Central Exclusive Production in pp collisions at LHCb

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on behalf of the LHCb collaboration

Poetic VI, Palaiseau, France.
7th – 11th September 2015.

Outline

- Theoretical background and motivation
- Experimental signatures

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

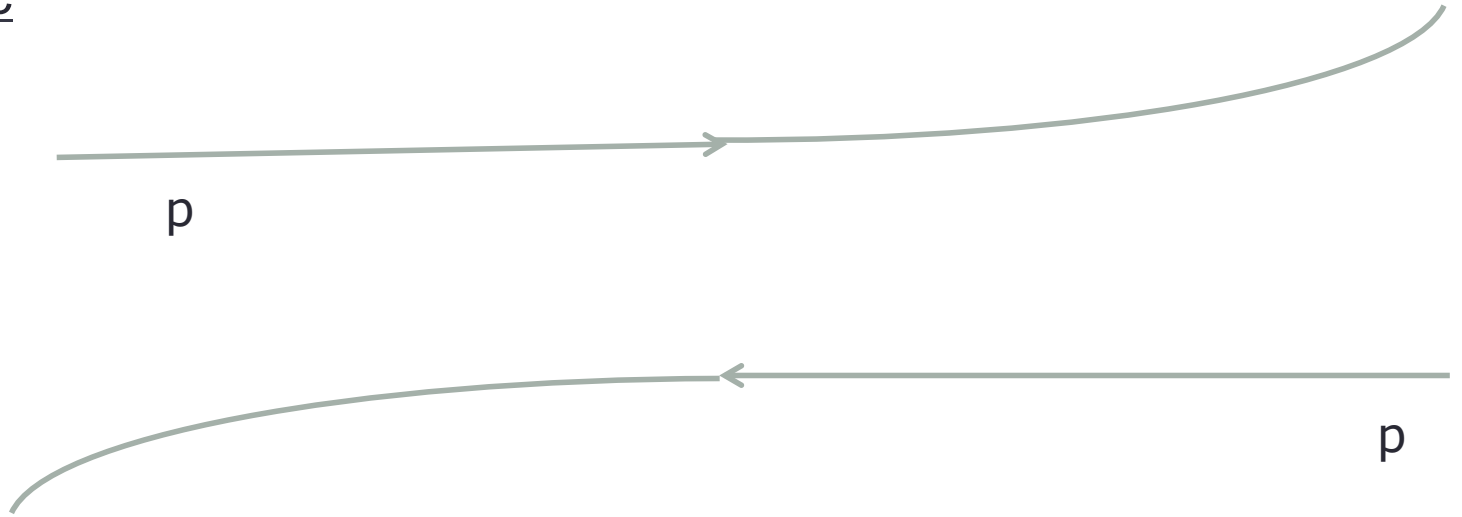
- Future Prospects

Theoretical background and motivation

- Understanding the vacuum
- Colourless objects in QCD (pomeron, reggeon, odderon)
- Search for new phenomena
  - exotics,
  - saturation,
  - glueballs.

Physics of the Vacuum

Elastic

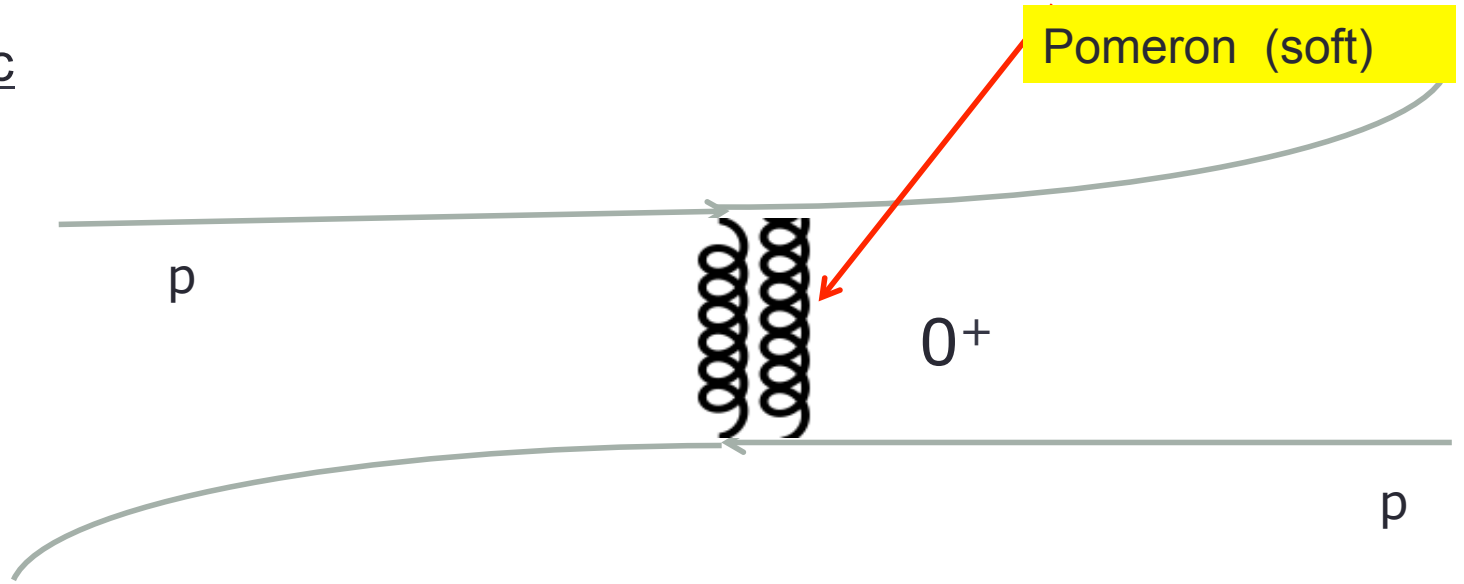


It's QCD – but not as we normally see it. It's colourless

$\sigma_{elastic}$ ≈ 40mb
$\sigma_{diffractive}$ ≈ 10mb
$\sigma_{inelastic}$ ≈ 60mb

Physics of the Vacuum

Elastic

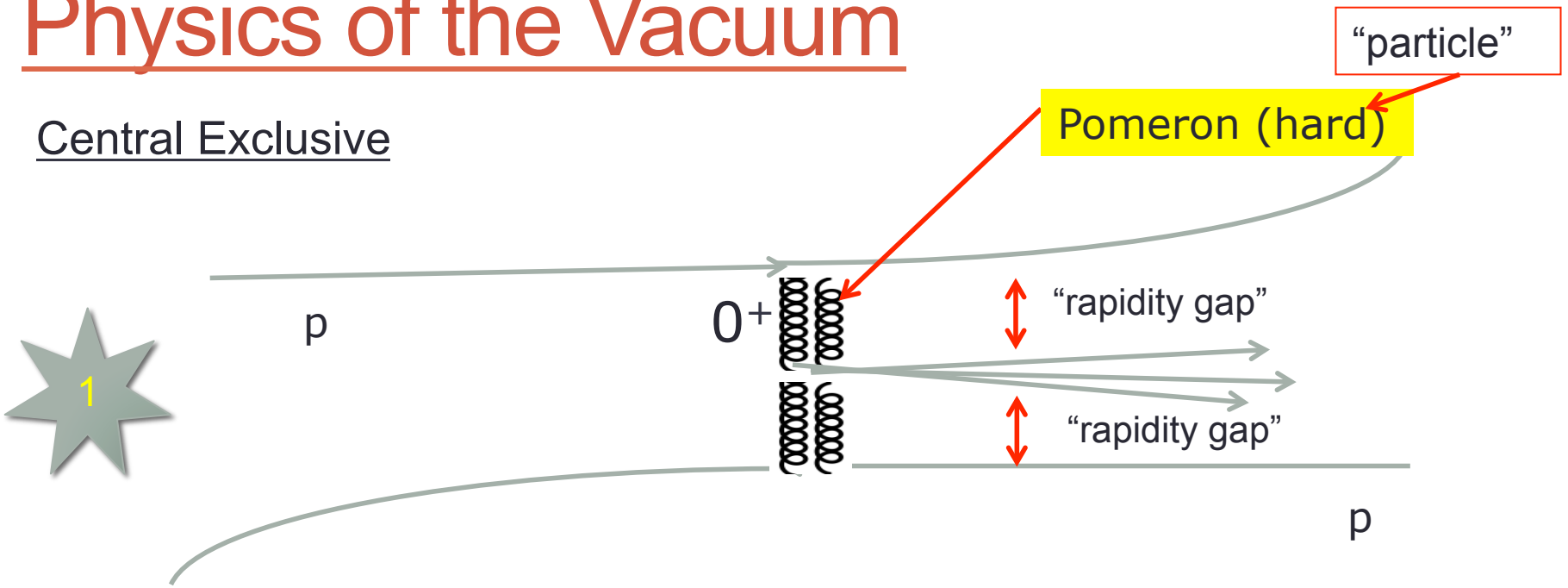


It's QCD – but not as we normally see it. It's colour-free

$\sigma_{elastic} \approx 40mb$
$\sigma_{diffractive} \approx 10mb$
$\sigma_{inelastic} \approx 60mb$

Physics of the Vacuum

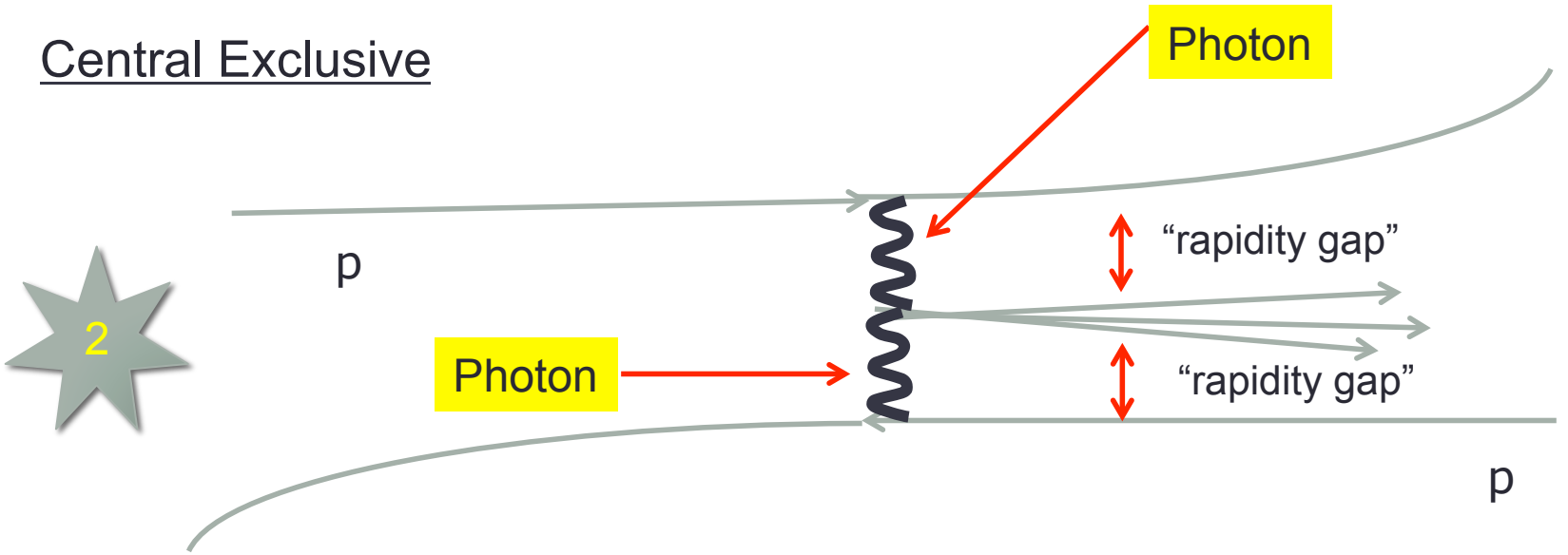
Central Exclusive



Double Pomeron Exchangle: $\chi_c, f_0, f_2, \eta\eta, J/\psi J/\psi$, H

Physics of the Vacuum

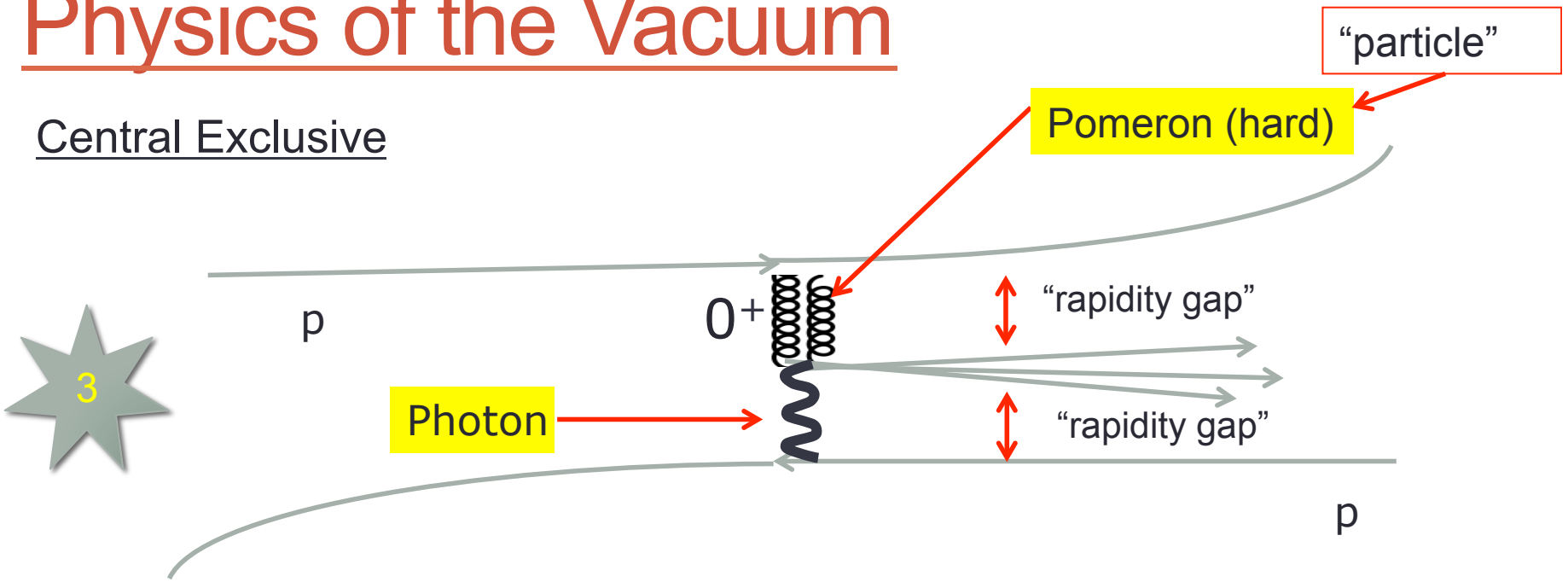
Central Exclusive



QED.

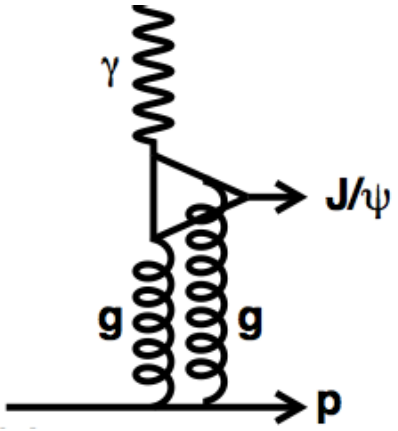
Physics of the Vacuum

Central Exclusive



Photoproduction of vector mesons

Photo-production cross-section

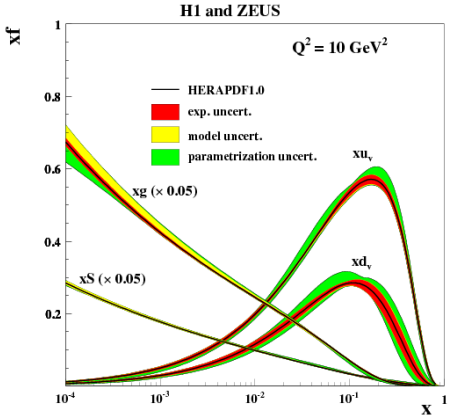


$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(\gamma^* p \to J/\psi\, p)\Big|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} x g(x,\bar{Q}^2)\right]^2 \left(1 + \frac{Q^2}{M_{J/\psi}^2}\right)$$

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

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

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

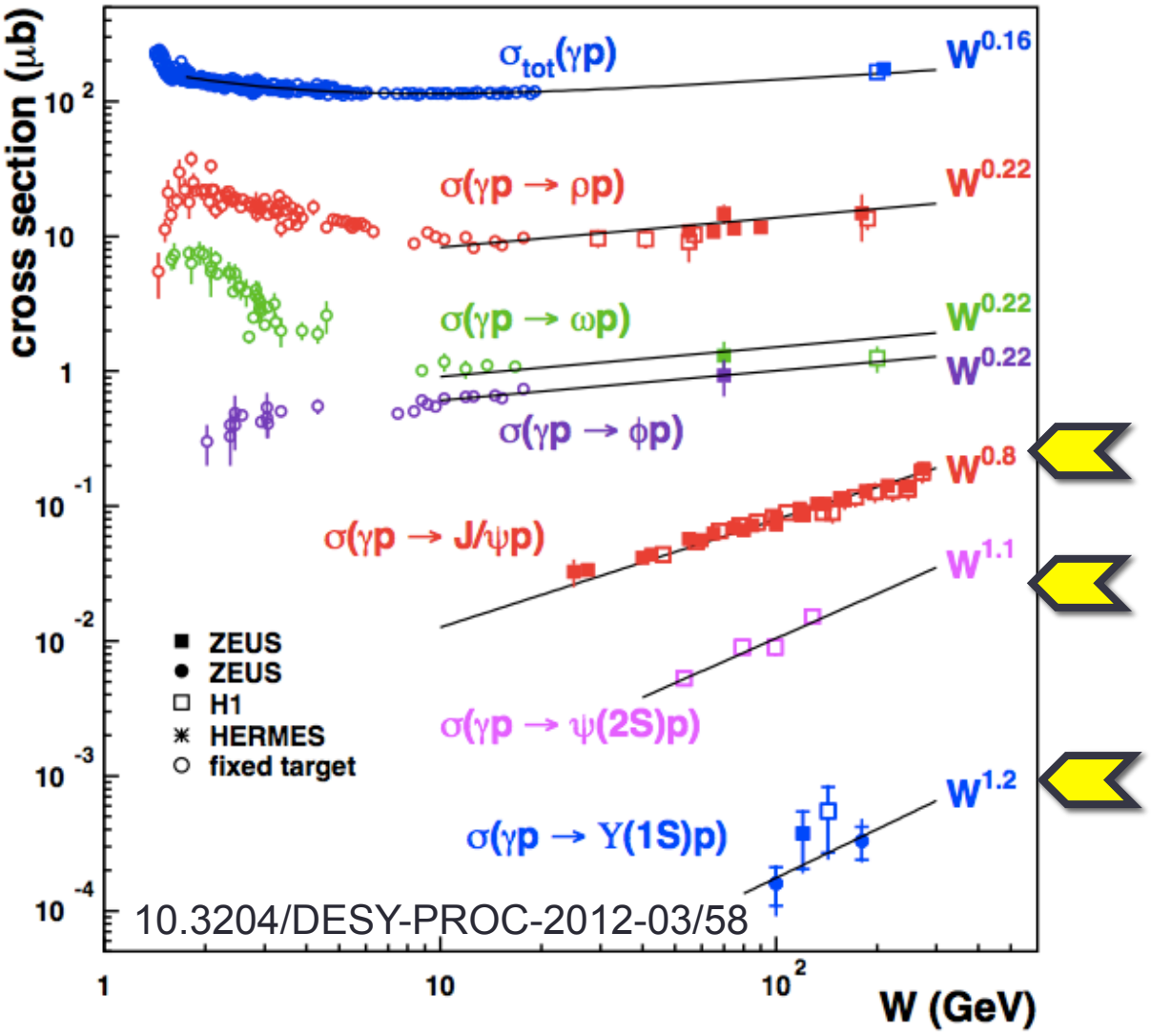
[3] Ryskin M G, Roberts R G, Martin A D and Levin E M 1997 Diffractive J/ψ photoproduction as a probe of the gluon density *Z. Phys.* C **76** 231 (arXiv:hep-ph/9511228)

[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.

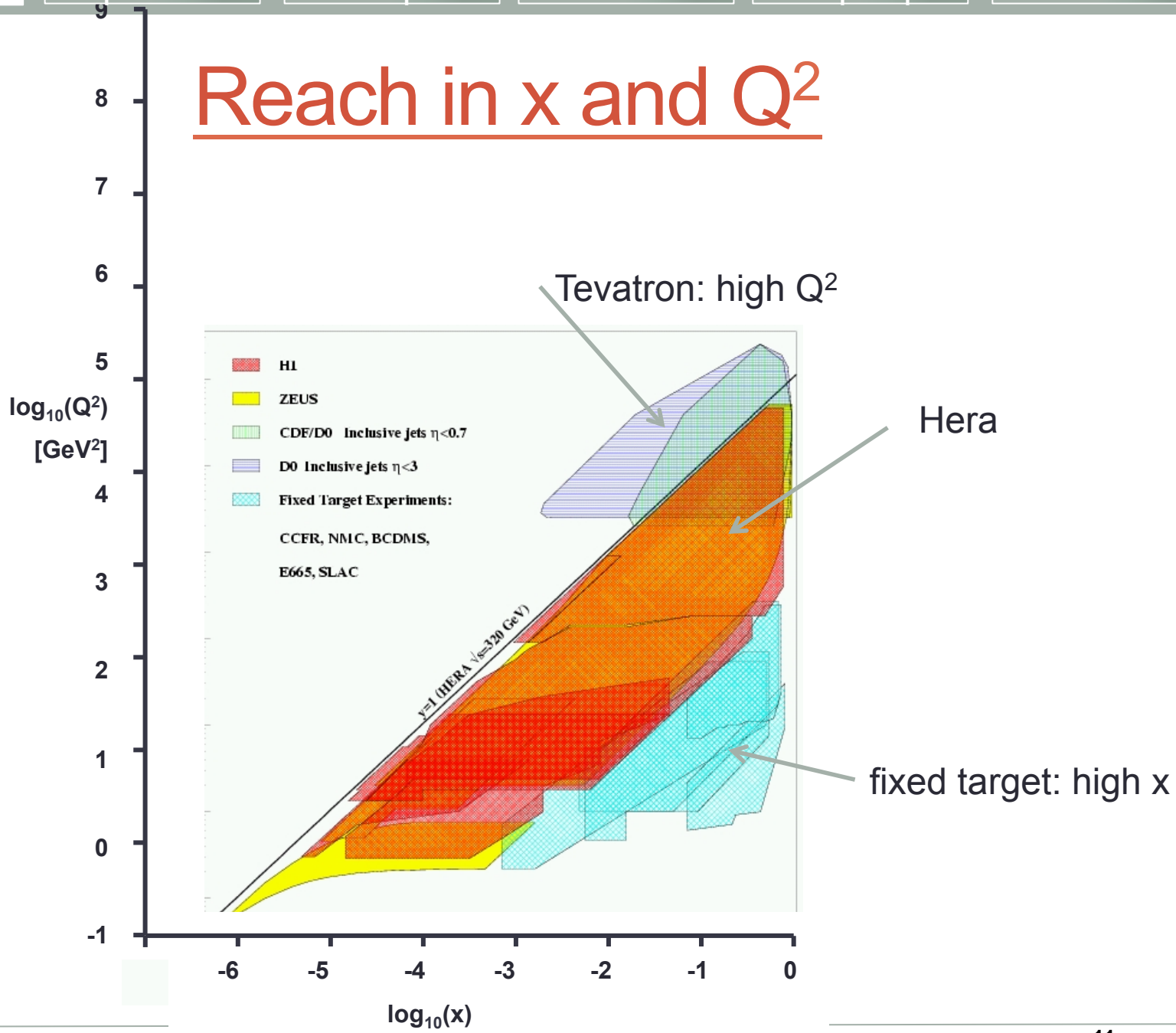
HERA vector meson photo-production results

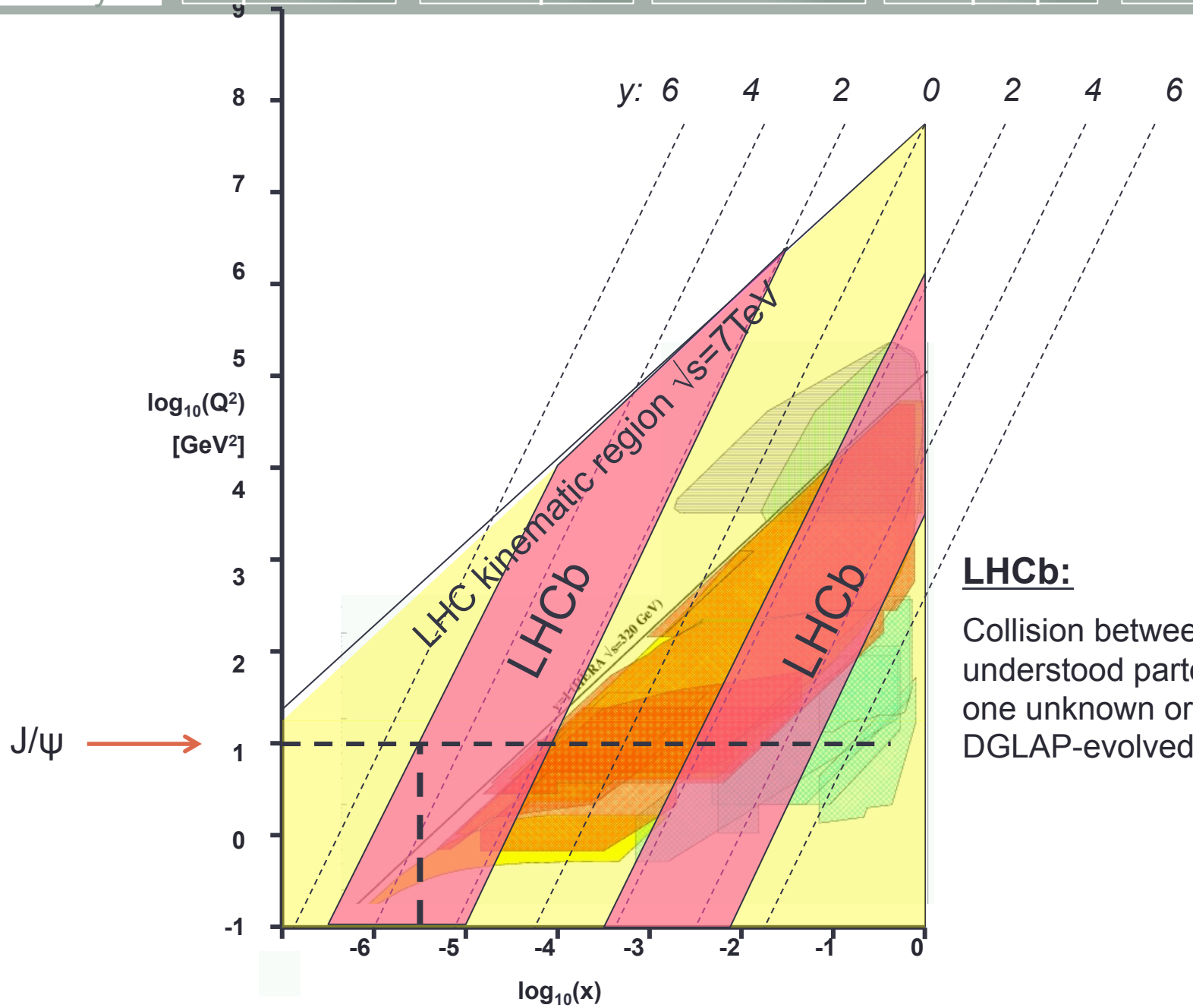
Note:

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



Reach in x and Q^2



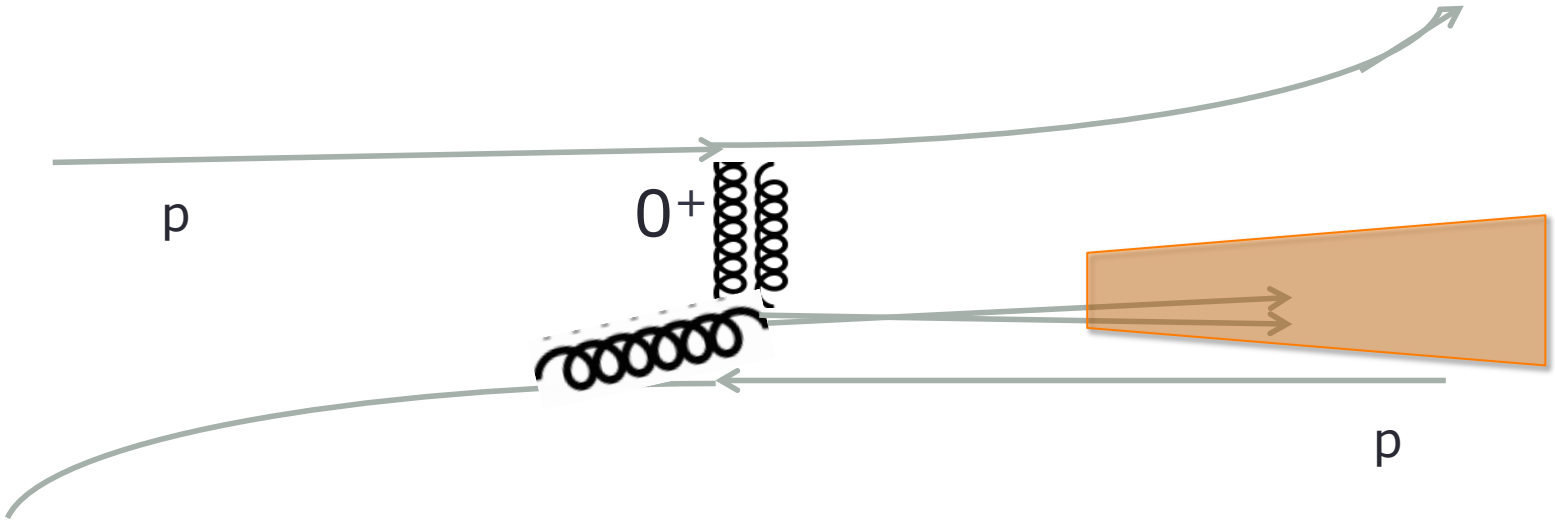


LHCb:

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

Experimental Signatures

Find rapidity gap

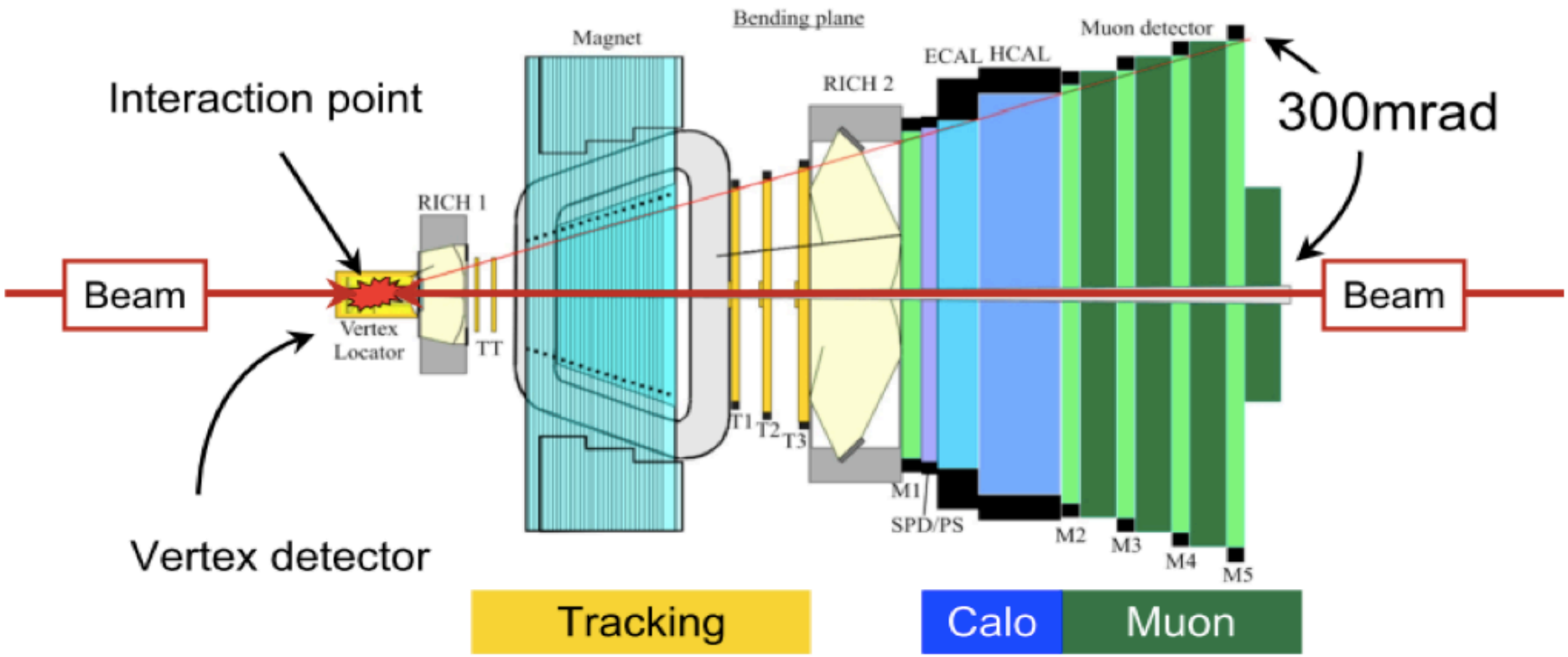


Detect ‘central’ system including presence of **rapidity gap**

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

Size of gap you can detect is critical

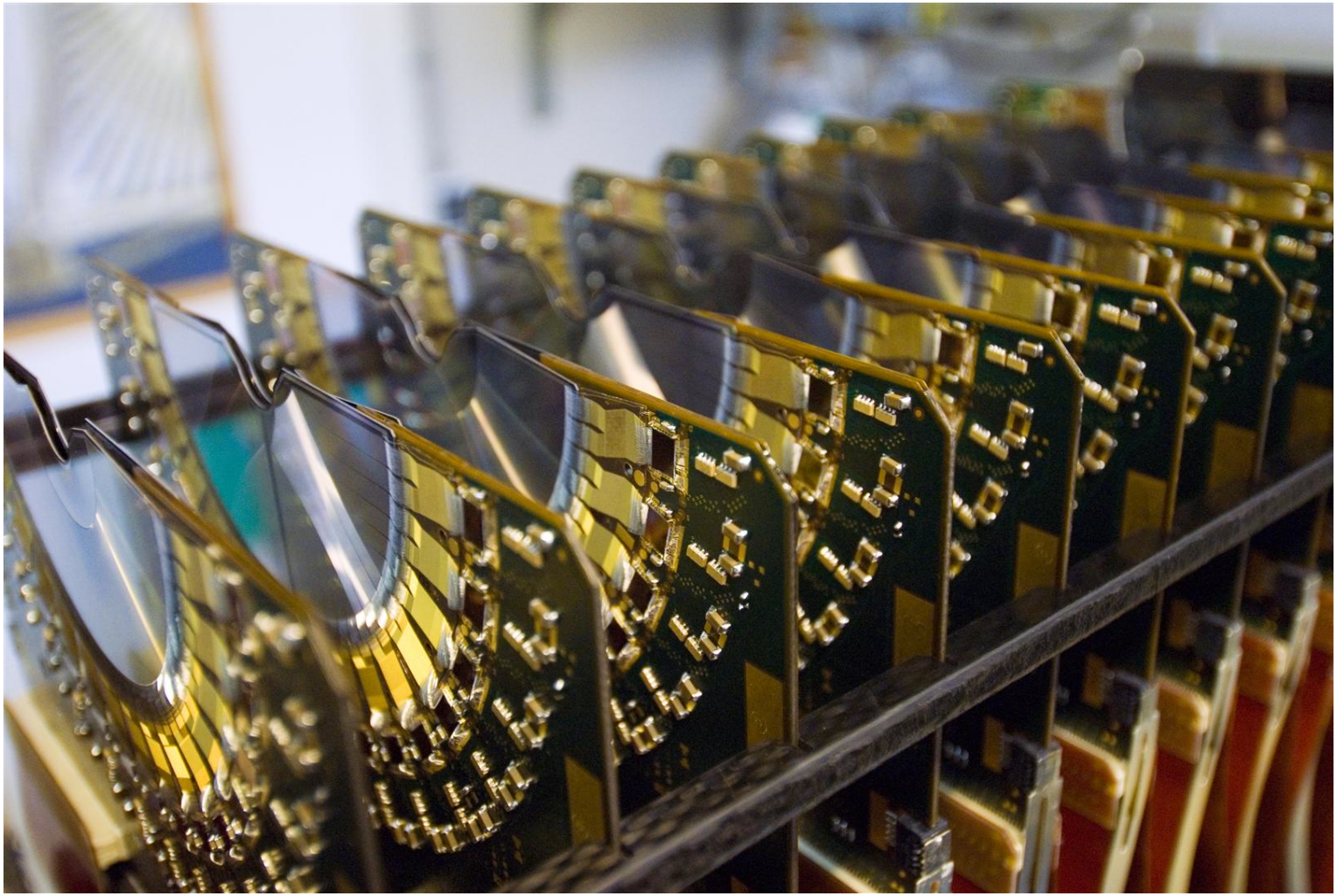
The LHCb detector



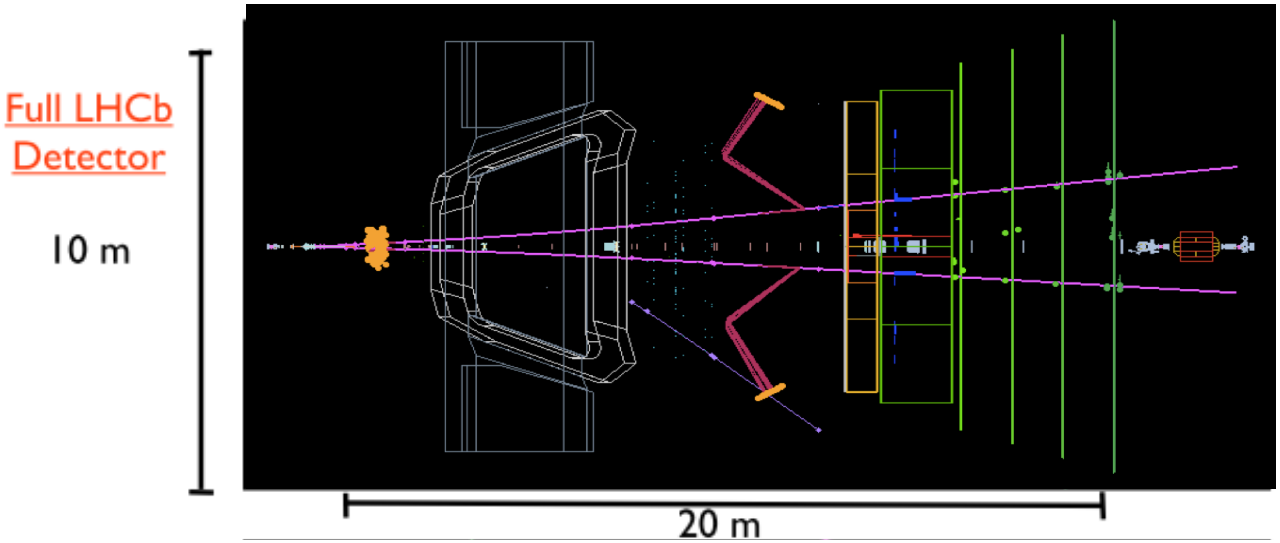
Fully instrumented: $2 < \eta < 5$

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

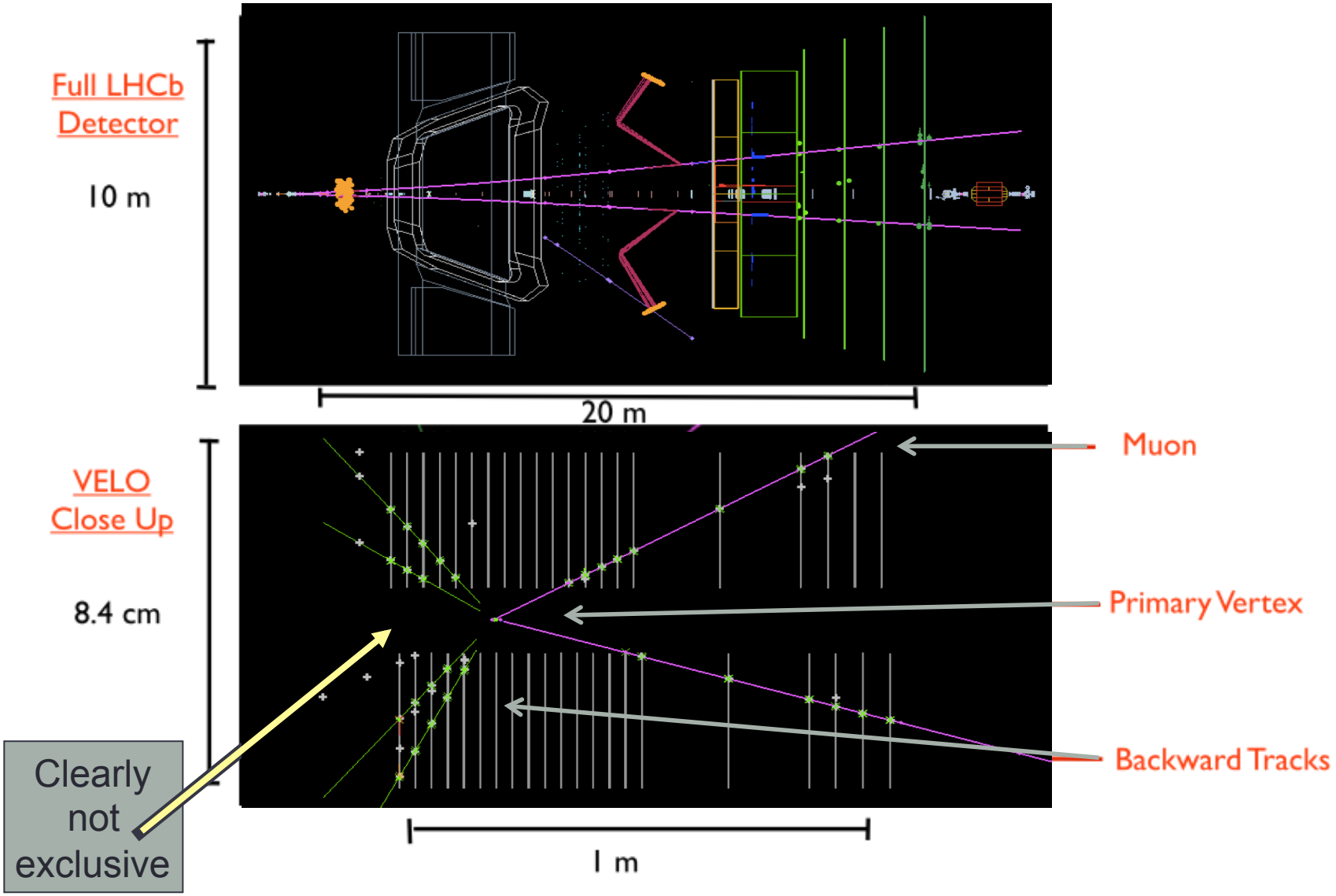
VELO sub-detector



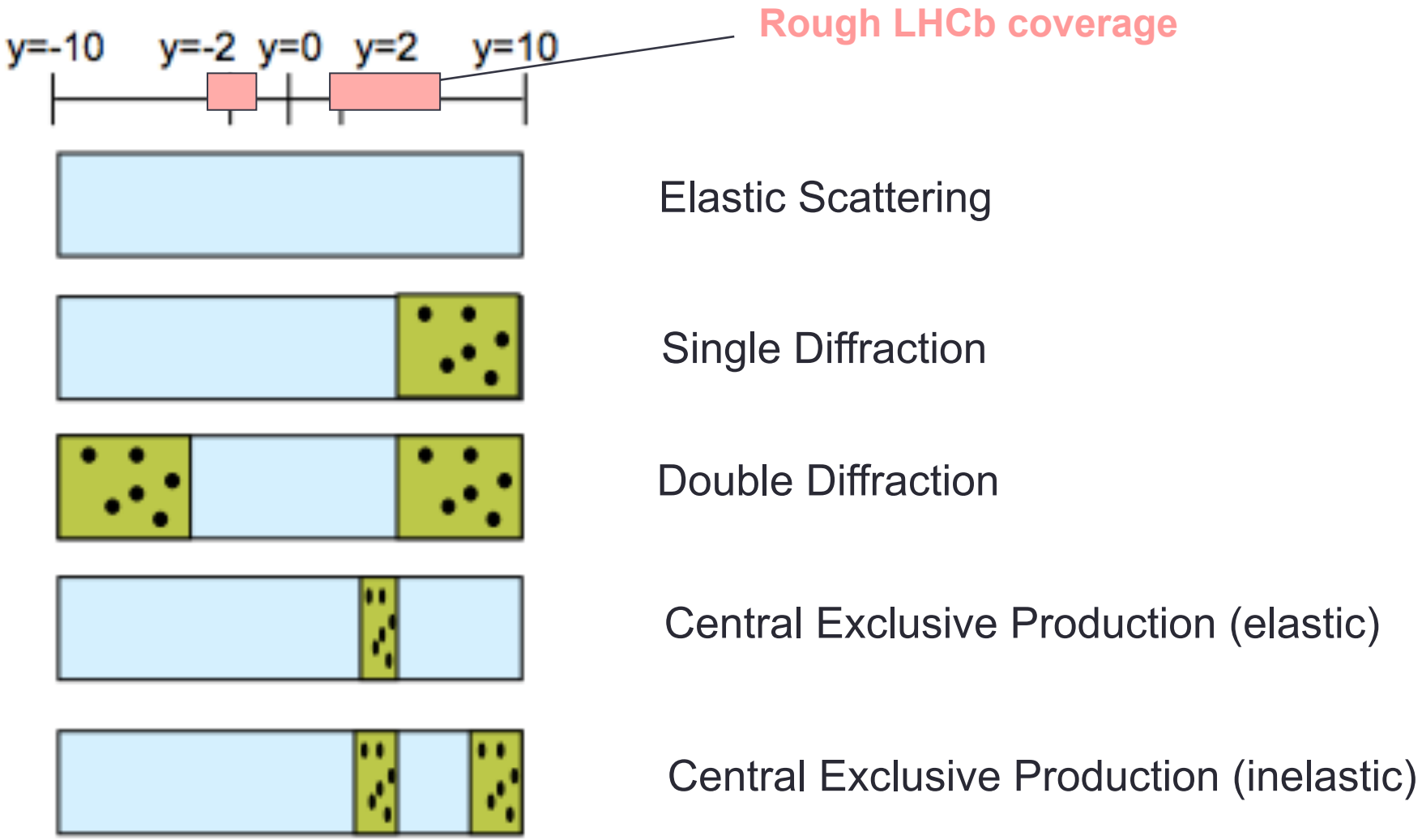
Use of backwards tracks

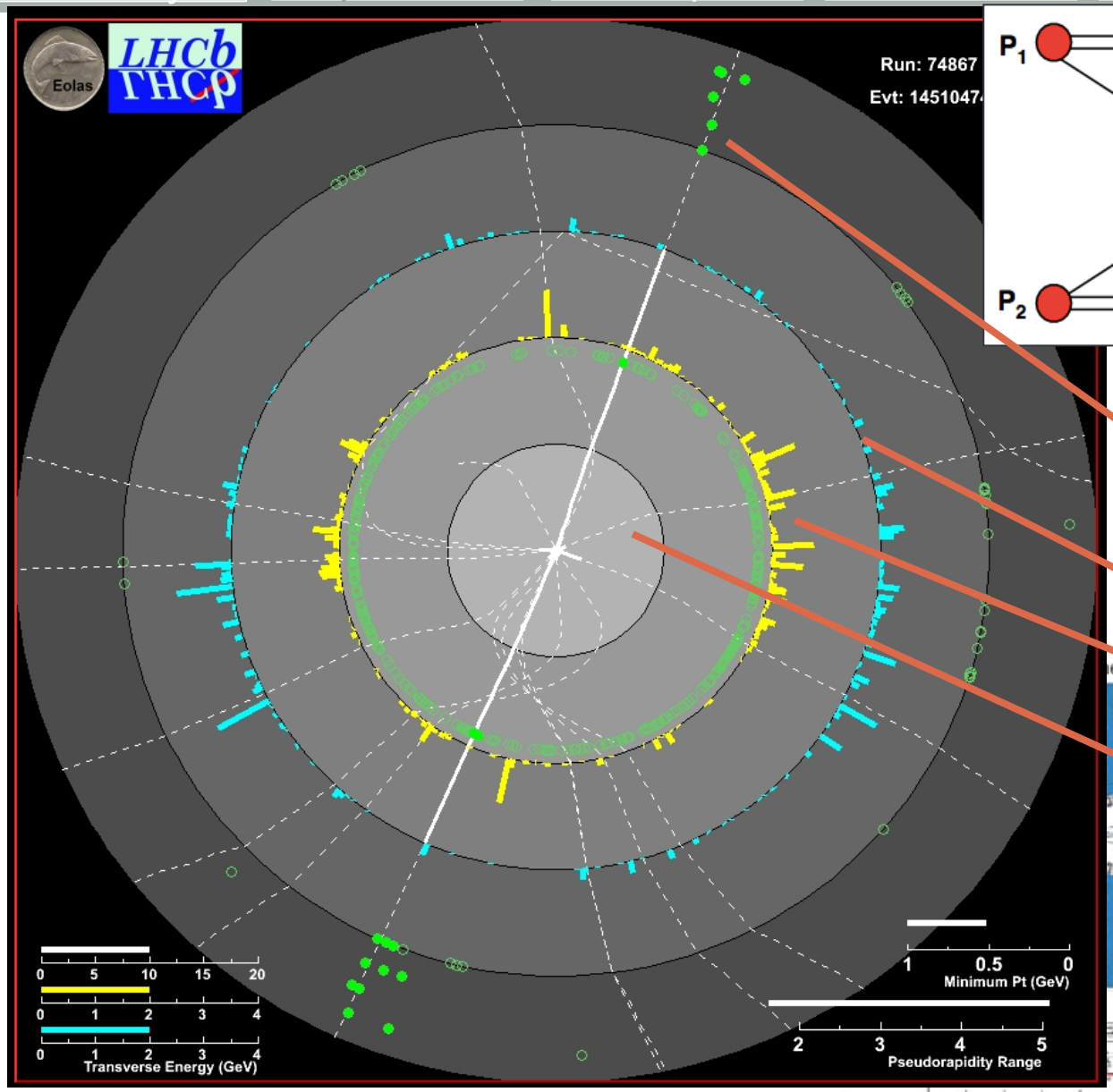


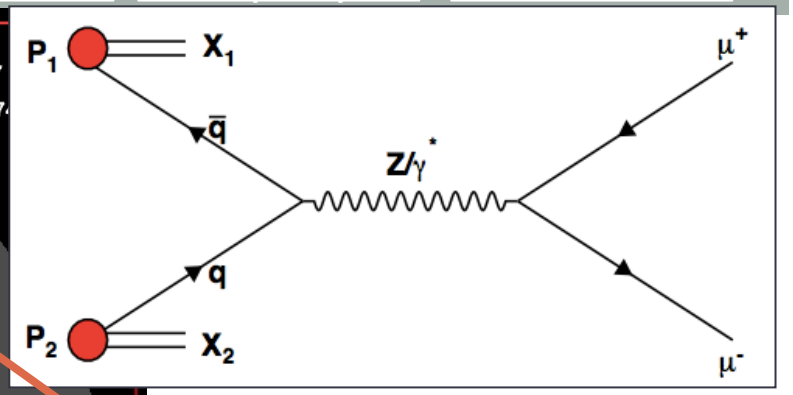
Use of backwards tracks

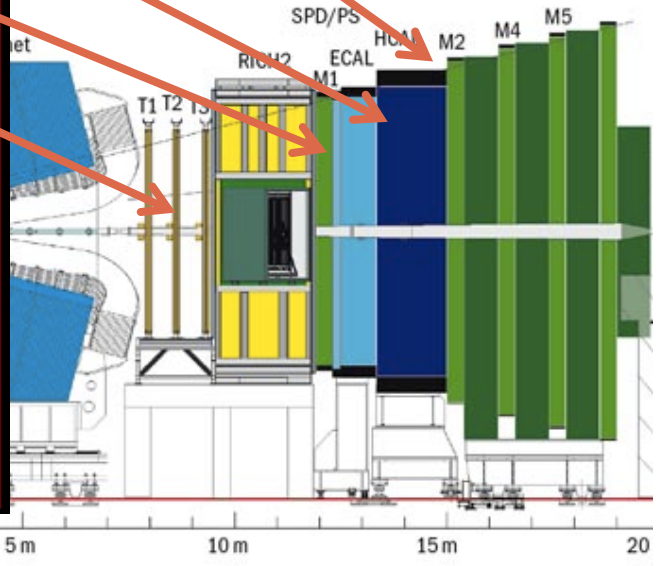


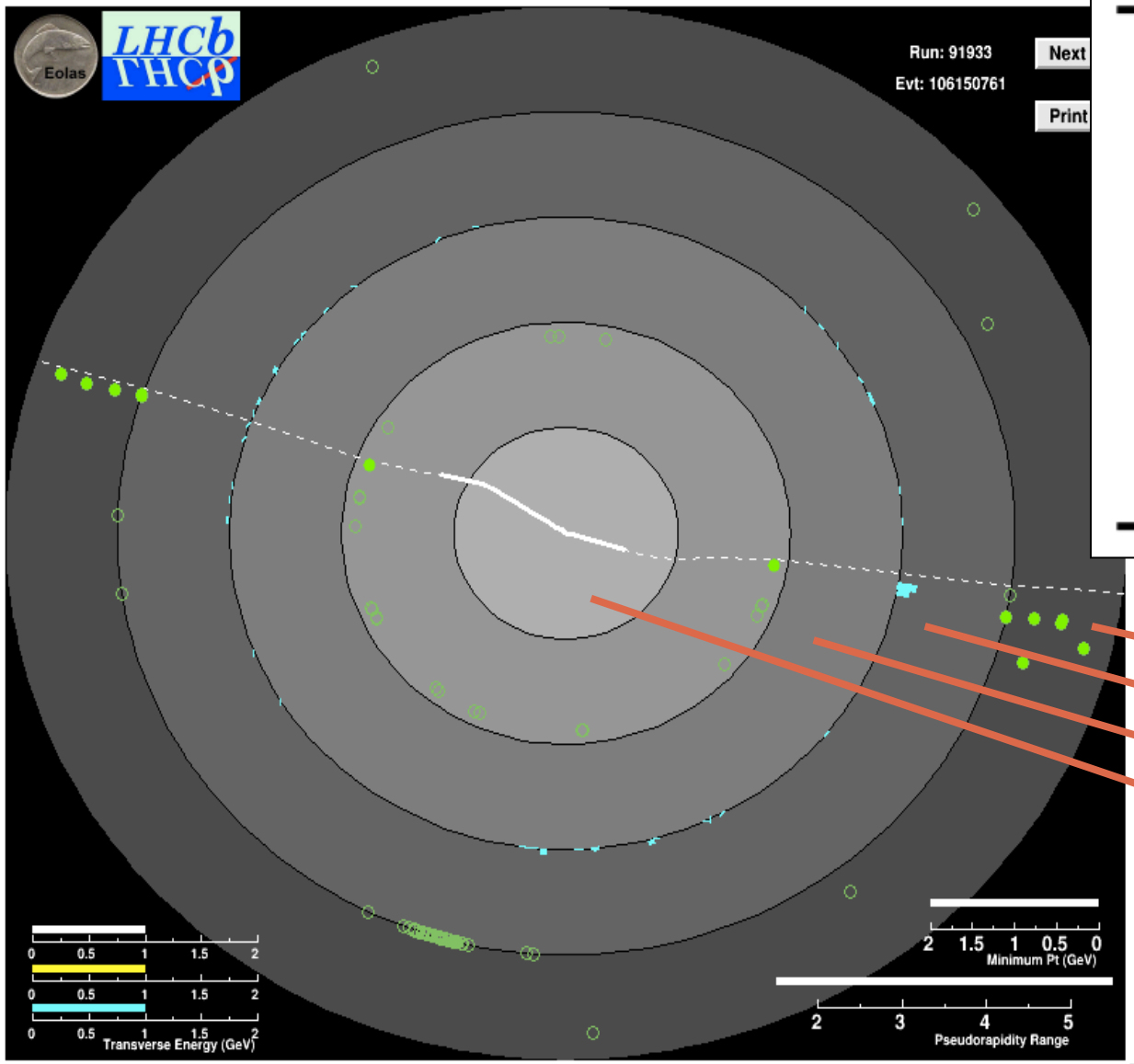
Graphical Representation

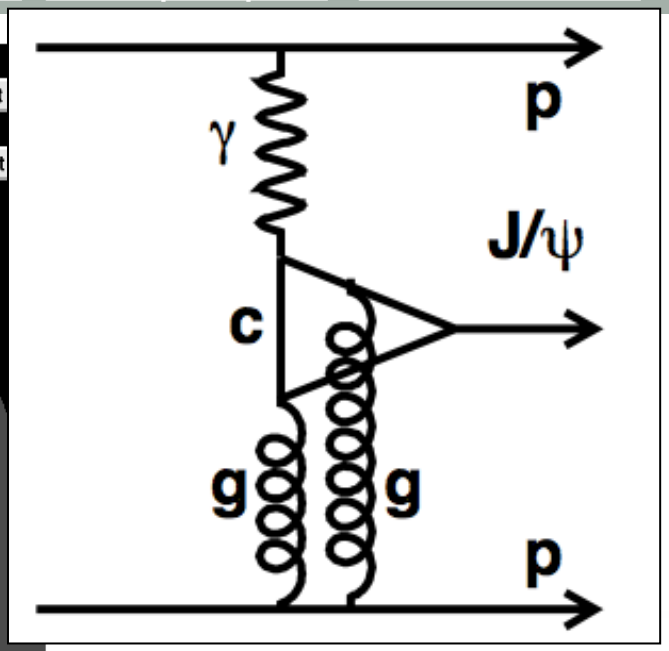


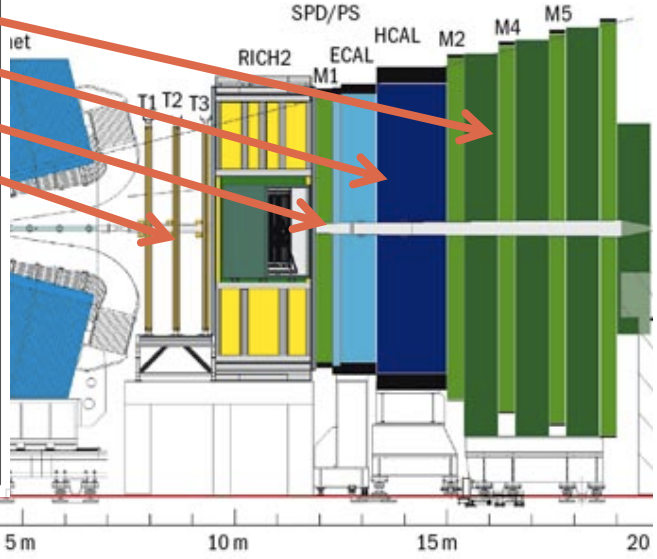

LHCb
Eolas
Run: 74867
Evt: 1451047
0 5 10 15 20
0 1 2 3 4
0 1 2 3 4
Transverse Energy (GeV)
1 0.5 0
Minimum Pt (GeV)
2 3 4 5
Pseudorapidity Range


P1
X1
q̄
Z/γ*
μ+
q
P2
X2
μ-

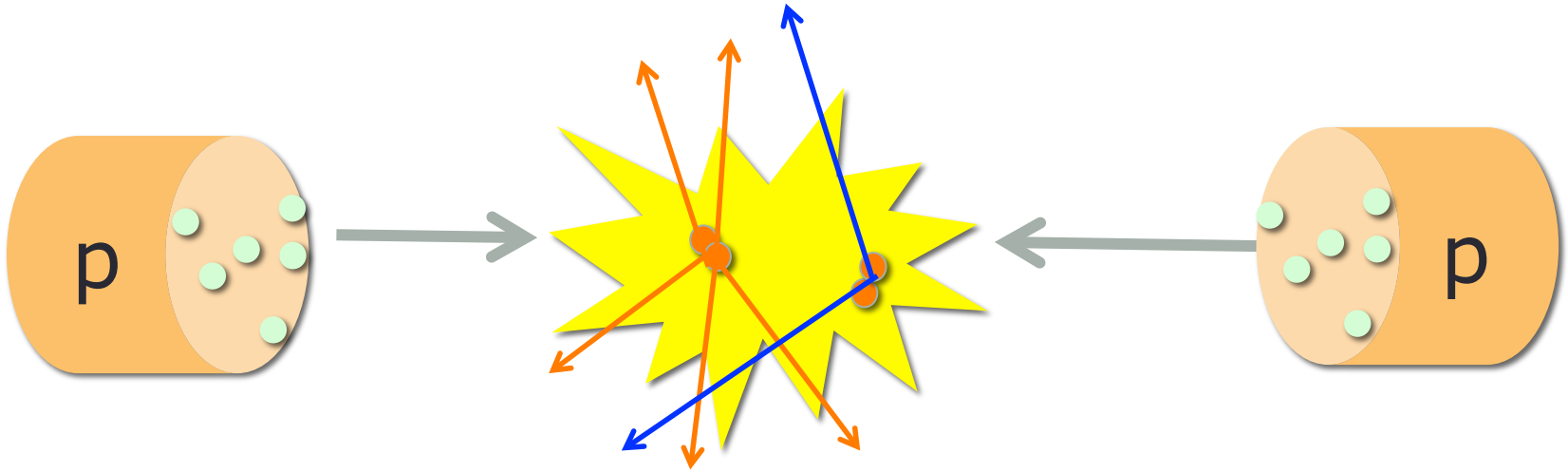

SPD/PS
M2
M4
M5
ECAL
M1
T1 T2
5 m
10 m
15 m
20


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
20

Beam pile-up

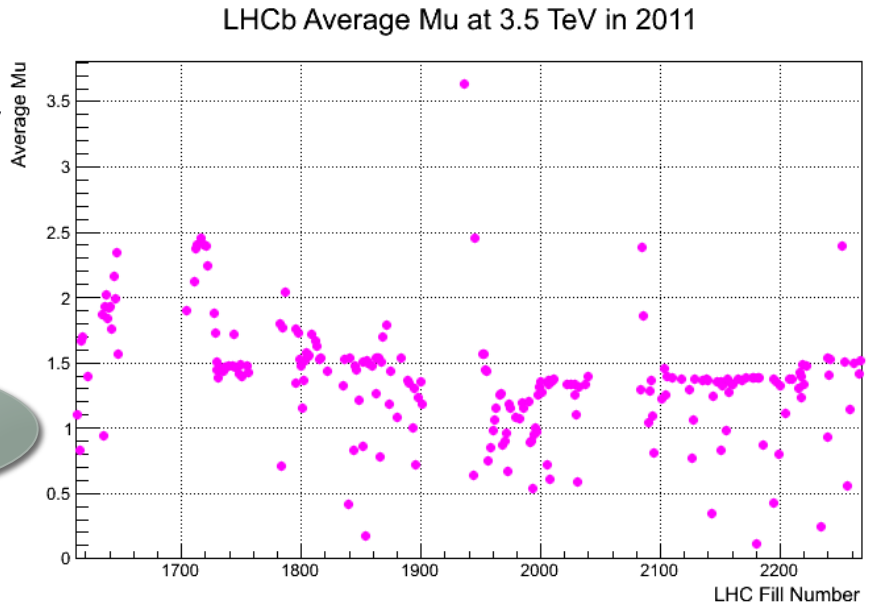


High luminosity requires multiple proton interactions per beam-crossing.

Number of interactions (N) /crossings, distributed

Average #interactions

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

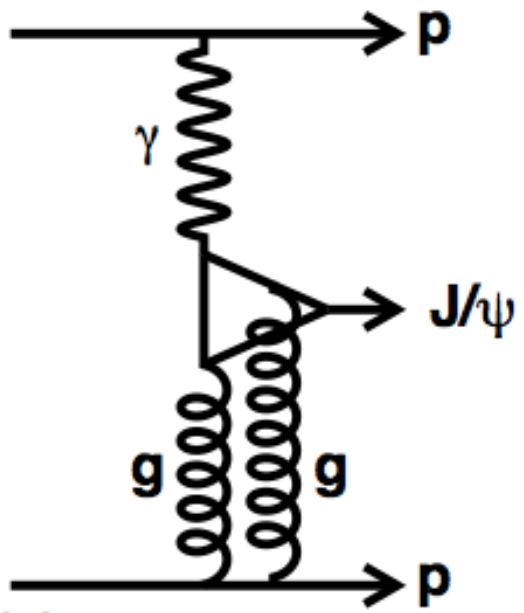


For LHCb in 2011, $\bar{\mu}$=1.4

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

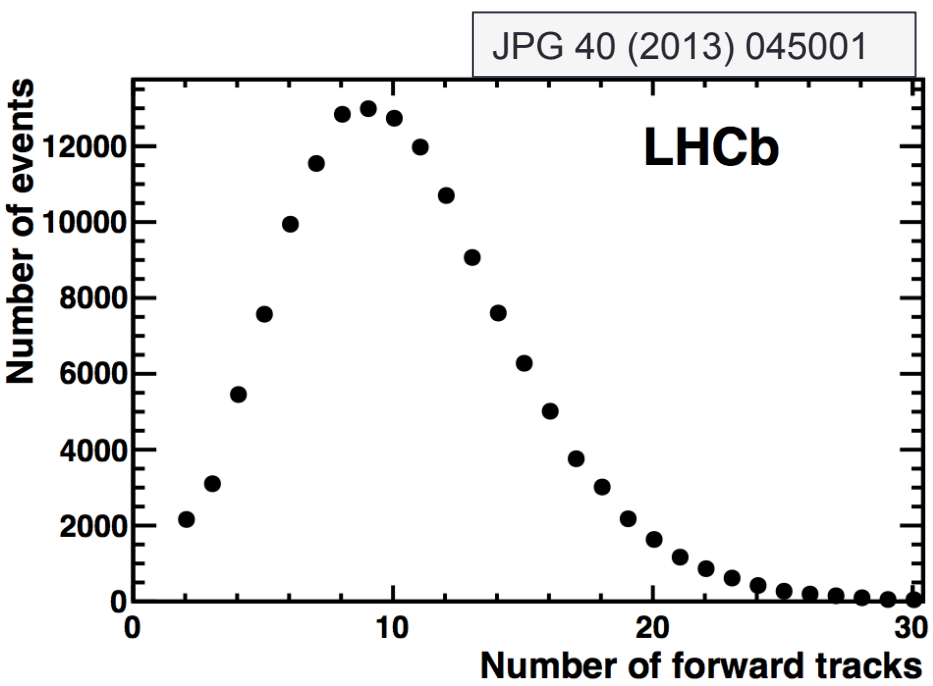
Simple Selection Criteria



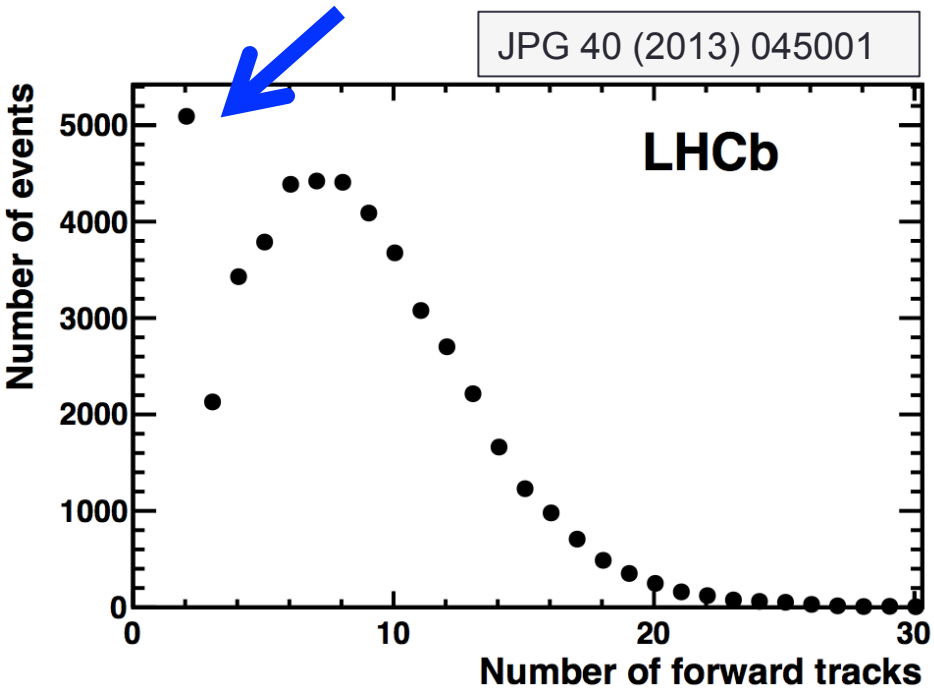
- **Precisely two forward muons**
- **No backward tracks**
- No photons
- p_T^2 of dimuon < 0.8 GeV^2
- Mass of dimuon within 65 MeV of J/ψ or ψ(2S)

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

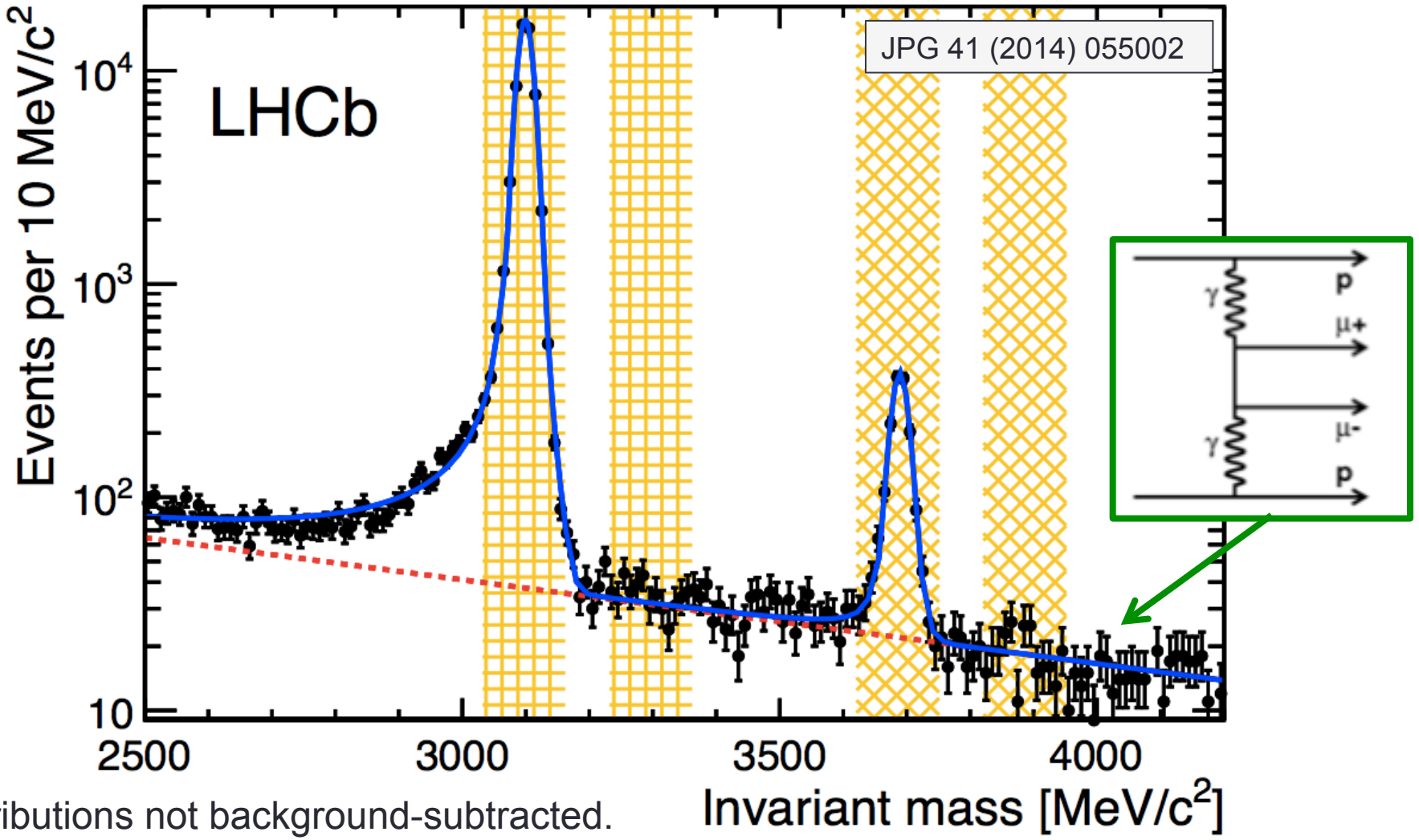


All triggered events



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

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

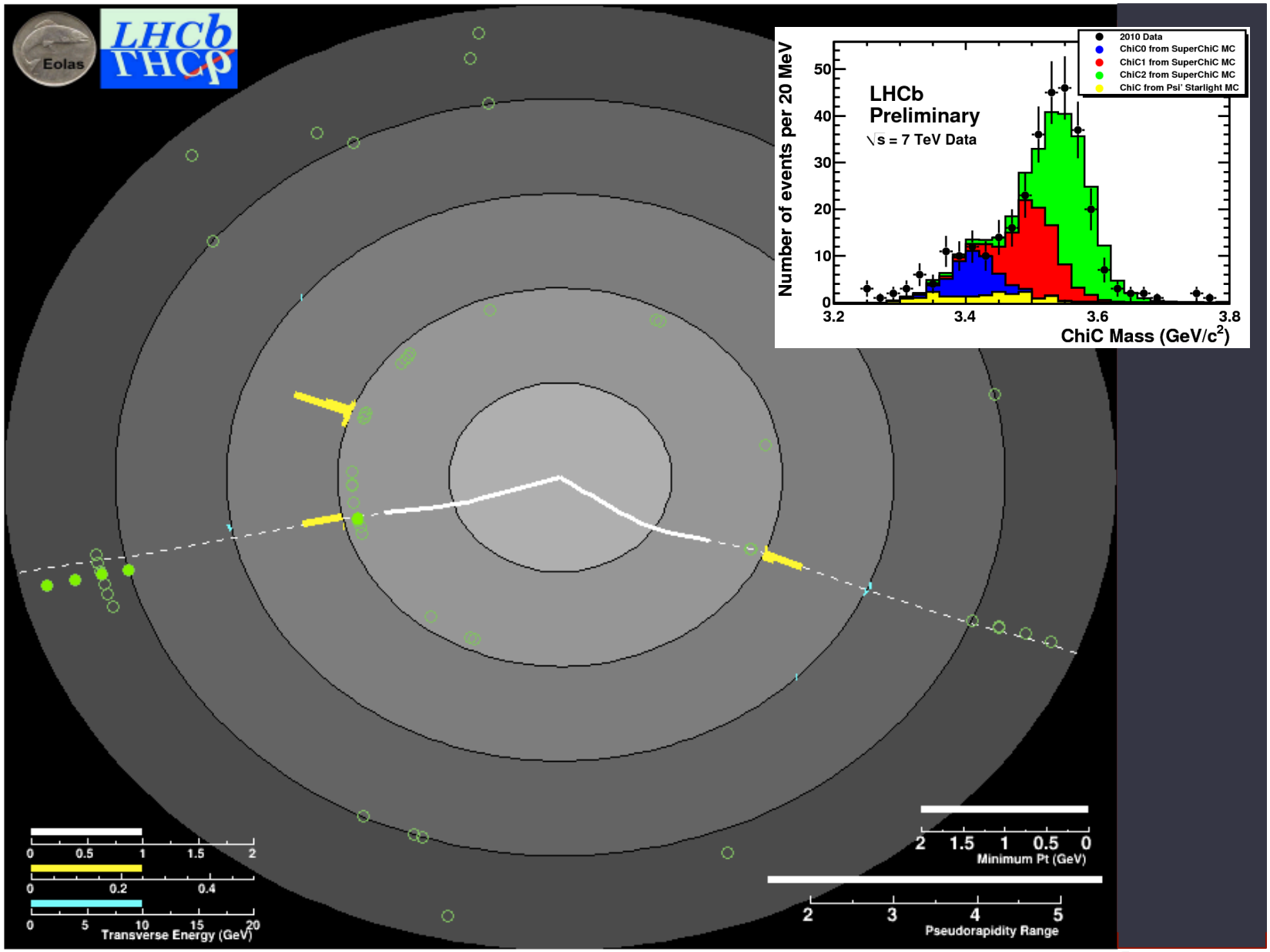
Luminosity

Acceptance (MC)

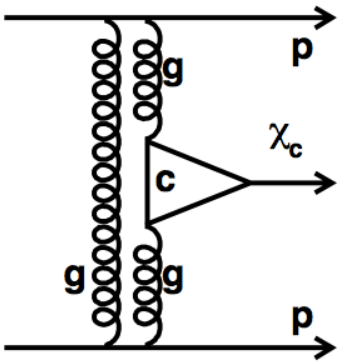
Efficiency: (found from data)
1. Trigger
2. Tracking & muon id.
3. Single interaction beam-crossing

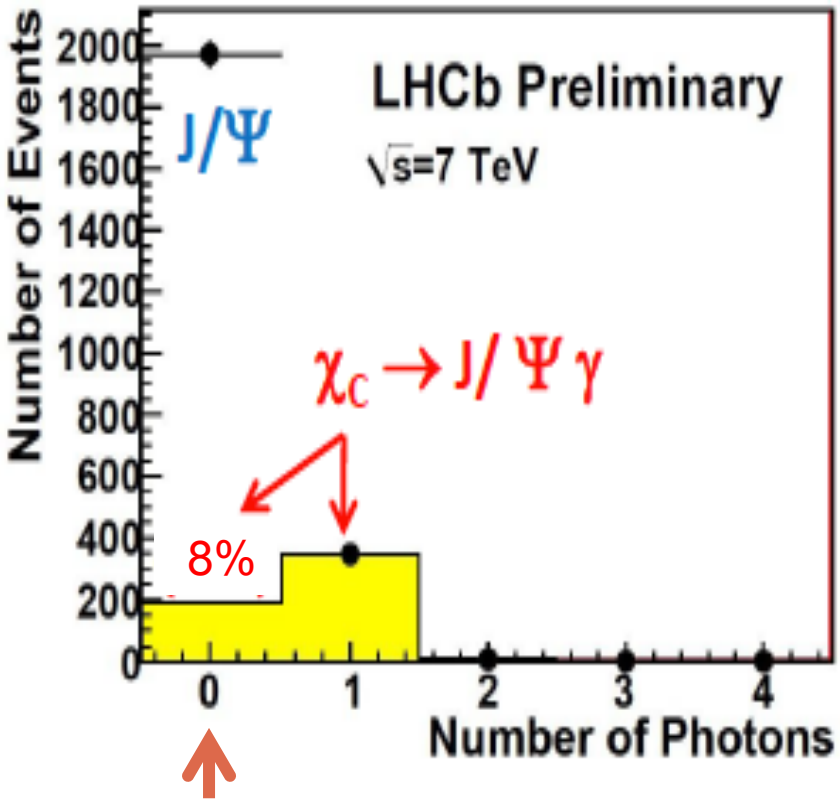
$$P(n) = \mu^n e^{-\mu} / n!$$

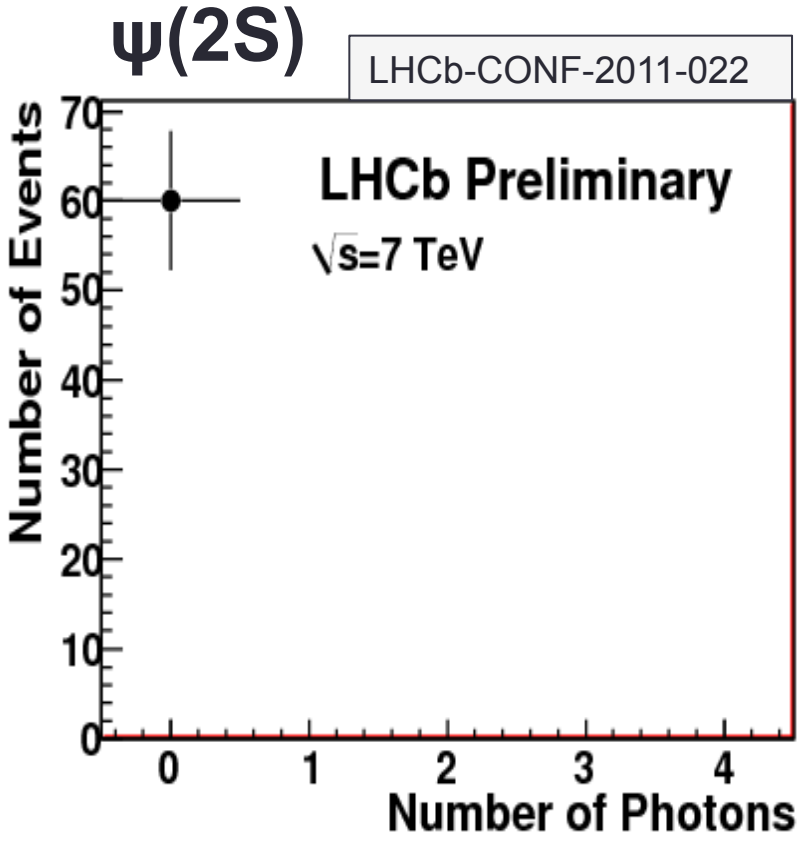
Candidate for χ_c decay to J/ψ+ϒ



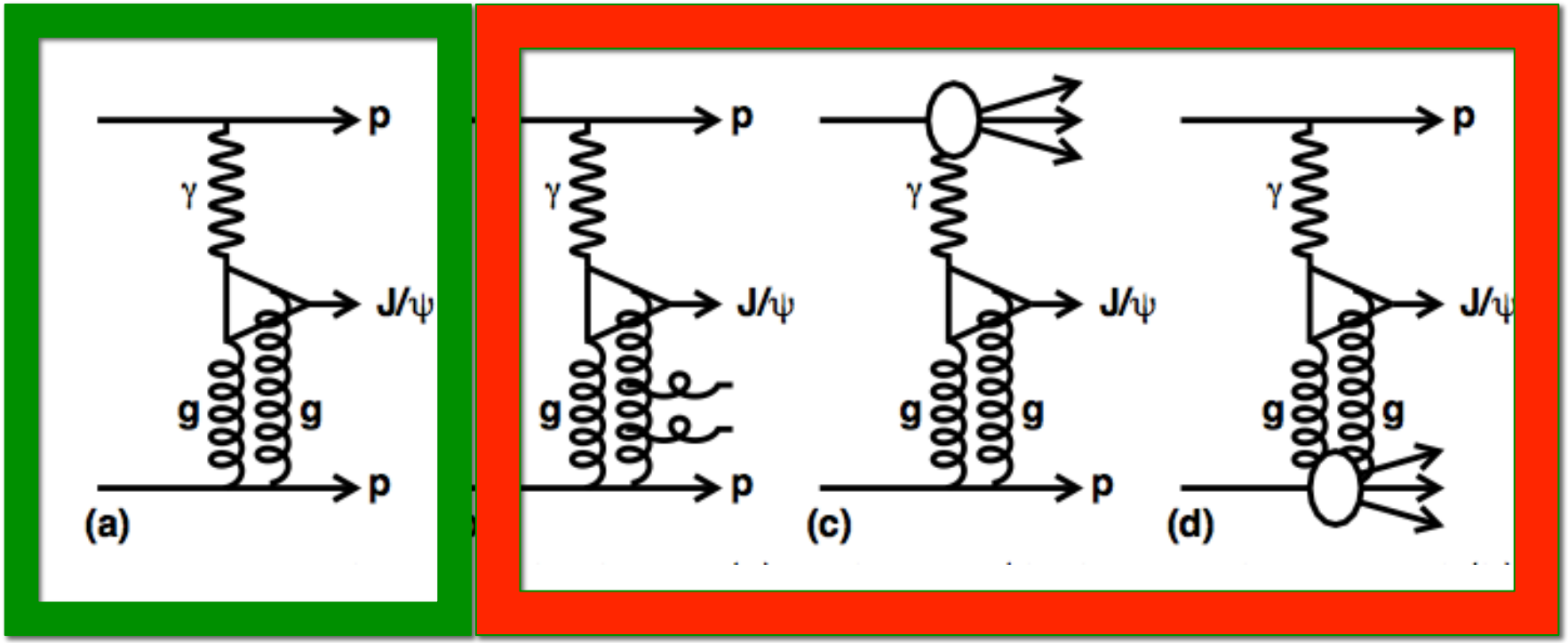
Feed-down background







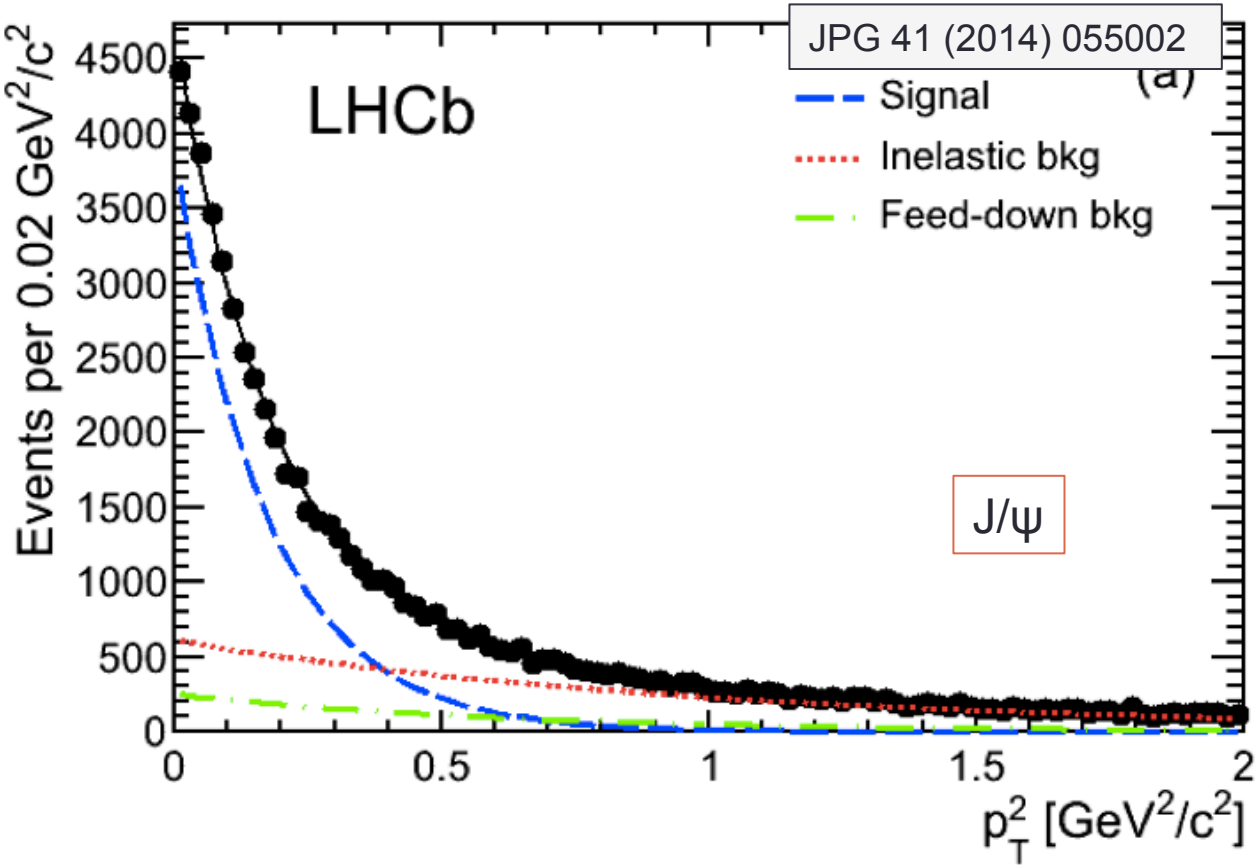
Inelastic background

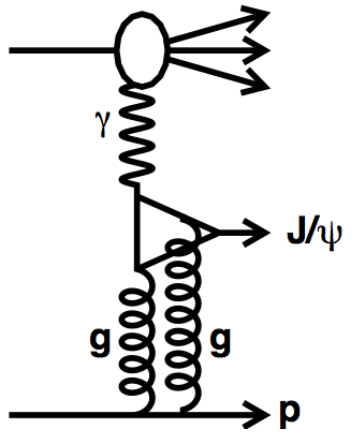


Signal

Background

Inelastic background J/ψ





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

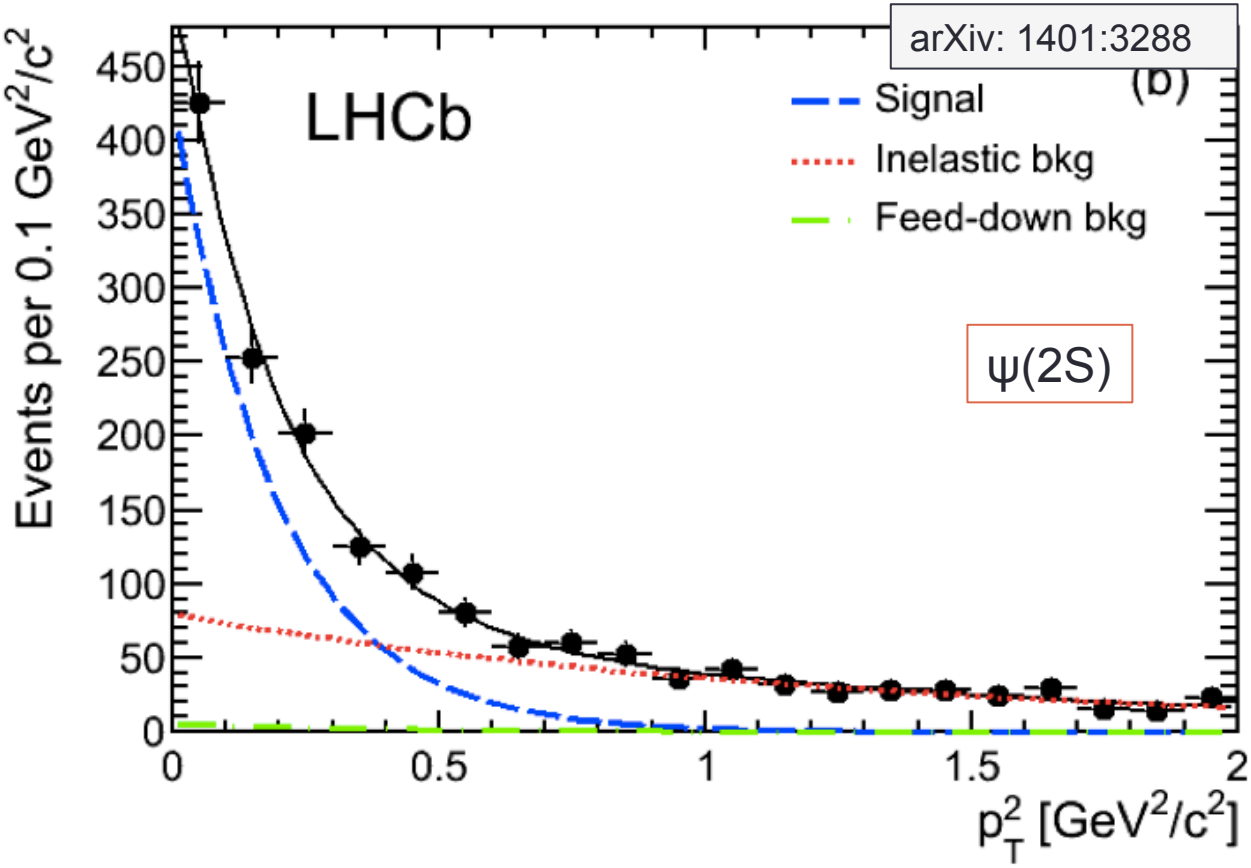
HERA measured:
b_s=4.9 GeV^{-2}
b_{pd}=1.1 GeV^{-2}

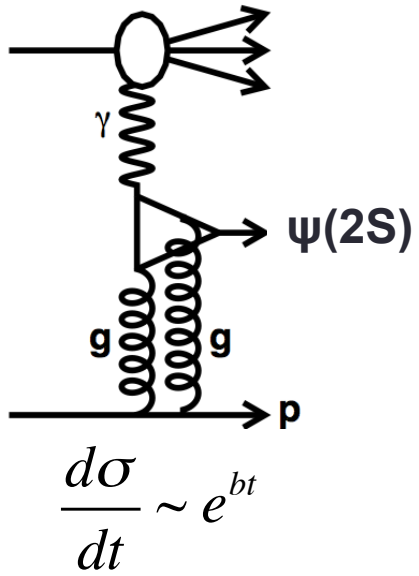
LHCb Expect:
b_s ~ 6 GeV^{-2}
b_{pd}~ 1 GeV^{-2}

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

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

Inelastic background ψ(2S)





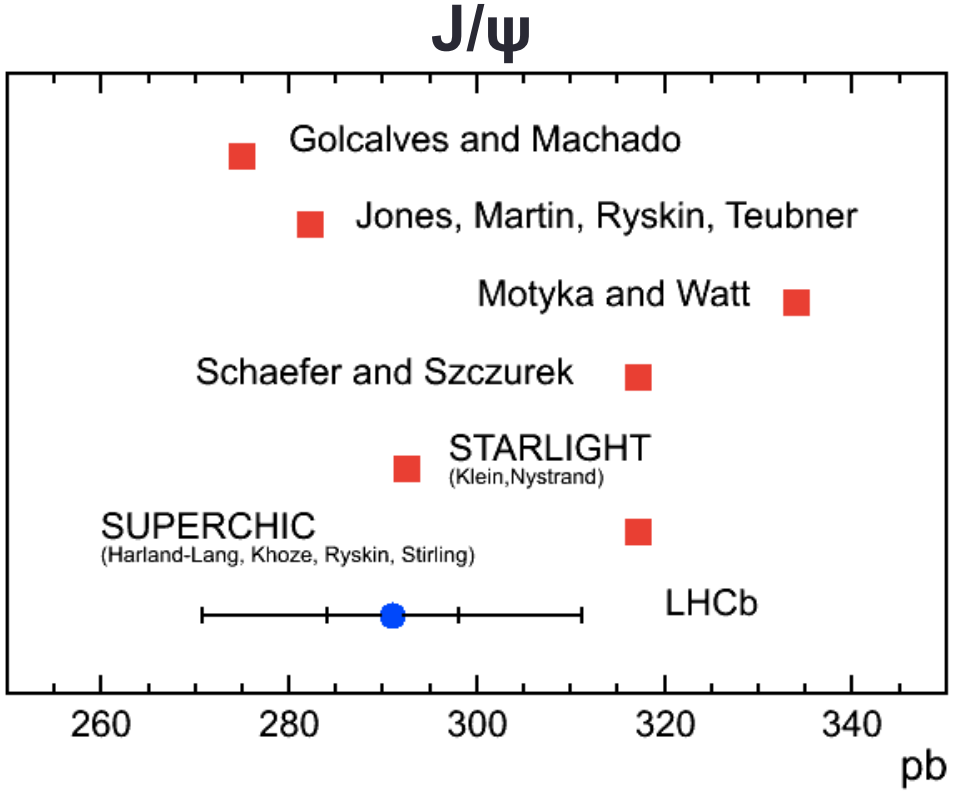
HERA measured:
b_s=4.2 GeV^{-2}
b_{pd}=0.6 GeV^{-2}

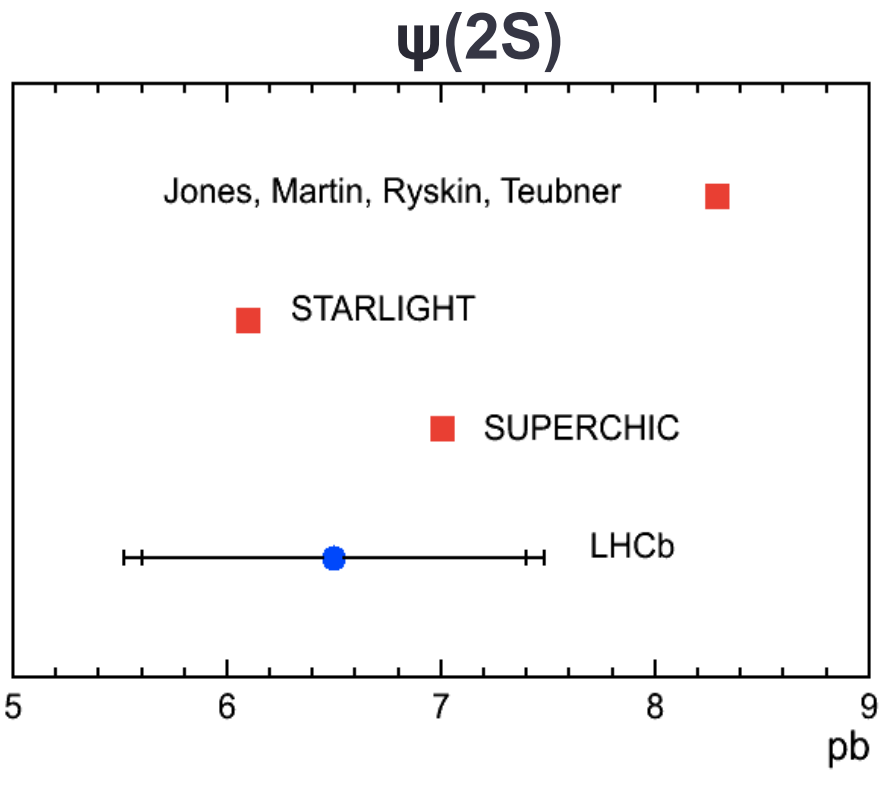
LHCb Expect:
b_s ~ 5.5 GeV^{-2}
b_{pd}~ 0.6 GeV^{-2}

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

Integrated Cross-sections

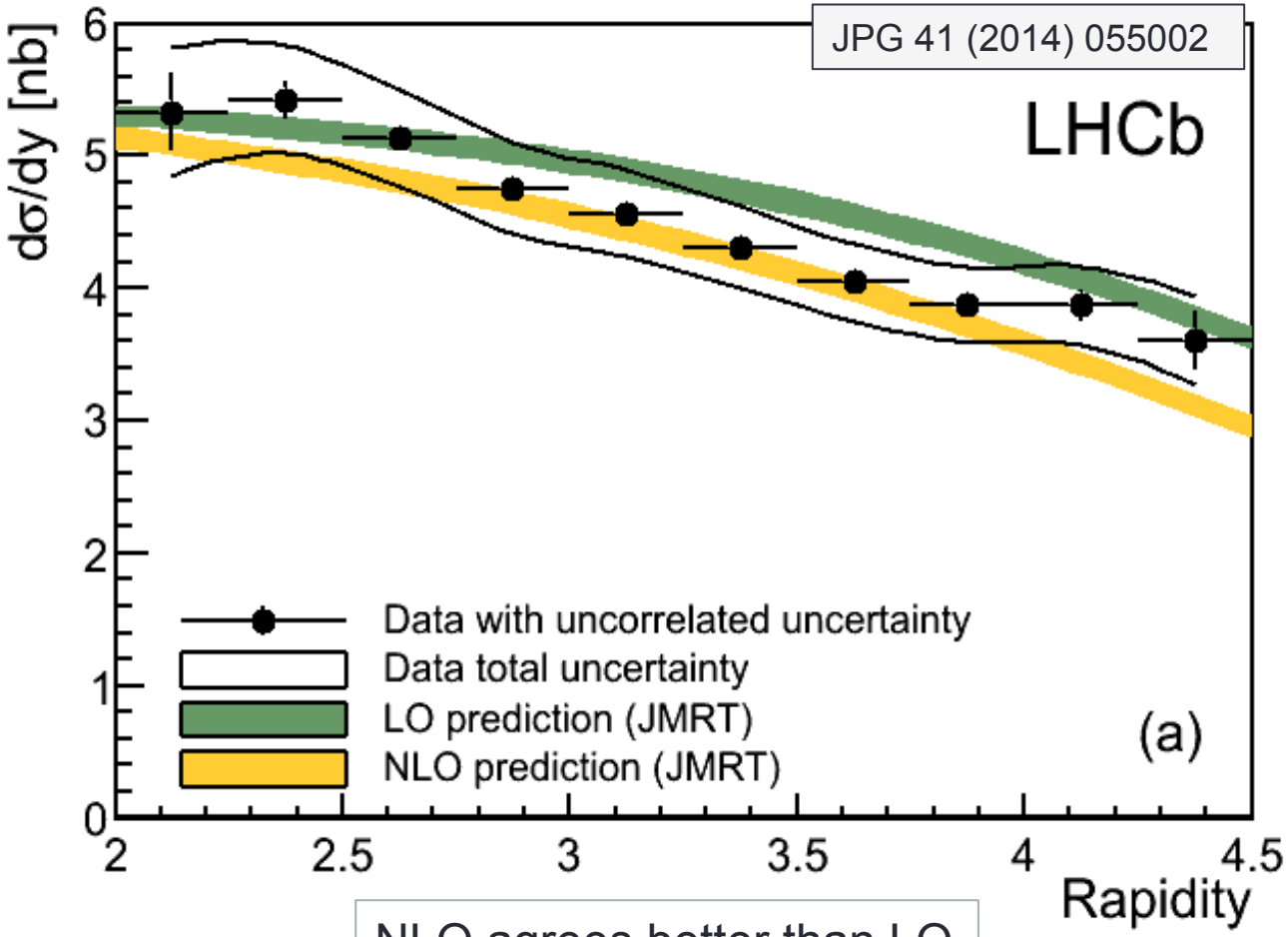
Cross-section*BR for both muons in pseudorapidity range 2<η<4.5:





Good agreement with all theory estimates

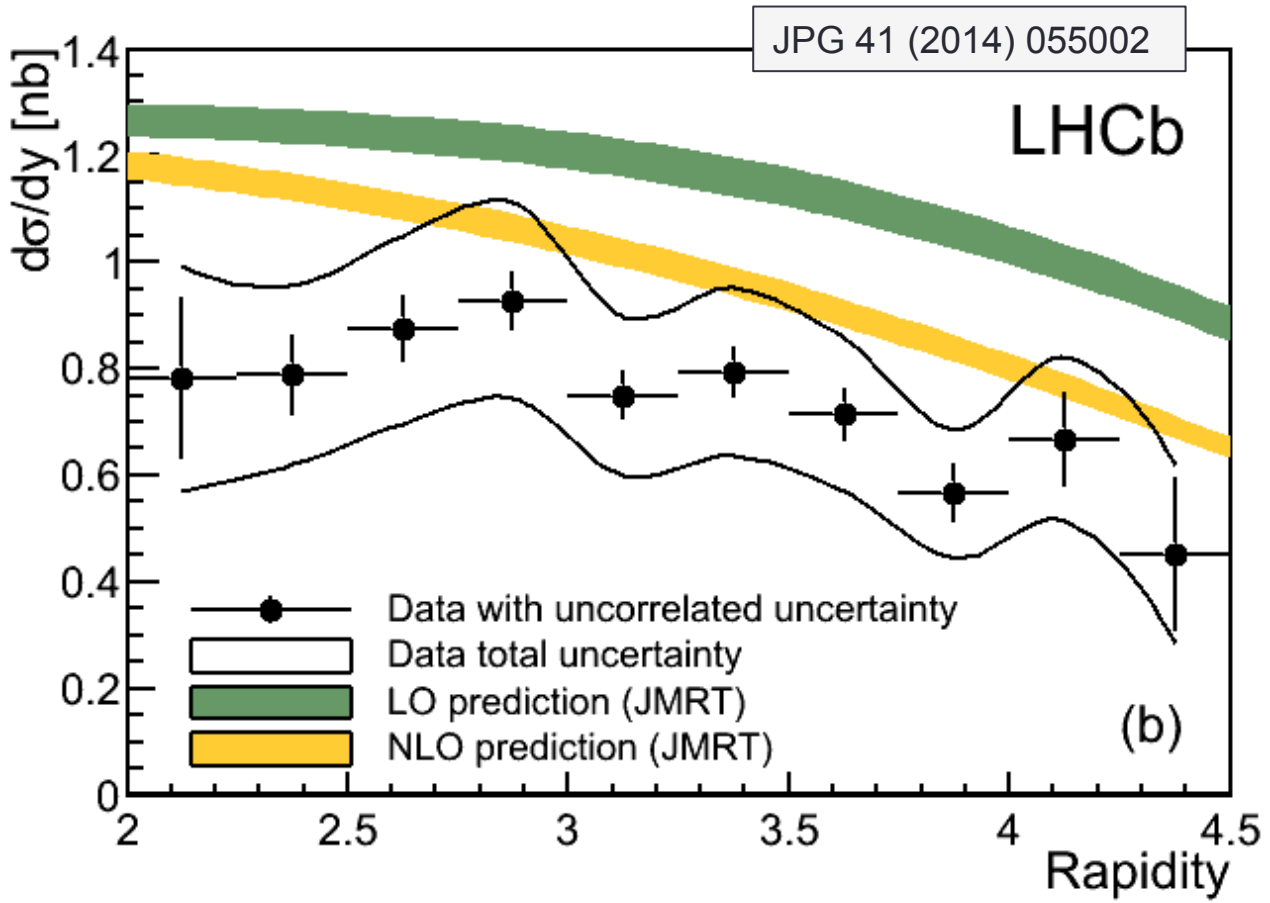
Differential cross-sections J/ψ



NLO agrees better than LO

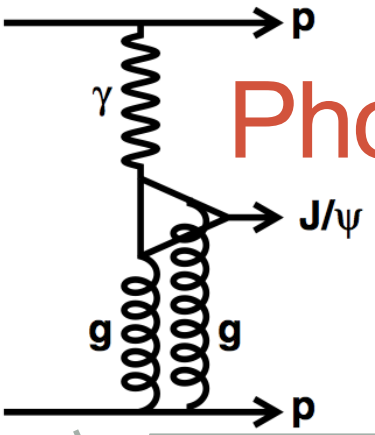
S. Jones, A. Martin, M. Ryskin, and T. Teubner, *Probes of the small x gluon via exclusive J/ψ and ϒ production at HERA and the LHC*, JHEP **1311** (2013) 085, arXiv:1307.7099.

Differential cross-sections ψ(2S)



NLO agrees better than LO

Photo-production cross-section



LHCb measure

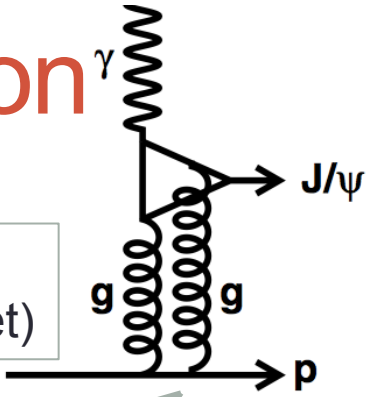


Photo-production
(HERA / fixed target)

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

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

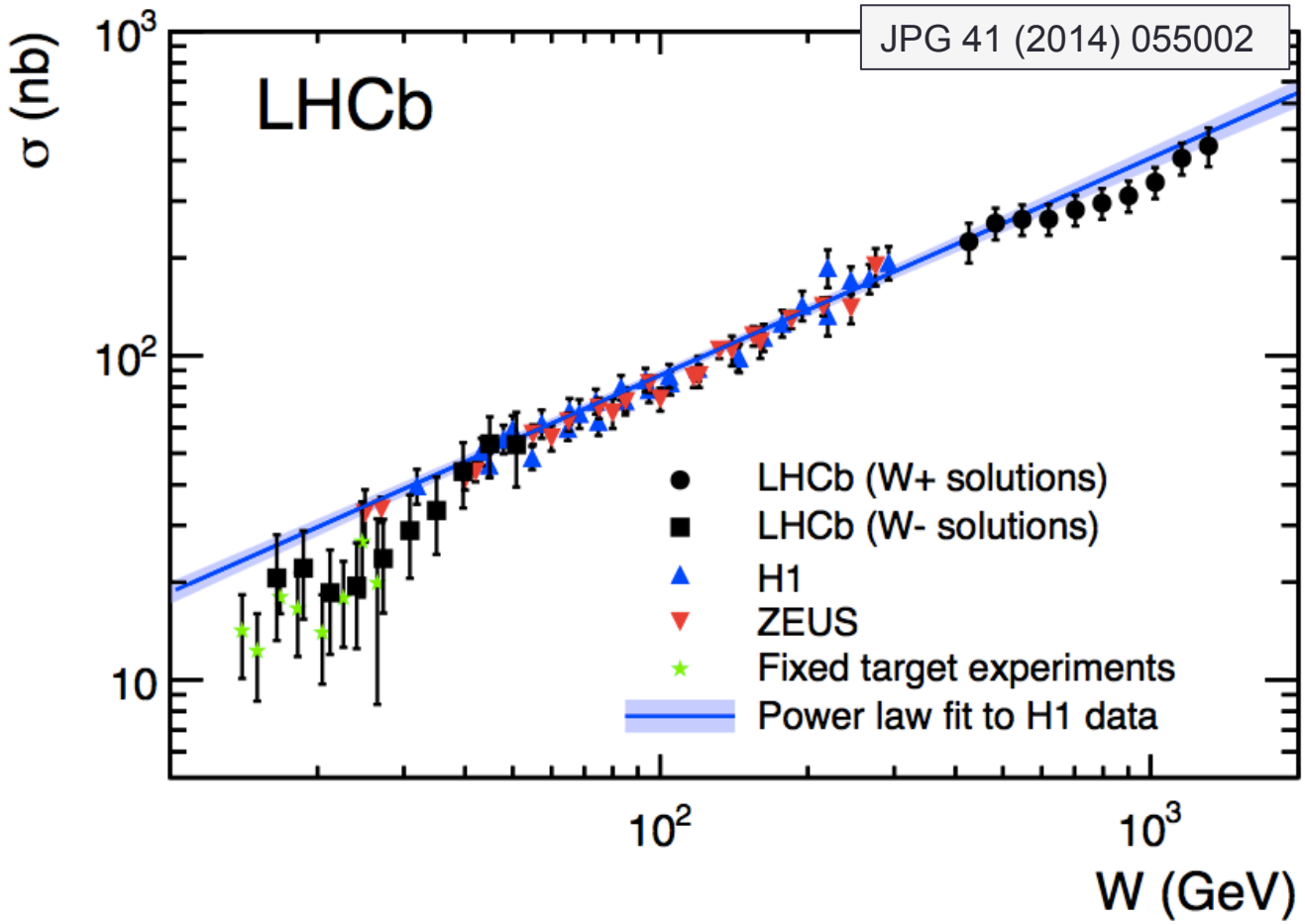
Photo-production cross-section

Measure

Plot

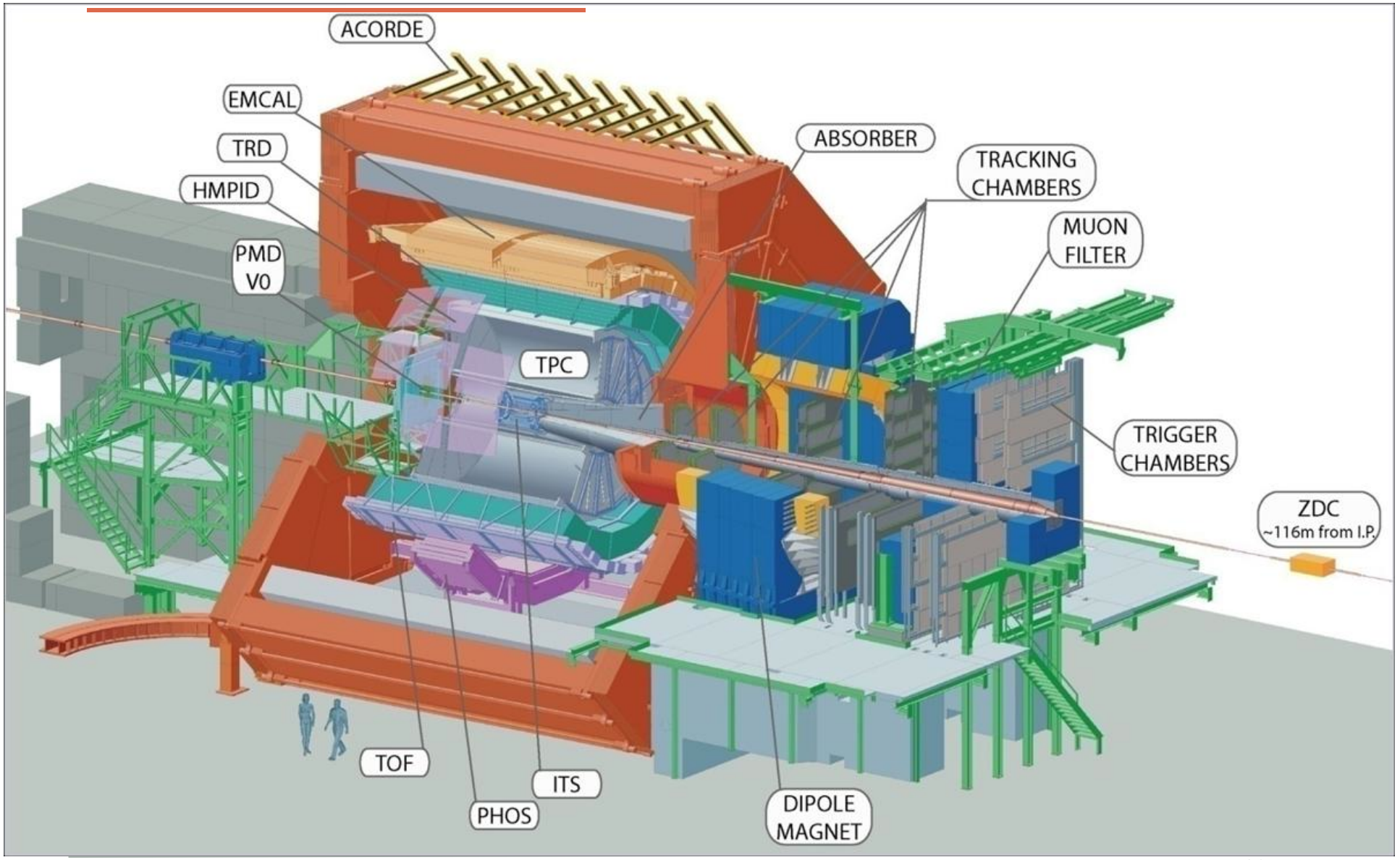
HERA

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

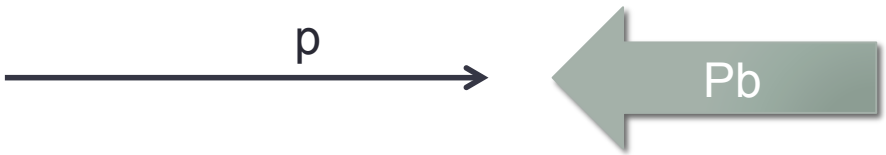


Deviation from pure power-law. i.e. NLO required or only power-law for $W>W_0$

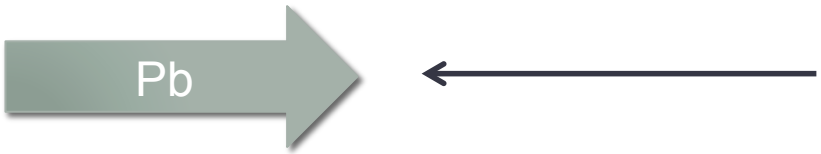
ALICE detector



p-Pb interactions



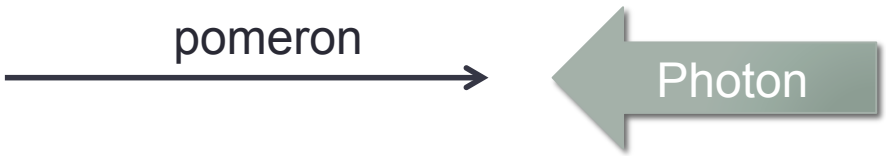
J/ψ sensitivity in 2.5<y<4.0



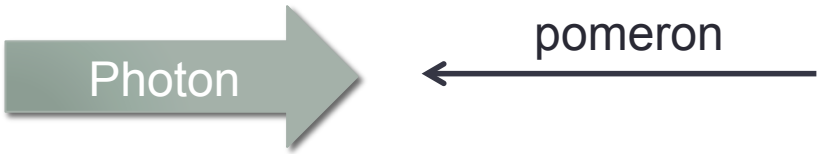
J/ψ sensitivity in -3.6<y<-2.6

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

p-Pb interactions



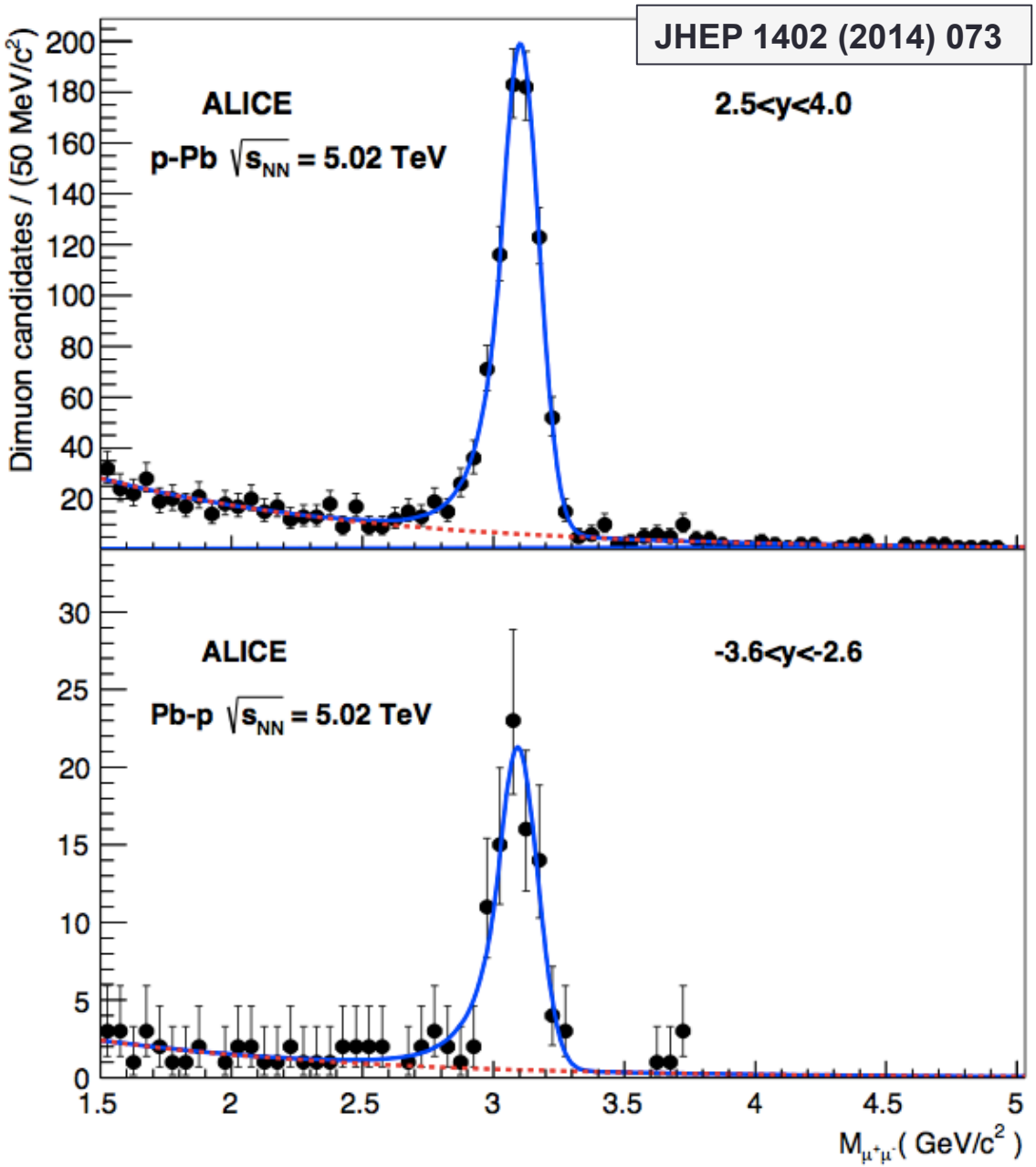
J/ψ sensitivity in 2.5<y<4.0
(Low W region)



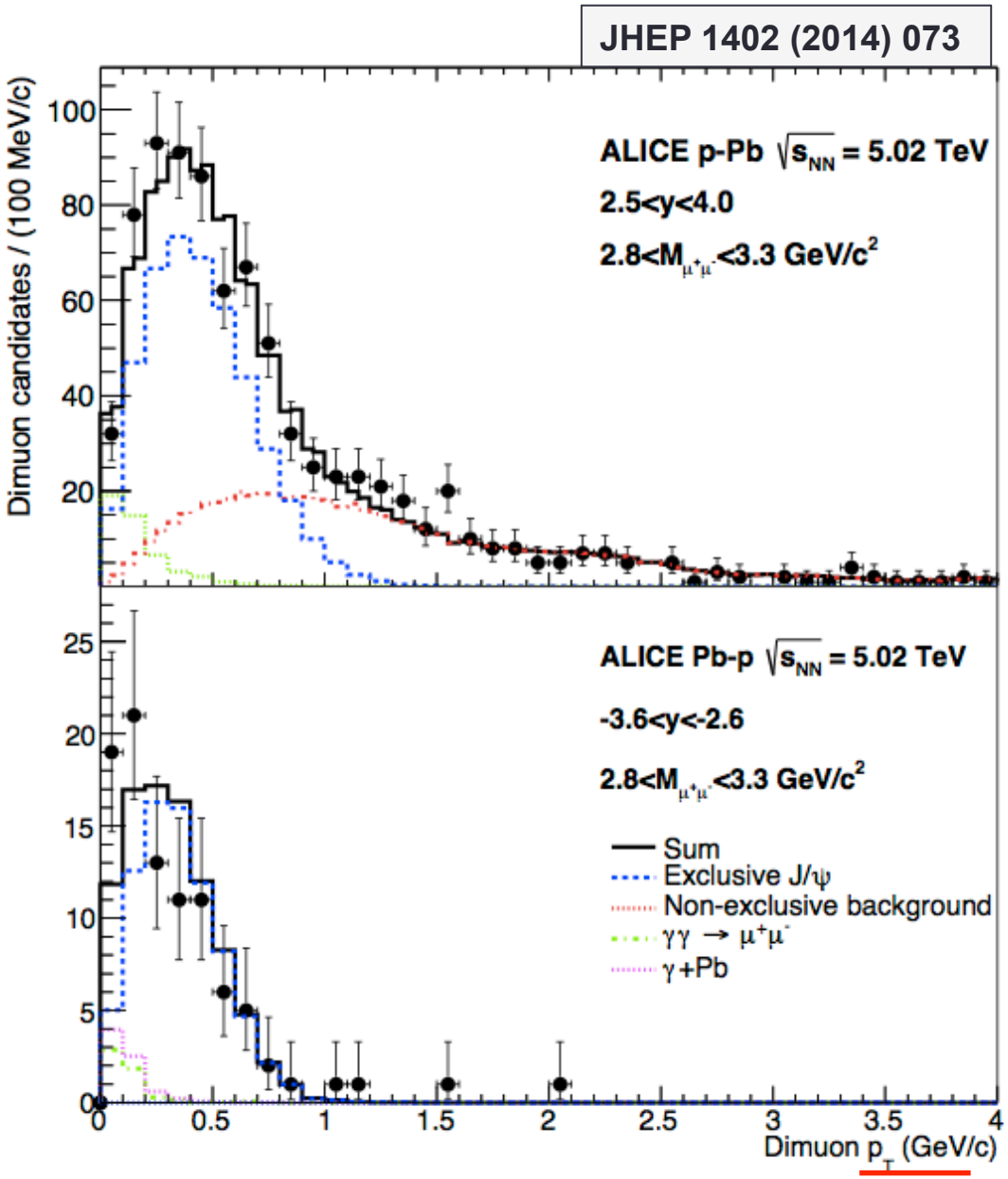
J/ψ sensitivity in -3.6<y<-2.6
(High W region)

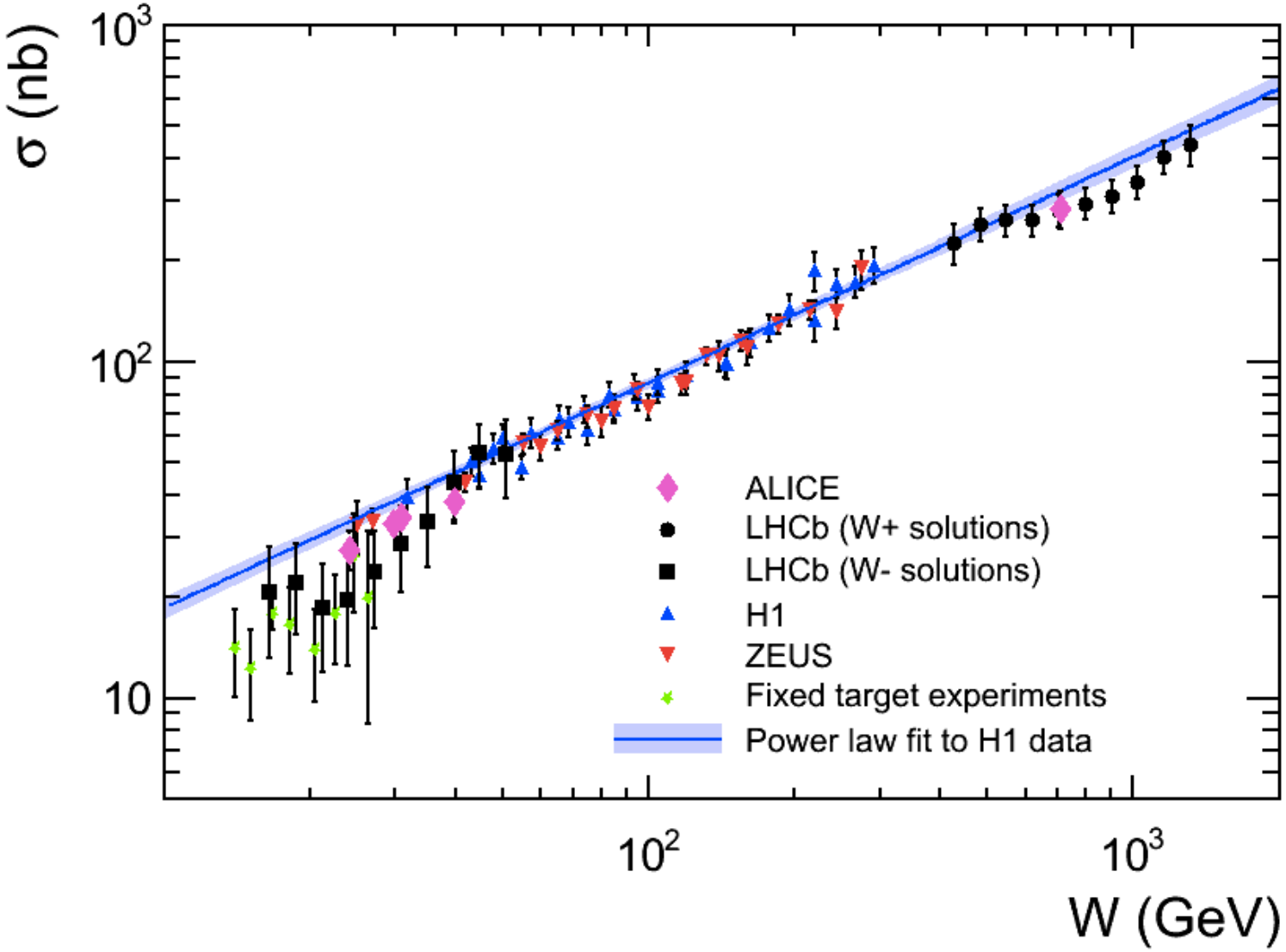
Photon flux proportional to Z^2. Removes two-fold ambiguity

Invariant mass of selected candidates



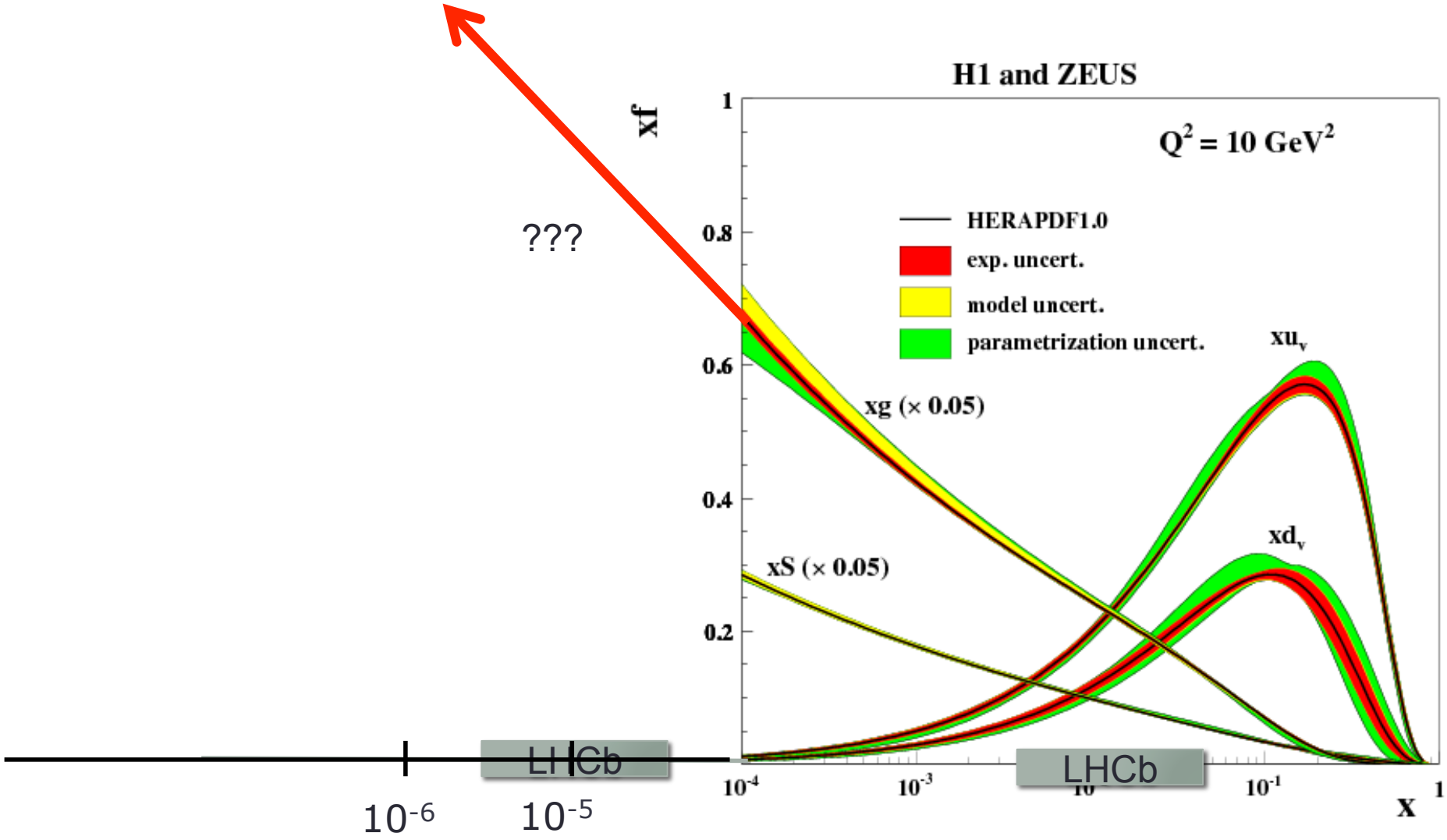
Transverse momentum of candidates



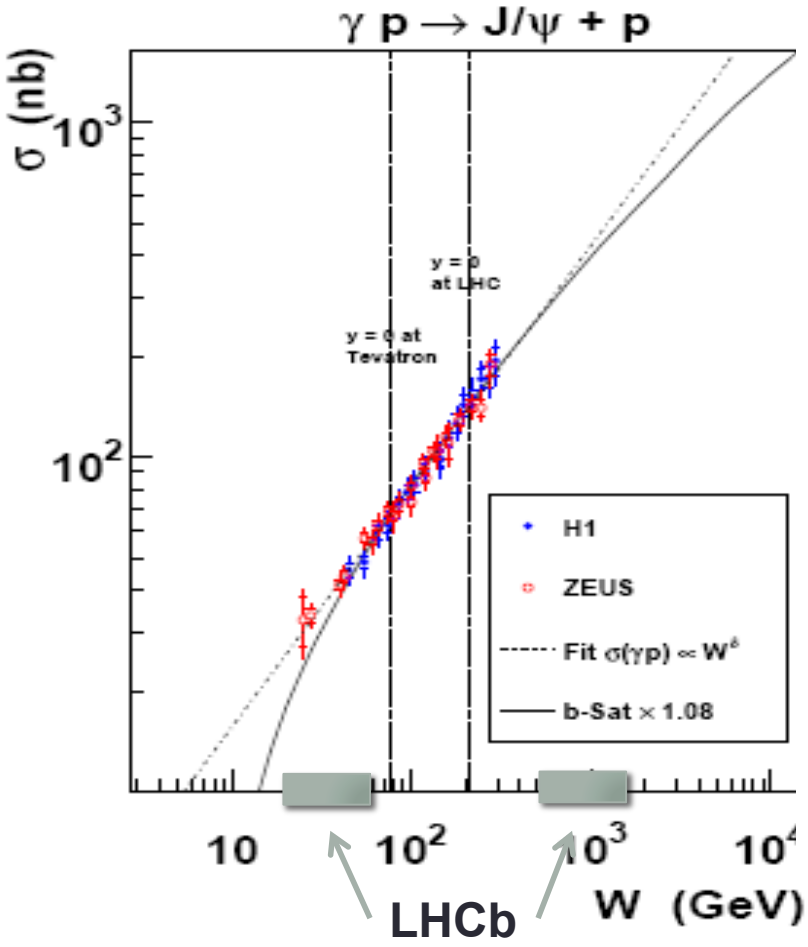


Consistent picture of J/ψ photo-production across wide range of energies and colliders

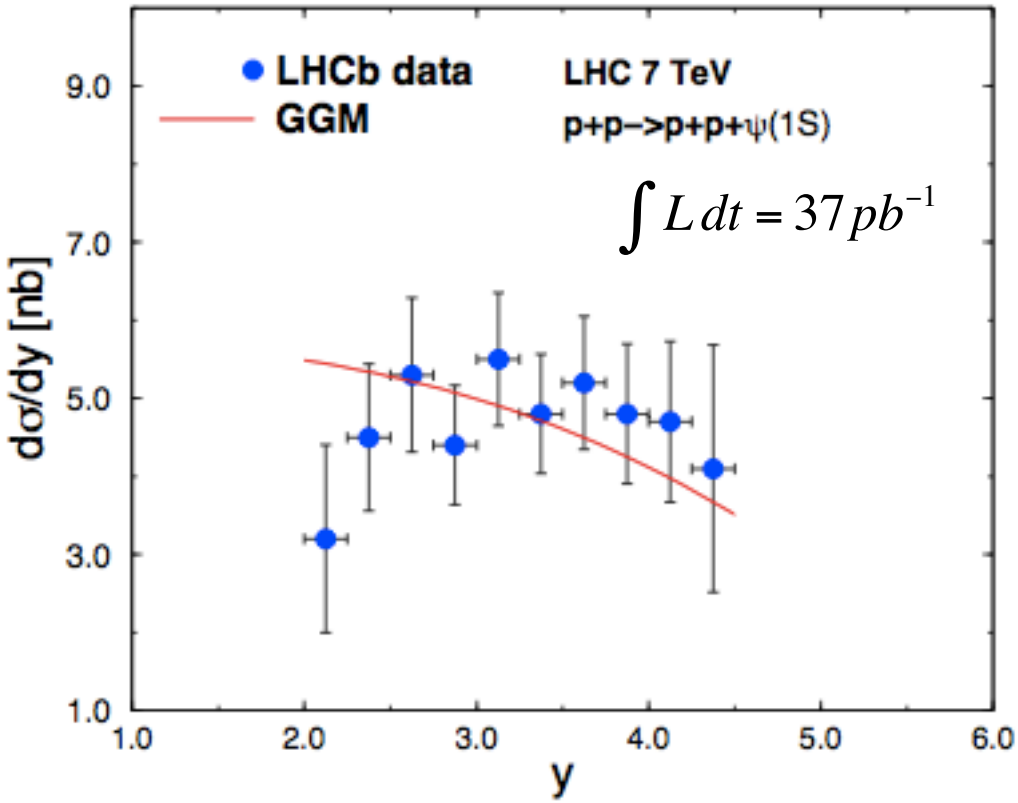
Sensitivity to saturation effects



Sensitivity to saturation effects

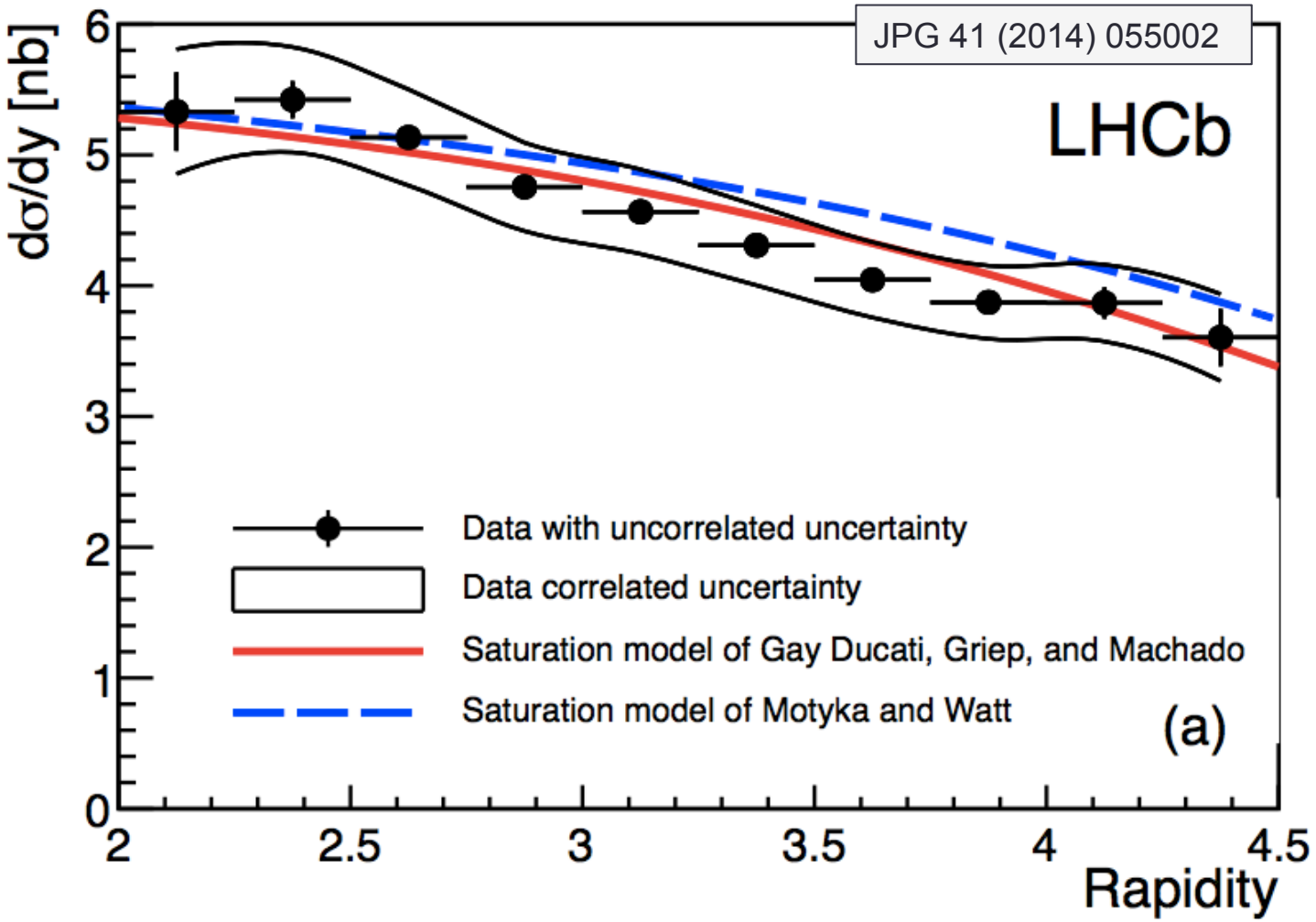


Motyka, Watt: PRD 78, 014023 (2008)



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

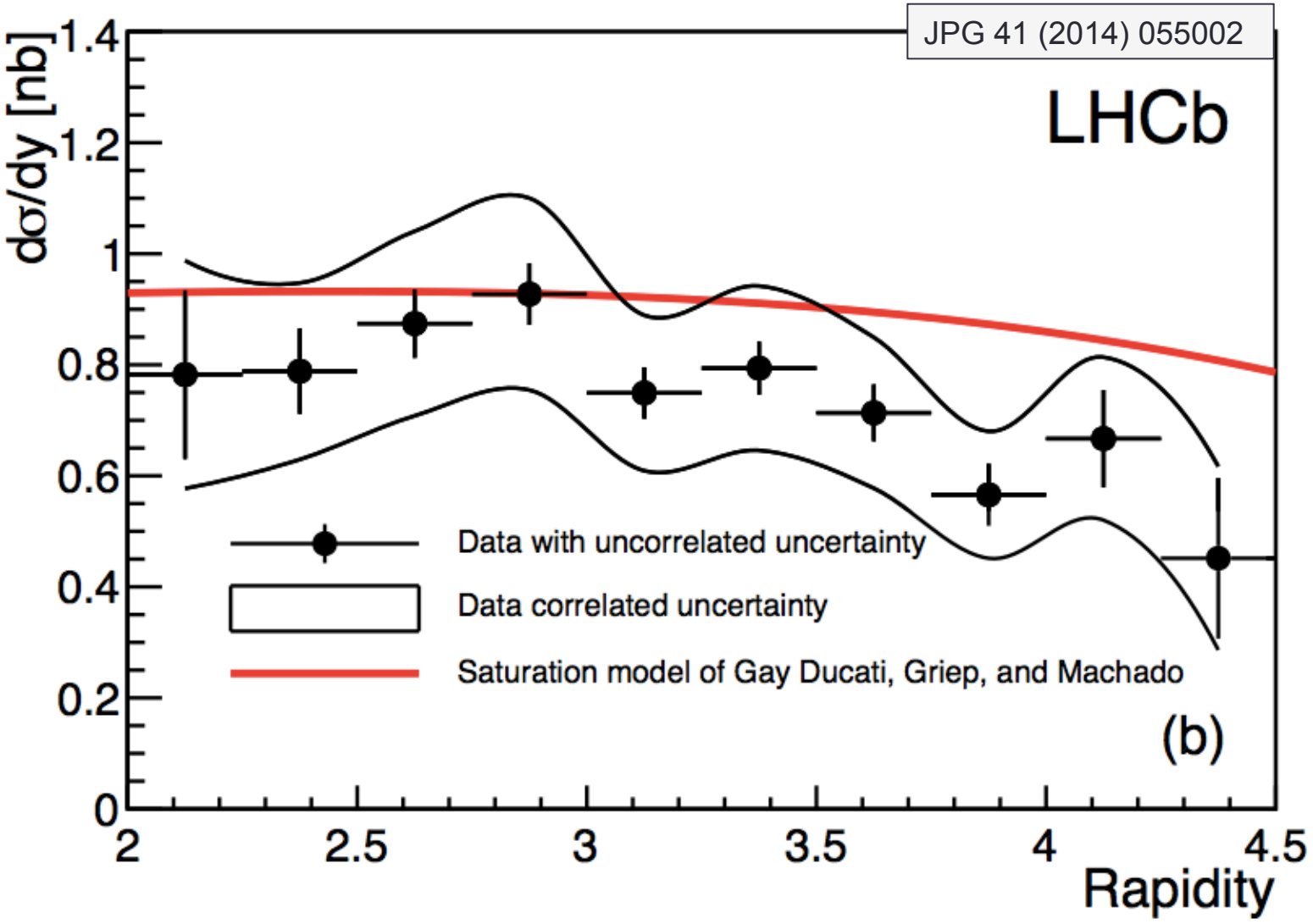
Sensitivity to saturation effects: J/ψ



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.

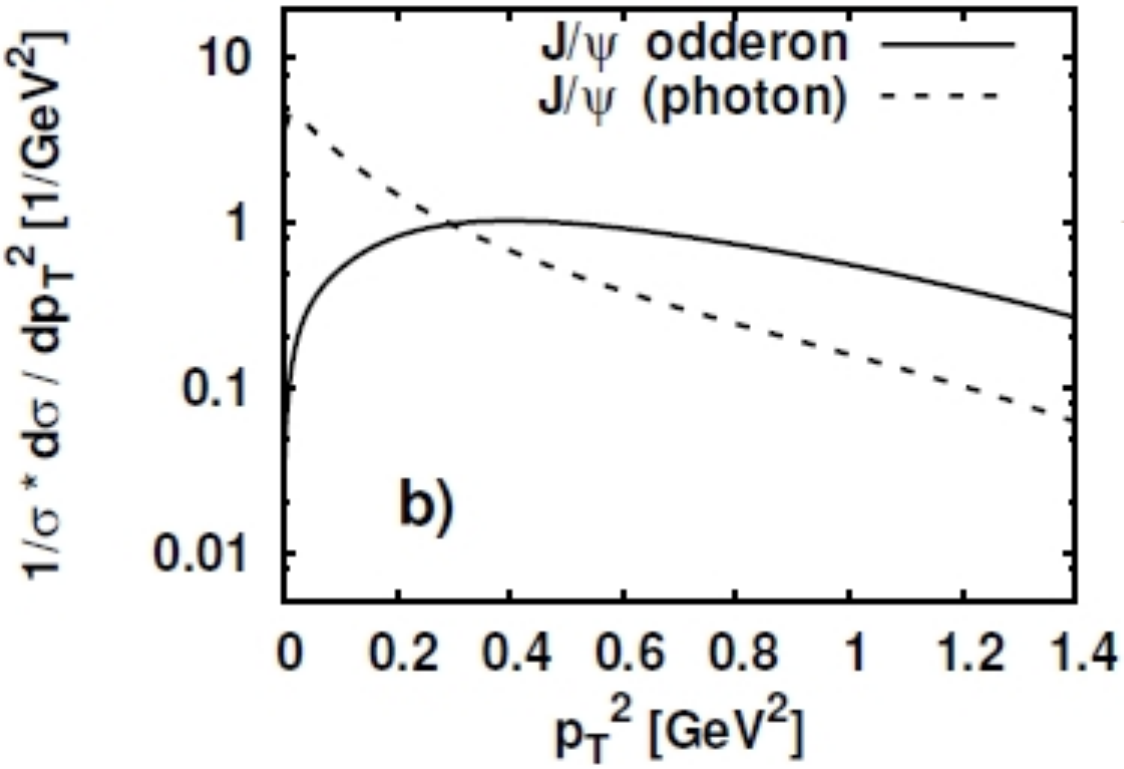
M. B. Gay Ducati, M. T. Griep, and M. V. T. Machado, *Exclusive photoproduction of J/ψ and ψ(2S) states in proton-proton collisions at the CERN LHC*, arXiv:1305.4611.

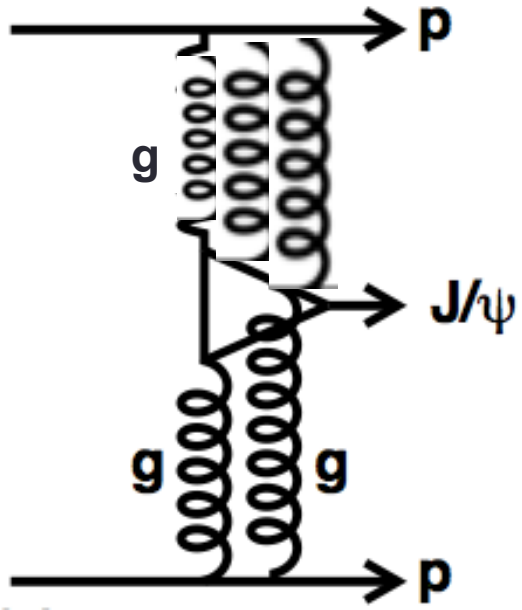
Sensitivity to saturation effects: ψ(2S)



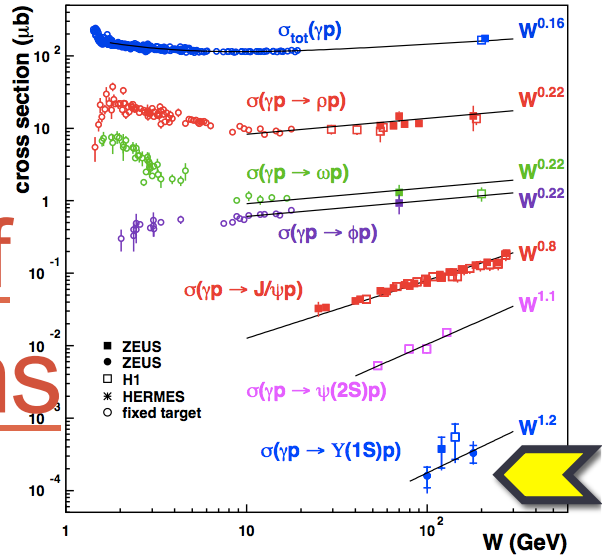
Search for odderon

- Motyka, DIS 2008.



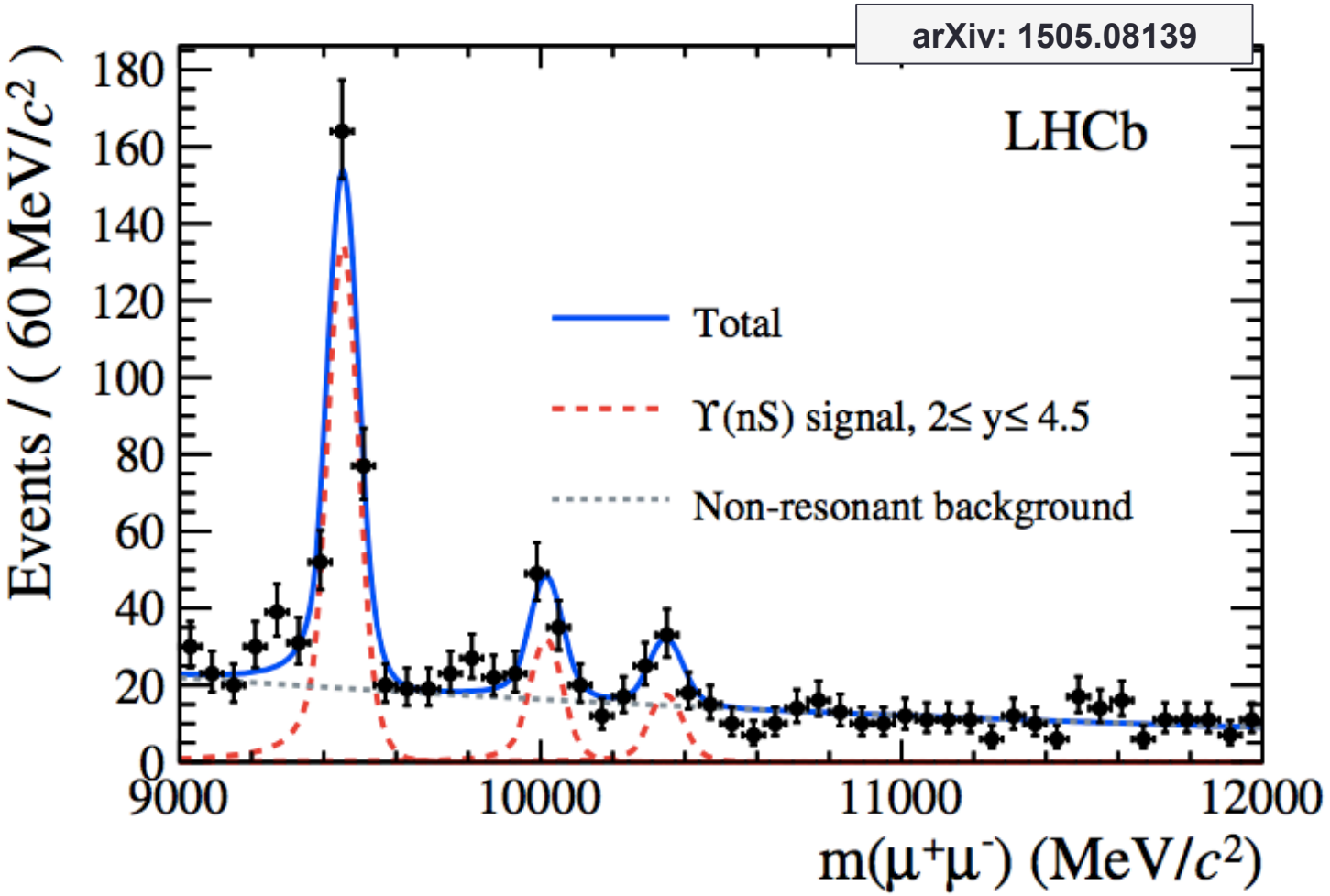


Central Exclusive Production of Υ(1S), Υ(2S), Υ(3S) mesons



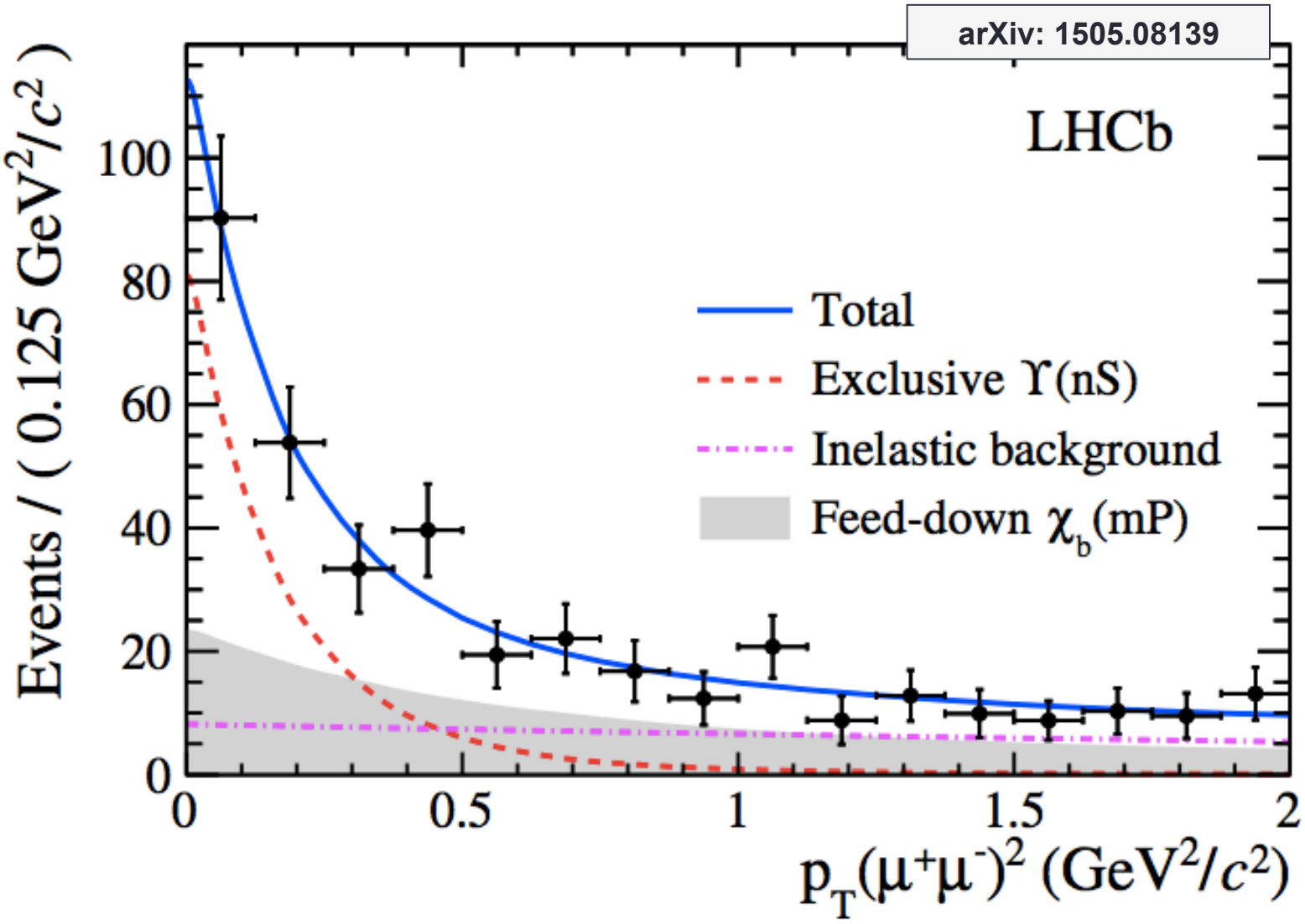
Data-taking year	Energy	Integrated Luminosity	Paper
2011	7 TeV	945 pb^{-1}	arXiv: 1505.08139
2012	8 TeV	1985 pb^{-1}	

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



Cross-sections and systematics

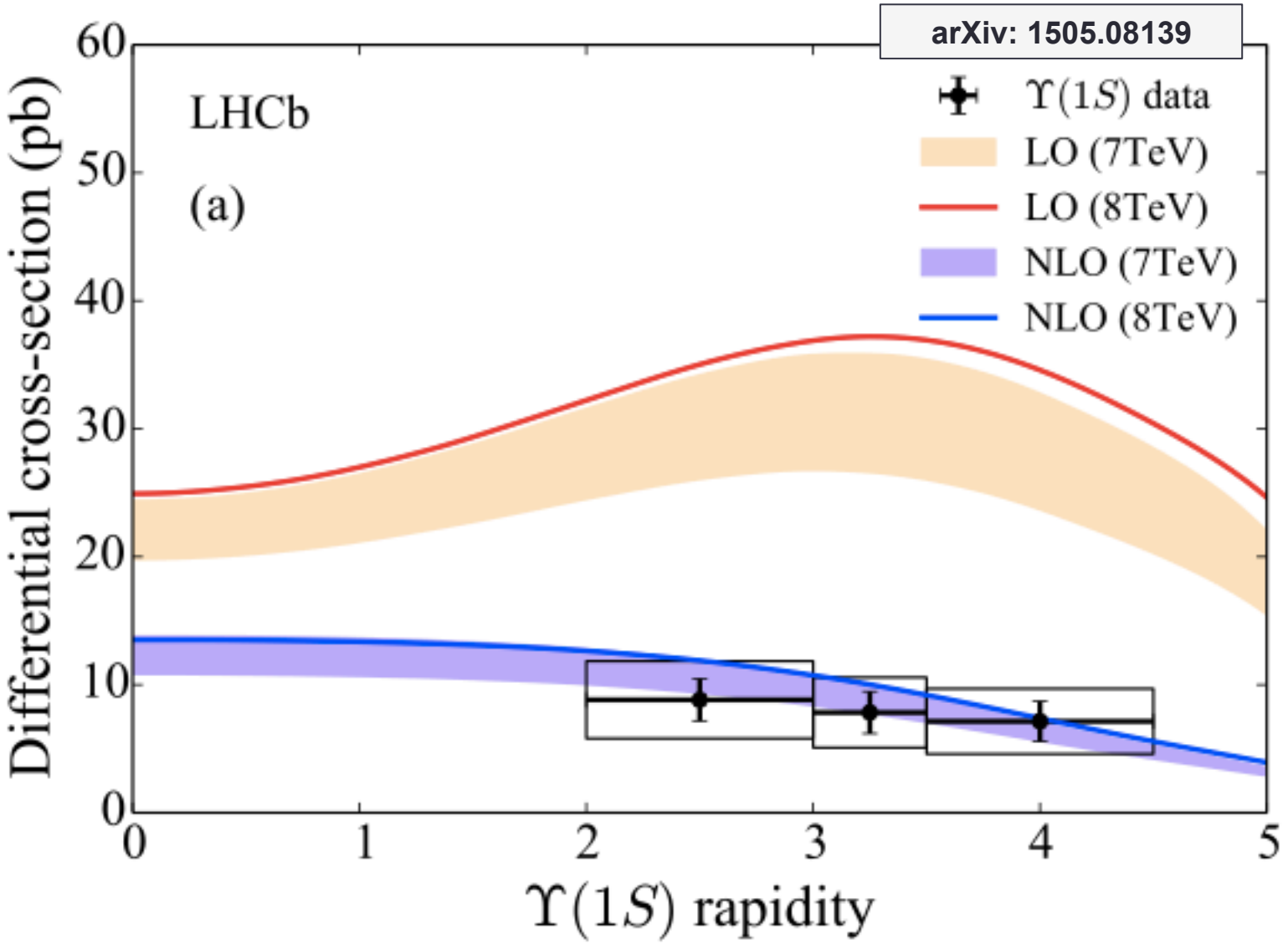
Cross-section*BR for both muons in pseudorapidity range 2<η<4.5:

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

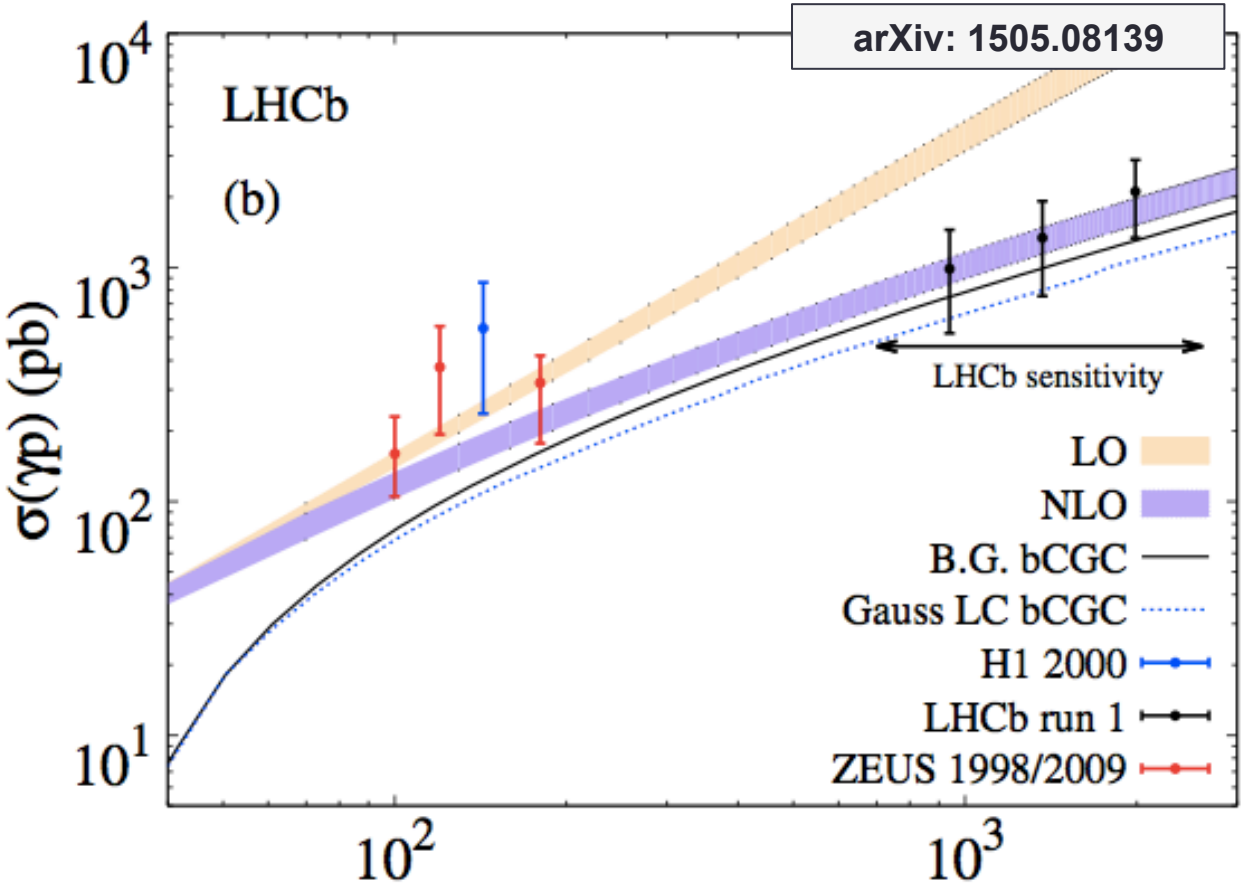
	$2 \le y < 3$	$3 \le y < 3.5$	$3.5 \le y \le 4.5$
$\sigma(\Upsilon(1S))$ (pb)	$3.4 \pm 0.9 \pm 0.7$	$2.9 \pm 0.8 \pm 0.6$	$2.6 \pm 0.8 \pm 0.5$

	$2 \le y < 3$ $\Upsilon(1S)$	$3 \le y < 3.5$ $\Upsilon(1S)$	$3.5 \le y \le 4.5$ $\Upsilon(1S)$	$2 \le y \le 4.5$ $\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
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

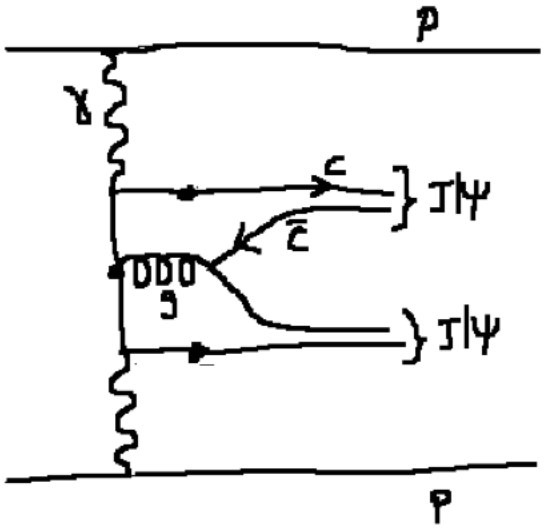


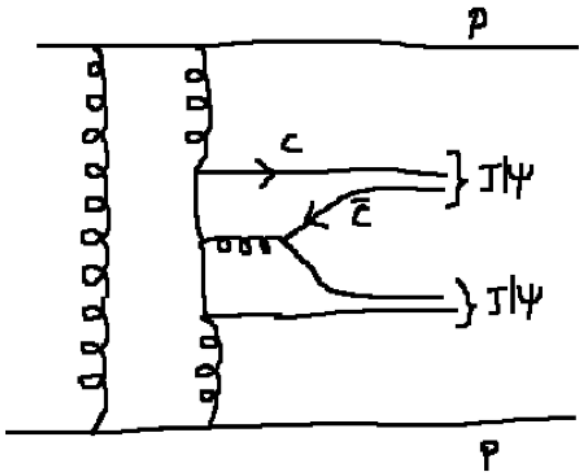
$$\frac{d\sigma}{dy}_{pp\to p,\,\Upsilon\,p} = r_+ k_+ \frac{dn}{dk_+}\sigma_{\gamma p\to\,\Upsilon\,p}(W_+) + r_- k_- \frac{dn}{dk_-}\sigma_{\gamma p\to J/\psi p}(W_-)$$

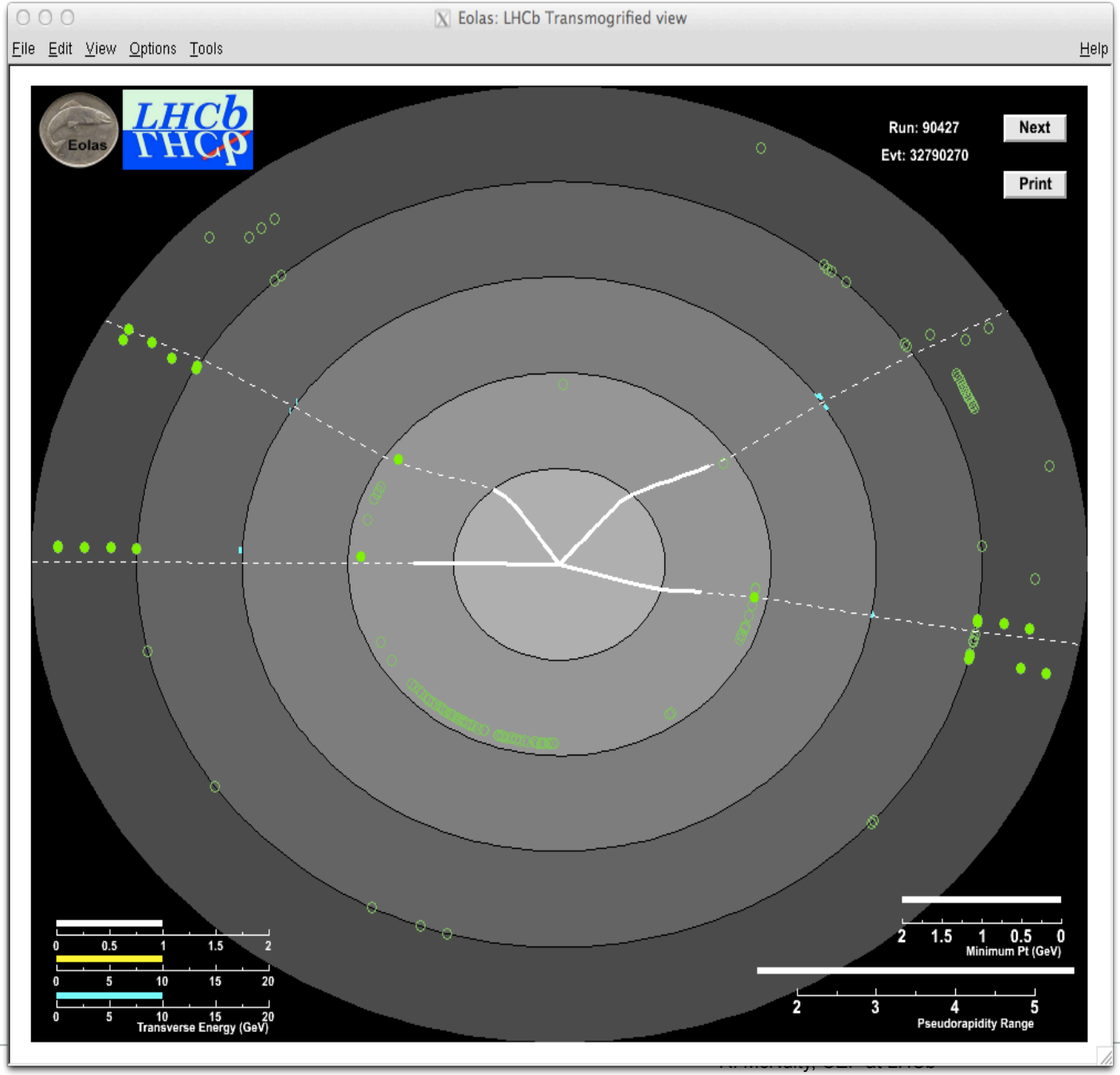
ignored

Double Charmonia

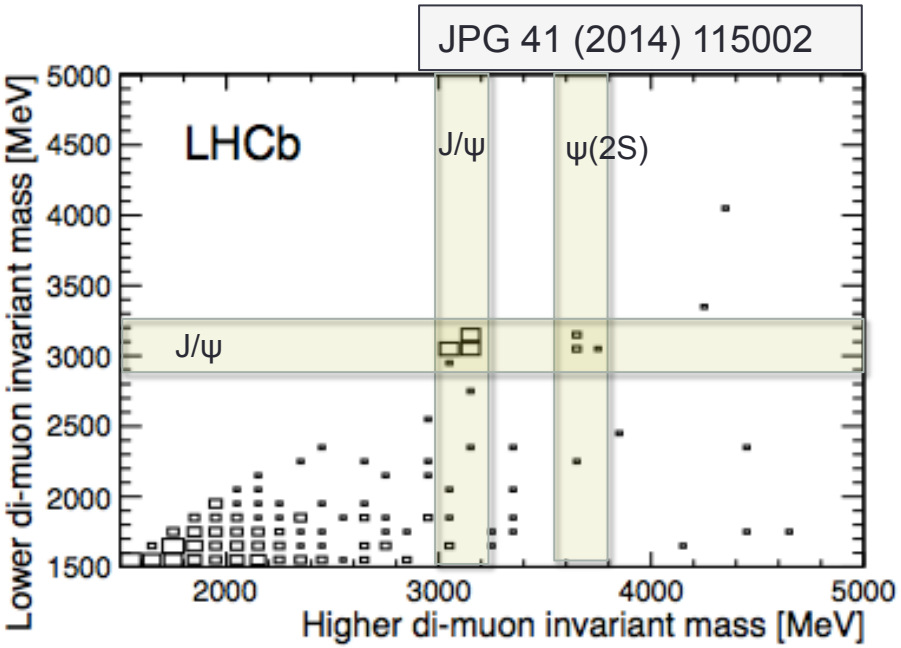
Data-taking year	Energy	Integrated Luminosity	Paper
2011	7 TeV	945 pb^{-1}	JPG 40 (2013) 045001
2012	8 TeV	1985 pb^{-1}	

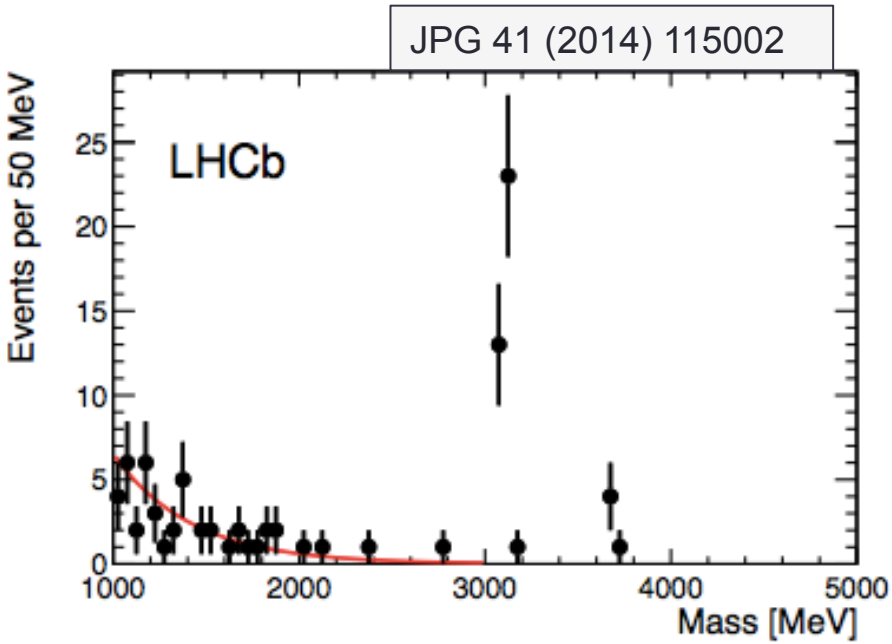





Eolas: LHCb Transmogrified view
File Edit View Options Tools
Help
Eolas
LHCb
Run: 90427
Evt: 32790270
Next
Print
0 0.5 1 1.5 2
0 5 10 15 20
0 5 10 15 20
Transverse Energy (GeV)
2 1.5 1 0.5 0
Minimum Pt (GeV)
2 3 4 5
Pseudorapidity Range

Select 4-muon exclusive events

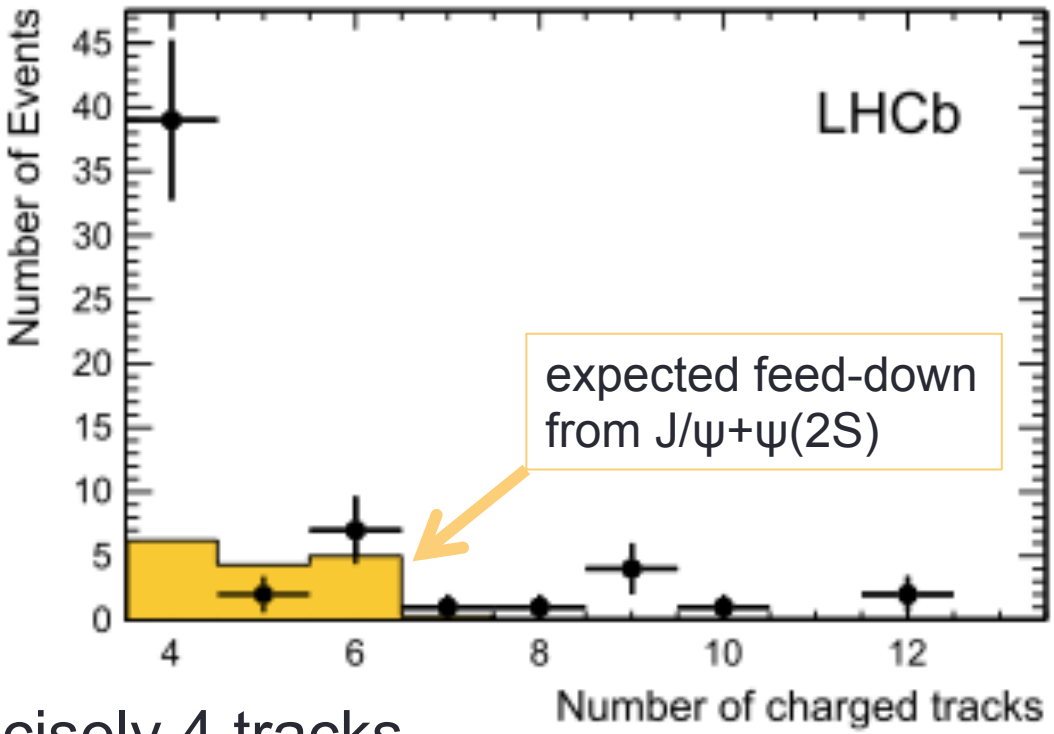




Dimuon spectrum having required other two muons have J/ψ mass

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

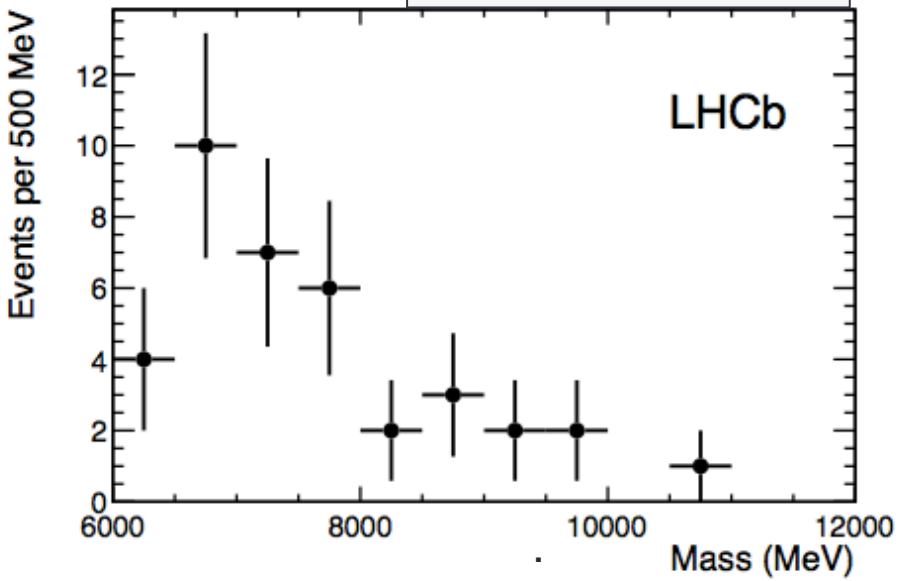
Search for extra photons due to χ_c ->J/ψγ

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

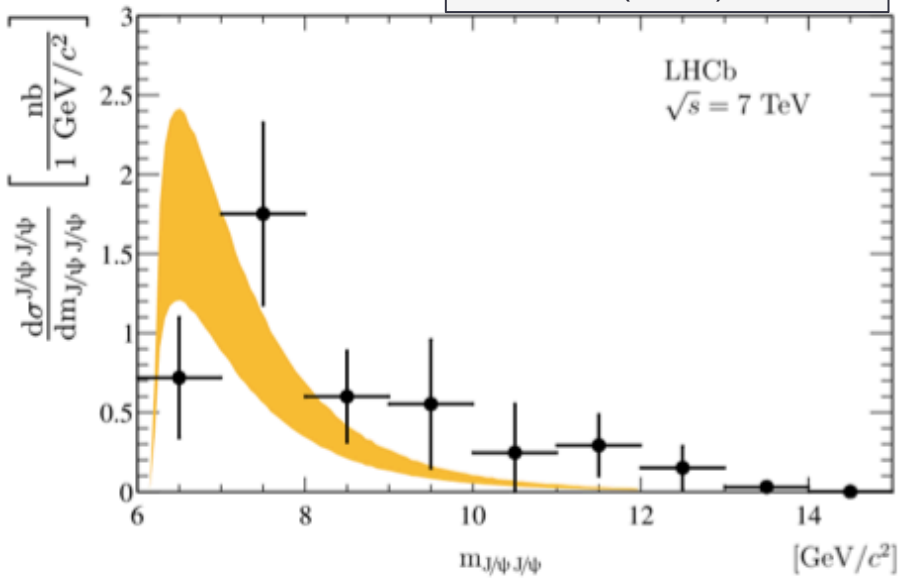
Cross-section results

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

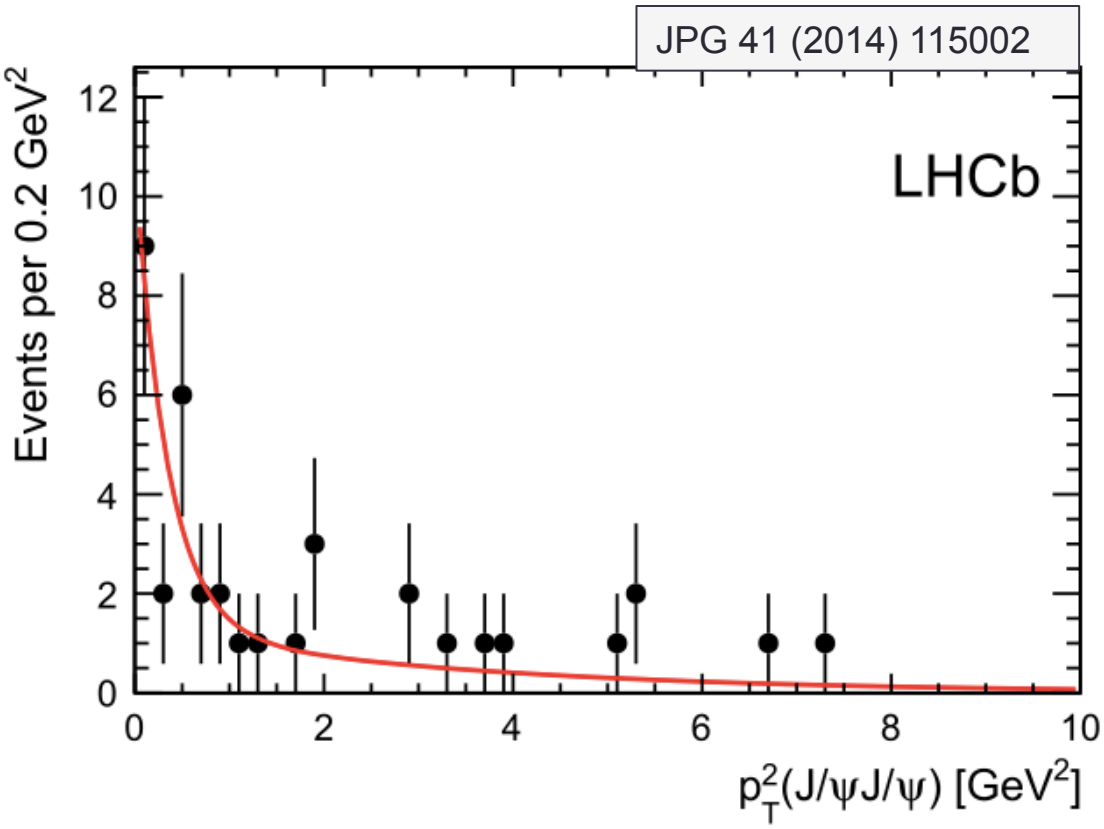
Exclusive JPG 41 (2014) 115002



Inclusive PLB 707 (2012) 52.



How much is exclusive?

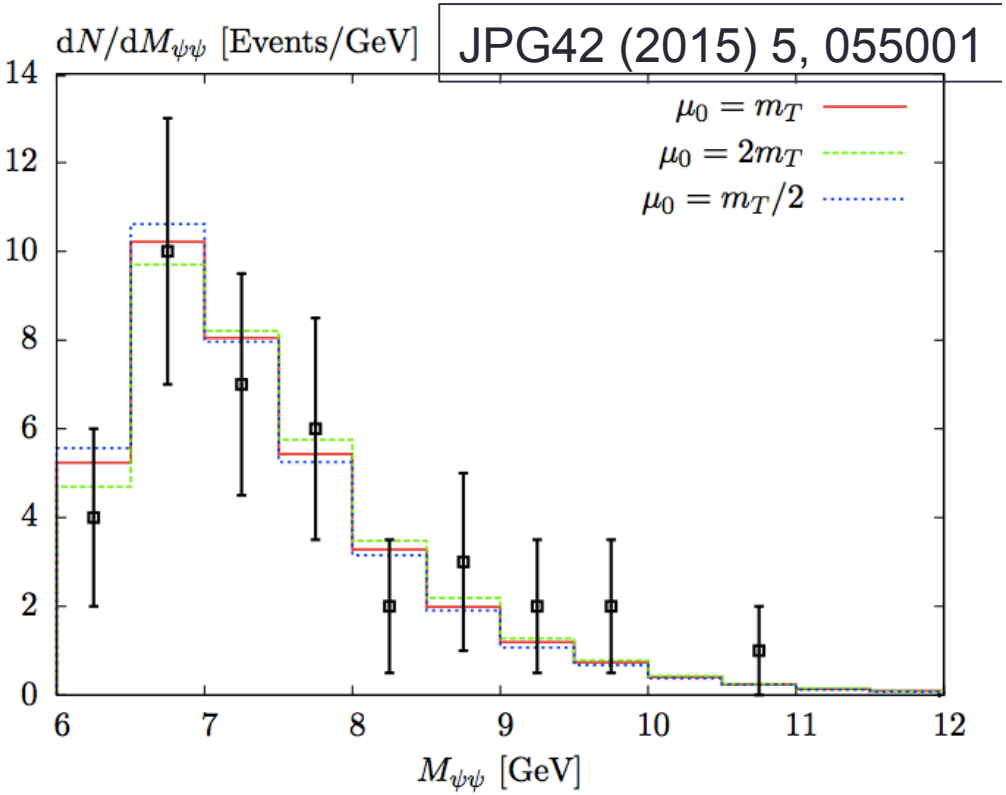


42+-13% but model dependence in describing inelastic contribution

Comparison to theory

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

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

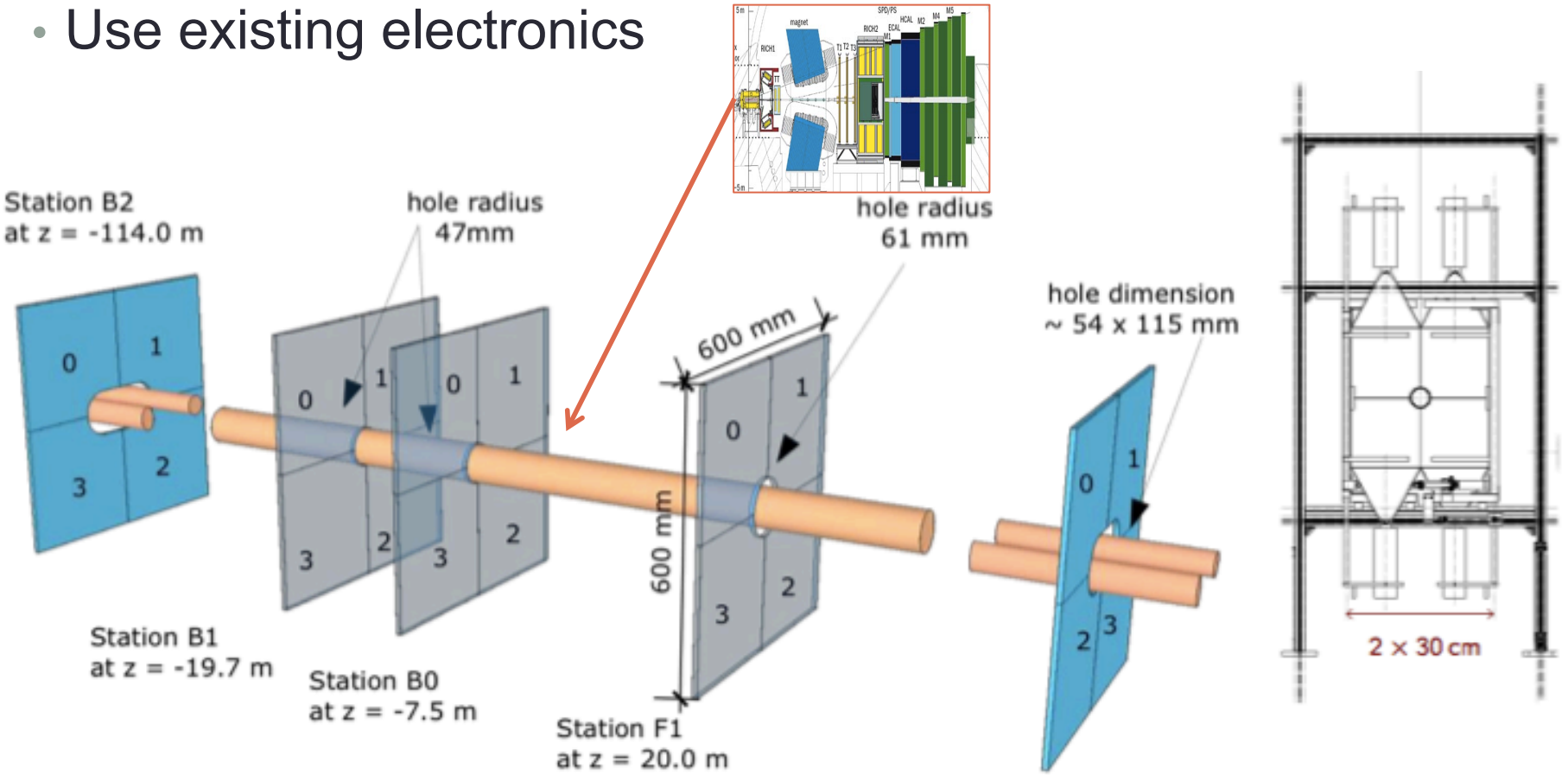


Shape agrees well (theory normalised to data).

Future Prospects

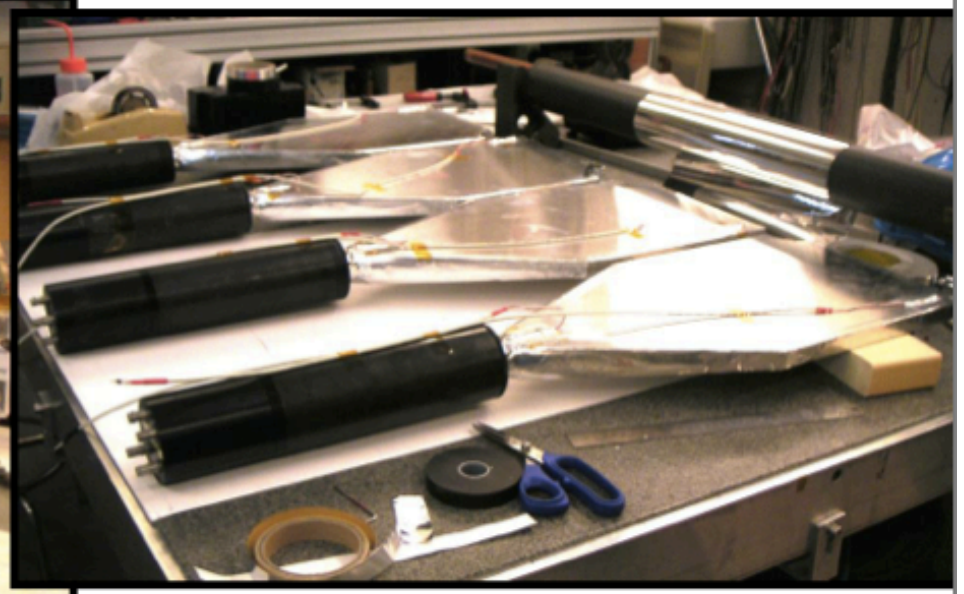
High rapidity shower counters for LHCb

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

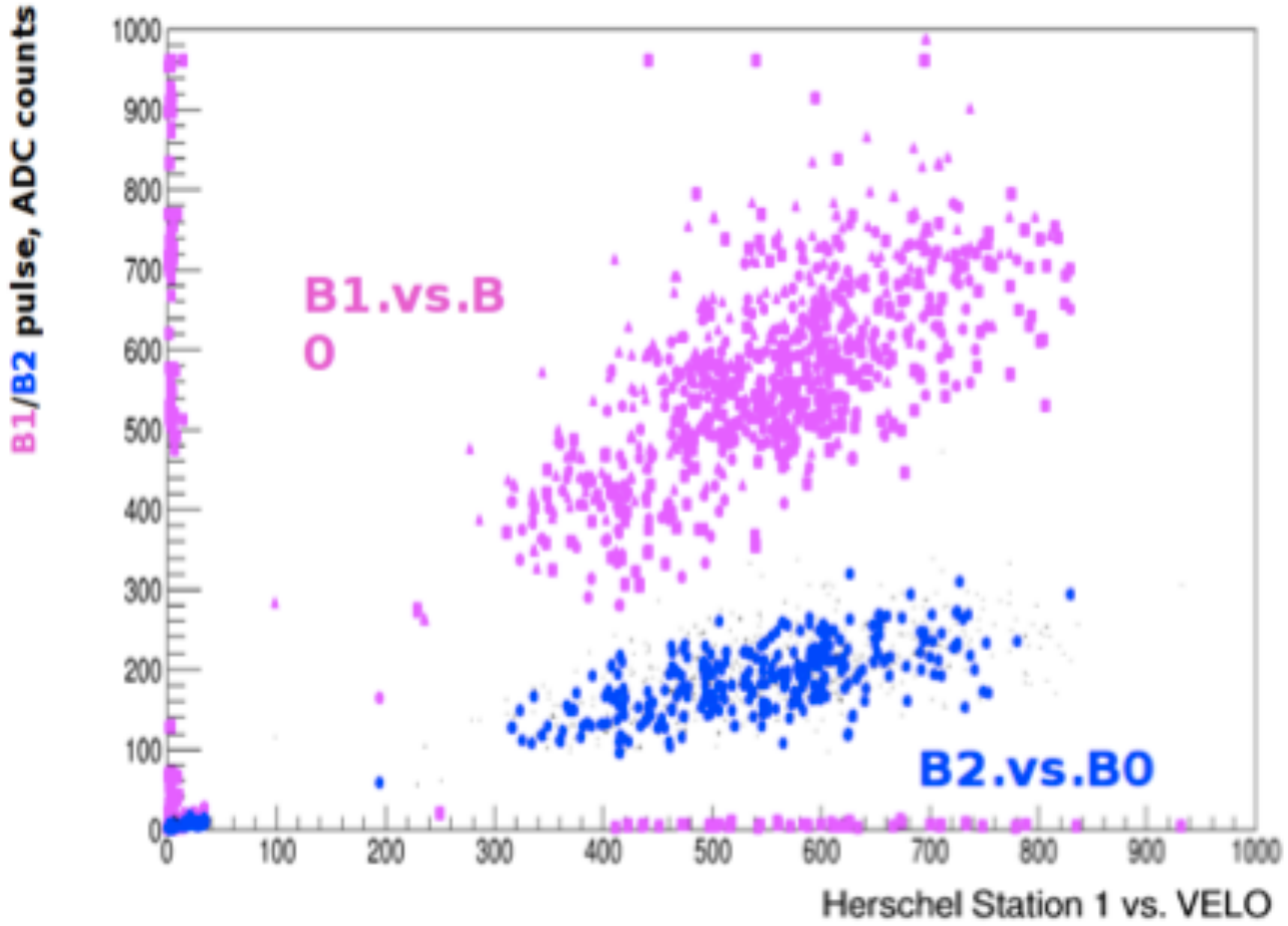


First simulations suggest veto region for charged and neutral particles can be extended to include $5<|\eta|<8$ - an extra 6 units in pseudorapidity.

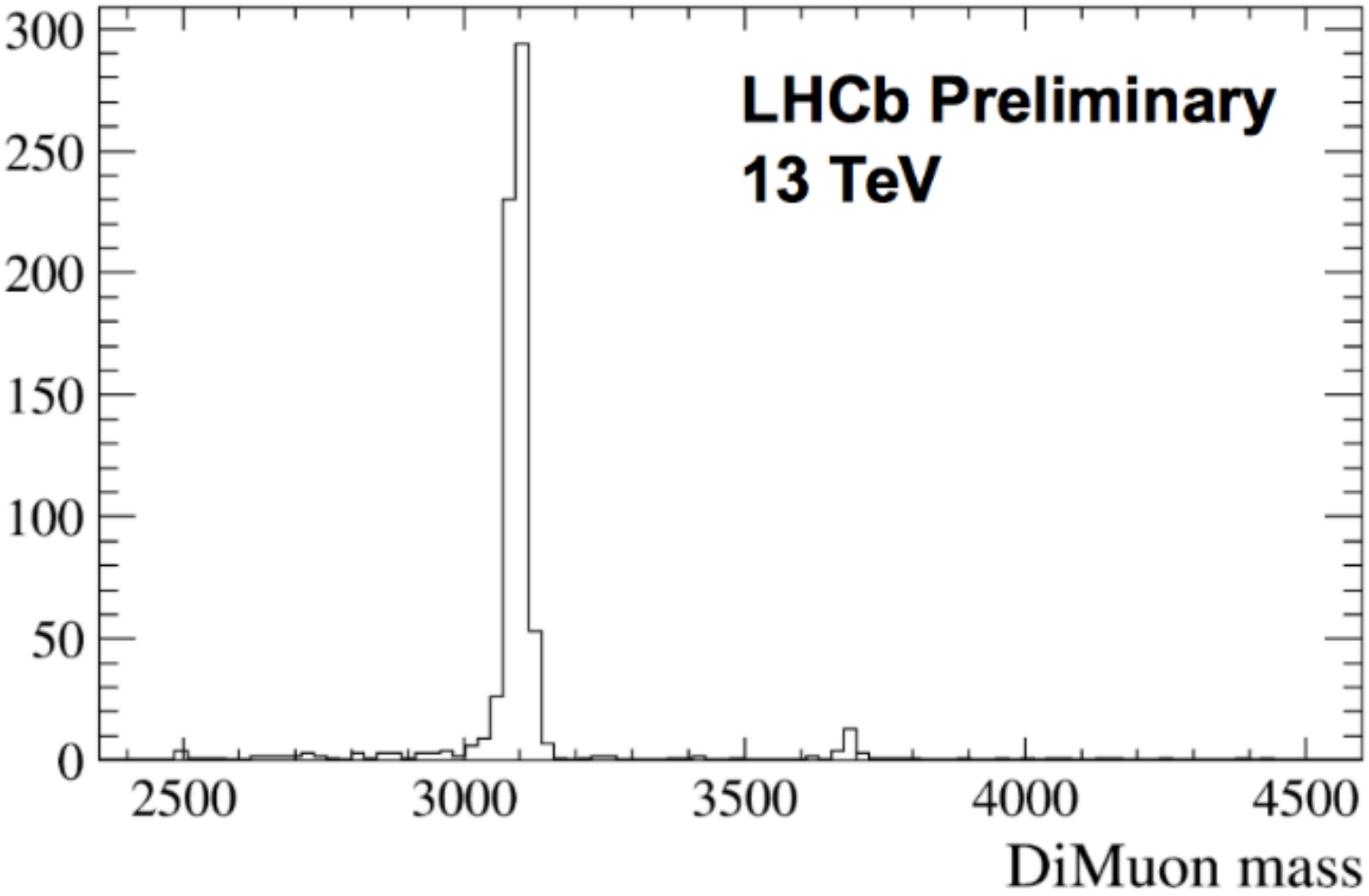
Scintillators and PMTs



Signals from TED running

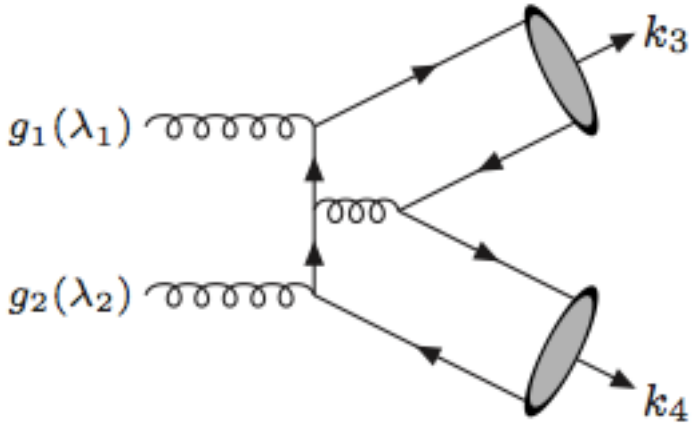


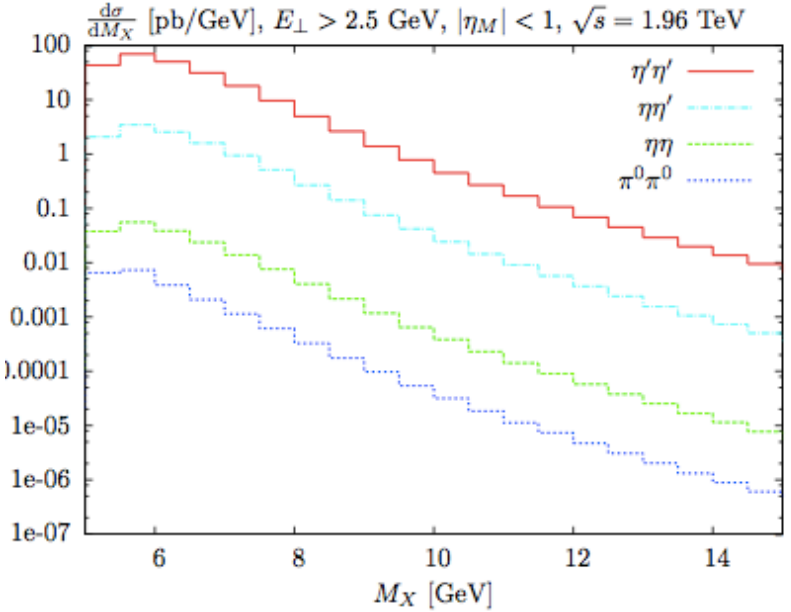
First collisions at 13 TeV !



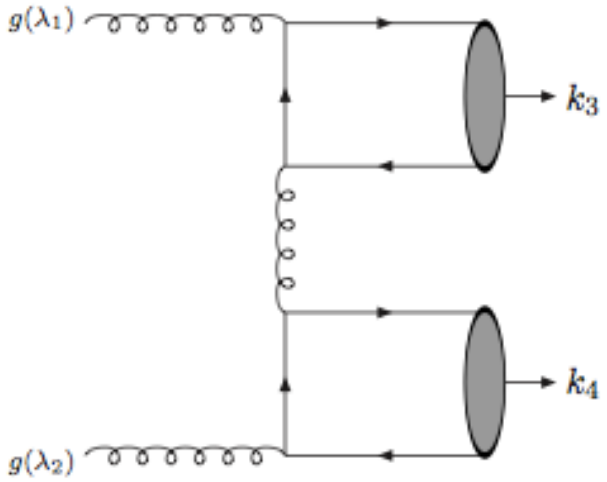
(Harland-Lang, Khoze, Ryskin, Stirling)

CEP meson-meson production arXiv:1105.1626

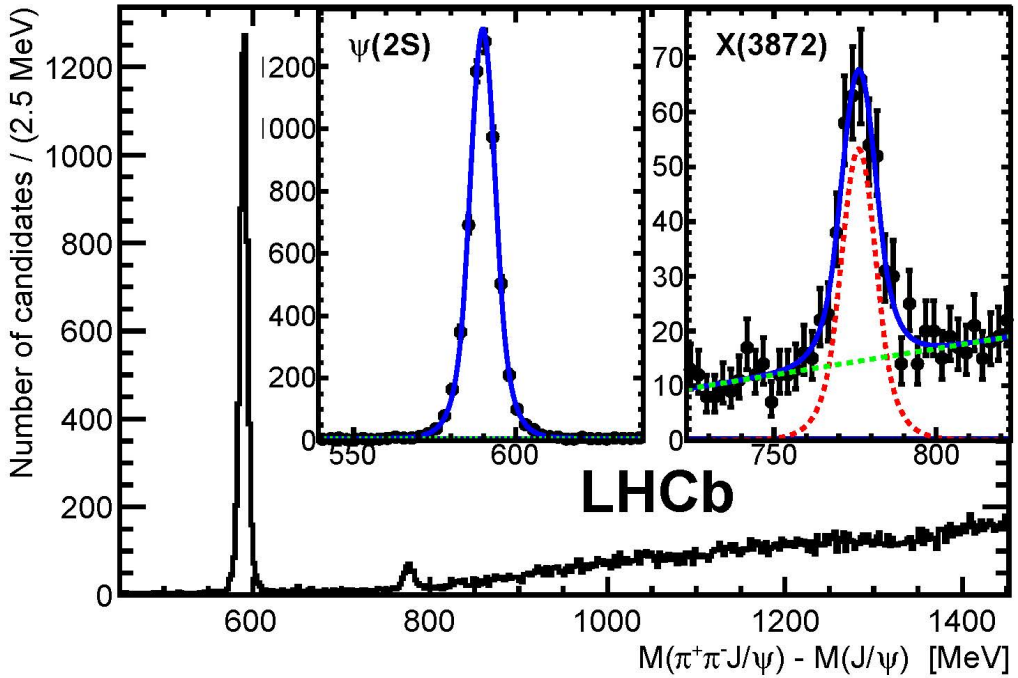




- Vanishing cs when gluons in J_z=0
- Flavour non-singlet mesons suppressed (thus ππ/KK small)
- Flavour singlet (e.g. η'η' production) can proceed via



X(3872)

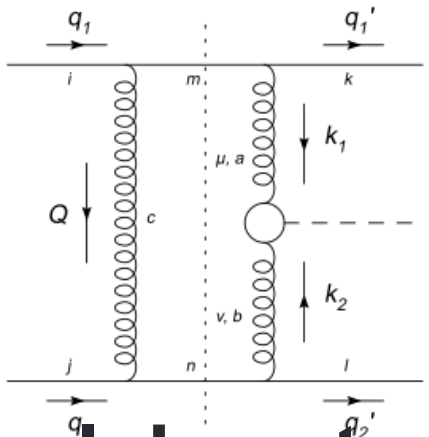


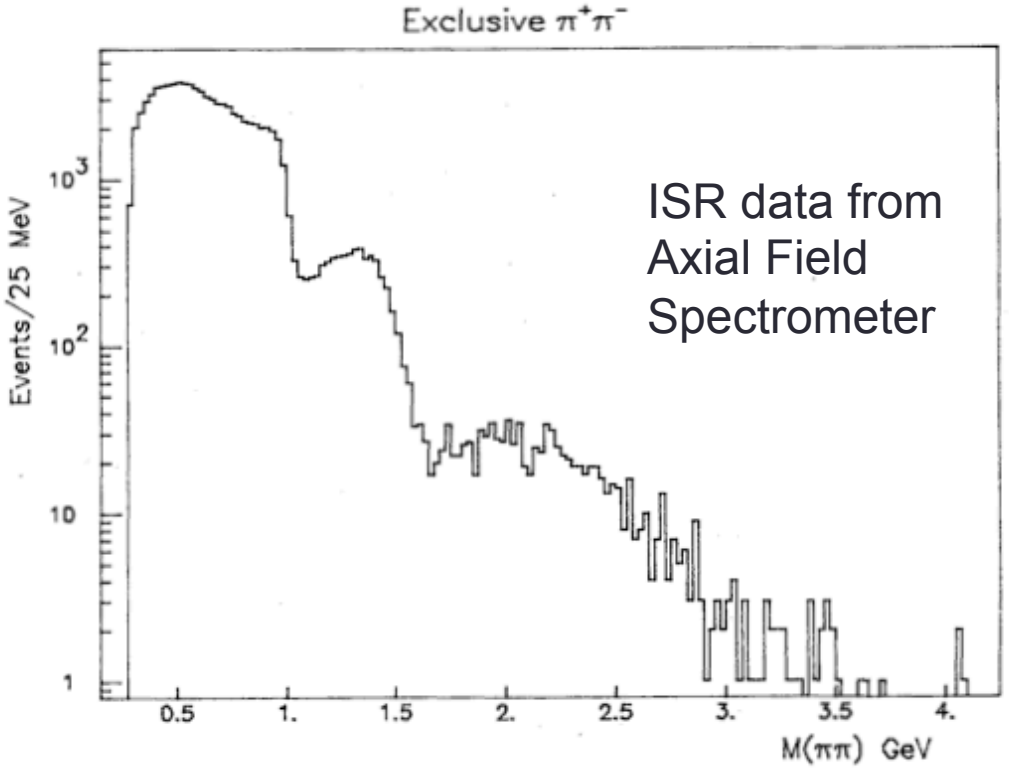
X(3872) observed inclusively. (arXiv:1112.5310) Could it be produced exclusively?

- 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

Low mass spectroscopy + glueballs

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



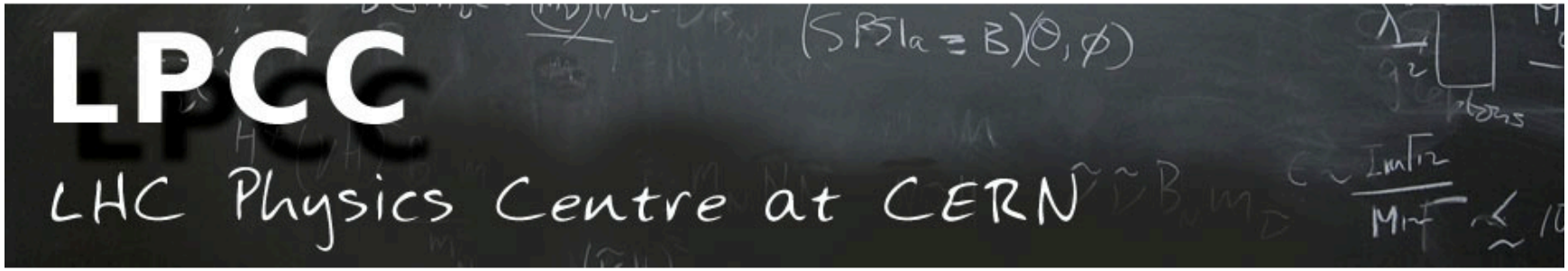


- **Glue laboratory**

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

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  - MB & UE WG
  - Electroweak WG
  - Rate normalization WG
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  - Forward Physics WG
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  - Forthcoming events
  - Past events
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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

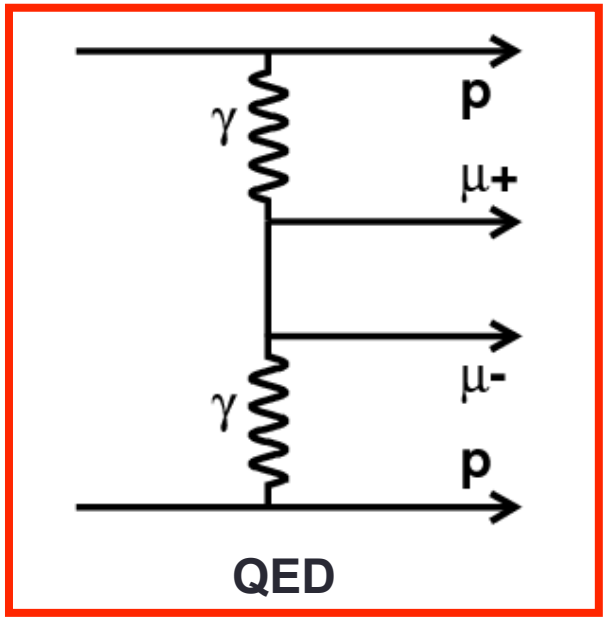
- WG Twiki page
- WG meetings
- WG documents

Summary

- Broad range of excellent physics measurements possible through central exclusive production:
  - Testing ground for QCD
  - Understanding the vacuum
  - Glueballs, saturation and other exotic phenomena
- 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)
- Limiting feature is determination of rapidity gap
- New detector for Run2

Backups

Central Exclusive Production with Dimuon final states



QED

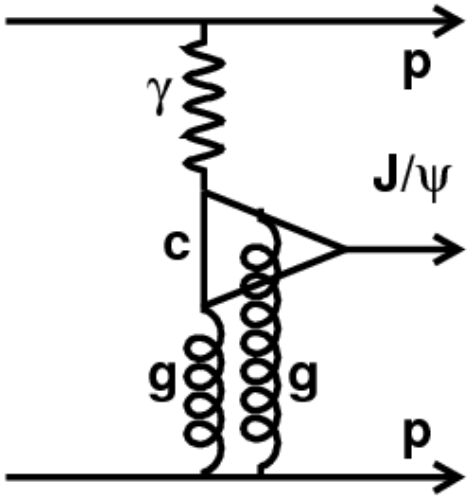
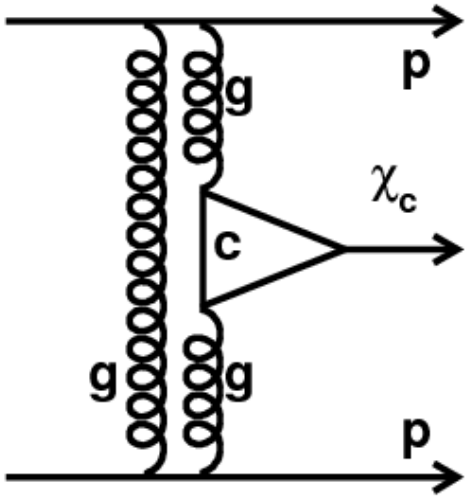


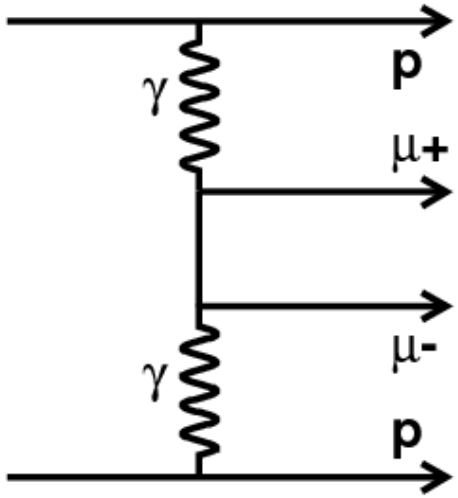
Photo production



Double pomeron exchange

- 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

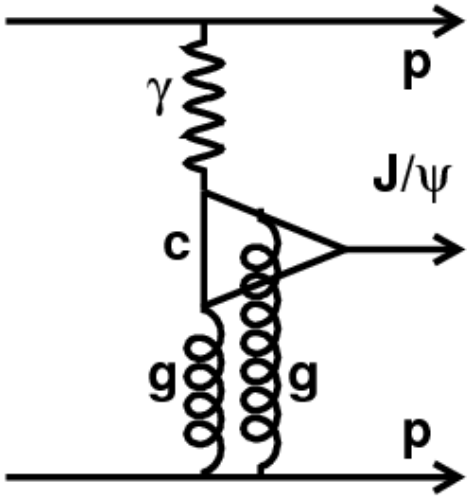
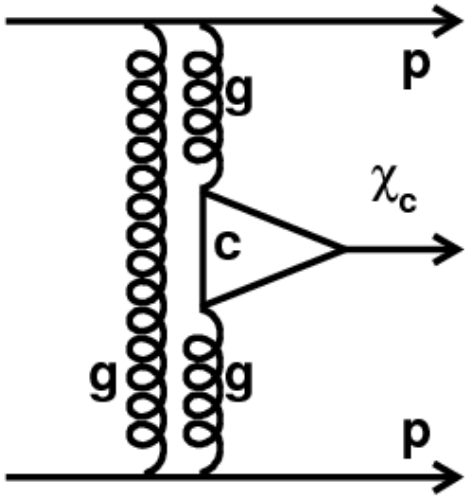


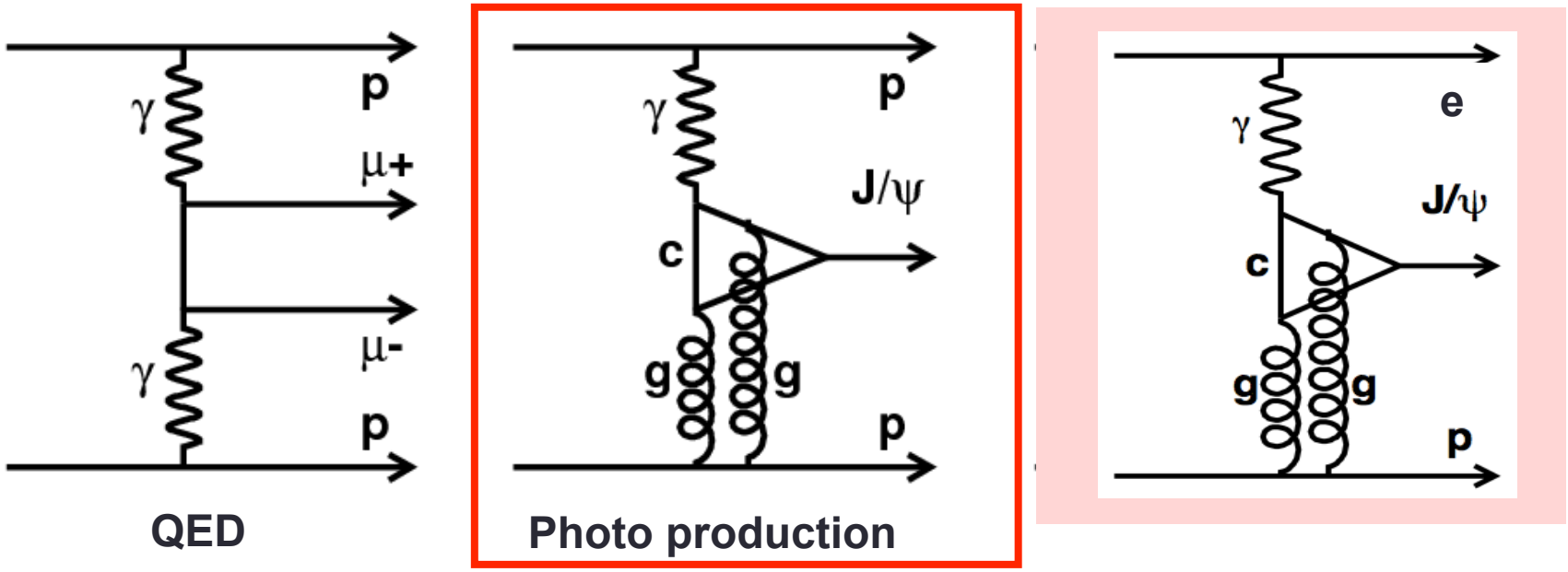
Photo production



Double pomeron exchange

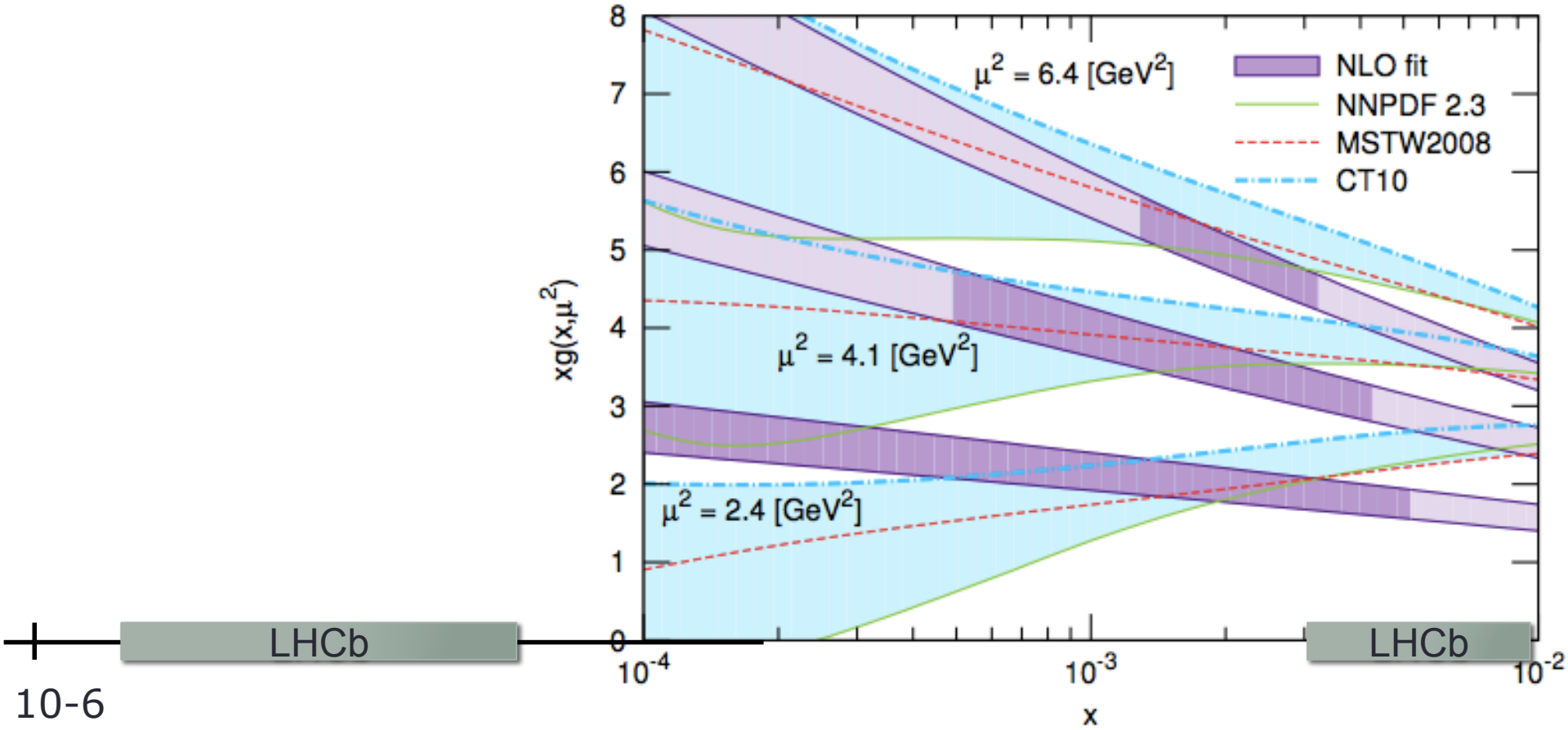
- Double pomeron exchange.
- Unambiguous evidence for pomeron
- 'Standard Candle' for other DPE processes, in particular, Higgs.

Central Exclusive Production with Dimuon final states



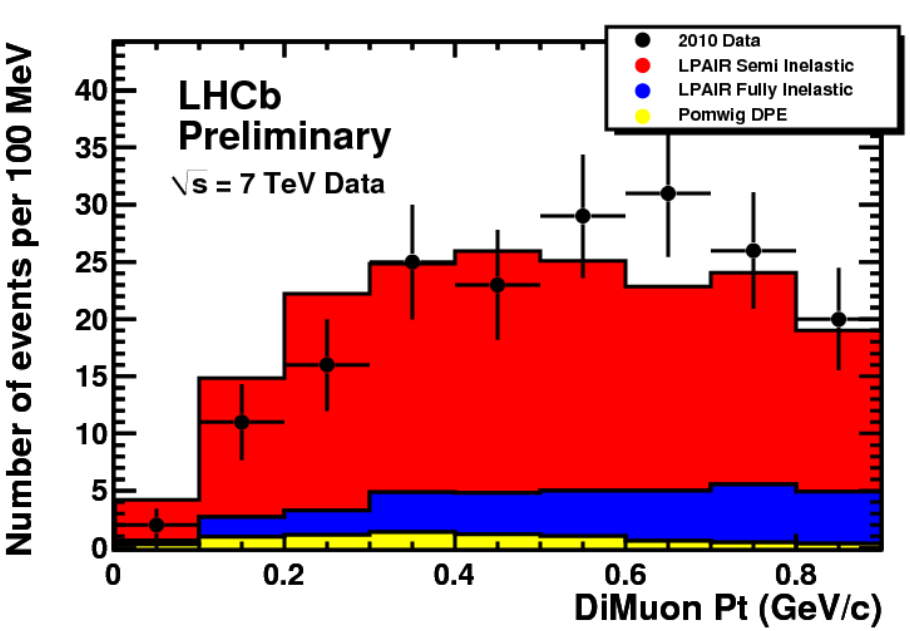
- Test of QCD and pomeron in clean environment
- Sensitive to diffractive PDF at very low x (to 5×10^{-6})
- Search for the odderon and saturation effects
- Measured at HERA/Tevatron but at different photon-proton energy, W

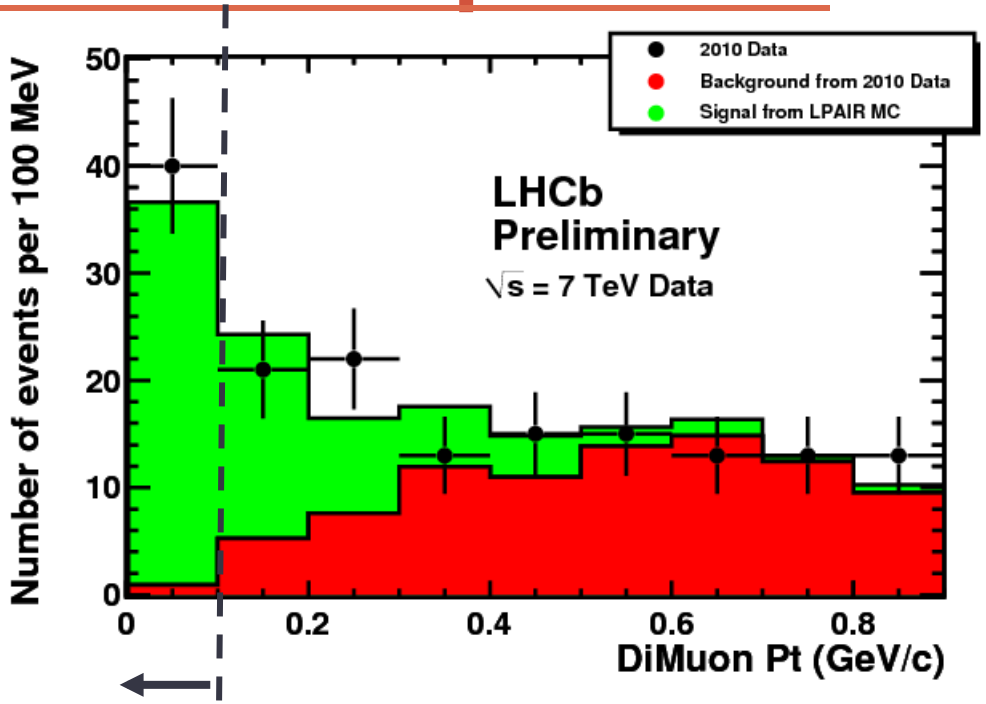
Sensitivity to gluon pdf (arXiv: 1307.7099)



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

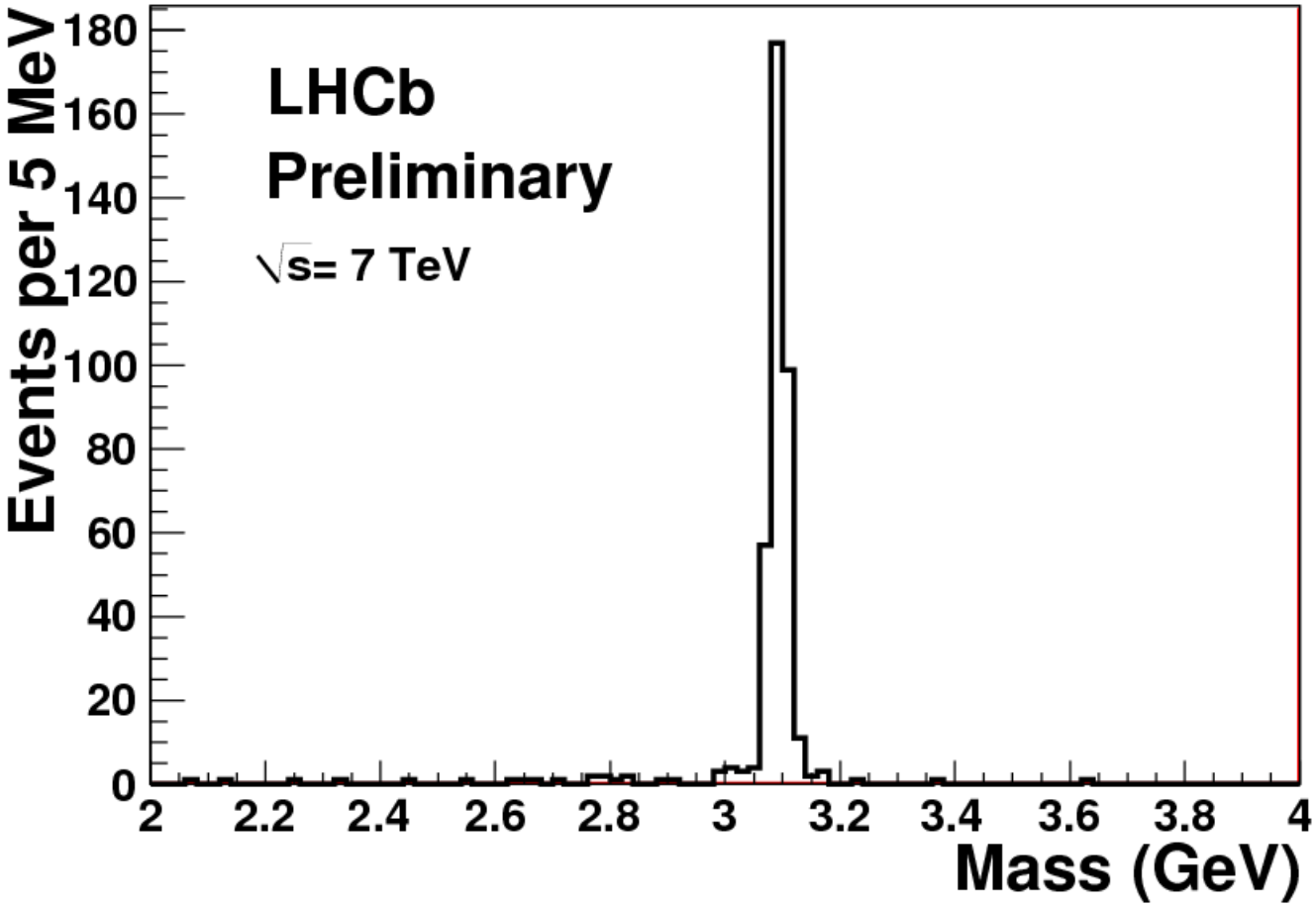
Note: this time we have simulation that predicts the shape for the three contributions.

Fit to signal events

Background shape from data
Signal shape from simulation.

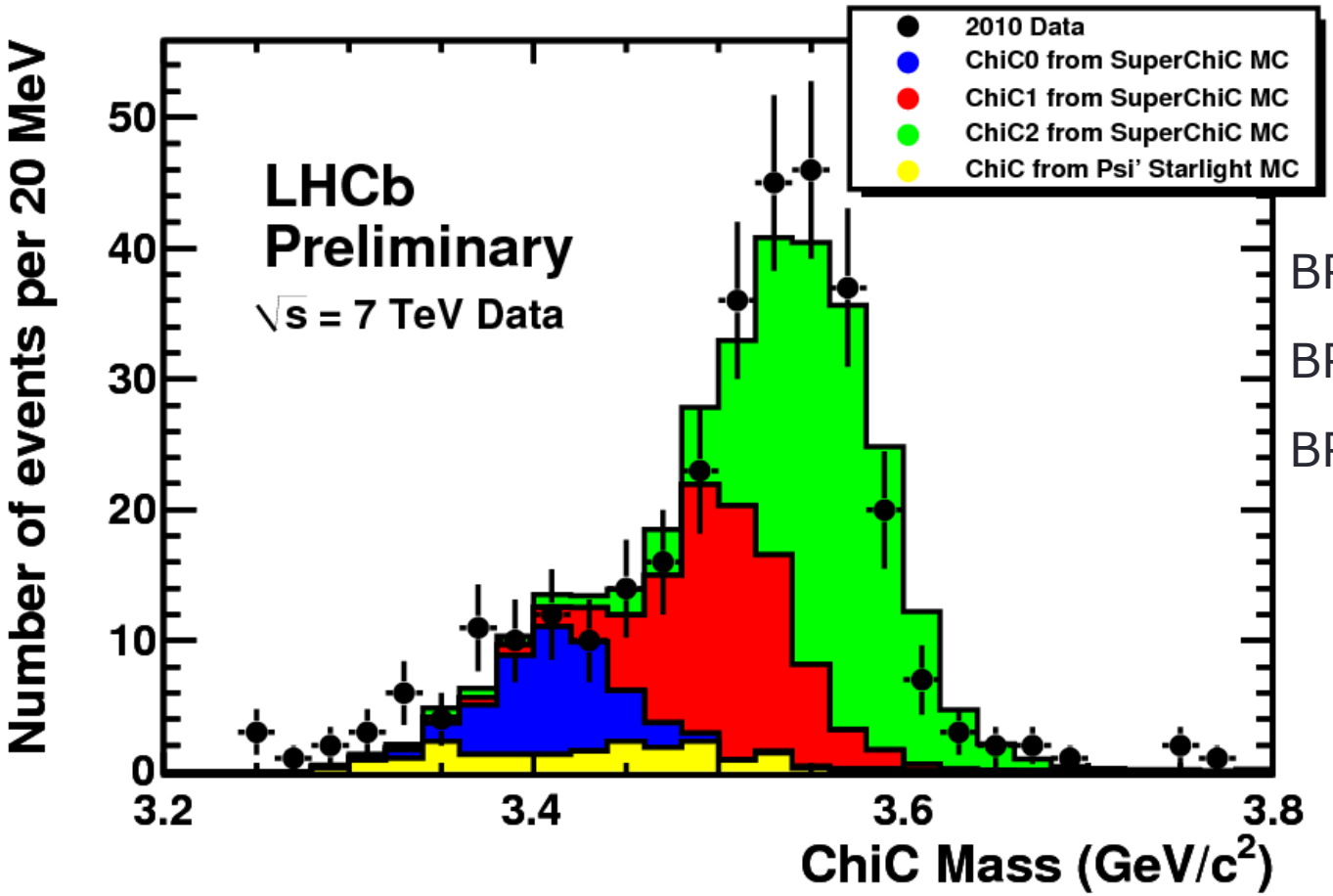
Measured cross-section pμμp: 67 +- 19 pb	LPAIR (J. Vermaseren) 42 pb

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

$\sigma_{\chi_{c0}\to\mu^+\mu^-\gamma} = 9.3 \pm 2.2 \pm 3.5 \pm 1.8$ pb

$\sigma_{\chi_{c1}\to\mu^+\mu^-\gamma} = 16.4 \pm 5.3 \pm 5.8 \pm 3.2$ pb

$\sigma_{\chi_{c2}\to\mu^+\mu^-\gamma} = 28.0 \pm 5.4 \pm 9.7 \pm 5.4$ pb

LHCb preliminary results with 2010 data

	χ_0	χ_1	χ_2
χ_0: 9.3 +- 4.5 pb χ_1: 16.4 +- 7.1 pb χ_2: 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.

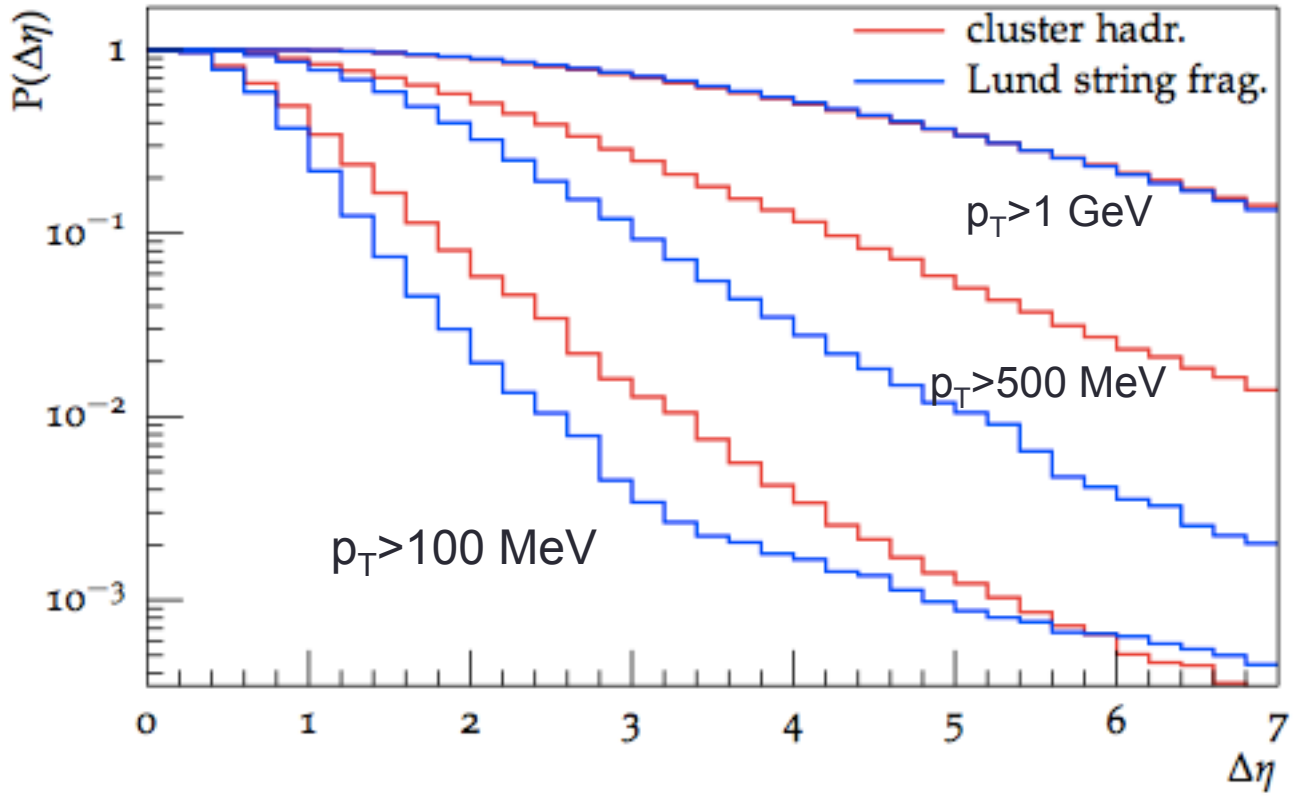
Integrated cross-sections

	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?

Probability for finding a rapidity gap>$\Delta\eta$ in inclusive QCD events



- 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 < ~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
$\epsilon^{\psi}_{\rm id} \times \epsilon^{\psi}_{\rm trig}$	0.71 ± 0.03	0.78 ± 0.02	0.81 ± 0.01	0.84 ± 0.01	0.85 ± 0.01
Purity	$0.592 \pm 0.012 \pm 0.030$				

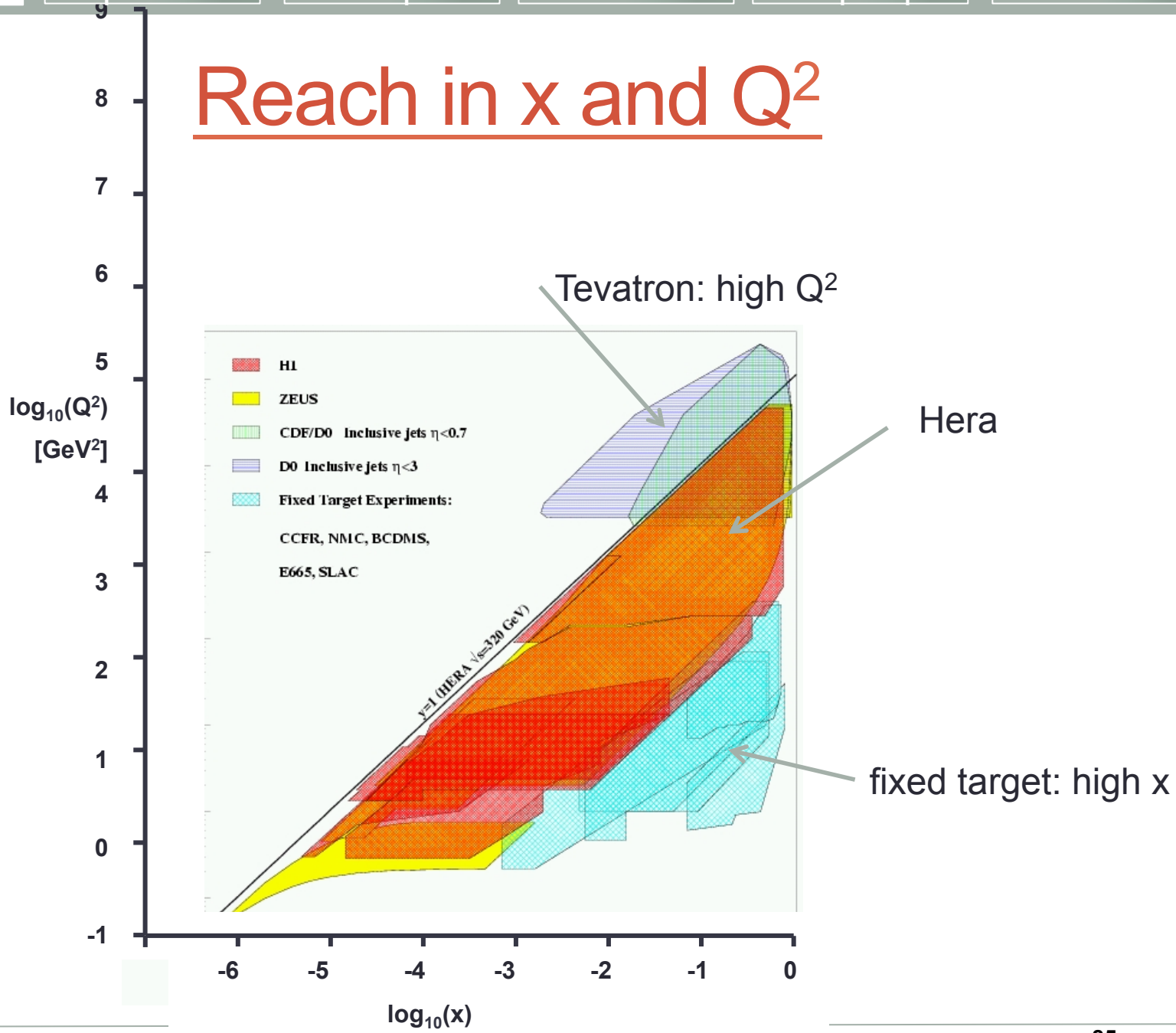
y range (J/ψ)	[3.25, 3.50]	[3.50,3.75]	[3.75,4.00]	[4.00,4.25]	[4.25,4.50]
# Events	9877	7907	5181	2496	596
Acceptance	0.739 ± 0.015	0.734 ± 0.015	0.674 ± 0.014	0.566 ± 0.011	0.401 ± 0.008
$\epsilon^{\psi}_{\rm id} \times \epsilon^{\psi}_{\rm trig}$	0.87 ± 0.01	0.88 ± 0.01	0.87 ± 0.01	0.83 ± 0.02	0.81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

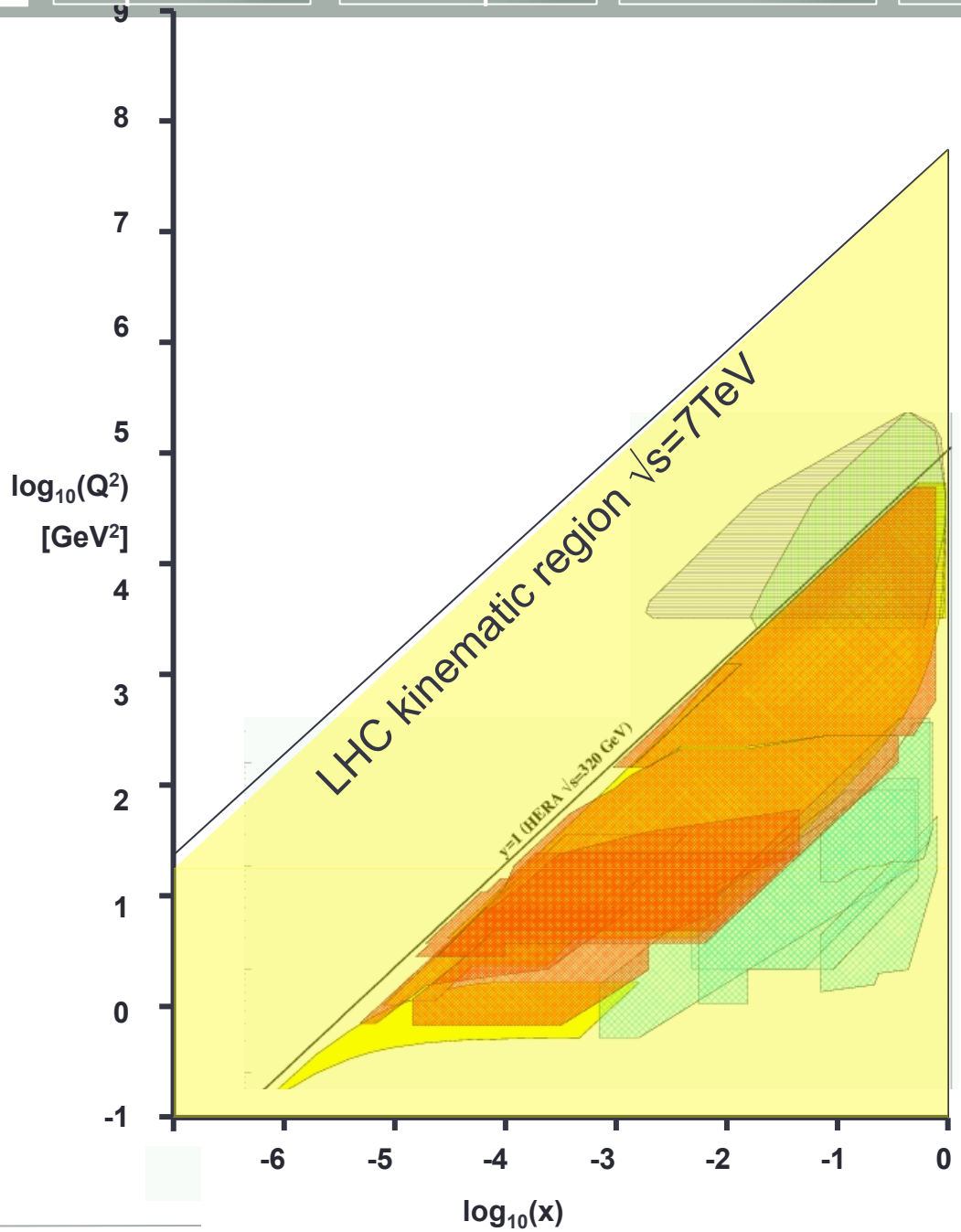
y range ($\psi(2S)$)	[2.00, 2.25]	[2.25,2.50]	[2.50,2.75]	[2.75,3.00]	[3.00,3.25]
# Events	31	111	208	1287	268
Acceptance	0.678 ± 0.013	0.800 ± 0.016	0.834 ± 0.017	0.787 ± 0.016	0.755 ± 0.015
$\epsilon^{\psi}_{\rm id} \times \epsilon^{\psi}_{\rm trig}$	0.80 ± 0.03	0.83 ± 0.02	0.86 ± 0.01	0.88 ± 0.01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

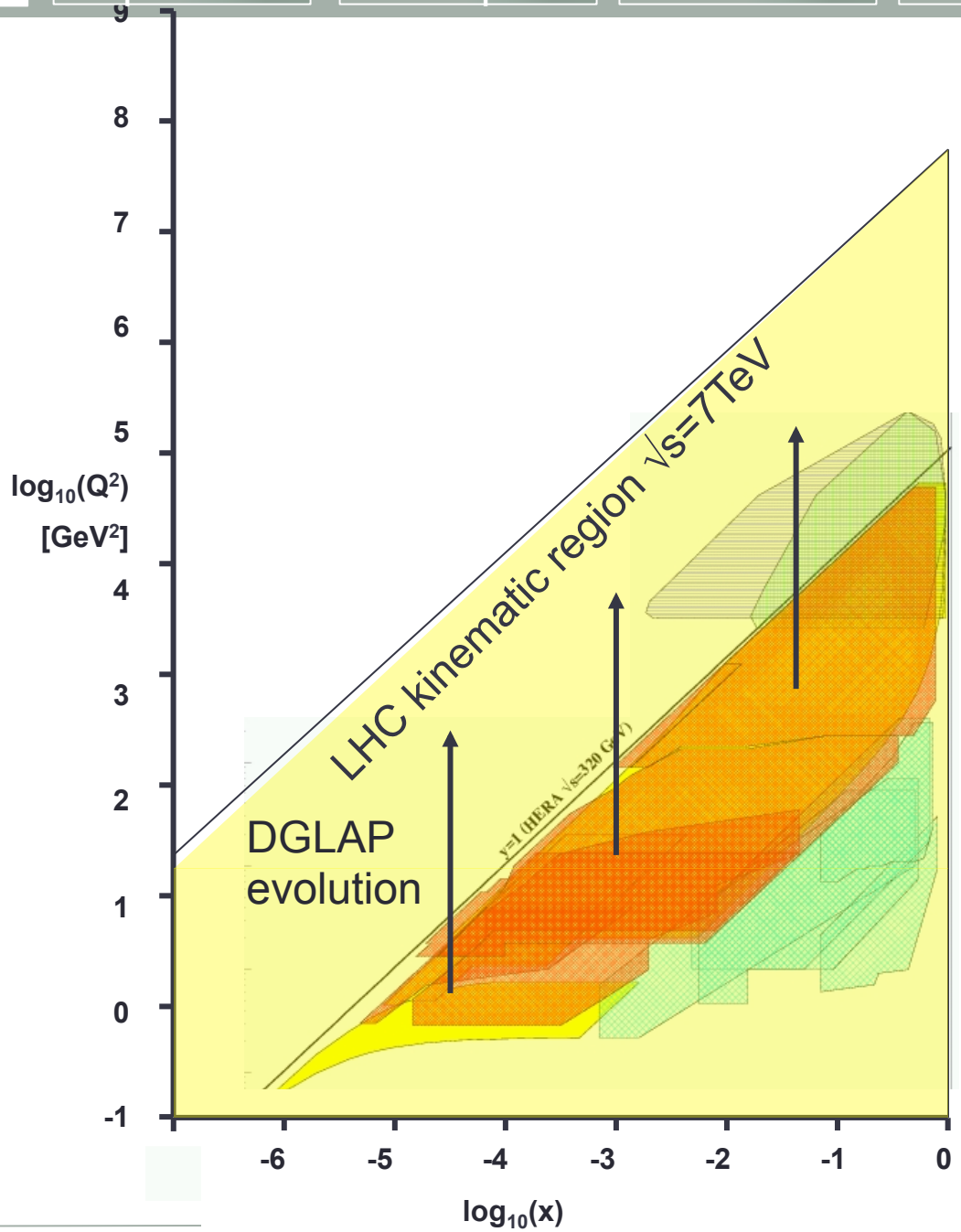
y range($\psi(2S)$)	[3.25, 3.50]	[3.50,3.75]	[3.75,4.00]	[4.00,4.25]	[4.25,4.50]
# Events	282	201	105	61	11
Acceptance	0.748 ± 0.015	0.702 ± 0.014	0.628 ± 0.013	0.524 ± 0.010	0.384 ± 0.008
$\epsilon^{\psi}_{\rm id} \times \epsilon^{\psi}_{\rm trig}$	0.90 ± 0.01	0.89 ± 0.01	0.87 ± 0.01	0.84 ± 0.02	0.77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

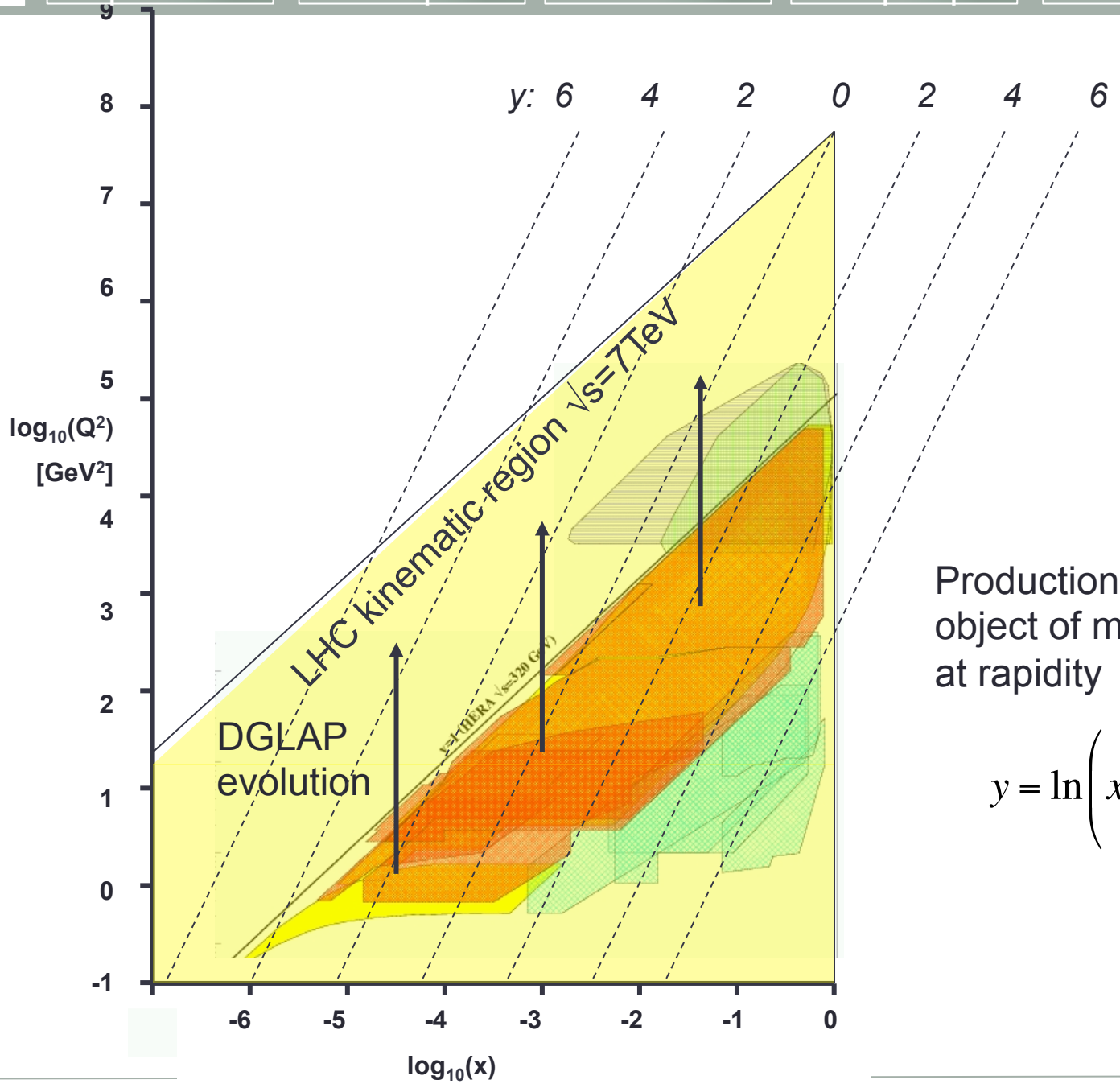
y range (J/ψ and $\psi(2S)$)	[2.00, 4.50]
$\epsilon_{\rm sel}$	0.87 ± 0.01
$\epsilon_{\rm single}$	0.241 ± 0.003
L ($\rm pb^{-1}$)	929 ± 33

Reach in x and Q^2



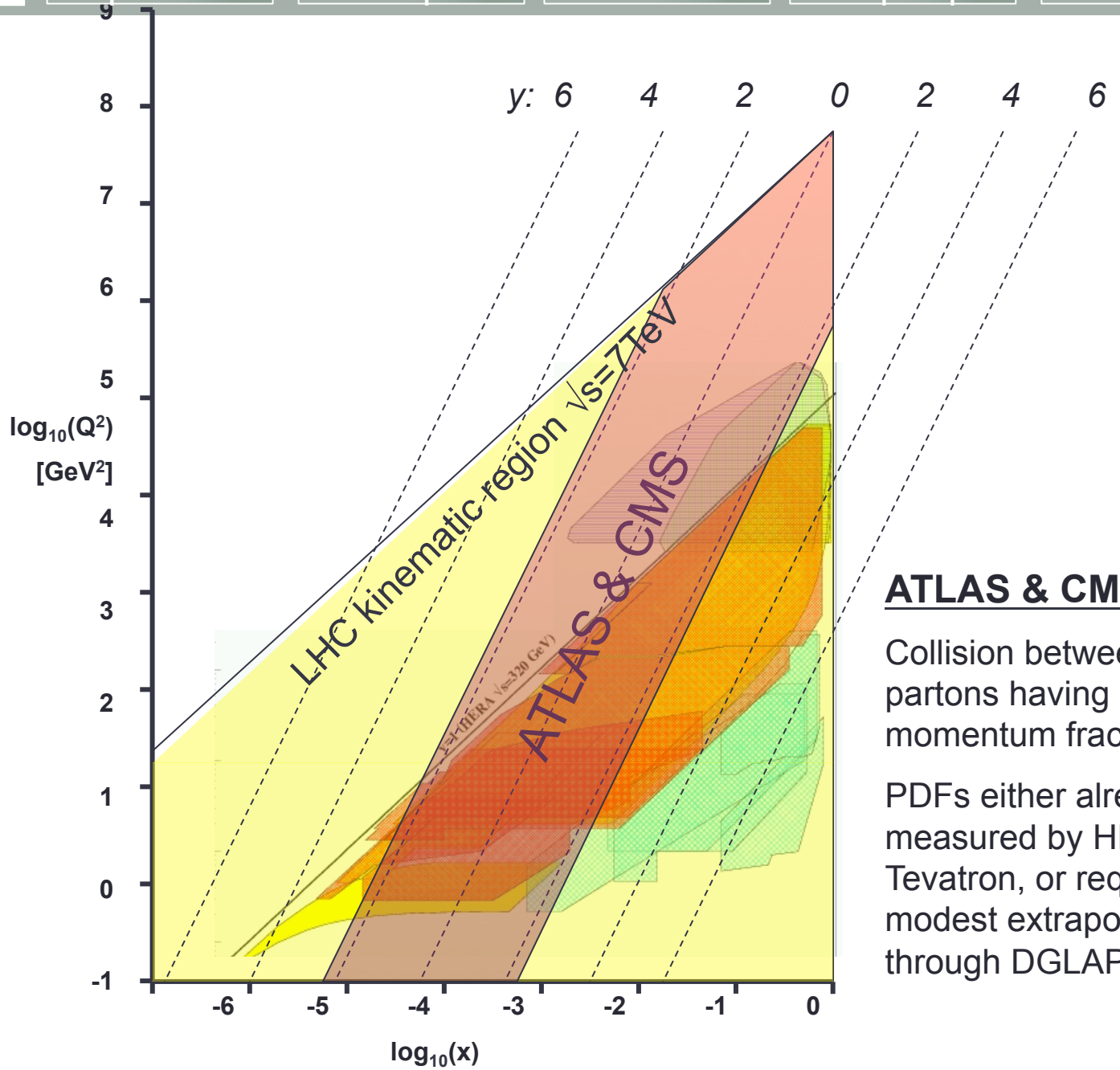

LHC kinematic region √s=7TeV
y=1 (HERA √s=320 GeV)
log10(Q2) [GeV2]
log10(x)
9
8
7
6
5
4
3
2
1
0
-1
-6
-5
-4
-3
-2
-1
0


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



Production of object of mass Q at rapidity

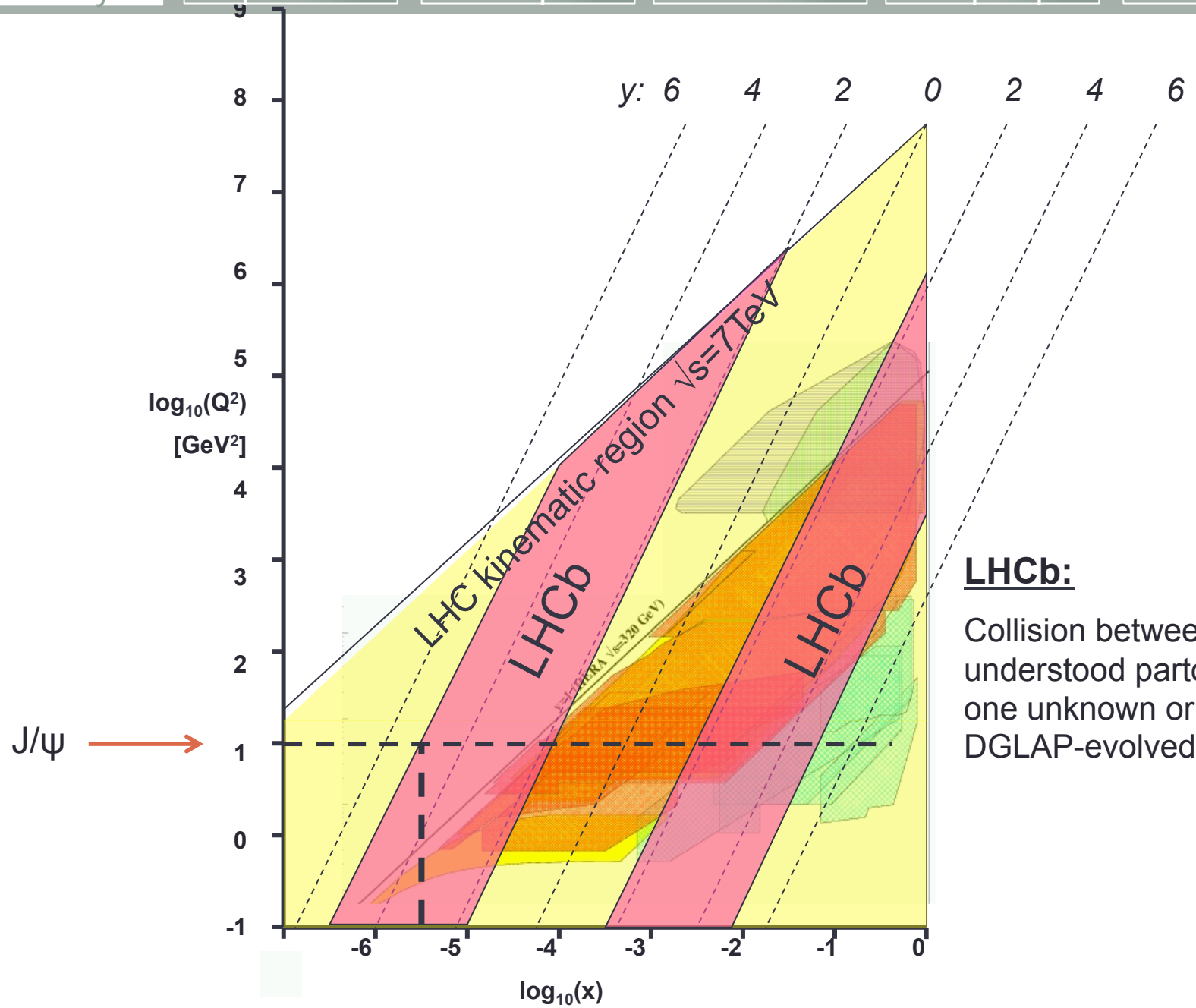
$$y = \ln\left(x\frac{\sqrt{s}}{Q}\right)$$



ATLAS & CMS:

Collision between two partons having similar momentum fractions.

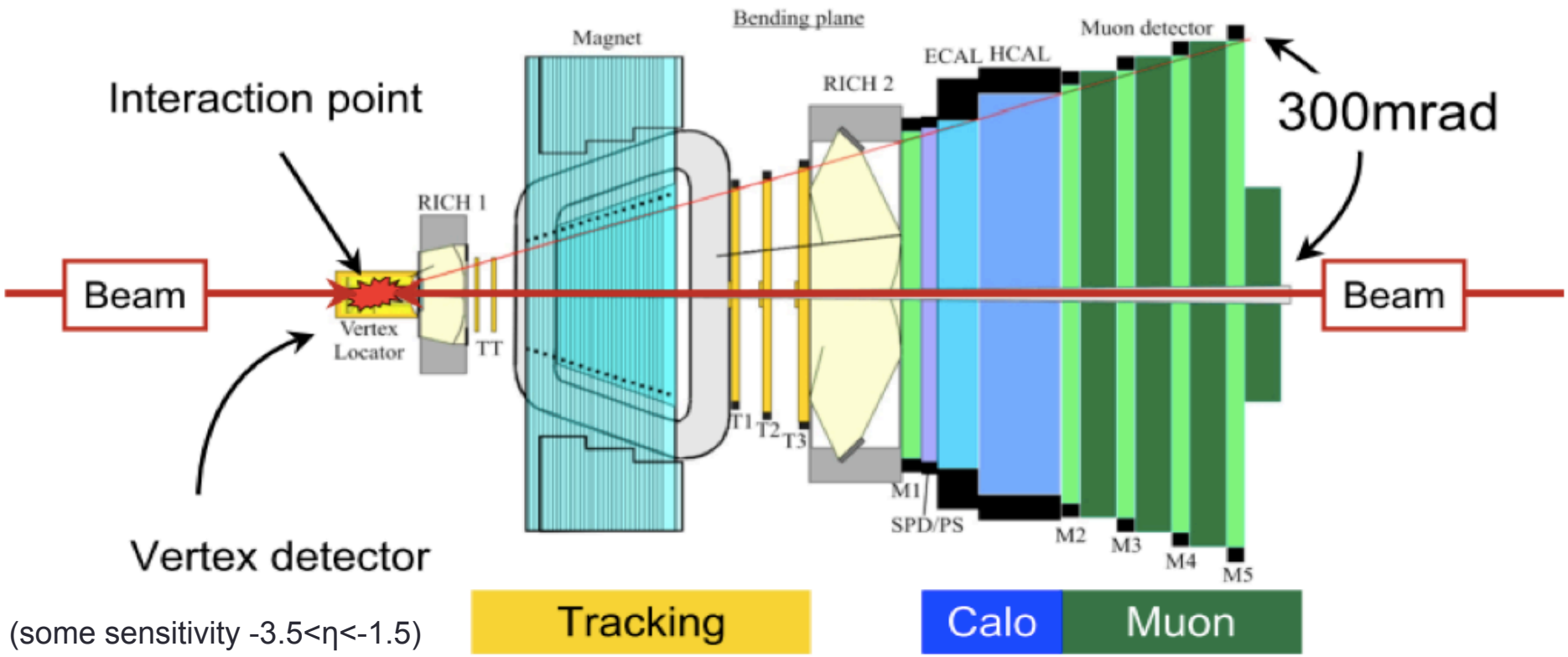
PDFs either already measured by HERA or Tevatron, or requiring modest extrapolation through DGLAP.



LHCb:

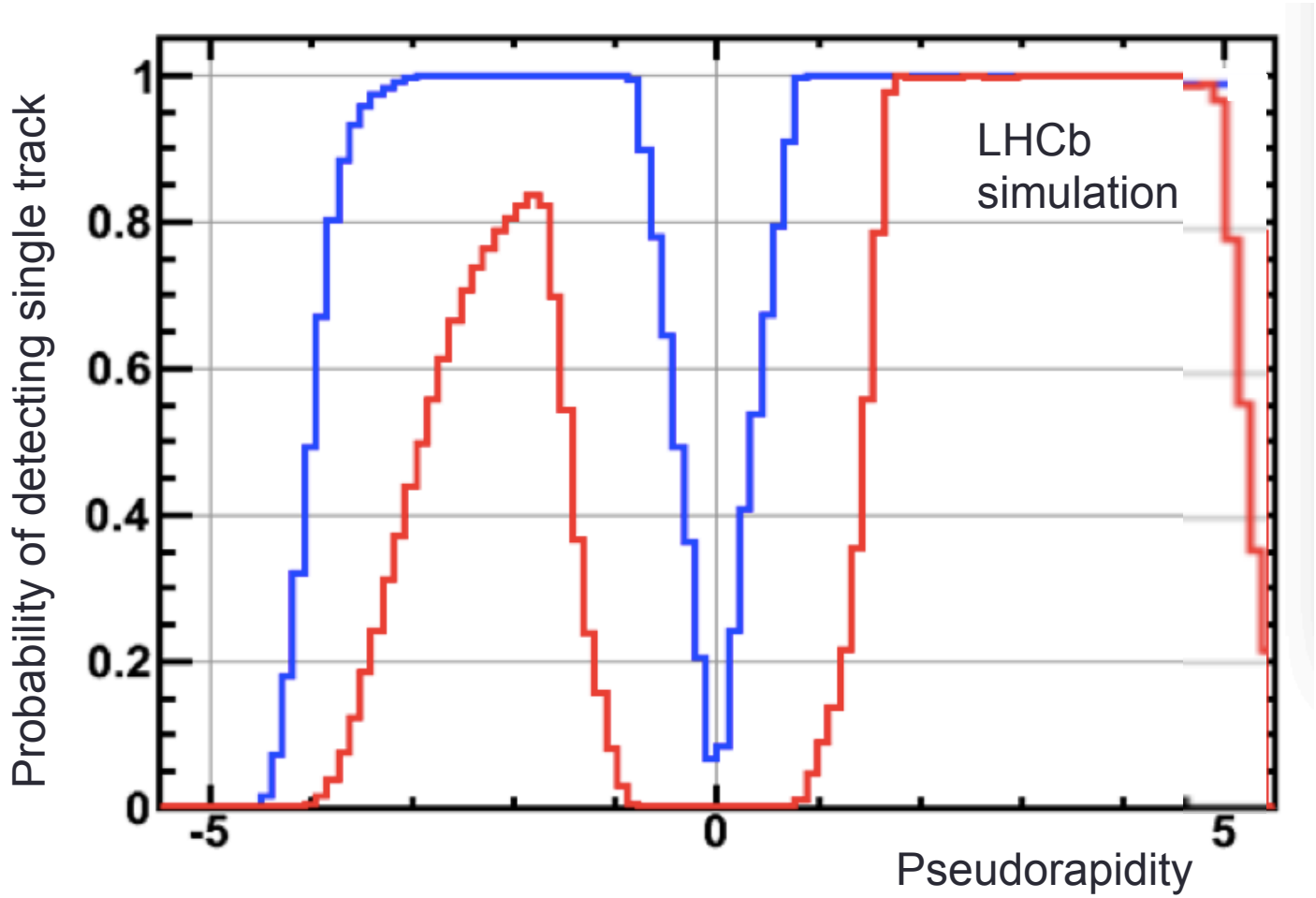
Collision between one well understood parton and one unknown or large DGLAP-evolved parton.

The LHCb detector



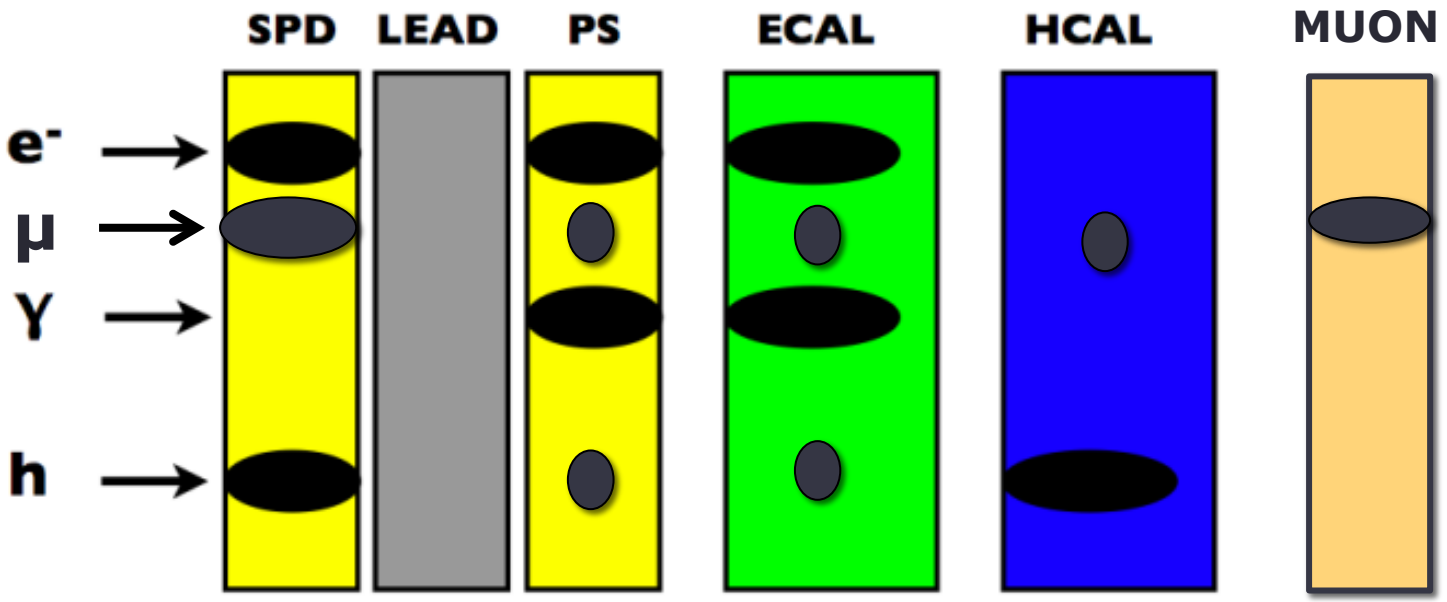
(some sensitivity -3.5<η<-1.5)

Pseudorapidity veto range



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

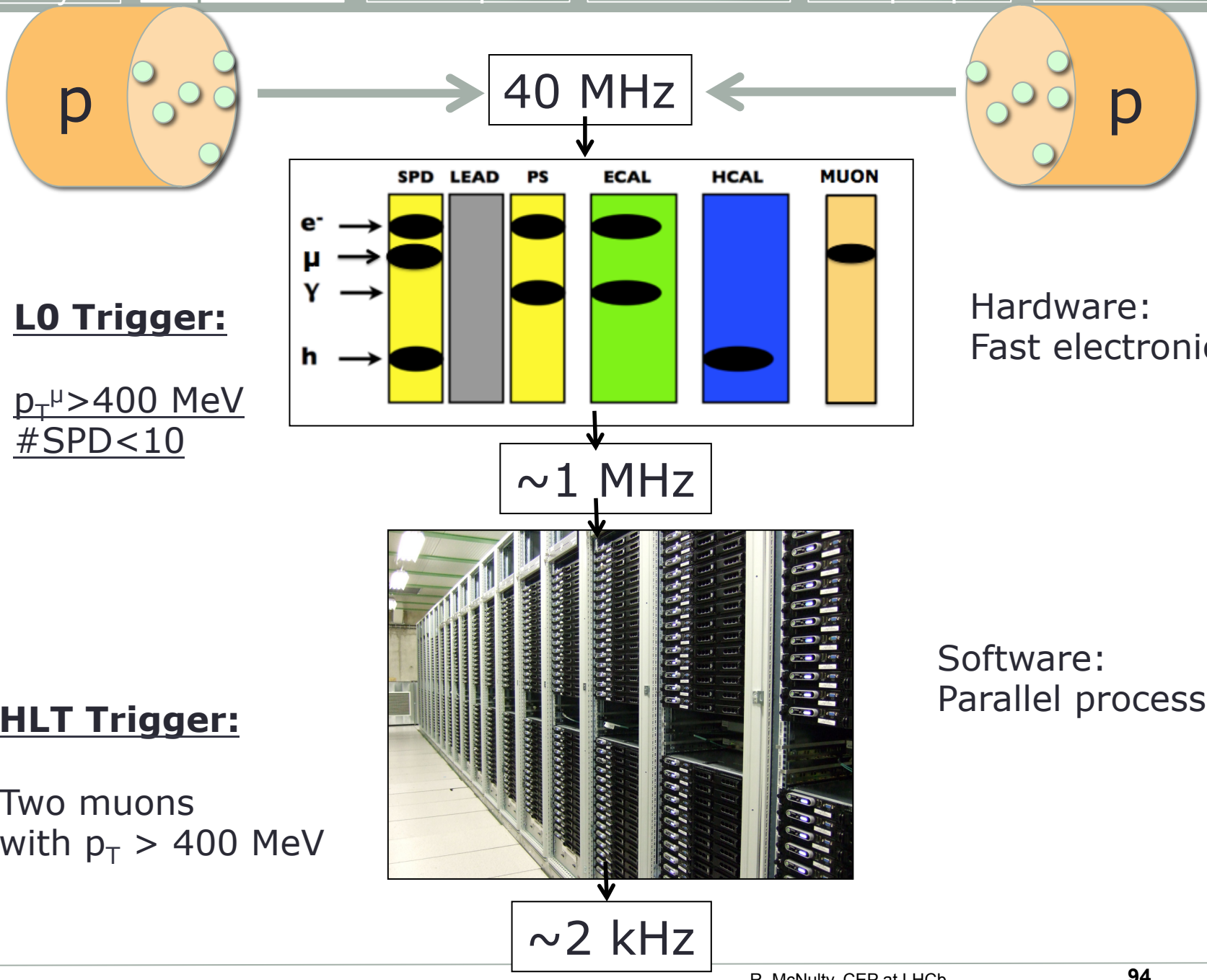
Calorimeter System in LHCb



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



L0 Trigger:

p_T^{μ}>400 MeV
#SPD<10

Hardware:
Fast electronics

HLT Trigger:

Two muons
with p_T > 400 MeV

Software:
Parallel processing

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.

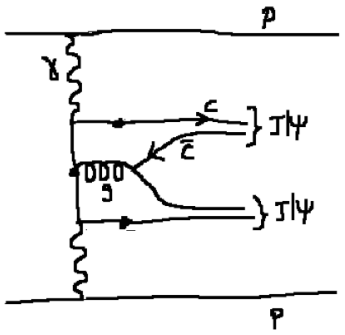
L. Motyka and G. Watt, *Exclusive photoproduction at the Fermilab Tevatron and CERN LHC within the dipole picture*, Phys. Rev. **D78** (2008) 014023, arXiv:0805.2113.

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



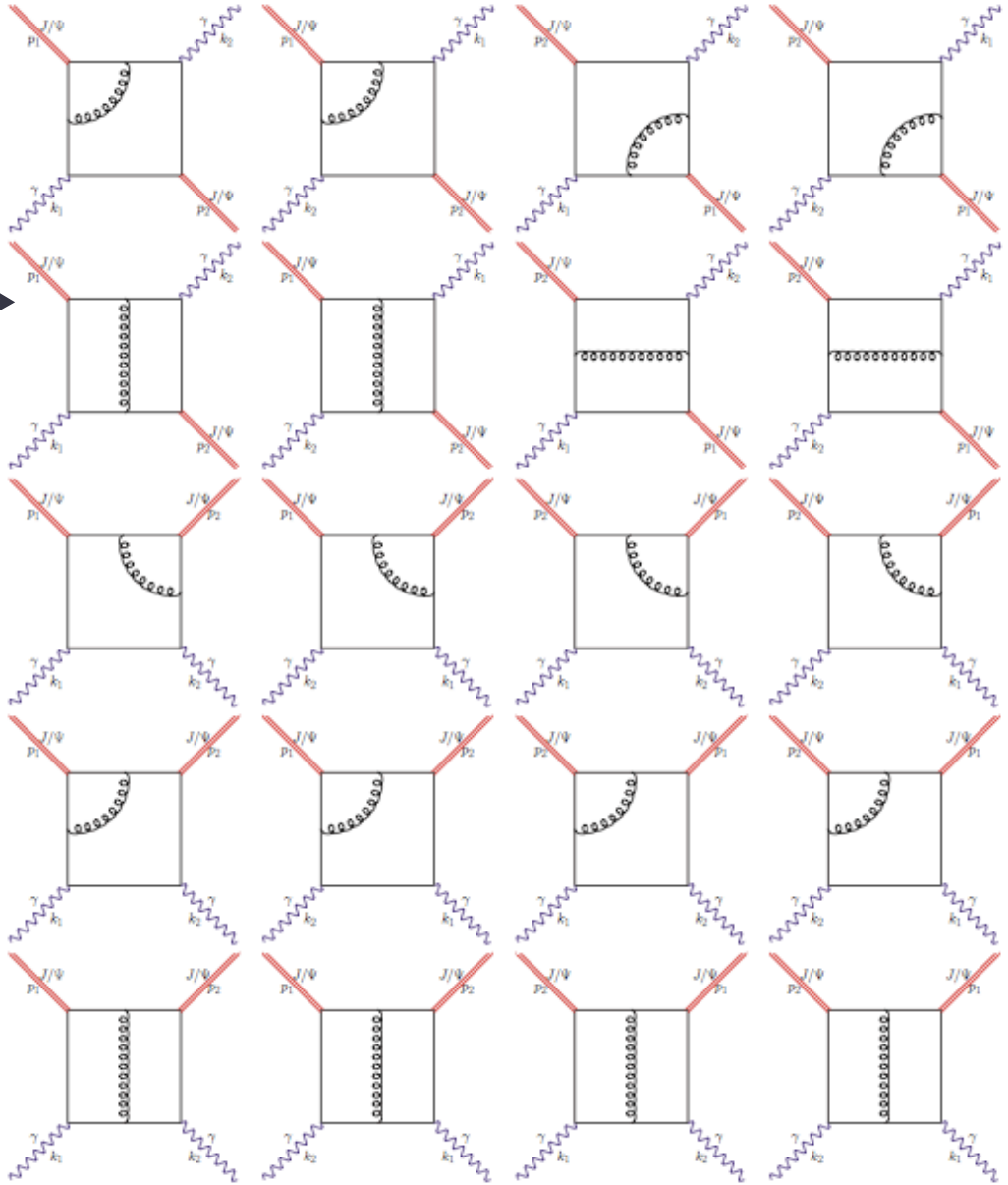
Large literature for γγ->J/ψJ/ψ

- 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.

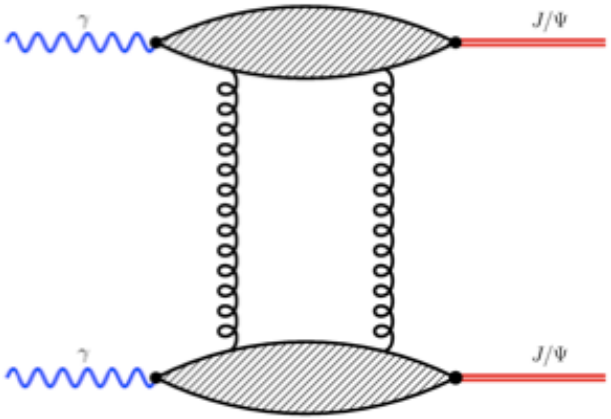
Requires large photon flux:
Heavy ion collisions or Linear colliders

Feynman diagrams

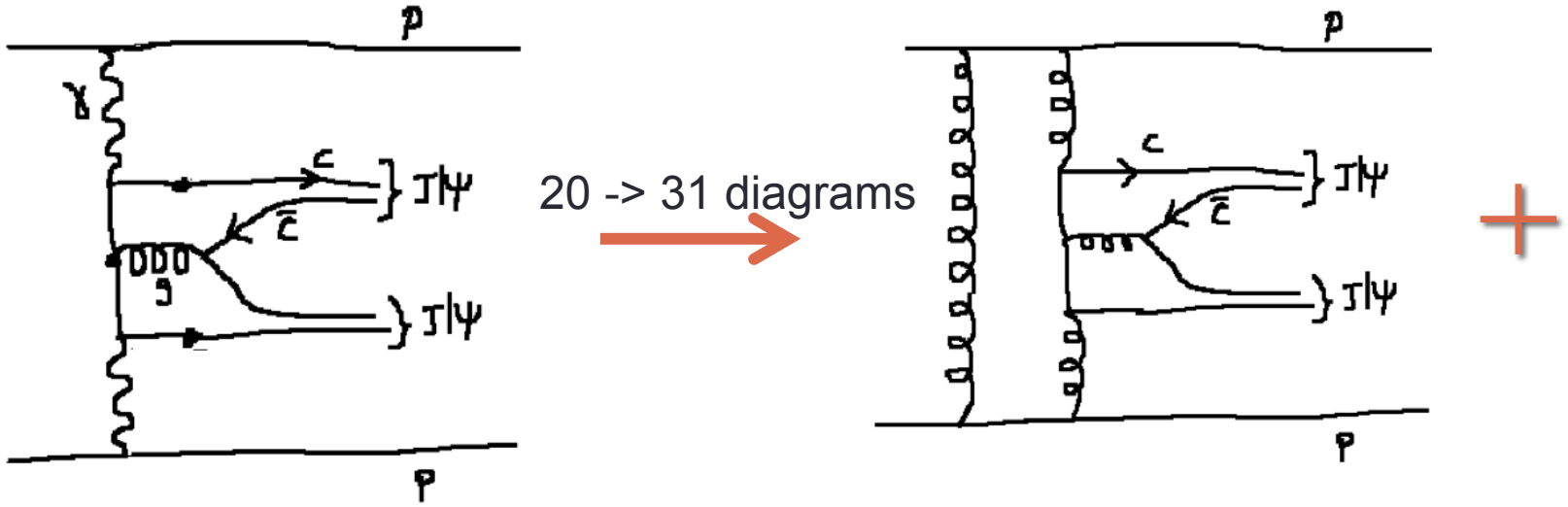
Box diagrams
(Fall off with increasing Q^2)



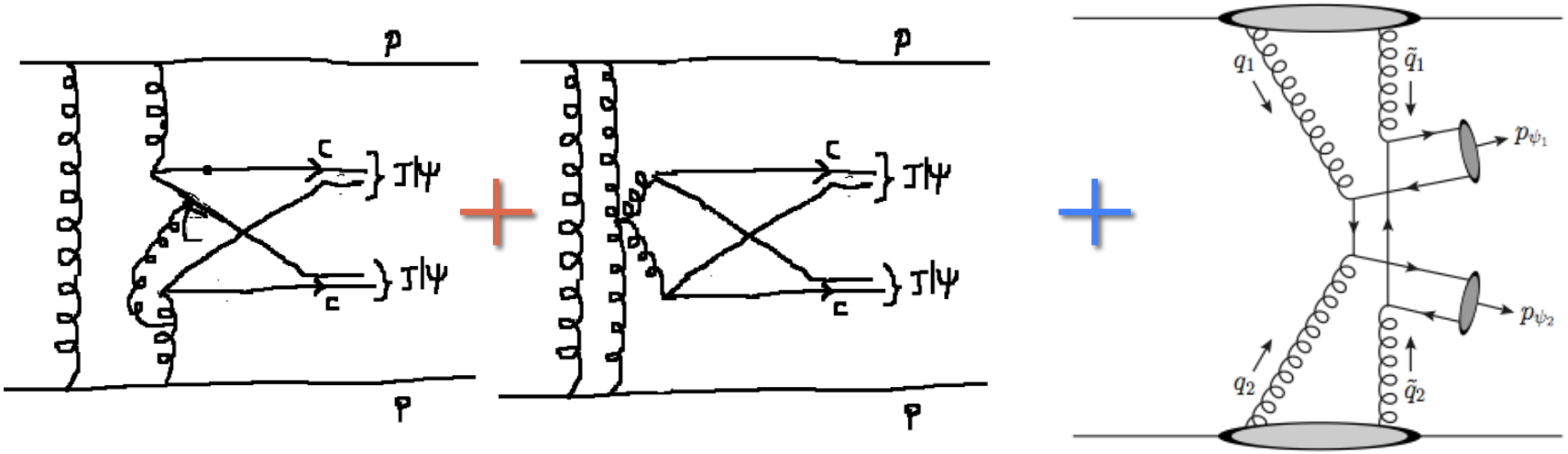
Pomeron exchange
(~constant with Q^2)



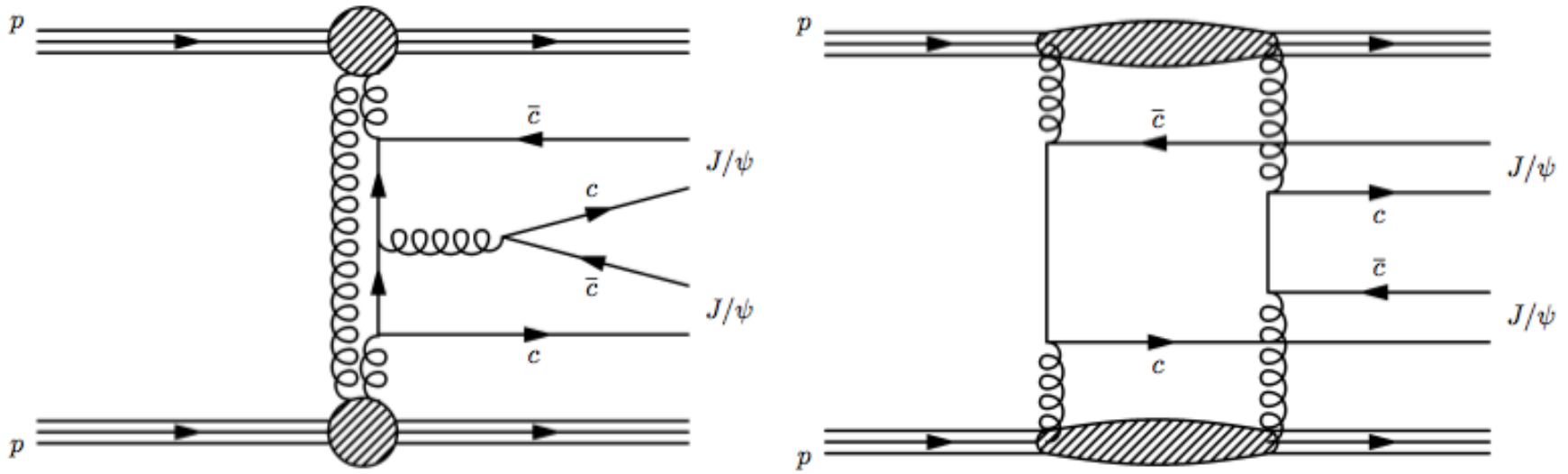
<1 event in 3fb^{-1} of pp interactions



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



Double J/ψ production

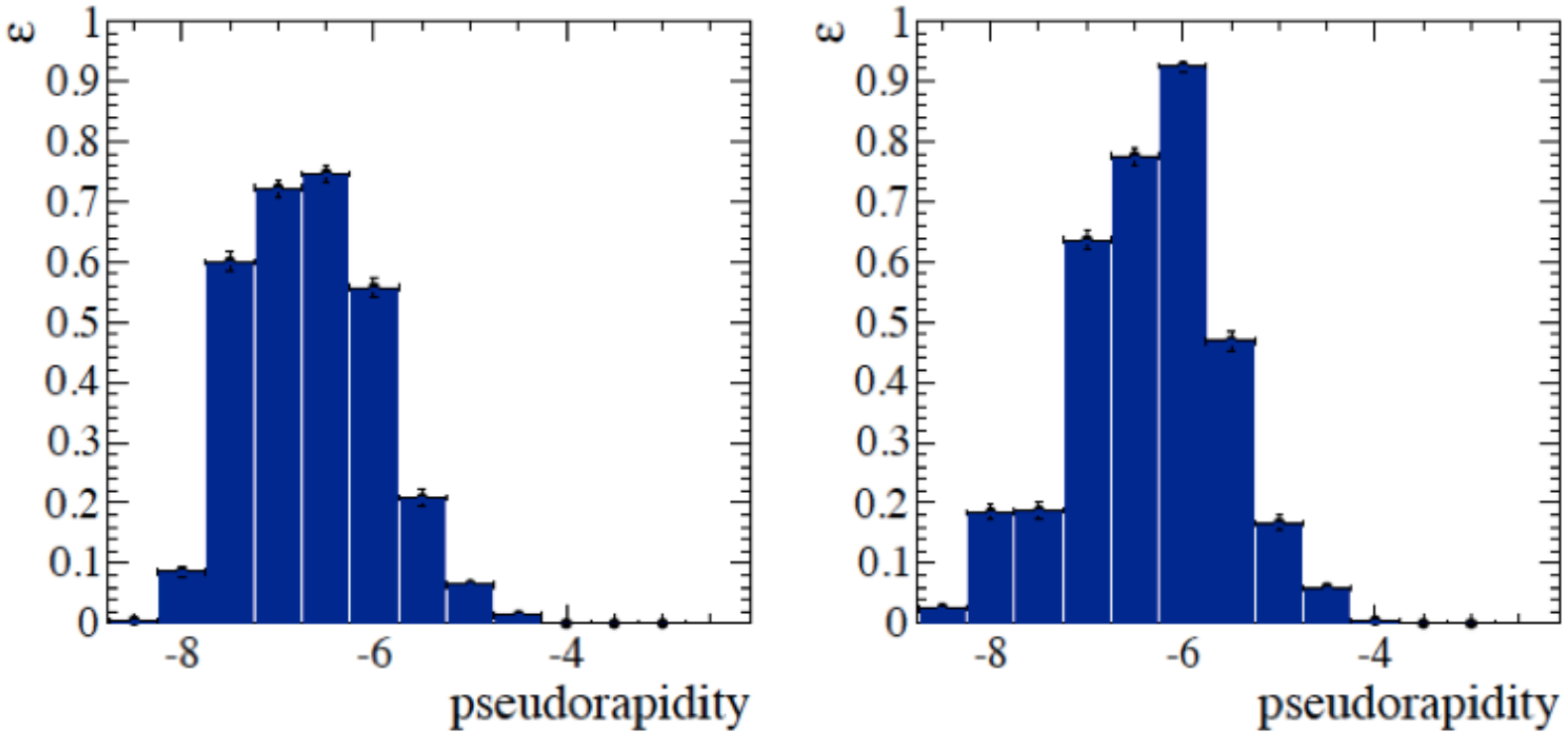


Final state theoretically studied in diphoton production (linear collider) but not through double pomeron exchange (hadron collider)

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