Υ near threshold production in EIC

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Detector-1 exclusive, diffractive and tagging WG meeting

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Physics motivation

- Near threshold photo-production of Υ (total cross section, $d\sigma/dt$) has been aroused plenty of interests from theory community
  - May be sensitive to proton gluonic gravitational form factor (although the connections still under debate)
    PRD 101(11) (2020) 114004
    PRD 103, 096010 (2021)
    PLB 822:10(2021), 136655
  - Extract the Υ -p scattering length PRD 102, 014016 (2020)
  - Understanding origin of proton mass EPJC 80 (6) (2020) 507
  - Proton mass radius PRD 105, 096033 (2022) 096033 PLB 803 (2020) 135321
  - Short range correlation from sub-threshold production in eA PLB, 781 664-671, 2018.
  - Gluon saturation from exclusive production in eA
  - …

Origin of proton mass

X. Ji, PRL 74 (1995) 1071,
PRD 52 (1995) 271
R. Wang et al, EPJC 80 (6) (2020) 507

Decomposition of proton mass

$$M_q = \frac{3}{4}\left(a - \frac{b}{1+\gamma_m}\right)M_N$$ quark energy contribution

$$M_g = \frac{3}{4}(1-a)M_N,$$ gluon energy contribution

$$M_m = \frac{4+\gamma_m}{4(1+\gamma_m)}bM_N,$$ quark mass contribution

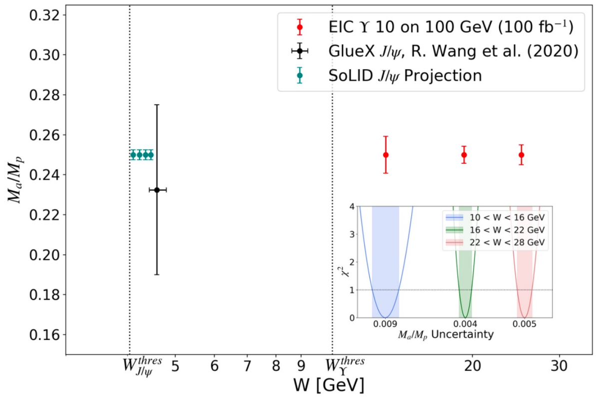
$$M_a = \frac{1}{4}(1-b)M_N,$$ trace anomaly

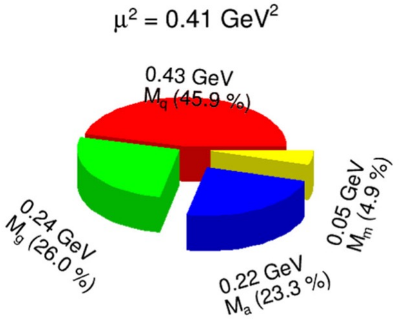
- Understanding proton mass from the shape / amplitude of J/psi (Upsilon) $d\sigma/dt$ at near threshold.

a: momentum fraction carried by all quarks
- constrained from PDF

b: the magnitude of the QCD trace anomaly contribution
- less known

From EIC Yellow report





EPJC 80 (6) (2020) 507

$$\left.\frac{d\sigma_{J/\Psi N \to J/\Psi N}}{dt}\right|_{t=0} = \frac{1}{64\pi}\frac{1}{m^2_{J/\Psi}(\lambda^2 - m^2_N)}\left|F_{J/\Psi N}\right|^2$$

$$F_{J/\Psi N} \simeq r_0^3 d_2 \frac{2\pi^2}{27} 2M_N^2(1-b)$$

Simulations results of Υ near threshold production in ep collisions (from ATHENA)

Event generator and photon flux

- Event generator: ***eStarlight*** detail intro: PRC 99, 015203 (2019) source code: https://github.com/eic/estarlight

$$\sigma(eA \to eAV) = \int \frac{dW}{W} \int dk \int dQ^2 \frac{d^2N_\gamma}{dk\,dQ^2} \sigma_{\gamma^* A \to VA}(W, Q^2)$$

→ photon flux

W: photon-p center of mass energy
k: photon energy
Q^2: photon virtuality

- Photo flux: In target rest framework

$$\frac{d^2N_\gamma}{dkdQ^2} = \frac{\alpha}{\pi}\frac{dk}{k}\frac{dQ^2}{Q^2}\left[1 - \frac{k}{Ee} + \frac{k^2}{2E_e^2} - \left(1 - \frac{k}{Ee}\right)\left|\frac{Q^2_{\min}}{Q^2}\right|\right]$$

E_e is the electron energy $\quad Q^2_{\min} = \frac{m_e^2 k^2}{E_e(E_e - k)}$

- Heavy meson cross-section:

$$\sigma_{\gamma^* A \to VA}(W, Q^2) = f(M_V)\sigma(W, Q^2 = 0)\left(\frac{M_V^2}{M_V^2 + Q^2}\right)^n$$

$$n = c_1 + c_2(Q^2 + M_V^2)$$

$$\sigma(W, Q^2 = 0) = \sigma_P W^\epsilon$$

Zeus: Phys. Lett. B 437:432-444,1998
Phys. Lett. B 680:4-12, 2009
H1: Phys. Lett. B 483:23-35, 2000
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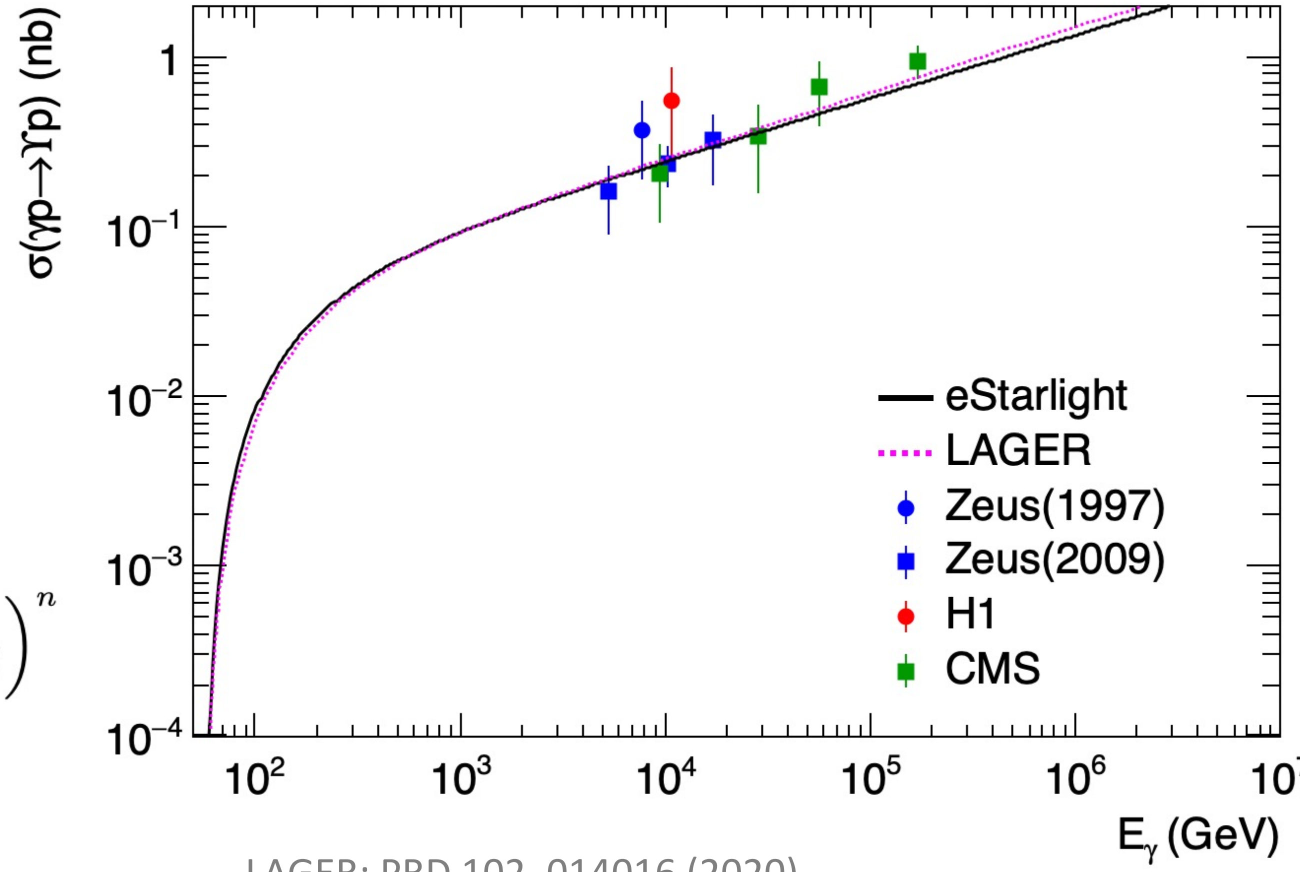


LAGER: PRD 102, 014016 (2020)

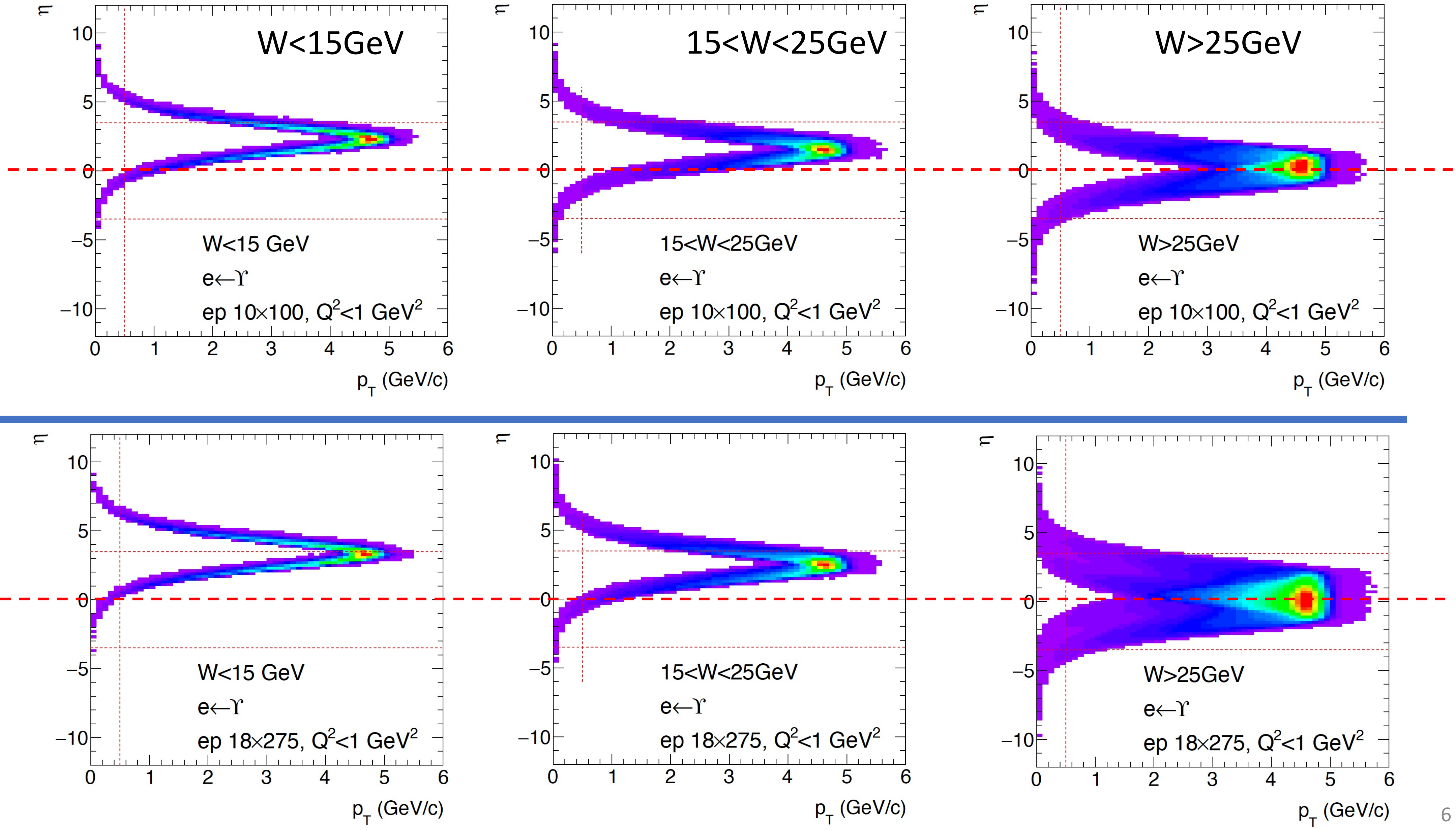
Kinematics of e ← ϒ at near threshold

ep 10x100 GeV

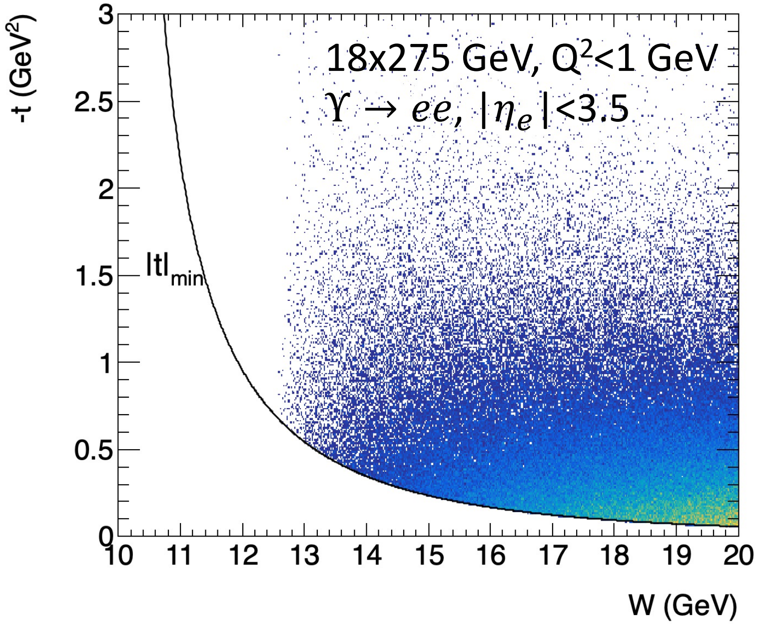
Center of the detector

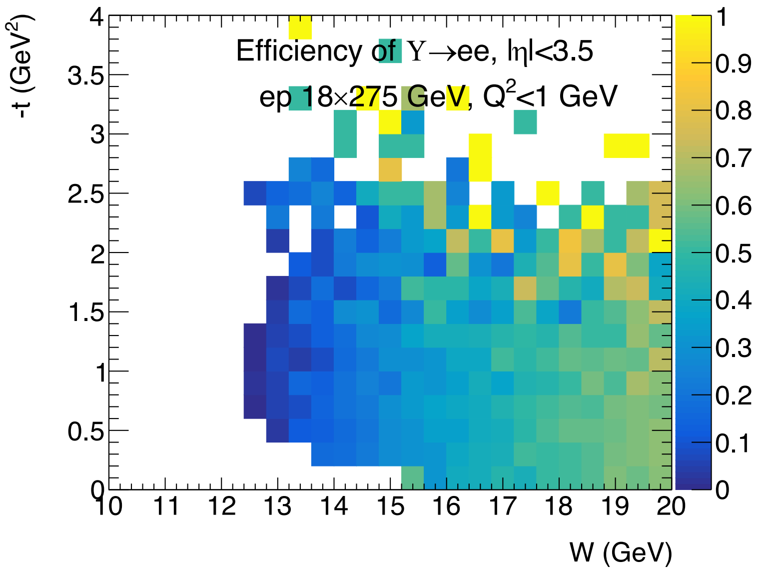
ep 18x275 GeV

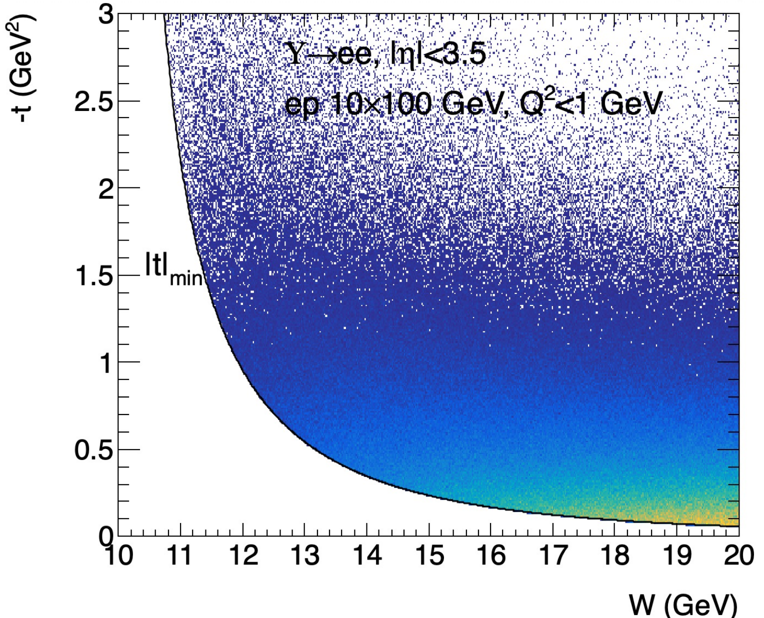
Center of the detector

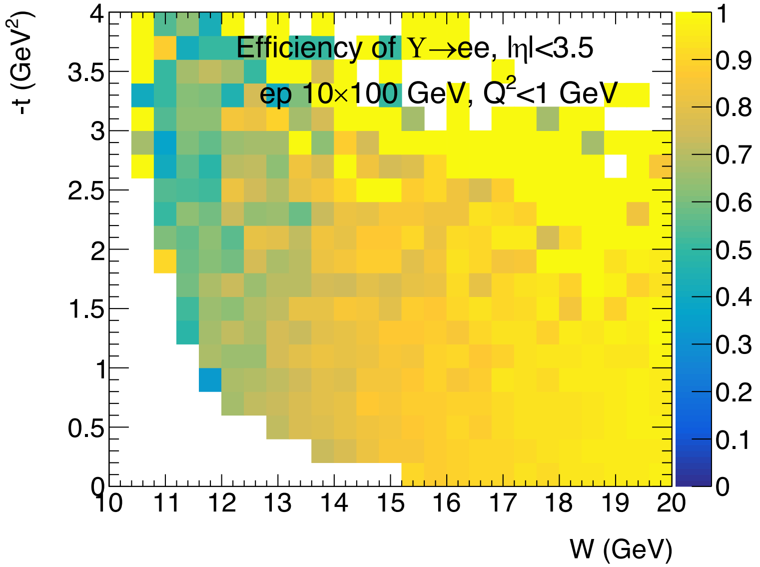


Υ distributions in –t and W ($|\eta_e|$<3.5)









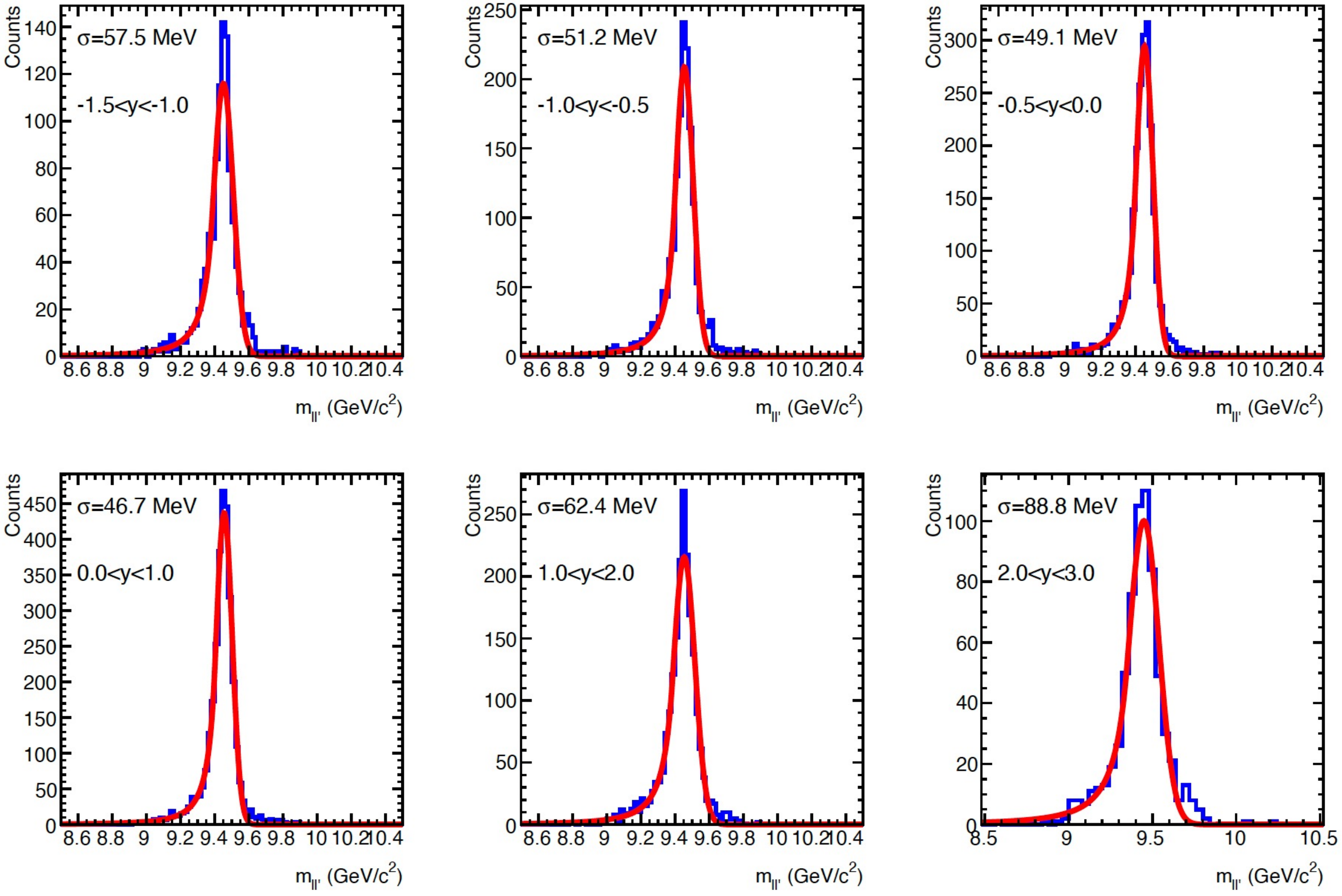
Efficiency (only considering acceptance):

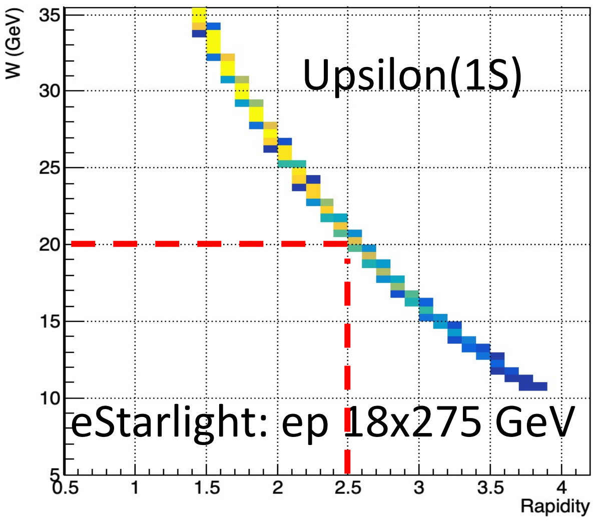
$$\frac{\text{daughters } |\text{eta}|<3.5}{\text{total upsilon counts}}$$

- Υ near threshold production limited by η acceptance in ep 18x275 GeV collisions
- Situation got much improved in lower collision energies, e.g. ep 10x100 GeV

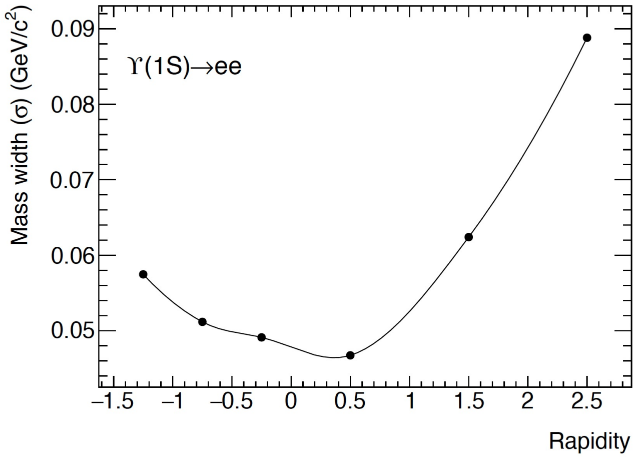
Projected $\Upsilon(1S) \rightarrow e^+e^-$ signals

From full ATHENA simulation

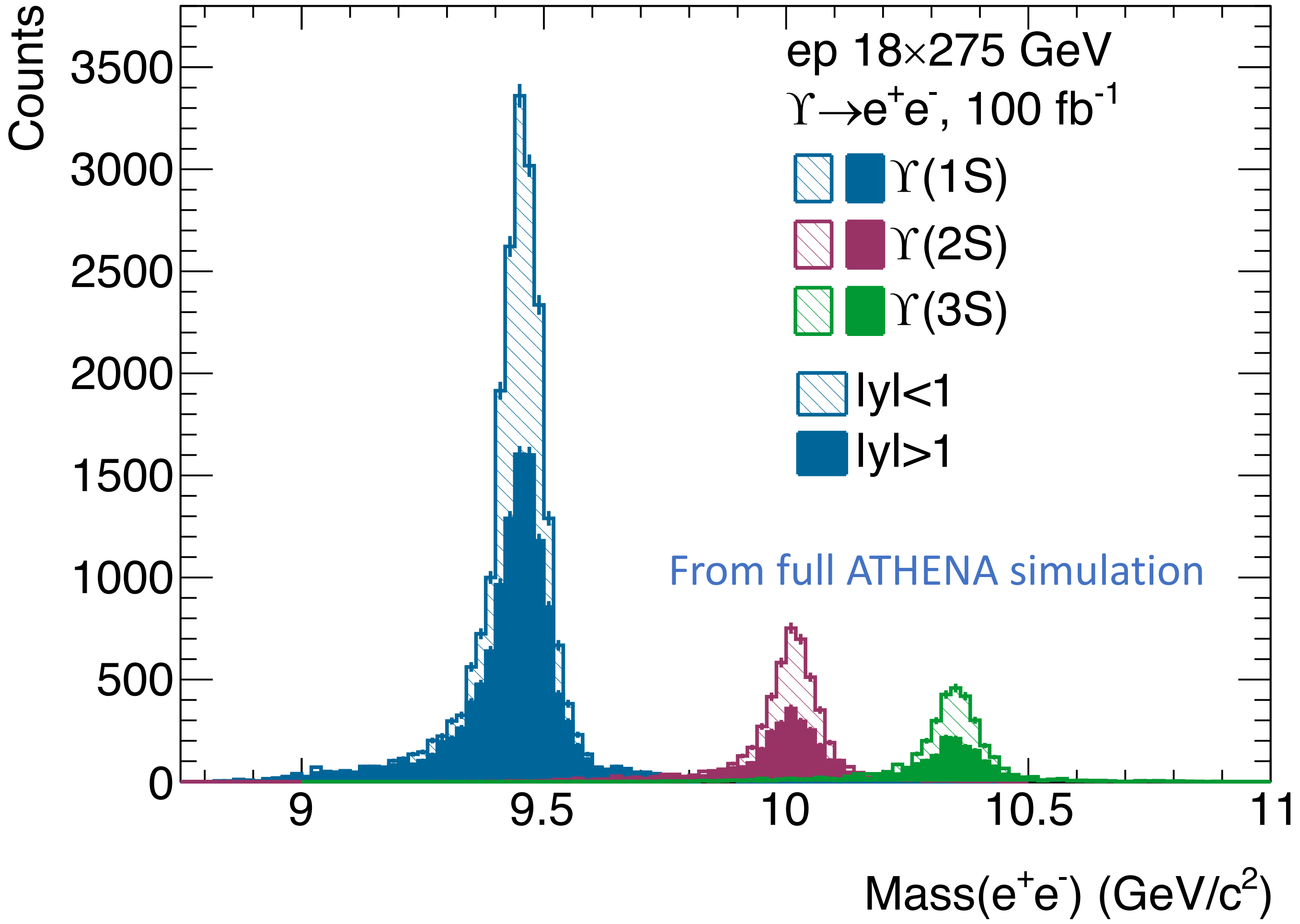




- Wider mass resolution in forward rapidity (near threshold) due to worse momentum resolution in forward compared to central.

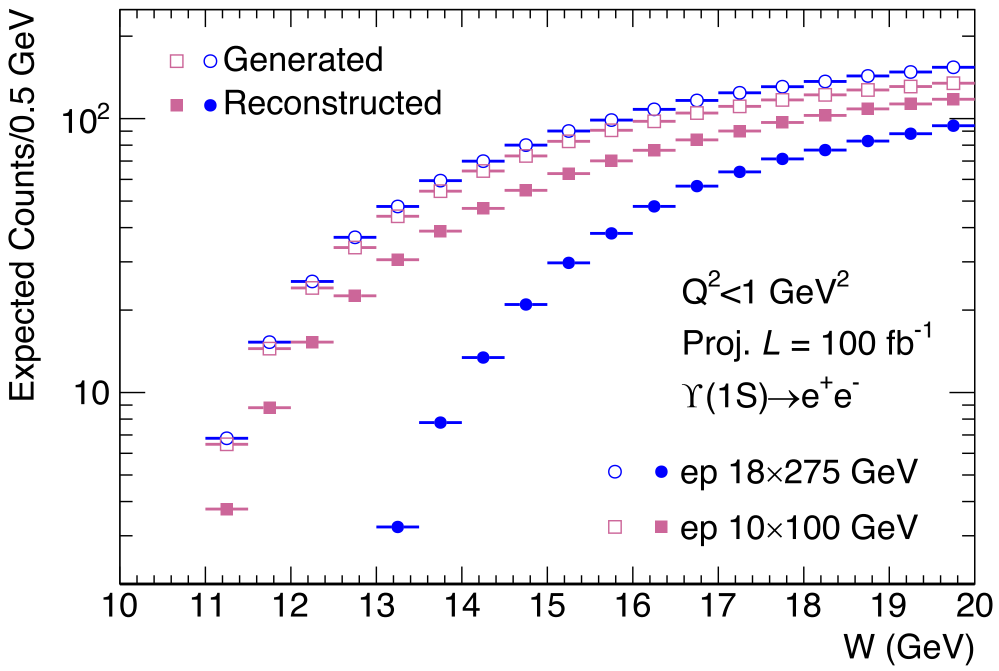


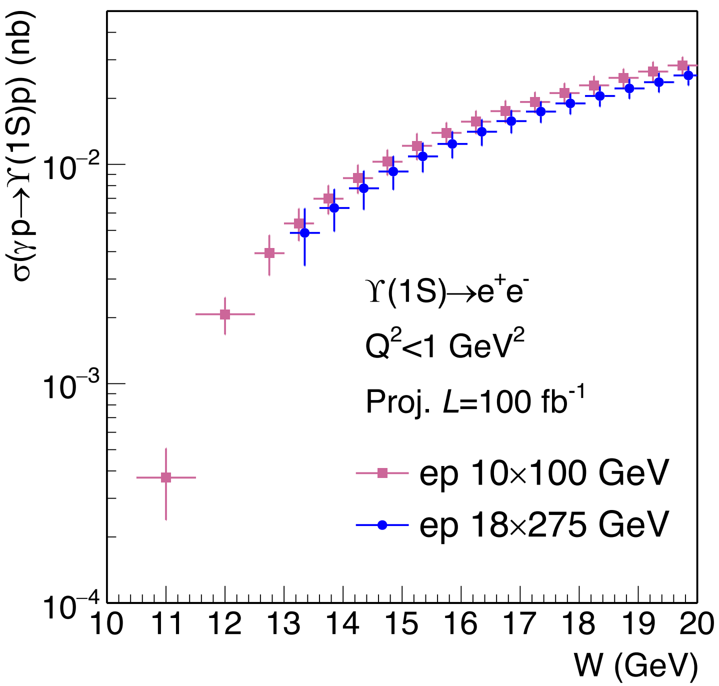
Projected ϒ(nS) signals



- Separation of ϒ different states requires mass resolution ~ 100 MeV/c^2
- Clear separation of ϒ 3 states signals in from ATHENA simulation
  ϒ(1S) mass resolution
  |y|<1, 49 MeV/c^2
  |y|>1, 65.9 MeV/c^2
- Looking forward to full Detector-1 simulation

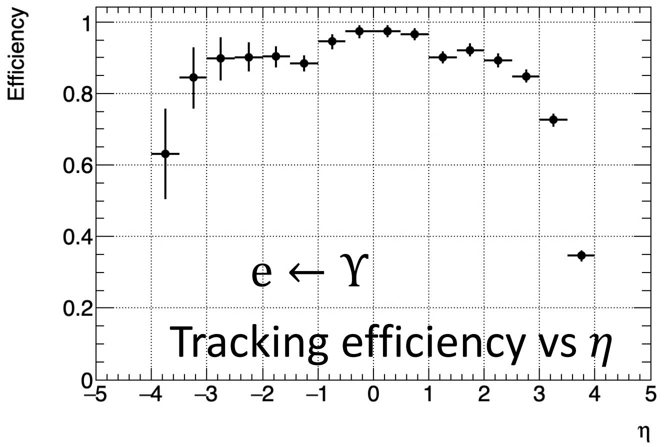
Projected ϒ production yield at near threshold

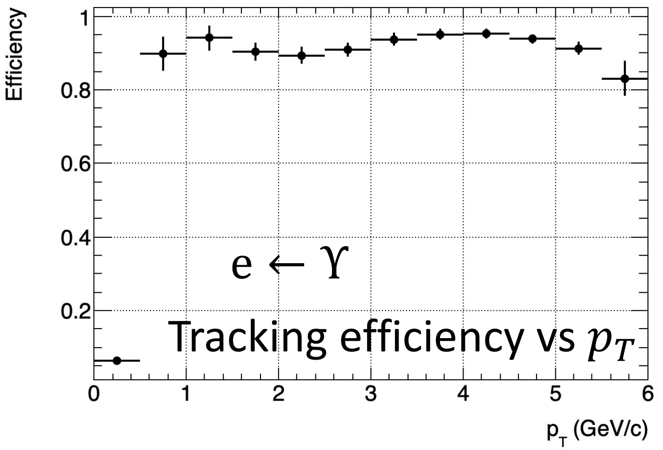


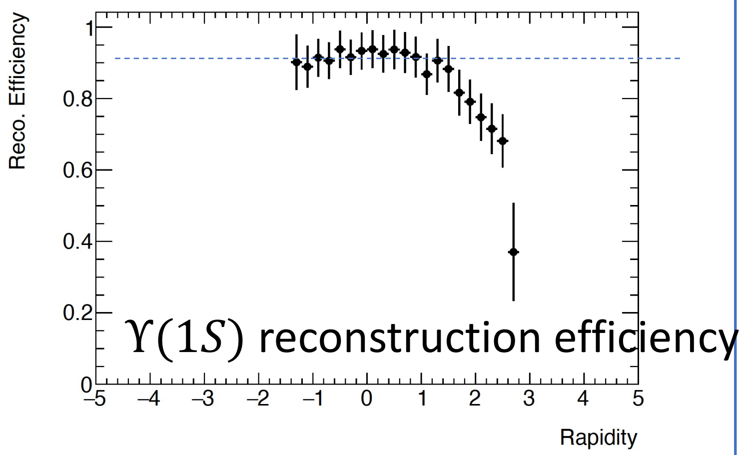


Plots are from full ATHENA simulation

- Measurements on ϒ near threshold production cross-section are promising in future EIC.

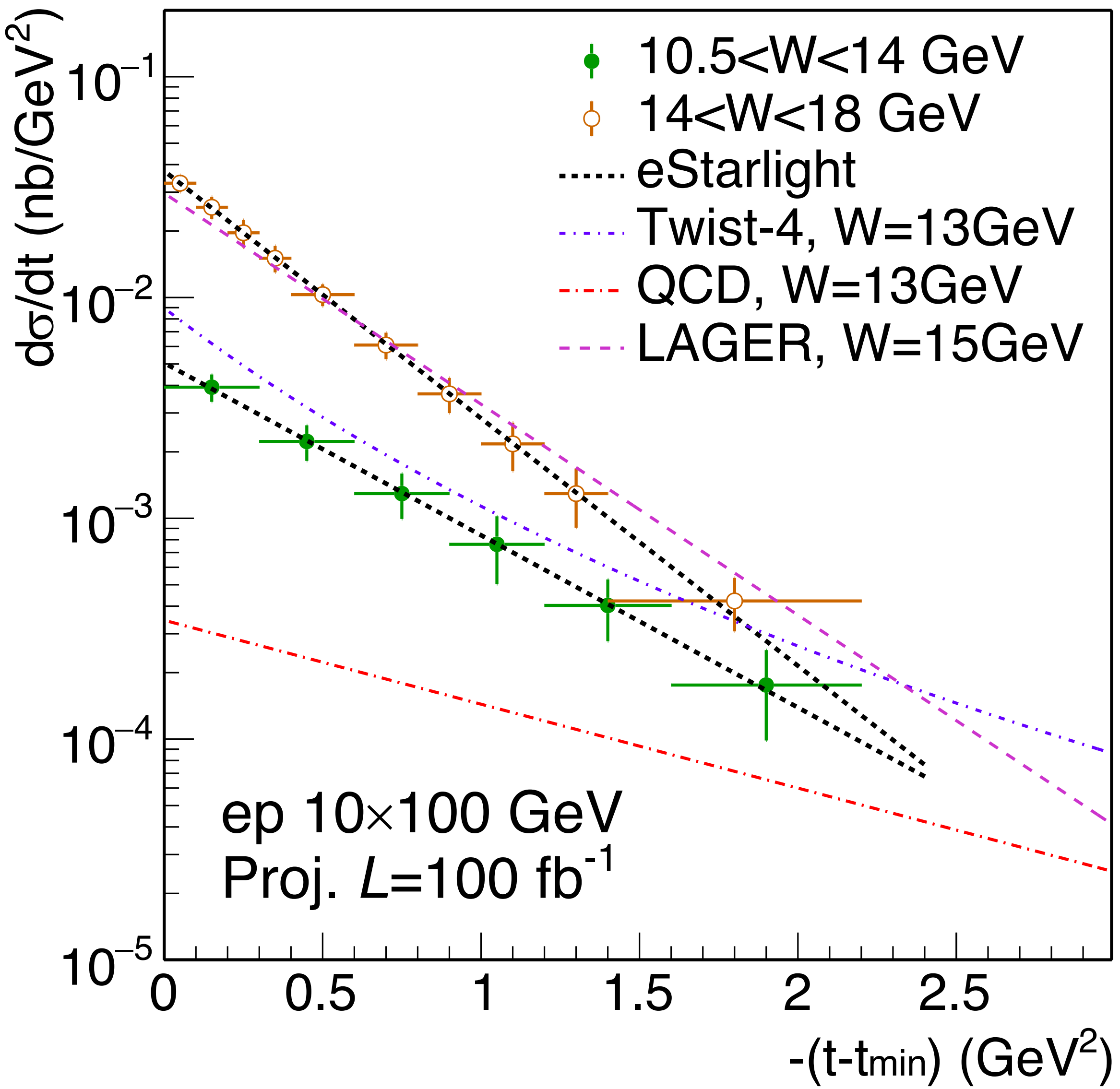






Projected Υ $d\sigma/dt$ at ep 10x100 GeV collisions

From full ATHENA simulation



$$t = (p'_{\text{proton}} - p_{\text{proton}})^2)$$

- Differential measurements of Υ near threshold production is feasible in EIC ep 10x100 GeV collisions.
  - Expected EIC will have separation power for different model calculations.

Twist-4 : PLB 822:10(2021), 136655
QCD (GPD factorization) : PRD 103, 096010 (2021)
LARGER: PRD 102, 014016 (2020)

Summary

- Measurements on Υ near threshold production at EIC is promising.
  - Physics observable: total cross section, differential cross section $d\sigma/dt$ (slope, $d\sigma/dt(\mathrm{t}=0)$ etc).

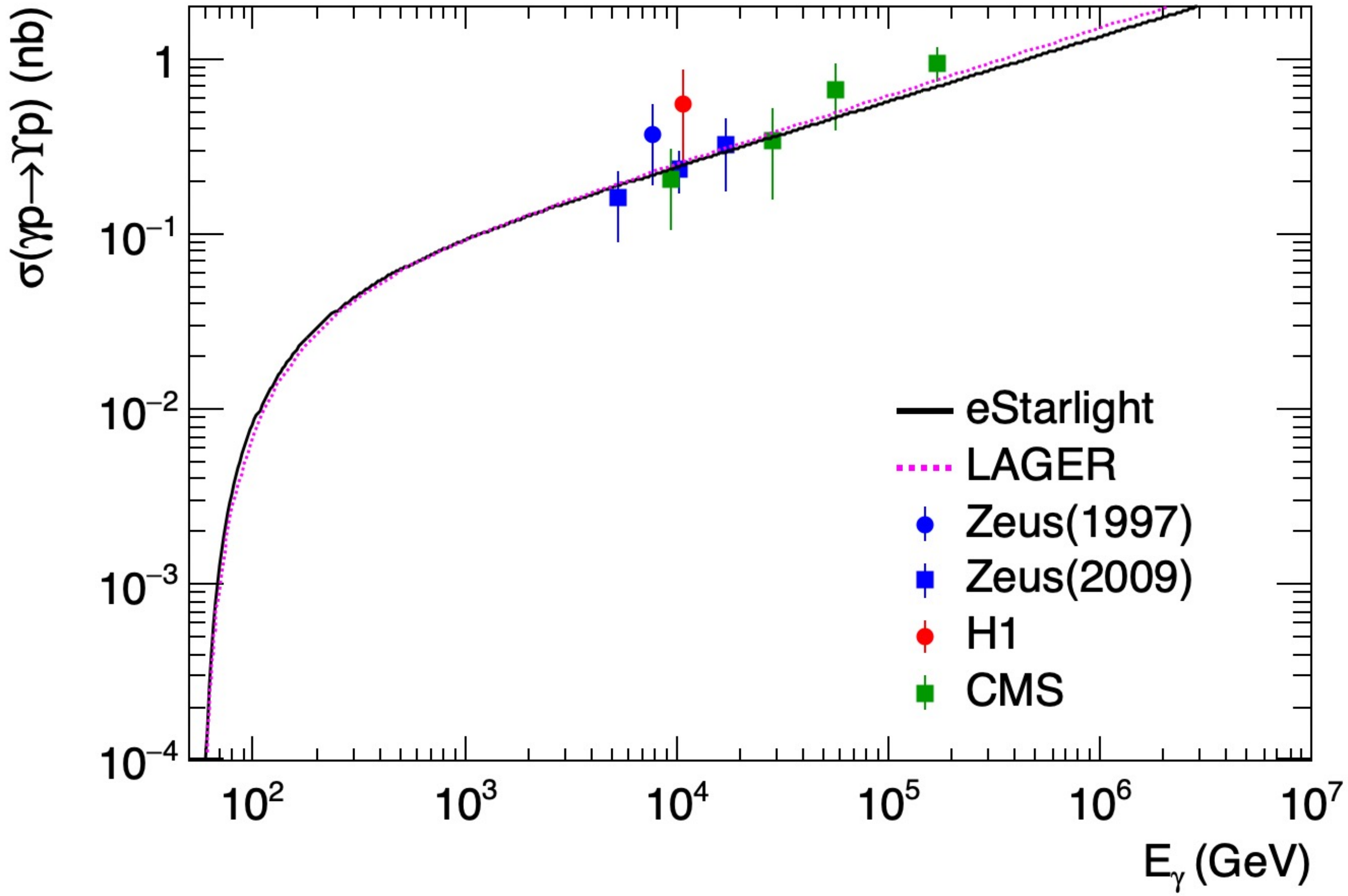
- Detector acceptance is cut-off at ep 18x275 GeV collisions at near threshold but feasible for lower energy collisions e.g. 10x100 GeV, 5x41 GeV etc.

- Outlook
  - Full simulation from Detector-1 in both ep and eA collisions

- Back ups

Upsilon(1S) cross section

Zeus: Phys. Lett. B 437:432-444,1998
Phys. Lett. B 680:4-12, 2009
H1: Phys. Lett. B 483:23-35, 2000
CMS: Eur. Phys. J. C 79:277, 2019



LAGER: PRD 102, 014016 (2020)

eStarlight/Lager prediction on the slope

LAGER: PRD 102, 014016 (2020)