Charmonium Physics with GlueX

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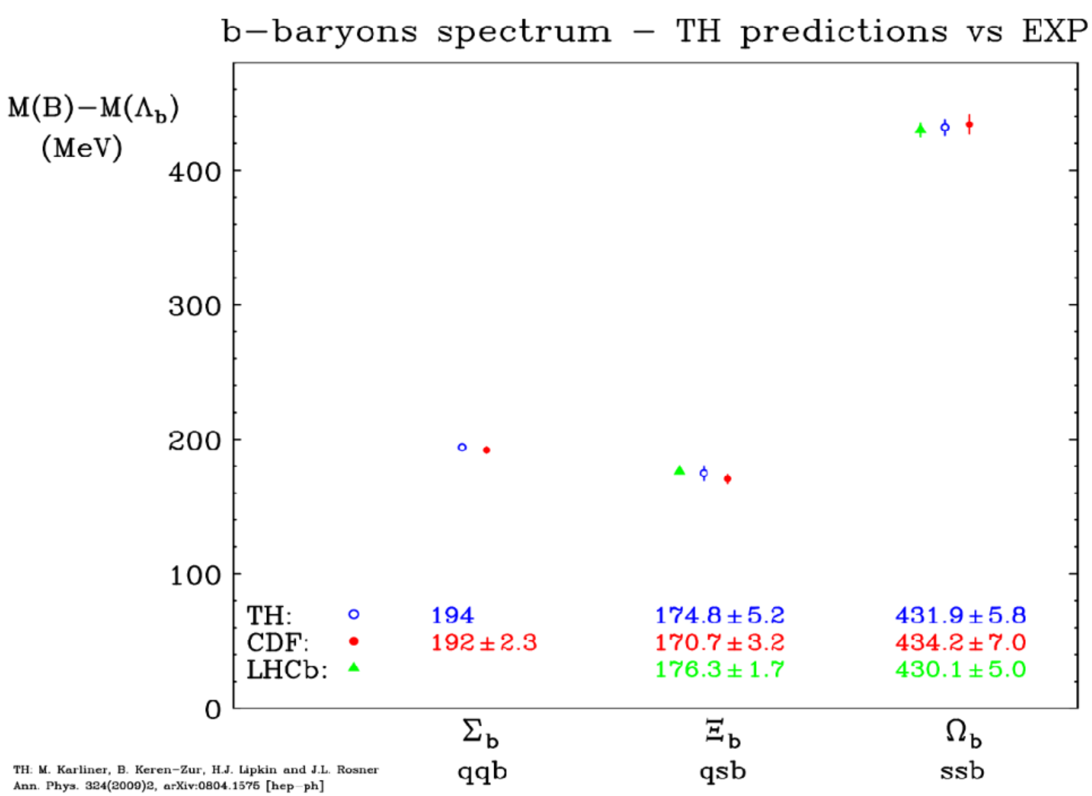
- JLab 12GeV accelerator has UNIQUE opportunity (high intensity, right energy) to study near threshold charmonium photo-production
- Physics motivation
  - Heavy vs light quark hadrons
  - Study charmonium-nucleon interaction
  - LHCb pentaquarks
  - Other dielectron physics: TCS, rare leptonic decays
- GlueX vs other Halls
  - maximum energy
  - full acceptance in both charge particles and photons
  - possibility to use linearly polarized beam
- Possible GlueX modification for charmonium running
  - Trigger, detector modifications at high intensity
  - Electron/pion separation

Why Heavy Quarks

- Hadrons with heavy quarks are much simpler: quarks are almost static, spin-dependent interaction ~ $1/m_Q$
- Very accurate theoretical prediction for the heavy hadrons
- Exotic states with heavy quarks: XYZ states, LHCb pentauqarks

Just an example:

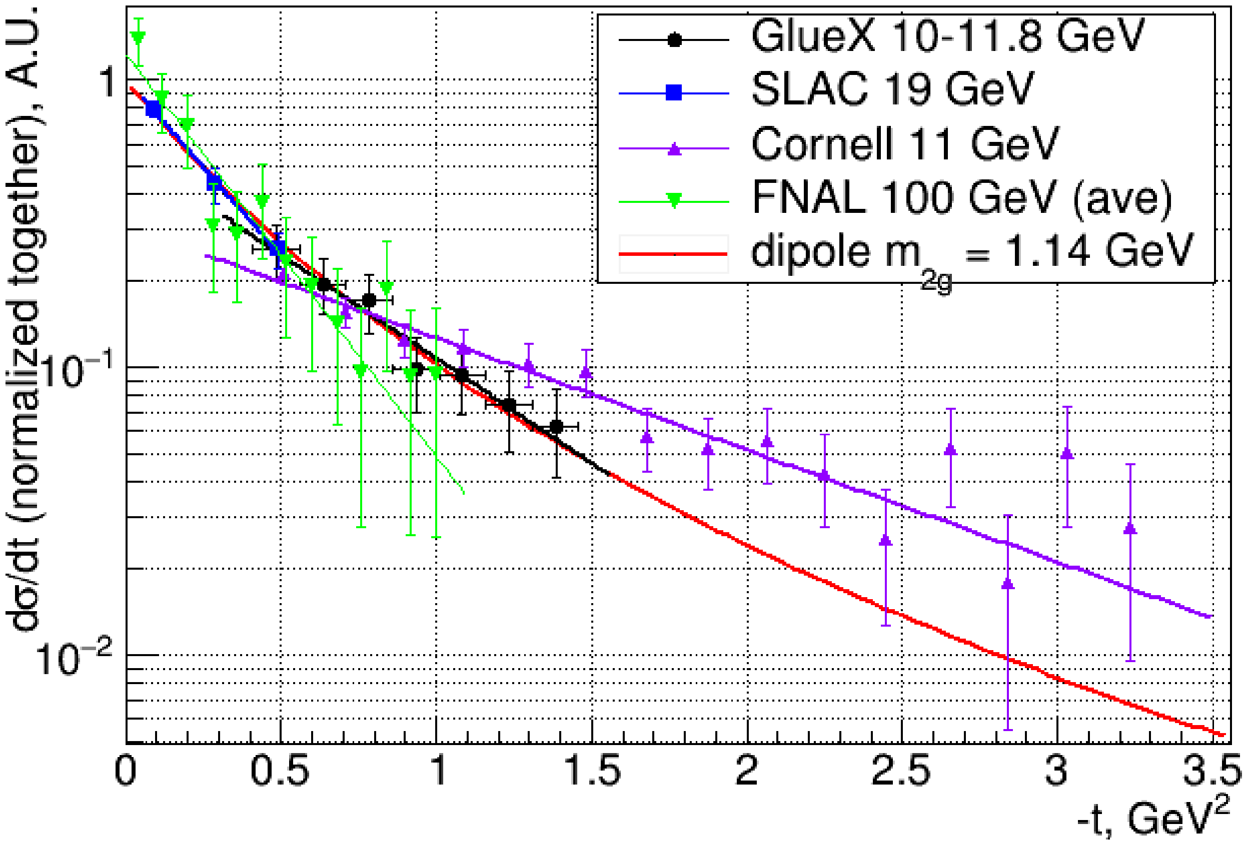


Charmonium-nucleon Interaction

- Charmonium excellent probe to study gluonic content of nucleon
- Using VMD ($\gamma \to J/\psi$) one can study $J/\psi\, p \to J/\psi\, p$
- Heavy quark system interacts with light quark proton via gluon exchange
- In analogy with the electro-magnetic Form Factor:

	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)

Proton Gluonic Form Factor



- *Frankfurt and Strikman PRD66 (2002)* suggested t-dependence defined by the proton gluonic FF
- Explains t-slope change with energy (due to t_{min} and t-range dependence) in wide energy range:
  - FNAL <E>=100 GeV
  - SLAC 19 GeV
  - Cornell 11 GeV
  - GlueX 10-11.8 GeV

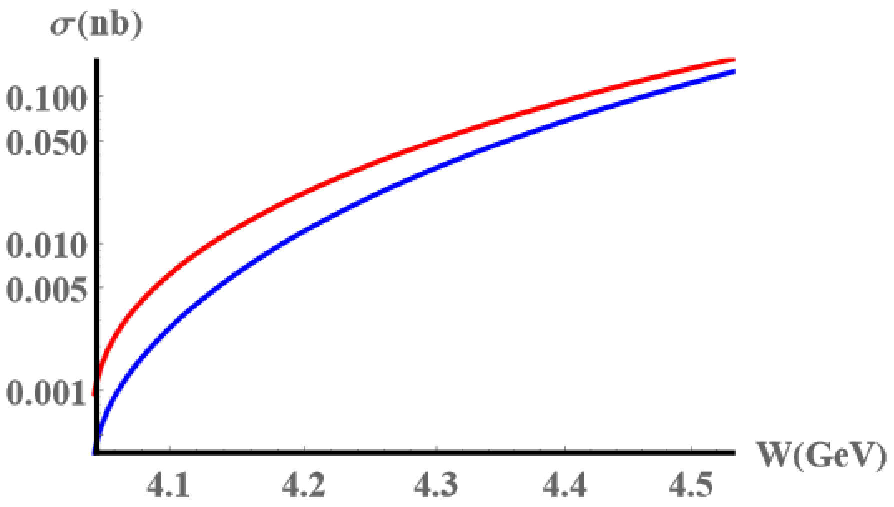
$$F(t) \sim \frac{1}{(1-t/m_{2g}^2)^4}$$

Proton Gluonic Form Factors: A,B,C

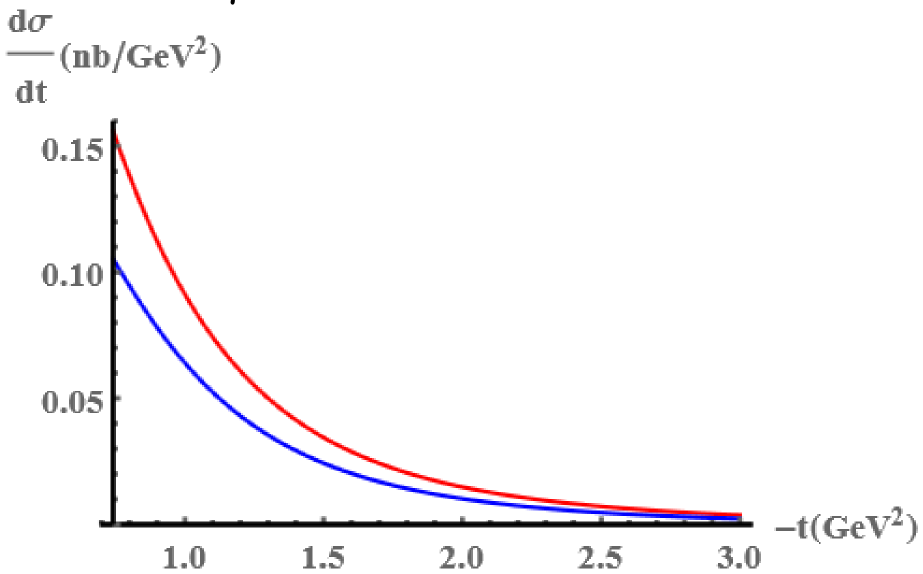
J/ψ p → J/ψ p:

$$\langle P'|(T_g)^\mu_\mu|P\rangle = \langle P'|\left(\frac{\beta(g)}{2g}F^a_{\mu\nu}F^{\mu\nu}_a + m\gamma_m\bar{\psi}\psi\right)|P\rangle$$
$$= \bar{u}(P')\left[A_g M + \frac{B_g}{4M}\Delta^2 - 3\frac{\Delta^2}{M}C_g + 4\bar{C}_g M\right]u(P)$$

- Red – maximal trace anomaly term (related to fraction of nucleon mass arising from gluons)
- Blue – no trace anomaly

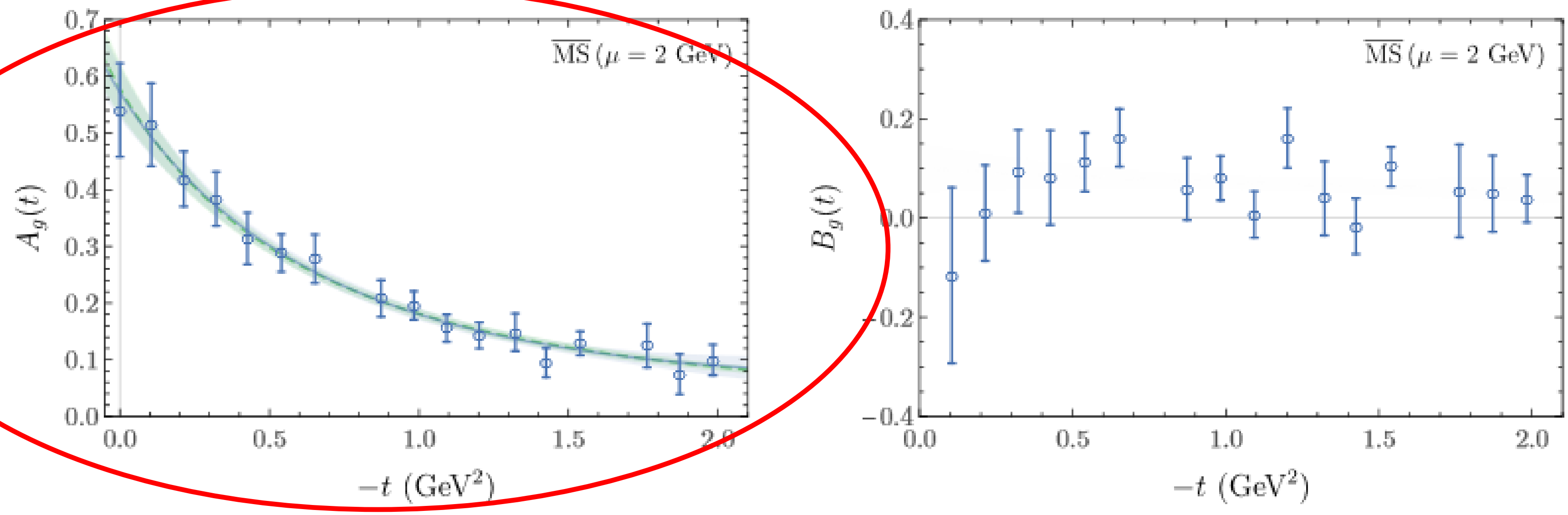


E_γ = 9.3 GeV



Yoshitaka Hatta and Di-Lun Yang
https://arxiv.org/pdf/1808.02163.pdf

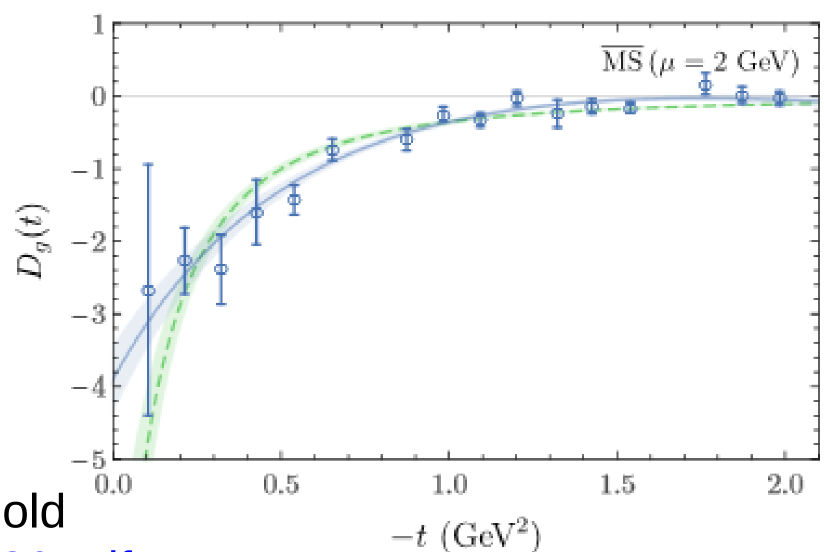
Proton Gluonic Form Factors: A,B,C (lattice calculations)



(a) (b)

Fits in dipole form:

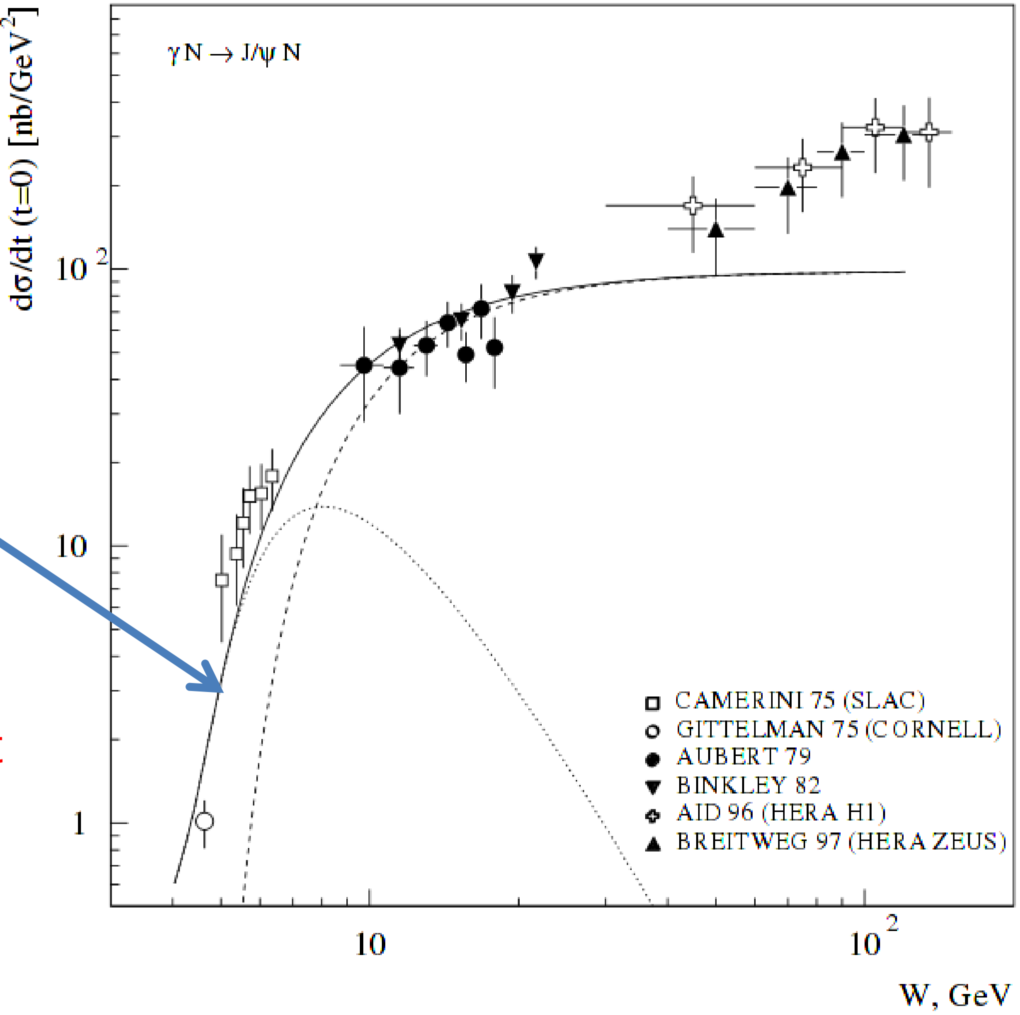
	m (GeV)	α
A_g	1.13(6)	0.58(5)
D_g	0.48(5)	-10(3)



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

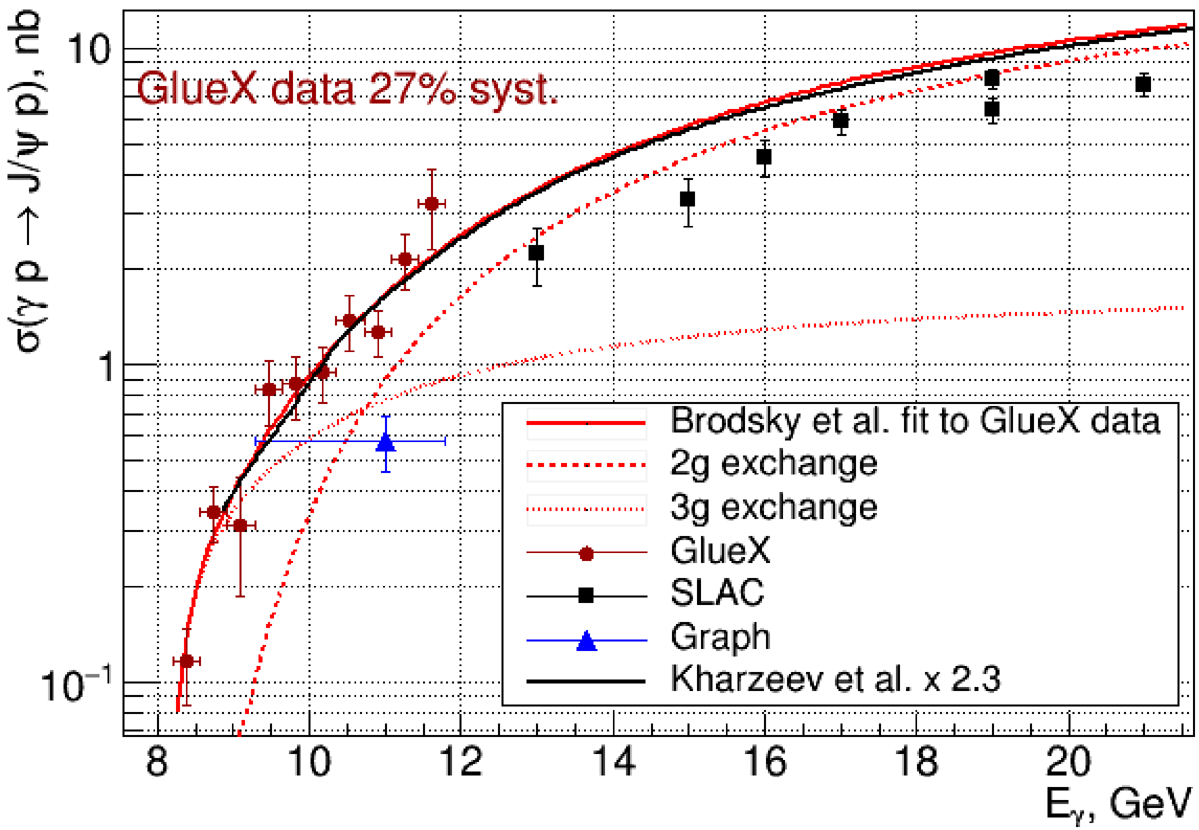
Why charmonium photoproduction NEAR THRESHOLD?

- *Kharzeev et al. Eur. Phys. C9 (1999)* The real part of the amplitude (dominates at low energies) is critically important – contains the conformal (trace) anomaly, related to the fraction of the nucleon's mass arising from gluons.



- *Brodsky et al. PLB 498, (2001)* Sensitive to proton gluonic content at high x. Energy dependence derived from dimensional scaling: hard 2-gluon or (near threshold) 3-gluon exchange.

J/ψ photoproduction: comparison to data and theory

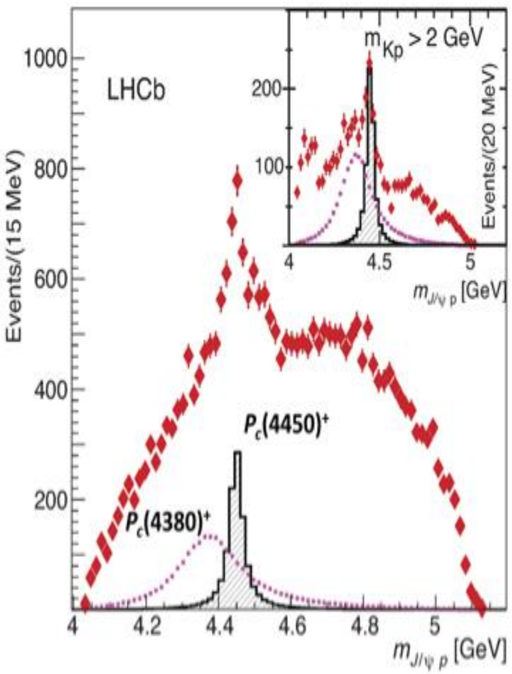


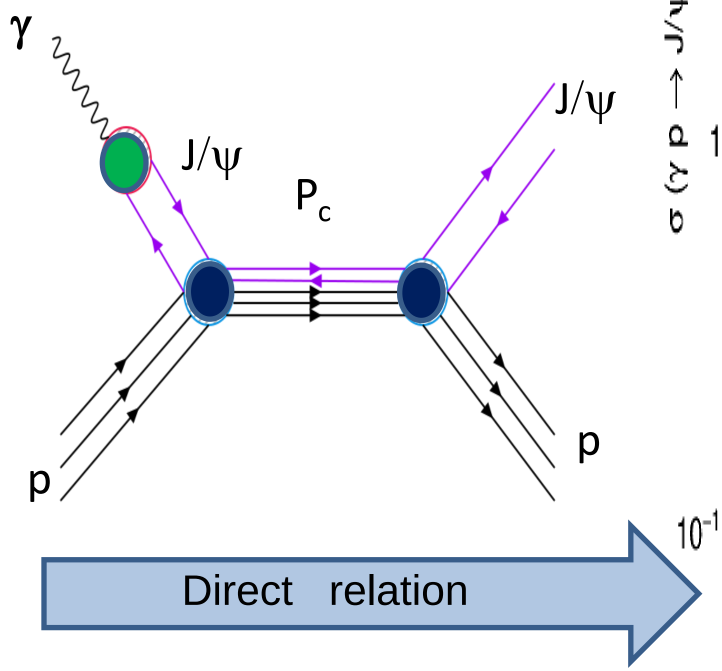
Brodsky at.al (2001)
fit of the GlueX data ONLY, using F(t) as t-dependence

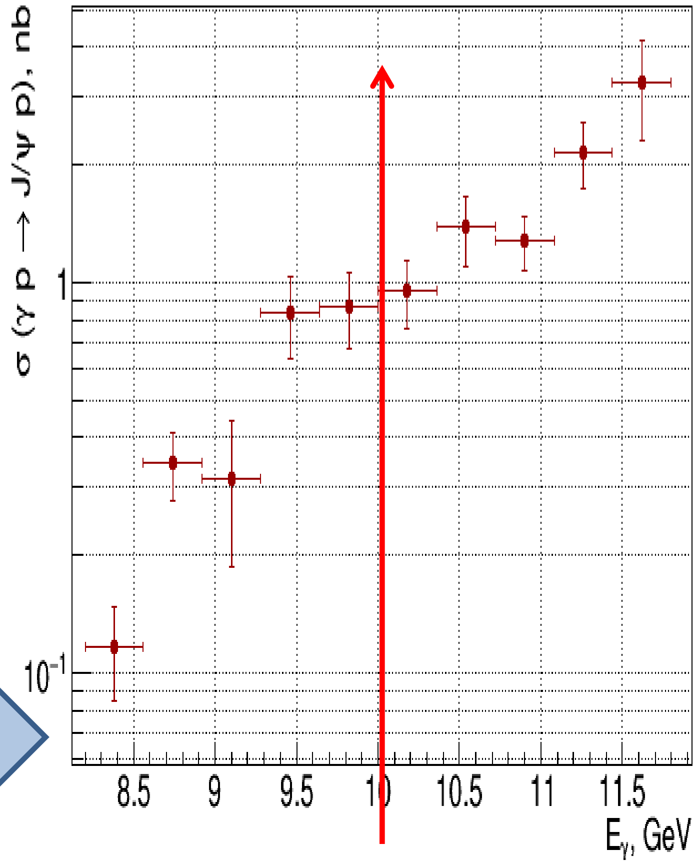
Kharzeev et al (1999)
absolute (factor 2-3 uncertainty) perturbative calculations using gluon PDFs - related to the gluonic contribution to the mass of the proton

LHCb petaquarks in s-channel production

- LHCb pentaquarks observed in $\Lambda_b \to K^-(J/\psi p)$ *R.Aaji et.el* PRL 115, (2015)
- DIRECT relation – if they exist they should be seen in s-channel photoproduction:



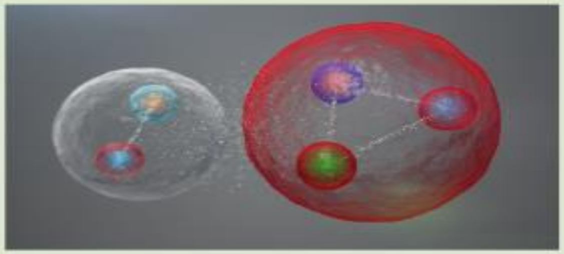
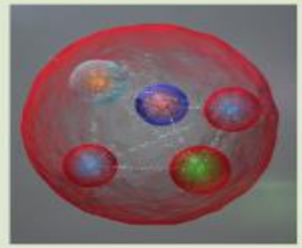
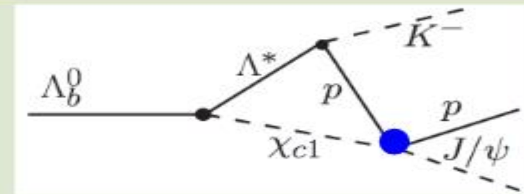




$P_c(4450)$

- 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).

LHCb pentaquark: possible explanations

Hadronic molecules	Tightly-bounded states	Kinematic effects
		 $\chi_{c1}p \to J/\psi p$
Close to two heavy hadron thresholds	Predicted more than 10 J^P states	Predicted no decay of $P_c(4450)^+ \to \chi_{c1}p$
Karliner&Rosner, PRL 115 (2015) 122001	Maiani et al, PLB 749 (2015) 289	Guo et al, PRD 92 (2015) 071502

Liming Zhang’s slide

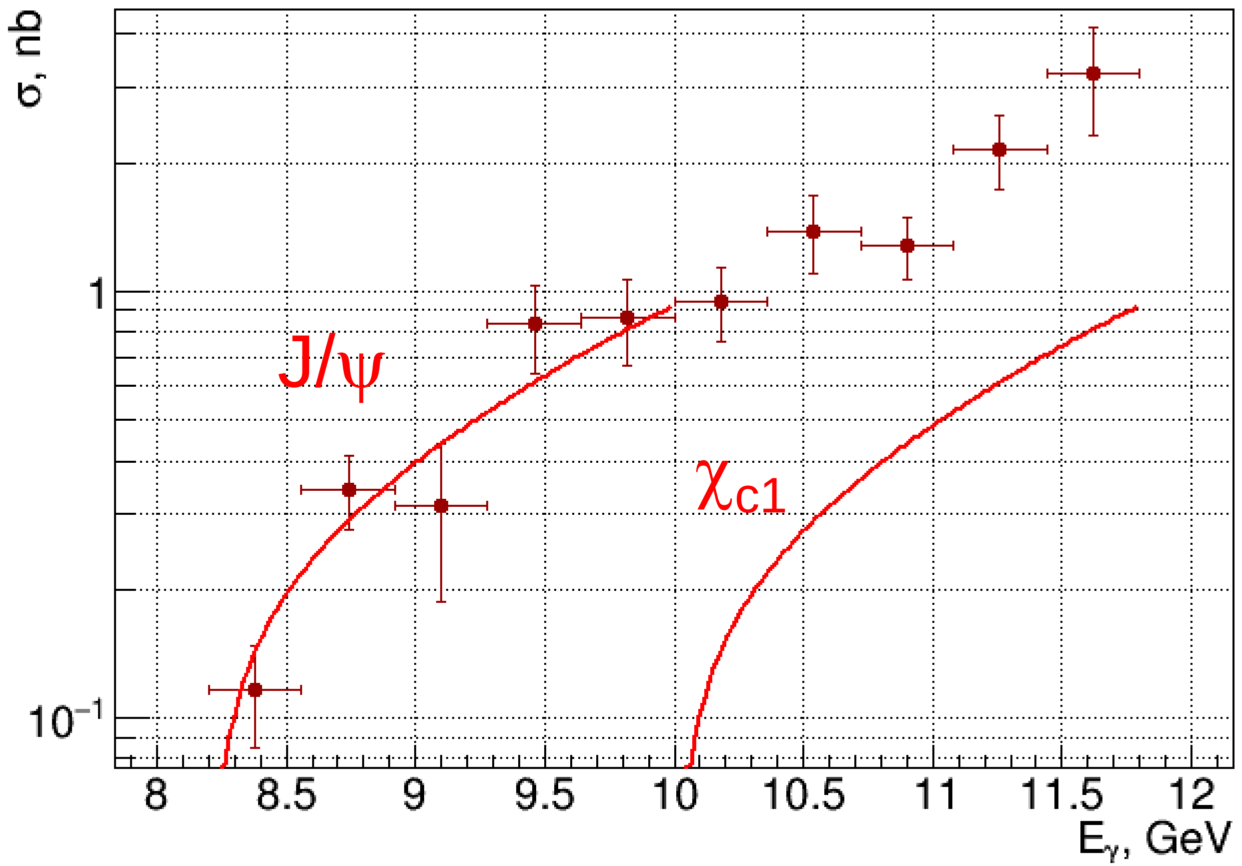
$P_c(4450)$ - $\Sigma_c \bar{D}^*$ molecule
Narrow width despite big phase space indicates small overlap with $J/\psi p$ state

Pc(4380) much wider – has potential to be explained as tightly-bound system

If $\chi_{c1}p$ decay found then it is not a kinematic effect

Photoproduction of χ_{c1}(3511) 1^{++}

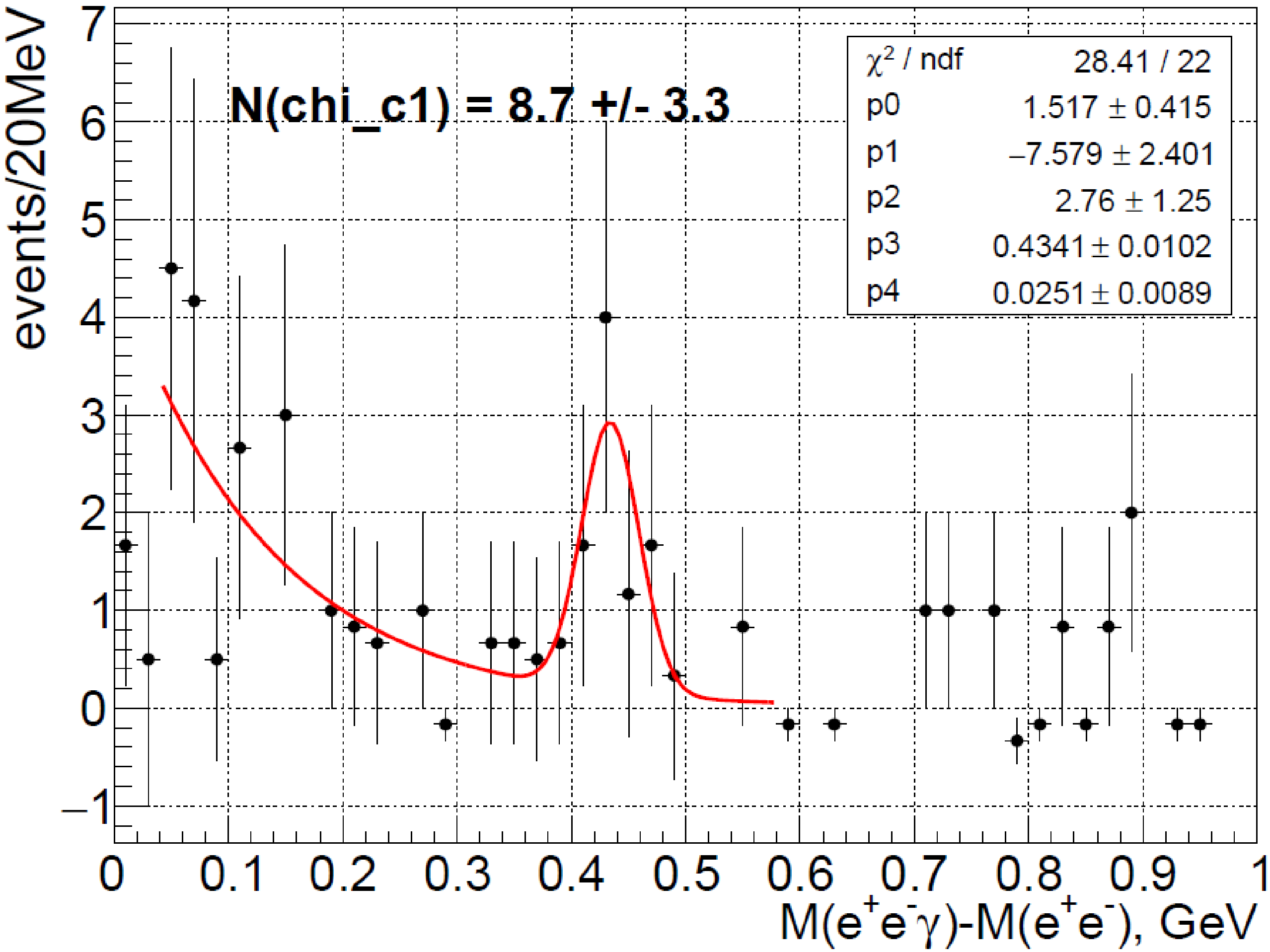
$\gamma\, p \rightarrow \chi_{c1}\, p \rightarrow J/\psi\, \gamma\, p \rightarrow e^{+} e^{-} \gamma\, p$



$N_{J/\psi}/N\chi_{c1}$ = 4.525 (σ) x 1.753 (flux) x 2.915 (χ_{c1} -> J/ψ γ 34.3%) = 23

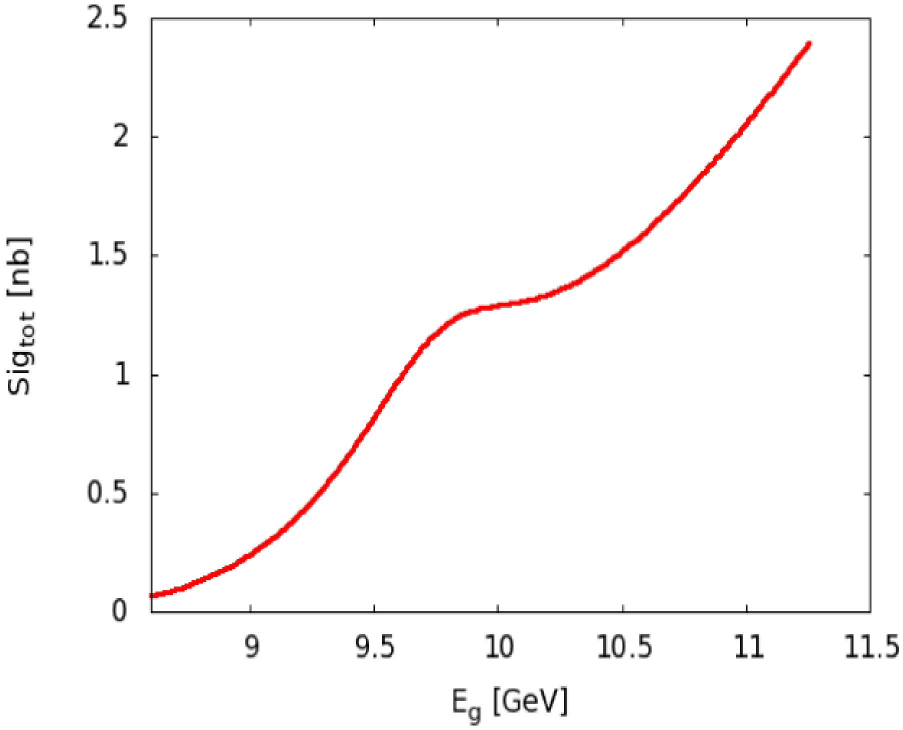
Photoproduction of $\chi_{c1}(3511)$

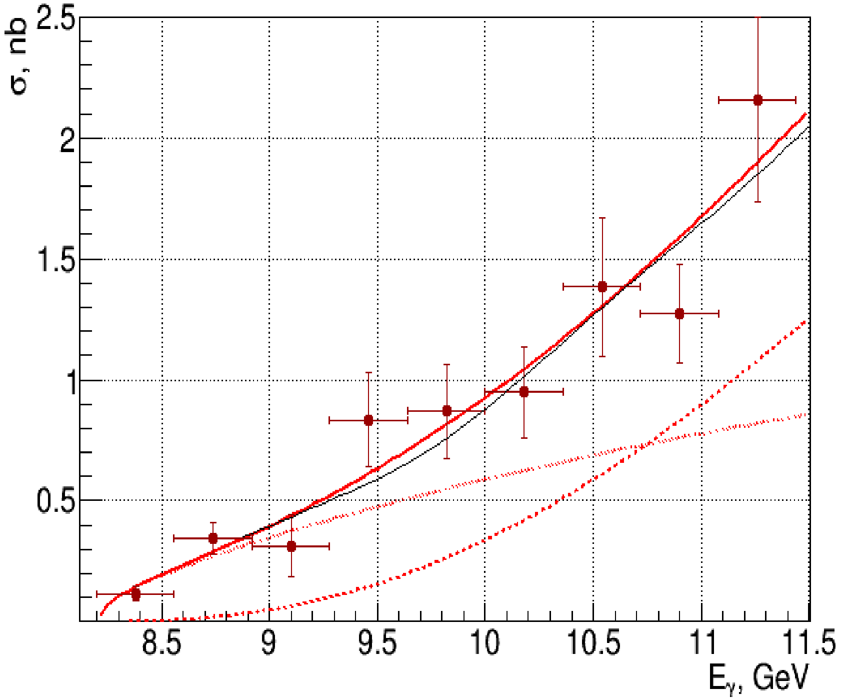
$\gamma\, p \to \chi_{c1}\, p \to J/\psi\, \gamma\, p \to e^+ e^- \gamma\, p$



2016 data only – expect ~11 events without efficiency corrections

What can we say about Pc(4380)





JPAC model for Pc(4380) J=3/2 BR=1.5%

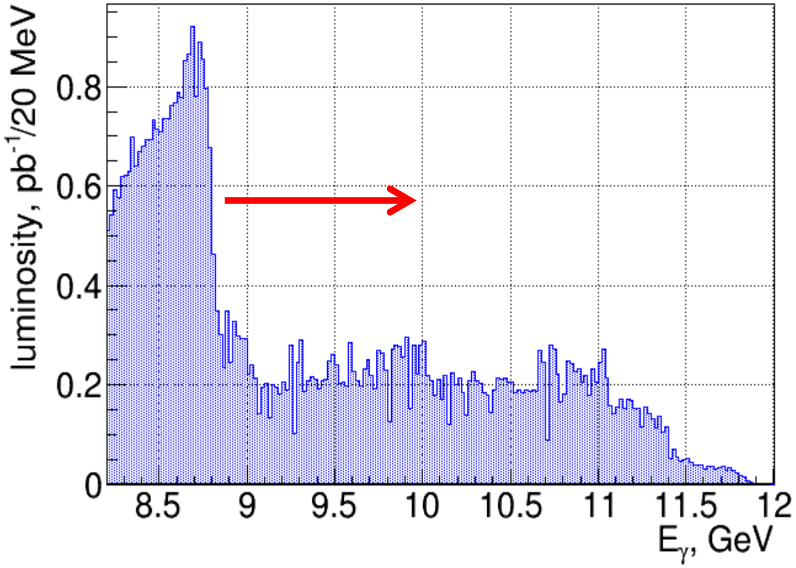
- Cross-section experiments can't separate t-channel from s-channel Pc(4380) production (too wide!)
- Polarization experiments will be needed (using linearly polarized photons in GlueX?)
- Expect results with higher statistics (x8) from LHCb

GlueX vs other Halls

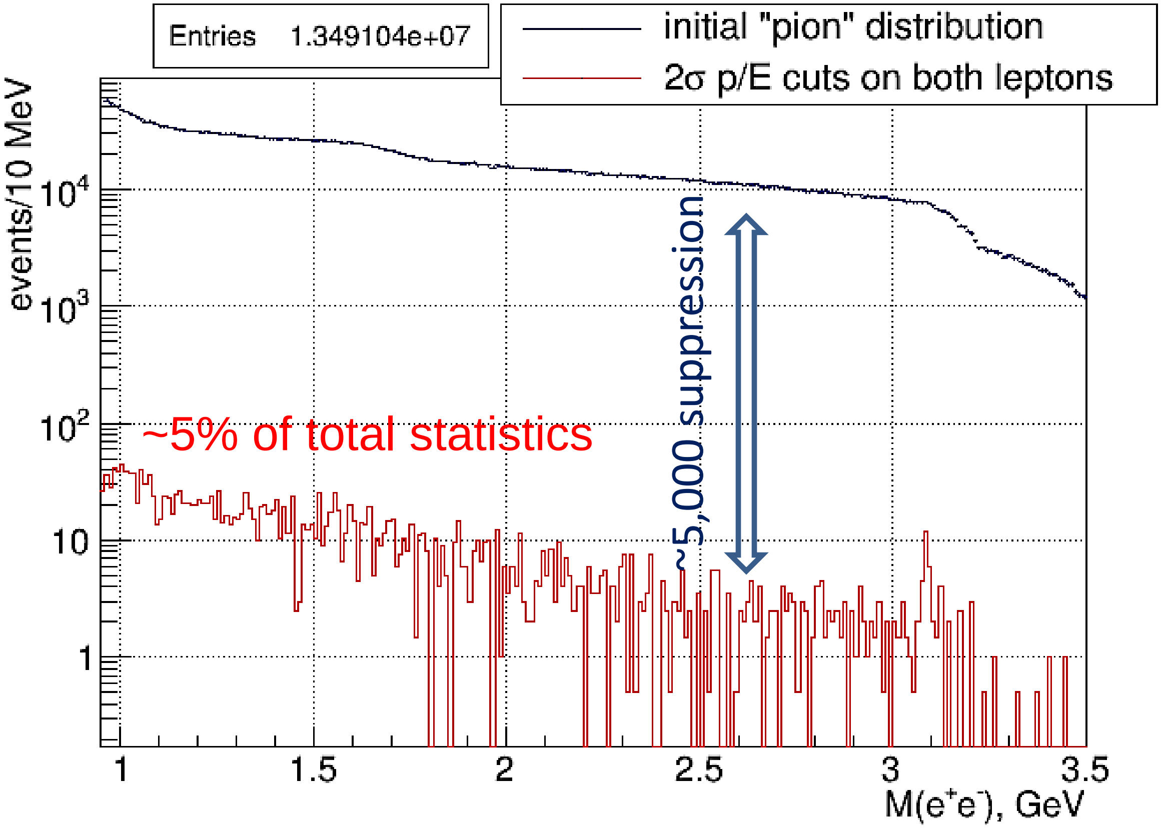
- Full acceptance for charged and neutral particles
  - J/ψ photoproduction very close to the threshold (θ_p>1^o)
  - t-dependence
  - γ p $\rightarrow \chi_{c1}$ p$\rightarrow$ J/ψ γ p$\rightarrow$ $e^+ e^- \gamma$ p
  - γ p $\rightarrow$ J/ψ π p$\rightarrow$ $e^+ e^- \pi$ p (target excitation - needed for inclusive experiments at other halls)
- Maximal beam energy
  - Bridge to high energy measurements
  - γ p $\rightarrow \chi_{c1}$ p$\rightarrow$ J/ψ γ p$\rightarrow$ $e^+ e^- \gamma$ p
- Possibility to use linearly polarized beam
  - Pc(4380) polarization experiment
- Other dielectron physics: TCS, rare leptonic decays requiring full acceptance

Possible GlueX modifications

- Most likely scenario: opportunistic physics with GlueX data
  - Currently we have ~450 J/ψ's using ~20% of statistics so far
  - With GlueX at high intensity expect ~10k in total
- Depending on results from the other halls and LHCb we may decide to have special charmonium running at very high intensity with some (or all) of the modifications:
  - Trigger: high threshold on sum of two calorimeters
  - Keeping only high energy tagger counters
  - Turning off (or lower HV) the inner part of some detectors (CDC, FDC, TOF, FCAL)
  - Move coherent peak up to 10 GeV:



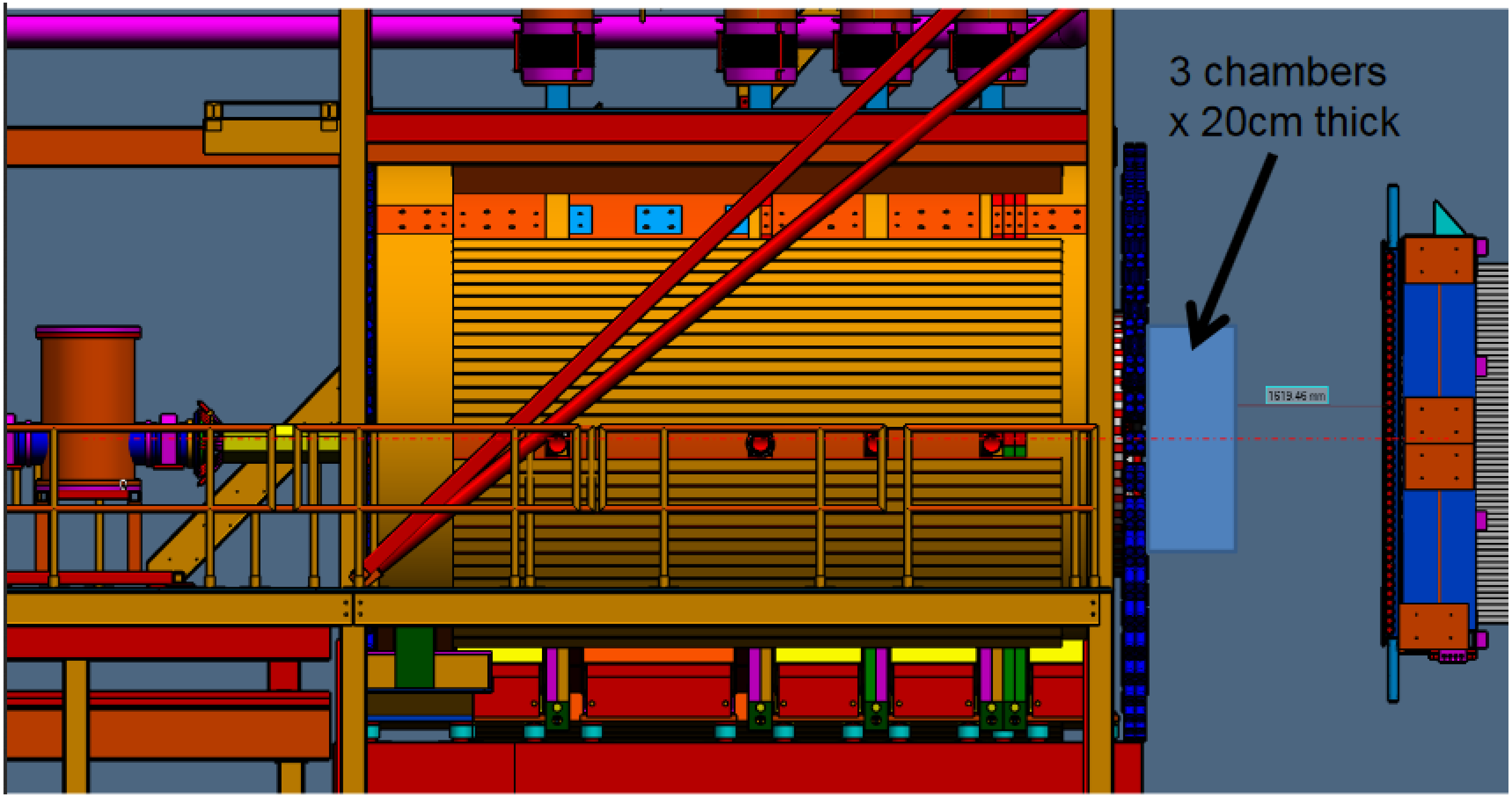
Possible GlueX modifications: e/π separation



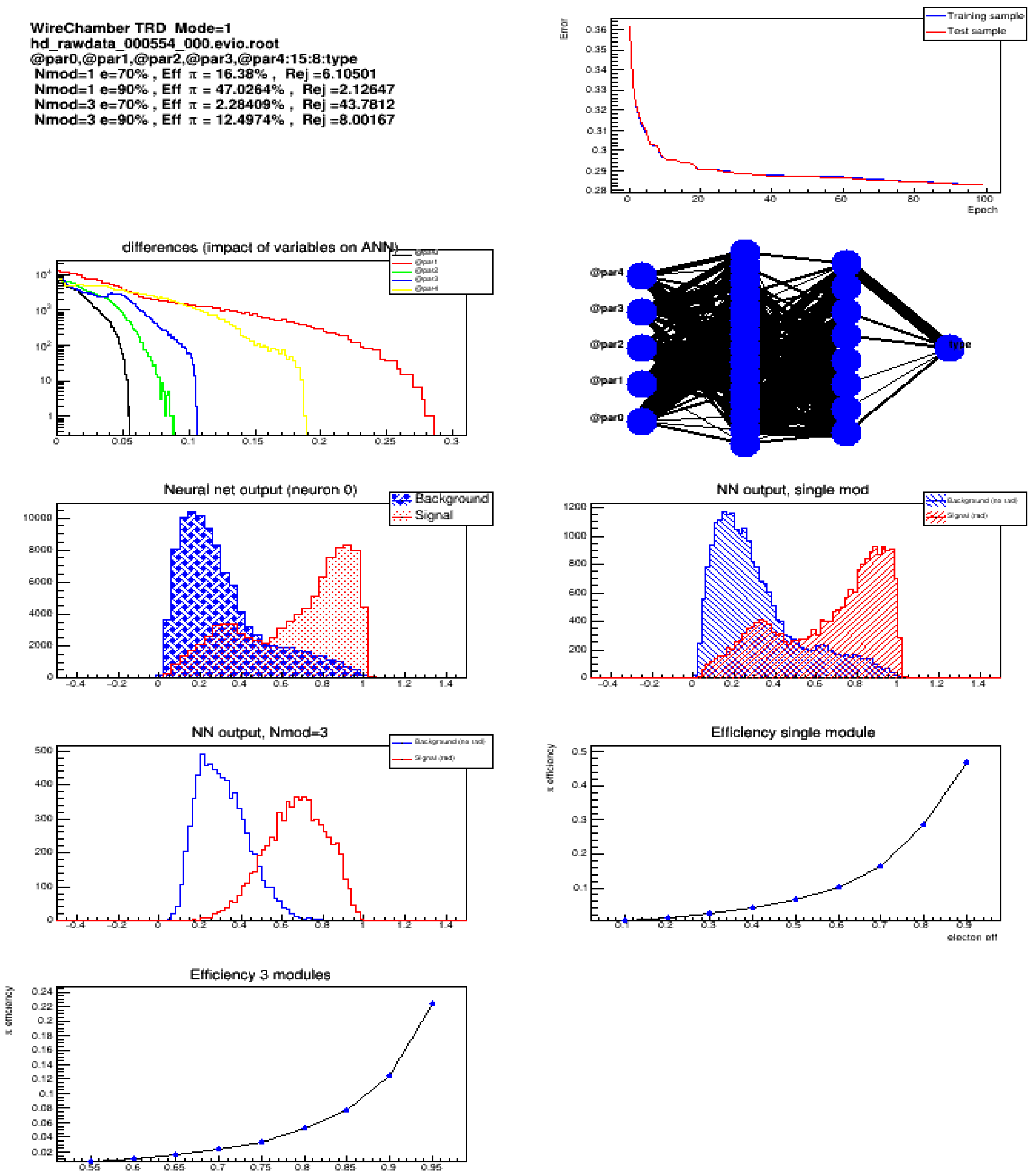
- Pions are 3 orders more numerous and GlueX detector doesn't have enough power to suppress them
- Suppression factor of ~5000 by E/p cuts (2σ) on both leptons using calorimeters

Possible GlueX modifications: e/π separation with TRD

- TRD in forward direction: with 3 chambers expect suppression factor of ~20-50 at 90% efficiency



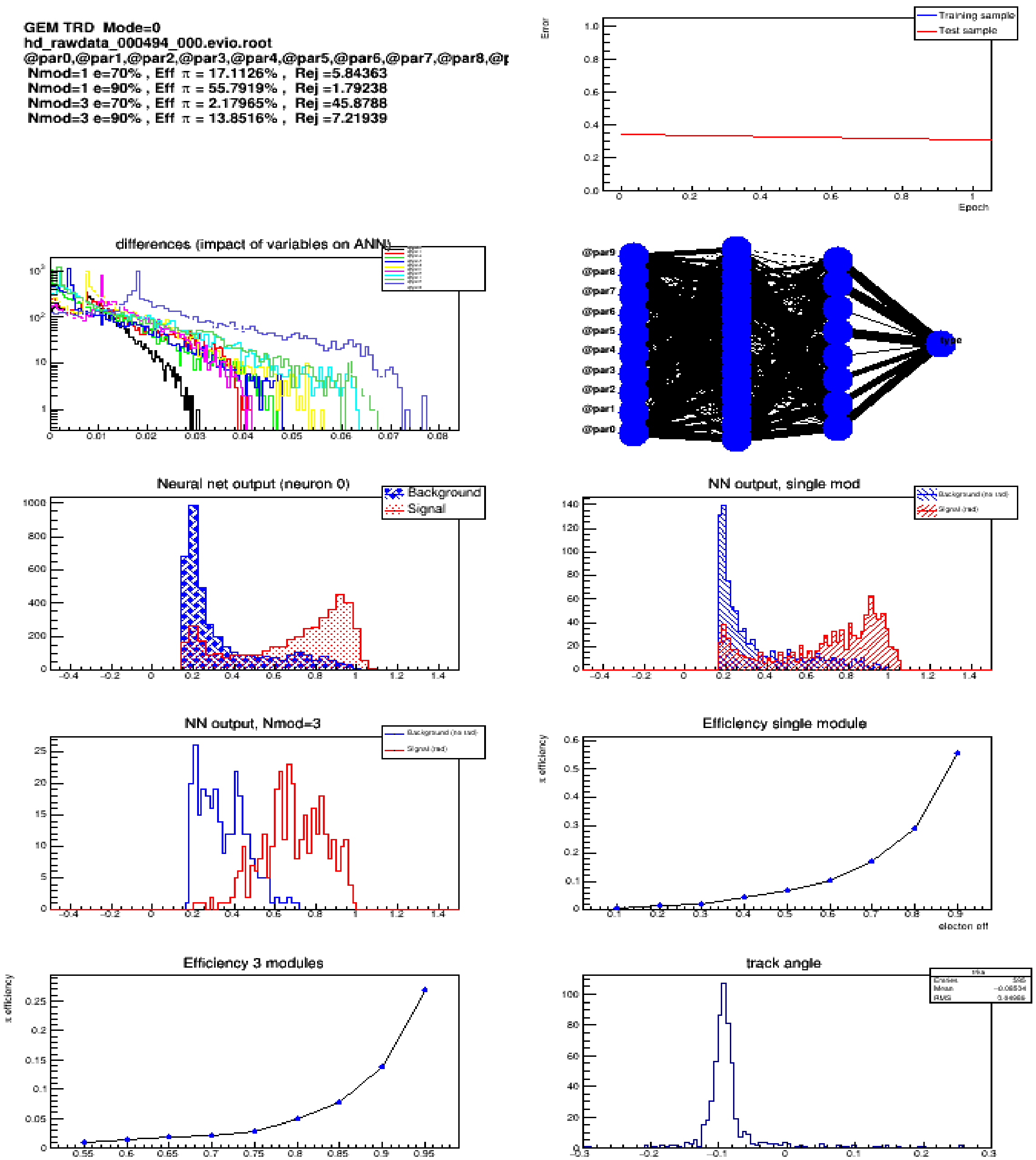
Possible GlueX modifications: WC-TRD prototype



- Results with WC-TRD prototype
- e/e with/without radiator – 1.9 suppression factor at 90% efficiency

Sergey Furletov reports these results on VCI 2019

Possible GlueX modifications: GEM-TRD prototype



- Results with GEM-TRD prototype
- e/e with/without radiator – 1.9 suppression factor at 90% efficiency

Sergey Furletov reports these results on VCI 2019

Possible GlueX modifications: extrapolation for e/π separation with TRD

Detector	Dead material in front	Radiator	e/π	$e/e_{no\ radiator}$	$DATA_{e/e_{noR}}$
20 mm	no dead material	20 cm	14.4	6.3	
20 mm	400 μm Xe, Kapton 75μm	20 cm	12.5	5.38	
20 mm	as above	5 cm	2.94	1.37	
20 mm	as above	9 cm	5.07	1.97	1.8
20 mm	as above	15 cm	8.0	3.94	
20 mm	as above	26 cm	16.0	6.3	
20 mm	as above	29 cm	16.1	6.66	
29 mm	400 μm Xe, Kapton 75μm	15 cm	11.5	4.22	
25 mm	as above	15 cm	11.55	4.62	
15 mm	as above	15cm	7.54	3.33	
10 mm	as above	15 cm	4.01	1.97	
5 mm	as above	15 cm	1.96	1.38	

Table 1: Rejection factor corresponding to 90% of electron efficiency

Sergey Furletov reports these results on VCI 2019

Summary (Q/A)

- Why charmonium: heavy quark system can probe nucleon gluonic distribution

- Why at threshold: anomaly terms coming from high twists (vanish at high energy)
- Why at threshold: LHCb pentaquarks are there

- Why with GlueX: highest energy (χ_{c1}), full coverage for charged and neutral particles (χ_{c1}, $\Delta J/\psi$ final state), possibly using linear polarization (P_c(4380))

- What is needed: nothing or higher luminosity (depending on results from other experimenst)
- How: high threshold on calorimeter sum; turn off (lower HV) on inner detectors and low energy tagger hodoscopes
- What is needed: electron/pion separation
- How: TRD in forward direction