Central exclusive production in LHCb

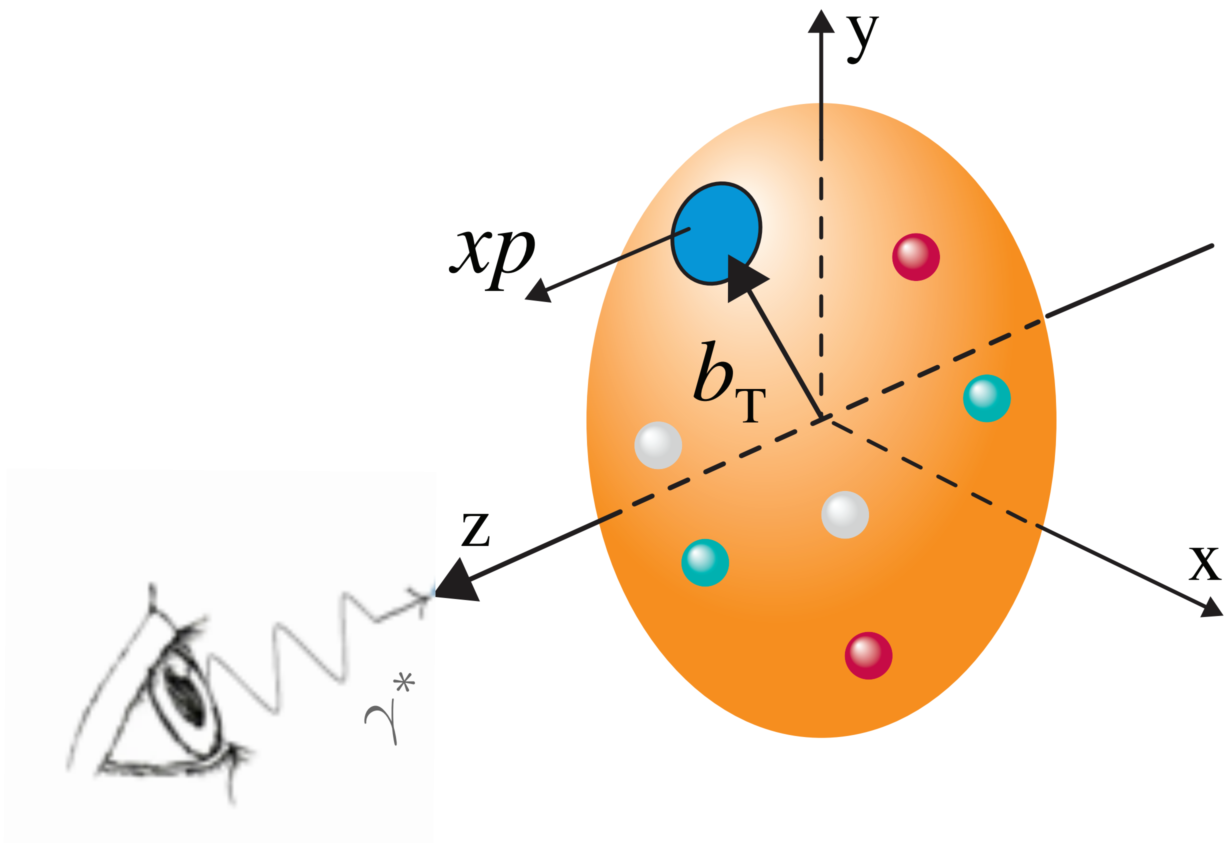
Charlotte Van Hulse, on behalf of the LHCb collaboration
University College Dublin

New Trends In High-Energy Physics
Odessa, Ukraine
May 12-18, 2019
Odessa

Outline

- physics of central exclusive production (CEP)
- CEP and instrumentation: LHCb detector
- single J/ψ, $\psi(2S)$, Υ production in proton-proton collisions
- pairs of charmonium in proton-proton collisions
- summary and outlook

Nucleon structure



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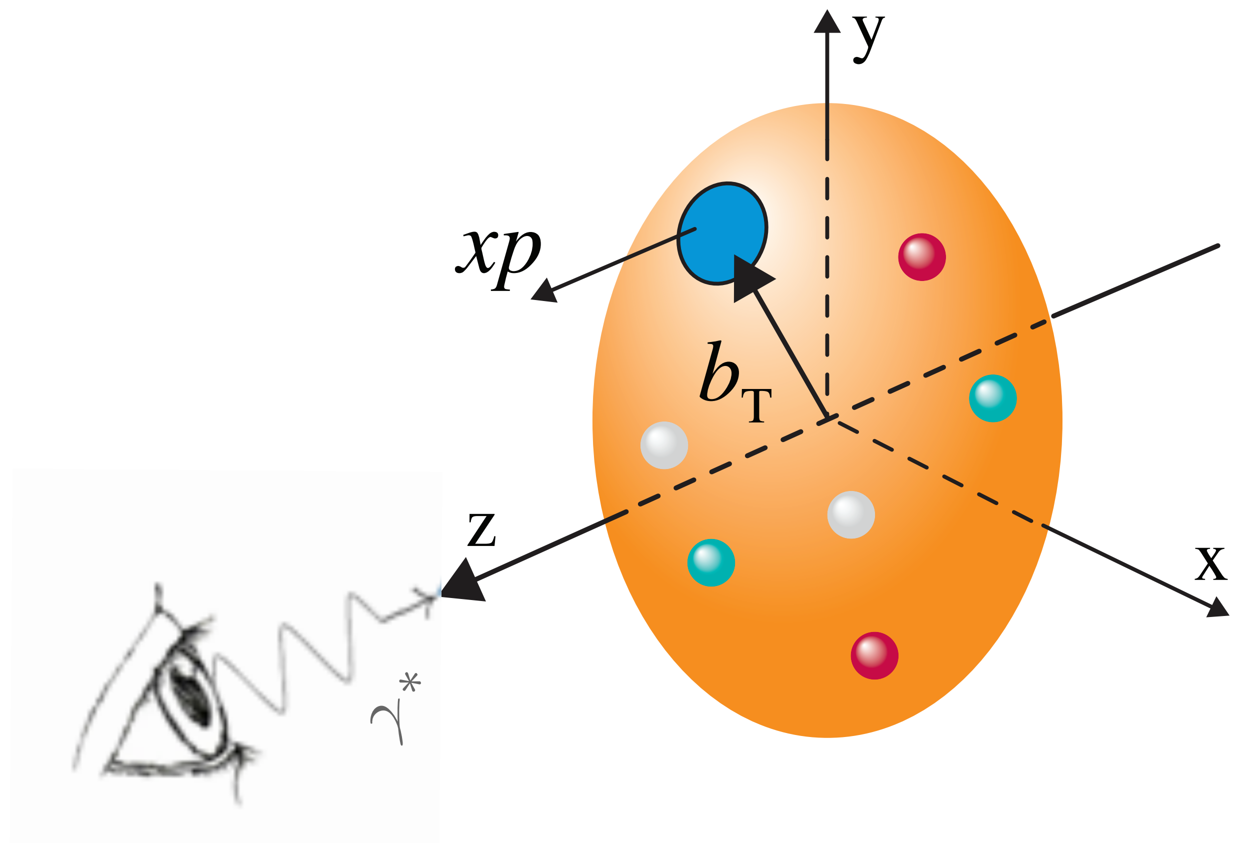

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Phys. Rev. D 62 (2000) 071503
Int. J. Mod Phys. A 18 (2003) 173

impact-parameter-dependent
parton distributions

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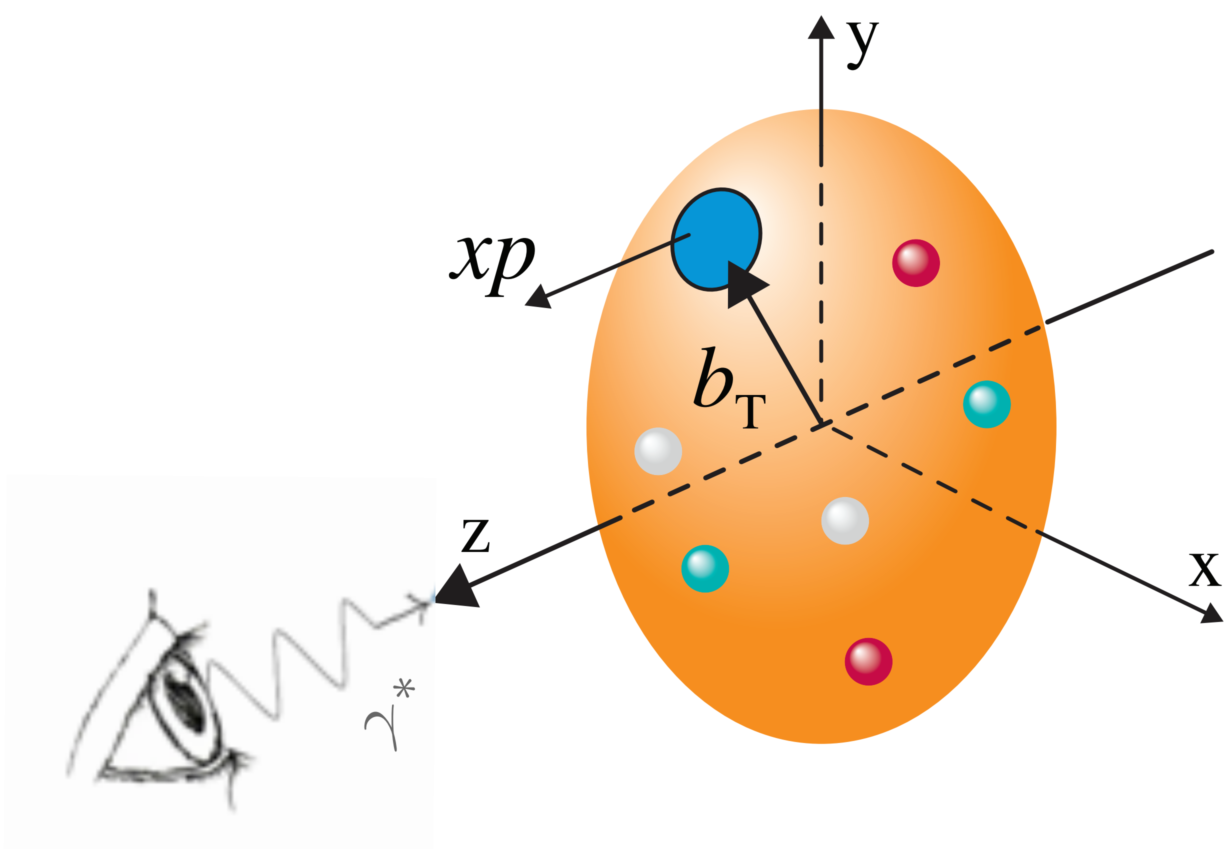

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↓ Fourier transform

generalised parton distributions (GPDs)

See e.g. M. Diehl, Phys. Rept. 388 (2003) 41

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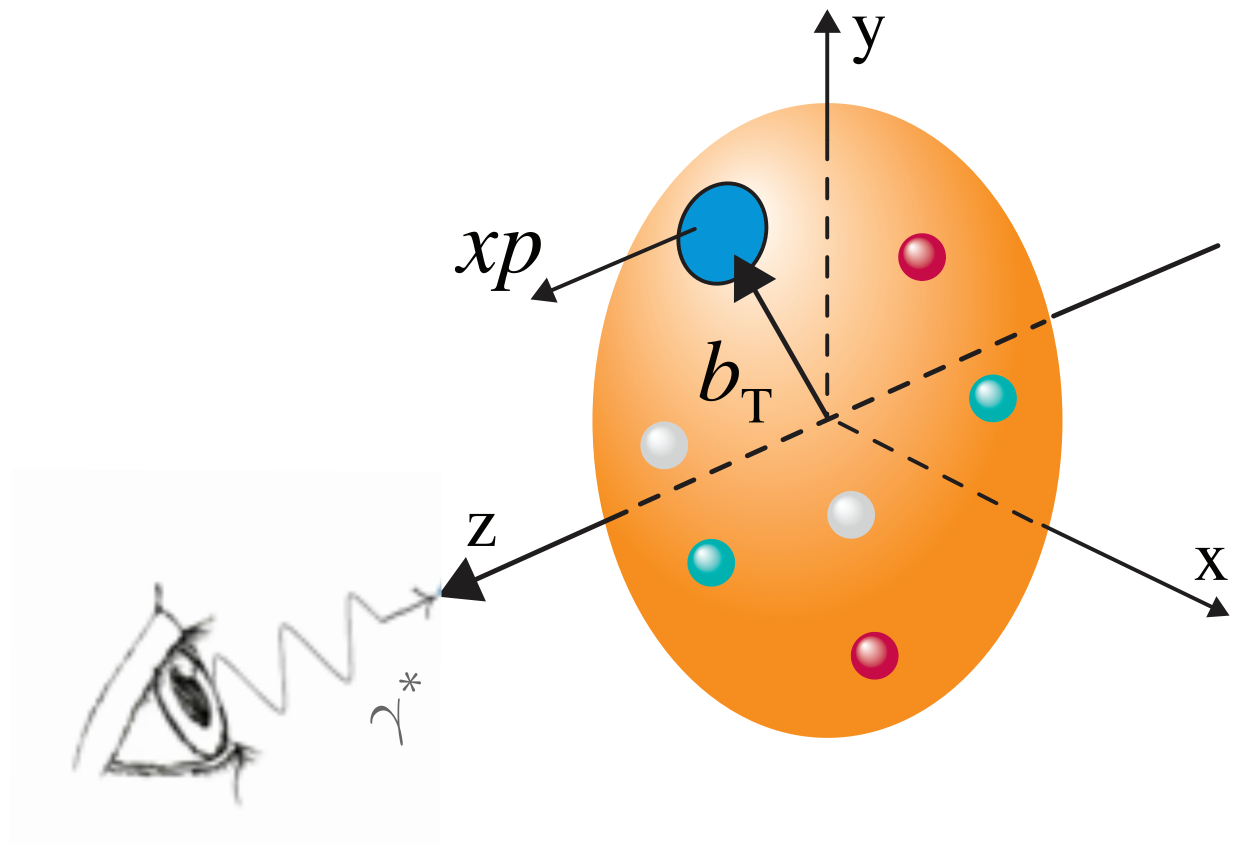

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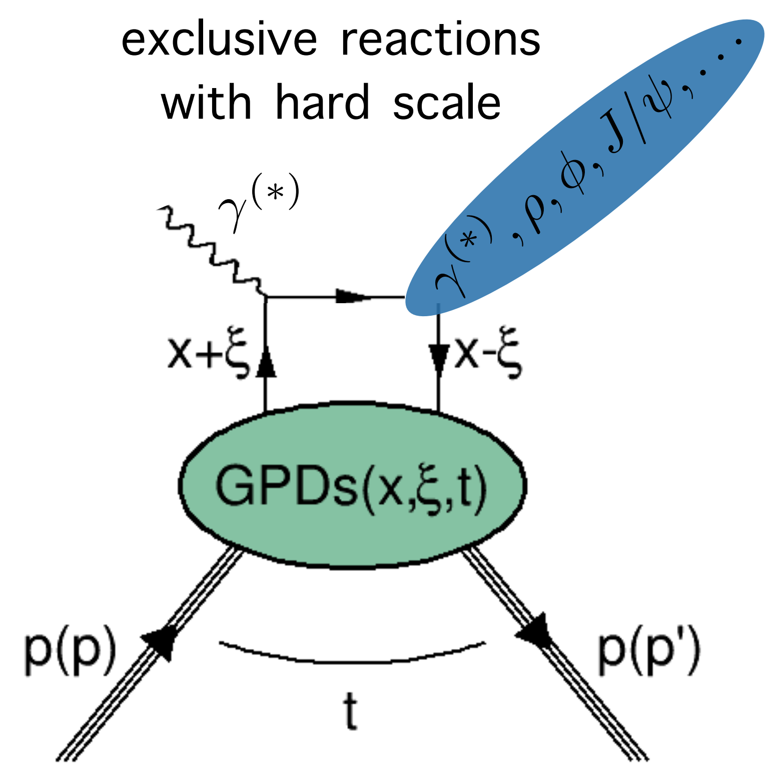

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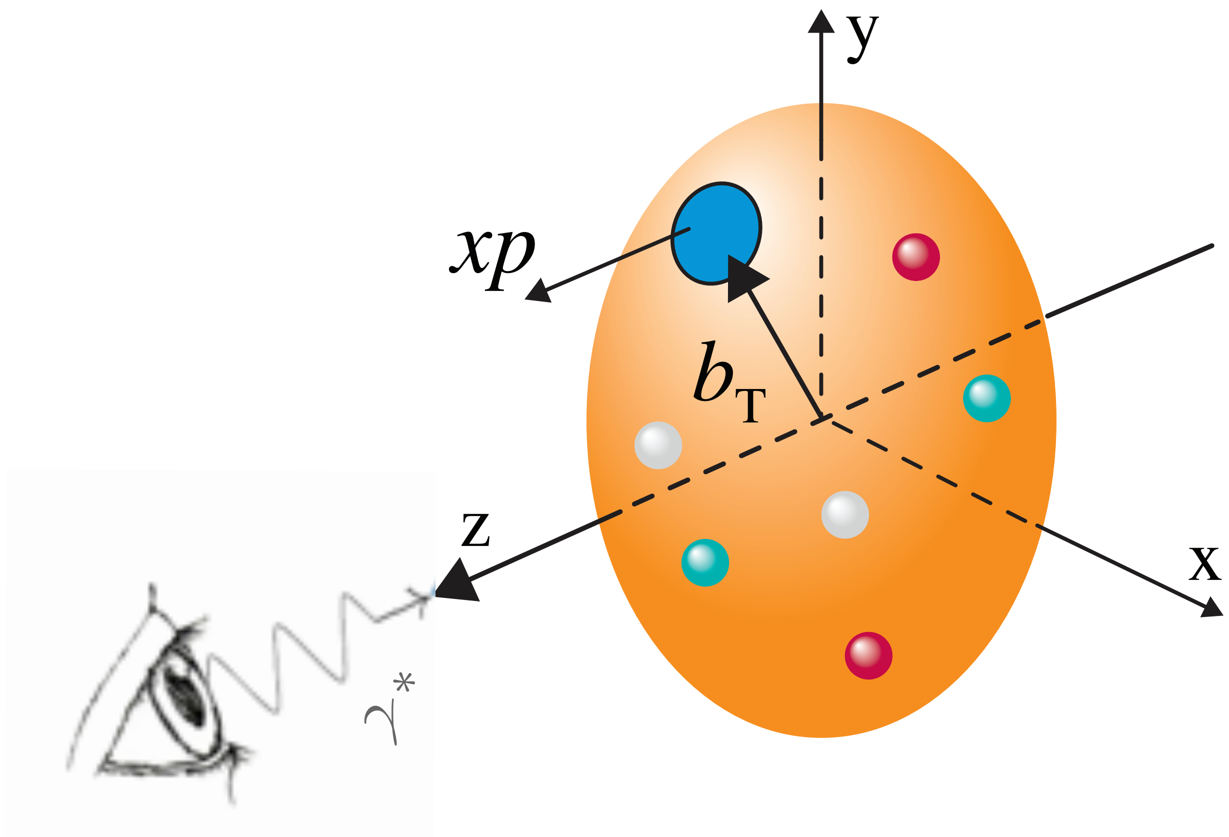

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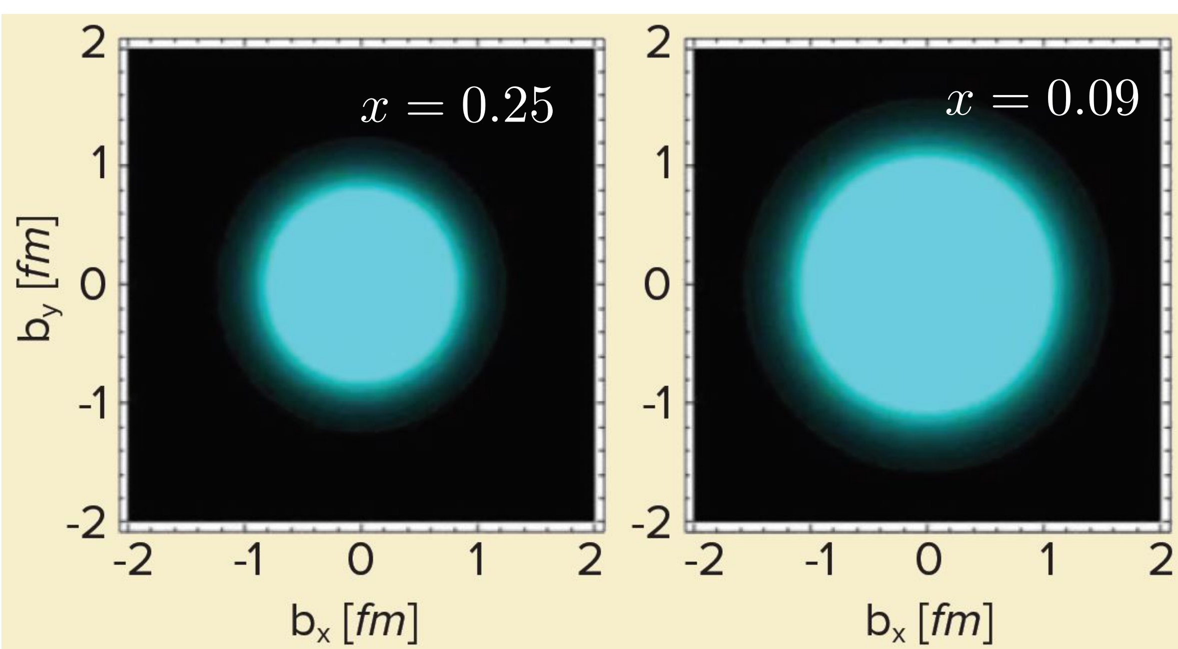
2015 Long Range Plan for Nuclear Science



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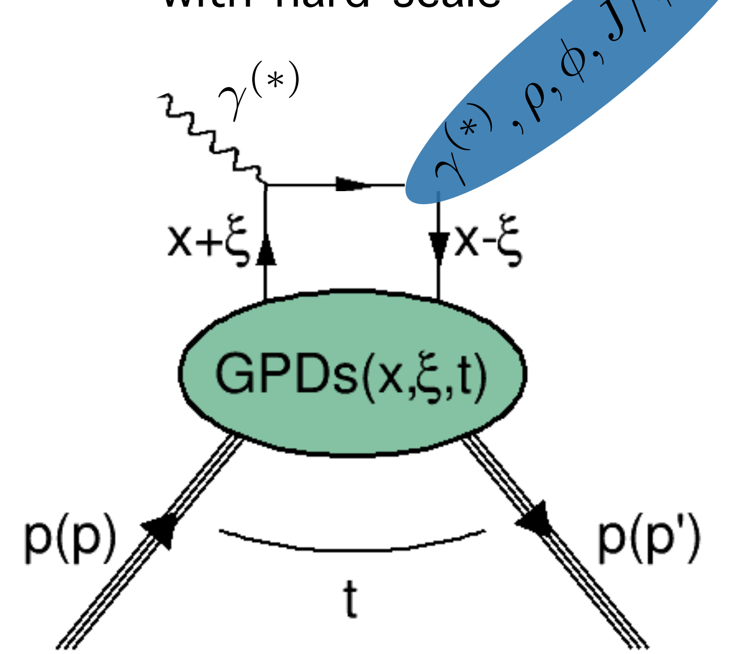
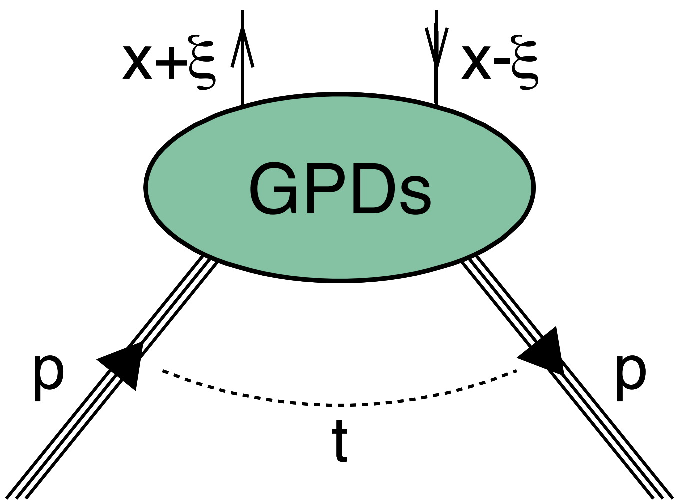


Experimental access to GPDs



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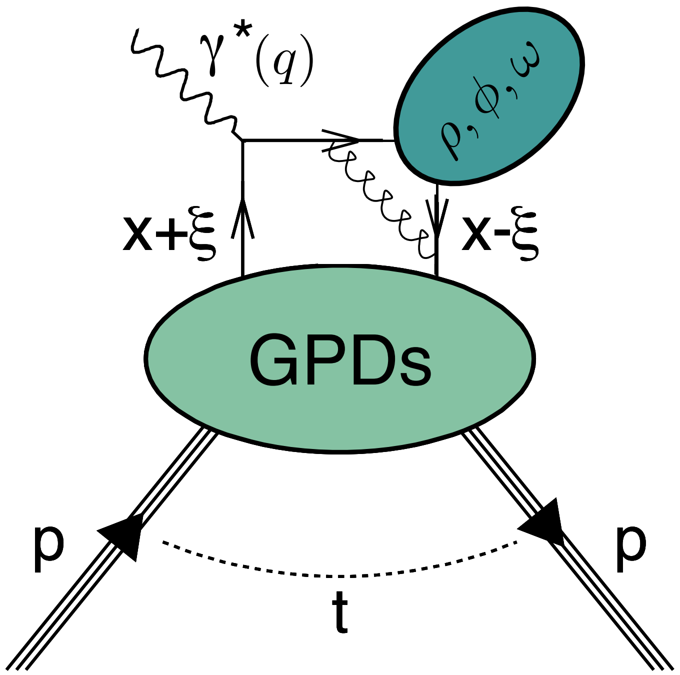

Hard exclusive meson production

hard scale = large Q^2 ($Q^2=-q^2$)

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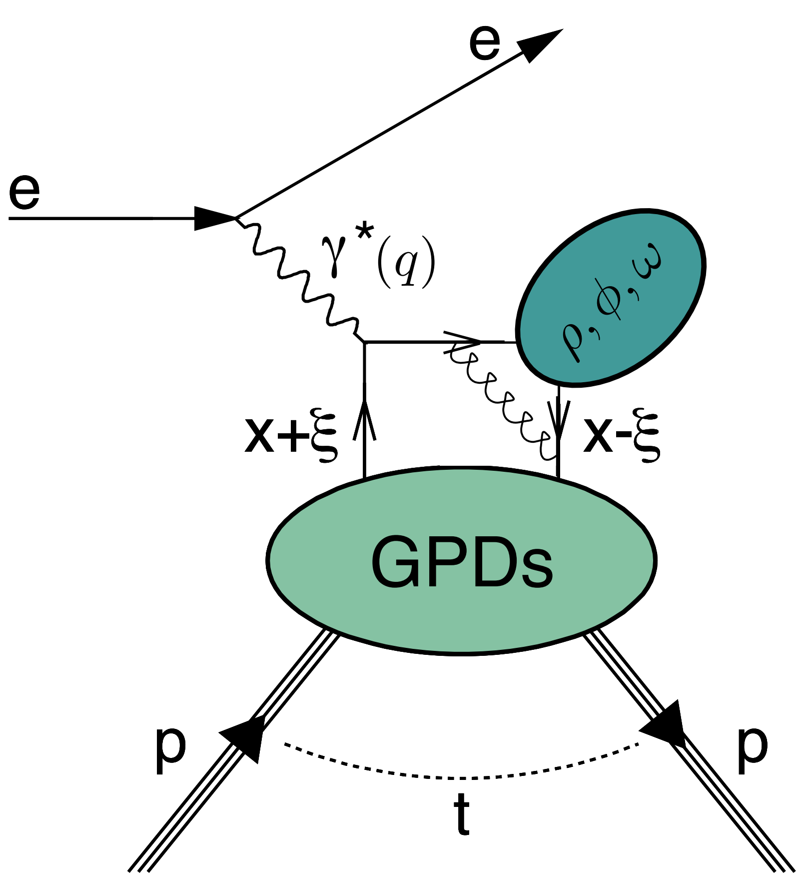

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HERMES – EPJ C 74 ('14) 3110; 75 ('15) 600; 77 ('17) 378

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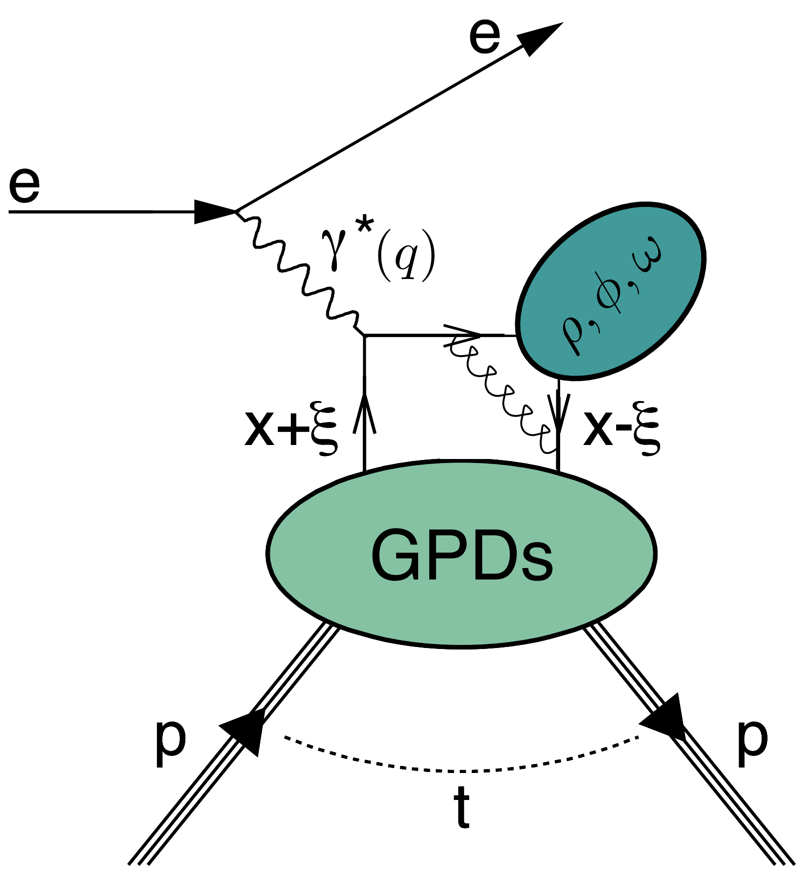

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fixed target: medium/large x_B , quarks

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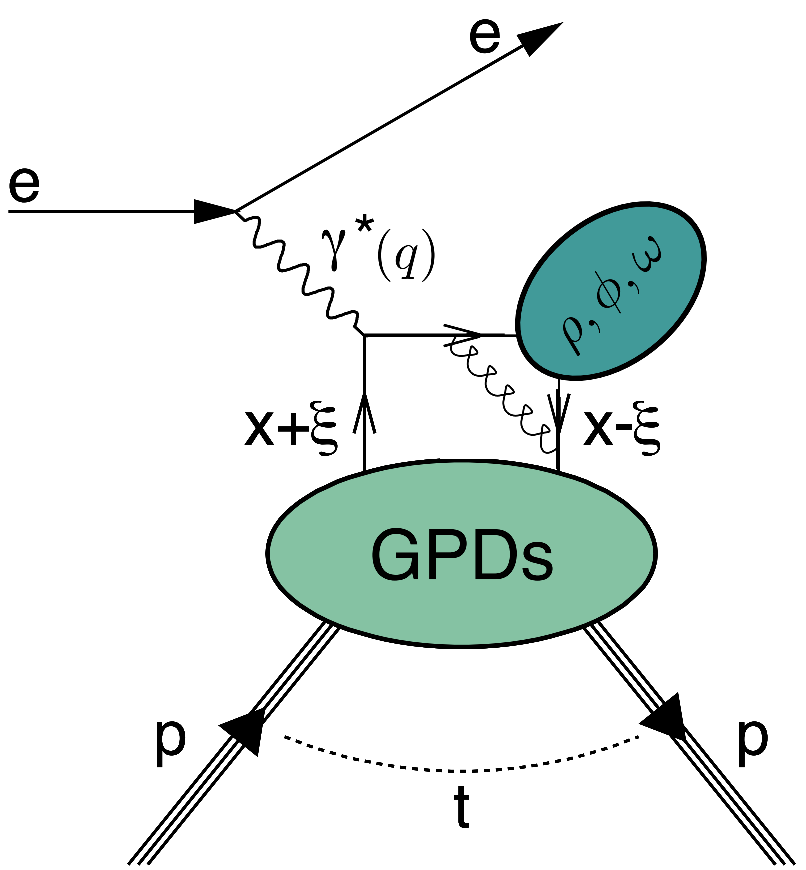

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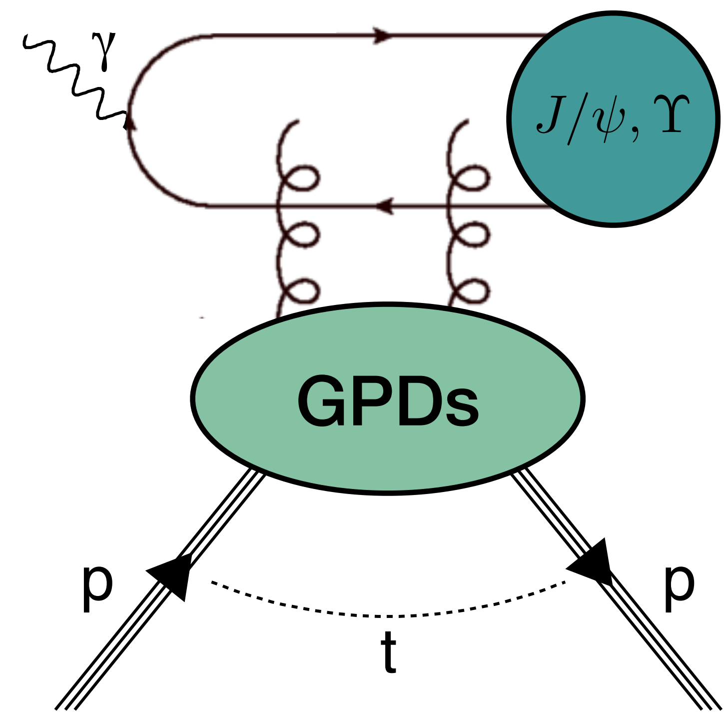

Exclusive meson photoproduction

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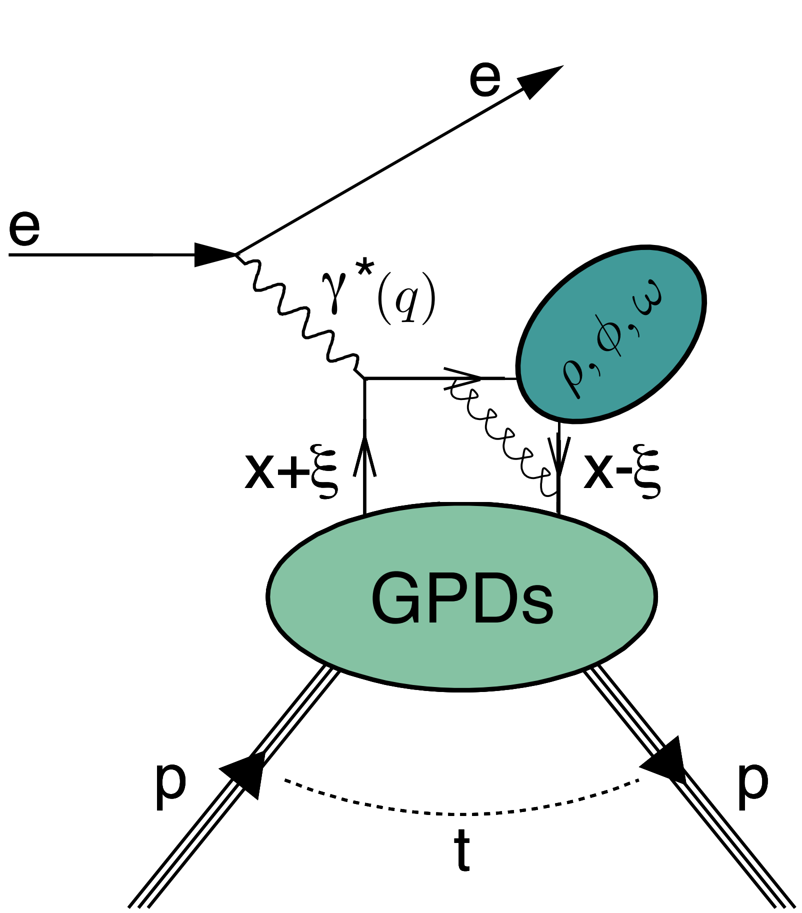

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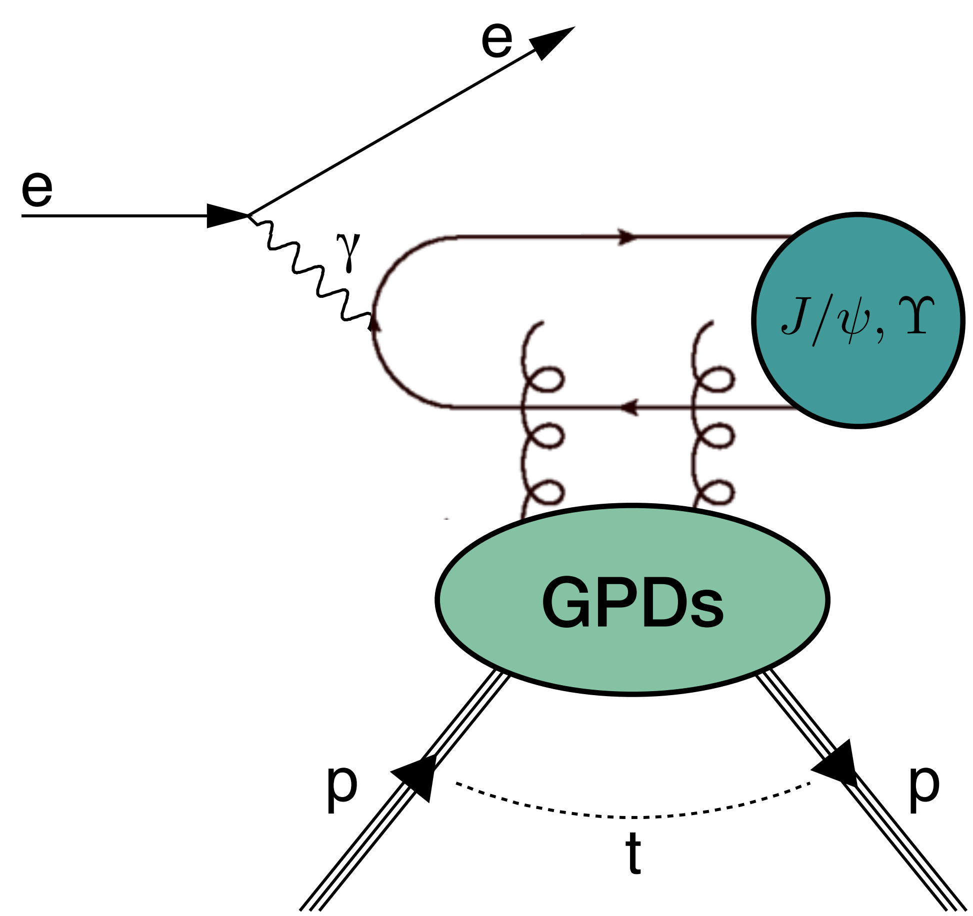

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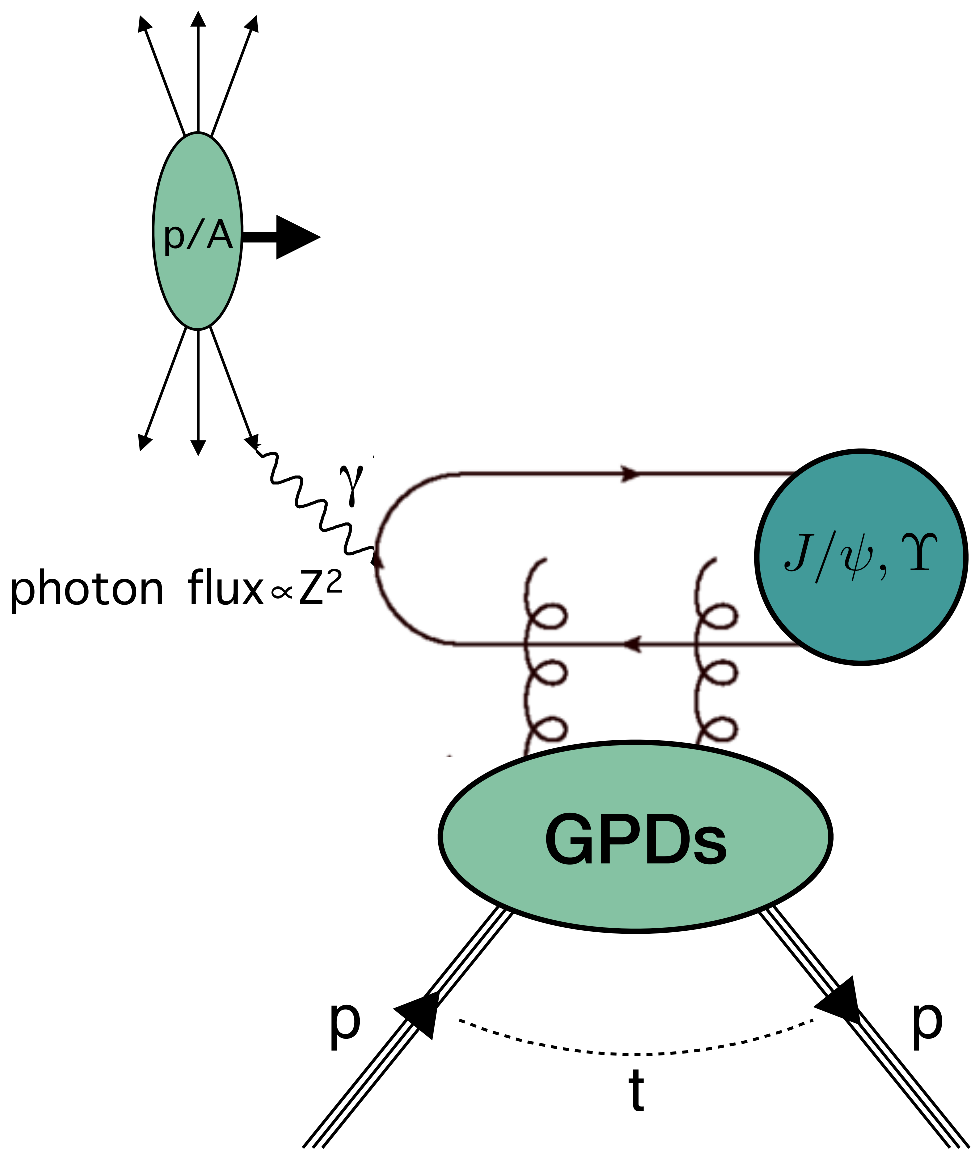
ZEUS – Nucl. Phys. B 695 ('04) 3; PLB 680 ('09) 4

$$W_{\gamma p} = [30, 300]\ \mathrm{GeV}$$

Ultra-peripheral exclusive quarkonia production



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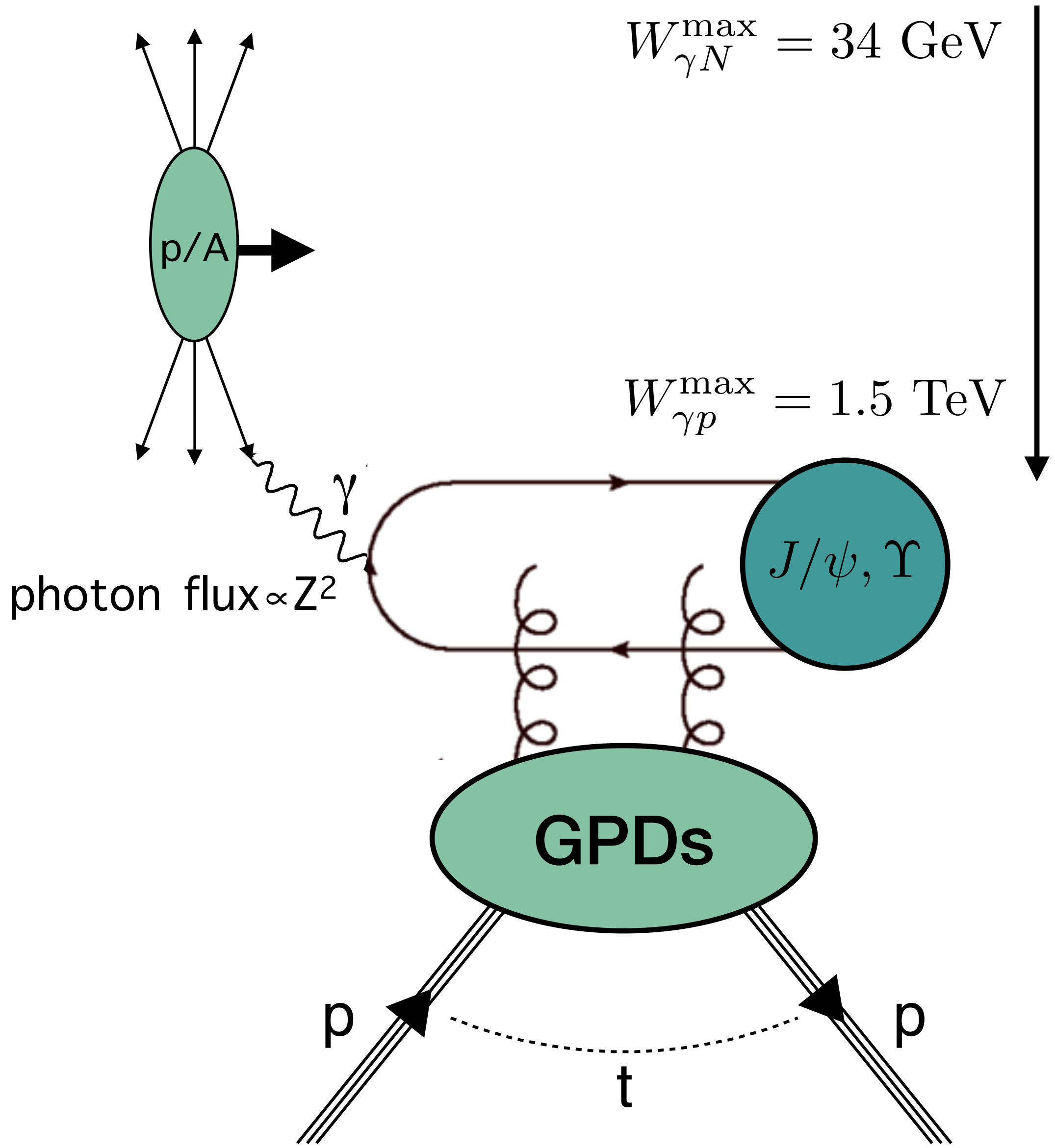

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LHCb: pp – J. Phys. G: Nucl. Part. Phys. 40 ('13) 045001; 41 ('14) 055002, arXiv:1806.04079. (Exclusive Υ in pp – JHEP 1509 (2015) 084).
LHCb: PbPb – CERN-LHCb-CONF-2018-003

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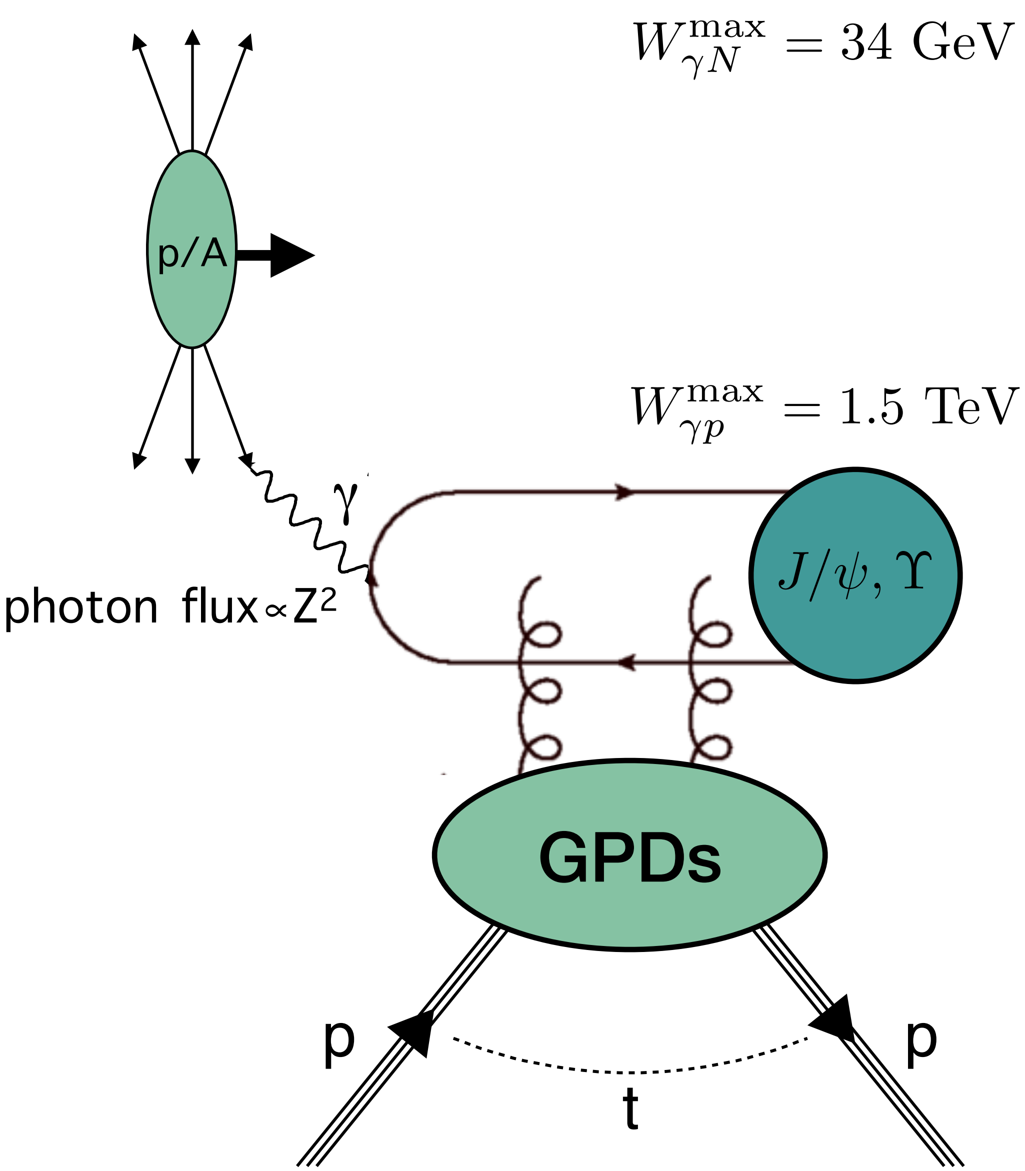

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see presentation on Friday morning by Vasyl Dobishuk

- high energy of LHC → extend to gluon GPDs, down to $x_B=2\times10^{-6}$.
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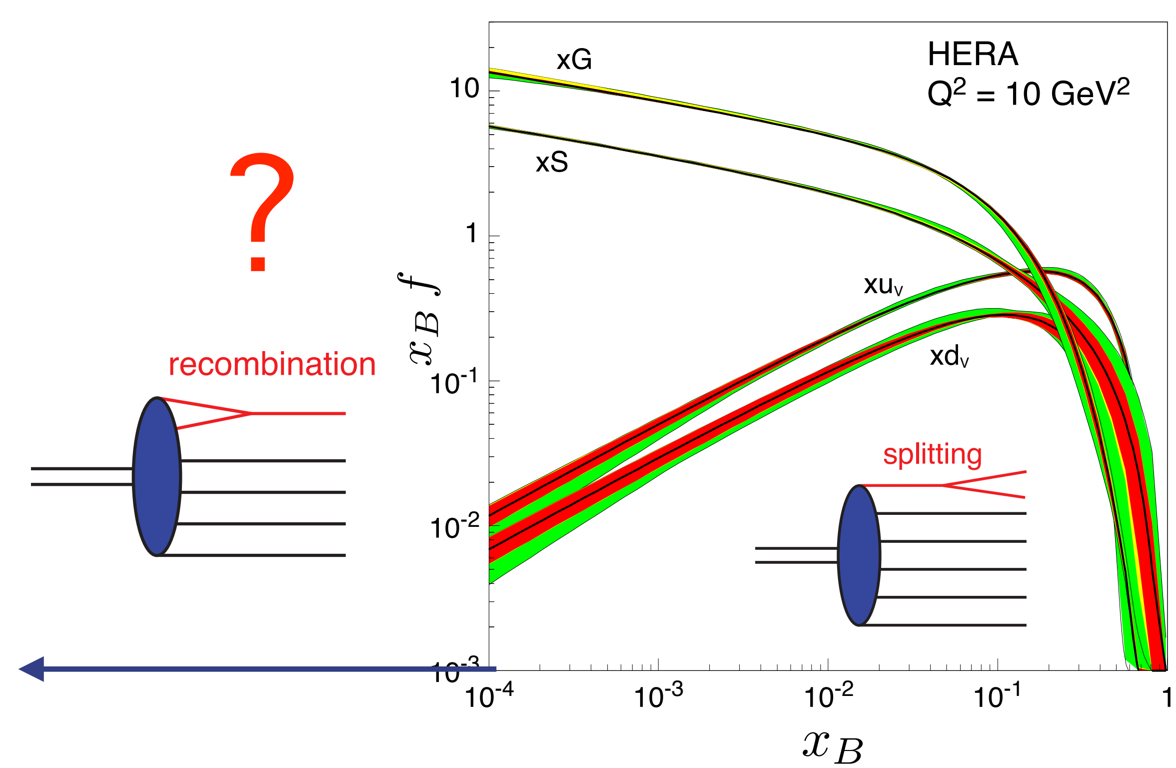

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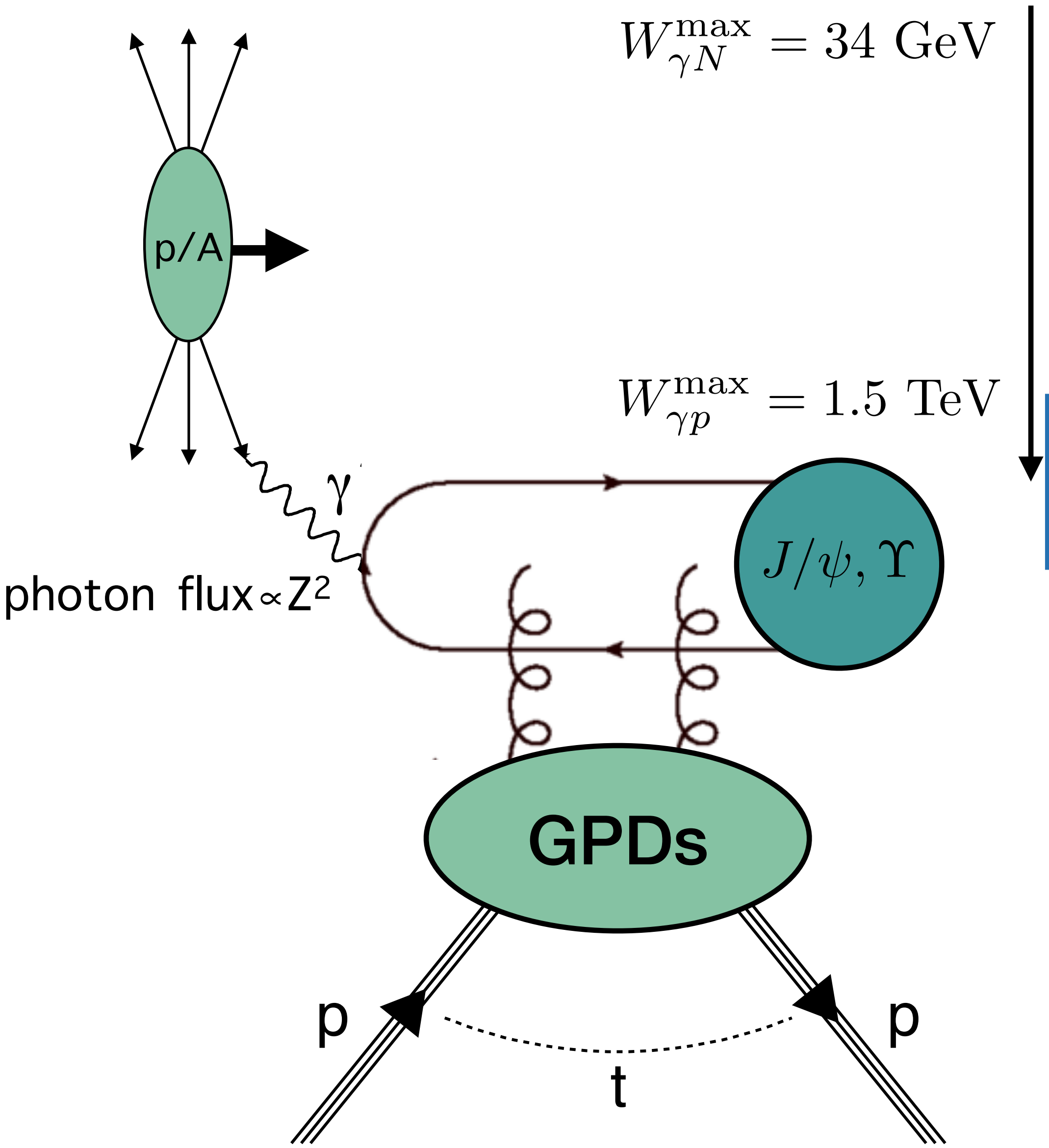

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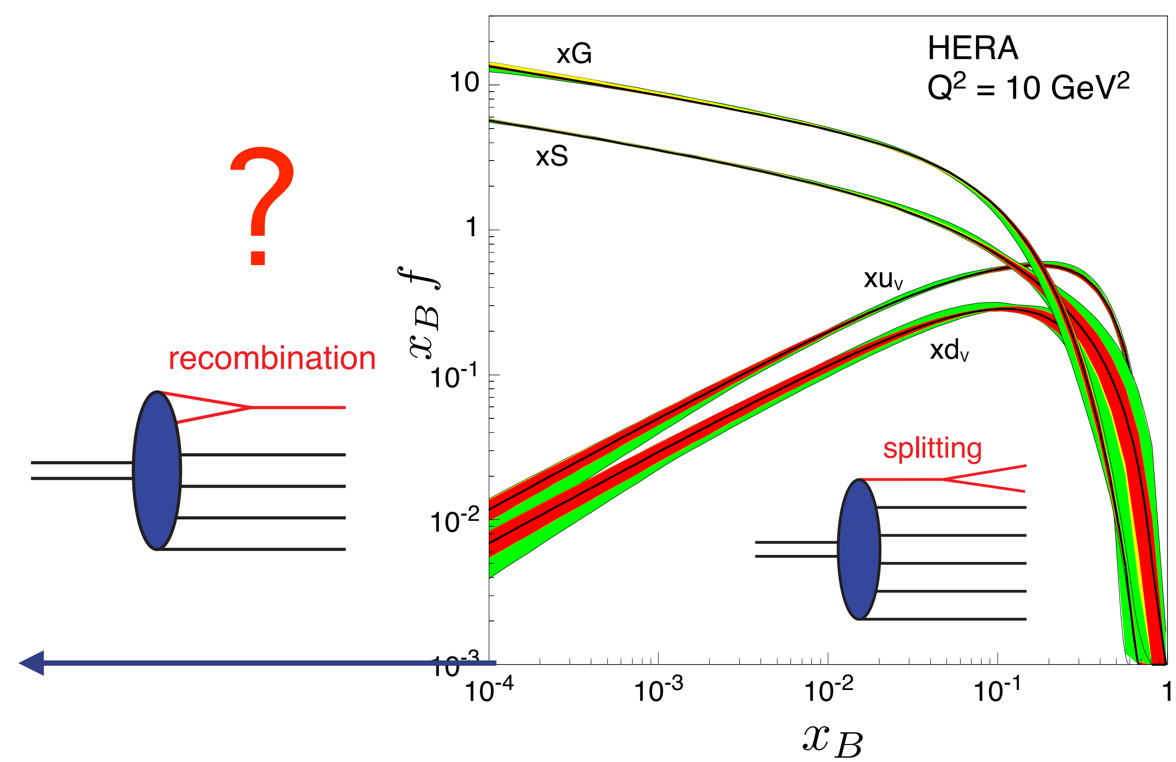
At low x_B: approximate access to gluon PDF

$$\left.\frac{d\sigma}{dt}\right|_{t=0} \propto [g(x_B)]^2$$

M. G. Ryskin, Z. Phys. C57 (1993) 89–92;
S. P. Jones et al., arXiv:1609.09738



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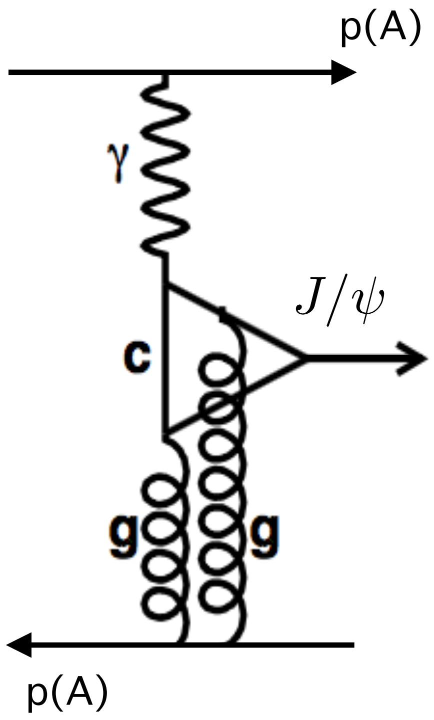

exclusive J/ψ production

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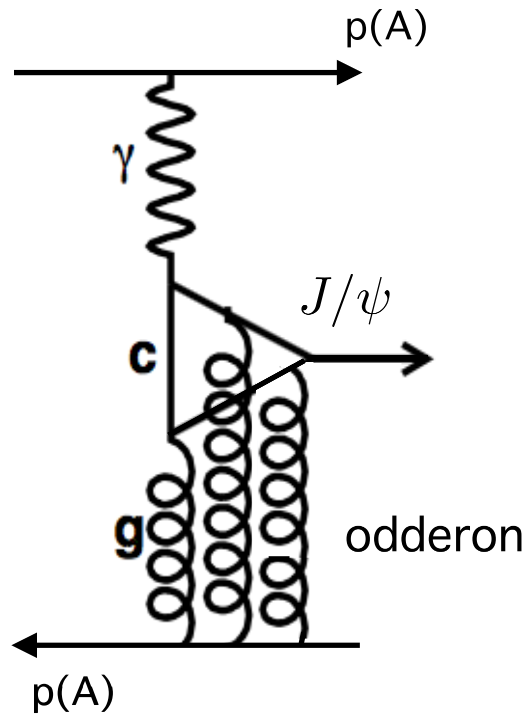

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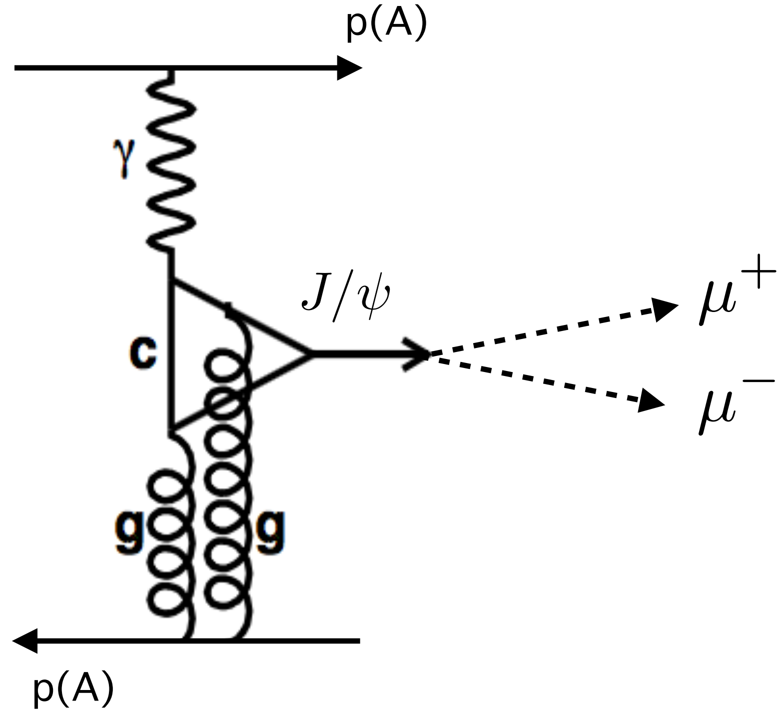

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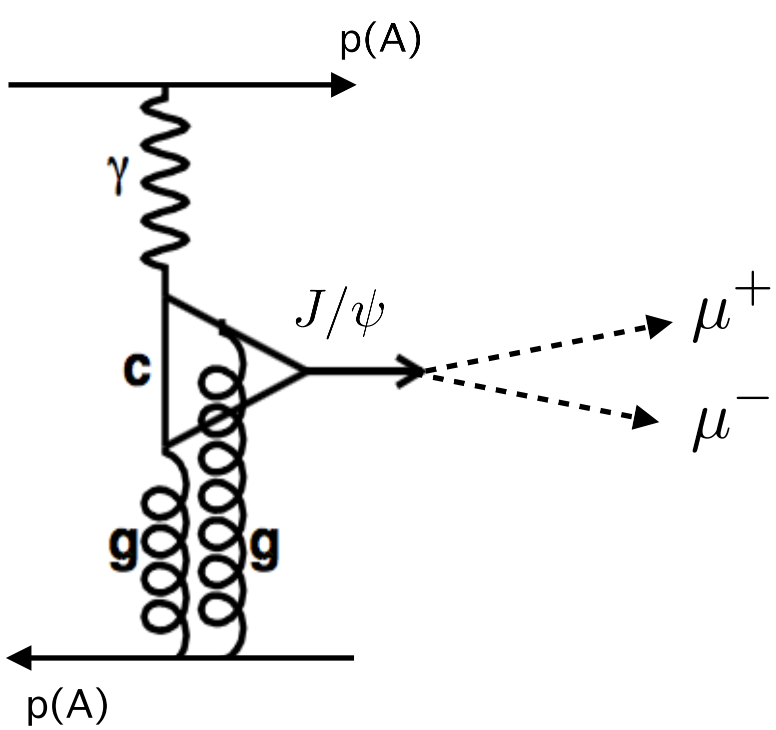

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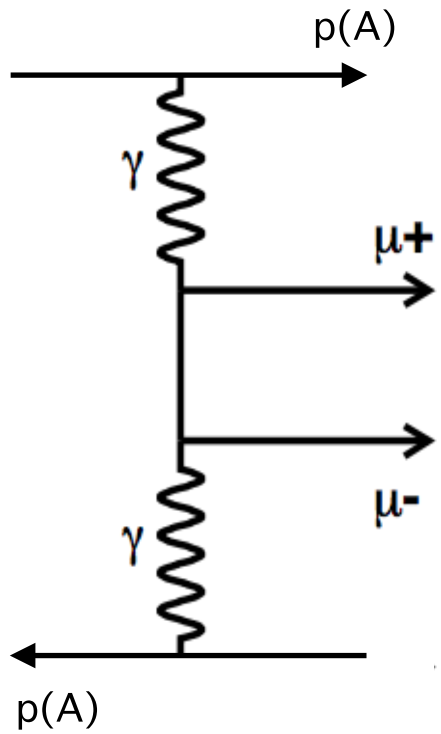
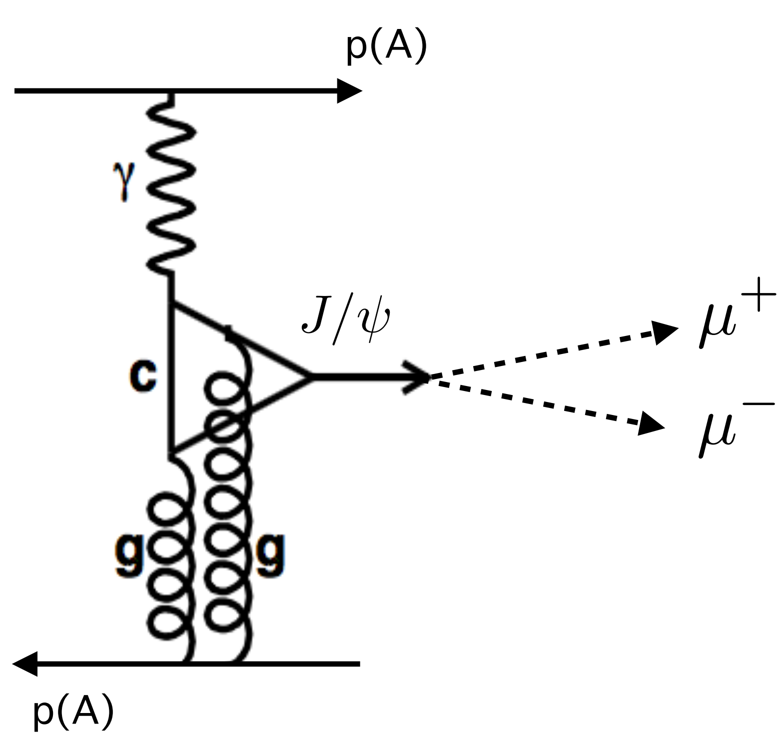


Bethe-Heitler process

Central exclusive production



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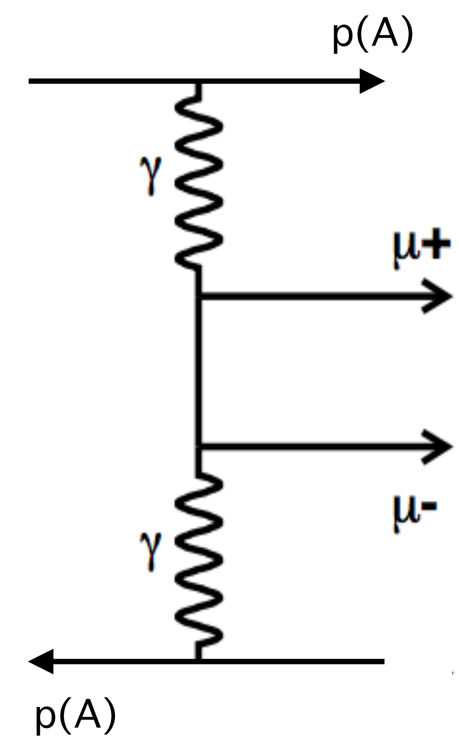

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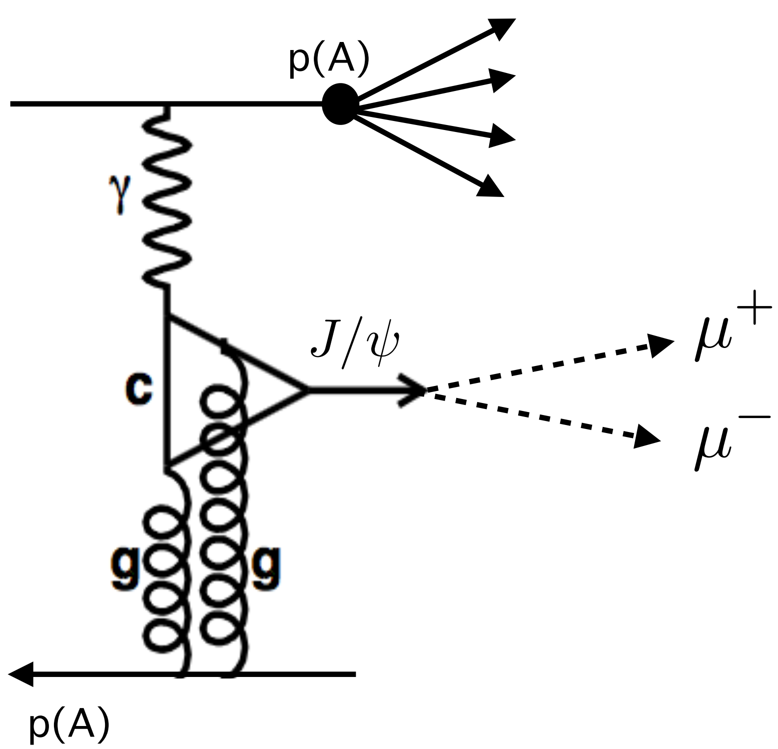

proton/ion dissociation

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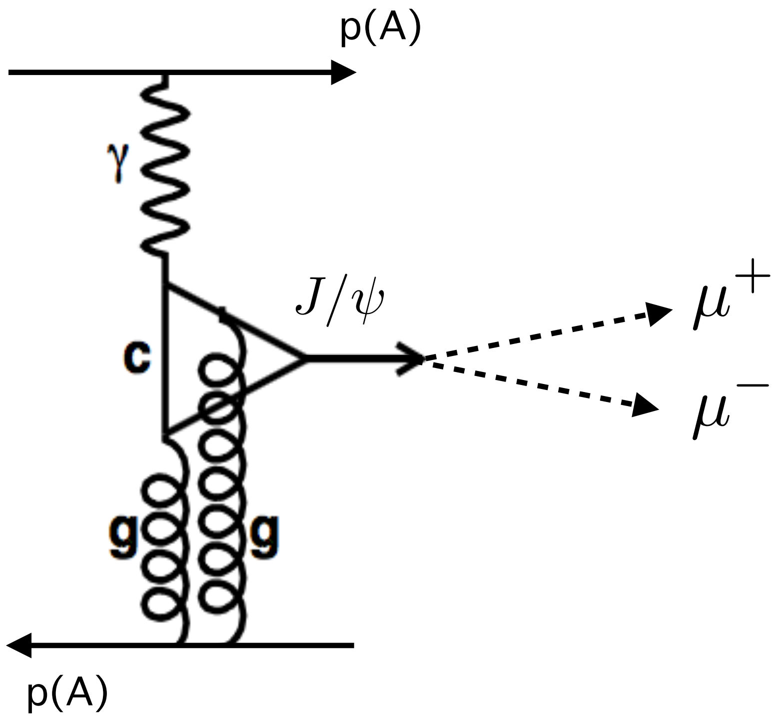

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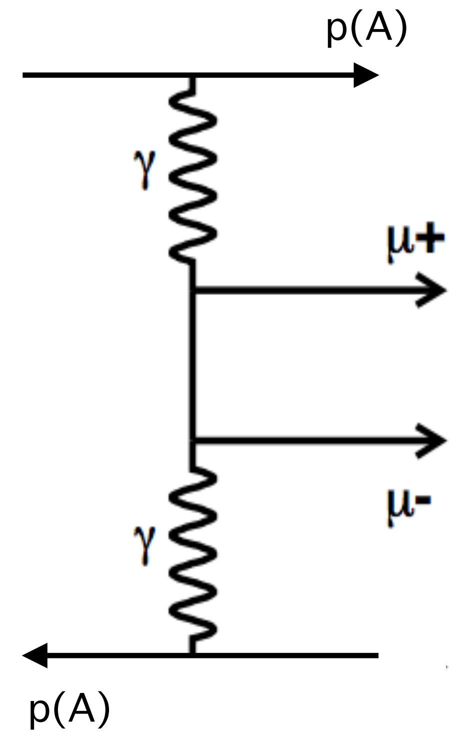

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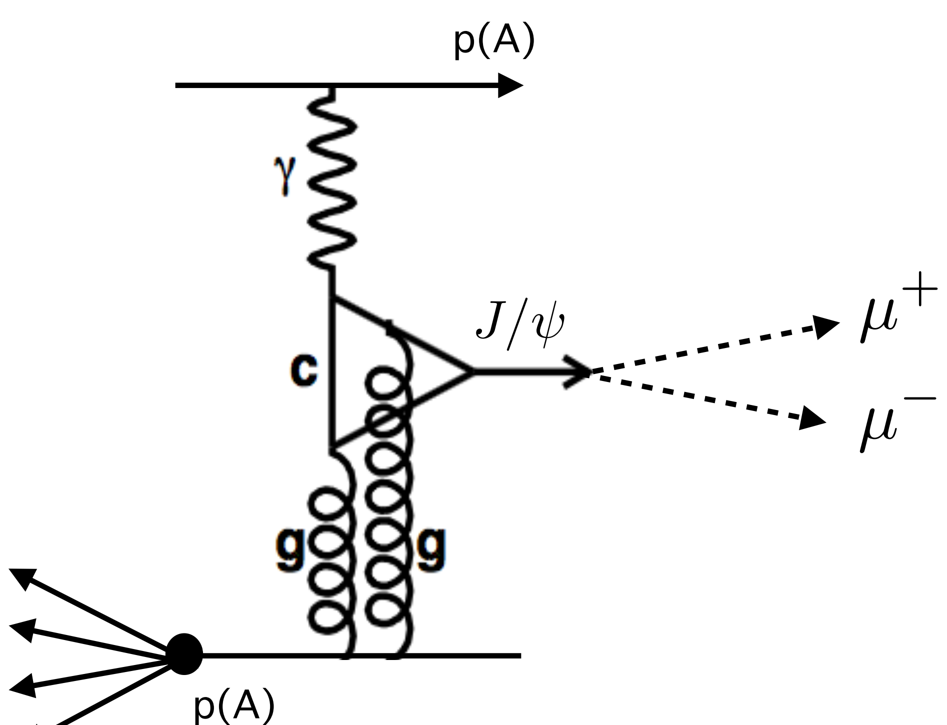

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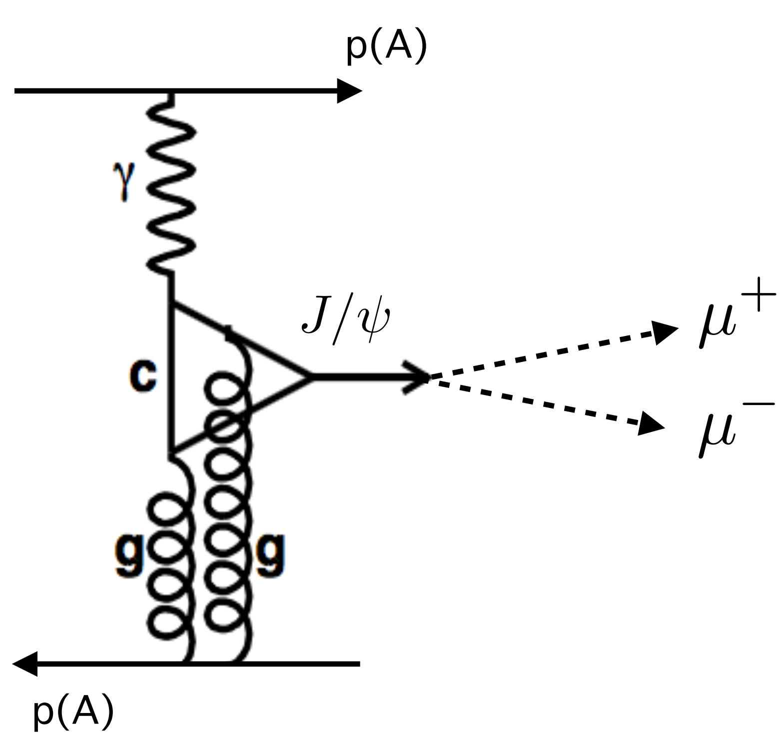

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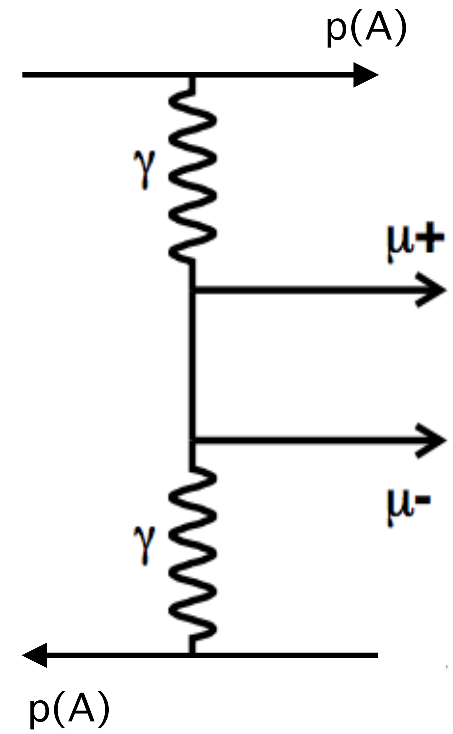

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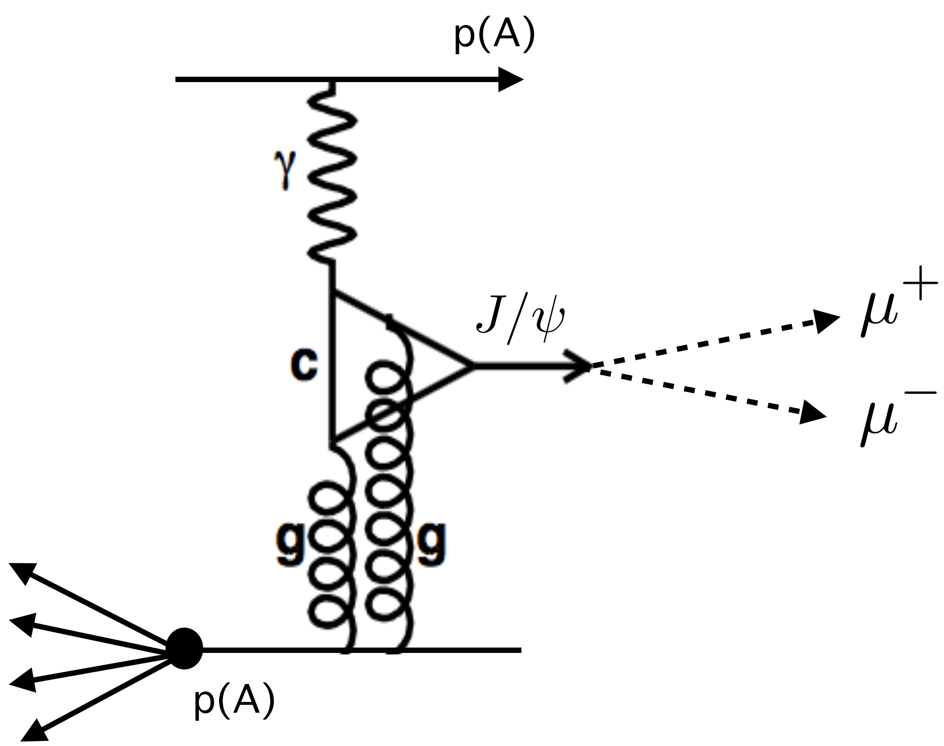

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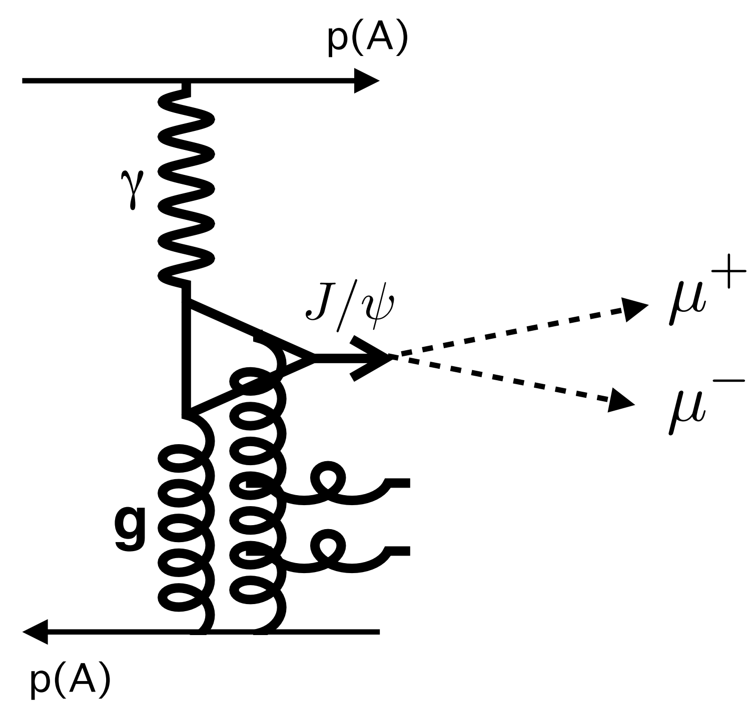
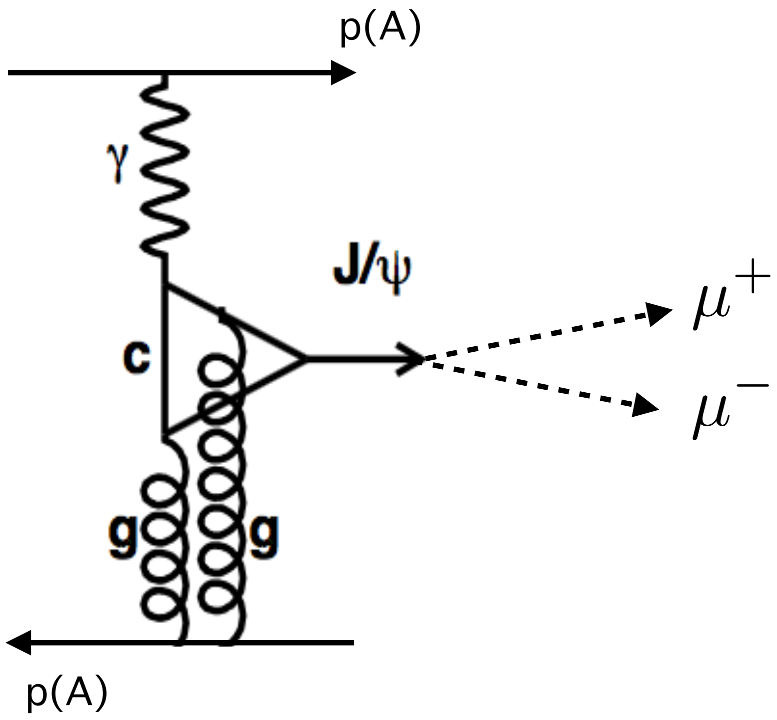


inelastic production

Central exclusive production



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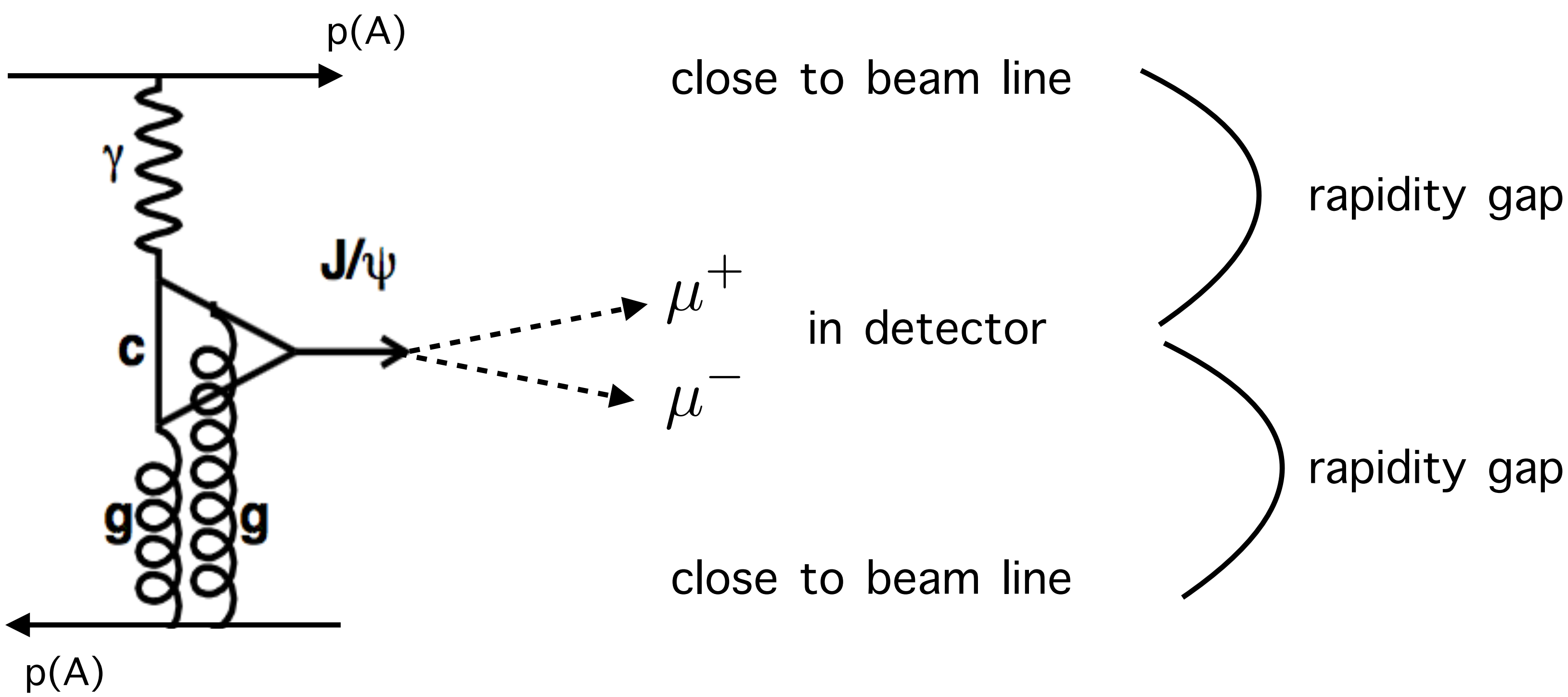

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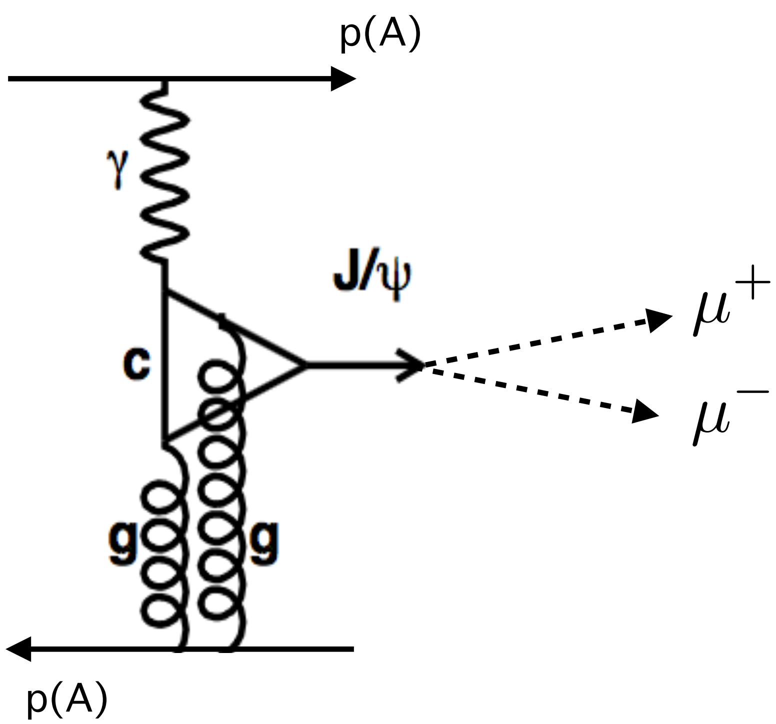

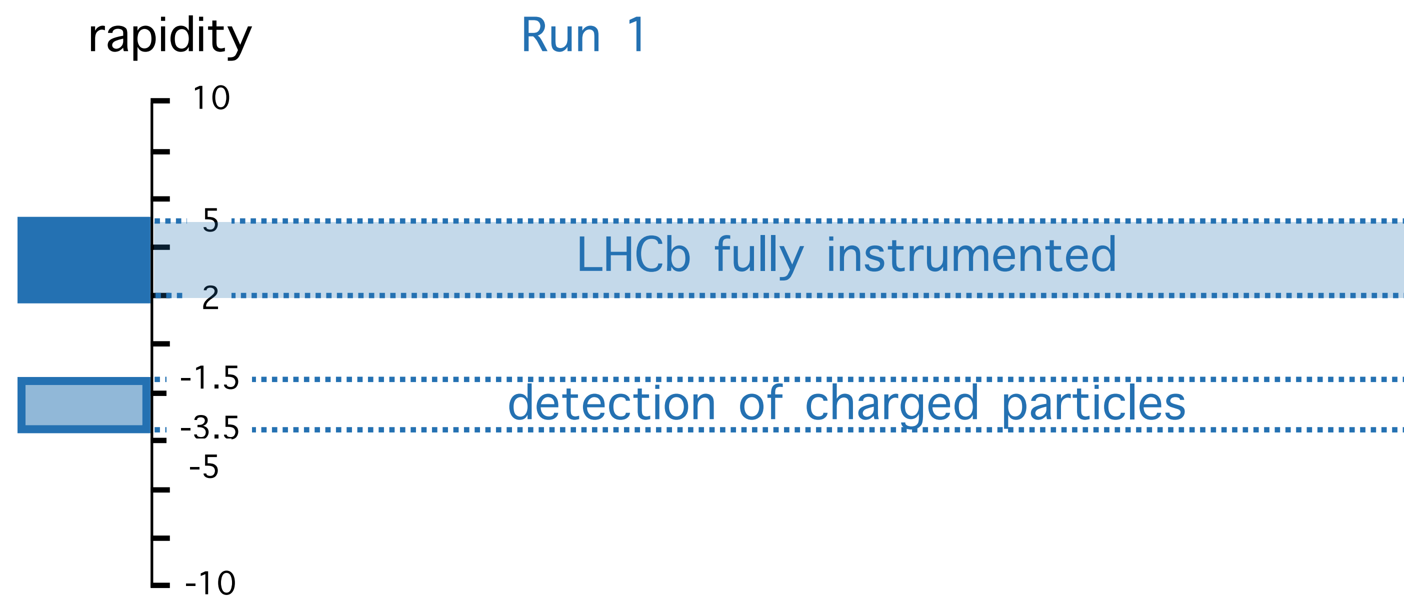

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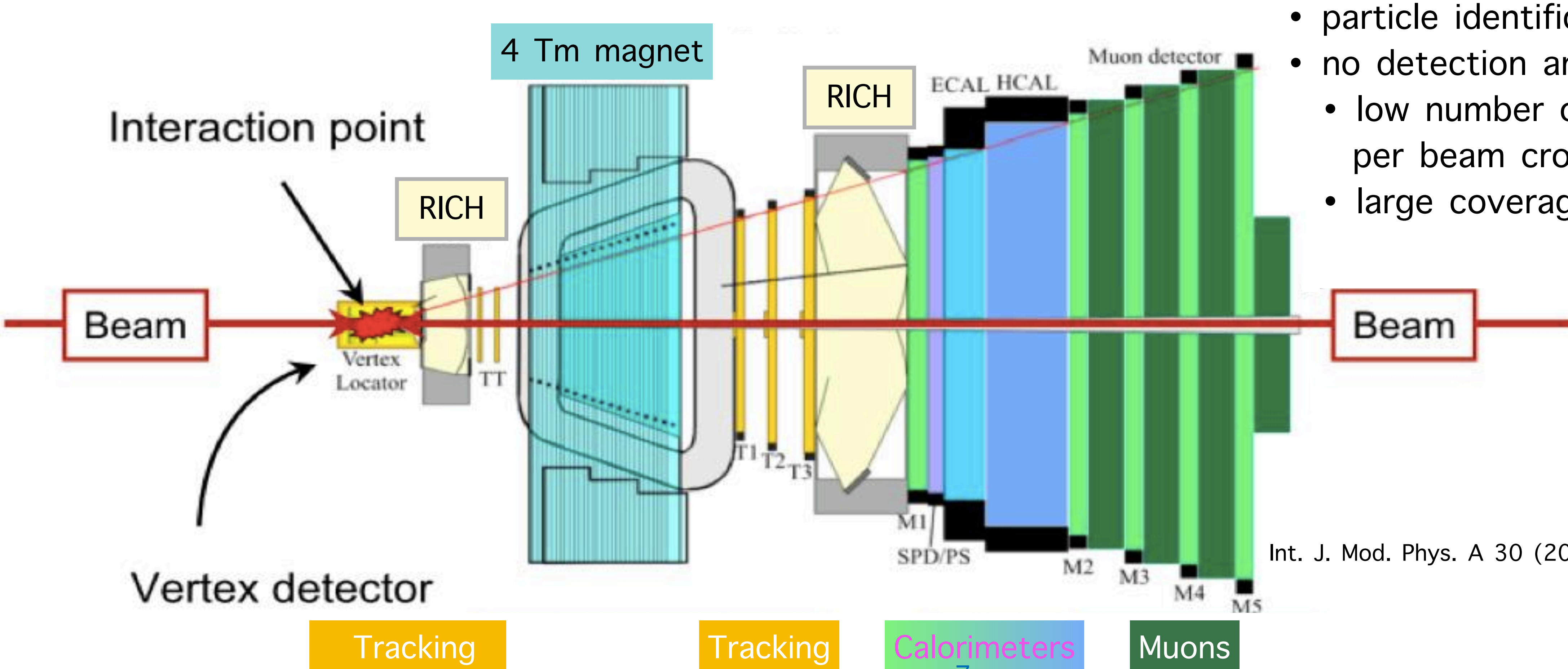
- particle identification
- no detection around beam line but
  - low number of interactions per beam crossing: 1.1–1.5
  - large coverage in rapidity



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

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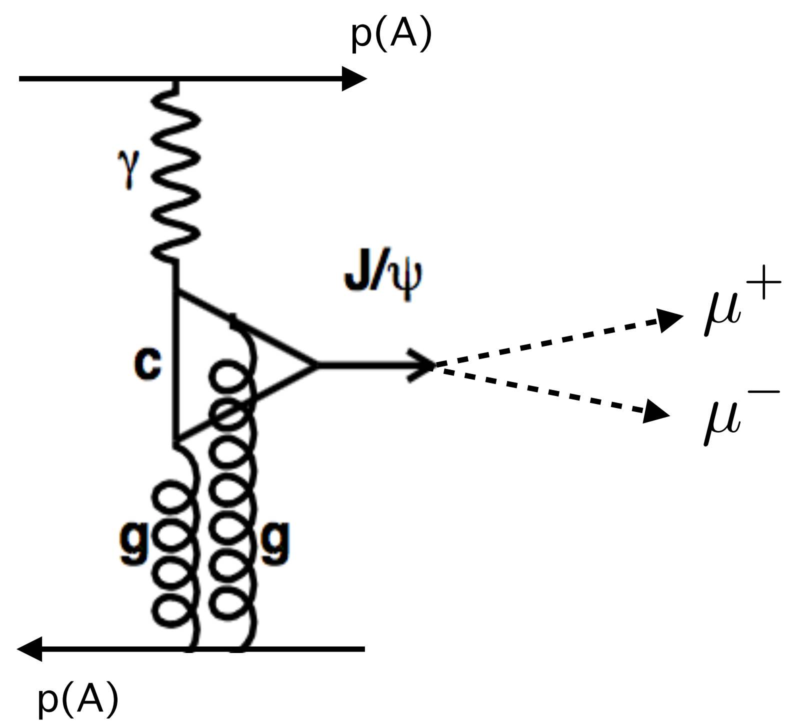

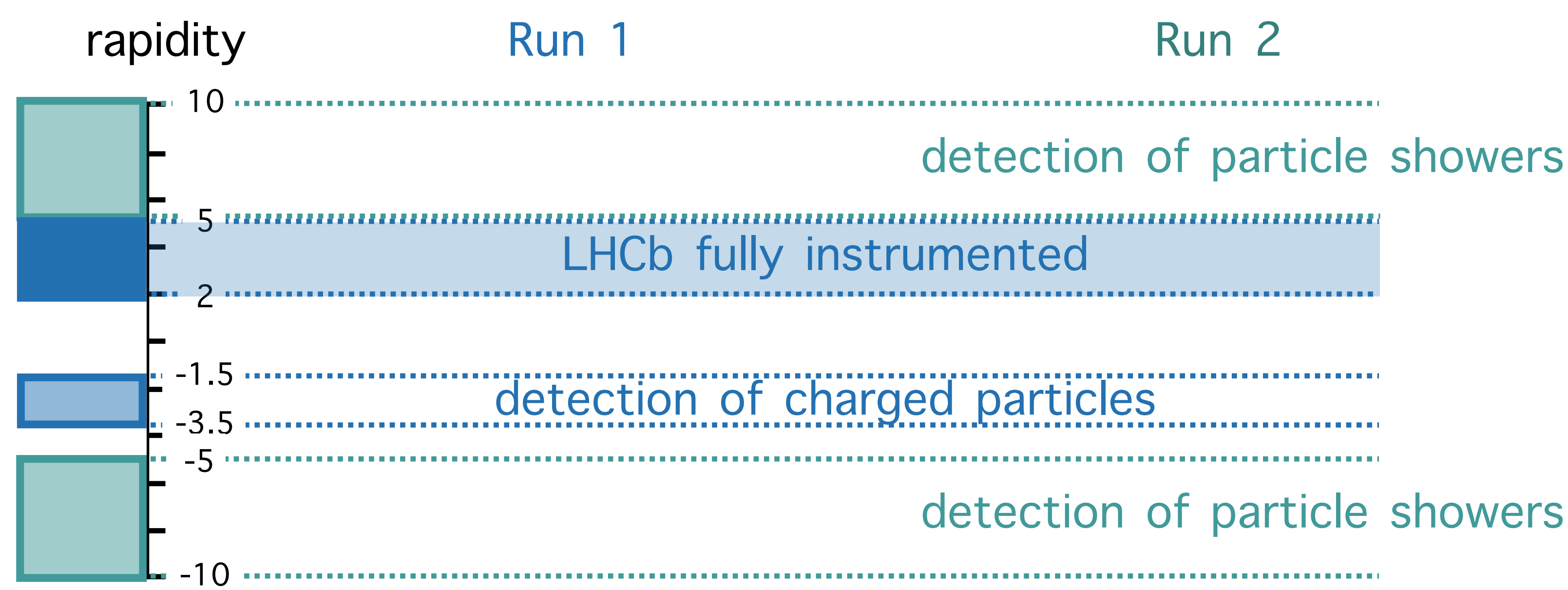

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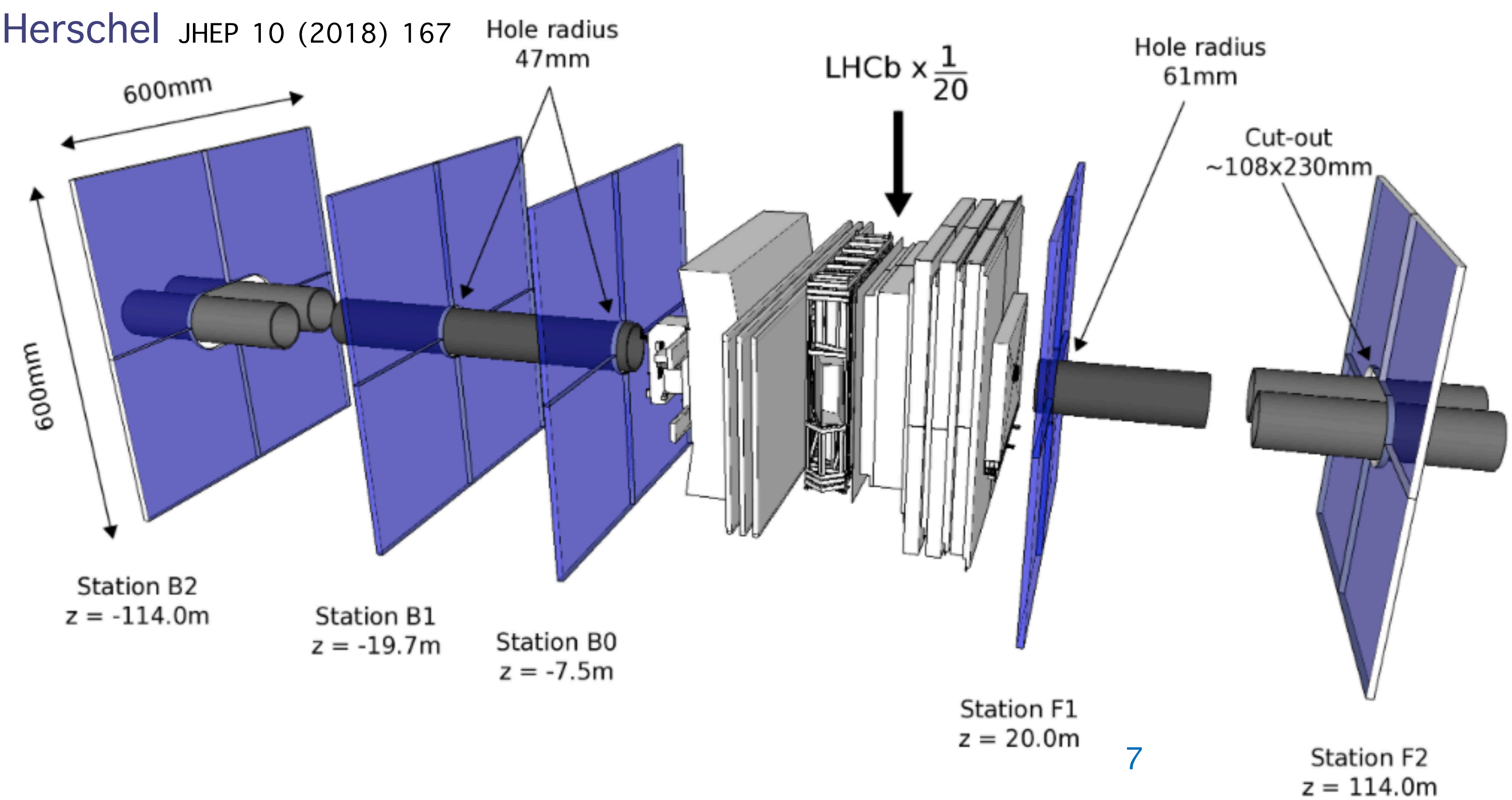
Herschel JHEP 10 (2018) 167



Exclusive J/ψ and ψ(2S) production

J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002

JHEP 10 (2018) 167

- pp collisions
  - run 1 - $\sqrt{s} = 7$ TeV: 929±33 pb^{-1}
  - run 2 (2015) - $\sqrt{s} = 13$ TeV: 204±8 pb^{-1}
- $J/\psi \rightarrow \mu^+\mu^-$
- $\psi(2S) \rightarrow \mu^+\mu^-$
- x_B down to 2×10^{-6}

- 2 muons with $2 < \eta < 4.5$
- no other detector activity
- $p_T^2 < 0.8\ \mathrm{GeV}^2/c^2$

  $p_T^2 \approx -t$

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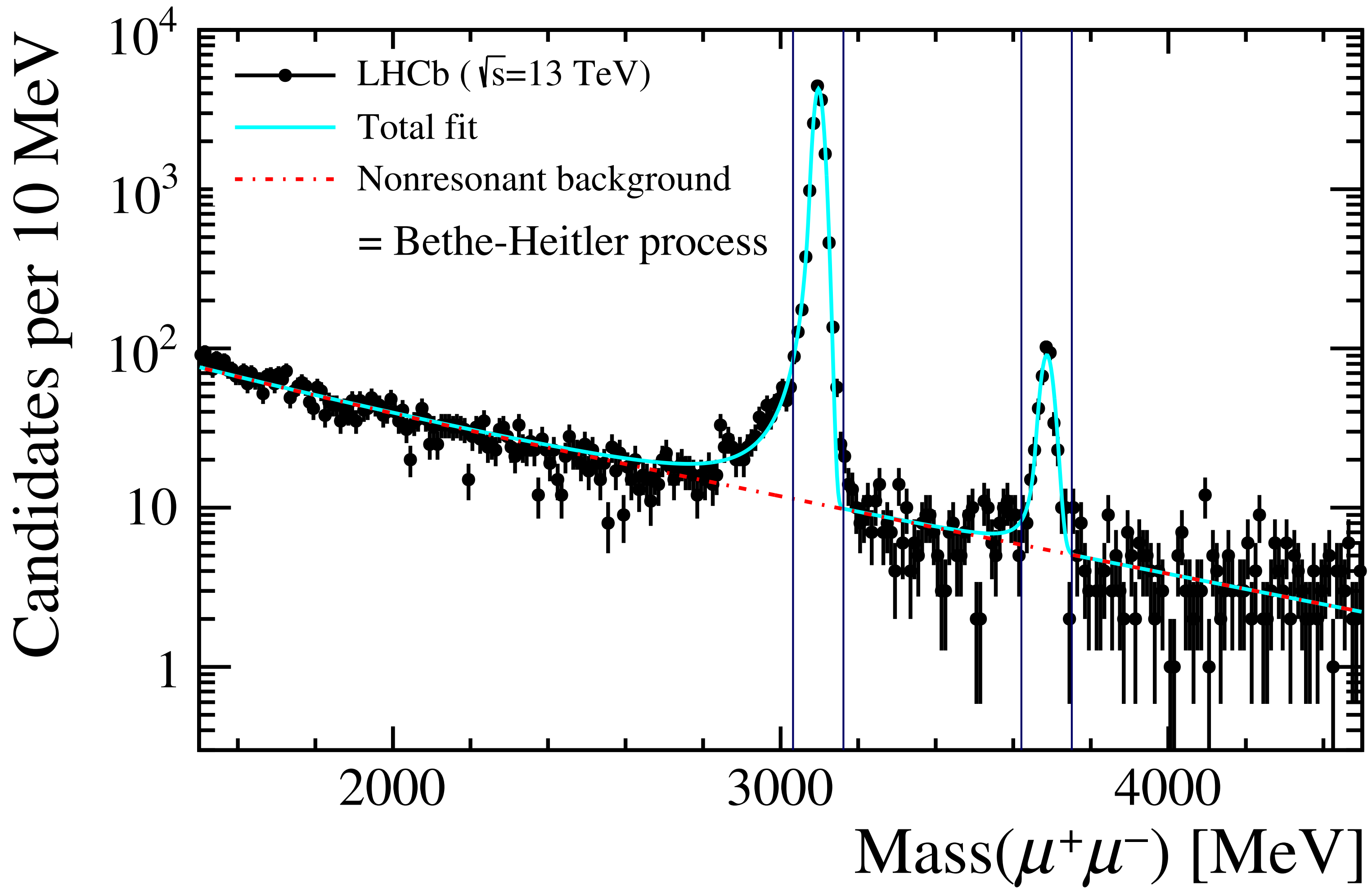
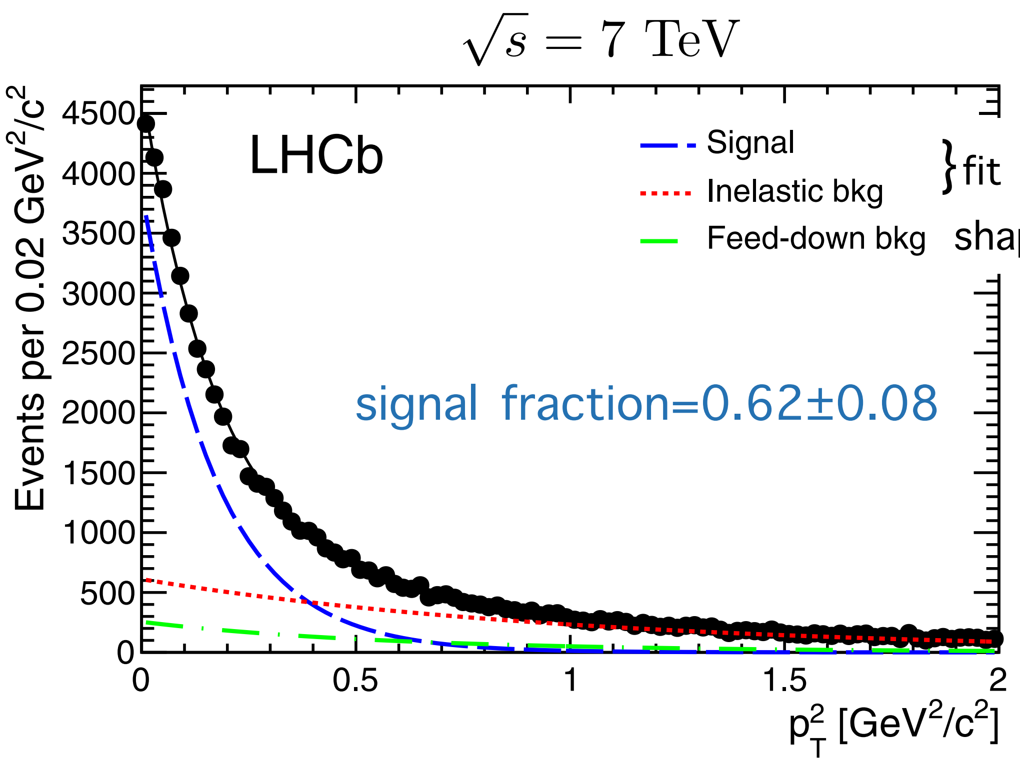


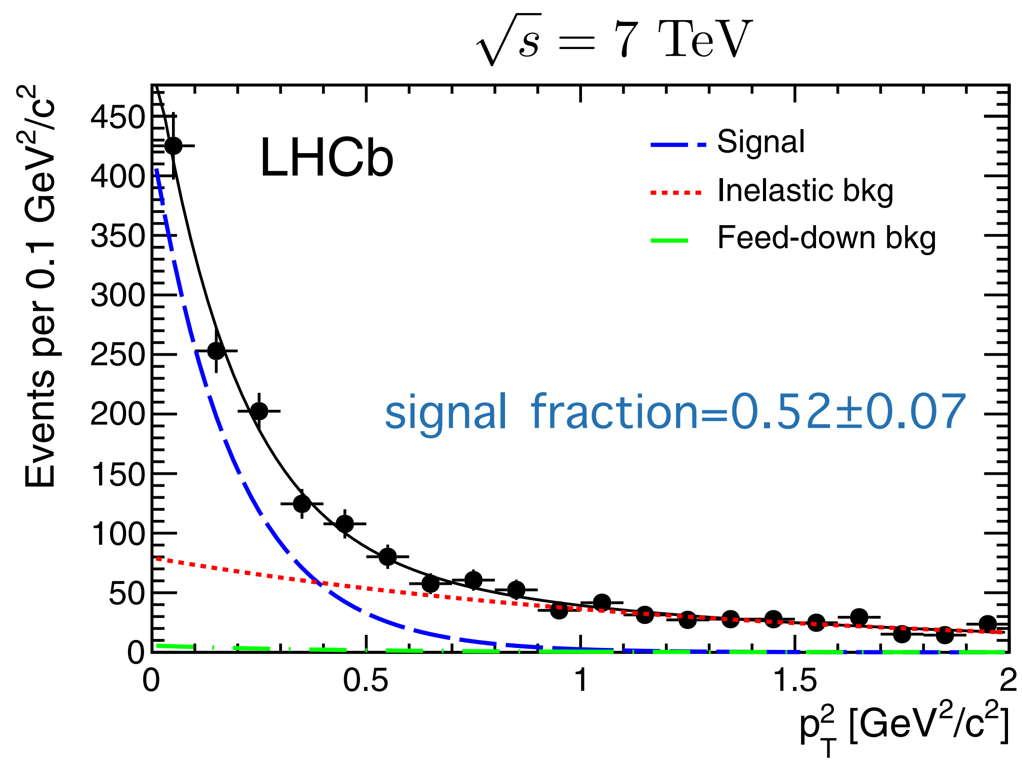
Proton dissociation and feed down

J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002

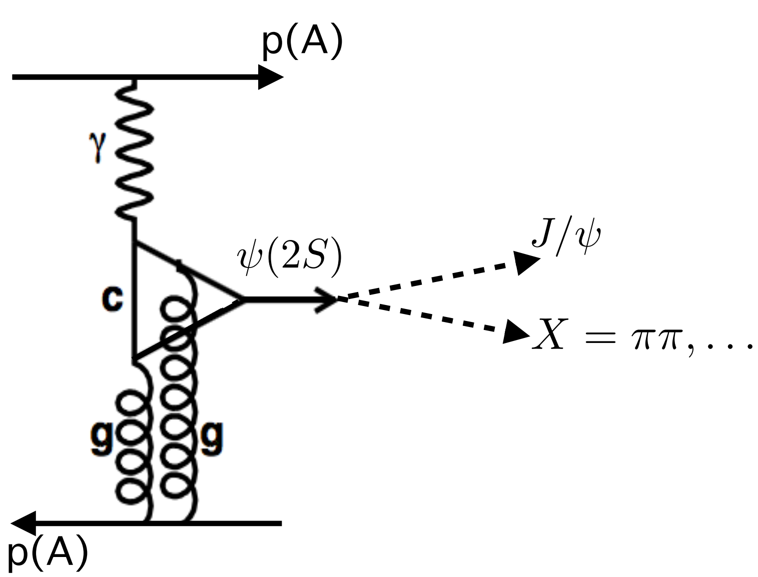
JHEP 10 (2018) 167

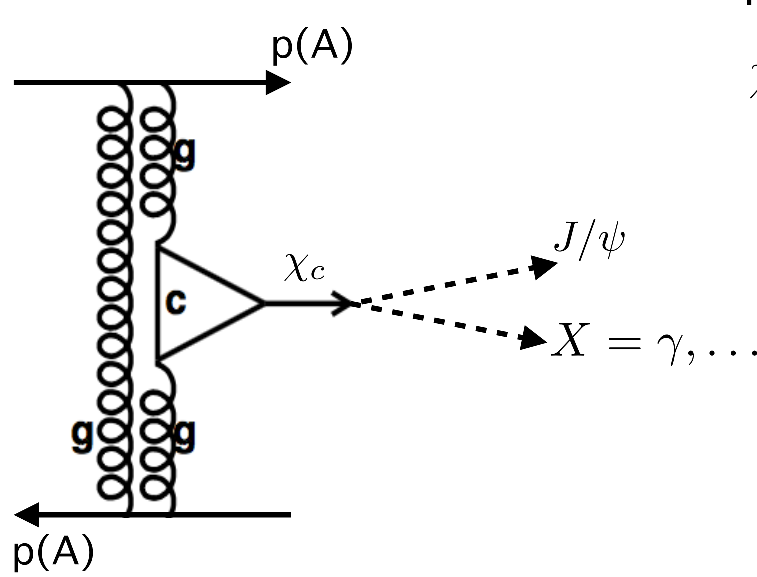


}fit with exponential shape from data



J/ψ feed-down background





ψ(2S) feed-down background expected from $\chi_c(2P)$ and $X(3872)$ decay

Proton dissociation and feed down: Herschel

J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002

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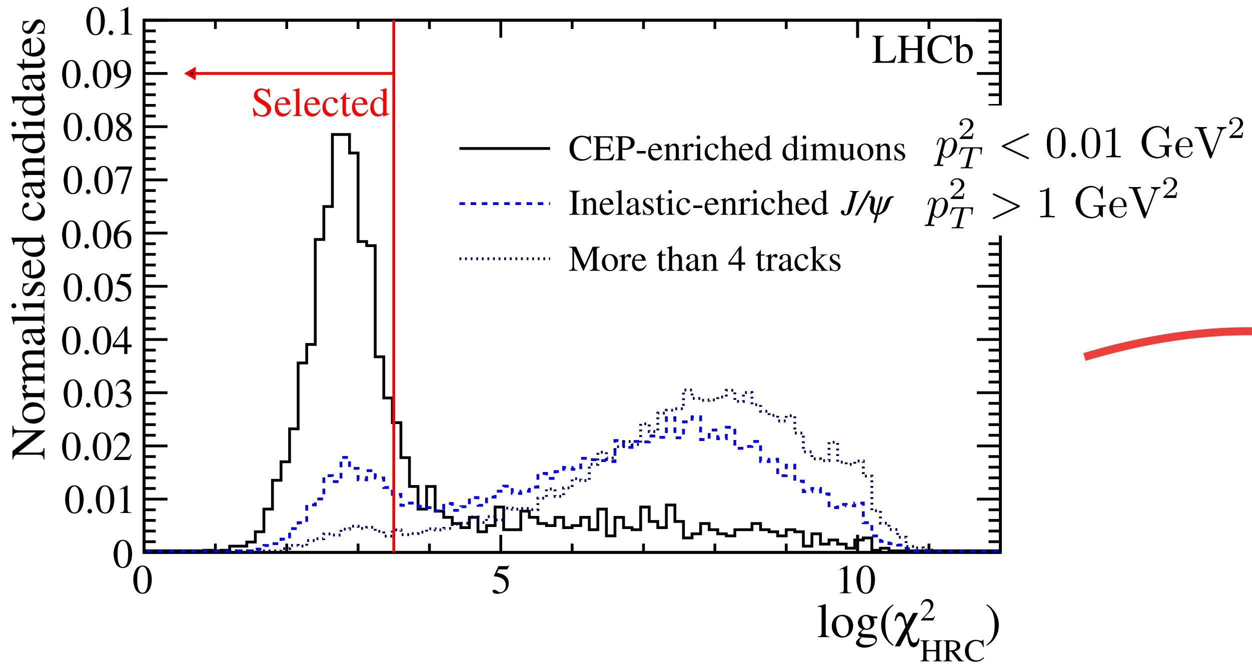
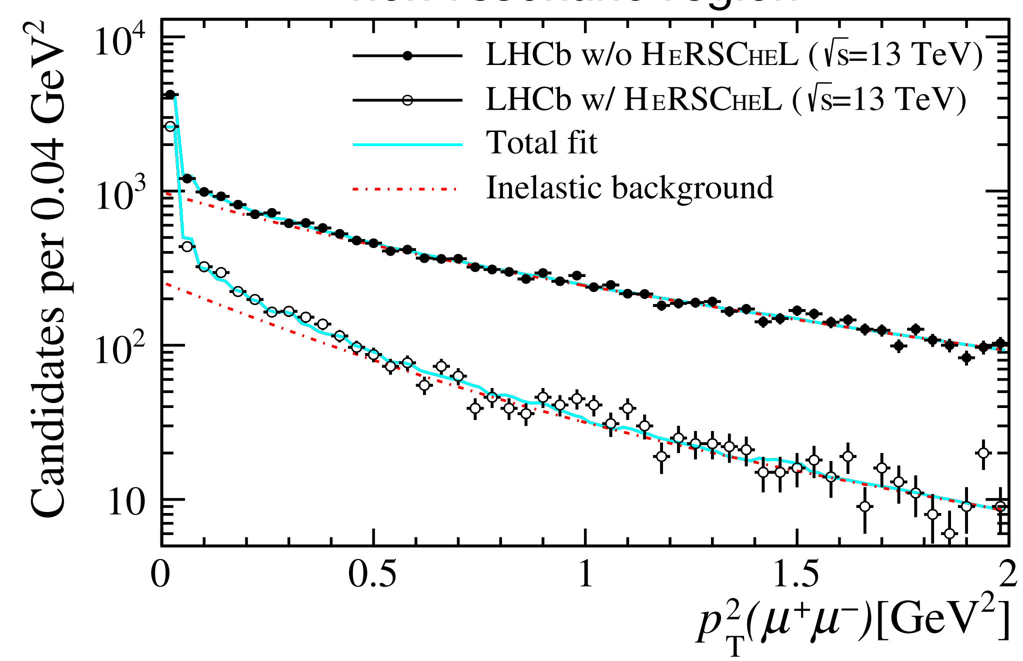
Herschel



non-resonant region



Proton dissociation and feed down: Herschel

J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002
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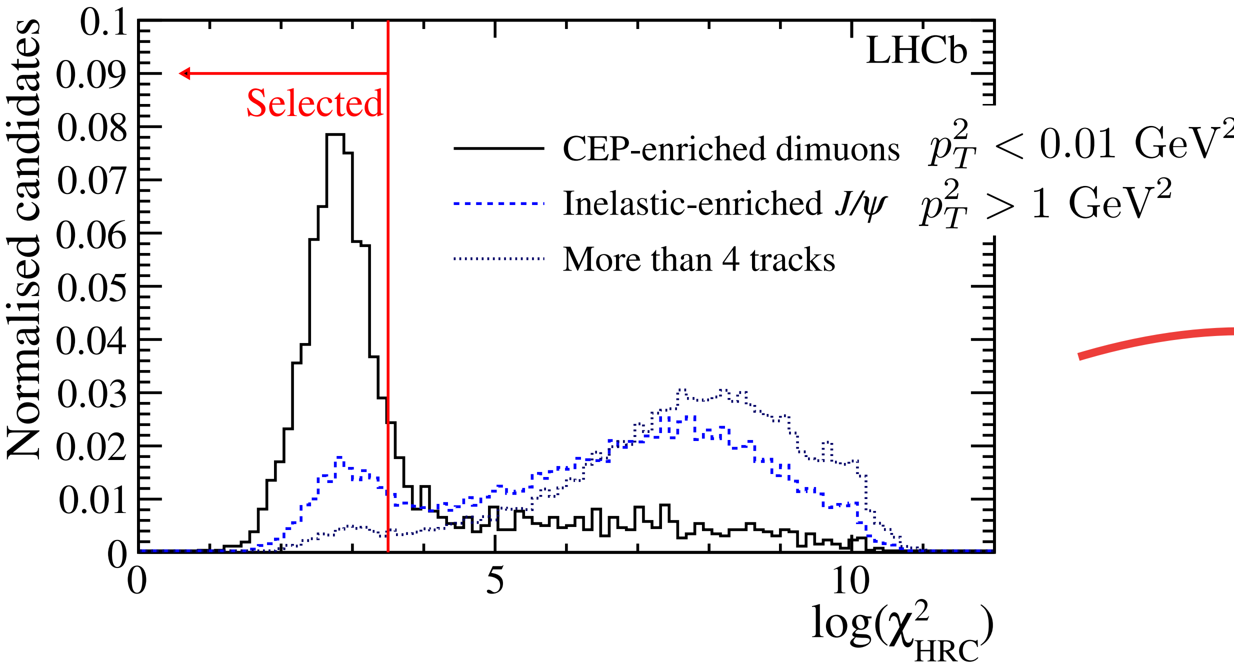
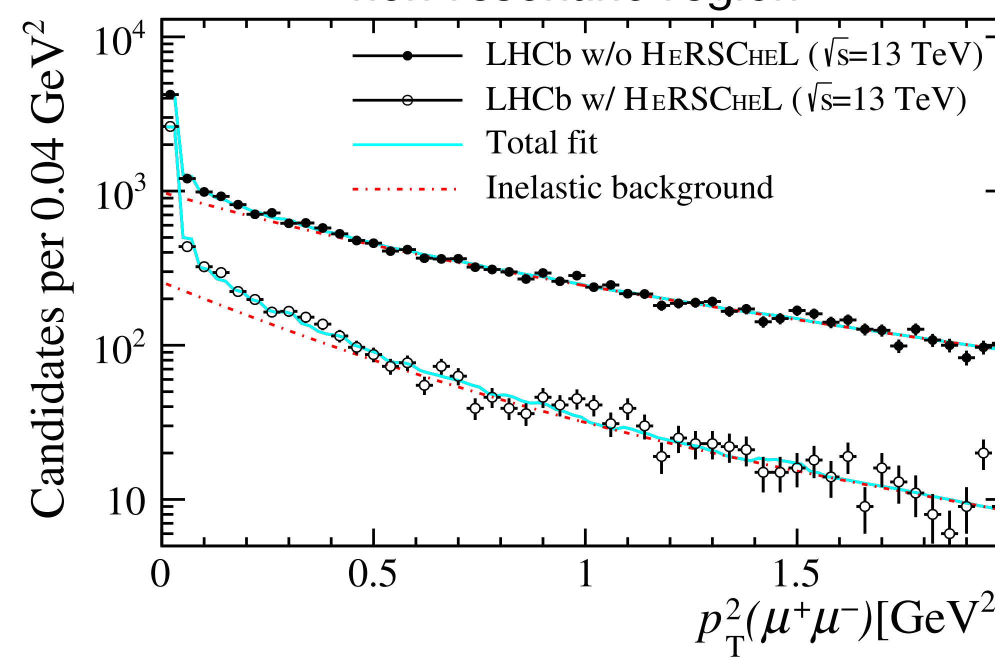
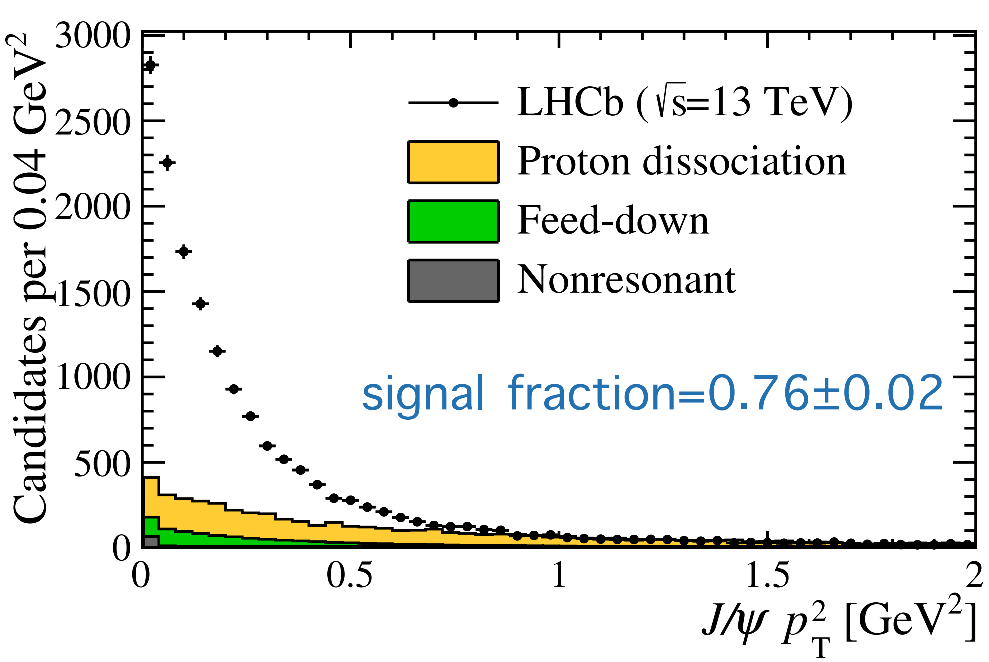
Herschel

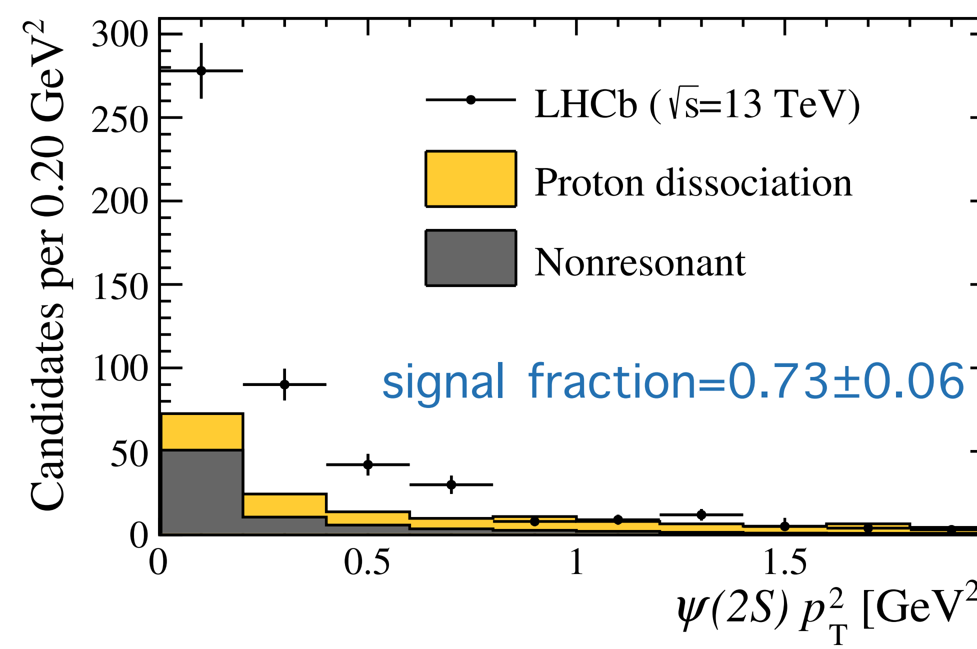


non-resonant region





shape of background from data



Run 1 - signal fraction:
0.62±0.08 for J/ψ
0.52±0.07 for ψ(2S)

Halving of inelastic background thanks to Herschel

Cross section calculation

$$\frac{d\sigma_{\psi\to\mu^+\mu^-}}{dy}(2.0 < \eta_\mu < 4.5) = \frac{\mathcal{P}N}{\epsilon_{\text{rec}}\epsilon_{\text{sel}}\Delta y\,\epsilon_{\text{single}}\mathcal{L}_{\text{tot}}}$$

signal purity ($\mathcal{P}$)

number of events (N)

reconstruction efficiency (ϵ_{rec}) ≈0.3–0.7/0.4–0.6

selection efficiency (ϵ_{sel}) ≈0.87/0.6-0.7

single-interaction efficiency (ϵ_{single}) ≈0.24/0.33

luminosity ($\mathcal{L}_{\text{tot}}$) 929 pb^{-1}/204 pb^{-1}

run1/run2

Cross section calculation

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run1/run2

$$\Downarrow \quad \frac{1}{\mathcal{B}(\psi\to\mu^+\mu^-)_{\rm acceptance}}$$

$$\frac{d\sigma_{pp\to p\psi p}}{dy}$$

Cross section

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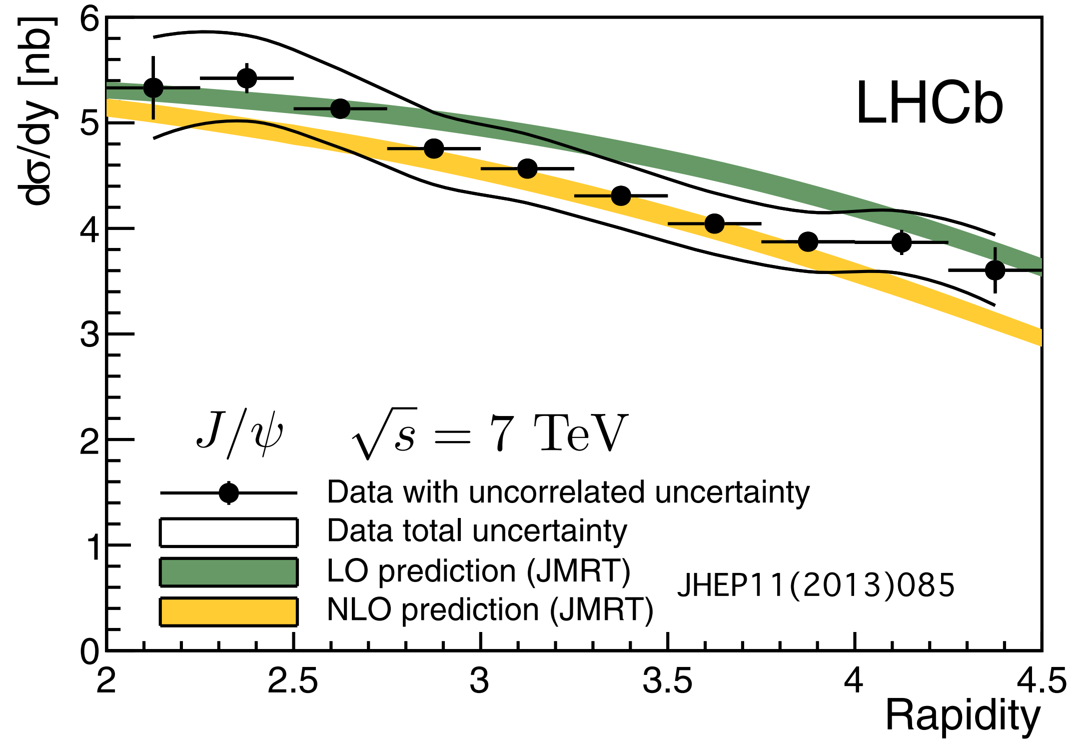
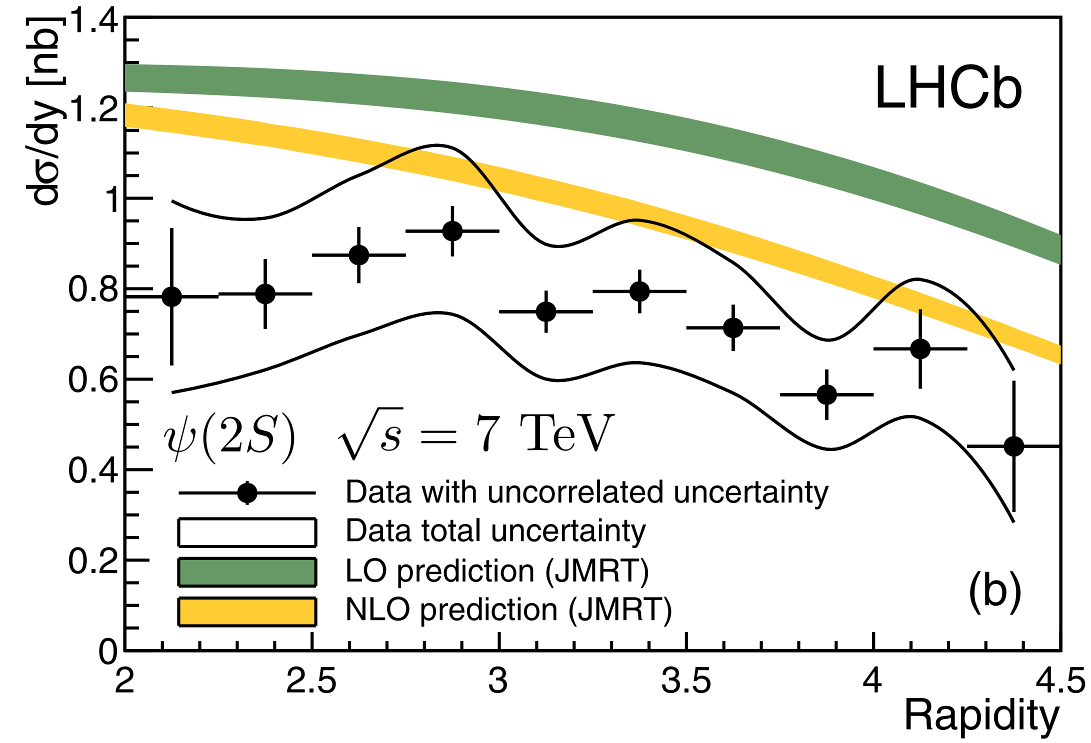
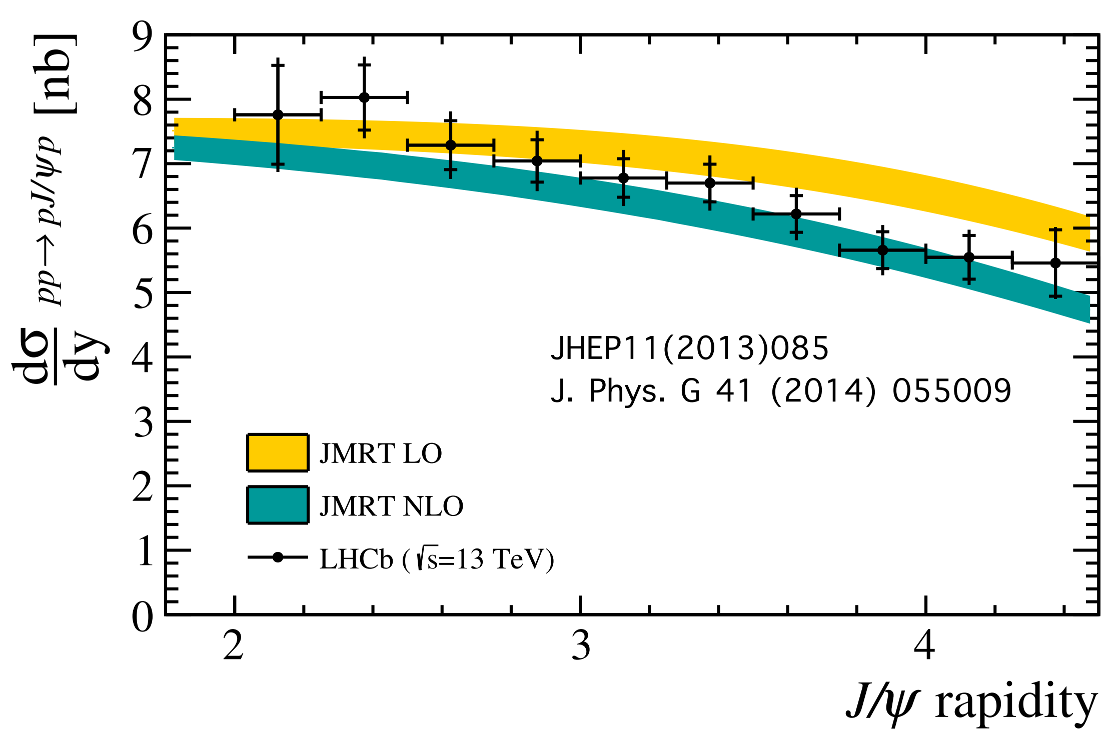
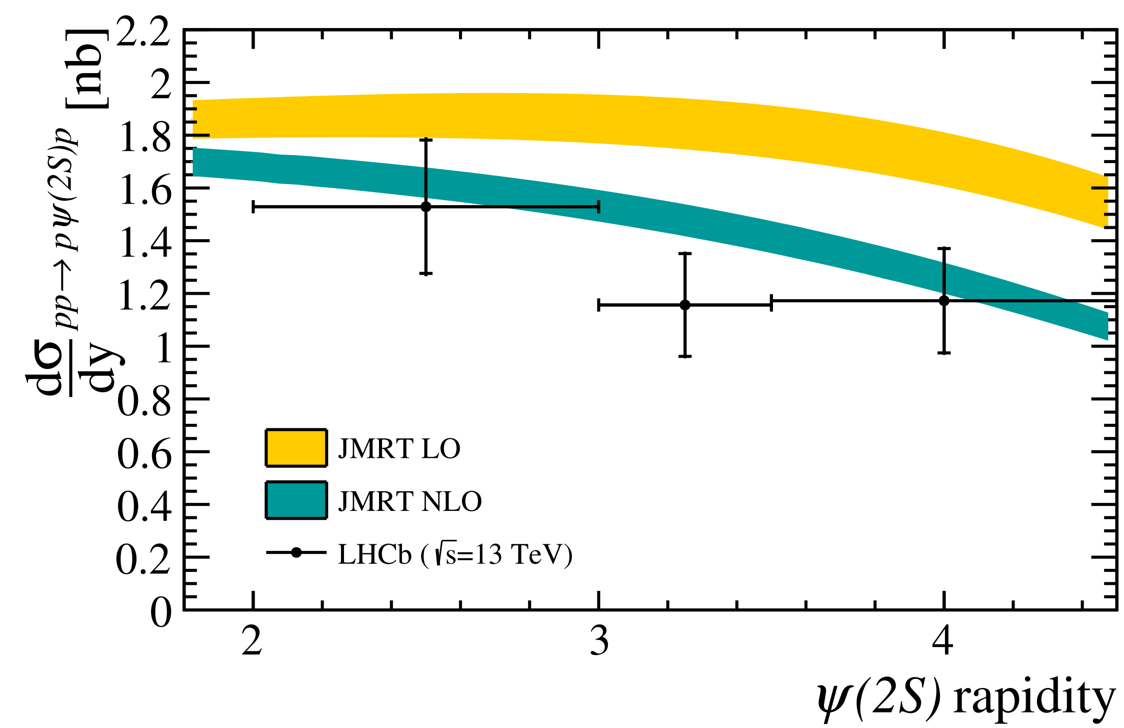
JMRT prediction: based on gluon PDF





Systematic uncertainty reduced by 1/2 thanks to Herschel





reasonable agreement with NLO prediction

Photo-production cross section

J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002

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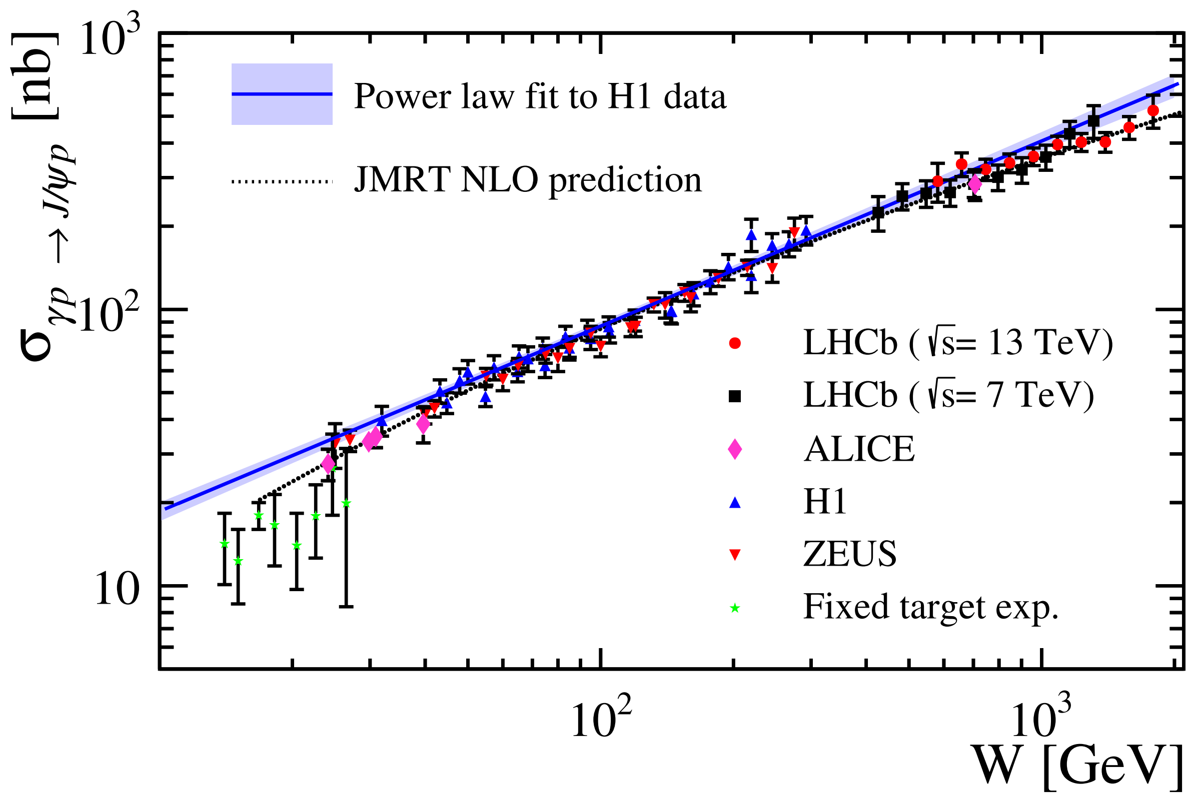
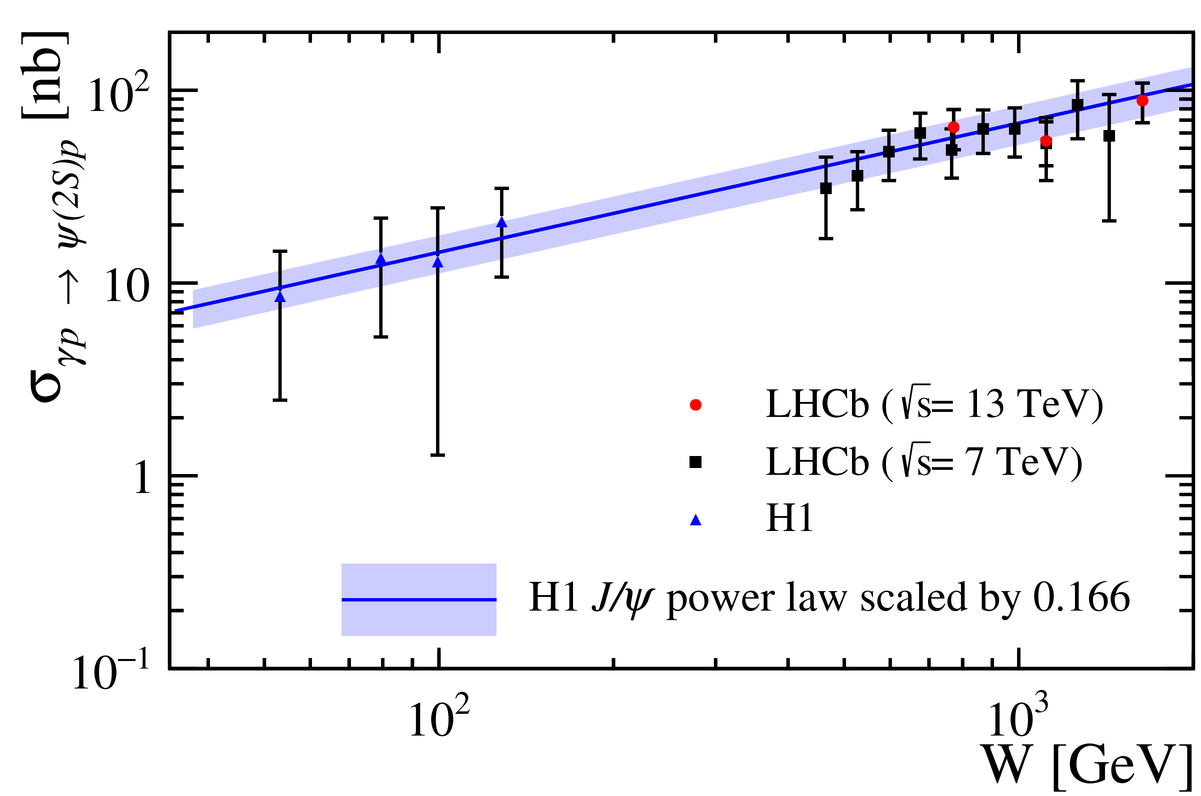
$$\sigma_{pp\to p\psi p} = r(W_+)k_+\frac{\mathrm{d}n}{\mathrm{d}k_+}\sigma_{\gamma p\to\psi p}(W_+) + r(W_-)k_-\frac{\mathrm{d}n}{\mathrm{d}k_-}\sigma_{\gamma p\to\psi p}(W_-)$$

- r = gap survival factor
- $\frac{dn}{dk_\pm}$ = photon flux
- $k_\pm = \frac{M_\psi}{2}e^{\pm y}$ = photon energy
- $W_\pm^2 = 2k_\pm\sqrt{s}$ = photon-proton invariant mass

ambiguity since unknown which proton emits the photon $\longrightarrow$ fix W- from H1 parametrisation (Eur. Phys. J. C 73 (2013) 2466)





good agreement with JMRT NLO prediction

Exclusive Υ production

JHEP 09 (2015) 084

- pp collisions – run 1
  - $\sqrt{s} = 7\ \mathrm{TeV}$: 0.9 fb^{-1}
  - $\sqrt{s} = 8\ \mathrm{TeV}$: 2.0 fb^{-1}
- $\Upsilon \to \mu^+\mu^-$
- x_B down to 2×10^{-5}

- 2 muons with $2<\eta<4.5$
- no other detector activity
- $p_T^2 < 2.0\ \mathrm{GeV}^2/c^2$

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JHEP 09 (2015) 084

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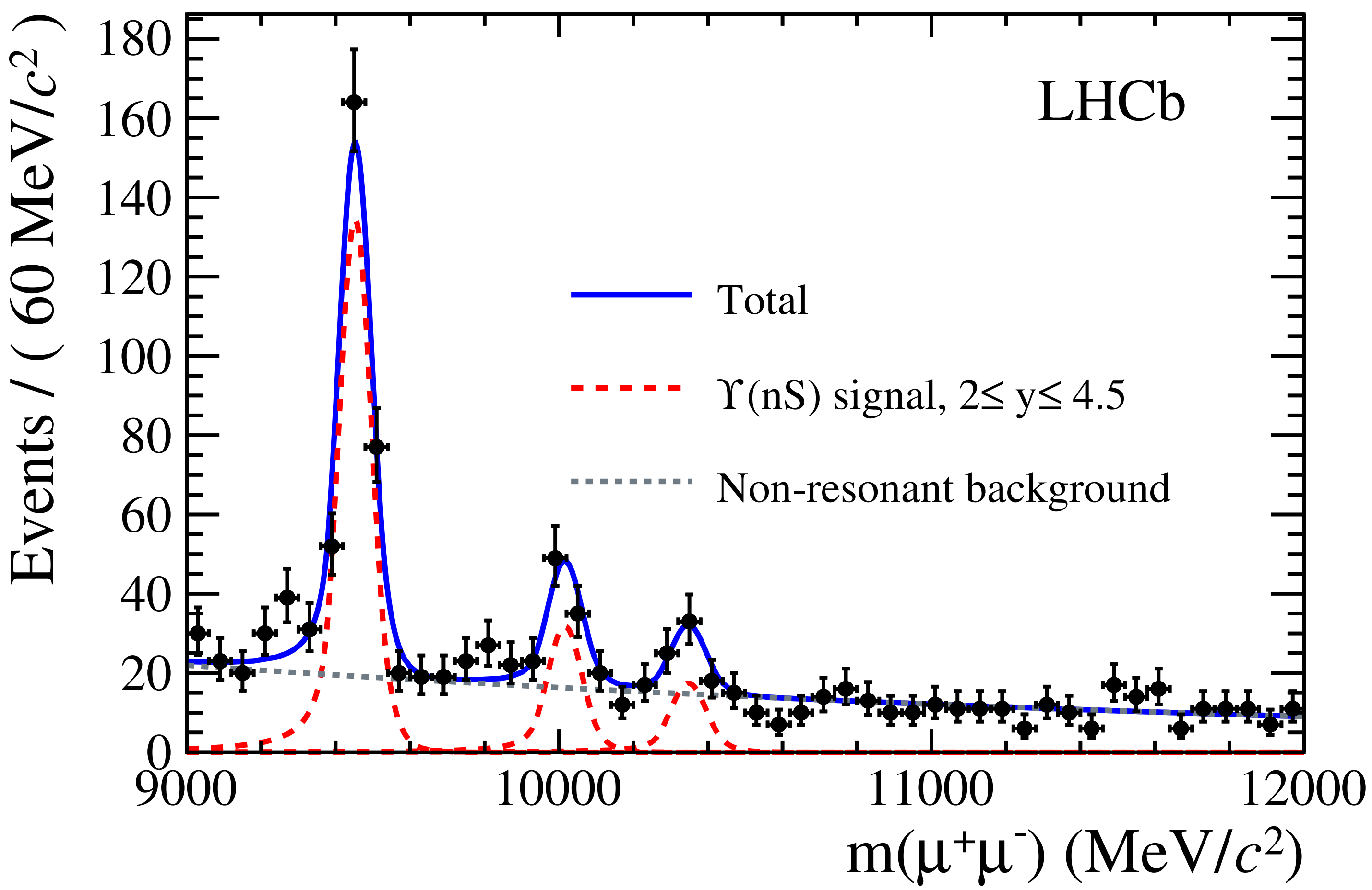

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JHEP 09 (2015) 084

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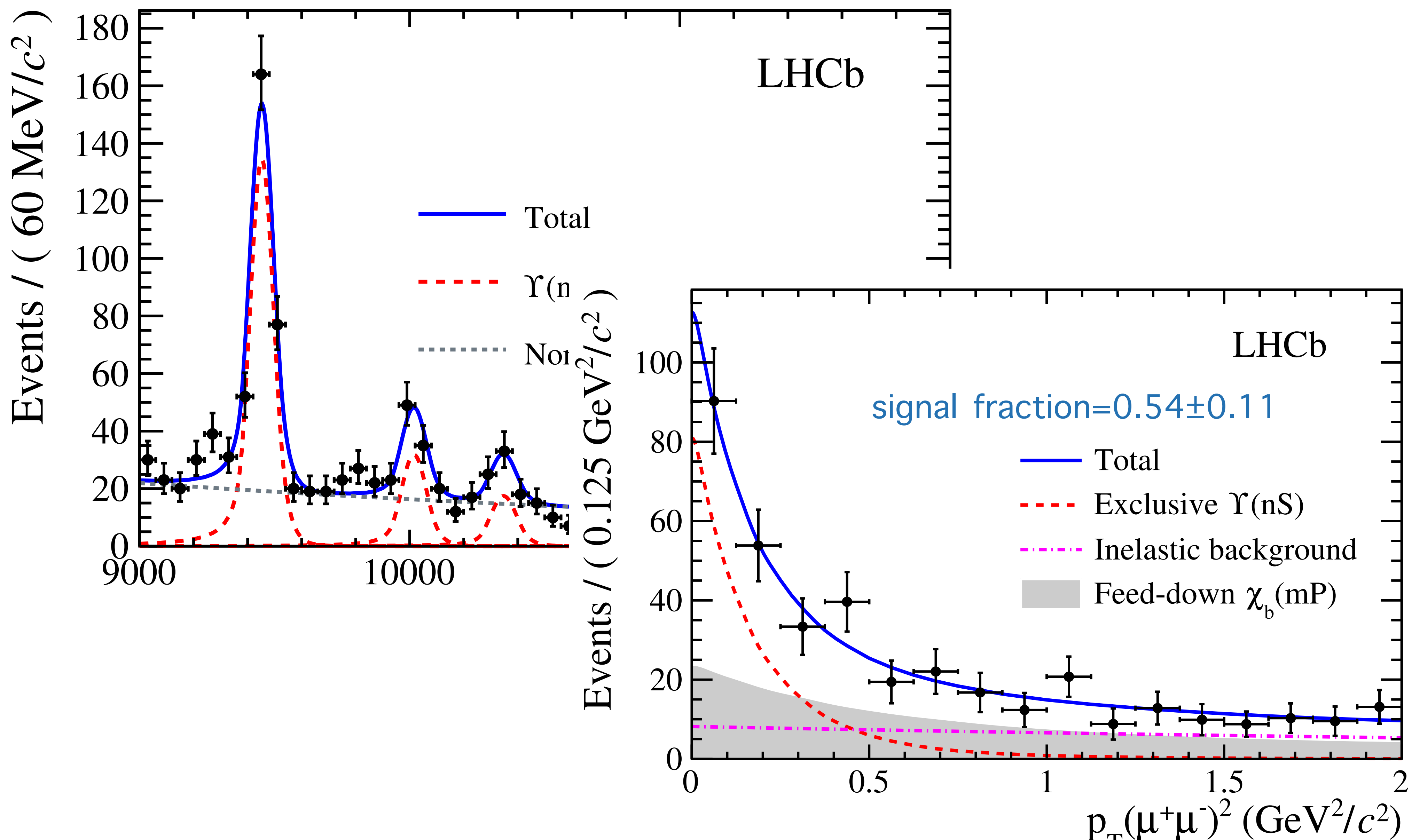
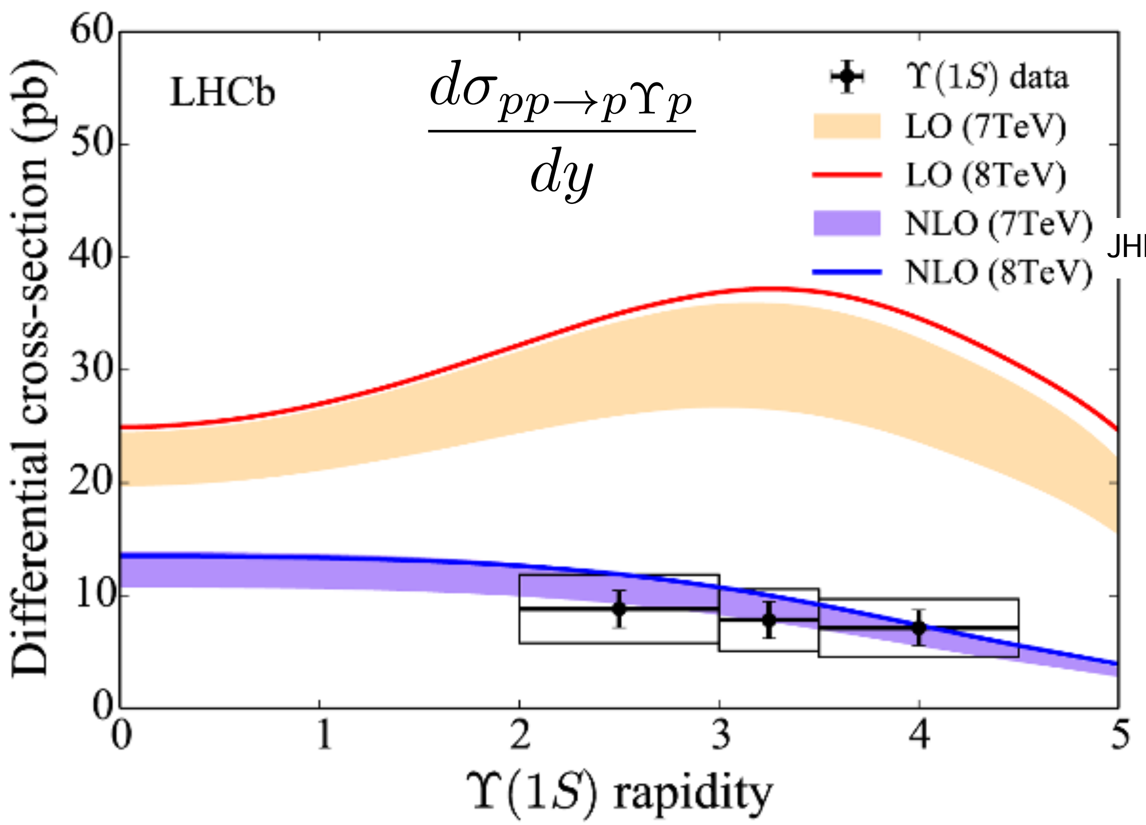
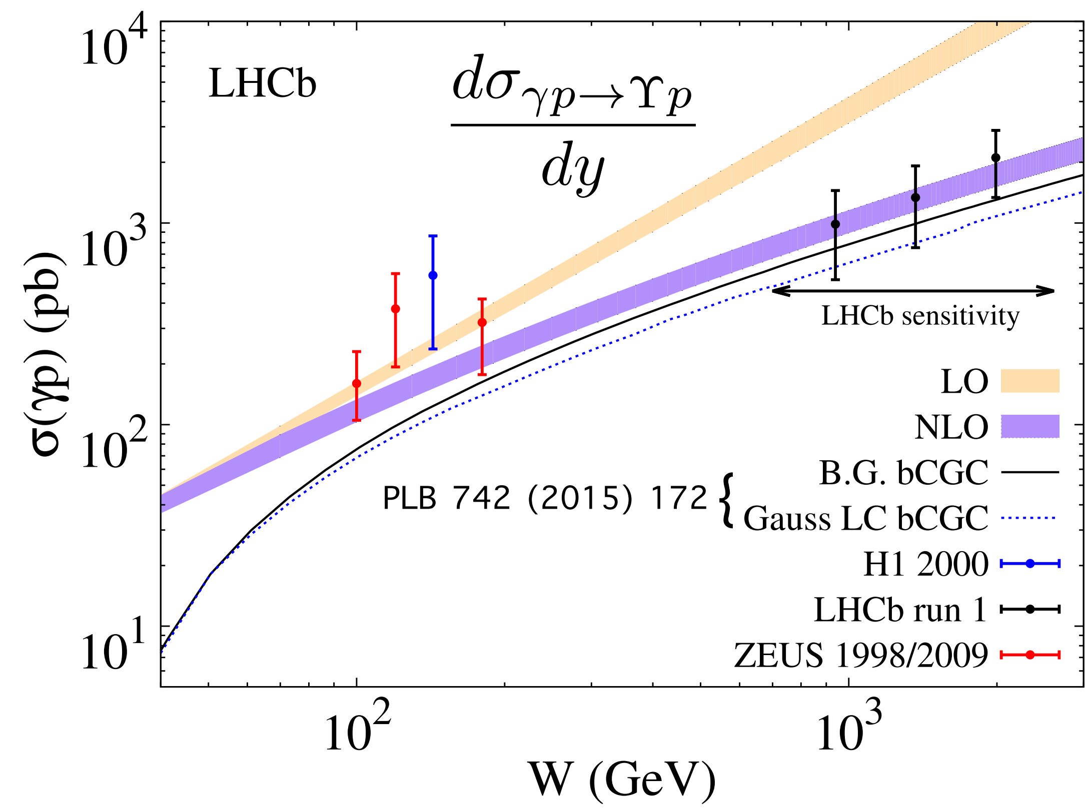


Υ cross section

JHEP 09 (2015) 084



JHEP11(2013)085



PLB 742 (2015) 172 {

contribution from W- is neglected

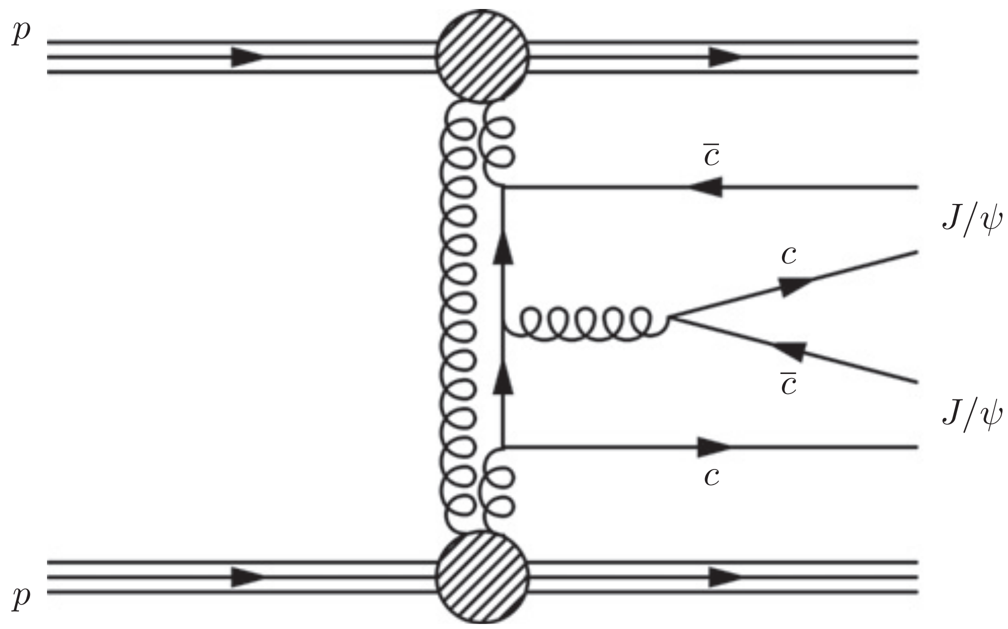
good agreement with JMRT NLO prediction

Production of charmonium pairs

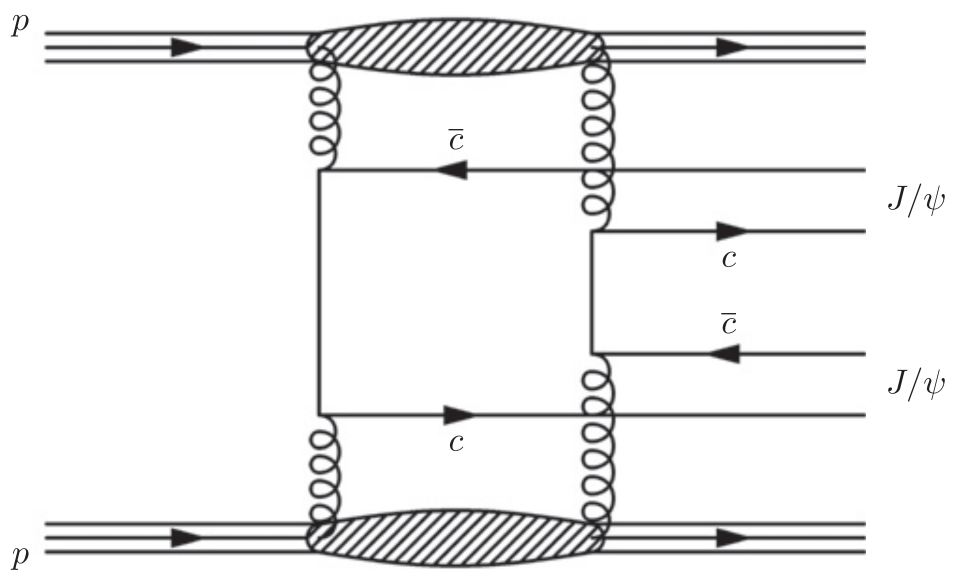
J. Phys. G: Nucl. Part. Phys. 41 (2014) 115002

- sensitive to glueballs, tetraquarks
- sensitive to gluon distribution

  $\propto [g(x_B)]^4$



dominant production mechanism



other possible production mechanism

Production of charmonium pairs

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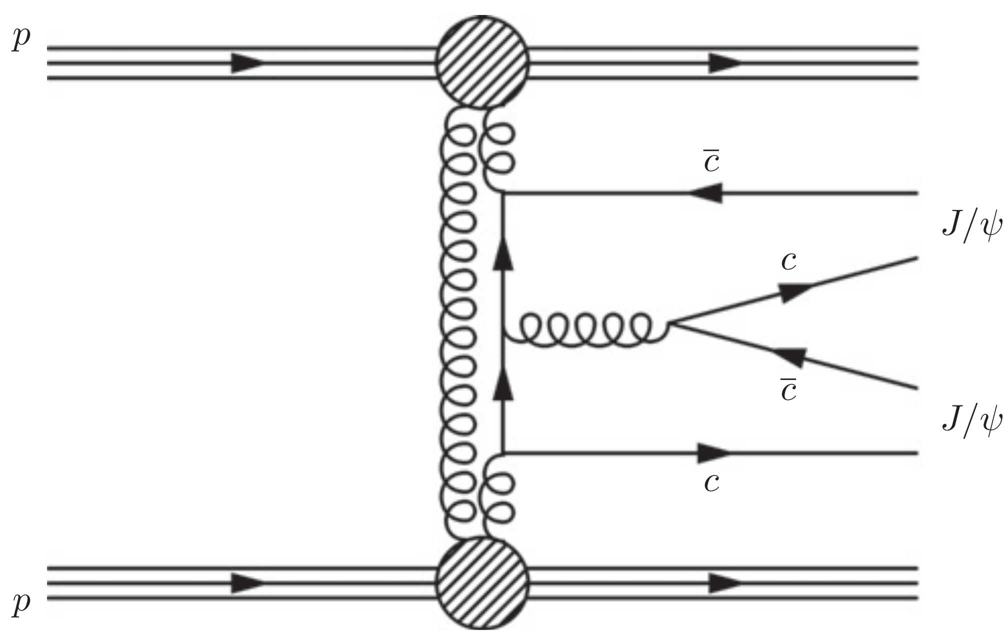
  - $\sqrt{s} = 7$ TeV: 0.9 fb^{-1}
  - $\sqrt{s} = 8$ TeV: 2.0 fb^{-1}
- $J/\psi J/\psi$, $J/\psi\psi(2S)$, $\psi(2S)\psi(2S)$
- $\chi_{c0}\chi_{c0}$, $\chi_{c1}\chi_{c1}$, $\chi_{c2}\chi_{c2}$

- $\chi_c \to J/\psi\gamma$
- $J/\psi,\ \psi(2S) \to \mu^+\mu^-$
- $2.0 < \eta_{\mu^+\mu^-} < 4.5$
- no other detector activity



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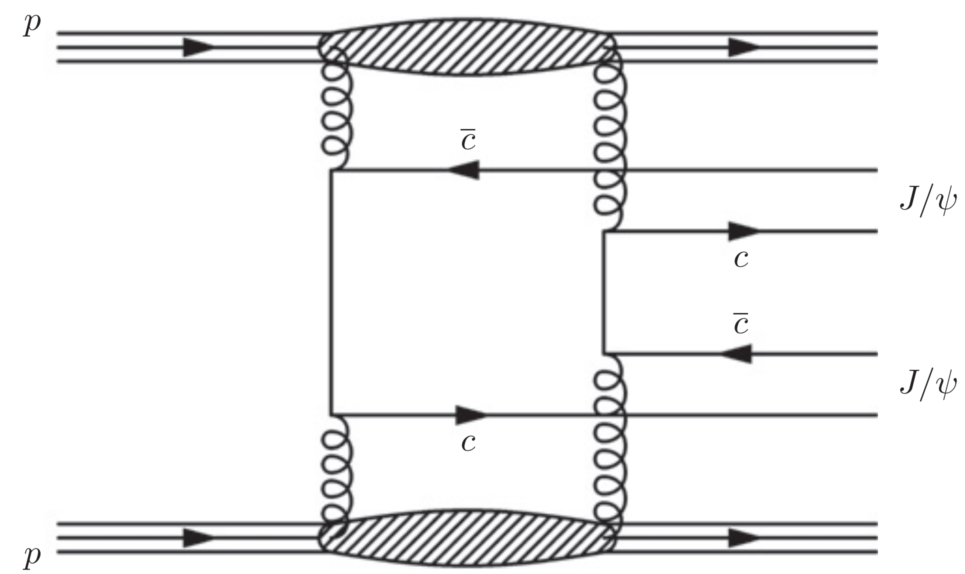
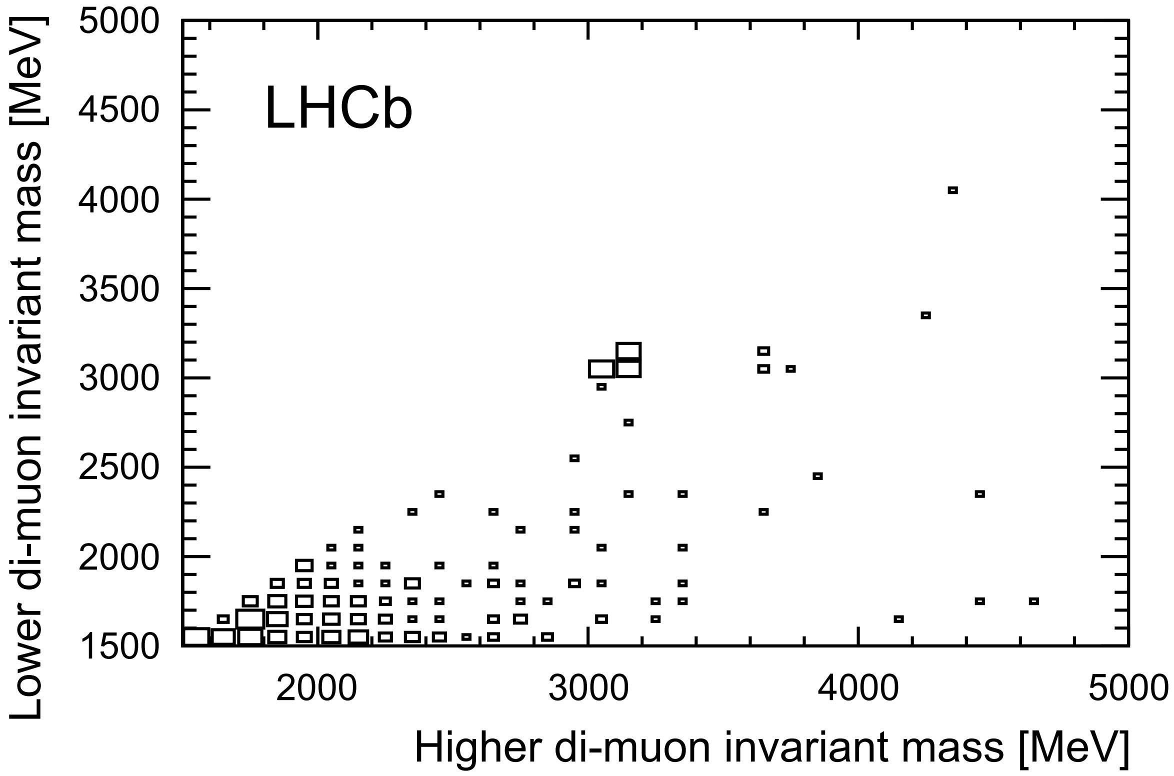


other possible production mechanism

Di-muon invariant mass distributions

J. Phys. G: Nucl. Part. Phys. 41 (2014) 115002



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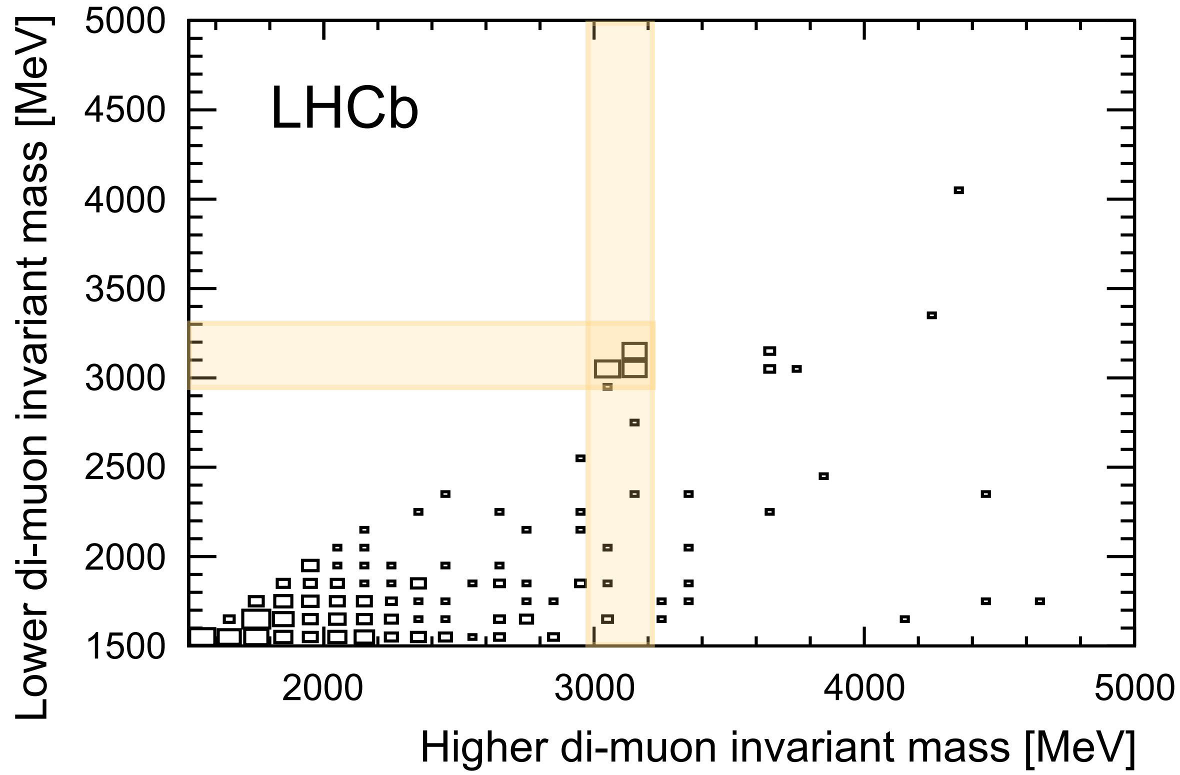
J. Phys. G: Nucl. Part. Phys. 41 (2014) 115002



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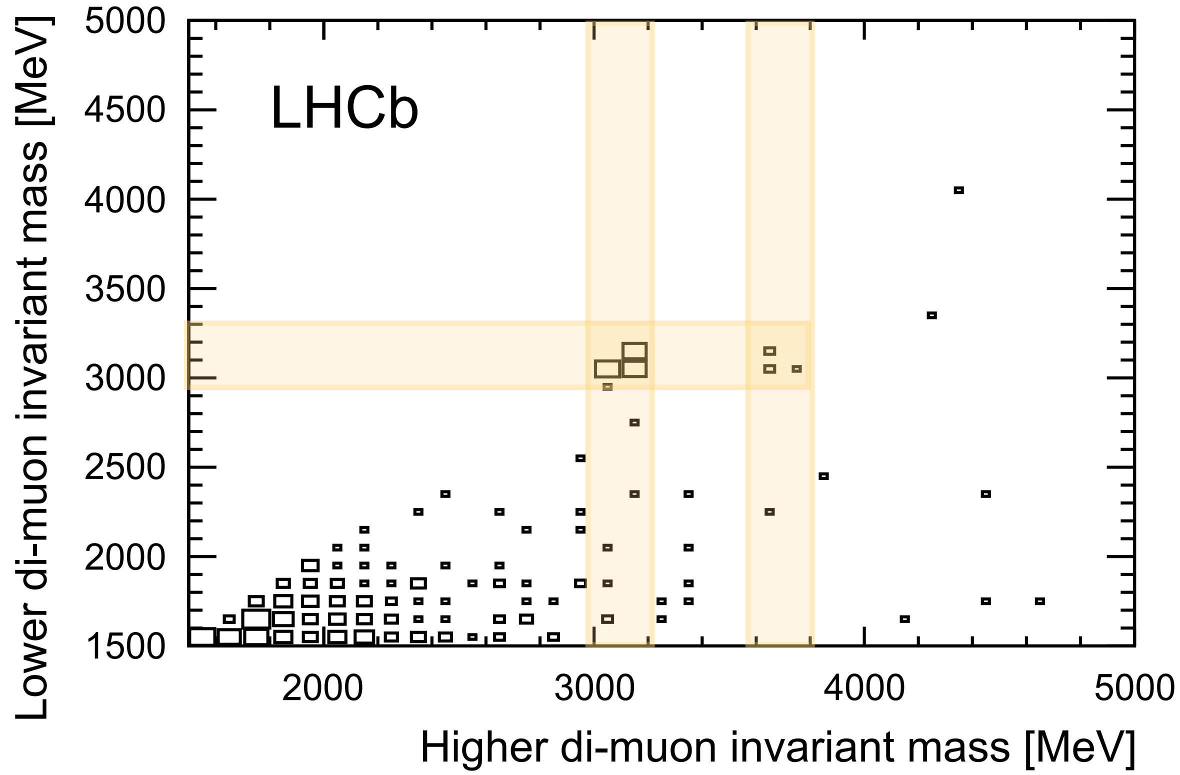

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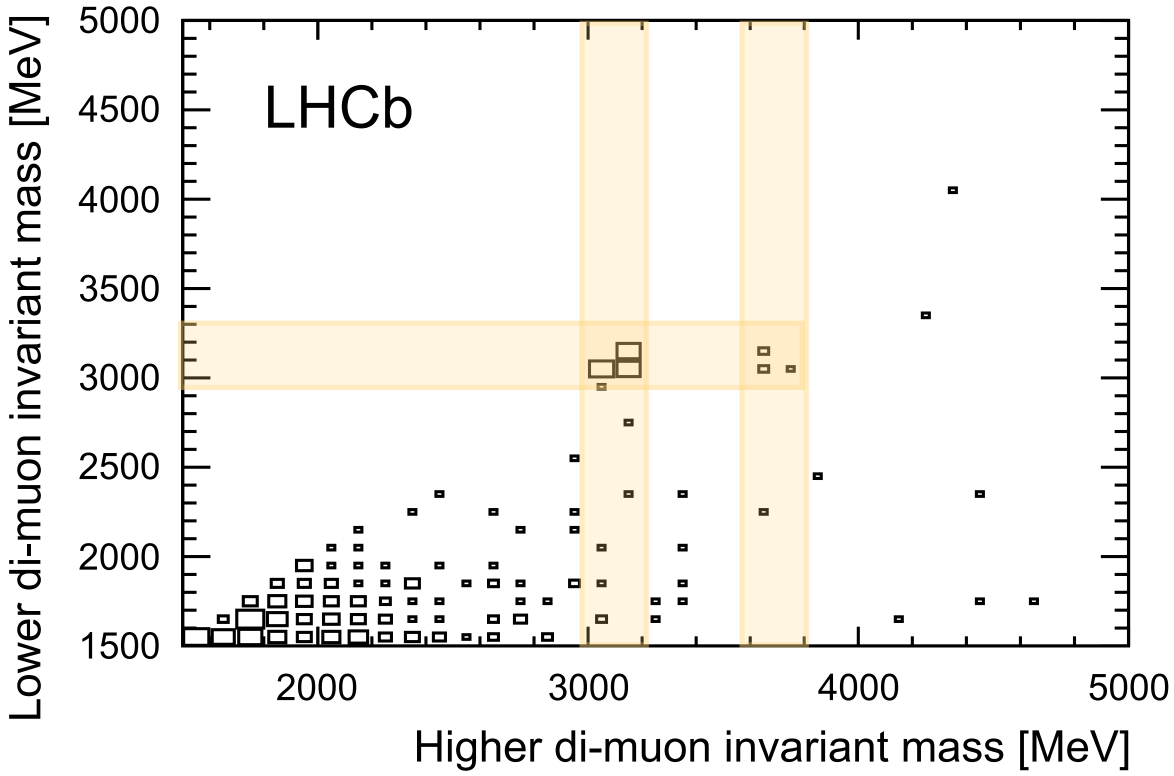

cross sections: not corrected for proton dissociation

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

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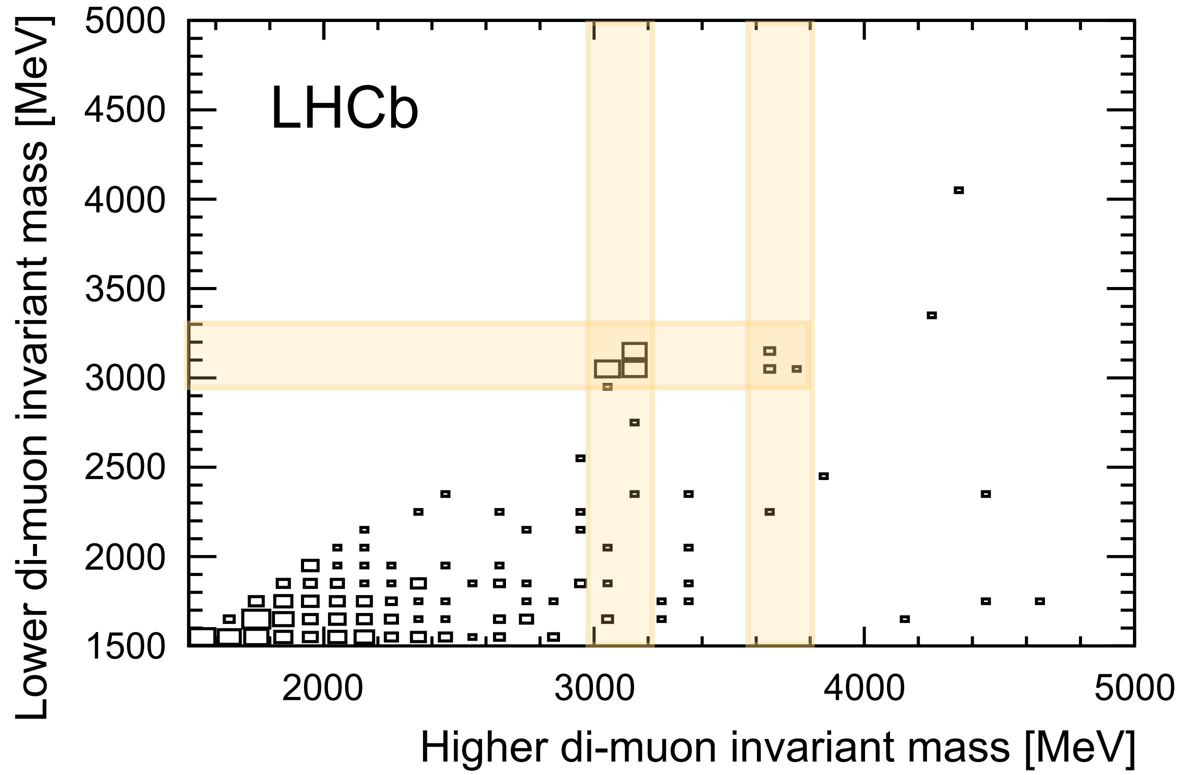
J. Phys. G: Nucl. Part. Phys. 41 (2014) 115002



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42% CEP →

corrected for proton dissociation

$$\sigma^{J/\psi J/\psi} = 24 \pm 9\ \text{pb}$$

Summary and outlook

- CEP: rich field of physics
- LHCb results on single J/ψ, ψ(2S), Υ production in pp collisions: gluon GPDs and PDFs, odderoproduction
- LHCb results on pairs of charmonium: double-pomeron exchange, tetraquarks, glueballs
- preliminary results on J/ψ and ψ(2S) in PbPb collisions (LHCb-CONF-2018-003): nuclear GPDs and PDFs, shadowing
- preliminary results on χ_c in pp collisions (LHCb-CONF-2011-022): double-pomeron exchange
- preliminary results on dimuon Bethe-Heitler production in pp collisions (LHCb-CONF-2011-022)
- various analysis in pp, pPb and PbPb collisions with dimuon and single and double meson-production are ongoing

Back up

Exclusive J/ψ and ψ(2S) production: systematic uncertainties $\sqrt{s} = 7$ TeV

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%				
*ϵ_{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%				

*: systematic uncertainties

Exclusive J/ψ and ψ(2S) production: systematic uncertainties $\sqrt{s} = 13$ TeV

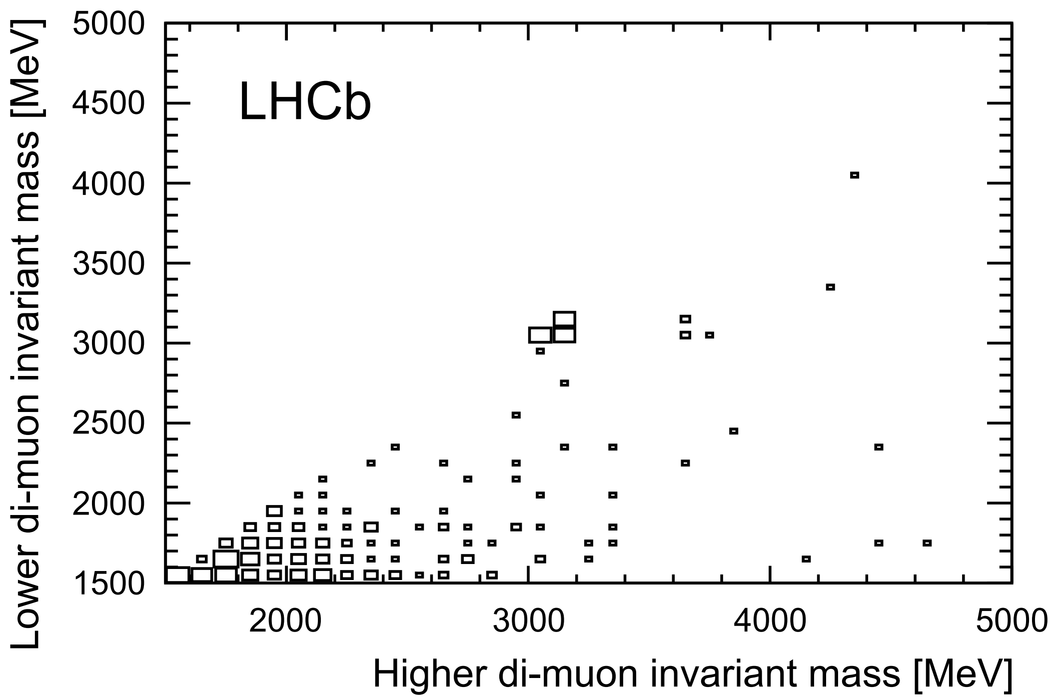
Source	J/ψ analysis (%)	$\psi(2S)$ analysis (%)
HeRSChel veto	1.7	1.7
2 VELO track	0.2	0.2
0 photon veto	0.2	0.2
Mass window	0.6	0.6
p_{T}^2 veto	0.3	0.3
Proton dissociation	0.7	0.7
Feed-down	0.7	-
Nonresonant	0.1	1.5
Tracking efficiency	0.7	0.7
Muon ID efficiency	0.4	0.4
Trigger efficiency	0.2	0.2
Total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

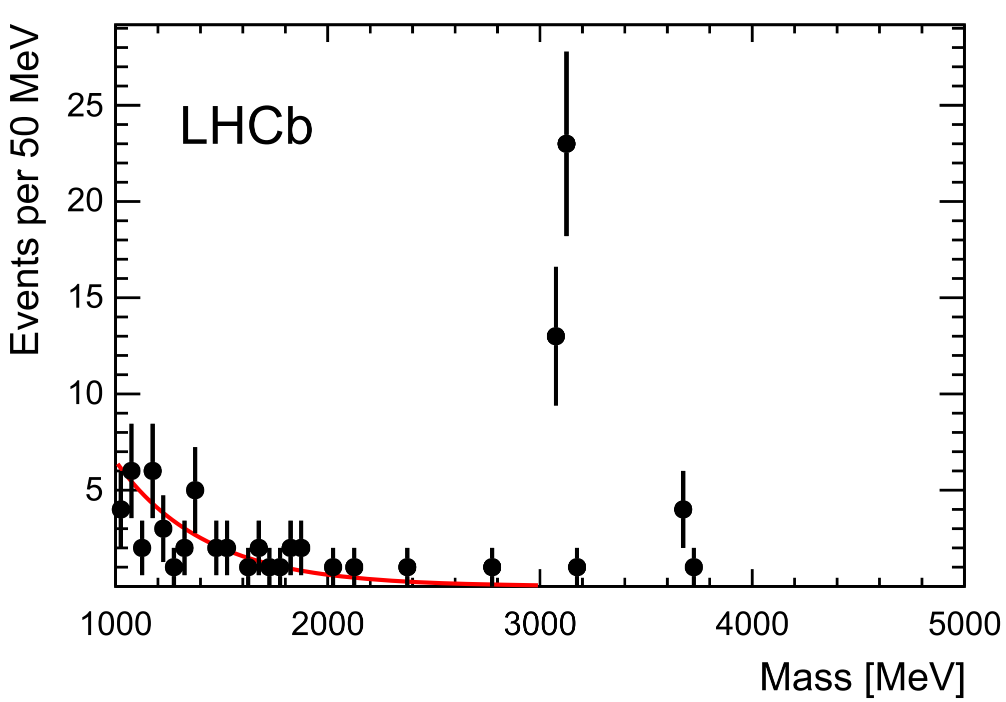
Exclusive Υ production: systematic uncertainties

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

Di-muon invariant mass distributions

J. Phys. G: Nucl. Part. Phys. 41 (2014) 115002





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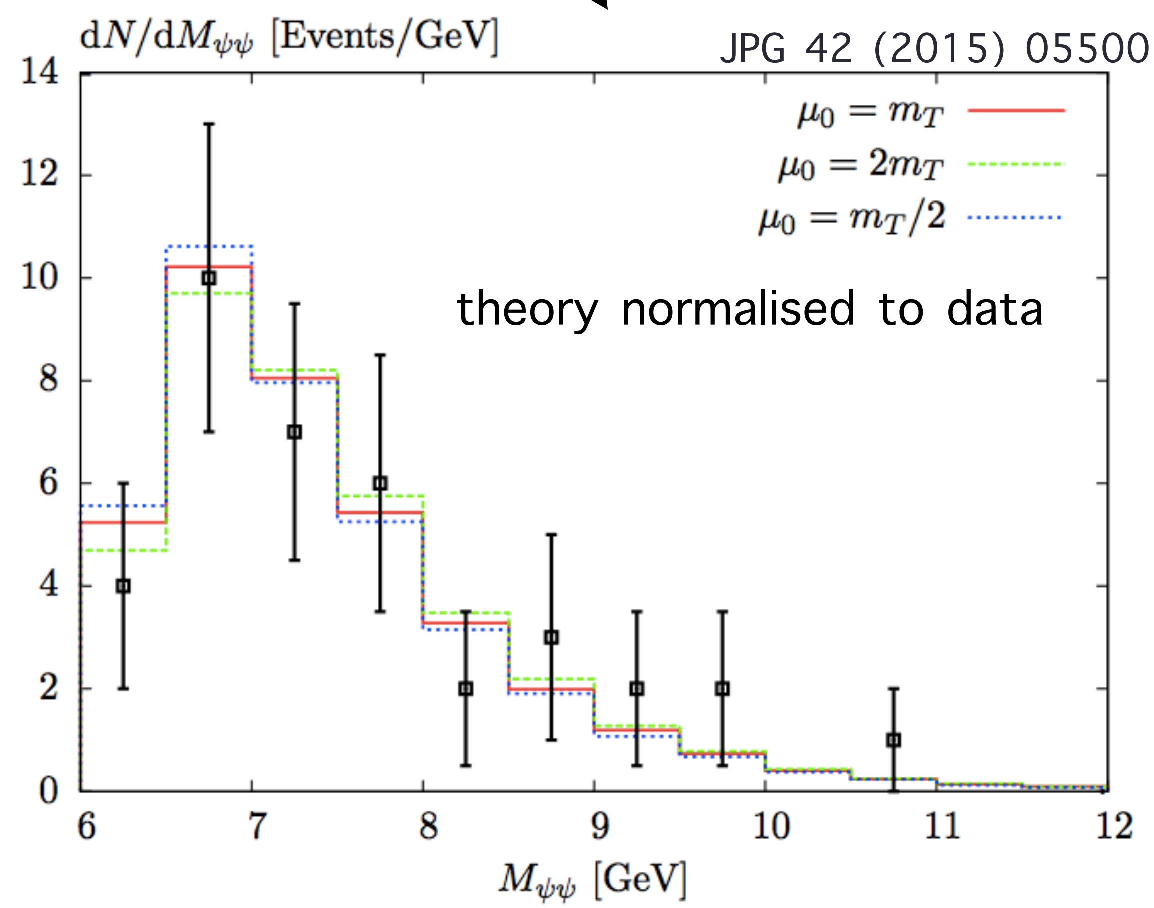
42% CEP

JPG 42 (2015) 055001



LHCb measurement:

$$\sigma^{J/\psi J/\psi} = 24 \pm 9\ \text{pb}$$

theory prediction

$$\sigma^{J/\psi J/\psi} = 2 - 7\ \text{pb}$$