Central Exclusive Diffraction at LHCb

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QCD@LHC
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General Motivation

- Much to understand about QCD
  - perturbative / non-perturbative regime
  - proton and nuclear structure (PDFs GPDs)
  - hot spots
  - saturation
  - quark model bound states (η_c,J/ψ, χ_c)
  - beyond the naïve quark model (hybrids, tetraquarks, glueballs)

- Can be addressed in diffractive DIS.

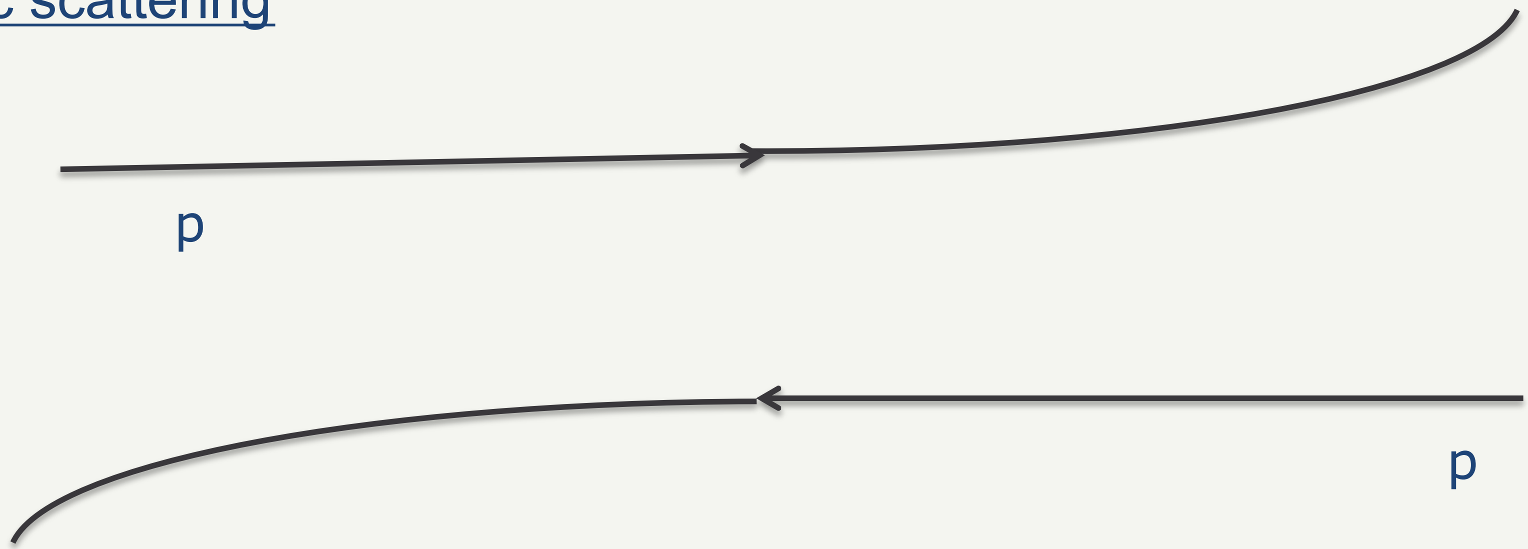
Specific Motivation

- ρ meson production in PbPb UPC
  - comparison with ep and Pbp gives nuclear shadowing (linear QCD)
  - sensitive to non-linear QCD (saturation)
  - spectroscopy of $\pi\pi$ system
  - understanding ρ parameters that differ in ee and tau decays
  - could help with hadronic corrections for g-2.

- $J/\psi+\phi$ production in exclusive pp collisions
  - sensitive to beyond the naïve quark model (hybrids, tetraquarks, glueballs)

Physics of the Vacuum

Elastic scattering

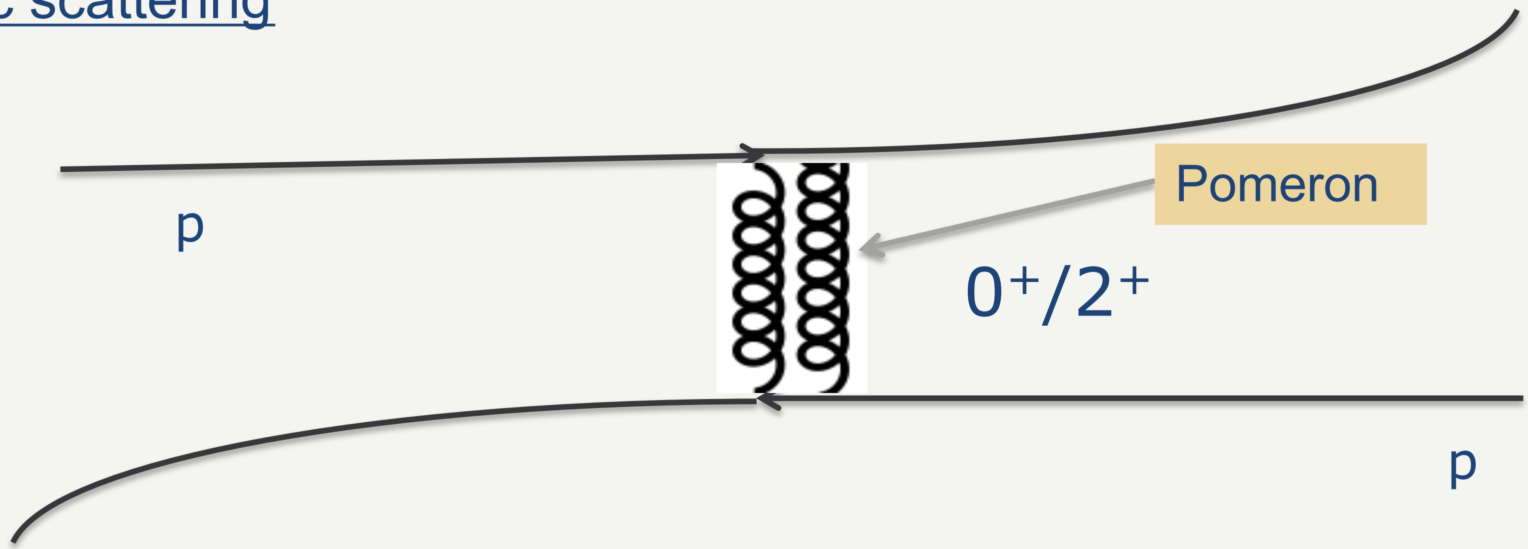


It's QCD – but not as we normally see it. It's colour-free

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

Physics of the Vacuum

Elastic scattering



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Physics of the Vacuum

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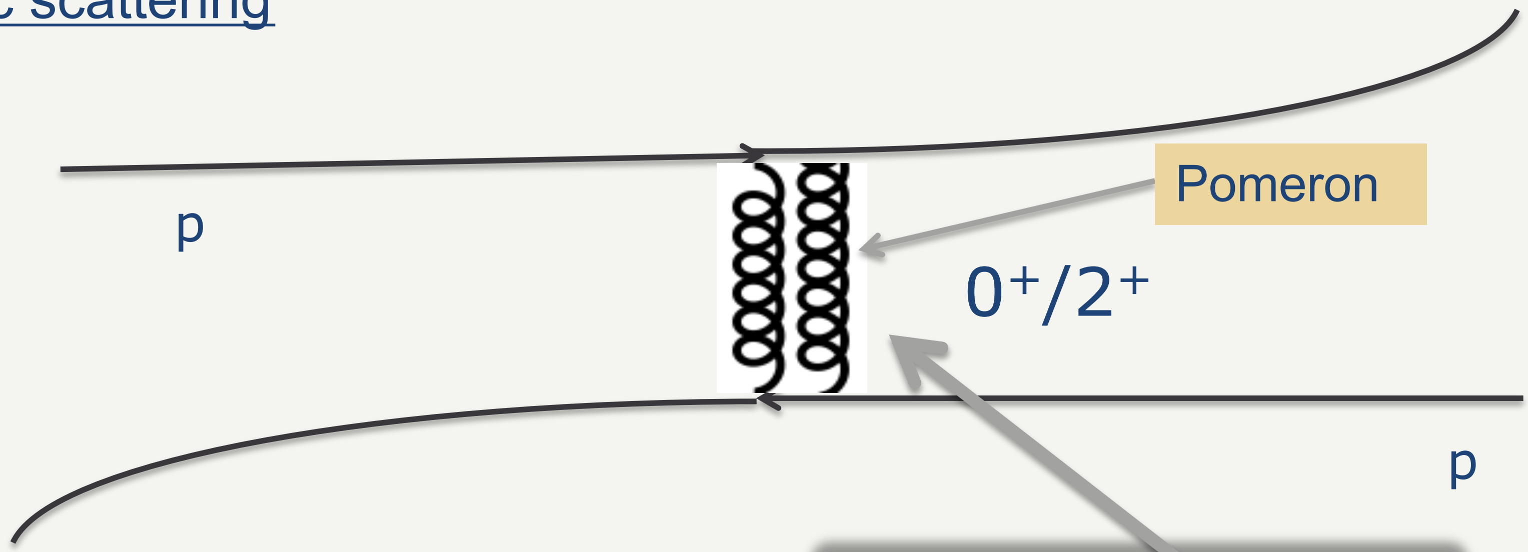

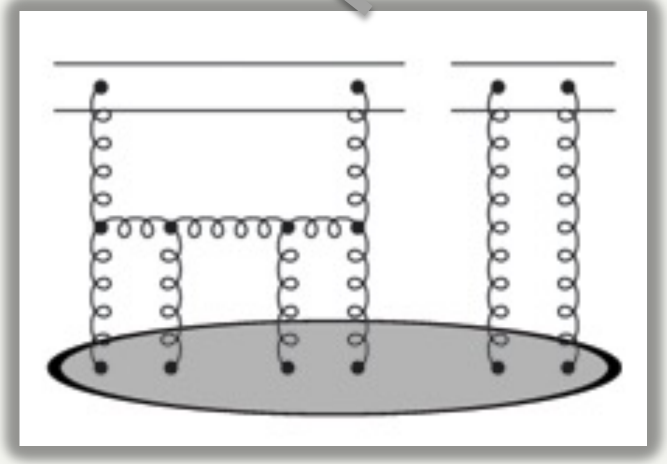

At high energy: $A(s,t)=s^{\alpha(t)}$

$\alpha_P(t)=\alpha_P(0)+\alpha' t$

$\sigma_{elastic} \approx 40mb$

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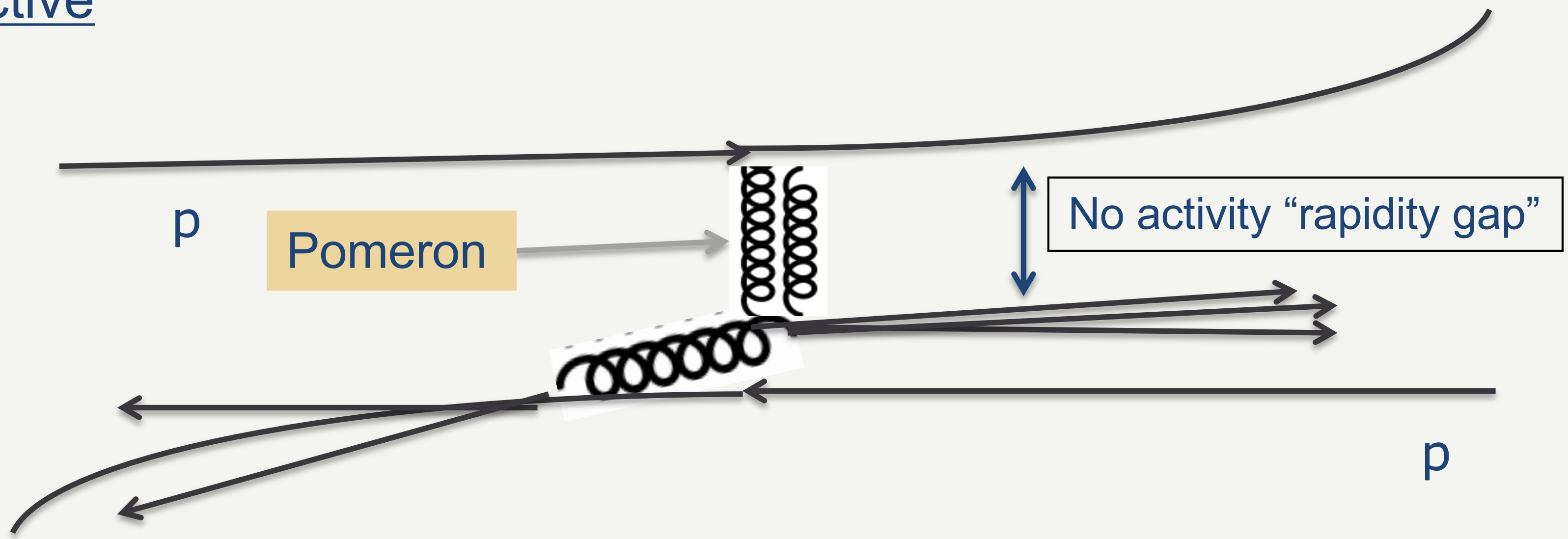
Physics of the Vacuum

Diffractive



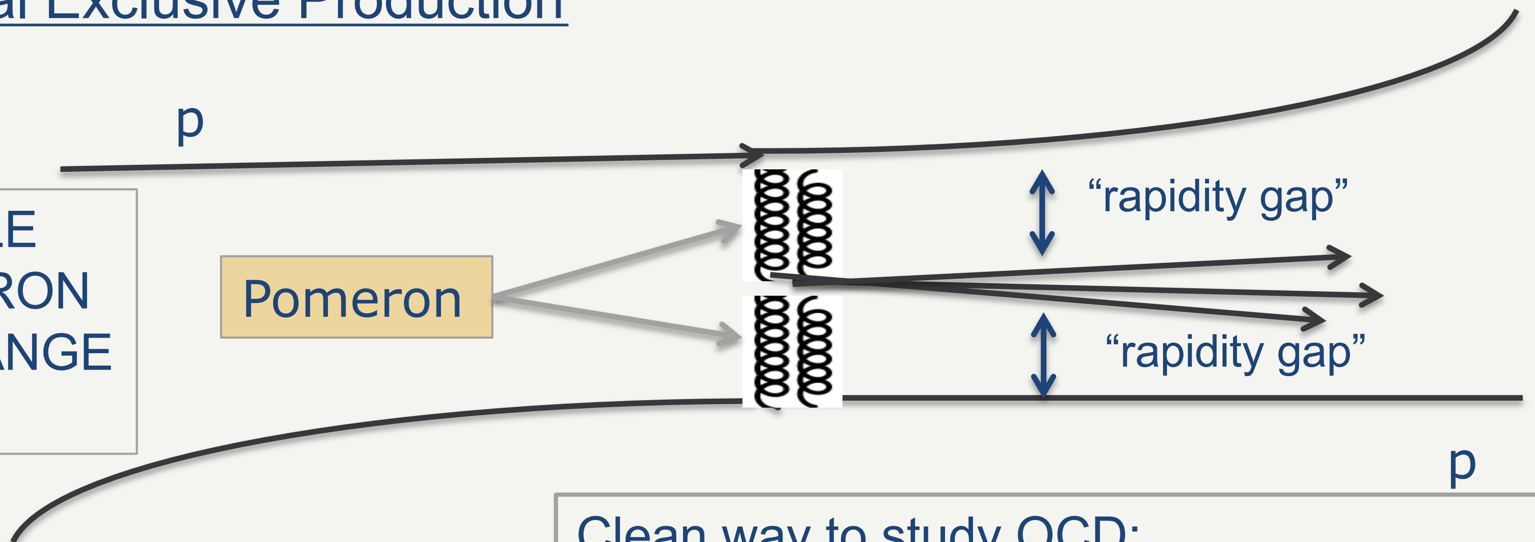
Experimental working definition of diffraction is presence of rapidity gap

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

Physics of the Vacuum

Central Exclusive Production

DOUBLE POMERON EXCHANGE (DPE)



Clean way to study QCD:

- structure of projectiles
- nature of colour-free propagators
- structure of what is produced out of vacuum

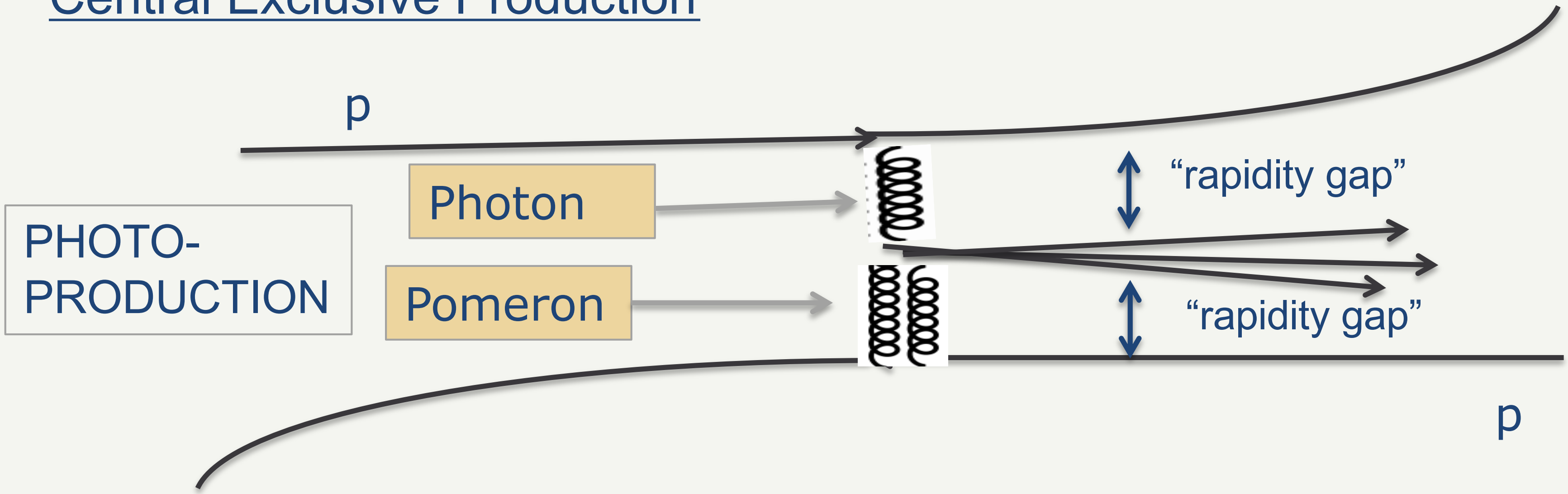
$\sigma_{elastic} \approx 40mb$ ⇐ 100 μb

$\sigma_{diffractive} \approx 10mb$ ⇐

$\sigma_{inelastic} \approx 60mb$

Physics of the Vacuum

Central Exclusive Production



$\sigma_{elastic} \approx 40mb$

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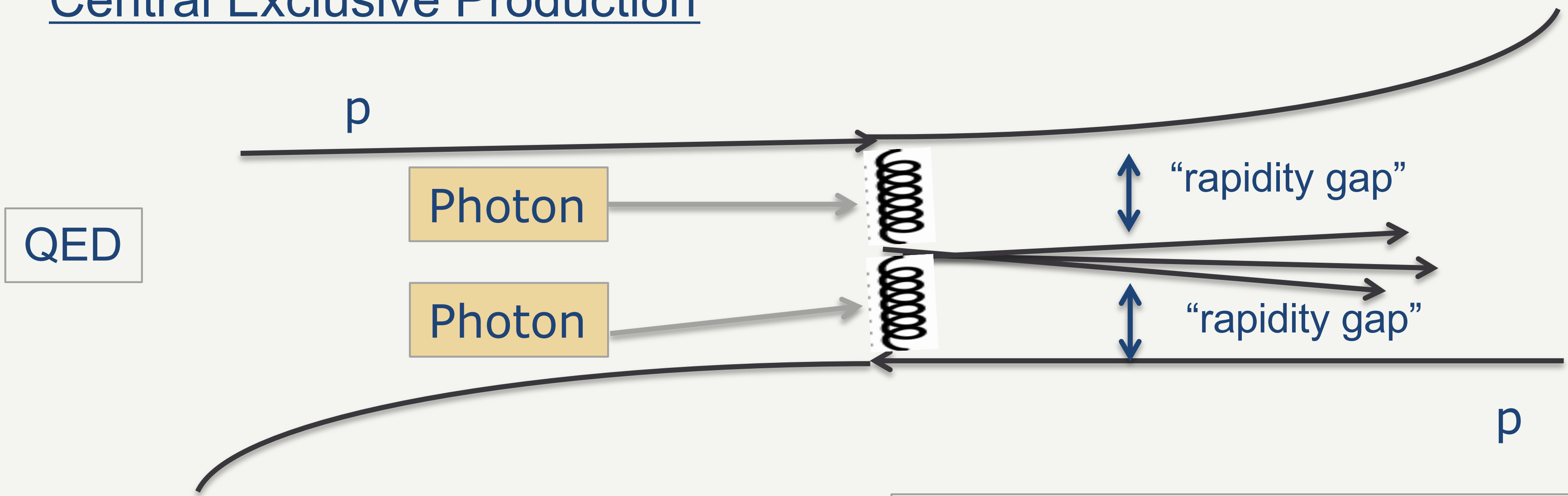
100 μb

Physics of the Vacuum

Central Exclusive Production



CEP is characterised by a rapidity gap all the way to the proton

Detect as large a gap as possible...

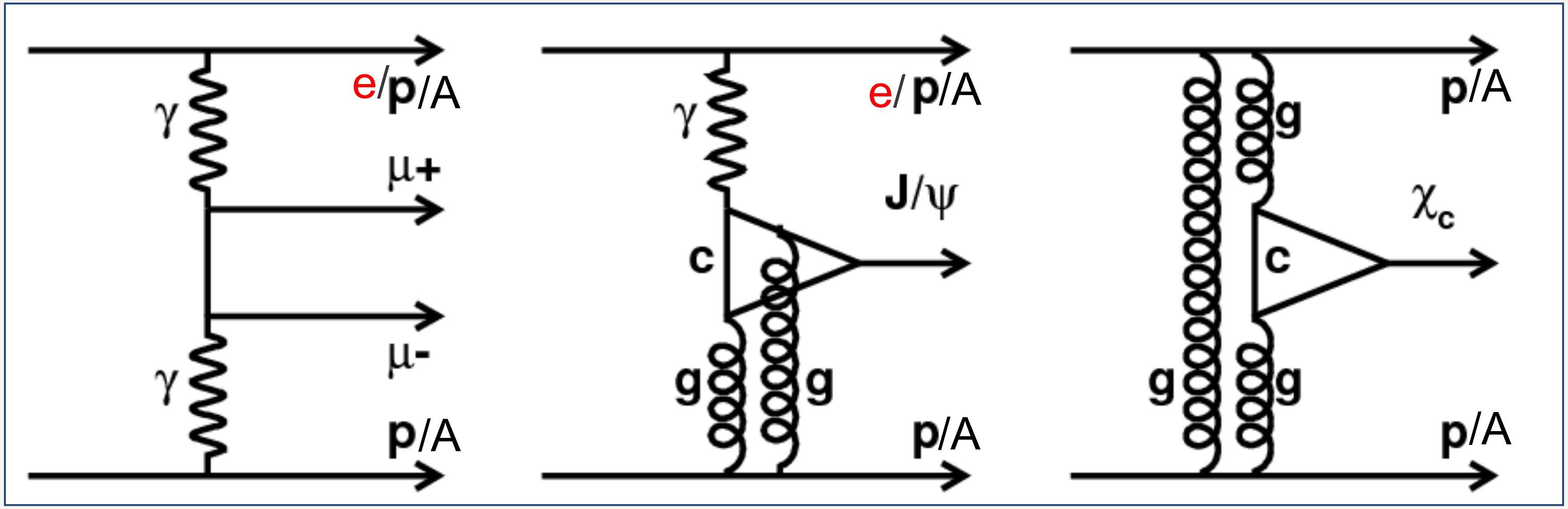
$\sigma_{elastic} \approx 40mb$

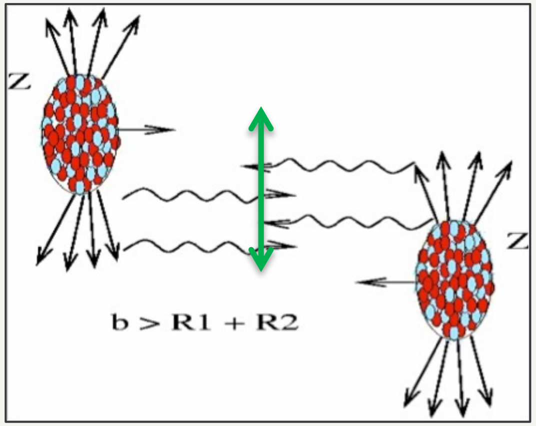
$\sigma_{diffractive} \approx 10mb$

$\sigma_{inelastic} \approx 60mb$

100 pb

Colourless propagators



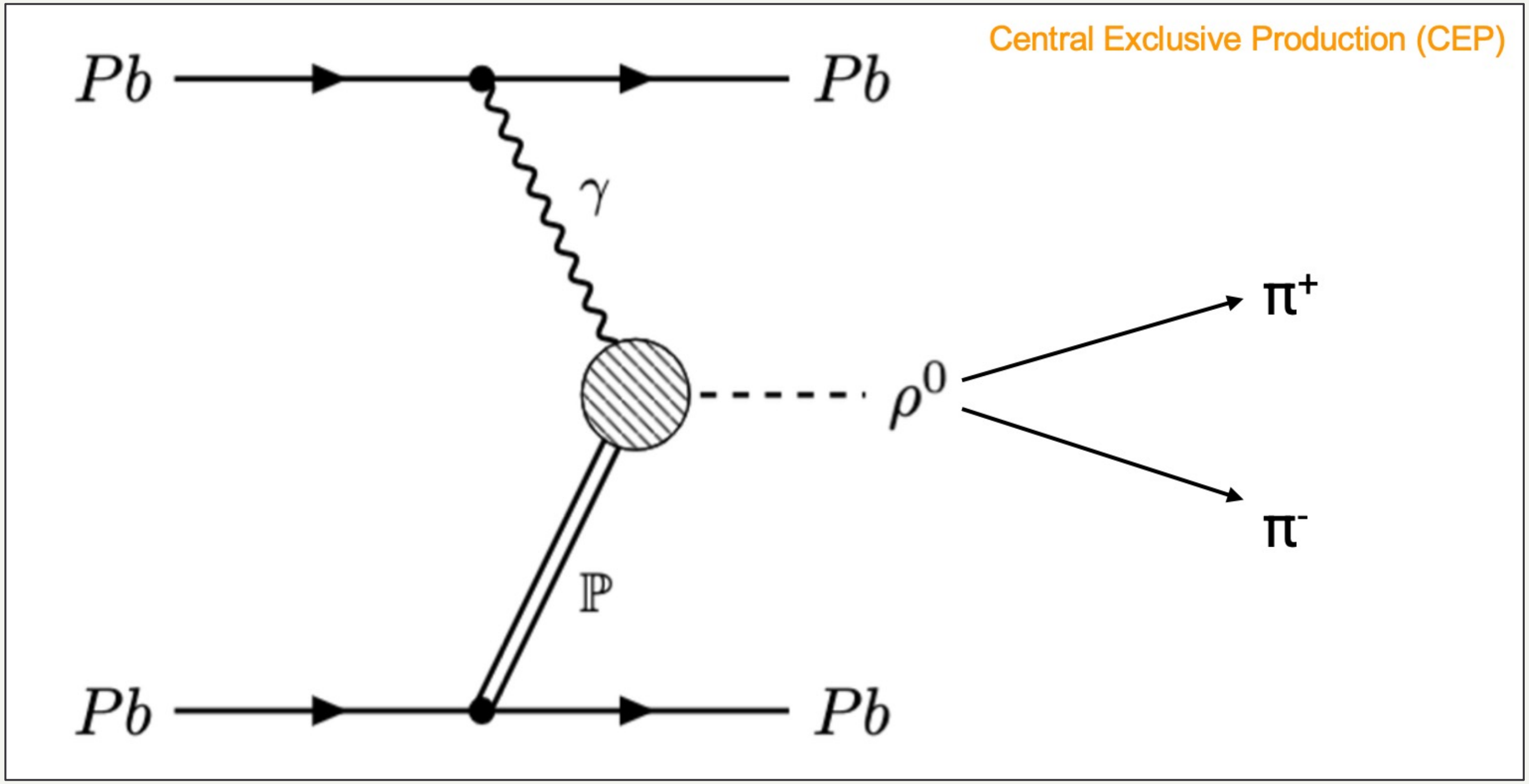


Hadron colliders:
Generally, to ensure no (colourful) QCD interaction, $d>R_1+R_2$ (1.5 - 6 fm).

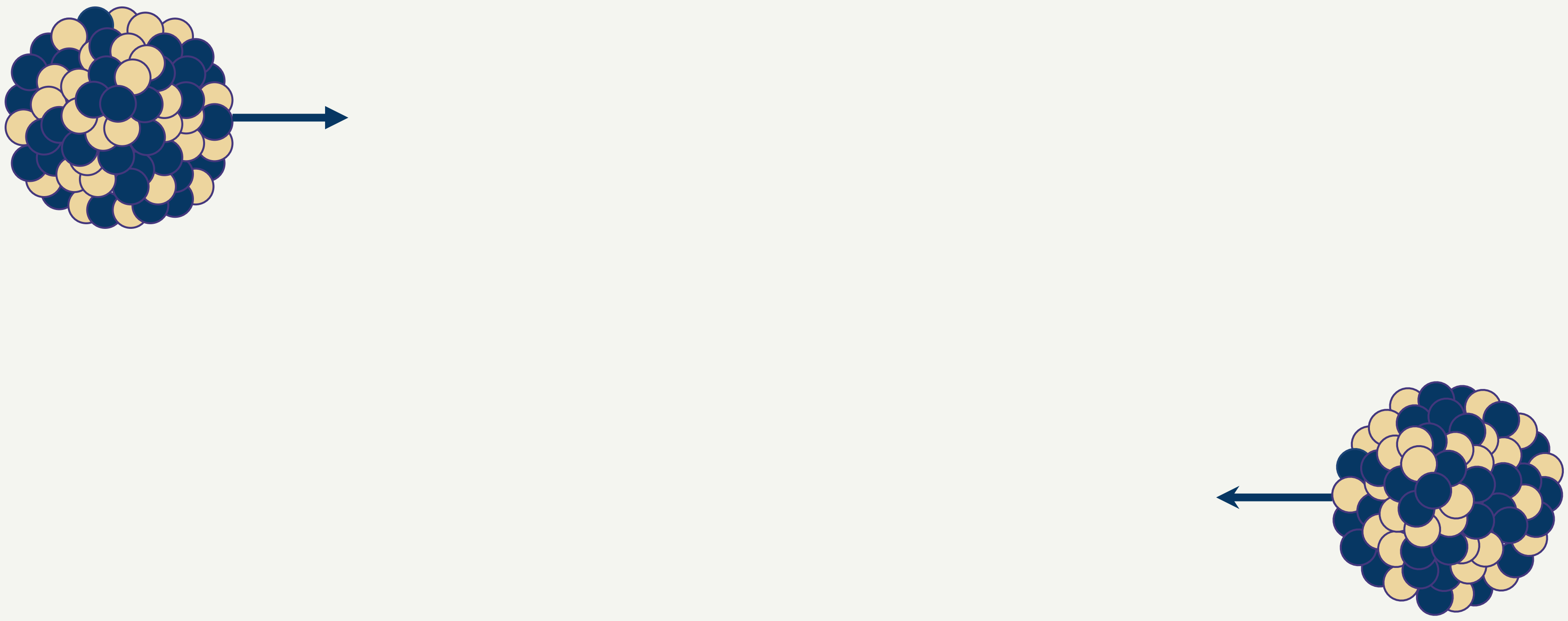
Large impact parameter ↔ Small p_T

Electron-hadron collider:
~70% of total cross-section is diffractive

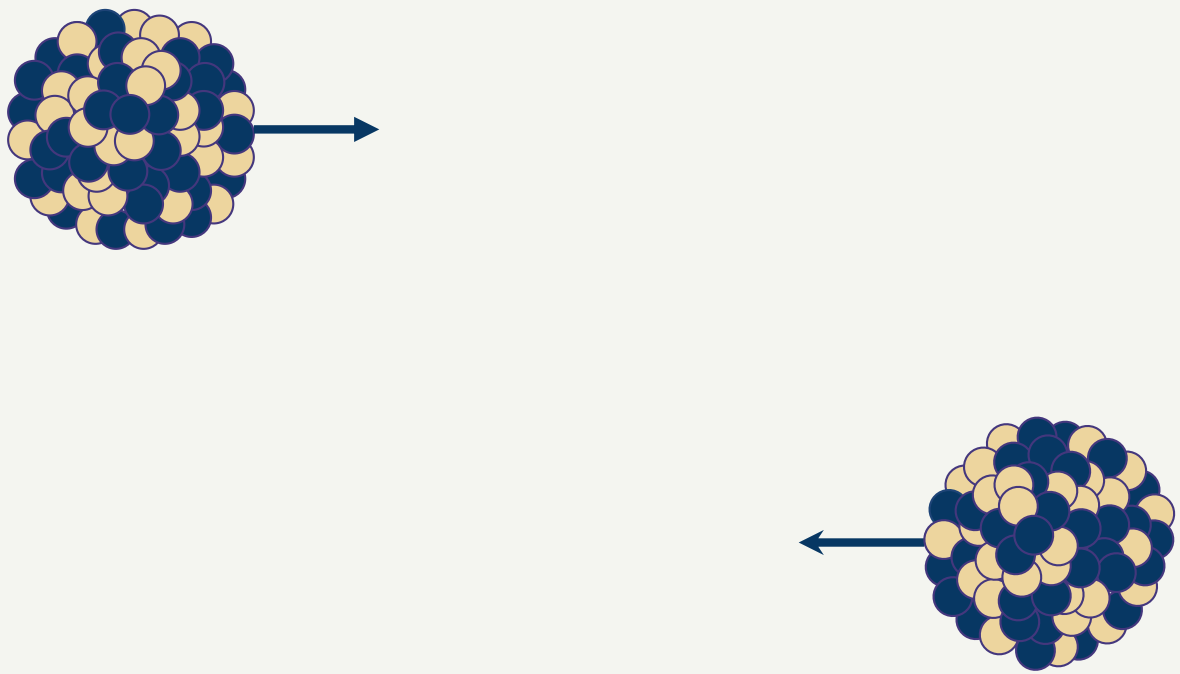
Photoproduction



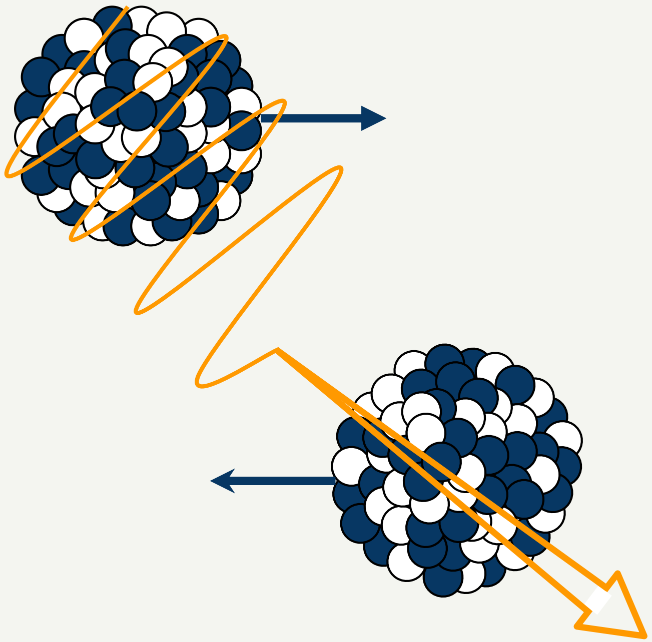
Ultra-Peripheral Collisions



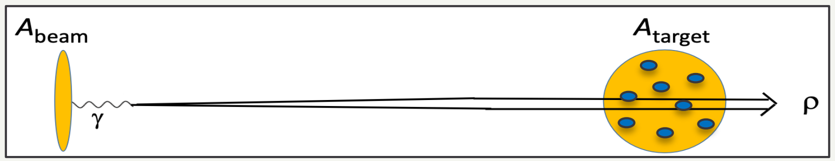
Ultra-Peripheral Collisions



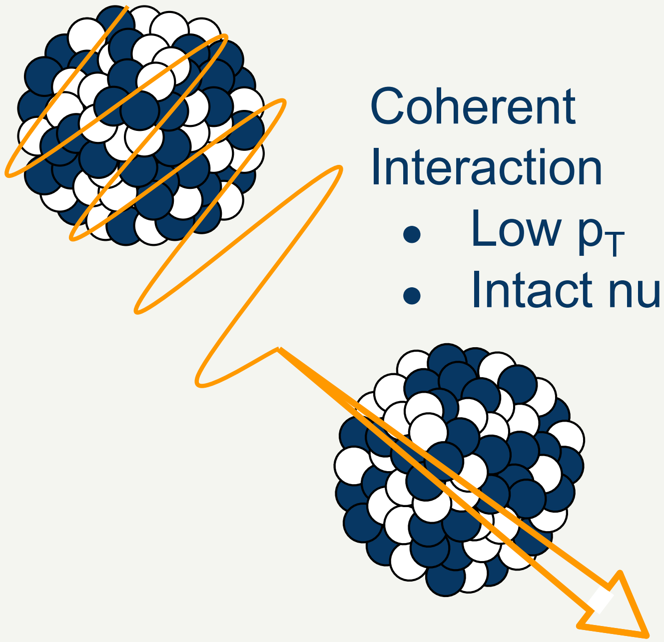
Ultra-Peripheral Collisions



Coherent production
Photon converts into ρ-meson before the target
Collision is between a ρ-meson and a nucleus.

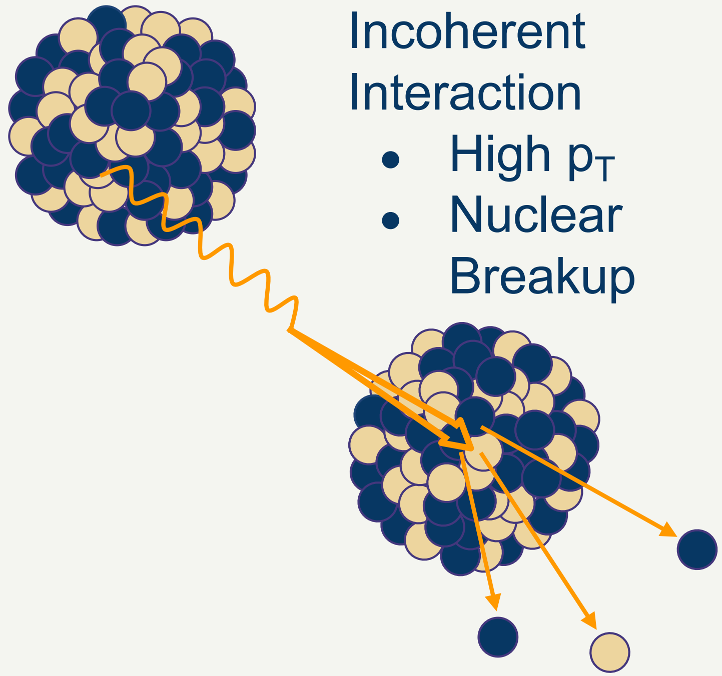


Coherent vs Incoherent Interactions



Coherent Interaction

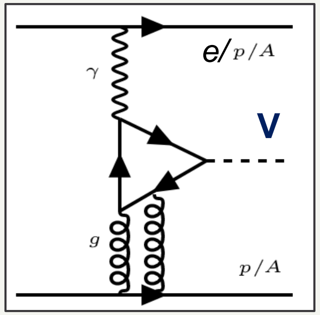
- Low p_T
- Intact nuclei



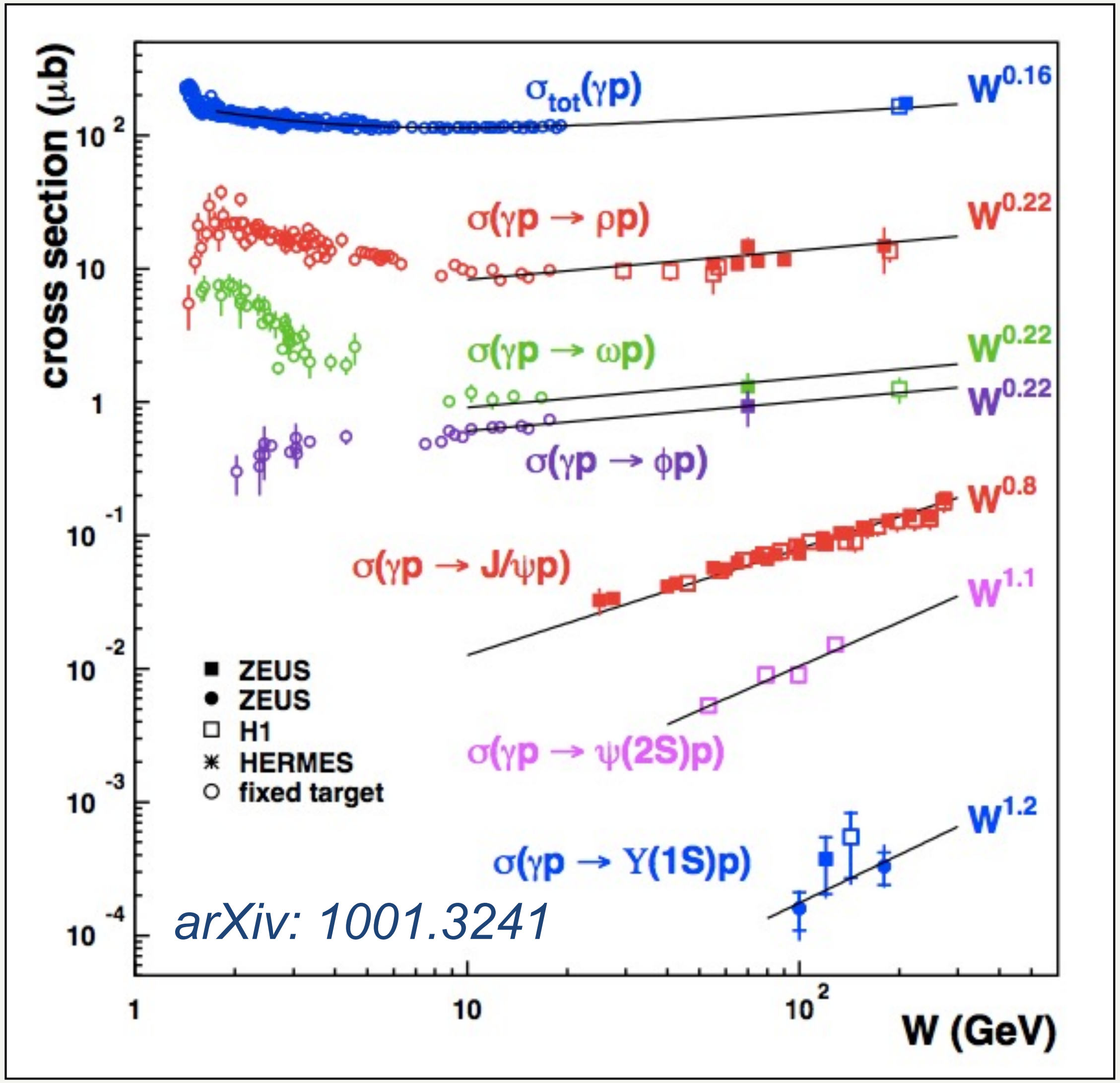
Incoherent Interaction

- High p_T
- Nuclear Breakup

Photoproduction

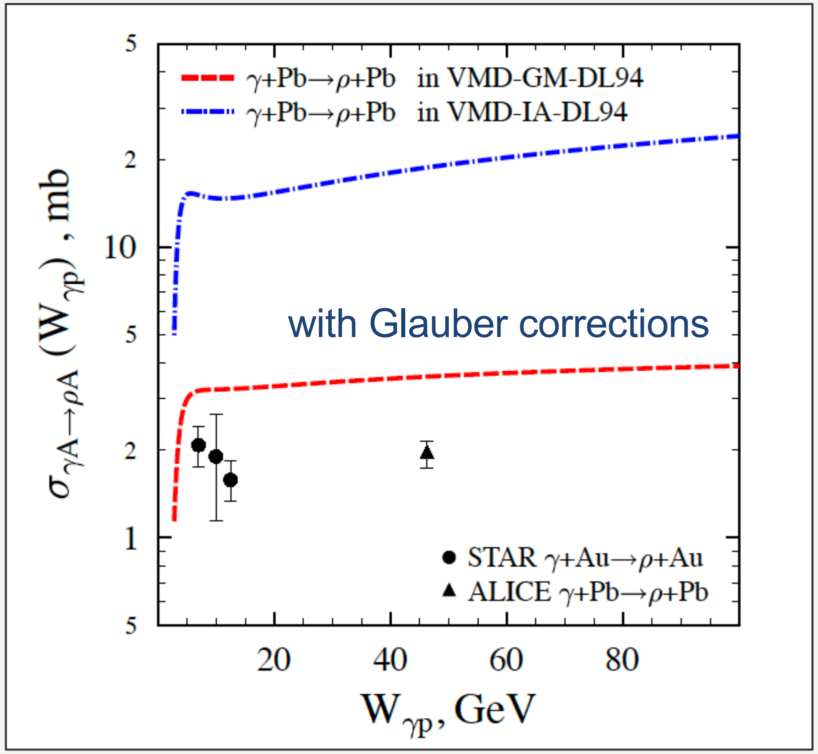


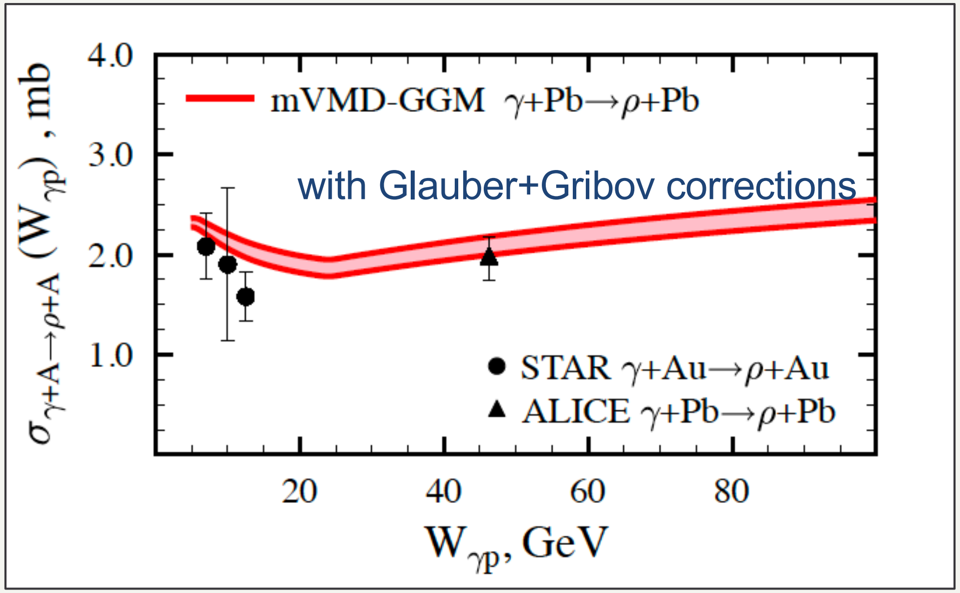
- Rise in σ related to Pomeron intercept
  - $\sigma \sim W^{\delta}$
  - $\delta = 4(\alpha_P(t) - 1)$
  - $\alpha_P(t) = \alpha_P(0) + \alpha' t$
- Compare slopes ρ,ω,ϕ to J/ψ,ψ’,Υ
- Extract $g(x,Q^2)$



Nuclear suppression

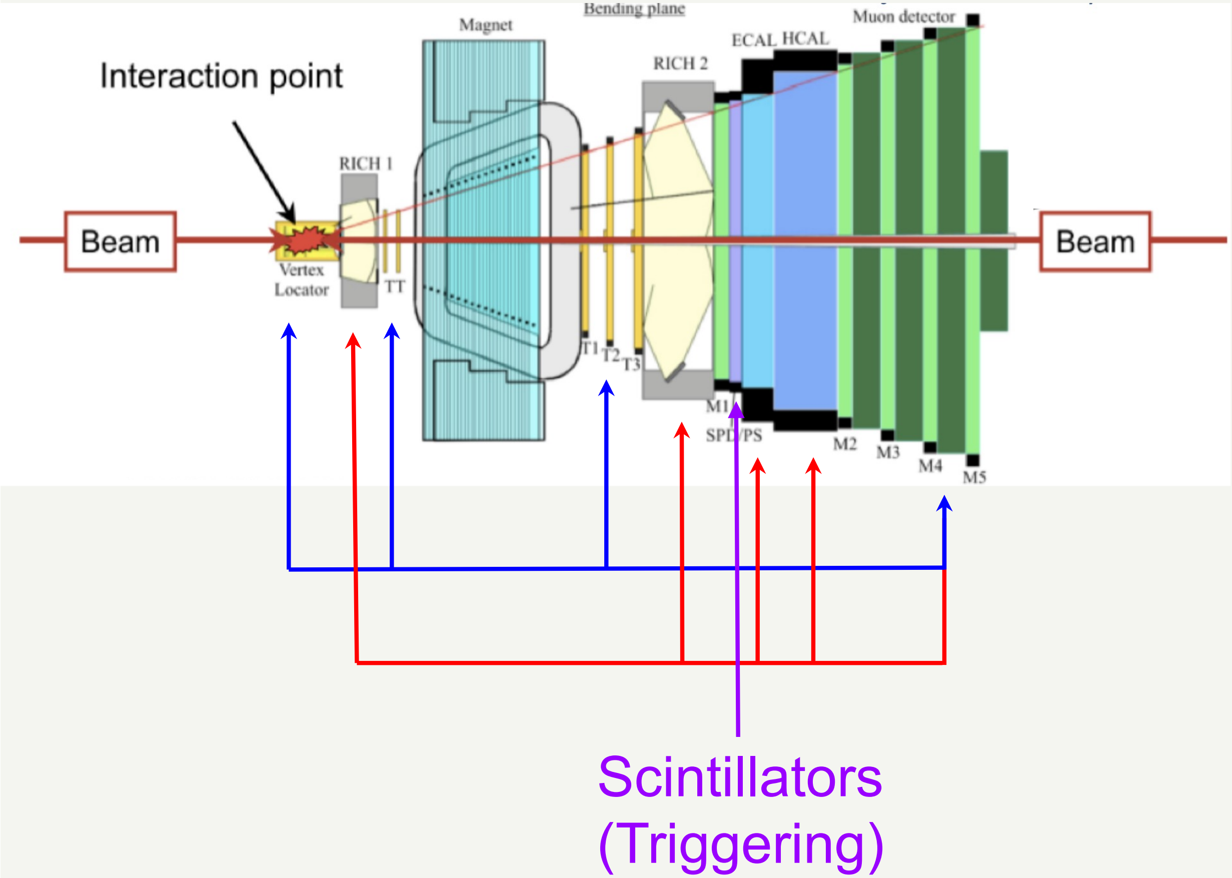
Frankfurt, Guzey, Strikman, Zhalov, Phys.Lett.B 752 (2016) 51-58





LHCb data is in range 6-20 GeV and 200-650 GeV

The LHCb detector



Forward-arm spectrometer ($2 < \eta < 5$)

- Unique acceptance and capabilities.
- Constraints nPDFs down to $x \sim 10^{-6}$

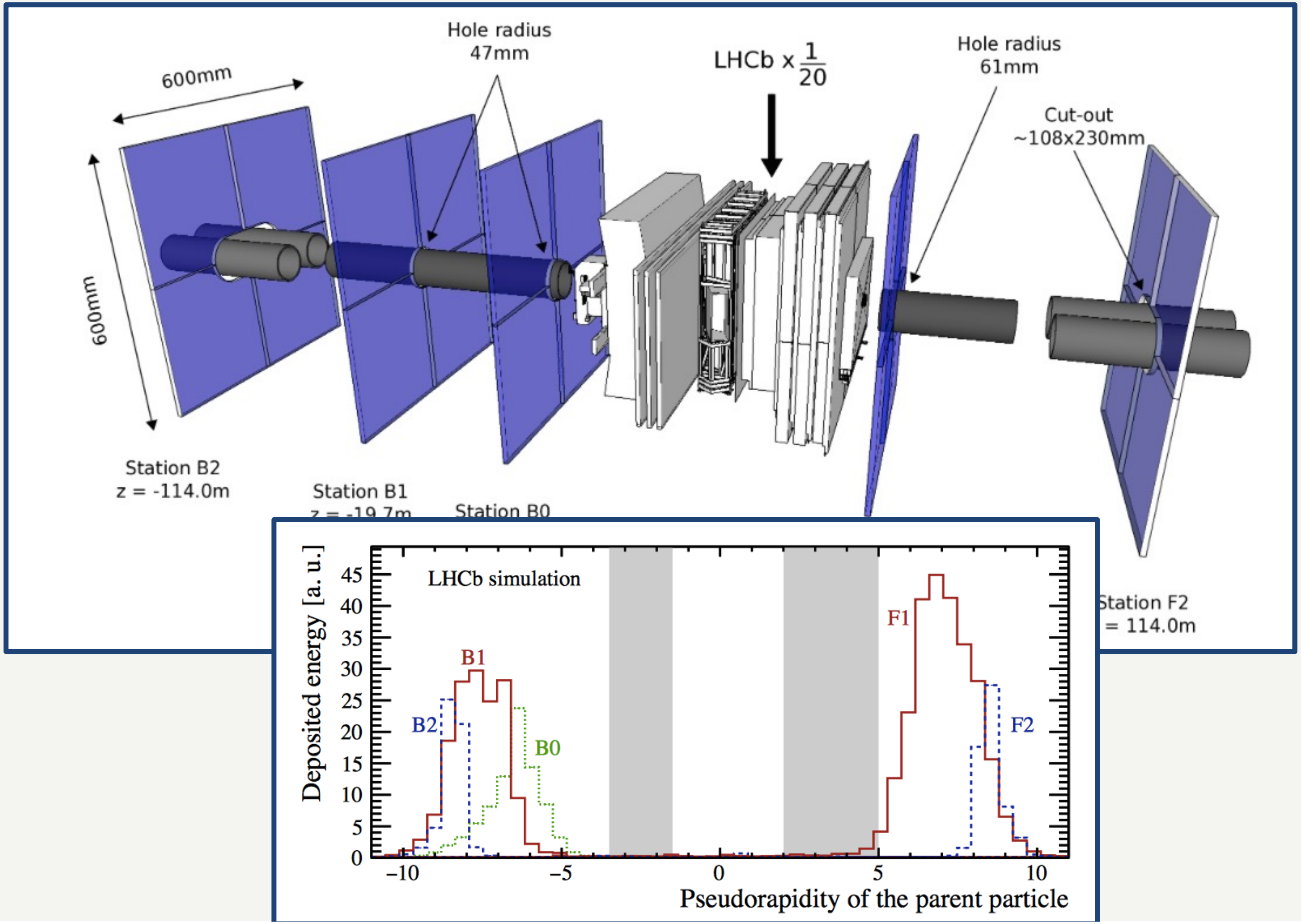
Precise Tracking

Full PID.

Mass resolution:
$m_{\pi\pi} \sim 5$ MeV.

Low background levels

The LHCb detector



Data Selection

Data

- 2018 PbPb LHCb data
- $\sqrt{s_{NN}}$ = 5.02 TeV
- Integrated luminosity: 228 ± 10 μb^{-1}

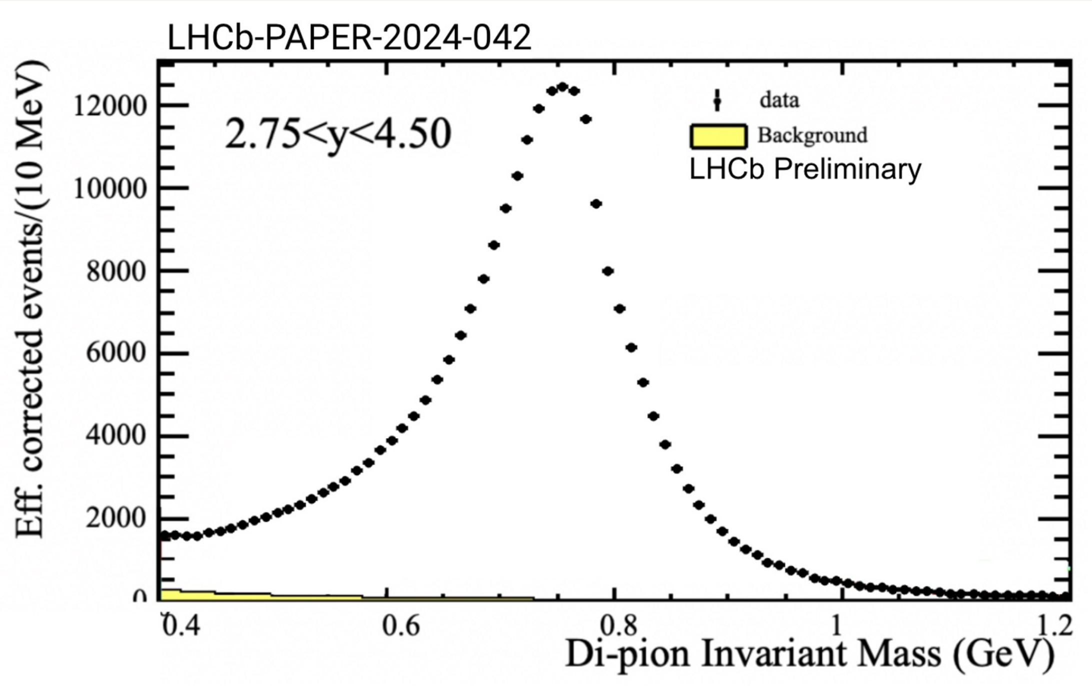
Selection Criteria

- Triggered Low Multiplicity Events (SPD < 50)
- Two oppositely charged tracks
- Fiducial region defined by $2.05 < y_{(parent)} < 4.9$, $p_{T(Track)} > 100$ Mev, and $2 < \eta_{Track} < 5$
- Invariant mass > 400 MeV
- Both tracks consistent with being a pion (using PID)
- Transverse momentum of the system < 100 MeV

Resultant Data

- Final sample contains ~12 million candidates

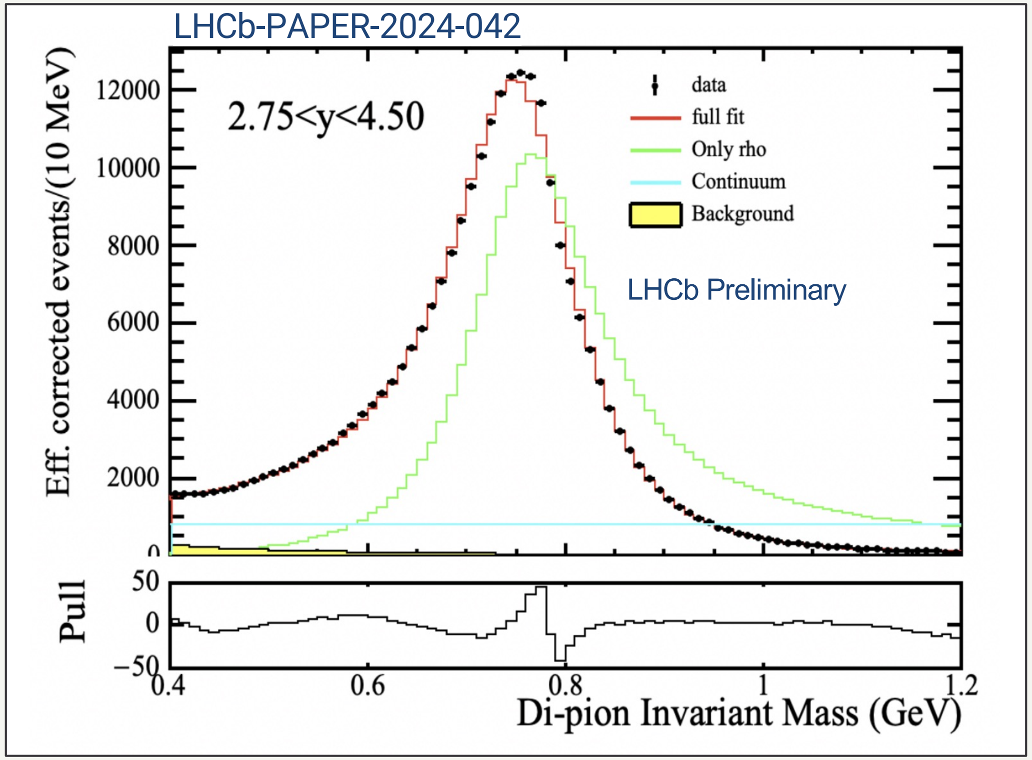
Backgrounds



Backgrounds ~<1%

- **Gamma-gamma production**:
  - Diphoton production peaked at low masses and low p_T
  - Shape of the $\gamma\gamma \rightarrow ee/\mu\mu$ determined by fitting identified electrons or muons.
  - Contamination from $\gamma\gamma \rightarrow ee$ and $\gamma\gamma \rightarrow \mu\mu$ processes ~0.5%.
- **Multi-hadron backgrounds ($\pi\pi\pi^0$/KK etc) at 0.1% level**

Fit to standard Söding model



$$\mathcal{S}(M_{\pi\pi}) \propto \left| A \frac{\sqrt{M_{\pi\pi} M_\rho \Gamma}}{M_{\pi\pi}^2 - M_\rho^2 + i M_\rho \Gamma} + B \right|^2$$

Experiment	Zeus [4]	H1 [5]	CMS [6]	ALICE [7]	LHCb Pb–Pb
Fit range [GeV]	[0.55,1.2]	[0.6,1.1]	[0.5,1.2]	[0.6,1.5]	[0.4,1.2]
M_ρ[MeV]	770 ± 2	769 ± 4	776 ± 1	$762^{+6.5}_{-3.8}$	771 ± 3
Γ_ρ [MeV]	146 ± 13	162 ± 8	154 ± 3	150^{+13}_{-7}	150 ± 4
$\|B/A\|$	0.70 ± 0.04	0.57 ± 0.09 [45]	0.50 ± 0.05	$0.50^{+0.10}_{-0.06}$	0.72 ± 0.04

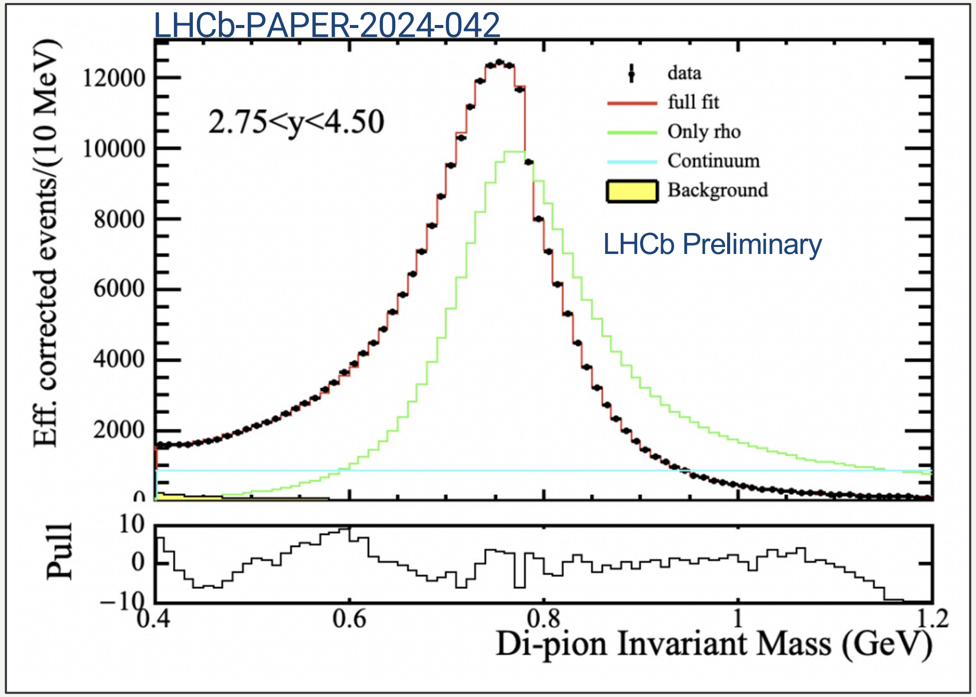
[4] ZEUS, J. Breitweg et al., Elastic and proton dissociative ρ 0 451 photoproduction at HERA, 452 Eur. Phys. J. C 2 (1998) 247, arXiv:hep-ex/9712020.

[5] H1, F. D. Aaron et al., Diffractive Electroproduction of rho and phi Mesons at HERA, 454 JHEP 05 (2010) 032, arXiv:0910.5831.

[6] CMS, A. M. Sirunyan et al., Measurement of exclusive ρ(770)0 455 photoproduction in ultraperipheral pPb collisions at √ 456 sNN = 5.02 TeV, Eur. Phys. J. C 79 (2019) 702, 457 arXiv:1902.01339.

[7] ALICE, J. Adam et al., Coherent ρ 0 400 photoproduction in ultra-peripheral Pb-Pb collisions at √ 401 sNN = 2.76 TeV, JHEP 09 (2015) 095, arXiv:1503.09177.

Add ω to Söding model

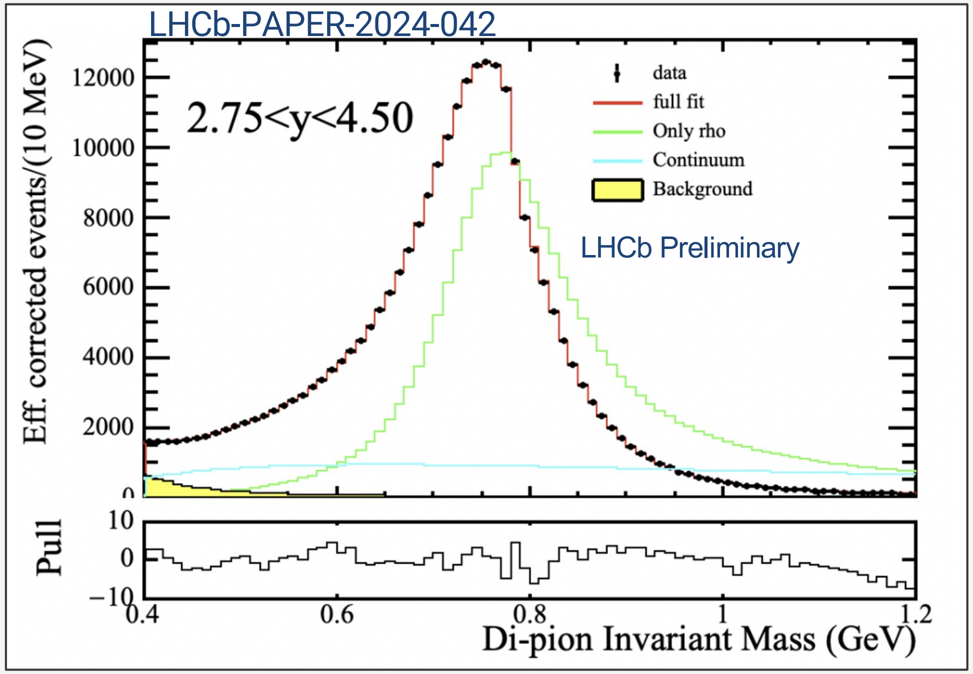


$$S = \left| A \frac{\sqrt{M_{\pi\pi} M_\rho \Gamma}}{M_{\pi\pi}^2 - M_\rho^2 + i M_\rho \Gamma} + B + C \exp(i\phi_\omega) \frac{\sqrt{M_{\pi\pi} M_\omega \Gamma_\omega}}{M_{\pi\pi}^2 - M_\omega^2 + i M_\omega \Gamma_\omega} \right|^2$$

(Parametrisation of STAR)

[8] STAR, L. Adamczyk et al., Coherent diffractive photoproduction of ρ 394 0mesons on gold 395 nuclei at 200 GeV/nucleon-pair at the Relativistic Heavy Ion Collider, Phys. Rev. C 396 96 (2017) 054904, arXiv:1702.07705.

Add ω to Söding model



$$S = \frac{q^3(m_{\pi\pi})}{q^3(m_\rho)} \left| \mathcal{BW}_\rho(m_{\pi\pi}) \left(1 + C\exp(i\phi_\omega)\frac{m_{\pi\pi}^2}{m_\omega^2}\mathcal{BW}_\omega(m_{\pi\pi})\right) + \frac{B}{(m_{\pi\pi}^2 - 4m_\pi^2 + \Lambda^2)^\delta} \right|^2$$

(Parametrisation of H1)

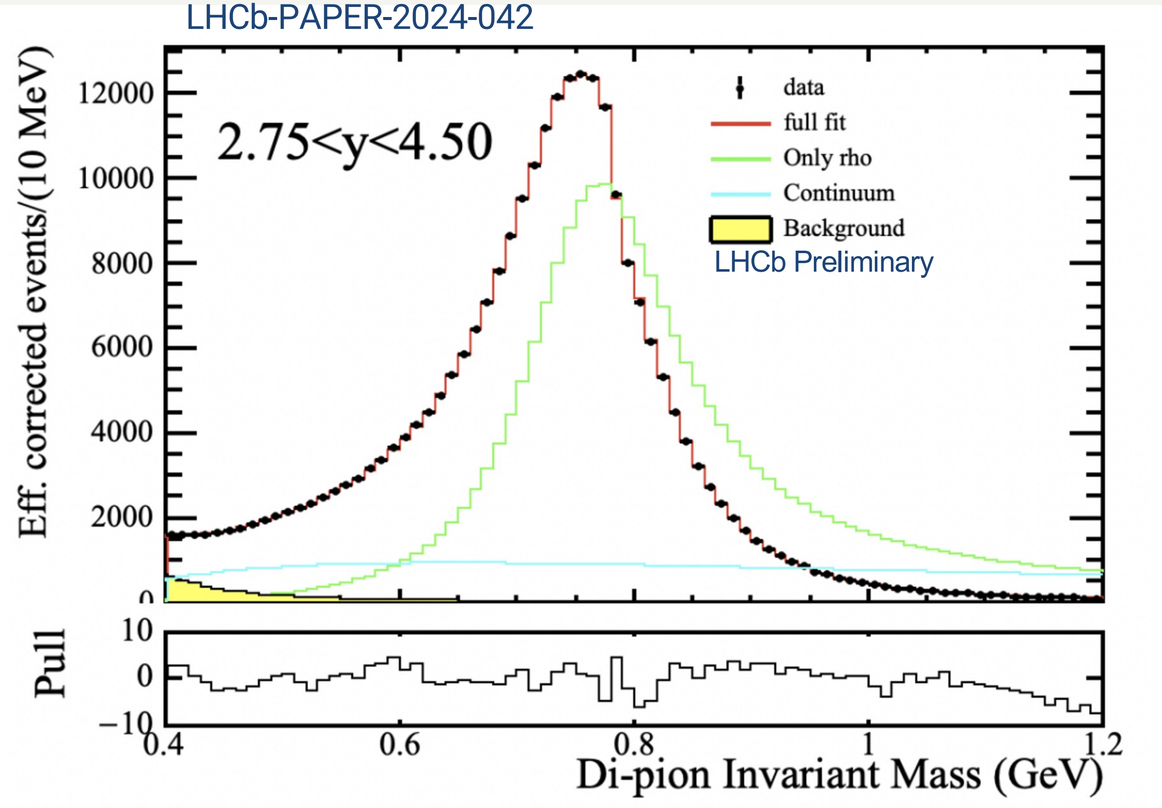
[9] H1, V. Andreev et al., Measurement of Exclusive π +π − and ρ 388 0 Meson Photoproduction 389 at HERA, Eur. Phys. J. C 80 (2020) 1189, arXiv:2005.14471.

Fit Results

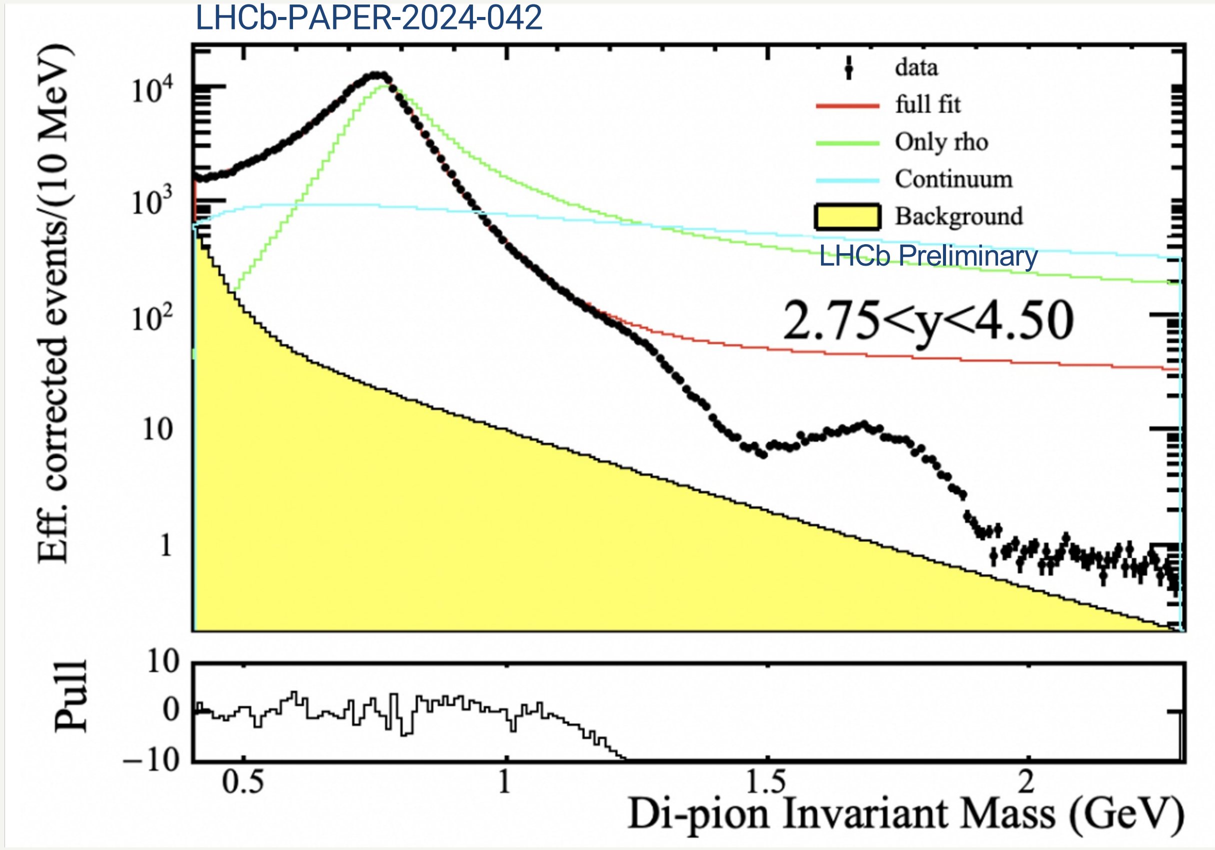
LHCb Preliminary LHCb-PAPER-2024-042	LHCb		STAR	H1
	STAR-fit	H1-fit		
M_ρ[MeV]	774 ± 3	776 ± 3	776.2 ± 0.2	771 ± 3
Γ_ρ [MeV]	156 ± 3	153 ± 3	156 ± 1	151 ± 3
$\|B/A\|$	0.73 ± 0.03	$0.19 \pm .02$	0.79 ± 0.08	0.19 ± 0.04
ϕ_ω[rad]	1.36 ± 0.03	$-0.23 \pm .04$	1.46 ± 0.11	-0.5 ± 0.3
$\|C/A\|$	0.34 ± 0.03	$0.18 \pm .01$	0.36 ± 0.05	0.17 ± 0.02
Λ[MeV]	-	366 ± 110		180 ± 590
δ	-	$1.07 \pm .11$	-	0.76 ± 0.35

Results consistent with previous experiments but model dependent.

Masses > 1.2 GeV?

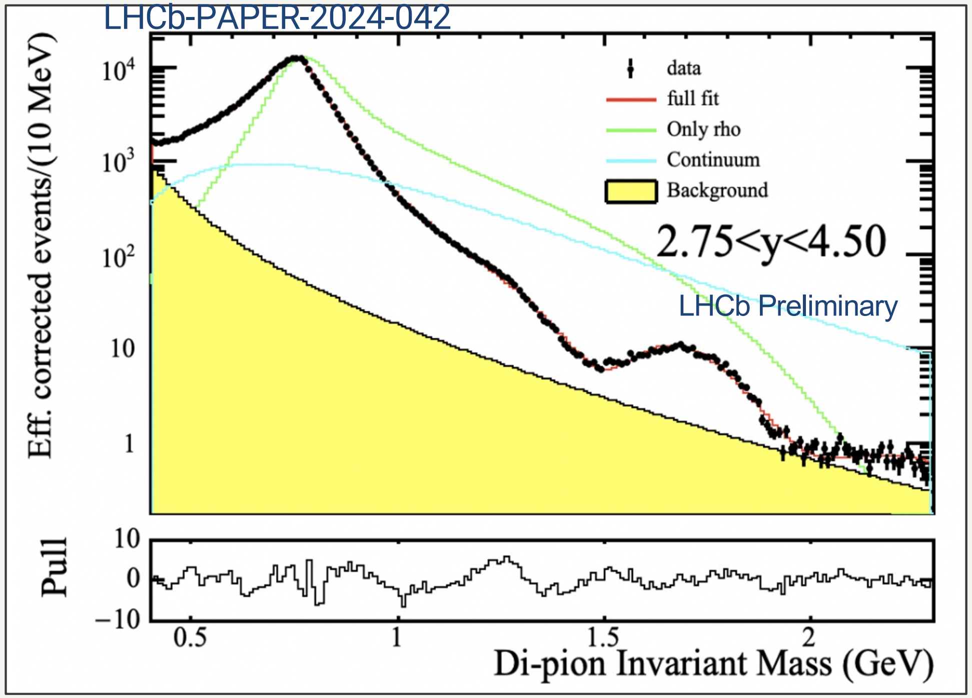


ππ spectrum 400 to 2300 MeV



- Data at high mass falls well below fit
- Does not account for clear structure around 1.7 GeV

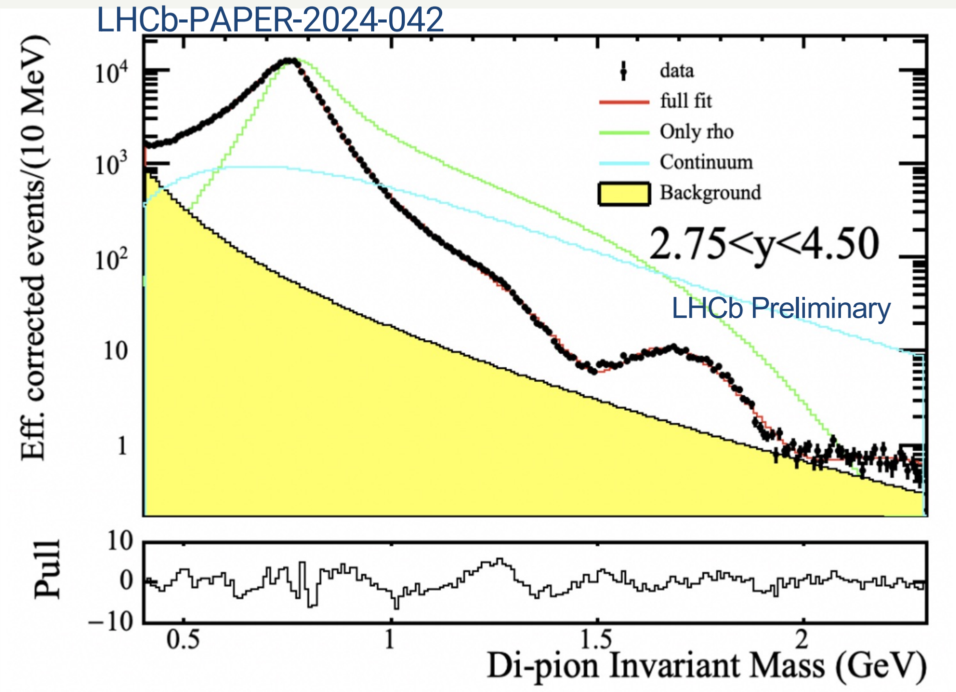
Add form-factor, continuum interference + extra BW to ω + Söding model



	Fit to Eq. 6
M_ρ[MeV]	777.0±0.1
Γ_ρ [MeV]	152.2±0.2
ϕ_c	-0.52±0.02
$\lvert B/A\rvert$	1.1 ± 0.1
$\phi_\omega[rad]$	-0.14±.01
$\lvert C/A\rvert$	0.160 ± 0.002
Λ[MeV]	1.04 ± 0.02
δ	2.98±0.05
Δ[MeV]	1.49±0.01
$\lvert D/A\rvert$	0.0124 ± 0.0003,
$M_{\rho'}$[MeV]	1620 ± 8
$\Gamma_{\rho'}$[MeV]	462 ± 10
$\phi_{\rho'}$	-0.26 ± 0.03

$$S = \frac{q^3(m_{\pi\pi})}{q^3(m_\rho)} \left| \exp\left(-\left(\frac{m_{\pi\pi}^2 - m_\rho^2}{\Delta^2}\right)^2\right) \mathcal{BW}_\rho(m_{\pi\pi}) \left(1 + C\exp(i\phi_\omega)\frac{m_{\pi\pi}^2}{m_\omega^2}\mathcal{BW}_\omega(m_{\pi\pi})\right) + \frac{B\exp(i\phi_c)}{(m_{\pi\pi}^2 - 4m_\pi^2 + \Lambda^2)^\delta} + D\exp(i\phi_{\rho'})\mathcal{BW}_{\rho'} \right|^2 \quad (6)$$

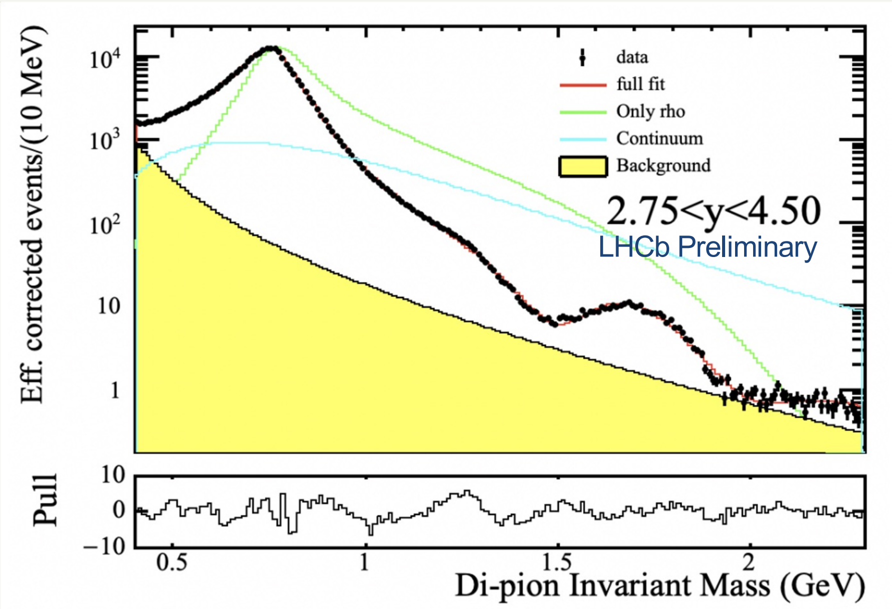
Add form-factor, continuum interference + extra BW to ω + Söding model

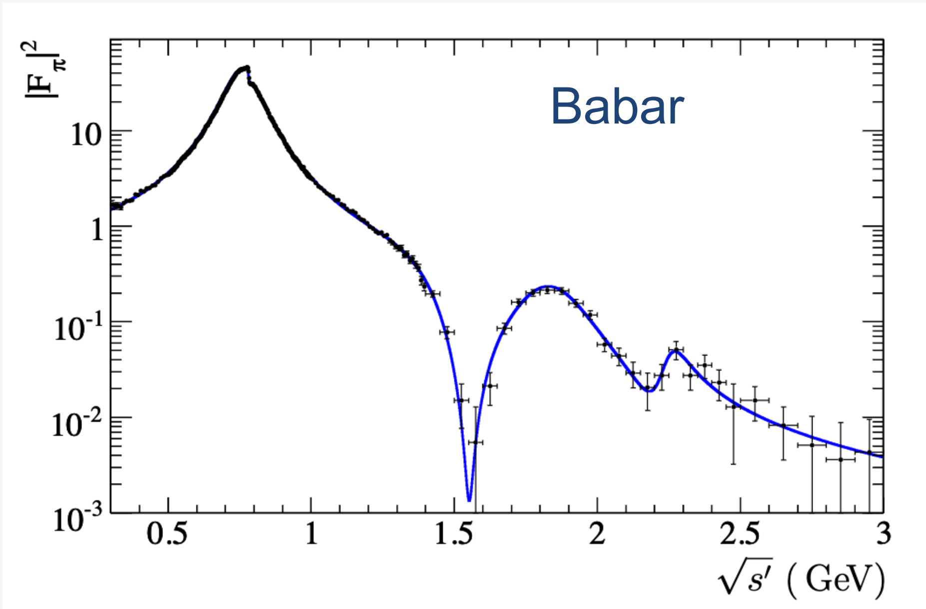


There is no unique way to fit the data.
Amount of ρ, continuum, omega, ρ', ρ'' are model dependent

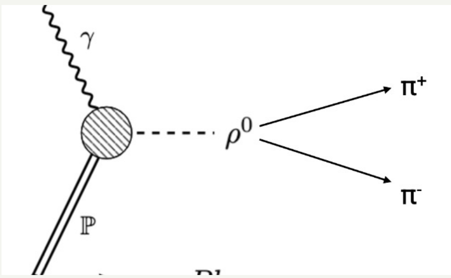
$$S = \frac{q^3(m_{\pi\pi})}{q^3(m_\rho)} \left| \exp\left(-\left(\frac{m_{\pi\pi}^2 - m_\rho^2}{\Delta^2}\right)^2\right) \mathcal{BW}_\rho(m_{\pi\pi}) \left(1 + C\exp(i\phi_\omega)\frac{m_{\pi\pi}^2}{m_\omega^2}\mathcal{BW}_\omega(m_{\pi\pi})\right) + \frac{B\exp(i\phi_c)}{(m_{\pi\pi}^2 - 4m_\pi^2 + \Lambda^2)^\delta} + D\exp(i\phi_{\rho'})\mathcal{BW}_{\rho'} \right|^2 \quad (6)$$

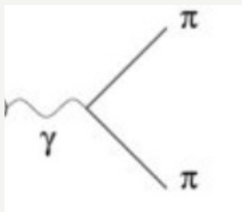
Aside: Useful for g-2?





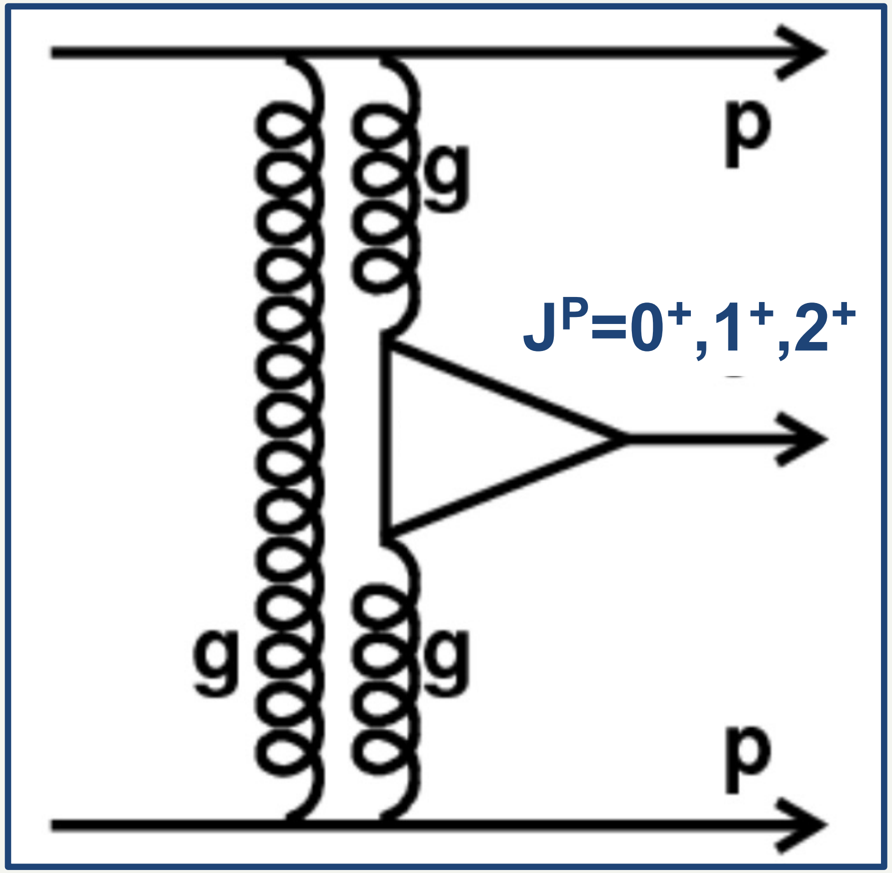
Phys.Rev.D 86 (2012) 032013





Qualitatively similar. If direct comparison not possible, may help understand structure.

Double Pomeron Exchange



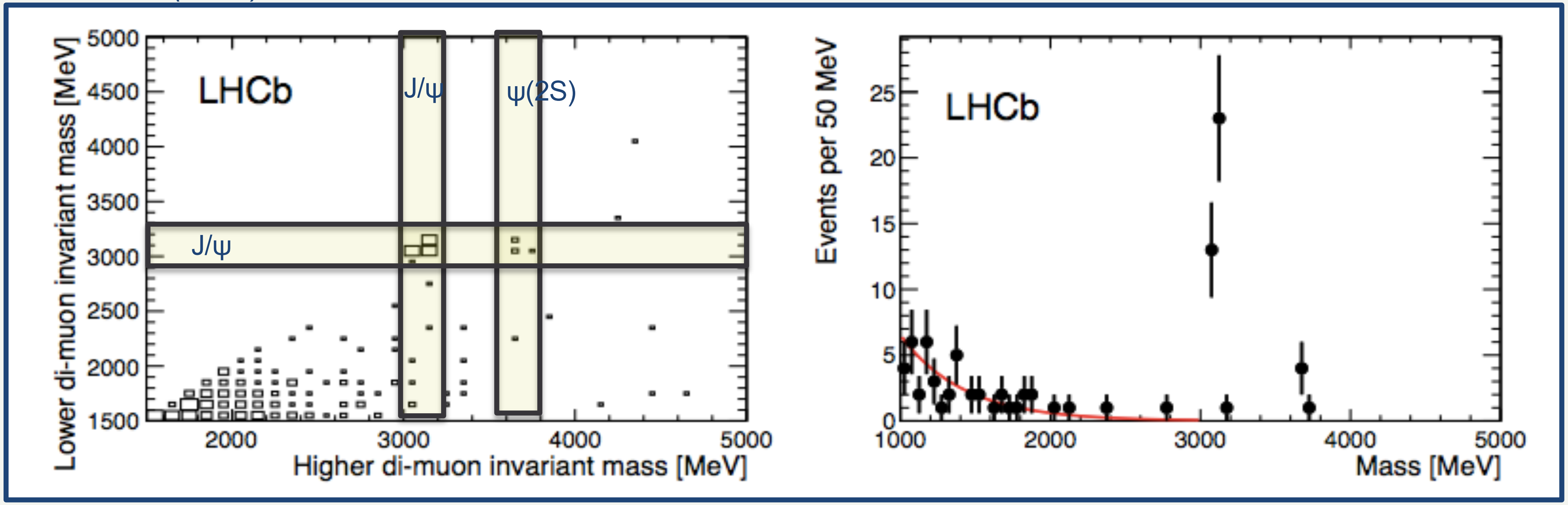
Understanding colourless strong interactions is fundamental

Also simple environment for spectroscopy, in particular, glueballs

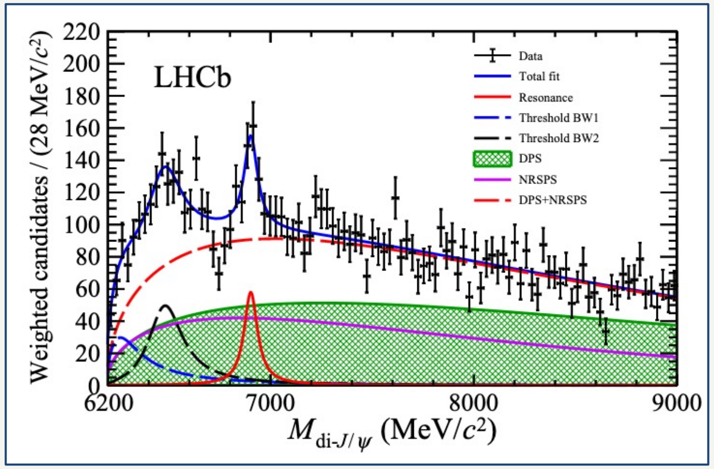
J/ψJ/ψ: search for exotica

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

JPG 41 (2014) 115002



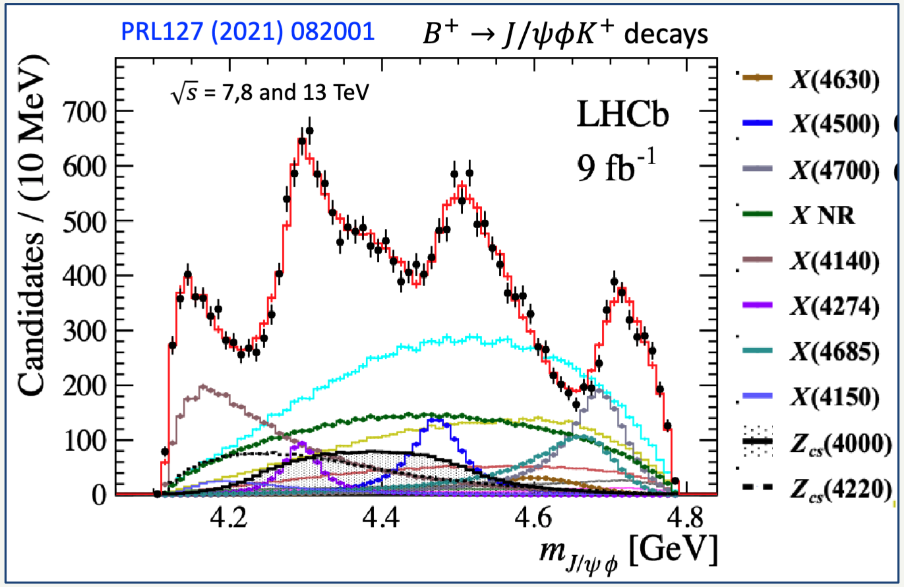
Sci.Bull. 65 (2020) 23, 1983-1993



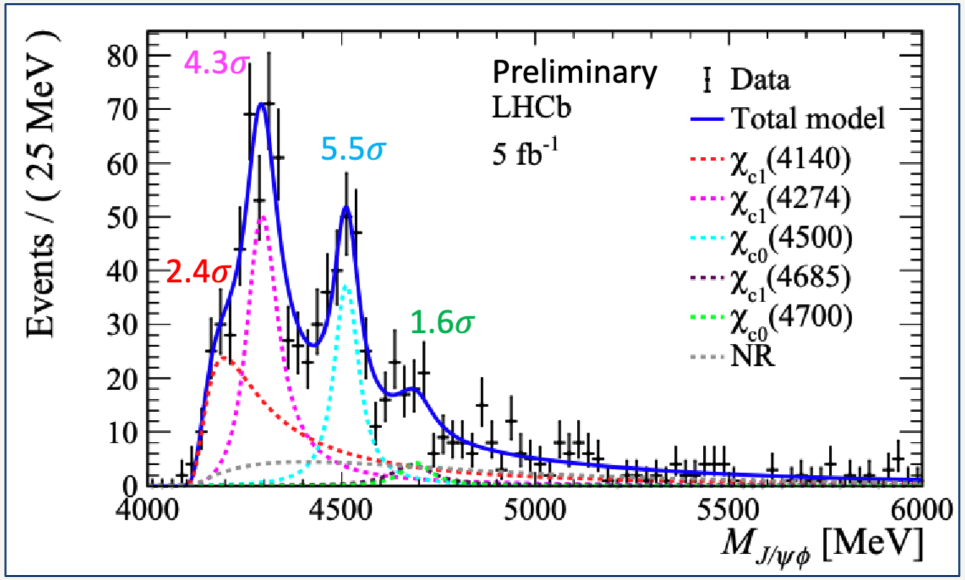
Today from inclusive measurements we know there is significant structure and tetraquark candidates

Diffractive measurements are cleaner and help identify quantum numbers

J/ψ+ϕ: search for exotica



Structure seen in Inclusive production of J/ψ+ϕ .



Similar and much cleaner structure now seen exclusively.

Summary

- New measurements from LHCb in central exclusive production
  - $\pi\pi$ production in PbPb collisions
  - $J/\psi+\phi$ in pp collisions

- Broad range of implications for understanding QCD