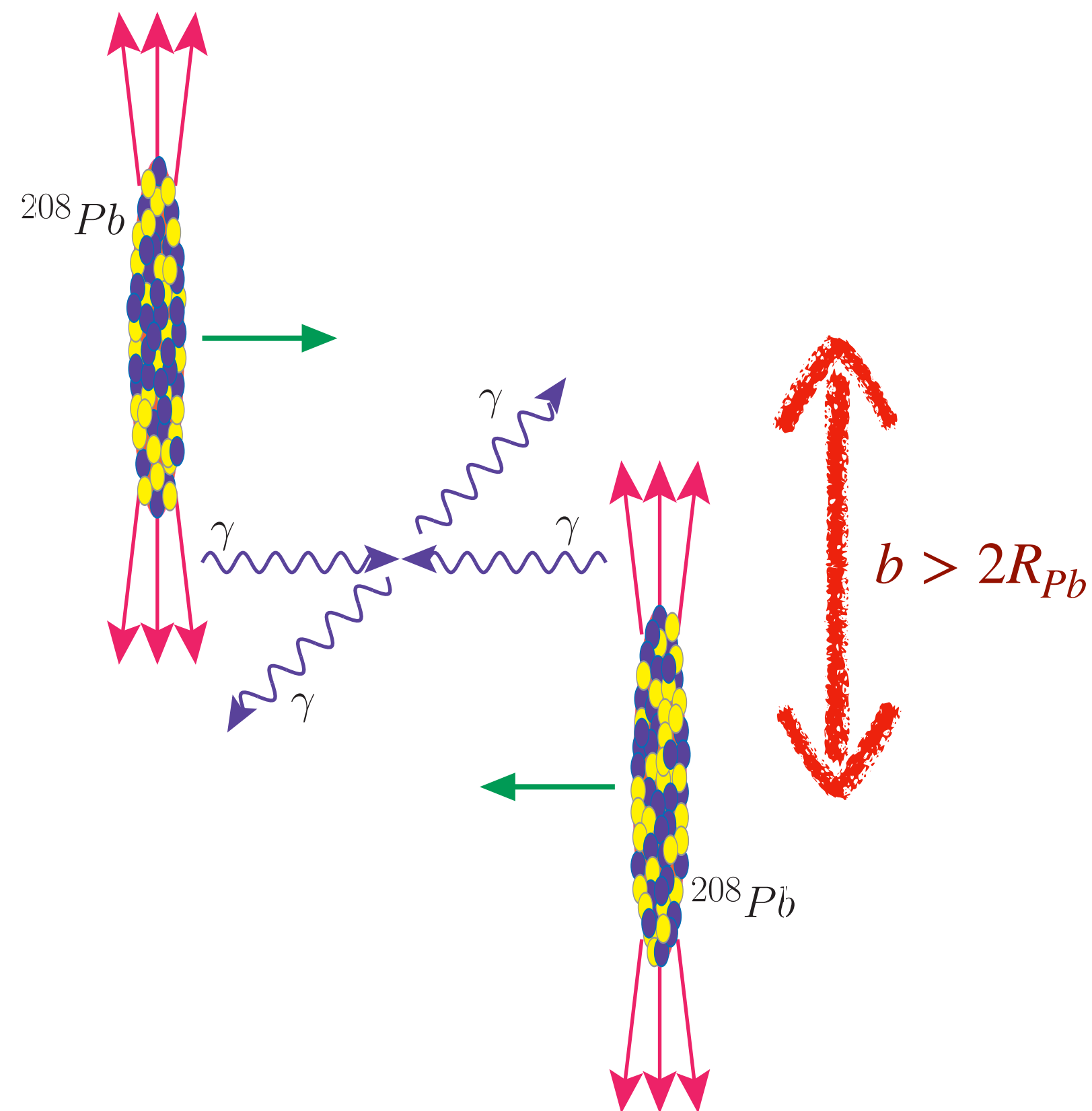




FUNDAMENTAL QED PROCESSES

- Light-by-light scattering: $\gamma\gamma \rightarrow \gamma\gamma$
- Exclusive dilepton production: $\gamma\gamma \rightarrow \ell^+\ell^-$

ELECTROMAGNETIC STRUCTURE

- Proton charge distribution & form factor
- Nuclear geometry & electromagnetic excitation

QCD AND HADRONIC STRUCTURE

- Vector meson photoproduction $\gamma A \rightarrow VA$
- Nuclear gluon distributions and shadowing

**Common theoretical framework -
different processes, complementary insights**

Photon-induced processes in ultraperipheral collisions: from QED to QCD

Mariola Kłusek-Gawenda



LIGHT-BY-LIGHT SCATTERING: BEYOND THE COHERENT PICTURE



A rare QED process accessible at the LHC:

- Strong el-mag fields of ultrarelativistic nuclei provide intense photon flux
- The dominant contribution comes from coherent photon emission
- Precision measurements require additional photon-induced mechanisms to be understood

$$\sigma^{LbL}(\sqrt{s_{NN}}) \propto f_{\gamma/Pb}^{el}(x_1) \otimes f_{\gamma/Pb}^{el}(x_2) \otimes \hat{\sigma}[\gamma\gamma \rightarrow \gamma\gamma; W_{\gamma\gamma}]$$

$$+ f_{\gamma/Pb}^{el}(x_1) \otimes f_{\gamma/Pb}^{inel}(x_2) \otimes \hat{\sigma}[\gamma\gamma \rightarrow \gamma\gamma; W_{\gamma\gamma}]$$

$$+ f_{\gamma/Pb}^{inel}(x_1) \otimes f_{\gamma/Pb}^{el}(x_2) \otimes \hat{\sigma}[\gamma\gamma \rightarrow \gamma\gamma; W_{\gamma\gamma}]$$

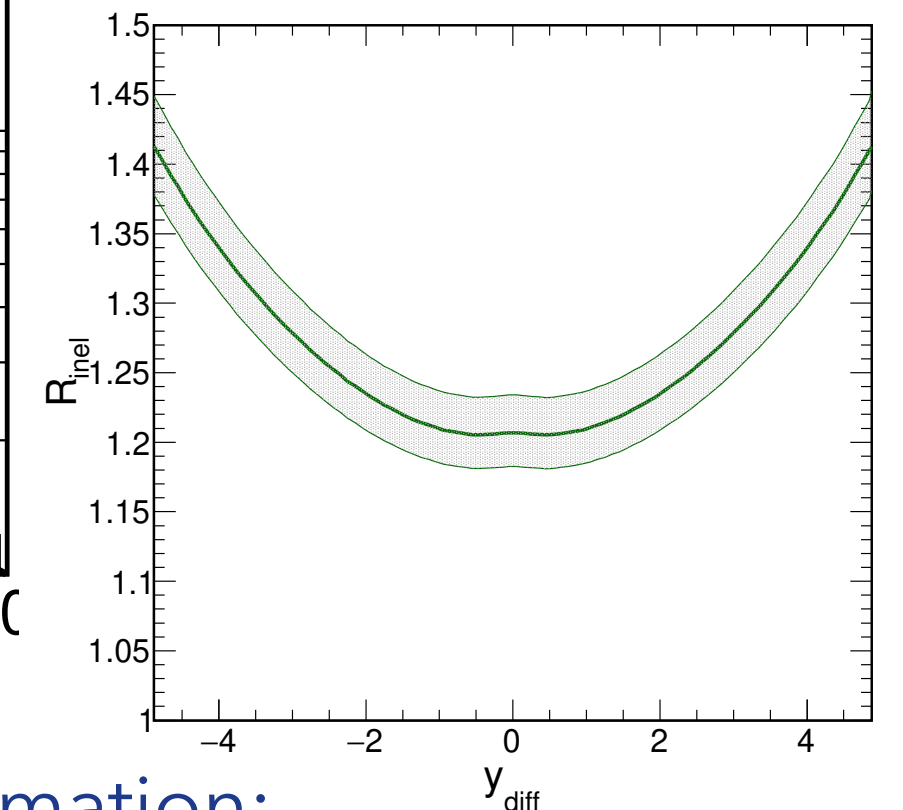
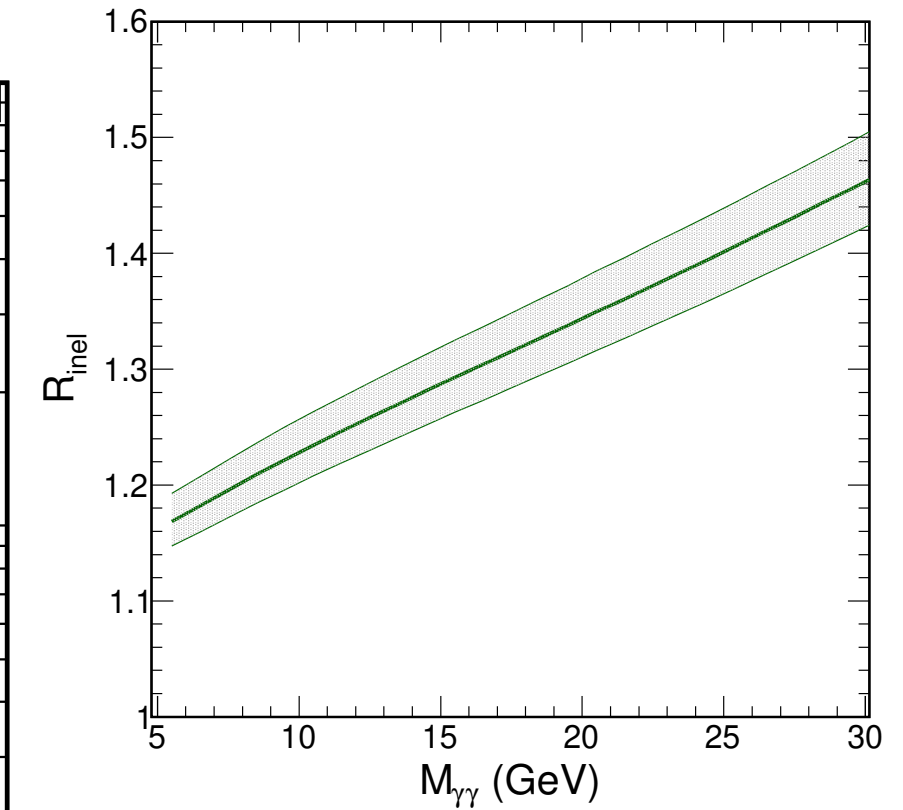
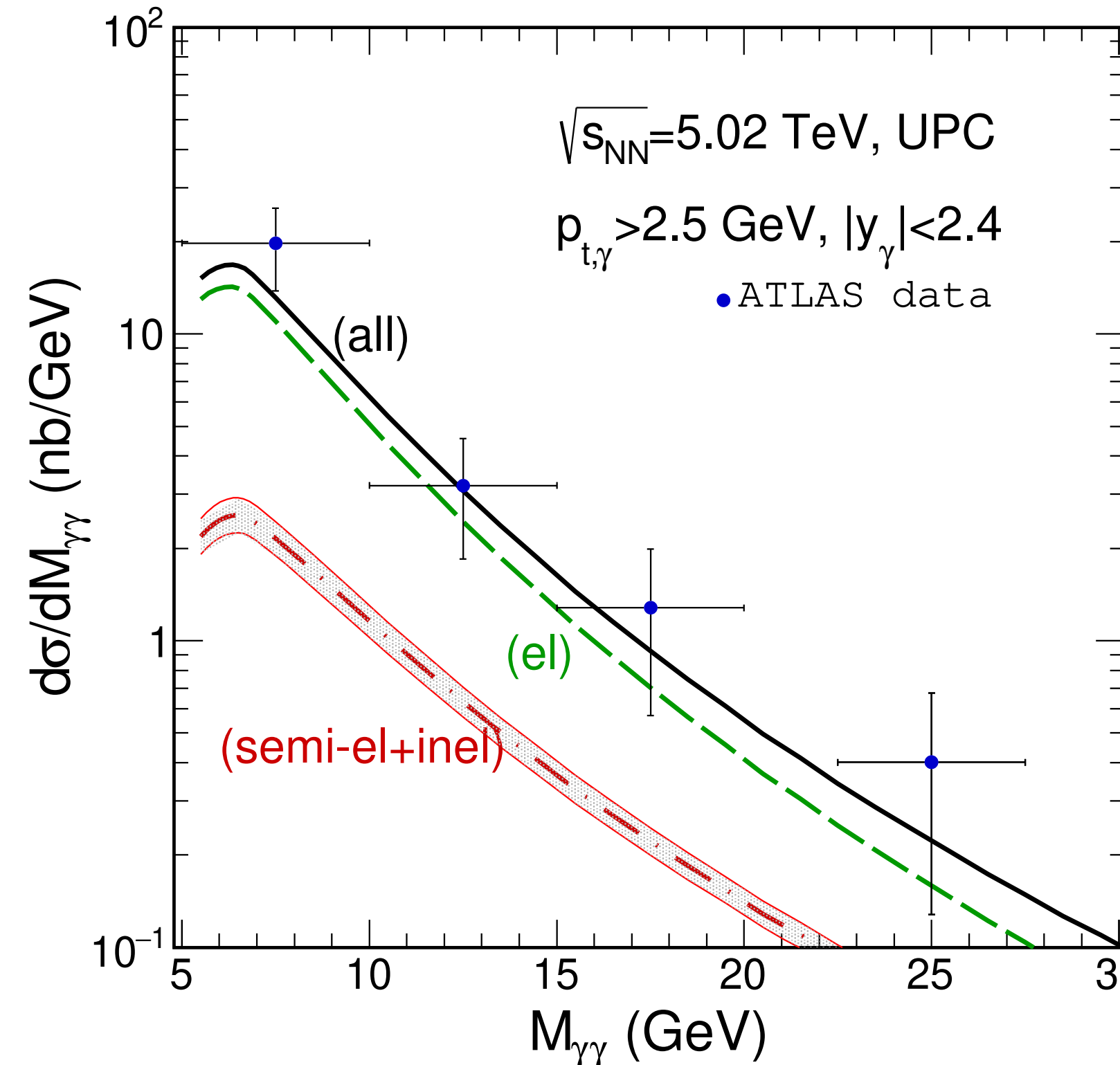
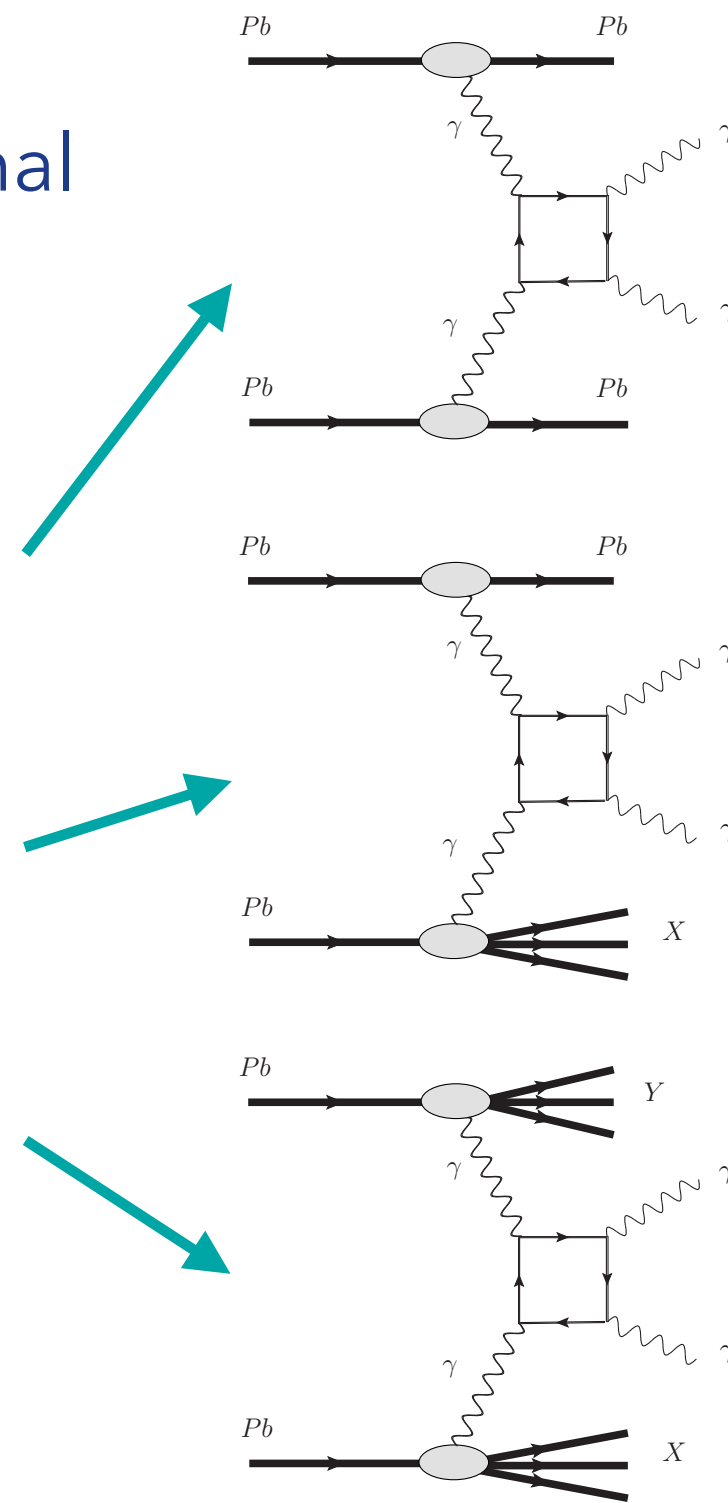
$$+ f_{\gamma/Pb}^{inel}(x_1) \otimes f_{\gamma/Pb}^{inel}(x_2) \otimes \hat{\sigma}[\gamma\gamma \rightarrow \gamma\gamma; W_{\gamma\gamma}]$$

$$f_{\gamma/Pb}^{el}(x) = \frac{\alpha Z^2}{\pi x} \{ 2\xi K_0(\xi) K_1(\xi) - \xi^2 [K_1^2(\xi) - K_0^2(\xi)] \}$$

$$f_{\gamma/Pb}^{inel}(x, \mu^2) = Z \times f_{\gamma/p}^{el}(x, \mu^2) + (A - Z) \times f_{\gamma/n}^{el}(x, \mu^2)$$

$$f_{\gamma/p}^{el}(x, \mu^2) = f_{\gamma/p}^{el}(x) + f_{\gamma/p}^{inel}(x, \mu^2) \quad f_{\gamma/n}^{el}(x, \mu^2) = f_{\gamma/n}^{el}(x) + f_{\gamma/n}^{inel}(x, \mu^2)$$

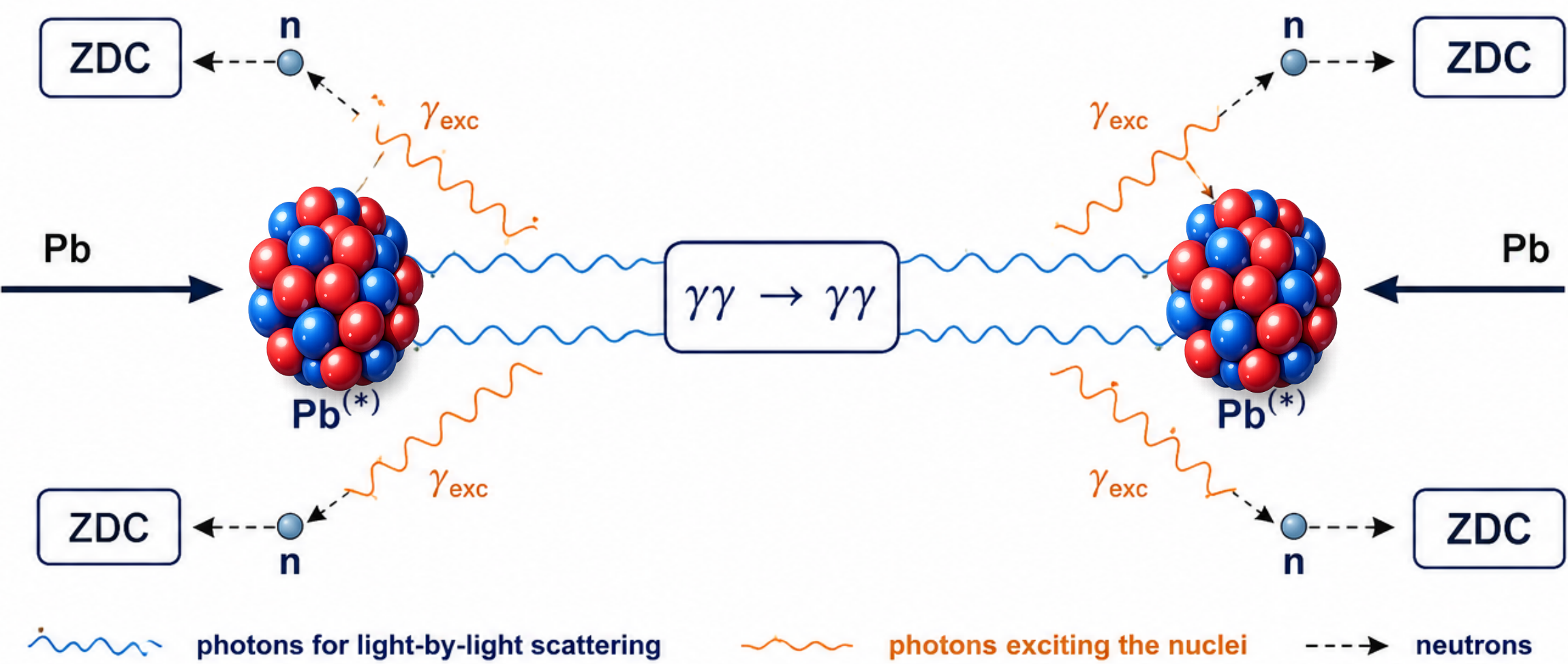
$$\sigma_{AA \rightarrow AA + \gamma\gamma} = \int \sigma_{\gamma\gamma \rightarrow \gamma\gamma}(W_{\gamma\gamma}) S^2(b) N(\omega_1, b_1) N(\omega_2, b_2) d^2b d\bar{b}_x d\bar{b}_y \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma} dY_{\gamma\gamma}$$



Beyond the standard coherent approximation:

- Contributions involving nuclear dissociation
- Inelastic mechanisms can provide **non-negligible corrections**
- Enhancements of ~20-40% in selected kinematic regions

LbL IN UPC & ASSOCIATED MEASUREMENT OF NEUTRON EMISSION FROM NUCLEI



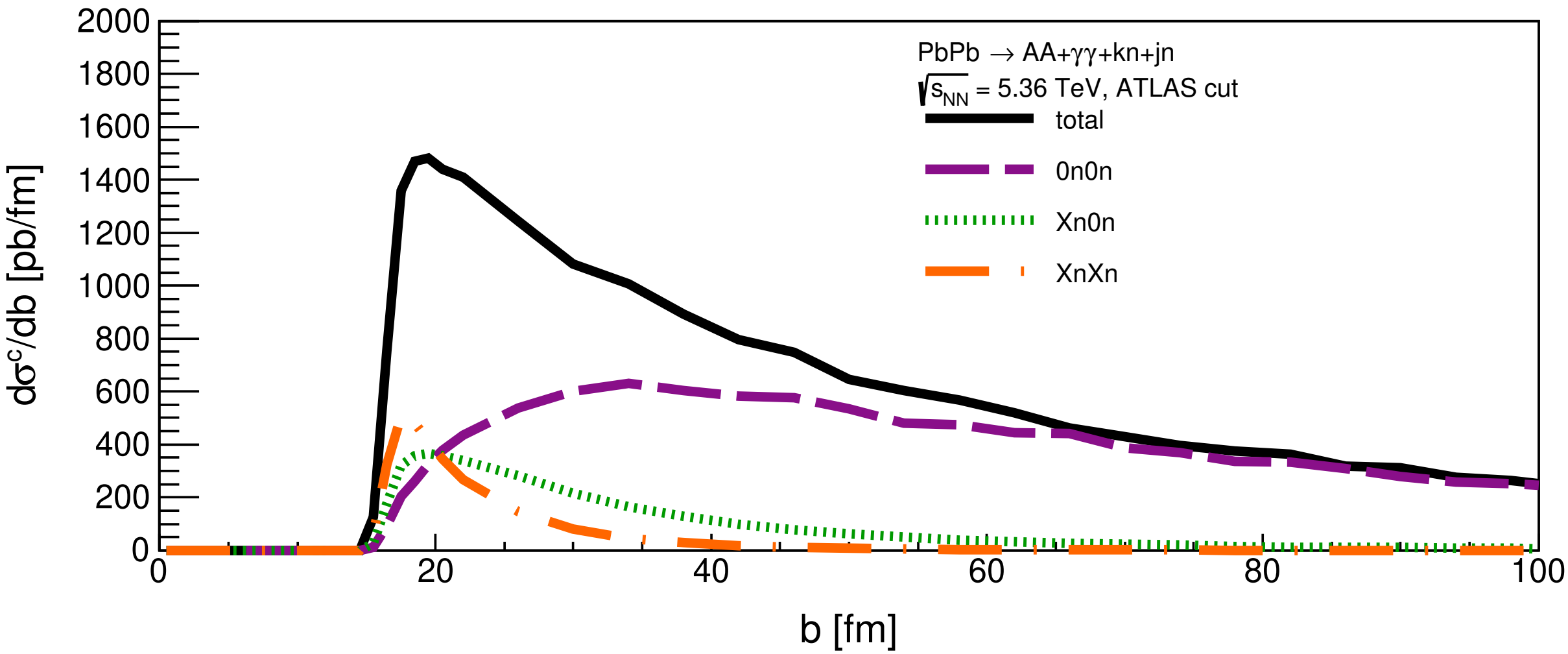
ATLAS acceptance region @ $\sqrt{s_{NN}} = 5.36$ TeV:

$$y_{\gamma_1}, y_{\gamma_2} \in (-2.4, 2.4)$$

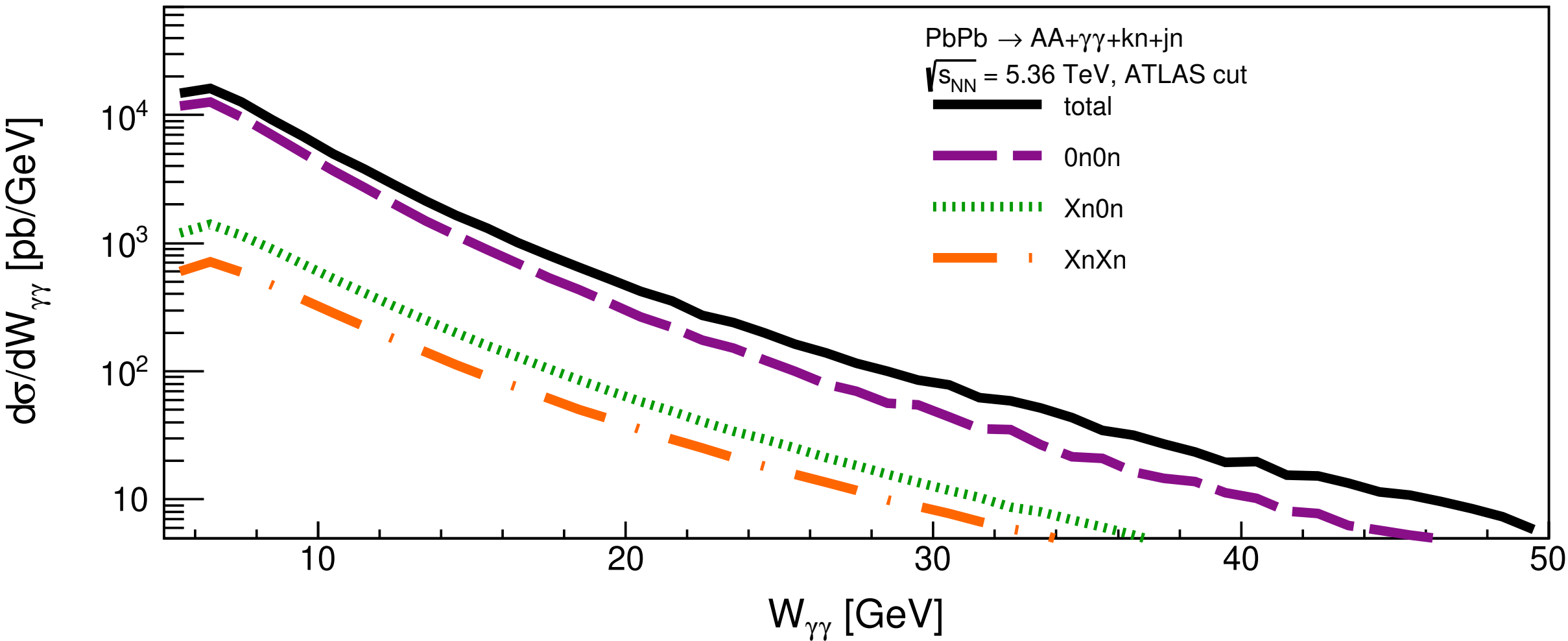
$$p_{t,\gamma} > 2.5 \text{ GeV}$$

	σ_{total}	$0n0n$	$XnXn$	$Xn0n + 0nXn$
Cross section [nb]	81.886	61.679	4.261	15.963
Percent of σ_{total} [%]		75.30	5.20	19.50

Nuclear cross section in nb for $PbPb \rightarrow Pb^{*}Pb^{*}\gamma\gamma$.



Impact parameter distribution for LbL for different categories.



Diphoton invariant mass for different categories.

$\approx 25\%$ of all LbL contain forward neutrons

EXCLUSIVE DILEPTON PRODUCTION: A PROBE OF PROTON STRUCTURE

Photon-induced dilepton production in proton-proton collisions

$$pp \rightarrow pp\ell^+\ell^-$$

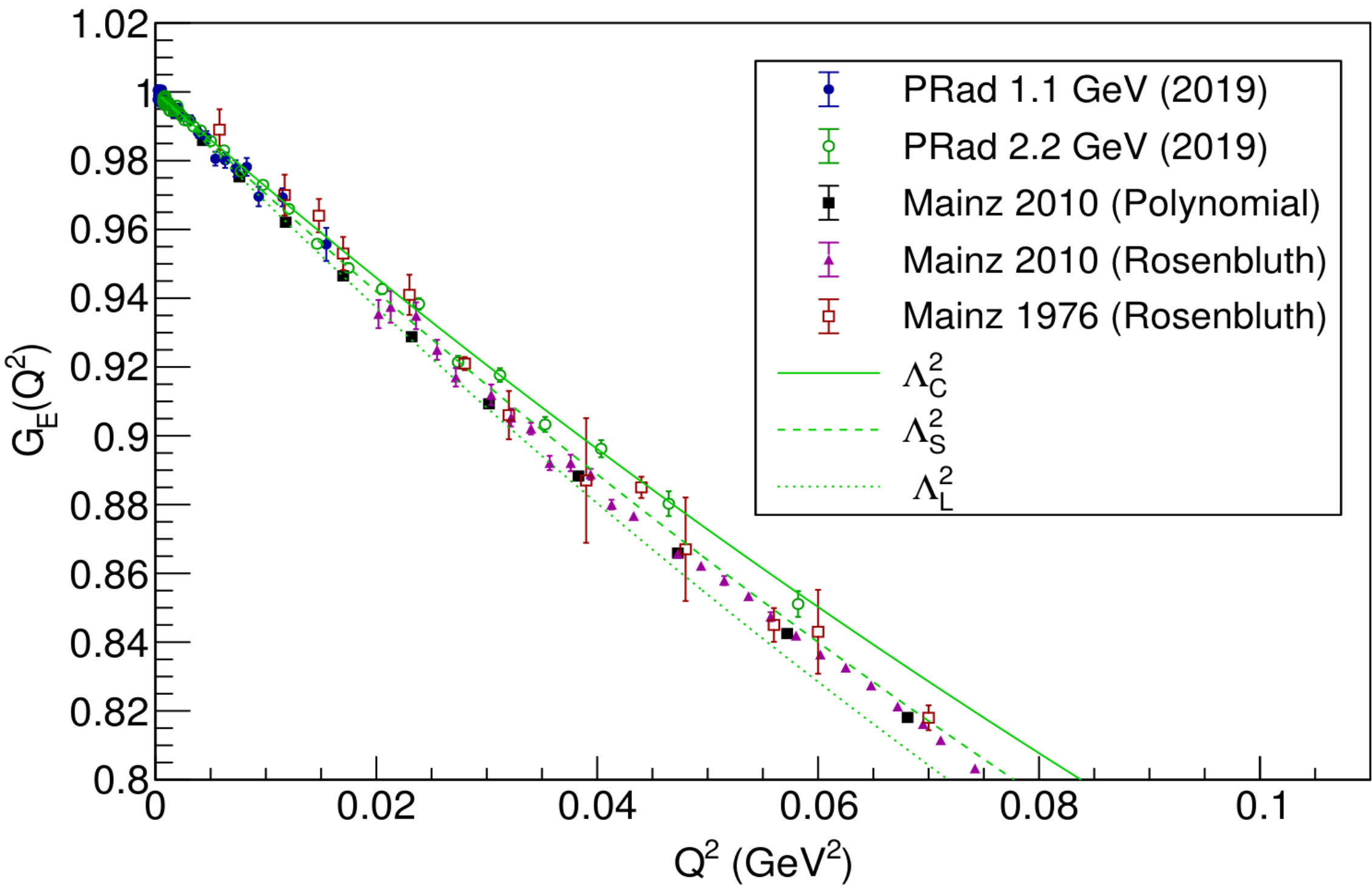
- A well-controlled QED subprocess: $\gamma\gamma \rightarrow \ell^+\ell^-$
- Photon emission depends on the electromagnetic form factors of the proton
- Exclusive dilepton measurements provide sensitivity to the proton charge distribution

Can exclusive dilepton production constrain the proton charge-radius scale?

The charge radius is encoded in the low- Q^2 slope of the electric form factor: $r_p^2 = -6(\hbar c)^2 \frac{dG_E(Q^2)}{dQ^2} \Big|_{Q^2=0}$

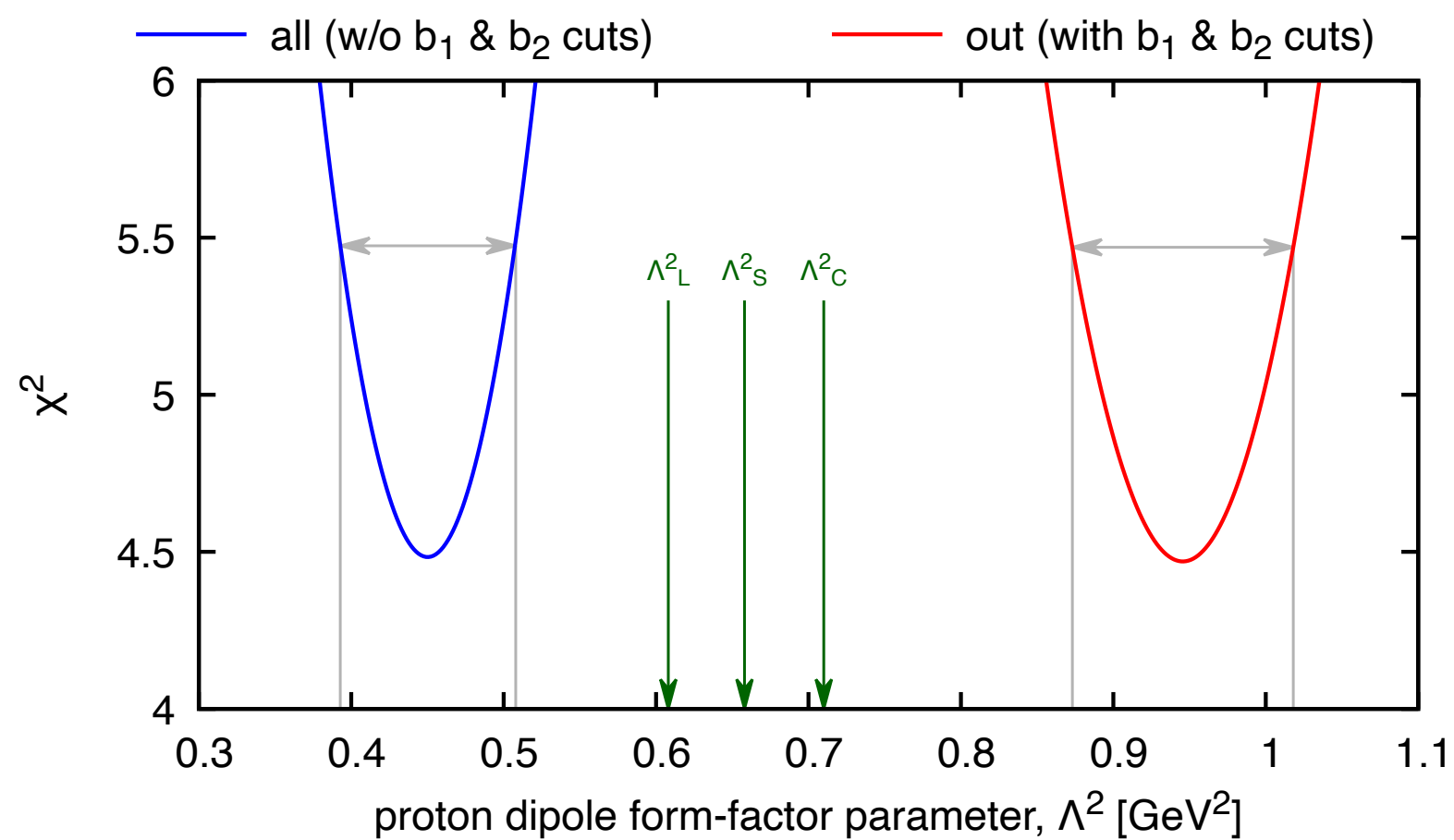
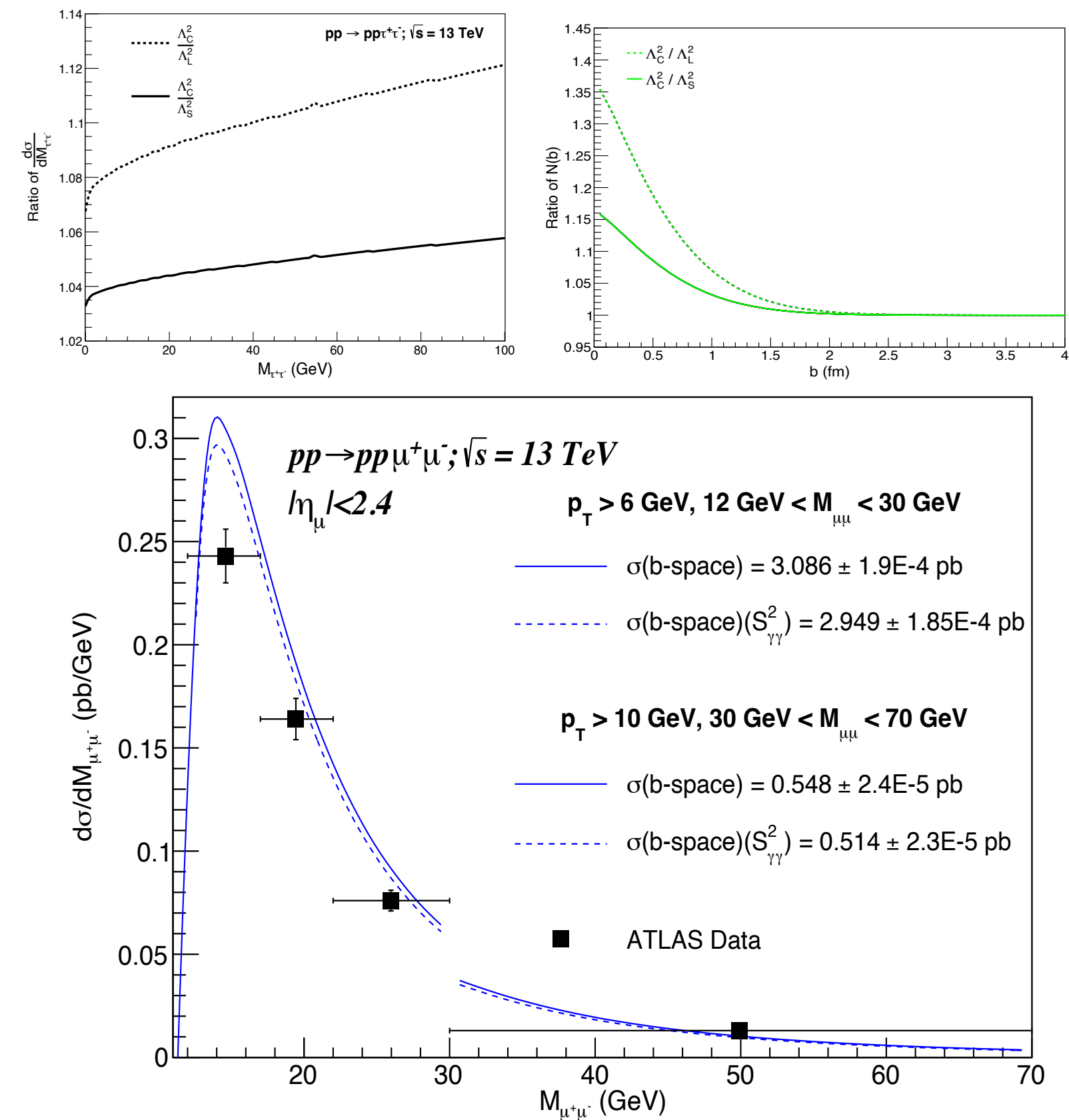
$$G_E(Q^2) = \left(1 + \frac{Q^2}{\Lambda^2}\right)^{-2} \longrightarrow r_p^2 = \frac{12(\hbar c)^2}{\Lambda^2}$$

PDG			
Scenario	L , large proton	S , small proton	C , conventional
Proton radius	$r_L = 0.8751$ fm	$r_S = 0.84087$ fm	$r_C = 0.81$ fm
Dipole cutoff	$\Lambda_L^2 = 0.6081$ GeV ²	$\Lambda_S^2 = 0.6587$ GeV ²	$\Lambda_C^2 = 0.71$ GeV ²



SENSITIVITY TO THE PROTON CHARGE-RADIUS SCALE

Process and kinematics	$\sigma_{\text{th}}(\Lambda_C^2)$ (pb)	$\sigma_{\text{th}}(\Lambda_L^2)$ (pb)	σ_{exp} (pb)
$pp \rightarrow pp\mu^+\mu^-$, $\sqrt{s} = 7$ TeV, ATLAS $M_{\mu^+\mu^-} > 20$ GeV, $p_T > 10$ GeV	0.745	0.708	$0.628 \pm 0.032 \pm 0.021$
$pp \rightarrow ppe^+e^-$, $\sqrt{s} = 7$ TeV, ATLAS $M_{e^+e^-} > 24$ GeV, $p_T > 12$ GeV	0.461	0.438	$0.428 \pm 0.035 \pm 0.018$
$pp \rightarrow pp\mu^+\mu^-$, $\sqrt{s} = 7$ TeV, CMS $M_{\mu^+\mu^-} > 11.5$ GeV, $p_T > 4$ GeV	3.914	3.753	$3.38^{+0.58}_{-0.55} \pm 0.21$
$pp \rightarrow pp\mu^+\mu^-$, $\sqrt{s} = 13$ TeV, ATLAS $12 < M_{\mu^+\mu^-} < 70$ GeV, $p_T > 6$ GeV	3.622	3.484	$3.12 \pm 0.07 \pm 0.14$



Our recent results (*PRD 114 (2026) 076003, N. Krishna, M. KG, R. Staszewski*)

- Comparison of theoretical predictions with ATLAS and CMS measurements
- Sensitivity of exclusive dilepton production to the proton electromagnetic form factor
- A model-dependent fit provides:

$$\Lambda^2 = 0.465 \pm 0.056 \text{ GeV}^2 \longrightarrow r_p = 1.002 \pm 0.038 \text{ fm}$$

Outlook:

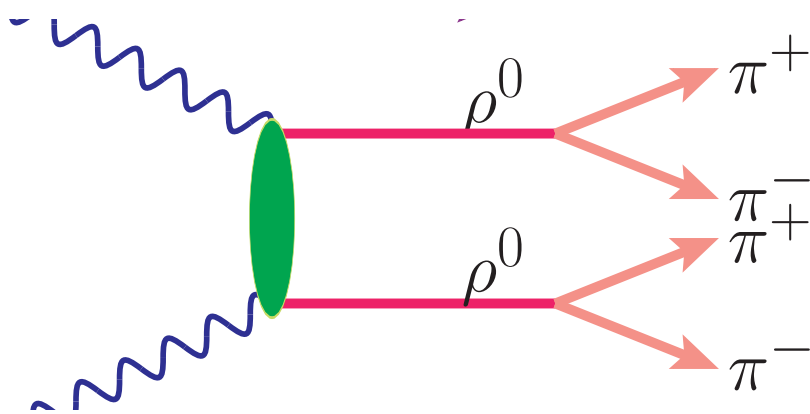
improved photon flux & survival factor uncertainties in precision $\ell^+\ell^-$ measurements

FROM PHOTONS TO HADRONS: EXPLORING NONPERTURBATIVE QCD

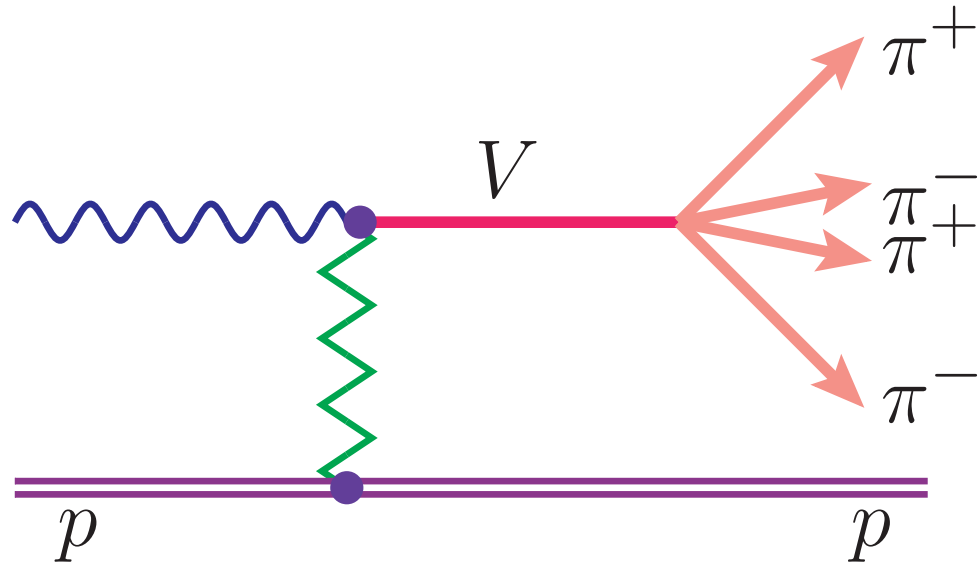
Photon-induced interactions provide access to exclusive hadronic final states

Different production mechanisms contribute to the same final state.
Two complementary production mechanisms:

$\gamma\gamma \rightarrow \text{hadrons}$

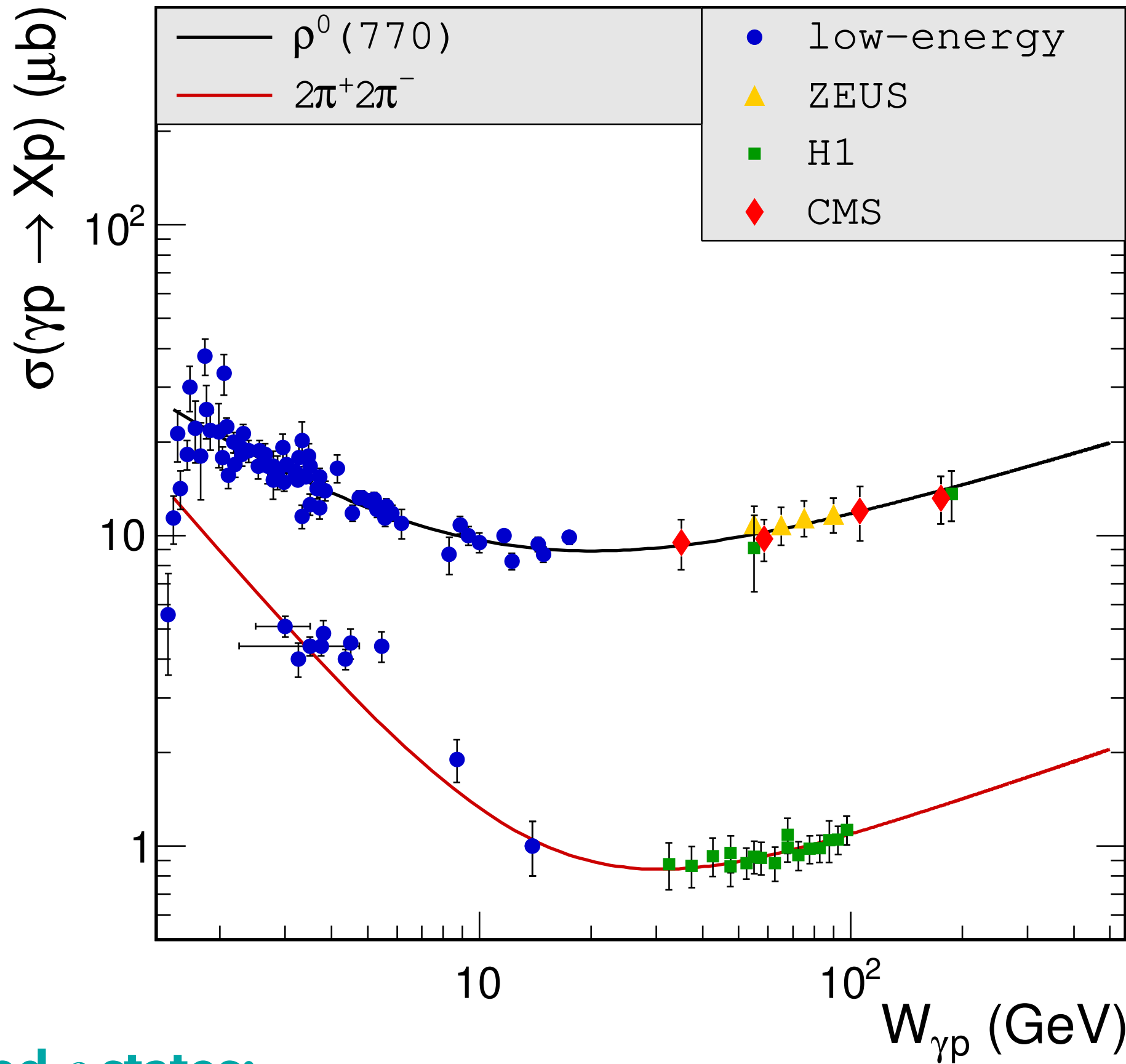


$\gamma A \rightarrow VA$



Physics opportunities:

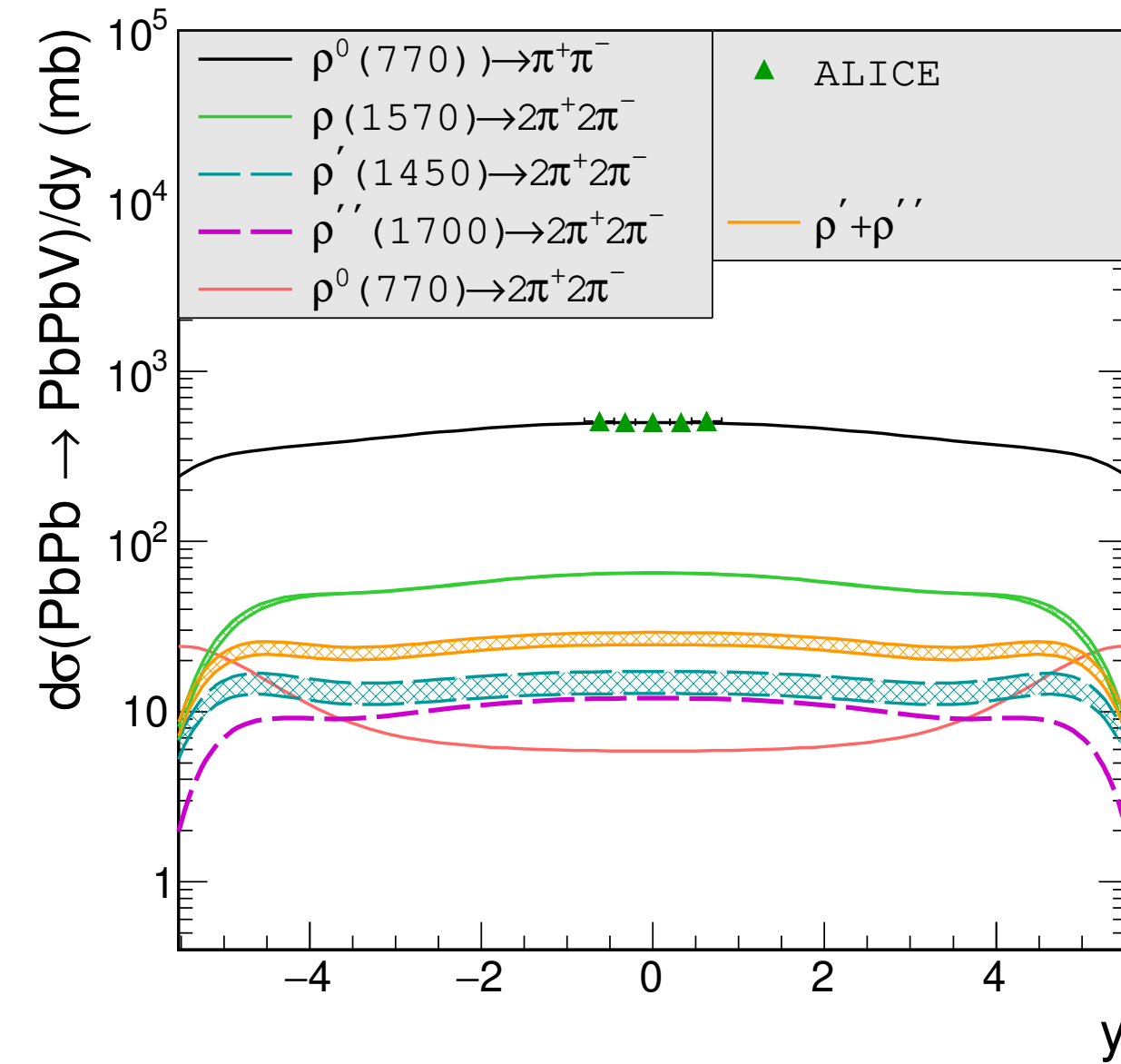
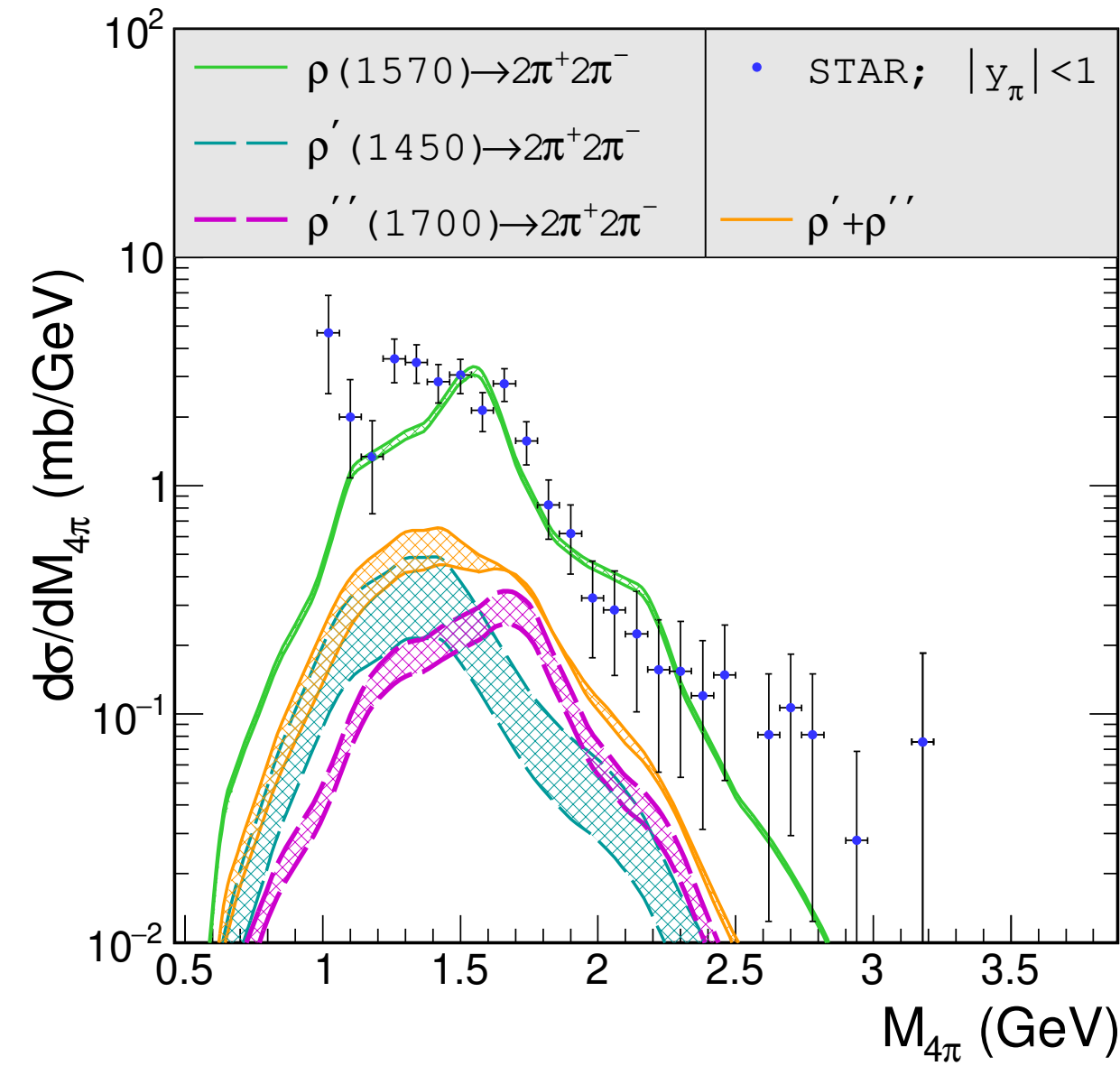
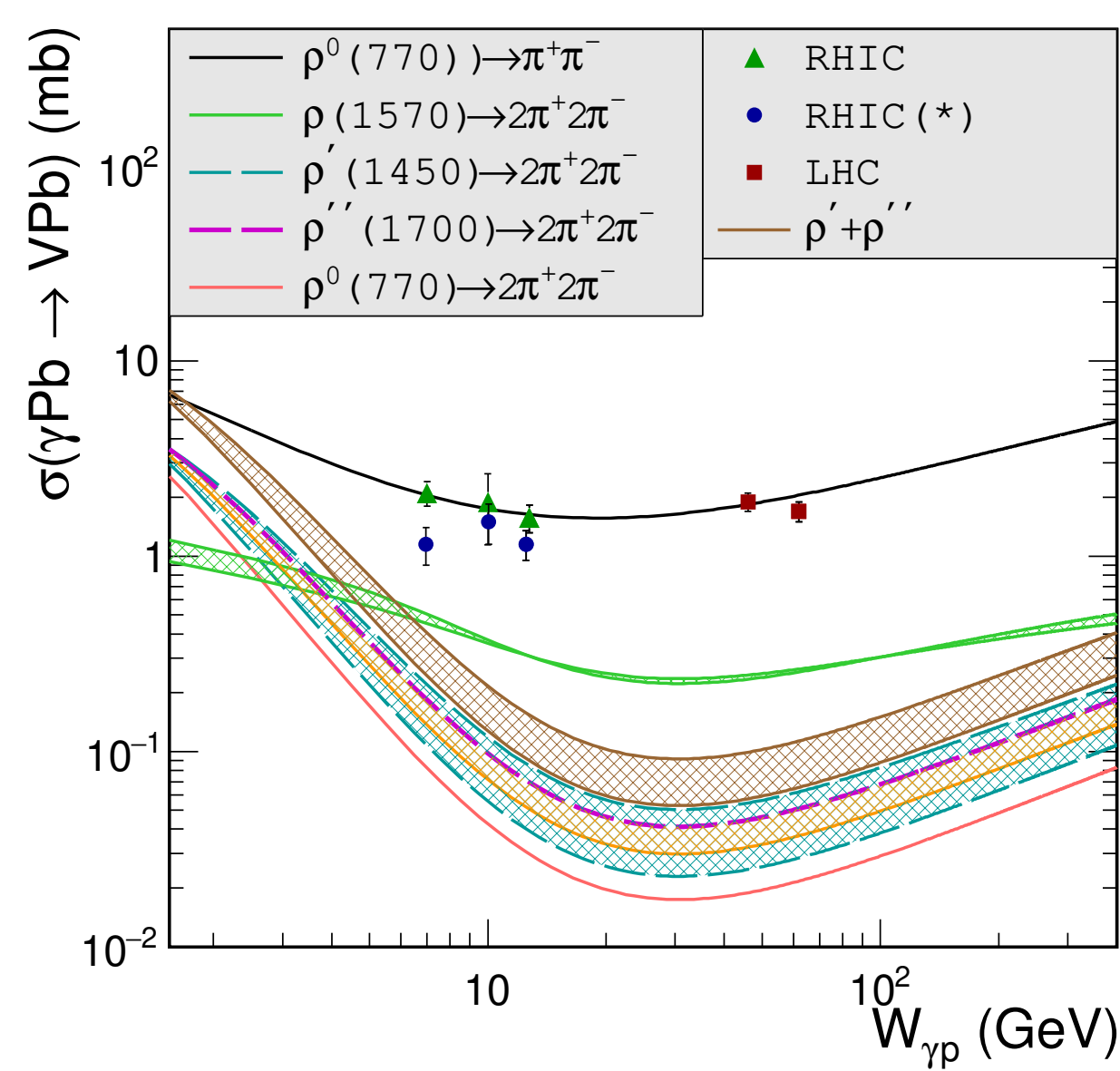
- Meson resonance production and spectroscopy
- Interference between resonant and non-resonant amplitudes
- $\gamma - IP$ interactions and nuclear effects



Excited ρ states:
resonance interpretation remains open

Resonance	m [GeV]	Γ [GeV]	$\Gamma_{e^+e^-}$ [keV]
$\rho(1450)$	1.465 ± 0.025	0.4 ± 0.05	$4.30 - 10$
$\rho(1570)$	1.570 ± 0.070	0.144 ± 0.09	$0.35 - 0.5$
$\rho(1700)$	1.720 ± 0.020	0.25 ± 0.01	$6.30 - 8.9$

FOUR-PION PHOTOPRODUCTION: EXCITED VECTOR MESONS



1. Validation

Ground state ρ^0 photoproduction

2. Extension

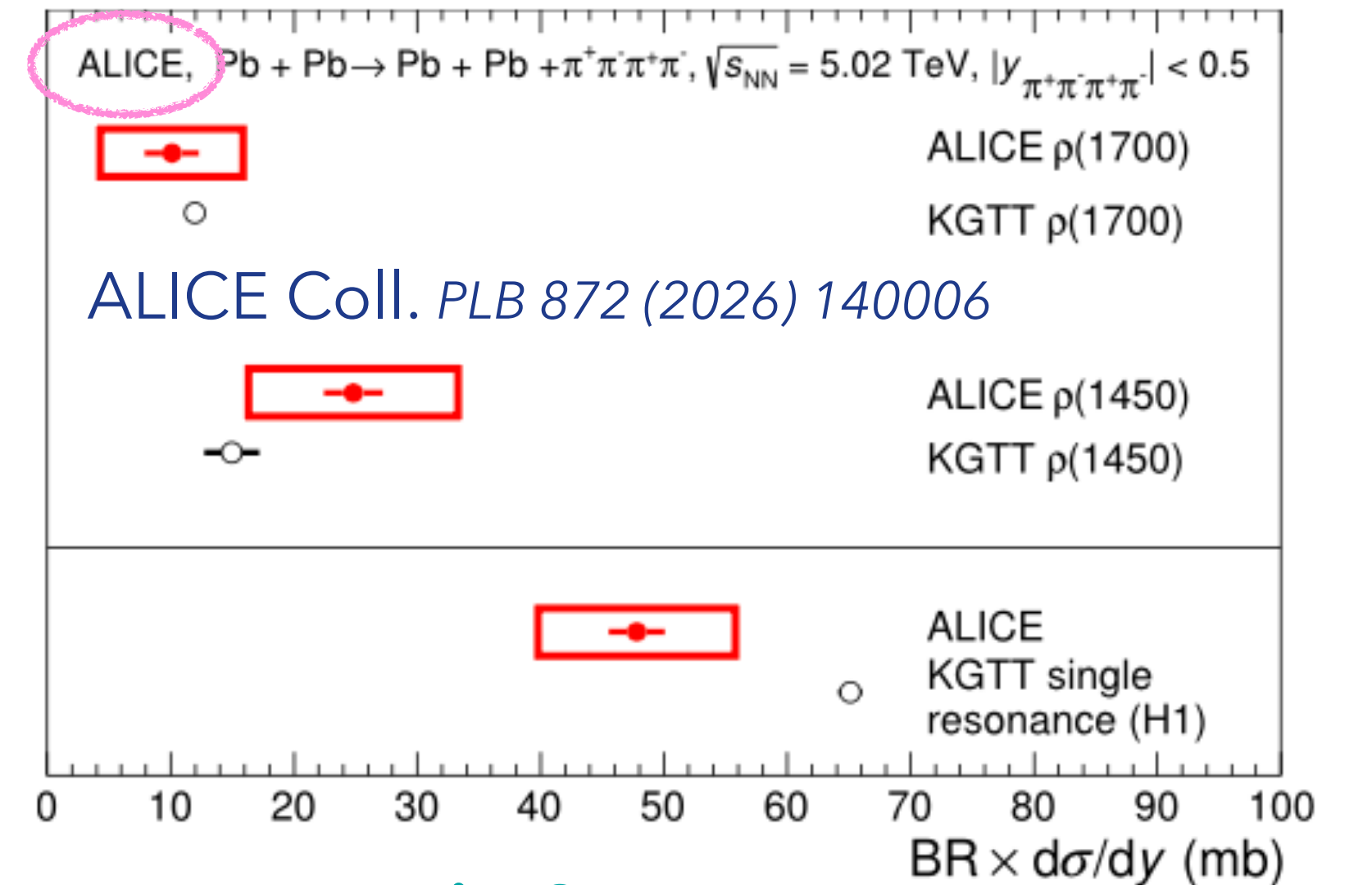
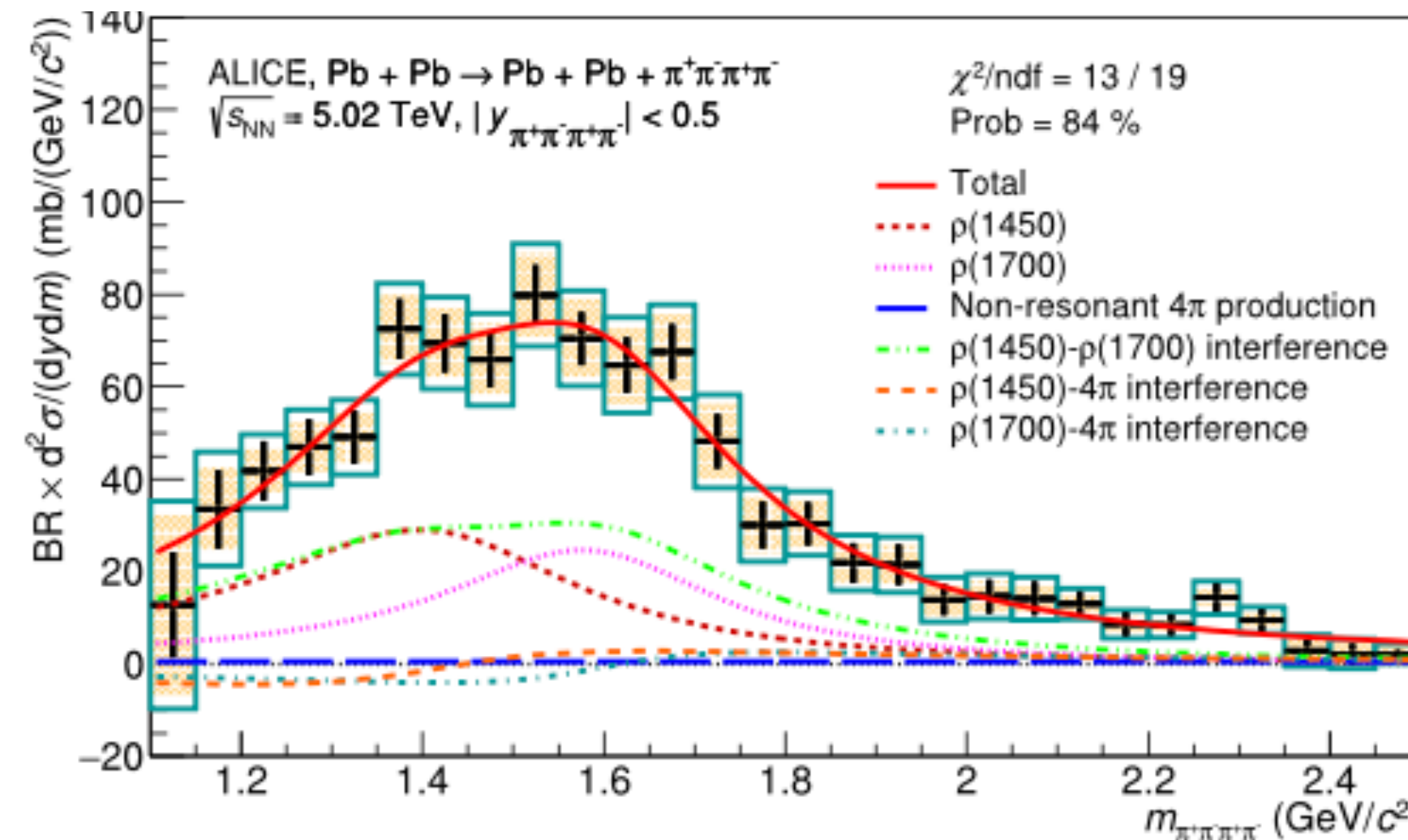
Excited ρ states and the STAR 4π spectrum

3. Predictions

4π photoproduction at LHC energies

First ALICE measurement of coherent 4π photoproduction in $Pb - Pb$ UPCS

The extracted masses and widths of the two resonances:
 $m_1 = 1385 \pm 14(stat.) \pm 3(syst.) MeV$
 $\Gamma_1 = 431 \pm 36(stat.) \pm 82(syst.) MeV$
 and
 $m_2 = 1663 \pm 13(stat.) \pm 22(syst.) MeV$
 $\Gamma_2 = 357 \pm 31(stat.) \pm 49(syst.) MeV$



Can the new data distinguish between different resonance scenarios?

FROM DIPIONS TO DIKAONS

- M. G. Ryskin and Y. M. Shabelski,

Elastic ρ^0 and Φ meson photoproduction and electroproduction with nonresonant background, Phys. At. Nucl. 62, 980 (1999):

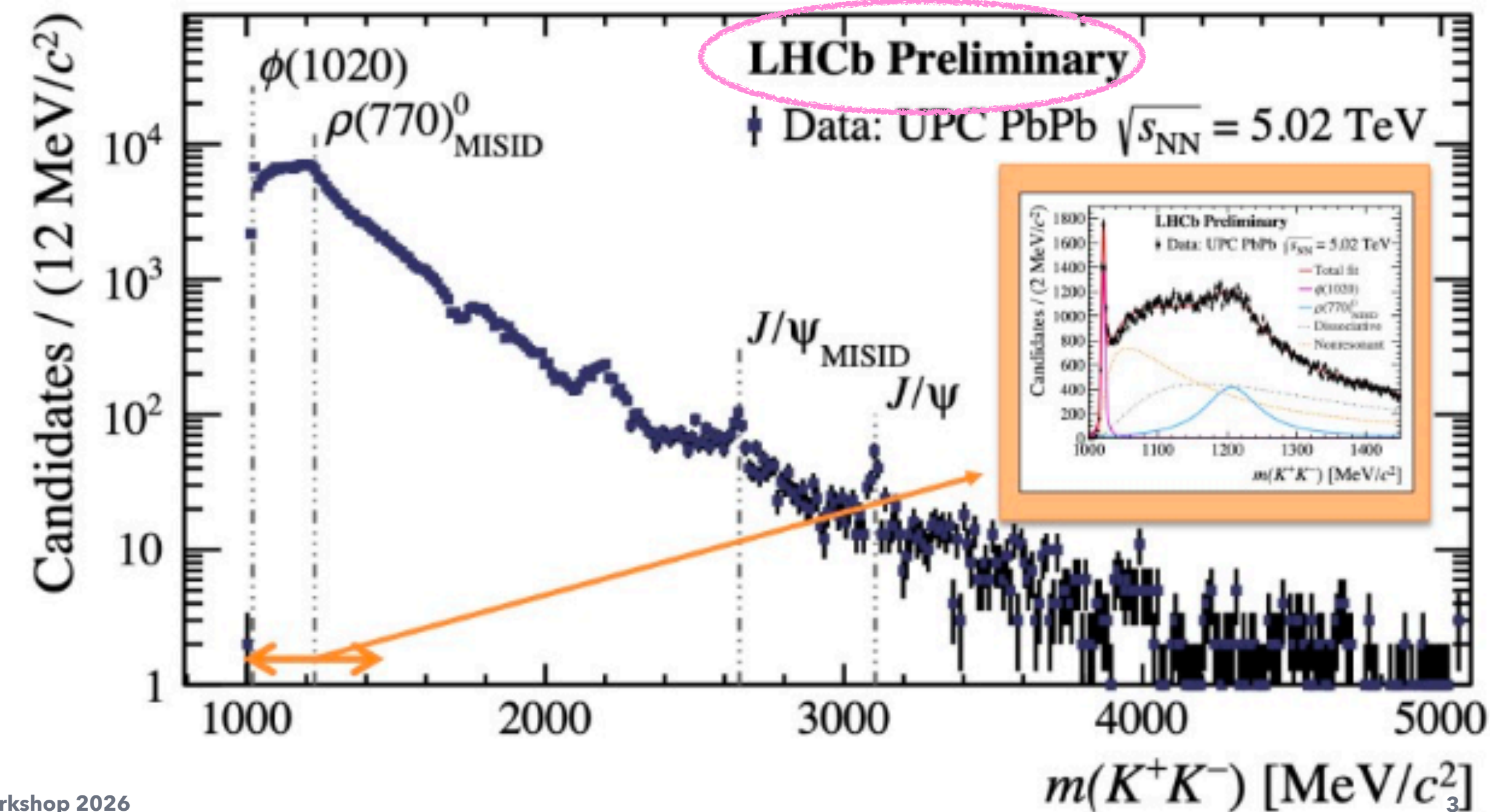
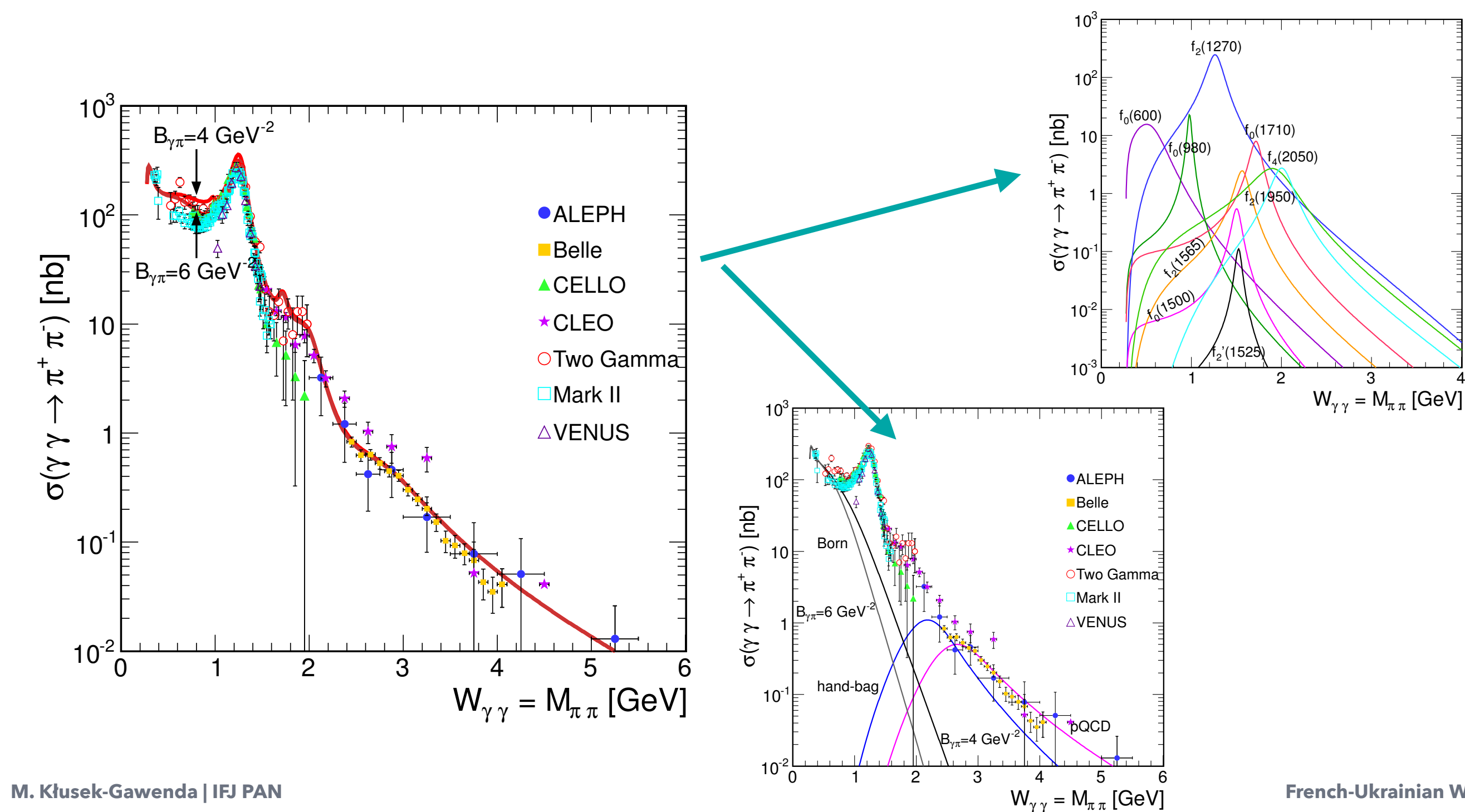
the corrections (some interference contribution) to the pure resonant production are small because the resonant peak is very narrow.

- P. Lebiedowicz, O. Nachtmann, and A. Szczurek, *Towards a complete study of central exclusive production of K^+K^- pairs in proton-proton collisions within the tensor Pomeron approach*, Phys. Rev. D98, 014001 (2018):

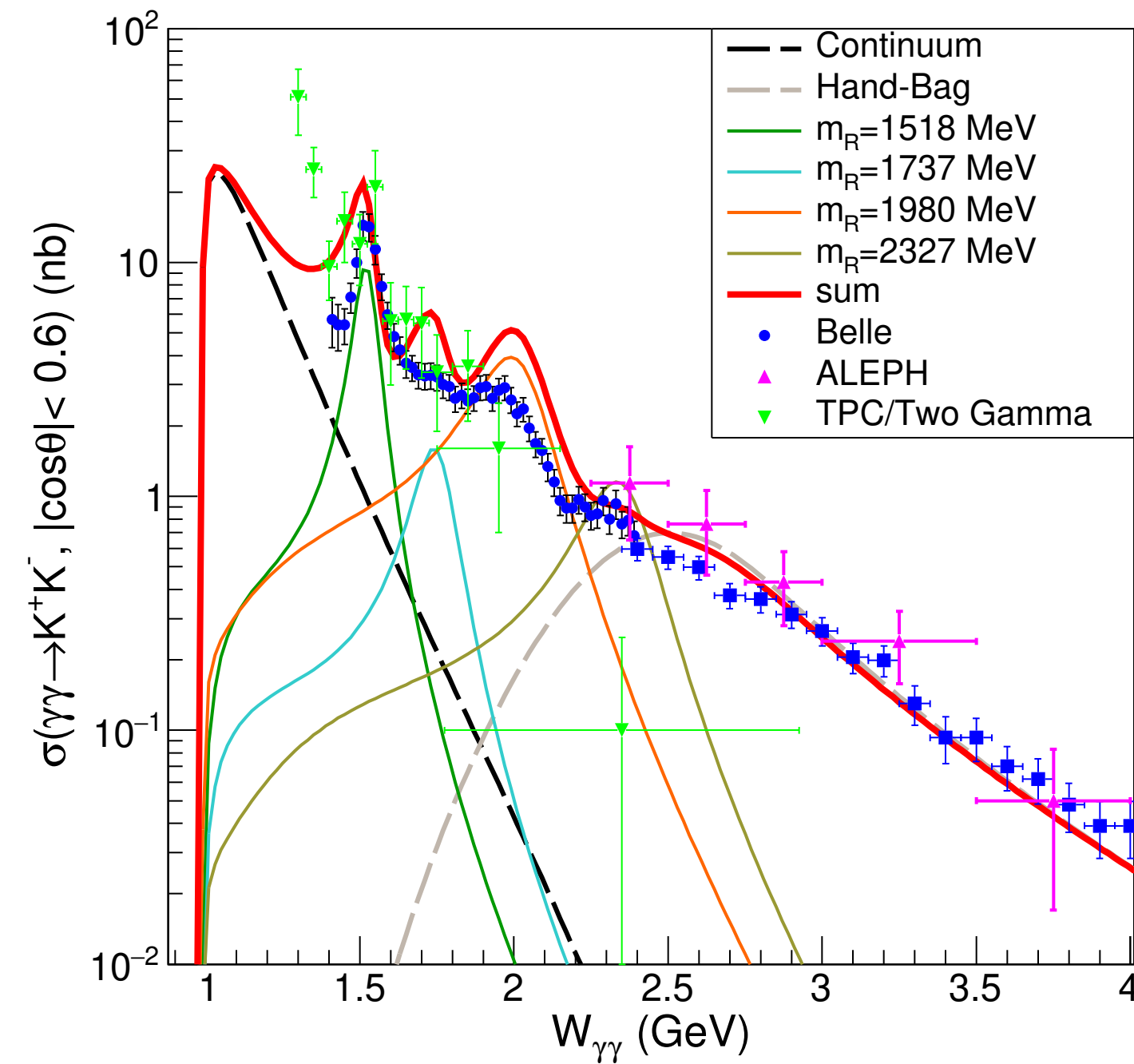
the dikaon system should behave similarly to the dipions

- In $\pi^+\pi^-$ interference between resonant and non-resonant amplitudes modifies the energy spectrum

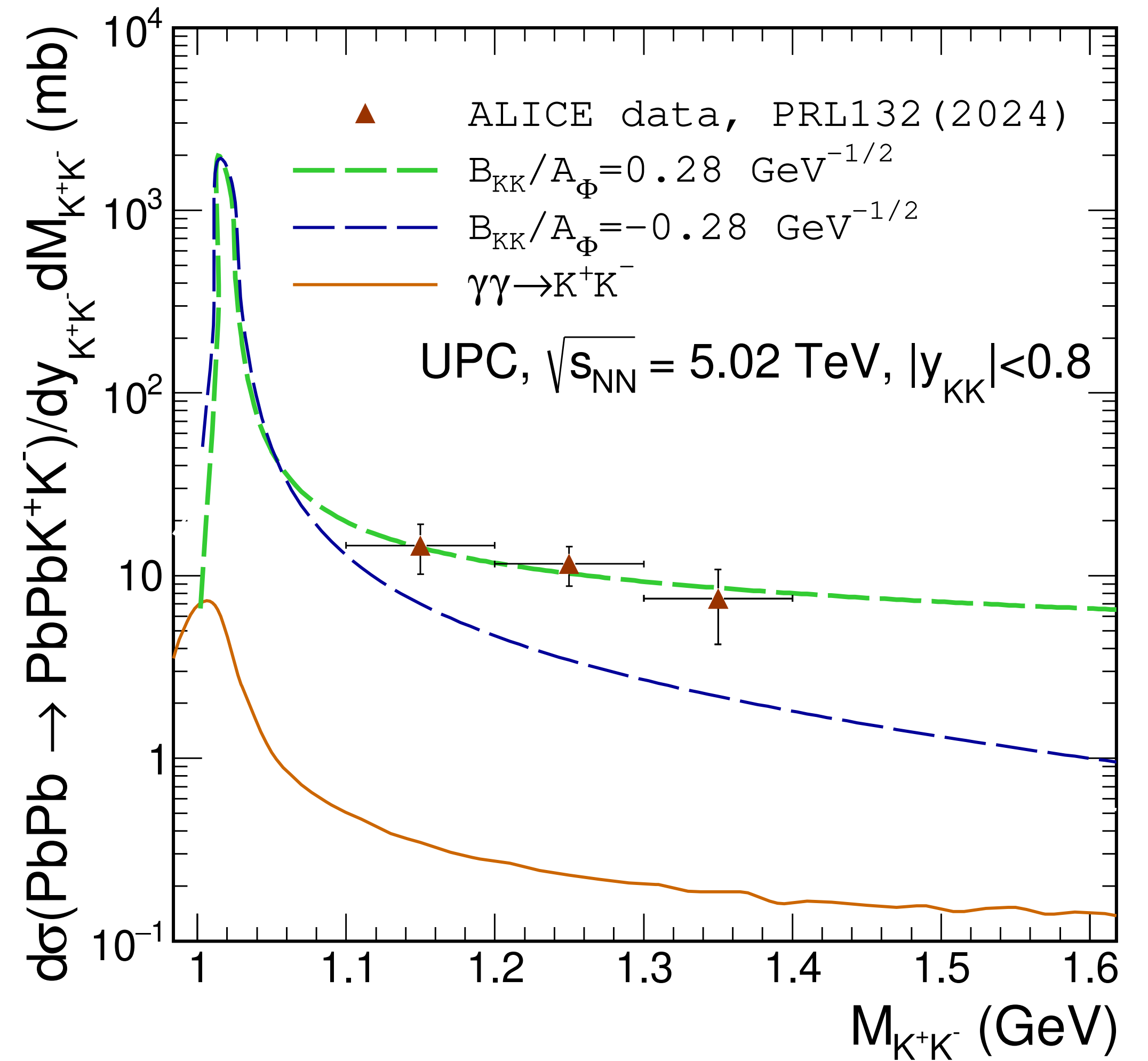
$$BR(\Phi \rightarrow K^+K^-) = 49.1 \% \text{ vs } BR(\rho^0(770) \rightarrow \pi^+\pi^-) = 100 \%$$



KAON-PAIR PRODUCTION: TWO COMPETING MECHANISMS



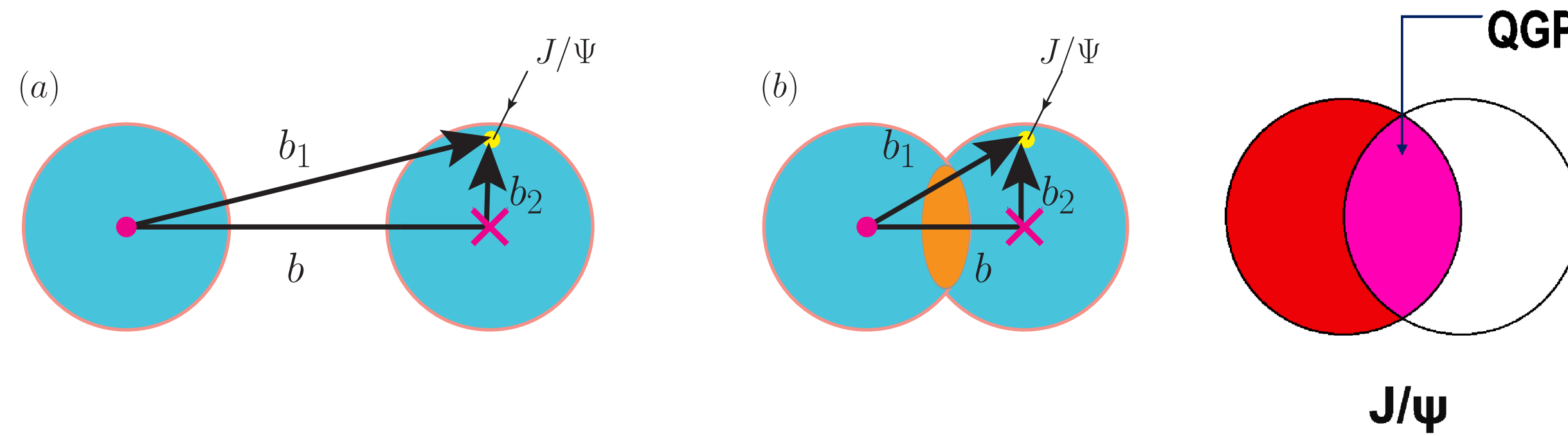
- Two competing mechanisms in Pb-Pb UPCs
- Comparison with Belle, ALEPH and TPC/Two-Gamma measurements
- Photonuclear production dominates the calculated spectrum near threshold
- The interference pattern depends on the relative phase of the amplitudes



The same final state probes different production mechanisms and resonance dynamics.

VECTOR MESON PHOTOPRODUCTION: FROM UPCs TO PERIPHERAL COLLISIONS

Can coherent photoproduction survive in peripheral collisions with nuclear overlap?



Our approach: geometry-dependent photon fluxes

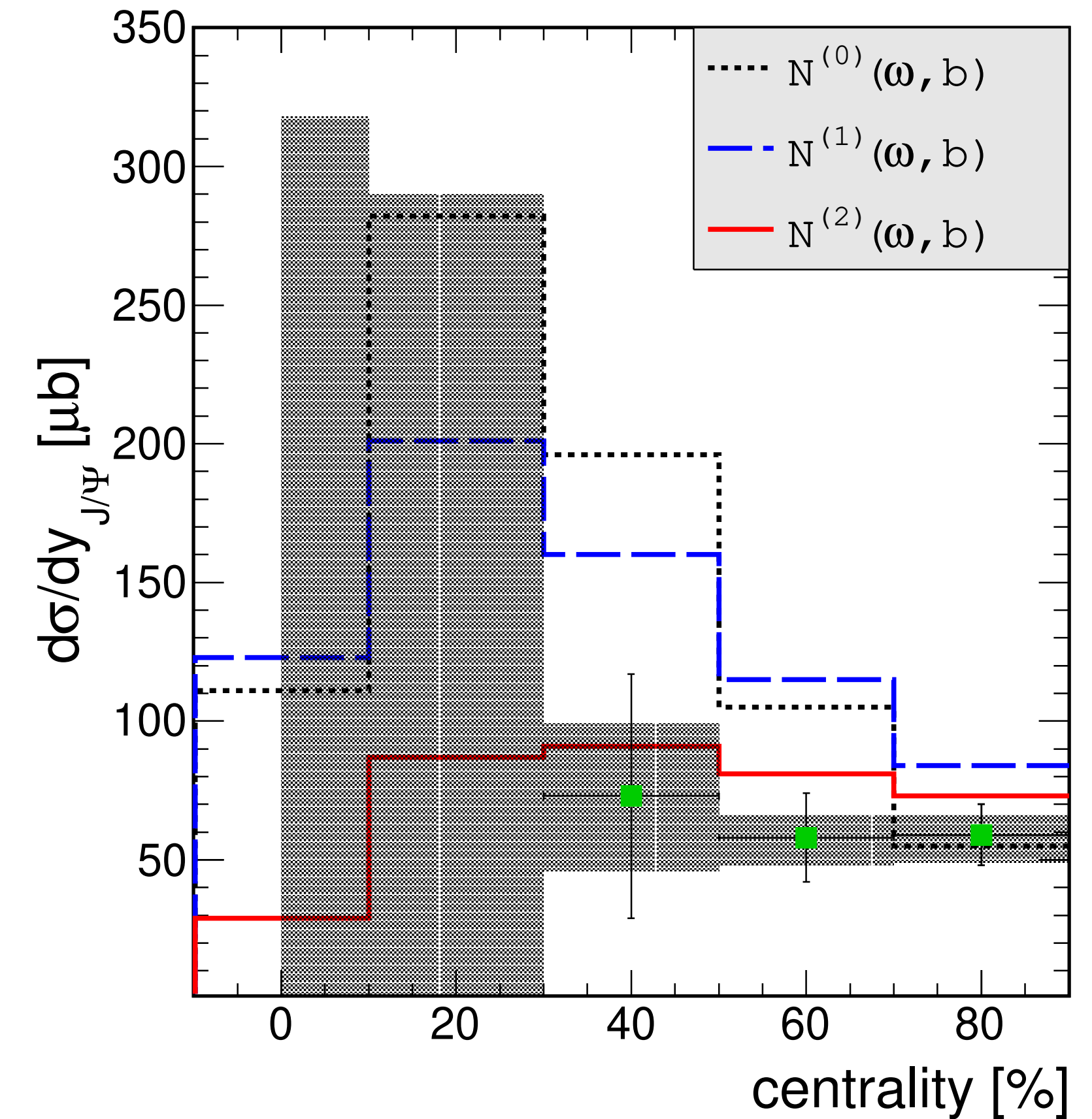
$N^{(0)}(\omega, b)$: Standard photon flux, without geometrical restrictions

$N^{(1)}(\omega, b)$: Photon flux averaged over the nuclear target

$N^{(2)}(\omega, b)$: Additional exclusion of the nuclear overlap region

$$N^{(1)}(\omega, b) = \int N(\omega, b_1) \frac{\theta(R_A - (|\mathbf{b}_1 - \mathbf{b}|))}{\pi R_A^2} d^2 b_1$$

$$N^{(2)}(\omega, b) = \int N(\omega, b_1) \frac{\theta(R_A - (|\mathbf{b}_1 - \mathbf{b}|)) \times \theta(b_1 - R_A)}{\pi R_A^2} d^2 b_1$$



Our calculations show that the treatment of nuclear geometry can substantially change the predicted J/ψ yield, even before introducing additional medium effects.

FROM CURRENT RESULTS TO FUTURE OPPORTUNITIES

PRECISION QED

What we learned: Inelastic photon emission can significantly modify LBL predictions; about 25% of events in the studied setup involve forward neutron emission.

What's next: A consistent description of nuclear dissociation, electromagnetic excitation and neutron-tagged observables.

ELECTROMAGNETIC PROTON STRUCTURE

What we learned: Exclusive dilepton production is sensitive to the proton electromagnetic form factor and charge-radius scale.

What's next: Precision LHC measurements, complemented by studies of the proton's spatial structure and gluonic hot spots.

LIGHT-HADRON SPECTROSCOPY

What we learned: Resonances, non-resonant contributions and their interference are essential for interpreting exclusive hadronic final states.

What's next: Testing competing resonance scenarios in $4\pi^\pm$ and K^+K^- production and exploring interference effects.

VECTOR MESONS AND NUCLEAR STRUCTURE

What we learned: Nuclear overlap geometry significantly modifies predictions for peripheral J/ψ photoproduction.

What's next: Connecting collision geometry with coherent/incoherent production and nuclear gluon fluctuations.

COMMON THEORETICAL TOOLS - COMPLEMENTARY PROBES OF QED & QCD

Wishing all us great success in our joint
French-Ukrainian-Polish
International Research Laboratory (IRL)!

