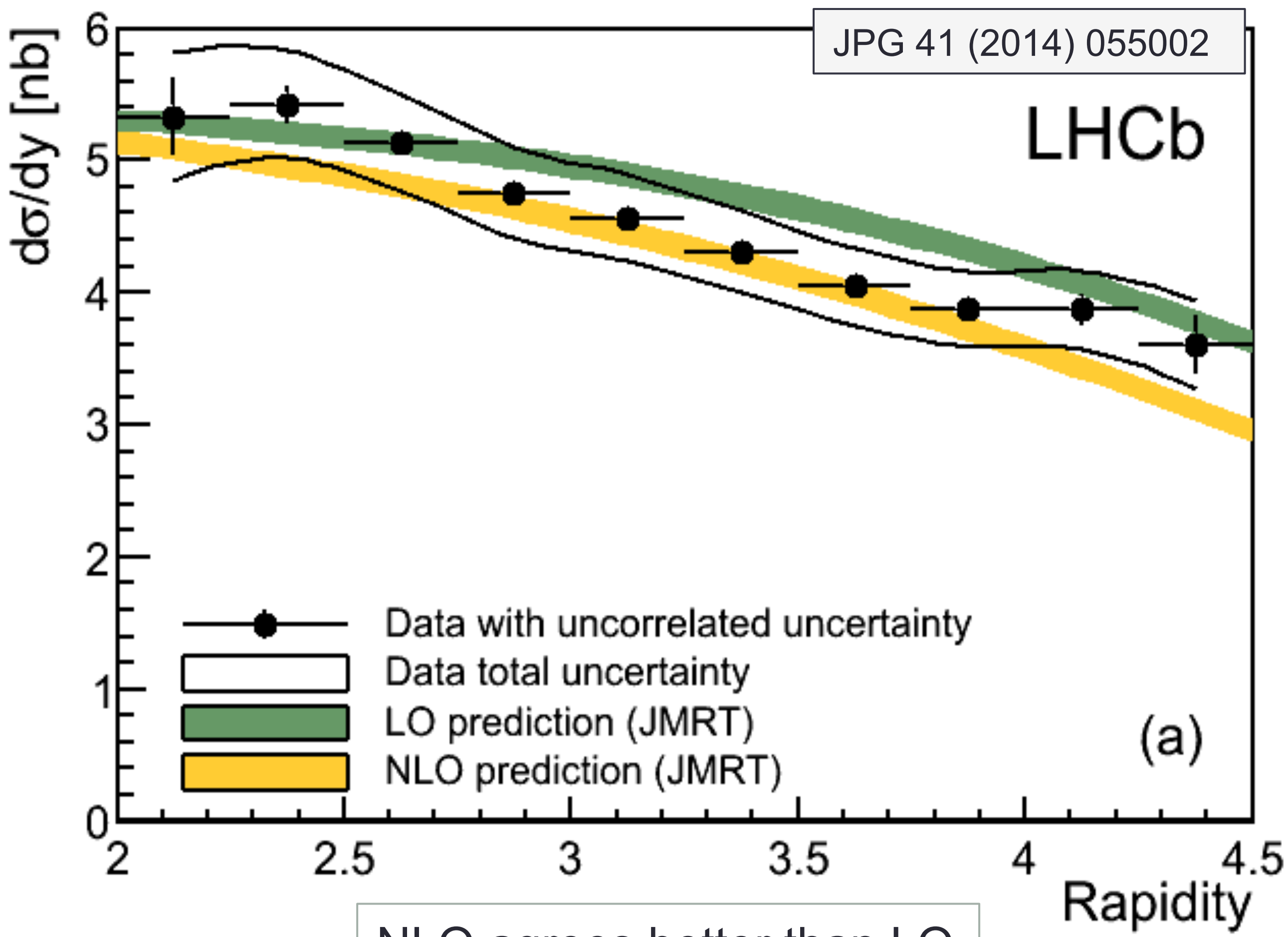
Cross-section*BR for both muons in pseudorapidity range 2<η<4.5:





Good agreement with all theory estimates

Differential cross-sections J/ψ

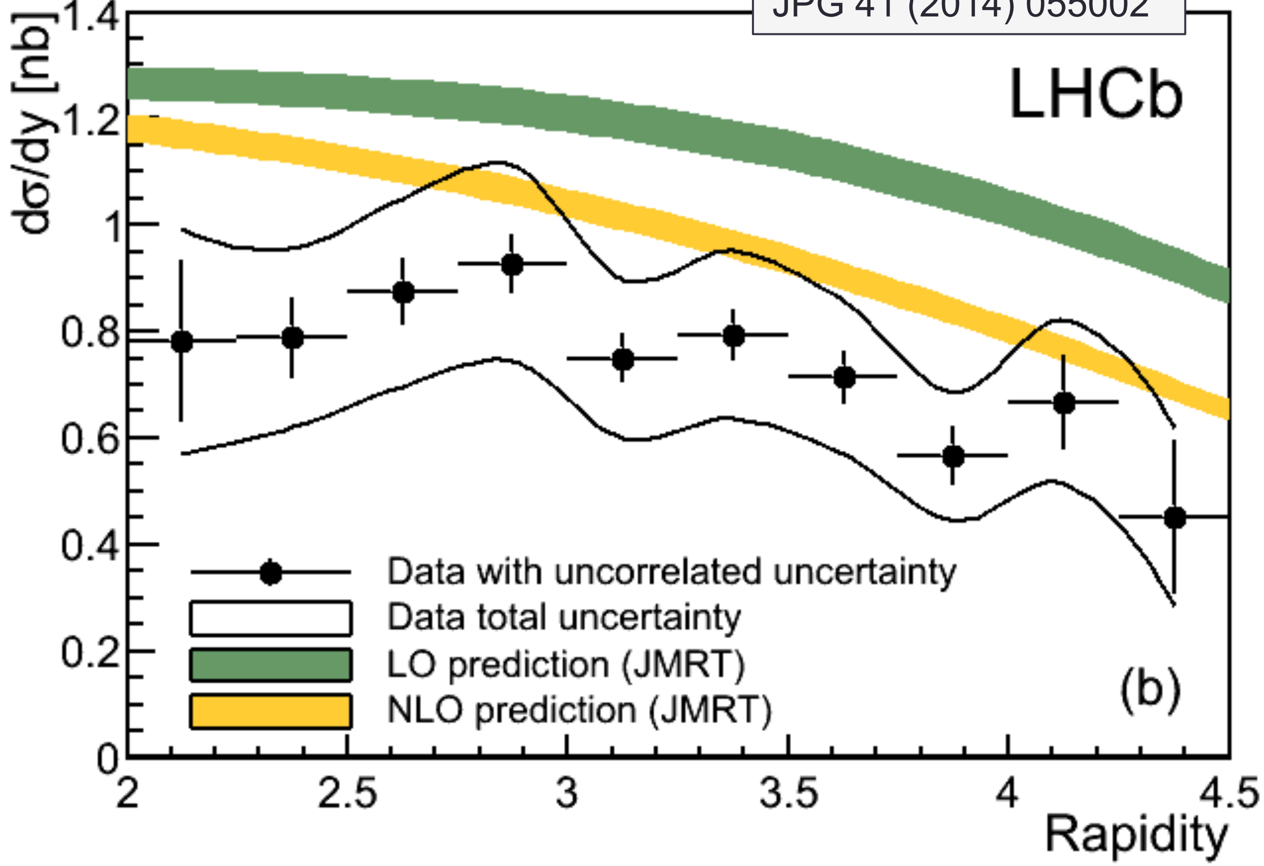


NLO agrees better than LO

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.

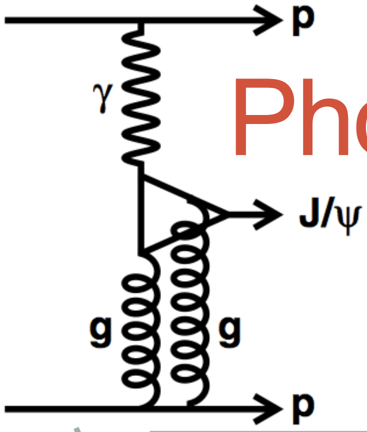
Differential cross-sections ψ(2S)

JPG 41 (2014) 055002



NLO agrees better than LO

Photo-production cross-section



LHCb measure

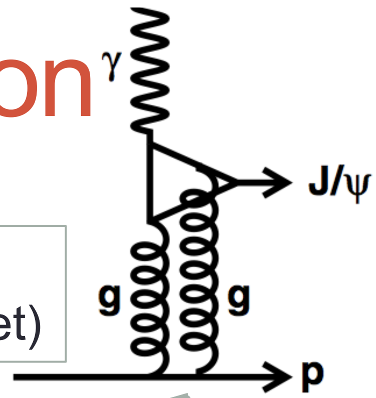


Photo-production (HERA / fixed target)

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

Gap Survival

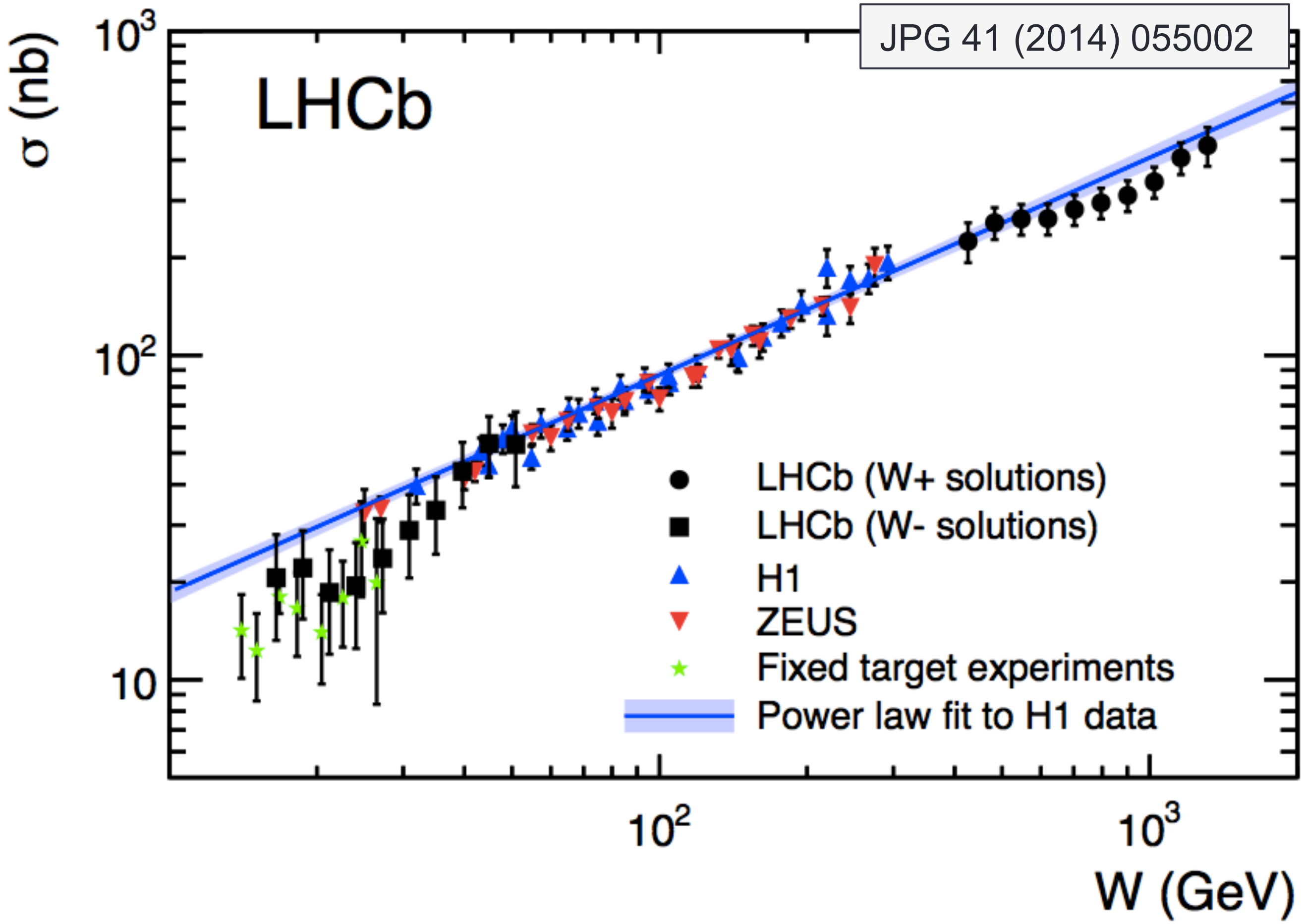
Photon Flux

HERA measured power-law: $\sigma_{\gamma p\to J/\psi p}(W) = 81(W/90\,\mathrm{GeV})^{0.67}\,\mathrm{nb}$
Use this for one cross-section on RHS – LHCb measure the other solution

Photo-production cross-section

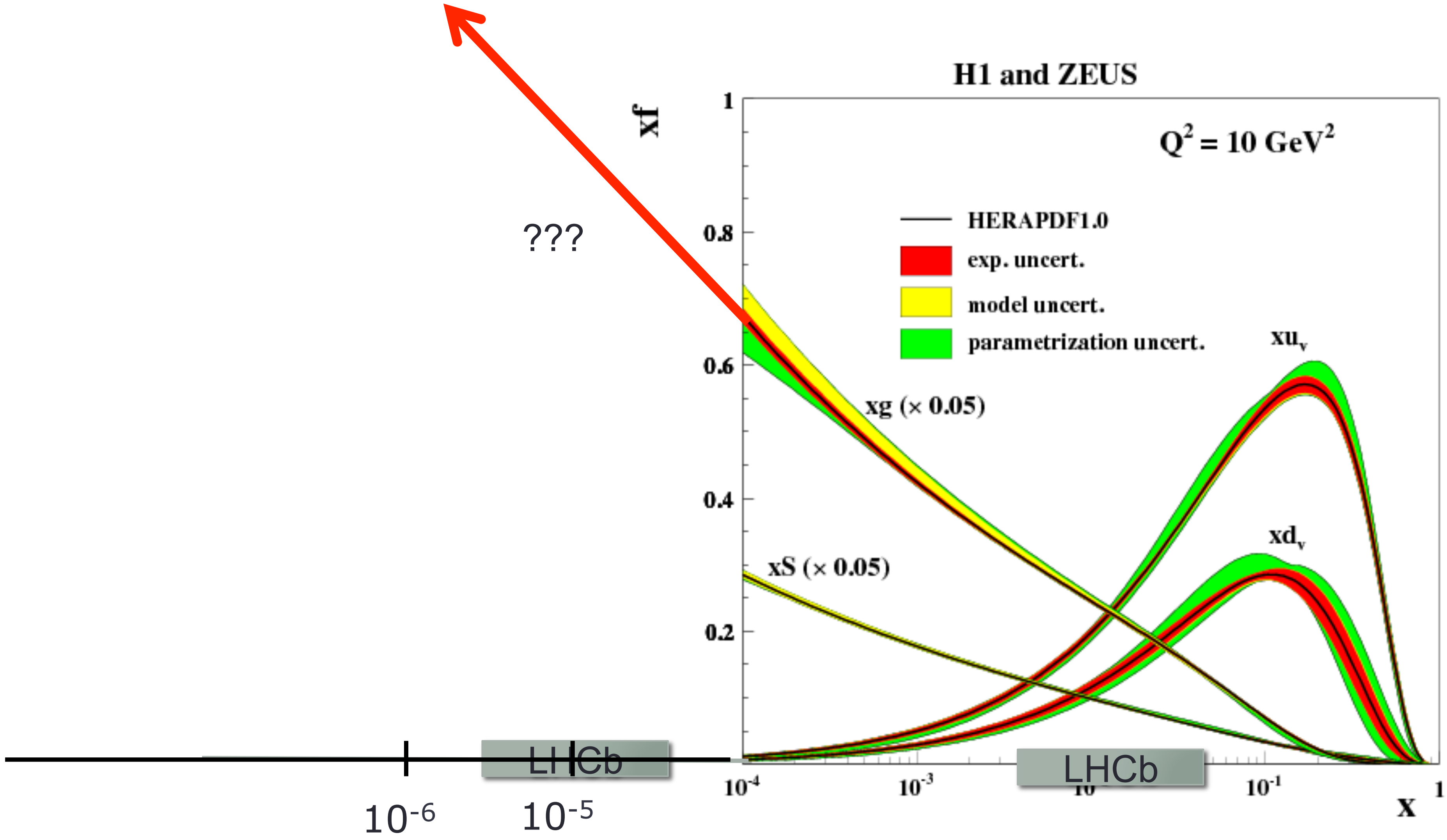
Measure   Plot   HERA

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

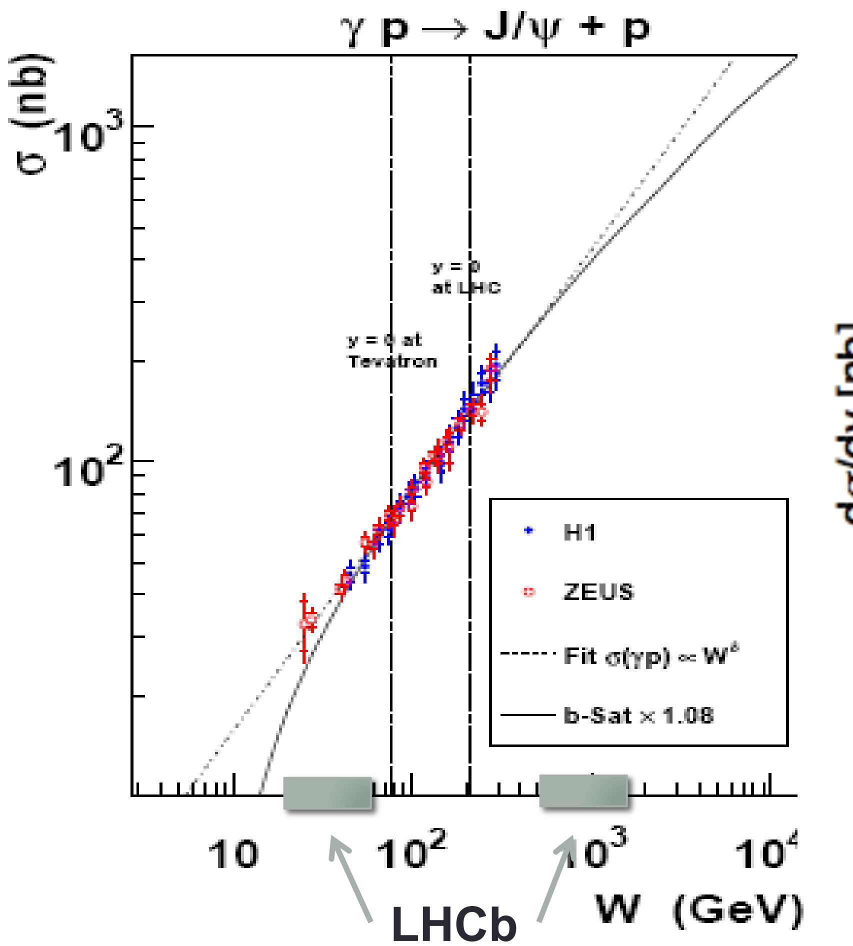


Deviation from pure power-law. i.e. NLO required or only power-law for $W>W_0$

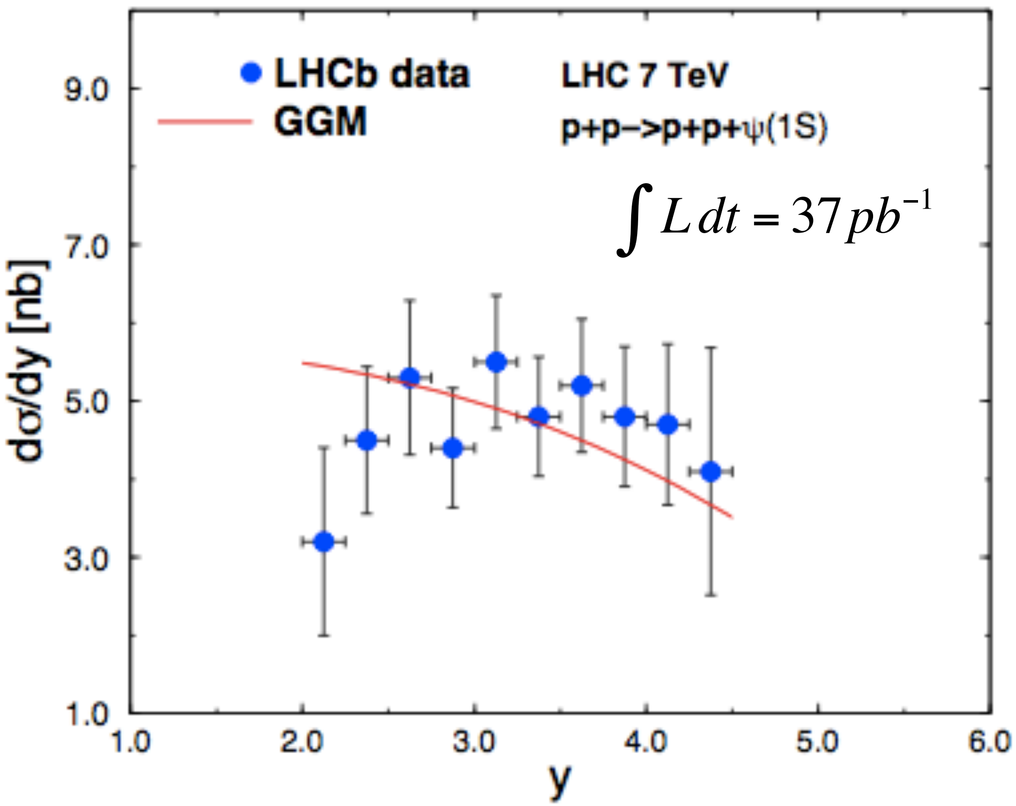
Sensitivity to saturation effects



Sensitivity to saturation effects

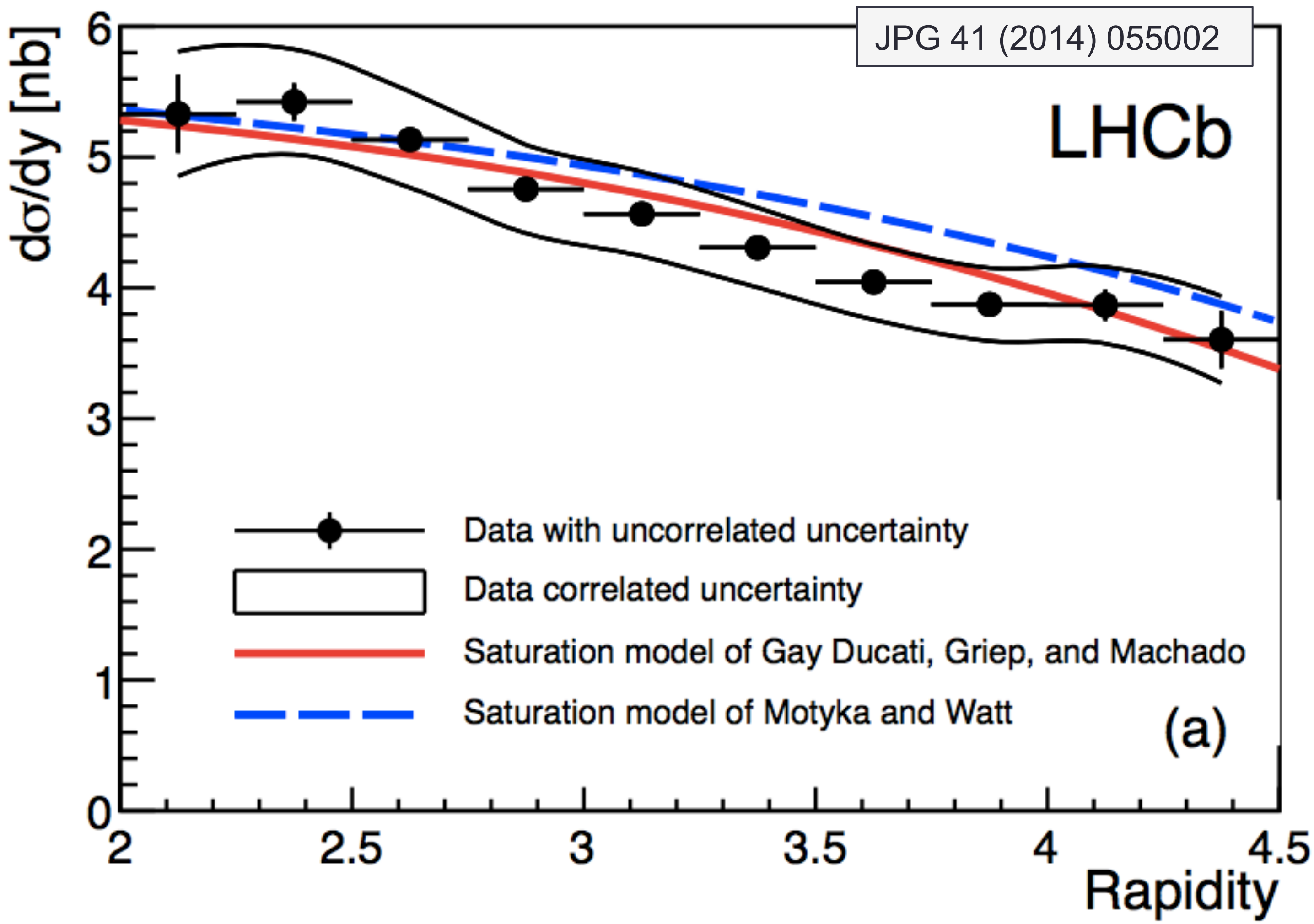


Motyka, Watt: PRD 78, 014023 (2008)



Gay Ducati, Griep, Machado, PRD88 01750 (2013)

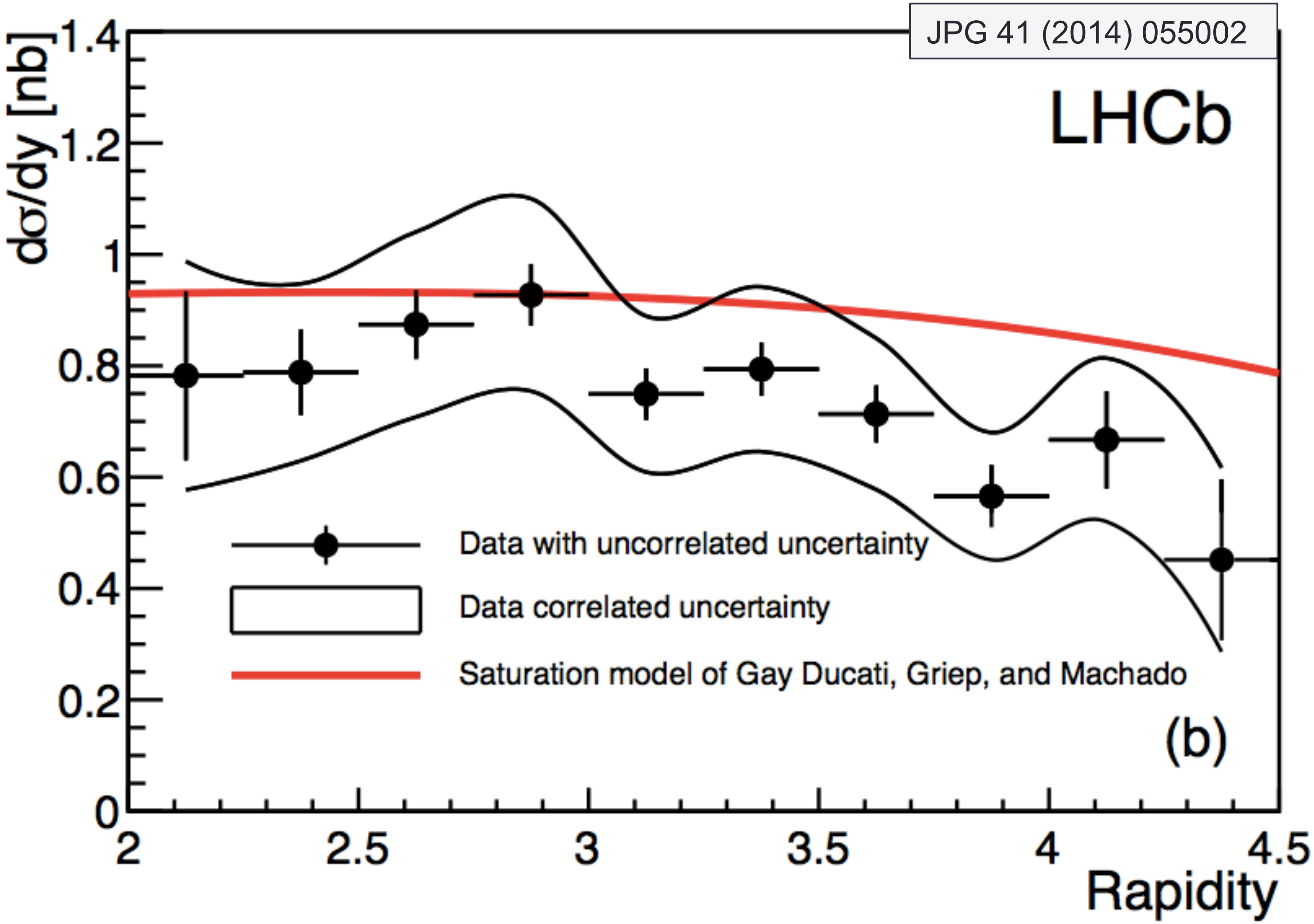
Sensitivity to saturation effects: J/ψ



L. Motyka and G. Watt, *Exclusive photoproduction at the Fermilab Tevatron and CERN LHC within the dipole picture*, Phys. Rev. **D78** (2008) 014023, arXiv:0805.2113.

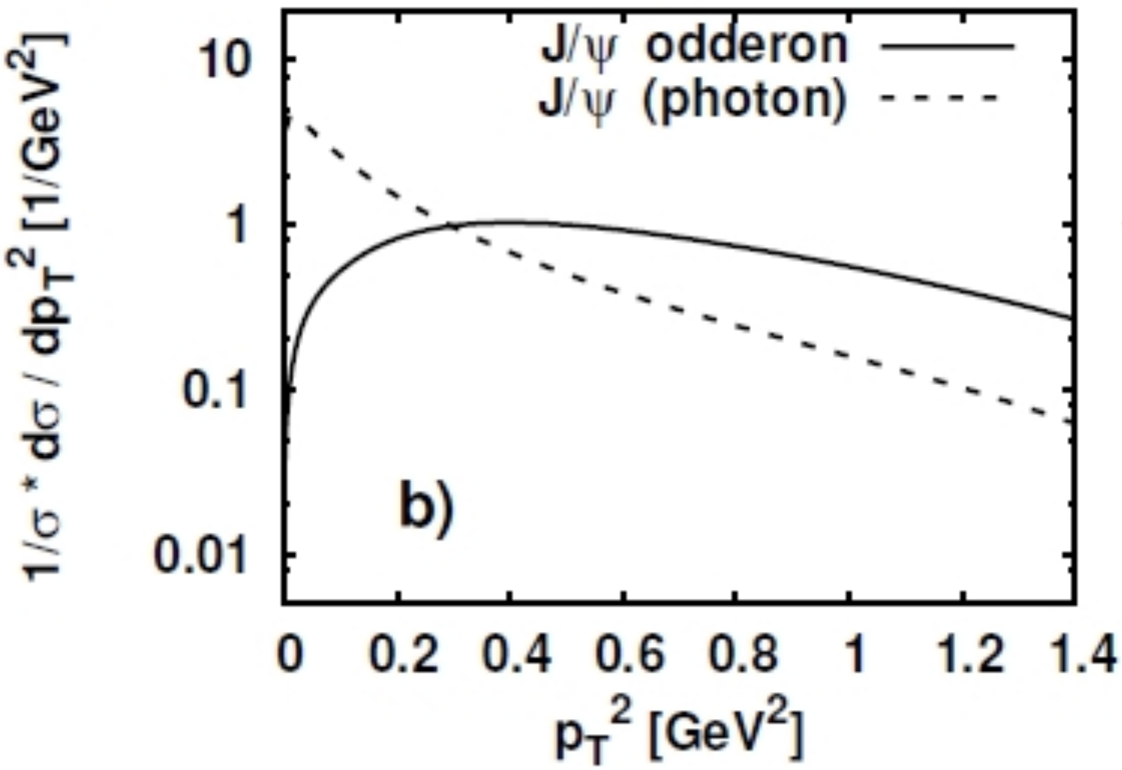
M. B. Gay Ducati, M. T. Griep, and M. V. T. Machado, *Exclusive photoproduction of J/ψ and ψ(2S) states in proton-proton collisions at the CERN LHC*, arXiv:1305.4611.

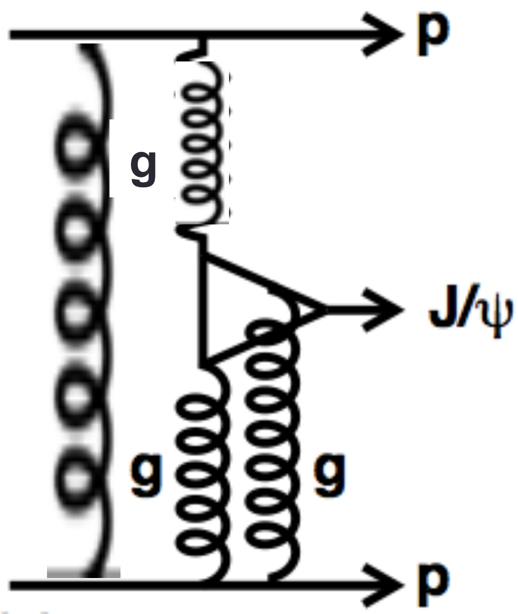
Sensitivity to saturation effects: ψ(2S)



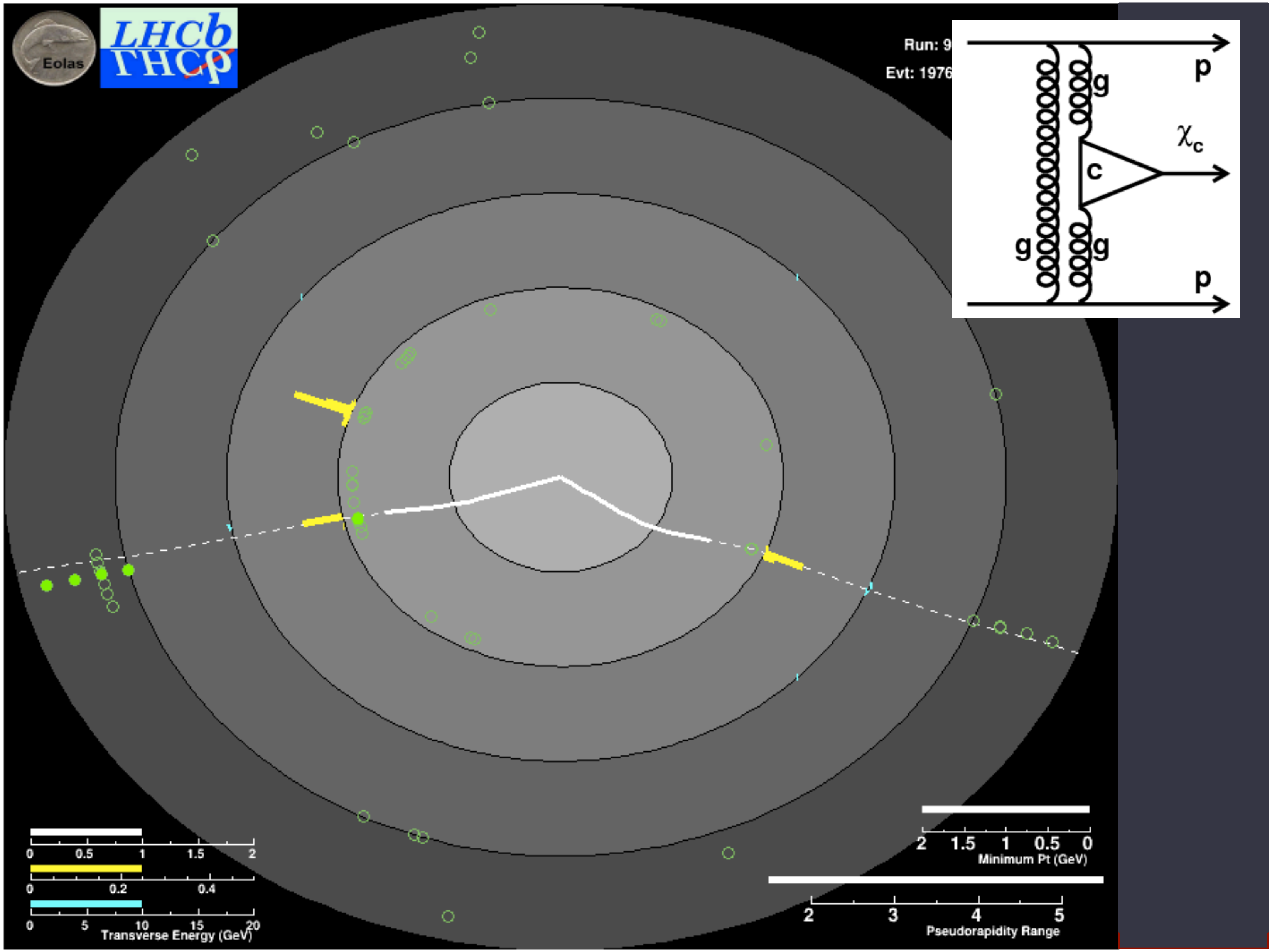
Search for odderon

- Motyka, DIS 2008.

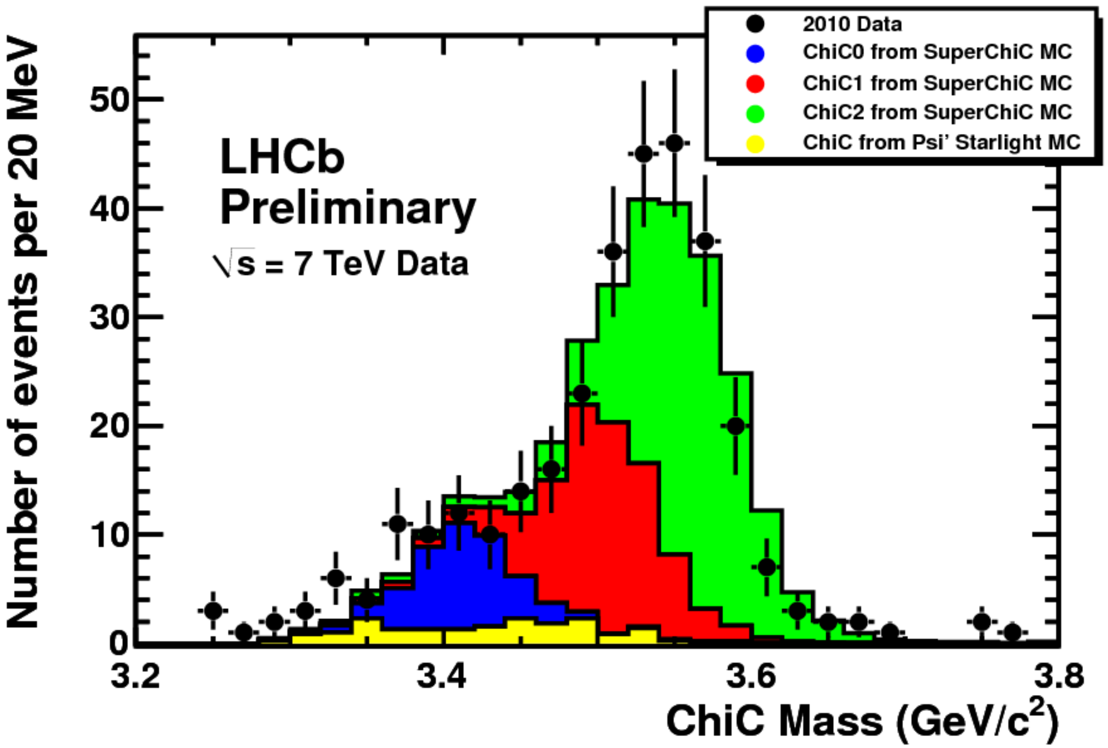




Candidate for χ_c decay to J/ψ+γ



Candidate for χ_c decay to J/ψ+γ



Photon resolution not quite good enough to completely resolve the three states.

About 40% of sample is CEP: other production mechanisms giving empty events.

Theory v experiment

$\sigma_{\chi_{c0} \to \mu^+\mu^-\gamma}$ = 9.3 +/- 2.2 +/- 3.5 +/- 1.8 pb
$\sigma_{\chi_{c1} \to \mu^+\mu^-\gamma}$ = 16.4 +/- 5.3 +/- 5.8 +/- 3.2 pb
$\sigma_{\chi_{c2} \to \mu^+\mu^-\gamma}$ = 28.0 +/- 5.4 +/- 9.7 +/- 5.4 pb

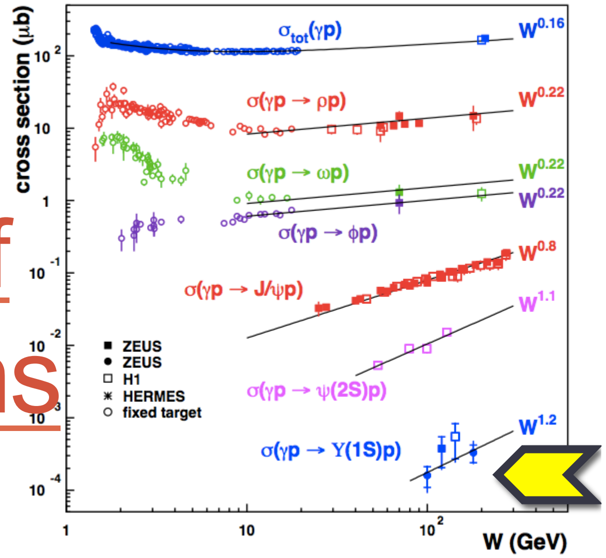
LHCb preliminary results with 2010 data

	χ_0	χ_1	χ_2
	9.3 +- 4.5 pb	16.4 +- 7.1 pb	28.0 +-12.3 pb
SuperChic:	14 pb	10 pb	3 pb

Large contribution due to X_{c0} is confirmed.

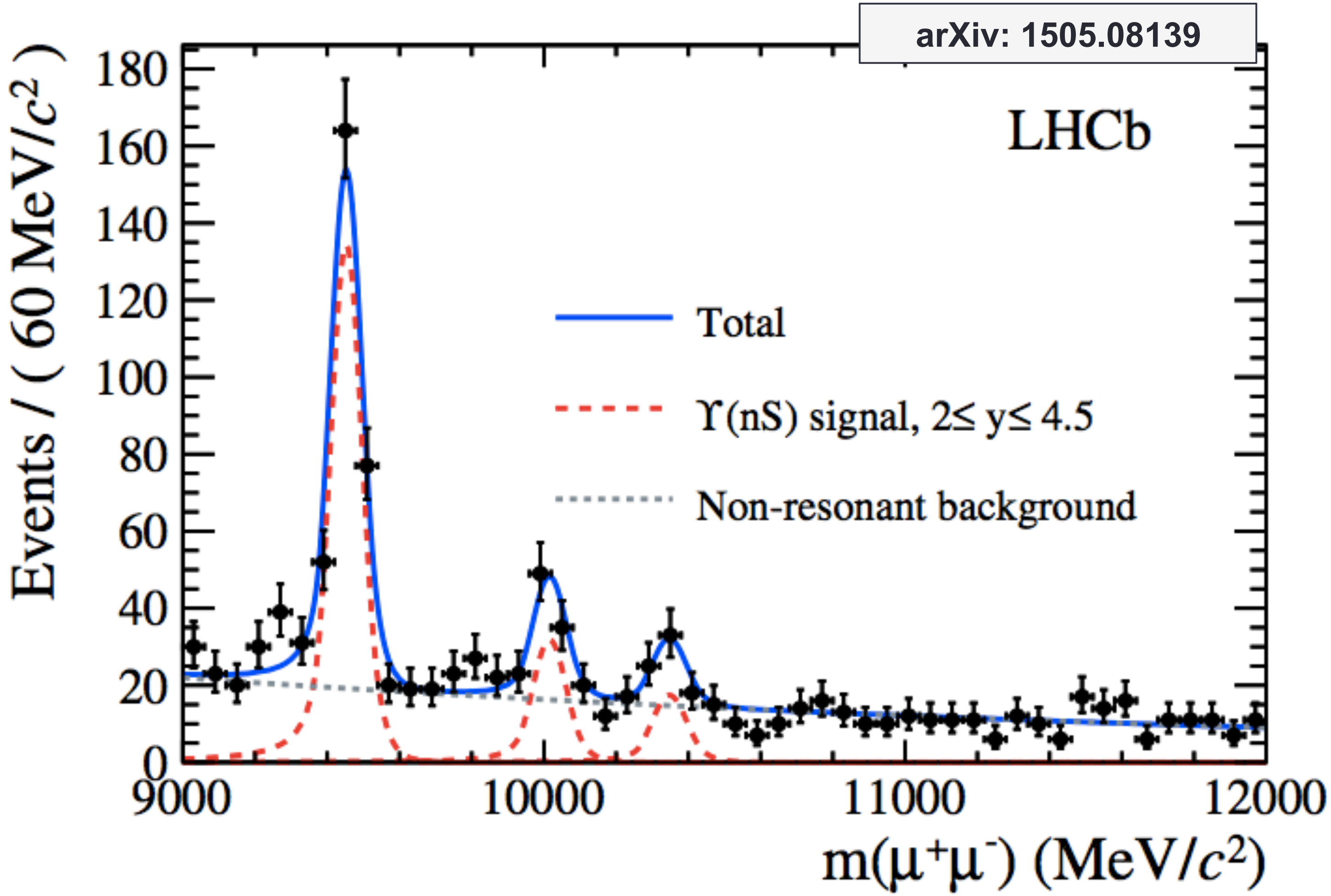
χ_{c2} larger than expected but note that non-elastic background has been assumed same for each resonance. More precise data required.

Central Exclusive Production of Υ(1S), Υ(2S), Υ(3S) mesons



Data-taking year	Energy	Integrated Luminosity	Paper
2011	7 TeV	945 pb^{-1}	arXiv: 1505.08139
2012	8 TeV	1985 pb^{-1}	

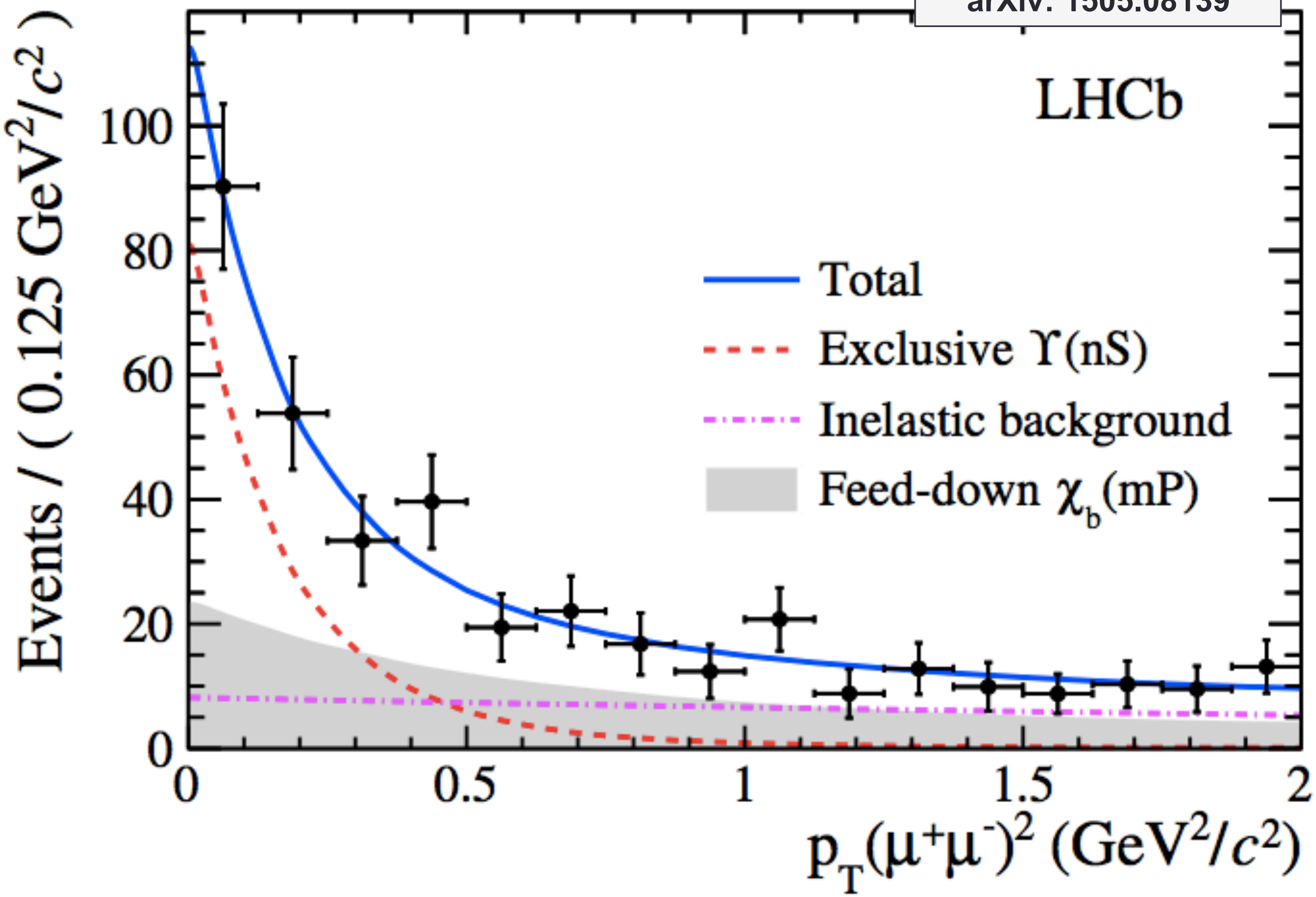
Non-resonant background relatively larger



Distributions not background-subtracted. 270 ϒ(1S), 70 ϒ(2S), 40 ϒ(3s)

Fit to (background subtracted) p_T^2

arXiv: 1505.08139



Cross-sections and systematics

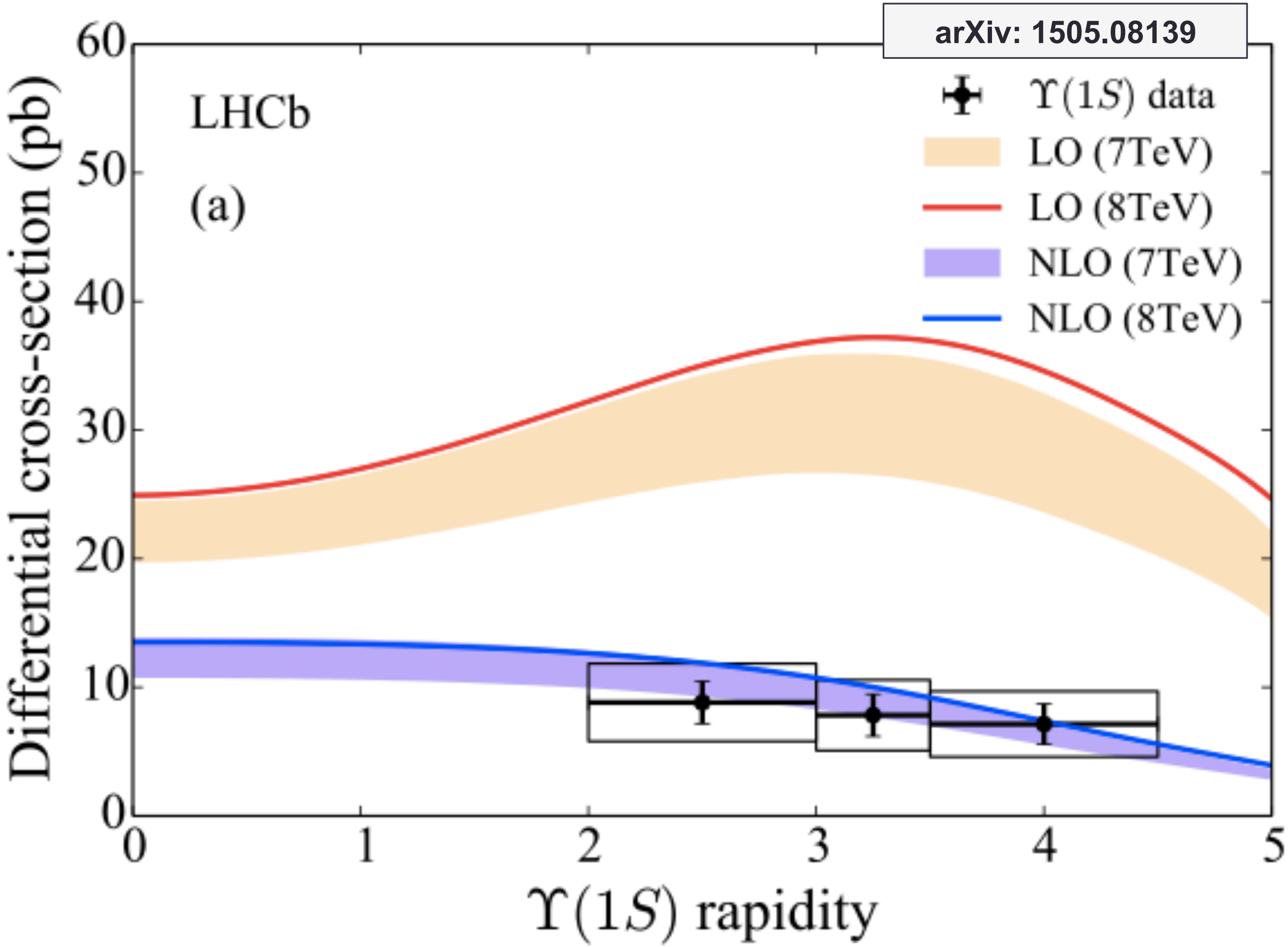
Cross-section*BR for both muons in pseudorapidity range 2<η<4.5:

$$\sigma(pp \to p\Upsilon(1S)p) = 9.0 \pm 2.1 \pm 1.7 \text{ pb},$$
$$\sigma(pp \to p\Upsilon(2S)p) = 1.3 \pm 0.8 \pm 0.3 \text{ pb}, \text{ and}$$
$$\sigma(pp \to p\Upsilon(3S)p) < 3.4 \text{ pb at the 95\% confidence level},$$

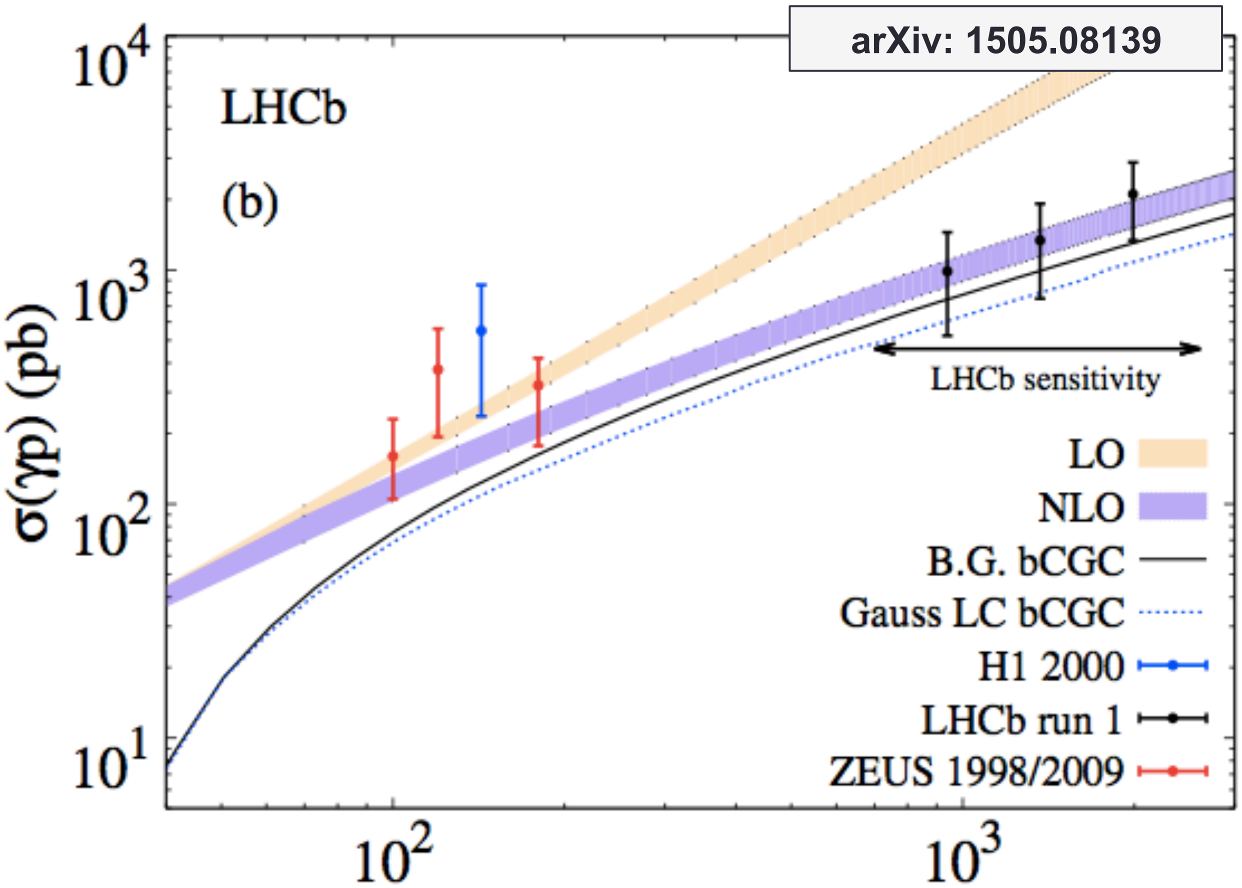
	$2 \le y < 3$	$3 \le y < 3.5$	$3.5 \le y \le 4.5$
$\sigma(\Upsilon(1S))$ (pb)	$3.4 \pm 0.9 \pm 0.7$	$2.9 \pm 0.8 \pm 0.6$	$2.6 \pm 0.8 \pm 0.5$

	$2 \le y < 3$	$3 \le y < 3.5$	$3.5 \le y \le 4.5$	$2 \le y \le 4.5$		
	$\Upsilon(1S)$	$\Upsilon(1S)$	$\Upsilon(1S)$	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Purity fit	14.2	14.2	14.2	13.7	13.7	13.7
Feed-down b.g.	12.2	12.2	12.3	12.2	14.6	12.5
Υ' feed-down	4.0	4.3	5.4	4.5	11.1	–
Mass fit	2.2	2.8	2.9	2.1	2.8	3.6
Int. lumi.	2.3	2.3	2.3	2.3	2.3	2.3
$\mathcal{B}(\Upsilon \to \mu^+\mu^-)$	2.0	2.0	2.0	2.0	8.8	9.6
Total	19.5	19.7	20.0	19.3	24.8	21.4

Cross-section compared to LO and NLO



Derived photo-production cross-section



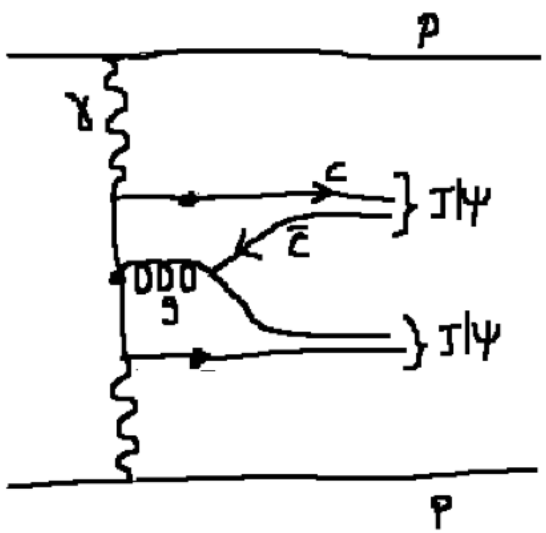
$$\frac{d\sigma}{dy}_{pp\to p\Upsilon p} = r_+ k_+ \frac{dn}{dk_+}\sigma_{\gamma p\to\Upsilon p}(W_+) + r_- k_- \frac{dn}{dk_-}\sigma_{\gamma p\to J/\psi p}(W_-)$$

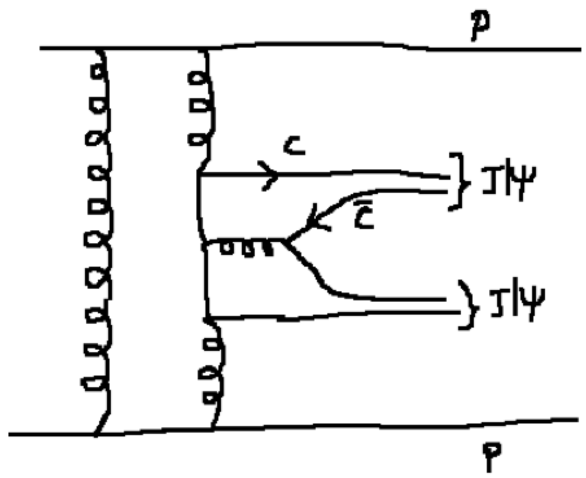
ignored

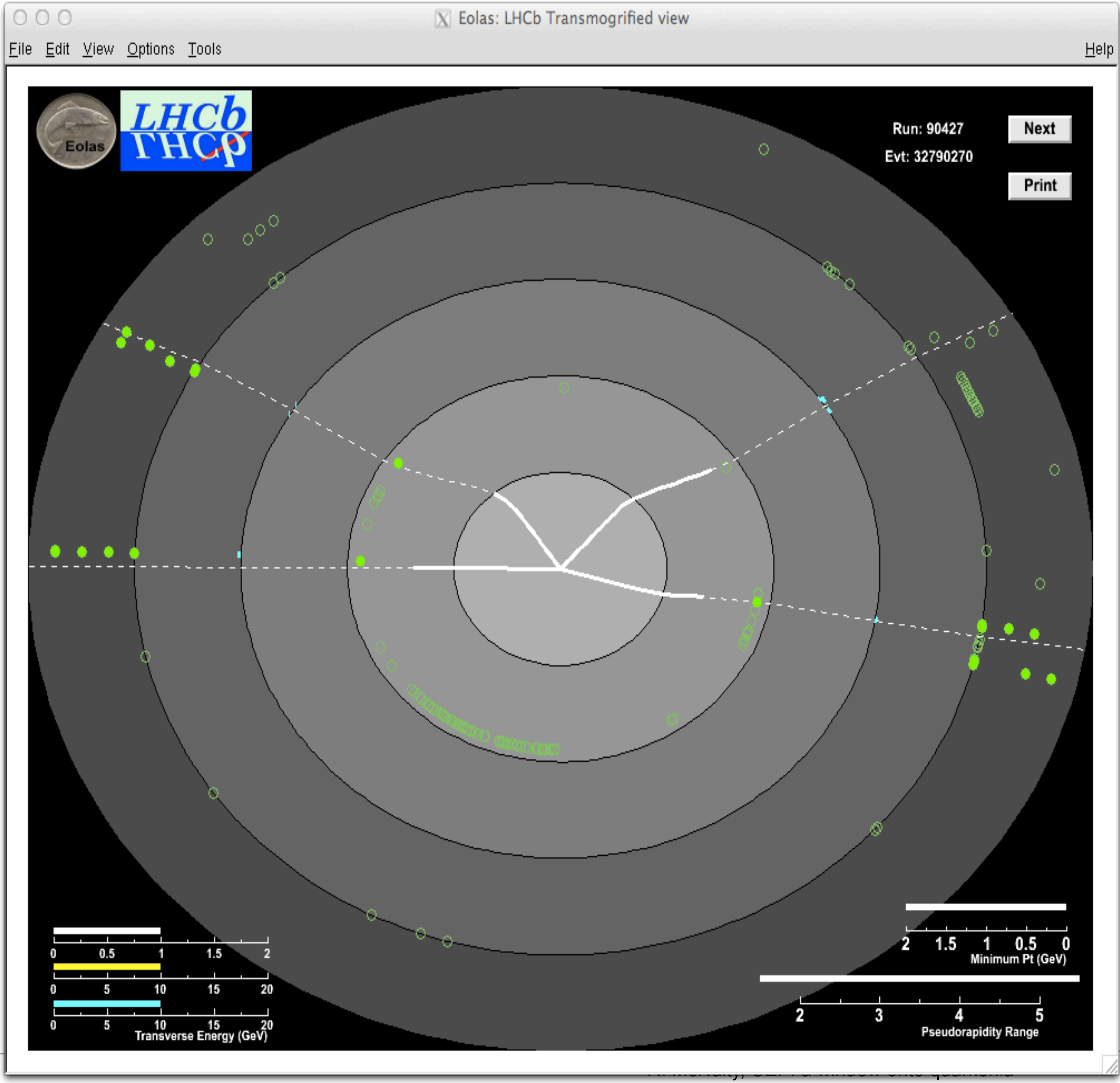
Double Charmonia

An example of the unexpected, visible when you have very clean signals....

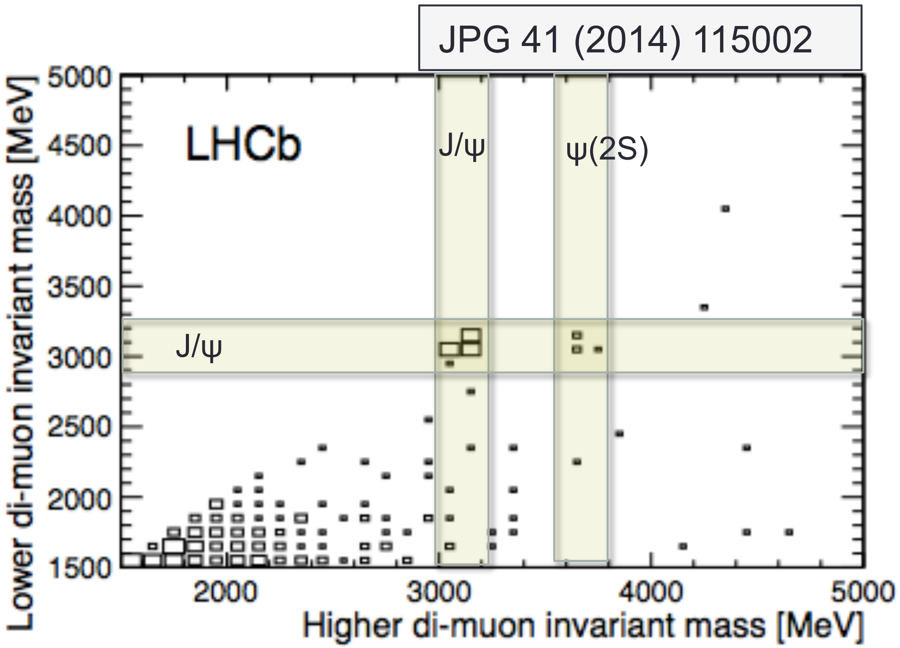
Data-taking year	Energy	Integrated Luminosity	Paper
2011	7 TeV	945 pb^{-1}	JPG 40 (2013) 045001
2012	8 TeV	1985 pb^{-1}	

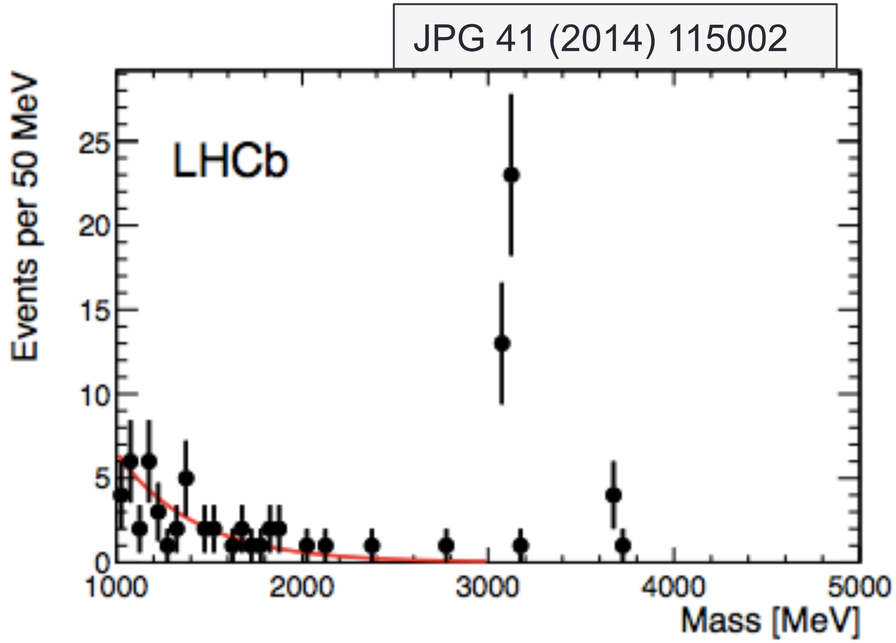





Eolas: LHCb Transmogrified view
File Edit View Options Tools
Help
Eolas
LHCb
Run: 90427
Evt: 32790270
Next
Print
0 0.5 1 1.5 2
0 5 10 15 20
0 5 10 15 20
Transverse Energy (GeV)
2 1.5 1 0.5 0
Minimum Pt (GeV)
2 3 4 5
Pseudorapidity Range

Select 4-muon exclusive events

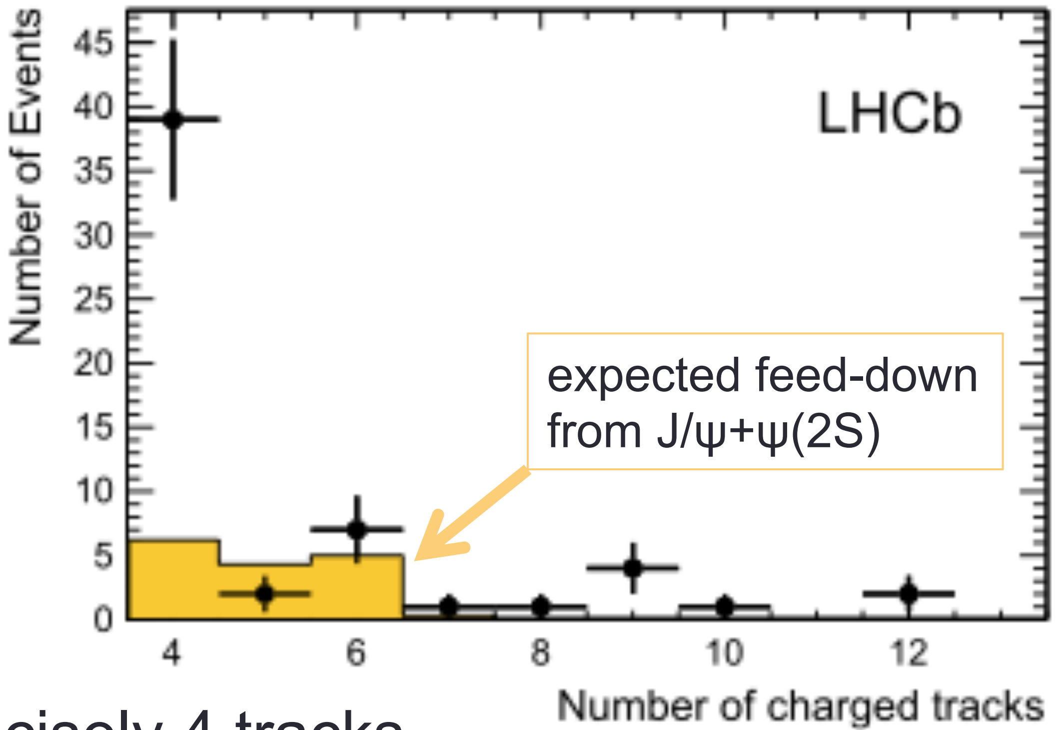




Dimuon spectrum having required other two muons have J/ψ mass

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

Allow >4 tracks



Excess of events with precisely 4 tracks.
Background from inclusive production of J/ψJ/ψ small

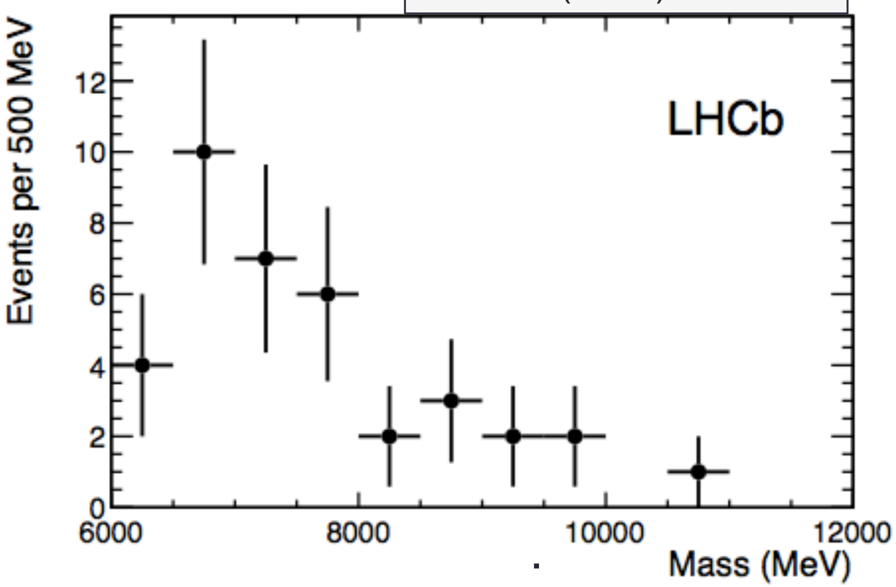
Search for extra photons due to χ_c ->J/ψγ

One candidate for χ_{c0}, which is also consistent with ψ(2s)
No candidates for χ_{c1} χ_{c2}

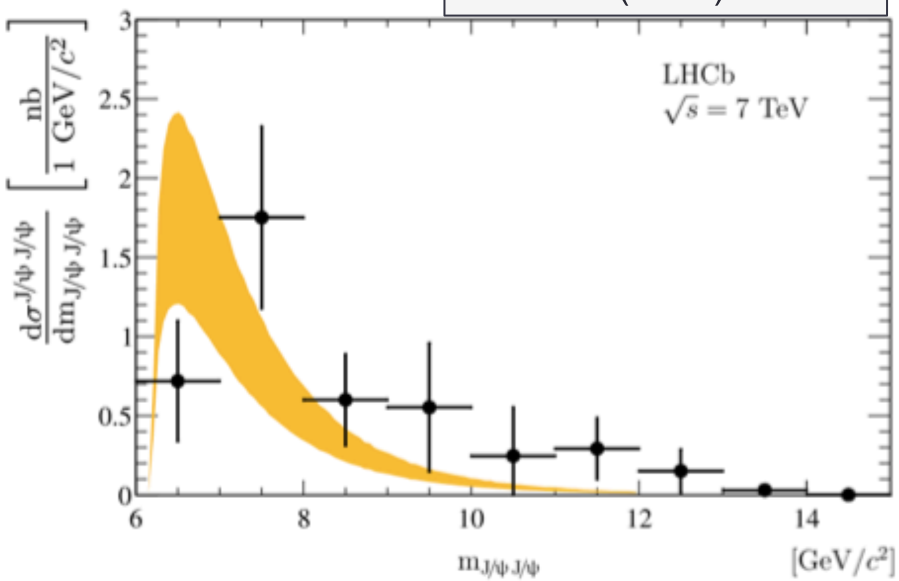
Cross-section results

$$\sigma^{J/\psi\,J/\psi} = 58 \pm 10(\text{stat}) \pm 6(\text{syst})\,\text{pb},$$
$$\sigma^{J/\psi\,\psi(2S)} = 63^{+27}_{-18}(\text{stat}) \pm 10(\text{syst})\,\text{pb},$$
$$\sigma^{\psi(2S)\psi(2S)} < 237\,\text{pb},$$
$$\sigma^{\chi_{c0}\chi_{c0}} < 69\,\text{nb},$$
$$\sigma^{\chi_{c1}\chi_{c1}} < 45\,\text{pb},$$
$$\sigma^{\chi_{c2}\chi_{c2}} < 141\,\text{pb},$$

Exclusive JPG 41 (2014) 115002

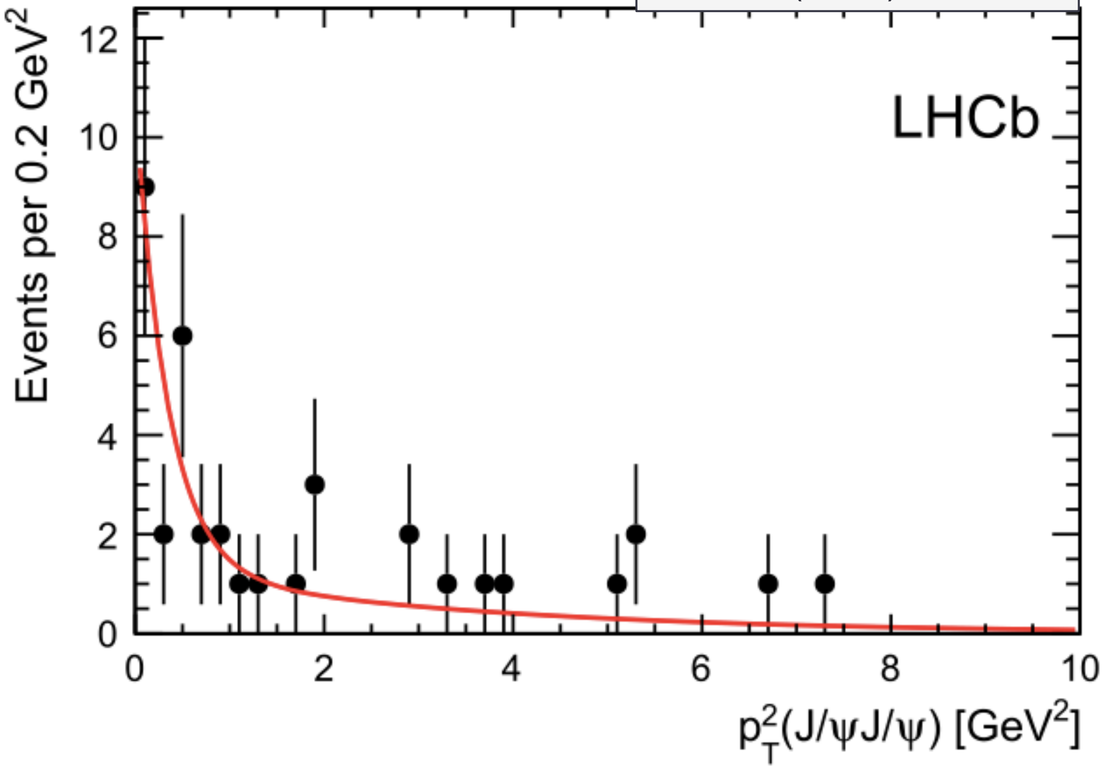


Inclusive PLB 707 (2012) 52.



How much is exclusive?

JPG 41 (2014) 115002



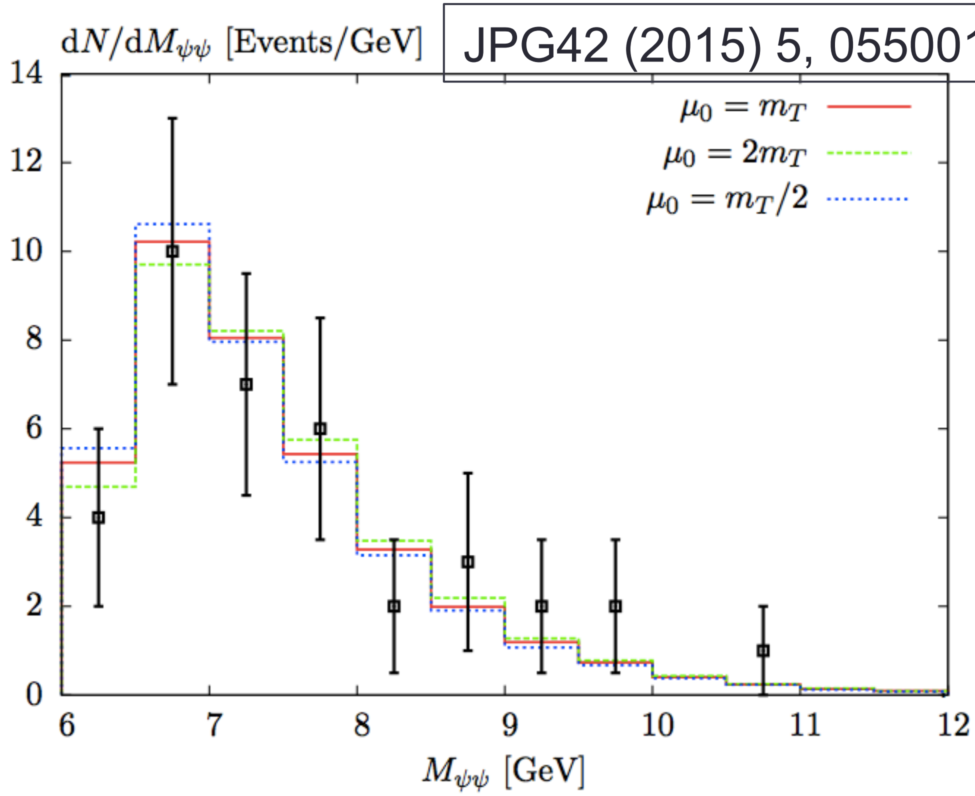
42+-13% but model dependence in describing inelastic contribution

Comparison to theory

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

Harland-Lang, Khoze, Ryskin: (arXiv: 1409.4785) **2-7 pb**

JPG42 (2015) 5, 055001

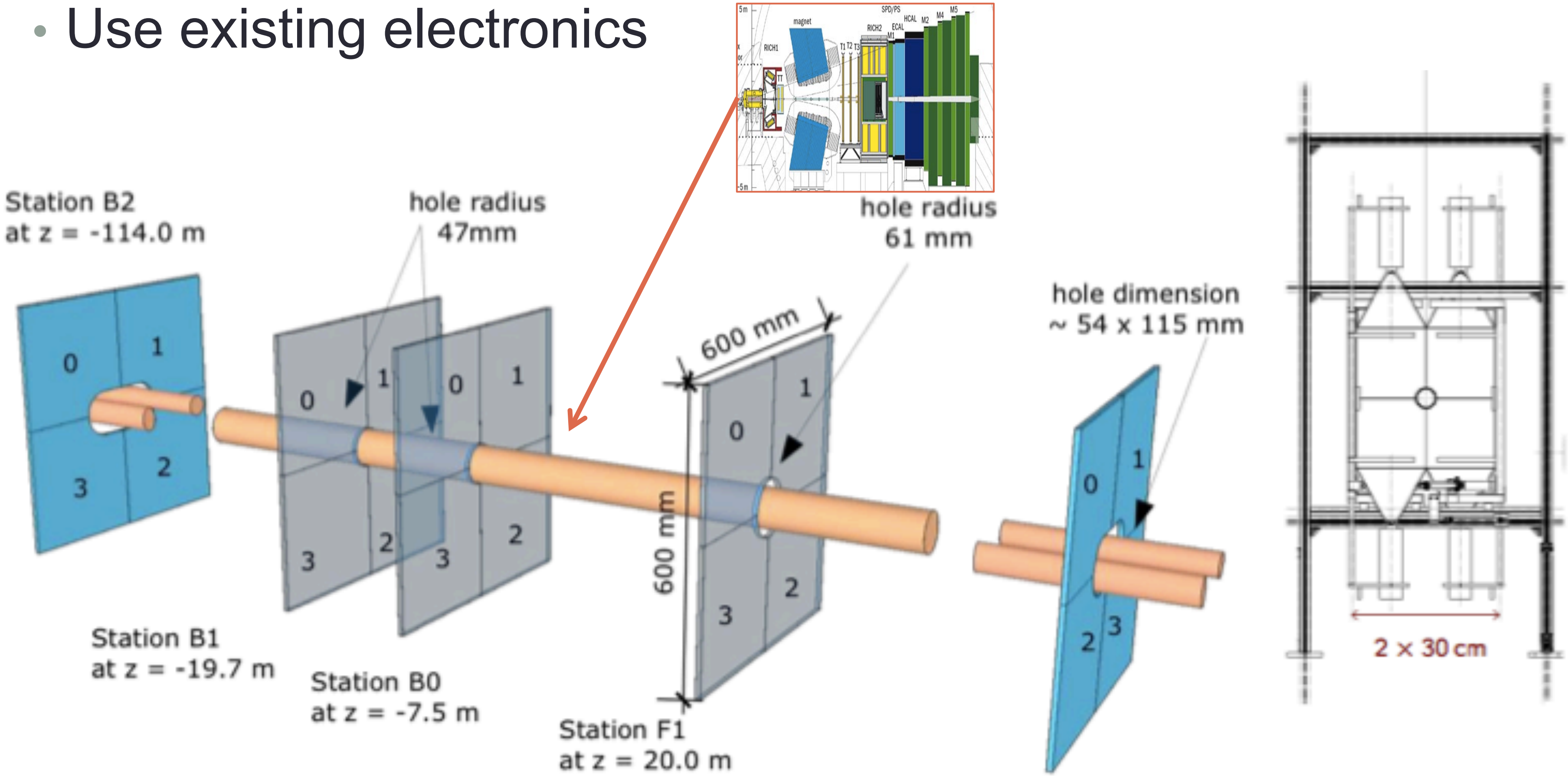


Shape agrees well (theory normalised to data).

Future Prospects

High rapidity shower counters for LHCb

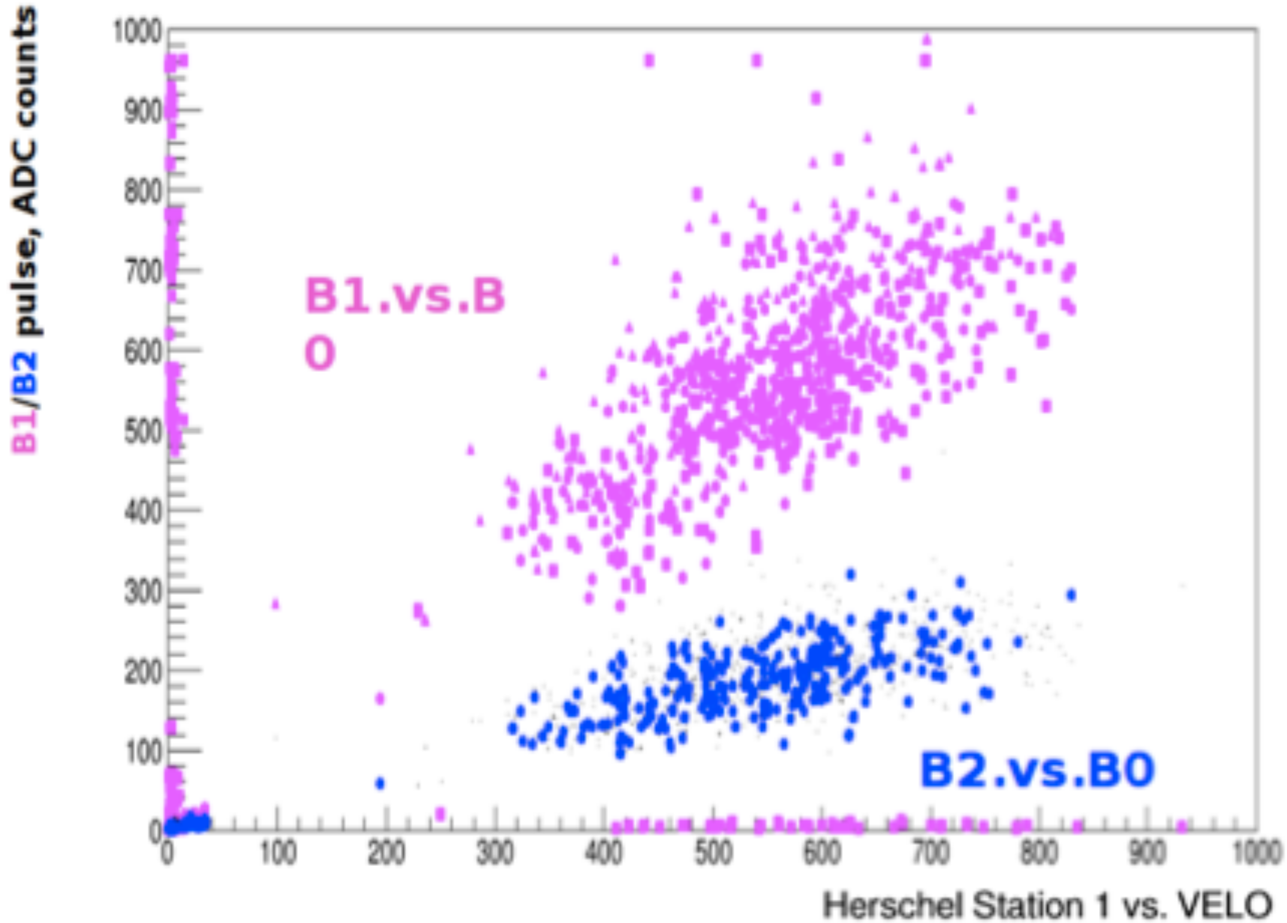
- Increase rapidity gap with scintillators in forward region
- Use existing electronics



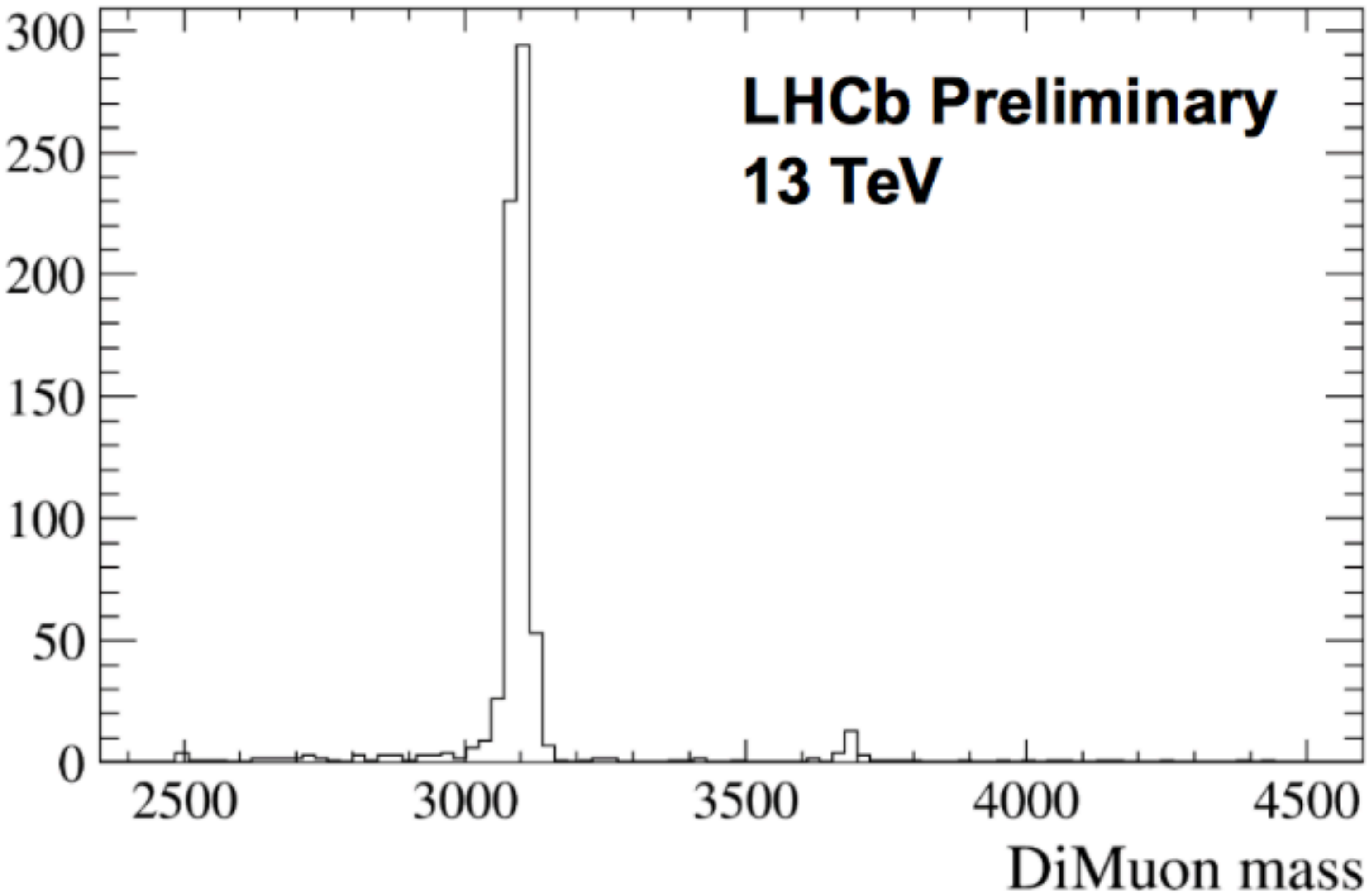
First simulations suggest veto region for charged and neutral particles can be extended to include $5<|\eta|<8$ - an extra 6 units in pseudorapidity.

Scintillators and PMTs

Signals from TED running

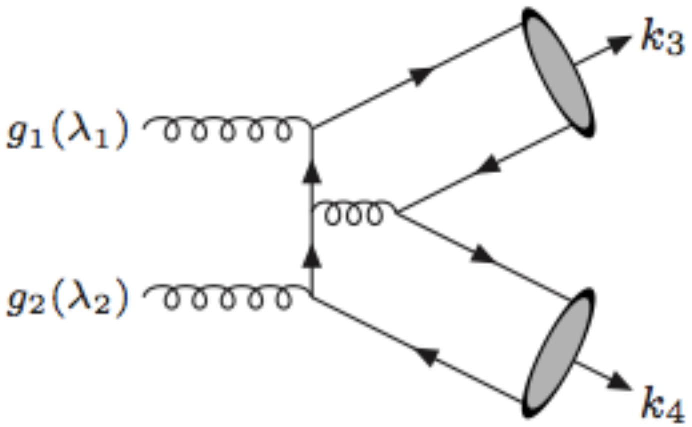


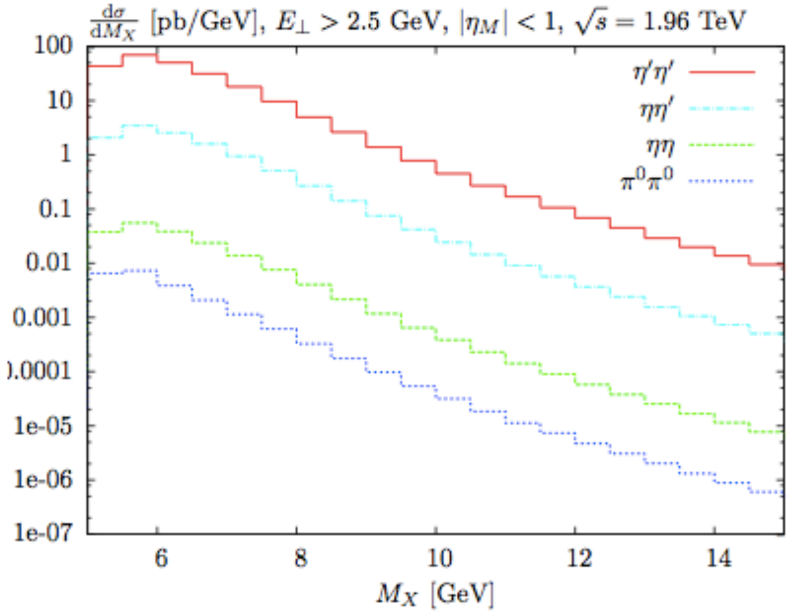
First collisions at 13 TeV !



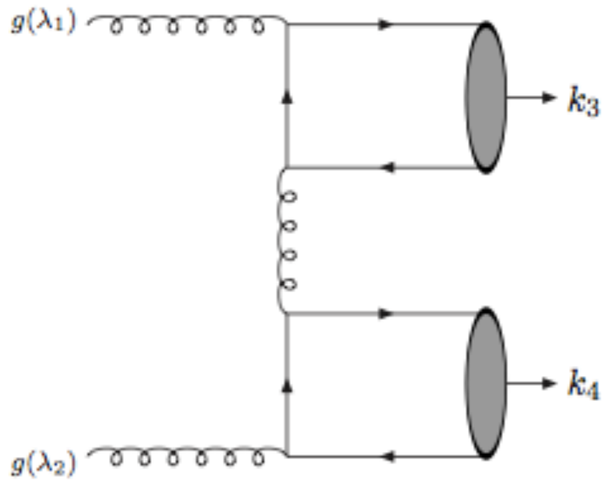
(Harland-Lang, Khoze, Ryskin, Stirling)

CEP meson-meson production arXiv:1105.1626

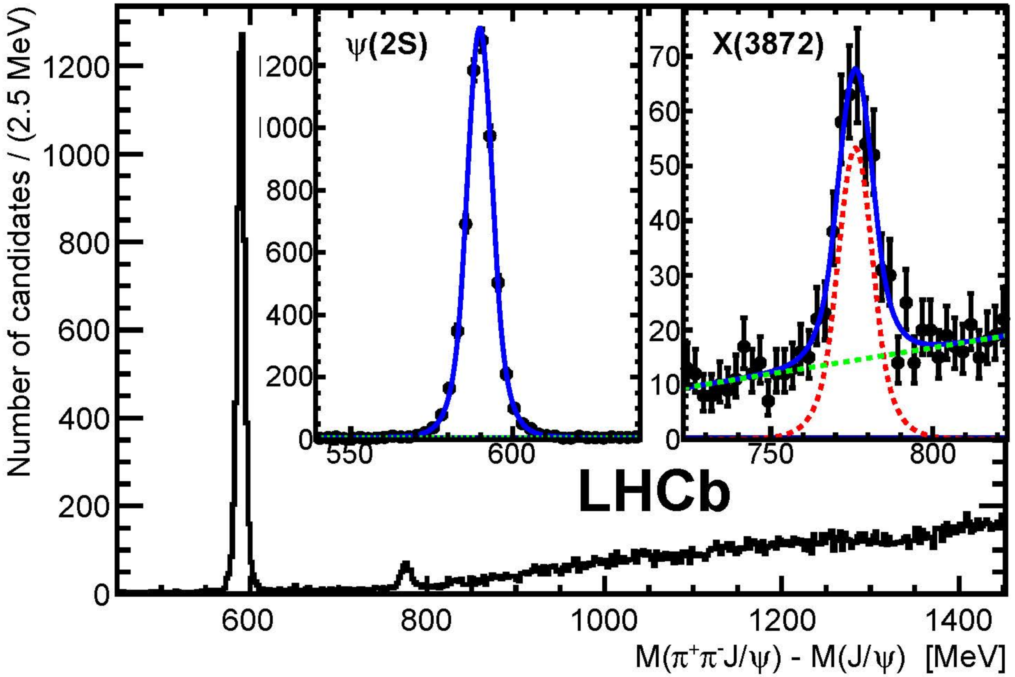




- Vanishing cs when gluons in J_z=0
- Flavour non-singlet mesons suppressed (thus ππ/KK small)
- Flavour singlet (e.g. η'η' production) can proceed via
- Like to look for $\eta_c\eta_c$, D^+D^-, D_sD_s etc



X(3872)

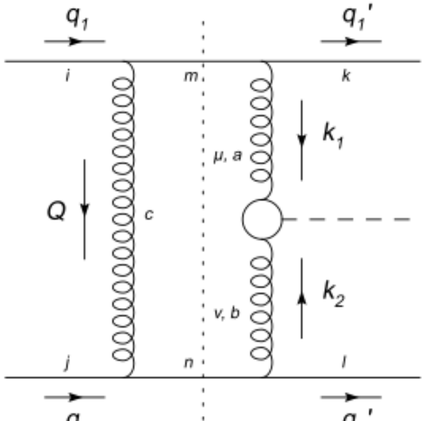


X(3872) observed inclusively. (arXiv:1112.5310) Could it be produced exclusively?

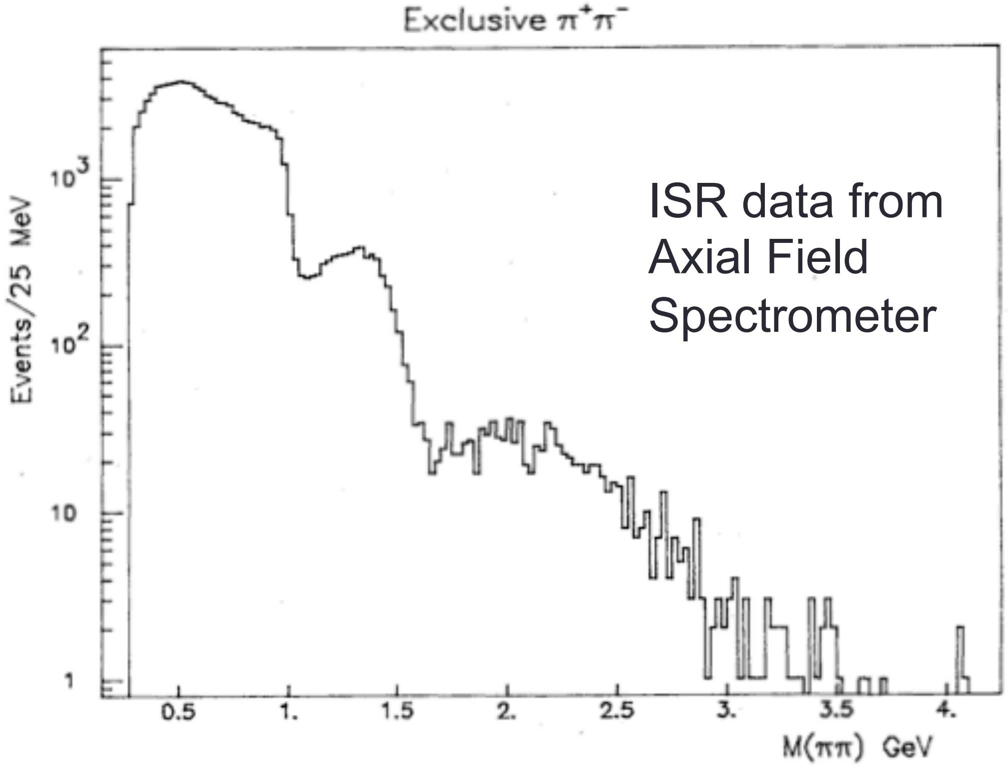
- J^{PC} of X(3872) shown by LHCb to be 1++ (arXiv:1302.6269)
- $\chi_{c(1++)}$ has been observed `exclusively' ?
- If X(3872) is a bound cc state, might expect to observe it in central exclusive production, possibly ruling out some molecular production mechanisms (e.g. 1305.0527)

Low mass spectroscopy + glueballs

- Data from ISR/Tevatron
- Accessible at LHCb
- DPE, probing the nature of the vacuum



- **Glue laboratory**

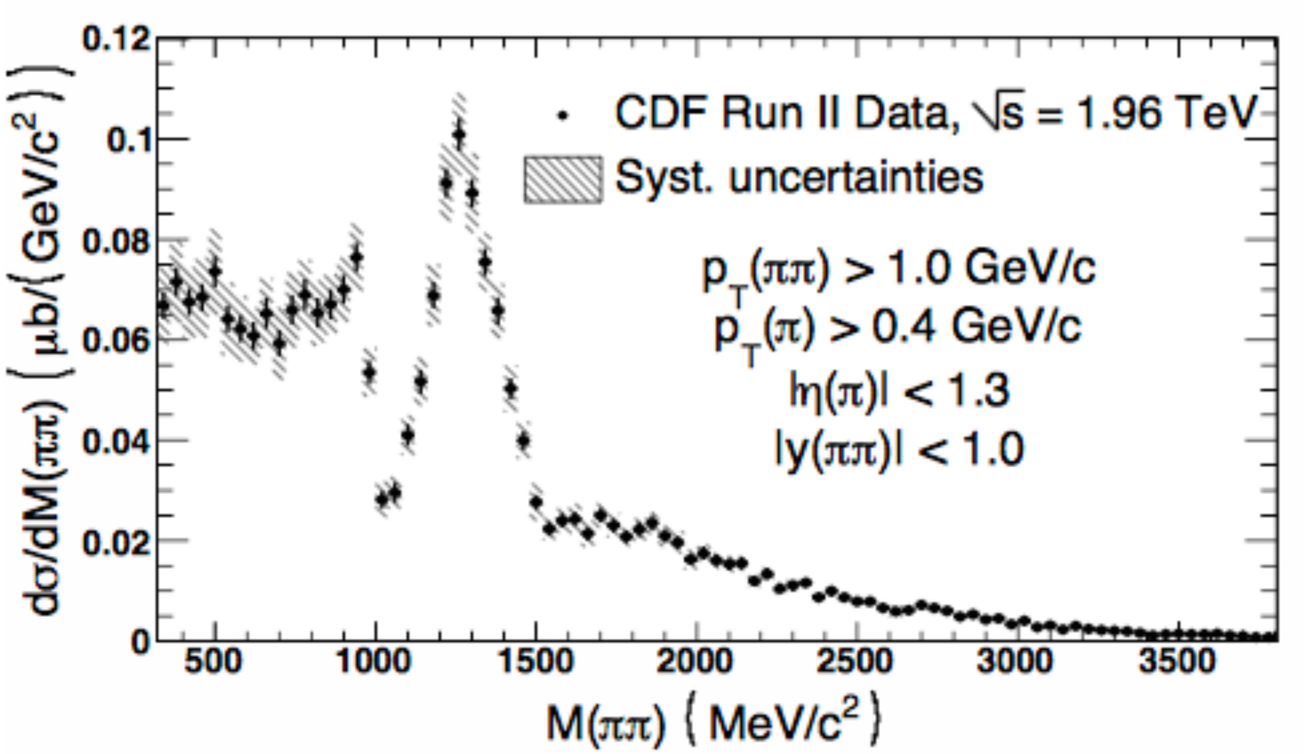


ISR data from Axial Field Spectrometer

M.G. Albrow, T.D. Coughlin, and J.R. Forshaw, Prog. Part. Nucl. Phys. **65**, 149 (2010). arXiv: 1006.1289

[101] T. Akesson, et al., A search for glueballs and a study of double pomeron exchange at the CERN Intersecting Storage Rings, Nucl. Phys. B264 (1986) 154.

Low mass spectroscopy + glueballs



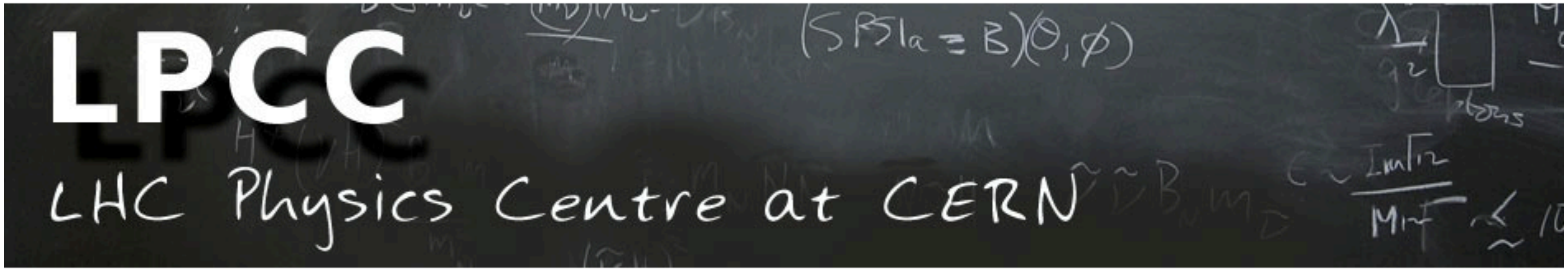
Recent CDF analysis.
PRD91 (2015) 9, 091101

- **Glue laboratory**

M.G. Albrow, T.D. Coughlin, and J.R. Forshaw, Prog. Part. Nucl. Phys. **65**, 149 (2010). arXiv: 1006.1289

[101] T. Akesson, et al., A search for glueballs and a study of double pomeron exchange at the CERN Intersecting Storage Rings, Nucl. Phys. B264 (1986) 154.

LHC-wide programme of work



LPCC links

- WELCOME
  - About the LPCC
  - Visit the LPCC
  - Subscribe to LPCC News
- LHC WORKING GROUPS
  - MB & UE WG
  - Electroweak WG
  - Rate normalization WG
  - Top WG
  - Forward Physics WG
- EVENTS
  - Forthcoming events
  - Past events
- LHC PUBLICATIONS
- STUDENTS RESOURCES
- MISC

LHC WG on Forward Physics and diffraction

To subscribe to the WG mailing list, go to
http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-fwdlhcwg

The WG is a forum for:

- interaction between theorists and experimentalists from the LHC experiments about forward physics
- definition of a physics programme for diffraction either using the rapidity gap method or proton tagging
- definition of a common strategy between the different LHC experiments (special runs...)
- discussion of the different forward detectors (roman pots, movable beam pipes, timing and position detectors)
- application to cosmic ray physics

Dedicated subgroup meetings and more general meetings will take place every 5-6 weeks and are opened to everybody.
WG documents and meeting agendas: see links in the right menu

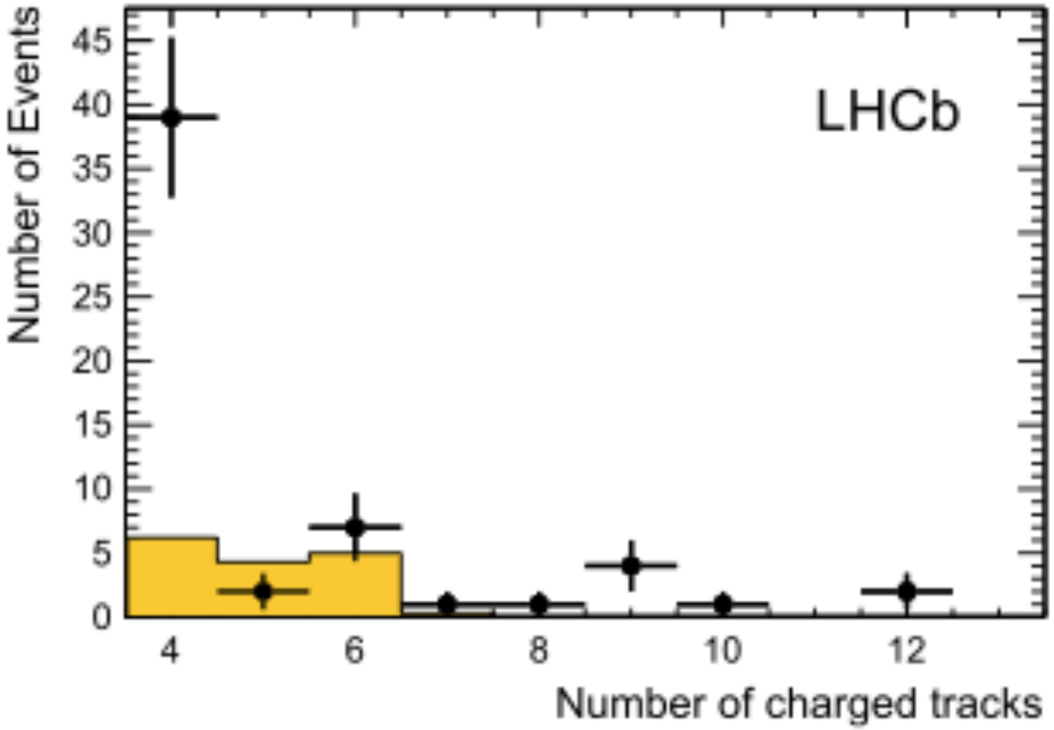
WG links

- WG Twiki page
- WG meetings
- WG documents

Questions and challenges

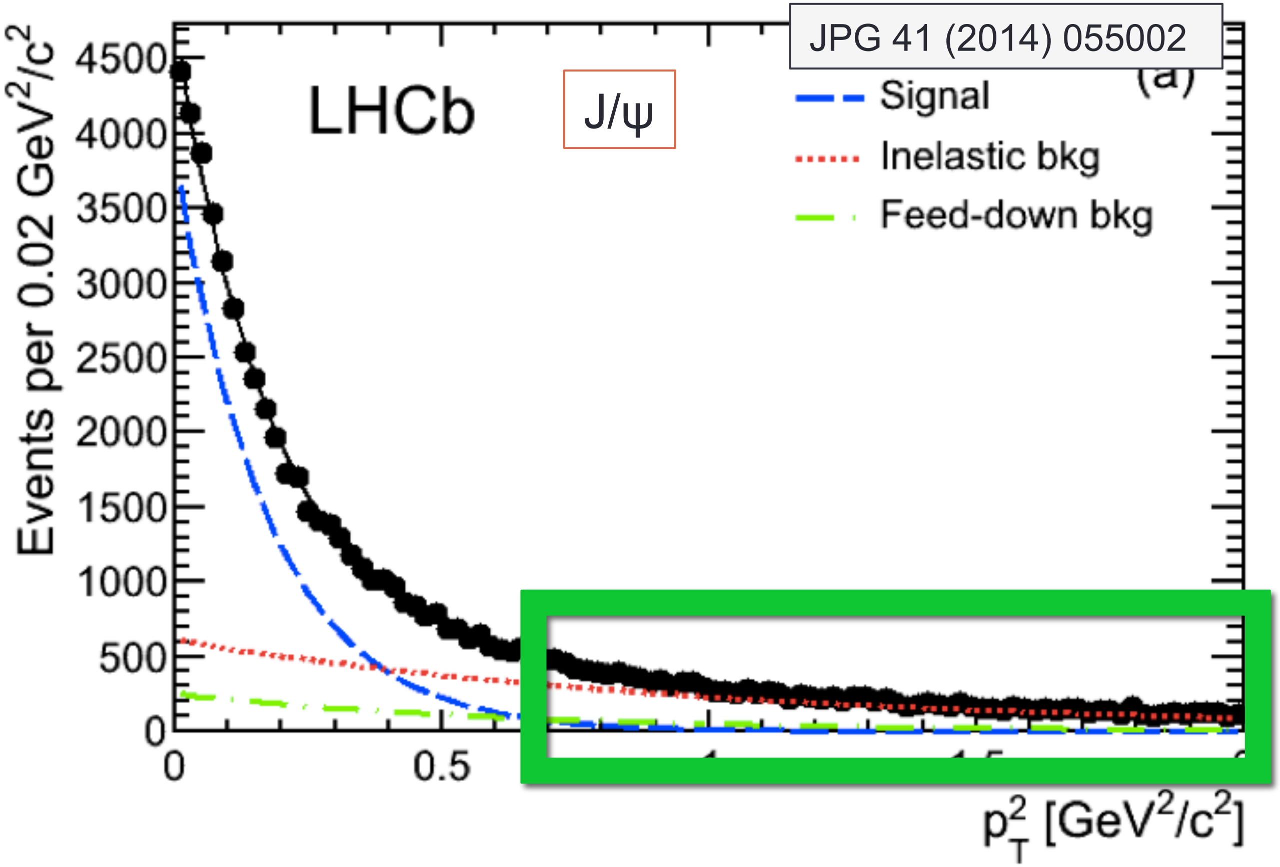
- Special class of low multiplicity events
- Hard scattering system produced with p_T< ~1 GeV
- Usual QCD backgrounds significantly reduced.
- Do we understand production processes: $\frac{d\sigma}{dt} \sim e^{bt}$
- What quantum numbers can be produced ?
- Excellent system for performing angular analysis.

Questions and challenges



Peak at precisely 4 tracks shows that production can not be explained in terms of underlying QCD event / hadronisation (which surely increases exponentially)

Questions and challenges



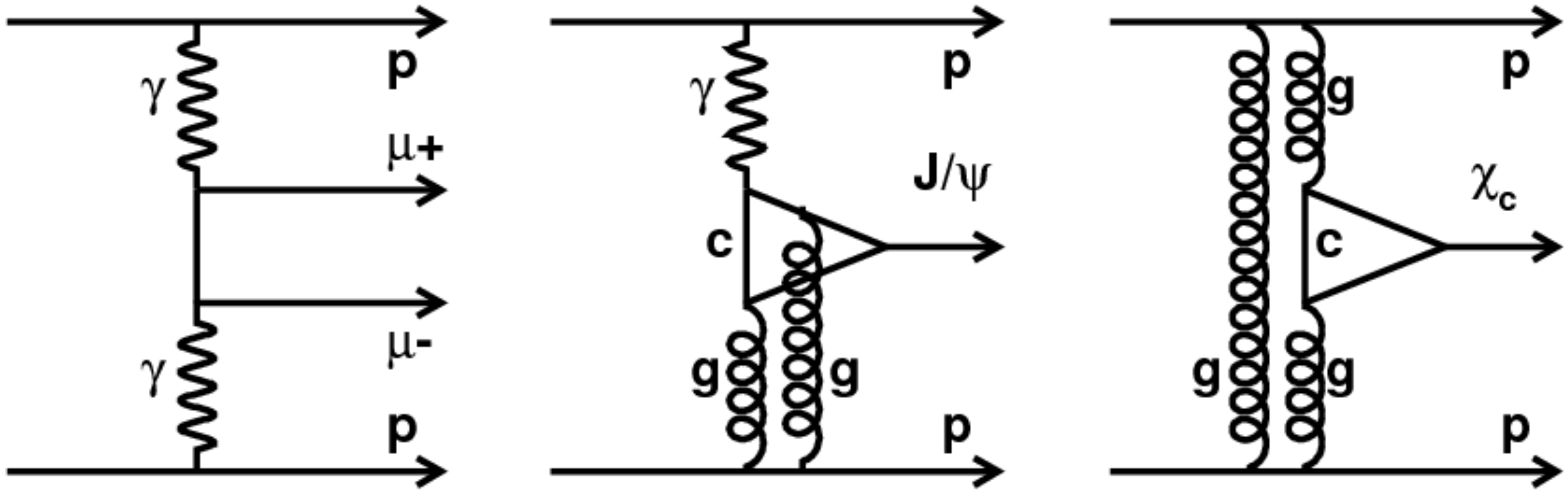
Signal fraction for J/ψ (photoproduction) ~70%

Signal from for χc and J/ψJ/ψ ~40%.

These events are NOT CEP, but still have large rapidity gap and are NOT consistent with underlying event / hadronisation.

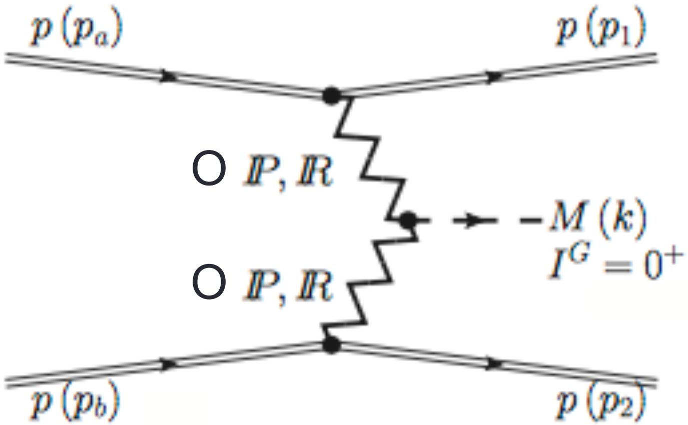
=> Other colourless propagators involved?

Questions and challenges



$J^{PC}=0^{++},1^{++},2^{++}$ $J^{PC}= 1^{--}$ $J^{PC}=0^{++},1^{++},2^{++}$

Questions and challenges



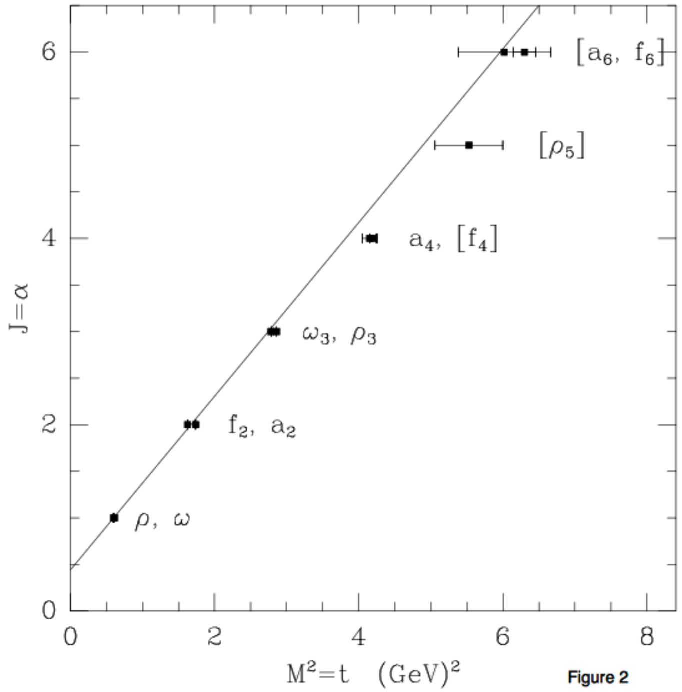
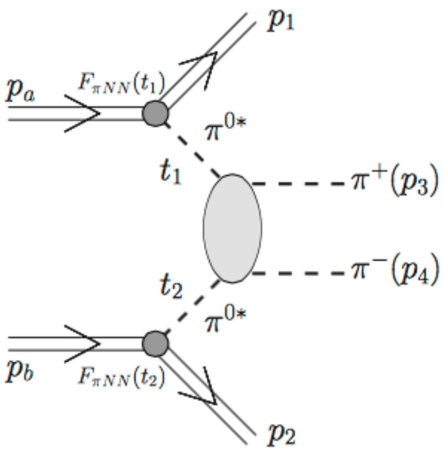


Figure 2



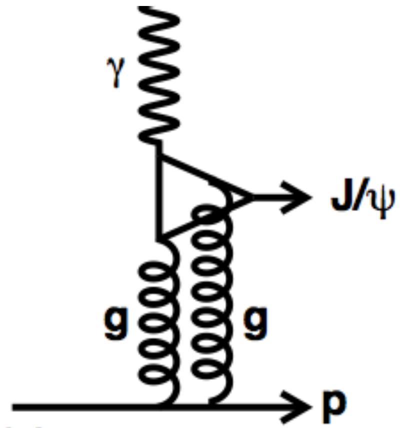
Many JPC states may be produced without backgrounds in CEP.

Summary

- Several measurements performed by LHCb
  - J/ψ and ψ(2S)
  - ϒ(1S) ϒ(2S) ϒ(3S)
  - μμ and χc (preliminary results)
  - J/ψJ/ψ, J/ψψ(2S), χcχc
- Experimentally clean production
- Potentially useful for isolating and studying exotic phenomena.

Backups

Photo-production cross-section

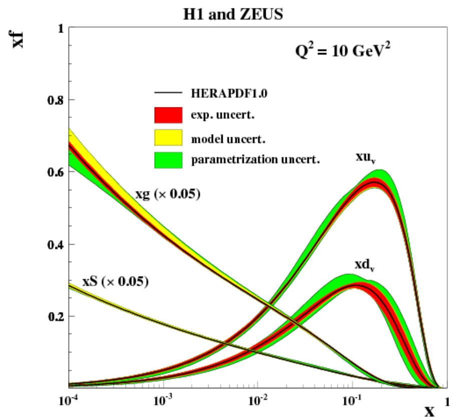


$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi\ p)\Big|_{t=0} = \frac{\Gamma_{ee} M^3_{J/\psi}\pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x,\bar{Q}^2)\right]^2 \left(1+\frac{Q^2}{M^2_{J/\psi}}\right)$$

$$\bar{Q}^2 = (Q^2 + M^2_{J/\psi})/4, \qquad x = (Q^2 + M^2_{J/\psi})/(W^2 + M^2_{J/\psi}).$$

Cross-section proportional to gluon² $\sigma \sim (xg)^2$

and so $\sigma \sim x^\lambda$



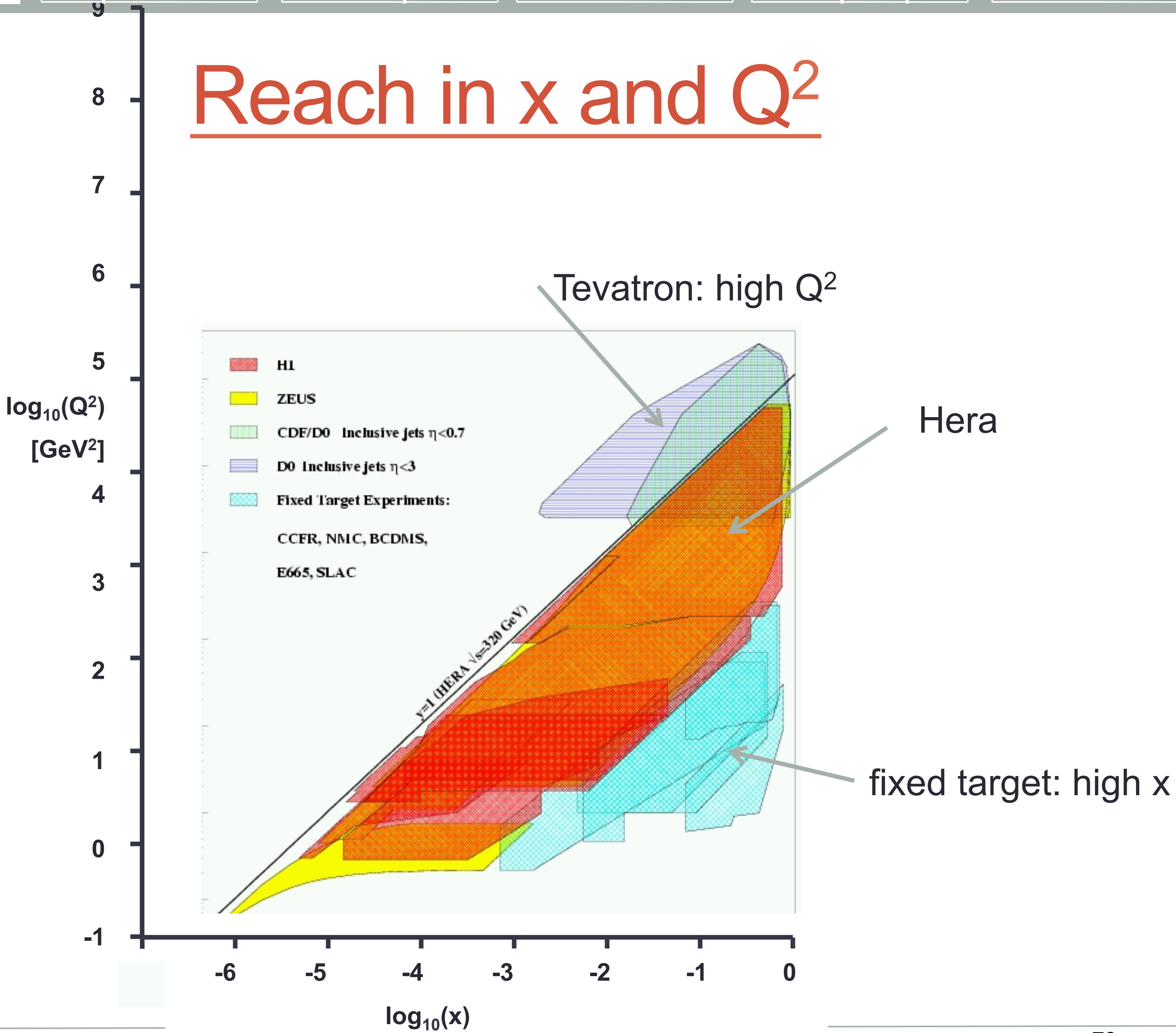
[1] Martin A D, Nockles C, Ryskin M and Teubner T 2008 Small x gluon from exclusive J/ψ production *Phys. Lett.* B **662** 252 (arXiv:0709.4406)

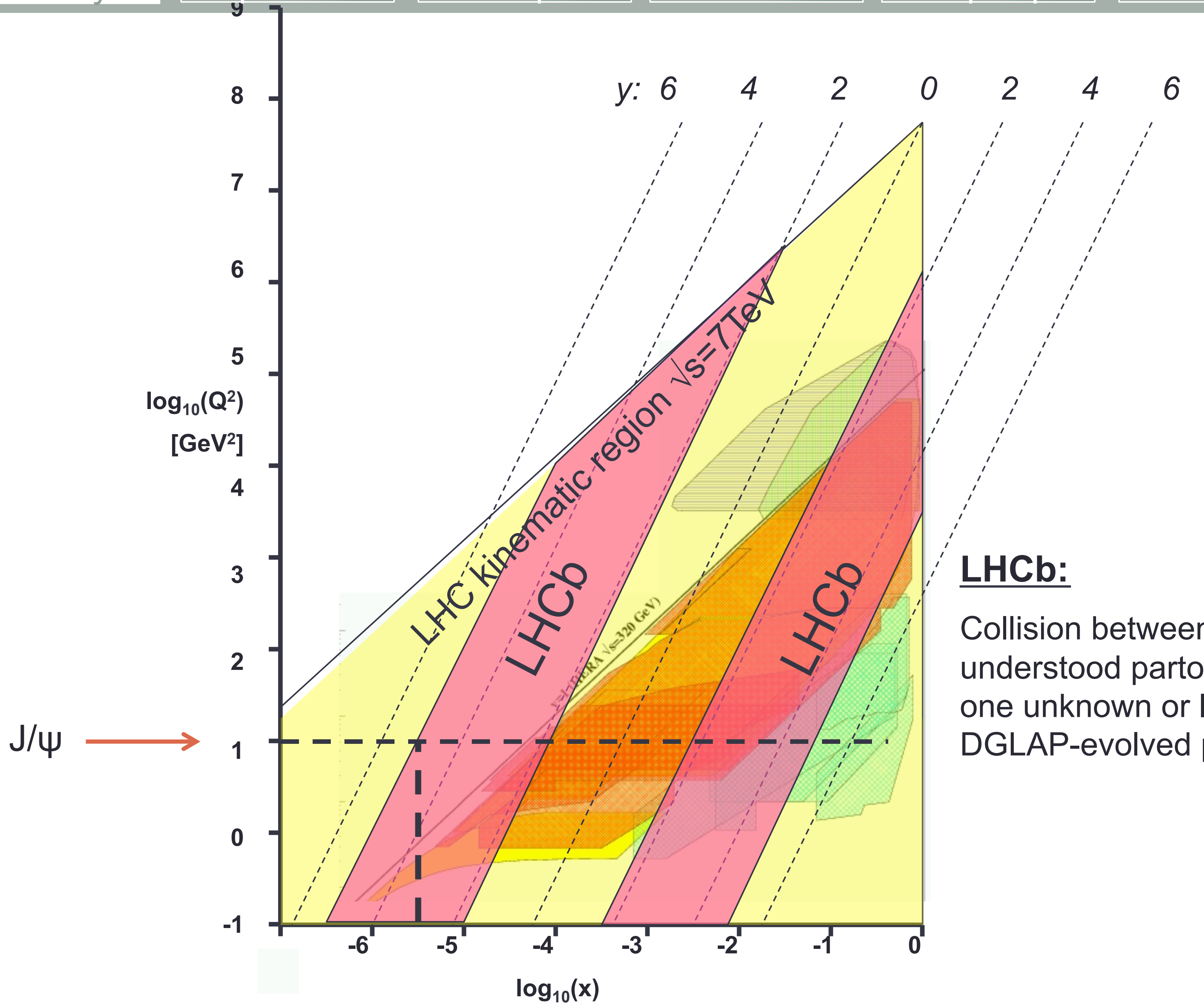
[2] Ryskin M G 1993 J/ψ electroproduction in LLA QCD *Z. Phys.* C **57** 89

[3] Ryskin M G, Roberts R G, Martin A D and Levin E M 1997 Diffractive J/ψ photoproduction as a probe of the gluon density *Z. Phys.* C **76** 231 (arXiv:hep-ph/9511228)

[4] 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.

Reach in x and Q^2

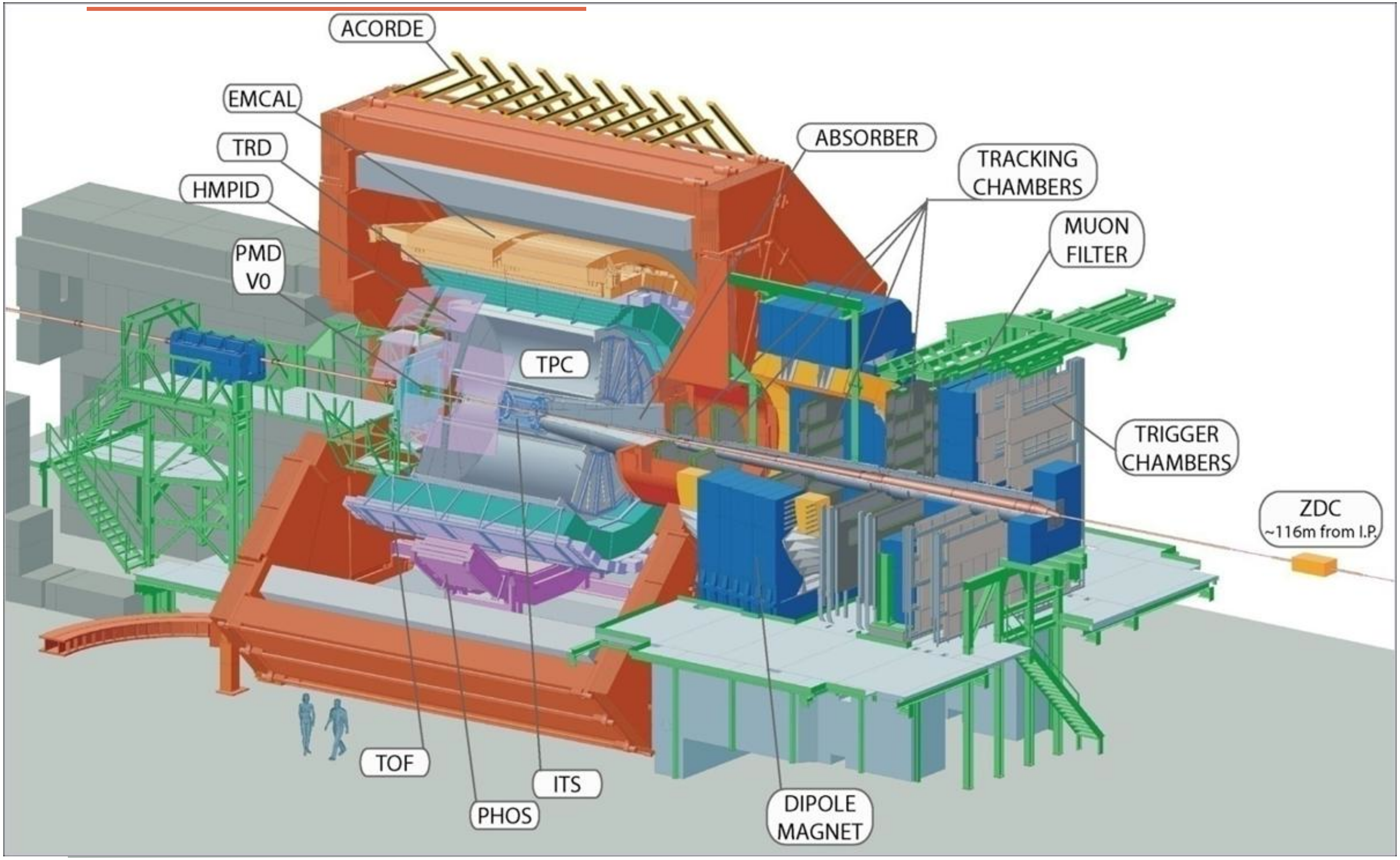




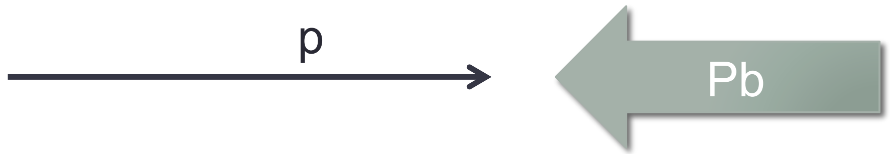
LHCb:

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

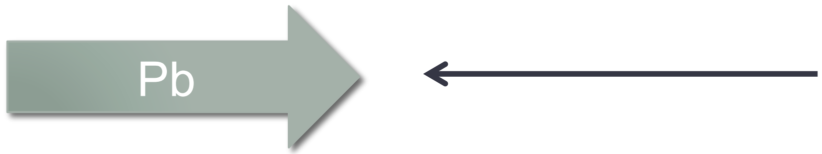
ALICE detector



p-Pb interactions



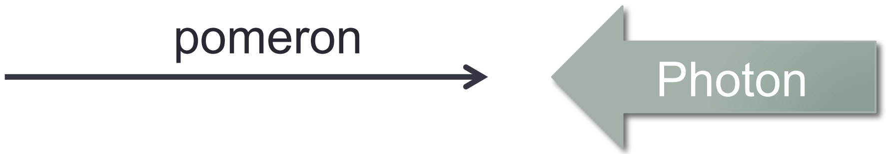
J/ψ sensitivity in 2.5<y<4.0



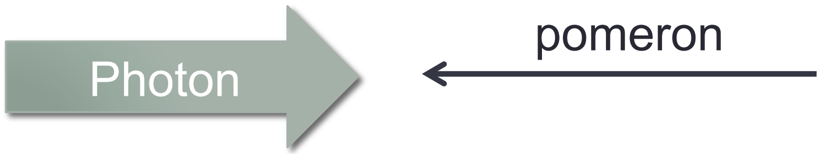
J/ψ sensitivity in -3.6<y<-2.6

Photon flux proportional to Z^2. Removes two-fold ambiguity

p-Pb interactions

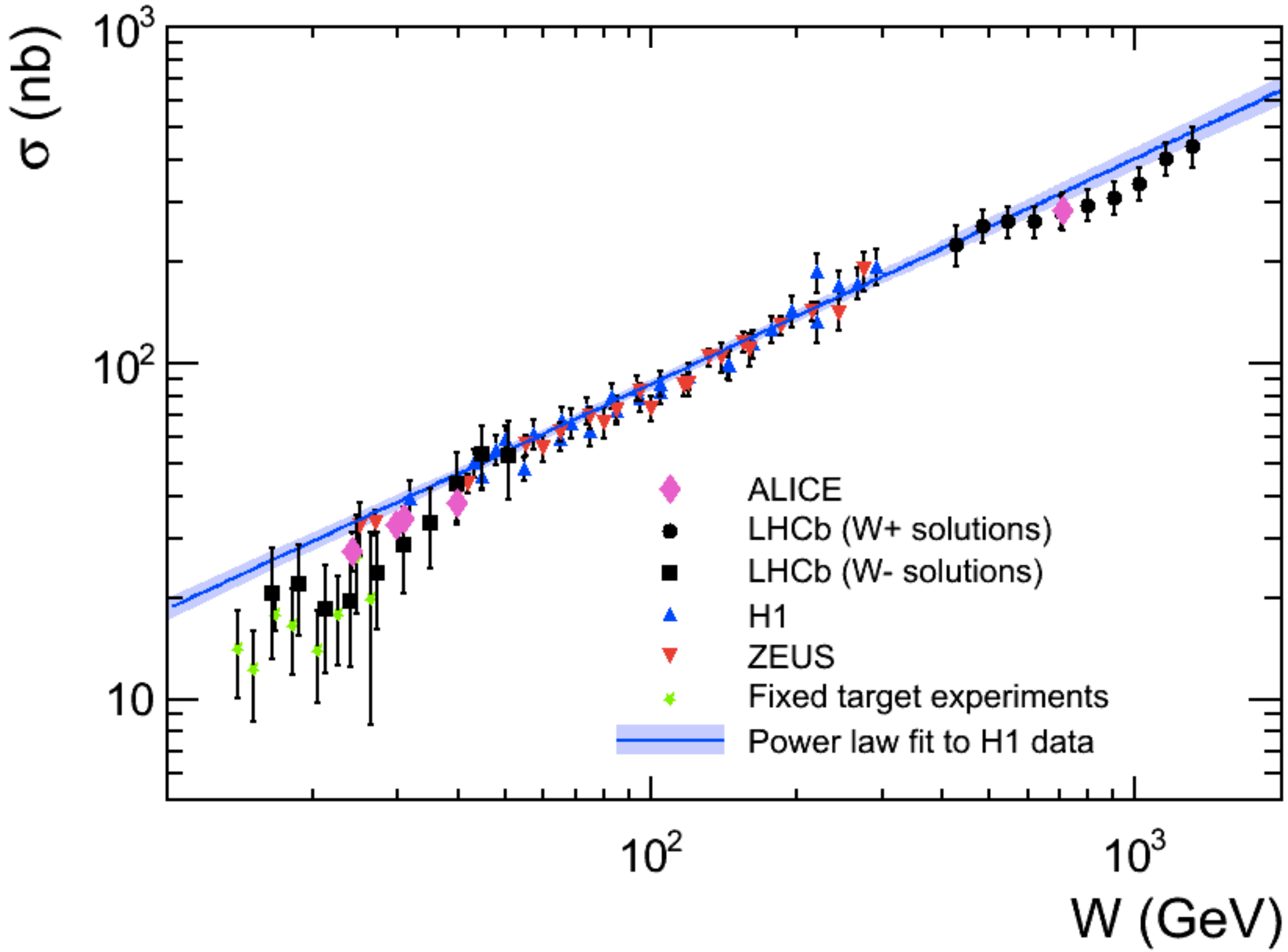


J/ψ sensitivity in 2.5<y<4.0
(Low W region)



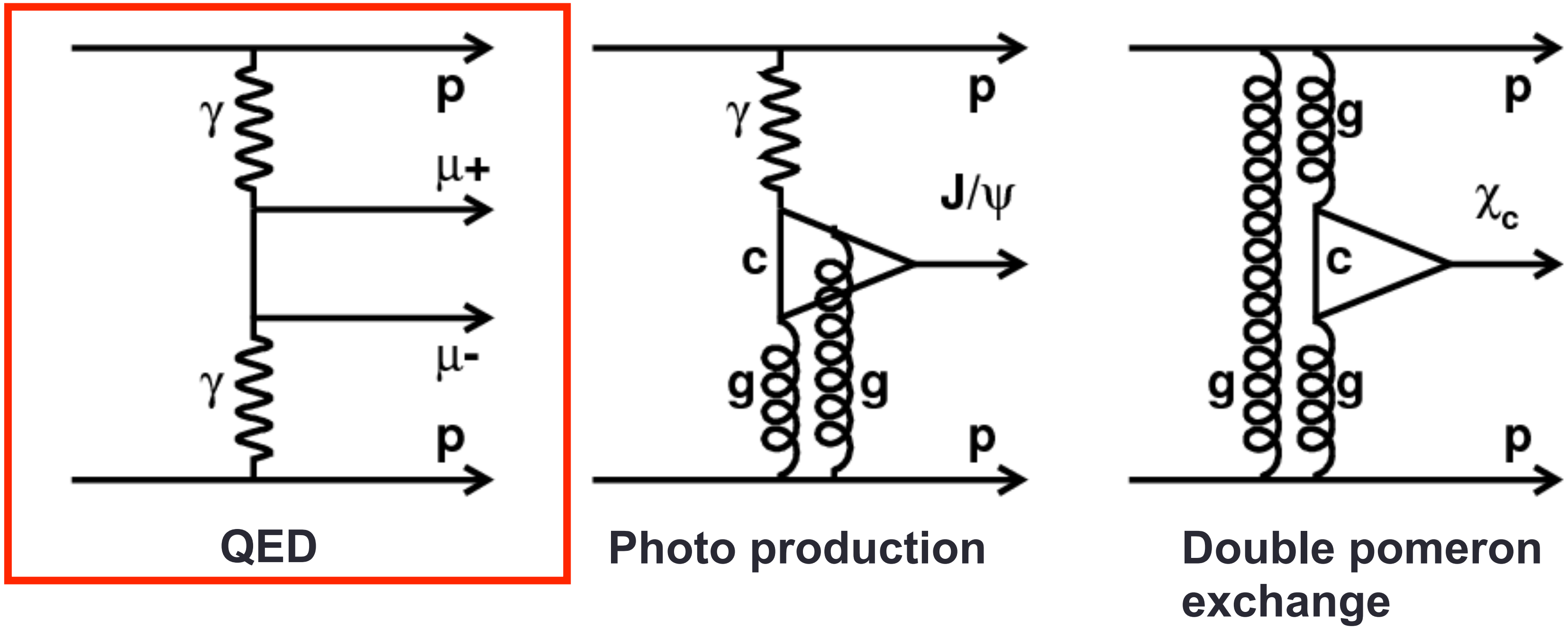
J/ψ sensitivity in -3.6<y<-2.6
(High W region)

Photon flux proportional to Z^2. Removes two-fold ambiguity



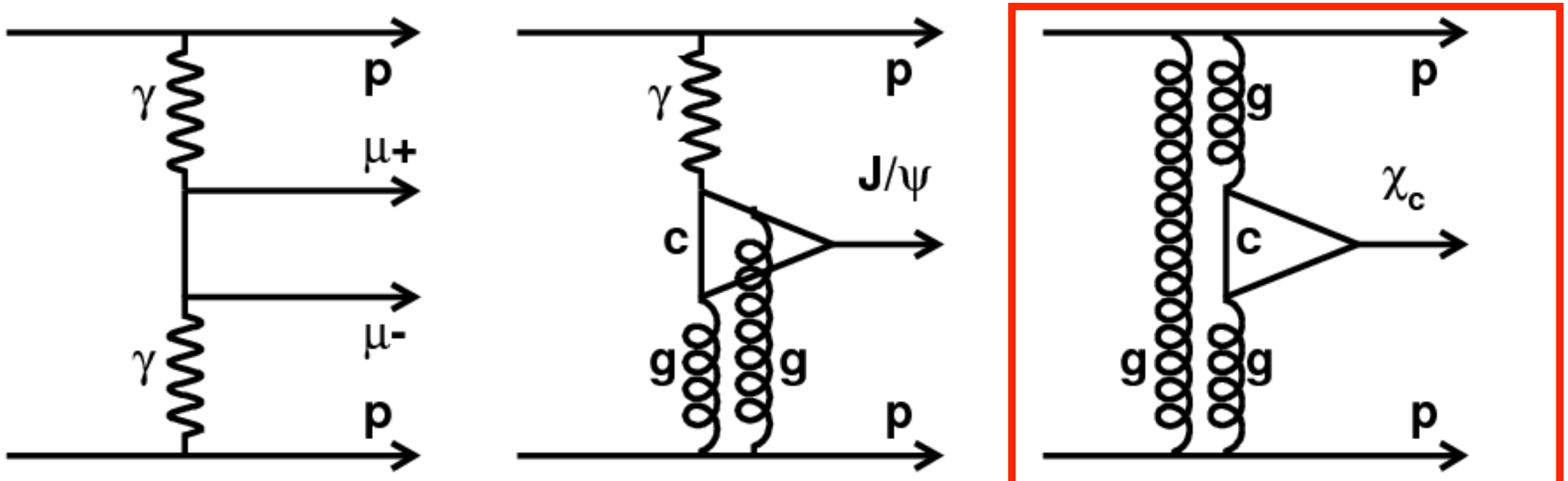
Consistent picture of J/ψ photo-production across wide range of energies and colliders

Central Exclusive Production with Dimuon final states



- QED process. Can be predicted with high accuracy (~1%)
- Candidate process for very precise luminosity determination at LHC

Central Exclusive Production with Dimuon final states



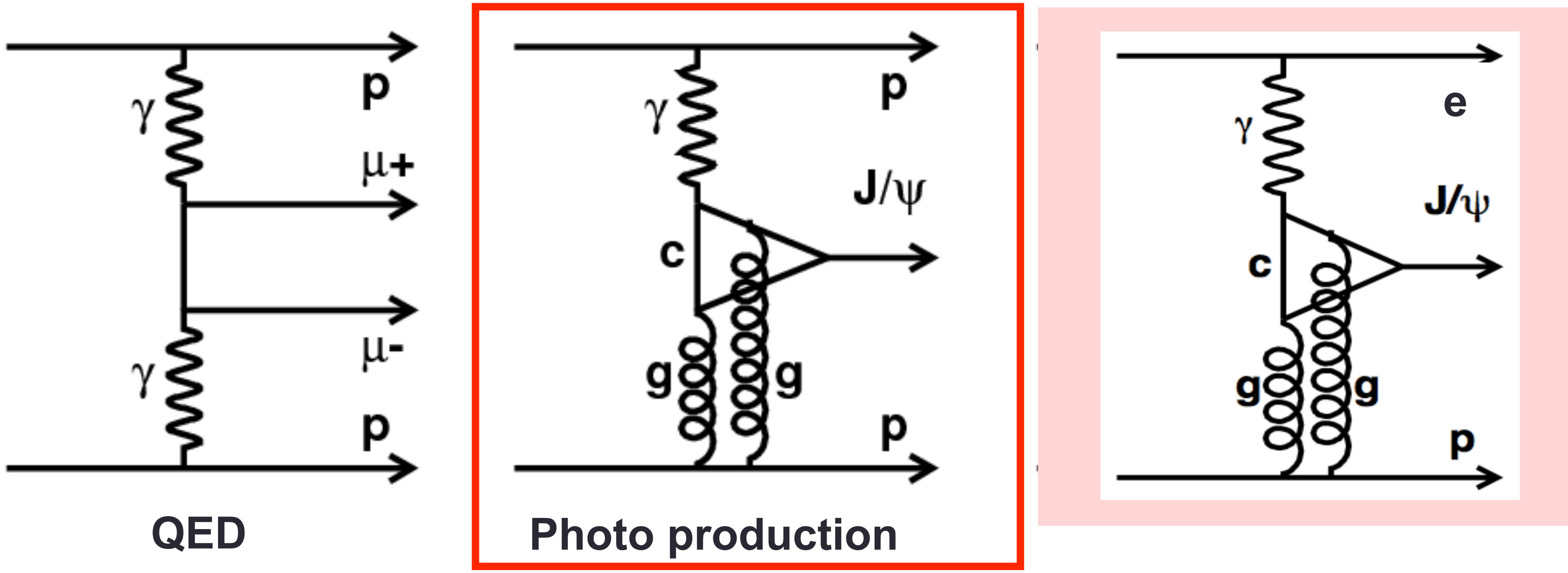
QED

Photo production

Double pomeron exchange

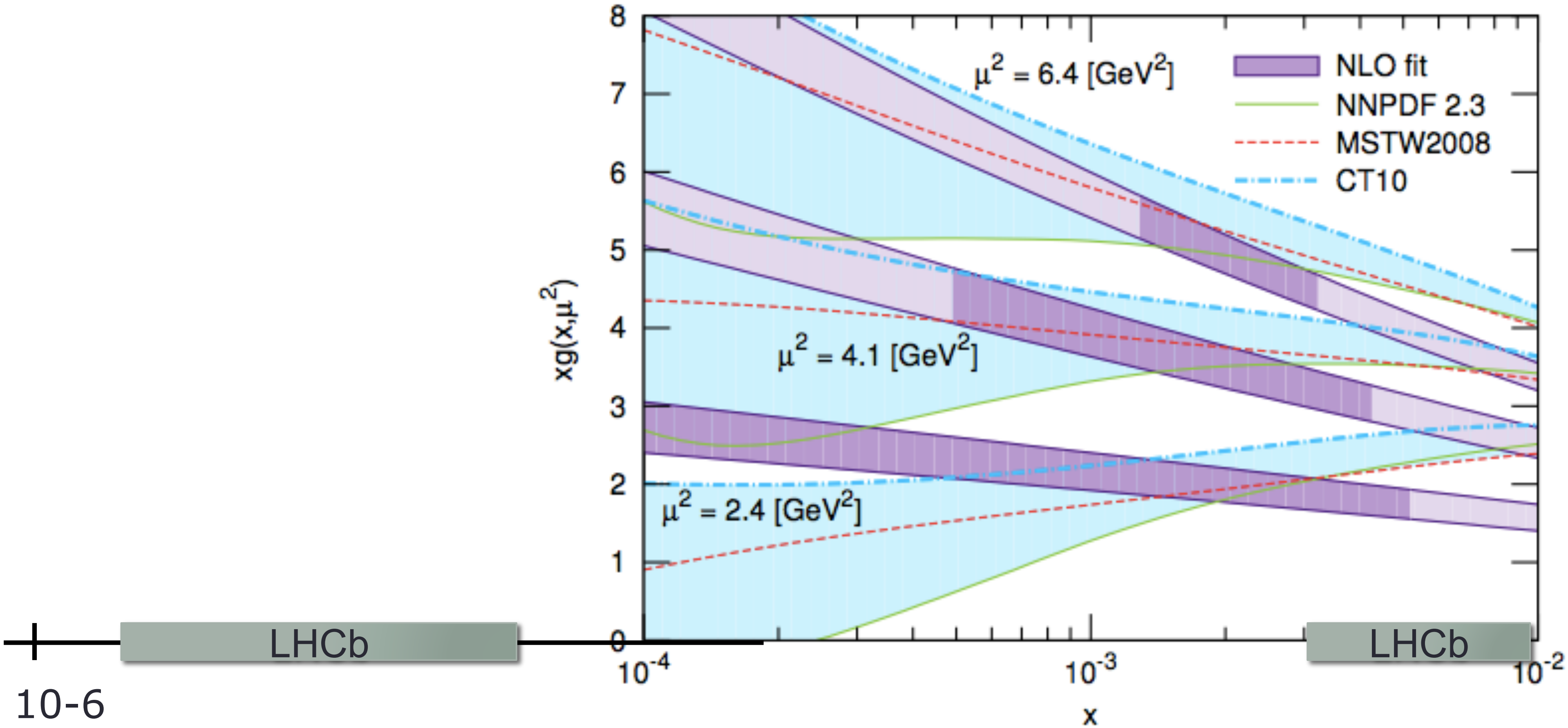
- Double pomeron exchange.
- Unambiguous evidence for pomeron
- ‘Standard Candle’ for other DPE processes, in particular, Higgs.

Central Exclusive Production with Dimuon final states



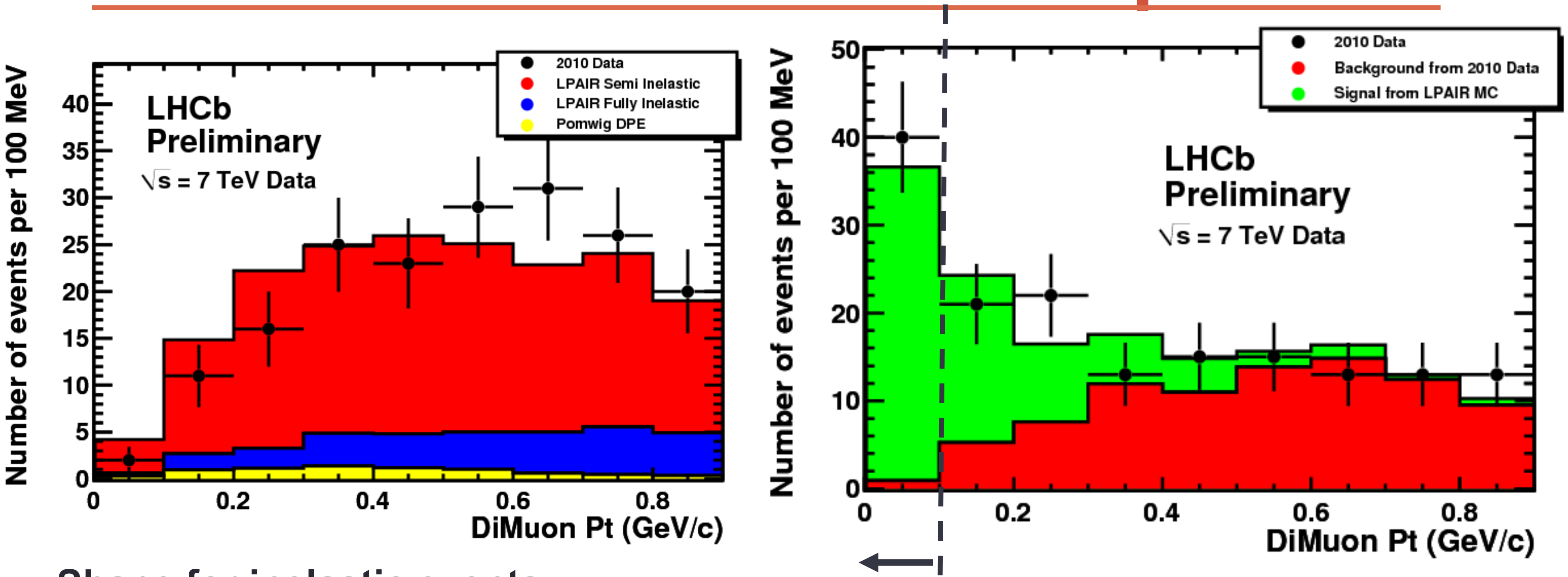
- Test of QCD and pomeron in clean environment
- Sensitive to diffractive PDF at very low x (to 5×10^{-6})
- Search for the odderon and saturation effects
- Measured at HERA/Tevatron but at different photon-proton energy, W

Sensitivity to gluon pdf (arXiv: 1307.7099)



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.

Fit elastic and inelastic components



Shape for inelastic events

Note: this time we have simulation that predicts the shape for the three contributions.

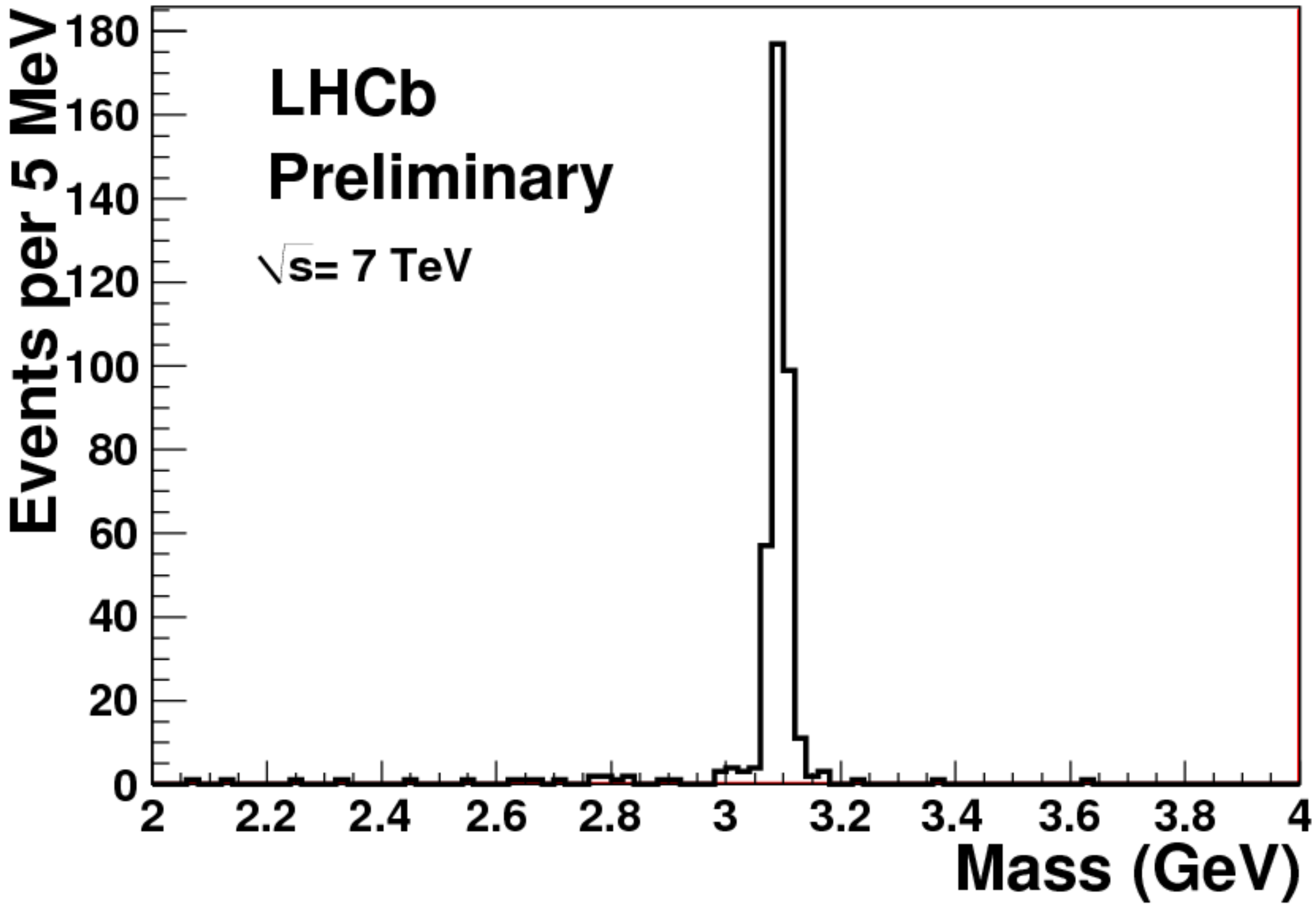
Fit to signal events

Background shape from data
Signal shape from simulation.

Measured cross-section pμμp: 67 +- 19 pb

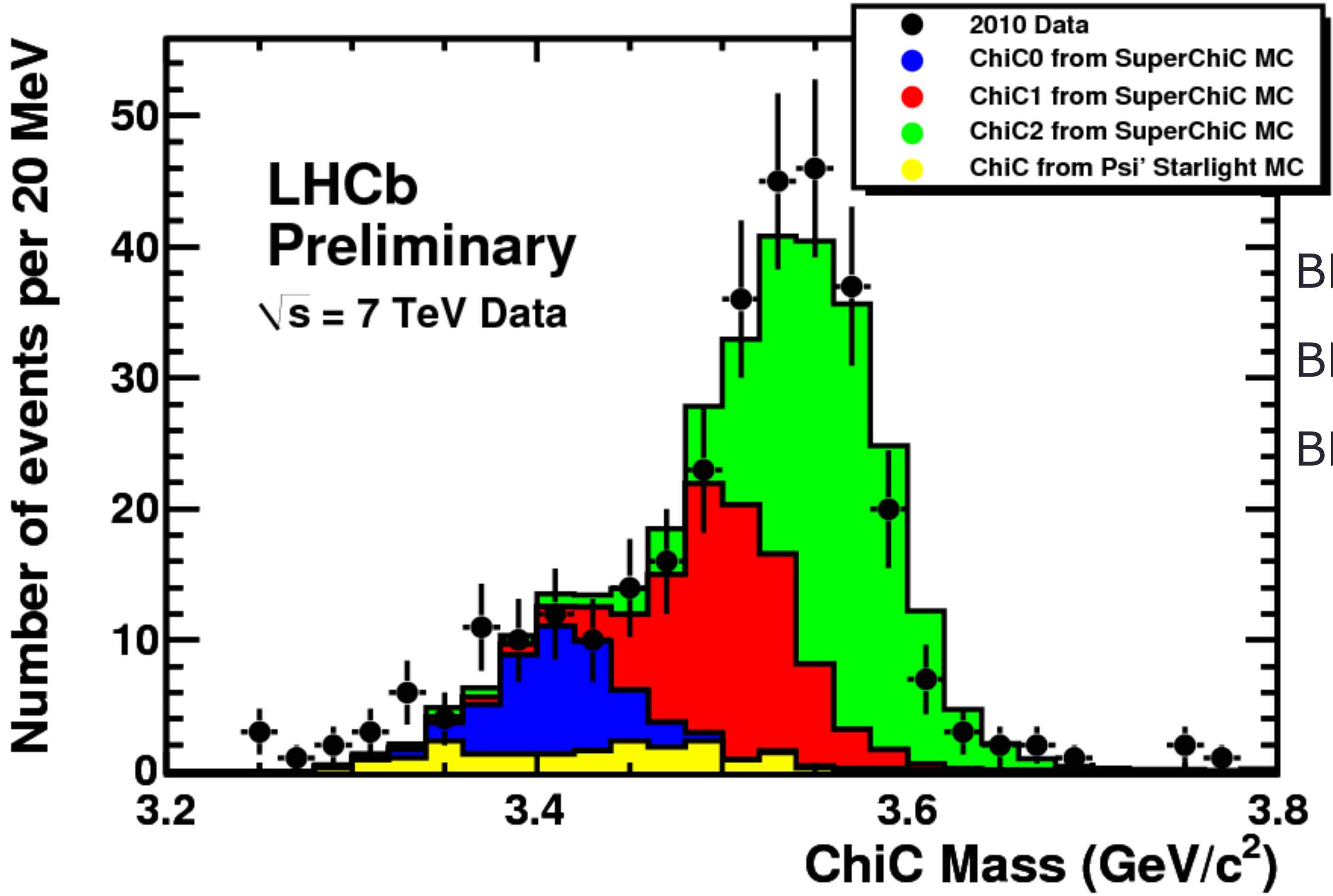
LPAIR (J. Vermaseren) 42 pb

χ_c: DiMuon Invariant Mass



About half the background that was observed in the exclusive J/ψ analysis (since no continuum process).

χ_c: DiMuon+Photon Invariant Mass



BR(χc0->J/$\psi\gamma$)=1.2%

BR(χc1->J/$\psi\gamma$)=34.4%

BR(χc2->J/$\psi\gamma$)=19.5%

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.

Theory v experiment

$\sigma_{\chi_{c0}\to\mu+\mu-\gamma}$ = 9.3 +/- 2.2 +/- 3.5 +/- 1.8 pb
$\sigma_{\chi_{c1}\to\mu+\mu-\gamma}$ = 16.4 +/- 5.3 +/- 5.8 +/- 3.2 pb
$\sigma_{\chi_{c2}\to\mu+\mu-\gamma}$ = 28.0 +/- 5.4 +/- 9.7 +/- 5.4 pb

LHCb preliminary results with 2010 data

	χ_0	χ_1	χ_2
	9.3 +- 4.5 pb	16.4 +- 7.1 pb	28.0 +-12.3 pb
SuperChic:	14 pb	10 pb	3 pb

Large contribution due to X_{c0} is confirmed.

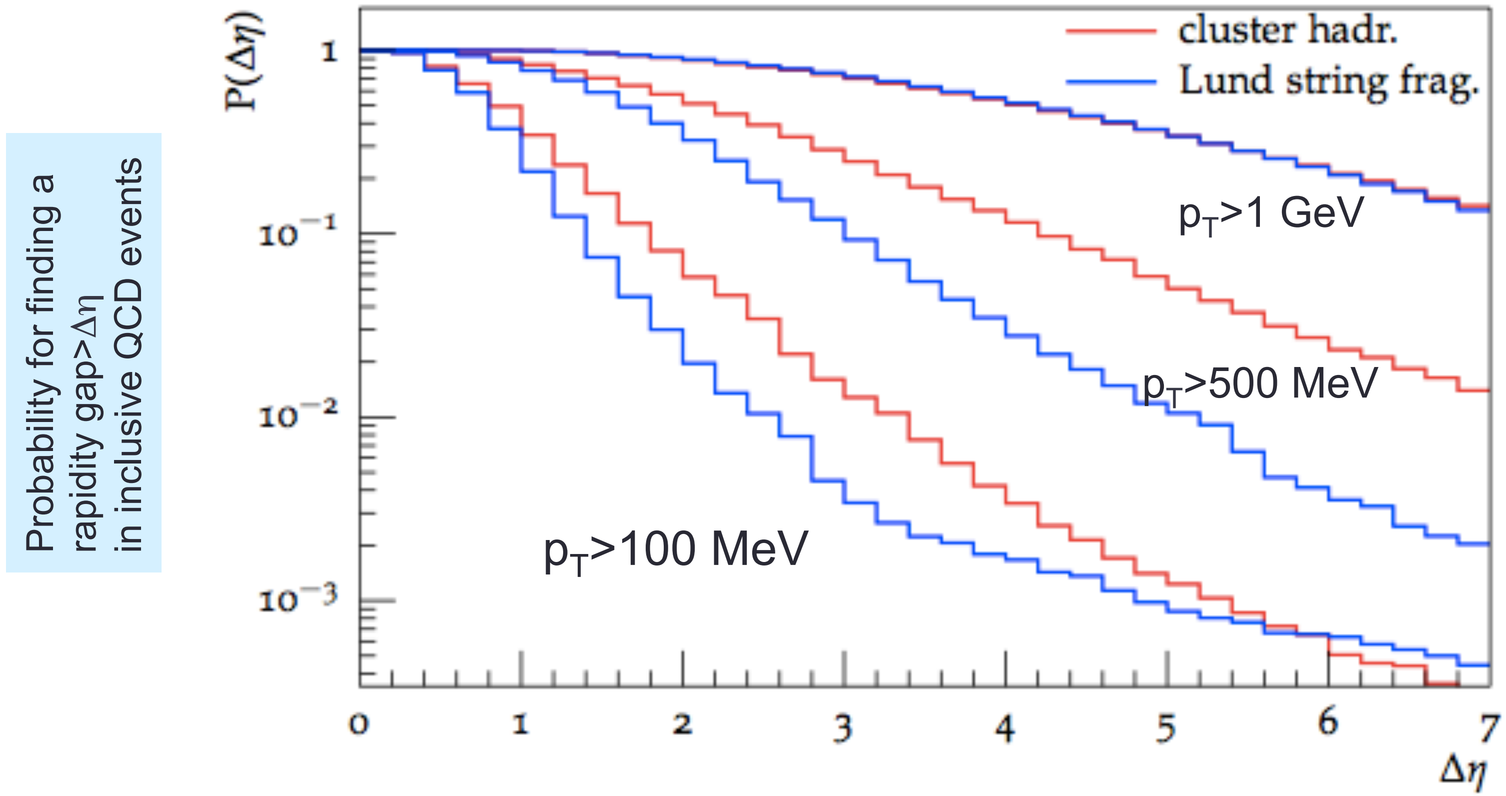
χ_{c2} larger than expected but note that non-elastic background has been assumed same for each resonance. More precise data required.

Integrated cross-sections

	J/ψ [pb]	$\psi(2S)$ [pb]
Gonçalves and Machado [29]	275	
JMRT [5]	282	8.3
Motyka and Watt [2]	334	
Schäfer and Szczurek [30]	317	
Starlight [31]	292	6.1
SuperChic [19]	317	7.0
LHCb measured value	$291 \pm 7 \pm 19$	$6.5 \pm 0.9 \pm 0.4$

Good agreement with all theory estimates

What's a large gap?



- Khoze, Kraus, Martin, Ryskin, Zapp, "Diffraction and correlations at the LHC: definitions and observables", arXiv:1005.4839v2
- Probability for inclusively produced J/ψ to give two muons and nothing else inside LHCb is < $\sim 10^{-5}$

Numbers entering calculation

Table 1: Quantities entering the cross-section calculations as a function of meson rapidity.

y range (J/ψ)	[2.00, 2.25]	[2.25,2.50]	[2.50,2.75]	[2.75,3.00]	[3.00,3.25]
# Events	798	3911	6632	8600	9987
Acceptance	0.467 ± 0.009	0.653 ± 0.013	0.719 ± 0.014	0.718 ± 0.014	0.713 ± 0.014
$\epsilon^{\psi}_{\text{id}} \times \epsilon^{\psi}_{\text{trig}}$	0.71 ± 0.03	0.78 ± 0.02	0.81 ± 0.01	0.84 ± 0.01	0.85 ± 0.01
Purity			$0.592 \pm 0.012 \pm 0.030$		

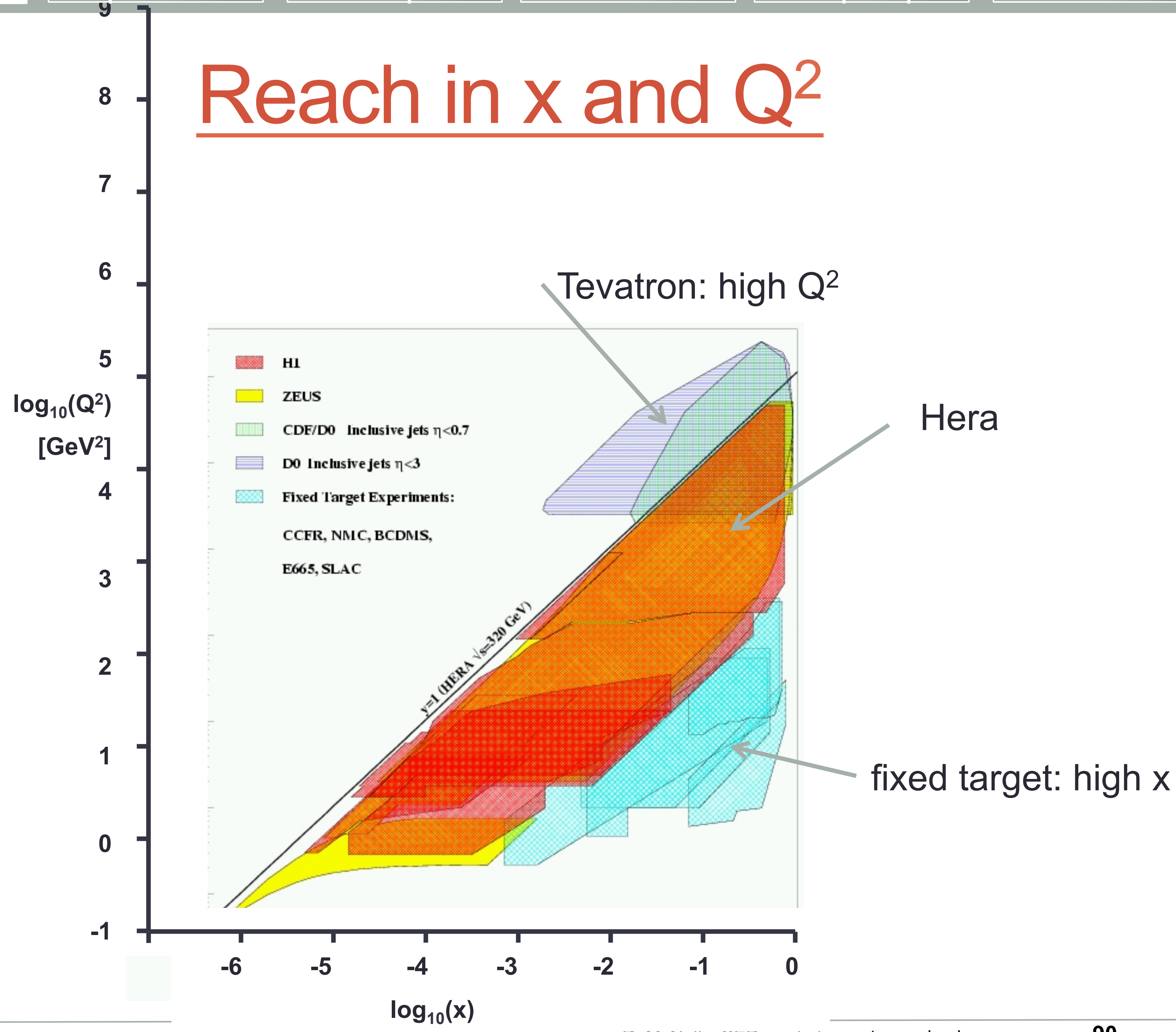
y range (J/ψ)	[3.25, 3.50]	[3.50,3.75]	[3.75,4.00]	[4.00,4.25]	[4.25,4.50]
# Events	9877	7907	5181	2496	596
Acceptance	0.739 ± 0.015	0.734 ± 0.015	0.674 ± 0.014	0.566 ± 0.011	0.401 ± 0.008
$\epsilon^{\psi}_{\text{id}} \times \epsilon^{\psi}_{\text{trig}}$	0.87 ± 0.01	0.88 ± 0.01	0.87 ± 0.01	0.83 ± 0.02	0.81 ± 0.03
Purity			$0.592 \pm 0.012 \pm 0.030$		

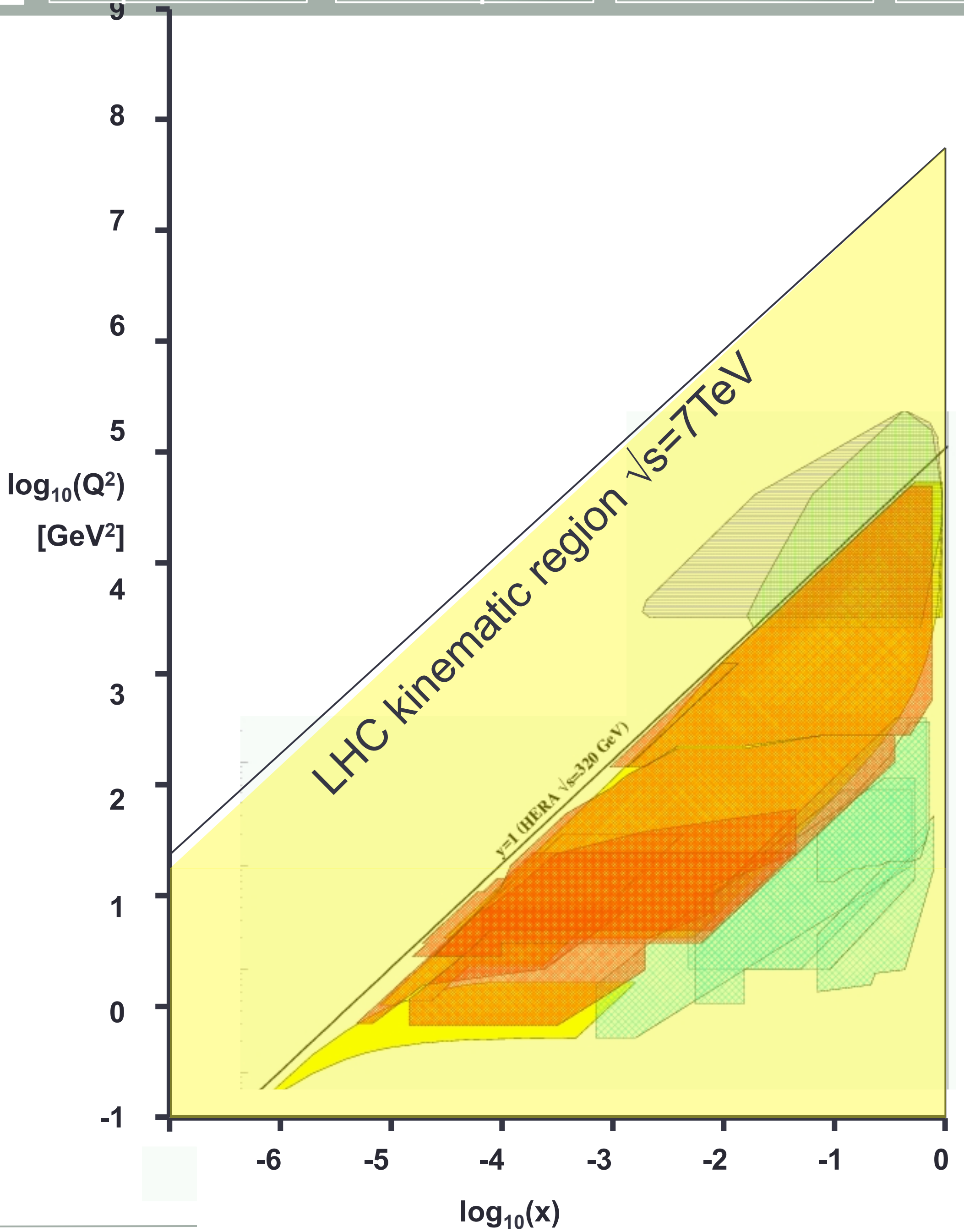
y range ($\psi(2S)$)	[2.00, 2.25]	[2.25,2.50]	[2.50,2.75]	[2.75,3.00]	[3.00,3.25]
# Events	31	111	208	1287	268
Acceptance	0.678 ± 0.013	0.800 ± 0.016	0.834 ± 0.017	0.787 ± 0.016	0.755 ± 0.015
$\epsilon^{\psi}_{\text{id}} \times \epsilon^{\psi}_{\text{trig}}$	0.80 ± 0.03	0.83 ± 0.02	0.86 ± 0.01	0.88 ± 0.01	0.88 ± 0.01
Purity ($\psi(2S)$)			$0.52 \pm 0.07 \pm 0.03$		

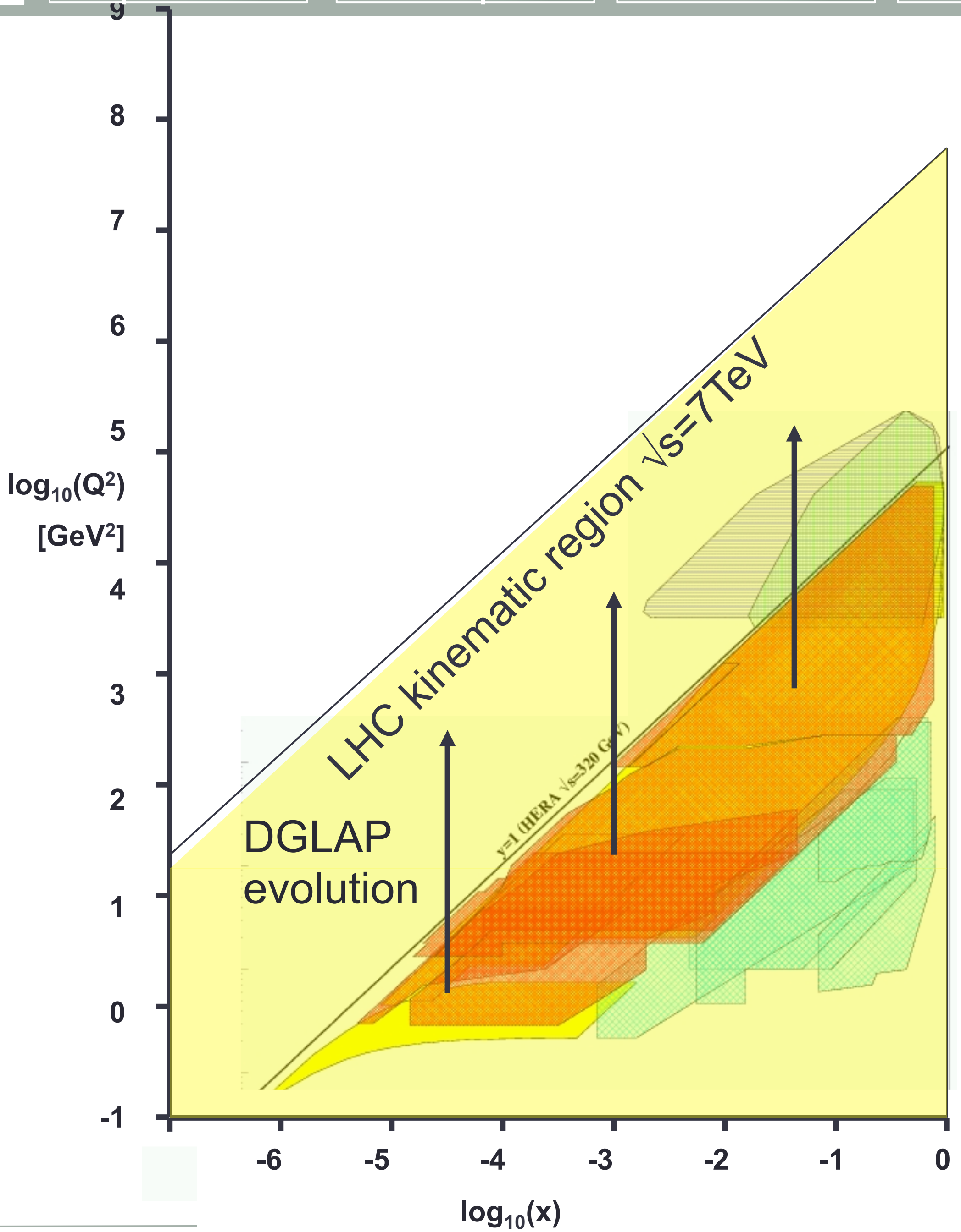
y range($\psi(2S)$)	[3.25, 3.50]	[3.50,3.75]	[3.75,4.00]	[4.00,4.25]	[4.25,4.50]
# Events	282	201	105	61	11
Acceptance	0.748 ± 0.015	0.702 ± 0.014	0.628 ± 0.013	0.524 ± 0.010	0.384 ± 0.008
$\epsilon^{\psi}_{\text{id}} \times \epsilon^{\psi}_{\text{trig}}$	0.90 ± 0.01	0.89 ± 0.01	0.87 ± 0.01	0.84 ± 0.02	0.77 ± 0.03
Purity ($\psi(2S)$)			$0.52 \pm 0.07 \pm 0.03$		

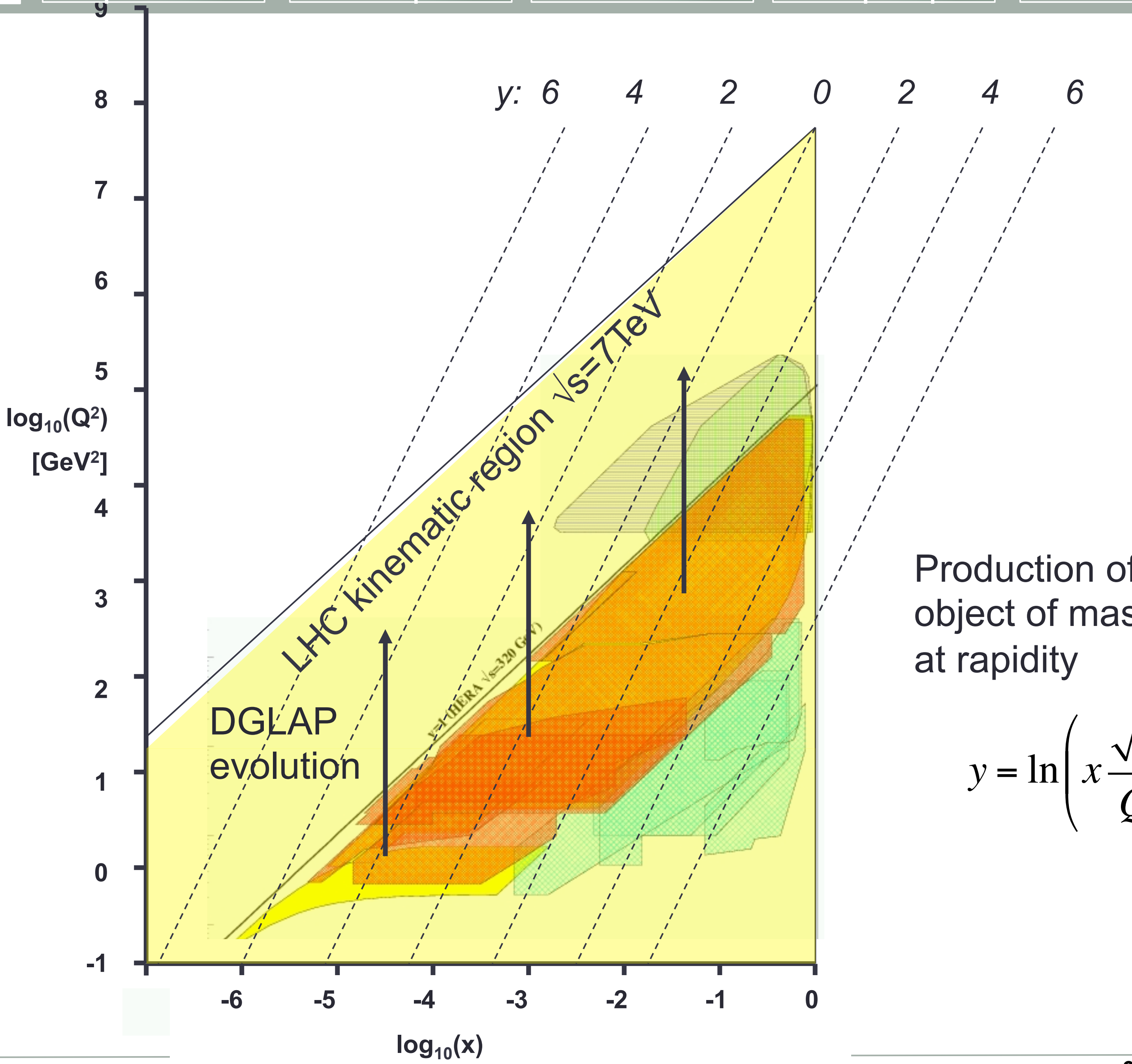
y range (J/ψ and $\psi(2S)$)	[2.00, 4.50]
ϵ_{sel}	0.87 ± 0.01
ϵ_{single}	0.241 ± 0.003
L (pb^{-1})	929 ± 33

Reach in x and Q^2



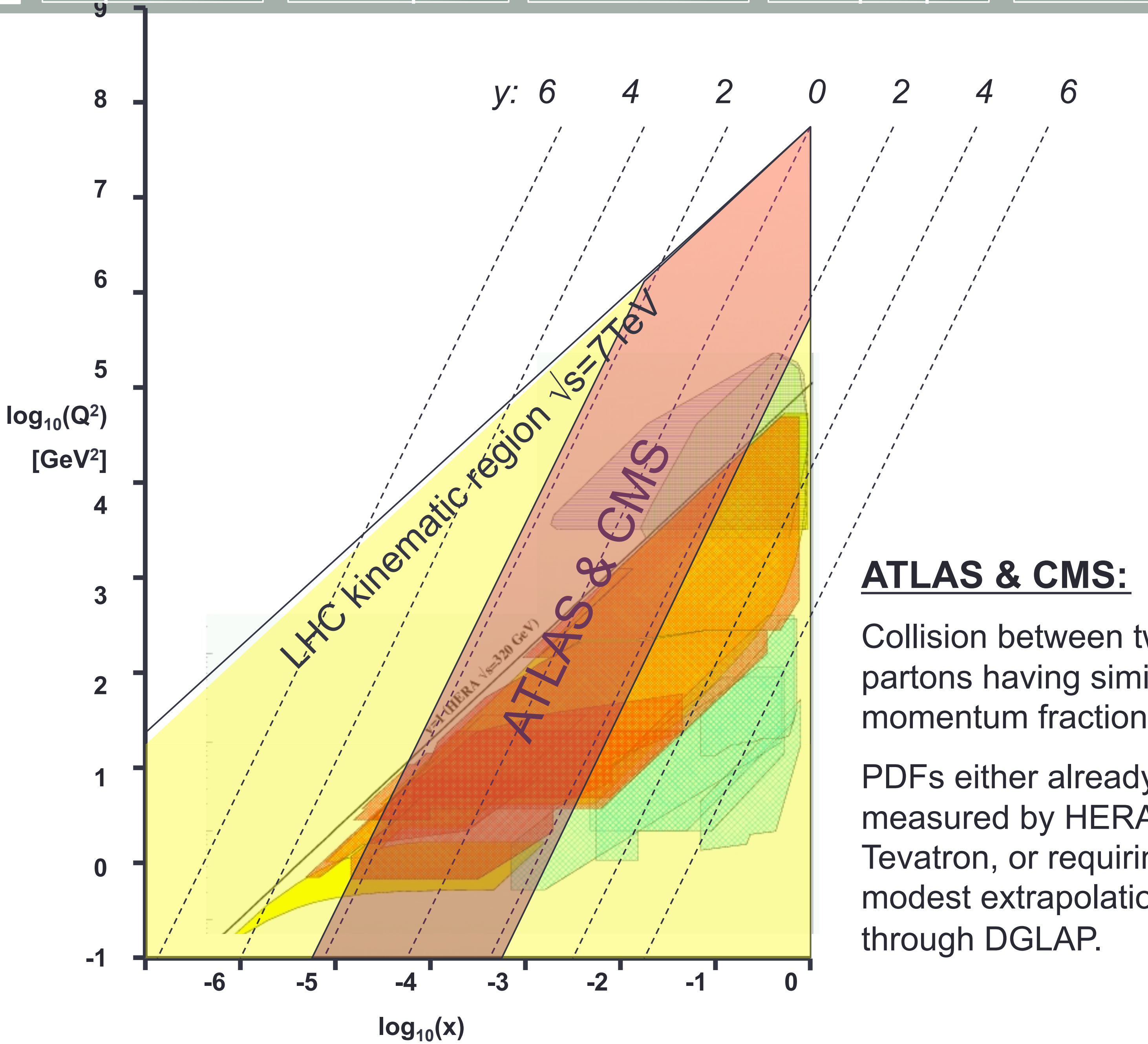

9
8
7
6
5
4
3
2
1
0
-1
log10(Q2) [GeV2]
-6
-5
-4
-3
-2
-1
0
log10(x)
LHC kinematic region √s=7TeV
y=1 (HERA √s=320 GeV)


log10(Q2) [GeV2]
9
8
7
6
5
4
3
2
1
0
-1
-6
-5
-4
-3
-2
-1
0
log10(x)
LHC kinematic region √s=7TeV
DGLAP evolution
y=1 (HERA √s=320 GeV)



Production of object of mass Q at rapidity

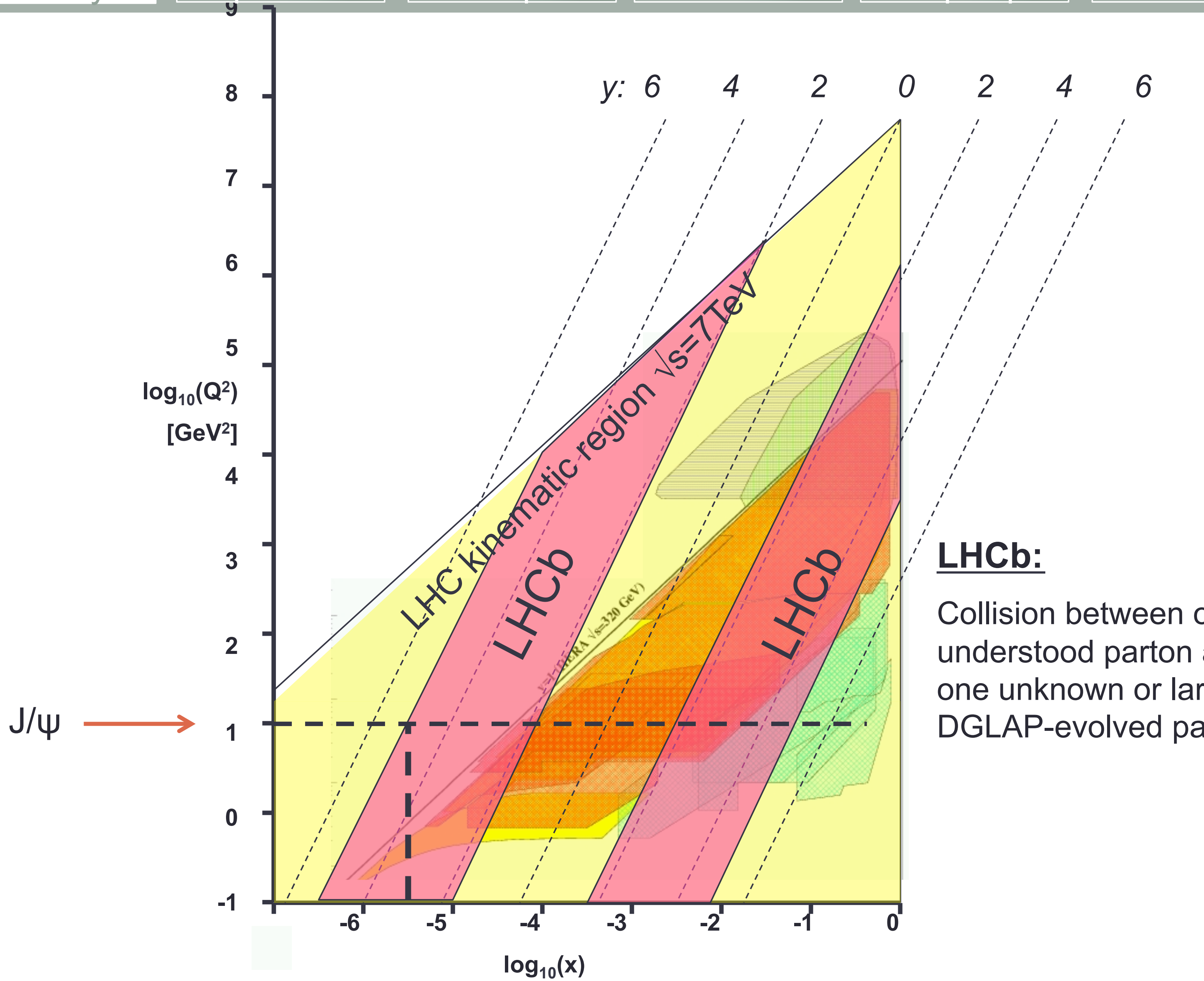
$$y = \ln\left(x\frac{\sqrt{s}}{Q}\right)$$



ATLAS & CMS:

Collision between two partons having similar momentum fractions.

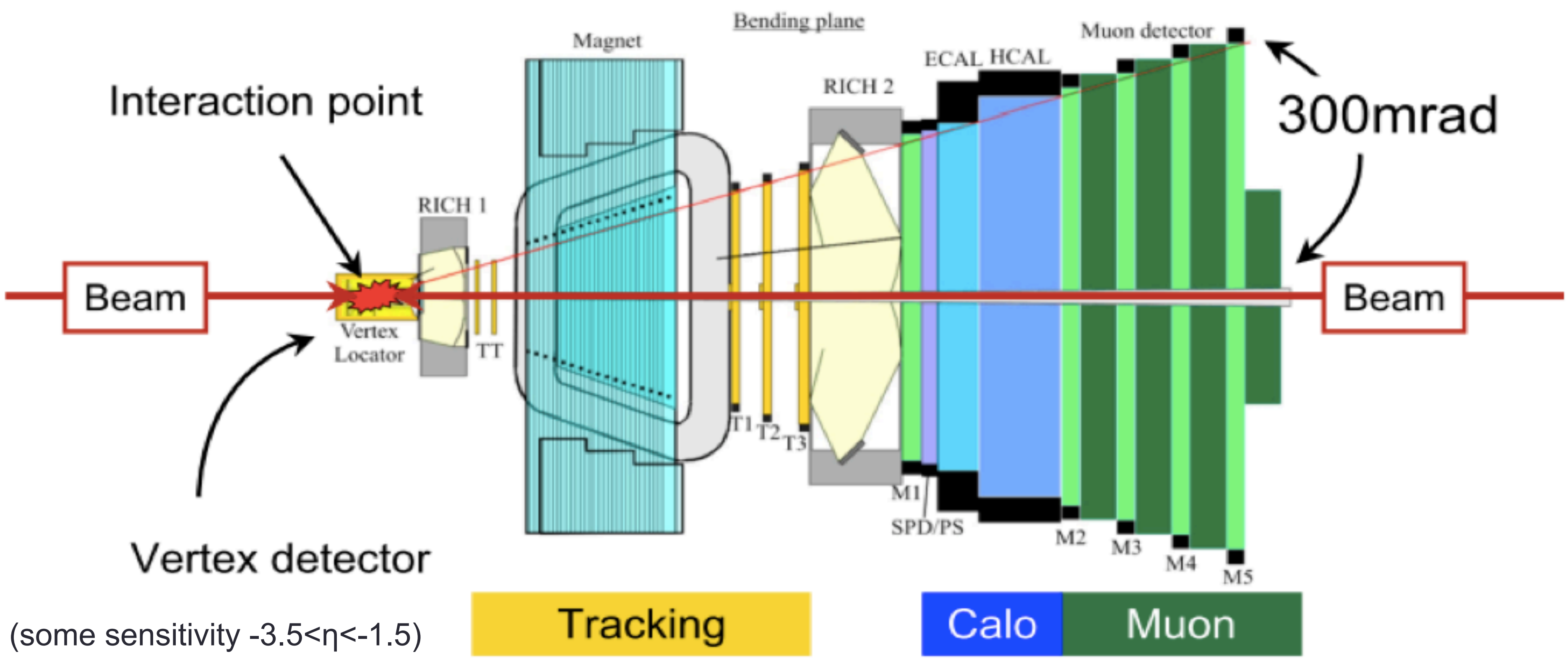
PDFs either already measured by HERA or Tevatron, or requiring modest extrapolation through DGLAP.



LHCb:

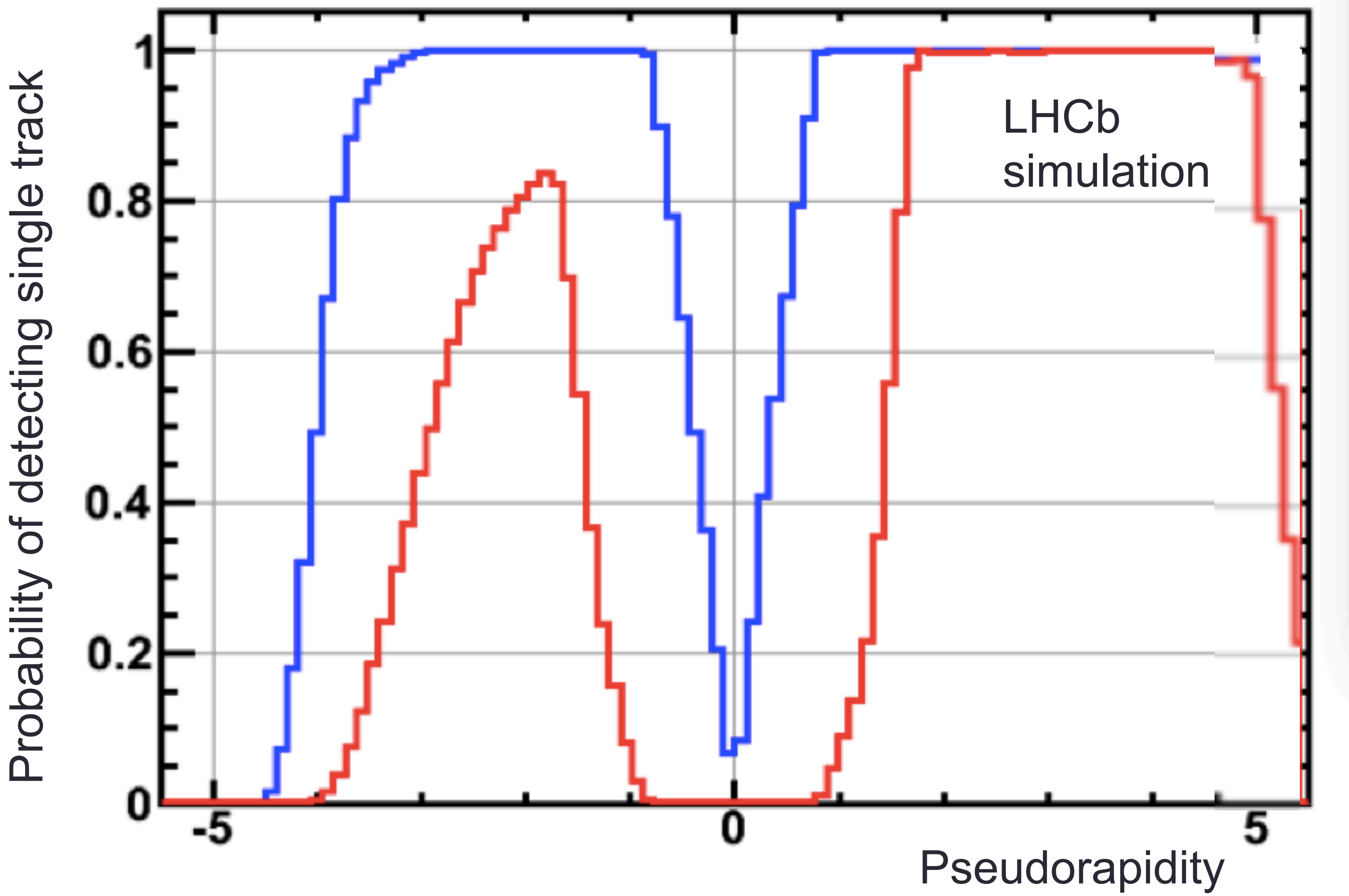
Collision between one well understood parton and one unknown or large DGLAP-evolved parton.

The LHCb detector



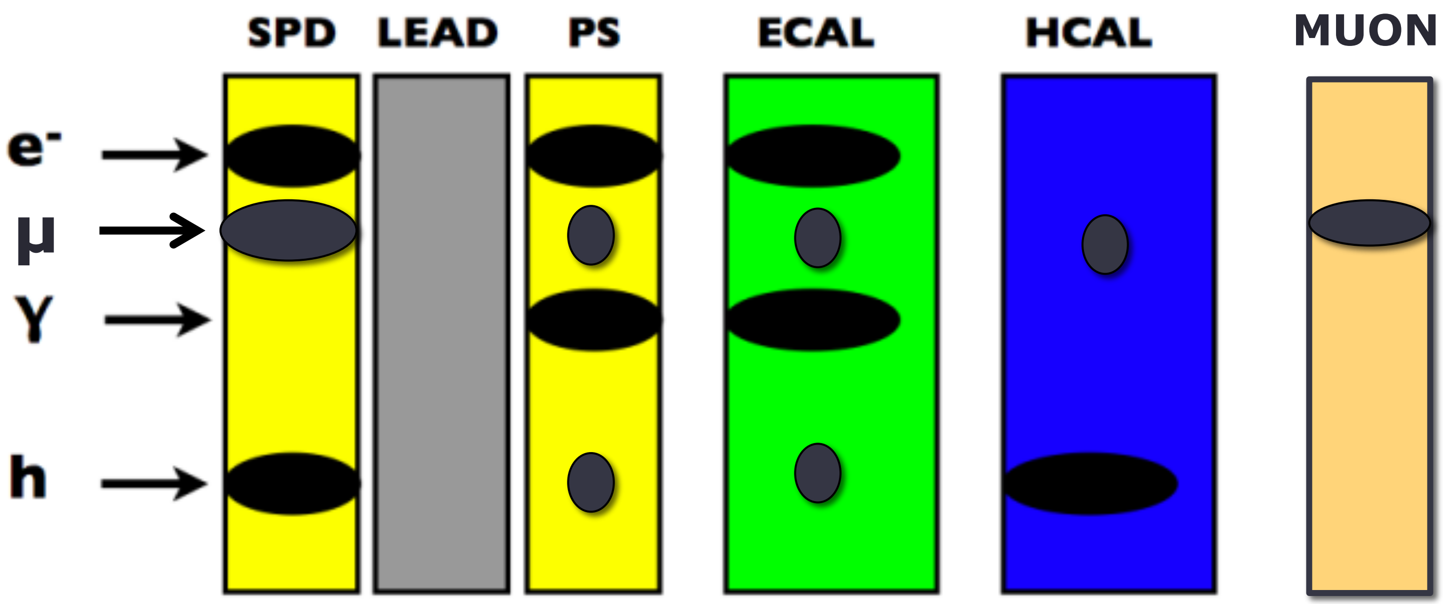
(some sensitivity $-3.5<\eta<-1.5$)

Pseudorapidity veto range



All results I show imply red region void, (except for muons from signal).

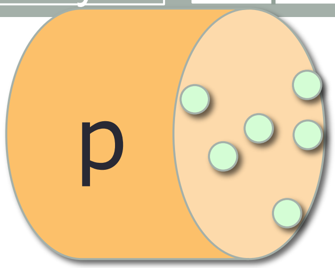
Calorimeter System in LHCb



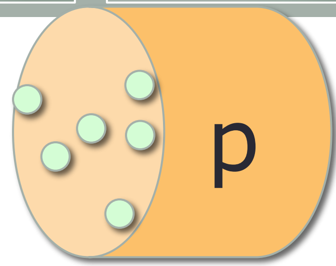
Scintillation Pad Detector.
If a charged particle goes through, we get a signal.
Rough count of number of charged particles.

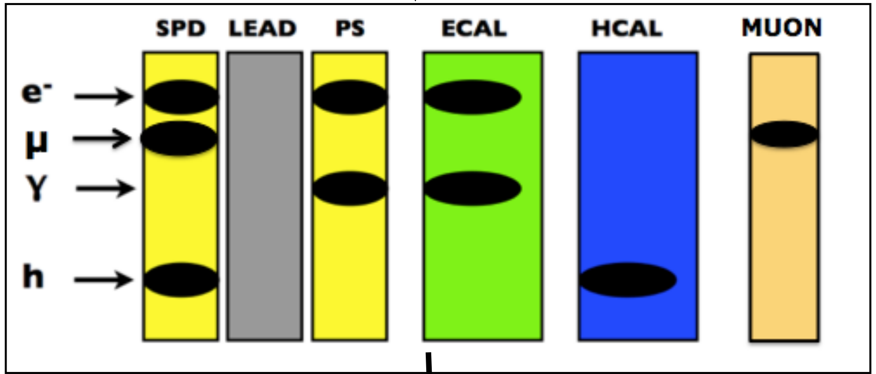
Use in trigger to select **low multiplicity** events for CEP. <10 hits

Triggering



40 MHz



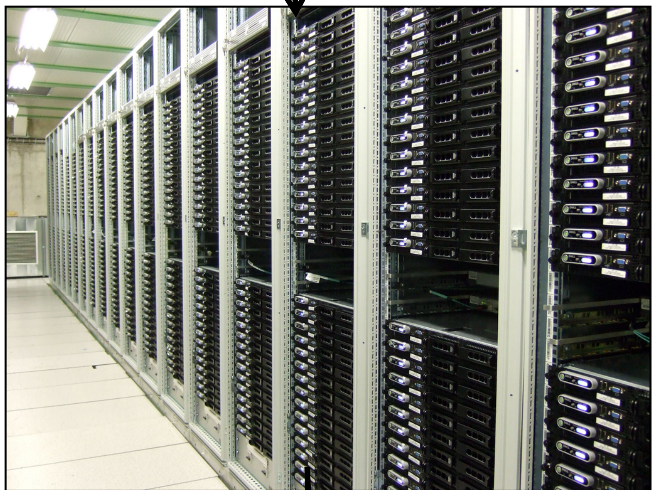


L0 Trigger:

p_T^{μ}>400 MeV
#SPD<10

Hardware:
Fast electronics

~1 MHz



HLT Trigger:

Two muons
with p_T > 400 MeV

Software:
Parallel processing

~2 kHz

Cross-sections and systematics

Cross-section*BR for both muons in pseudorapidity range 2<η<4.5:

y range	[2.00, 2.25]	[2.25,2.50]	[2.50,2.75]	[2.75,3.00]	[3.00,3.25]
$\frac{d\sigma}{dy}$ J/ψ	29.3 ± 1.7	92.5 ± 2.4	137.8 ± 2.4	173.1 ± 2.6	198.0 ± 2.7
$\frac{d\sigma}{dy}$ $\psi(2S)$	0.56 ± 0.11	1.75 ± 0.17	3.06 ± 0.22	4.41 ± 0.26	4.24 ± 0.26

y range	[3.25, 3.50]	[3.50,3.75]	[3.75,4.00]	[4.00,4.25]	[4.25,4.50]
$\frac{d\sigma}{dy}$ J/ψ	187.6 ± 2.6	148.9 ± 2.4	107.4 ± 2.1	65.3 ± 2.0	21.9 ± 1.3
$\frac{d\sigma}{dy}$ $\psi(2S)$	4.51 ± 0.27	3.43 ± 0.25	2.05 ± 0.20	1.47 ± 0.19	0.36 ± 0.11

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

ψ(2S)

J/ψ

Comparison to theory

V. P. Gonçalves and M. V. T. Machado, *Vector meson production in coherent hadronic interactions: an update on predictions for RHIC and LHC*, Phys. Rev. **C84** (2011) 011902, arXiv:1106.3036.

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.

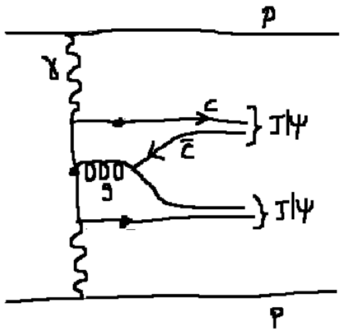
L. Motyka and G. Watt, *Exclusive photoproduction at the Fermilab Tevatron and CERN LHC within the dipole picture*, Phys. Rev. **D78** (2008) 014023, arXiv:0805.2113.

W. Schäfer and A. Szczurek, *Exclusive photoproduction of J/ψ in proton-proton and proton-antiproton scattering*, Phys. Rev. **D76** (2007) 094014, arXiv:0705.2887.

S. R. Klein and J. Nystrand, *Photoproduction of quarkonium in proton proton and nucleus nucleus collisions*, Phys. Rev. Lett. **92** (2004) 142003, arXiv:hep-ph/0311164.

L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin, and W. J. Stirling, *Central exclusive χ_c meson production at the Tevatron revisited*, Eur. Phys. J. **C65** (2010) 433, arXiv:0909.4748.

J/ψJ/ψ production



Large literature for γγ->J/ψJ/ψ

- I. F. Ginzburg, S. L. Panfil, and V. G. Serbo, Nucl. Phys. B296 (1988) 569.
- C.-F. Qiao, Phys. Rev. D64 (2001) 077503, arXiv:hep-ph/0104309
- V. P. Gonçalves and M. V. T. Machado,
  Eur. Phys. J. C28 (2003) 71, arXiv:hep-ph/0212178.
- A. Cisek, W. Schäfer, and A. Szczurek,
  Phys. Rev. C86 (2012) 014905, arXiv:1204.5381.
- S. Baranov et al., Eur. Phys. J. C73 (2013) 2335, arXiv:1208.5917.

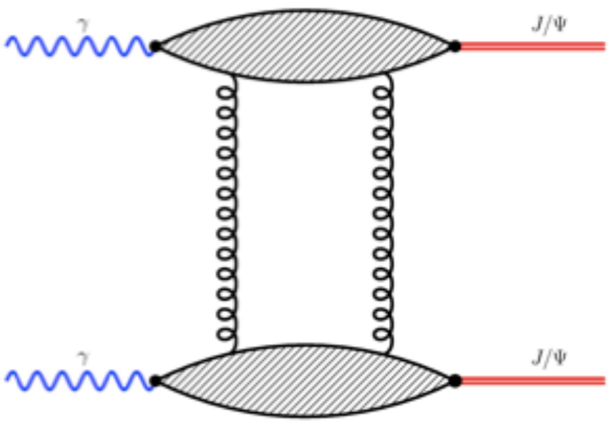
Requires large photon flux:

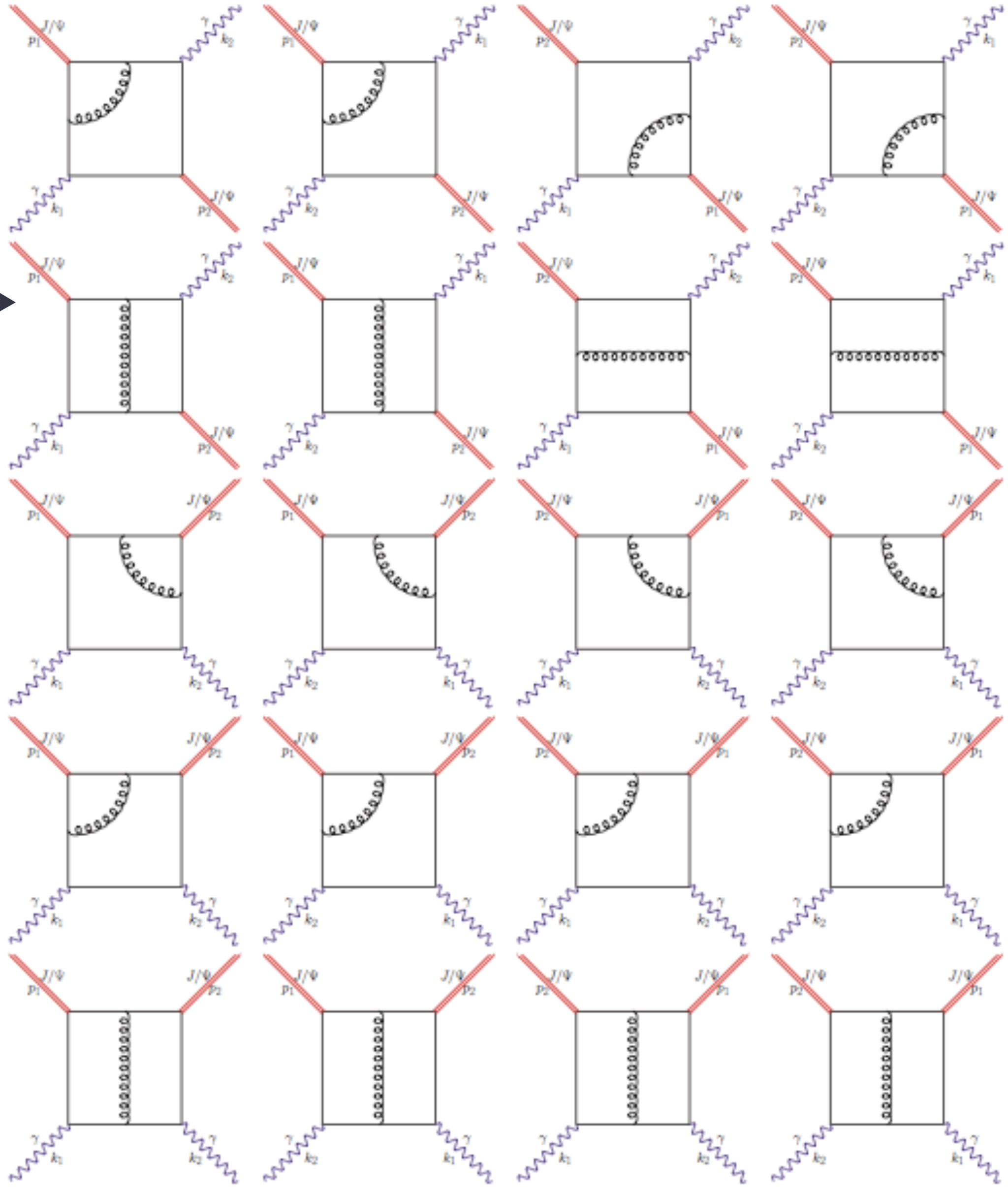
Heavy ion collisions or Linear colliders

Feynman diagrams

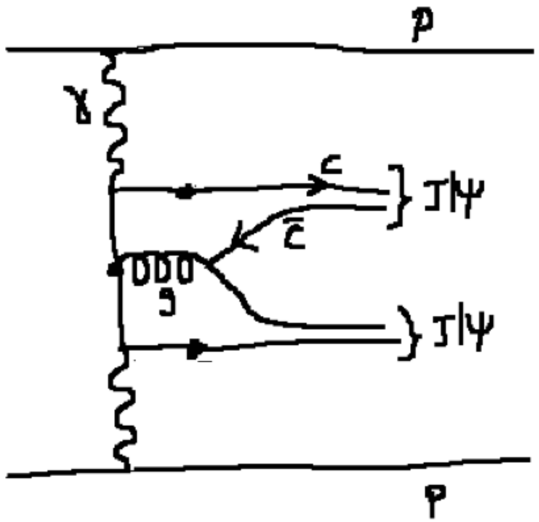
Box diagrams
(Fall off with increasing Q^2)

Pomeron exchange
(~constant with Q^2)

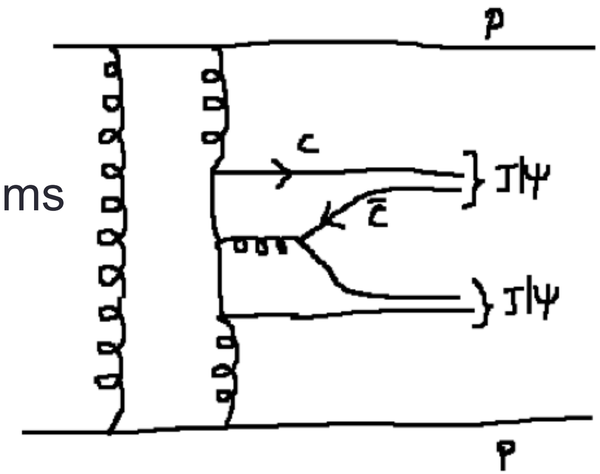




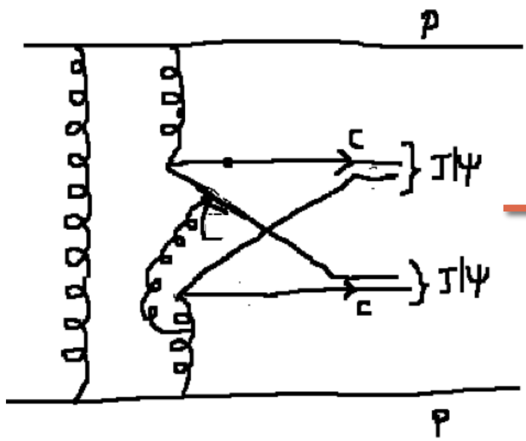
<1 event in $3fb^{-1}$ of pp interactions

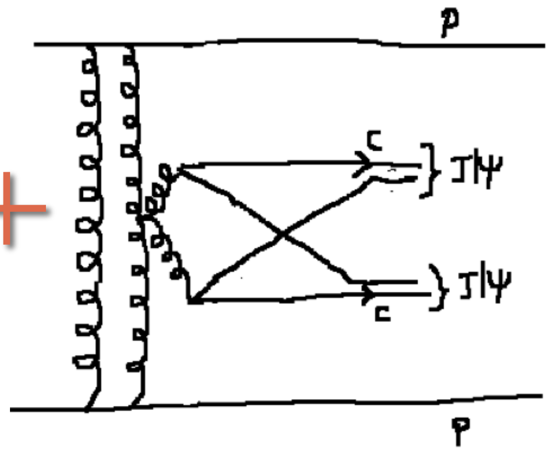


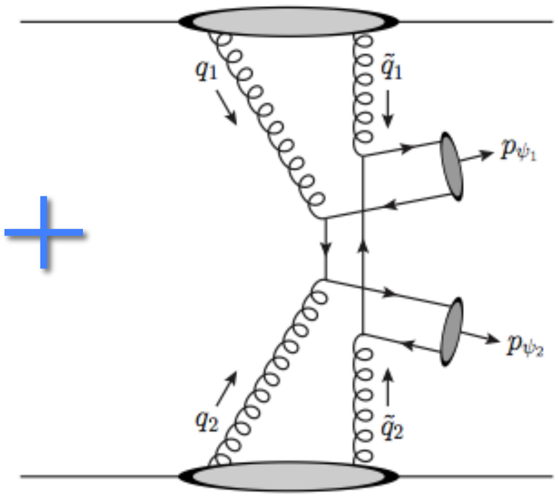
20 -> 31 diagrams



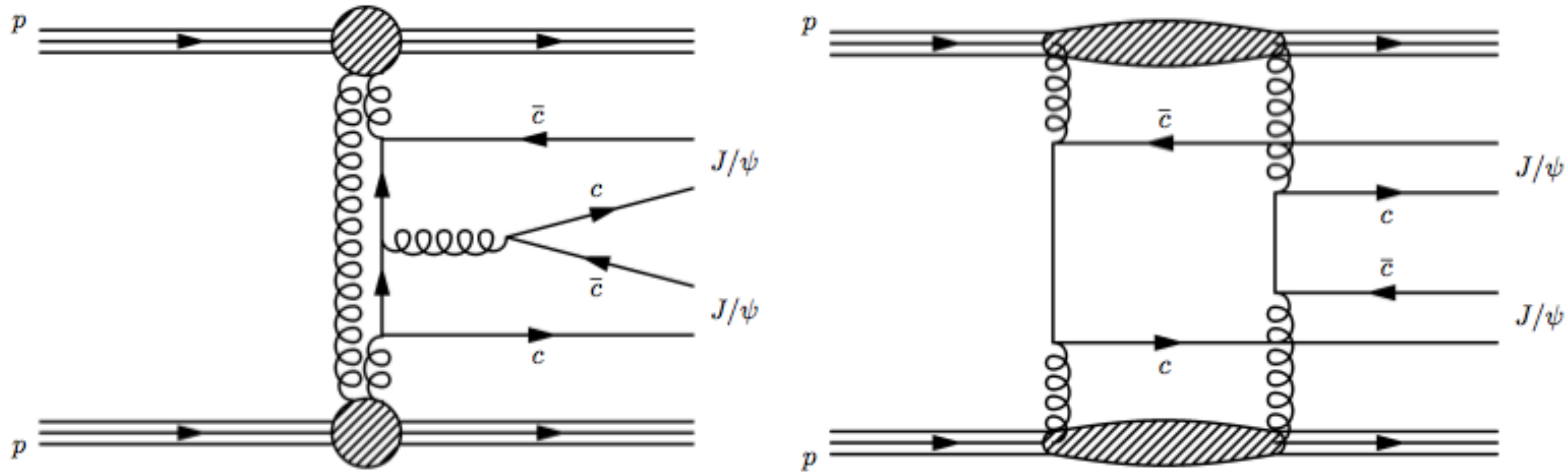
+ non-abelian diagrams + ‘symmetric’ gluons in the pomeron
(see Harland-Lang, Khoze, Ryskin, arXiv: 1409.4785)







Double J/ψ production

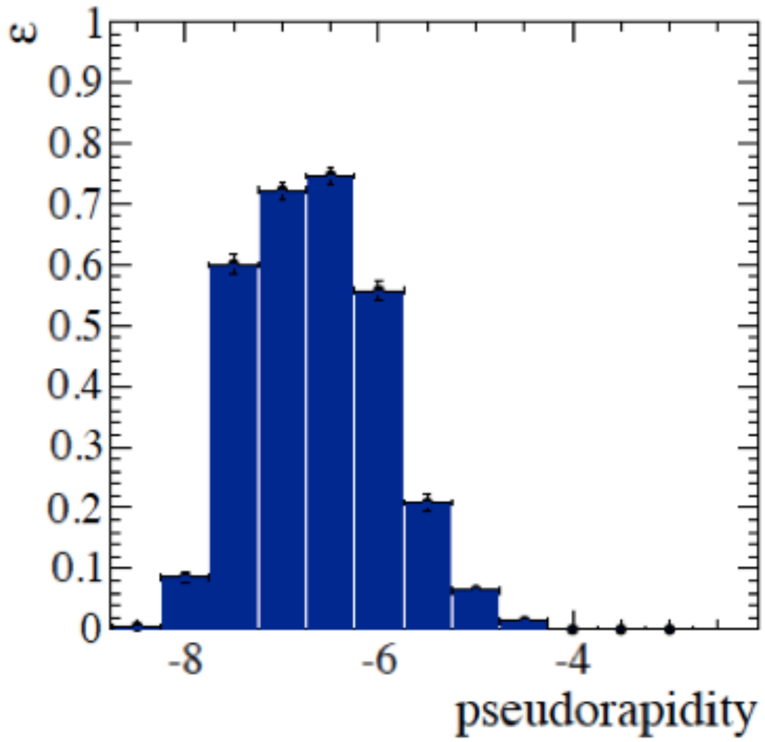


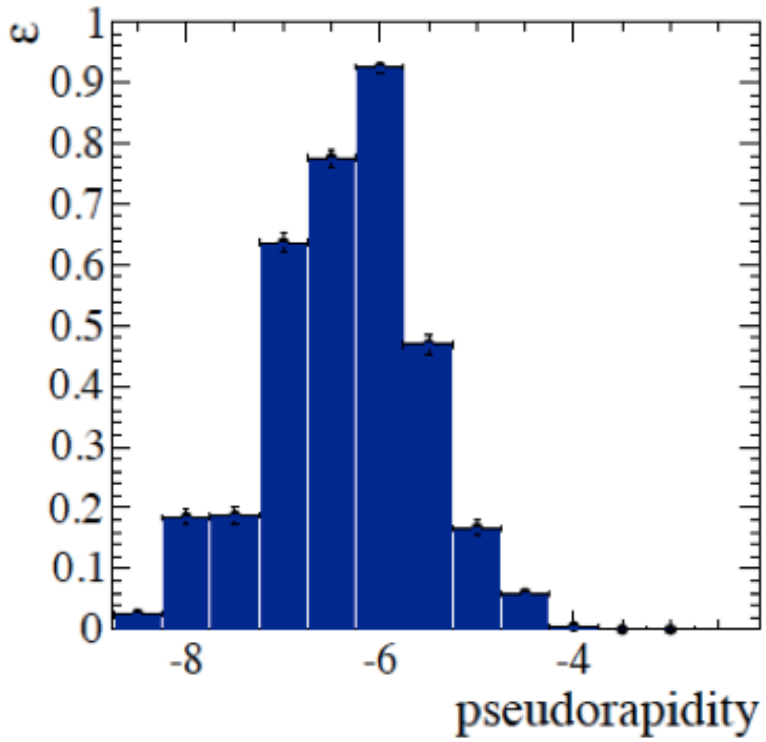
Final state theoretically studied in diphoton production (linear collider) but not through double pomeron exchange (hadron collider)

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

Estimated improvement in pseudorapidity

Checked with particle gun, down to very low p_T values





Efficiency to detect 5 or more hits extends beyond nominal pseudorapidity coverage, due to showering