First measurement of near threshold J/ψ photoproduction

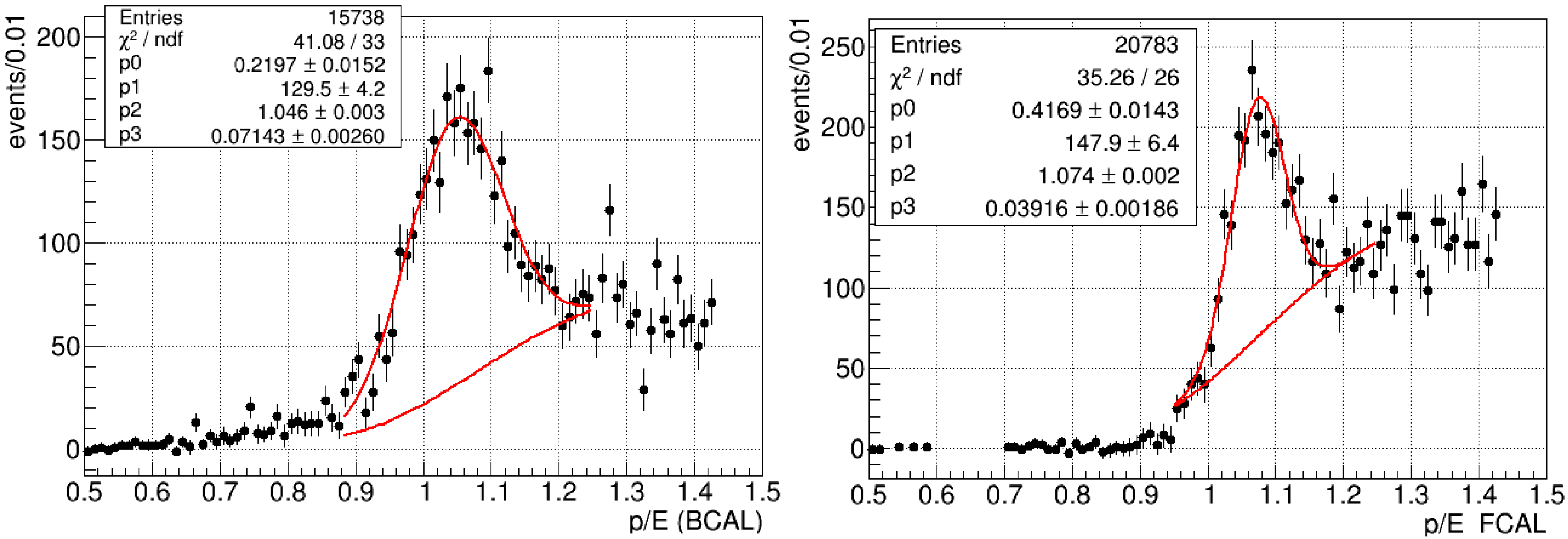
- Study $\gamma p \rightarrow J/\psi p$ in the energy range – from the threshold at 8.2 to 11.8 GeV – poorly covered by old experiments, while our measurements are the first one that extend down to the threshold
- Significant interest due to the LHCb pentaquarks, $P_c(4380)$ and $P_c(4450)$, if exist should be seen in the s-channel of the reaction. Can set upper limit on the $P_c(4450) \rightarrow J/\psi p$ branching ratio.
- Using VMD, can study $J/\psi p \rightarrow J/\psi p$ reaction and make important conclusions about:
  - proton gluonic form-factor
  - contribution of the gluons to the proton mass
  - gluon distributions at high x

Note: Hall C pentaquark experiment ($007^{J/\psi}$) starts January 30 2019; the intent is to get some online results and publication within 6 months

Data reconstruction

- Standard Hall D framework: REST files from latest reconstruction (August 2018) for all 2016 and 2017 data
- Plugin ($\gamma p \rightarrow e^+e^-p$) with looser (than standard) cuts on timing, missing mass. Using KF with 4-momentum and vertex constrained.
- No requirements about the number of unused tracks, but additional cuts on $p_{Tmiss}<0.5$ GeV, $\chi^2_{KF}<5000$ (NDF=7)
- Most restrictive cuts are needed for the pion suppression
- Simulations: BH, ϕ, and J/ψ simulated data analyzed in exactly the same way as the experimental data

e/π separation: p/E cuts

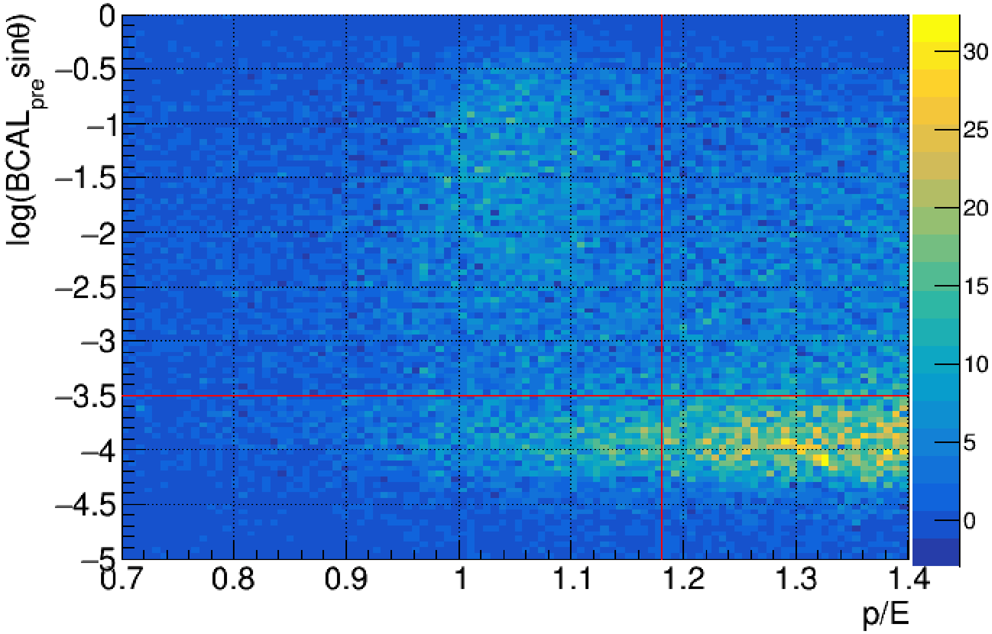


Calorimeter/data type	$\langle p/E \rangle$	σ	2σ cut
BCAL data	1.0462	0.0683	1.1827
BCAL MC	1.0290	0.0466	1.1827
FCAL data	1.0738	0.0392	1.1521
FCAL MC	1.0135	0.0271	1.1521

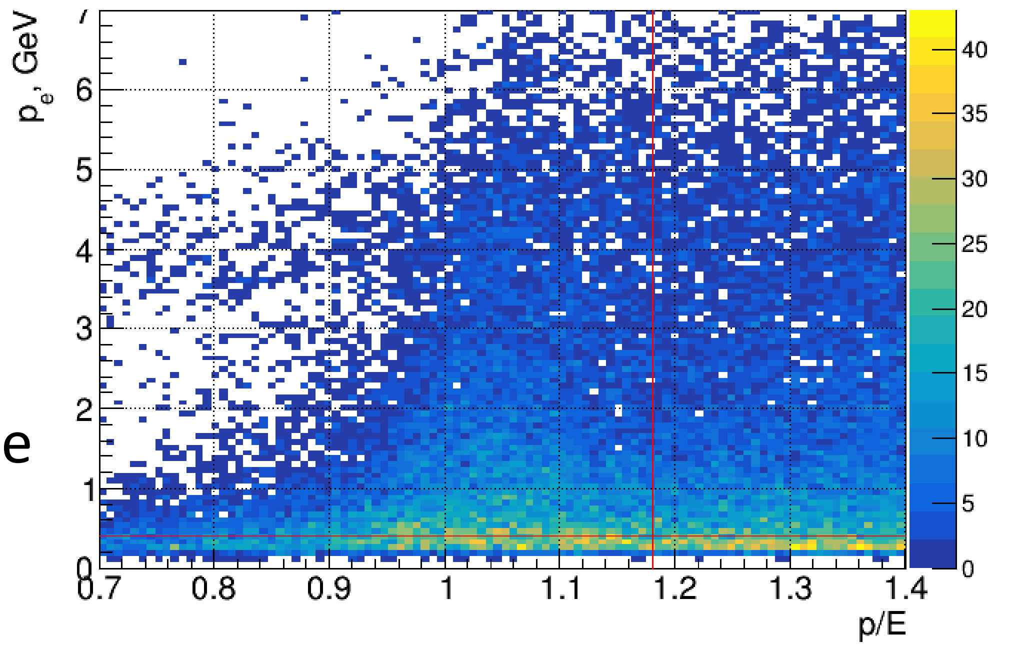
TABLE I: p/E mean, R.M.S. and cuts for the data and MC and the two calorimeters.

Note: before applying the cuts, MC is smeared and shifted to match the data.

e/π separation: BCAL pre-shower and fiducial cuts



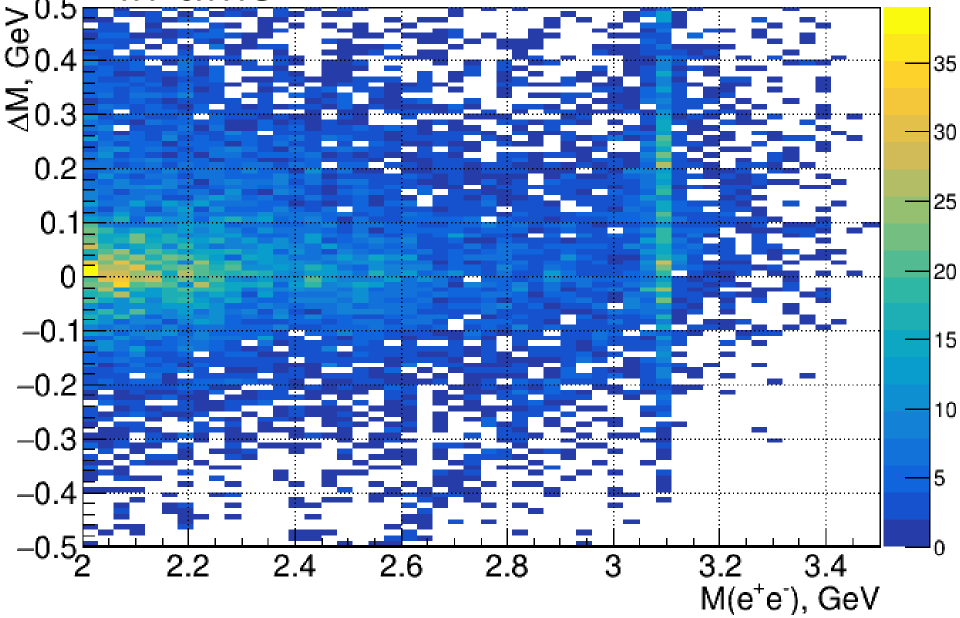
- $BCAL_{pre}\sin(\theta)<0.03$ GeV



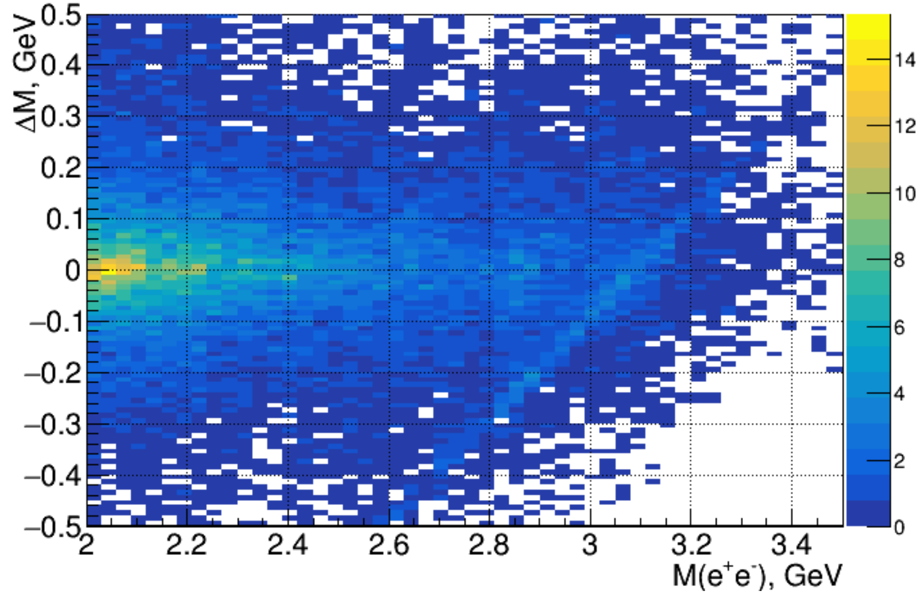
- $p_e>0.4$ GeV
- $\theta_e>2$deg
- These cuts practically include abs(M(πp)-1.232)<0.1 GeV cut on Δ

Accidental background

in-time

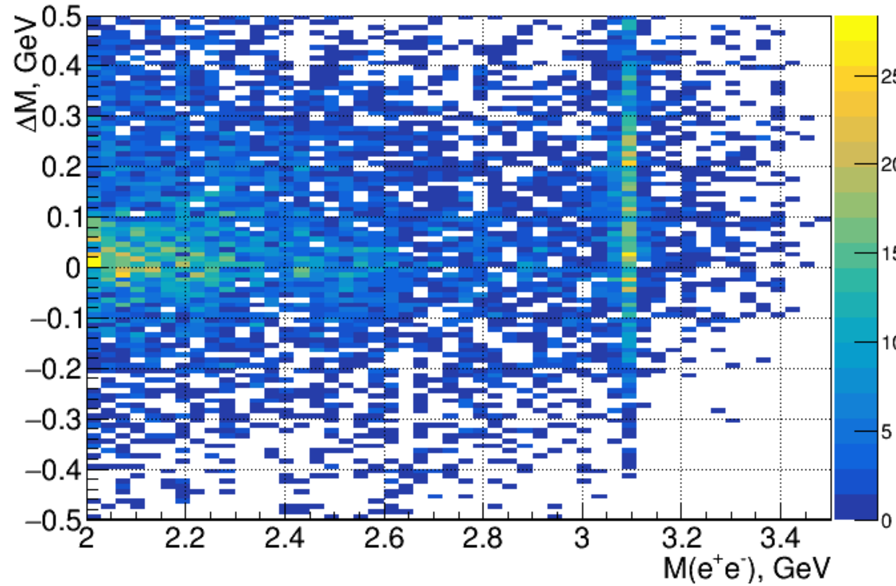


out-of-time

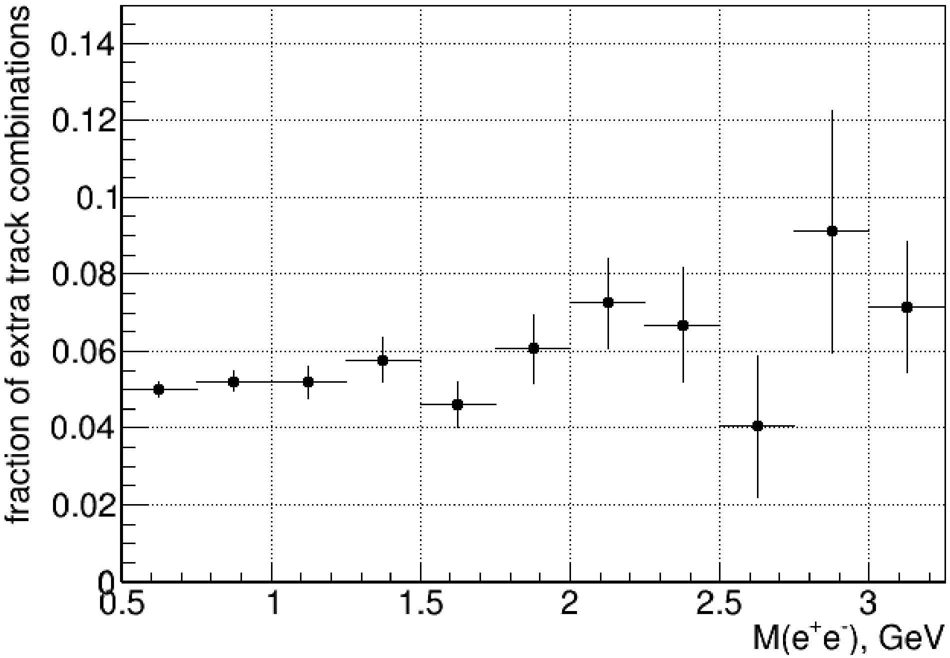


- Within each events: energy (accidental) and track combinations
- Three beam bunches on each side of the in-time peak
- ΔM for each pair of combos vs M
- The 45^0-band disappears in the difference

difference

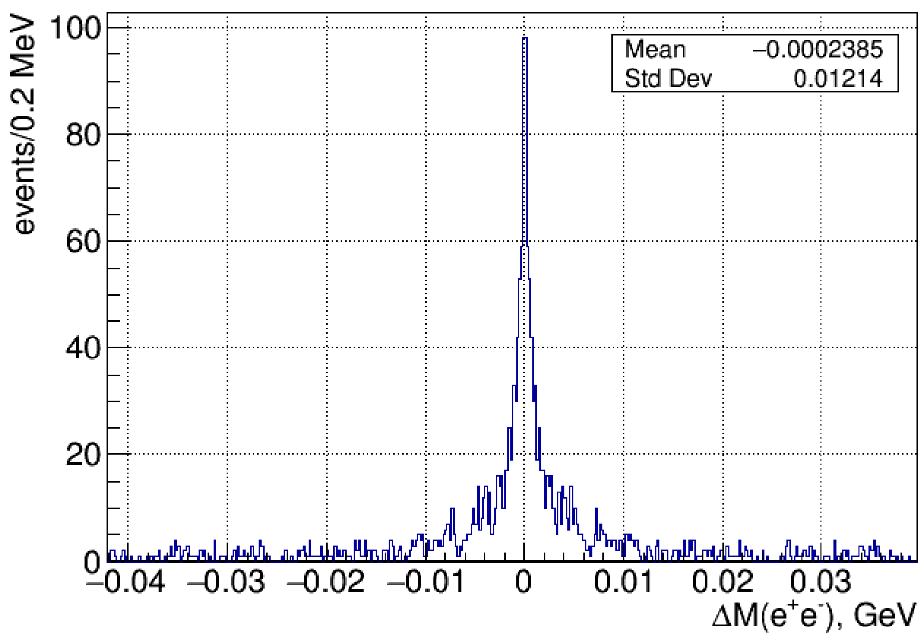


Track combinatorial background



- Not accidental: due to track splitting, (p,e+) combinations
- 5-7% effect

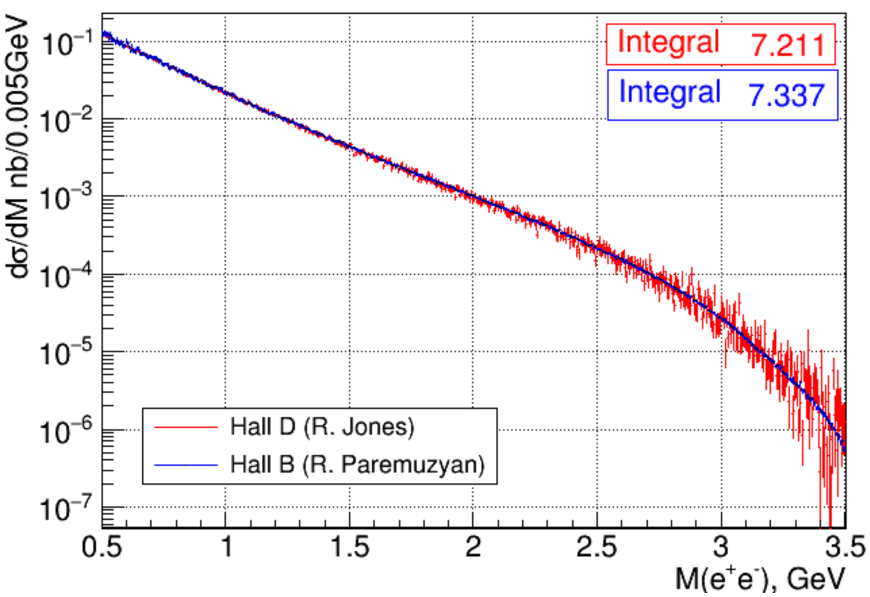
- Which combo to choose: most of the combos have very close parameters- few MeV difference in invariant mass
- Extra combos counted and subtracted

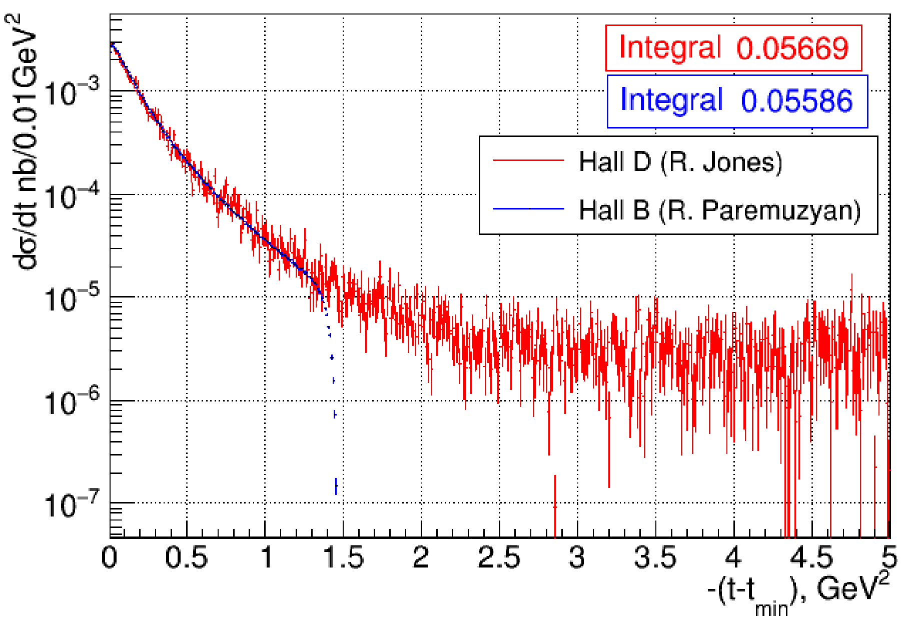


Bethe-Heitler process: generators

- Two generators using completely different methods giving almost identical results within kinematic region used for normalization (t<0.6 GeV2, p_e>0.4 GeV, $\theta_e > 2^0$):

- Hall B (R.Paremuzyan) – based on analytical formulas
- Hall D (R.Jones) – numerical calculations of Feynman diagrams

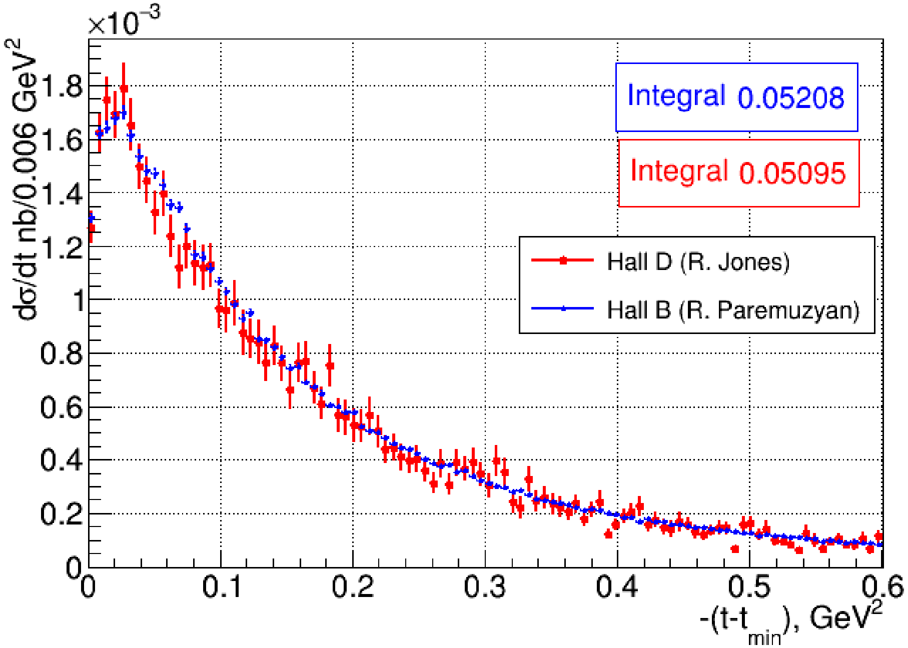


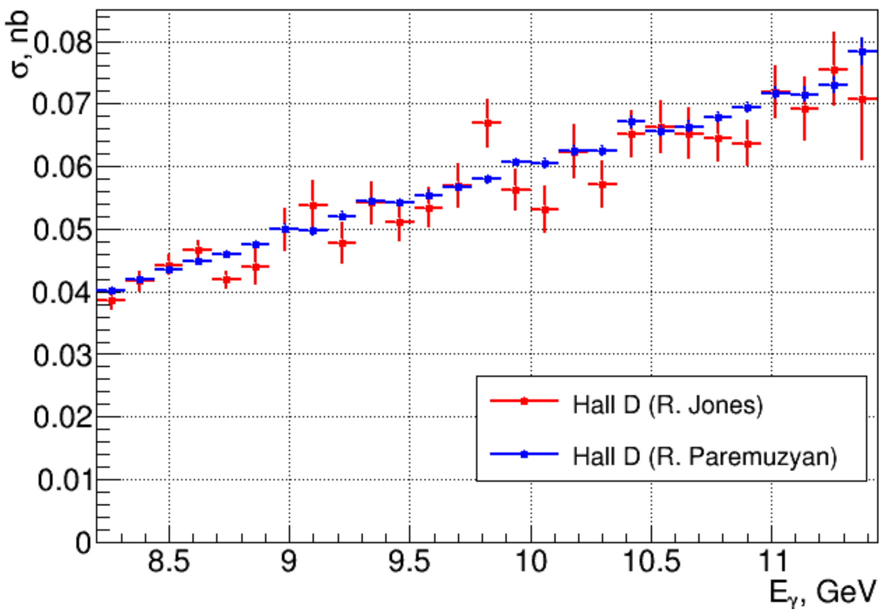


Bethe-Heitler process: generators

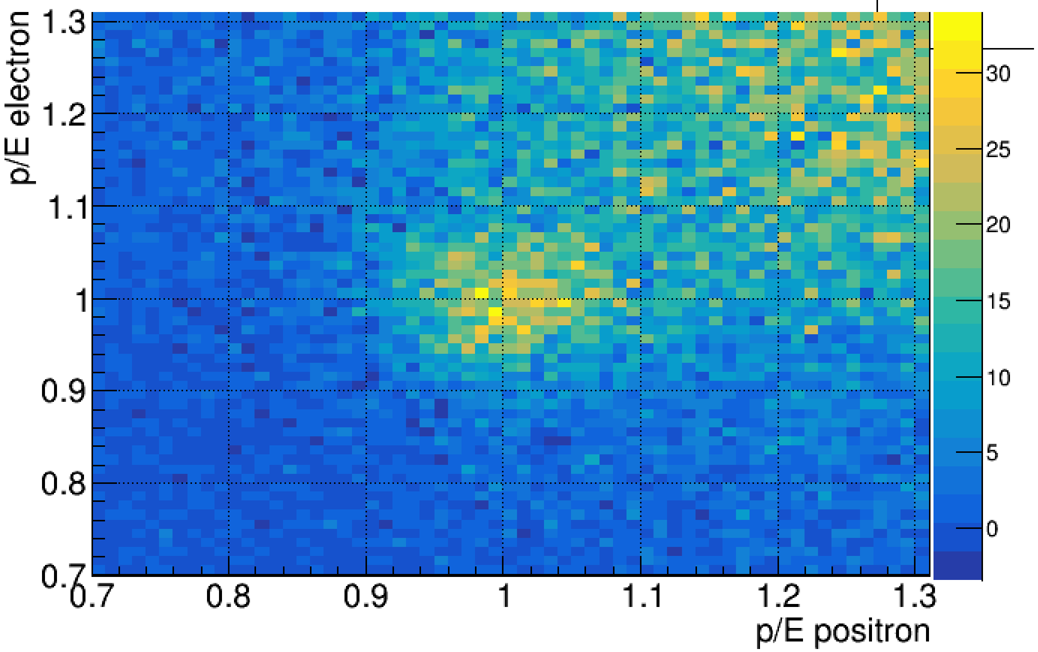
- Two generators using completely different methods giving almost identical results within kinematic region used for normalization (t<0.6 GeV2, p_e>0.4 GeV, θ_e>2^0, 2<M<2.5 GeV):

- Hall B (R.Paremuzyan) – based on analytical formulas
- Hall D (R.Jones) – numerical calculations of Feynman diagrams



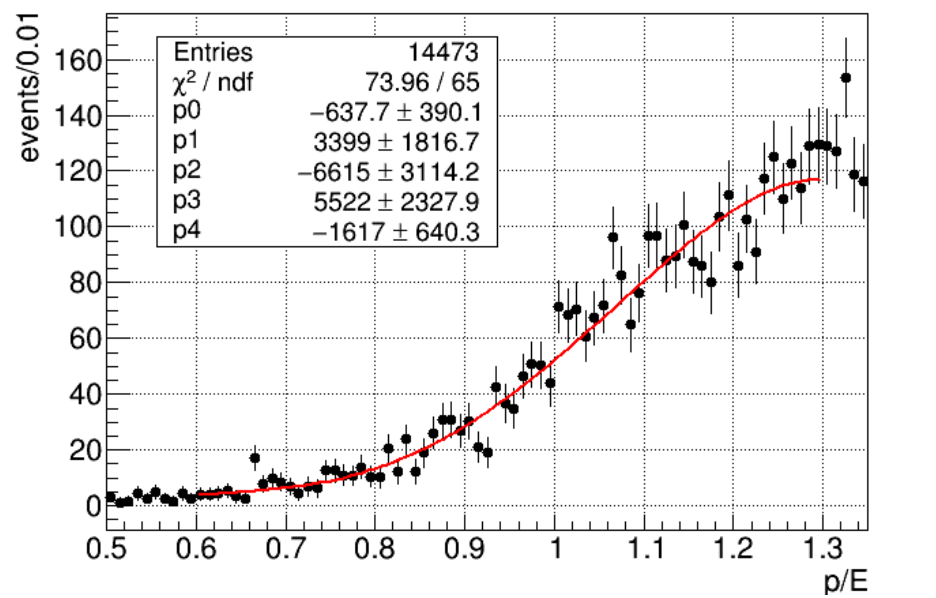


Bethe-Heitler process: π background

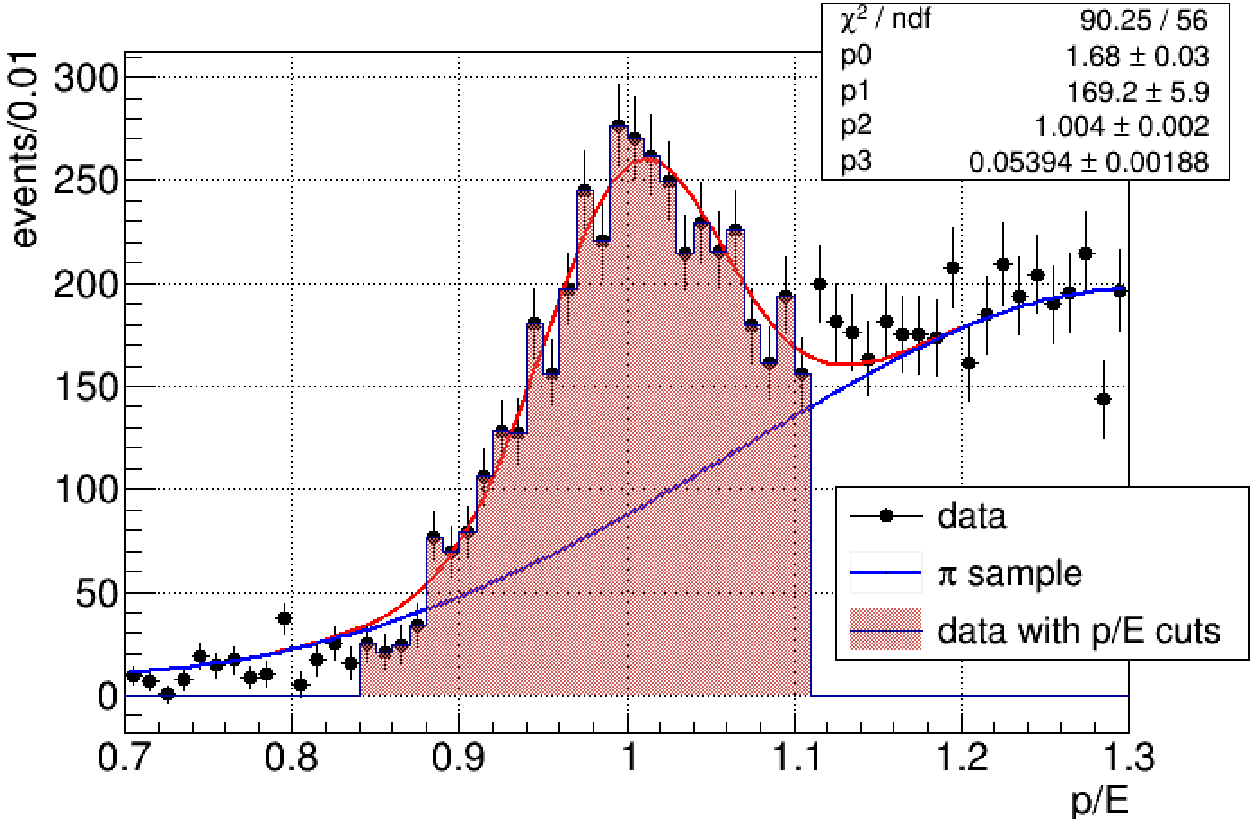


- After applying all the cuts still significant background in the continuum

- First, create π sample using 3σ anti-electron cut on one of the lepton candidate
- Fit p/E distribution with polynomial used as background shape

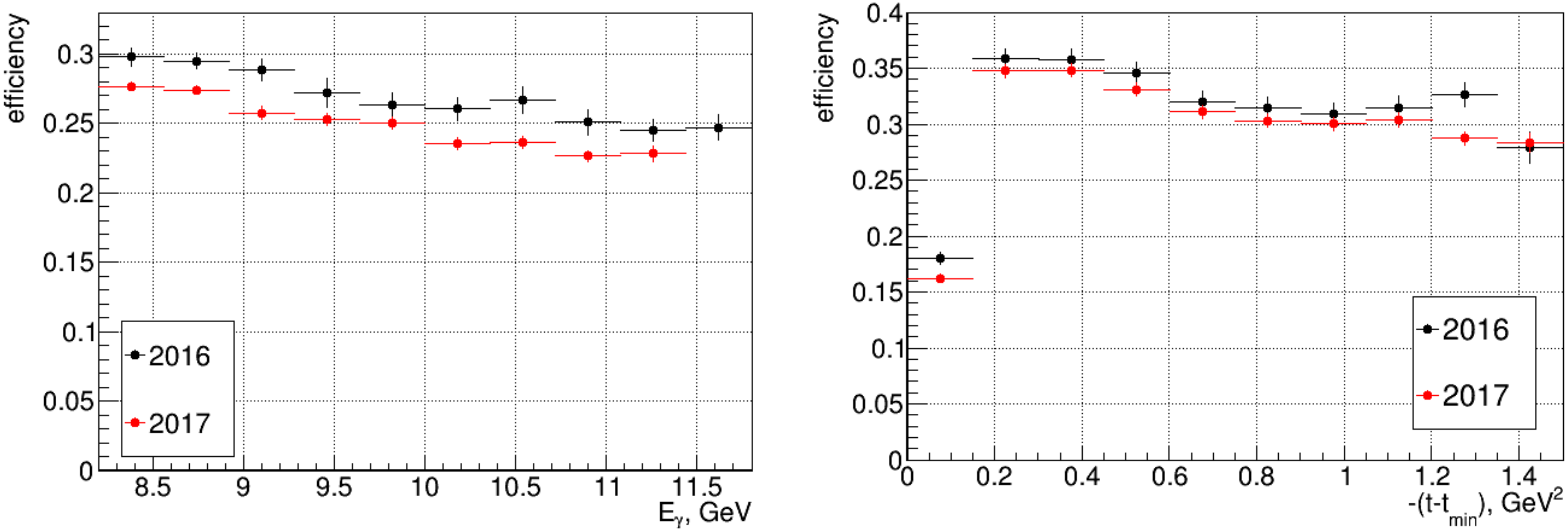


Bethe-Heitler process: π background



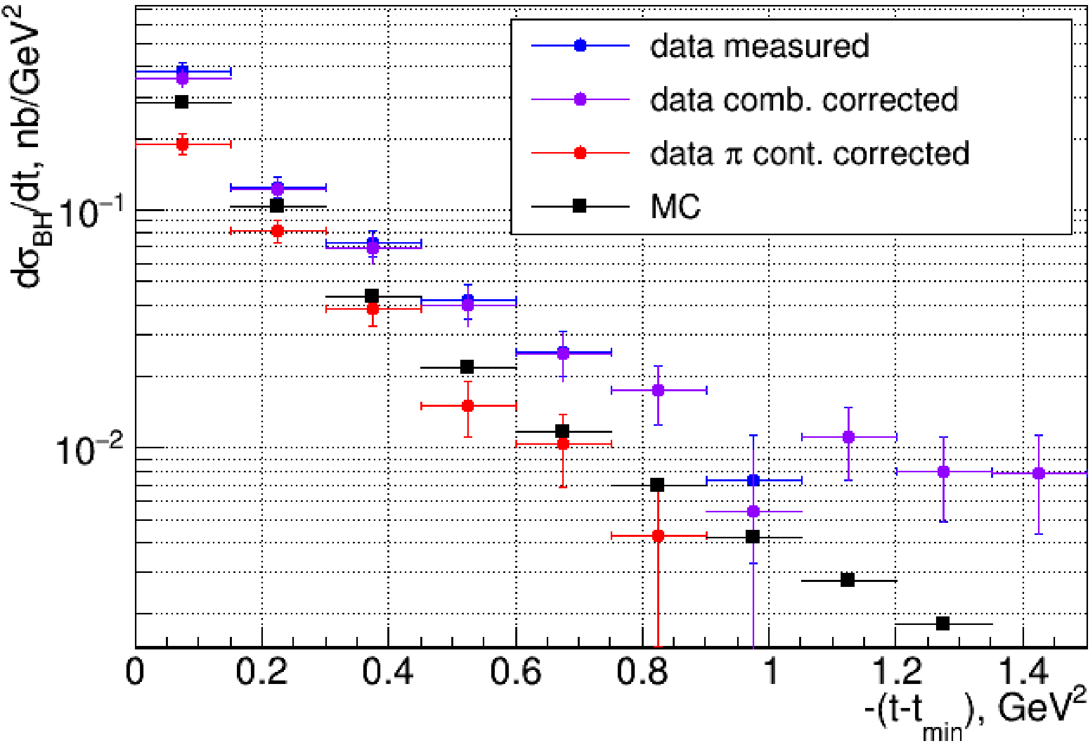
- 2<M<2.5 GeV, -t<0.6 GeV^2 using both calorimeters (p/E shifted to 1)
- Apply all the cuts on one of the leptons and look at p/E for the other
- Fit with background normalization (p0) and Gaussian (p1-p3)
- background/all = 0.508 ± 0.013
- Same procedure done in bins of E_γ and t

Bethe-Heitler process: efficiencies

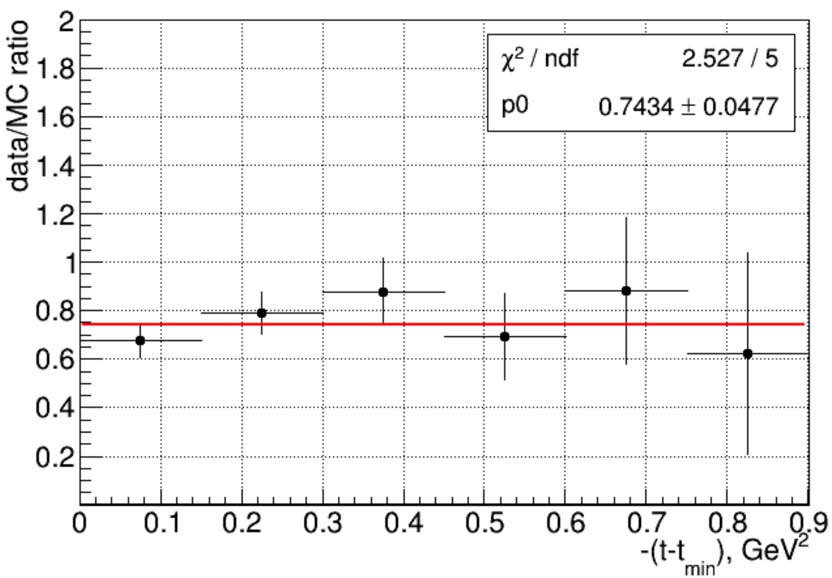


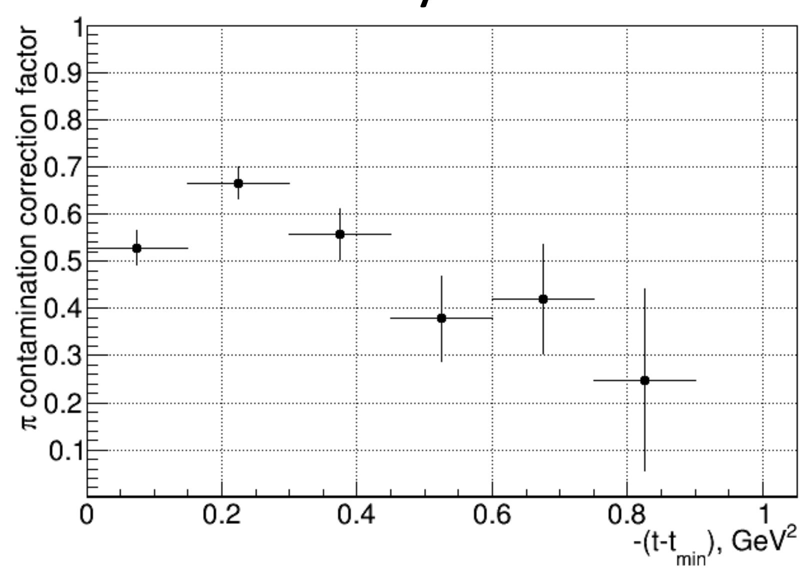
- Flat, except at low t (small proton momentum)
- 2017 efficiencies lower due to higher rates – random hits included in the simulations proportionally from each run

Bethe-Heitler process: t-dependence

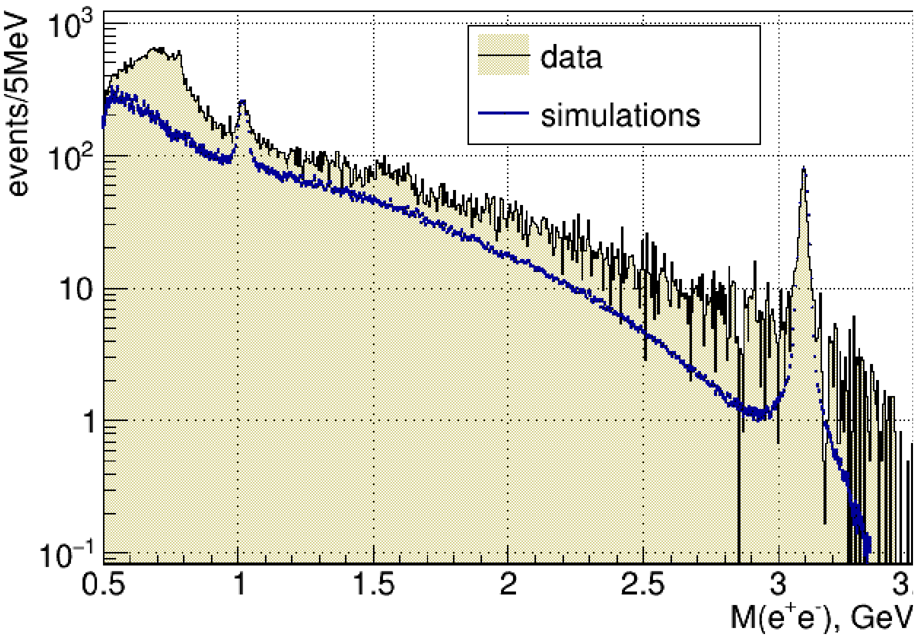


- Data corrected for background (π cont. and combinatorial) 10-11.8 GeV
- π increasingly dominate at high t (no el. peak visible above 0.9 GeV^2) – using t<0.6 GeV^2 for norm.
- Data/MC consistent with constant – 30% additional inefficiency

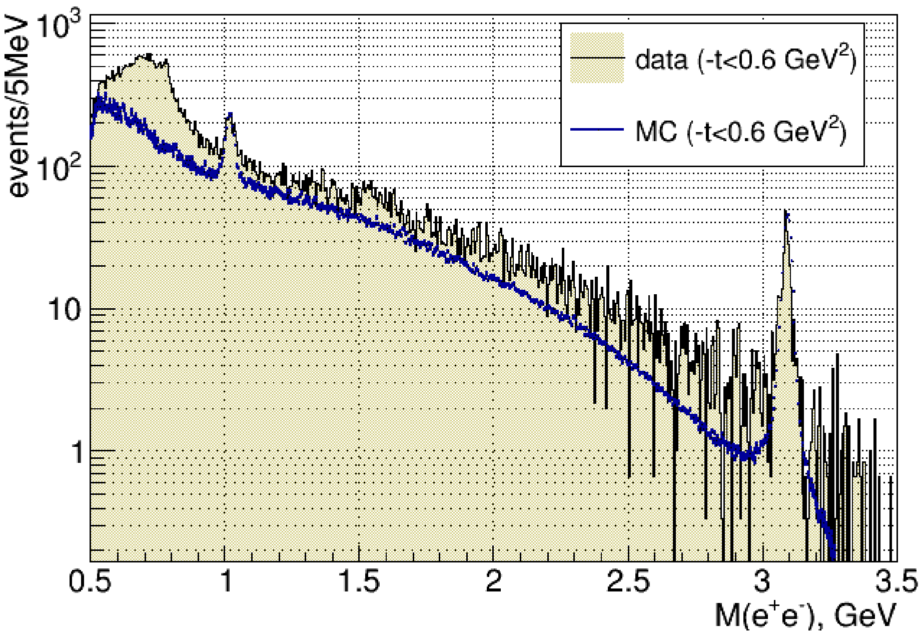




Invariant mass spectrum: t-depedence

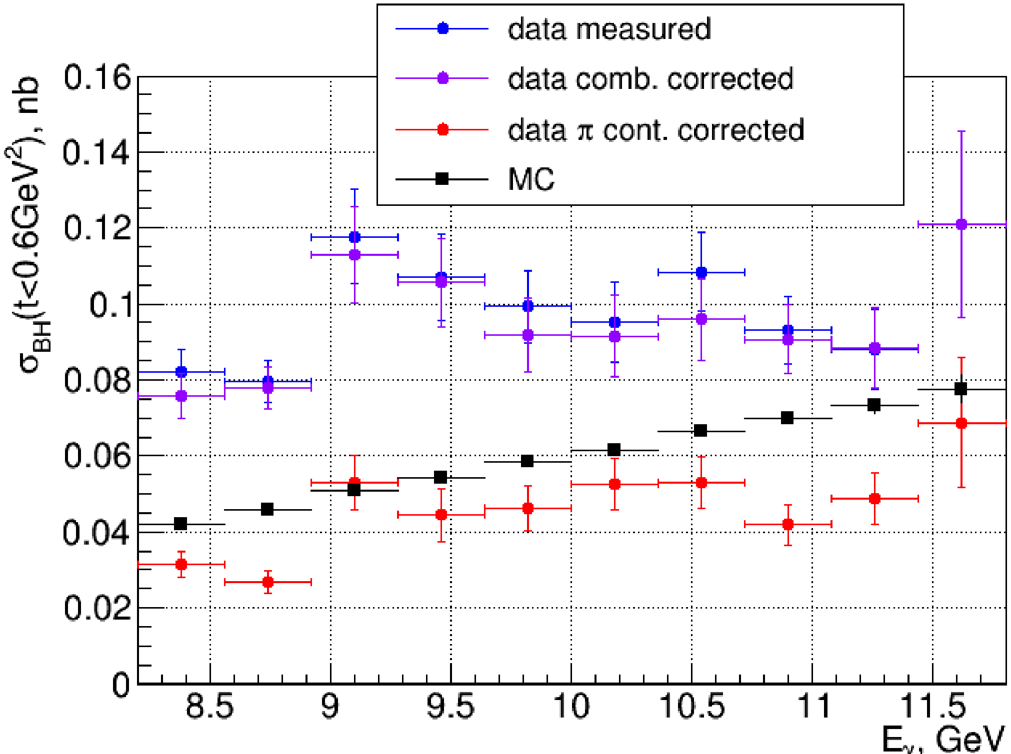


all t

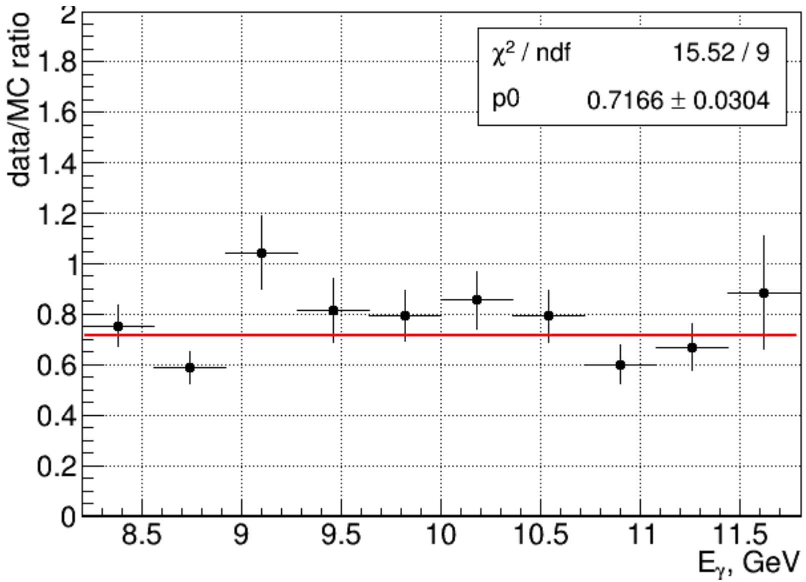


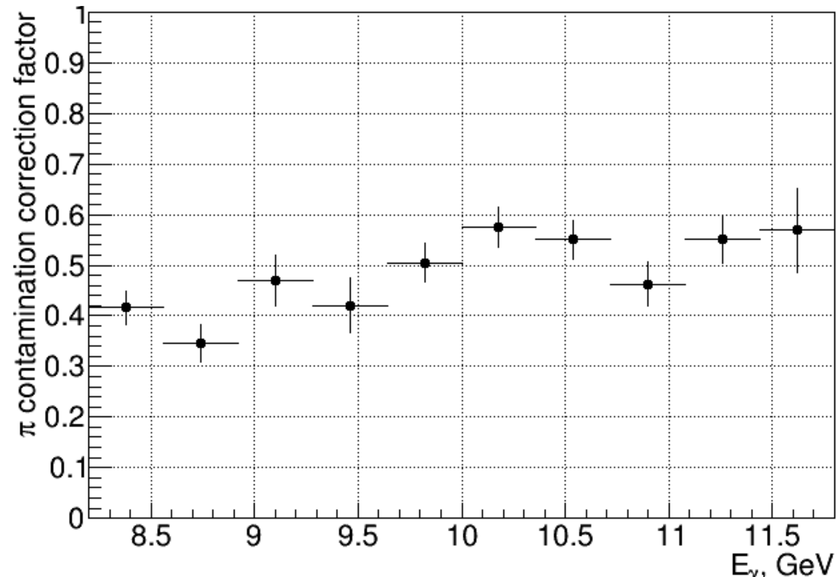
$-(t-t_{min})<0.6$ GeV^2

Bethe-Heitler process: beam energy dependence

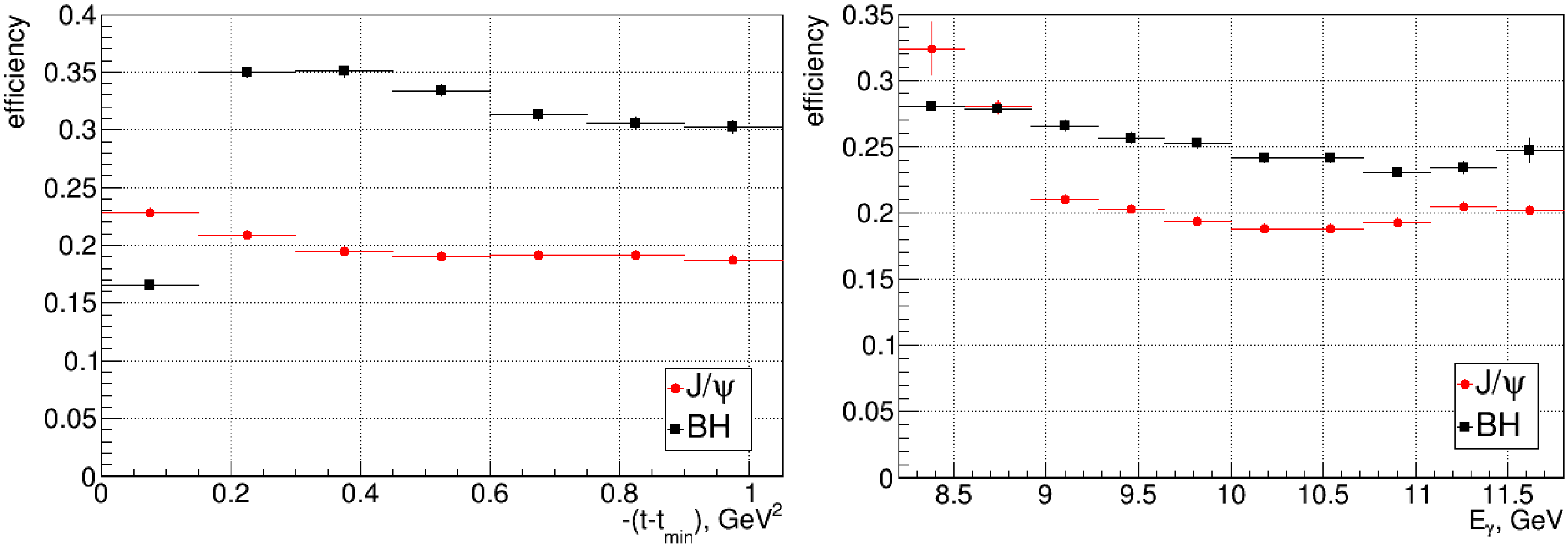


- Data corrected for background (π cont. and combinatorial)
- Contamination decreases slightly at high energies
- Data/MC varies with energy – ~30% additional inefficiency



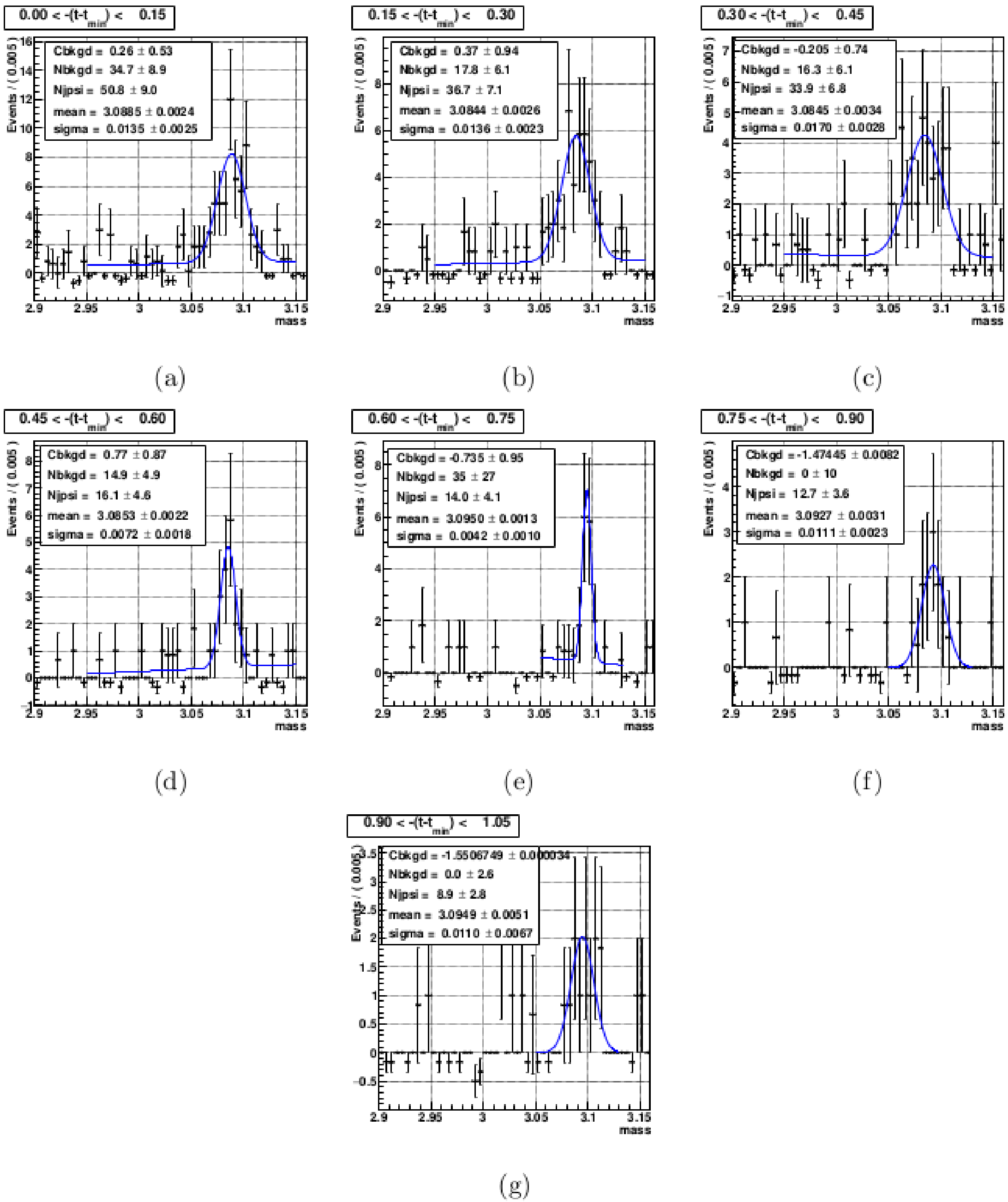


J/ψ photoproduction: efficiency



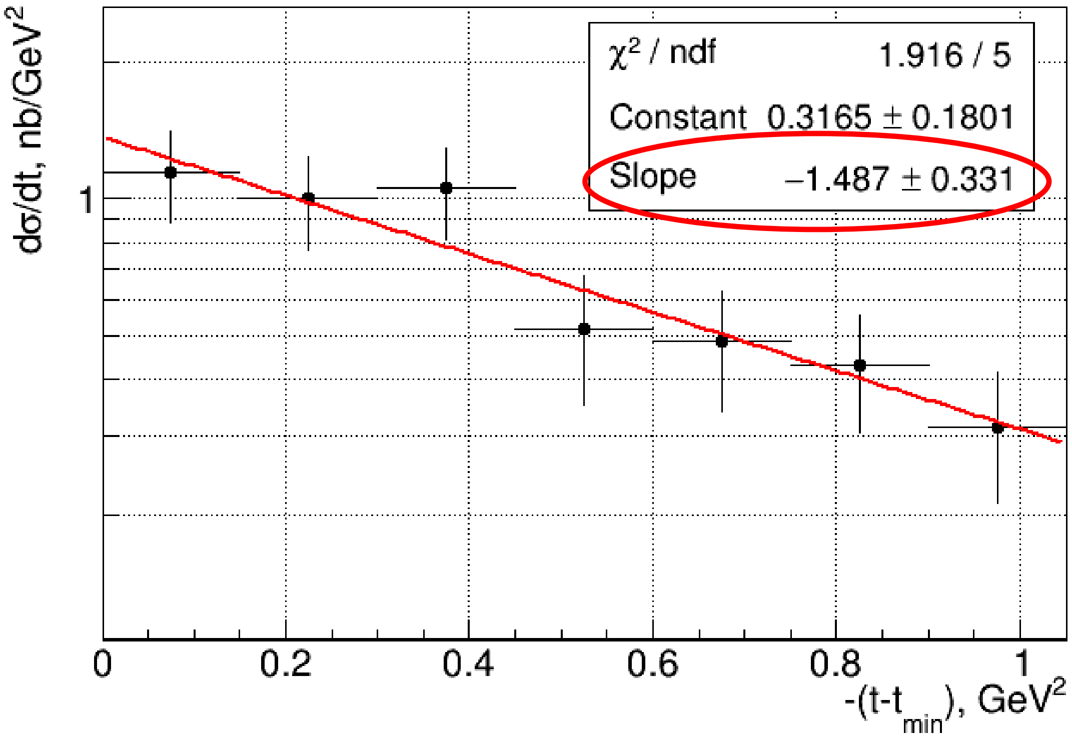
- J/ψ events generated using *bggen_jpsi* generator within standard *MCwrapper*
- Assumptions:
  - t-slope of 1.4 GeV-2 (discussed later)
  - helicity conservation
  - certain energy dependence

J/ψ photoproduction: t-dependence



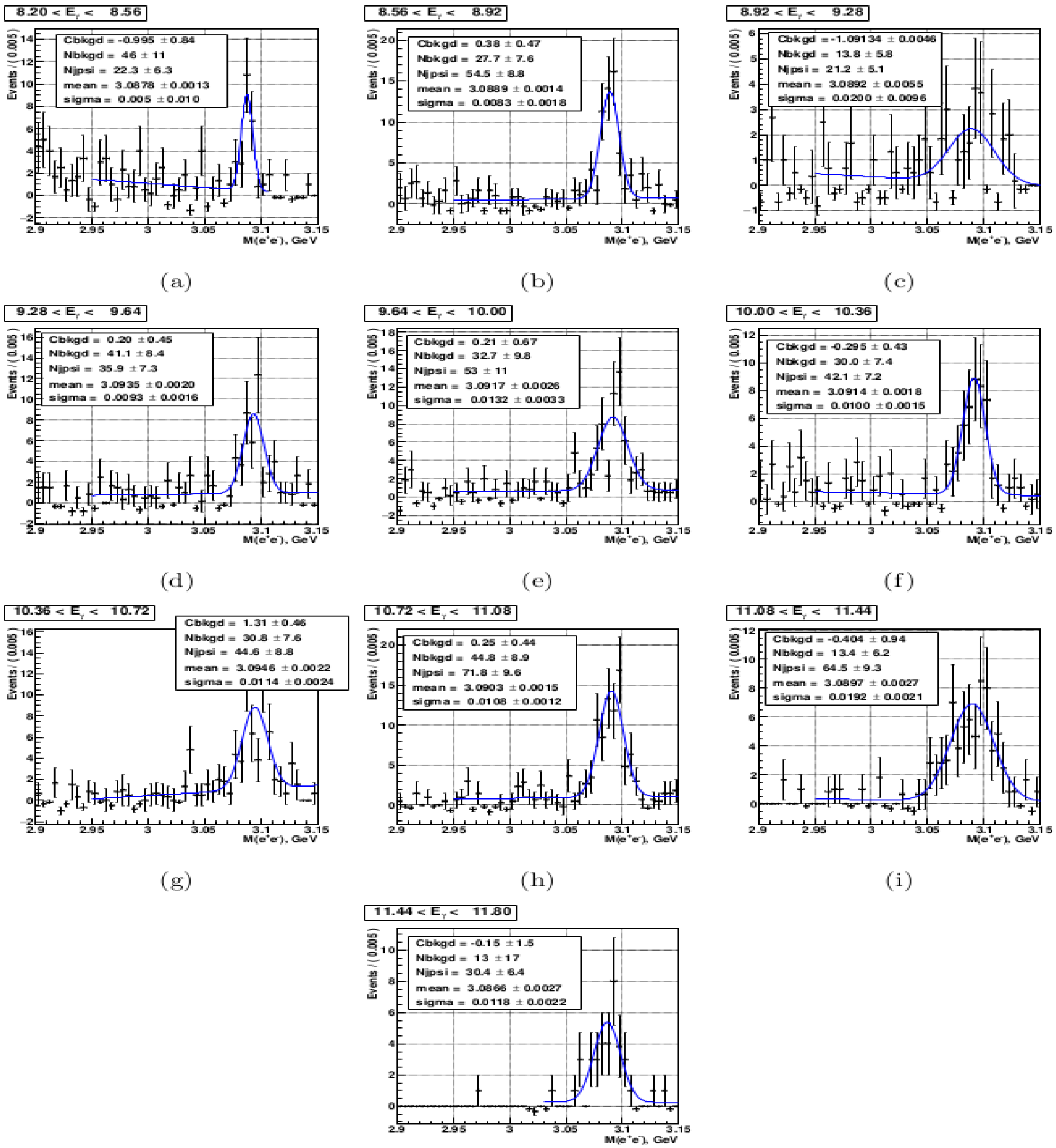
- Invariant mass peak fits in bins of t using RooFit, binned likelihood method
- Accidentals subtracted before fitting
- All fits stable

J/ψ photoproduction: t-dependence



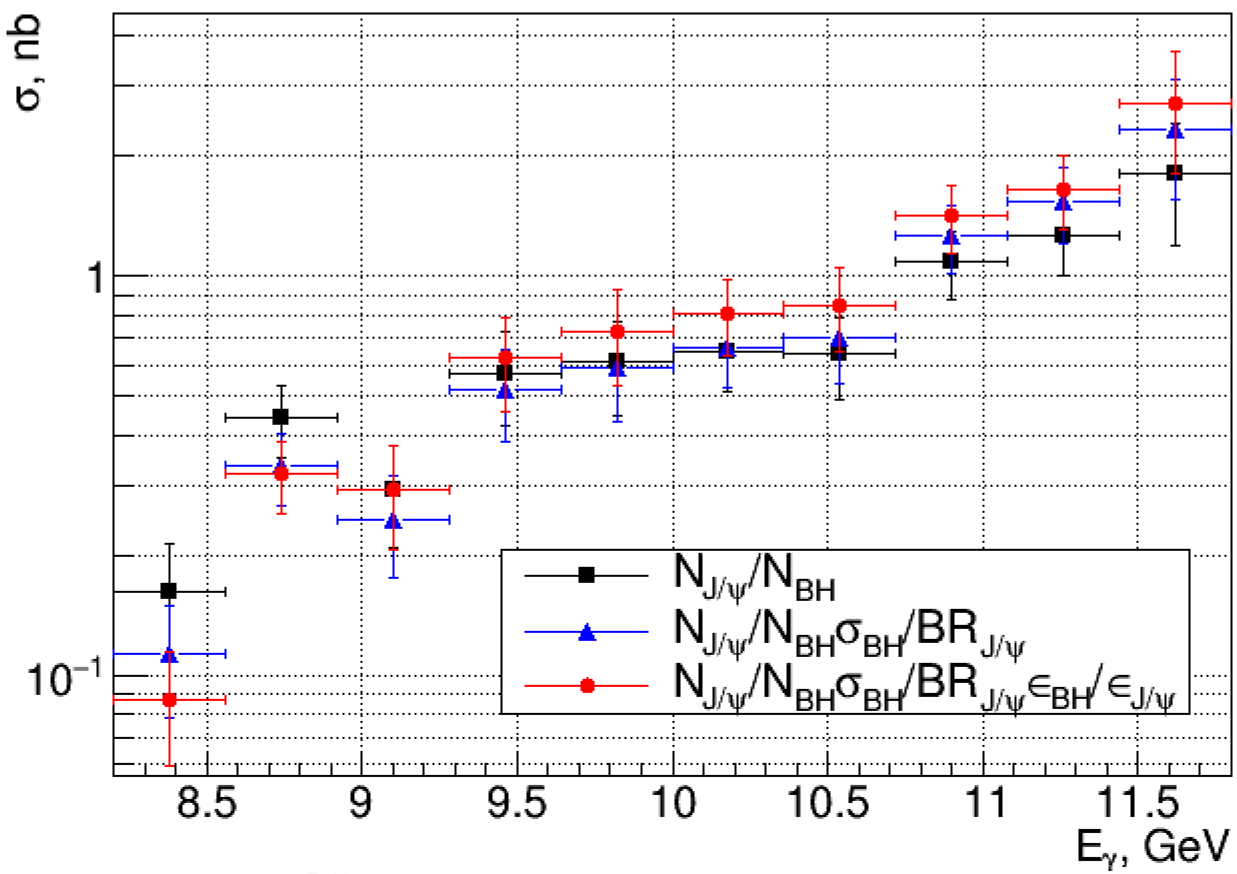
- Only 10-11.8 GeV region – t_{min} changes significantly with E
- Yields corrected for accidentals, track combos, efficiency and flux
- Overall cross-section normalized to BH (factor of 1.34 ± 0.086)

J/ψ photoproduction: beam energy dependence



- Invariant mass peak fits in bins of E using RooFit, binned likelihood method
- Accidentals subtracted before fitting
- All fits converge, 3rd bin not always stable

J/ψ photoproduction: beam energy dependence

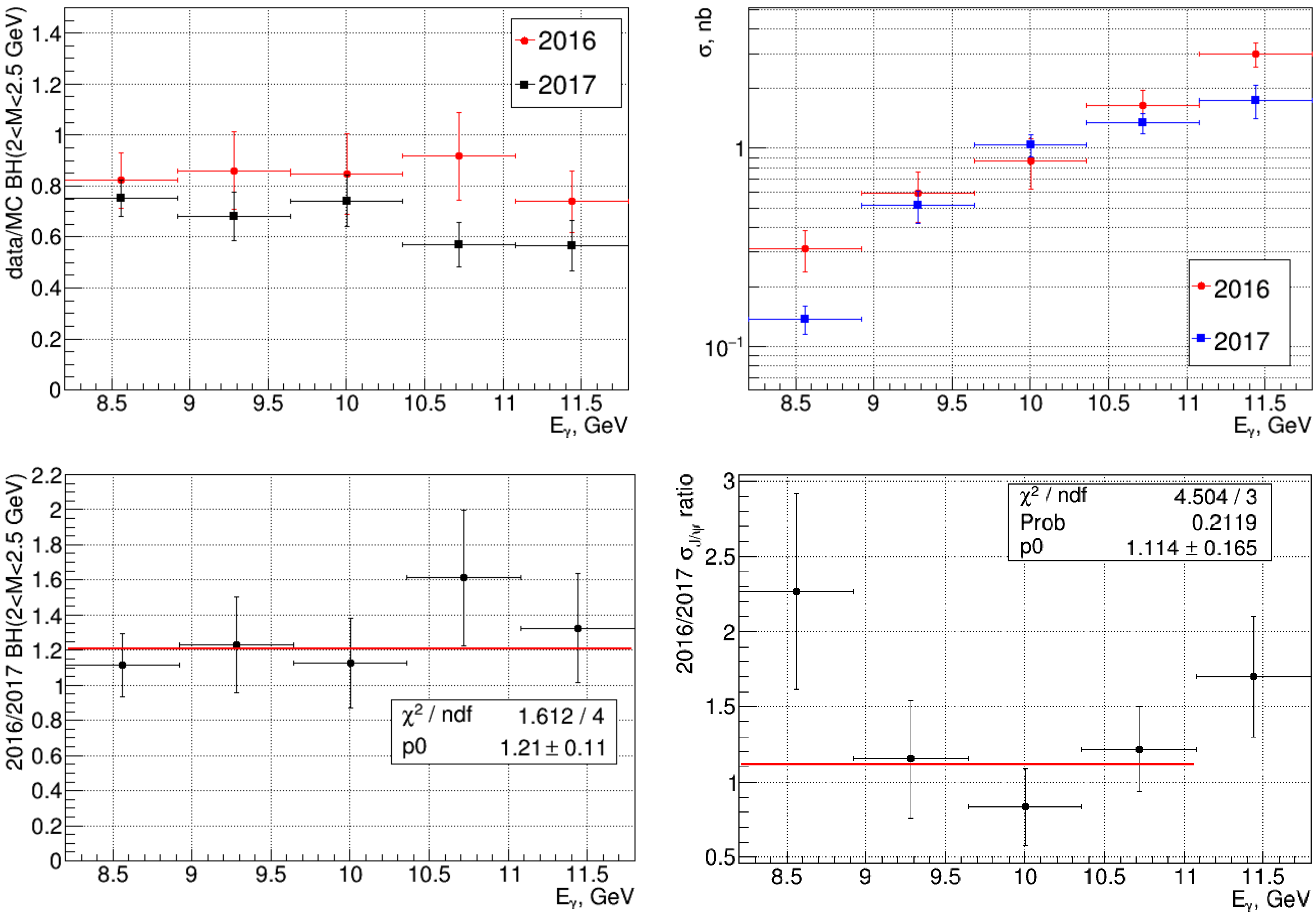


- Cross-section calculations: contributions from different terms
- BH kinematic region used for normalization doesn't matter

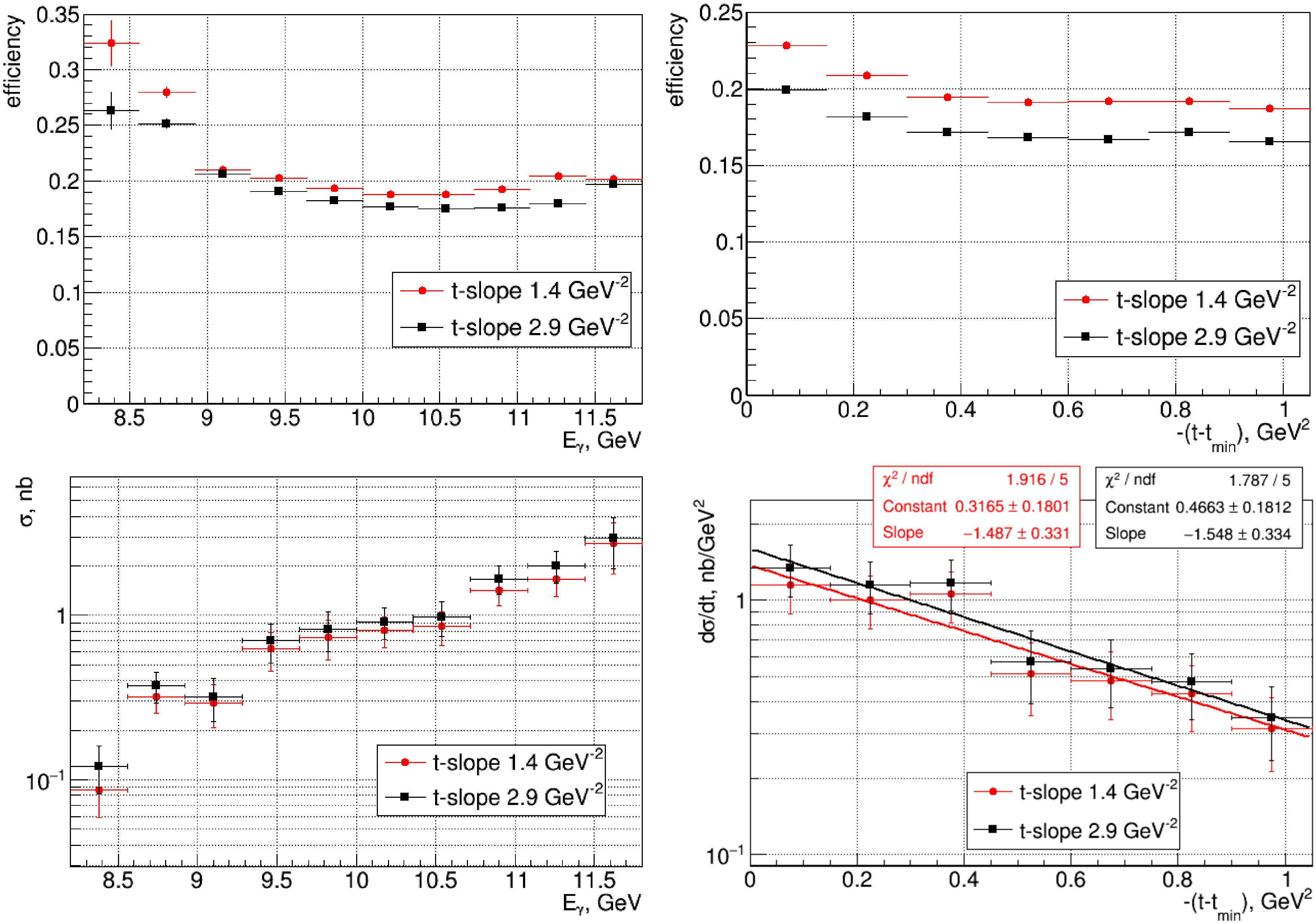
$$\sigma = \frac{N_{J/\psi}}{N_{BH}} \frac{\sigma_{BH}}{BR_{J/\psi}} \frac{\varepsilon_{BH}}{\varepsilon_{J/\psi}}$$

$$\sigma = \frac{N_{J/\psi}}{N_{BH}} \frac{N^{all}_{BH,MC}}{flux_{MC}} \frac{N^{cut}_{BH,MC}}{N^{all}_{BH,MC}} \frac{1}{BR_{J/\psi}\varepsilon_{J/\psi}}$$

Systematics: 2016 vs 2017



Systematics: J/ψ simulations



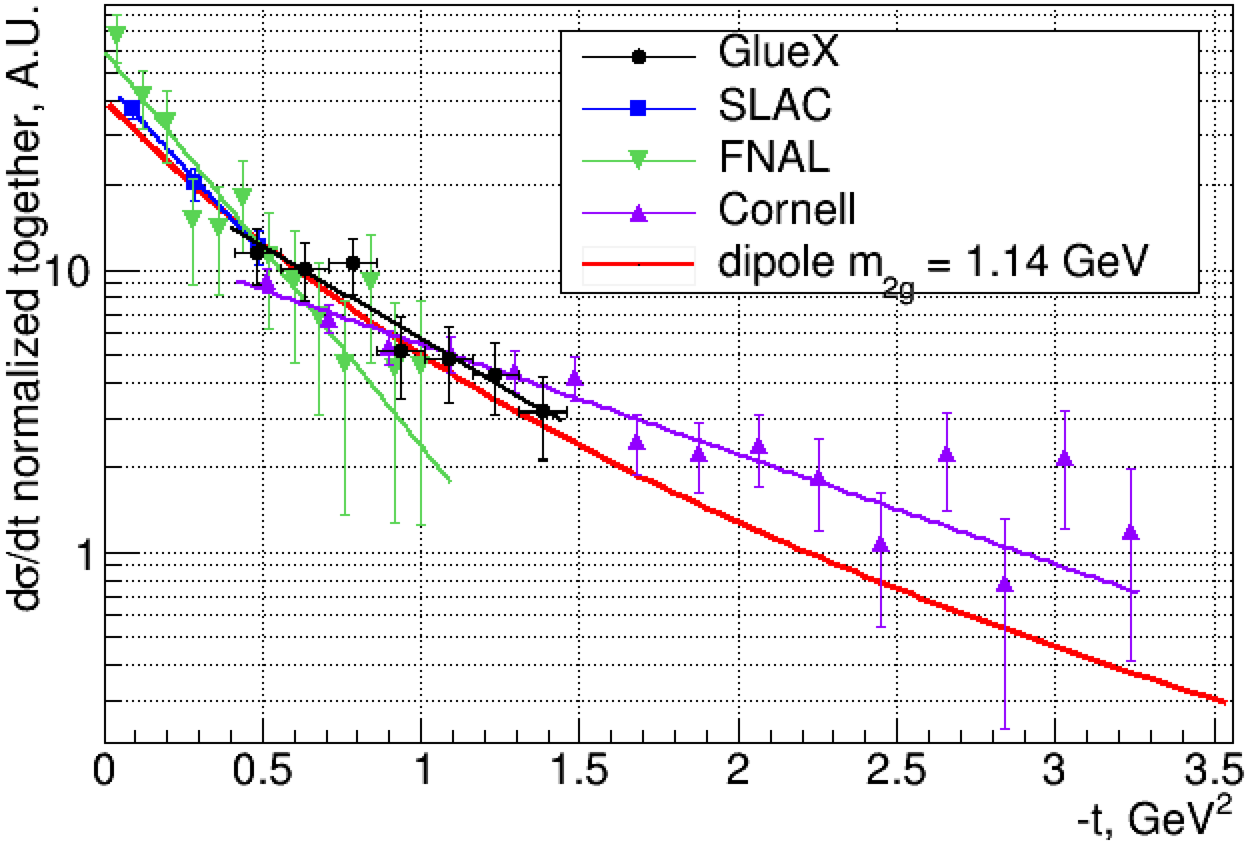
Systematics: other and summary

Systematic error from	Estimate, %
BH to J/ψ relative efficiency	17
BH cross-section calculations (TCS)	10
J/ψ simulations	9
Pion contamination in BH	7
total	22.8

Remarks:

- 17% is the error of the average comparison 2016/2017, may require additional syst. error for the lowest energy point – delicate balance b/n two effects near threshold: proton momentum increase and angle decrease
- Max TCS contribution is 10%, Marie Boer is working on estimating more precise limit
- Systematics from the t-dependence in J/ψ simulations has to be estimated point-by-point
- Other effects expected to have lower contribution but have to be checked: helicity conservation, slope of the J/ψ cross-section with energy

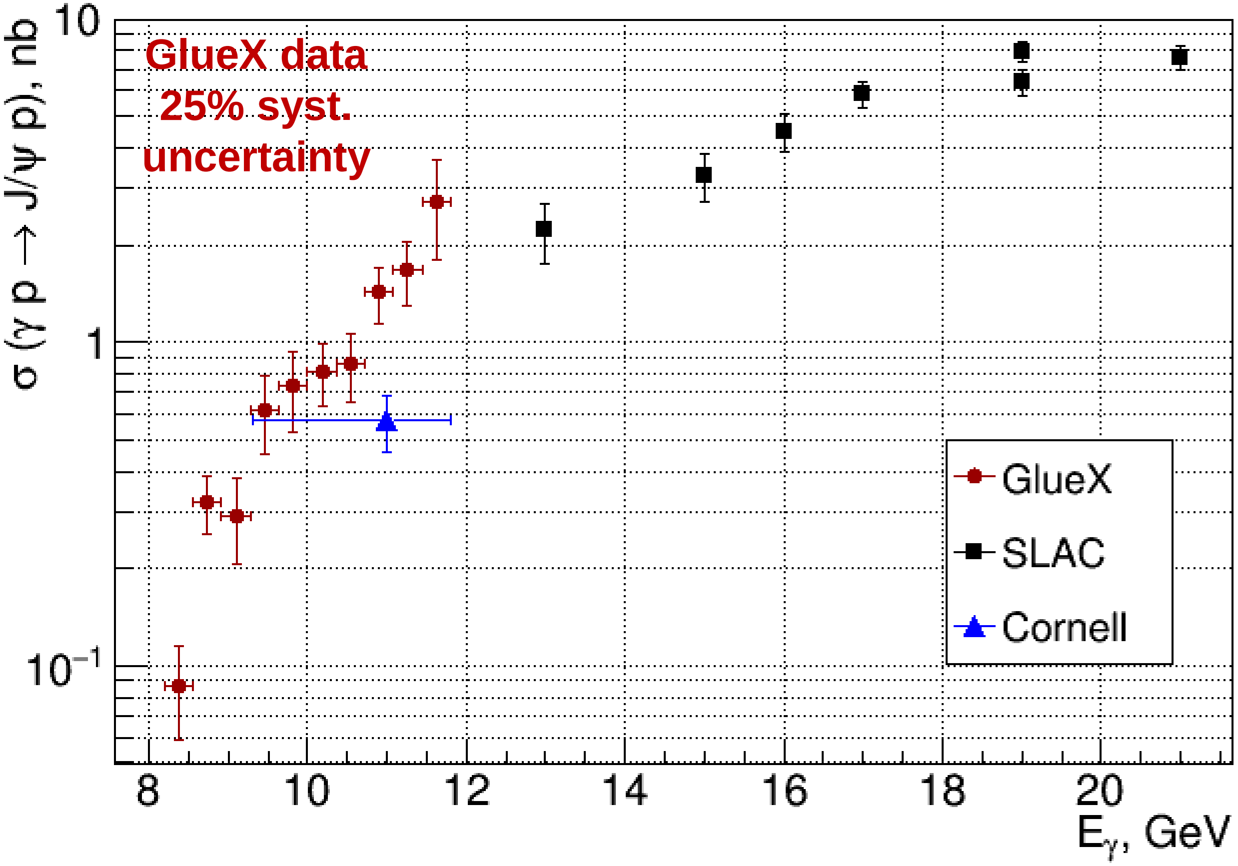
Interpretation of the results – t-dependence and proton gluonic form factor



- Frankfurt and Strikman PRD66 (2002) suggested t-depedence defined by the proton gluonic FF
- Explains t-slope change with energy (due to t_{min} dependence) in wide energy range:
  - FNAL <E>=100 GeV
  - SLAC 13-21 GeV
  - Cornell 11 GeV
  - GlueX 10-11.8 GeV

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

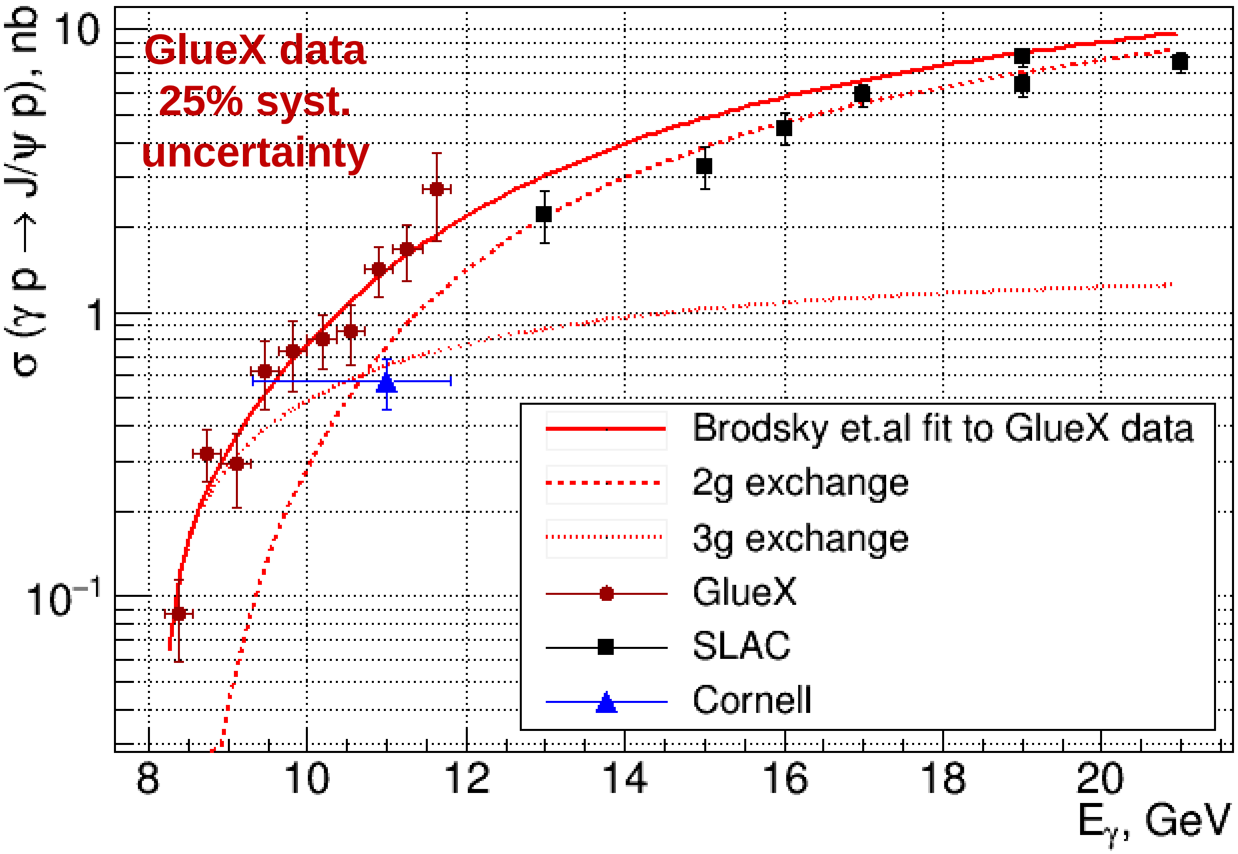
J/ψ cross-section – comparison with other measurements



Using F(t) to calculate total cross-section from the SLAC dσ/dt at t_{min}

Cornell data: horizontal errors represent acceptance

J/ψ cross-section – near threshold production mechanism

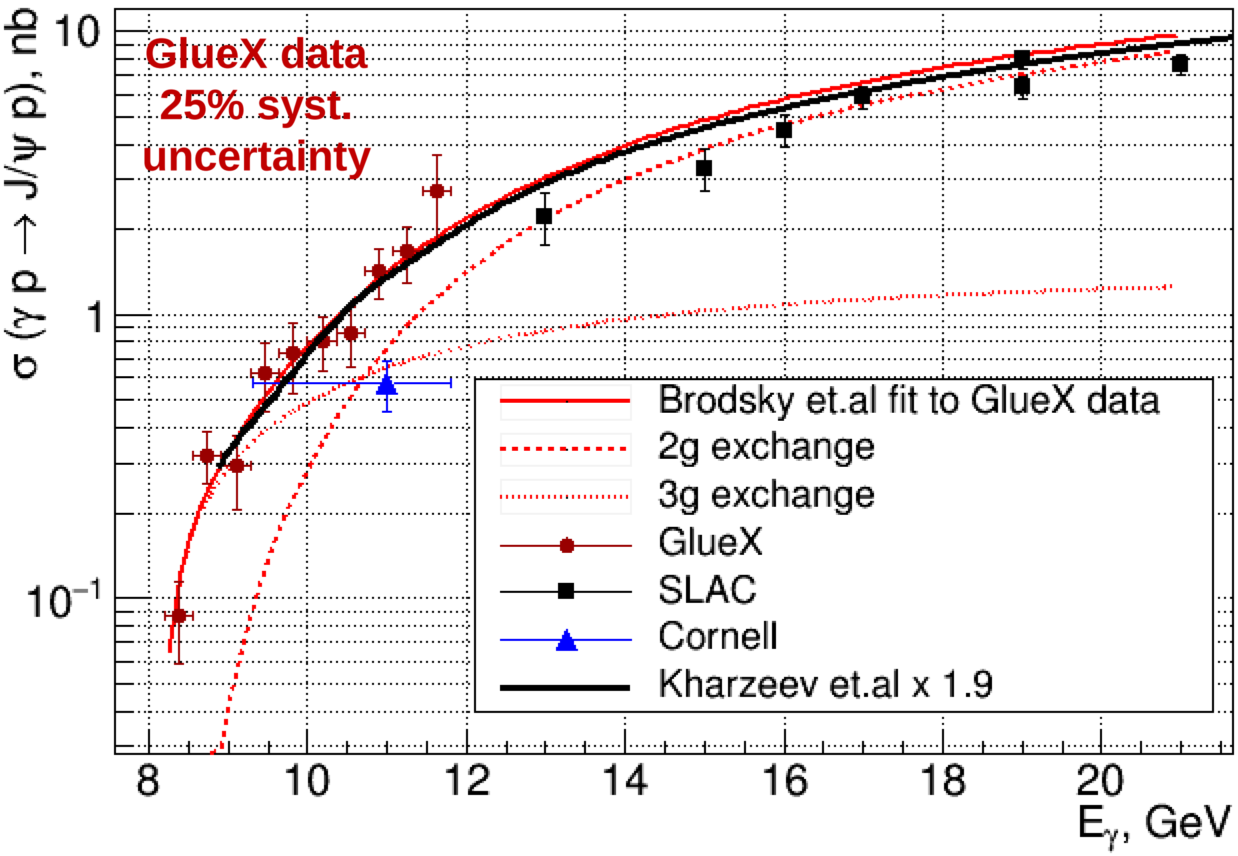


Using F(t) to calculate total cross-section from the SLAC $d\sigma/dt$ at t_{min}

Cornell data: horizontal errors represent acceptance

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

J/ψ cross-section – mass of the proton



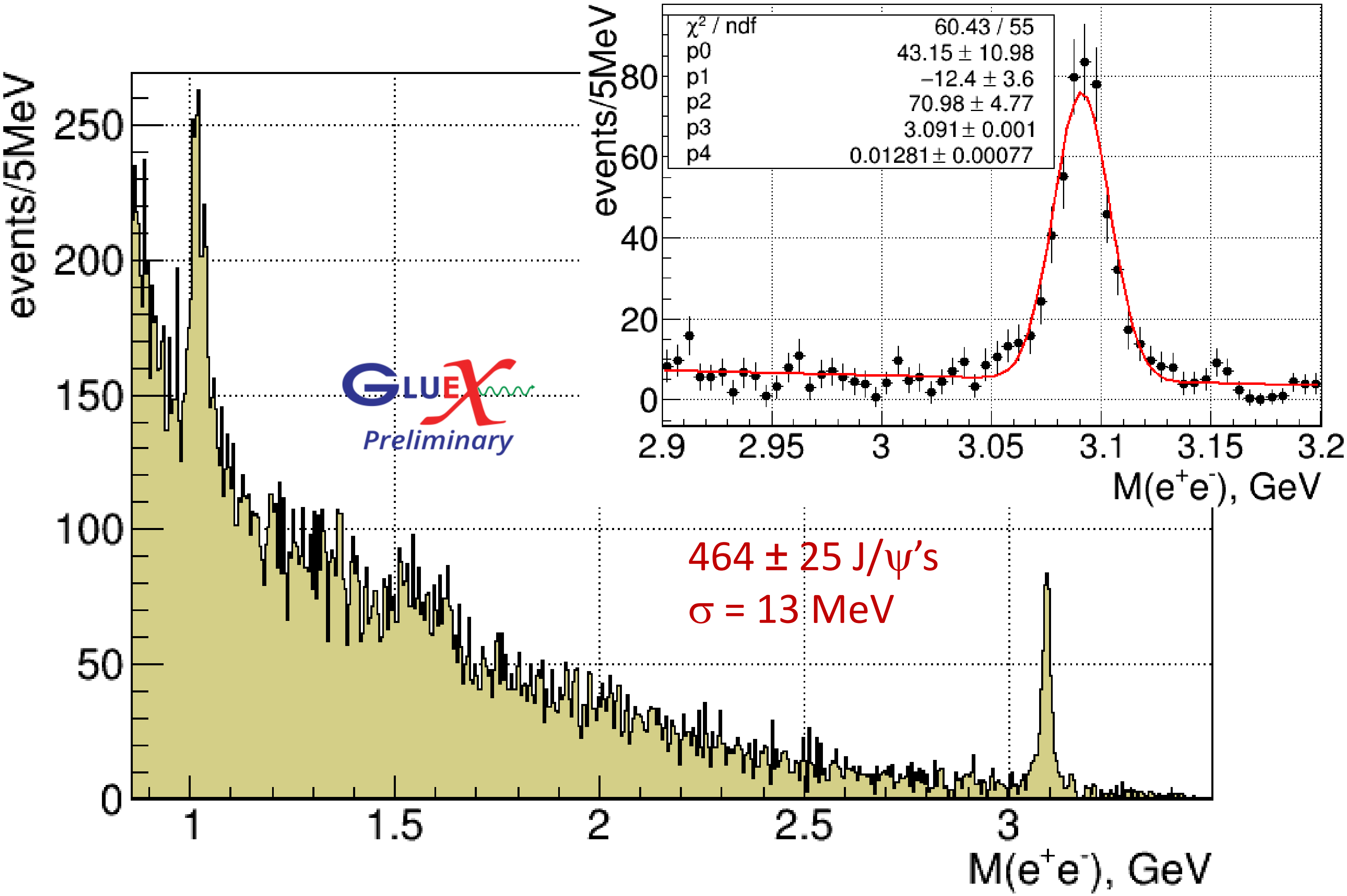
Using F(t) to calculate total cross-section from the SLAC dσ/dt at t_{min}

Cornell data: horizontal errors represent acceptance

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

Kharzeev et al. 1999 – gluonic contribution to the mass of the proton – 80% if calculations are verified

Plots for QNP2018 Conference



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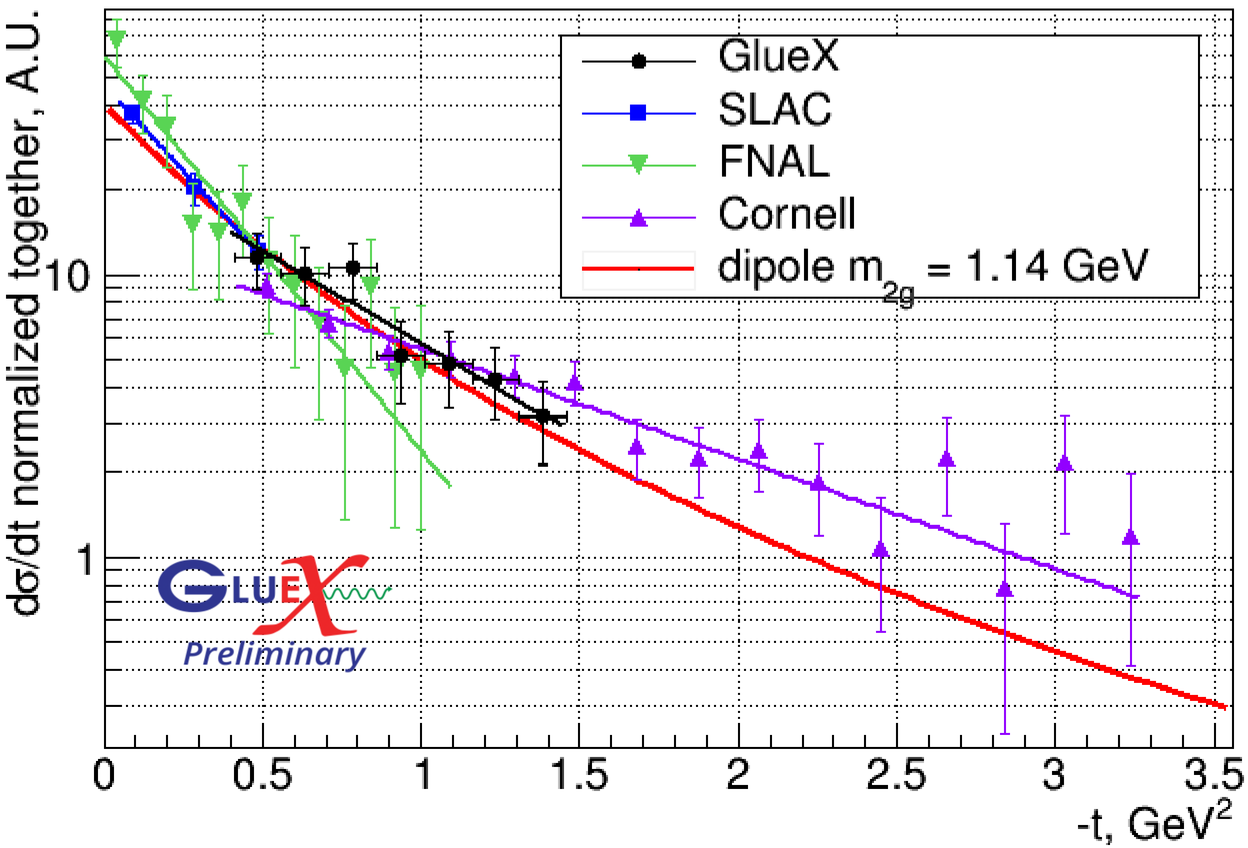

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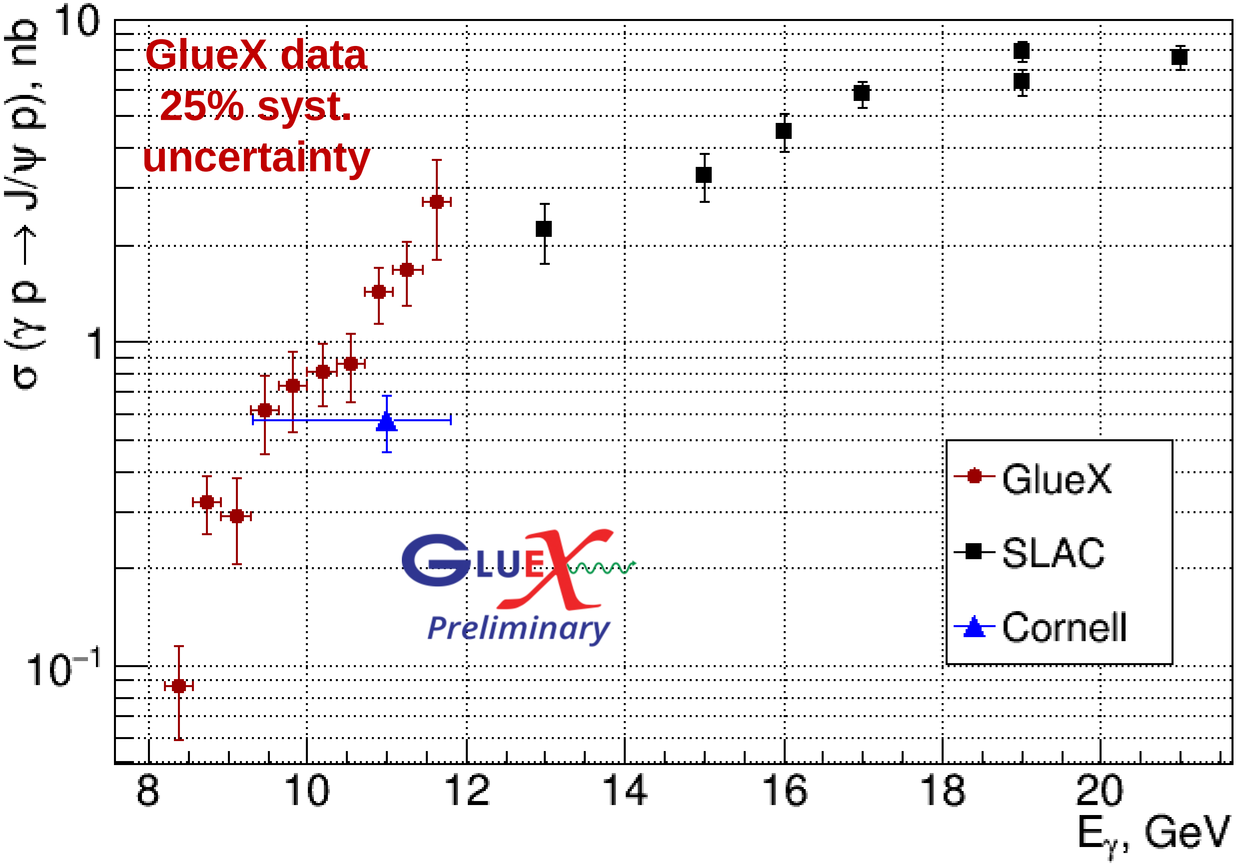

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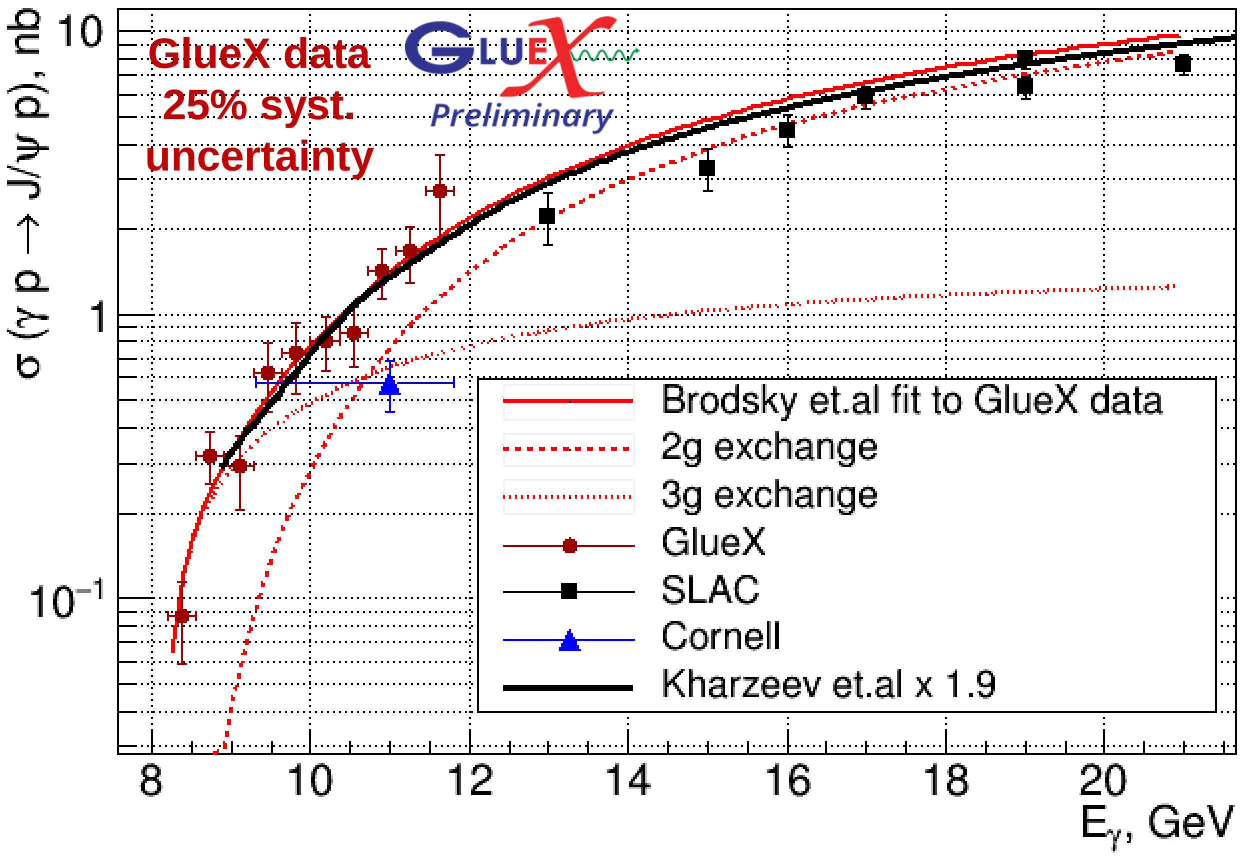


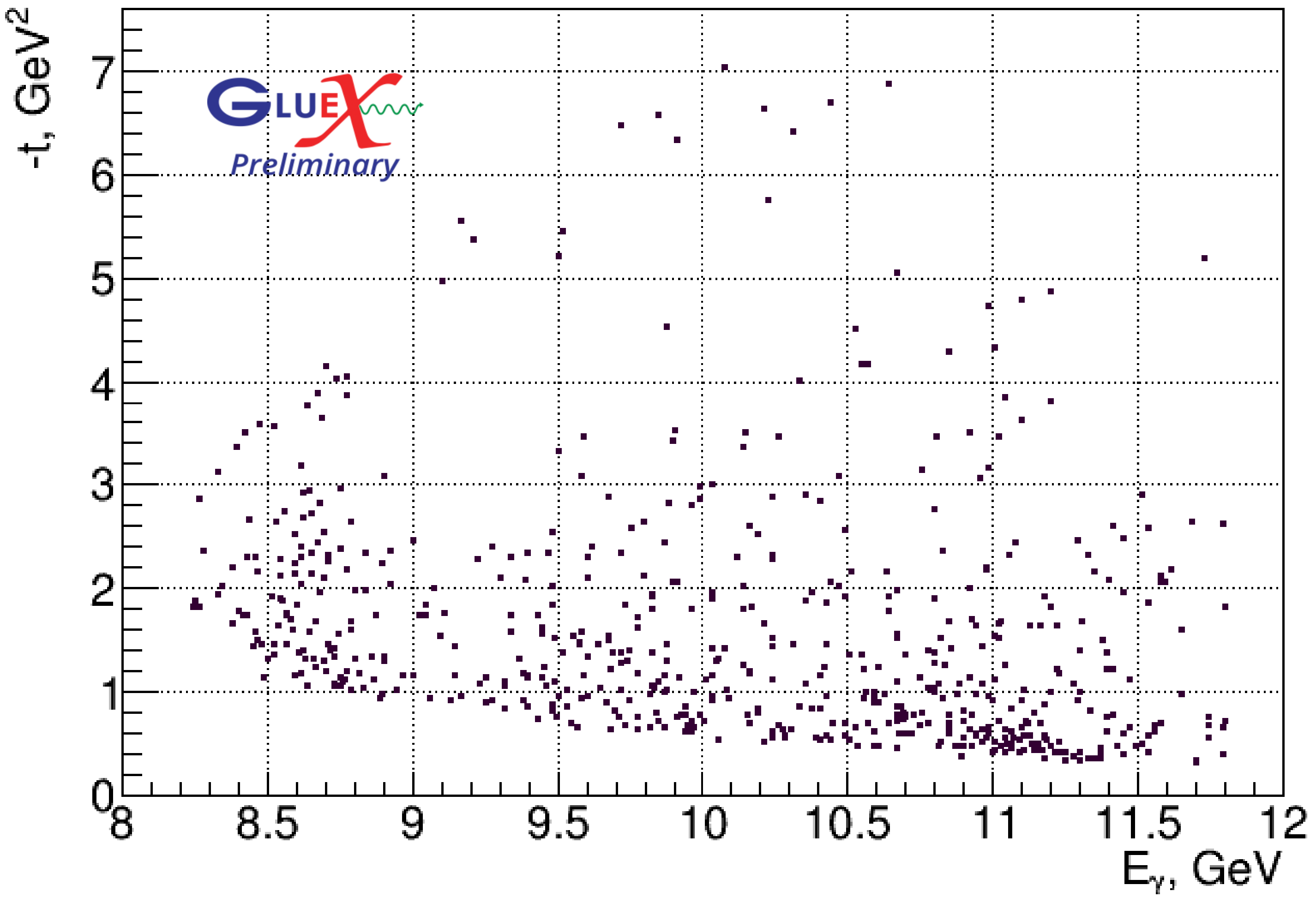
Using F(t) to calculate total cross-section from the SLAC dσ/dt at t_{min}

Cornell data: horizontal errors represent acceptance

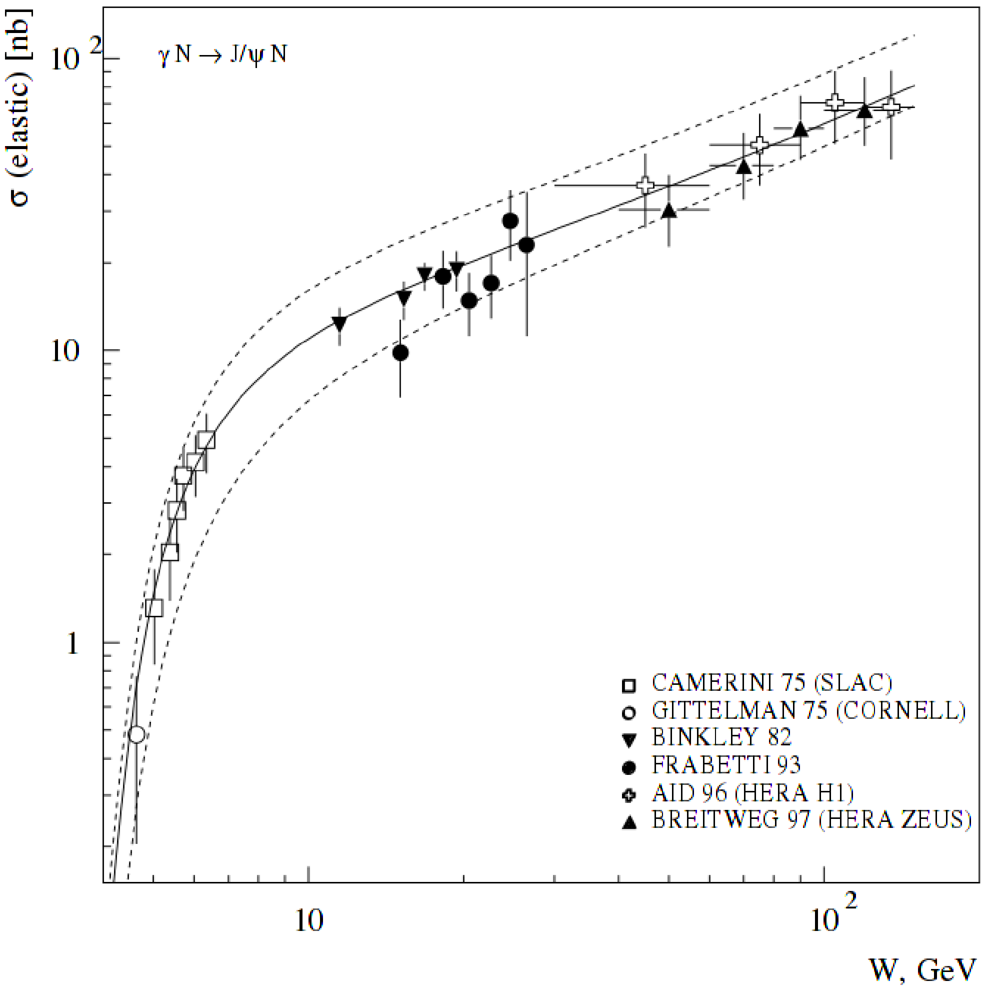
Brodsky at.al fit of the GlueX data ONLY using F(t) as t-dependence

Kharzeev et al. 1999 – gluonic contribution to the mass of the proton – 80% if calculations are verified

Plots for QNP2018 Conference



Backup slide: J/ψ threshold photoproduction and the mass of the proton



Kharzeev et al. Eur. Phys. C9 (1999) – Absolute (factor 2-3 uncertainty) perturbative calculations using gluon PDFs

"… at low energies the photoproduction amplitude is proportional to the matrix element of the gluon part of the trace of the QCD energy-momentum tensor evaluated over the nucleon state; this quantity arises from the scale anomaly of QCD. The resulting contribution to the photoproduction amplitude is real …The low-energy J/ψ photoproduction data can thus be used to extract the fraction of the nucleon's mass arising from gluons…"