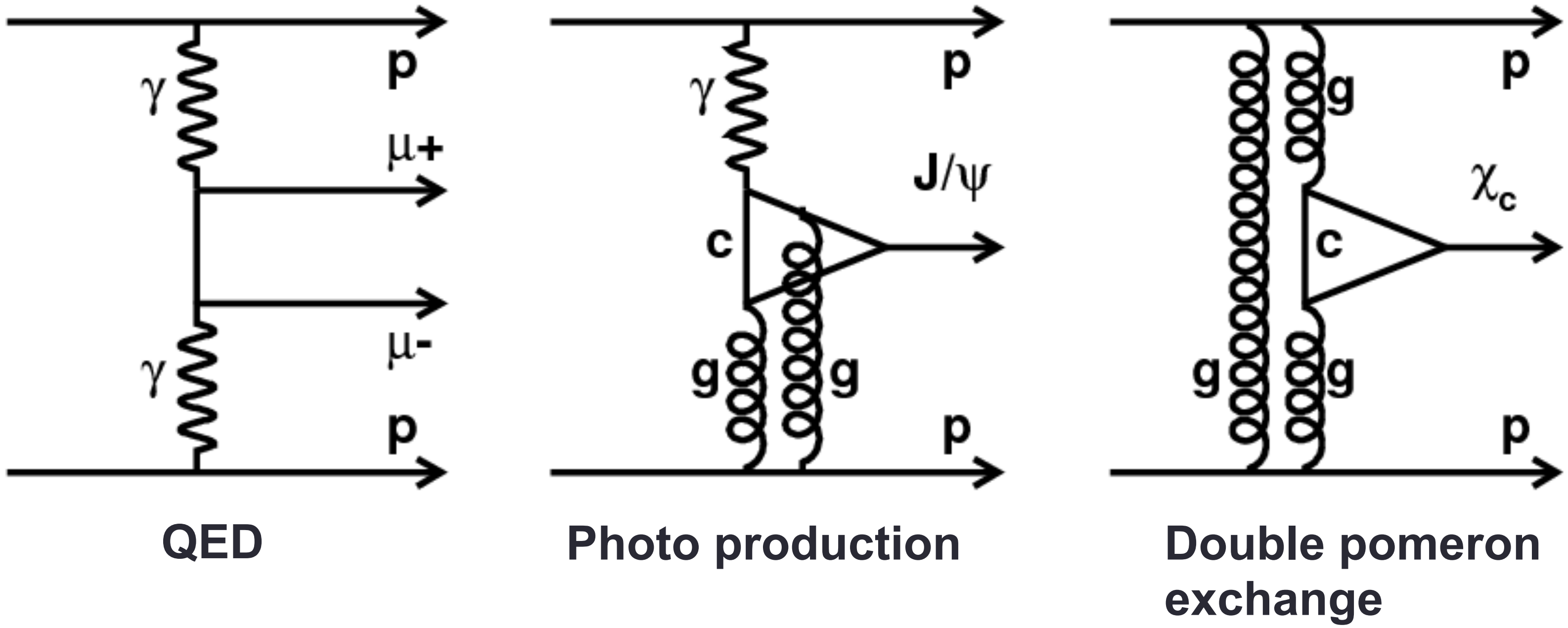
Central Exclusive Single and Double Charmonium Production at LHCb

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

Workshop on QCD and Diffraction at the LHC
15-17 December 2014 Krakow

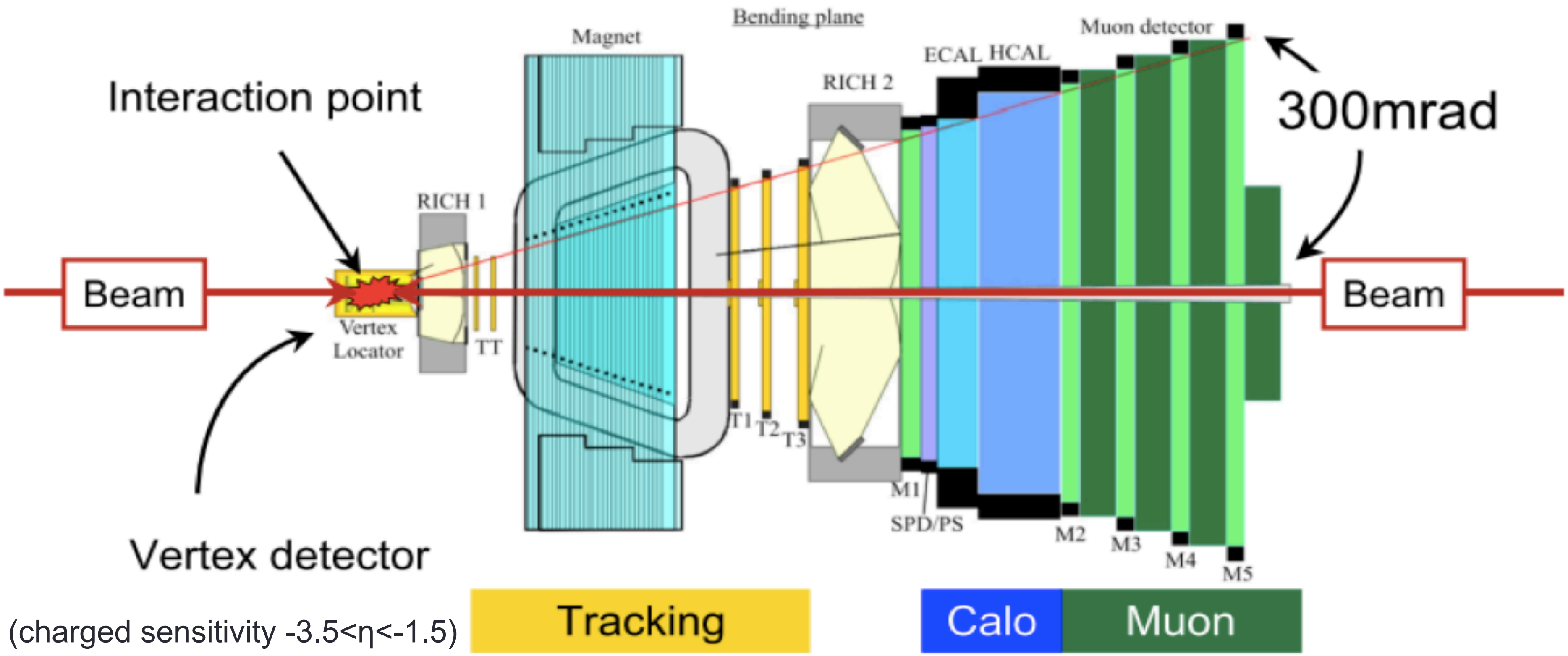
Central Exclusive Production: Colourless propagators



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

Related phenomena where the colourless object creates a particle

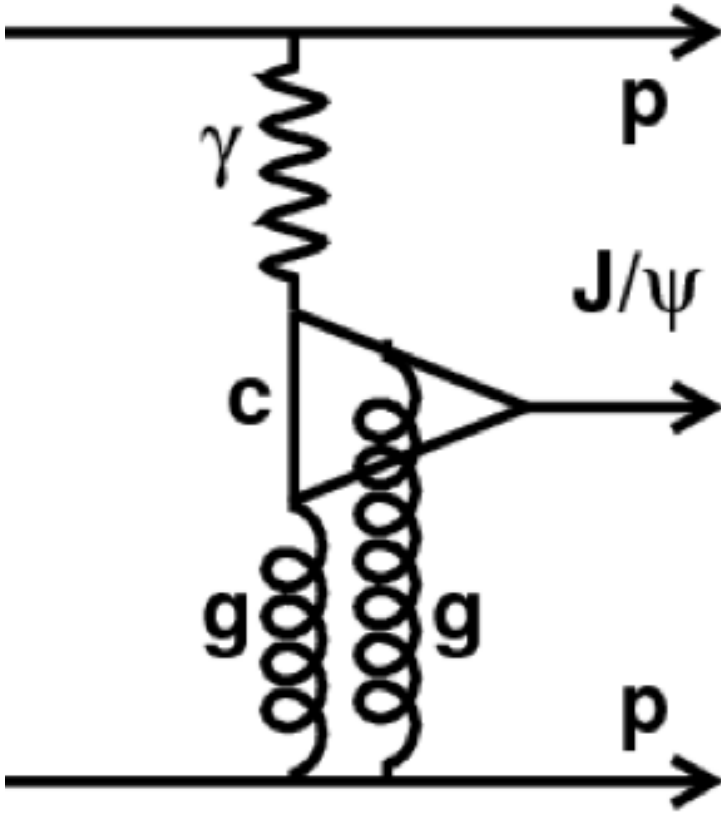
The LHCb detector



(charged sensitivity -3.5<η<-1.5)

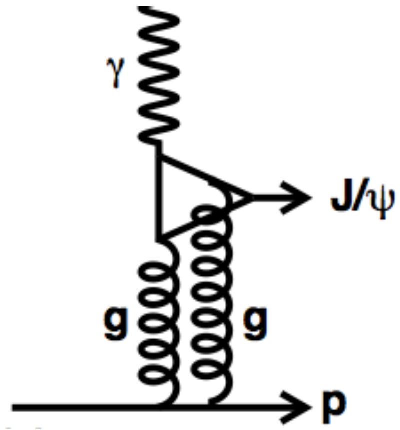
Fully instrumented from $2 < \eta < 5$
Trigger on muons > 400 MeV, and on $J/\psi > 0$ MeV.
Average pp collisions per beam crossing of ~1.5

Photoproduction



- Test of QCD over wide $W_{\gamma p}$ range
- Determination of gluon PDF
- Sensitivity to saturation / odderon

Photo-production cross-section

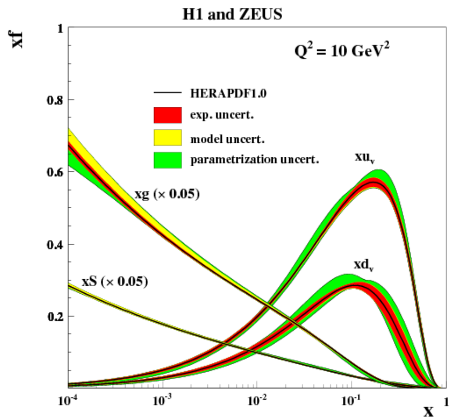


$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi\ p)\Big|_{t=0} = \frac{\Gamma_{ee} M^3_{J/\psi}\pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x,\bar{Q}^2)\right]^2\left(1+\frac{Q^2}{M^2_{J/\psi}}\right)$$

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

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

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



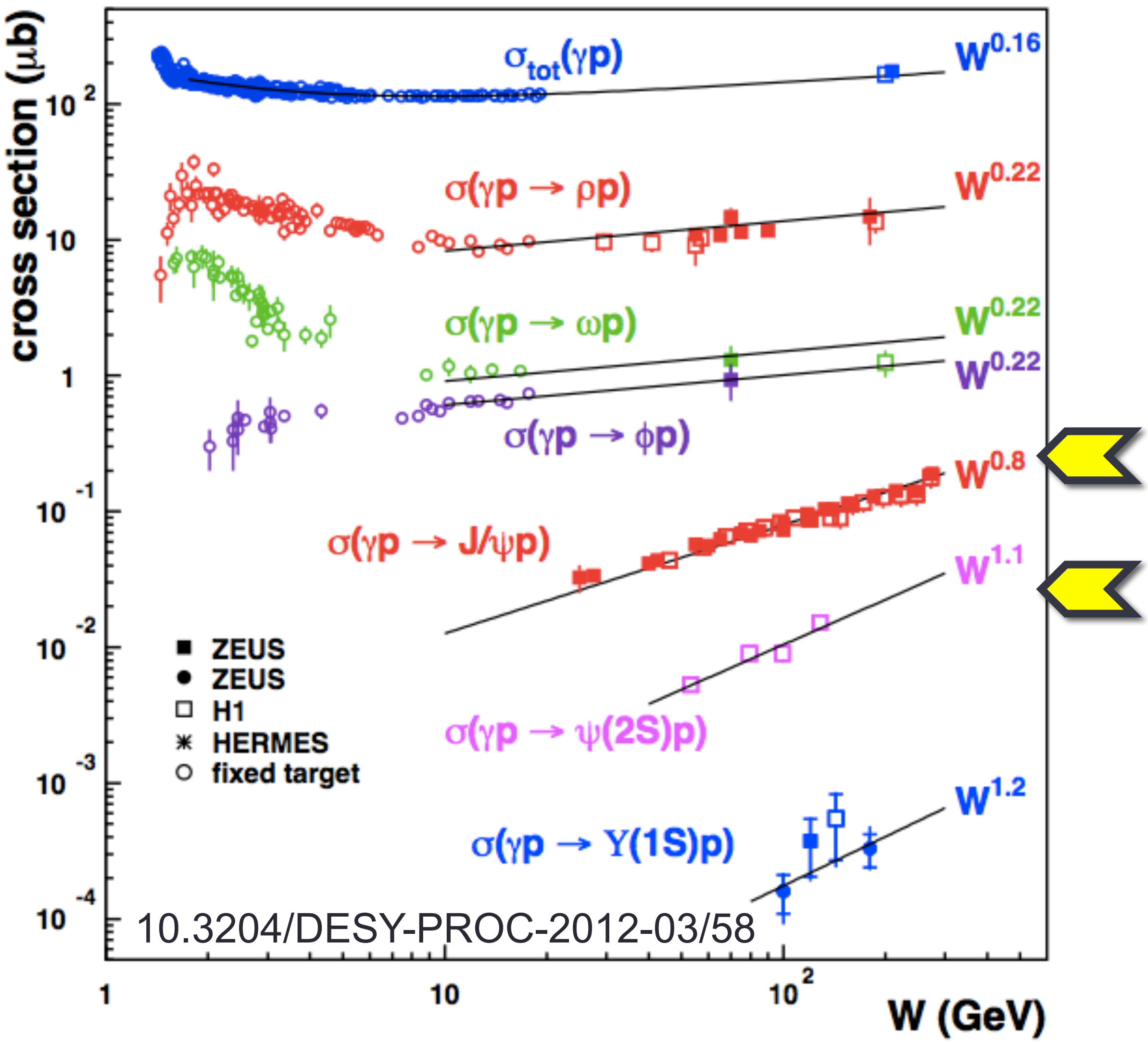
[1] Martin A D, Nockles C, Ryskin M and Teubner T 2008 Small x gluon from exclusive J/ψ production *Phys. Lett.* B **662** 252 (arXiv:0709.4406)

[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)

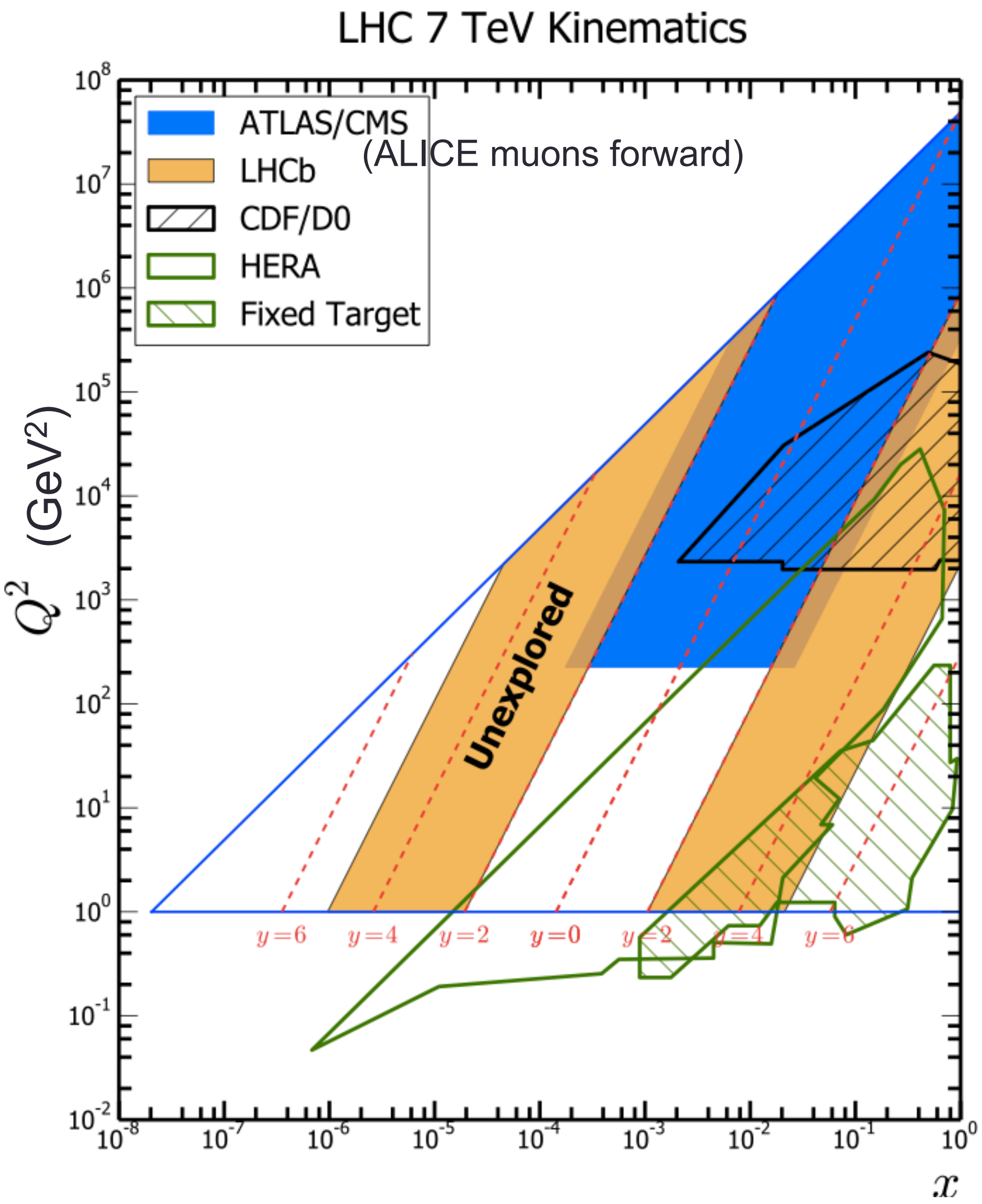
[4] S. Jones, A. Martin, M. Ryskin, and T. Teubner, *Probes of the small x gluon via exclusive J/ψ and Υ production at HERA and the LHC*, JHEP **1311** (2013) 085, arXiv:1307.7099.

HERA vector meson photo-production results



Note:

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

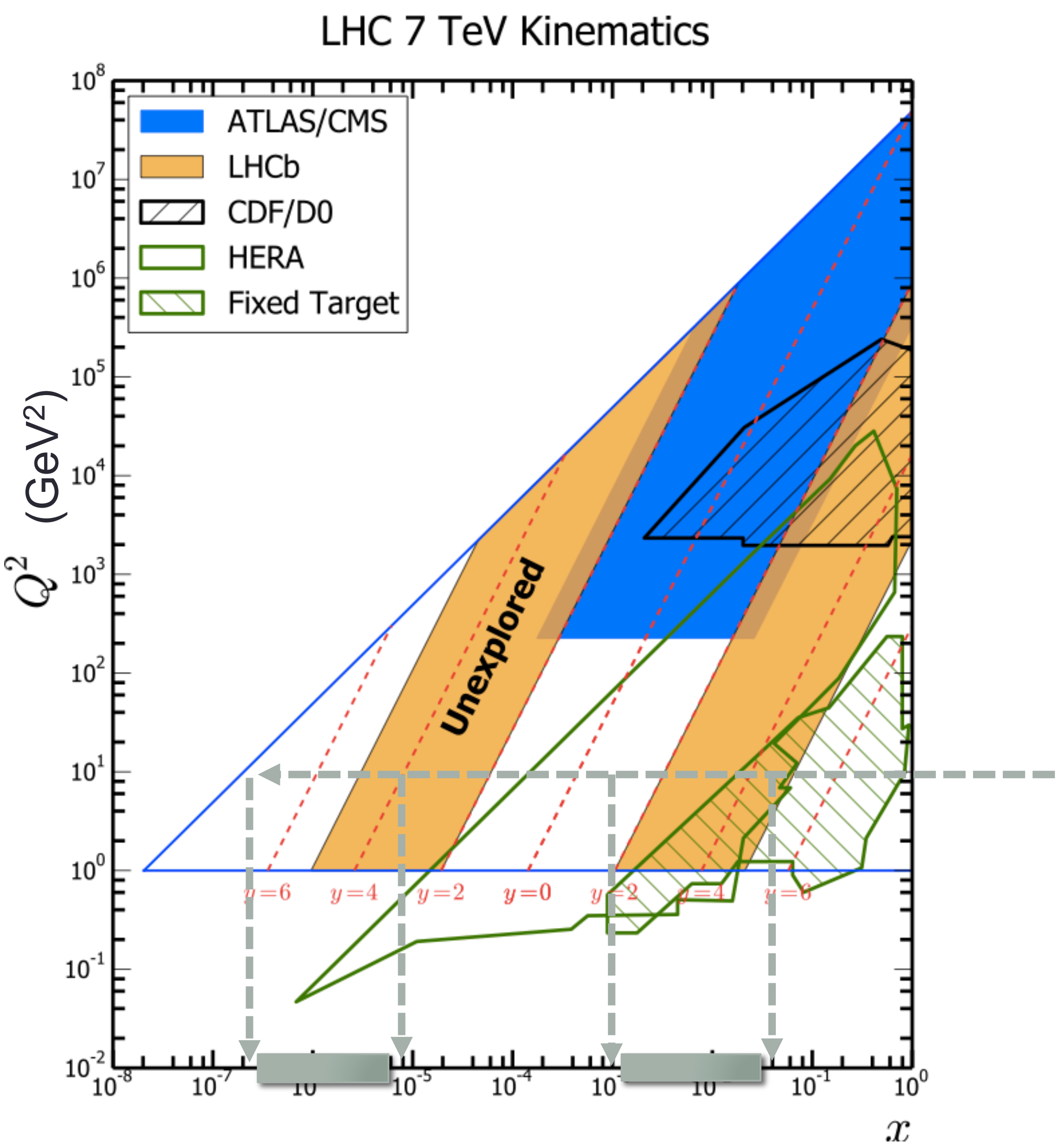


Scatters in central region involve similar x partons.

Scatters in forward region are between one high-*x* and one low-*x* parton.

One region overlaps strongly with HERA.

One region is either unexplored or requires large DGLAP evolution from HERA.



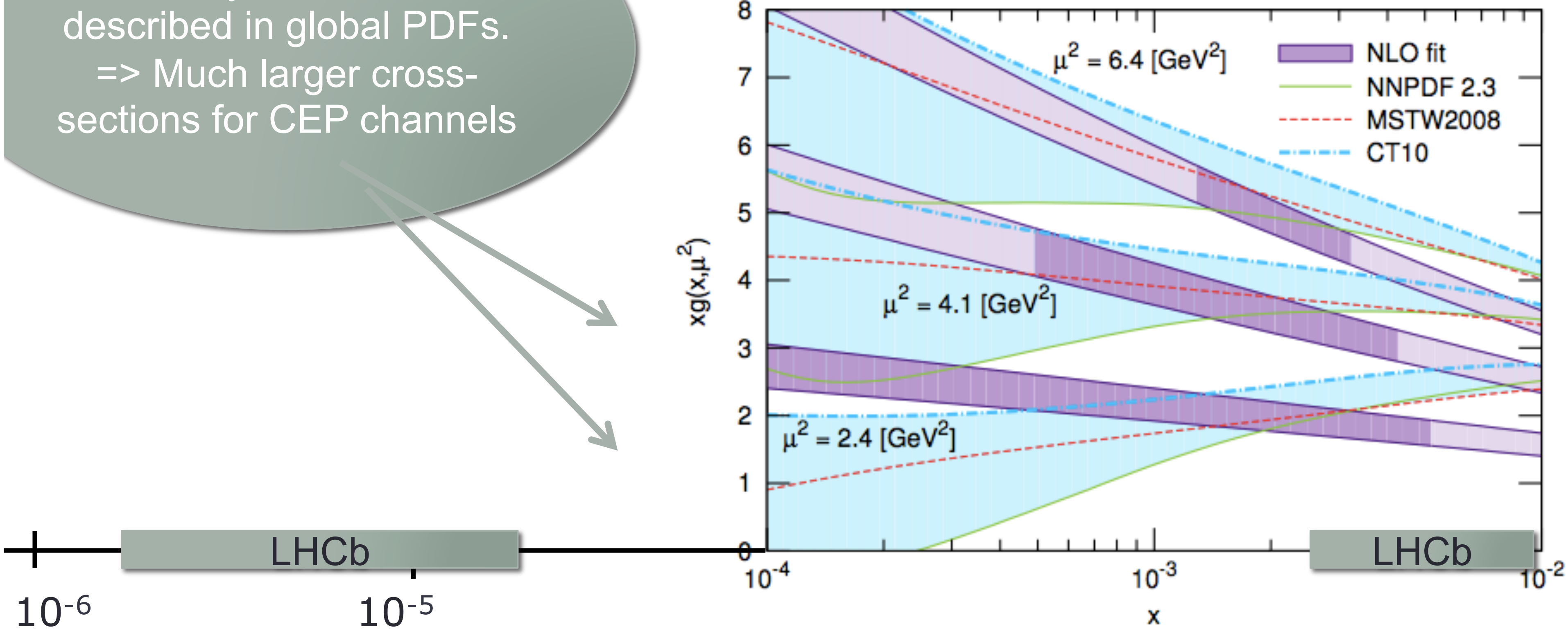
J/ψ, χ_c in central region probe similar kinematics as HERA

Forward: $x\sim10^{-5}$ / $x\sim10^{-2}$

Sensitivity to gluon pdf

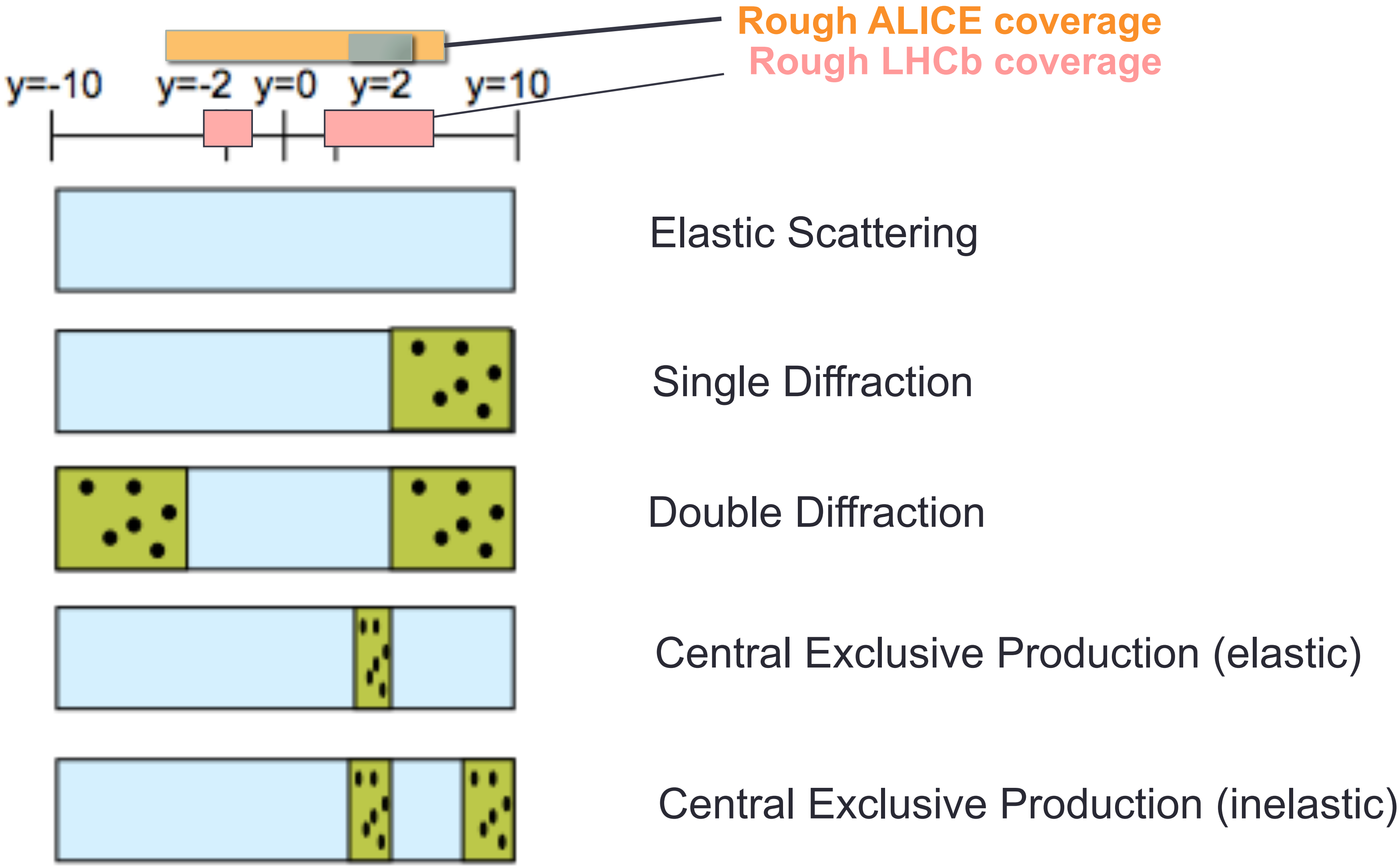
Jones, Martin, Ryskin, Teubner, JHEP 1311 (2013) 085

Gluon may rise faster than described in global PDFs.
=> Much larger cross-sections for CEP channels

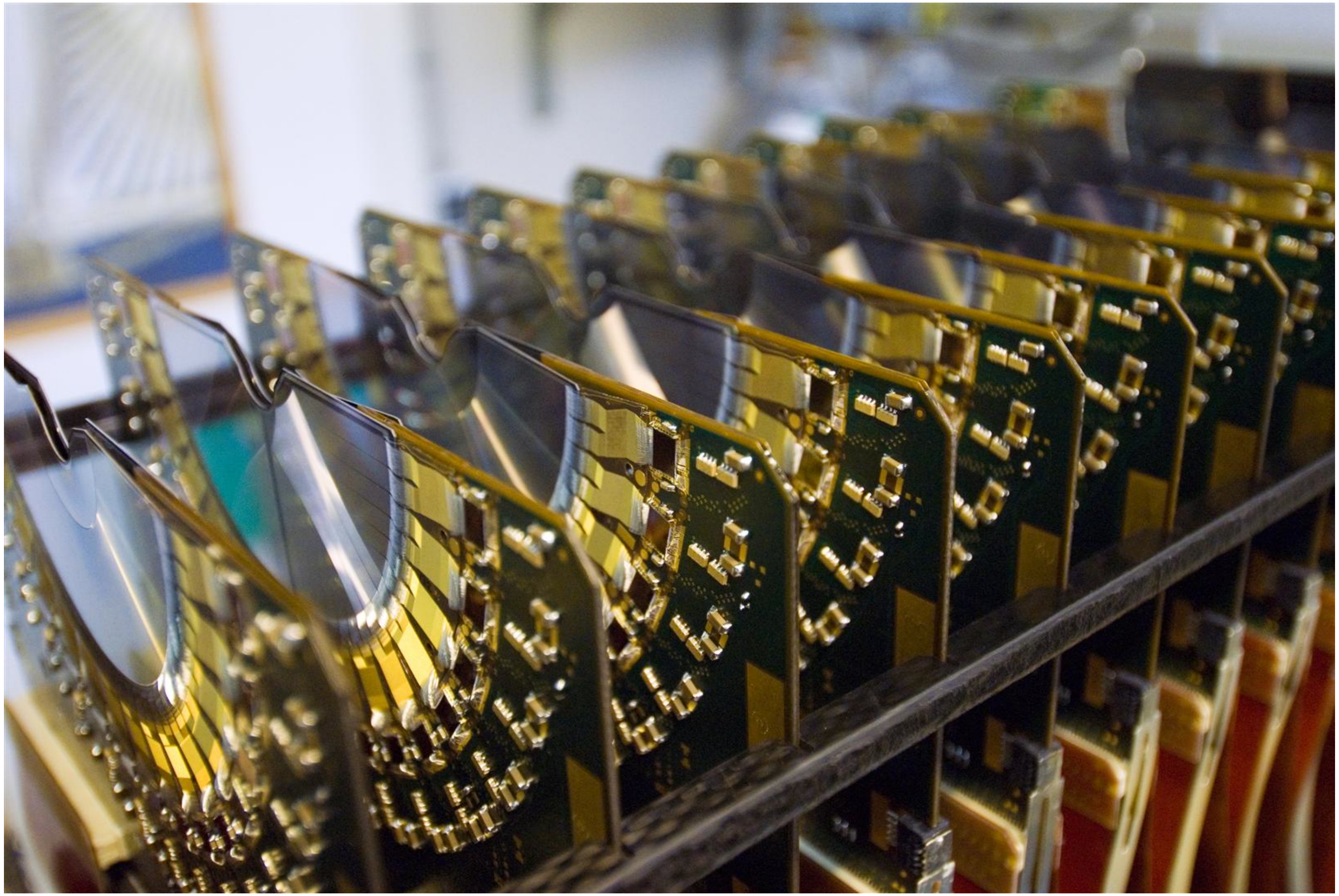


S. Jones, A. Martin, M. Ryskin, and T. Teubner, *Probes of the small x gluon via exclusive J/ψ and Υ production at HERA and the LHC*, JHEP **1311** (2013) 085, arXiv:1307.7099.

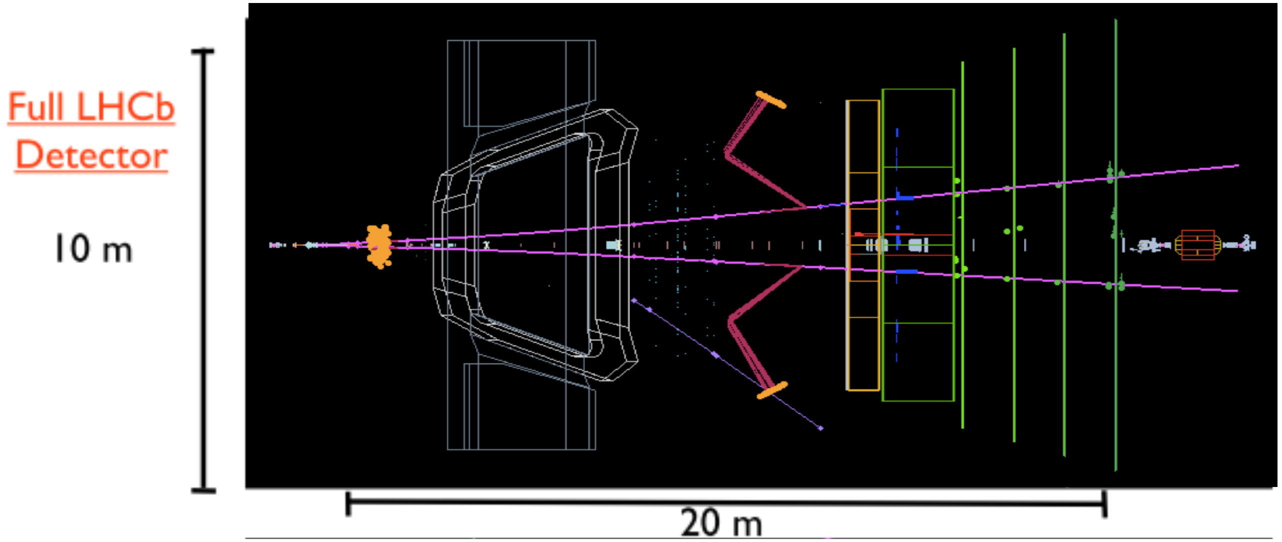
Graphical Representation



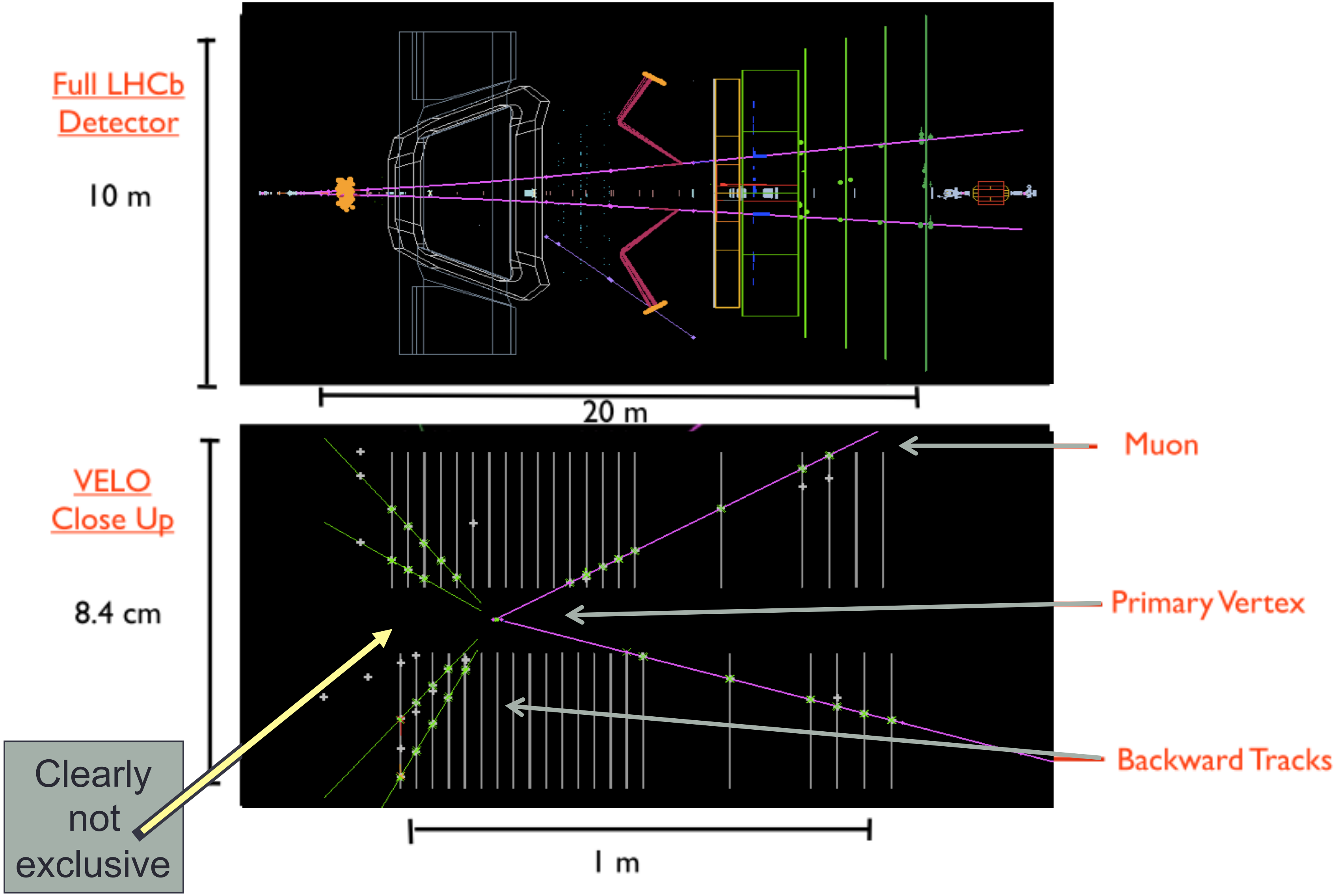
VELO sub-detector

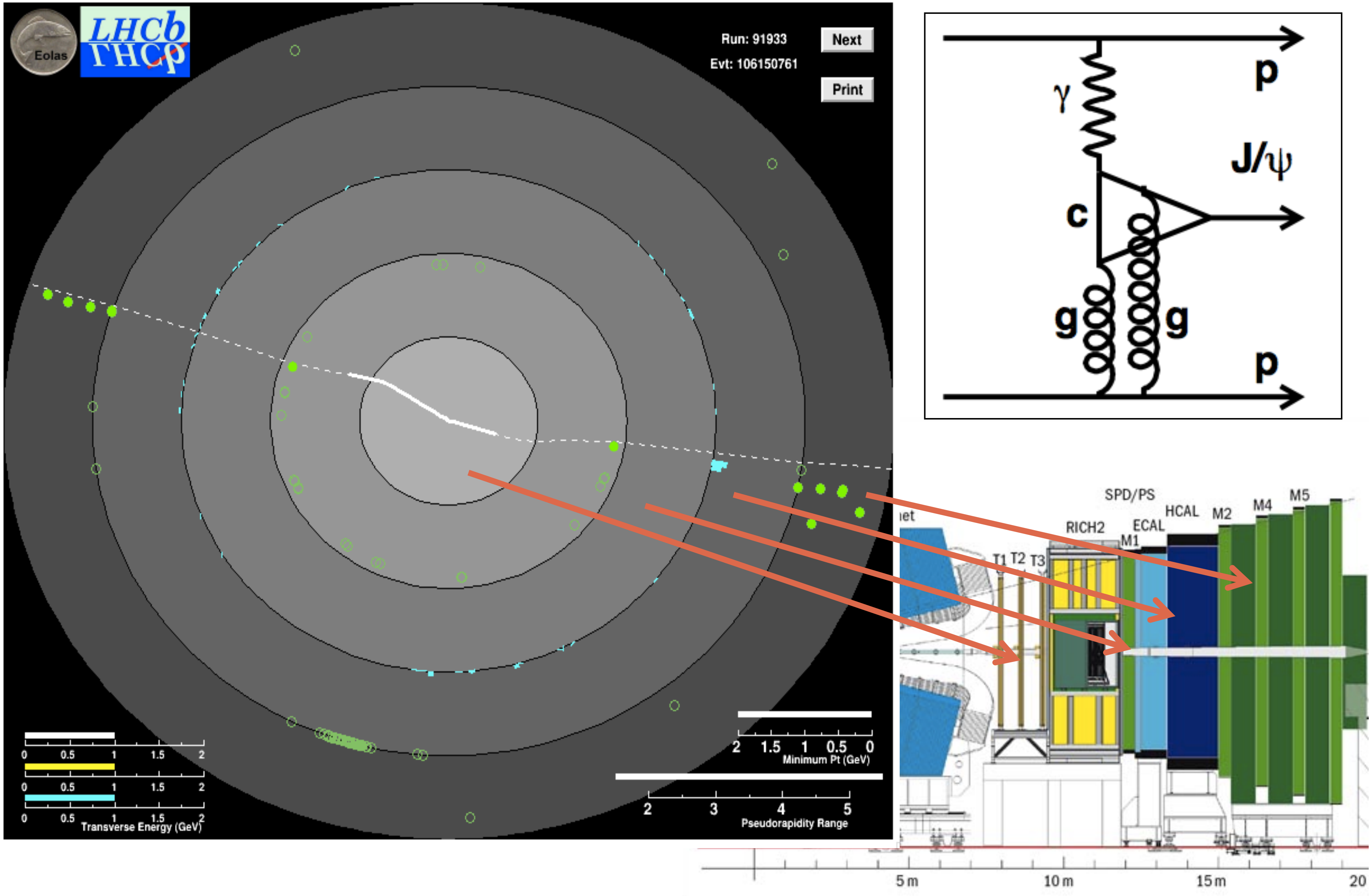


Use of backwards tracks

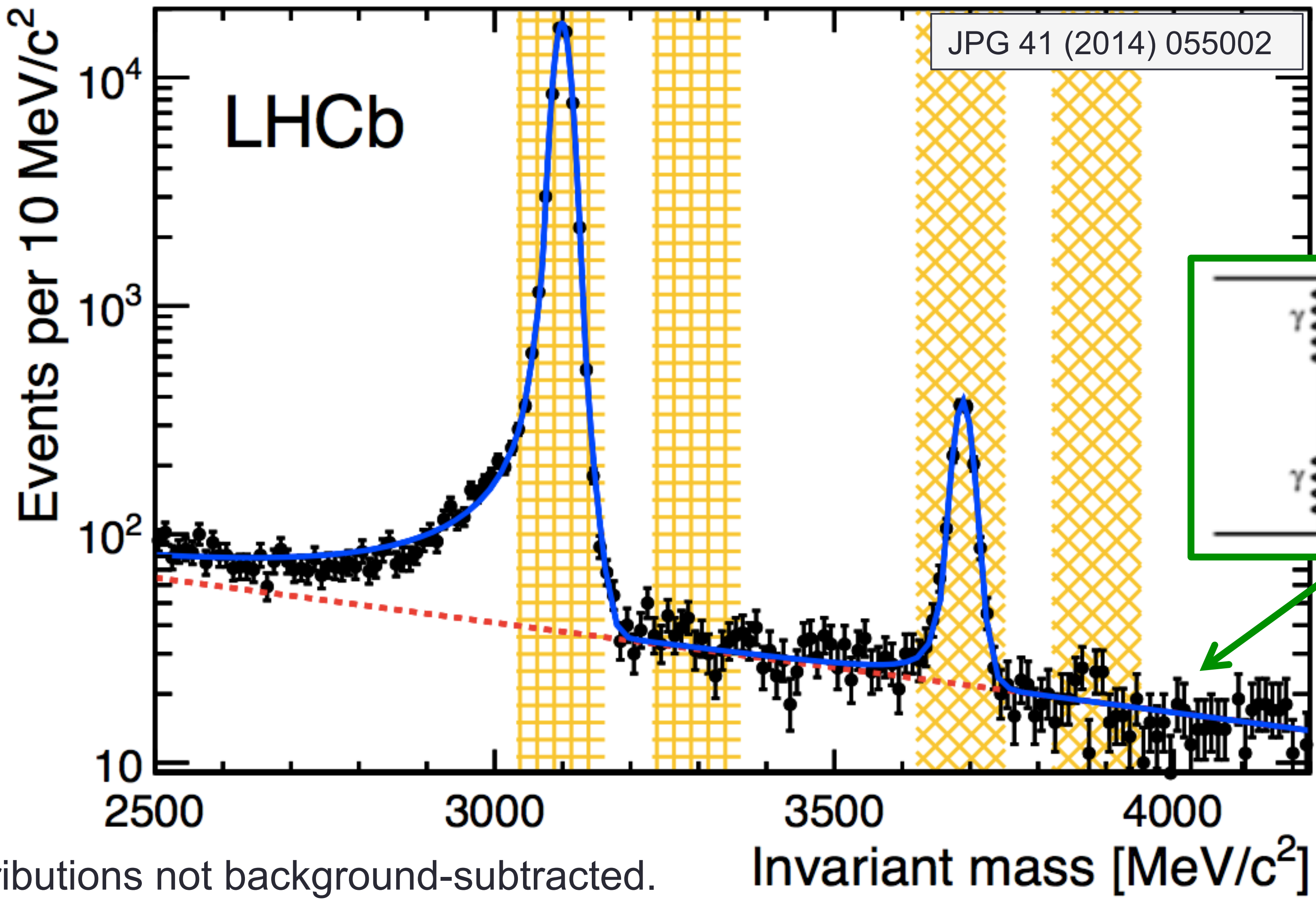


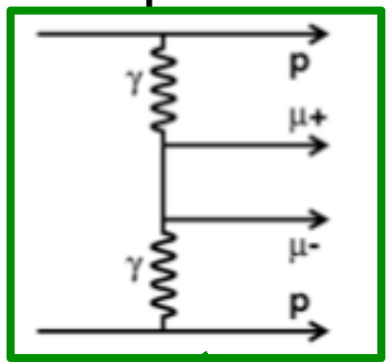
Use of backwards tracks




Eolas
LHCb
Run: 91933
Evt: 106150761
Next
Print
Transverse Energy (GeV)
Minimum Pt (GeV)
Pseudorapidity Range
γ
c
g
g
p
p
J/ψ
SPD/PS
HCAL
M2
M4
M5
RICH2
ECAL
M1
T1 T2 T3
5 m
10 m
15 m
20

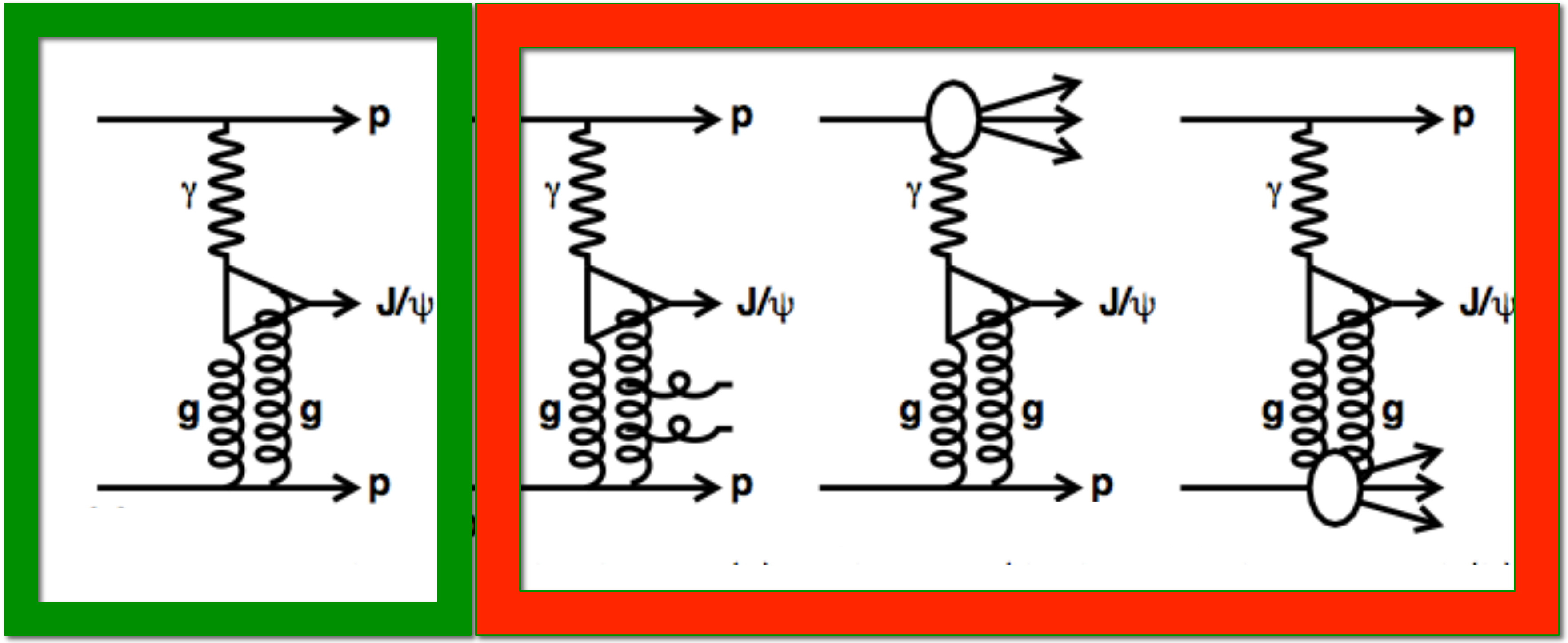
Invariant mass of exclusive muon pairs (2<η_μ<4.5)





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

Inelastic background



Signal

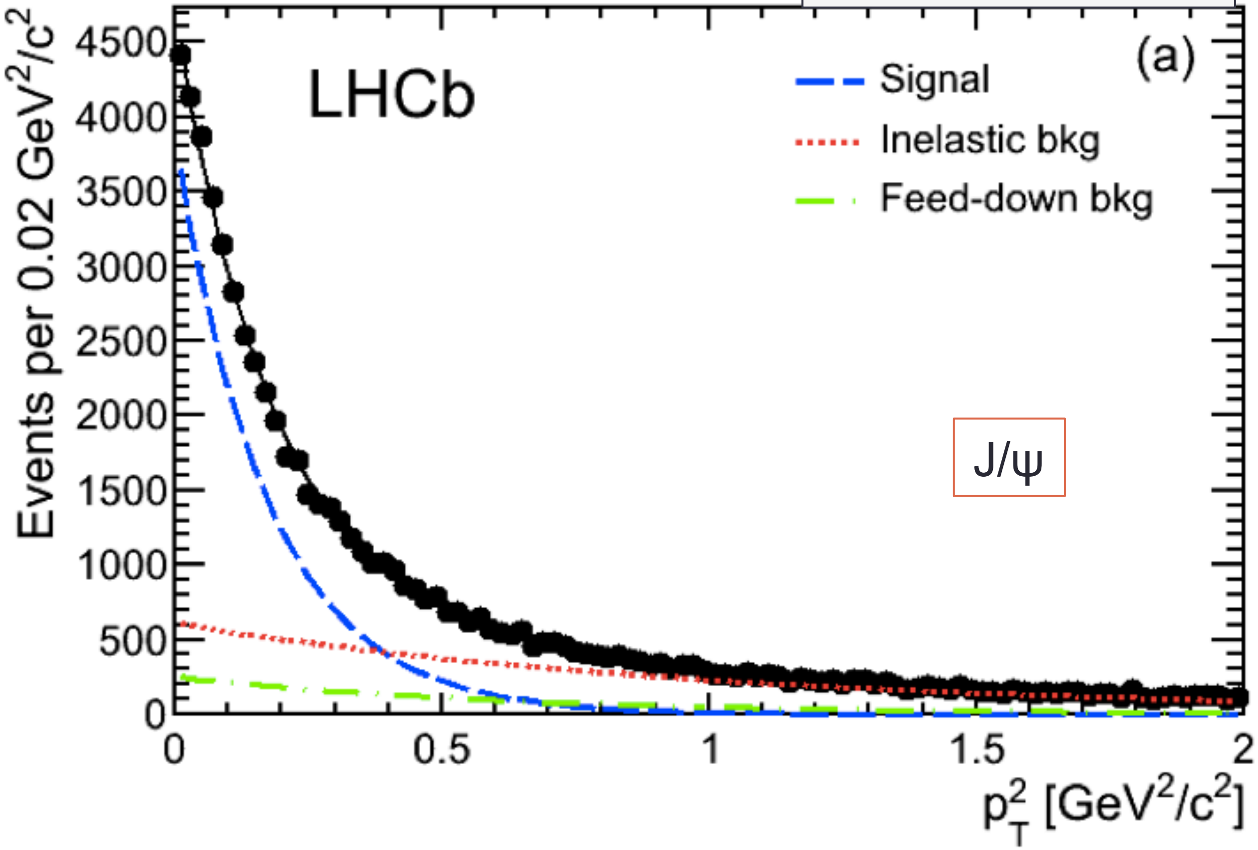
Background

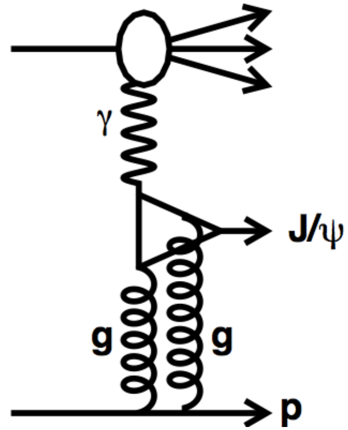
How to reject what you can't see?

...Regge theory suggests exponential dependence $\frac{d\sigma}{dt} \sim e^{bt}$

Inelastic background J/ψ

JPG 41 (2014) 055002





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

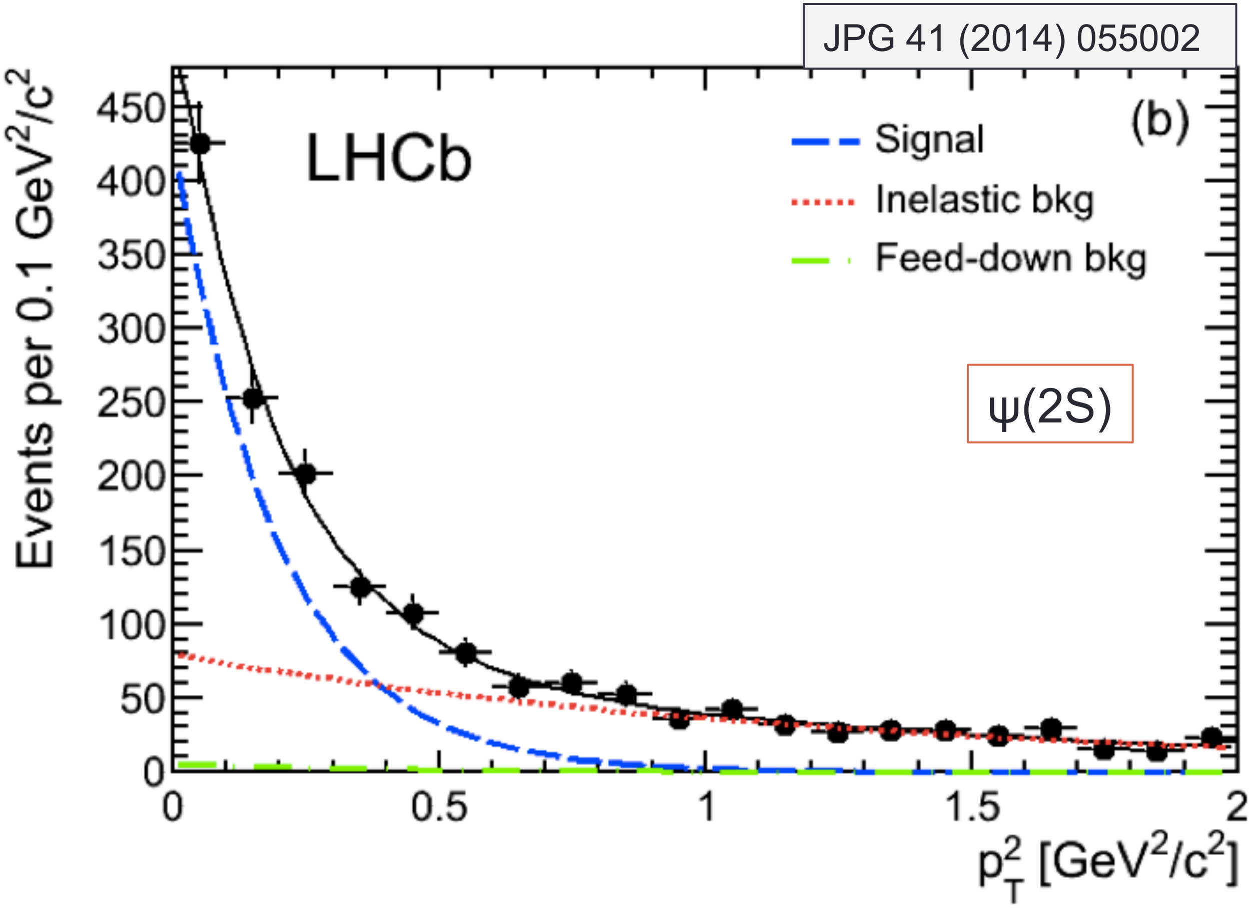
Over greater range, H1 require $(1 + b_{\rm pd} p_{\rm T}^2/n)^{-n}$
(EPJ C73 (2013) 2466)

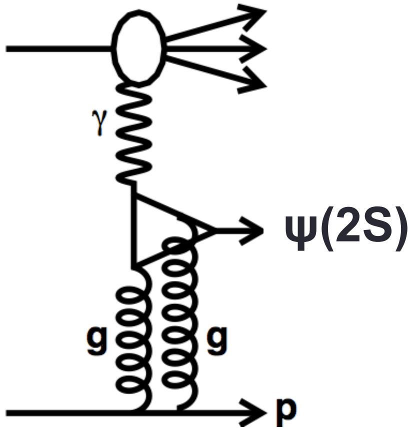
HERA measured:
b_s=4.9 GeV^{-2}
b_{pd}=1.1 GeV^{-2}

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}

Inelastic background ψ(2S)





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

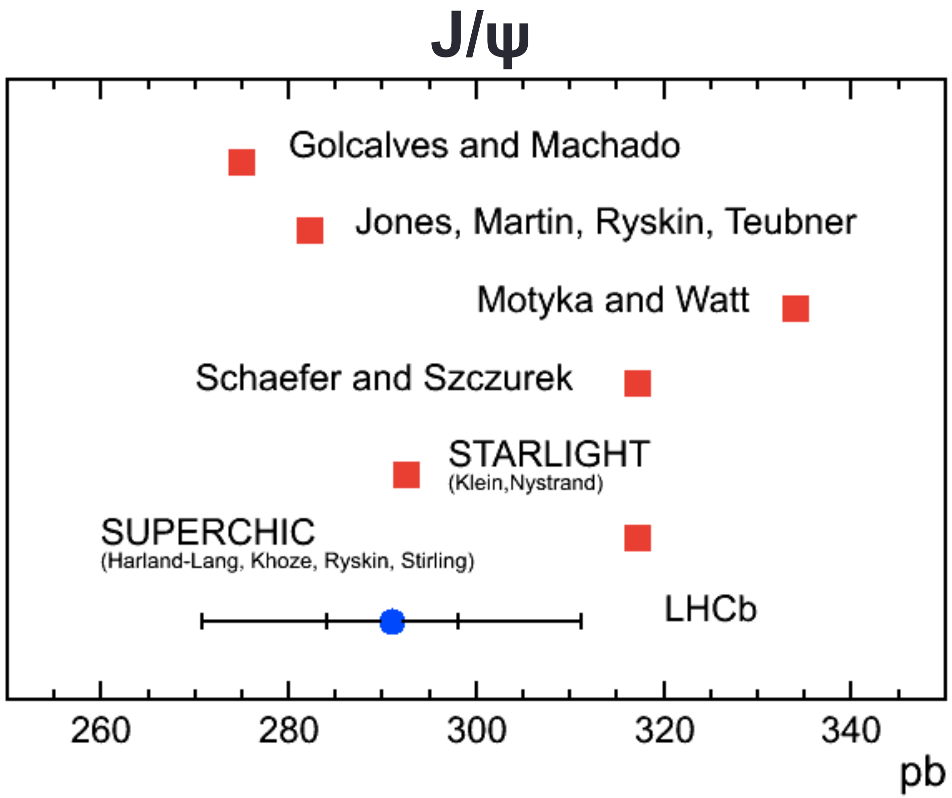
HERA measured:
b_s=4.2 GeV^{-2}
b_{pd}=0.6 GeV^{-2}

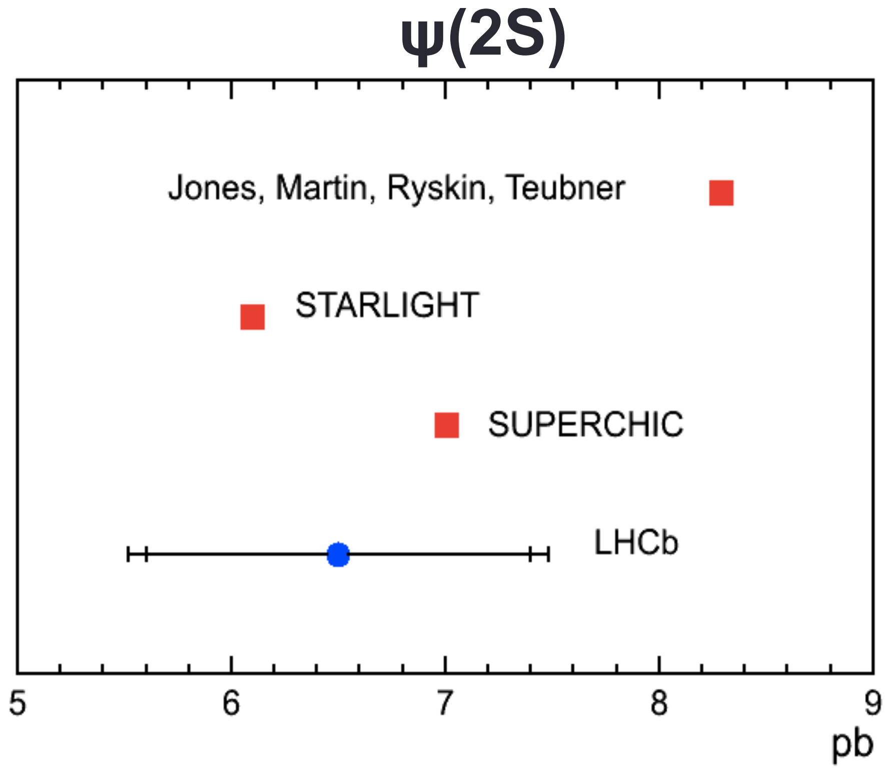
LHCb Expect:
b_s ~ 5.5 GeV^{-2}
b_{pd}~ 0.6 GeV^{-2}

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

Integrated Cross-sections

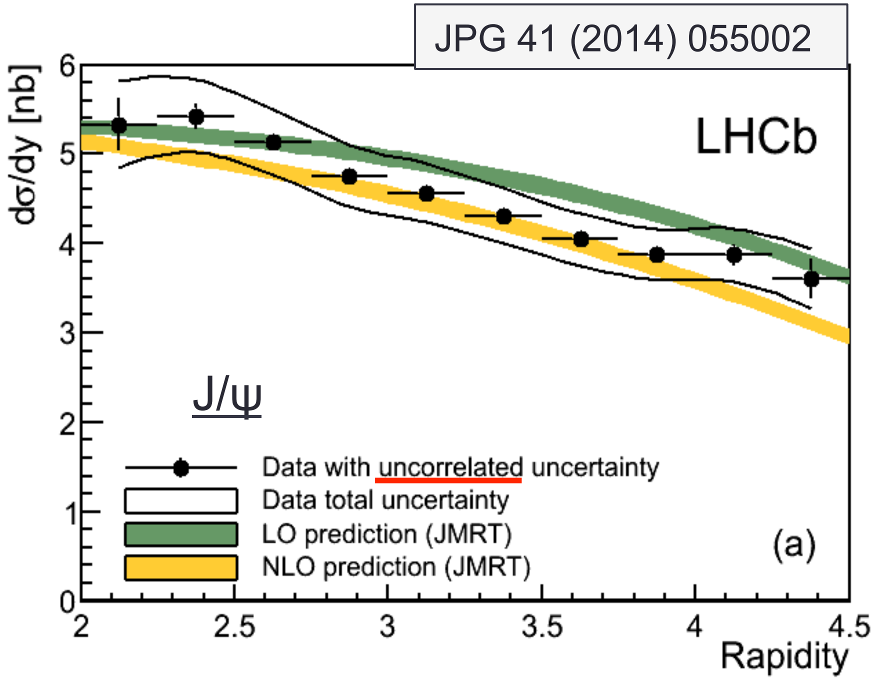
Cross-section*BR for both muons in pseudorapidity range **2<η<4.5**:

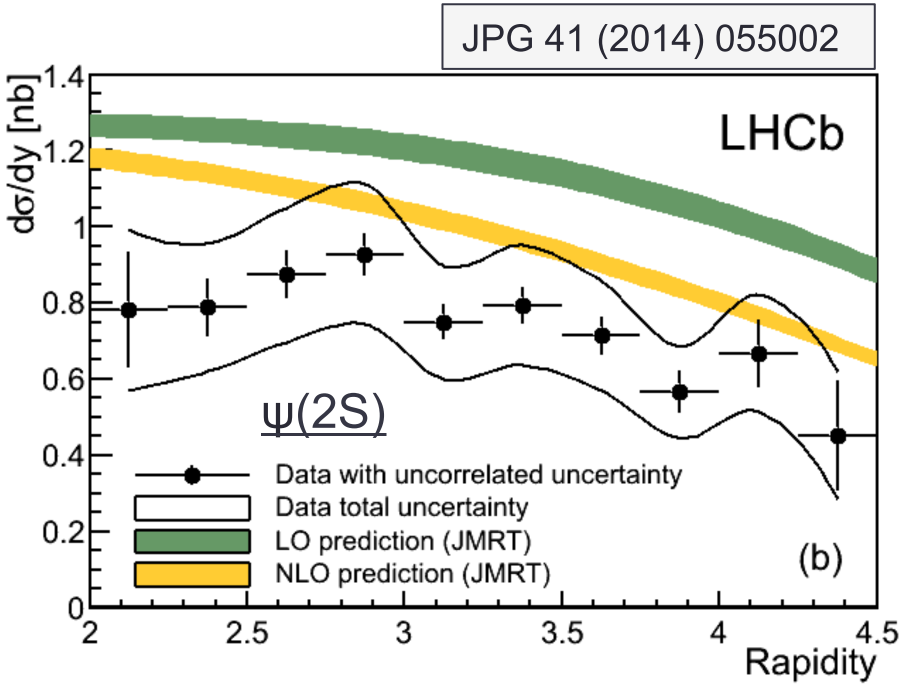




Good agreement with all theory estimates

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

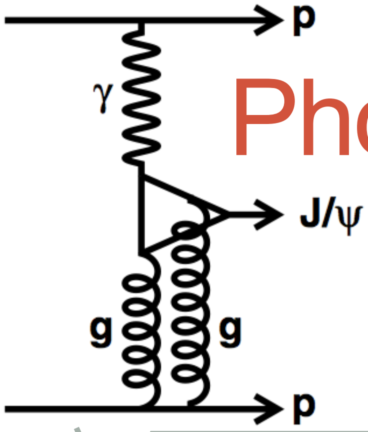




NLO agrees better than LO

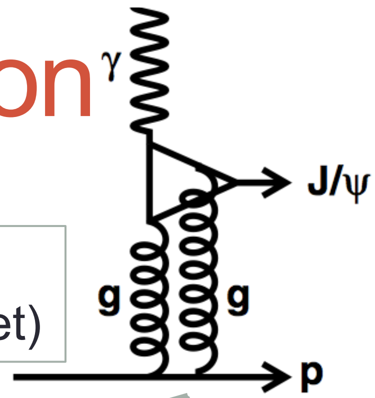
S. Jones, A. Martin, M. Ryskin, and T. Teubner, *Probes of the small x gluon via exclusive J/ψ and Υ production at HERA and the LHC*, JHEP **1311** (2013) 085, arXiv:1307.7099.

Photo-production cross-section



LHCb measure

Photo-production (HERA / fixed target)



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

Gap Survival

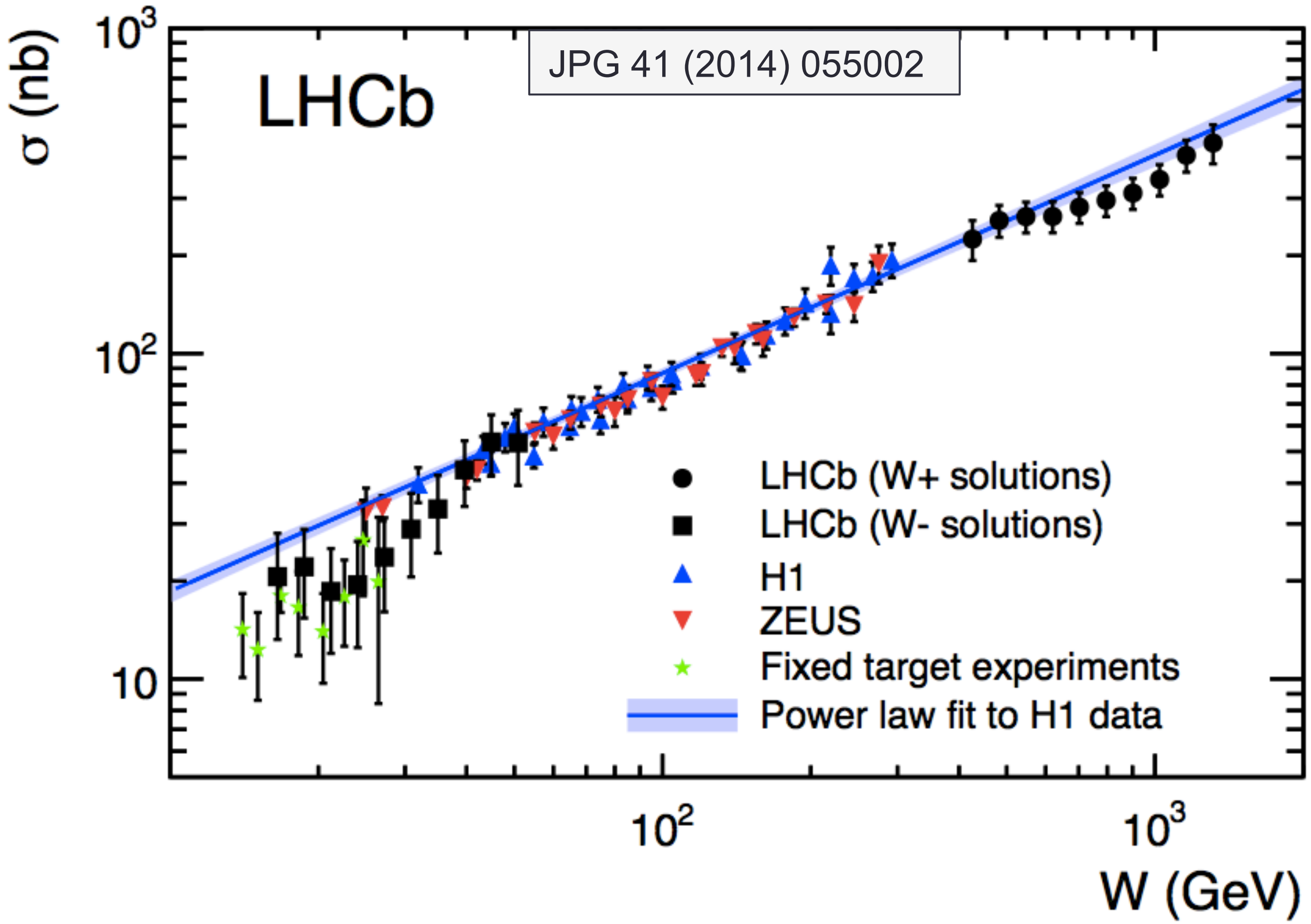
Photon Flux

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

Photo-production cross-section

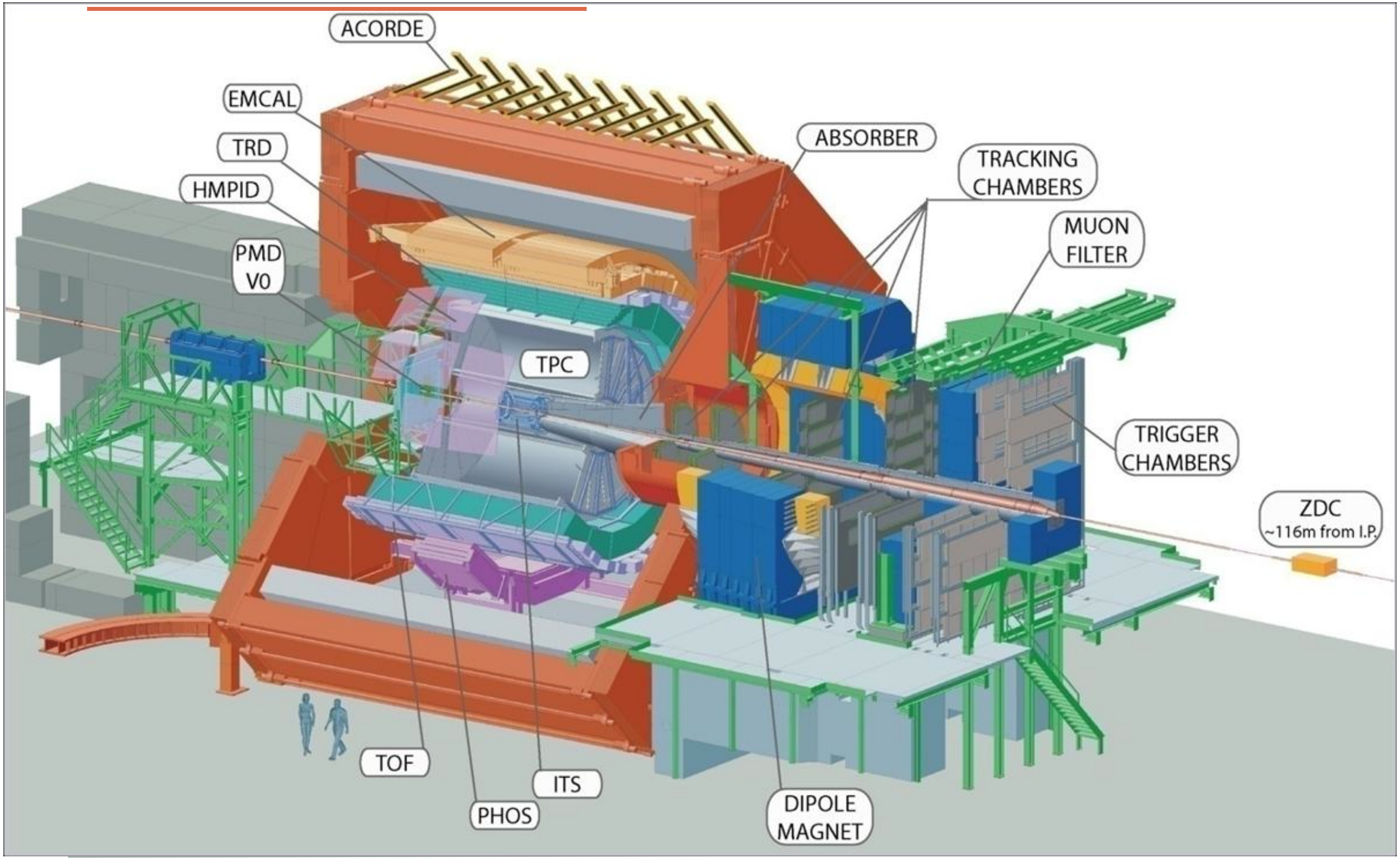
Measure — Plot — HERA

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

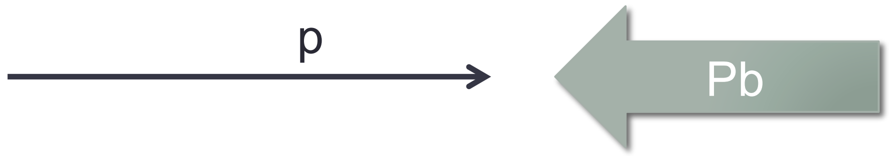


Deviation from pure power-law. i.e. NLO required or only power-law for $W>W_0$

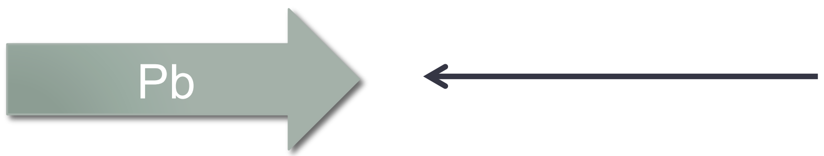
ALICE detector



p-Pb interactions



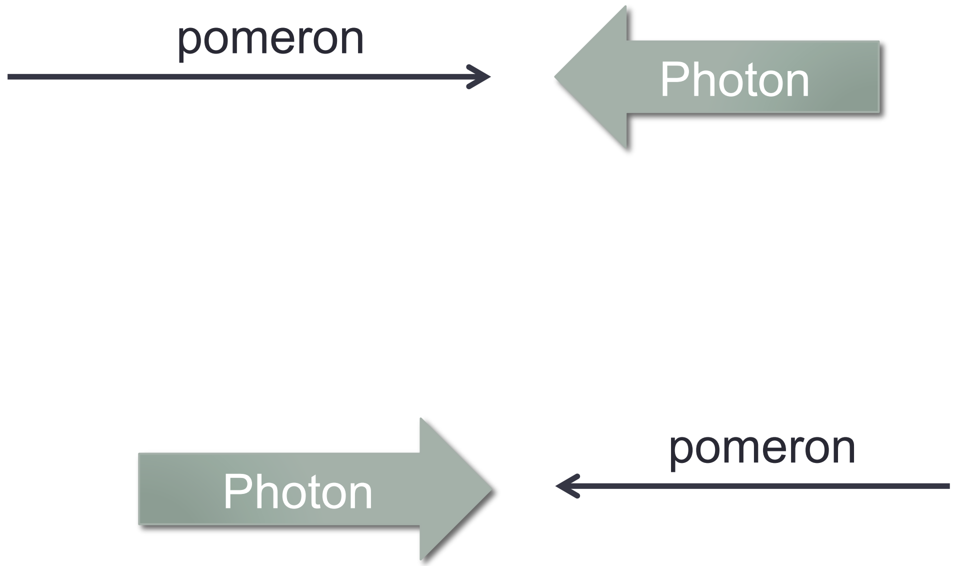
J/ψ sensitivity in $2.5<y<4.0$



J/ψ sensitivity in $-3.6<y<-2.6$

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

p-Pb interactions

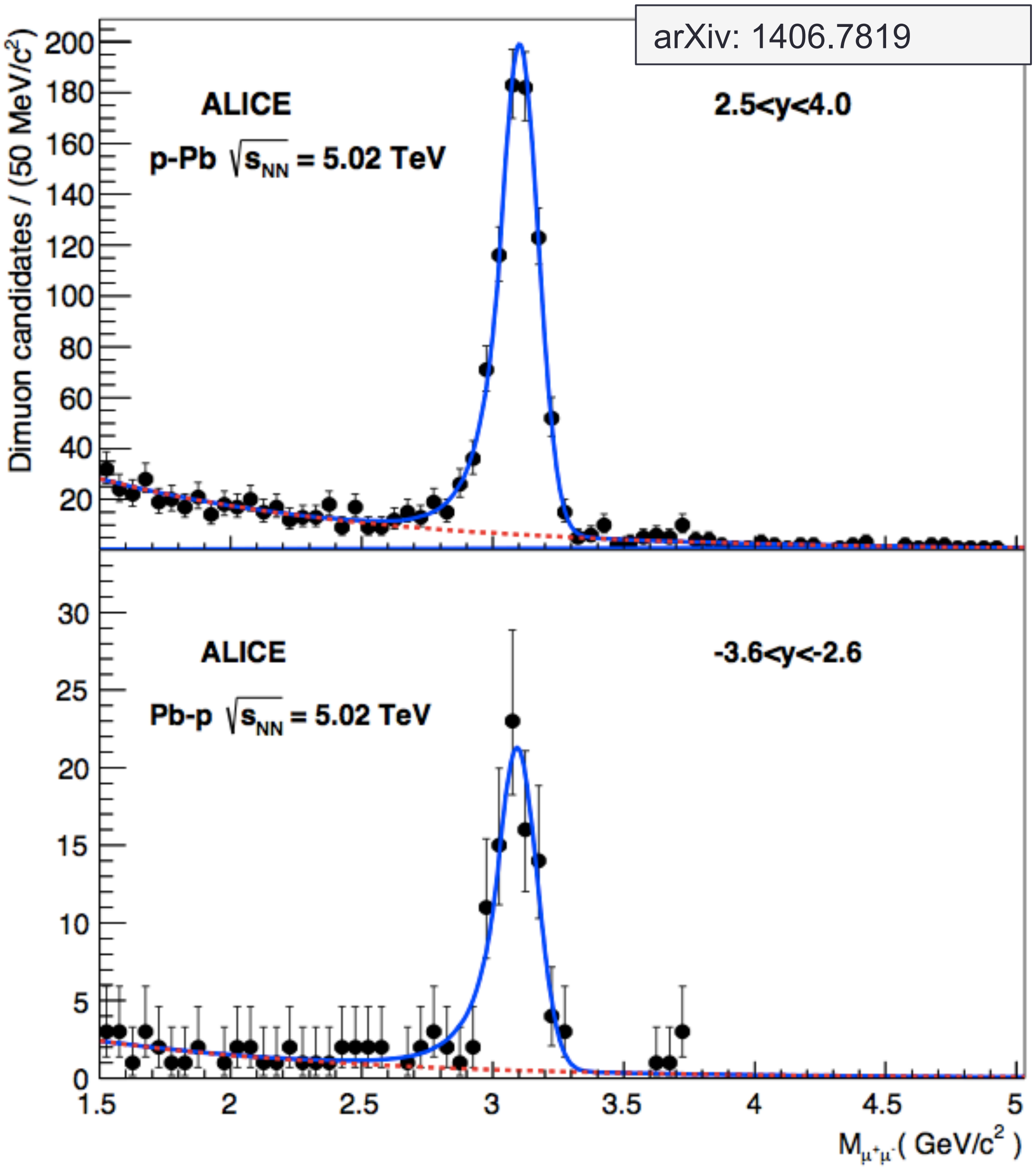


J/ψ sensitivity in $2.5<y<4.0$
(Low W region)

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

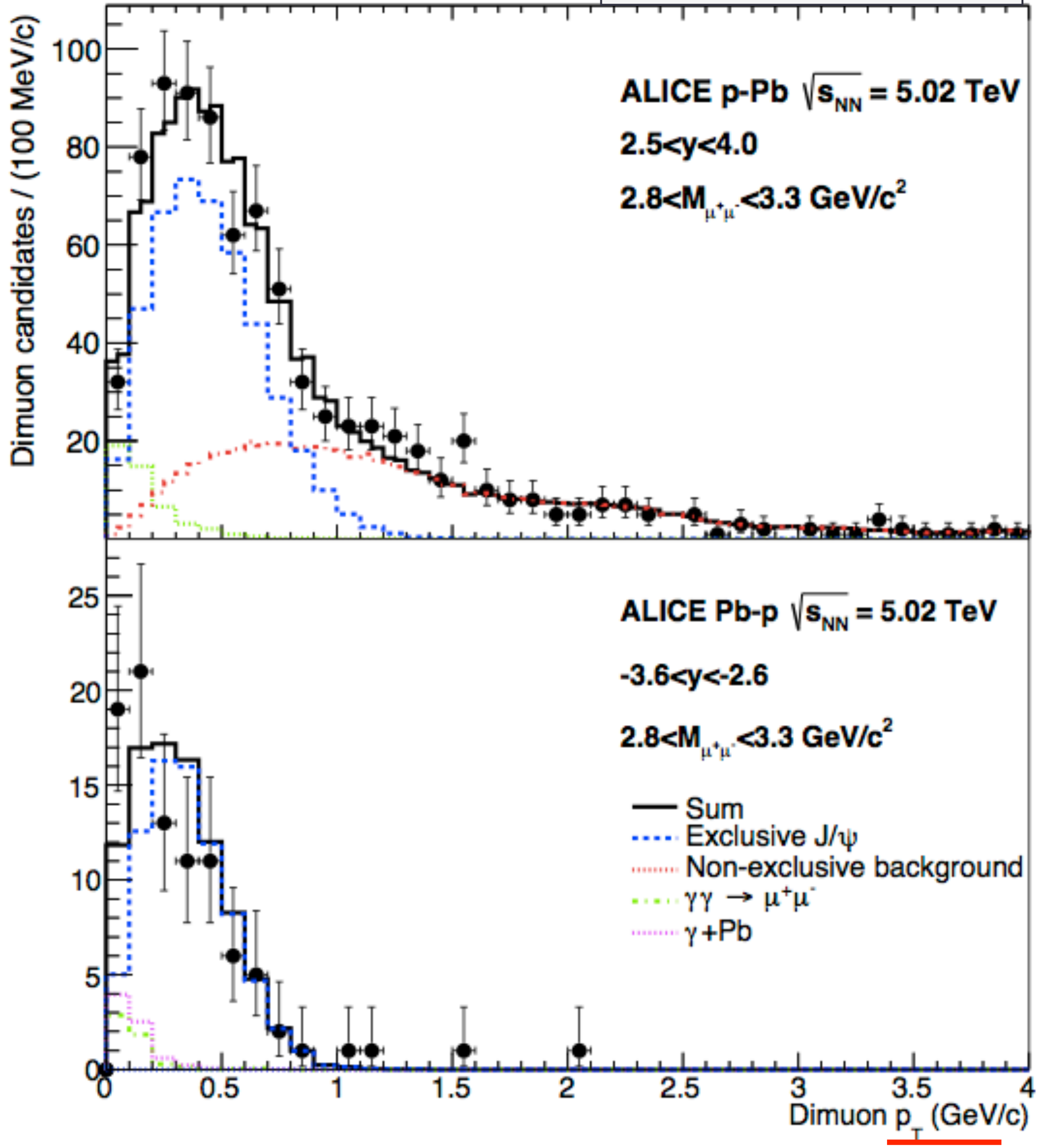
Photon flux proportional to Z^2. Removes two-fold ambiguity

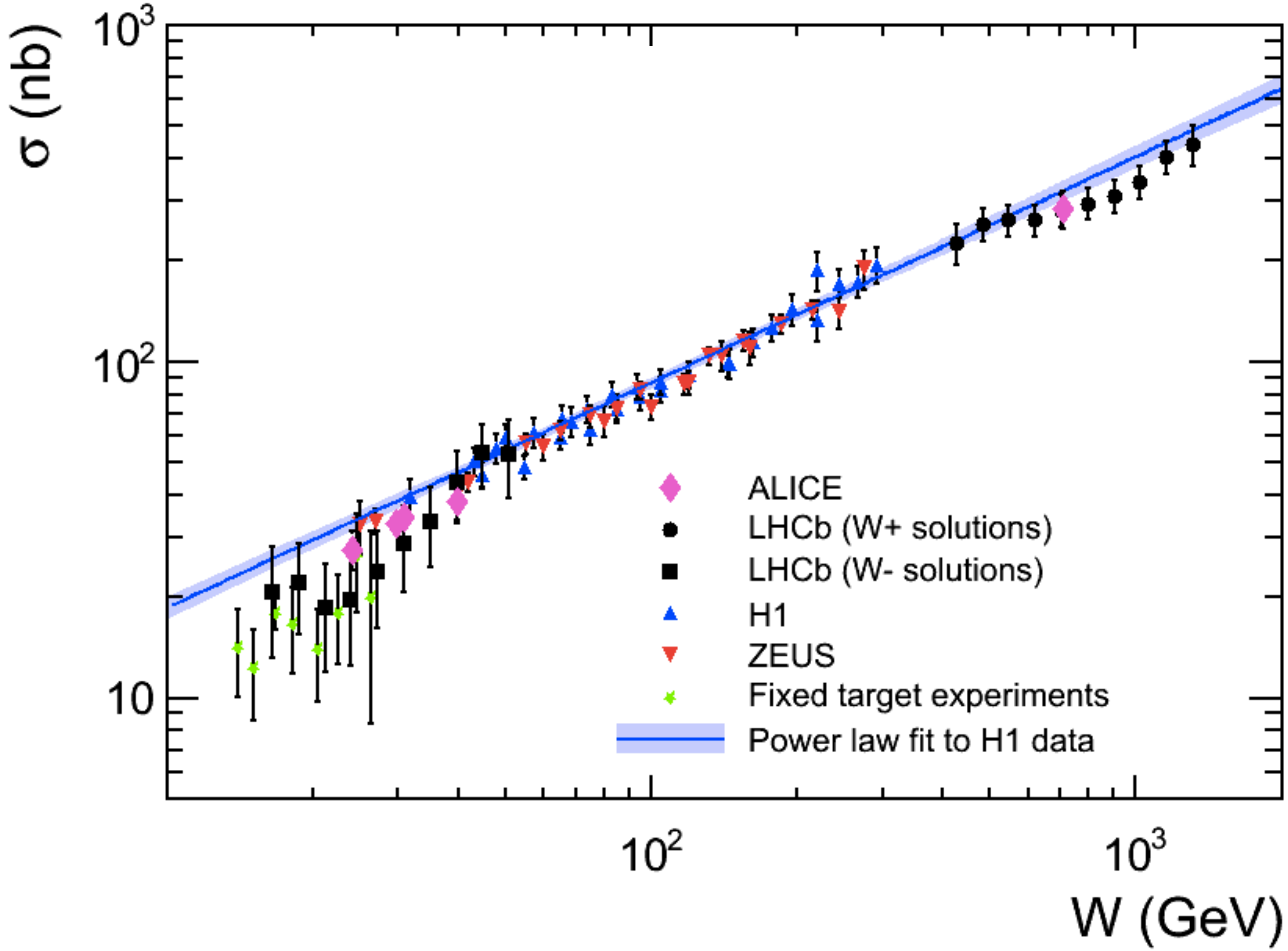
Invariant mass of selected candidates



Transverse momentum of candidates

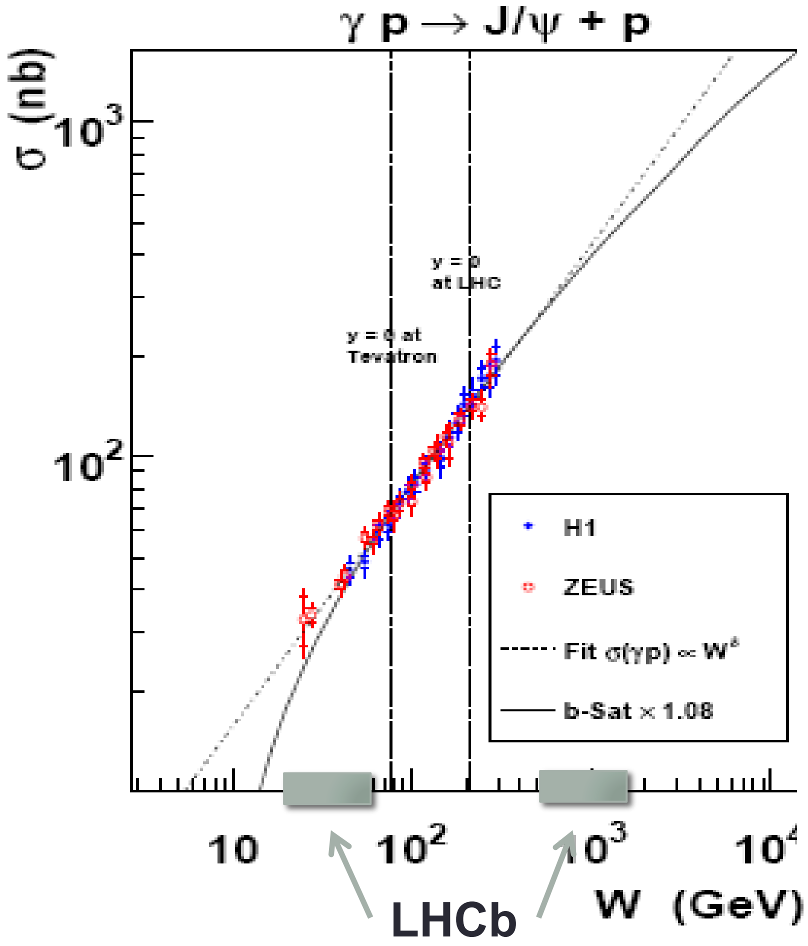
arXiv: 1406.7819



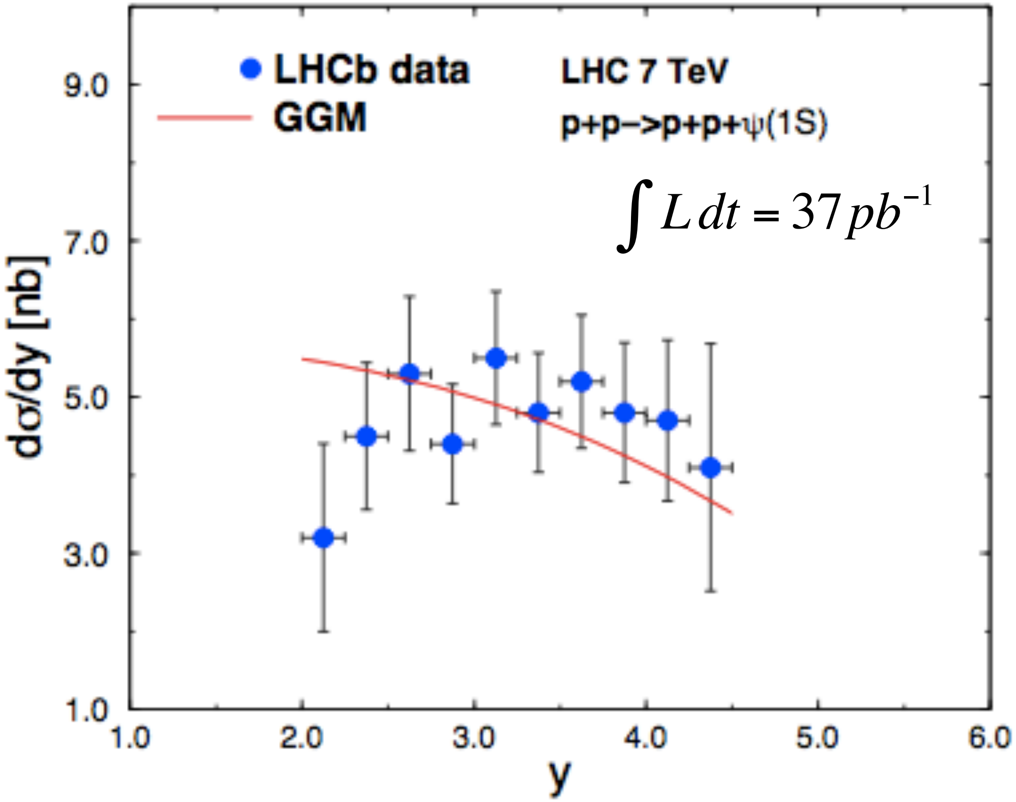


Consistent picture of J/ψ photo-production across wide range of energies and colliders

Sensitivity to saturation effects

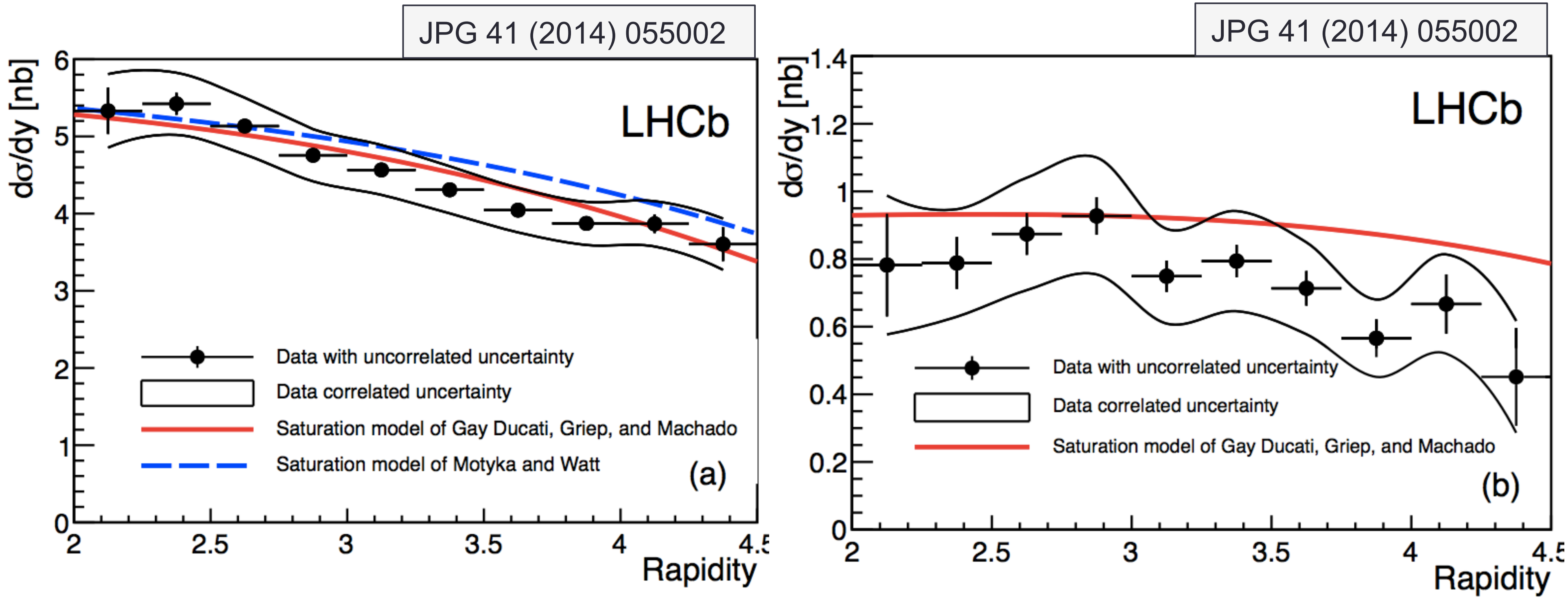


Motyka, Watt: PRD 78, 014023 (2008)



Gay Ducati et al., arXiv: 1305.4611

Sensitivity to saturation effects: J/ψ ψ(2S)

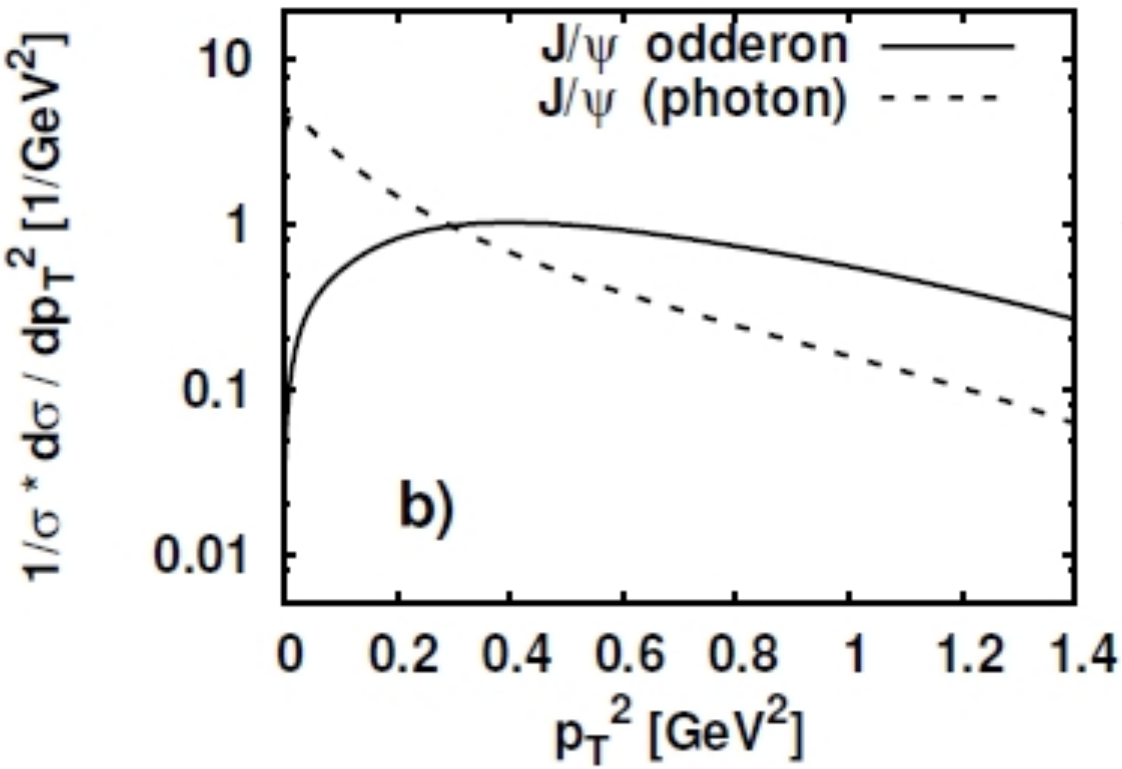


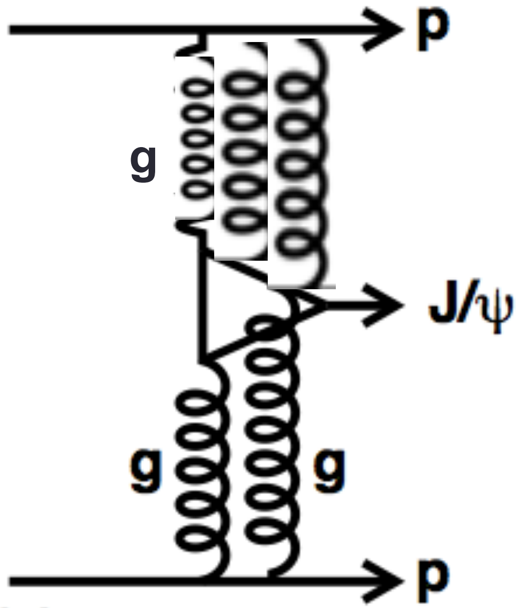
L. Motyka and G. Watt, *Exclusive photoproduction at the Fermilab Tevatron and CERN LHC within the dipole picture*, Phys. Rev. **D78** (2008) 014023, arXiv:0805.2113.

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.

Search for odderon

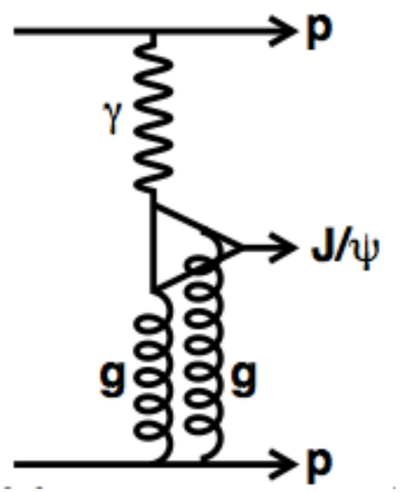
- Motyka, DIS 2008.



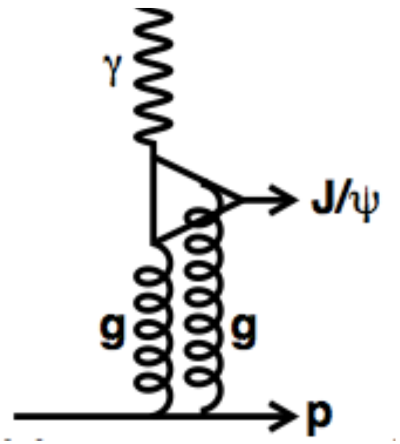


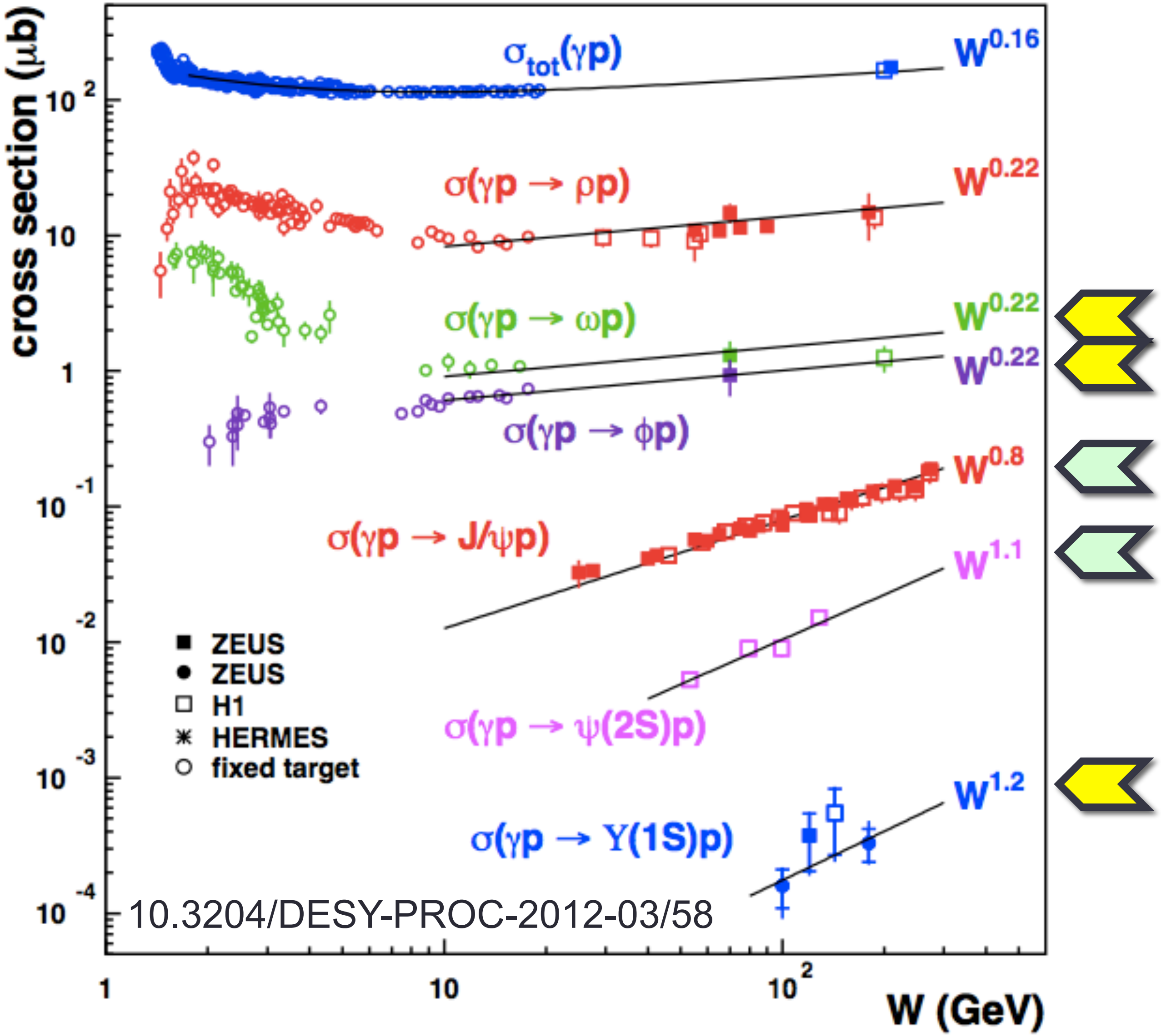
Odderon identification requires good modelling of inelastic background

Future: Investigate other vector mesons

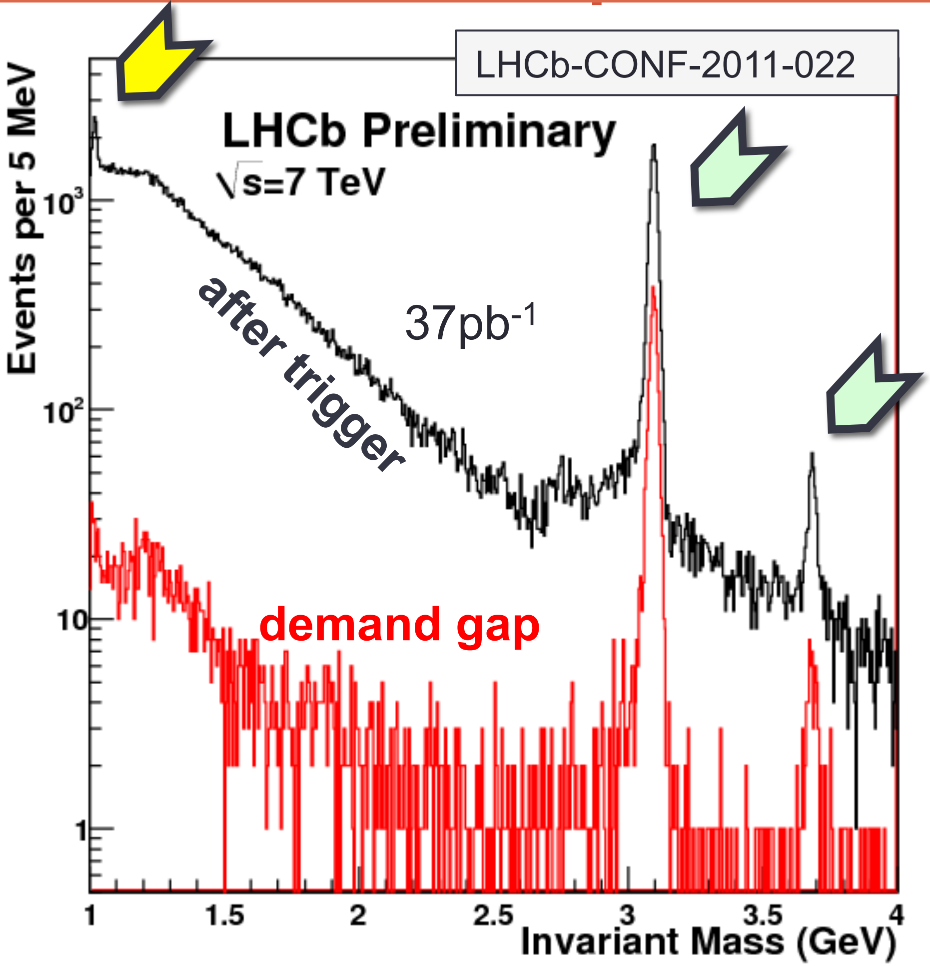


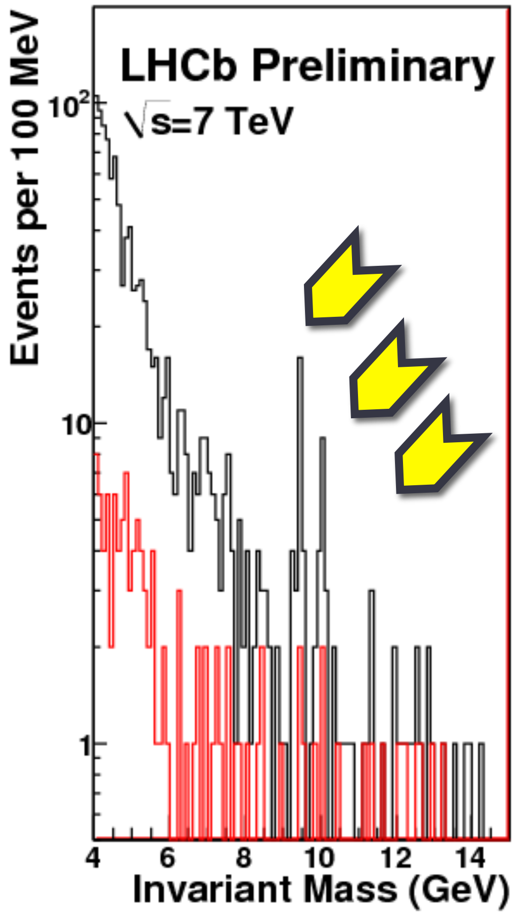
looks very like





Dimuon Mass Spectrum

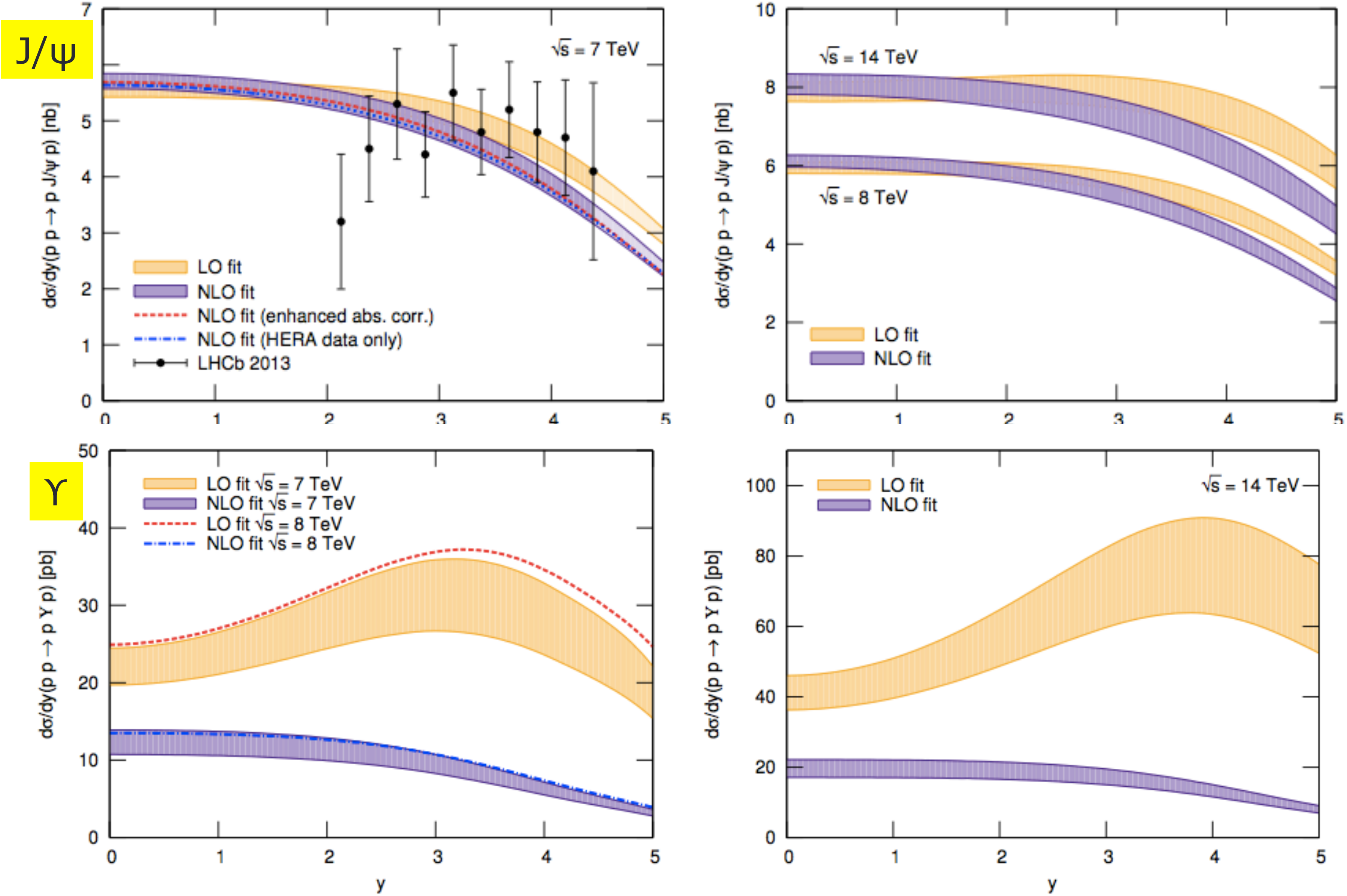




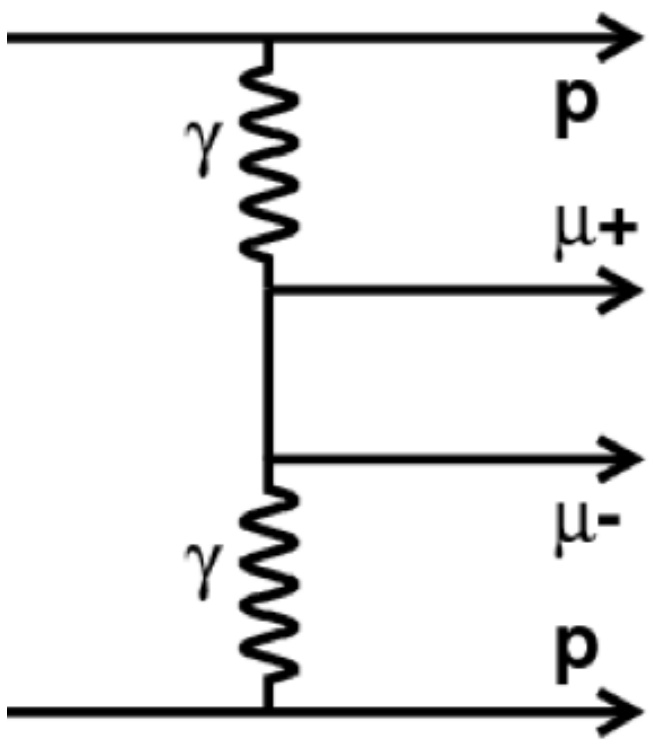
Factor ~ *100 data now available with 2011+2012 (~3fb^{-1})

Predictions

Jones, Martin, Ryskin, Teubner, JHEP 1311 (2013) 085

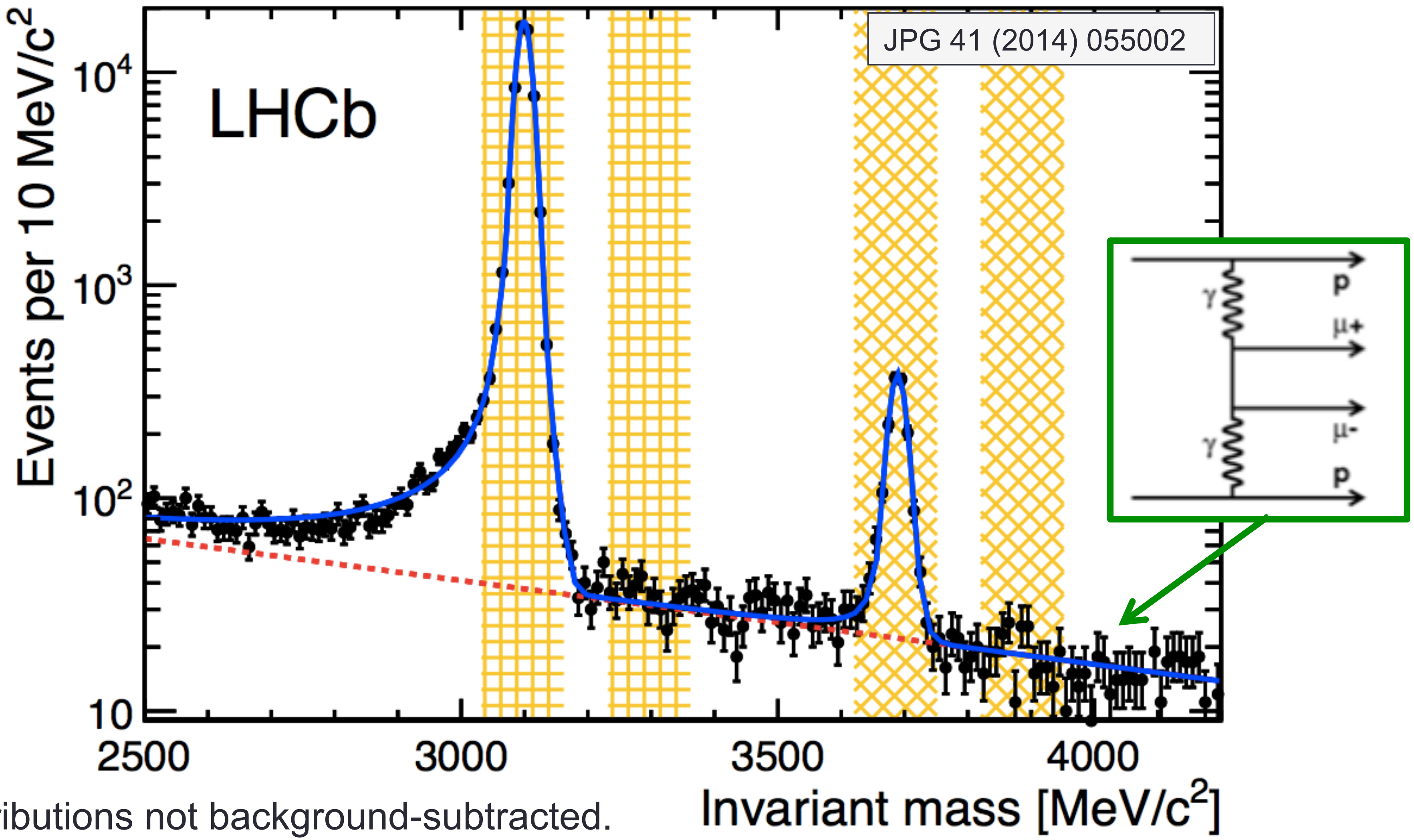


Diphoton fusion



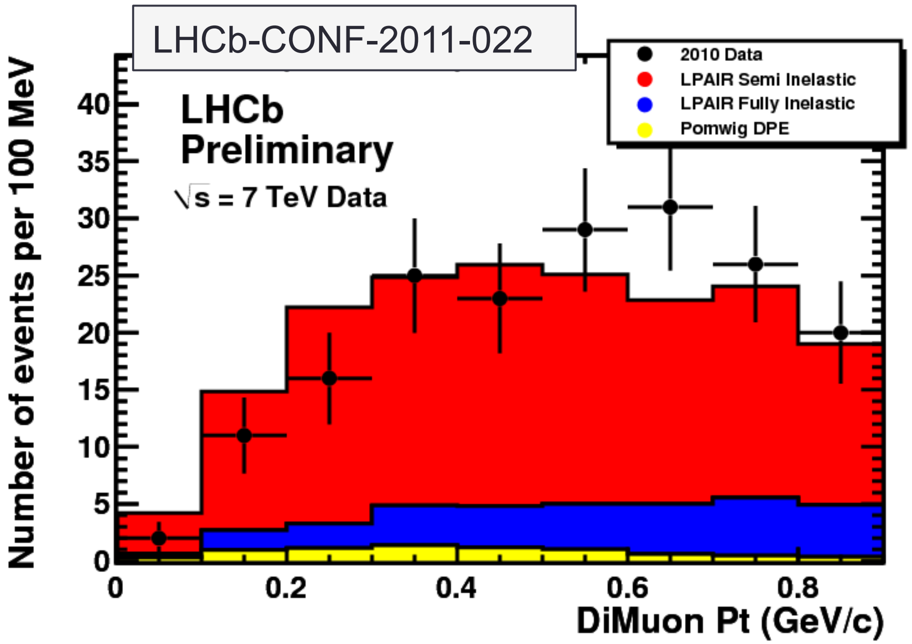
- Precise QED prediction: 1% (?)
- Luminosity determination
- Triple gauge couplings (γγ->WW)

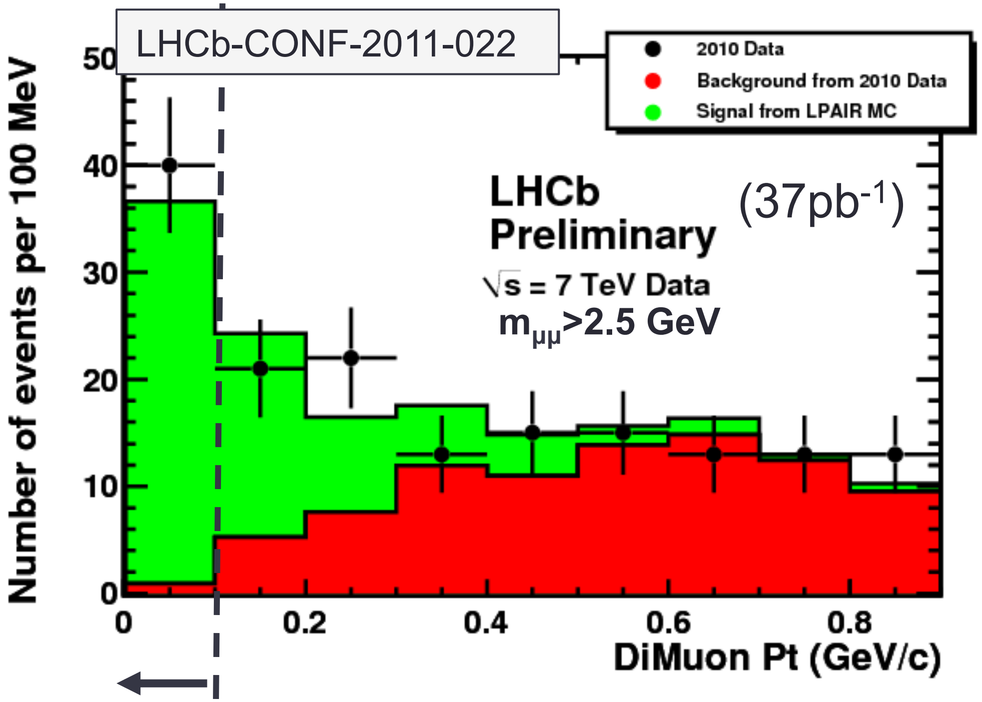
Invariant mass of exclusive muon pairs



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

Exclusive dimuon (LHCb)





Shape for inelastic events

LPAIR simulation predicts shape for exclusive / single dissociation / double dissociation .

Fit to signal events

Background shape from data
Signal shape from simulation.

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

J/ψJ/ψ production

Large literature for γγ->J/ψJ/ψ

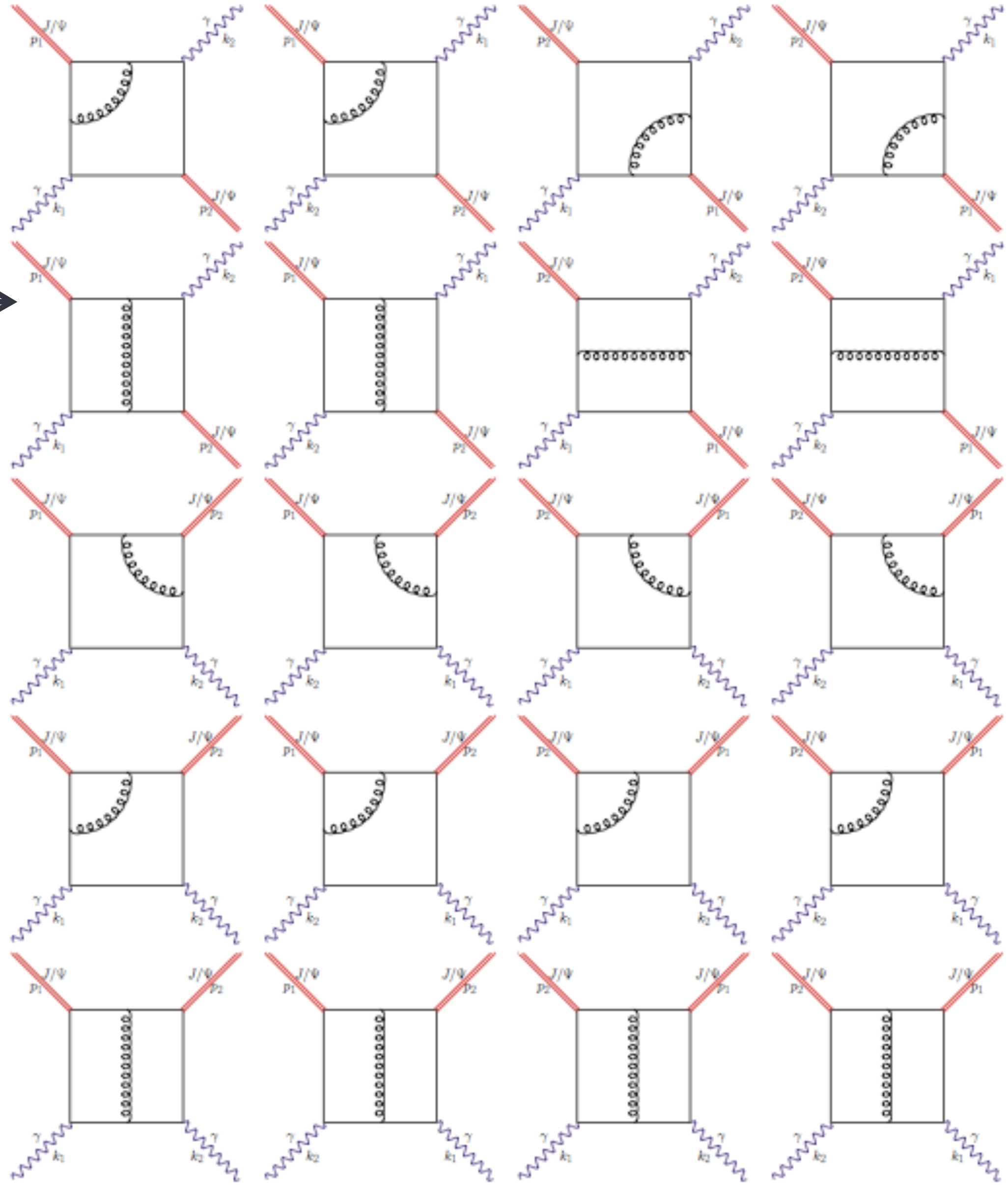
- I. F. Ginzburg, S. L. Panfil, and V. G. Serbo, Nucl. Phys. B296 (1988) 569.
- C.-F. Qiao, Phys. Rev. D64 (2001) 077503, arXiv:hep-ph/0104309
- V. P. Gonçalves and M. V. T. Machado,
  Eur. Phys. J. C28 (2003) 71, arXiv:hep-ph/0212178.
- A. Cisek, W. Schäfer, and A. Szczurek,
  Phys. Rev. C86 (2012)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

Requires large photon flux:

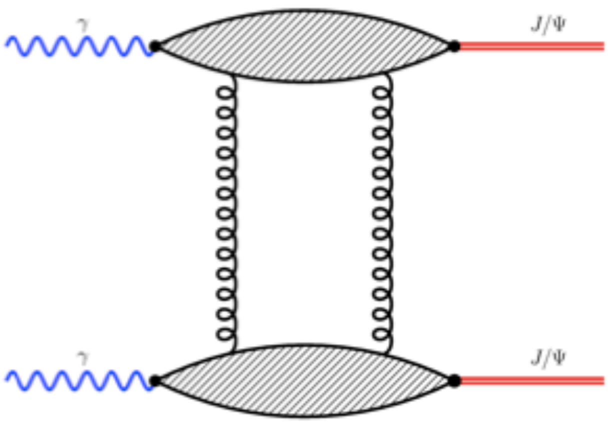
Heavy ion collisions or Linear colliders

Feynman diagrams

Box diagrams
(Fall off with increasing Q^2)

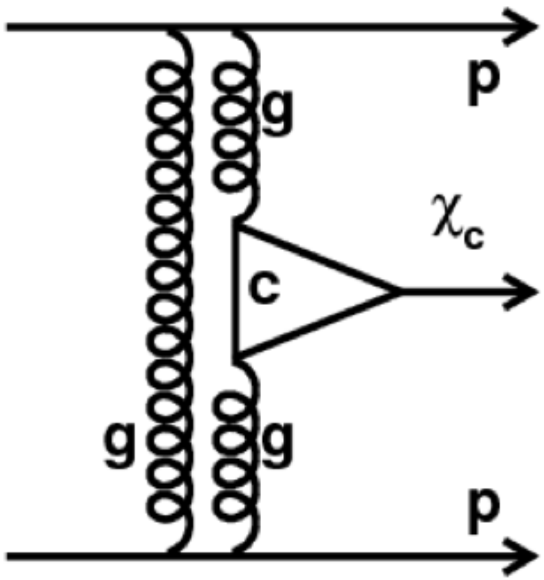


Pomeron exchange
(~constant with Q^2)



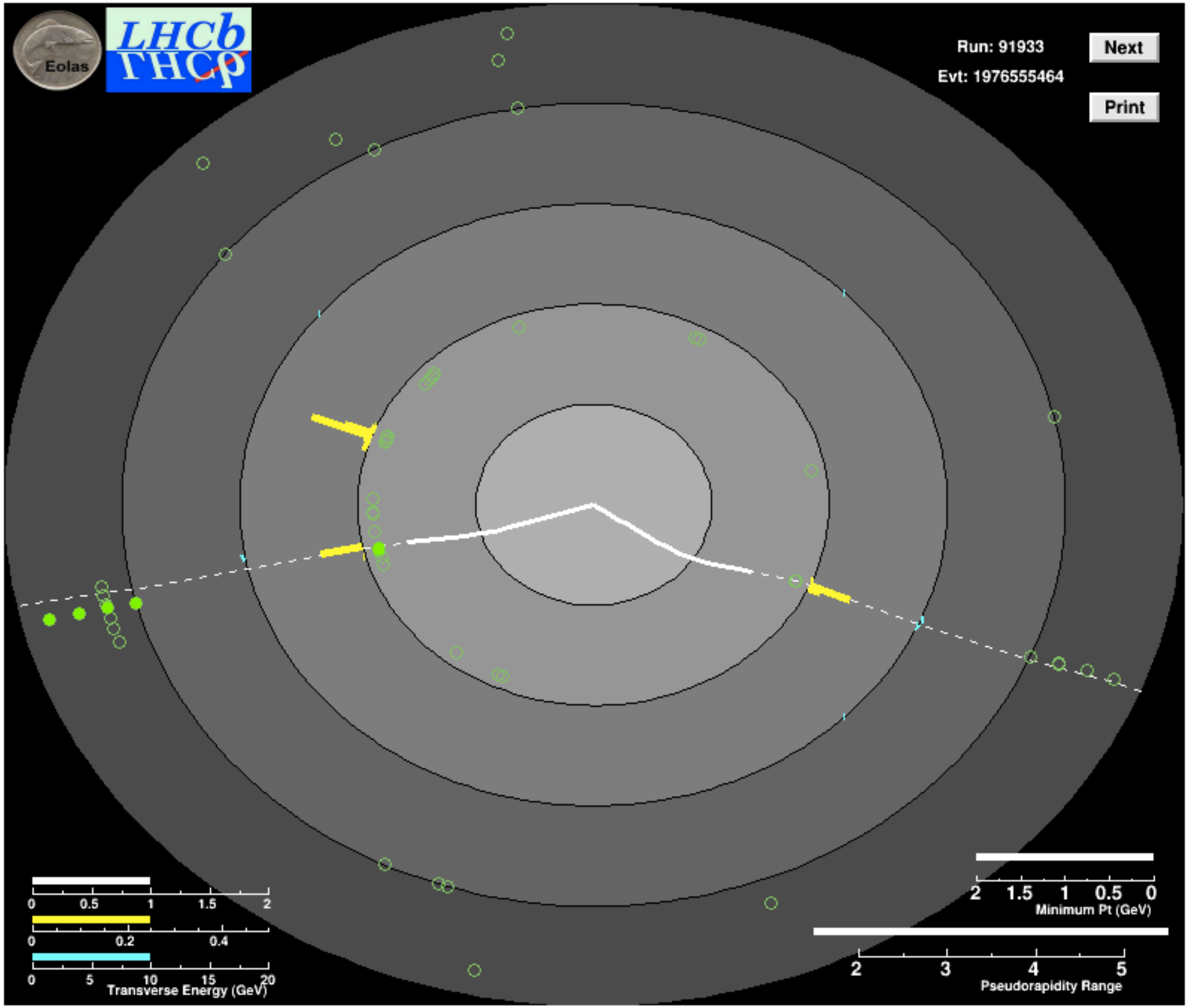
<1 event in $3fb^{-1}$ of pp interactions

Double pomeron exchange

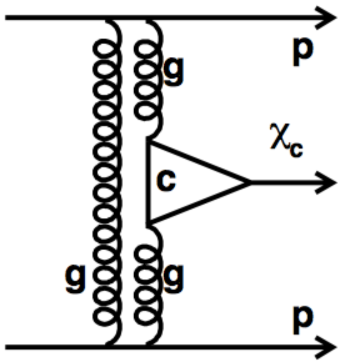


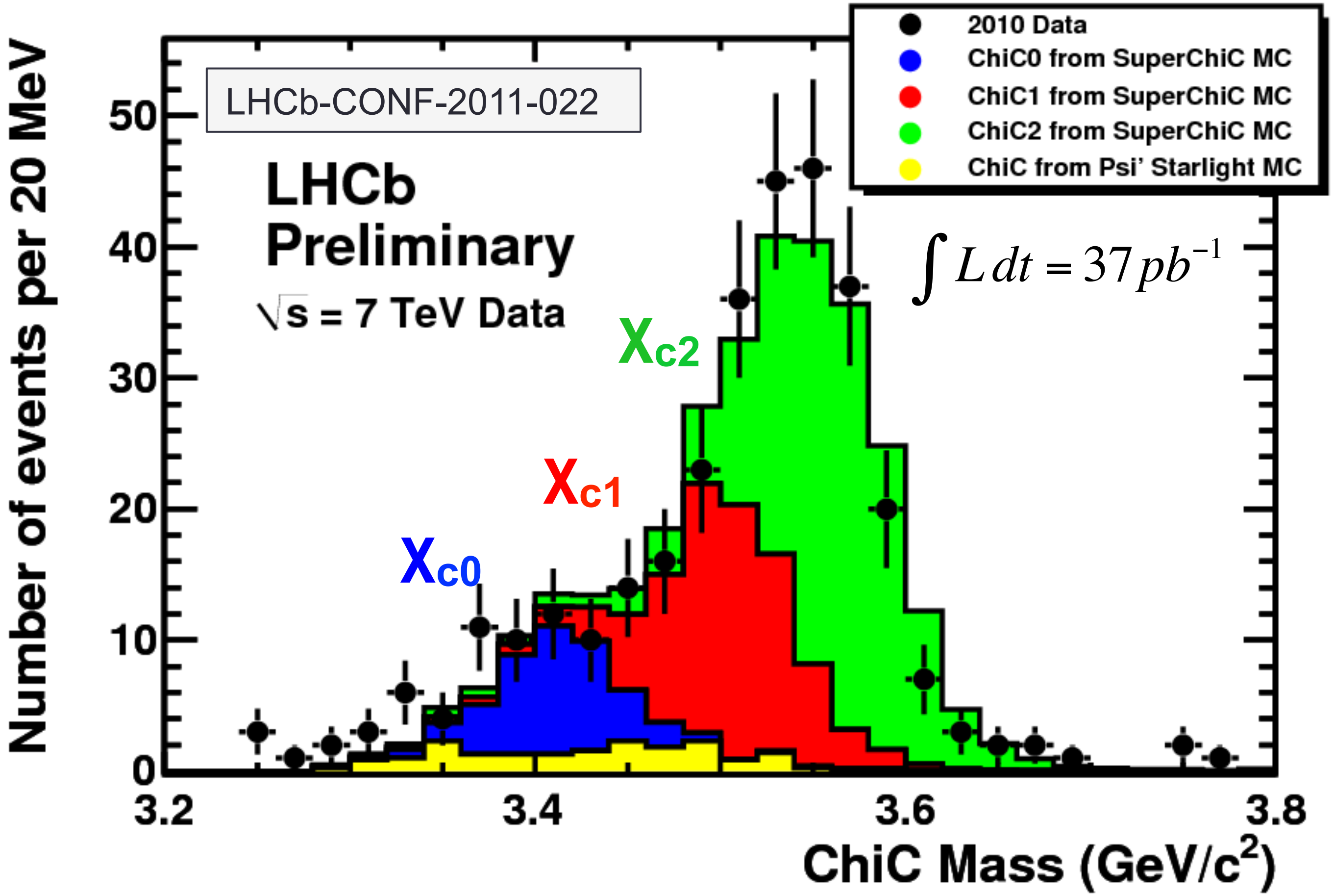
- Pure QCD process
- J^{PC}=(even)$^{++}$
- Glueballs
- Higgs
- J/ψJ/ψ (but no predictions one year ago)

Candidate for χ_c decay to $J/\psi+\gamma$



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





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

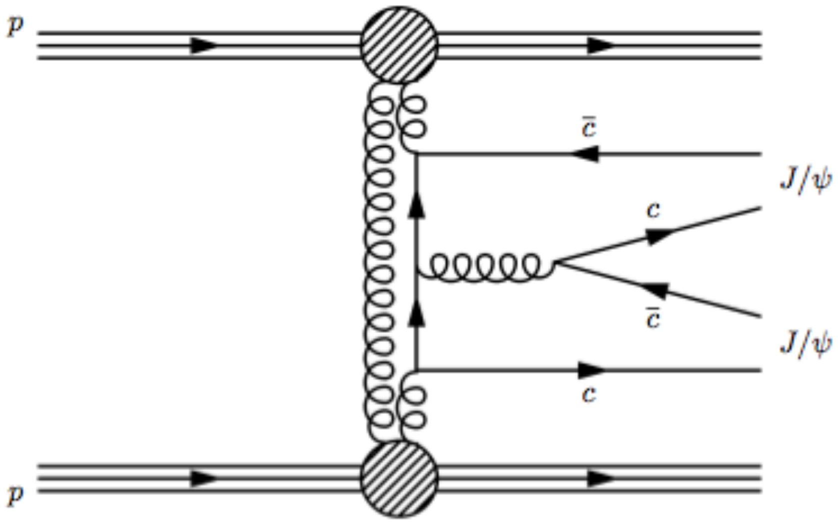
	χ_0	χ_1	χ_2
	9.3 +- 4.5 pb	16.4 +- 7.1 pb	28.0 +-12.3 pb
SuperChic:	14 pb	10 pb	3 pb

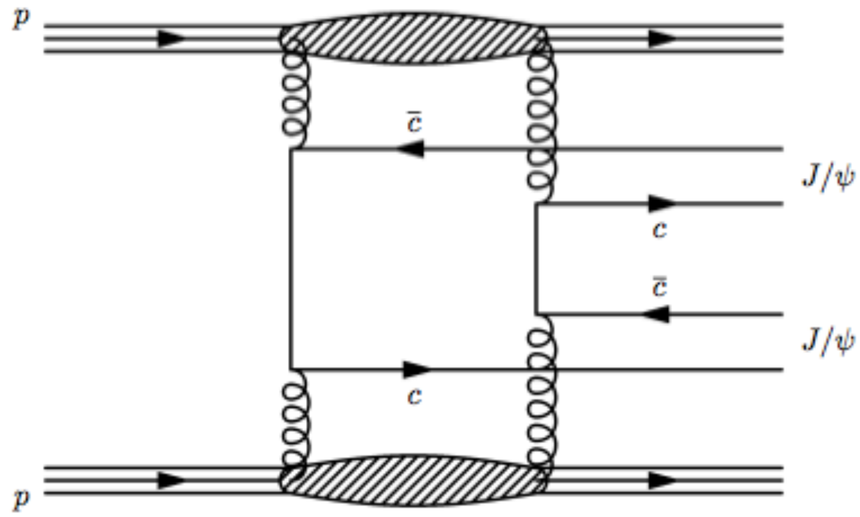
Large contribution due to X_{c0} as expected.

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

Work ongoing to reconstruct in ππ, KK channels

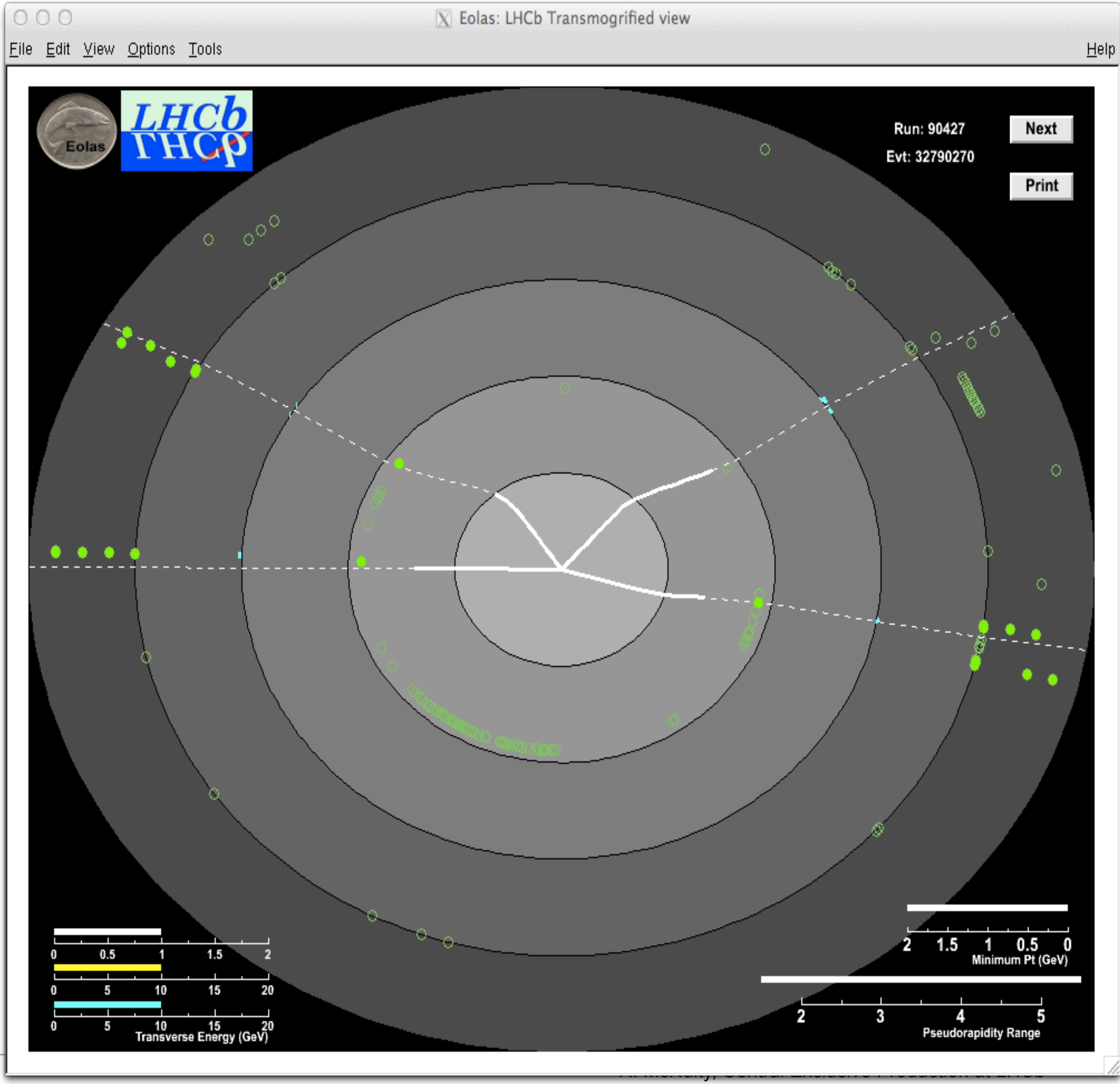
Double J/ψ production





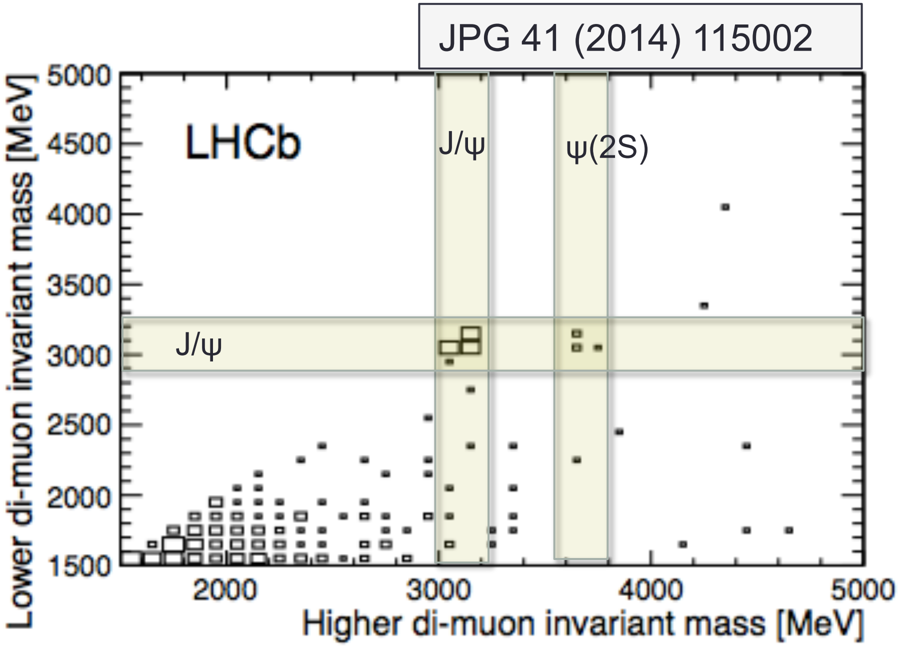
Final state theoretically studied in diphoton production (linear collider) but not through double pomeron exchange (hadron collider)

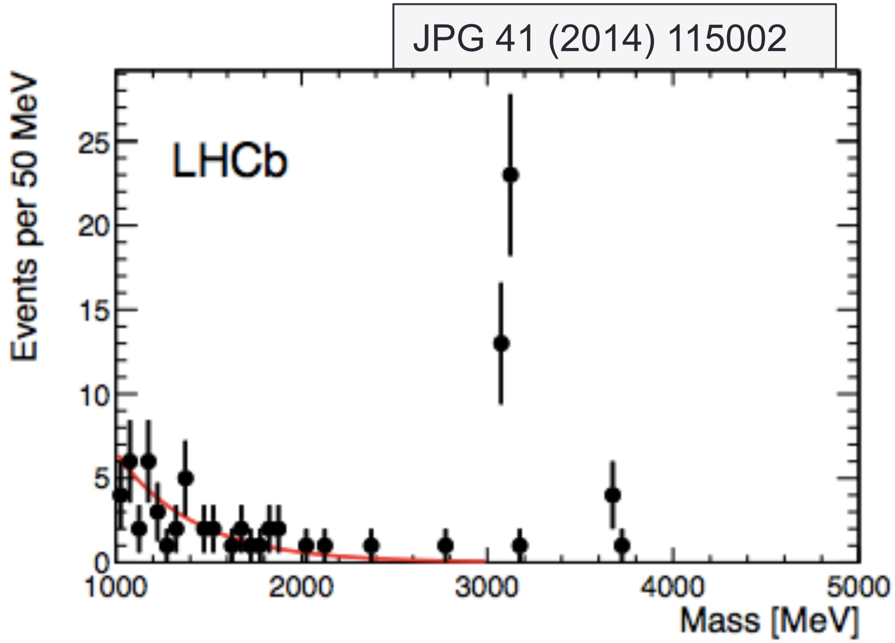
Sensitivity to higher mass states (tetraquarks, η_b)
Inclusive production has attracted much interest (DPS effects)



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

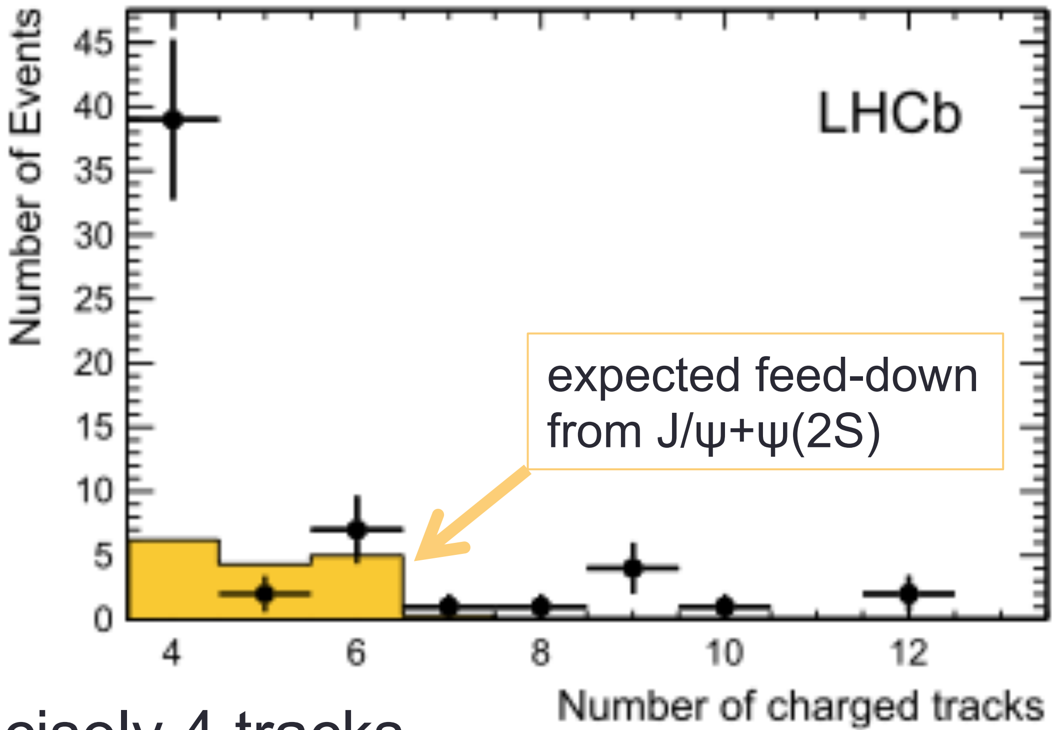




Dimuon spectrum having required other two muons have J/ψ mass

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 $\chi_c \to J/\psi\gamma$

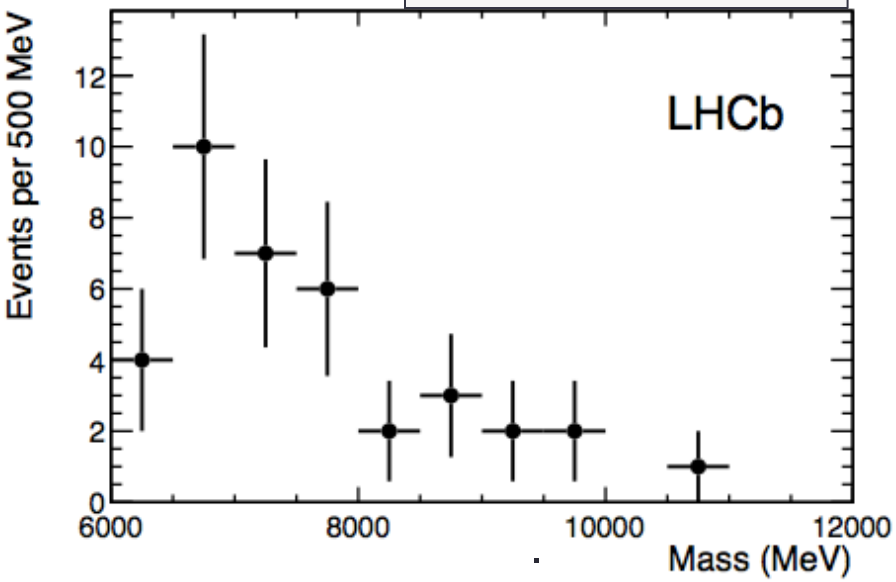
One candidate for χ_{c0}, which is also consistent with ψ(2s)
No candidates for χ_{c1} χ_{c2}

Cross-section results

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

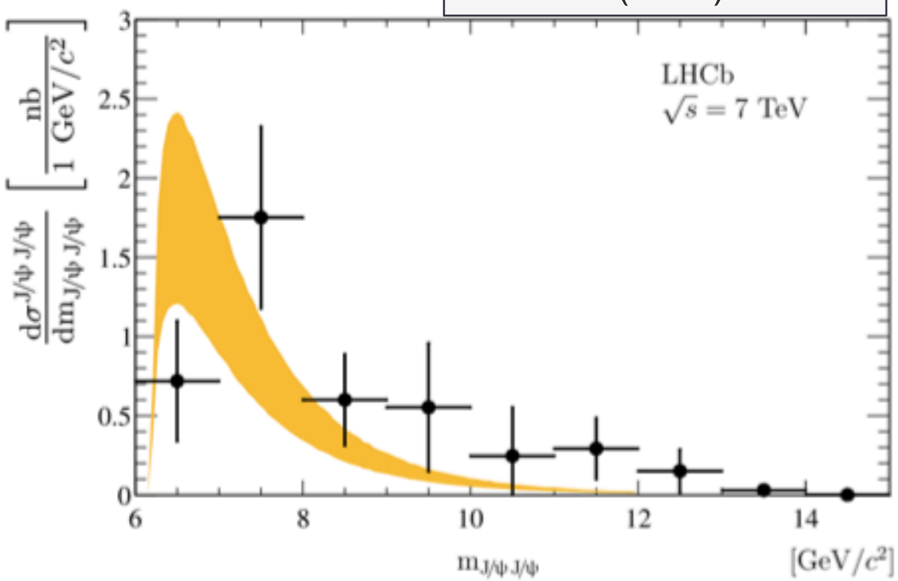
Exclusive

JPG 41 (2014) 115002

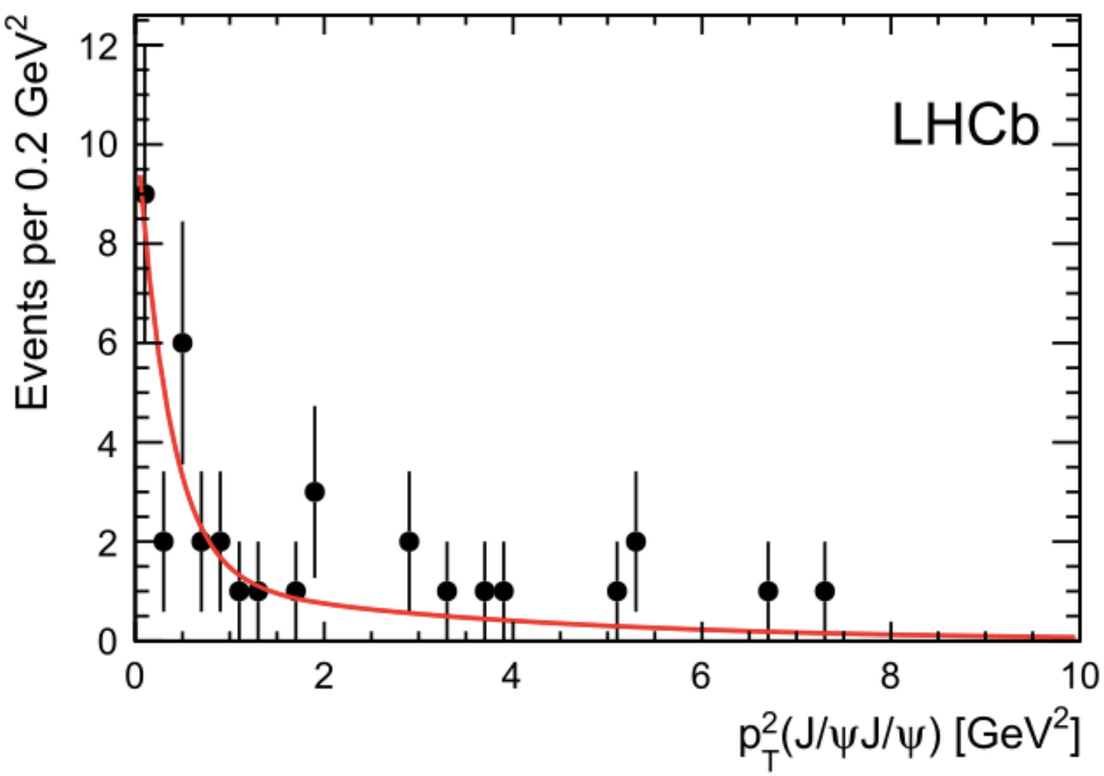


Inclusive

PLB 707 (2012) 52.



How much is exclusive?

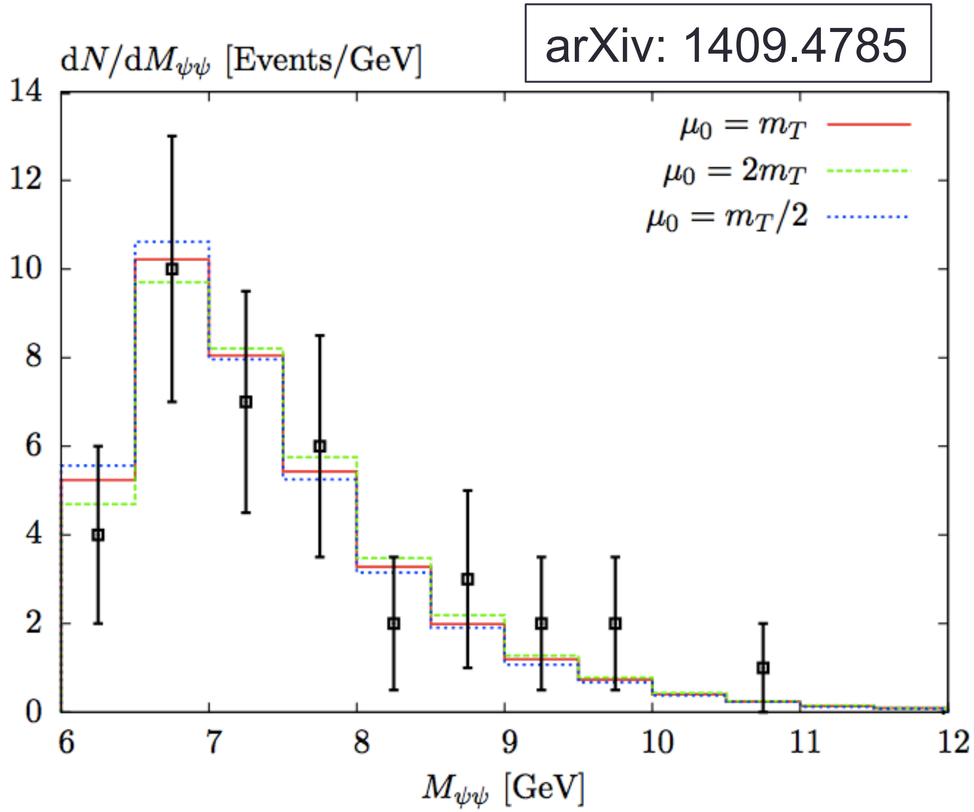


42+-13% but model dependence in describing inelastic contribution

Comparison to theory

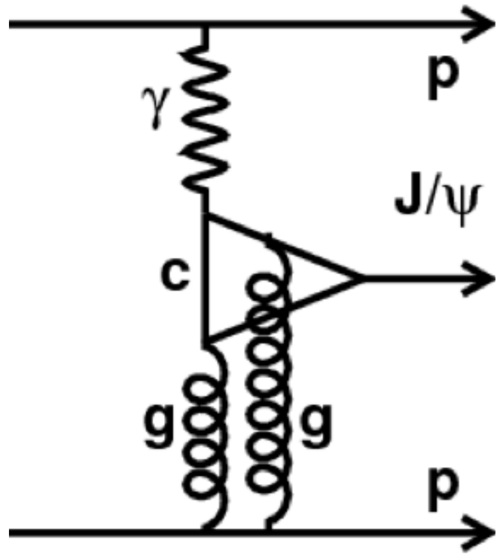
LHCb estimate exclusive cross-section. **24+-9 pb**

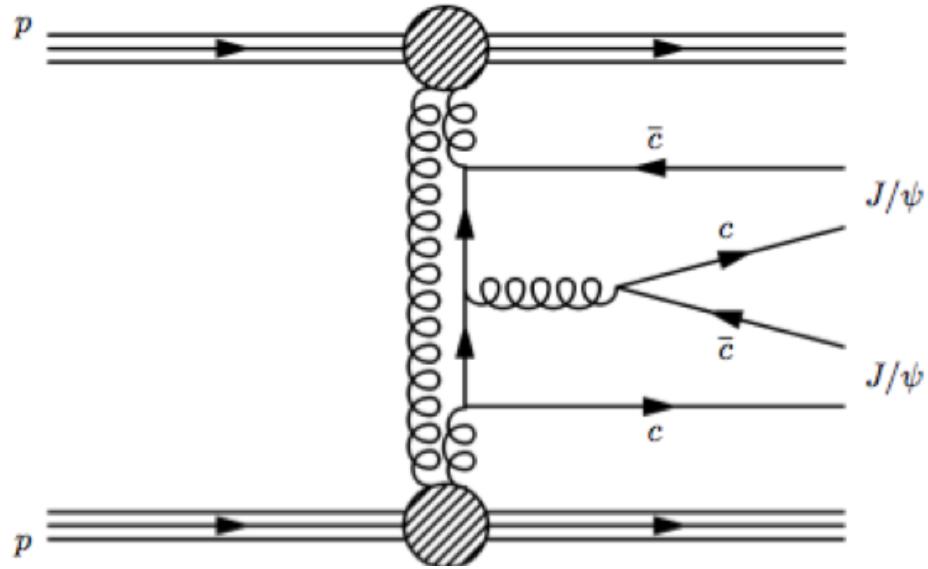
Harland-Lang, Khoze, Ryskin: (arXiv: 1409.4785) **2-7 pb**



Shape agrees well
(theory normalised to data).

Conclusions





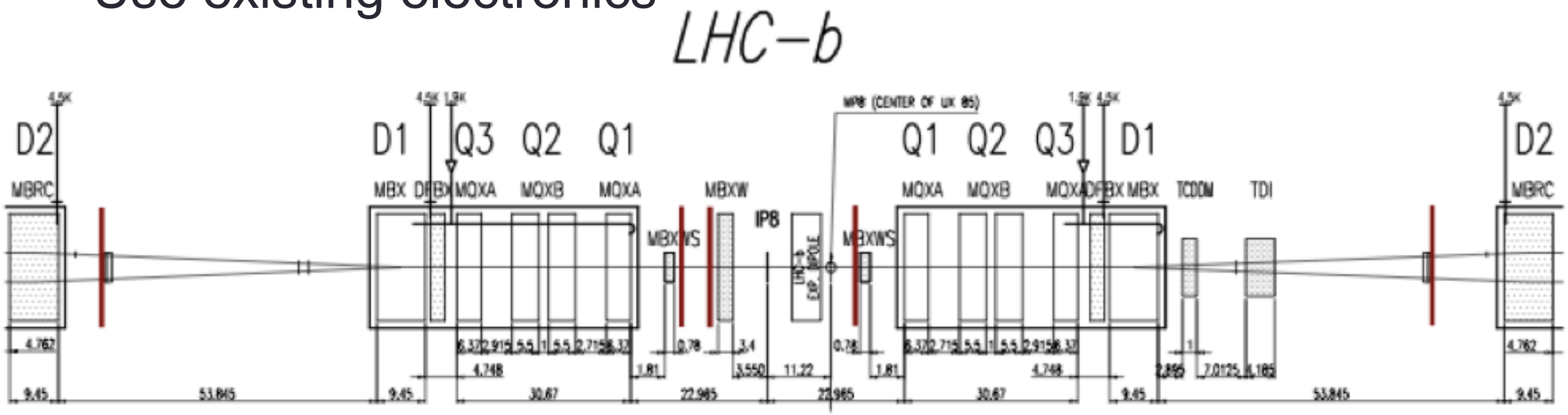
Consistent picture of J/ψ photoproduction at different energies and different colliders

'Surprising' observation of J/ψJ/ψ: consistent with DPE mechanism

What other surprises/insights might central exclusive production hold?

High rapidity shower counters for LHCb

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

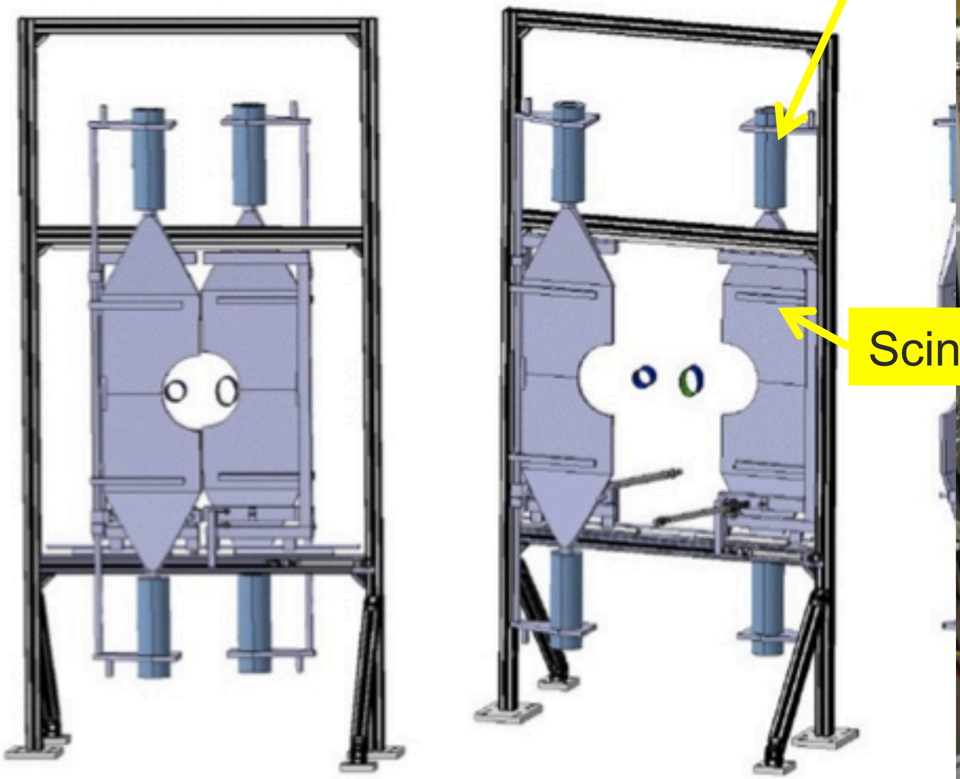


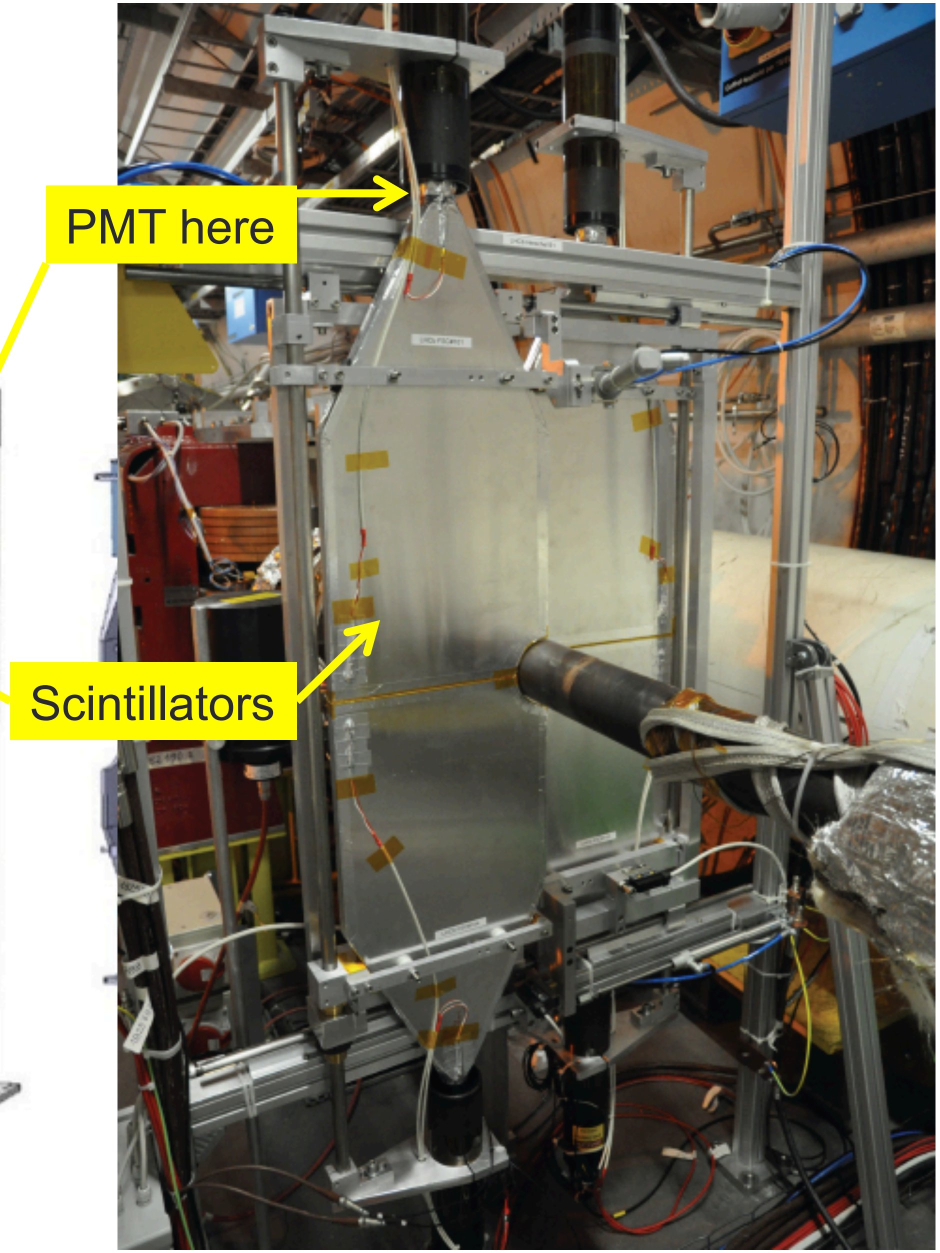
Left
1. z ~ -7.5 m (after MBXW)
2. z ~ -19m (before MBXWS)
3. z ~ -114m (after BRANS)

Right
1. z ~ 19 m (close to MBXWS)
2. z ~ 114m (after BRANS)

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

Herschel Integration inside Tunnel





Backup

p_T^2 spectrum