Quarkonium detection and physics opportunities at the EIC

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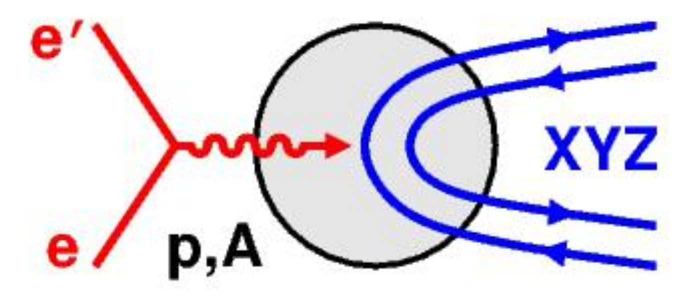
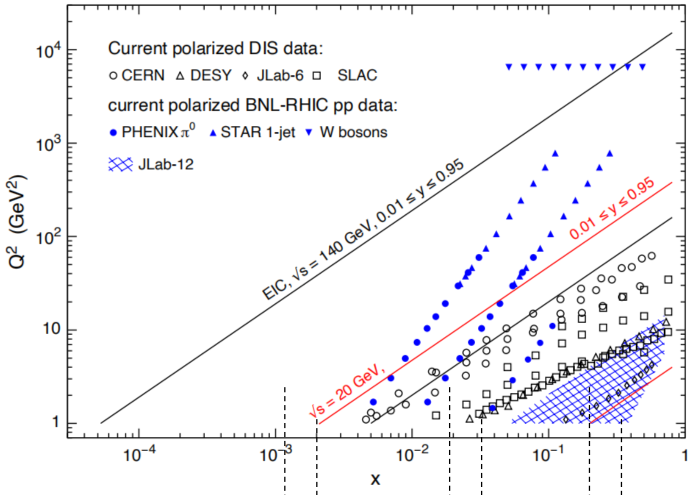
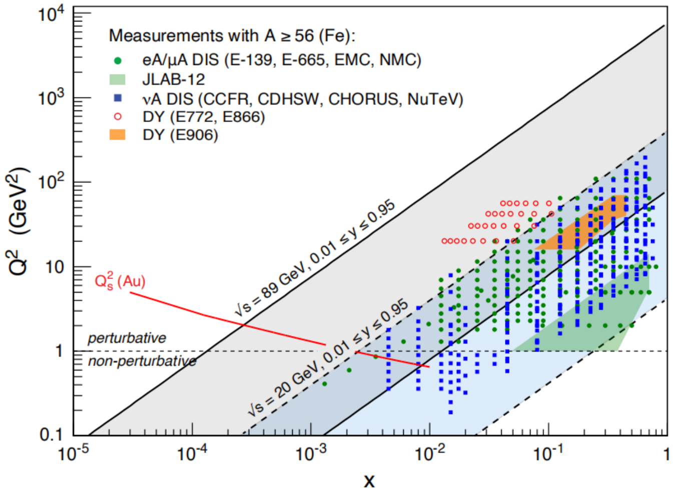


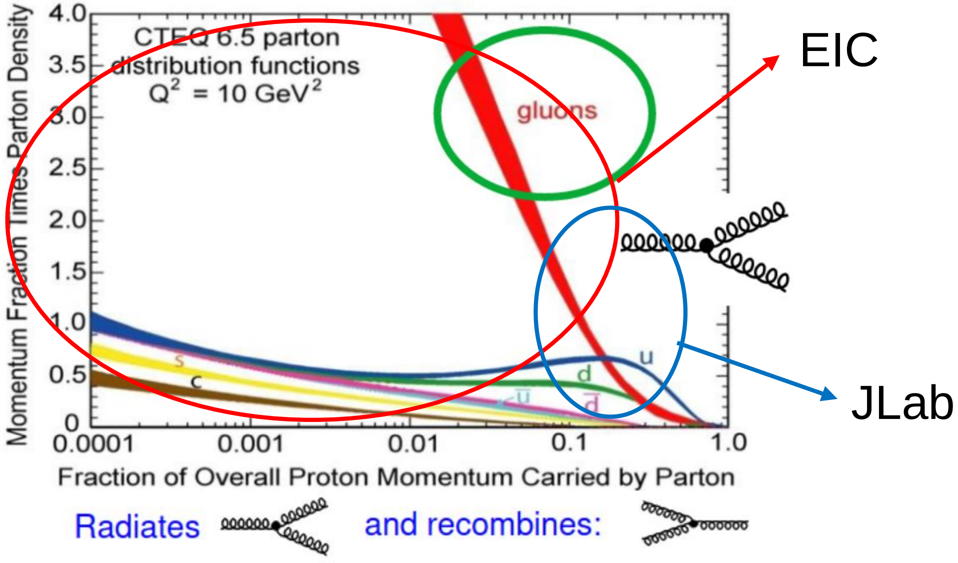
CFNS Workshop "Exotic heavy meson spectroscopy and structure with EIC",
Aug. 15 -19, 2022

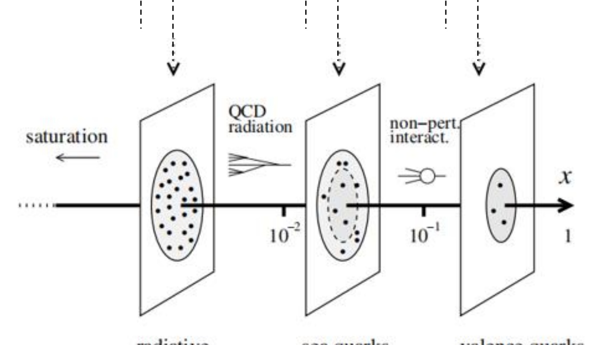
Why EIC ?

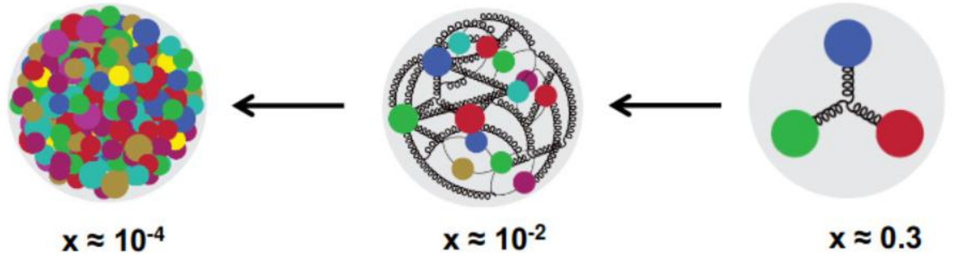
- One of the most cleanest environment to study QCD.
- Large kinematic coverage
- 100/1000 times (10^{33} – 10^{34} cm^{-2}s^{-1}) higher luminosity than HERA.
- Highly polarized electron (~ 70%) and proton (~ 70%) beams.
- Variable Ion beam species: from deuterons to heavy nuclei such as gold, lead or uranium.





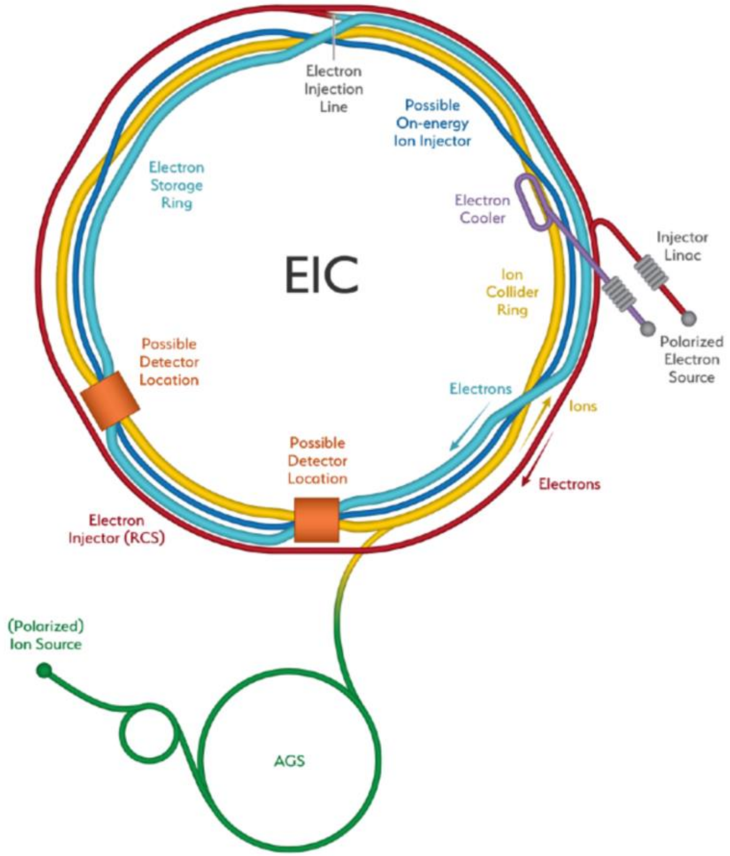






The proton sea has a non-trivial structure (abundant gluons)

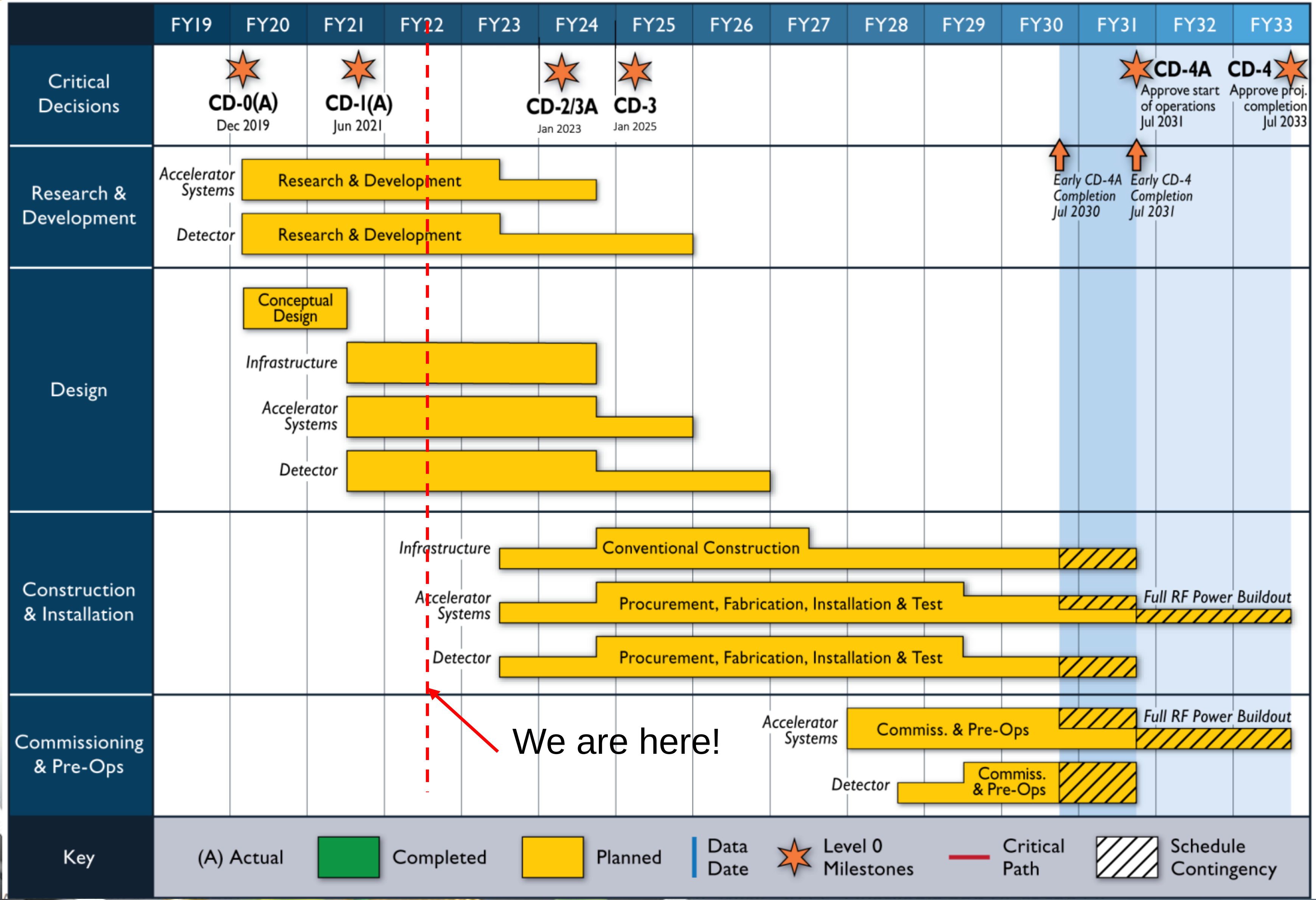
The facility: EIC at BNL



- ✓ Luminosity: 10^{33-34} cm^{-2}sec^{-1} (100-1000 times HERA)
- ✓ Hadrons up to 275 GeV
- ✓ Electrons : 5-10 (20) GeV
- ✓ CM energy: 20-100 (140) GeV
- ✓ Polarized beams

- ✓ >1200 scientists, 250 institutions [Webpage]
- ✓ CD0 and site selection at Brookhaven National Lab in 2019
- ✓ Framework for international participation being set up CD1 achieved in 2021 [Webpage]
- ✓ Project hosted/managed jointly by BNL and JLab
- ✓ EIC Yellow Report Physics-Detector studies completed 2021 [2103.05419]
- ✓ Call for Collaboration Proposals for EIC detectors (1 Dec, 2021) [Webpage]
- ✓ CD4 and operations expected in 2030+

The EIC status/timeline



We are here!

<u>ECCE</u> <u>ATHENA</u> <u>CORE</u>

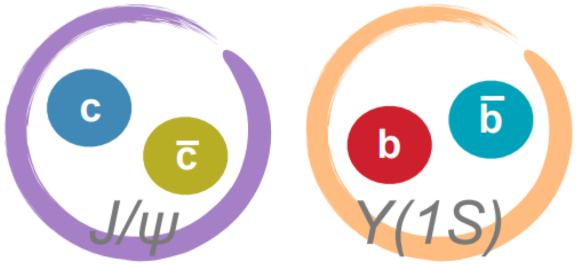
IP6 IP8

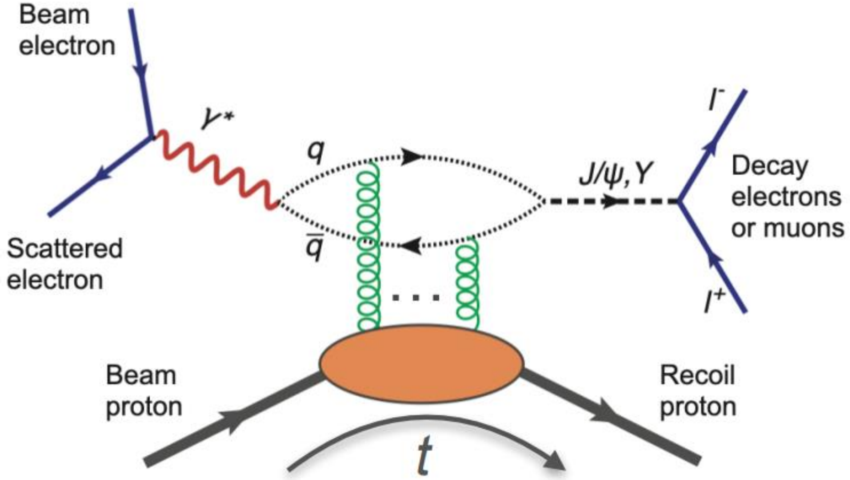
New community (Det-1)
New name—EPIC

start of operations: 2031
full-fledged accelerator: 2034

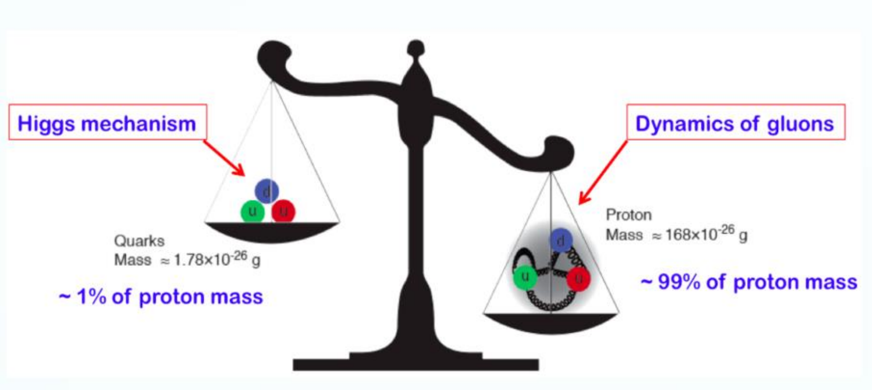
Why Exclusive Quarkonium ?

Gluons are massless, yet, responsible for nearly all visible mass
Gluons are hard to probe, as they do not carry electromagnetic charge



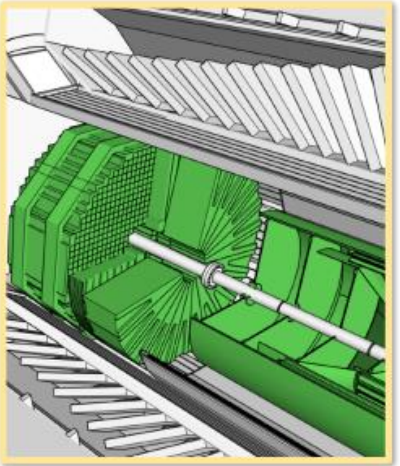


- **J/ψ and Y(1S) couple to gluons**
- **Production near threshold is promising to directly probe gluons**



Exclusive processes allow precise measurement of t
Low-x quarkonium mainly produced by PGF (photon-gluon fusion) process

The EIC detector (reference design)



Backward Endcap

Tracking:
- ITS3 MAPS Si discs (x4)
- AC-LGAD

PID:
- mRICH
- AC-LGAD TOF
- PbWO$_4$ EM Calorimeter (EEMC)

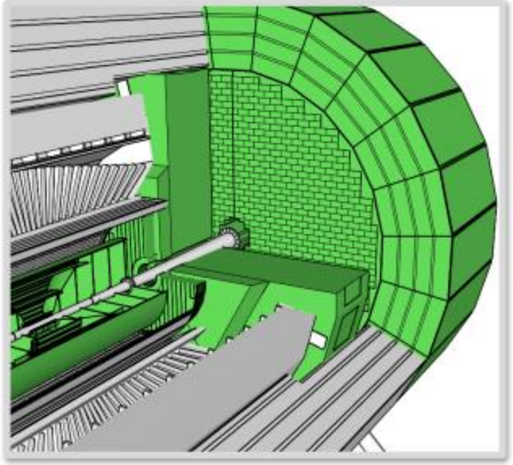
Barrel

Tracking:
- ITS3 MAPS Si (vertex x3; sagitta x2)
- µRWell outer layer (x2)
- AC-LGAD (before hpDIRC)
- µRWell (after hpDIRC)

h-PID:
- AC-LGAD TOF
- hpDIRC

Electron ID:
- SciGlass EM Cal (BEMC)

Hadron calorimetry:
- Outer Fe/Sc Calorimeter (oHCAL)
- Instrumented frame (iHCAL)



Forward Endcap

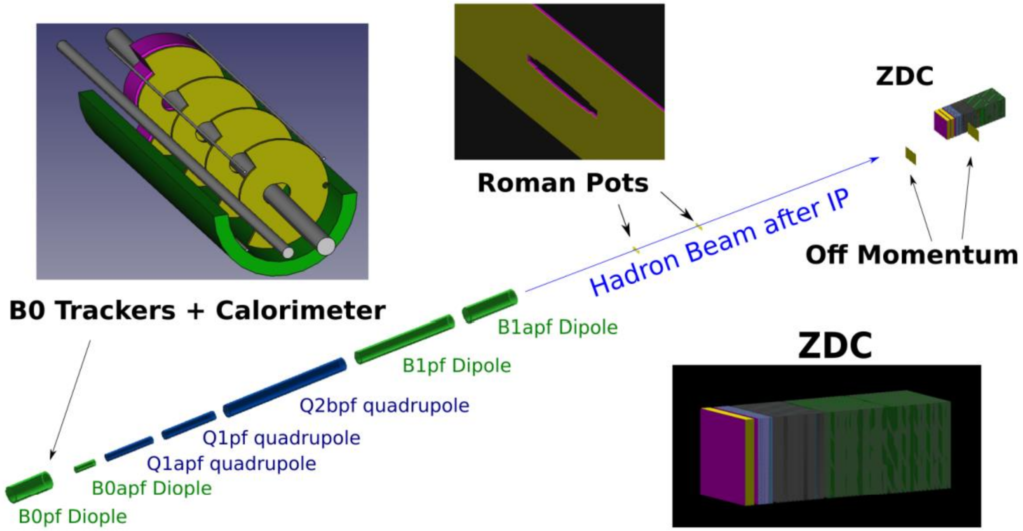
Tracking:
- ITS3 MAPS Si discs (x5)
- AC-LGAD

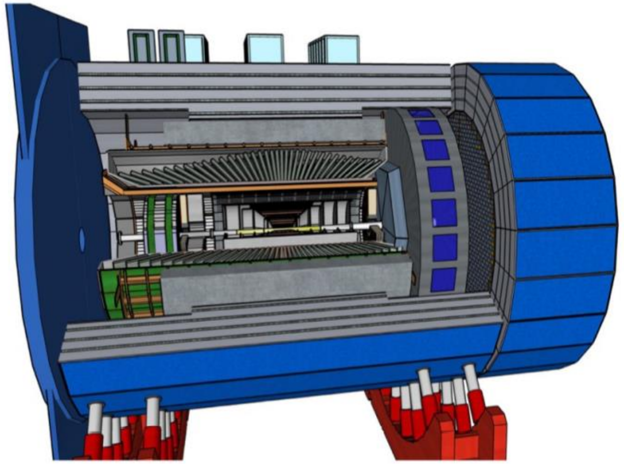
PID:
- dRICH
- AC-LGAD TOF

Calorimetry:
- Pb/ScFi shashlik (FEMC)
- Longitudinally separated hadronic calorimeter (LHFCAL)

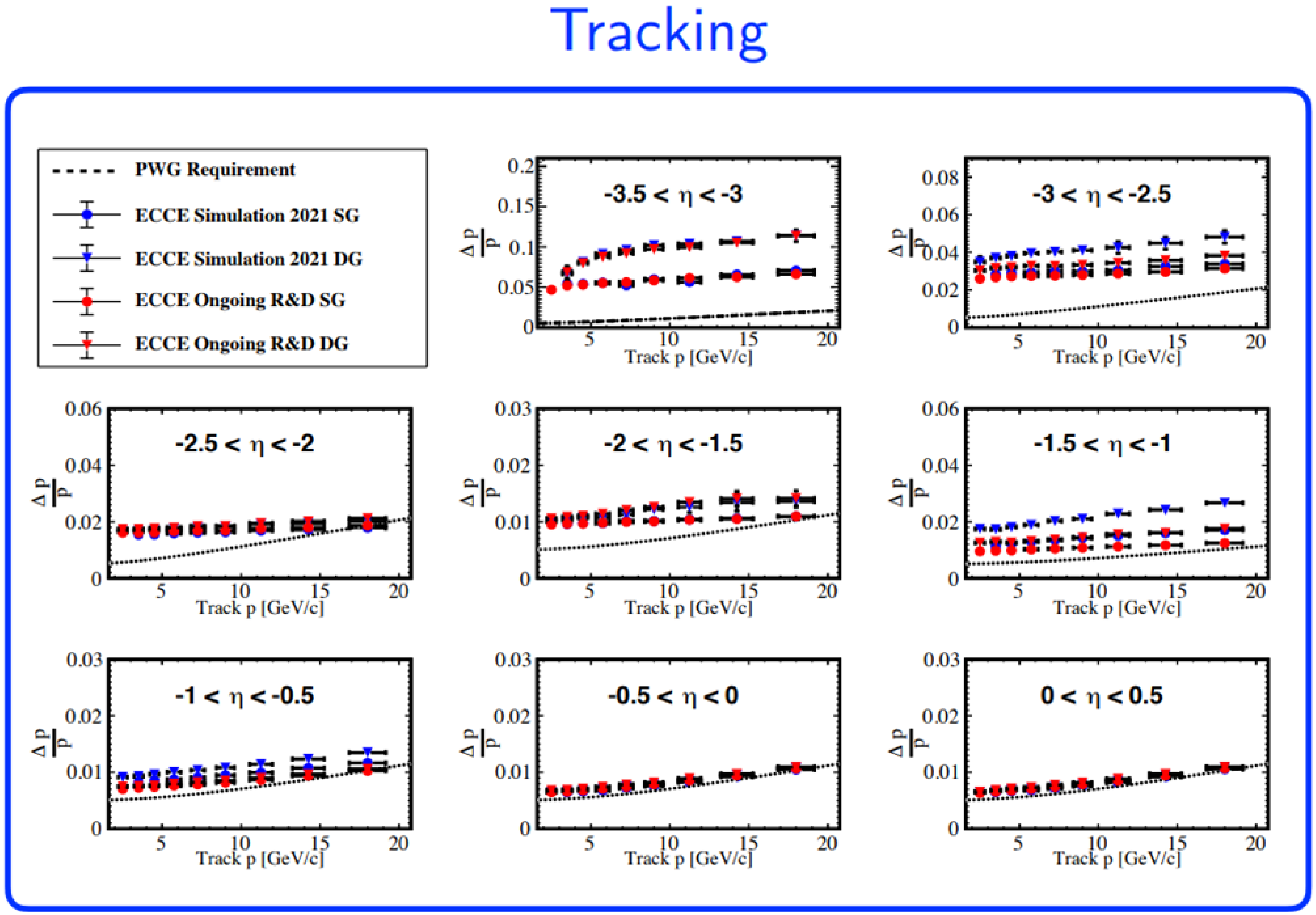
e-going

h-going





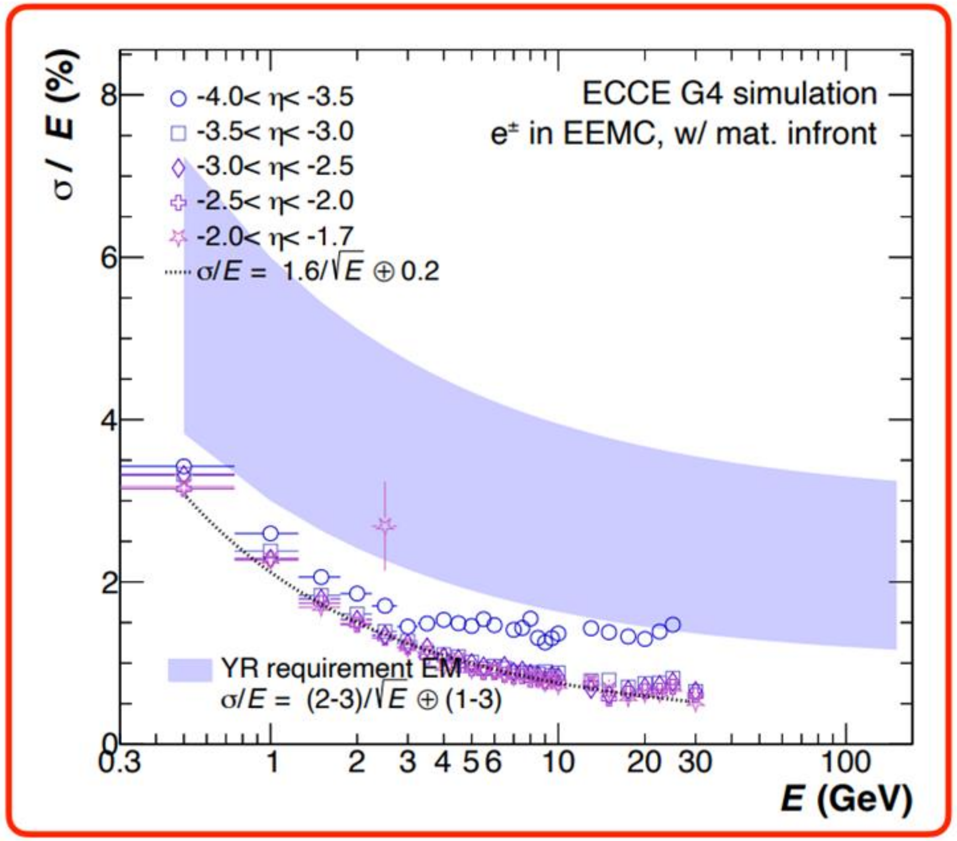
Tracking performance

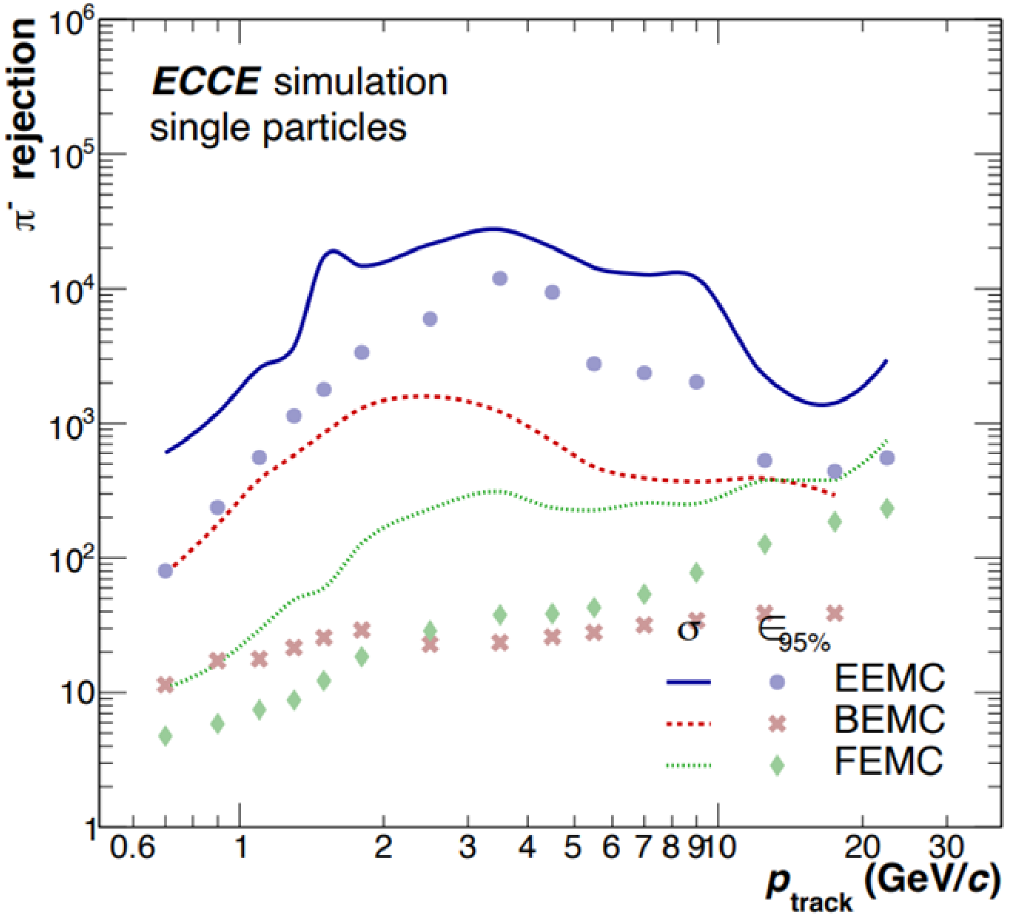


Good momentum resolution.

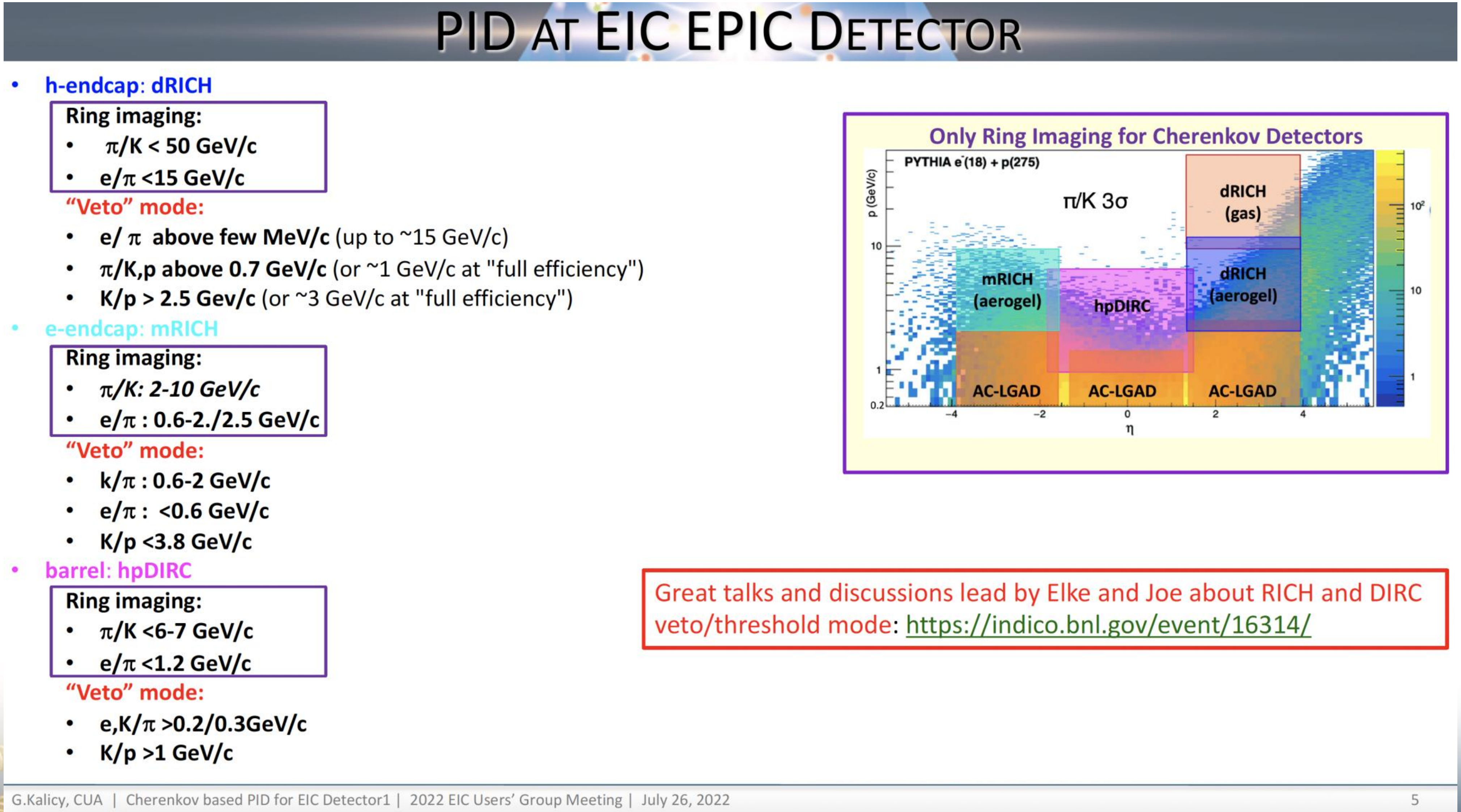
PID at EPIC

Calorimeter





PID at EPIC

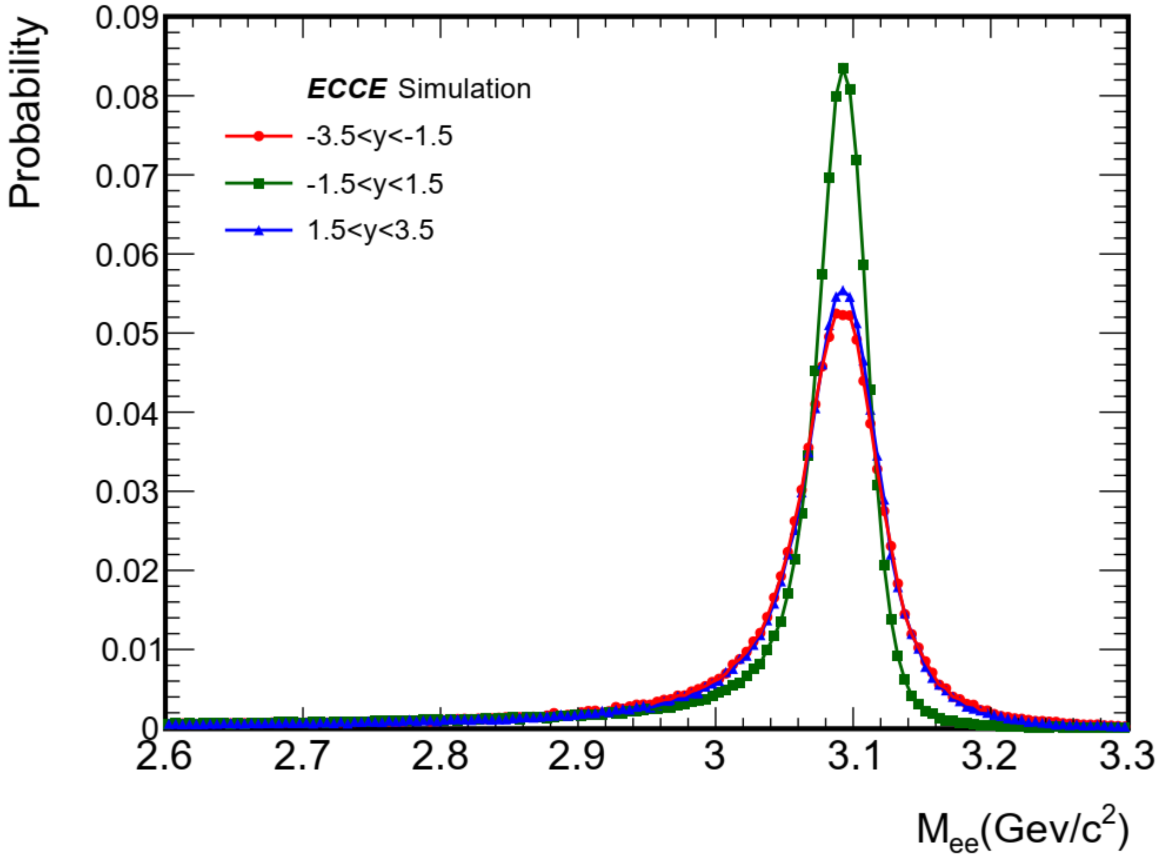


PID AT EIC EPIC DETECTOR

- **h-endcap: dRICH**
  - **Ring imaging:**
    - **$\pi/K < 50$ GeV/c**
    - **$e/\pi < 15$ GeV/c**
  - **"Veto" mode:**
    - **e/π above few MeV/c** (up to ~15 GeV/c)
    - **π/K,p above 0.7 GeV/c** (or ~1 GeV/c at "full efficiency")
    - **K/p > 2.5 Gev/c** (or ~3 GeV/c at "full efficiency")
- **e-endcap: mRICH**
  - **Ring imaging:**
    - ***π/K: 2-10 GeV/c***
    - **e/π : 0.6-2./2.5 GeV/c**
  - **"Veto" mode:**
    - **k/π : 0.6-2 GeV/c**
    - **e/π : <0.6 GeV/c**
    - **K/p <3.8 GeV/c**
- **barrel: hpDIRC**
  - **Ring imaging:**
    - **π/K <6-7 GeV/c**
    - **e/π <1.2 GeV/c**
  - **"Veto" mode:**
    - **e,K/π >0.2/0.3GeV/c**
    - **K/p >1 GeV/c**

Great talks and discussions lead by Elke and Joe about RICH and DIRC veto/threshold mode: https://indico.bnl.gov/event/16314/

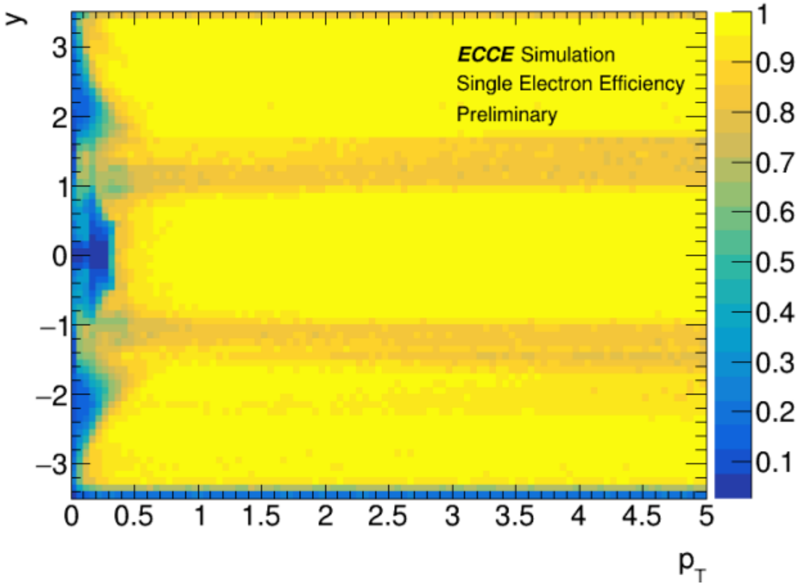
J/ψ Reconstruction

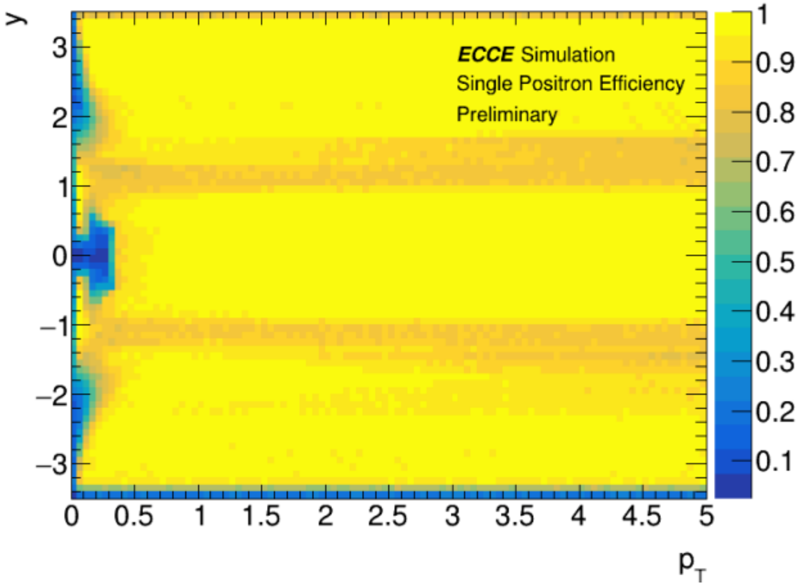


Generator: eSTARlight + Full Geant simulation (fun4All)

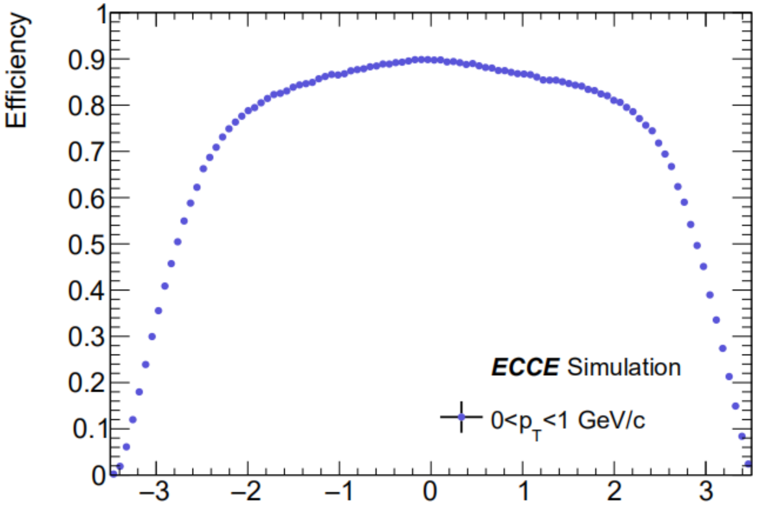
J/ψ Reconstruction Efficiency

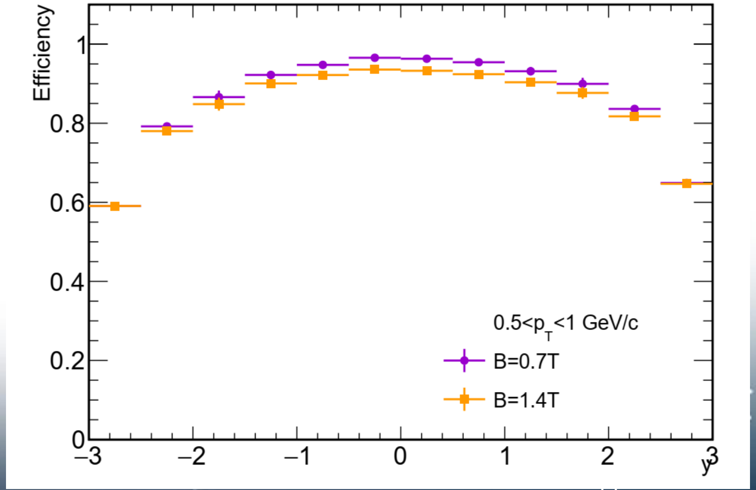
Single electron efficiency





J/ψ efficiency





High J/ψ efficiency in central region

Forward region with a low efficiency

The theoretical setup for projection

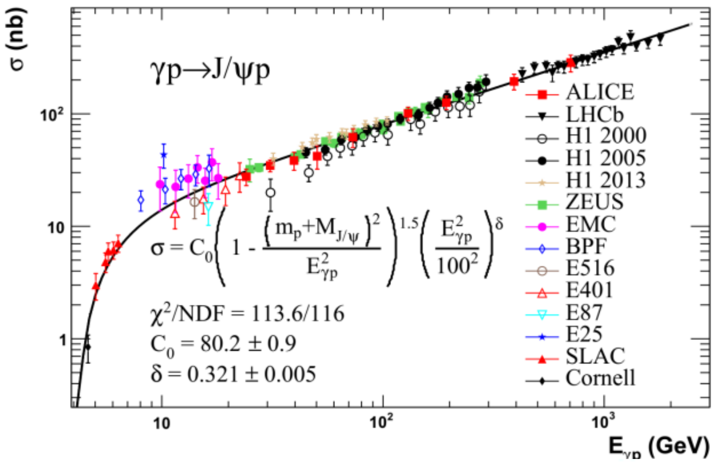
$$\sigma(eA\to eAV)=\int\frac{dW}{W}\int dk\int dQ^2\,\frac{d^2N_\gamma}{dkdQ^2}\,\sigma_{\gamma^*A\to VA}\left(W,Q^2\right),$$

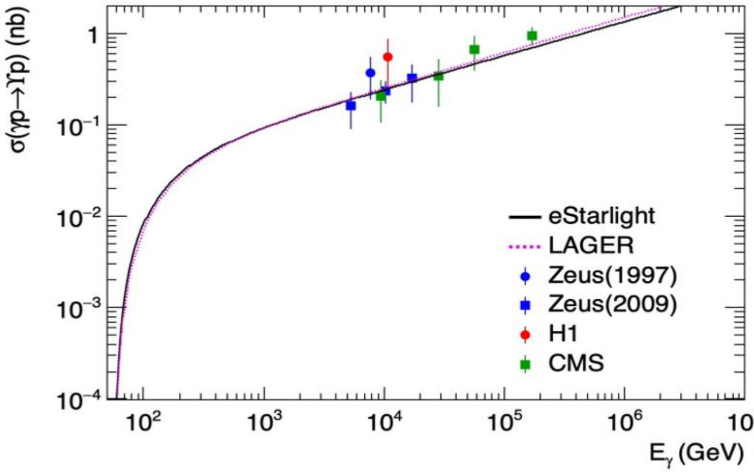
$$\frac{d^2N_\gamma}{dkdQ^2}=\frac{\alpha}{\pi kQ^2}\left[1-\frac{k}{Ee}+\frac{k^2}{2E_e^2}-\left(1-\frac{k}{Ee}\right)\left|\frac{Q^2_{\rm min}}{Q^2}\right|\right].$$

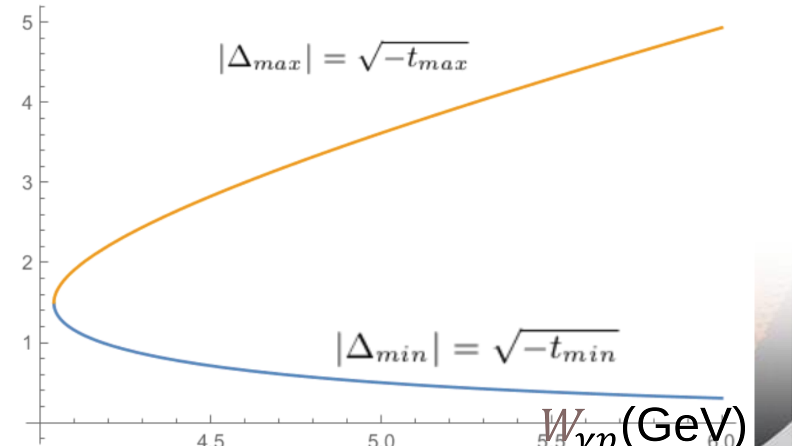
$$\sigma_{\gamma^*A\to VA}\left(W,Q^2\right)=f\left(M_V\right)\sigma\left(W,Q^2=0\right)\left(\frac{M_V^2}{M_V^2+Q^2}\right)^n$$

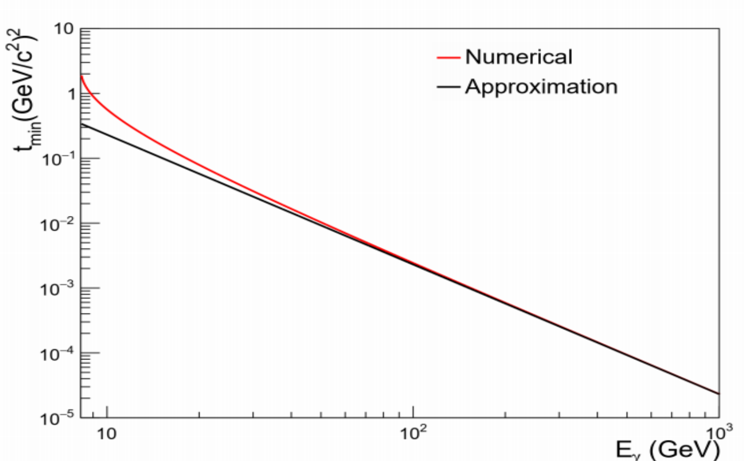
$$n=c_1+c_2\left(Q^2+M_V^2\right),$$

$$\sigma\left(W,Q^2=0\right)=\int_{t_{\rm min}}^{\infty}dt\left.\frac{d\sigma(\gamma A\to VA)}{dt}\right|_{t=0}|F(t)|^2,$$









eSTARLight: Michael Lomnitz and Spencer Klein, Phys. Rev. C **99** (2019) 015203

Wangmei Zha etal, Phys. Rev. C **97** (2018) 044910

The theoretical input for ep and eAu

$$W_{\gamma p} = \sqrt{m_p^2 + 2 m_p E_\gamma}$$

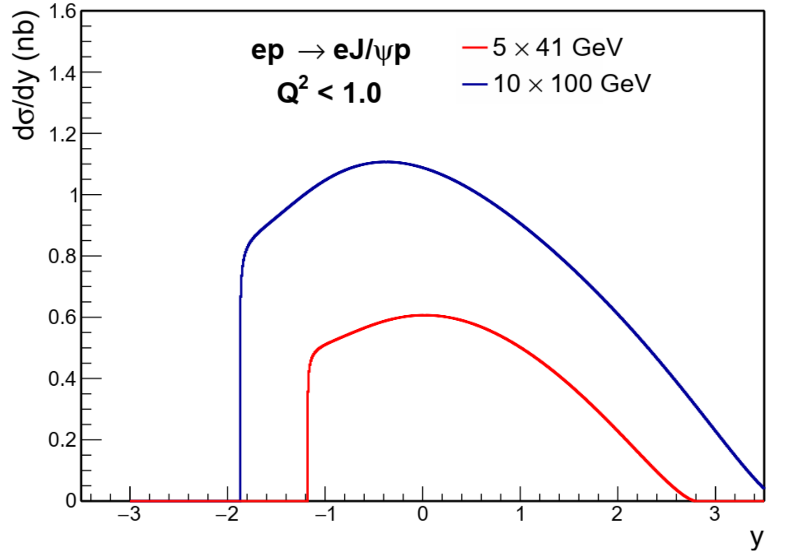
$$E_\gamma = \frac{M_v}{2} e^{-y}$$

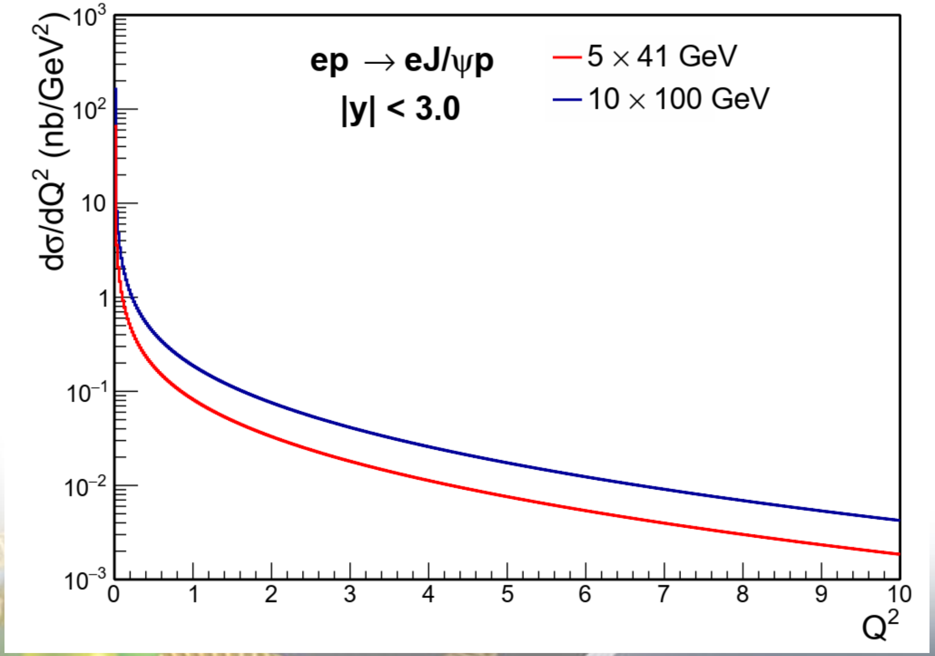
$$x = \frac{{M_v}^2}{{W_{\gamma p}}^2}$$

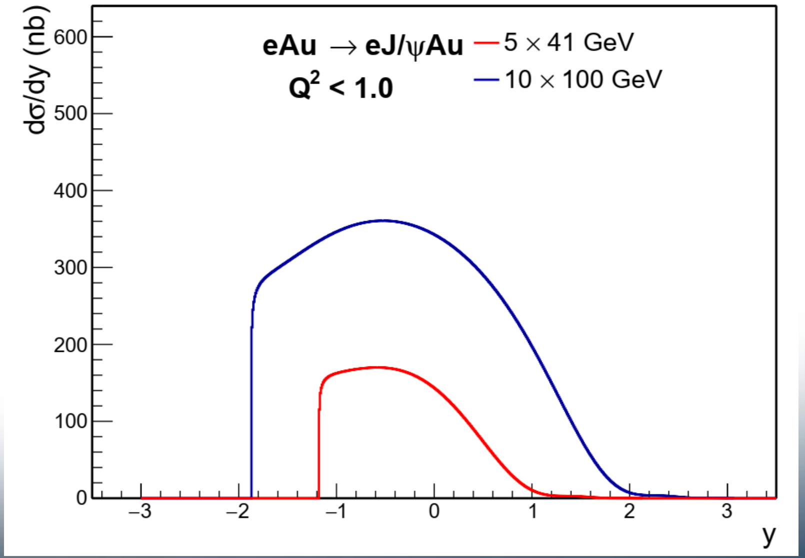
Large electron beam energy

↓

Large Q^2 range and low x







Projection statistics with designed luminosity

$$W_{\gamma p} = \sqrt{m_p^2 + 2m_p E_\gamma}$$

$$E_\gamma = \frac{M_v}{2} e^{-y}$$

$$x = \frac{{M_v}^2}{{W_{\gamma p}}^2}$$

Large electron beam energy

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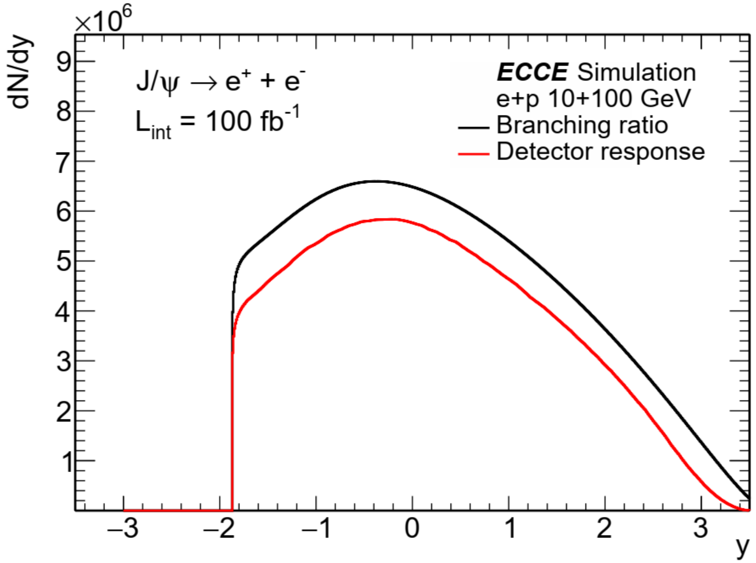
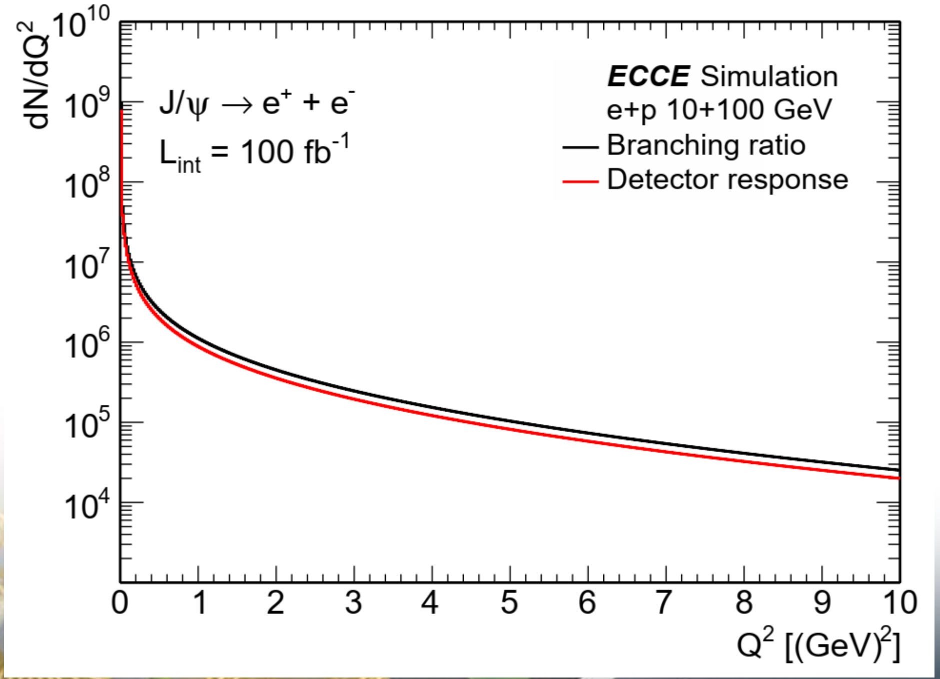
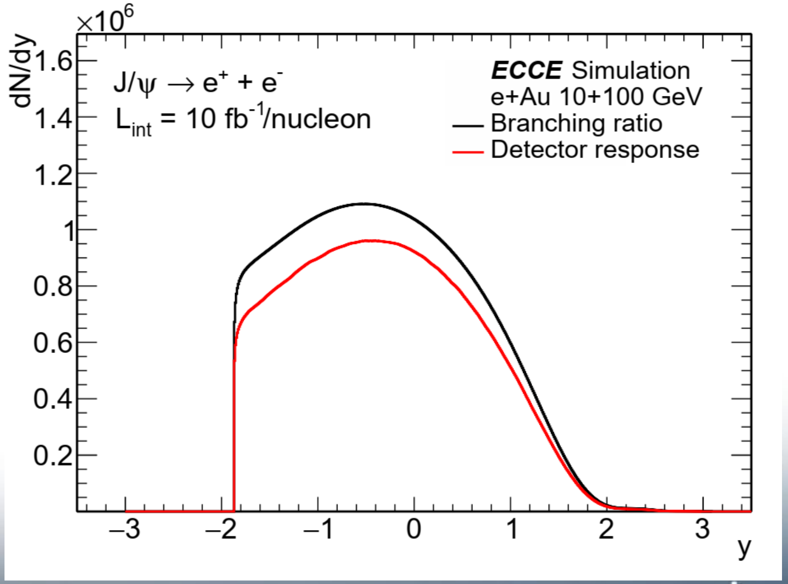
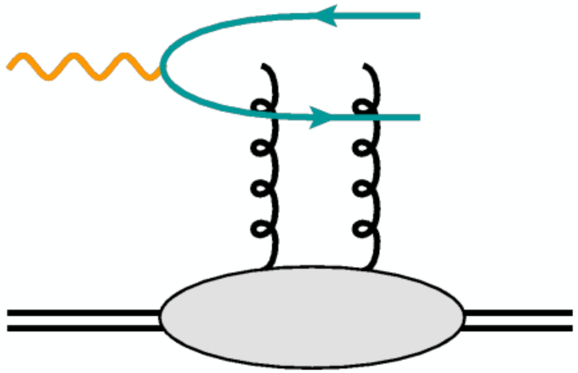
Large Q^2 range and low x







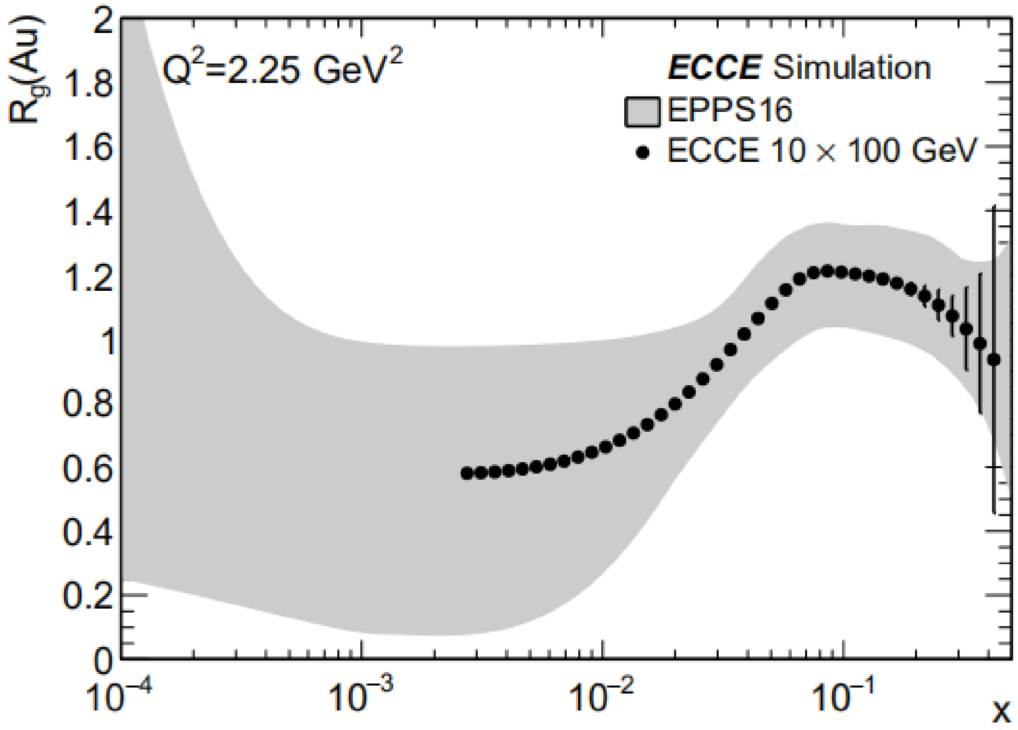
Probe the nuclear gluon PDF



$$\left.\frac{d\sigma(\gamma A\rightarrow VA)}{dt}\right|_{t=0}=\frac{\alpha_s^2\Gamma_{ee}}{3\alpha M_V^5}16\pi^3\left[xG_A(x,Q^2)\right]^2$$

$$x=\frac{M_V e^{\pm y}}{\sqrt{s}}\quad Q^2=M_V^2/4$$

Guzey, Zhalov, JHEP 10 (2013) 207; JHEP 02 (2014) 046



The nuclear gluon PDF can be model-independently quantified by R_g

$$R_g=\sqrt{\frac{\left.\frac{d\sigma(\gamma A\rightarrow VA)}{dt}\right|_{t=0}}{\left.\frac{d\sigma(\gamma p\rightarrow Vp)}{dt}\right|_{t=0}}}$$

Eskola,K.J., Paakkinen, et al.
EPPS16: EPJC 77 (2017) 163

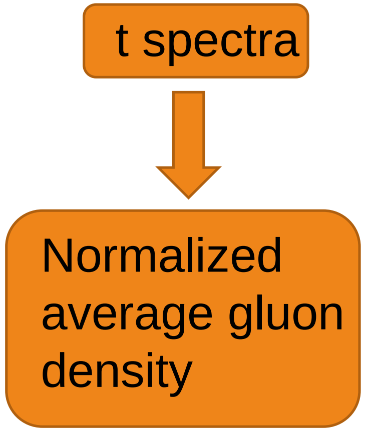
DVMP and gluon GPD

Average unpolarized gluon GPD

$$|\langle \mathcal{H}_g \rangle|(t) \propto \sqrt{\frac{d\sigma}{dt}(t) / \frac{d\sigma}{dt}(t=0)}$$

$$\rho(|\vec{b}_T|, x_V) = \int \frac{d^2\vec{\Delta}_T}{(2\pi)^2} e^{i\vec{\Delta}_T \vec{b}_T} |\langle H_g \rangle|(t = -\vec{\Delta}_T^2)$$

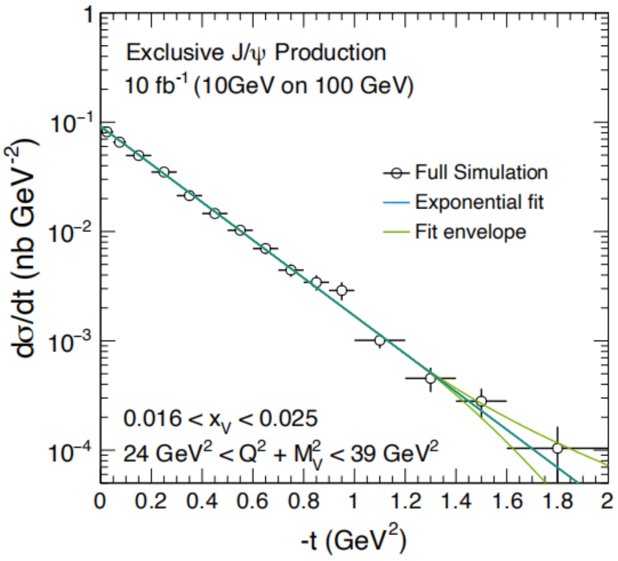
$$F(b) = \frac{1}{2\pi} \int_0^\infty d\Delta \cdot \Delta J_0(\Delta b) \sqrt{\frac{d\sigma_{\text{coherent}}}{d|t|}(\Delta)} \Bigg|_{\text{mod}}$$

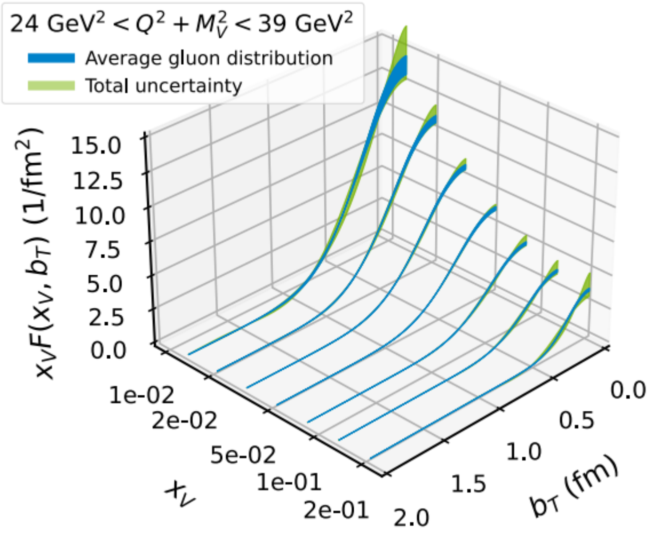

t spectra

Normalized average gluon density

Hard scale: $Q^2 + M_V^2$

Modified Bjorken-x: $x_V = \frac{Q^2 + M_V^2}{2p \cdot q}$





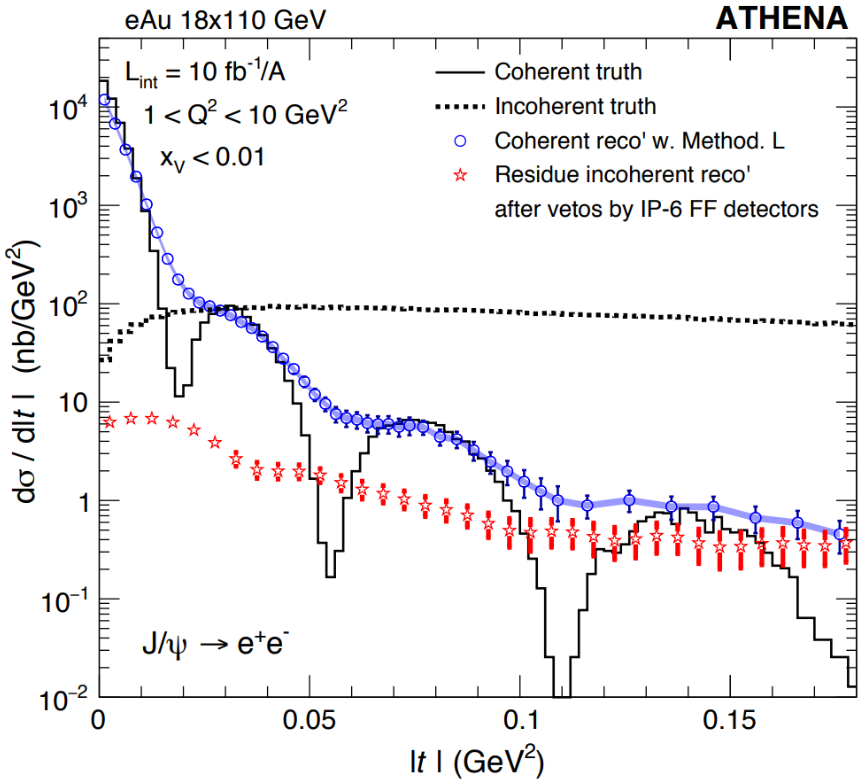
- ✓ Simplest possible GPD extraction approach
- ✓ NLO effects could be significant
- ✓ Heavier (ϒ) would be better

S. Joosten and Z. Meziani,
arXiv:1802.02616

Slide from S. Joosten

Spatial distribution of the nuclear gluons

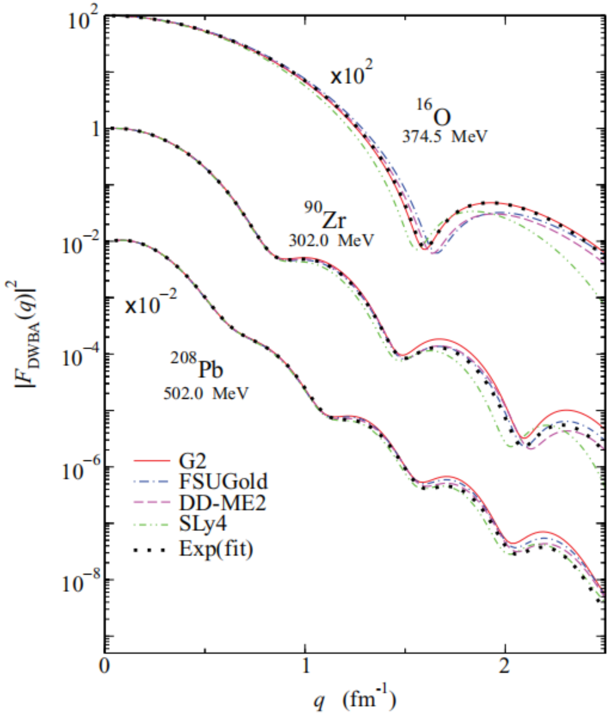
t distribution (Wood-Saxon, Good-Walker)



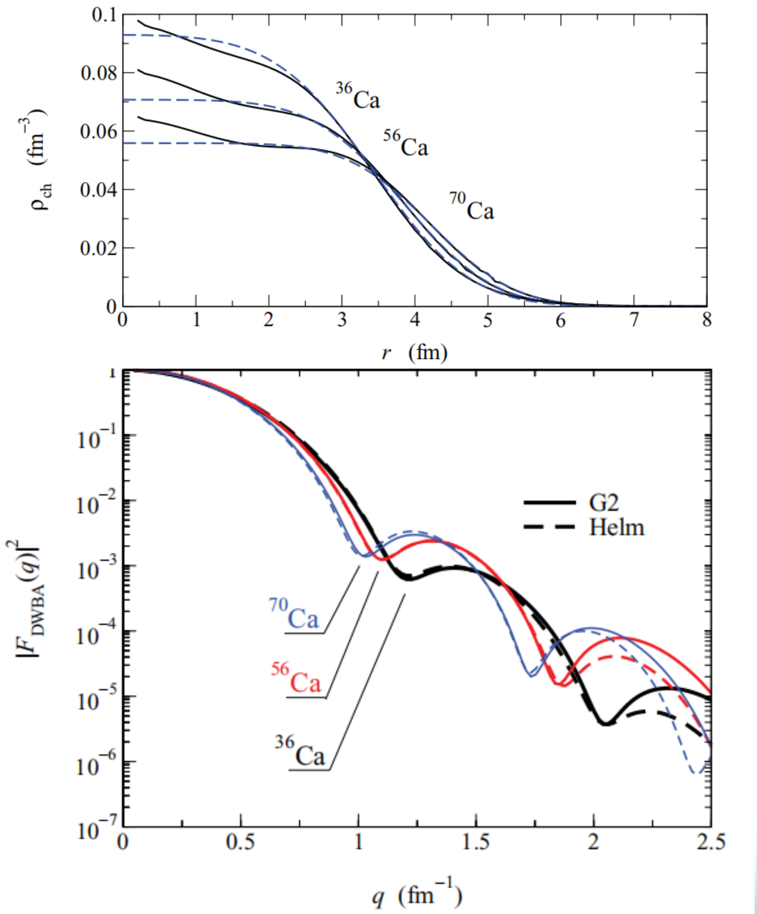
W. Chang etal., Phys. Rev. D **104**, 114030

The plane-wave diffraction patterns will survive to a large extent in EIC.

State-of-the-art theoretical model of elastic electron scattering off stable and exotic nuclei



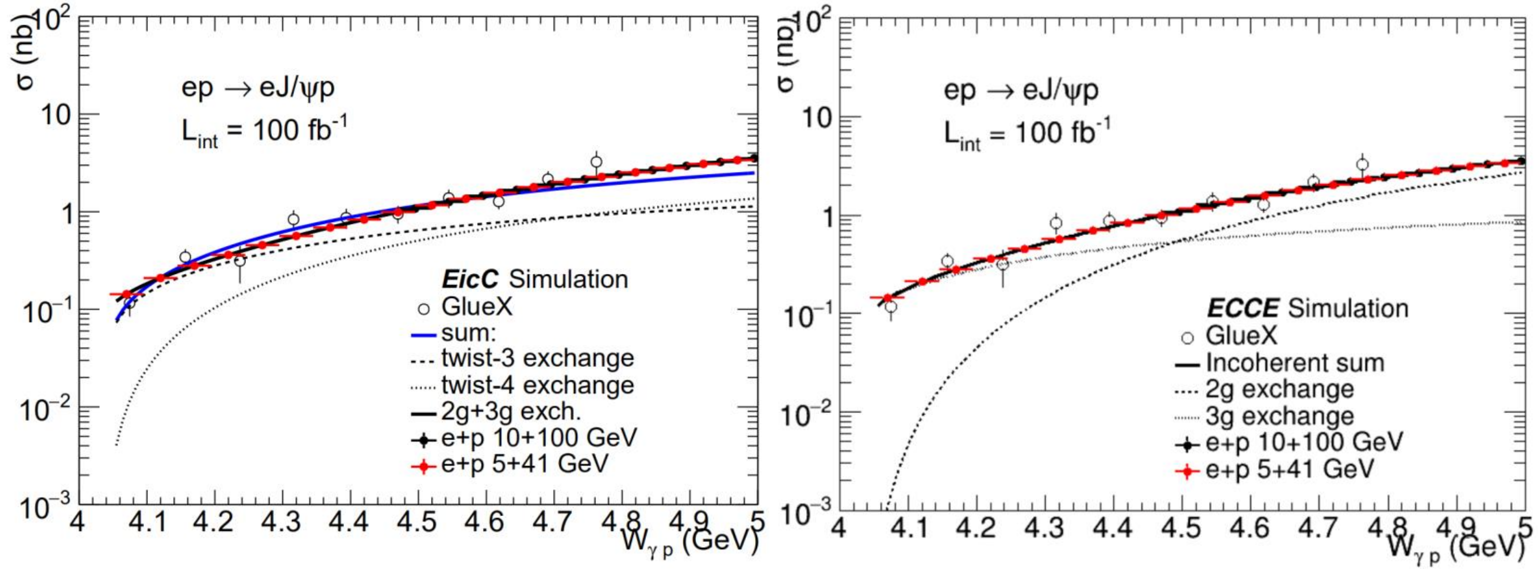
X. Roca-Maza et al., PRC 78 (2018) 044332



Smearing (distortion) of the diffraction minima due to Coulomb interaction.

The near threshold production mechanism

- 2g+3g is still used to describe the GlueX data in YR
- While due to C-parity conservation, 3g will not have a contribution
- EIC and JLab can dramatically improve the statistics near threshold to optimize models



2g+3g fits data well but not real? !

$$\frac{d\sigma}{dt} = \mathcal{N}_{2g} v \frac{(1-x)^2}{R^2 \mathcal{M}^2} F_{2g}^2(t) \left(W_{\gamma p}^2 - m_p^2\right)^2$$

$$\frac{d\sigma}{dt} = \mathcal{N}_{3g} v \frac{(1-x)^0}{R^4 \mathcal{M}^4} F_{3g}^2(t) \left(W_{\gamma p}^2 - m_p^2\right)^2$$

S.J. Brodsky, et al., PLB 498 (2001) 23–28

New power law twist 3+4 form factor, 5?

$$\frac{d\sigma}{dt}\Big|_{(-t)\gg\Lambda_{QCD}^2} = \frac{1}{16\pi \left(W_{\gamma p}^2 - M_p^2\right)^2}\left(|\overline{\mathcal{A}_3}|^2 + |\overline{\mathcal{A}_4}|^2\right)$$
$$\approx \frac{1}{(-t)^4}\left[(1-\chi)\mathcal{N}_3 + \widetilde{m}_t^2 \mathcal{N}_4\right],$$

P. Sun, X. Tong and F. Yuan, PLB 822 (2021) 136655

Proton mass decomposition (trace anomaly)

$$M_N = M_m + M_q + M_g + M_a$$

Ji, PRD 52 (1995) 271; Hatta and Yang, PRD 98 (2018) 074003

$$M_m = \frac{4+\gamma_m}{4(1+\gamma_m)} b\, m_p$$

$$M_q = \frac{3}{4}\left(a - \frac{b}{1+\gamma_m}\right) m_p$$

$$M_g = \frac{3}{4}(1-a)\, m_p$$

$$M_a = \frac{1}{4}(1-b)\, m_p$$

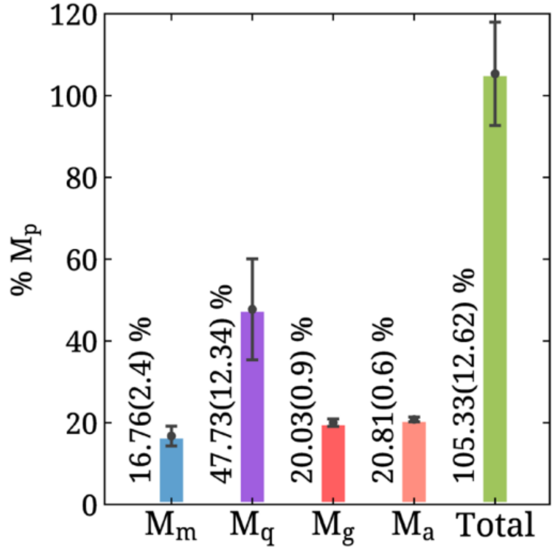
- $a(\mu)$ related to PDFs, well constrained
- **$b(\mu)$ related to quarkonium-proton scattering amplitude $T_{\psi p}$ near-threshold**

$$T^\mu_\mu = \underbrace{\frac{\tilde{\beta}(g)}{2g} G^2}_{\text{Trace Anomaly}} + \underbrace{\sum_{q=u,d,s} m_q(1+\gamma_m)\bar{\psi}_q\psi_q}_{\text{Light Quark Mass}}$$

$$\left.\frac{d\sigma_{\gamma N\to J/\psi N}}{dt}\right|_{t=0} = \frac{3\Gamma(J/\psi \to e^+e^-)}{\alpha m_{J/\psi}} \left(\frac{k_{J/\psi N}}{k_{\gamma N}}\right)^2 \left.\frac{d\sigma_{J/\psi N\to J/\psi N}}{dt}\right|_{t=0}$$

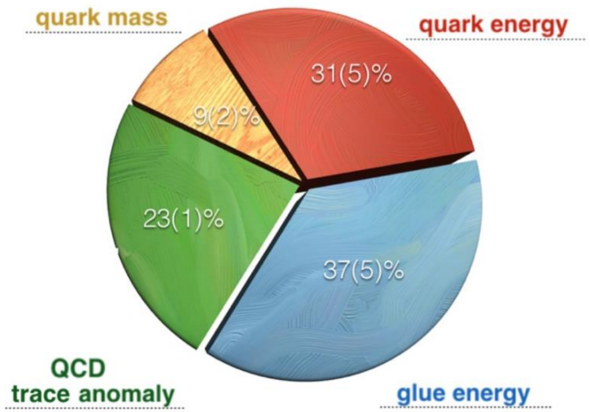
$$\begin{aligned} F_{J/\psi N} &\simeq r_0^3 d_2 \frac{2\pi^2}{27}\left(2M_N^2 - \left\langle N\left|\sum_{i=u,d,s} m_i \bar{q}_i q_i\right|N\right\rangle\right) \\ &\simeq r_0^3 d_2 \frac{2\pi^2}{27}\left(2M_N^2 - 2bM_N^2\right) \\ &\simeq r_0^3 d_2 \frac{2\pi^2}{27} 2M_N^2 \boxed{(1-b),} \end{aligned}$$

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



C. Alexandrou et al., (ETMC), PRL 116, 252001 (2016)

C. Alexandrou et al., (ETMC), PRL 119, 142002 (2017)

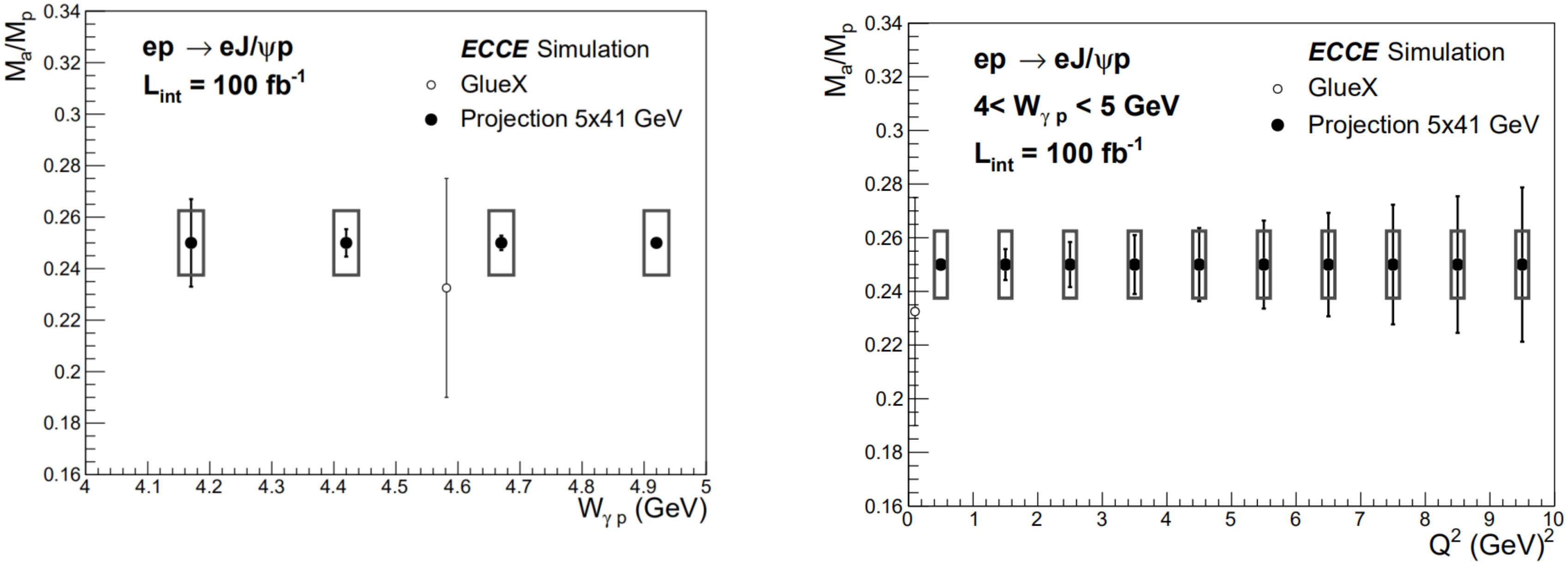


Yi-Bo Yang et al, EPJ Web of Conferences 175, (2018) 14002

To maximize the sensitivity to the twist-4 operator G^2, center-of-mass should be as low as possible—— near threshold

Proton mass decomposition (trace anomaly)

X. Li et al., arXiv: 2207.10356

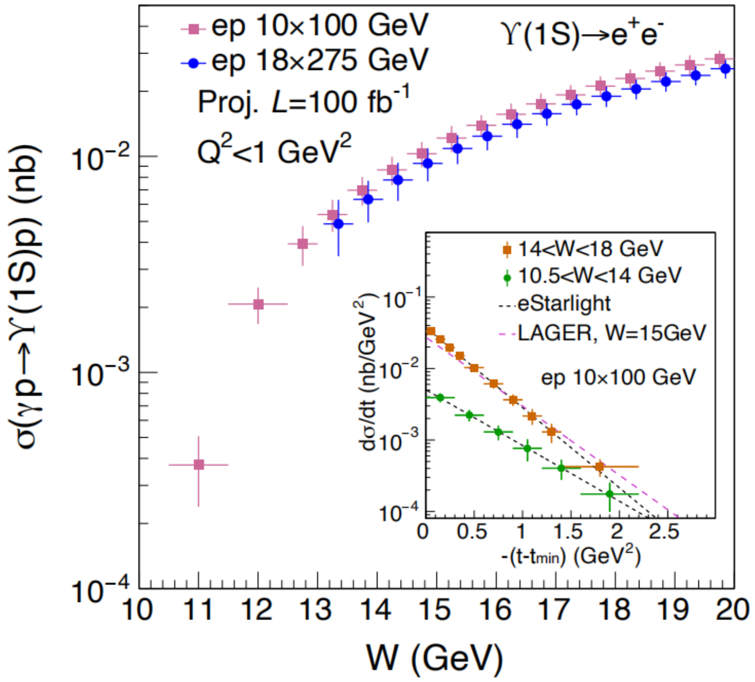


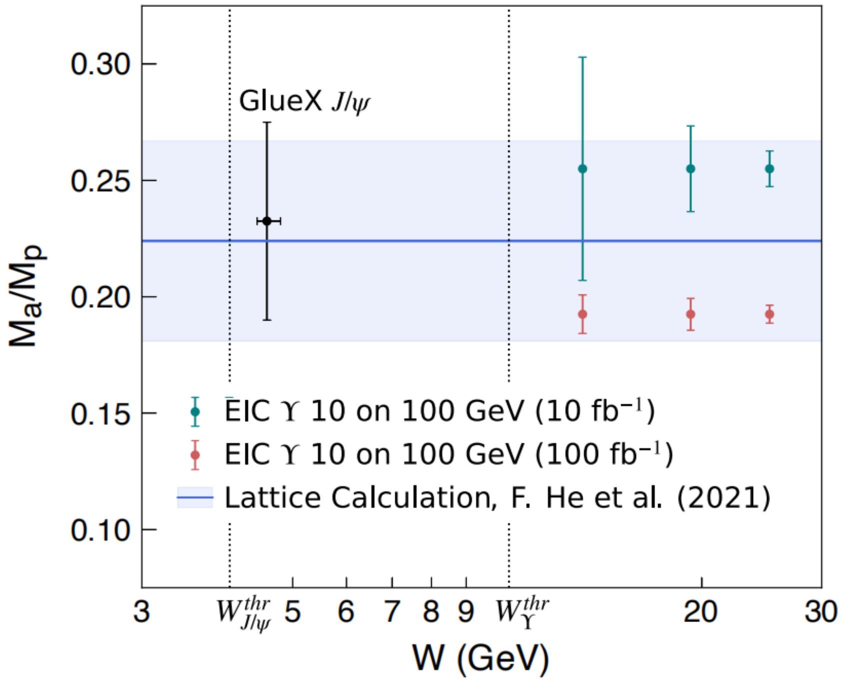
GlueX extraction from R. Wang, J. Evslin and X. Chen, Eur. Phys. J. C 80 (2020) no.6, 507

Large Q^2 lever arm will allow to constrain the production mechanism and reduce the model dependence of the trace anomaly contribution.

Proton mass decomposition (trace anomaly)

Negligible uncertainty from higher order corrections for ϒ





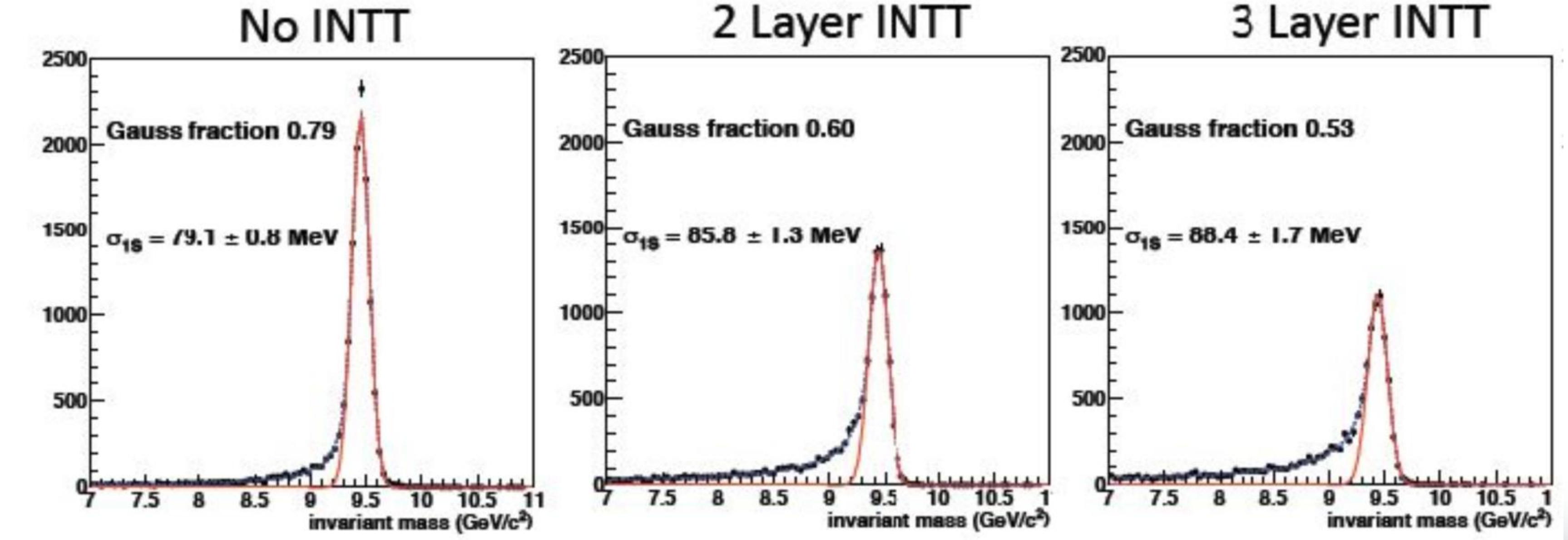
Uncertainty from ϒ near threshold one-year yield at EIC seems comparable to GlueX J/ψ

Slide from Y. Ji

Muon ID at EIC?

- ✓ Less bremsstrahlung
- ✓ Internal photon radiation
- ✓ Combinatorial background

- ✓ Detector technology?
- ✓ R&D and cost evaluation?
- ✓ Space limitations?



Impact from material to Upsilon (ee) measurement [early sPHENIX optimization]

Summary

- Quarkonia as powerful probe of gluons at EIC
- Excellent detector response and high luminosity allows to provide promising constraining power to theory
  - ✓ Unprecedented precision, unexplored low-x region (deep into proton sea)
  - ✓ Address profound open questions in the fundamental structure of matter (proton mass…)

- Many other physics with exclusive quarkonia production:
  - ✓ Gluonic Van der Waals force (scattering length, binding energy)
  - ✓ Proton mass radius

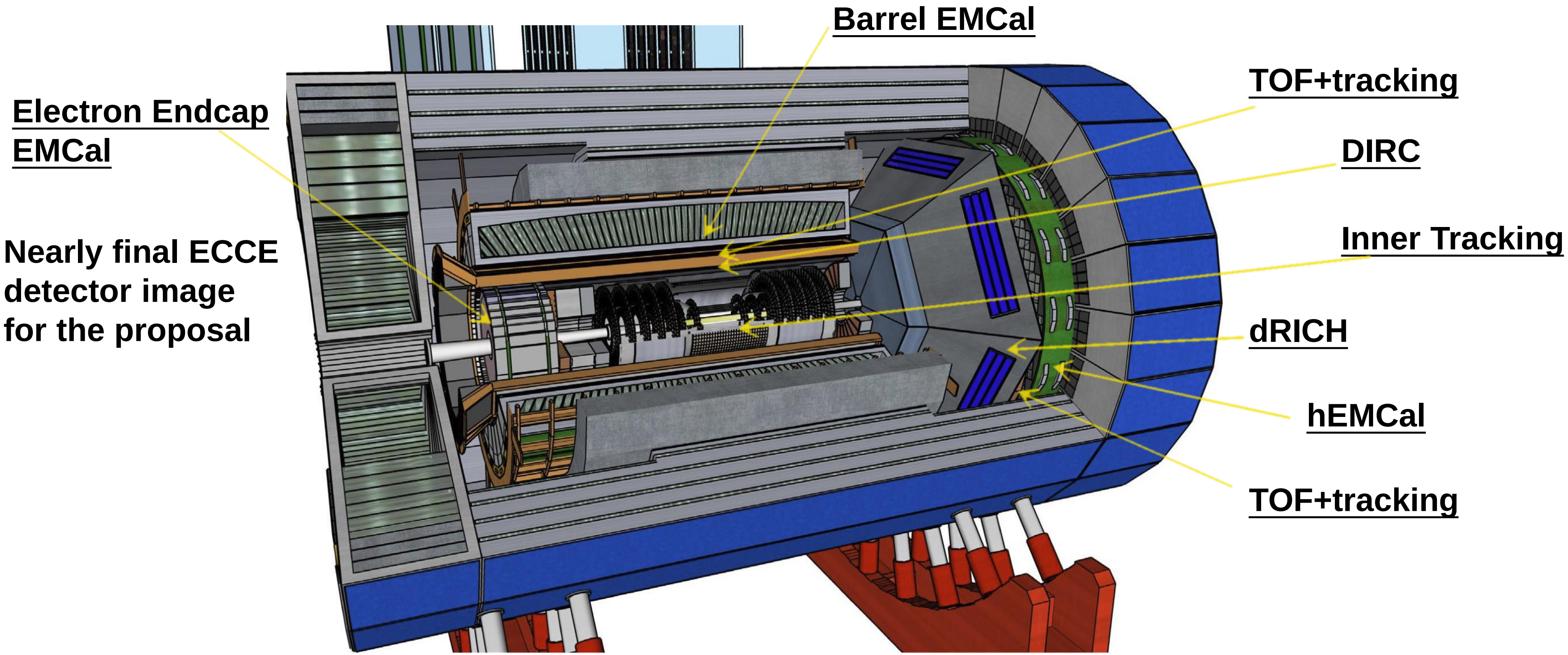
…

Thank you!

Backup

Detector Configuration (July Concept)

Nearly final ECCE detector image for the proposal

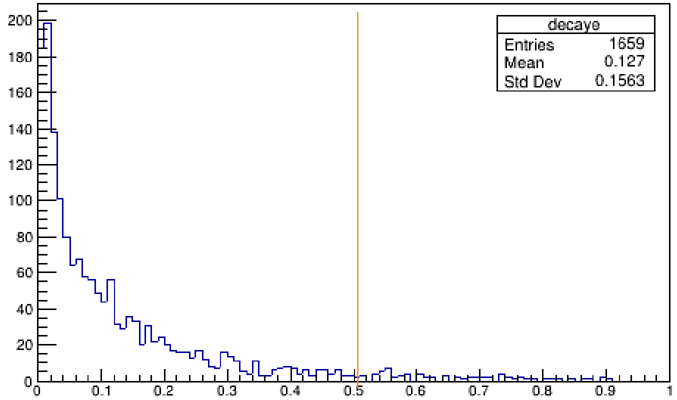


J/ψ detection

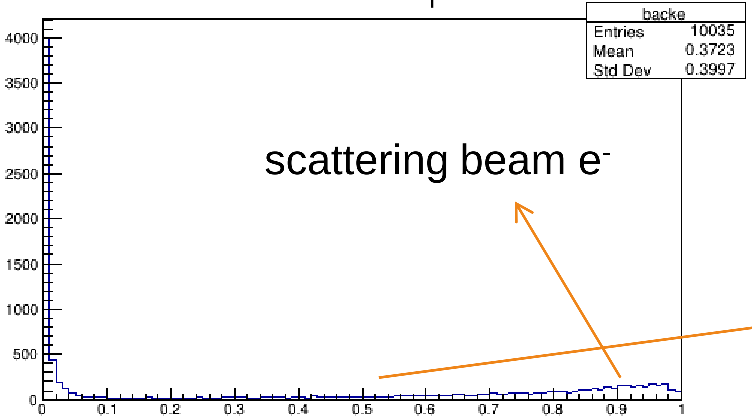
a forward light cone variables can be used to see scattering beam e$^-$ influence

$x_+ = \frac{b_0+(-b_z)}{a_0+(-a_z)}$ (cause beam e$^-$ moves along negative z axis), b is beam e$^-$.

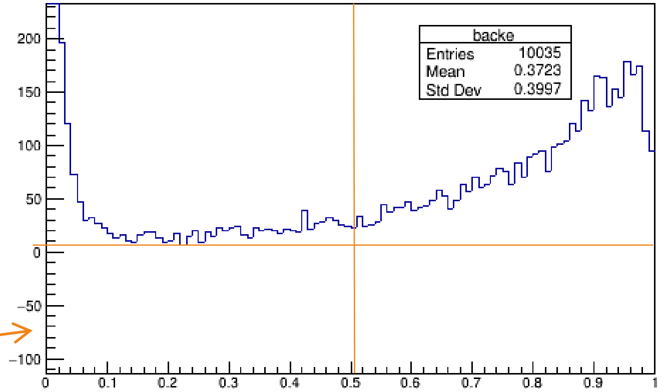
e$^+$ and e$^-$ of J/ψ decay x_+ distribution



other e$^+$ and e$^-$ x_+ distribution :

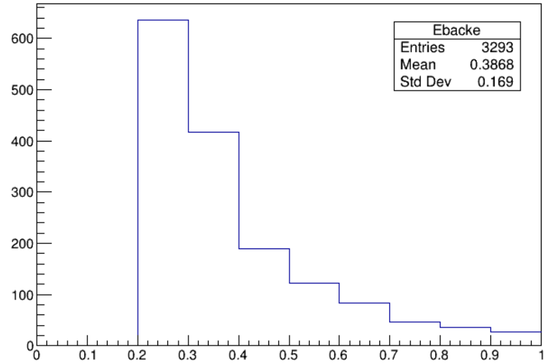


scattering beam e$^-$

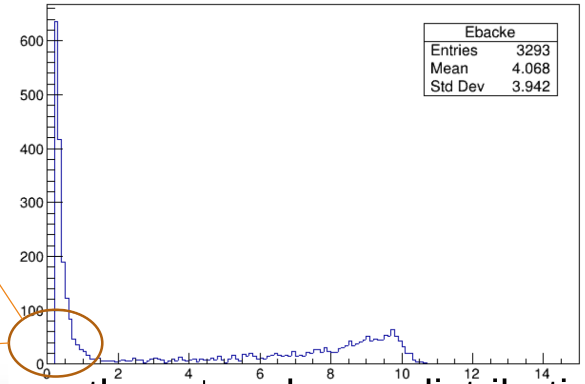


cut: $x_+ < 0.5$

influence of e$^-$ from light hadron decay

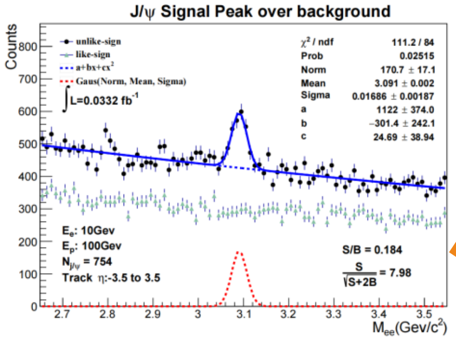


e$^+$ and e$^-$ of J/ψ decay x_+ distribution



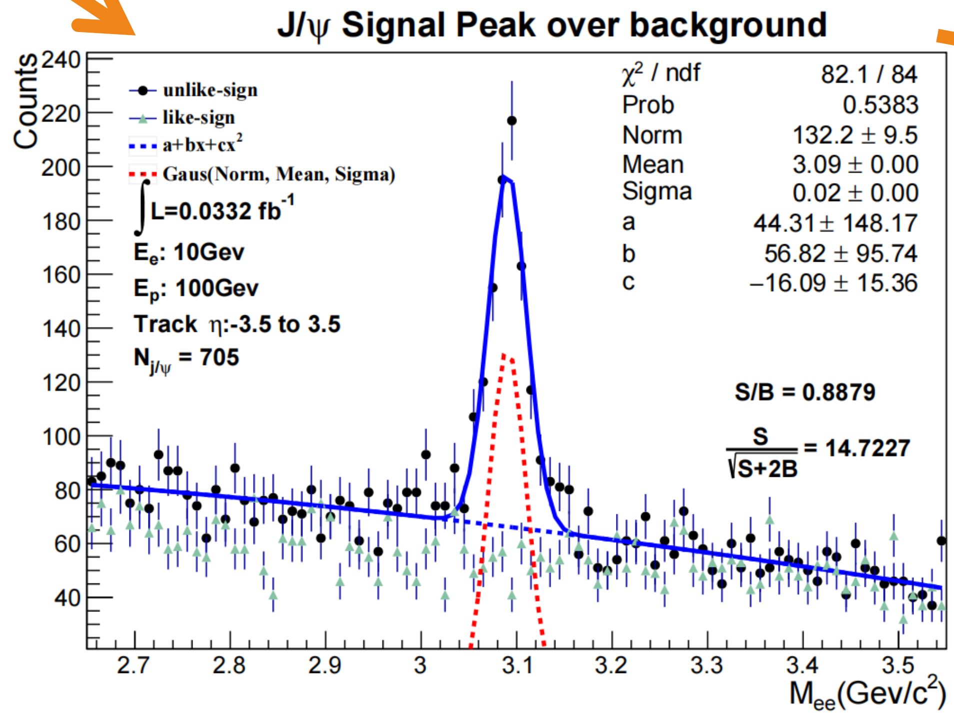
other e$^+$ and e$^-$ x_+ distribution :

J/ψ detection



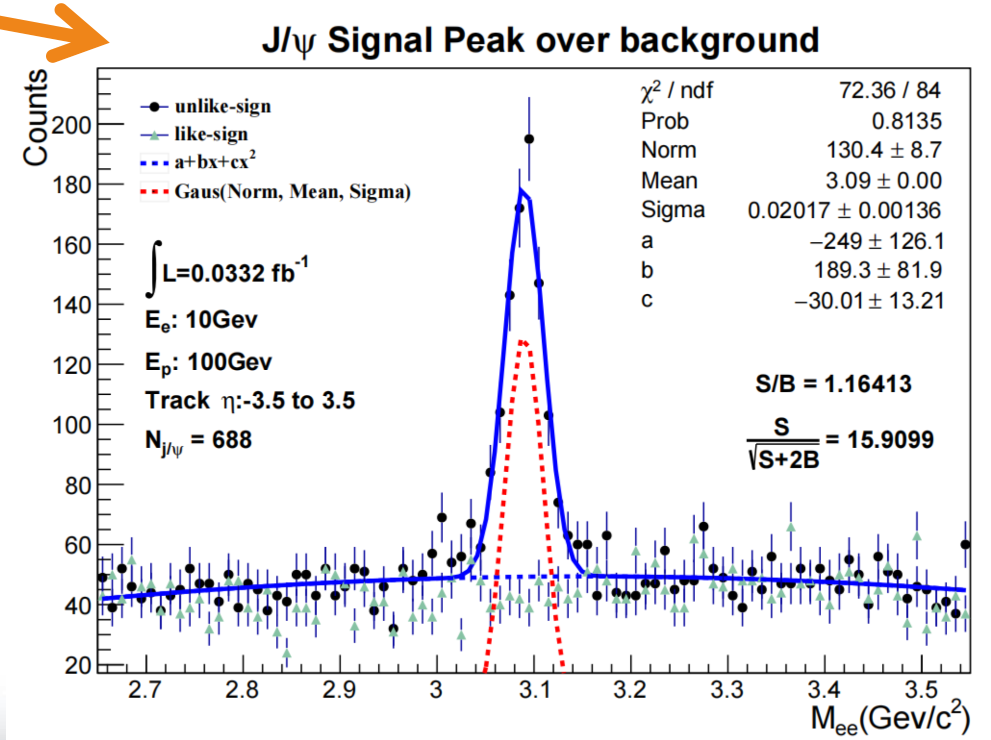
cut: $x_+ < 0.5$

S/B: 0.184 —> 0.888



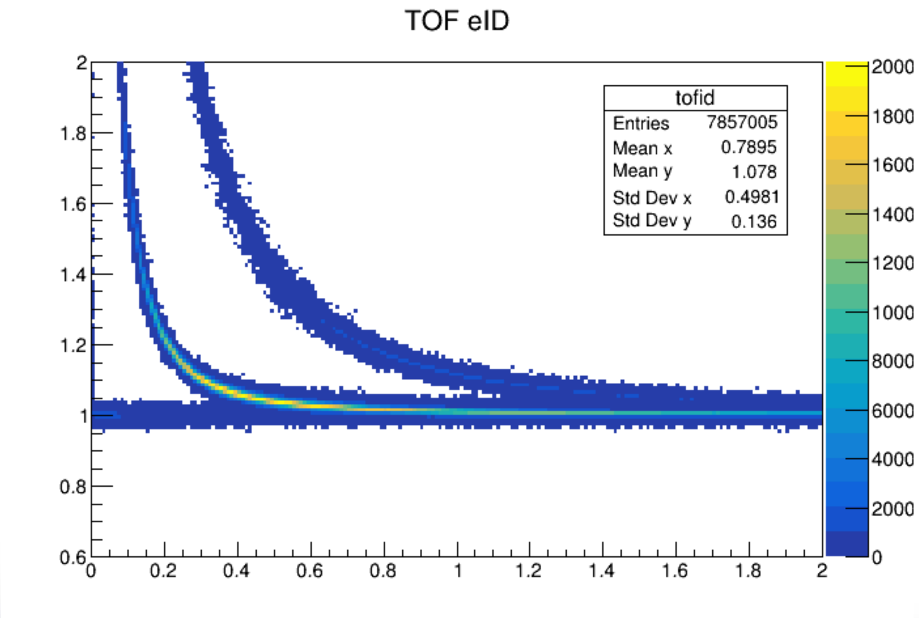
cut: E>0.6

S/B: 0.888 —> 1.164



eID——TOF(fastsimulation)

	η range	path length	time resolution
forward	-1.5>η>-3.5	|250(cm) / cos(Θ)|	20 (ps)
barrel	1.5>η>-1.5	50 / sin(Θ)	20
end	3.5>η>1.5	|150 / cos(Θ)|	20

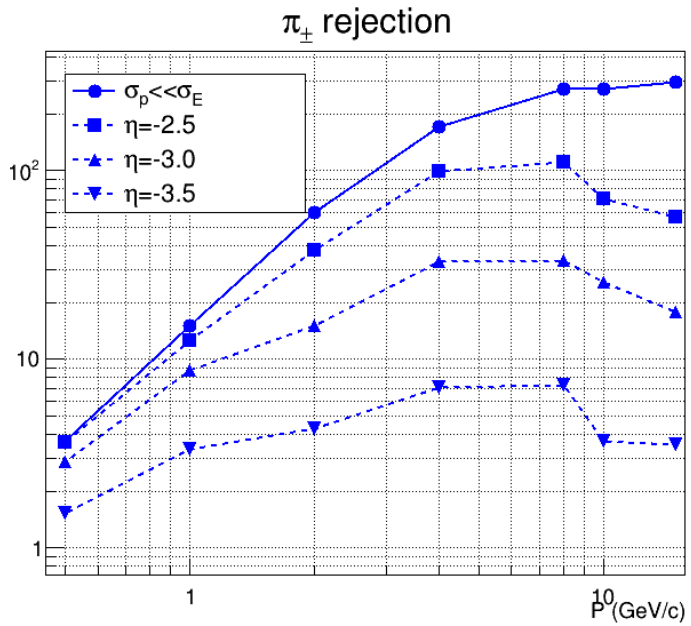


$p < 0.4$(GeV/c) $|1/\beta-1|<0.04$

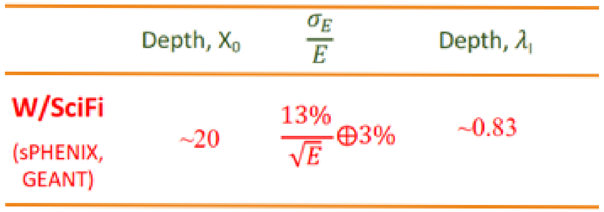
survival possibility:

e: 99.5%   π: 0.1%

Electron identification capability at ECCE



E/p > 1 - 1.6· $\sqrt{\sigma_{EMC}^2 + \sigma_p^2}$ to keep $\boldsymbol{\varepsilon}_e$=95%



	Depth, X_0	$\frac{\sigma_E}{E}$	Depth, λ_I
W/SciFi (sPHENIX, GEANT)	~20	$\frac{13\%}{\sqrt{E}} \oplus 3\%$	~0.83

Electron identification capability at ECCE