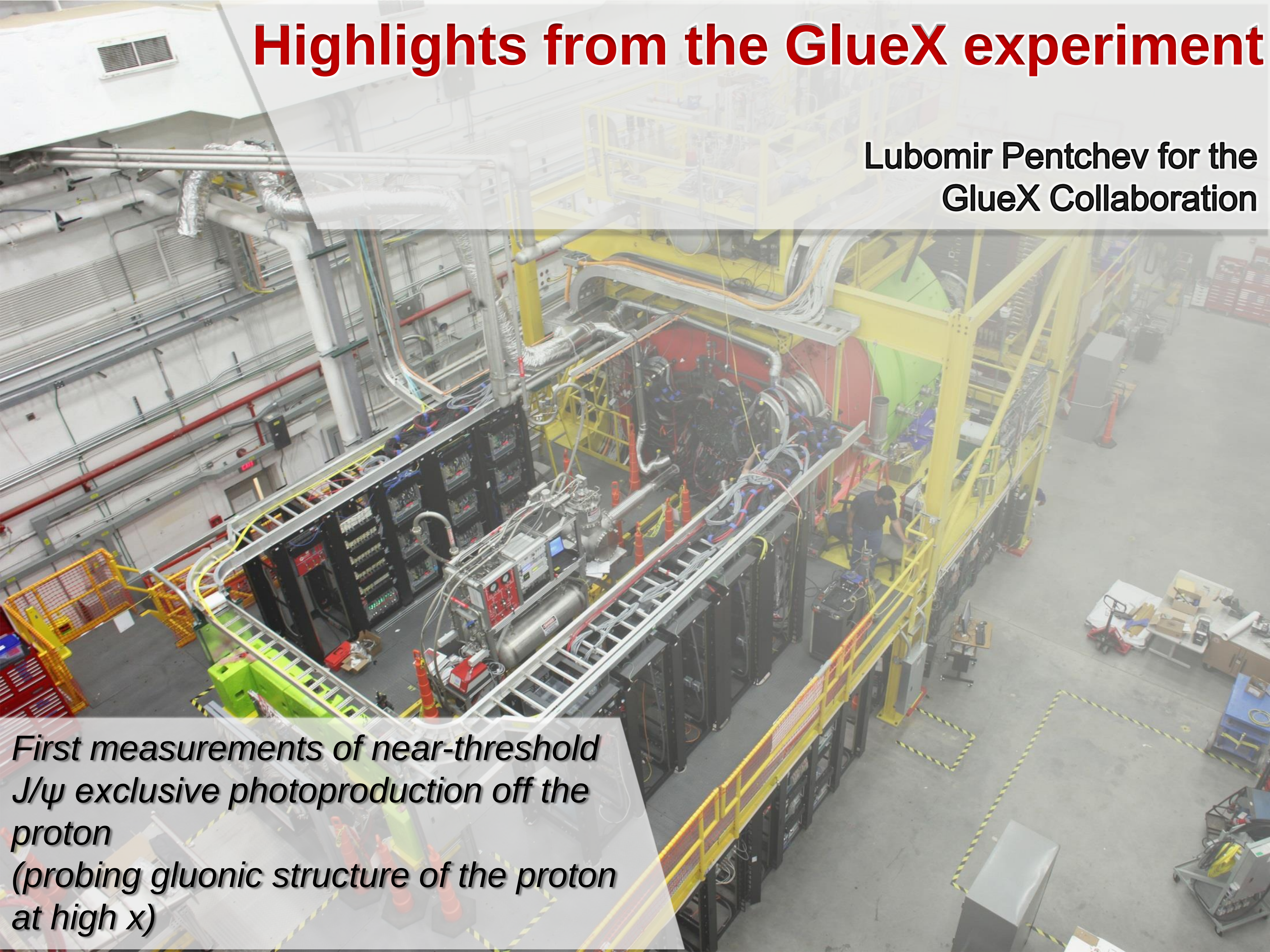
Highlights from the GlueX experiment

Lubomir Pentchev for the
GlueX Collaboration



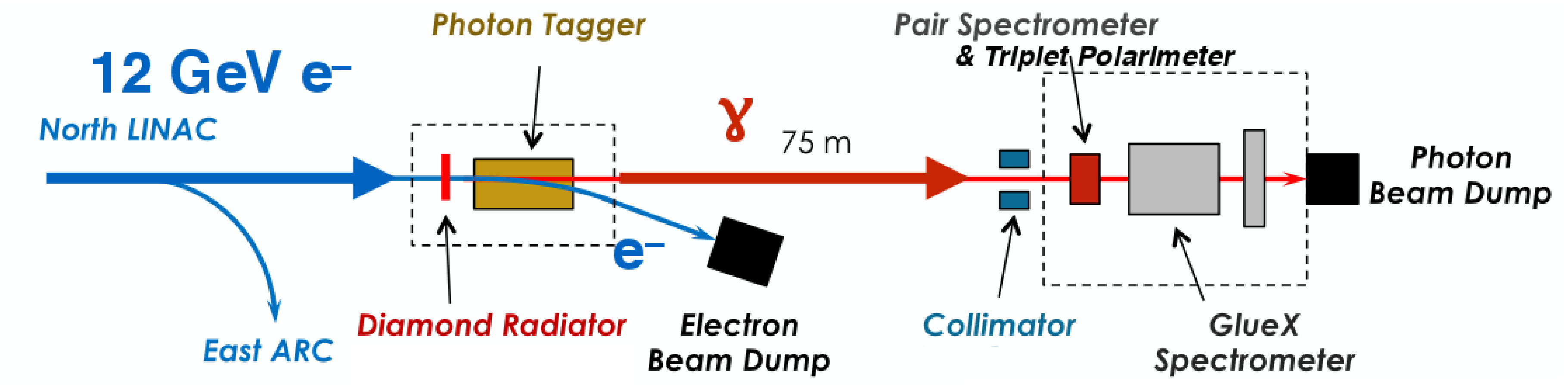
First measurements of near-threshold J/ψ exclusive photoproduction off the proton
(probing gluonic structure of the proton at high x)

Introduction

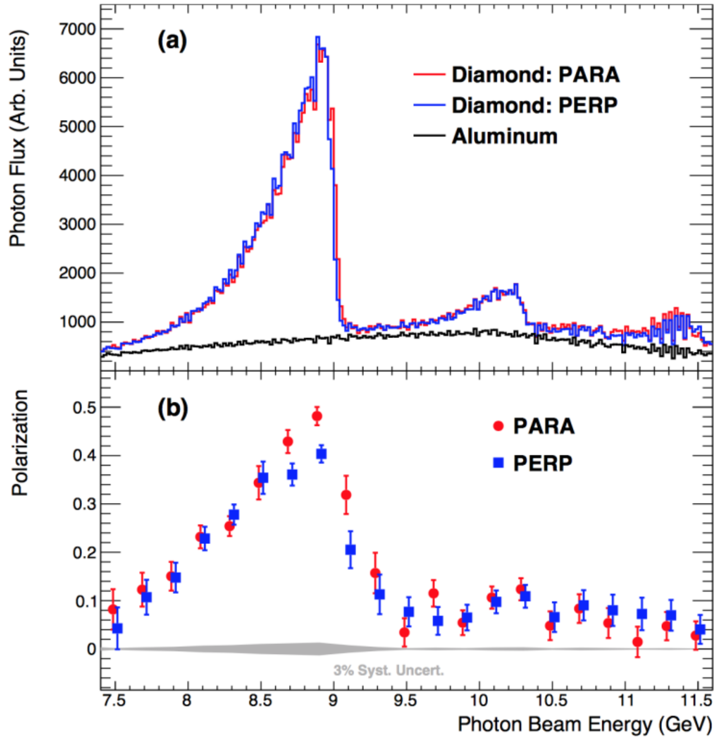
- Overview of Hall D/Gluex apparatus
- Selected results from GlueX/Hall D experiments:
  - searching for hybrid mesons
  - beam asymmetries
  - η decay via Primakoff reaction
- Near-threshold J/ψ photoproduction:
  - the experiment
  - proton gluonic distributions at high-x
  - search for LHCb pentaquarks
  - future expected results

Experiment	Description	PAC days complete
GlueX-I	Spectroscopy of light and hybrid mesons (low intensity)	80+40 80+40
GlueX-II	Spectroscopy of hadrons with strange quarks (high intensity)	220+
PrimEx-eta	Eta radiative decay width	79 24
CPP	Charge pion polarizability	25
JEF	Rare eta decays	-
SRC	Short-range correlations with real photon beams	15

Hall D Apparatus



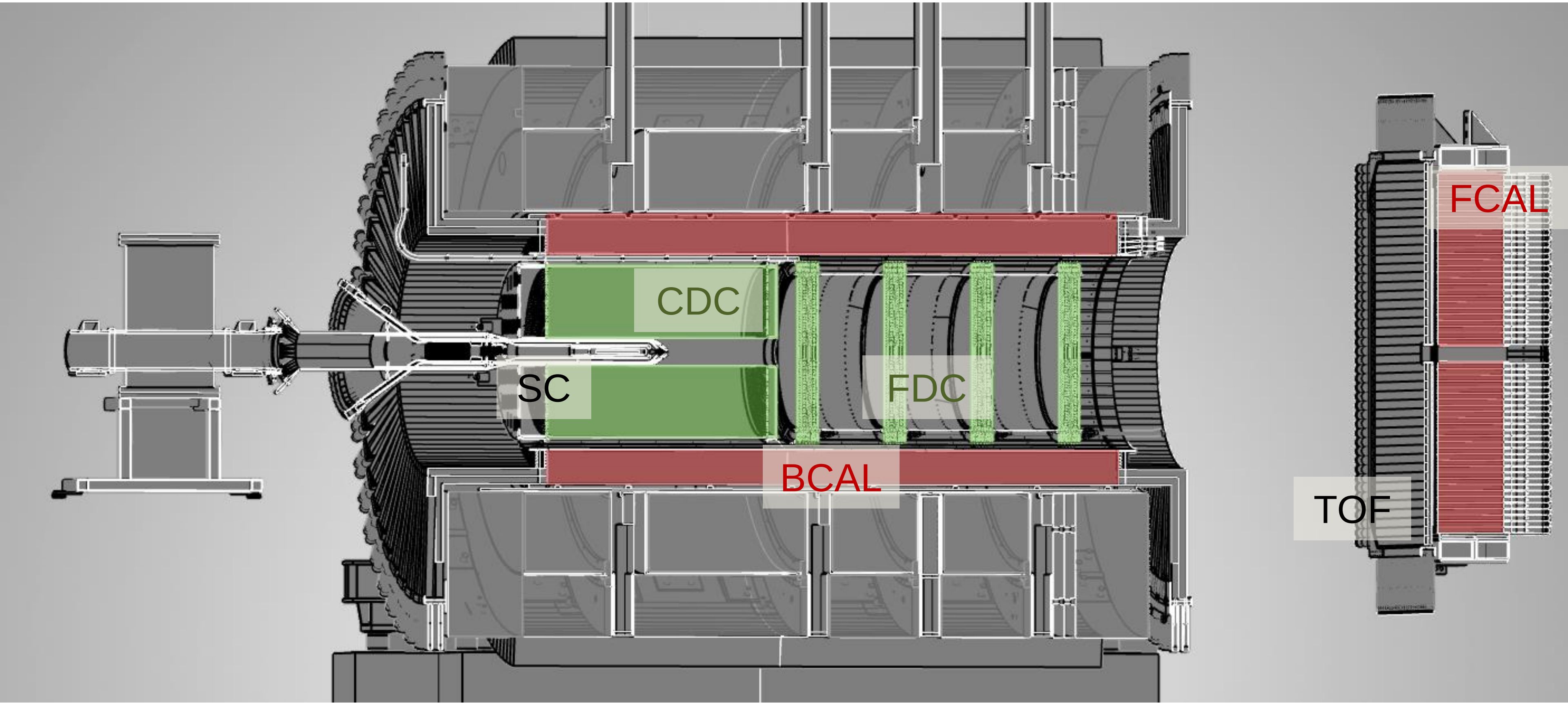
- Photon beam from coherent Bremsstrahlung off thin diamond
- Photon energy tagged by scattered electron ~ 0.2% resolution
- Beam collimated at 75m, <35 μrad
- Intensity: ~ 2 10^7 - 5 10^7 γ/sec above J/ψ threshold (8.2 GeV) – total ~68 pb^{-1} in 2016-2017 runs (25% of total statistics up to date)
- Photons are linearly polarized ~ 40% at peak; polarization plane angle alternates from run to run: PERP, PARA



GlueX spectrometer

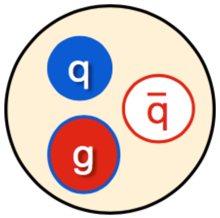
2T-solenoid, LH target

Tracking (FDC,CDC) , Calorimetry (BCAL,FCAL) , Timing (TOF,SC)



- Hermetic detector: 1 – 120° polar and full azimuthal acceptance
- Tracking: $\sigma_p/p \sim 1 - 5\%$
- Calorimetry: $\sigma_E/E \sim 6\%/\sqrt{E} + 2\%$

Searching for light hybrid mesons ($q\bar{q}g$)



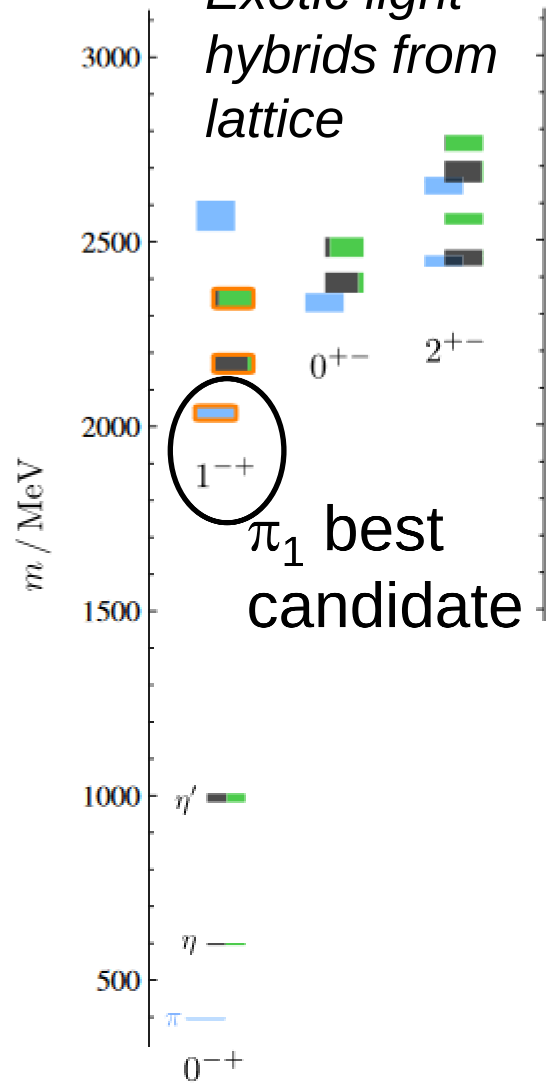
Hybrids with exotic quantum numbers (not allowed in $q\bar{q}$ model)

Experiment	p_{beam}, GeV	Reaction	Resonance
GAMS	32,38,100	$\pi^- p \to \pi^0 \eta n$	$\pi_1(1400)$
E852	18	$\pi^- p \to \pi^- \eta^{(\prime)} p$	$\pi_1(1400/1600)$
Crystal Barrel	Annihilation	$\bar{p}n \to \pi^- \pi^0 \eta$	$\pi_1(1400)$
VES	37	$\pi^- p \to \pi^- \eta^{(\prime)} p$	$\pi_1(1600)$
COMPASS	190	$\pi^- p \to \pi^- \eta' p$	$\pi_1(1600)$
COMPASS	190	$\pi^- p \to \pi^- \eta p$	$\pi_1(1400)$

COMPASS: $\pi_1 \to \pi^- \eta^{(\prime)}$

COMPASS, PLB 740 (2015)

Exotic light hybrids from lattice



Dudek et al. PRD 88 (2013)

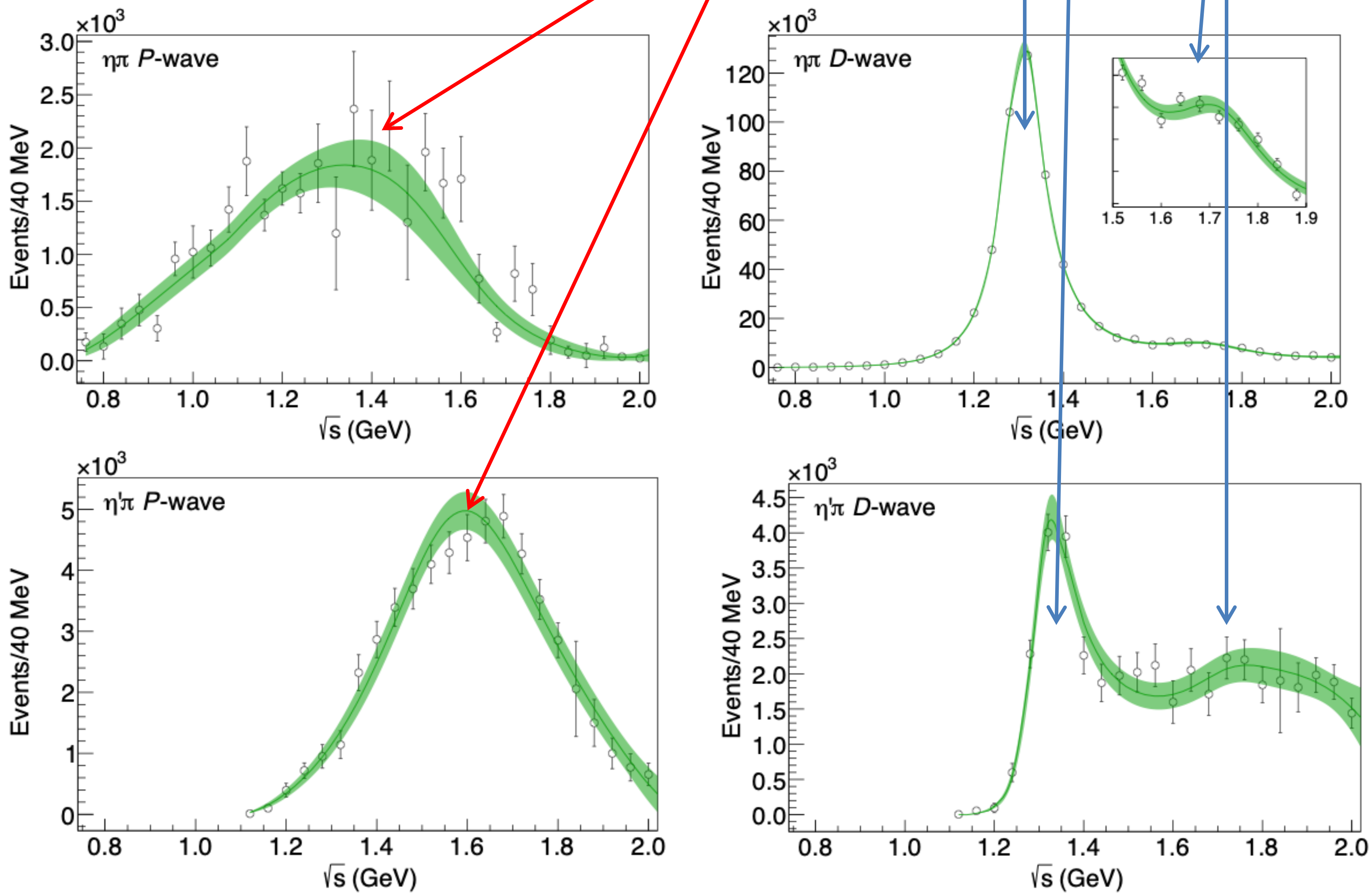
Searching for hybrids: JPAC analysis of COMPASS data

Coupled channel analysis finds one pole for exotic $\pi_1(1564)$, describing both $\eta\pi$ and $\eta'\pi$ channels in the P-wave intensities

$a_2(1320)$ $a_2'(1700)$

$\pi^- \eta$

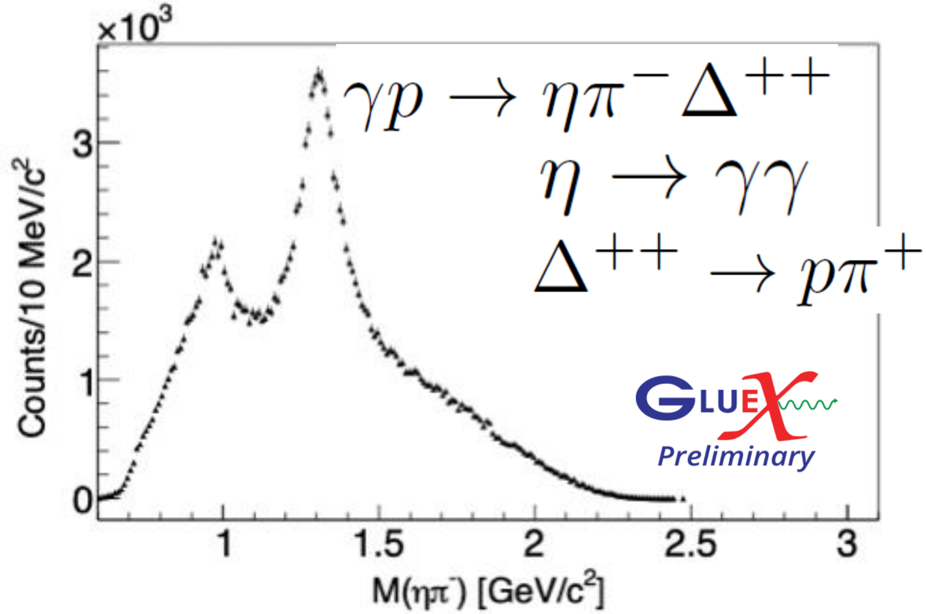
$\pi^- \eta'$

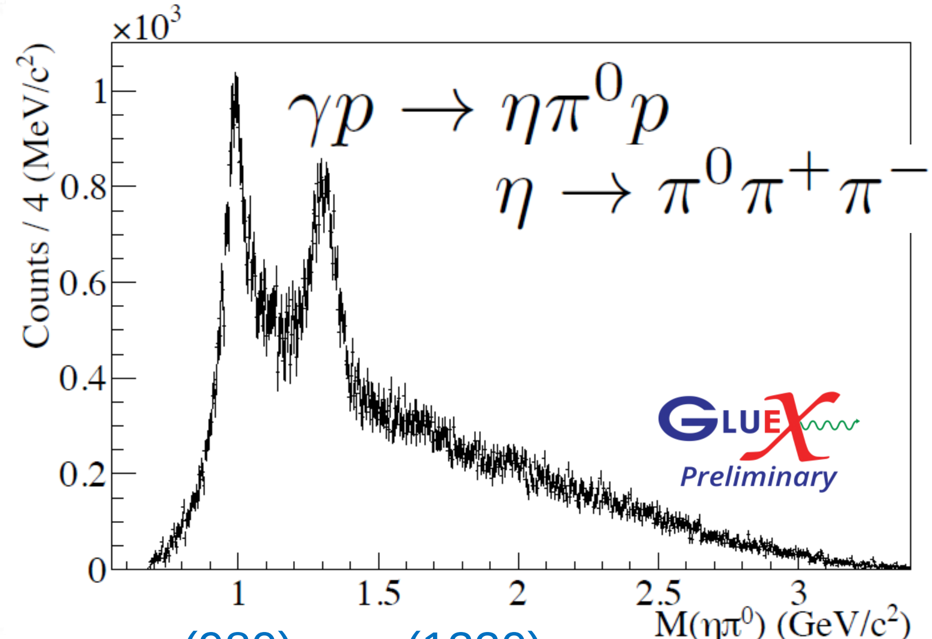


JPAC, PRL 122 (2019)

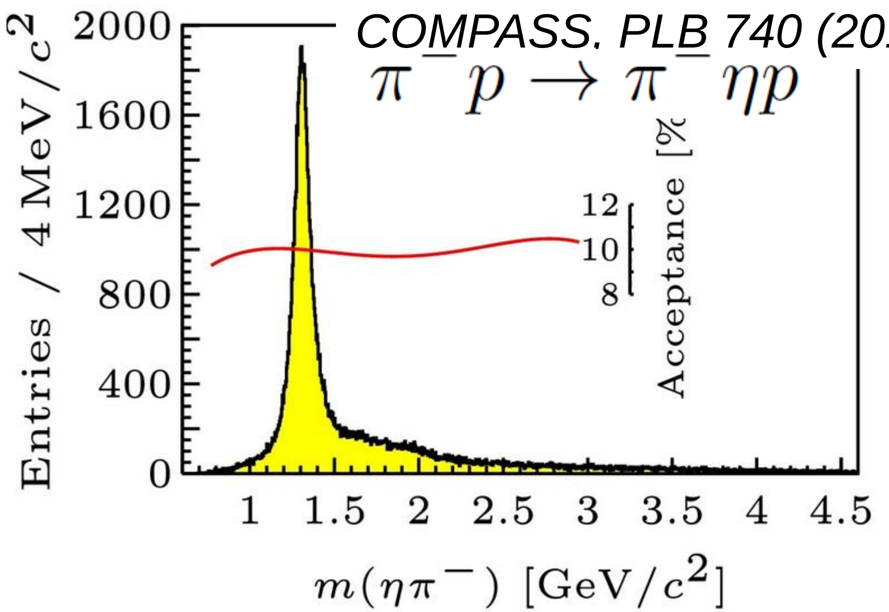
$\pi^-\eta^{(\prime)}$ can have J^{pc} 0^{++} 1^{-+} 2^{++}

Searching for hybrids: GlueX ηπ/η'π spectroscopy





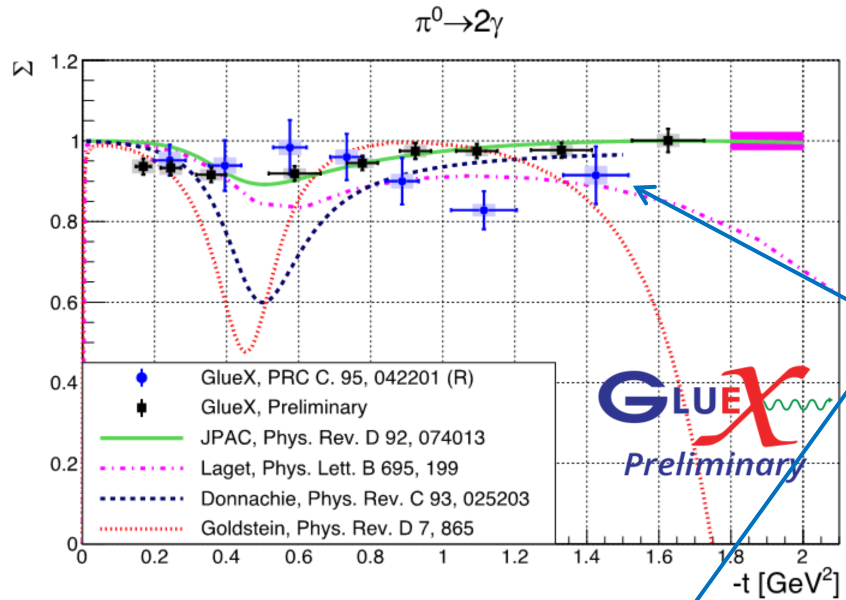
$a_0(980)$ $a_2(1320)$



COMPASS, PLB 740 (2015)

- GlueX statistics competitive with COMPASS one
- Different production mechanism, different background, multiple final states available
- GlueX linearly polarized photon beam – important tool in understanding the ηπ spectrum

Beam Asymmetry

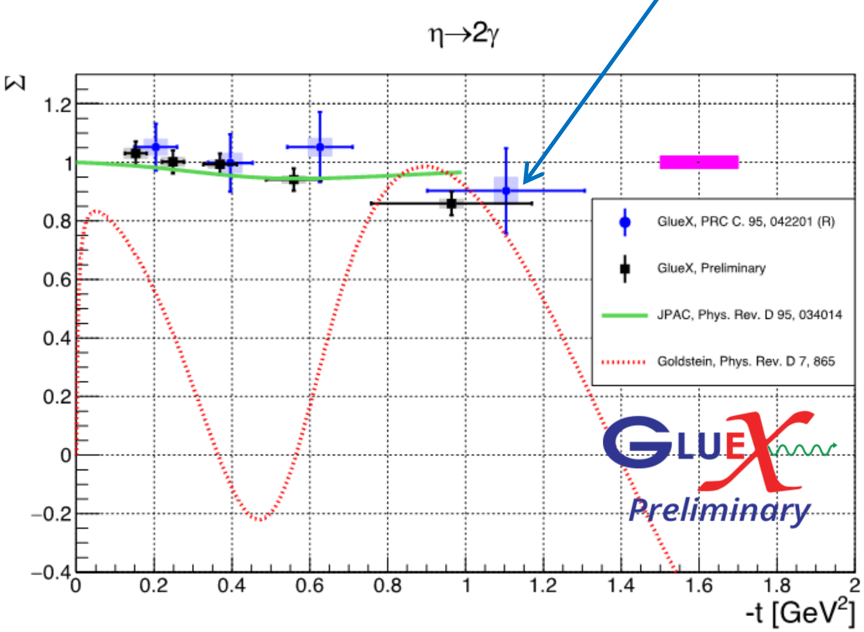


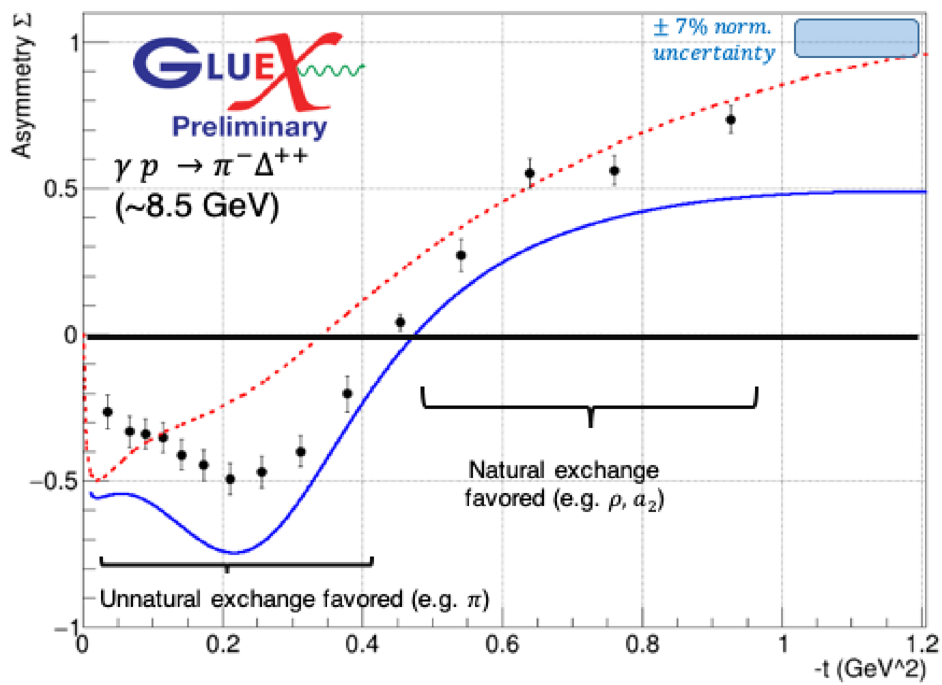
$$\gamma p \to (\pi^0, \eta, \eta')p$$

$$Y(\phi) \sim (1 - P_\gamma \Sigma \cos 2(\phi - \phi_\gamma))$$

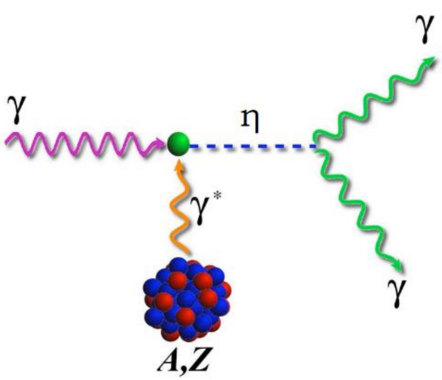
GlueX, PRC 95 (R) (2017) –
first Jlab 12 GeV paper

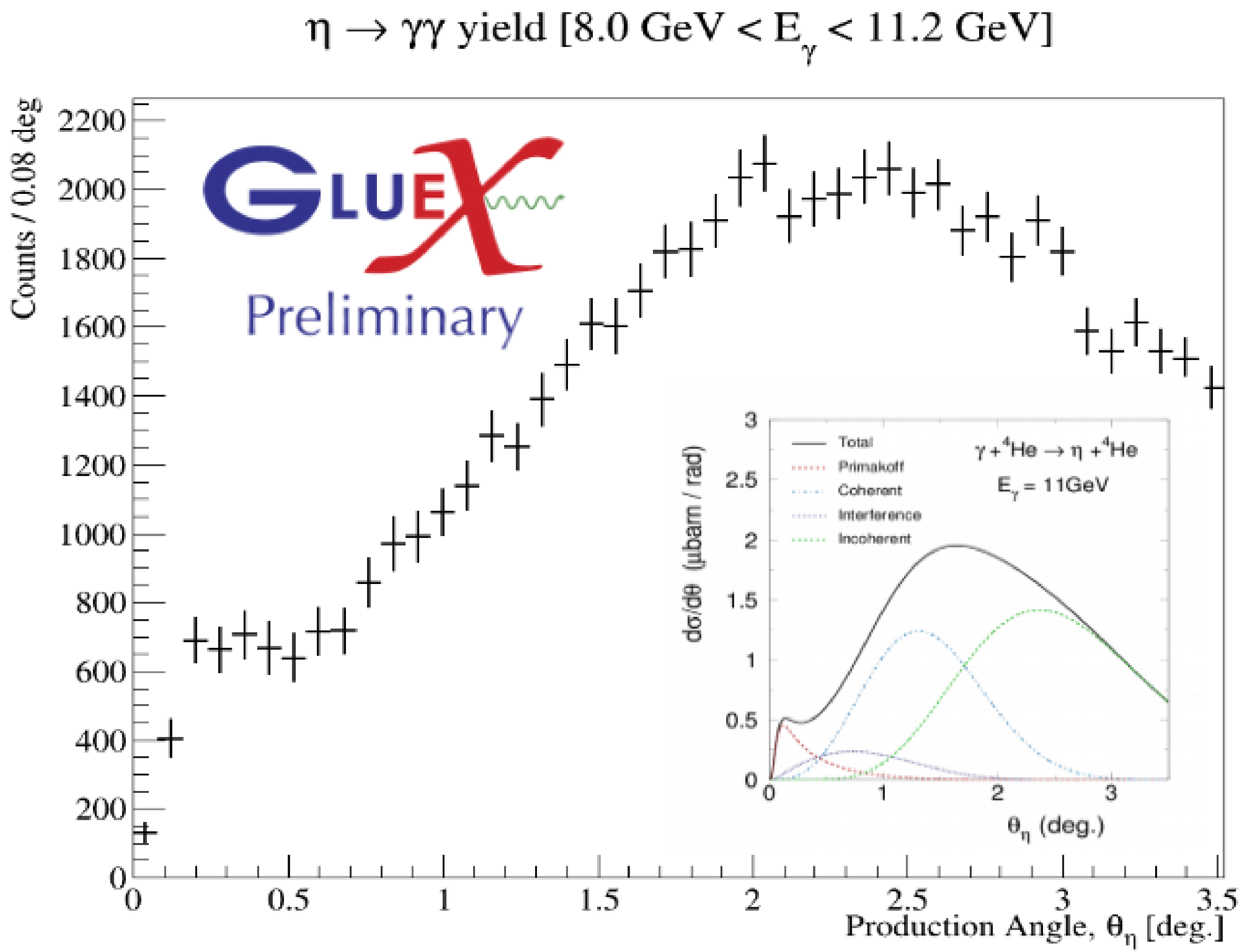
Natural exchange dominates if $\Sigma \sim 1$
More papers on asymmetries expected in 2019





η radiative decay via Primakoff reaction

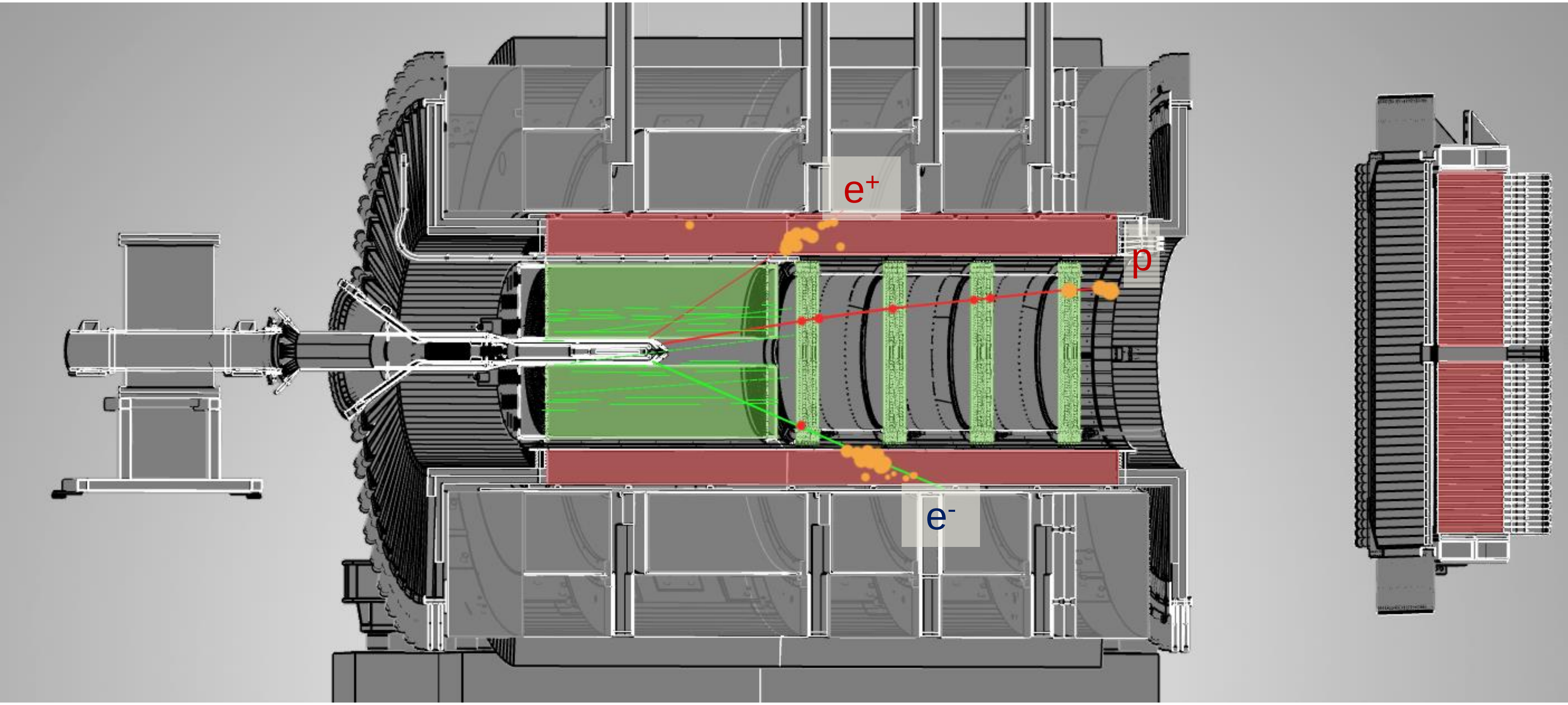




Precision measurement of $\Gamma\eta\to\gamma\gamma$:
significant impact on fundamental QCD parameters (Goldstone nature of light pseudoscalars, light quark mass ratios, chiral anomaly etc.)

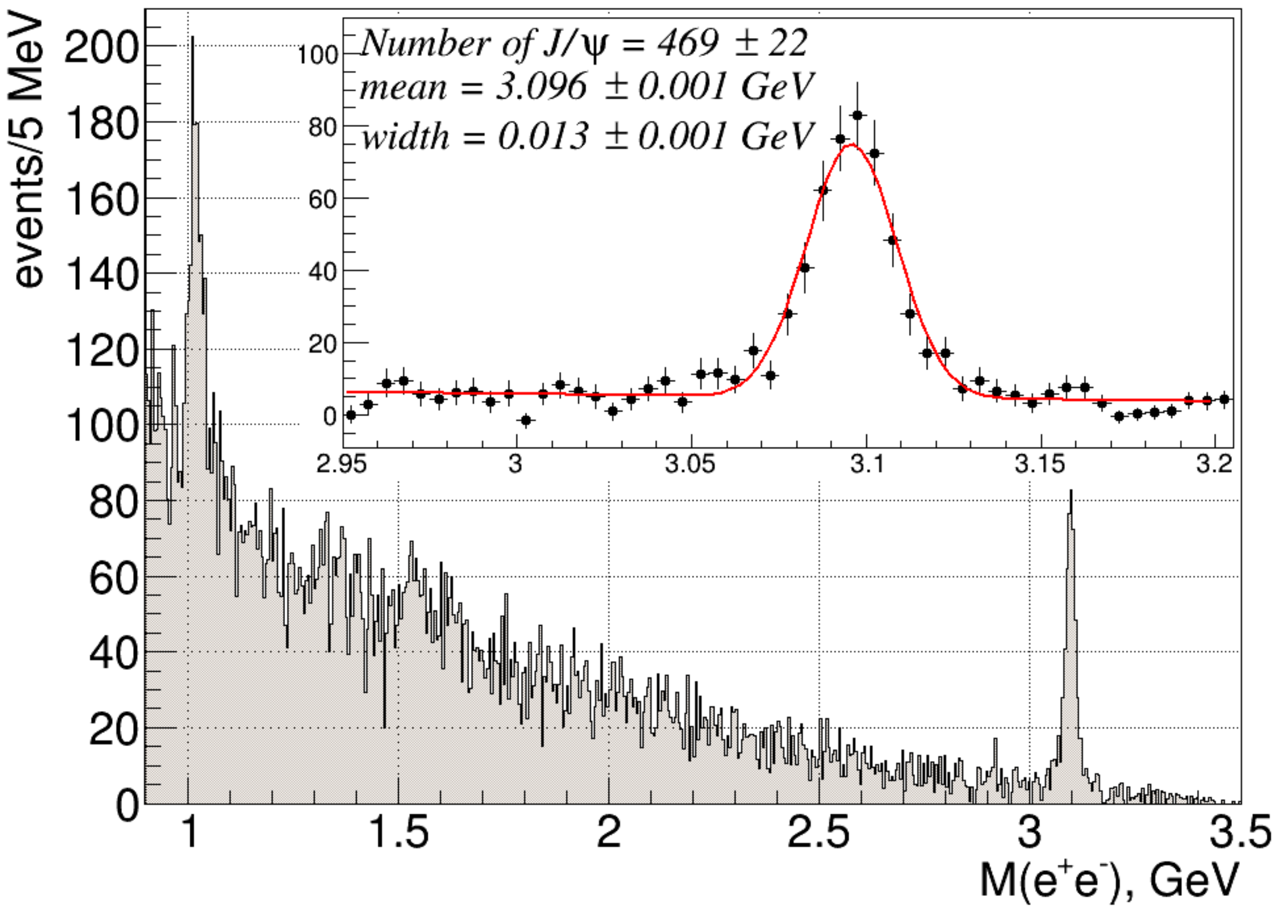
Near-threshold J/ψ photoproduction

Exclusive reaction $\gamma p \rightarrow J/\psi p \rightarrow e^+e^-p$



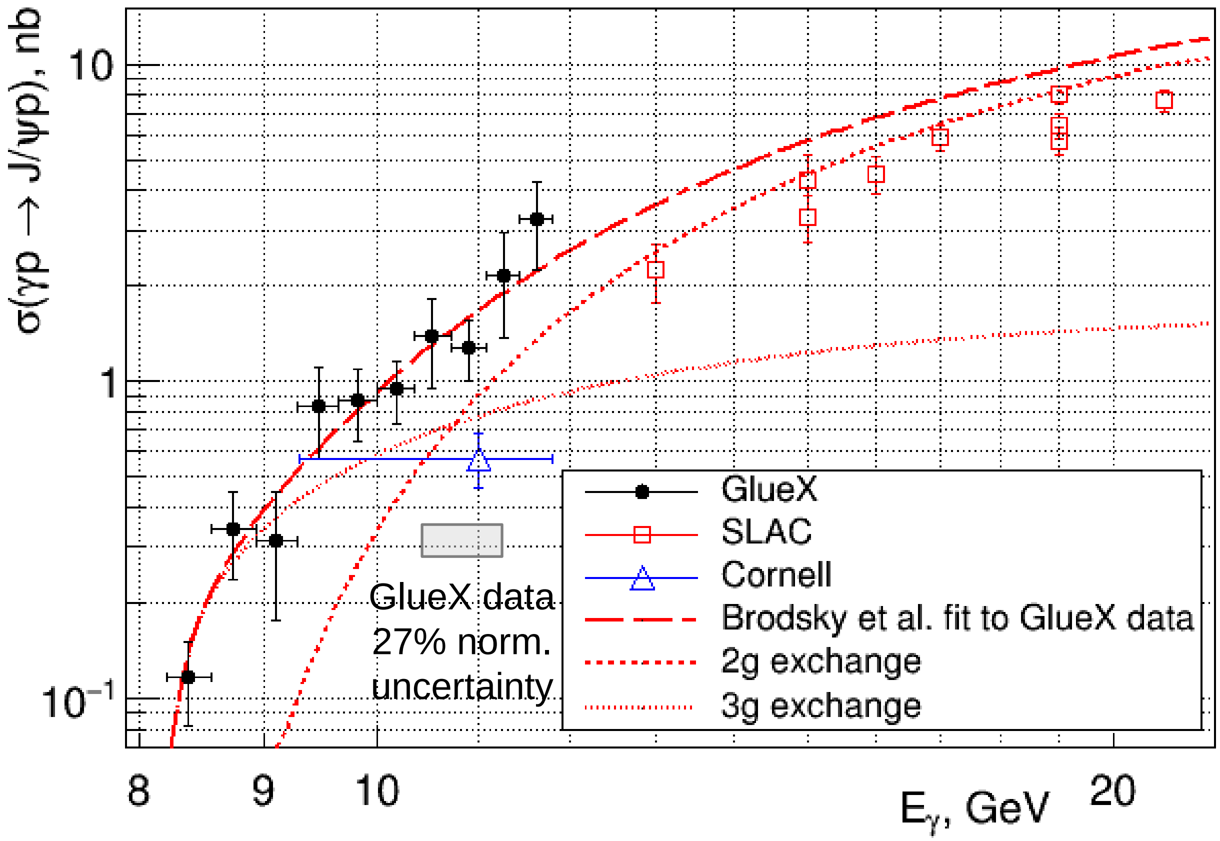
- Near threshold – all valence quarks participate, corresponding to high-x gluon exchange
- Using VMD ($\gamma \rightarrow J/\psi$) one can study $J/\psi\ p \rightarrow J/\psi\ p$
- Look for LHCb P_c: $\gamma\ p \rightarrow Pc \rightarrow J/\psi\ p$

Near-threshold J/ψ photoproduction

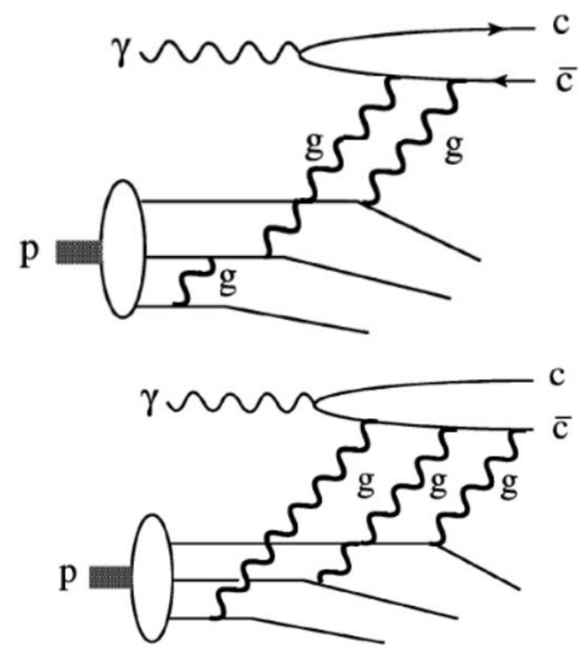


- Electrons identified by E/p
- Tagged photon beam, 0.2% energy resolution
- Kinematic fit: 13 MeV mass resolution
- Presented results (~470 J/ψ): 25% of statistics accumulated up to date
- Preliminary results (ERRORS ONLY!) will be shown based on 70% of data

J/ψ total cross-section



Brodsky et al.: $\sigma(E_\gamma)$ depending on number of hard-gluons exchanged using dimensional scaling



GlueX errors: quadratic sums of statistical and systematic ones

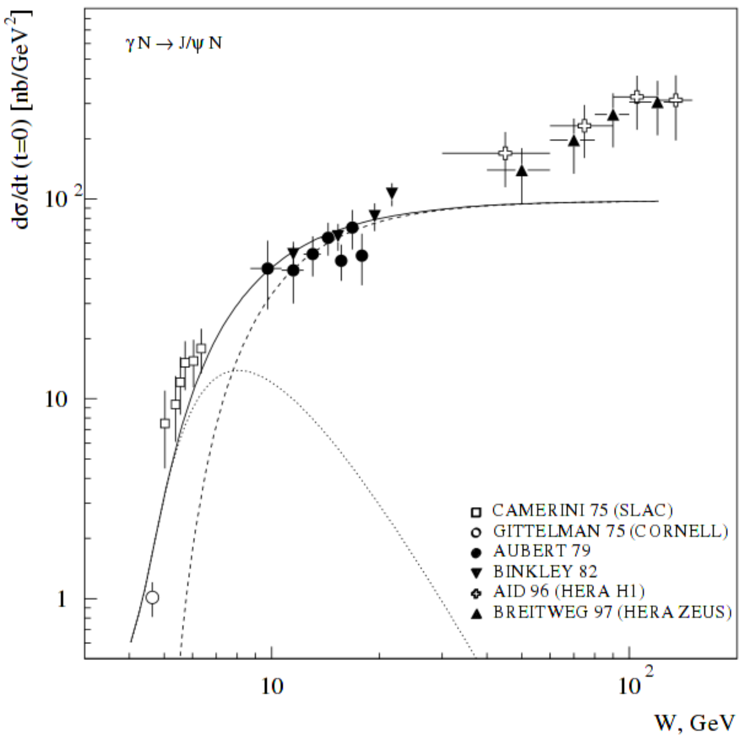
SLAC data: $\gamma d(p) \rightarrow J/\psi X$ from $d\sigma/dt(t = t_{min})$

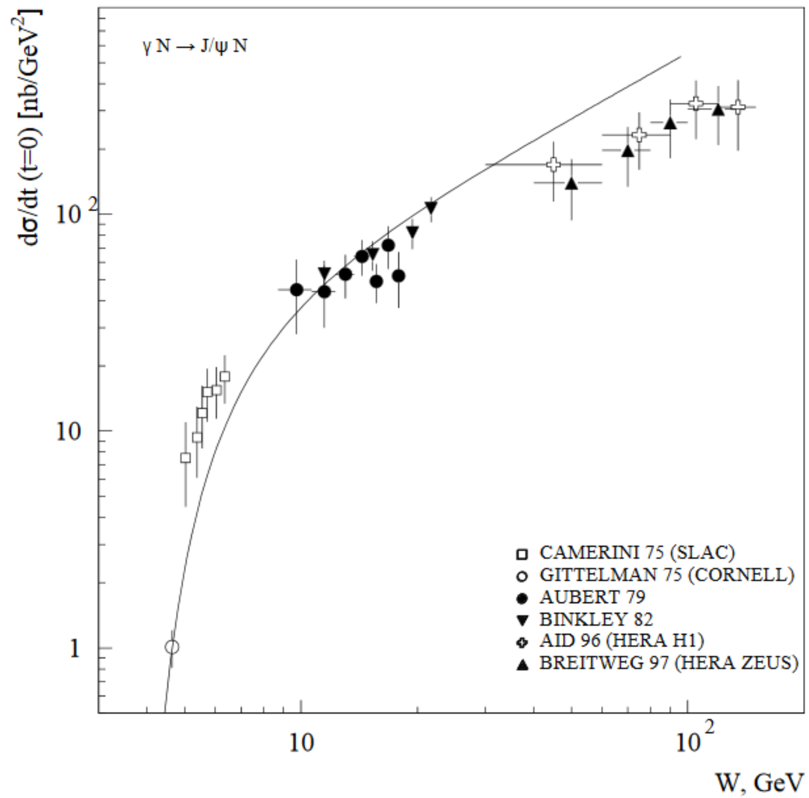
$$F^2(t) \sim (1 - t/m_{2g}^2)^{-4} \;\; m_{2g} = 1.14 \text{ GeV}$$

Cornell data: γBe→J/ψX

GlueX data falls toward threshold less steeply than 2g exchange model

J/ψ differential cross-section – perturbative calculations





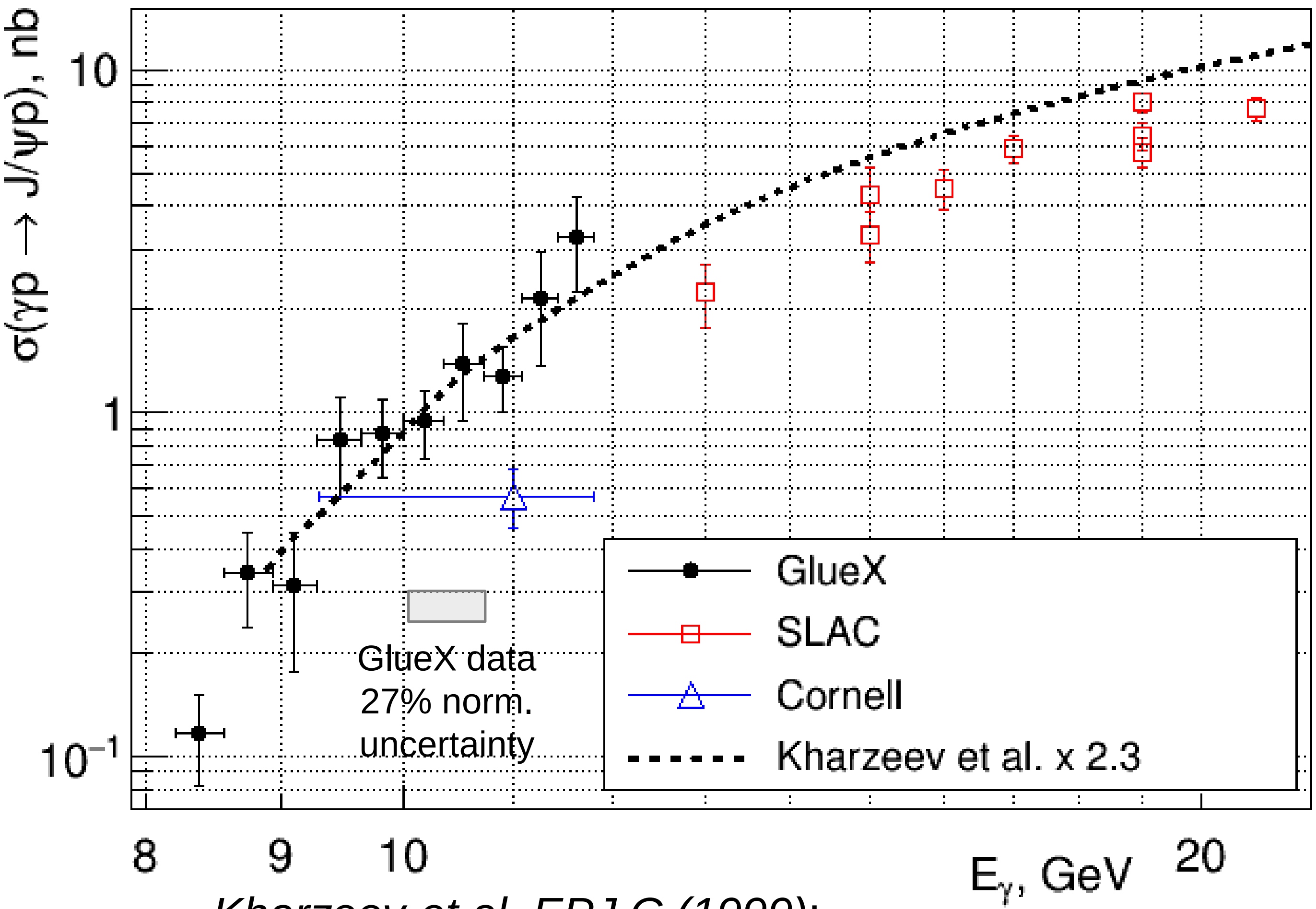
Kharzeev et al. EPJ C (1999):

- Forward J/ψ–p scattering amplitude calculated using gluonic PDF and dispersion relations.
- Very sensitive to gPDF at high x:

$$d\sigma/dt(t=0) \sim x^2 g^2(x) \text{ where } x = m_{J/\psi}^2/s$$

- real part of the amplitude dominates, contains scale anomaly term related to the mass of the proton arising from gluons.

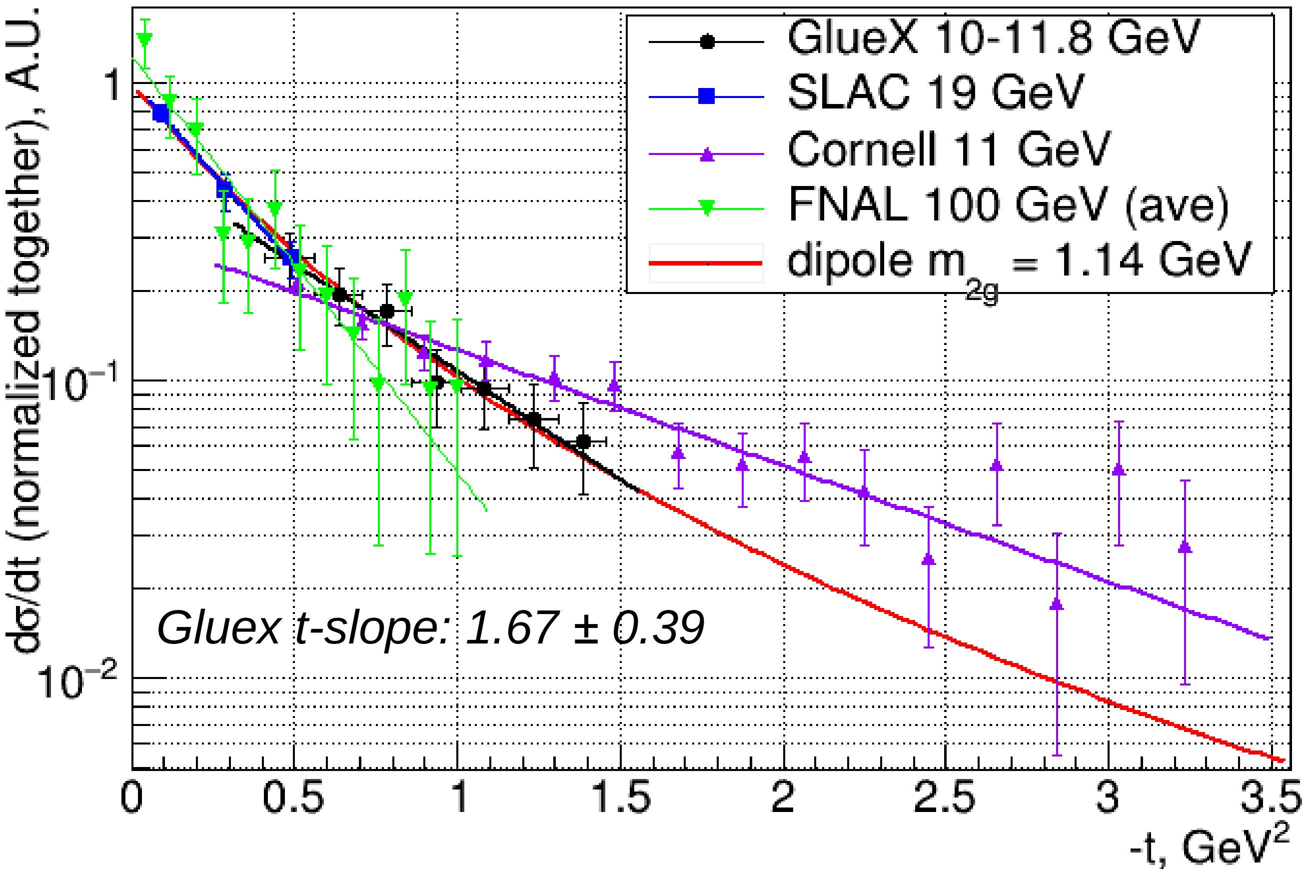
J/ψ total cross-section – perturbative calculations



Kharzeev et al. EPJ C (1999):

- t-dependence from fit of the exponential slopes at different energies
- Shape of the theoretical curve similar to Gluex data
- Absolute normalization within the uncertainties of the model

J/ψ differential cross-section and proton gluonic FF



gluonic form factor (dipole form in analogy with the e.-m. FF):

$$F(t) \sim 1/(1 - t/m_0^2)^2$$

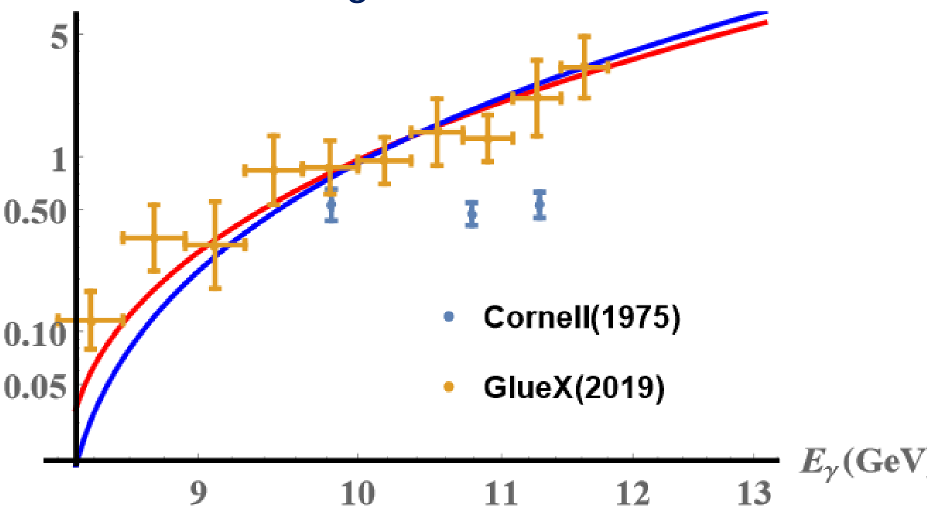
Frankfurt and Strikman PRD66 (2002)

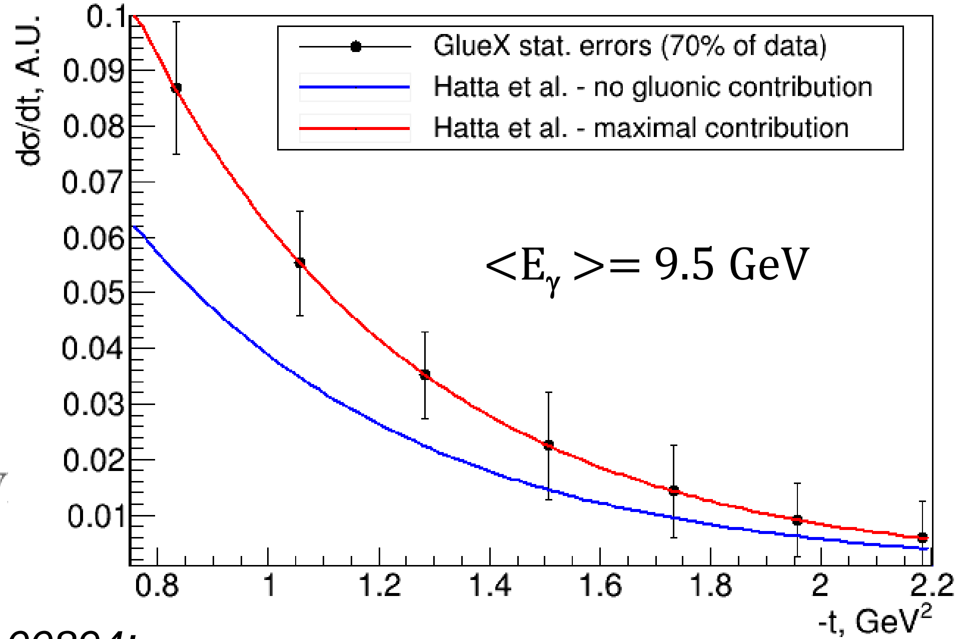
	e.m. FF	gluonic FF
reaction	$ep \to ep$	$J/\psi p \to J/\psi p$
transverse size of probe	0	$<< 1\ fm$
effective mass scale m_0	$0.84\ GeV$ (vector meson)	$\sim 1.1\ GeV$ (two-gluon mass)

J/ψ total cross-section – non-perturbative (holographic) calculations

Red – maximal contribution from gluons, favored by GlueX data

Blue – no gluonic contribution





Y. Hatta, A. Rajan, and D.-L. Yang, arXiv:1906.00894:

Proton gluonic FF: *"..these are nothing but the gravitational form factors* $A_g, B_g, C_g, \bar{C}_g$"

$$\langle P'|(T_g)^\mu_\mu|P\rangle = \langle P'|\left(\frac{\beta(g)}{2g}F^a_{\mu\nu}F^{\mu\nu}_a + m\gamma_m\bar{\psi}\psi\right)|P\rangle$$

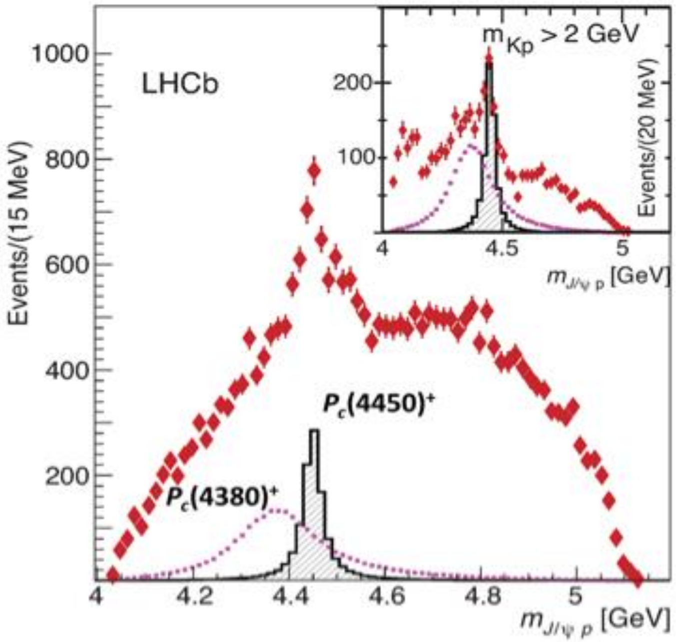
$$= \bar{u}(P')\left[A_g M + \frac{B_g}{4M}\Delta^2 - 3\frac{\Delta^2}{M}C_g + 4\bar{C}_g M\right]u(P)$$

A_g, B_g, C_g were recently calculated on lattice:

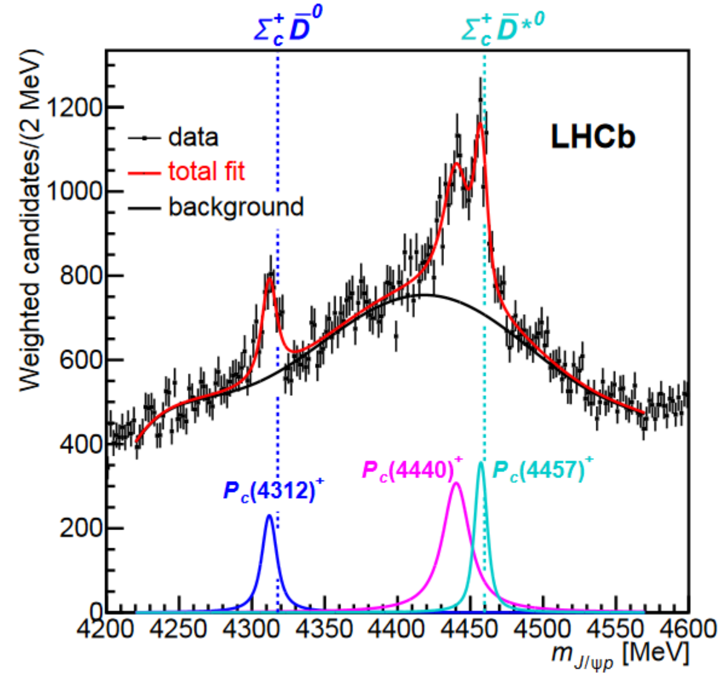
P. E. Shanahan and W. Detmold, arXiv:1810.04626

LHCb pentaquarks

$$\Lambda_b^0 \to J/\psi p K^-$$



Phys. Rev. Lett.,115,072001 (2015)



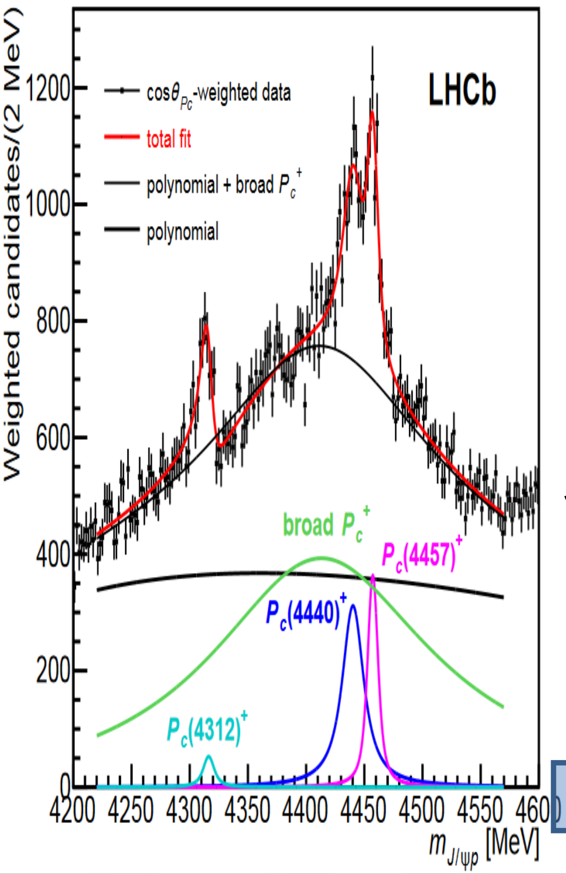
Phys. Rev. Lett. 122, 222001 (2019)

- J^P of P_c states not determined yet
- Molecules (most likely), but compact states or rescattering effects not excluded

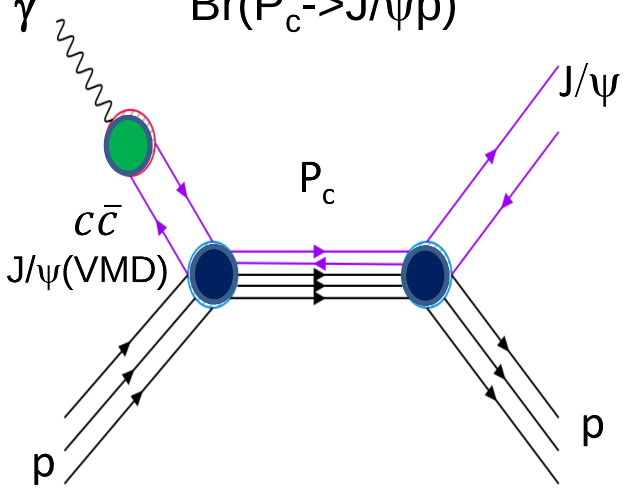
State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

LHCb pentaquarks and J/ψ photo-production

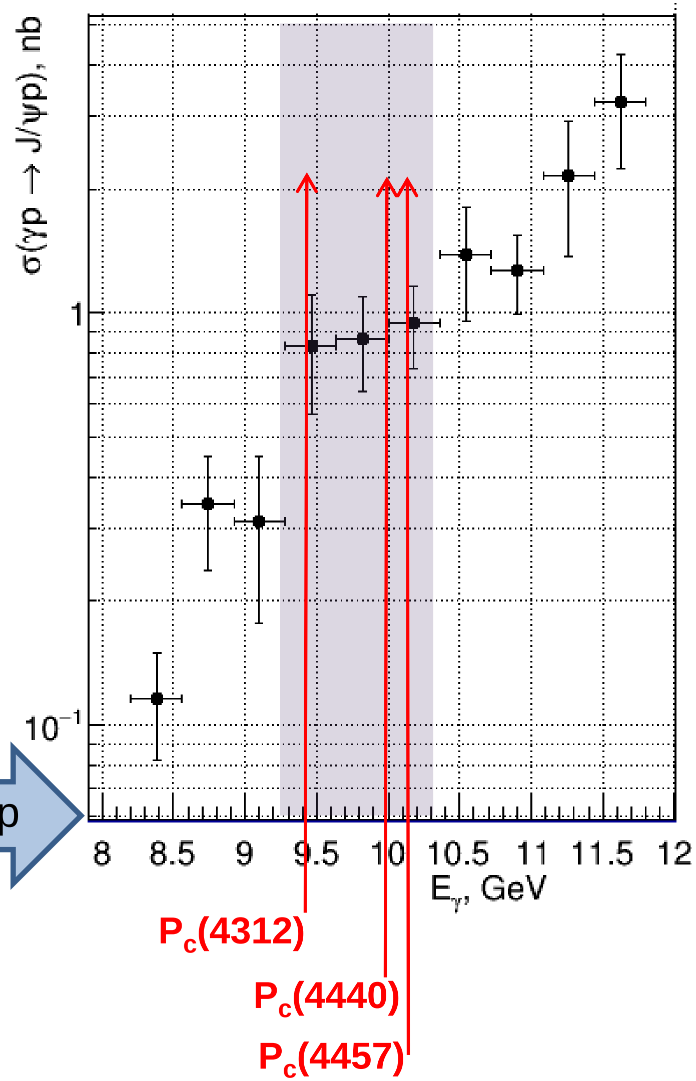
- If LHCb pentaquarks exist they should be seen in s-channel photoproduction (free of rescattering effects in the final state):



Main uncertainty
Br(P_c->J/ψp)

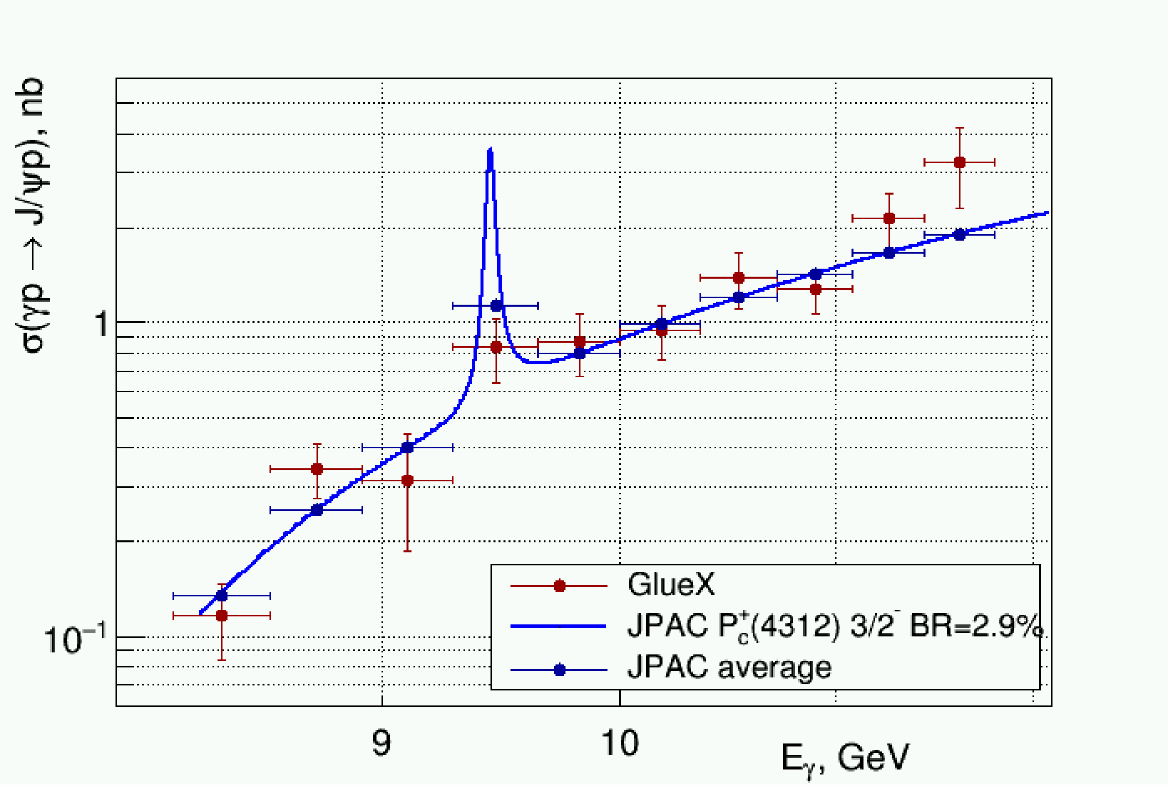


LHCb P_c related to γp ->P_c->J/ψp



- *V.Kubarovsky and M.B.Voloshin, PRD 92.031502 (2015).*
- *M.Karliner and J.Rosner, arXiv: PLB 752, 329 (2016).*
- *A.Blin, C.Fernandez-Ramirez, A.Jackura, V.Mathieu, V.Mokeev, A.Pilloni, and A.Szczepaniak, PRD 94,034002 (2016).*

J/ψ cross-section: model-dependent upper limits



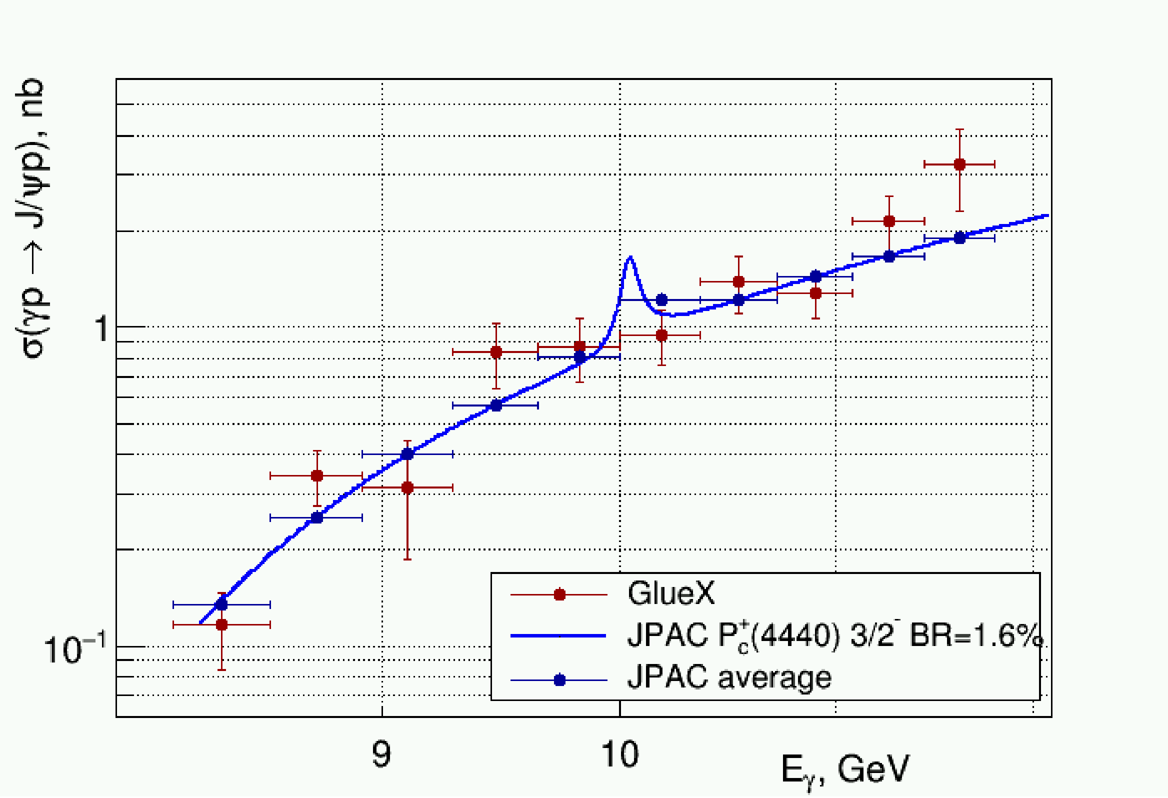
Assuming:

- all P_c independent $J^P = 3/2^-$
- s-channel model:
  $\sigma(\gamma p \to P_c \to J/\psi p) \approx$
  $0.35\ \mu b\ Br^2(P_c \to J/\psi p)\ (2J+1)$
- JPAC model for t-channel: Pomeron and tensor part extracted at high energies

	$\mathcal{B}(P_c^+ \to J/\psi p)$ Upper Limits, %		$\sigma_{max} \times \mathcal{B}(P_c^+ \to J/\psi p)$ Upper Limits, nb	
	p.t.p. only	total	p.t.p only	total
$P_c^+(4312)$	2.9	4.6	3.7	4.6
$P_c^+(4440)$	1.6	2.3	1.2	1.8
$P_c^+(4457)$	2.7	3.8	2.9	3.9

Upper limits at 90% confidence level

J/ψ cross-section: model-dependent upper limits



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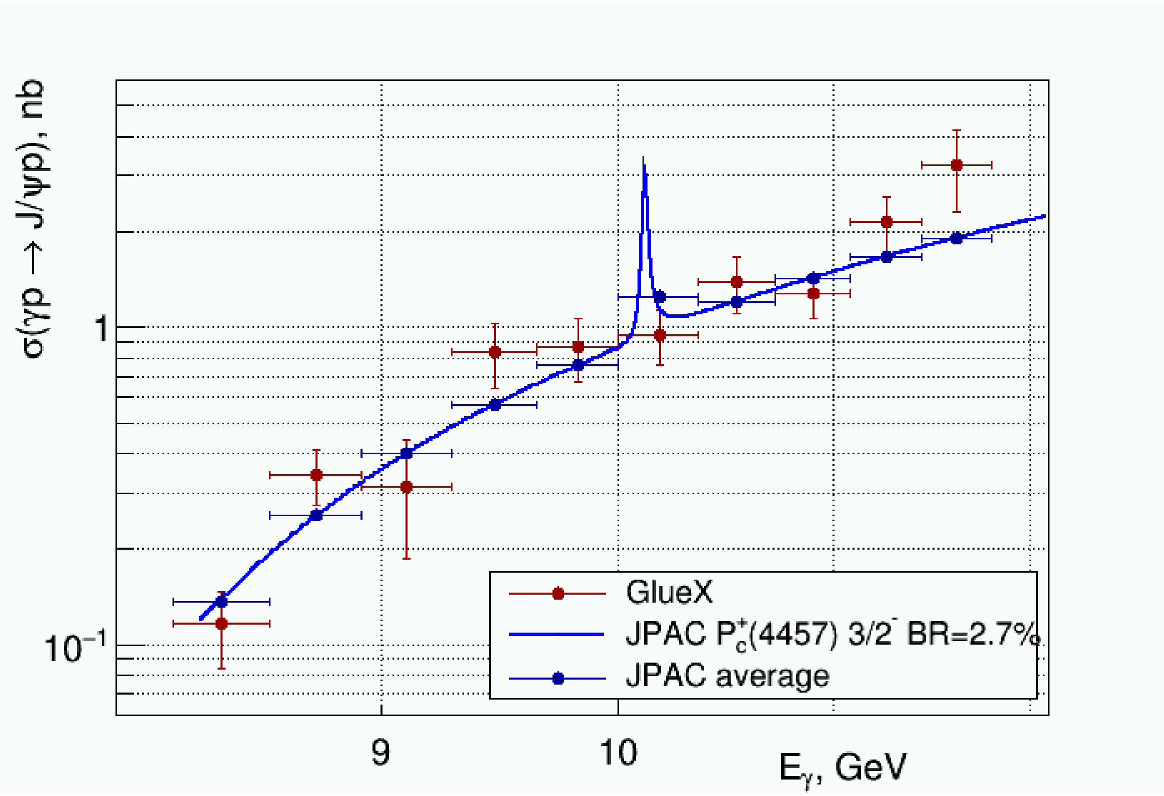

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	p.t.p. only	total	p.t.p only	total
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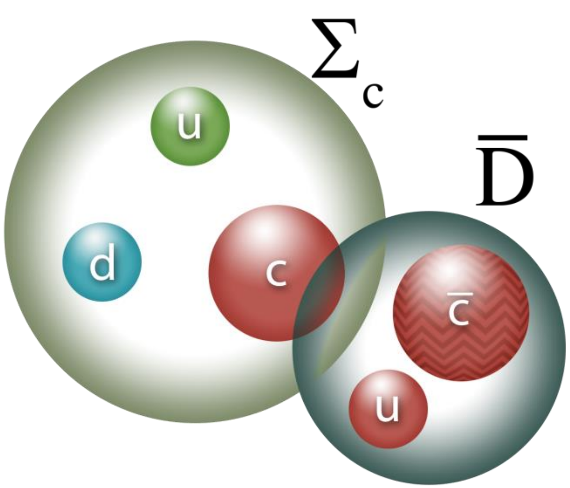
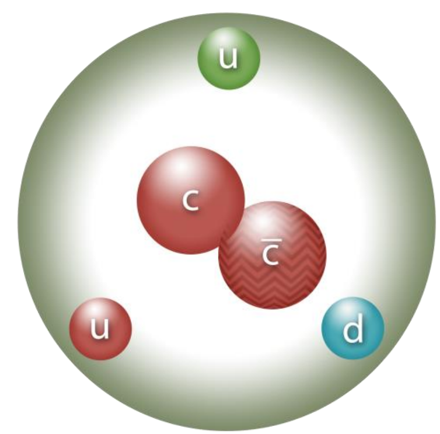
Upper limits at 90% confidence level

Br(Pc → J/ψp) calculations: molecular vs hadrocharmonium

model	Γ_{P_c}, MeV	$\Gamma_{J/\psi p}$, MeV	$\mathcal{B}(P_c \to J/\psi p)$	J^P	reference
molecular	21.7 (4450)	0.03 (4450)	0.14% (4450)	$1/2^-$ (4312)	M.Eides and V.Petrov
(OPE)				$1/2^-$ (4440)	Phys.Rev.D98, 114037
$\Sigma_c \bar{D}^{(*)}$				$3/2^-$ (4457)	
hadro-	– (4312)	suppr.(4312)	suppr. (4312)	$1/2^+$ (4312)	same as above
charmonium	44.8 (4440)	11 (4440)	25% (4440)	$1/2^-$ (4440)	and M.Eides, V.Petrov
	16.2 (4457)	11 (4457)	68% (4457)	$3/2^-$ (4457)	M.Polyakov,arXiv:1904.1161

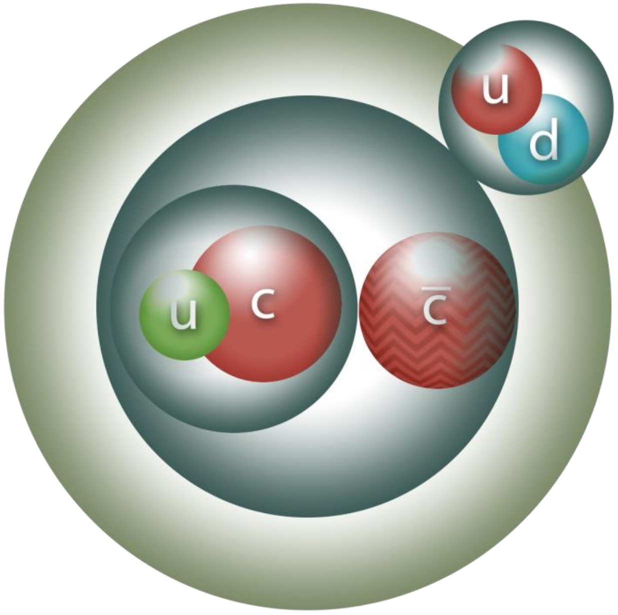
all subsystems in color singlet states





Br(Pc → J/ψp) calculations: compact diquark

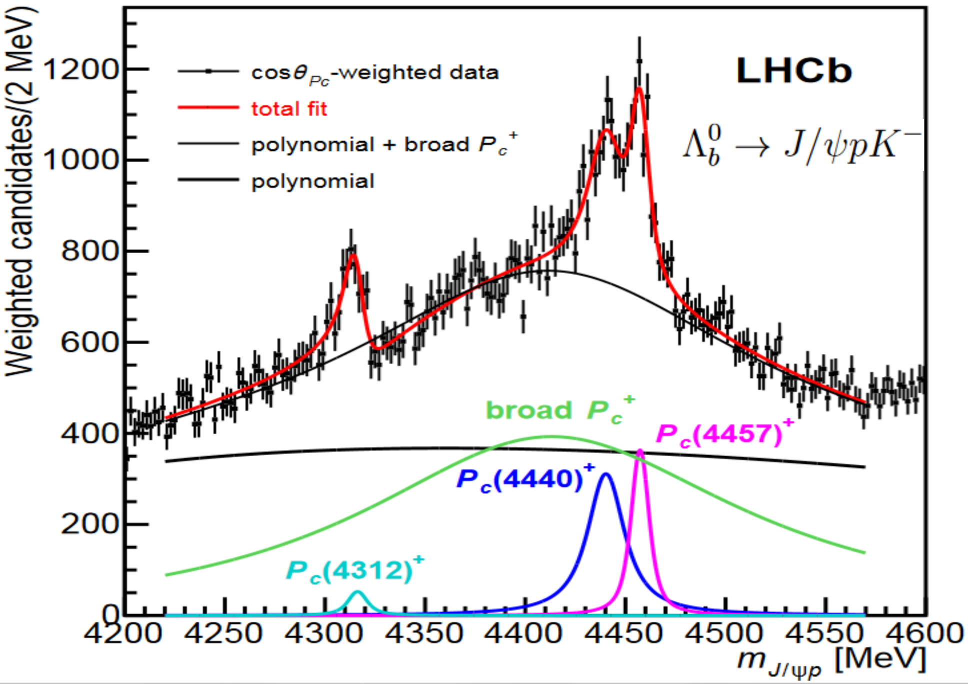
model	Γ_{P_c}, MeV	$\Gamma_{J/\psi p}$, MeV	$\mathcal{B}(P_c \to J/\psi p)$	J^P	reference
compact diquark	–	suppressed	suppressed	$3/2^-$ (4312) $3/2^+$ (4440) $5/2^+$ (4457)	A.Ali, A.Parkhomenko Phys.Lett.B793, 365



diquarks in color anti-triplet states

The bound-state effect in (uC)-diquark
reduces the probability to form $C\bar{C}$ -state

Lower limits on Br($P_c \rightarrow J/\psi p$) from data?



X. Cao, J-P. Dai *arXiv:1904.06015*

$$\mathcal{R} = \frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}$$

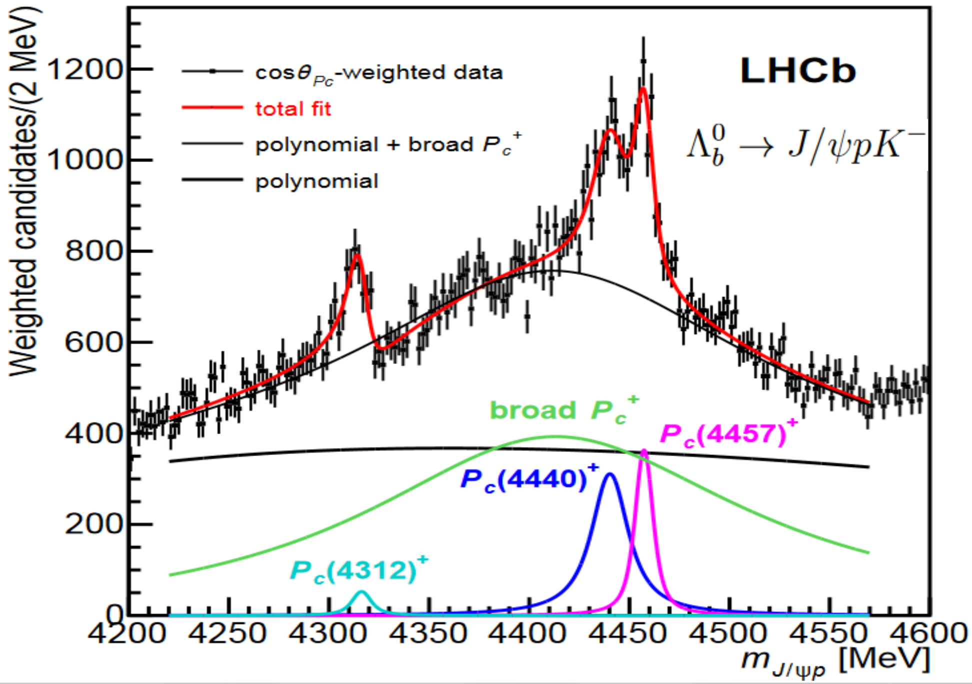
$$\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-) = (3.2^{+0.6}_{-0.5}) \times 10^{-4}$$

$\mathcal{B}(\Lambda_b \to P_c^+ K^-) < 10^{-3}$ at the level of $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)$ and $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^+ \pi^- \pi^-)$

(model dependent 2-4%) $> \mathcal{B}(P_c^+ \to J/\psi p) > 0.05\%$

GlueX

Lower limits on Br($P_c \to J/\psi p$) from data?



X. Cao, J-P. Dai *arXiv:1904.06015*

$$\mathcal{R} = \frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}$$

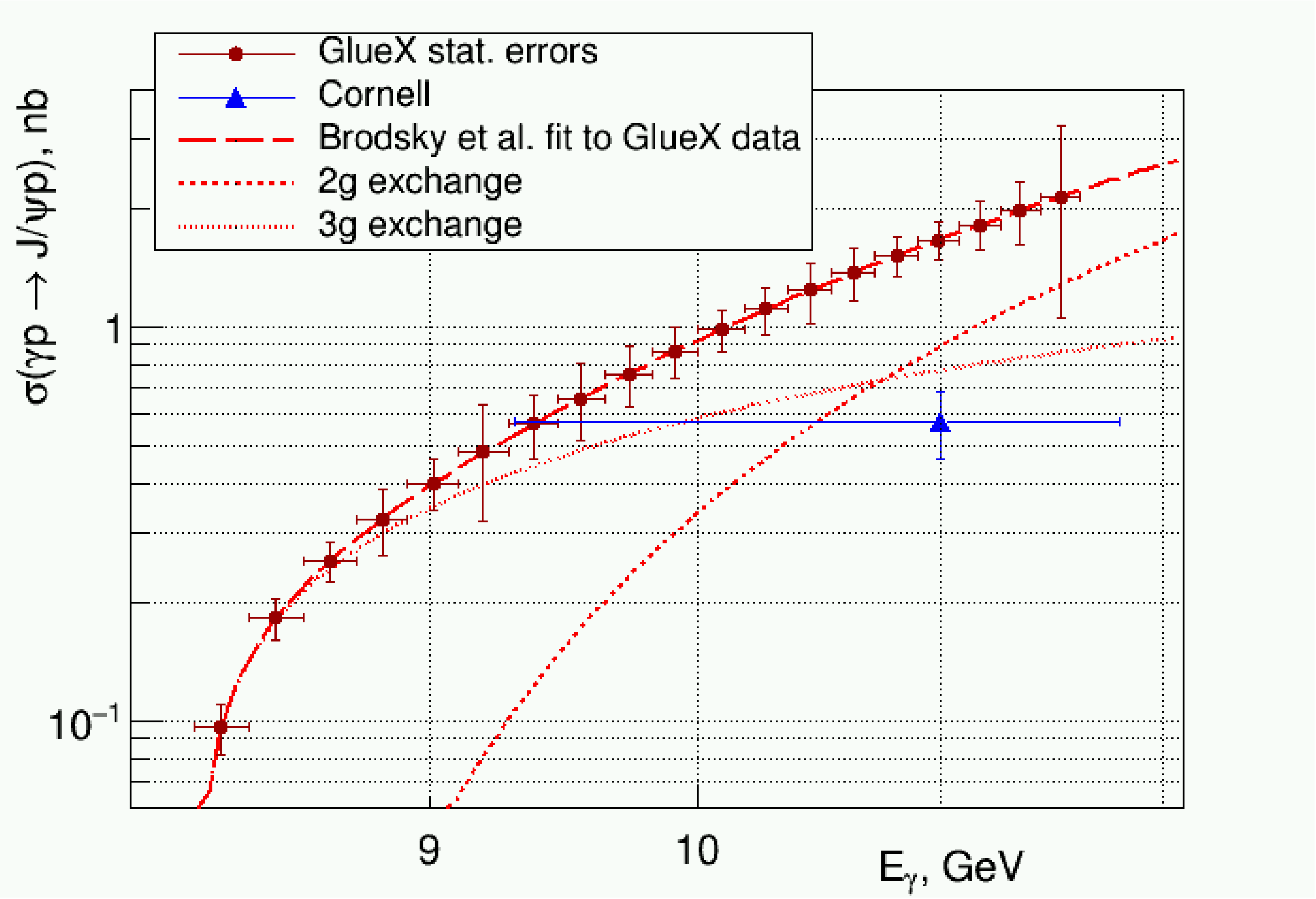
$$\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-) = (3.2^{+0.6}_{-0.5}) \times 10^{-4}$$

$\mathcal{B}(\Lambda_b \to P_c^+ K^-) < 10^{-3}$ at the level of $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)$ and $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^+ \pi^- \pi^-)$

(model dependent 2-4%) $> \mathcal{B}(P_c^+ \to J/\psi p) > 0.05\%$

GlueX

J/ψ total cross-section – future results



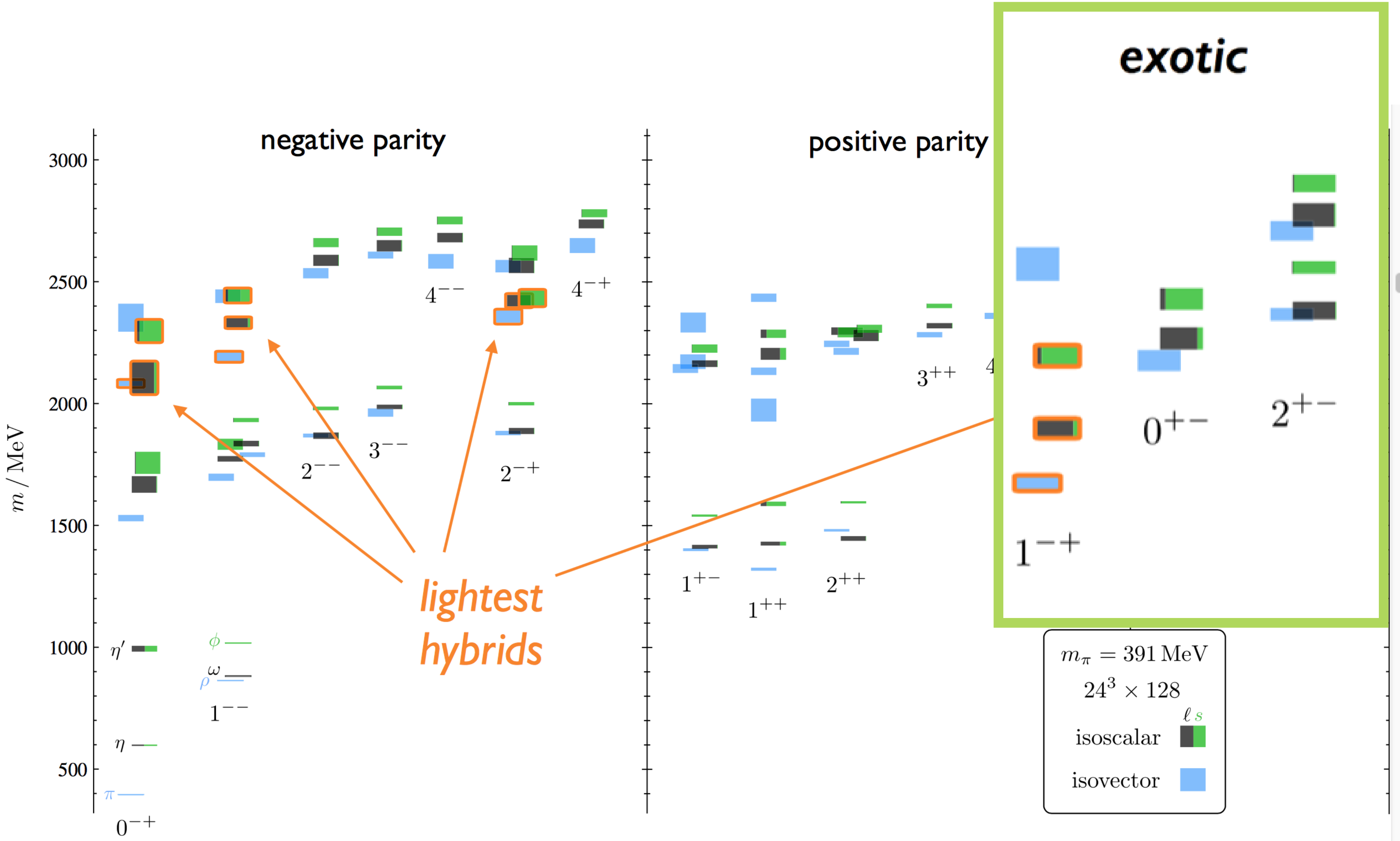
Preliminary results with 70% of statistics up to date –
only errors (stat.) shown

Outlook

- First phase of GlueX experiment finished and already producing results.
- Next phase – strangeness program and higher intensity.
- First measurement of near-thershold J/ψ exclusive photoproduction – important input to models of the gluonic structure of the proton at high X.
- Do not see evidence for LHCb pentaquarks and set model-dependent limits on $Br(P_c \rightarrow J/\psi p)$ at several percent level. This allows us to discriminate between different pentaquark models.

Back-ups

Searching for hybrids: light mesons lattice QCD



Br(Pc → J/ψp) calculations: pentaquark models

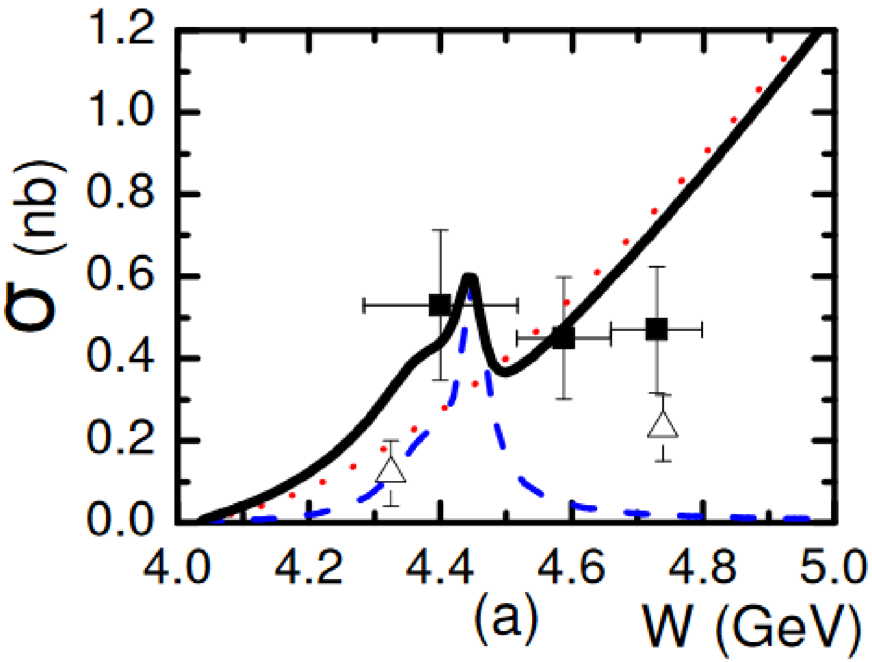
model	Γ_{P_c}, MeV	$\Gamma_{J/\psi p}$, MeV	$\mathcal{B}(P_c \to J/\psi p)$	J^P	reference
molecular	21.7 (4450)	0.03 (4450)	0.14% (4450)	$1/2^-$ (4312)	M.Eides and V.Petrov
(OPE)				$1/2^-$ (4440)	Phys.Rev.D98, 114037
$\Sigma_c \bar{D}^{(*)}$				$3/2^-$ (4457)	
hadro-	– (4312)	suppr.(4312)	suppr. (4312)	$1/2^+$ (4312)	same as above
charmonium	44.8 (4440)	11 (4440)	25% (4440)	$1/2^-$ (4440)	and M.Eides, V.Petrov
	16.2 (4457)	11 (4457)	68% (4457)	$3/2^-$ (4457)	M.Polyakov,arXiv:1904.1161
compact	–	suppressed	suppressed	$3/2^-$ (4312)	A.Ali, A.Parkhomenko
diquark				$3/2^+$ (4440)	Phys.Lett.B793, 365
				$5/2^+$ (4457)	
molecular	9.8* (4312)	6.5	66%	$1/2^-$ (4312)	Z.-H. Guo and J.Oller
(ERE)	20.6* (4440)	16.3	79%	$1(3)/2^-$ (4440)	Phys.Lett.B793, 144
$\Sigma_c \bar{D}^{(*)}$	6.4* (4457)	3.5	55%	$1(3)/2^-$ (4457)	
molecular	15.2 (4306)	4**	26%	$1/2^-$ (4306)	C.Xiao, J.Nieves, E.Oset,
(DSE)	23.4 (4453)	18**	77%	$1/2^-$ (4453)	arxiv:1904.01296
$\Sigma_c \bar{D}^{(*)}$	3.0(4453)	2**	67%	$3/2^-$ (4453)	Phys.Rev.D88, 056012

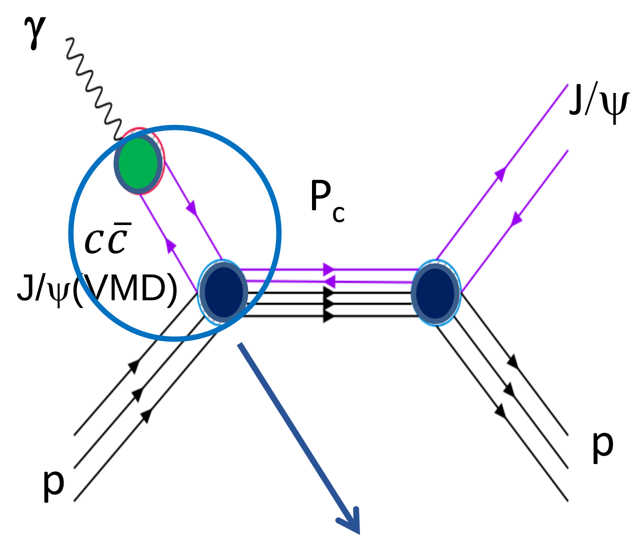
* The total width measured by LHCb has been used.

** The width calculated from coupling constants.

Attempts to suppress VMD coupling

J.-J. Wu, T.-S. Lee, B-S. Zou arXiv:1906.05375



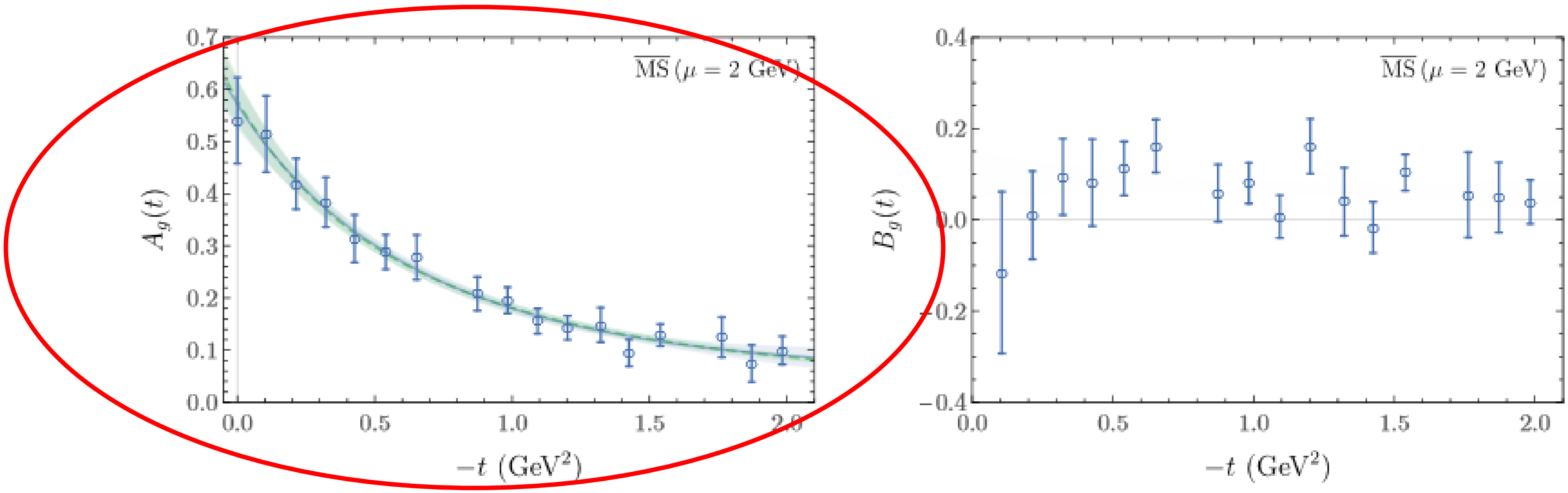


$$F_V(q) = \frac{\Lambda_V^4}{\Lambda_V^4 + (q^2 - m_V^2)^2}$$

$$\Lambda = 0.55 \text{ GeV}$$

- J/ψ is suppressed by 10^{-3}, VMD coupling dominated by ρ and ω
- How to explain J/ψ photoproduction at high energies with such suppression???
- Other papers (*J. Phys. G4 (1978) 989, Phys. Rev. Lett. 38 (1977) 263)* suggest some moderate suppression (factor of *2-3*)

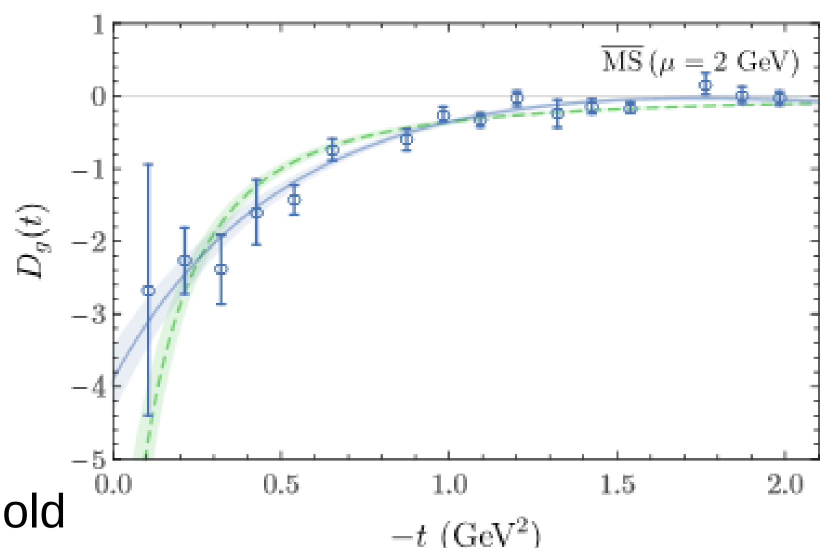
Proton Gluonic Form Factors: A,B,C (lattice calculations)



(a) (b)

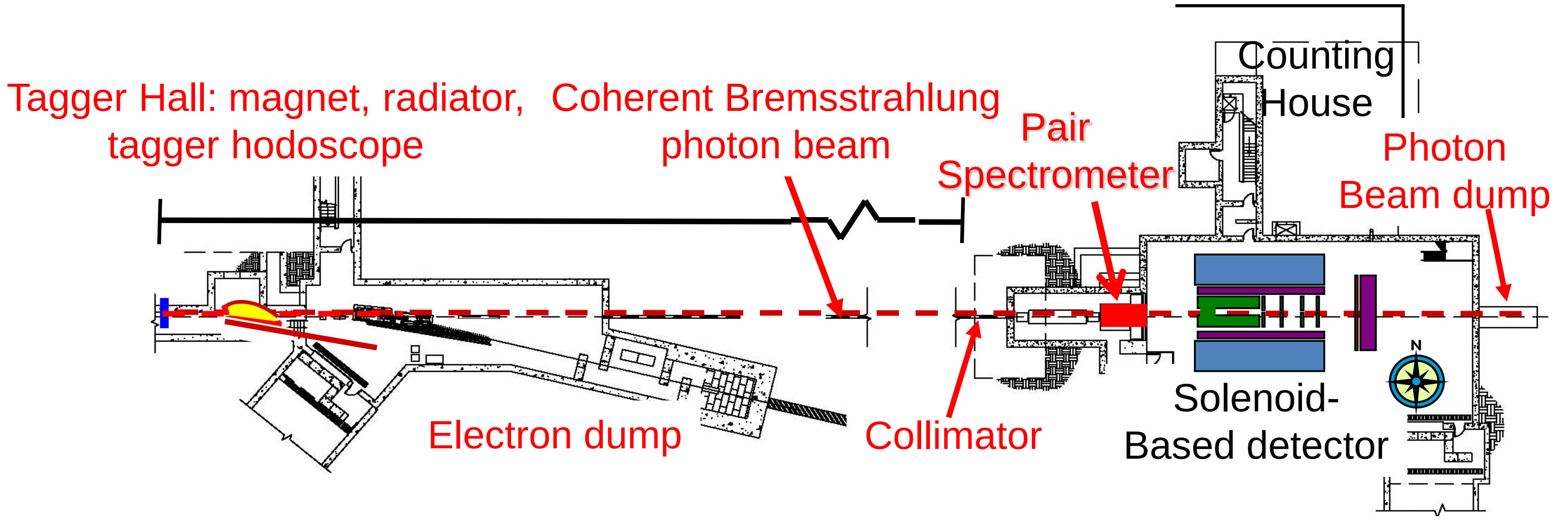
Fits in dipole form:

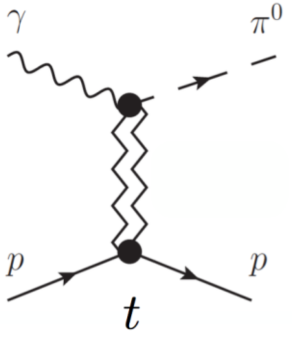
	m (GeV)	α
A_g	1.13(6)	0.58(5)
D_g	0.48(5)	-10(3)



P. E. Shanahan and W. Detmold
https://arxiv.org/pdf/1810.04626.pdf

Hall D layout





Exchange J^{PC}

1^{--} : ω, ρ

1^{+-} : b, h