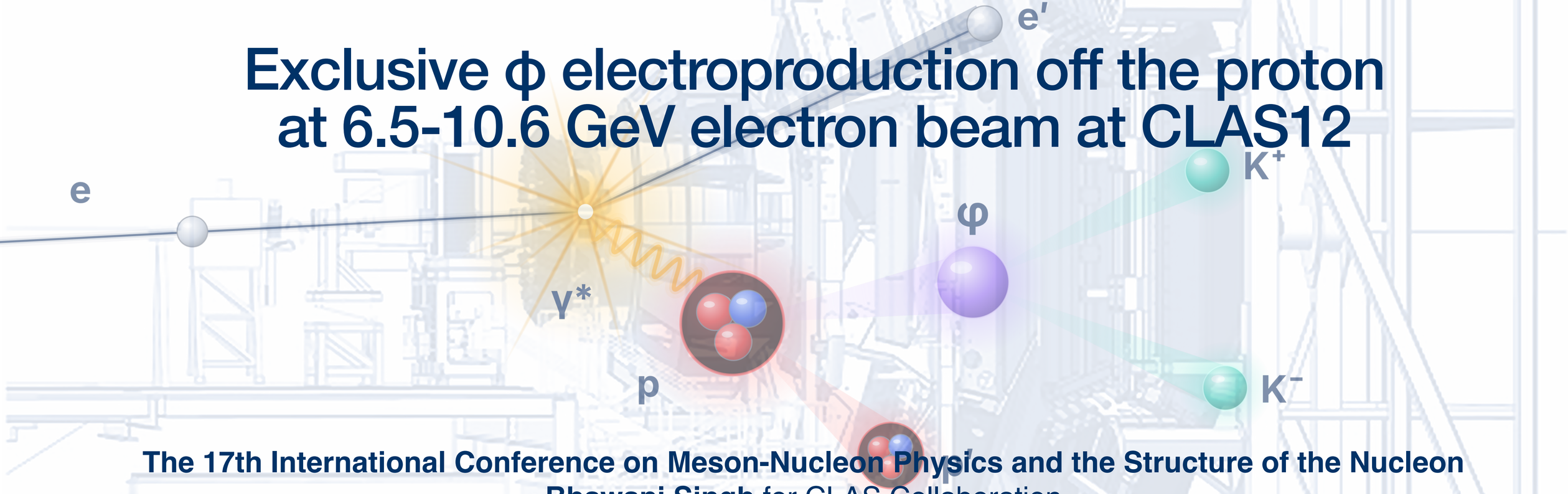


Exclusive ϕ electroproduction off the proton at 6.5-10.6 GeV electron beam at CLAS12



The 17th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon

Bhawani Singh for CLAS Collaboration

Jefferson Lab

Thursday, Oct 22, 2026

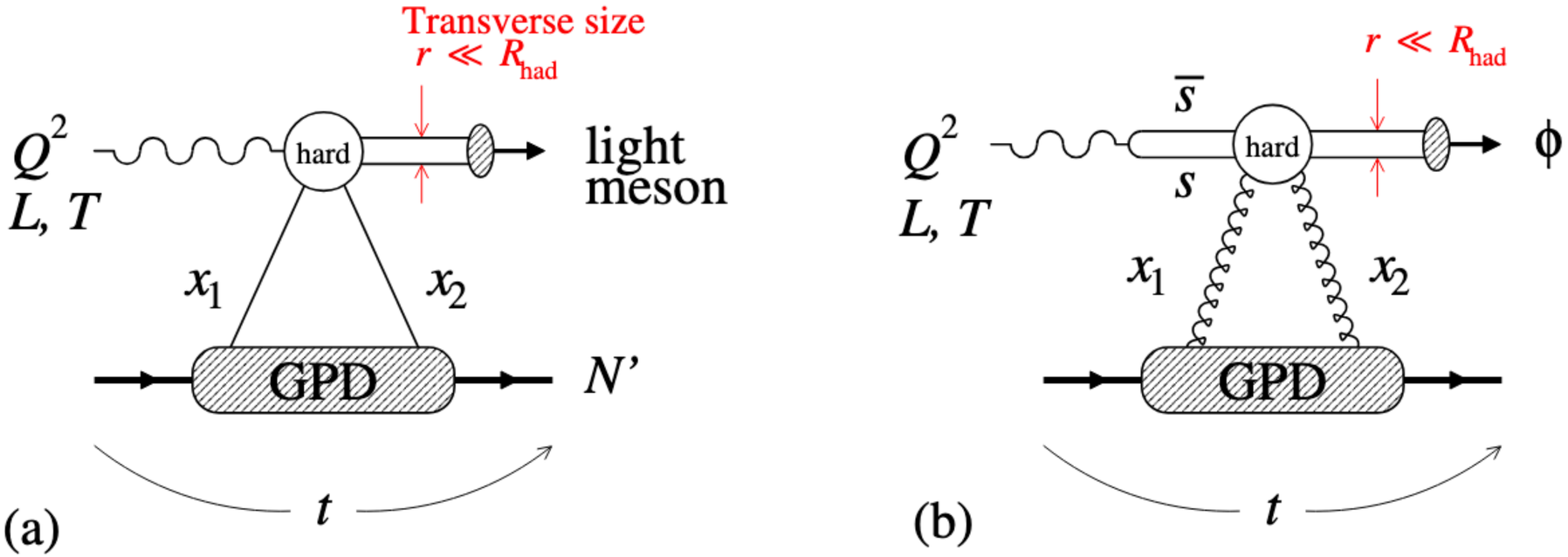
Subgroup

* Jefferson Lab: H. Avakian, V. Burkert, L. Elouadrhiri, and V. Kubarovsky
* ODU: Y. Li MIT: R. G. Milner and Y. Wang,
* UConn: S. Bhattacharya, Glasgow University: D. Leahy and D. I. Glazier

singh@jlab.org

Clean Probe For Gluonic Structure of Nucleon

- ϕ meson is a **pure** $s\bar{s}$ **state**, its coupling to light quarks (u,d) is suppressed (by OZI rule)
- Access to the gluon GPD even at low energy due to its flavor content $s\bar{s}$



- Q^2 scaling of ϕ production cross section: opens doors to test **QCD factorization** ($\sigma_L \sim 1/Q^6$, $\sigma_L/\sigma_T \sim Q^2$)
- Change of |t|–dependence with Q^2 ➡ **gluonic radius** of the proton

Strange D-term and ϕ meson production

- Total D-term includes different contributions at the partonic level!

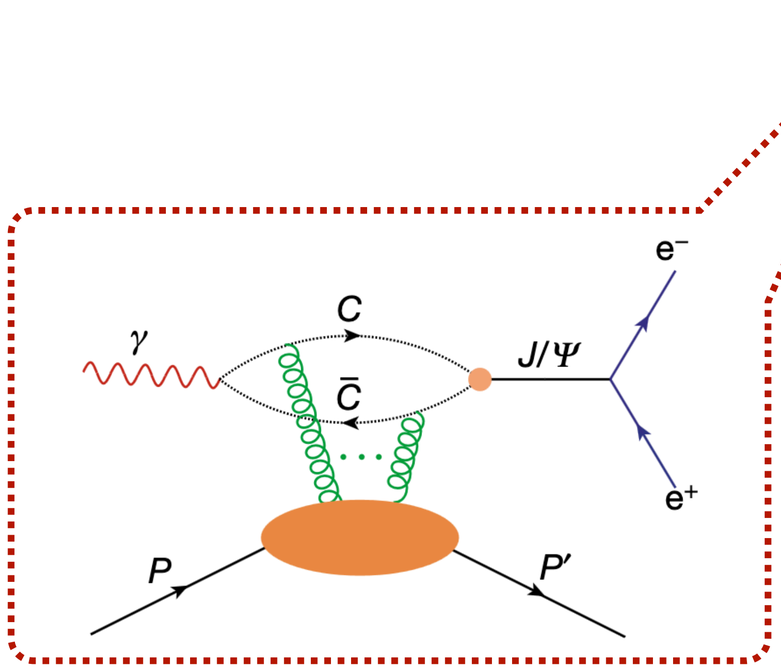
Tuesday: Chi Kin Tam Igor Strakovsky, Kazuhiro Tanaka, Adam Freese , Rado Marchevski
Today: Kiminad Mamo @4:40 PM

$$D(0) = \underbrace{D_g(0) + D_u(0) + D_d(0) + D_s(0) + \ldots}_{\text{Partonic } D\text{-term contributions}}$$

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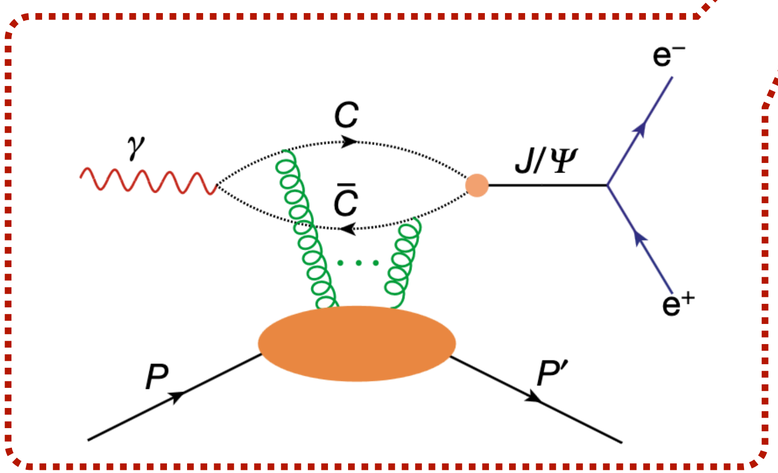
Near threshold J/ψ and Υ production

B. Duran et al, Nature 615, 813–816 (2023)

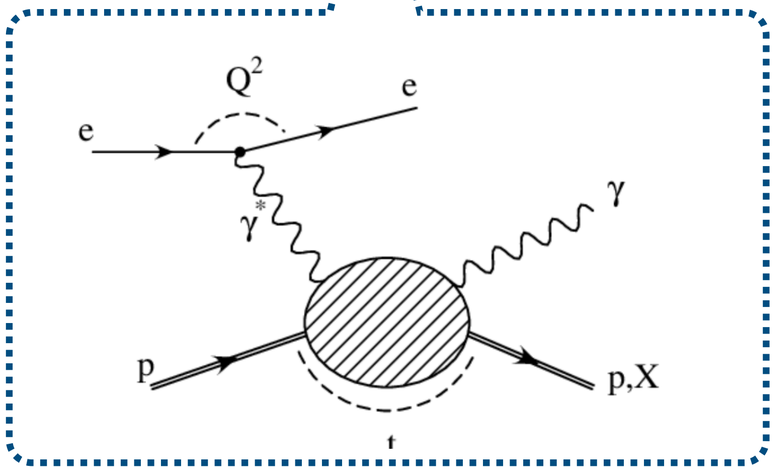
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Near threshold J/ψ and Υ production



Up & Down quarks: DVCS cross section & beam-spin asymmetries

B. Duran et al, Nature 615, 813–816 (2023)

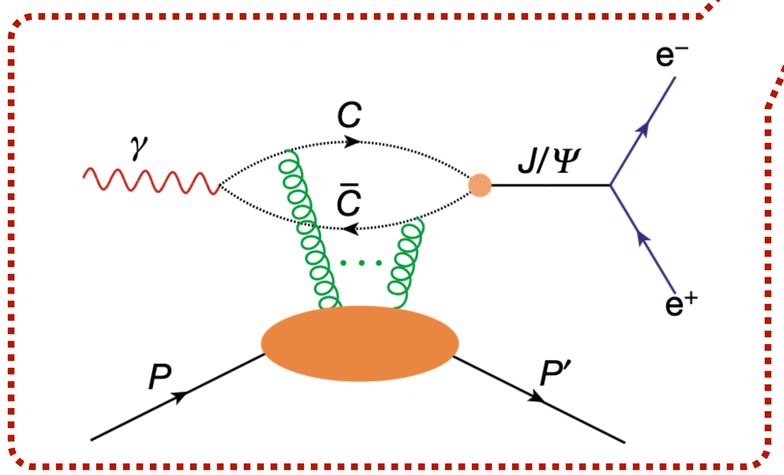
V. D. Burkert, L. Elouadrhiri & F. X. Girod Nature 557, 396–399 (2018)

Strange D-term and ϕ meson production

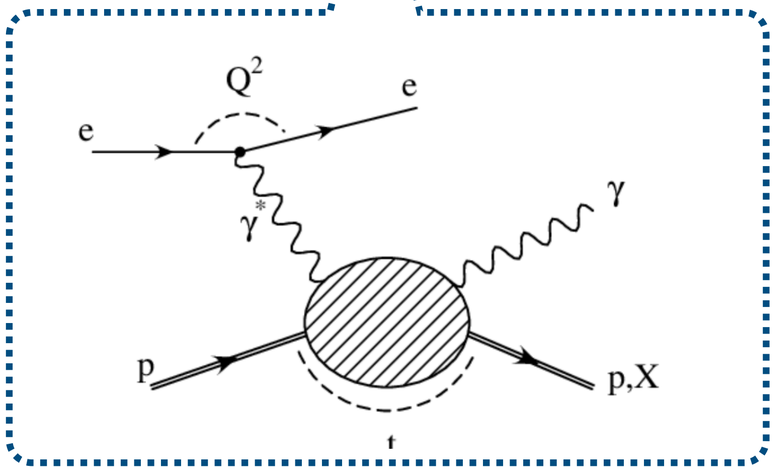
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Strange quarks: negligible..?



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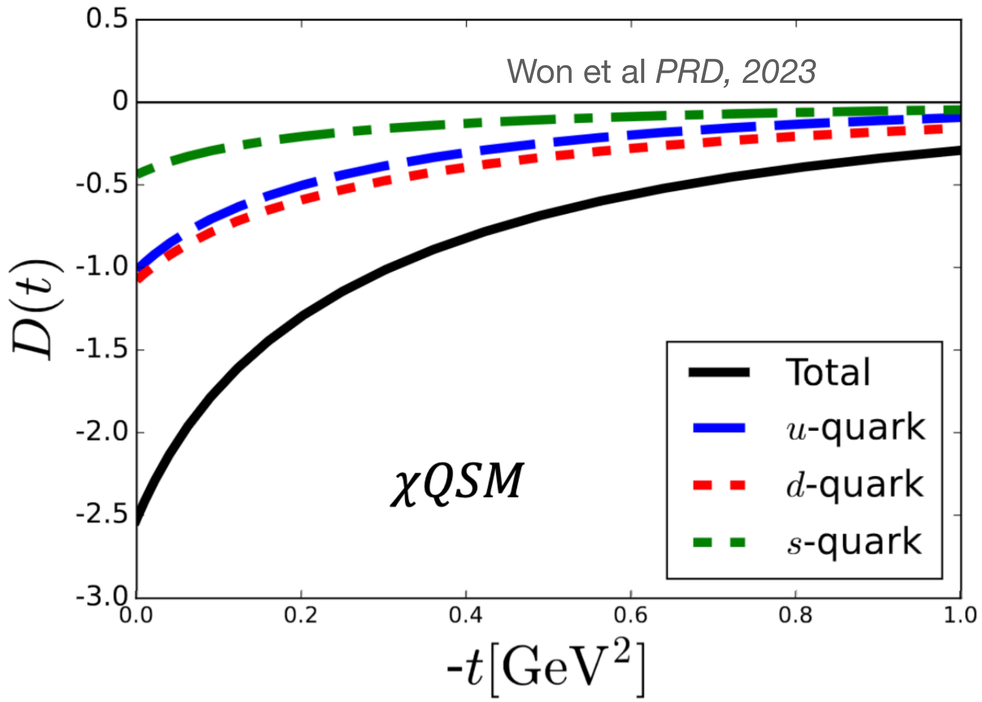
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- According to large-N_c, $D_u \sim D_d$ despite their different number densities, "flavor-blind" Goeke et al, *Prog.Part.Nucl.Phys, 2001*
- Lattice calculations supported this argument; Hackett et al., *PRL, 2024*
- Chiral Quark Soliton model model prediction Won et al *PRD, 2023*

$$D_u \sim D_d \sim 2D_s \qquad \frac{d\sigma_L}{dt} \to D_s$$



Strange D-term and ϕ meson production

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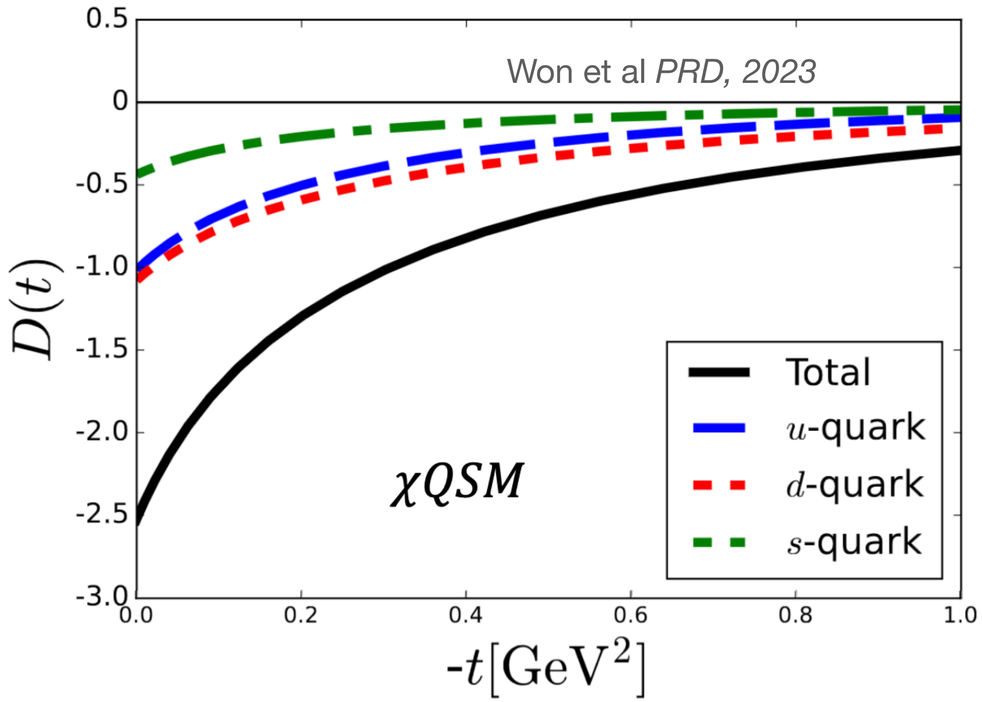
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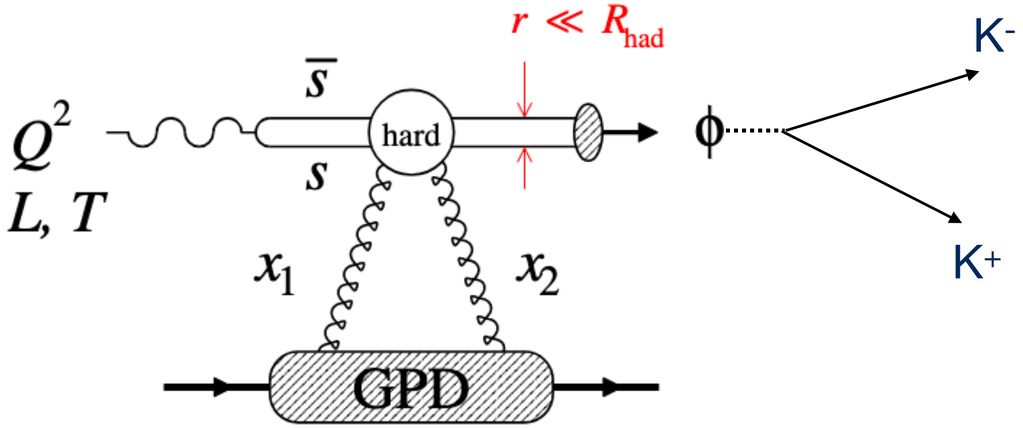
$$D_u \sim D_d \sim 2D_s \qquad \frac{d\sigma_L}{dt} \to D_s$$

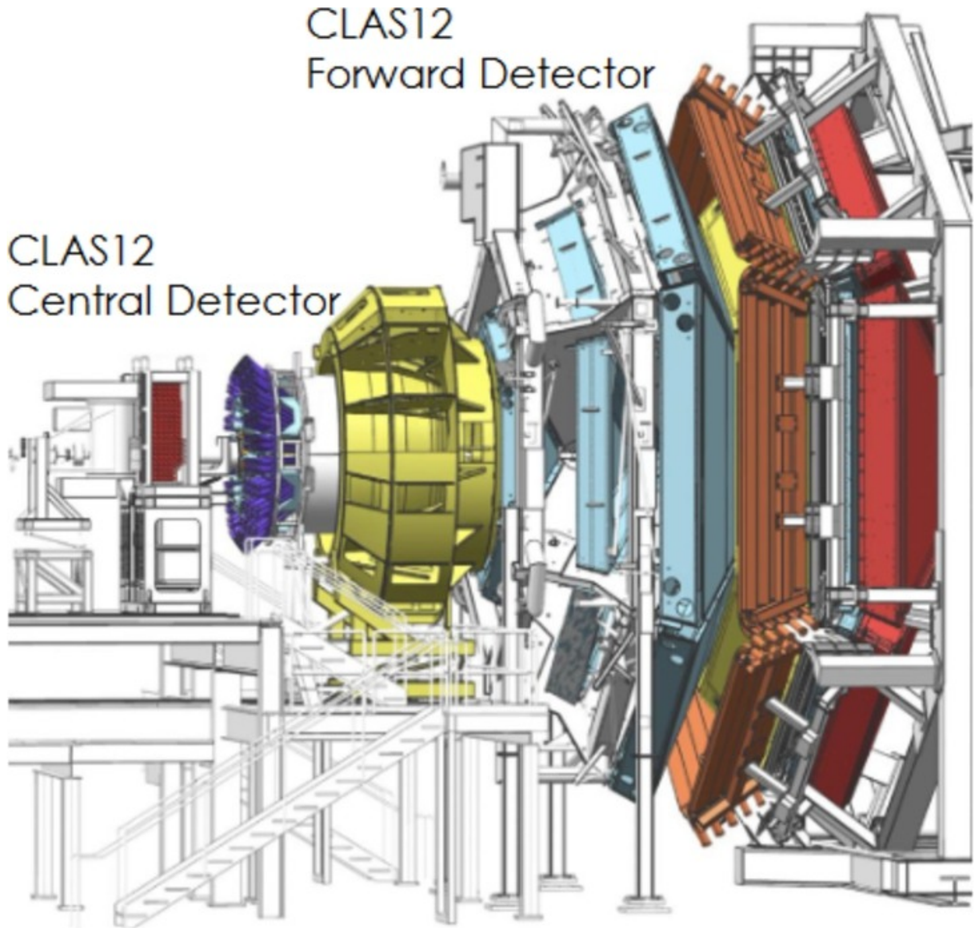
- CLAS (Lukashin et al., PRC 63, 065205, 2001): 4.2 GeV beam, Q^2 = 0.7–2.2 GeV²
- CLAS (Santoro et al., PRC 78, 025210, 2008): 5.75 GeV beam, Q^2 = 1.4–3.8 GeV² & t′ = 0.0–3.6 GeV²



Exclusive ϕ production with proton target

- Beam energy **Run Group K** (RGK: 6.5, 7.5 GeV), and **Run Group A** (RGA: 10.2 & 10.6) GeV from **2018-19**
- Analysis strategy: select charged decay daughters ep—> e'p'K^+ K^- (branching ratio: ~49.2%)





CLAS Collaboration Nucl. Instrum. Meth. A 959 (2020) 163419

- **Forward Detector (FD)** covers the range of polar angles from 5 to 35 degrees segmented into 6 sectors in azimuthal angle
- **Central Detector (CD)** covers the range of polar angles from 35 to 125 degrees
- Electron is selected in only FD while protons and kaons are selected in both CD and FD

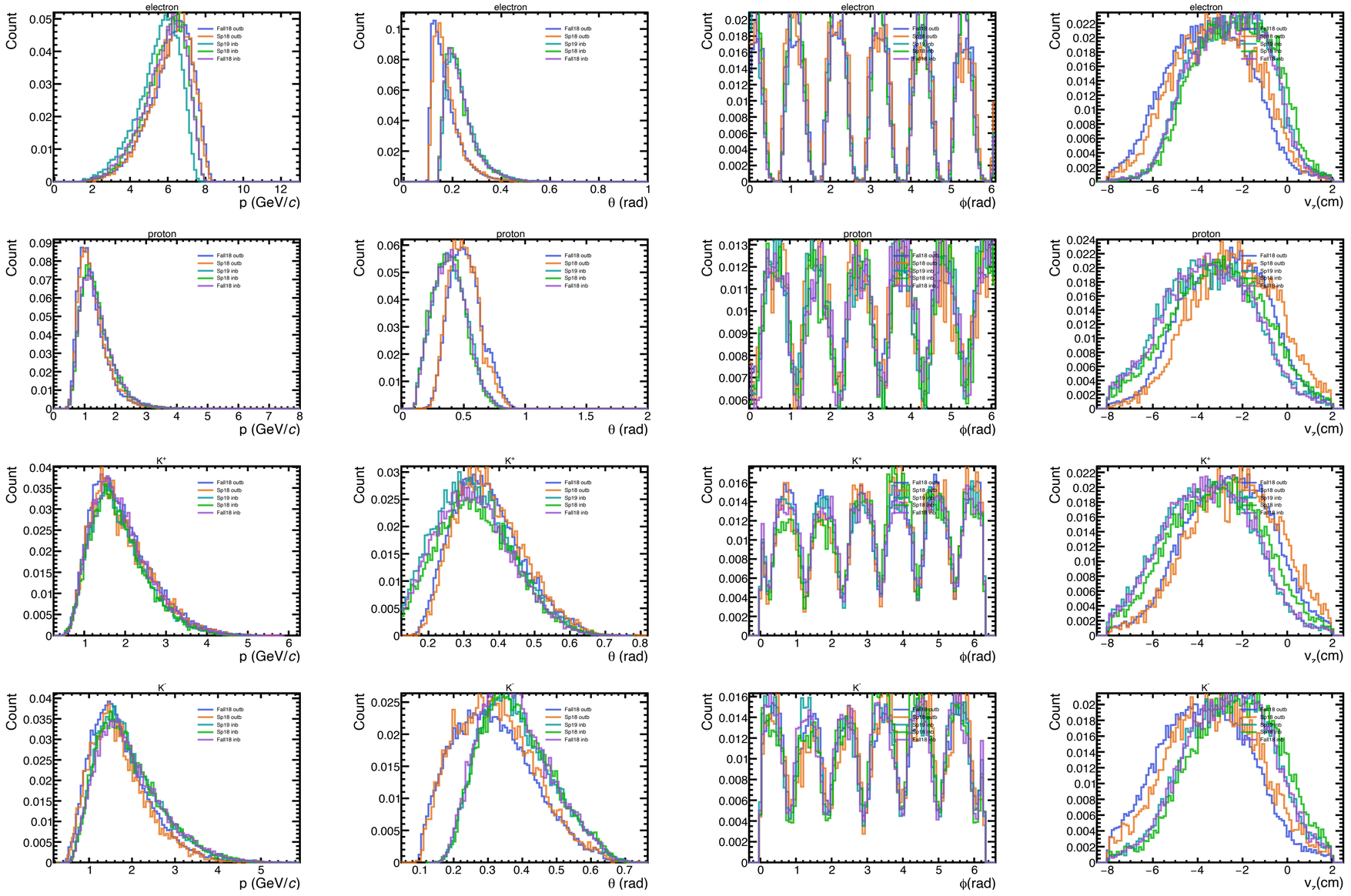
Particle Kinematics for RGA

- **Datasets** from Run group A (10.6 & 10.2 GeV beam)
- Torus -1 (inbending) Spring & Fall 2018, and Spring 2019
- Torus+1 (outbending) Spring & Fall 2018

Fall18 outb
Sp18 outb
Sp19 inb
Sp18 inb
Fall18 inb

p_e>1.5 GeV in FD
p_p>.4 GeV in FD and CD

0.2 < K_p< 7.5 GeV in FD
Vertex for all particles
-8cm < v_z< 2 cm
p_K<1.8 GeV with PID,
p_K>1.8 h^+ h^-



Particle Kinematics for RGA

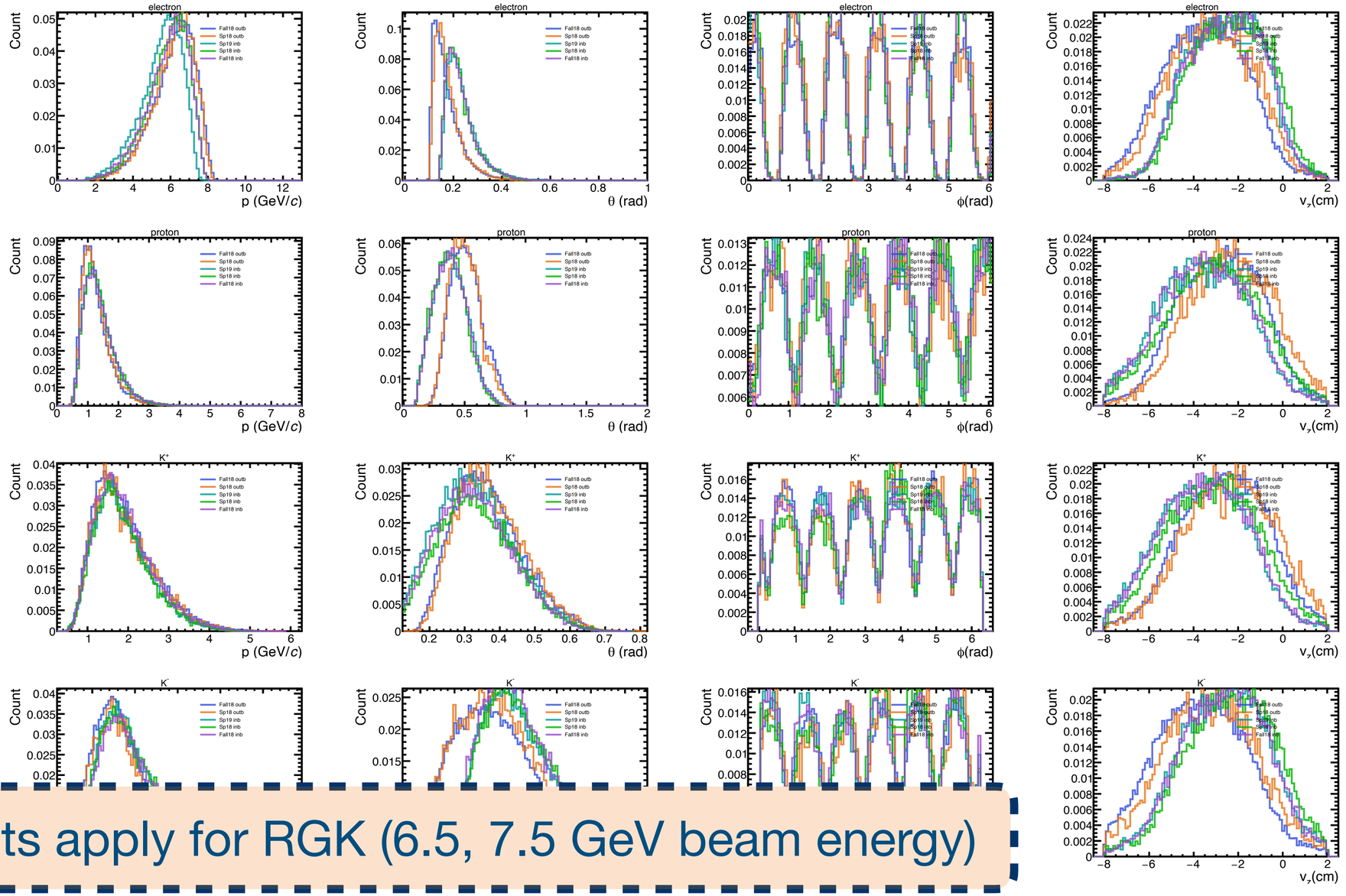
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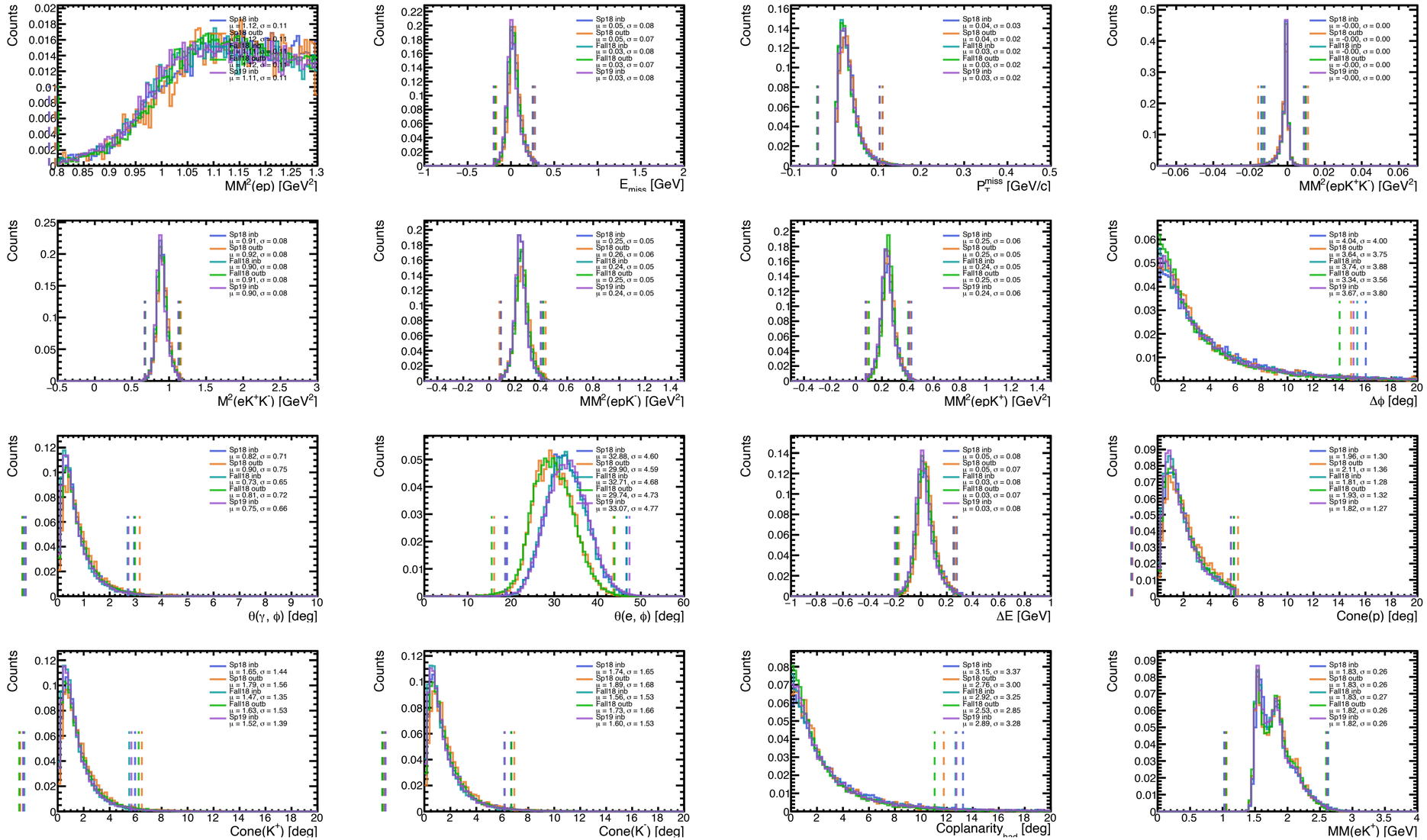


Similar cuts apply for RGK (6.5, 7.5 GeV beam energy)

Exclusivity cuts for further refinements

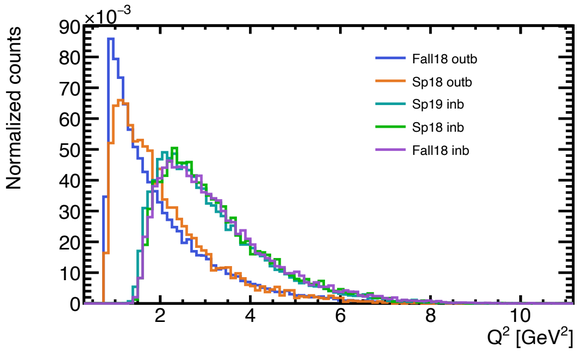
- Exclusivity variables are prior to phi mass peak cut
- Exclusivity cuts

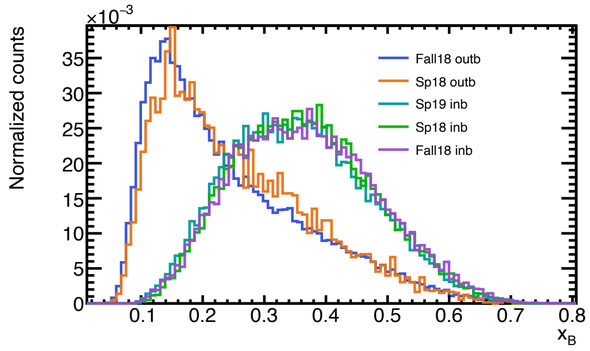
$E_{miss} \in [-0.0075, 0.32]$ GeV
$P_{Tmiss} < 0.11$ GeV
$Mx^2\,(eK^+K^-) \in [0.64, 1.1664]$ GeV^2
$Mx^2\,(epK^+K^-) < 0.0075$ GeV^2
$Mx^2\,(epK^-) \in [0.08, 0.48]$ GeV^2
$Mx^2\,(epK^+) \in [0.08, 0.48]$ GeV^2
cone angles Kp/Km/p < 6 deg
coplanarity < 15 degrees

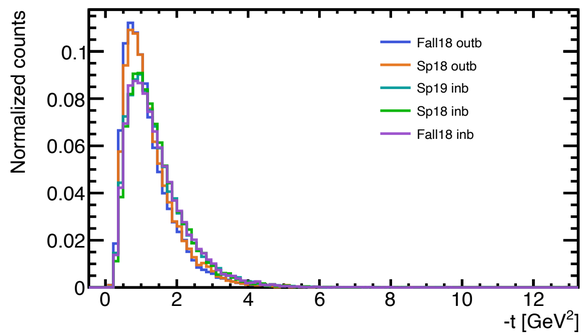


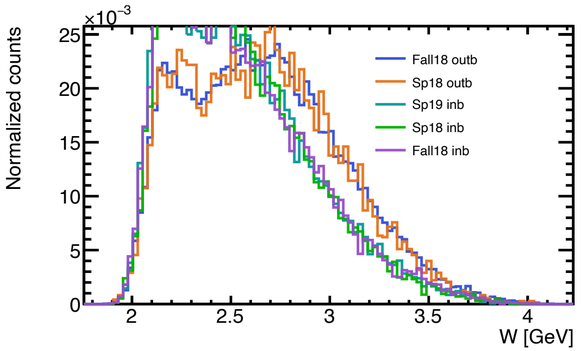
DVEP Kinematic variables: RGA

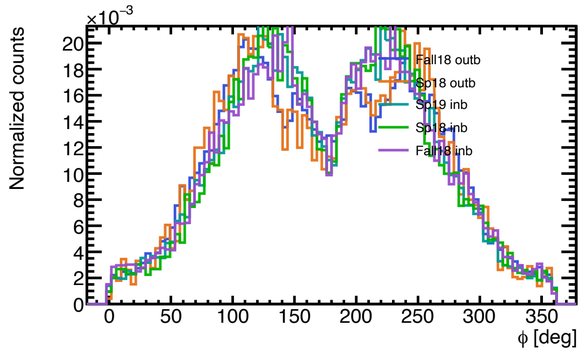
- W > 2.0 GeV and Q^2 > 1.0 GeV^2

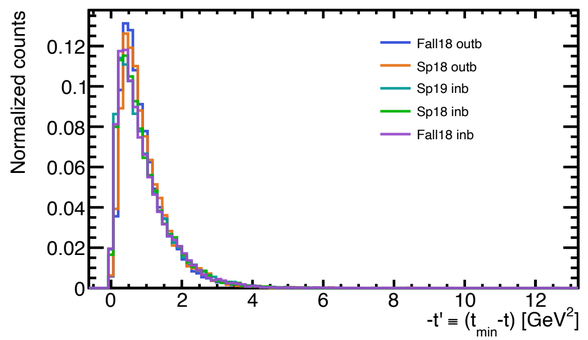


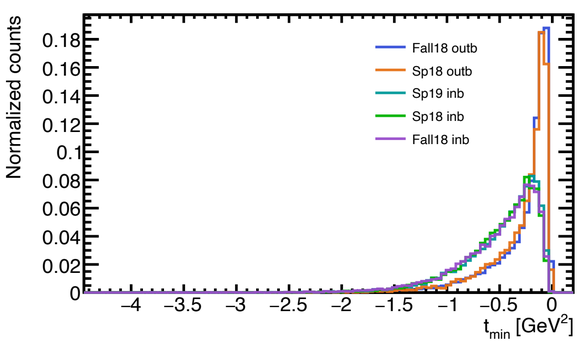


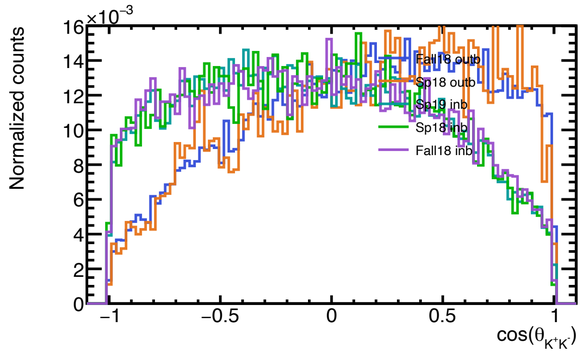


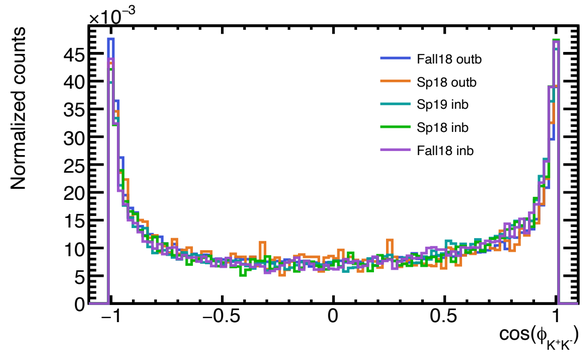






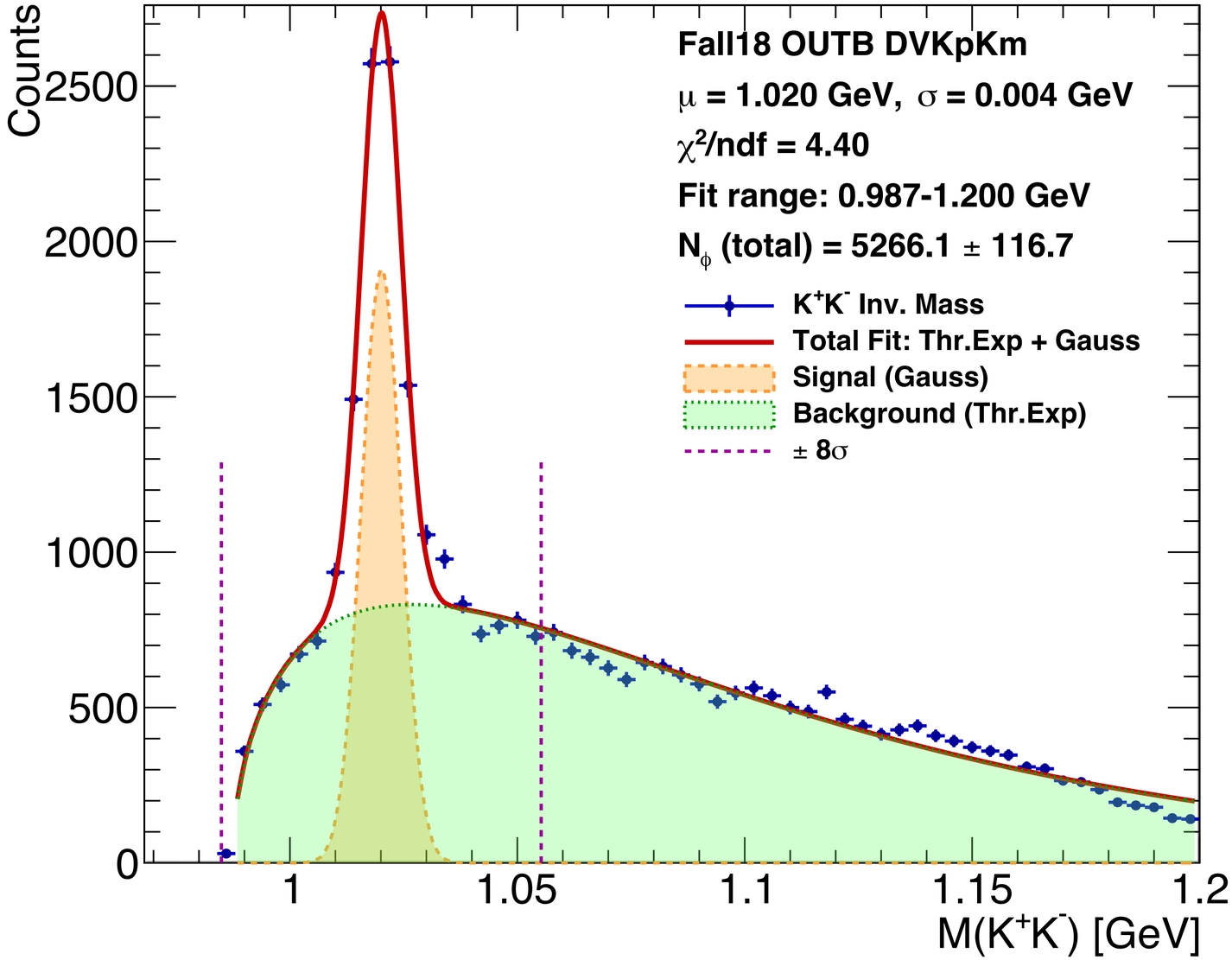






K^+K^- Invariant Mass Distributions

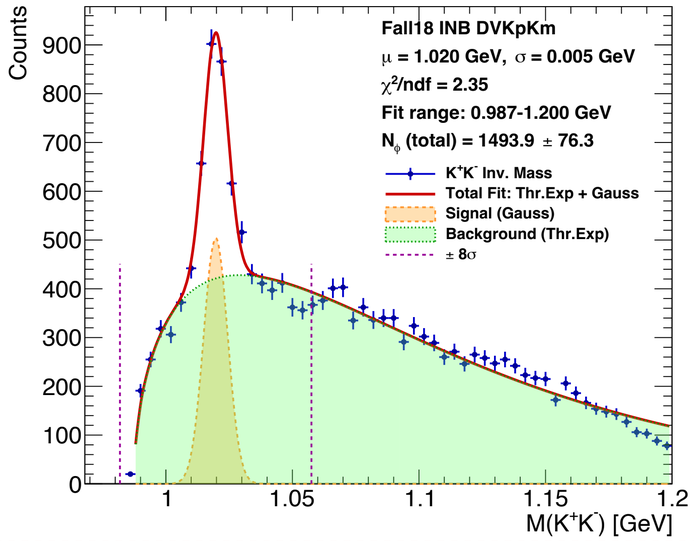
- ϕ candidate counts from the invariant mass peak at ~1.019 GeV of K^+K^- in $ep \rightarrow epK^+K^-$
- Signal: Gaussian distribution
- Background: threshold exponential function
- Extracted yield as integral of the Gaussian function
- Exclusive selection: ~**5200** candidates from fall 2018 outb alone

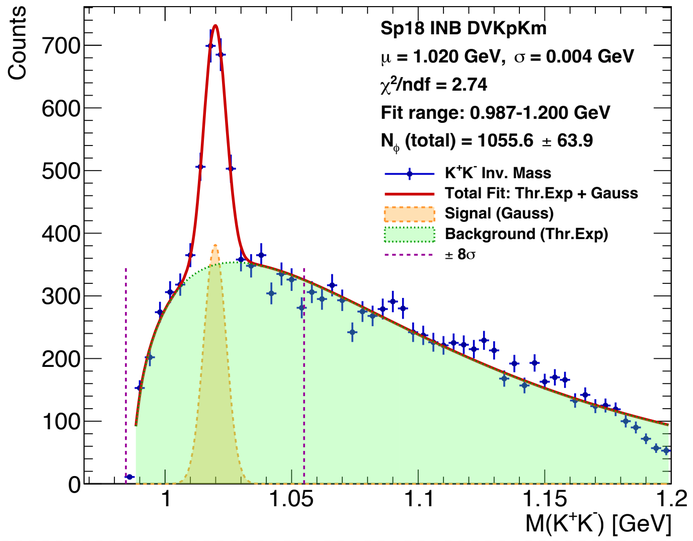


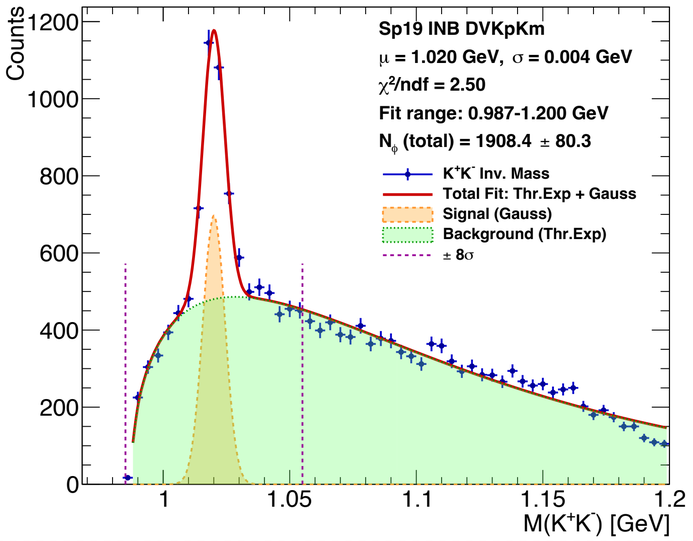
All phi K^+K^- Invariant Mass all periods of 2018-19 run

- ϕ peak at ~1020 MeV, total ~**10000** candidates from 2018-19 Run group A datasets

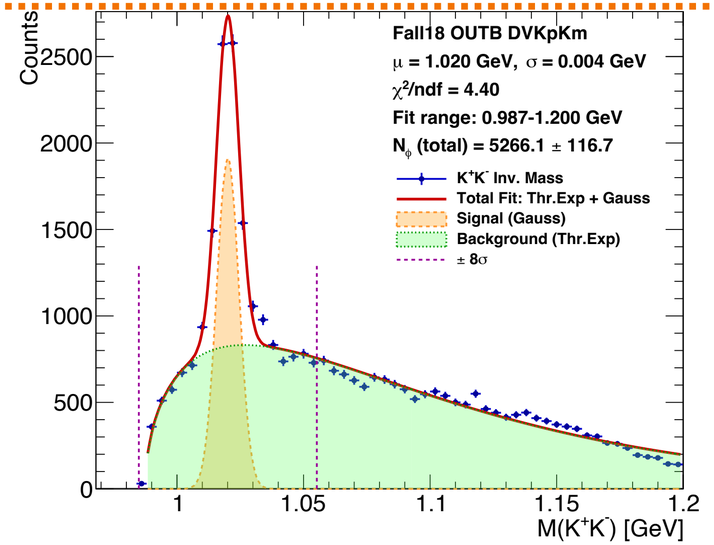
Inb

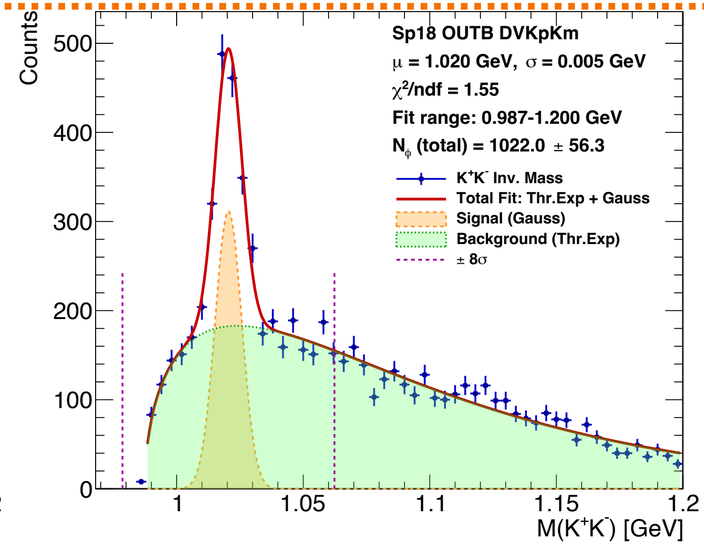






Outb

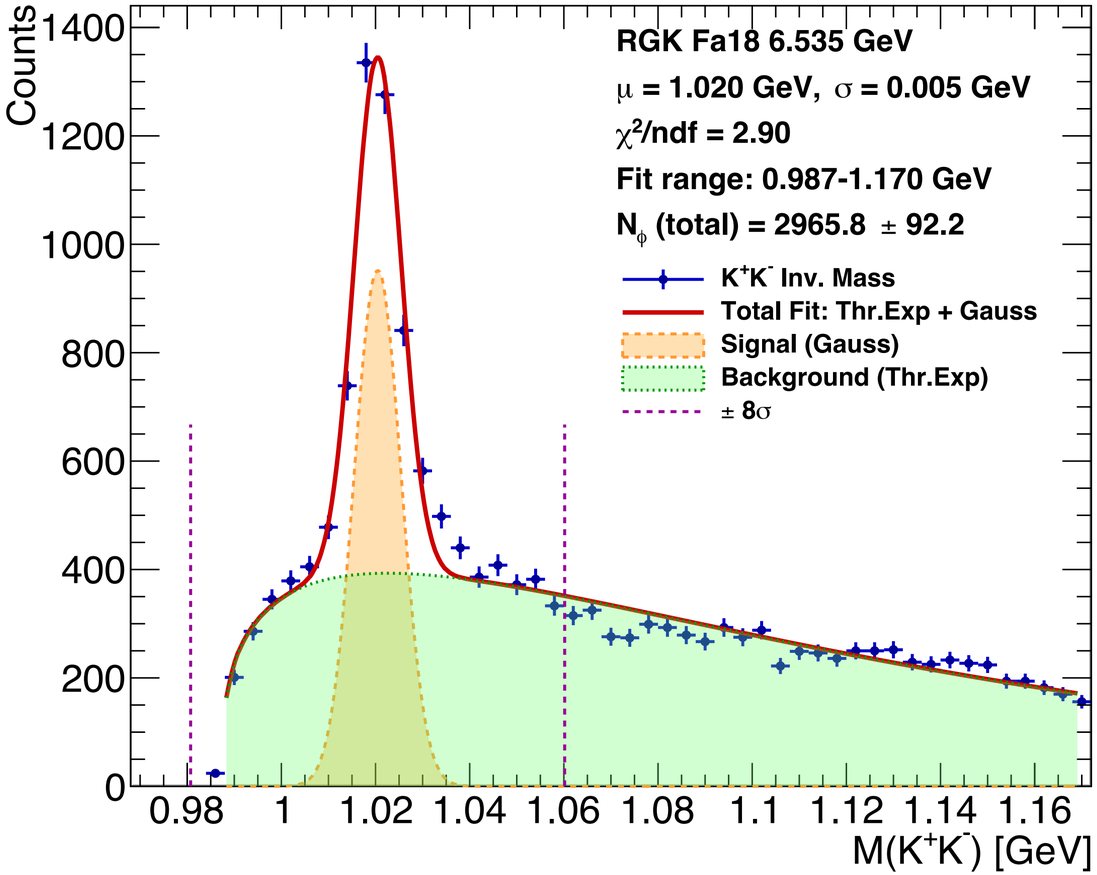


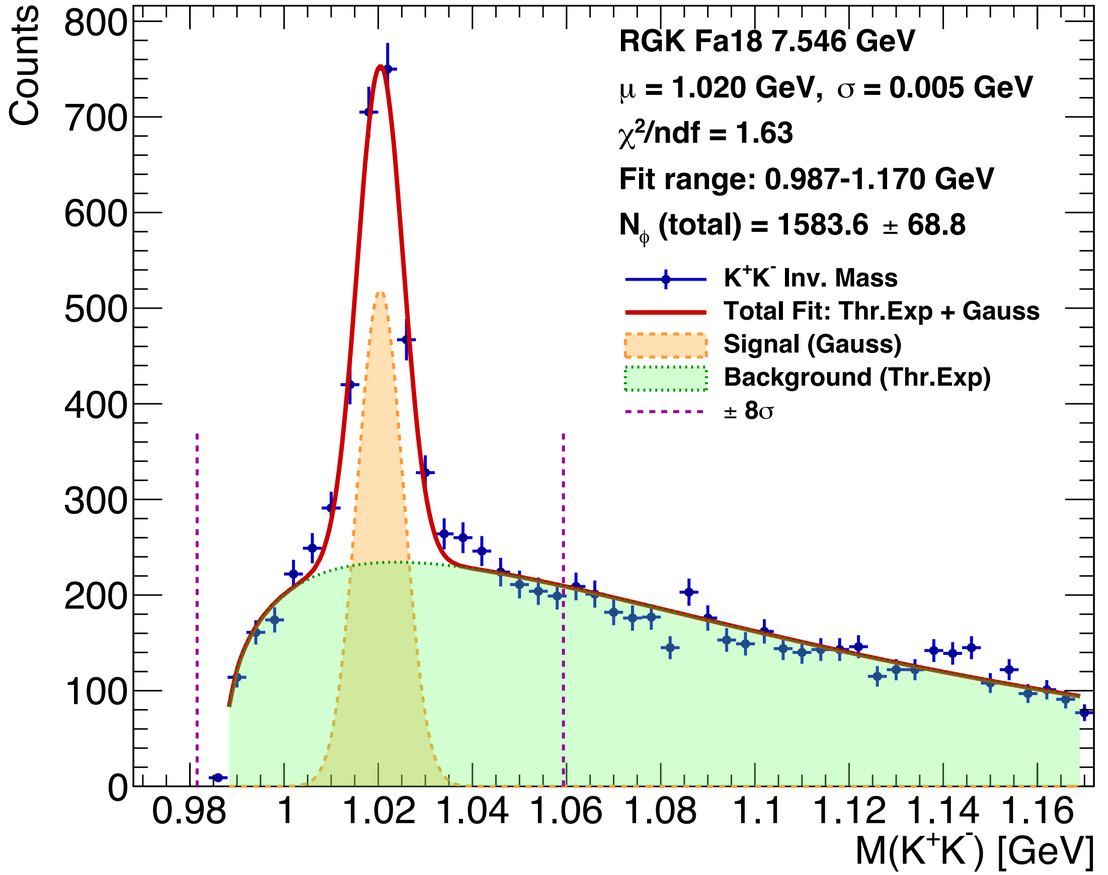


Beam Energies 6.5 and 7.5

- 6.5 and 7.5 GeV fall 2018 data, $Q^2>0.6$ GeV^2, after all fiducial cuts and sampling fraction cuts for electron, energy loss correction for proton, 3 sigma exclusivity cuts

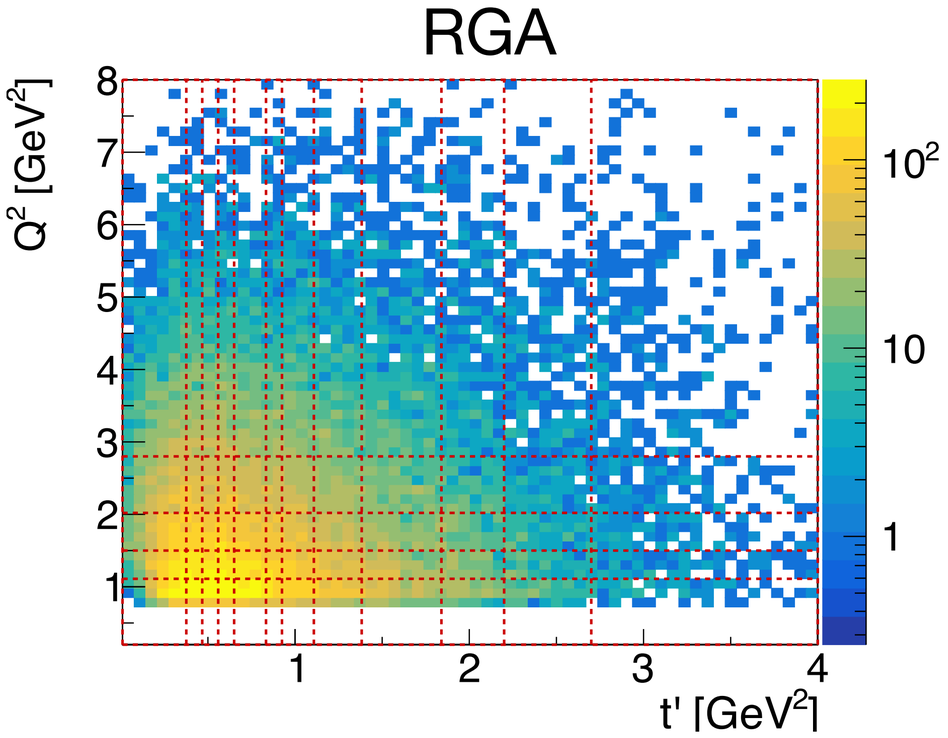
- Statistics **3K (6.535 GeV) and 1.5K (7.546 GeV)**

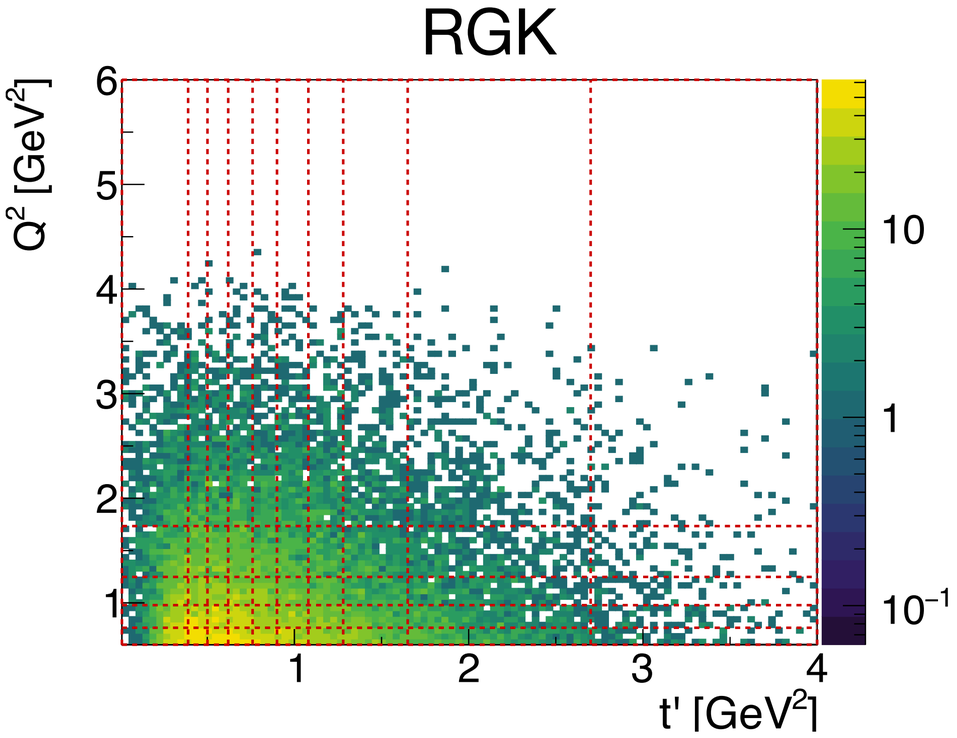




Extraction of cross-section: RGA and RGK binning

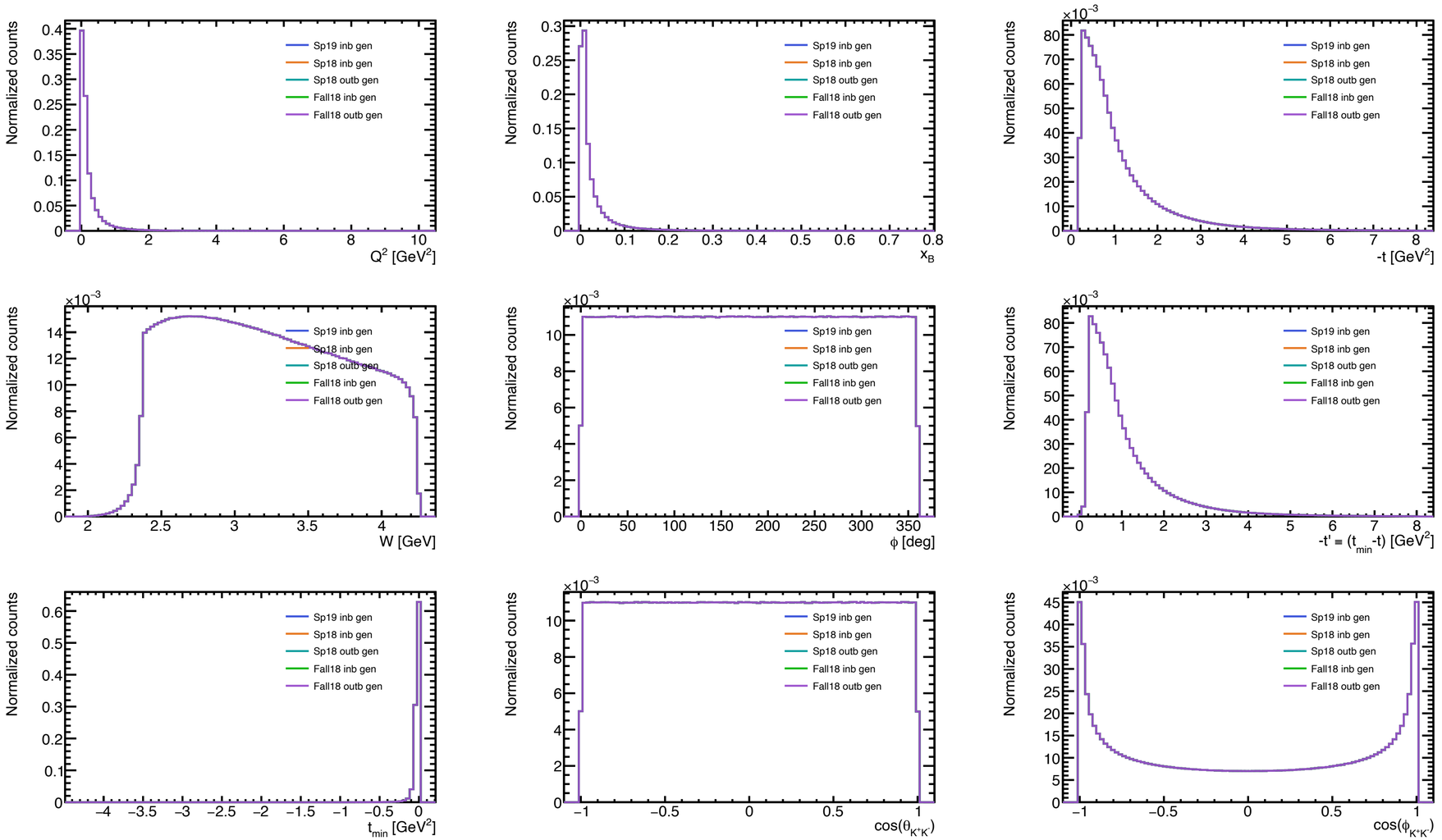
- Divide the total sample with equal statistics in each Q^2 and t' bin
- Currently **5** Q^2 and **12** t' bins
- In each -t' bin, we used a $InvM_{K^+K^-}$ distribution to extract the counts of ϕ





Event Generator CLAS12

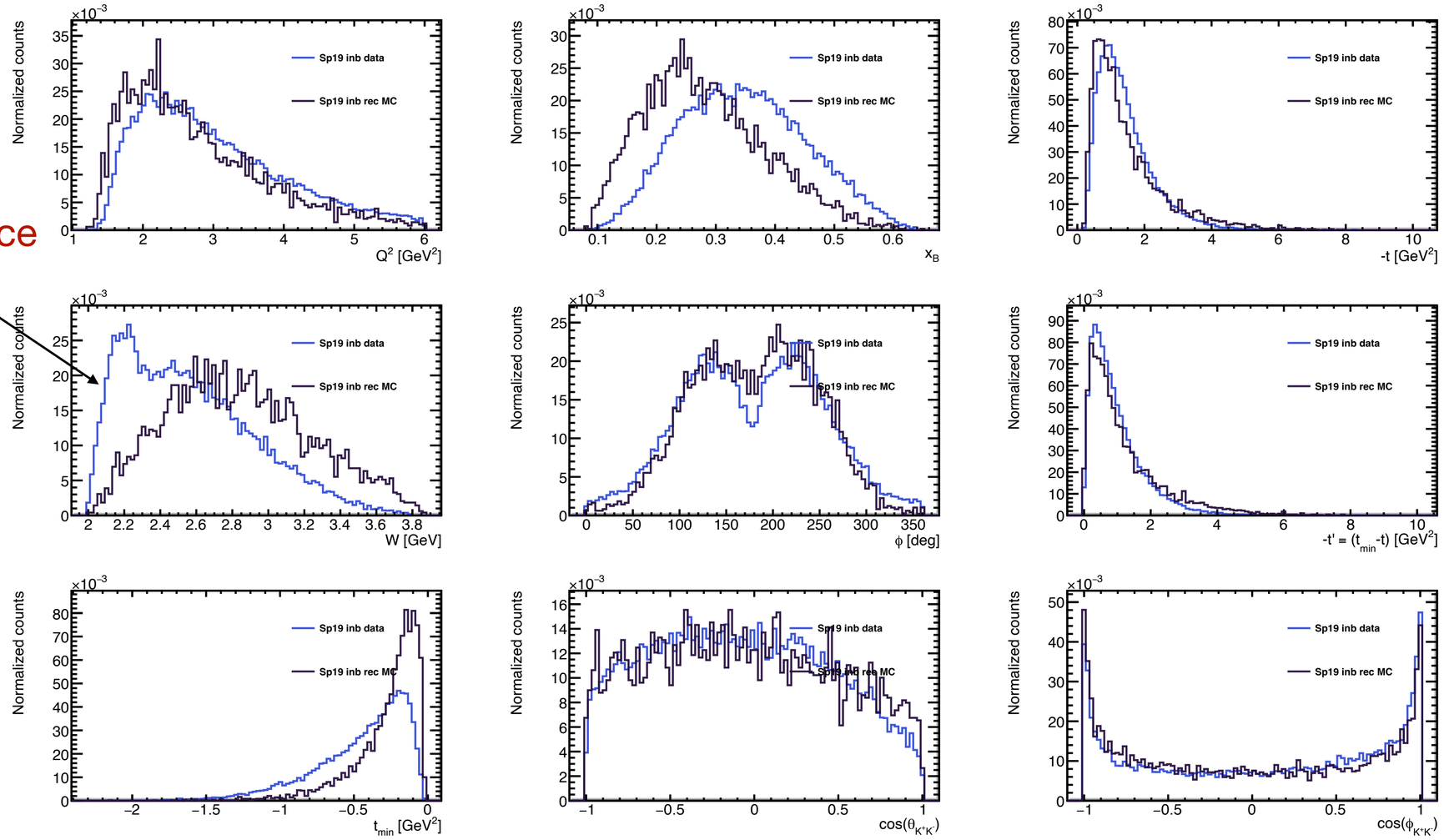
- Simulations based on the Argonne ϕ Event Generator tuned to Clas 6 data and **ϕ event decay in rest mass is considered as isotropic (flat distribution)** [Y. Hatta, H. Klest, et al, PTEP, 2025]



Simulation vs Data

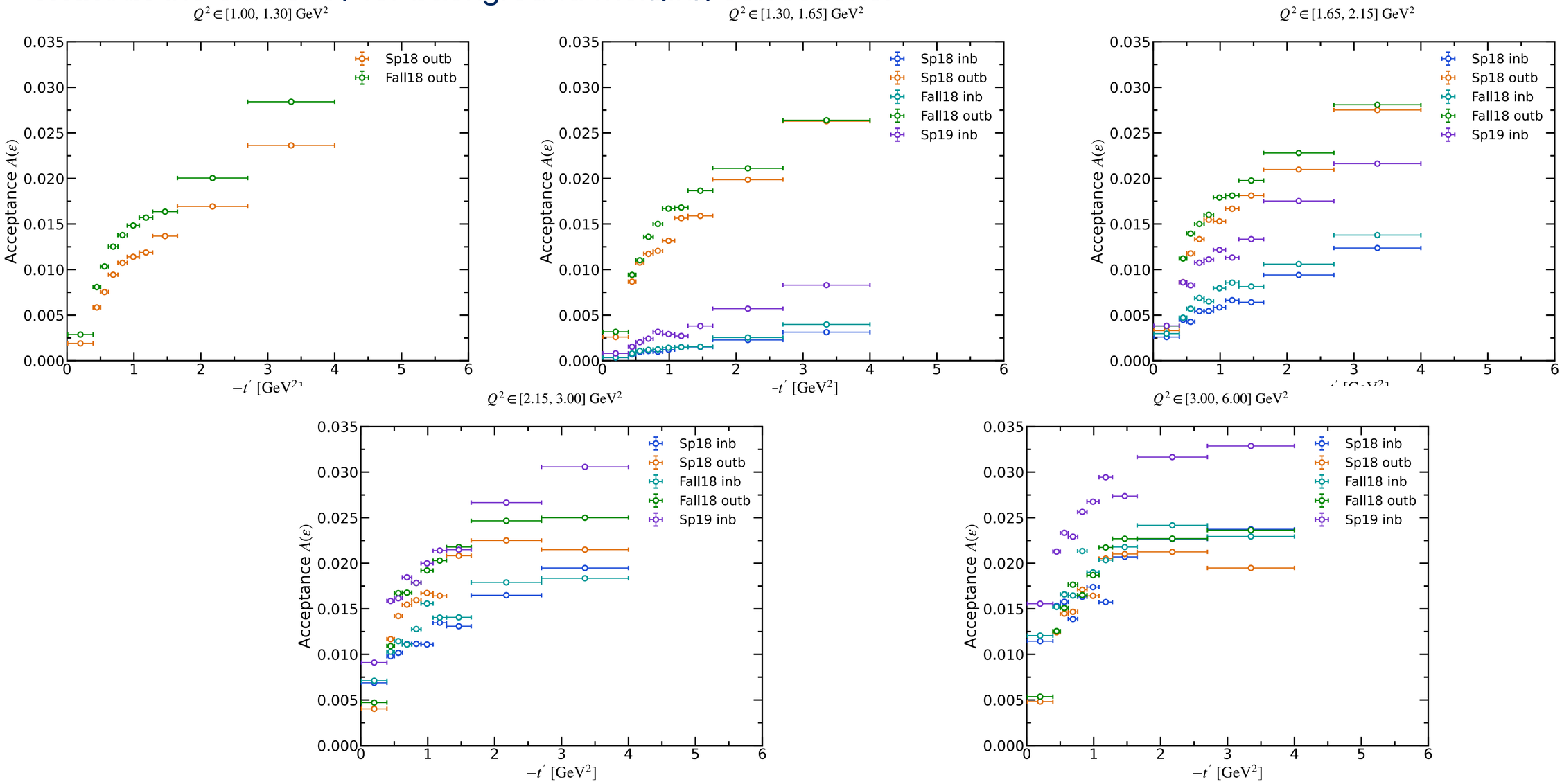
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Possible resonance contributions!



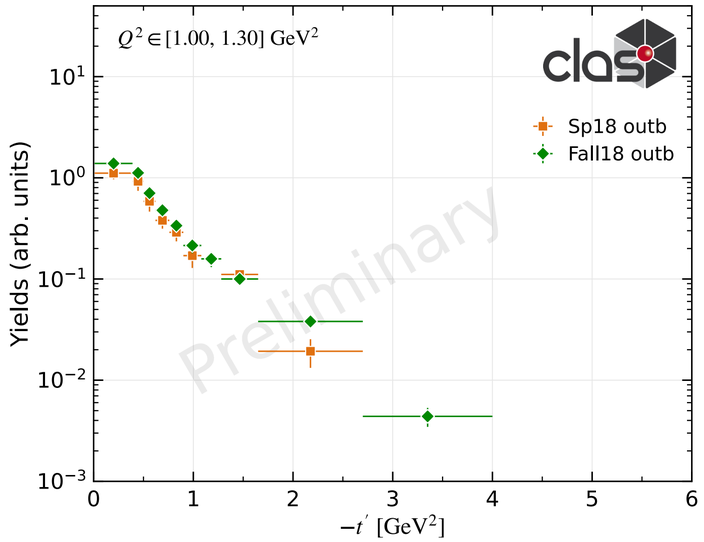
Detector acceptance effects RGA

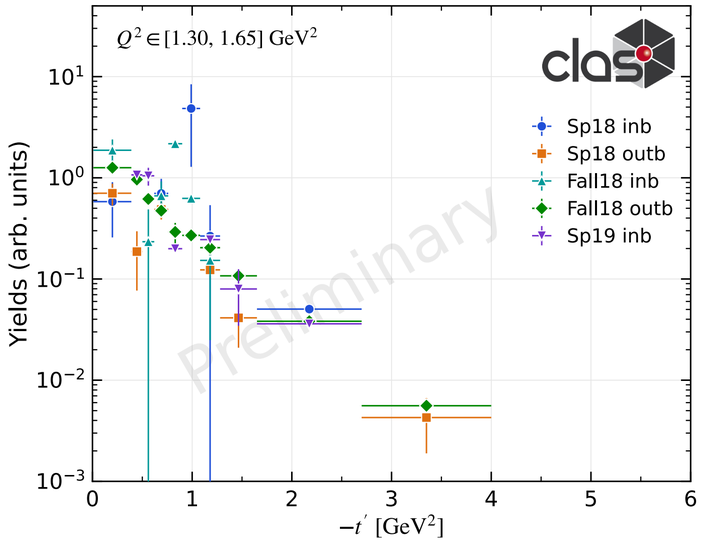
- **Without** the efficiency for background merging corrections!

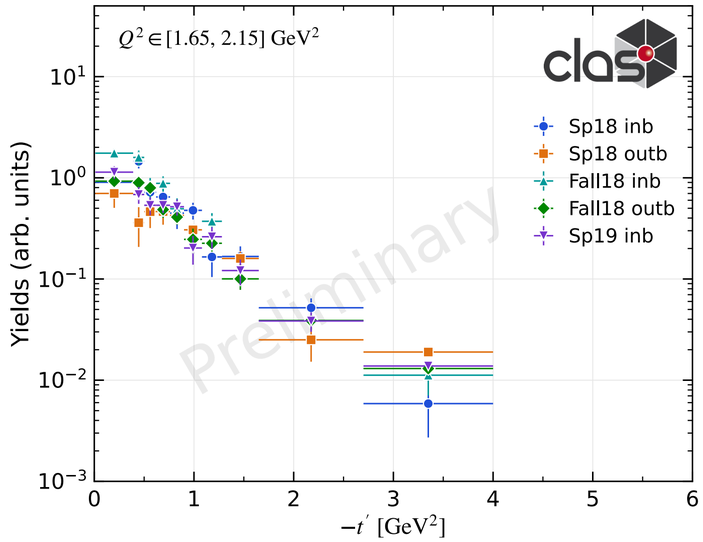


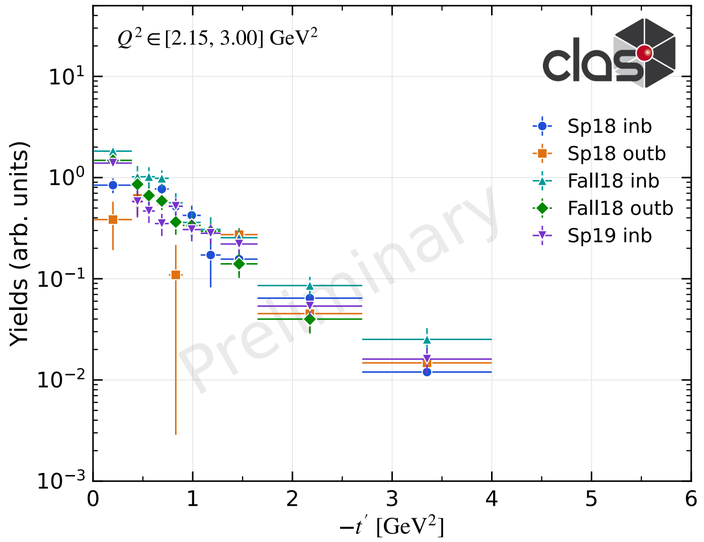
Reduced Yields: Run Group A (10.2 & 10.6 GeV Beam)

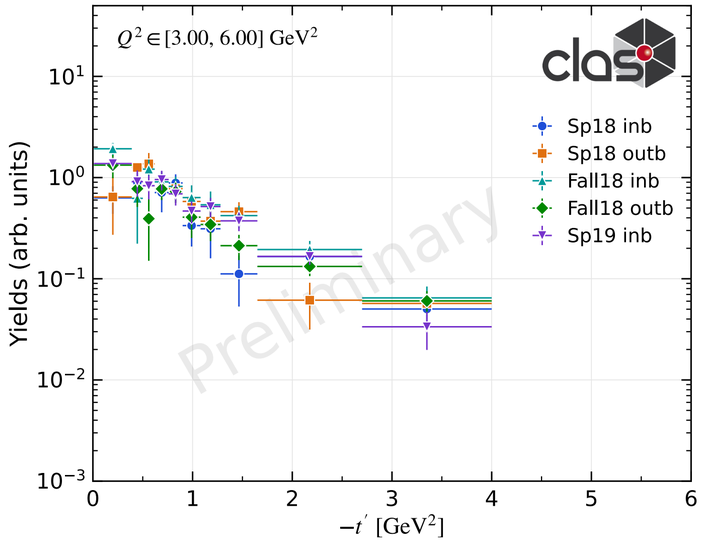
- **Without** the **efficiency** for background merging corrections and **radiative** loss corrections! ~50% effects





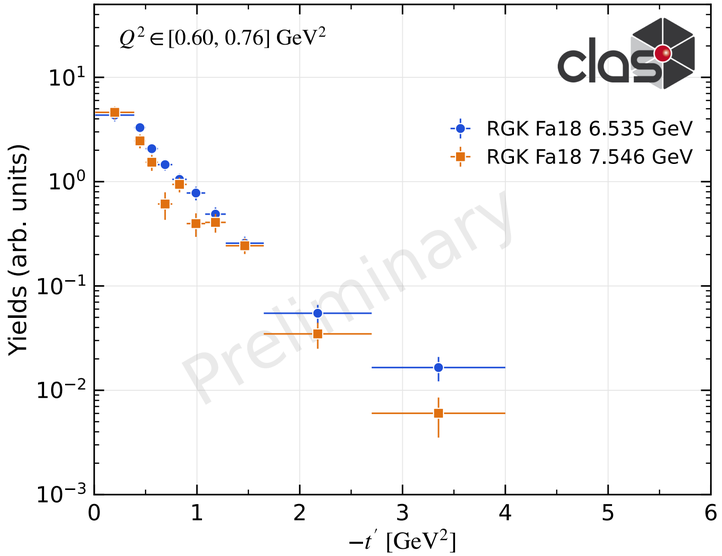


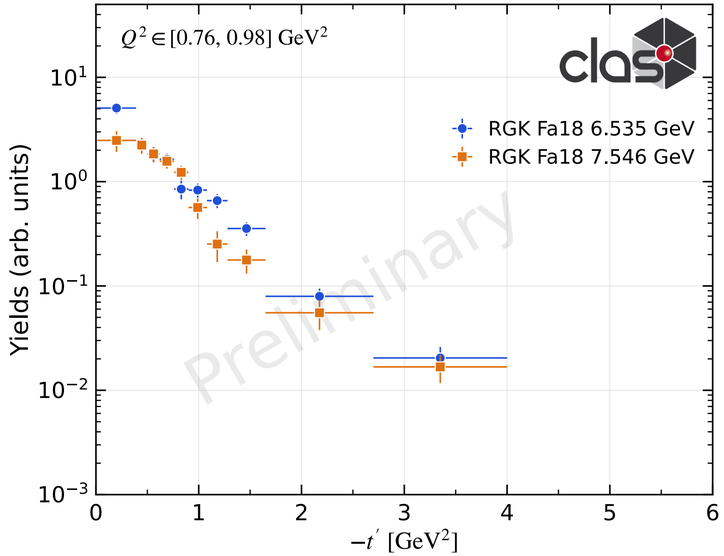


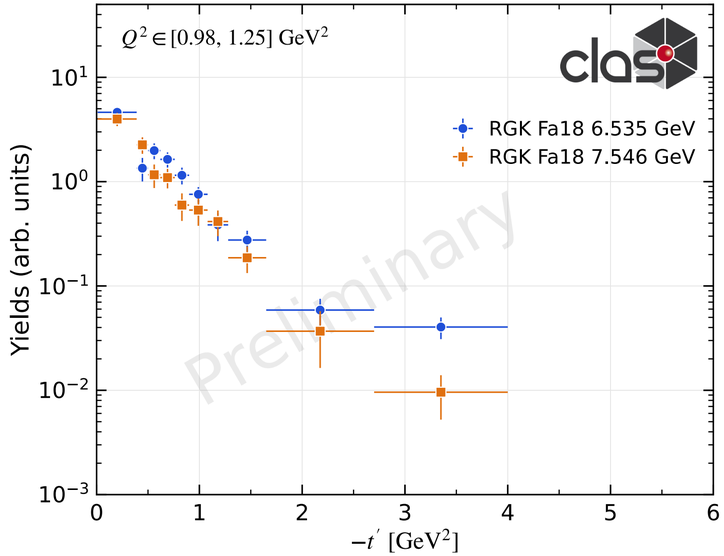


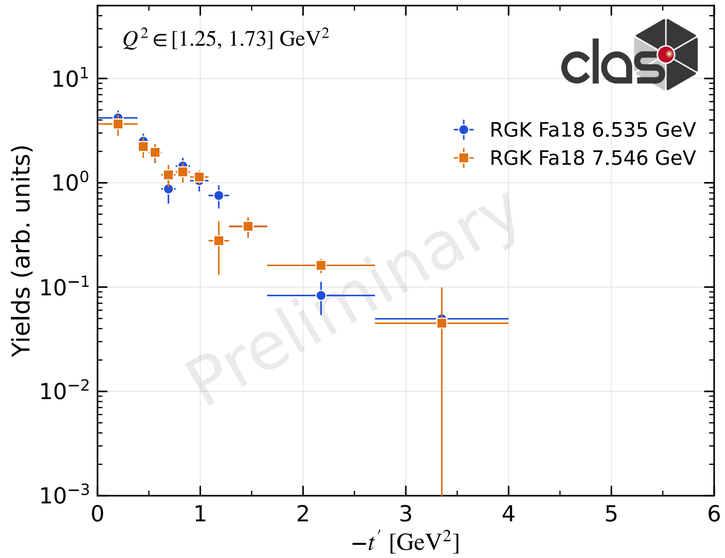
Reduced Yields: Run Group K (6.5 & 7.5 GeV Beam)

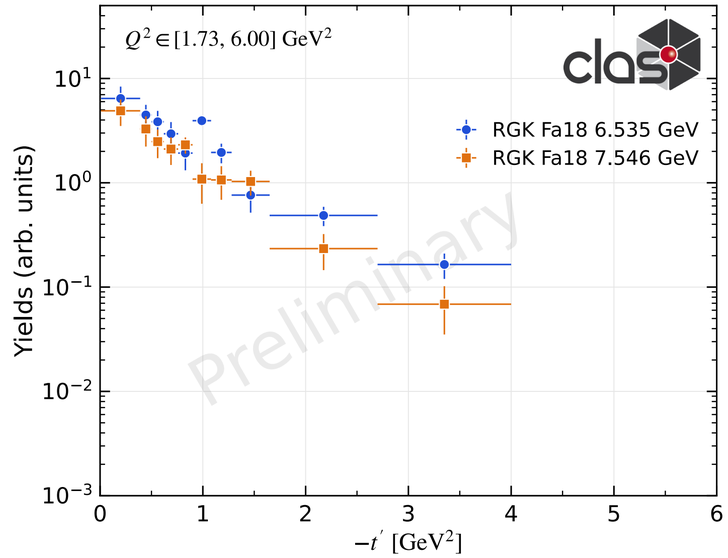
- **Without** the **efficiency** for background merging corrections and **radiative** loss corrections! ~50% effects





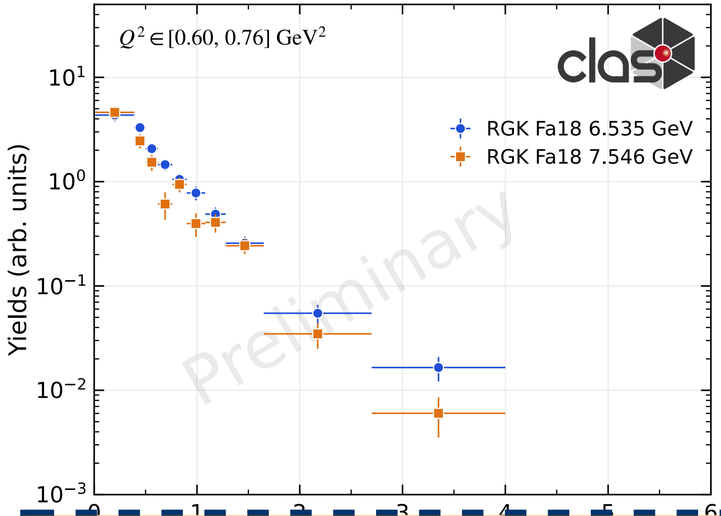


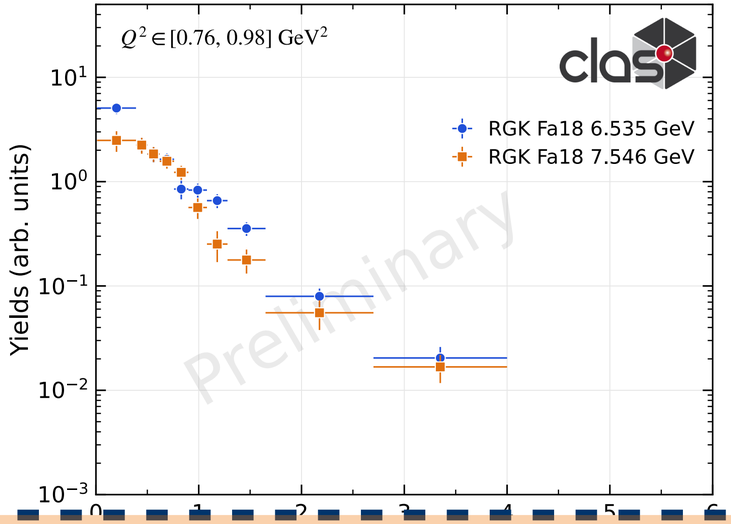


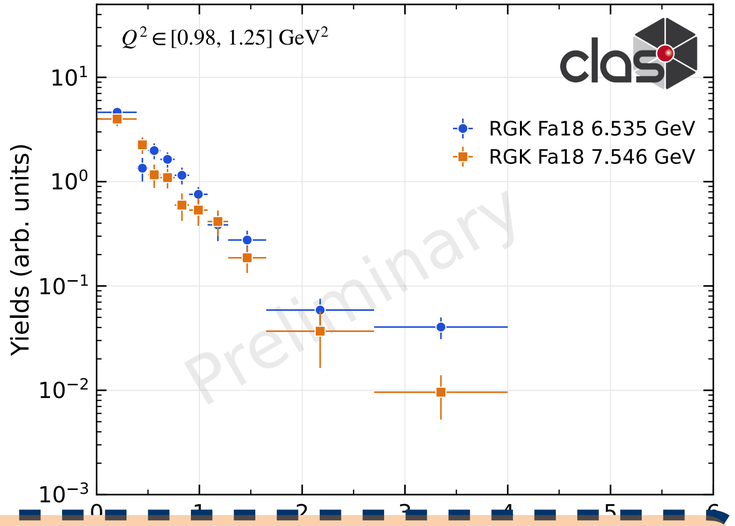


Reduced Yields: Run Group K (6.5 & 7.5 GeV Beam)

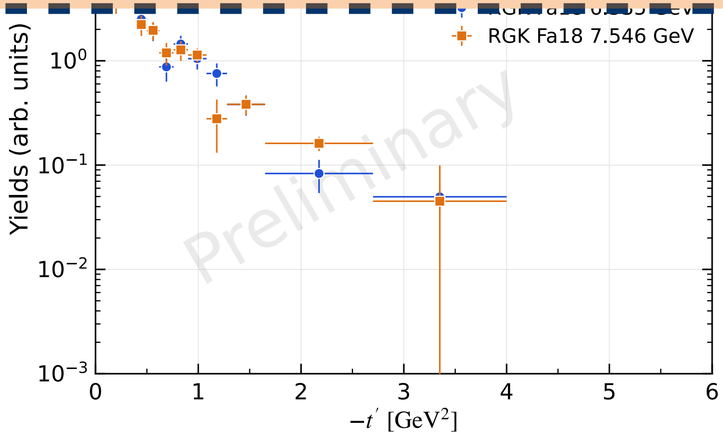
- **Without** the **efficiency** for background merging corrections and **radiative** loss corrections! ~50% effects

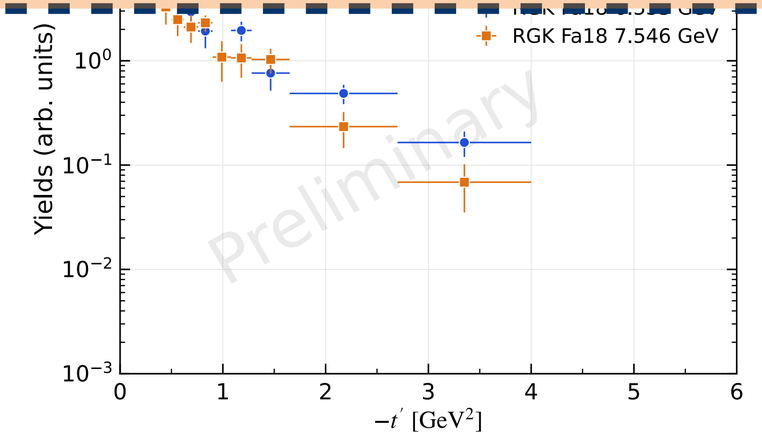




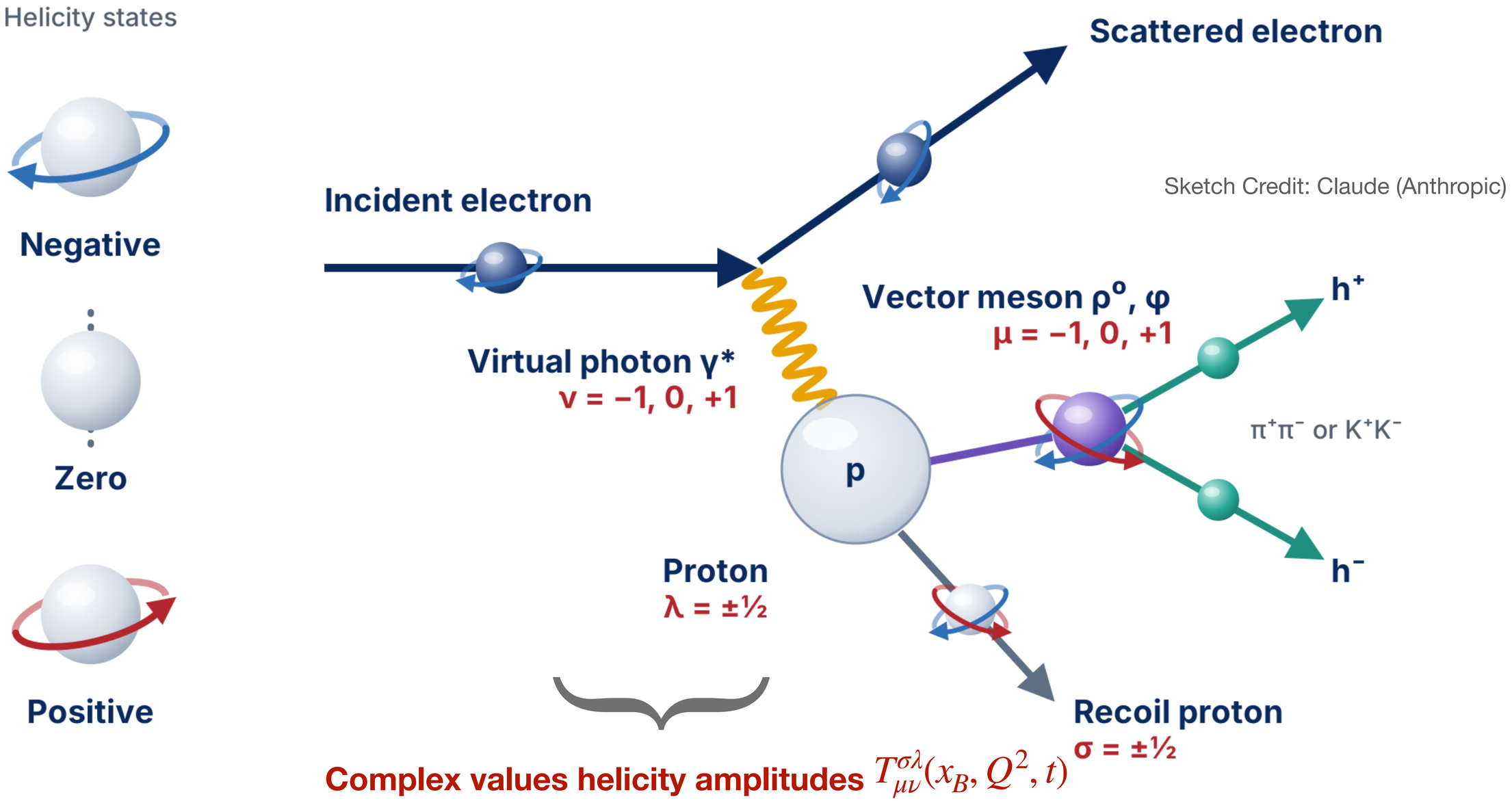


Combined Rosenbluth Separation would provide access to $\sigma_L \longrightarrow D_s$-term





Exclusive vector-meson electroproduction



Polarized target: the full amplitude set

- Full cross-section stages unpolarized **(U)** +Longitudinally polarized **(L)**+ Transversely Polarized **(T)**

$$\frac{d\sigma}{dx_B\, dQ^2\, dt\, d\Omega} = \Gamma(x_B, Q^2, y)\, W(\Omega; \varepsilon, P_b, S_L, S_T)$$

- Angular intensities

$$W(\Omega; \varepsilon, P_b) = \frac{3}{4\pi}\left[\mathcal{U} + \varepsilon\,\mathcal{L}_2 + \sqrt{2\varepsilon(1+\varepsilon)}\,\mathcal{L}_1 + P_b\left(\sqrt{1-\varepsilon^2}\,\mathcal{B} + \sqrt{2\varepsilon(1-\varepsilon)}\,\mathcal{B}_1\right)\right]$$

- Short-hand notations

$$\mathcal{U} = \left[\frac{1}{2}\left(|T_{11}|^2 + |T_{1\text{-}1}|^2 + |U_{11}|^2 + |U_{1\text{-}1}|^2\right) + \varepsilon\left(|T_{10}|^2 + |U_{10}|^2\right)\right]\sin^2\theta + \left(|T_{01}|^2 + \varepsilon|T_{00}|^2 + |U_{01}|^2\right)\cos^2\theta + \ldots\text{more angles}$$

- Including nucleon spin flip and non-flip cases (3(μ)x3(ν)x2(σ)x2(λ)/2(parity factor)-2(global phase, real T_{11}))

$$T_{\mu\nu}^{--} = +\,T_{\mu\nu}^{++}, \qquad U_{\mu\nu}^{--} = -\,U_{\mu\nu}^{++} \qquad \text{(non-flip)}$$

$$T_{\mu\nu}^{+-} = -\,T_{\mu\nu}^{-+}, \qquad U_{\mu\nu}^{+-} = +\,U_{\mu\nu}^{-+} \qquad \text{(flip)}$$

- Full Angular distributions: U+L+T (**34**)

Spin Density Matrix Elements (SDMEs)

$$\rho_{\mu\mu',\lambda\lambda'}^{\nu\nu'} = \frac{1}{N_T + \epsilon N_L}\sum_{\sigma} T_{\mu\lambda}^{\nu\sigma}\left(T_{\mu'\lambda'}^{\nu'\sigma}\right)^*$$

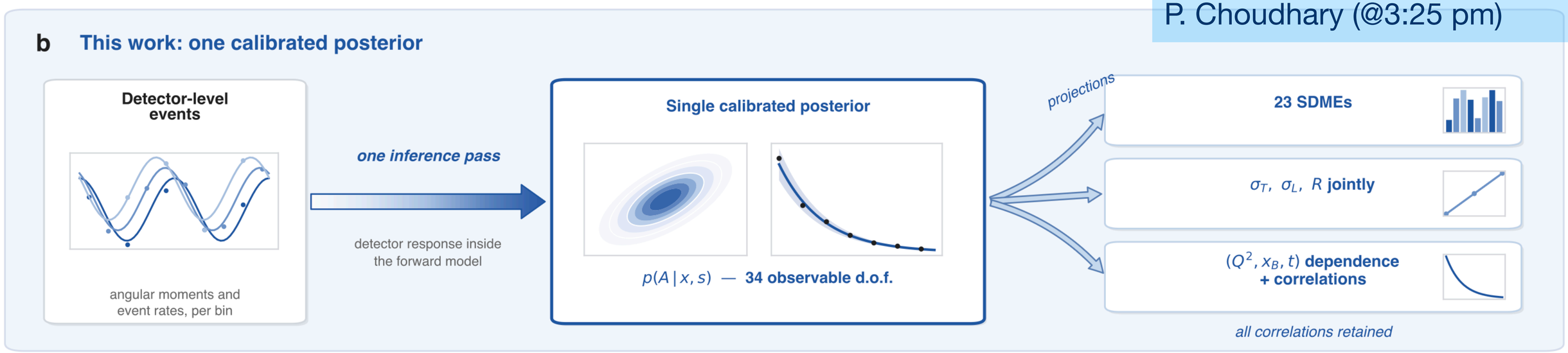
$$W = W_{UU} + P_b W_{LU} + S_L\left(W_{UL} + P_b W_{LL}\right) + S_T\left(W_{UT} + P_b W_{LT}\right)$$

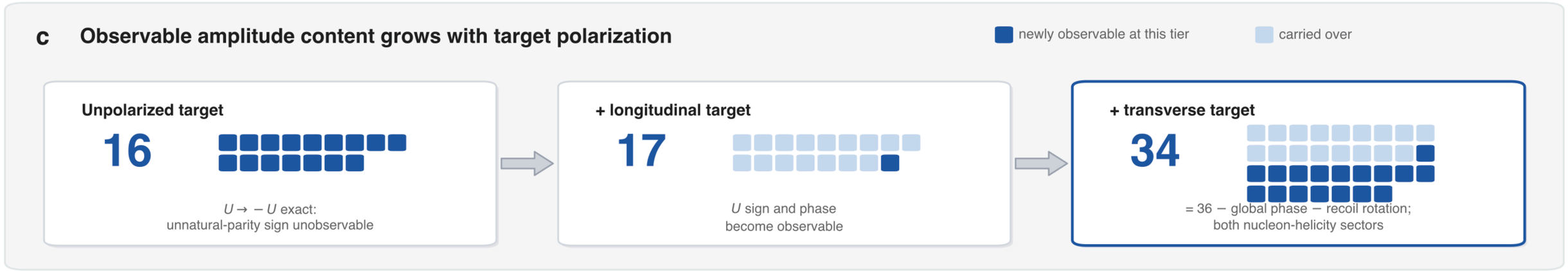
Formalism: M. Diehl, JHEP 09 (2007) 064

Full derivation given in appendix of **B. Singh** et al arXiv:2608.27683 [nucl-ex] (2026)

Inference in one pass

W. Melnitchouk (Wednesday)
P. Choudhary (@3:25 pm)

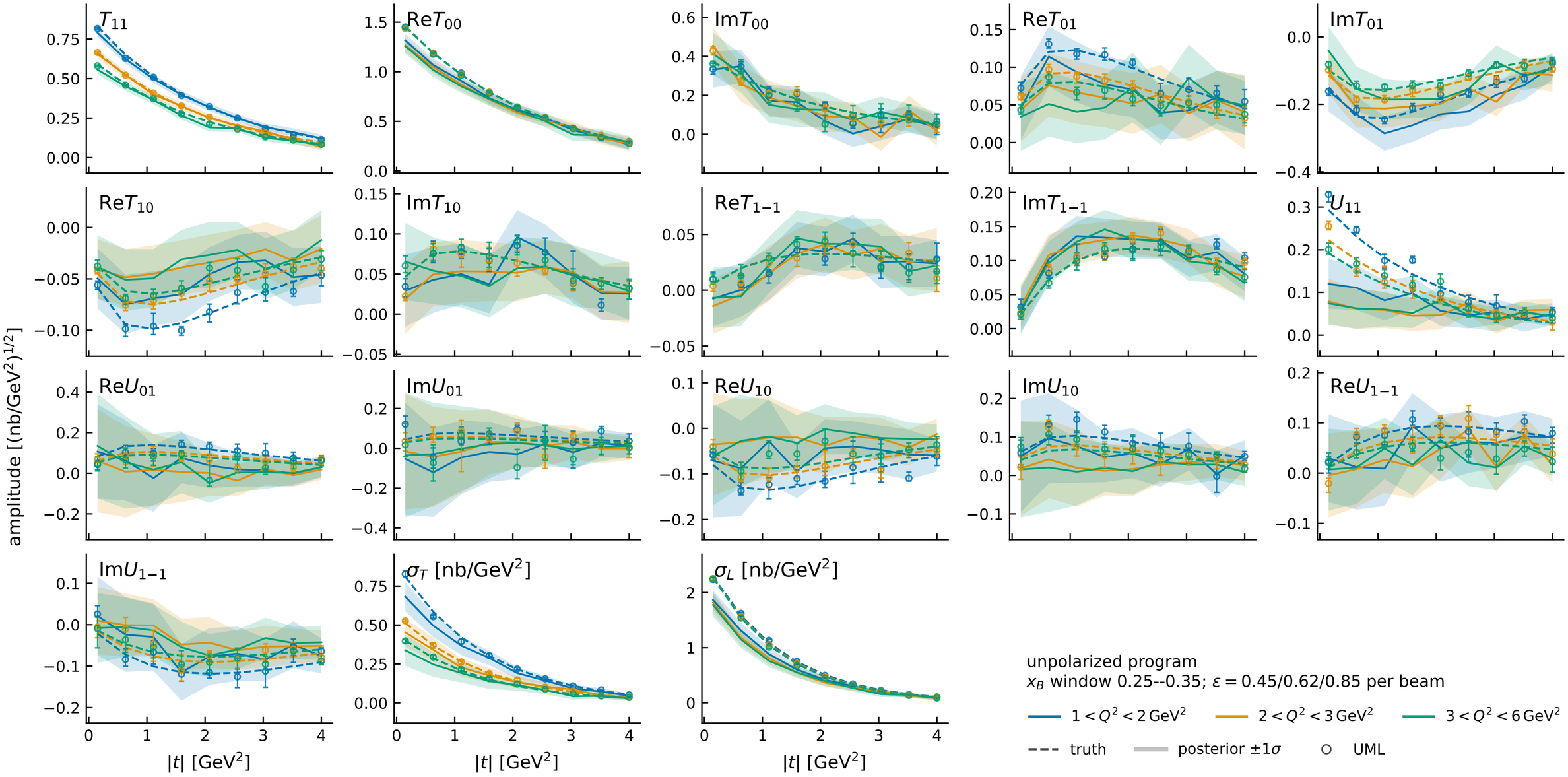




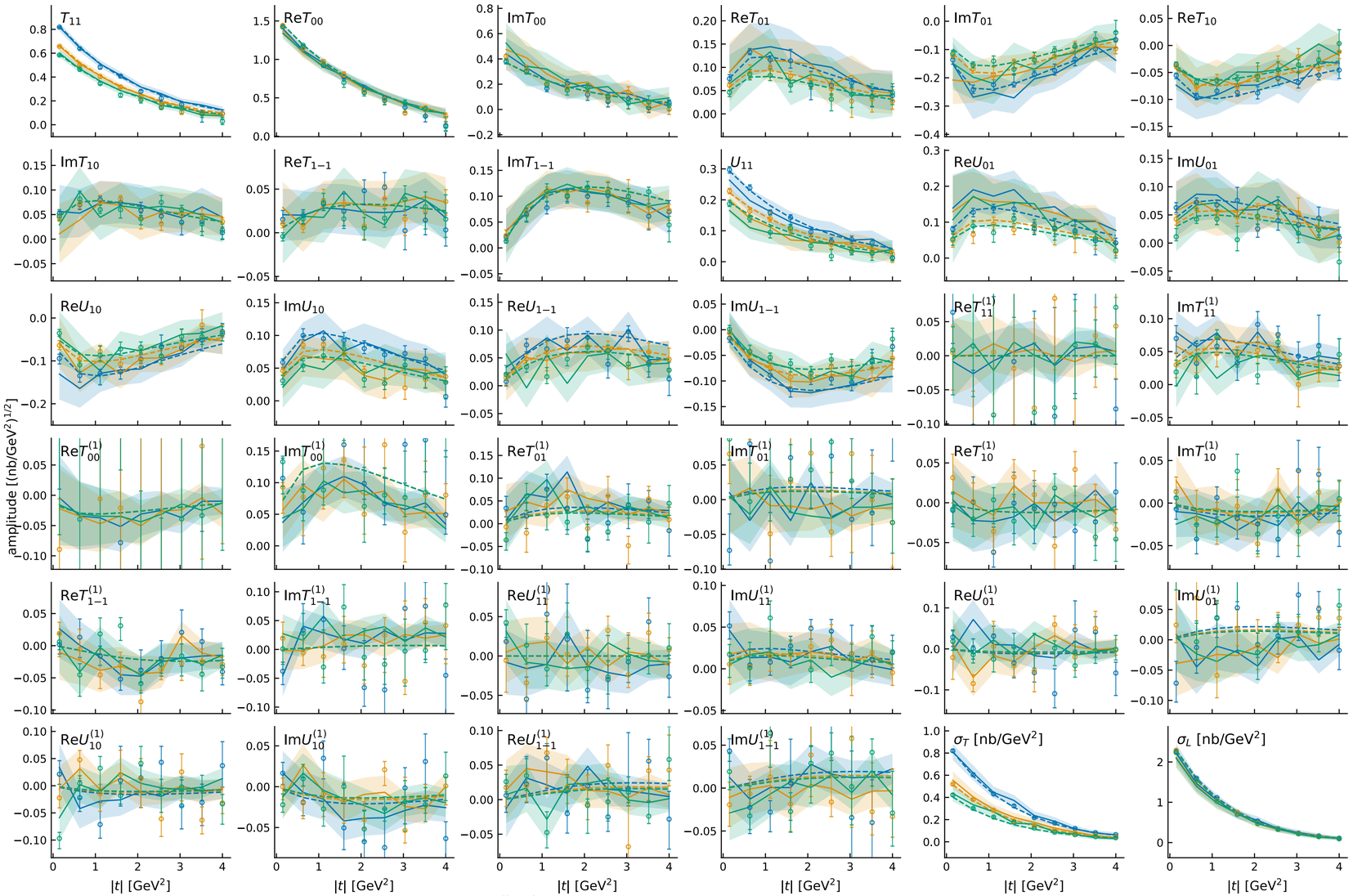
The detector response is carried by the forward model instead of being corrected out. The 23 SDMEs, the separated cross sections and their dependence on Q^2, x_B and t all follow as projections of one posterior, with every correlation retained!

Recent work B. Singh et al arXiv:2608.27683 [nucl-ex] (2026)

ϕ meson production on unpolarized target



Longitudinally+transversely polarized target (ϕ)

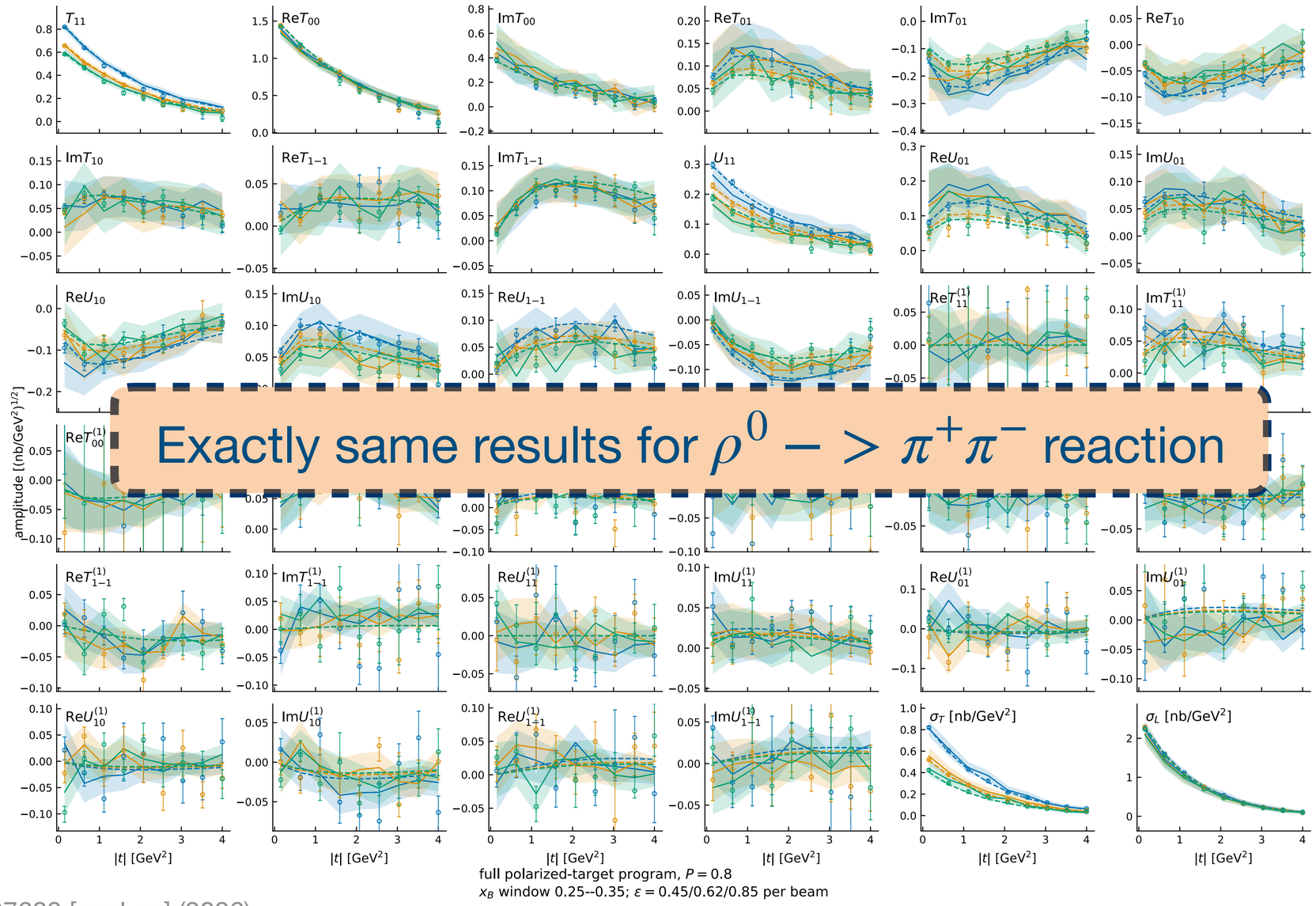


full polarized-target program, $P = 0.8$
x_B window 0.25--0.35; $\varepsilon = 0.45/0.62/0.85$ per beam

B. Singh et al arXiv:2608.27683 [nucl-ex] (2026)

$1 < Q^2 < 2\,\mathrm{GeV}^2$ $2 < Q^2 < 3\,\mathrm{GeV}^2$ $3 < Q^2 < 6\,\mathrm{GeV}^2$ truth posterior $\pm 1\sigma$ UML

Longitudinally+transversely polarized target (ϕ)

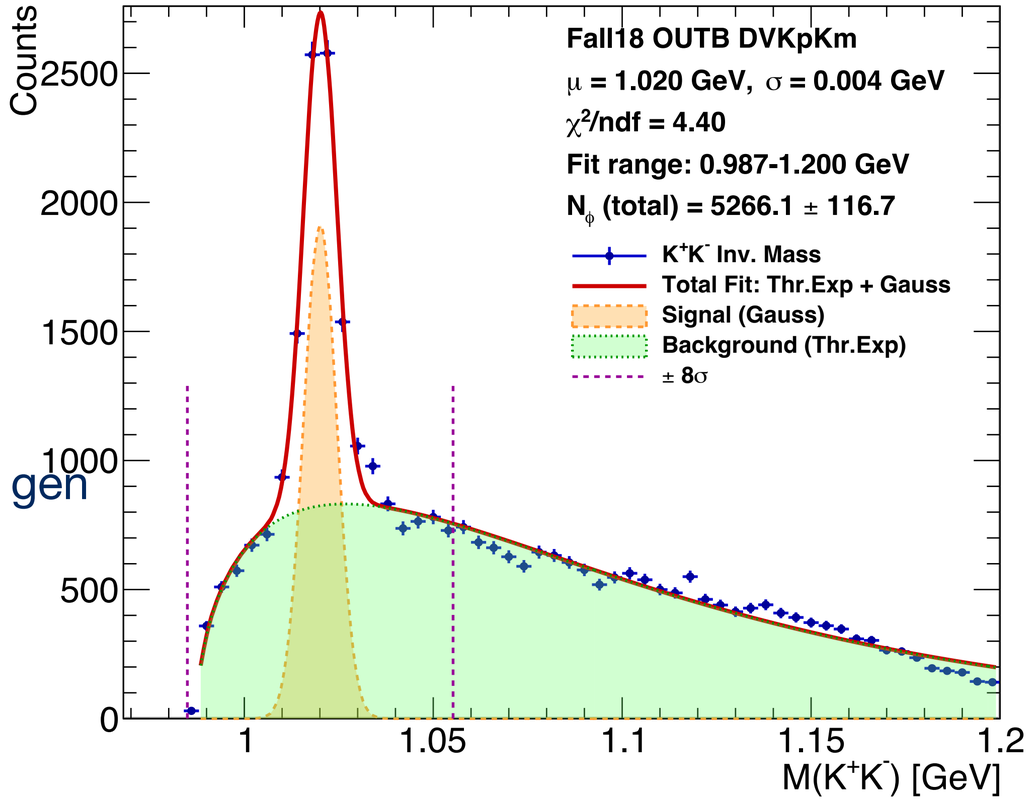


Exactly same results for $\rho^0 -> \pi^+\pi^-$ reaction

B. Singh et al arXiv:2608.27683 [nucl-ex] (2026)

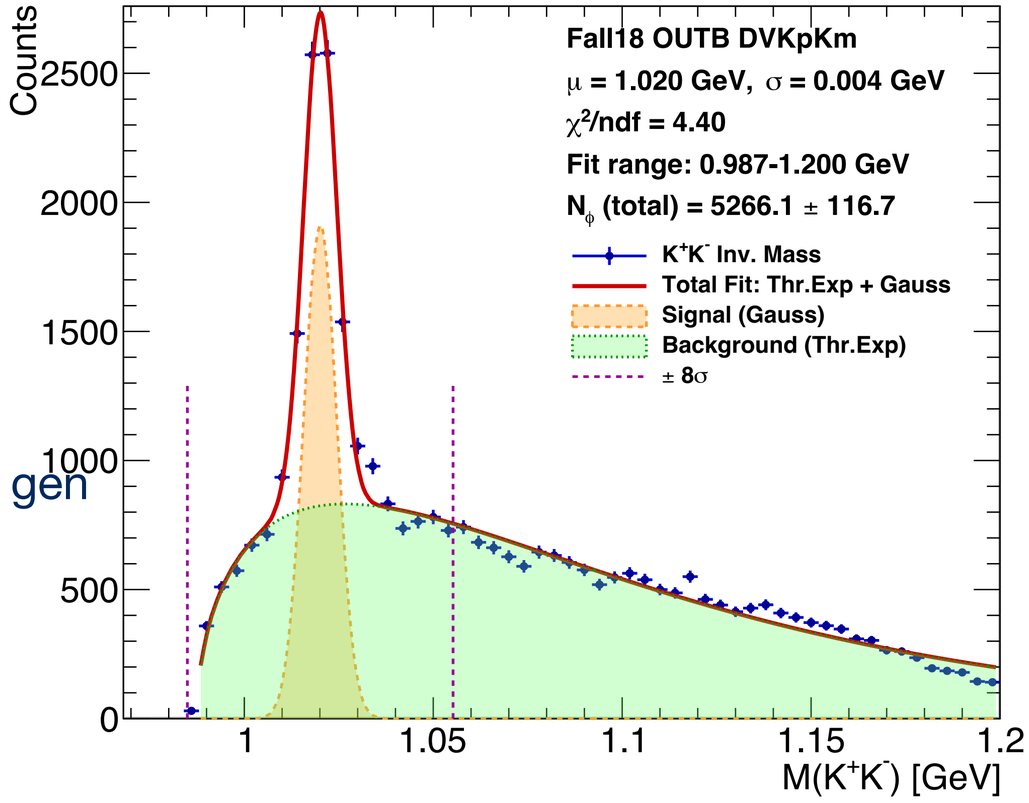
Summary

- So far
  - First look at the exclusive ϕ meson production combining all data set from RGA and RGK 6.5, 7.5, and 10.2-10.6 GeV
  - We raw yields corrected for flat angles event generators
  - Radiative correction in progress
- Next steps
  - Extraction of helicity amplitudes and acceptance with true event gen
  - Systematics on **acceptance** and efficiency corrections!
  - **More** data from **8.4 GeV**!



Summary

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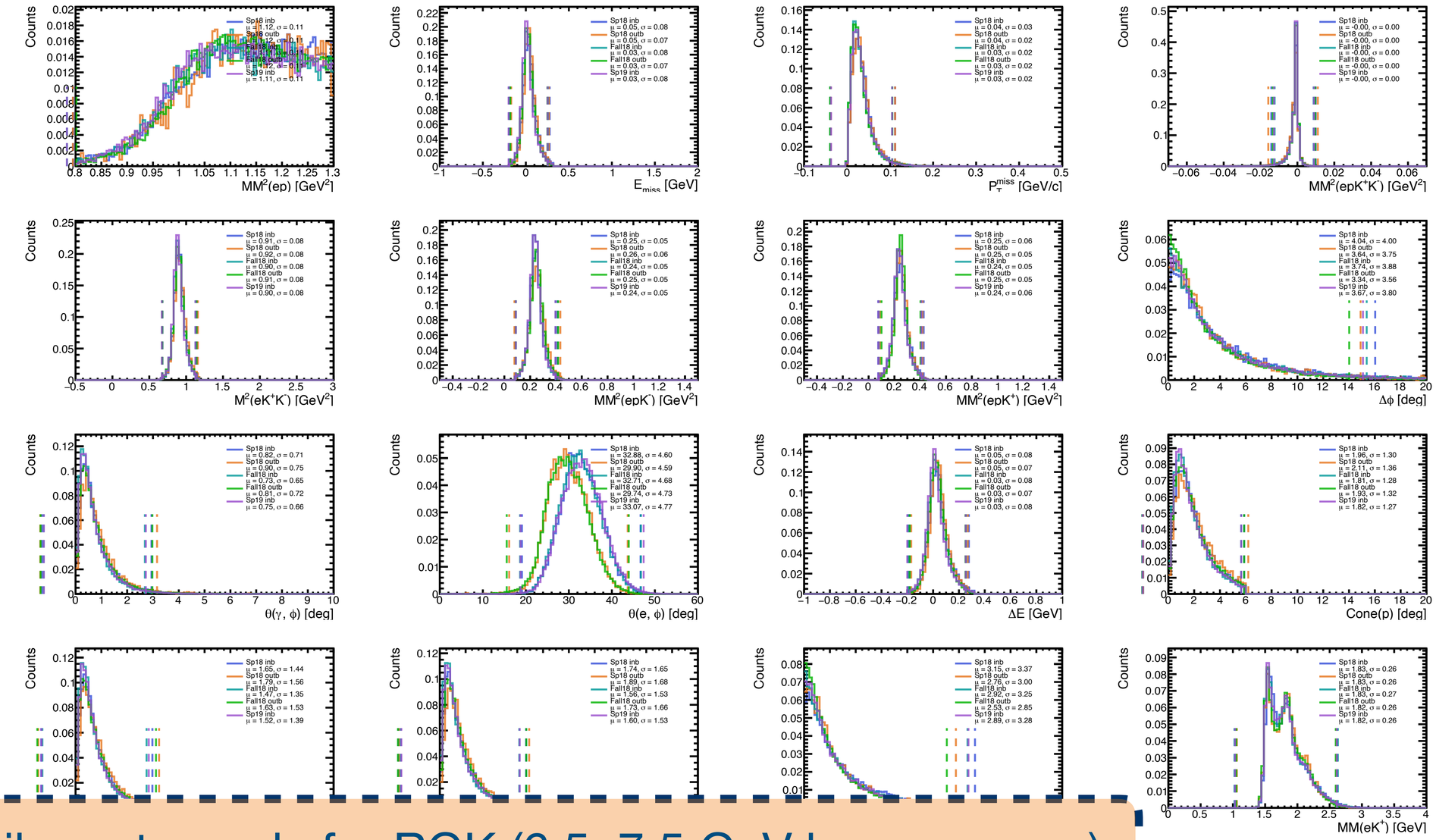


Thank you for your time!

Exclusivity cuts for further refinements

- Exclusivity variables are prior to phi mass peak cut
- Exclusivity cuts

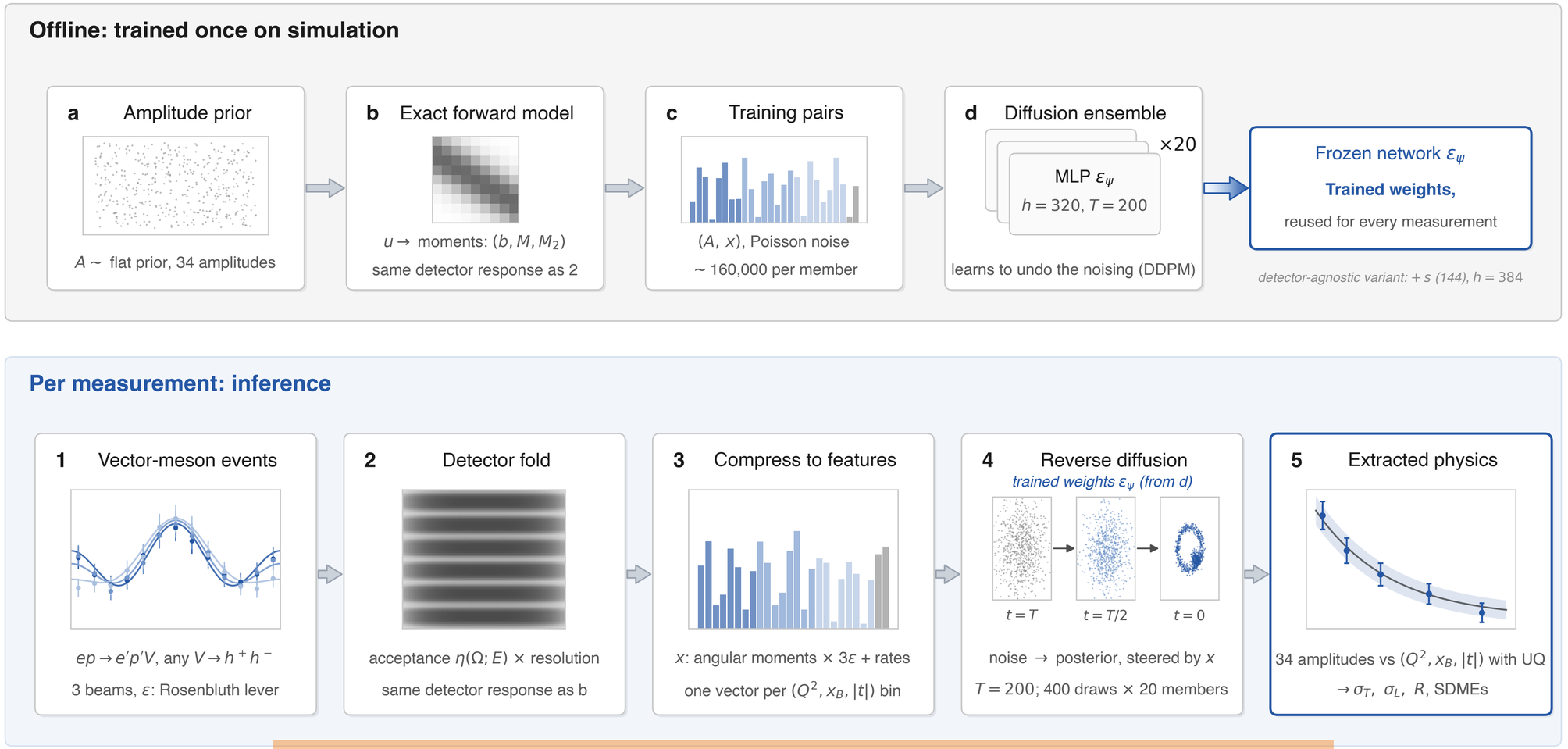
$E_{miss} \in [-0.0075, 0.32]$ GeV
$P_{Tmiss} < 0.11$ GeV
$Mx^2\,(eK^+K^-) \in [0.64, 1.1664]$ GeV^2
$Mx^2\,(epK^+K^-) < 0.0075$ GeV^2
$Mx^2\,(epK^-) \in [0.08, 0.48]$ GeV^2
$Mx^2\,(epK^+) \in [0.08, 0.48]$ GeV^2
cone angles Kp/Km/p < 6 deg
coplanarity < 15 degrees



Similar cuts apply for RGK (6.5, 7.5 GeV beam energy)

Work flow for extraction

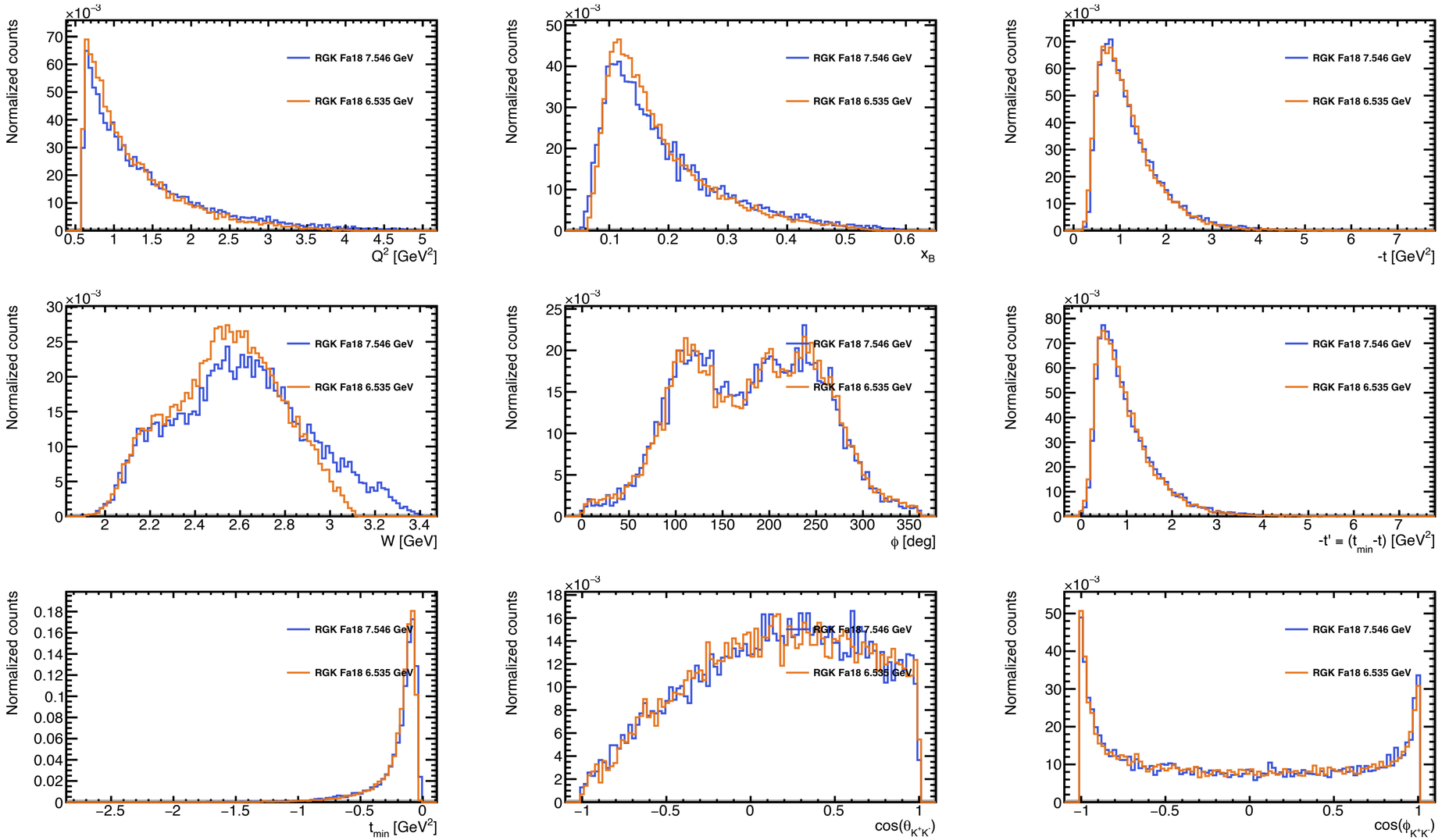
- **A conditional diffusion model:** $q_\psi(u \mid x)$ — the third neural route, twin of the normalizing-flow NPE.
- Different engine: iterative denoising instead of one invertible map (flexible, correlated posteriors).



Recent work B. Singh et al arXiv:2608.27683 [nucl-ex] (2026)

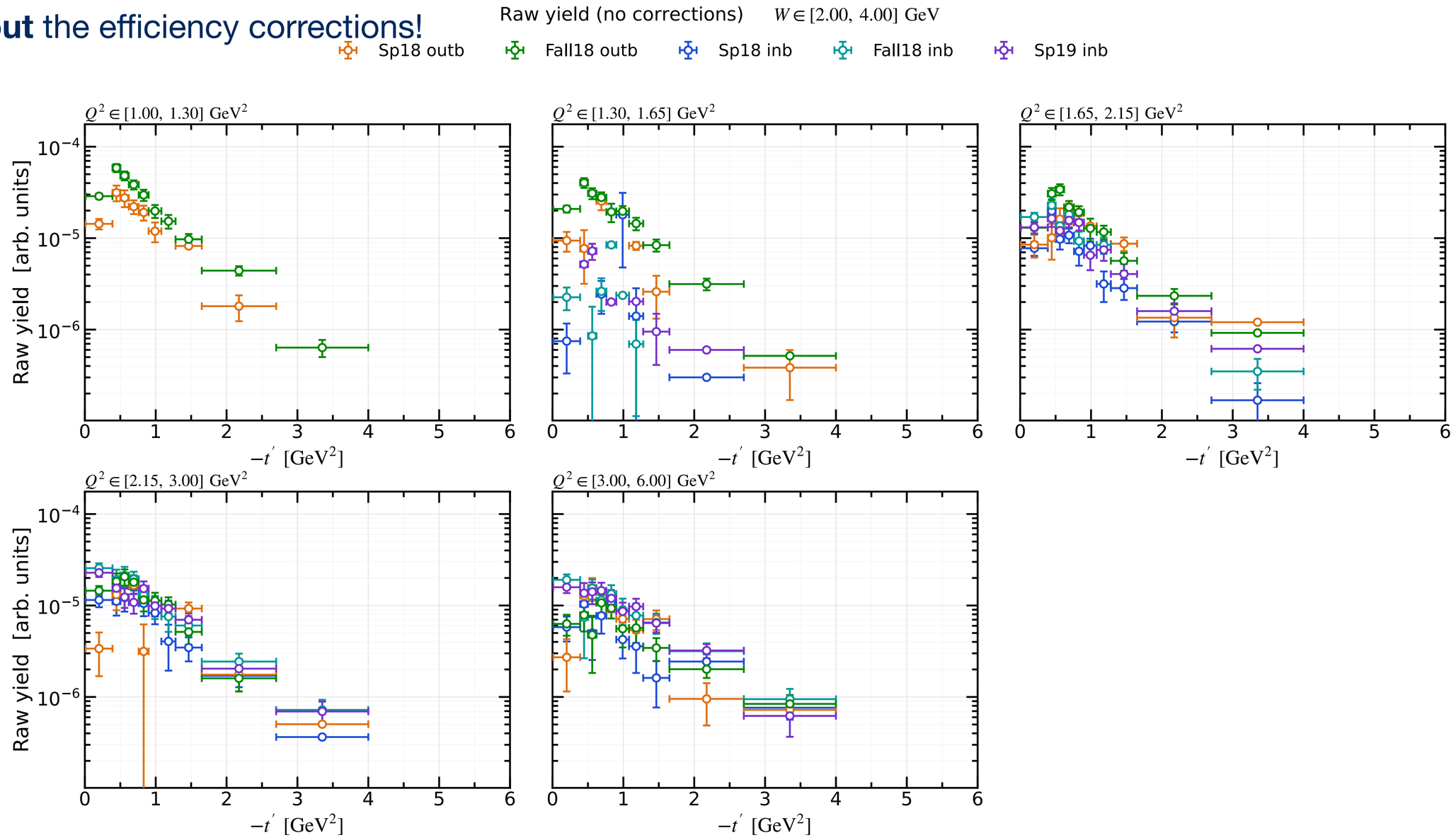
DVEP Kinematics: RGK

- W distribution becomes slightly smaller for 6.5 GeV data but overall they look comparable and similar to RGA



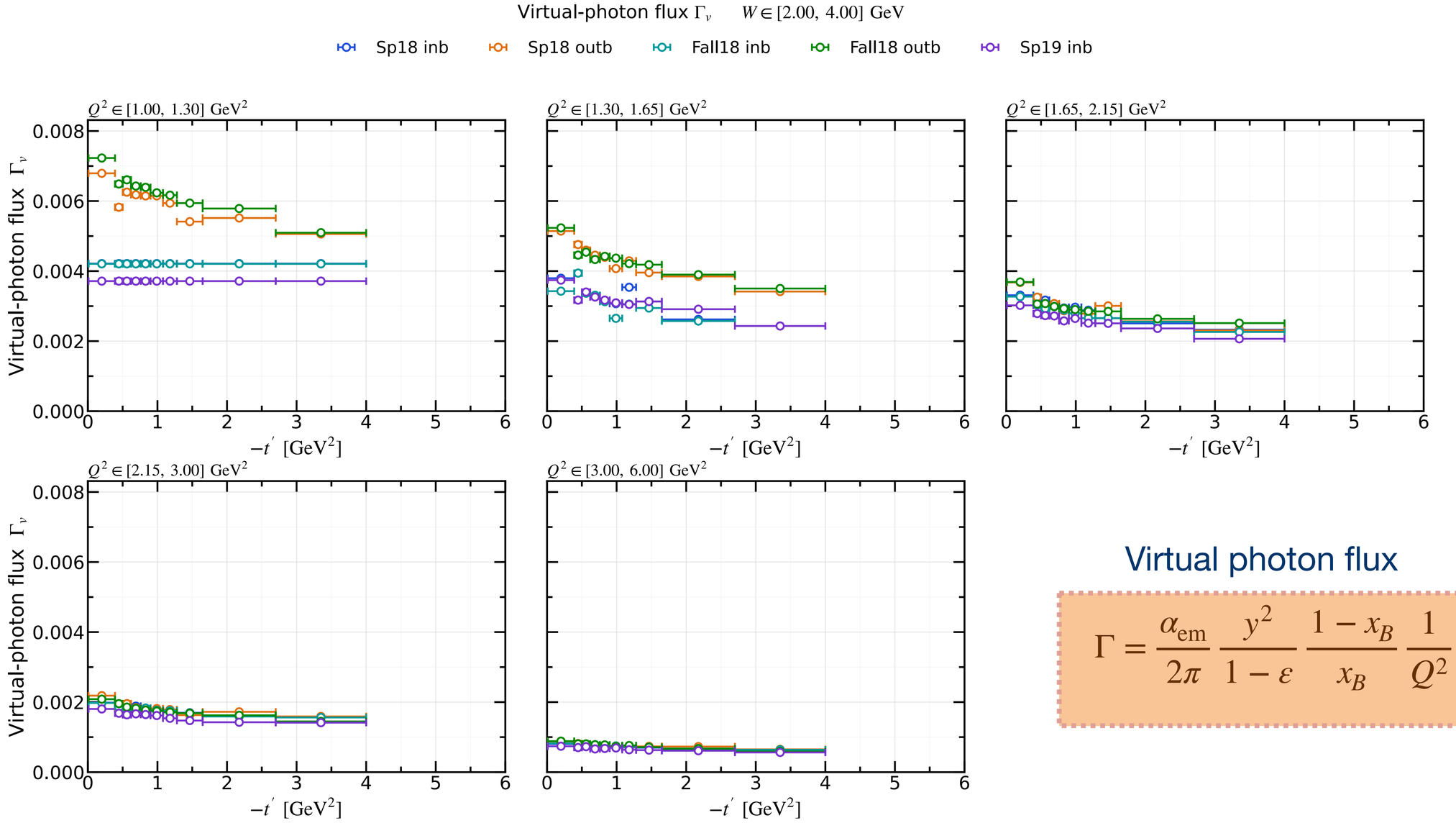
The raw yields RGA

- **Without** the efficiency corrections!



Virtual Photon Flux correction: RGA

- Each kinematics point carry virtual photon flux correction

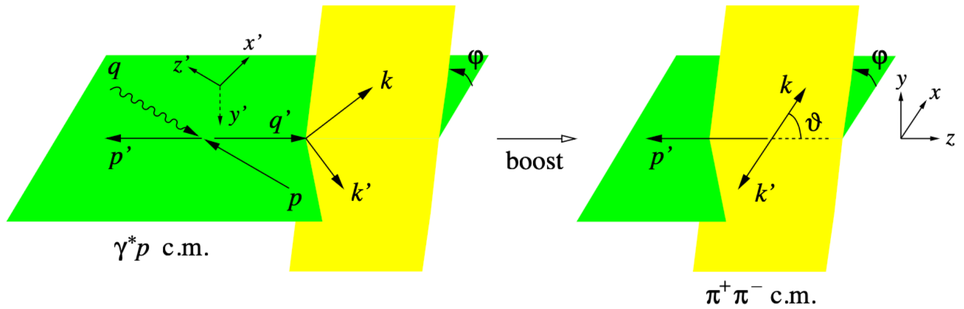


Virtual photon flux

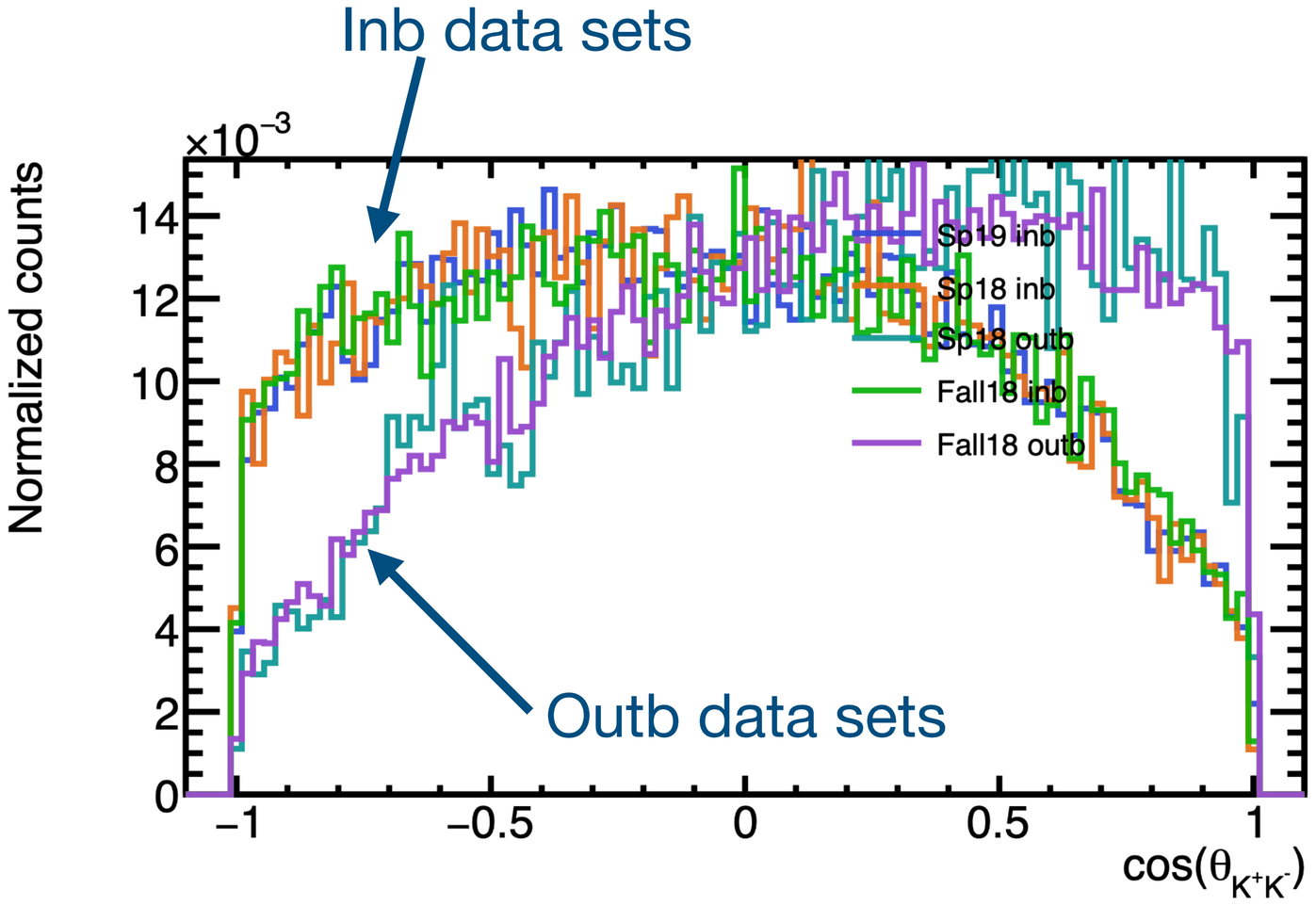
$$\Gamma = \frac{\alpha_{\mathrm{em}}}{2\pi} \frac{y^2}{1-\varepsilon} \frac{1-x_B}{x_B} \frac{1}{Q^2}$$

Challenge : acceptance effects

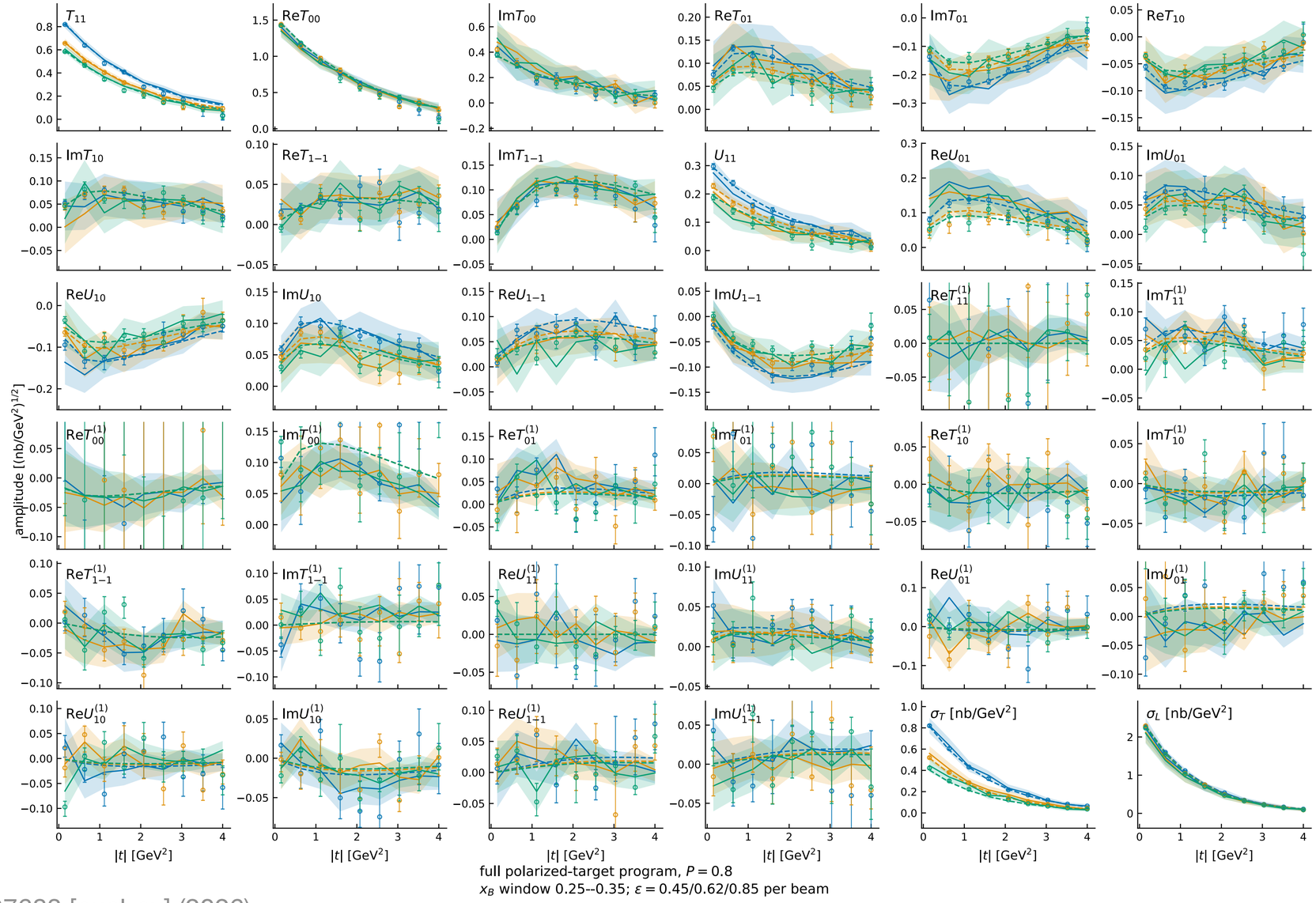
- Vector meson with spin 1 possible decay is expected to be a non-flat distribution



Markus Diehl JHEP09(2007)064



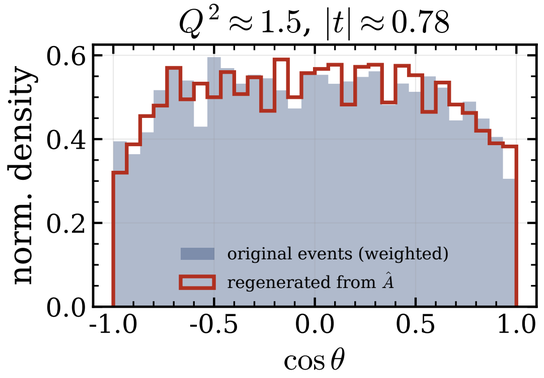
Longitudinally+transversely polarized target (ρ^0)

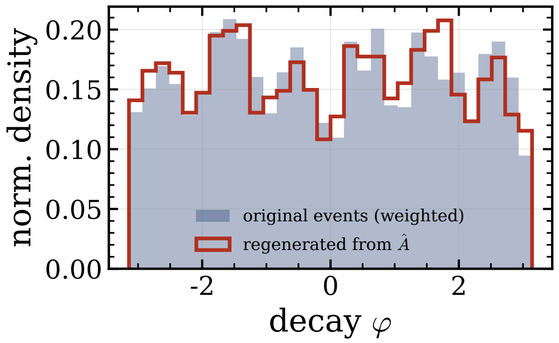


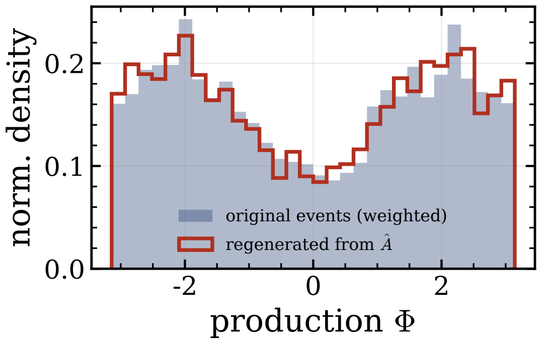
B. Singh et al arXiv:2608.27683 [nucl-ex] (2026)

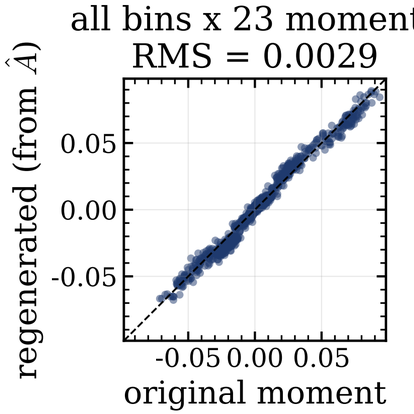
A closure loop test

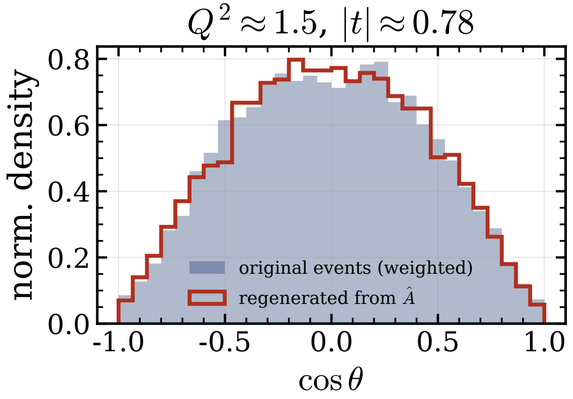
- Consider N event sample for phi and rho0
- Pass it to inference stage, get the amplitudes, use those amplitudes to generate the events and compare

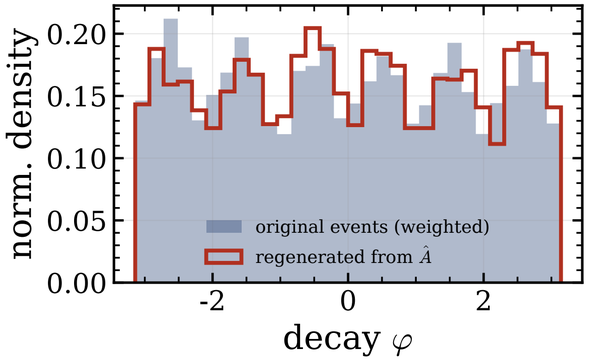


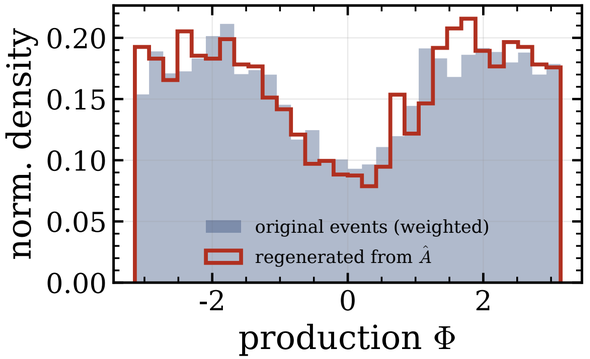


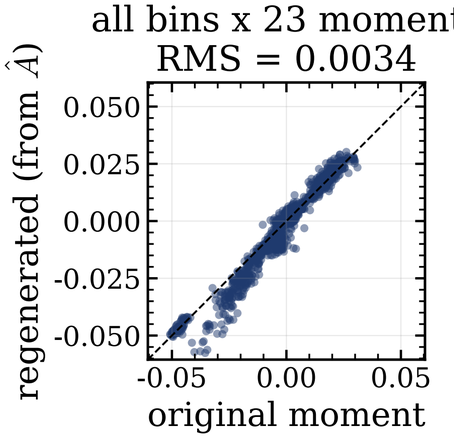






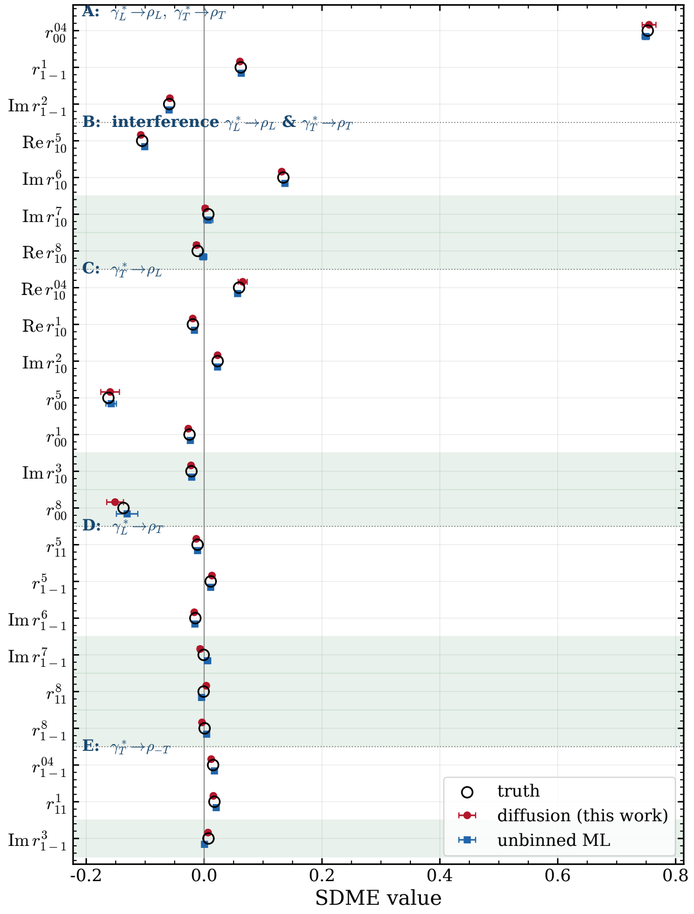


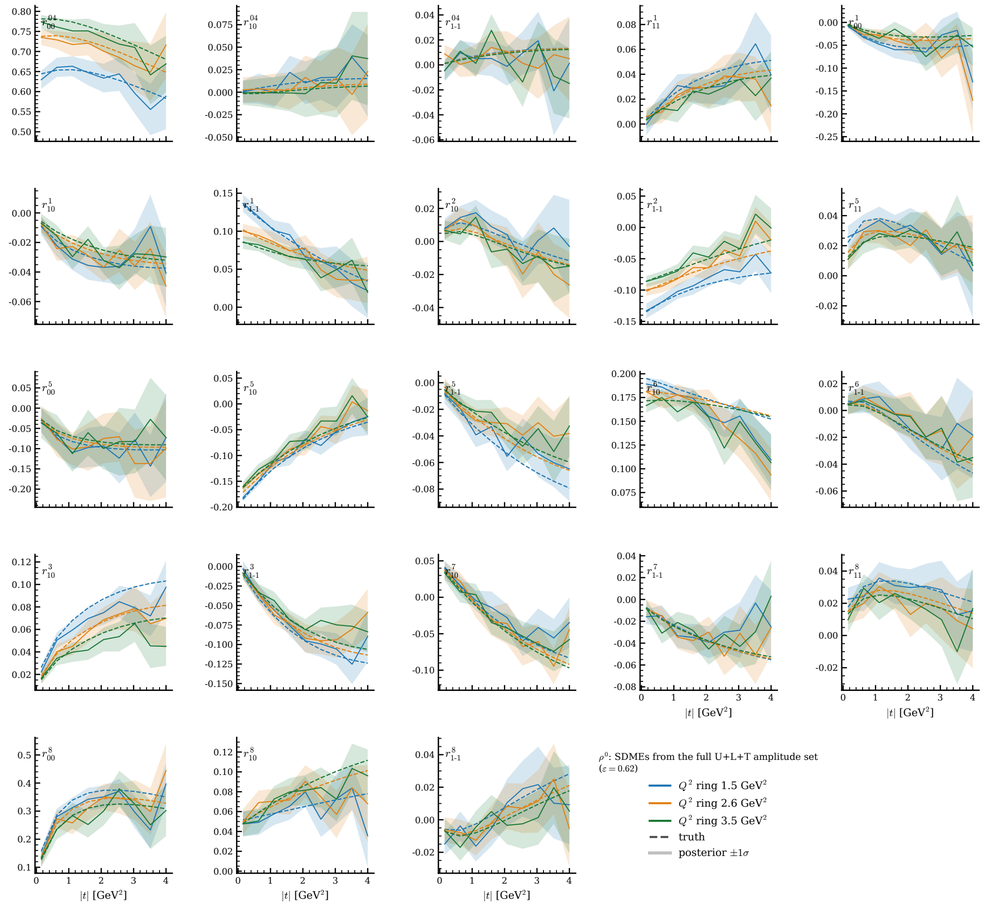




SDMEs just one case in the paper

- 23 SDMEs in the COMPASS/HERMES (A–E by helicity transition), at a representative bin (Q_z=2.4, |t|=0.2 GeV², ε=0.8)
- Three independent results overlap: the diffusion posterior (red, error bars = total statistical ⊕model uncertainty), an unbinned maximum-likelihood fit of the same events (blue), and the injected truth (open circles).





Multi-Detector Model

- We train over a family, not a detector but 140 detectors
  - 16 random smooth fields: log-acceptance as a random low-order harmonic expansion through a logistic
  - a random resolution matrix
  - 12 hard-edged multi-sector geometries with random sector counts (4, 5, 7, 8), dead gaps and forward cuts
  - 16 deliberately hostile stress geometries beyond the nominal range
  - Rest smooth functions
- Network does not know which one it is: network learns from but through the measured response
  - through measured responses: how the detector folds the amplitudes into moments and rates

One network learns $q\psi(A \mid x, s)$ over the whole family. We try to go close to the true detector model, however it never says true detector is unnecessary

Angular modulations

- L block alone is very large

$$W_{UL}^{LL} = -2\sqrt{\varepsilon(1+\varepsilon)}\,\sin\Phi\,\mathrm{Im}\,l_{0+}^{00} - \varepsilon\,\sin 2\Phi\,\mathrm{Im}\,l_{-+}^{00}, \tag{A11}$$

$$\begin{aligned} W_{UL}^{LT} = {} & \sqrt{\varepsilon(1+\varepsilon)}\,\sin(\Phi-\varphi)\,\mathrm{Im}\left(l_{0+}^{0+}-l_{0+}^{-0}\right) + \sin\varphi\,\mathrm{Im}\left[\left(l_{++}^{0+}-l_{++}^{-0}\right)+2\varepsilon\,l_{00}^{0+}\right] + \varepsilon\,\sin(2\Phi-\varphi)\,\mathrm{Im}\,l_{-+}^{0+} \\ & - \sqrt{\varepsilon(1+\varepsilon)}\,\sin(\Phi+\varphi)\,\mathrm{Im}\left(l_{0+}^{0-}-l_{0+}^{+0}\right) + \varepsilon\,\sin(2\Phi+\varphi)\,\mathrm{Im}\,l_{-+}^{+0}, \end{aligned} \tag{A12}$$

$$\begin{aligned} W_{UL}^{TT} = {} & \tfrac{\varepsilon}{2}\,\sin(2\Phi-2\varphi)\,\mathrm{Im}\,l_{-+}^{-+} - \sqrt{\varepsilon(1+\varepsilon)}\,\sin\Phi\,\mathrm{Im}\left(l_{0+}^{++}+l_{0+}^{--}\right) + \sqrt{\varepsilon(1+\varepsilon)}\,\sin(\Phi-2\varphi)\,\mathrm{Im}\,l_{0+}^{-+} \\ & + \sin 2\varphi\,\mathrm{Im}\left[l_{++}^{-+}+\varepsilon\,l_{00}^{-+}\right] - \varepsilon\,\sin 2\Phi\,\mathrm{Im}\,l_{-+}^{++} + \sqrt{\varepsilon(1+\varepsilon)}\,\sin(\Phi+2\varphi)\,\mathrm{Im}\,l_{0+}^{+-} \\ & + \tfrac{\varepsilon}{2}\,\sin(2\Phi+2\varphi)\,\mathrm{Im}\,l_{-+}^{+-}, \end{aligned} \tag{A13}$$

$$W_{LL}^{LL} = 2\sqrt{\varepsilon(1-\varepsilon)}\,\cos\Phi\,\mathrm{Re}\,l_{0+}^{00} - \sqrt{1-\varepsilon^2}\,\mathrm{Re}\,l_{++}^{00}, \tag{A14}$$

$$W_{LL}^{LT} = -\sqrt{\varepsilon(1-\varepsilon)}\,\cos(\Phi-\varphi)\,\mathrm{Re}\left(l_{0+}^{0+}-l_{0+}^{-0}\right) + \sqrt{1-\varepsilon^2}\,\cos\varphi\,\mathrm{Re}\left(l_{++}^{0+}-l_{++}^{-0}\right) + \sqrt{\varepsilon(1-\varepsilon)}\,\cos(\Phi+\varphi)\,\mathrm{Re}\left(l_{0+}^{0-}-l_{0+}^{+0}\right), \tag{A15}$$

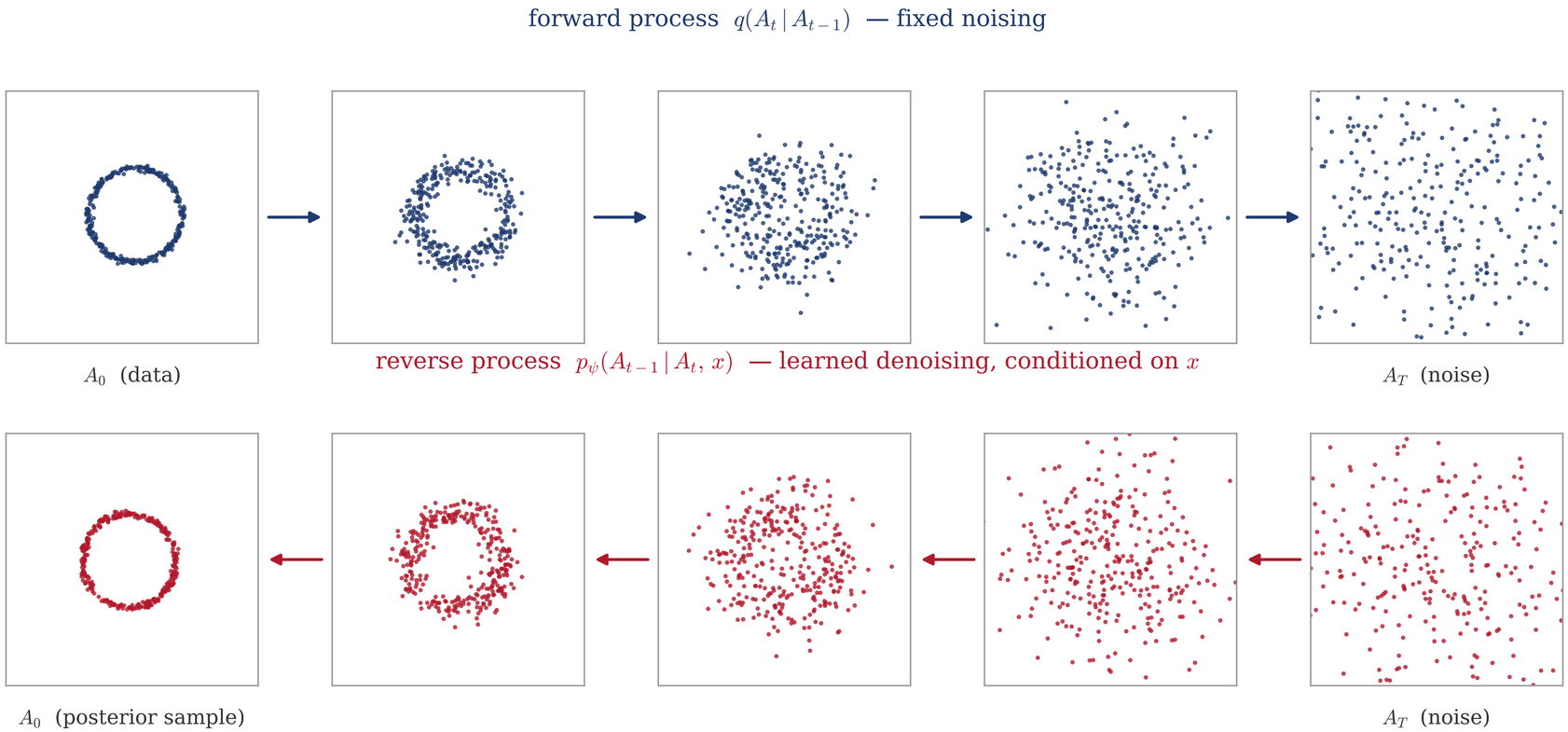
$$\begin{aligned} W_{LL}^{TT} = {} & -\tfrac{\sqrt{1-\varepsilon^2}}{2}\,\mathrm{Re}\left[l_{++}^{++}+l_{++}^{--}\right] + \sqrt{\varepsilon(1-\varepsilon)}\,\cos\Phi\,\mathrm{Re}\left(l_{0+}^{++}+l_{0+}^{--}\right) - \sqrt{\varepsilon(1-\varepsilon)}\,\cos(\Phi-2\varphi)\,\mathrm{Re}\,l_{0+}^{-+} \\ & + \sqrt{1-\varepsilon^2}\,\cos 2\varphi\,\mathrm{Re}\,l_{++}^{-+} - \sqrt{\varepsilon(1-\varepsilon)}\,\cos(\Phi+2\varphi)\,\mathrm{Re}\,l_{0+}^{+-}. \end{aligned} \tag{A16}$$

All relations of structure function and amplitudes

coeff.	SW SDME	u-combination	amplitude content (T, U)
$\mathcal{U}$: unpolarized, Φ-independent			
A_{00}	r^{04}_{00}	$u^{00}_{++}+\varepsilon u^{00}_{00}$	$\lvert T_{01}\rvert^2+\varepsilon\lvert T_{00}\rvert^2+\lvert U_{01}\rvert^2$
A_{10}	$\mathrm{Re}\, r^{04}_{10}$	$\frac{1}{2}\mathrm{Re}(u^{0+}_{++}-u^{-0}_{++})+\varepsilon\mathrm{Re}\, u^{0+}_{00}$	$\varepsilon\mathrm{Re}\, T_{00}T^*_{10}+\frac{1}{2}\mathrm{Re}\, T_{01}T^*_{11}-\frac{1}{2}\mathrm{Re}\, T_{01}T^*_{1\text{-}1}+\frac{1}{2}\mathrm{Re}\, U_{01}U^*_{11}+\frac{1}{2}\mathrm{Re}\, U_{01}U^*_{1\text{-}1}$
$A_{1\text{-}1}$	$r^{04}_{1\text{-}1}$	$\mathrm{Re}\, u^{-+}_{++}+\varepsilon\mathrm{Re}\, u^{-+}_{00}$	$\mathrm{Re}\, T_{11}T^*_{1\text{-}1}-\varepsilon\lvert T_{10}\rvert^2-\mathrm{Re}\, U_{11}U^*_{1\text{-}1}+\varepsilon\lvert U_{10}\rvert^2$
$\mathcal{L}_2$: linear polarization $(\cos 2\Phi, \sin 2\Phi)$			
B^c_{11}	r^1_{11}	$\mathrm{Re}\, u^{++}_{-+}$	$\mathrm{Re}\, T_{11}T^*_{1\text{-}1}+\mathrm{Re}\, U_{11}U^*_{1\text{-}1}$
B^c_{00}	r^1_{00}	u^{00}_{-+}	$-\lvert T_{01}\rvert^2+\lvert U_{01}\rvert^2$
B^c_{10}	$\mathrm{Re}\, r^1_{10}$	$\frac{1}{2}\mathrm{Re}(u^{0+}_{-+}+u^{+0}_{-+})$	$-\frac{1}{2}\mathrm{Re}\, T_{01}T^*_{11}+\frac{1}{2}\mathrm{Re}\, T_{01}T^*_{1\text{-}1}+\frac{1}{2}\mathrm{Re}\, U_{01}U^*_{11}+\frac{1}{2}\mathrm{Re}\, U_{01}U^*_{1\text{-}1}$
$B^c_{1\text{-}1}$	$r^1_{1\text{-}1}$	$\frac{1}{2}(u^{-+}_{-+}+u^{+-}_{-+})$	$\frac{1}{2}(\lvert T_{11}\rvert^2+\lvert T_{1\text{-}1}\rvert^2)-\frac{1}{2}(\lvert U_{11}\rvert^2+\lvert U_{1\text{-}1}\rvert^2)$
B^s_{10}	$\mathrm{Im}\, r^2_{10}$	$\frac{1}{2}\mathrm{Re}(u^{+0}_{-+}-u^{0+}_{-+})$	$\frac{1}{2}\mathrm{Re}\, T_{01}T^*_{11}+\frac{1}{2}\mathrm{Re}\, T_{01}T^*_{1\text{-}1}-\frac{1}{2}\mathrm{Re}\, U_{01}U^*_{11}+\frac{1}{2}\mathrm{Re}\, U_{01}U^*_{1\text{-}1}$
$B^s_{1\text{-}1}$	$\mathrm{Im}\, r^2_{1\text{-}1}$	$\frac{1}{2}(u^{+-}_{-+}-u^{-+}_{-+})$	$\frac{1}{2}(\lvert T_{1\text{-}1}\rvert^2-\lvert T_{11}\rvert^2)+\frac{1}{2}(\lvert U_{11}\rvert^2-\lvert U_{1\text{-}1}\rvert^2)$
$\mathcal{L}_1$: L–T interference $(\cos\Phi, \sin\Phi)$			
C^c_{11}	r^5_{11}	$-\frac{1}{\sqrt{2}}(u^{++}_{0+}+u^{--}_{0+})$	$\frac{1}{\sqrt{2}}(\mathrm{Re}\, T_{10}T^*_{1\text{-}1}-\mathrm{Re}\, T_{10}T^*_{11})+\frac{1}{\sqrt{2}}(\mathrm{Re}\, U_{10}U^*_{1\text{-}1}-\mathrm{Re}\, U_{10}U^*_{11})$
C^c_{00}	r^5_{00}	$-\sqrt{2}\,\mathrm{Re}\, u^{00}_{0+}$	$-\sqrt{2}\,\mathrm{Re}\, T_{00}T^*_{01}$
C^c_{10}	$\mathrm{Re}\, r^5_{10}$	$\frac{1}{2\sqrt{2}}\mathrm{Re}[(u^{0-}_{0+}-u^{+0}_{0+})-(u^{0+}_{0+}-u^{-0}_{0+})]$	$\frac{1}{2\sqrt{2}}(\mathrm{Re}\, T_{00}T^*_{1\text{-}1}-\mathrm{Re}\, T_{00}T^*_{11}-2\mathrm{Re}\, T_{01}T^*_{10})$
$C^c_{1\text{-}1}$	$r^5_{1\text{-}1}$	$-\frac{1}{\sqrt{2}}\mathrm{Re}(u^{-+}_{0+}+u^{+-}_{0+})$	$\frac{1}{\sqrt{2}}(\mathrm{Re}\, T_{10}T^*_{11}-\mathrm{Re}\, T_{10}T^*_{1\text{-}1})+\frac{1}{\sqrt{2}}(\mathrm{Re}\, U_{10}U^*_{1\text{-}1}-\mathrm{Re}\, U_{10}U^*_{11})$
C^s_{10}	$\mathrm{Im}\, r^6_{10}$	$\frac{1}{2\sqrt{2}}\mathrm{Re}[(u^{0+}_{0+}-u^{-0}_{0+})+(u^{0-}_{0+}-u^{+0}_{0+})]$	$\frac{1}{2\sqrt{2}}(\mathrm{Re}\, T_{00}T^*_{11}+\mathrm{Re}\, T_{00}T^*_{1\text{-}1})-\frac{1}{\sqrt{2}}\mathrm{Re}\, U_{01}U^*_{10}$
$C^s_{1\text{-}1}$	$\mathrm{Im}\, r^6_{1\text{-}1}$	$\frac{1}{\sqrt{2}}\mathrm{Re}(u^{-+}_{0+}-u^{+-}_{0+})$	$-\frac{1}{\sqrt{2}}(\mathrm{Re}\, T_{10}T^*_{11}+\mathrm{Re}\, T_{10}T^*_{1\text{-}1})+\frac{1}{\sqrt{2}}(\mathrm{Re}\, U_{10}U^*_{11}+\mathrm{Re}\, U_{10}U^*_{1\text{-}1})$
$\mathcal{B}$: beam spin, Φ-independent *			
D_{10}	$\mathrm{Im}\, r^3_{10}{}^\star$	$-\frac{1}{2}\mathrm{Im}(u^{0+}_{++}-u^{-0}_{++})$	$-\frac{1}{2}(\mathrm{Im}\, T_{01}T^*_{11}+\mathrm{Im}\, T_{01}T^*_{1\text{-}1})-\frac{1}{2}\mathrm{Im}\, U_{01}U^*_{11}+\frac{1}{2}\mathrm{Im}\, U_{01}U^*_{1\text{-}1}$
$D_{1\text{-}1}$	$\mathrm{Im}\, r^3_{1\text{-}1}{}^\star$	$-\mathrm{Im}\, u^{-+}_{++}$	$\mathrm{Im}\, T_{11}T^*_{1\text{-}1}-\mathrm{Im}\, U_{11}U^*_{1\text{-}1}$
$\mathcal{B}_1$: beam spin $\times$ L–T interference *			
E^c_{10}	$\mathrm{Im}\, r^7_{10}{}^\star$	$\frac{1}{2\sqrt{2}}\mathrm{Im}[(u^{0+}_{0+}-u^{-0}_{0+})+(u^{0-}_{0+}-u^{+0}_{0+})]$	$\frac{1}{2\sqrt{2}}(\mathrm{Im}\, T_{00}T^*_{11}+\mathrm{Im}\, T_{00}T^*_{1\text{-}1})+\frac{1}{\sqrt{2}}\mathrm{Im}\, U_{01}U^*_{10}$
$E^c_{1\text{-}1}$	$\mathrm{Im}\, r^7_{1\text{-}1}{}^\star$	$\frac{1}{\sqrt{2}}\mathrm{Im}(u^{-+}_{0+}-u^{+-}_{0+})$	$-\frac{1}{\sqrt{2}}(\mathrm{Im}\, T_{10}T^*_{11}+\mathrm{Im}\, T_{10}T^*_{1\text{-}1})+\frac{1}{\sqrt{2}}(\mathrm{Im}\, U_{10}U^*_{11}+\mathrm{Im}\, U_{10}U^*_{1\text{-}1})$
E^s_{11}	$r^8_{11}{}^\star$	$\frac{1}{\sqrt{2}}\mathrm{Im}(u^{++}_{0+}+u^{--}_{0+})$	$\frac{1}{\sqrt{2}}(\mathrm{Im}\, T_{10}T^*_{11}-\mathrm{Im}\, T_{10}T^*_{1\text{-}1})+\frac{1}{\sqrt{2}}(\mathrm{Im}\, U_{10}U^*_{11}-\mathrm{Im}\, U_{10}U^*_{1\text{-}1})$
E^s_{00}	$r^8_{00}{}^\star$	$\sqrt{2}\,\mathrm{Im}\, u^{00}_{0+}$	$\sqrt{2}\,\mathrm{Im}\, T_{00}T^*_{01}$
E^s_{10}	$\mathrm{Re}\, r^8_{10}{}^\star$	$\frac{1}{2\sqrt{2}}\mathrm{Im}[(u^{0+}_{0+}-u^{-0}_{0+})-(u^{0-}_{0+}-u^{+0}_{0+})]$	$\frac{1}{2\sqrt{2}}(\mathrm{Im}\, T_{00}T^*_{11}-\mathrm{Im}\, T_{00}T^*_{1\text{-}1}-2\mathrm{Im}\, T_{01}T^*_{10})$
$E^s_{1\text{-}1}$	$r^8_{1\text{-}1}{}^\star$	$\frac{1}{\sqrt{2}}\mathrm{Im}(u^{-+}_{0+}+u^{+-}_{0+})$	$-\frac{1}{\sqrt{2}}(\mathrm{Im}\, T_{10}T^*_{11}-\mathrm{Im}\, T_{10}T^*_{1\text{-}1})+\frac{1}{\sqrt{2}}(\mathrm{Im}\, U_{10}U^*_{11}-\mathrm{Im}\, U_{10}U^*_{1\text{-}1})$

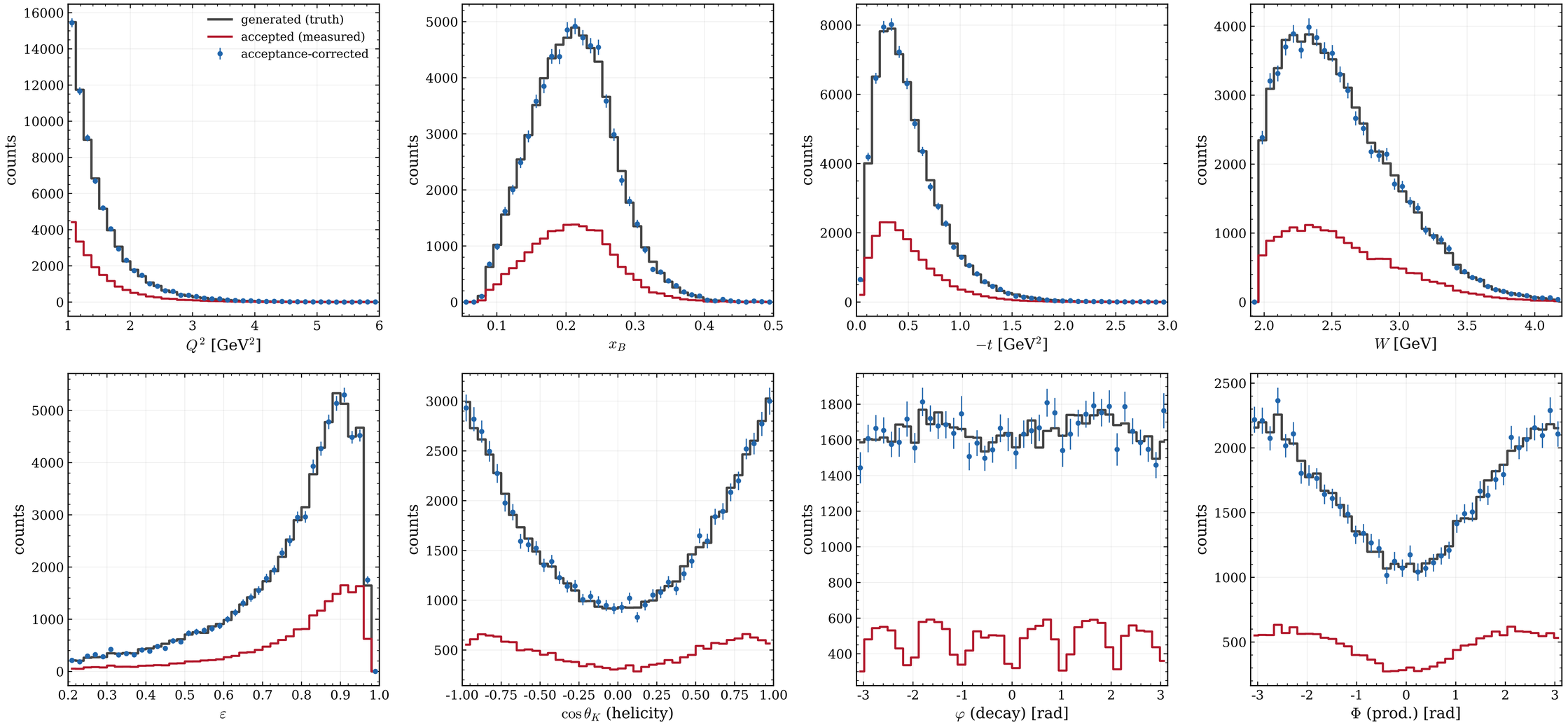
How diffusion model can help

- From those angles we want 34 numbers, the amplitude parameters that describe the spin state of the process
- Amplitudes → data is easy: we have the formula. [**New generator based on amplitudes VecGen]**
- Going data → Amplitudes is the hard INVERSE problem! A diffusion model is a tool that learns this inverse and gives honest error bars, we used **Denoising Diffusion Probabilistic Model!**



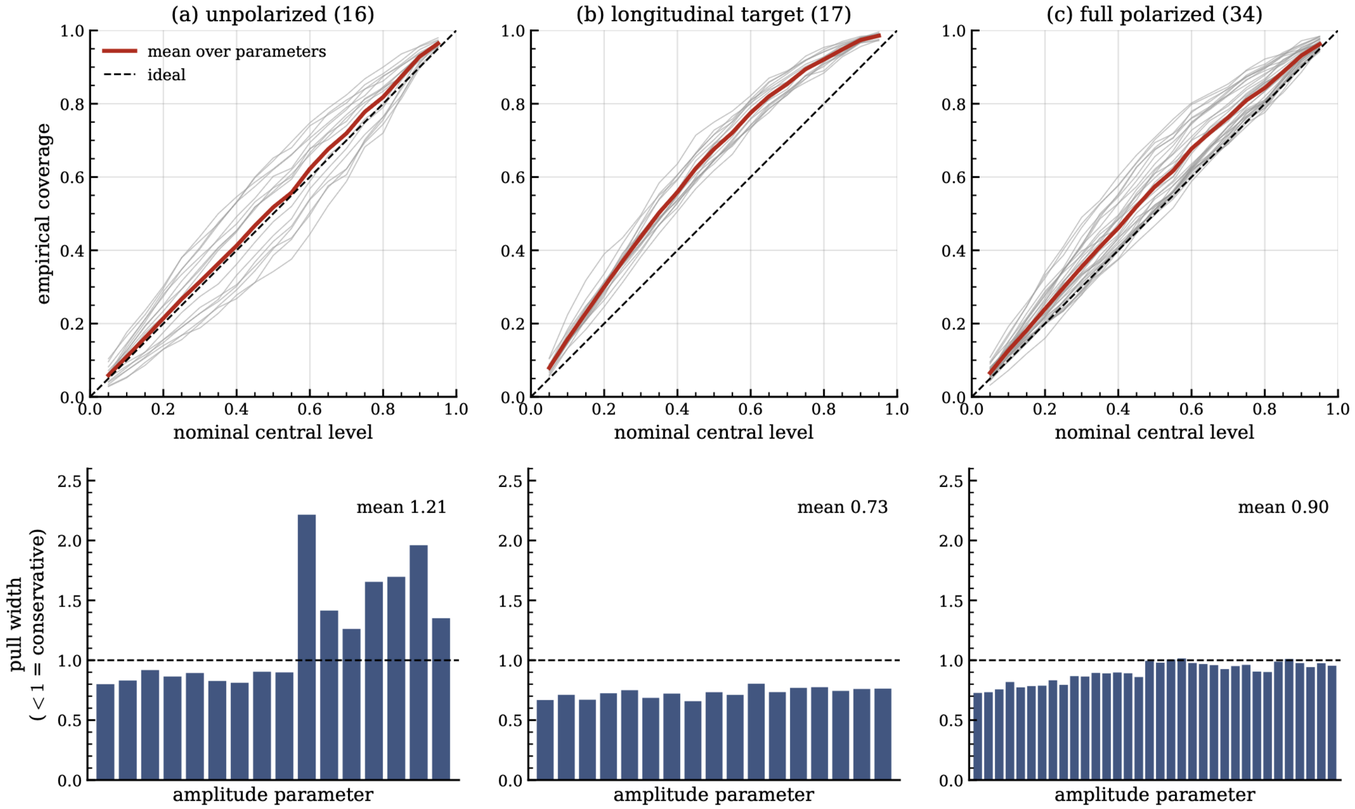
Acceptance correction to the data

- Once we extract the amplitudes we can apply inverse correction to the data and get proper acceptance corrected cross-section from the measurements

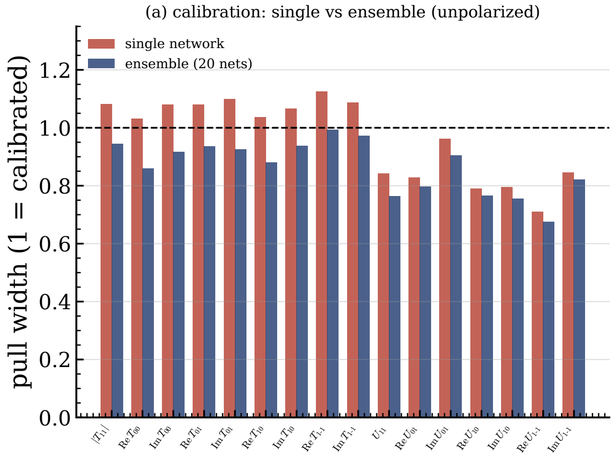


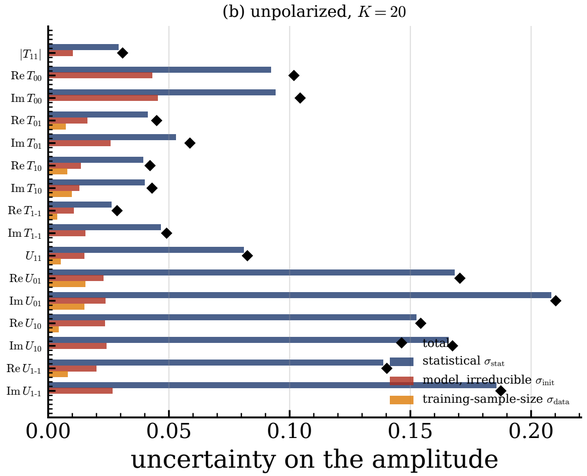
Calibration needed in case of diffusion approach

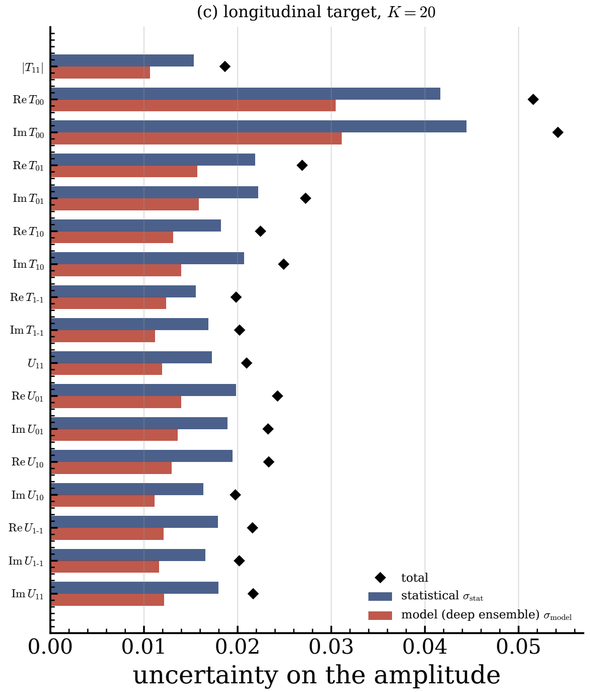
- A maximum-likelihood fit carries an asymptotic coverage guarantee through its parabolic errors
- A learned posterior $q_\phi(A|x)$ carries none, which is why the simulation-based calibration (SBC) is run before any error bar here is quoted
- SBC: draw a truth from the prior, simulate it, infer it, and rank that truth among its own posterior samples. The ranks are uniform if and only if the posterior is correctly calibrated

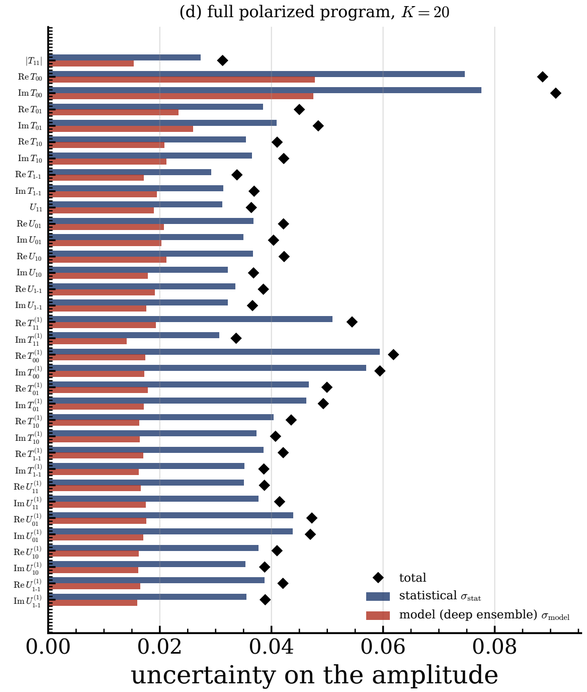


Uncertainty Quantification for all modes



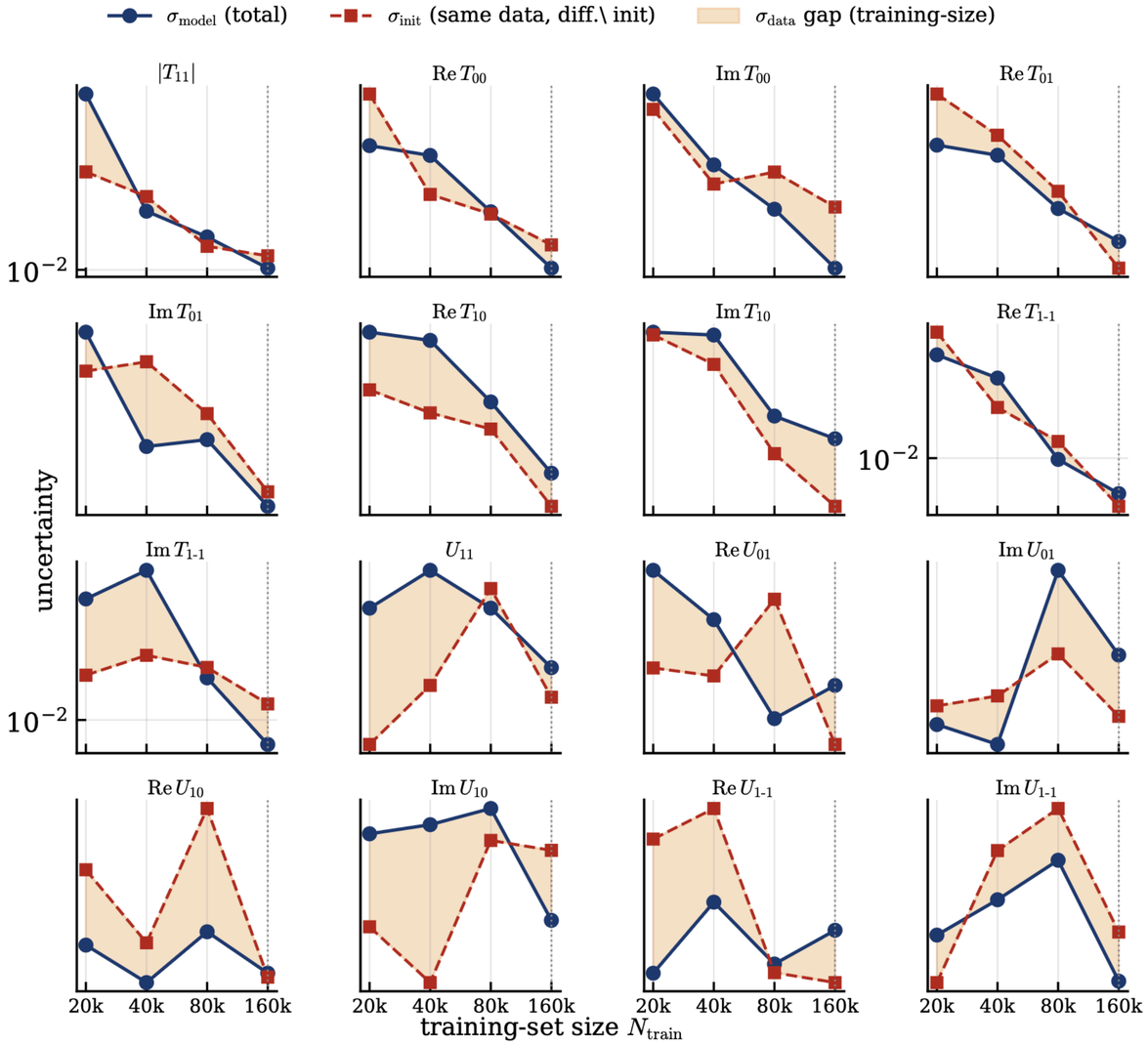






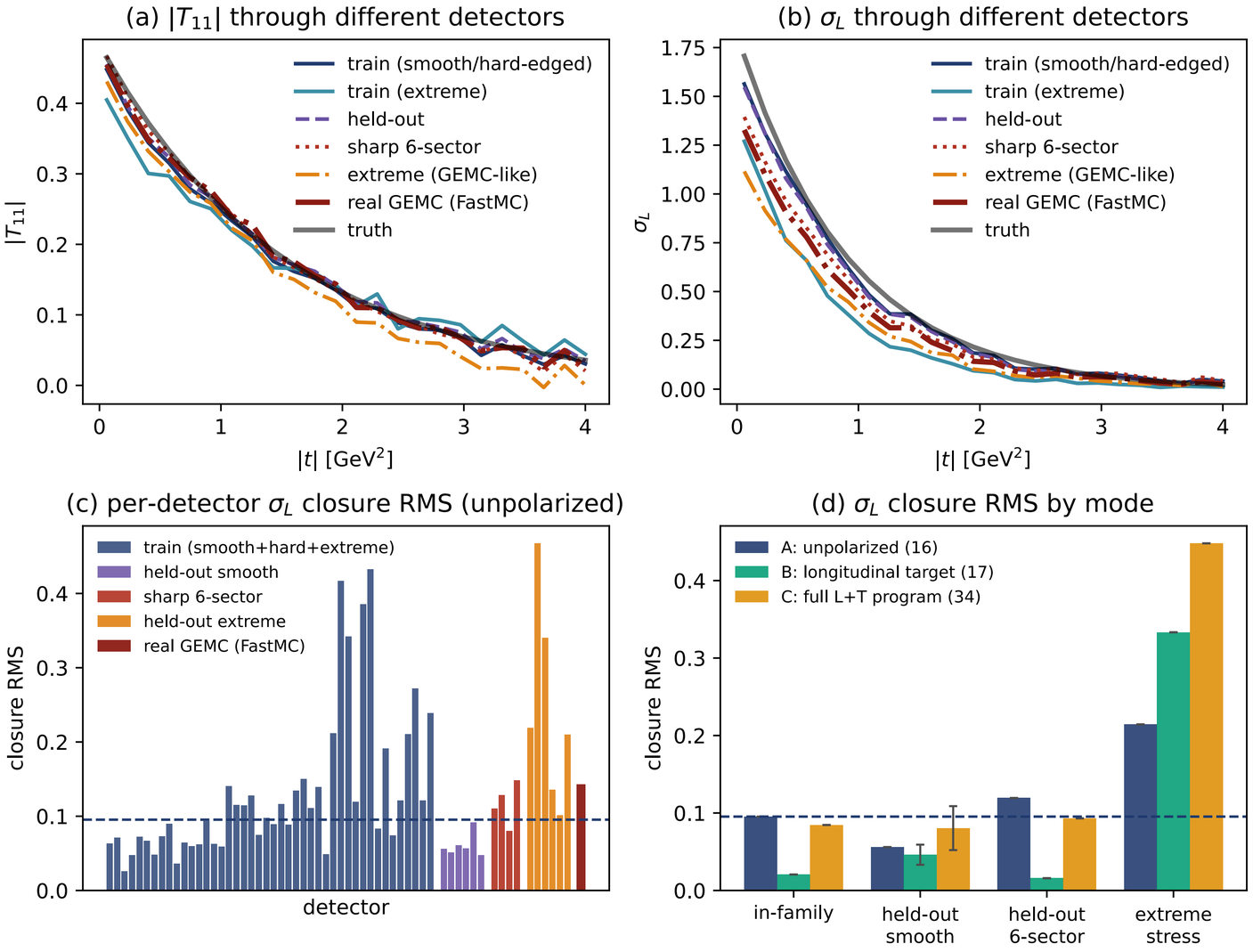
Training size uncertainties

- The dominant source is the statistical uncertainties



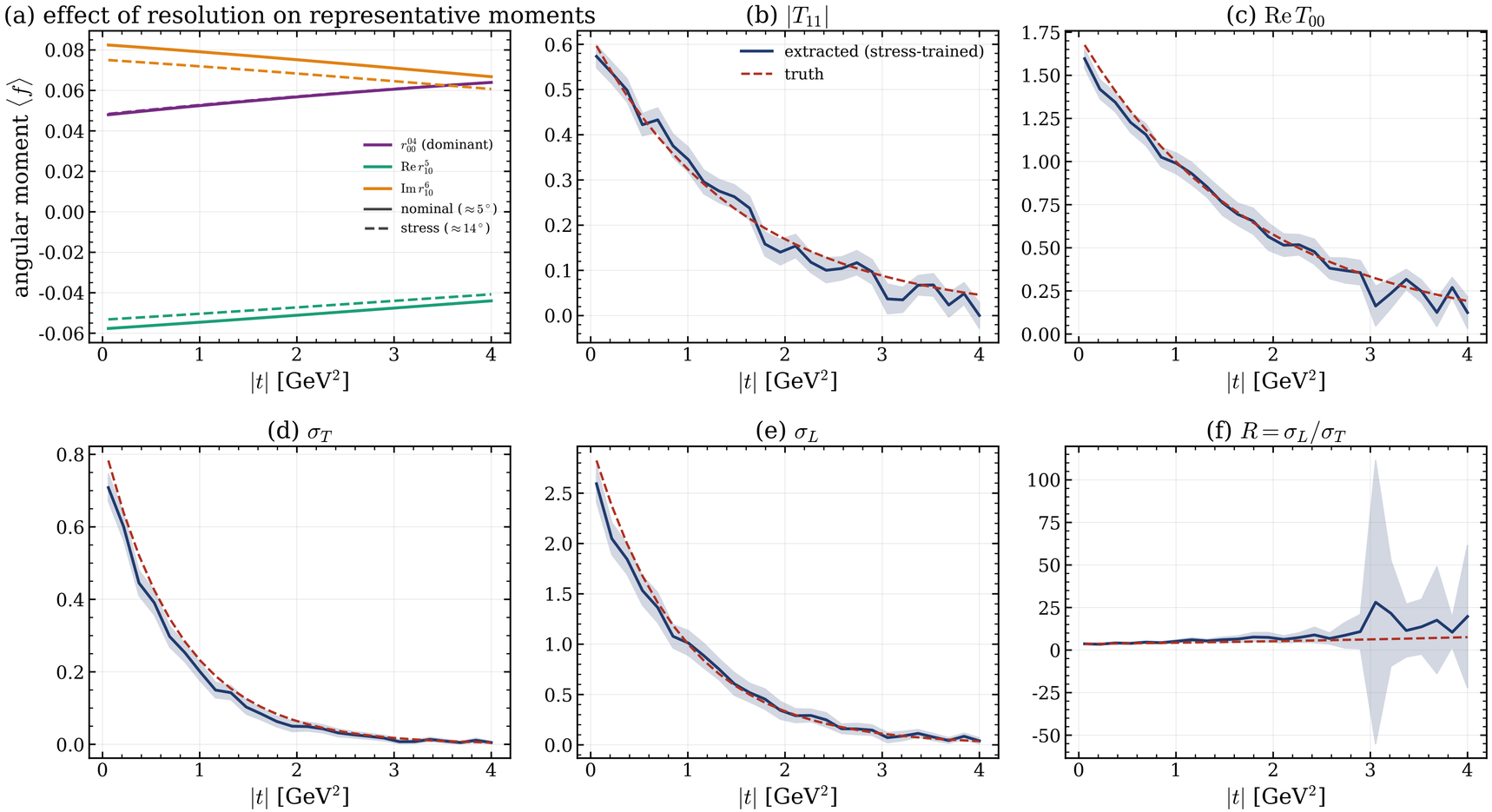
Detector amortization

- We take difference test cases for detectors which are not part of the training and extract the physics



Effects of resolution of the detector: Resolution robustness

- A realistic detector model always have finite resolutions
- The same is taken into account in the toy approach to see if this can smear the extractions

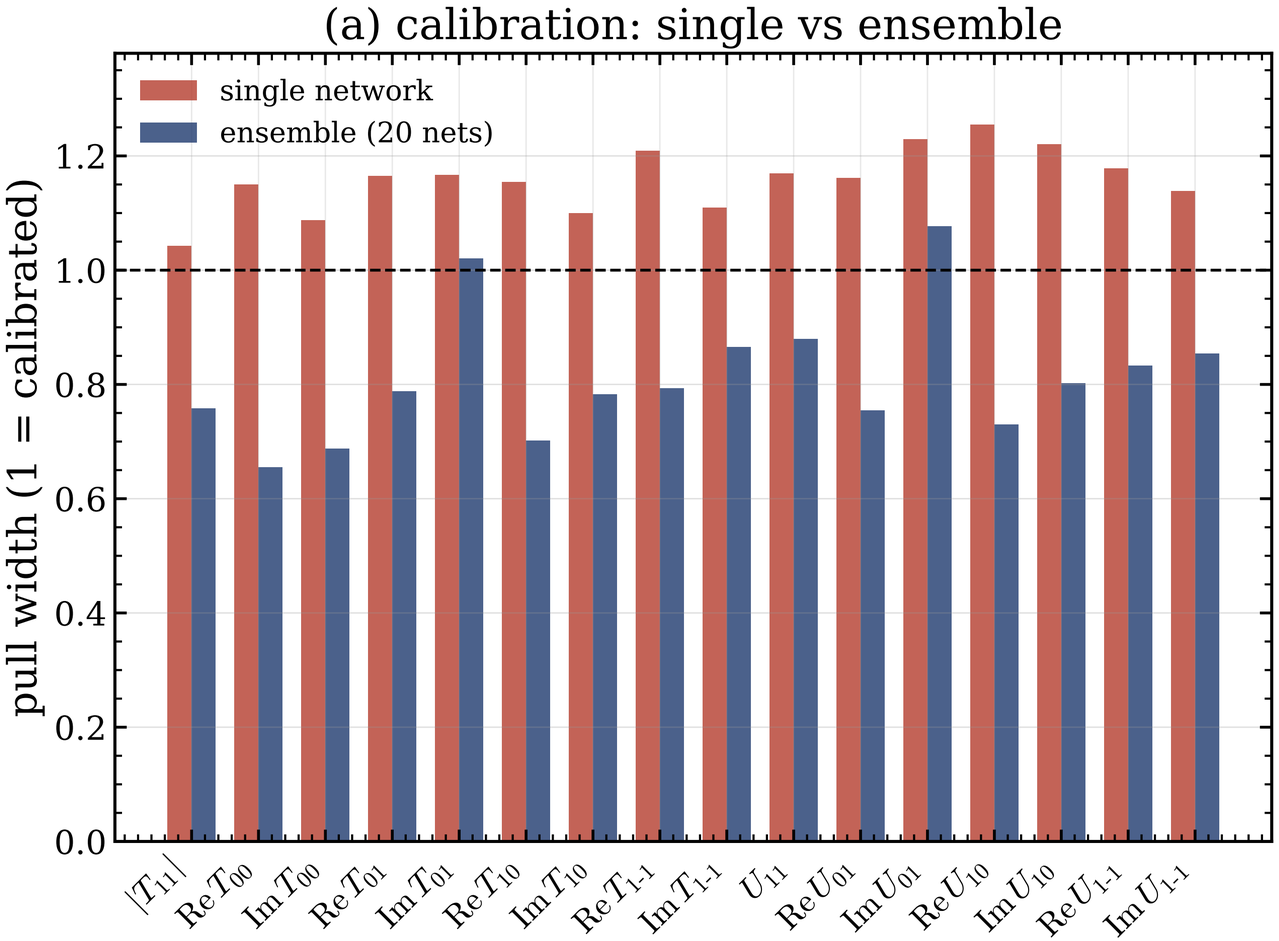


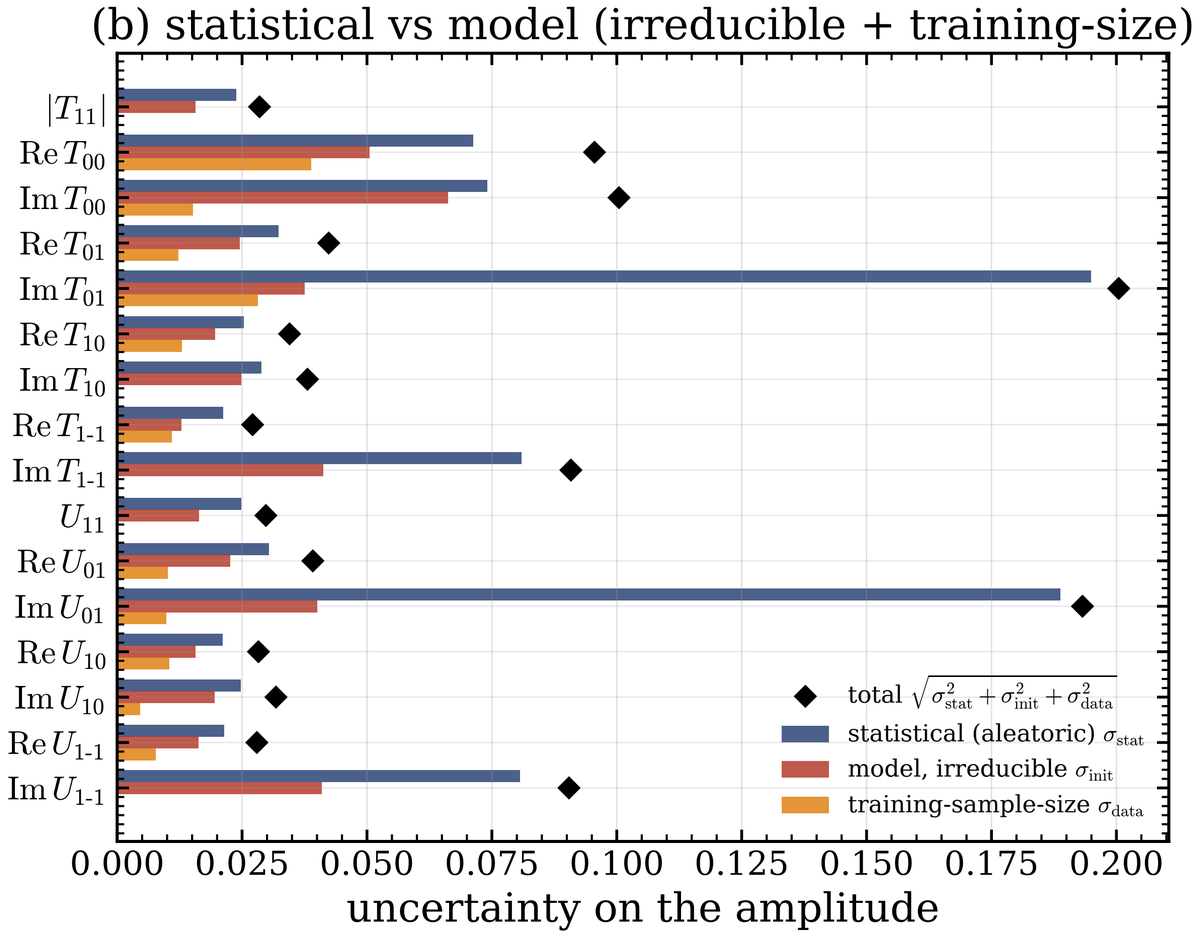
Architectural details:

- Extractor: estimator ε_ψ
  - Conditional DDPM denoiser, and deliberately a plain MLP — the conditioning vector
  - Inputs: A_t (34, amplitudes) - sinusoidal embedding · x (moments × 3ε + 3 rates) · s (144, measured detector response)
  - x and s enter through a conditioner sub-network: Linear → SiLU → Linear
  - Trunk: 4 × (Linear + SiLU), width h = 320 fixed-detector / 384 detector-amortized
  - Head: Linear → 34. Output is $\hat{\varepsilon}$, the predicted noise — same dimension as A
- - ≈ 0.9 M parameters · loss = $\|\varepsilon - \varepsilon_\psi(A_t, t, x, s)\|^2$, denoising score matching · Adam 2×10^{-4}, gradient clipping, EMA weights · K = 20 members
- Fast MC
  - Acceptance: 5 × 512 SiLU → 1 logit → P(reconstructed) to resolve the six-sector ϕ edges
  - Resolutions: 3 × 384 SiLU → 10 diagonal Gaussians over the momentum residuals (means, log-widths, mixture logits).

Diffusion model uncertainties

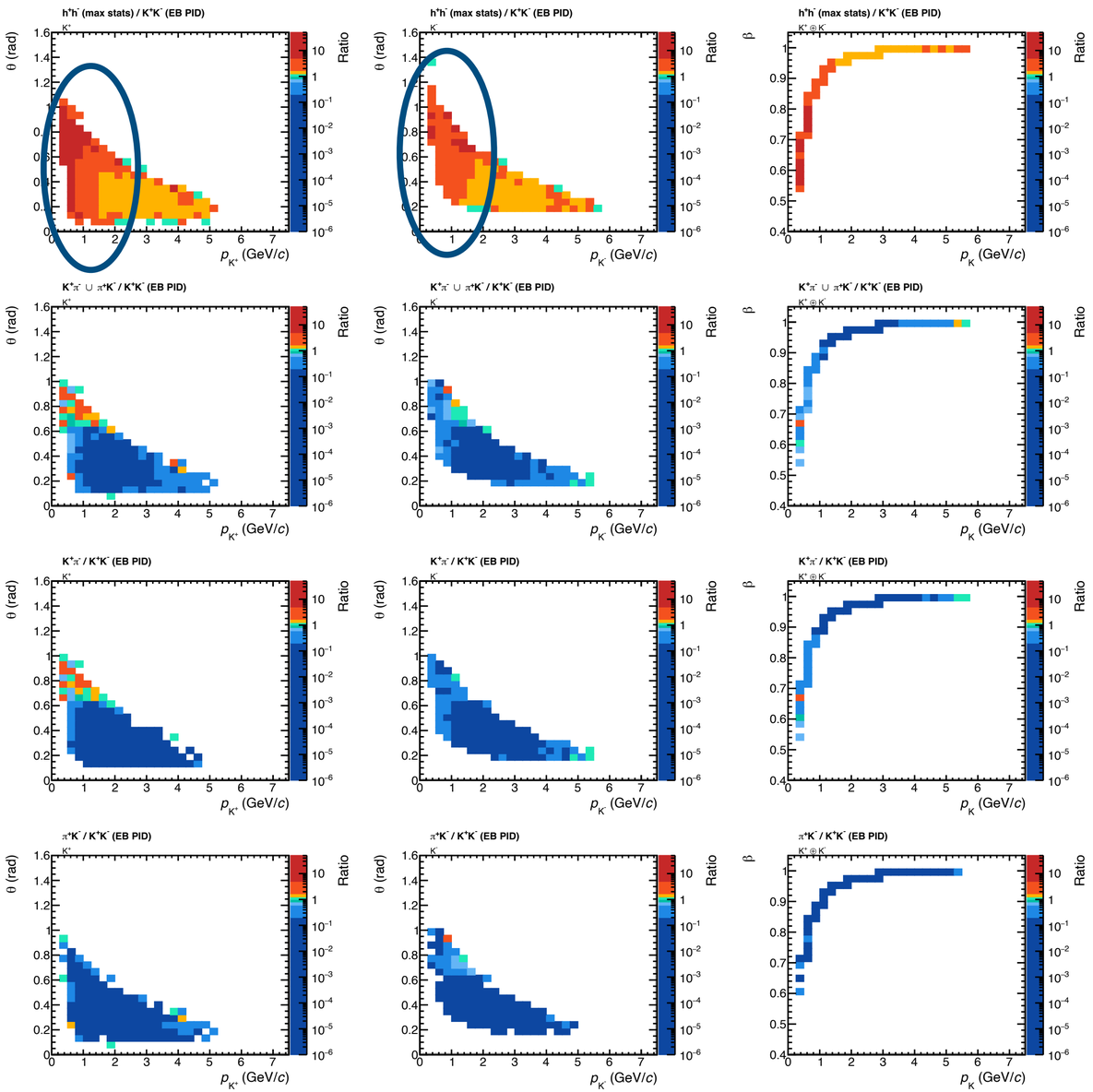
- Generally a AI based diffusion model always comes with uncertainties associated with trainings
- We try unto cluster of 5 different networks to get a conservative estimate on the uncertainties arising from it



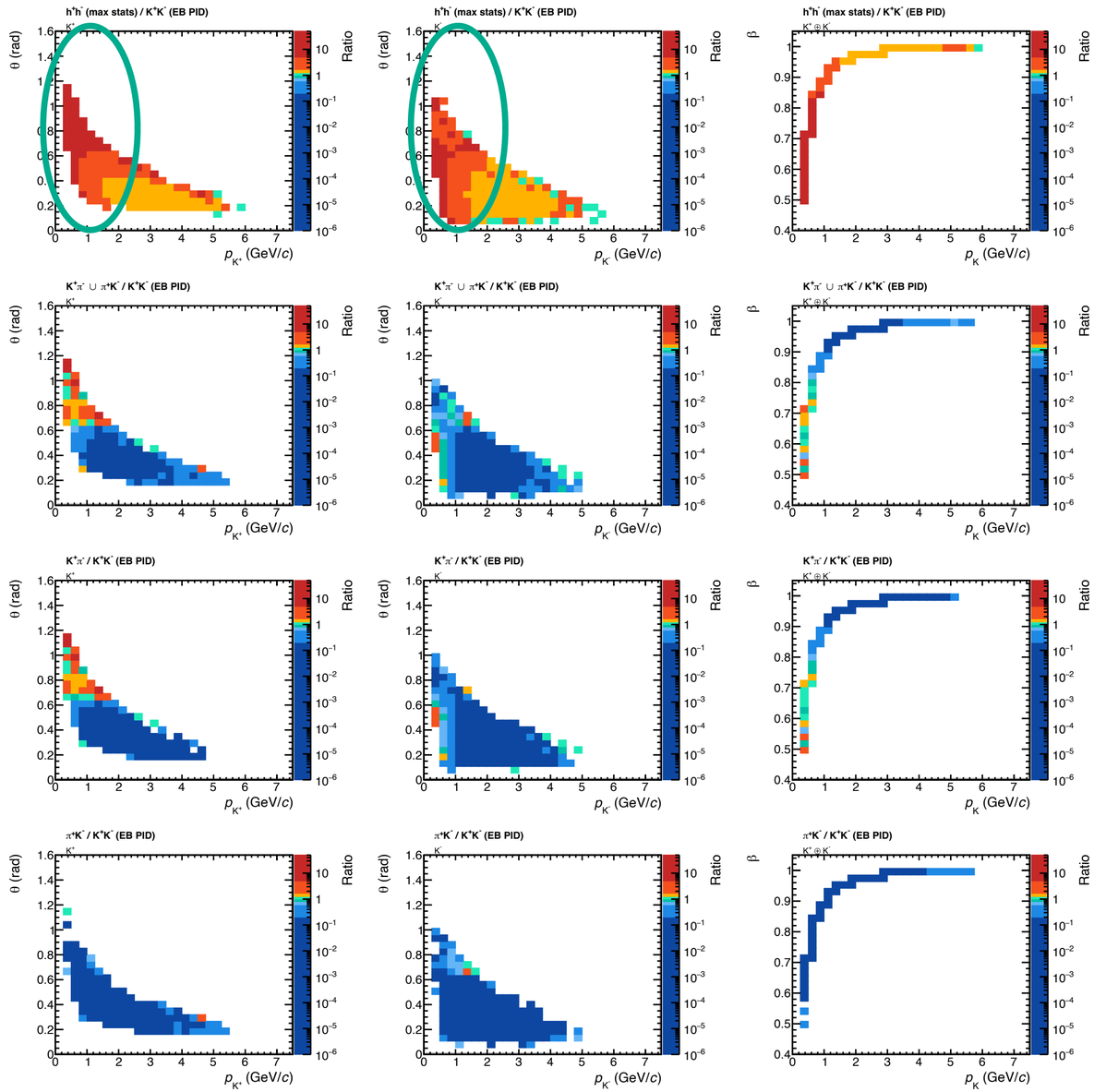


Challenge II: Pion Contamination

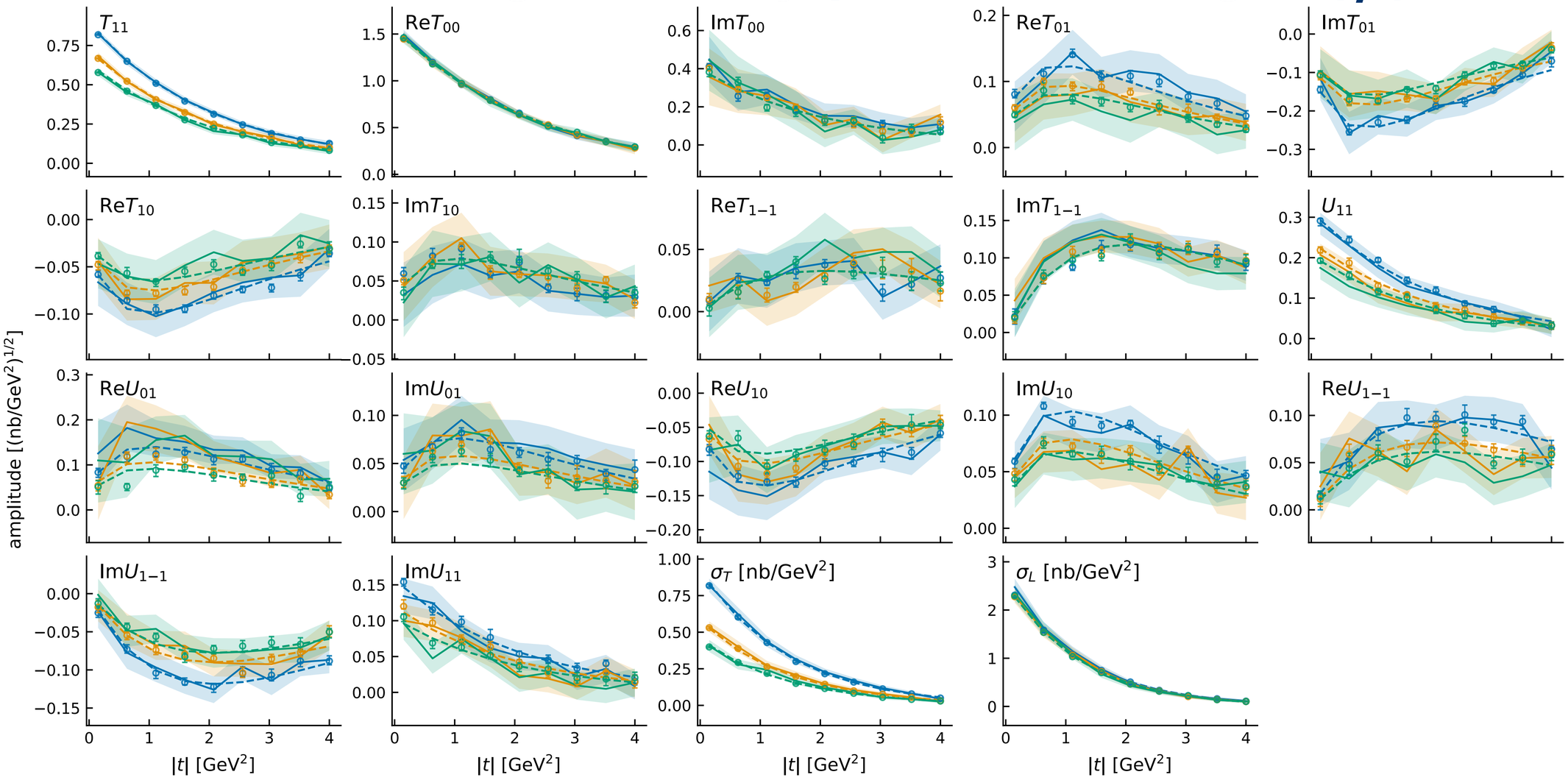
Yield Ratio: Fall18 INB



Yield Ratio: Fall18 OUTB



Results: longitudinally polarized target (ϕ)



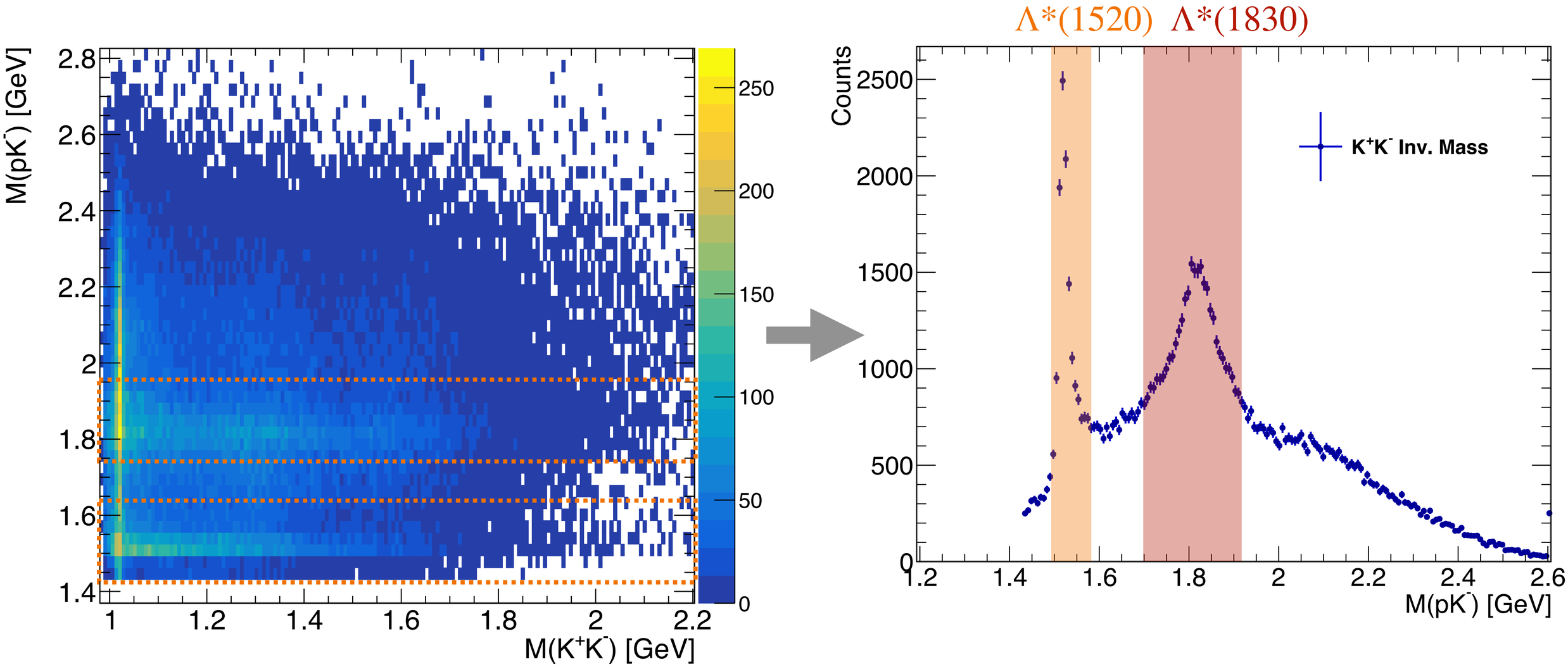
longitudinal-target program, $P = 0.8$
x_B window 0.25--0.35; $\varepsilon = 0.45/0.62/0.85$ per beam

B. Singh et al arXiv:2608.27683 [nucl-ex] (2026)

$1 < Q^2 < 2\,\mathrm{GeV}^2$ $2 < Q^2 < 3\,\mathrm{GeV}^2$ $3 < Q^2 < 6\,\mathrm{GeV}^2$ truth posterior $\pm 1\sigma$ UML

Challenge I: Background under the signal

- Production of $\Lambda^*(1520,1830)$ can lead to contamination in the ϕ DVMP channel

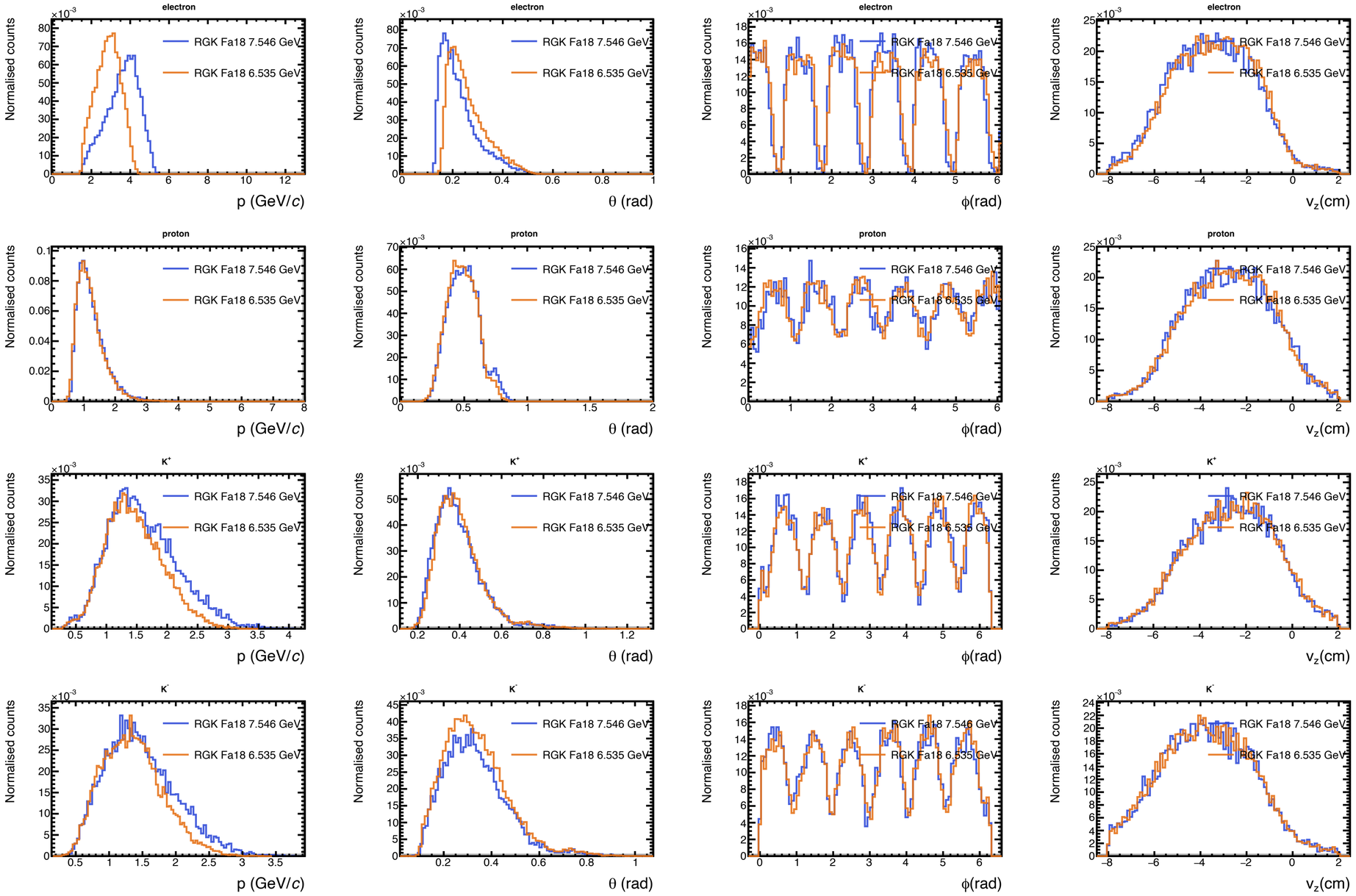


Particle Kinematics (exclusive reaction) for RGK

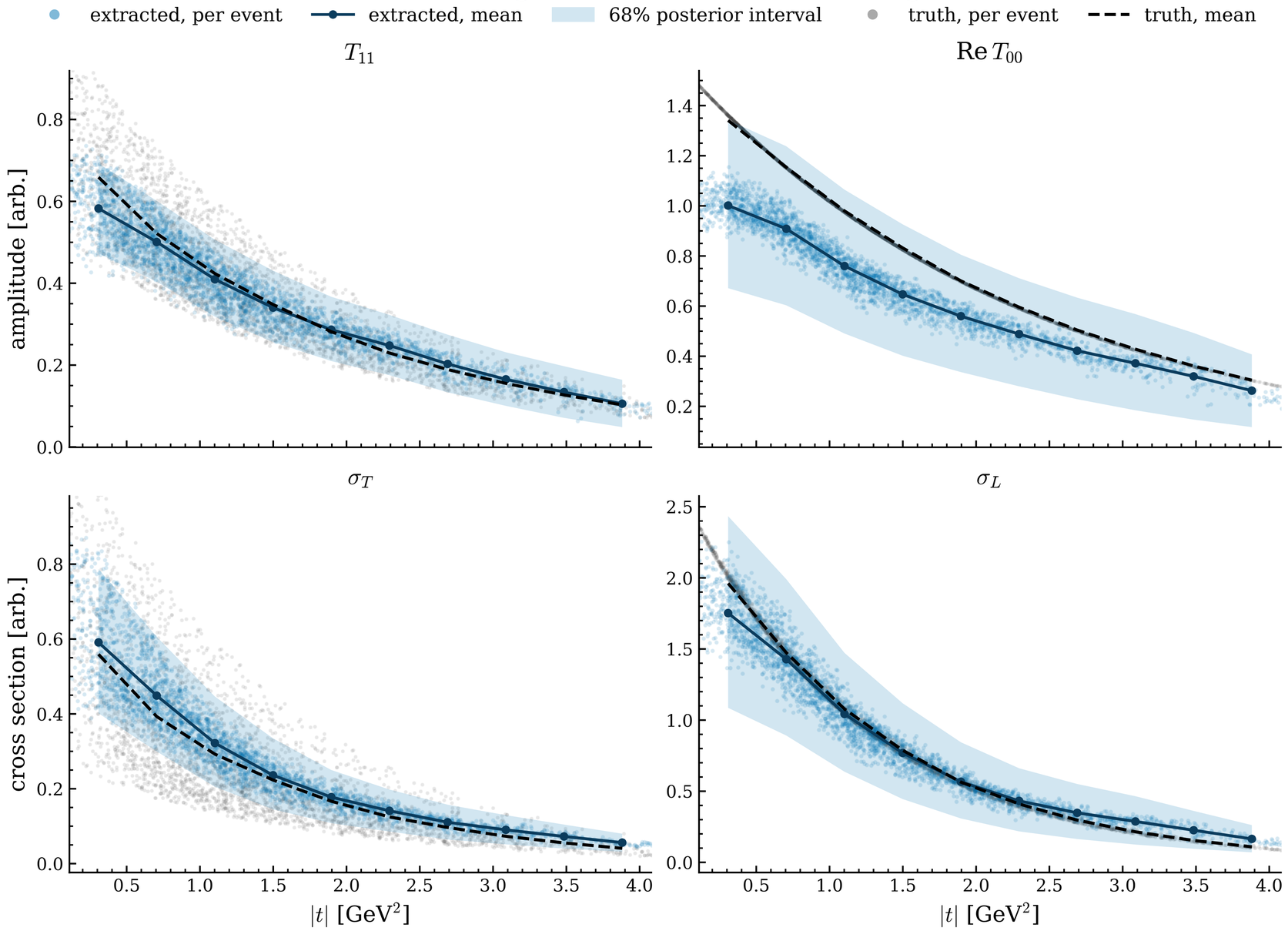
- Fall 2018 6.5 and 7.5 GeV
- Electron momentum differs from each other due to the beam energies
- Same effects observed for Kaon momenta

p_e>1.5 GeV in FD
p_p>.4 GeV in FD and CD

0.2 < K_p< 7.5 GeV in FD
Vertex for all particles
-8cm < v_z< 2 cm
p_K<1.8 GeV with PID,
p_K>1.8 h^+ h^-

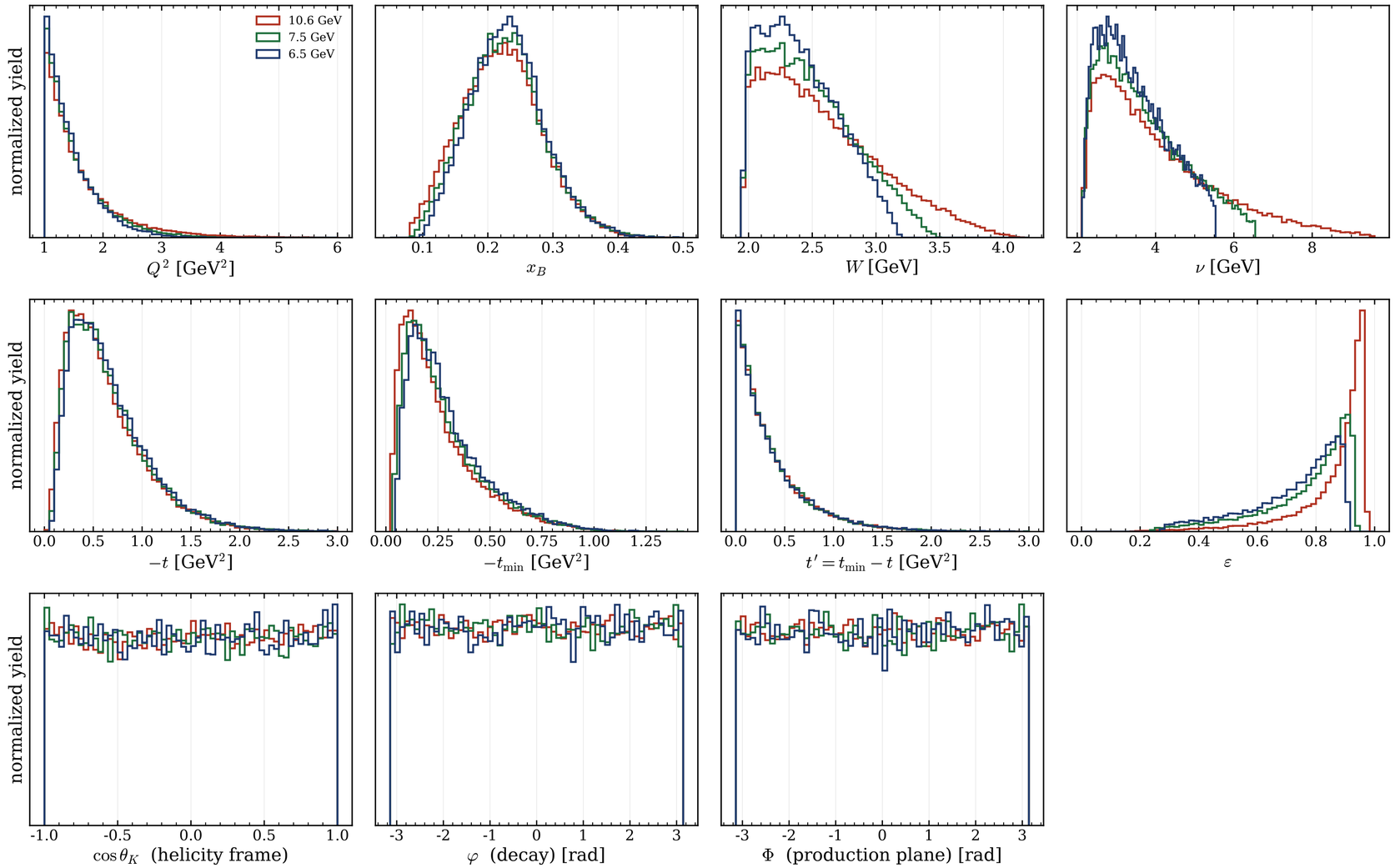


Event-by-event analysis



Forward model

- **Amplitude level generator**: real physics case set of amplitudes $T^{\sigma\lambda}_{\mu\nu}(x_B, Q^2, t)$, give event distributions [**VecGen**]



Forward model

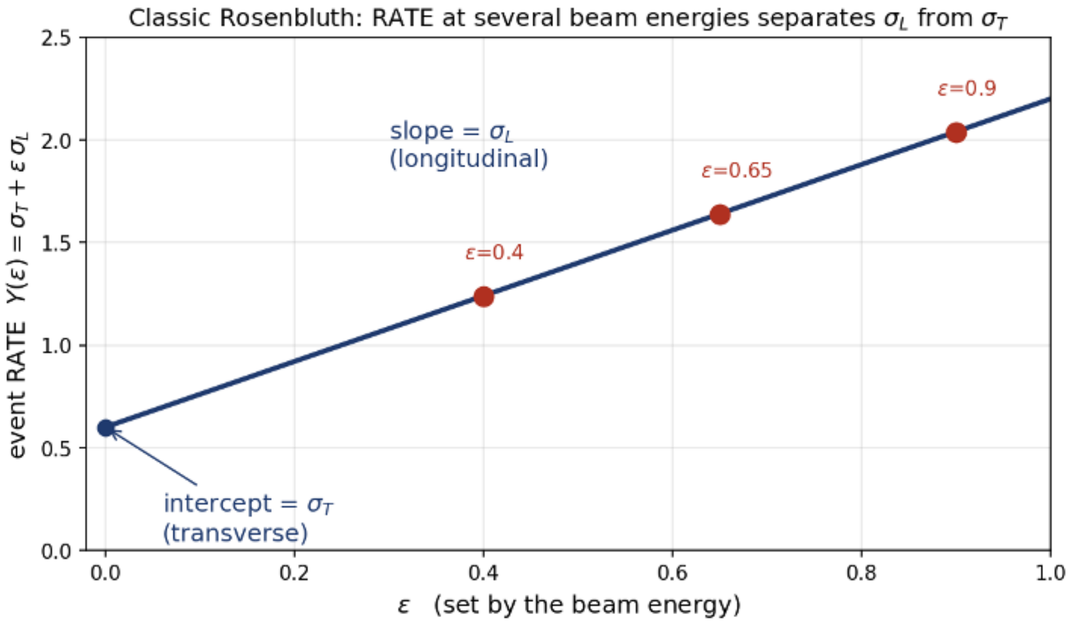
- **Amplitude level generator**: real physics case set of amplitudes $T_{\mu\nu}^{\sigma\lambda}(x_B, Q^2, t)$, give event distributions [**VecGen**]

- **Collect in terms of moments** 106 (full polarized case) angular moments of basis functions over $[\cos(\theta), \varphi, \Phi]$

Forward model

- **Amplitude level generator**: real physics case set of amplitudes $T^{\sigma\lambda}_{\mu\nu}(x_B, Q^2, t)$, give event distributions [**VecGen**]
- **Collect in terms of moments** 106 (full polarized case) angular moments of basis functions over $[\cos(\theta), \varphi, \Phi]$
- **Rosenbluth separation**: $Y(\varepsilon) = \sigma_T + \varepsilon\sigma_L$ at 6.5, 7.5 and 10.6 GeV the energies of existing CLAS12

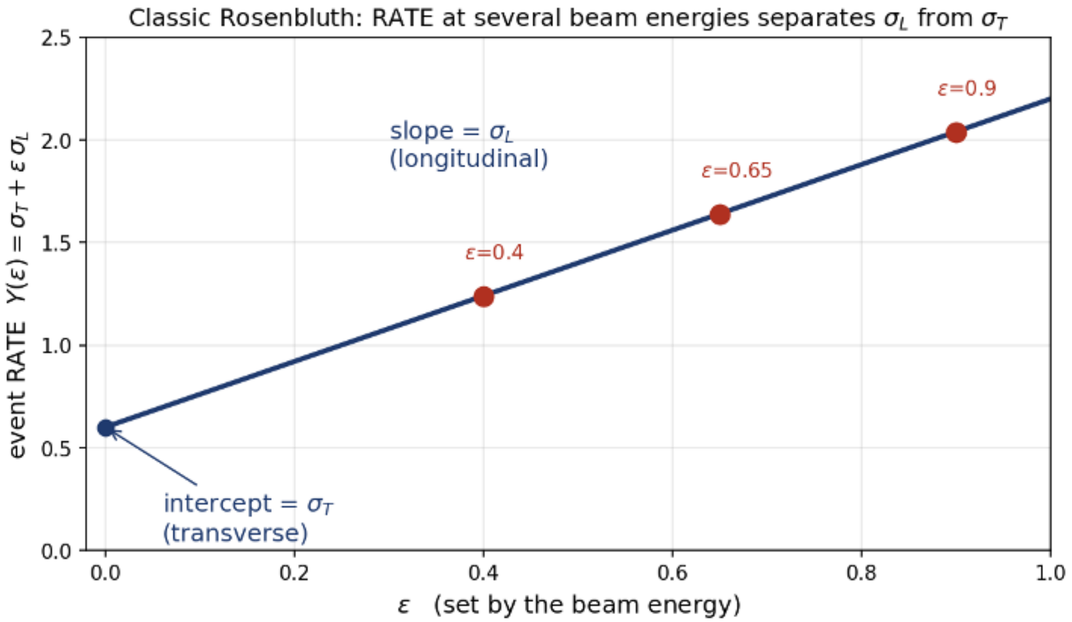
absolute size lives in the event RATE, not the angles. At each ε, the reduced yield is Y(ε)



Forward model

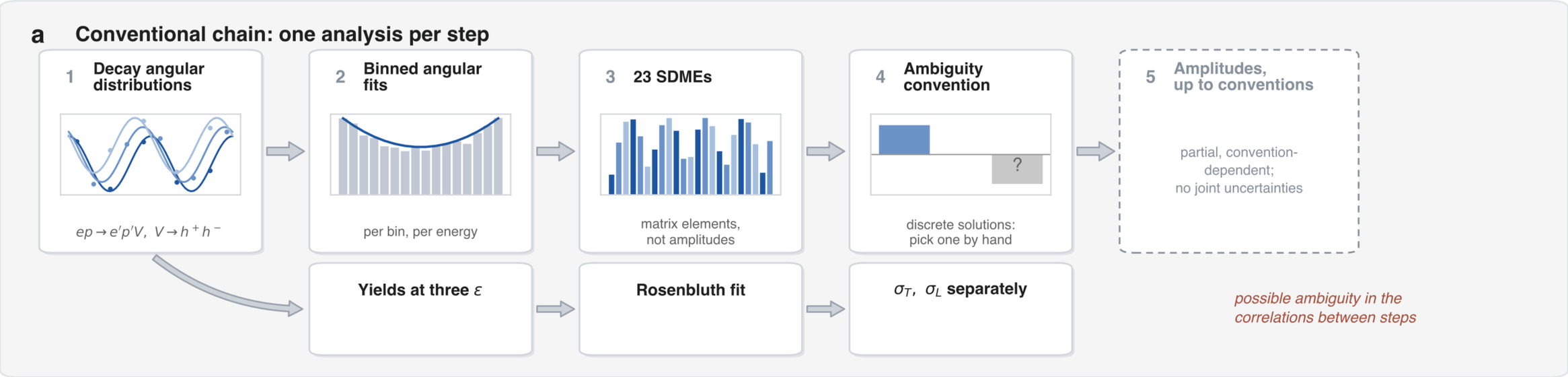
- **Amplitude level generator**: real physics case set of amplitudes $T^{\sigma\lambda}_{\mu\nu}(x_B, Q^2, t)$, give event distributions [**VecGen**]
- **Collect in terms of moments** 106 (full polarized case) angular moments of basis functions over $[\cos(\theta), \varphi, \Phi]$
- **Rosenbluth separation**: $Y(\varepsilon) = \sigma_T + \varepsilon\sigma_L$ at 6.5, 7.5 and 10.6 GeV the energies of existing CLAS12

  absolute size lives in the event RATE, not the angles. At each ε, the reduced yield is Y(ε)



- **Realistic Detector model**: We include a detector model in **7 Dim acceptance η**(Q^2, x_B, t, ε, $\cos(\theta), \varphi, \Phi$), crucial role of the acceptances into the raw data and the results (acceptance model)

Traditionally: the extraction step-by-step process



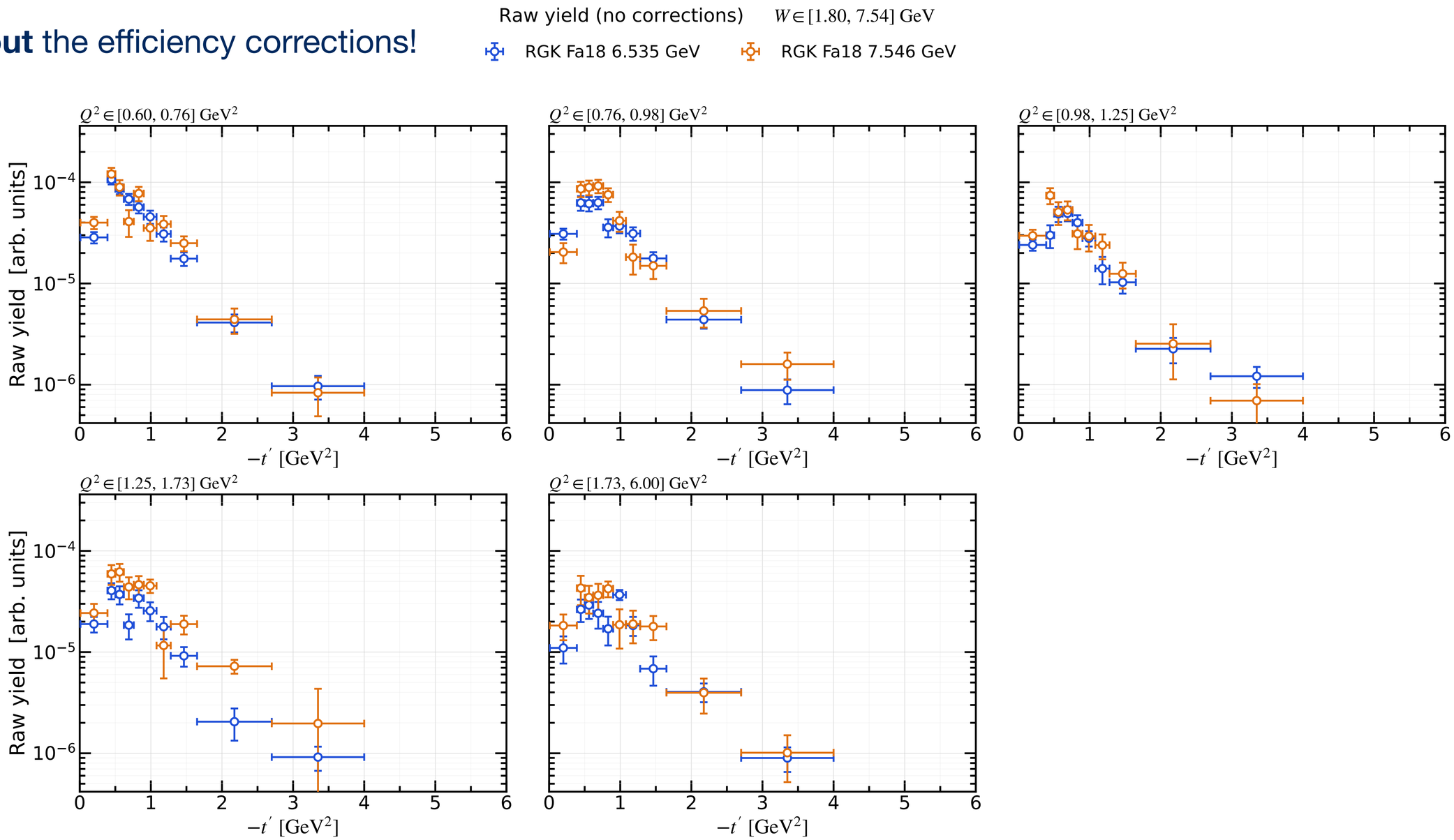
- Angular fits → 23 SDMEs → hand-chosen ambiguity convention → amplitudes (up to conventions); a separate Rosenbluth fit gives σ_T and σ_L

- A highly successful strategy: HERMES, COMPASS, H1, ZEUS, CLAS, GlueX:

  - HERMES ρ^0, H and D: 23 SDMEs, EPJC 62, 659 (2009); amplitude ratios, EPJC 71, 1609 (2011)
  - COMPASS ρ^0: 23 SDMEs by unbinned maximum likelihood, EPJC 83, 924 (2023)
  - GlueX ρ(770) photoproduction, linearly polarized 8.2–8.8 GeV, Phys. Rev. C 108, 055204 (2023)
  - GlueX $\phi(1020) \to K_0^S K_0^L$, $-t = 0.15$–1.0 GeV^2, Phys. Rev. C 112, 025203 (2025)

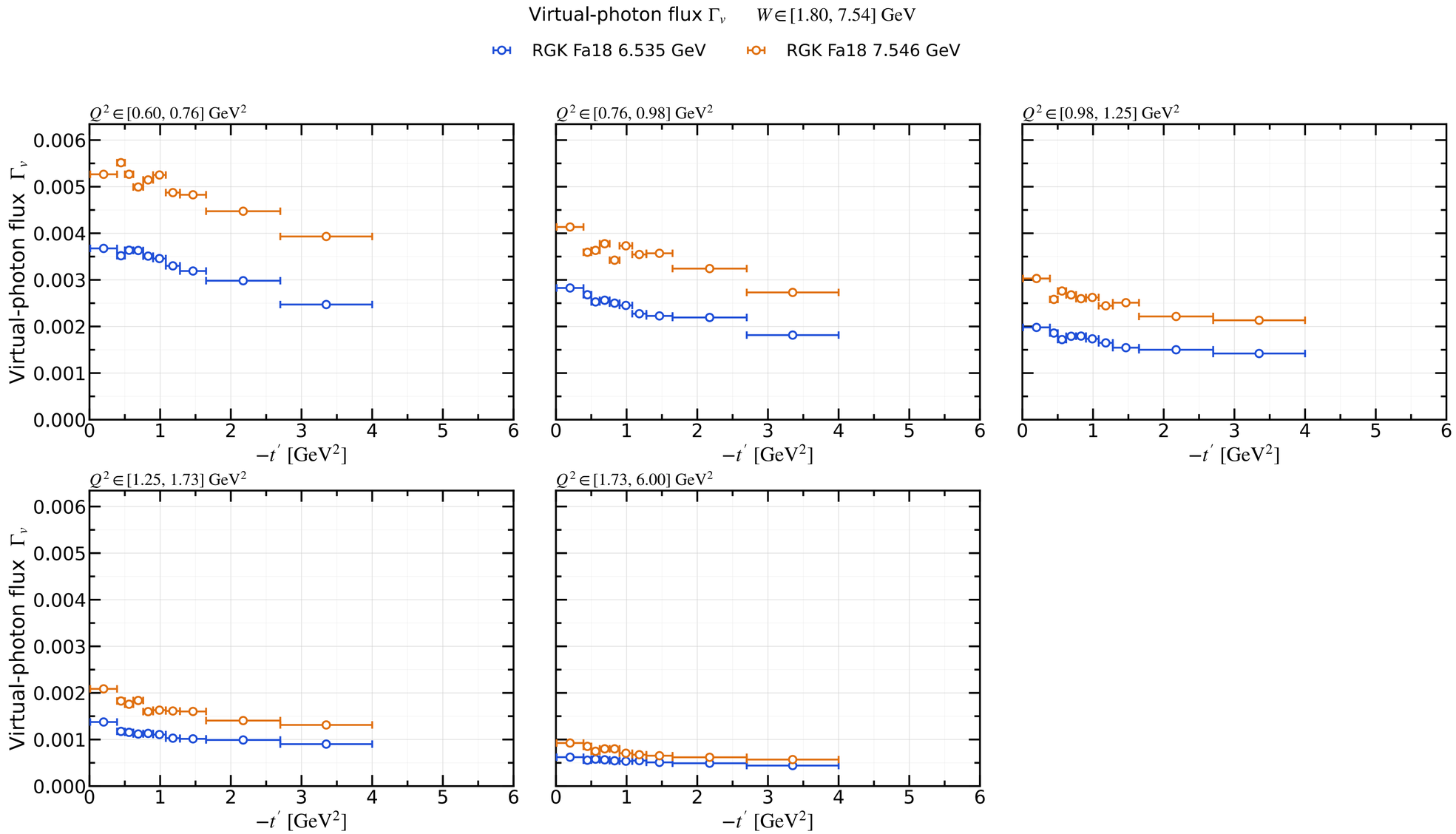
The raw yields RGK

- **Without** the efficiency corrections!



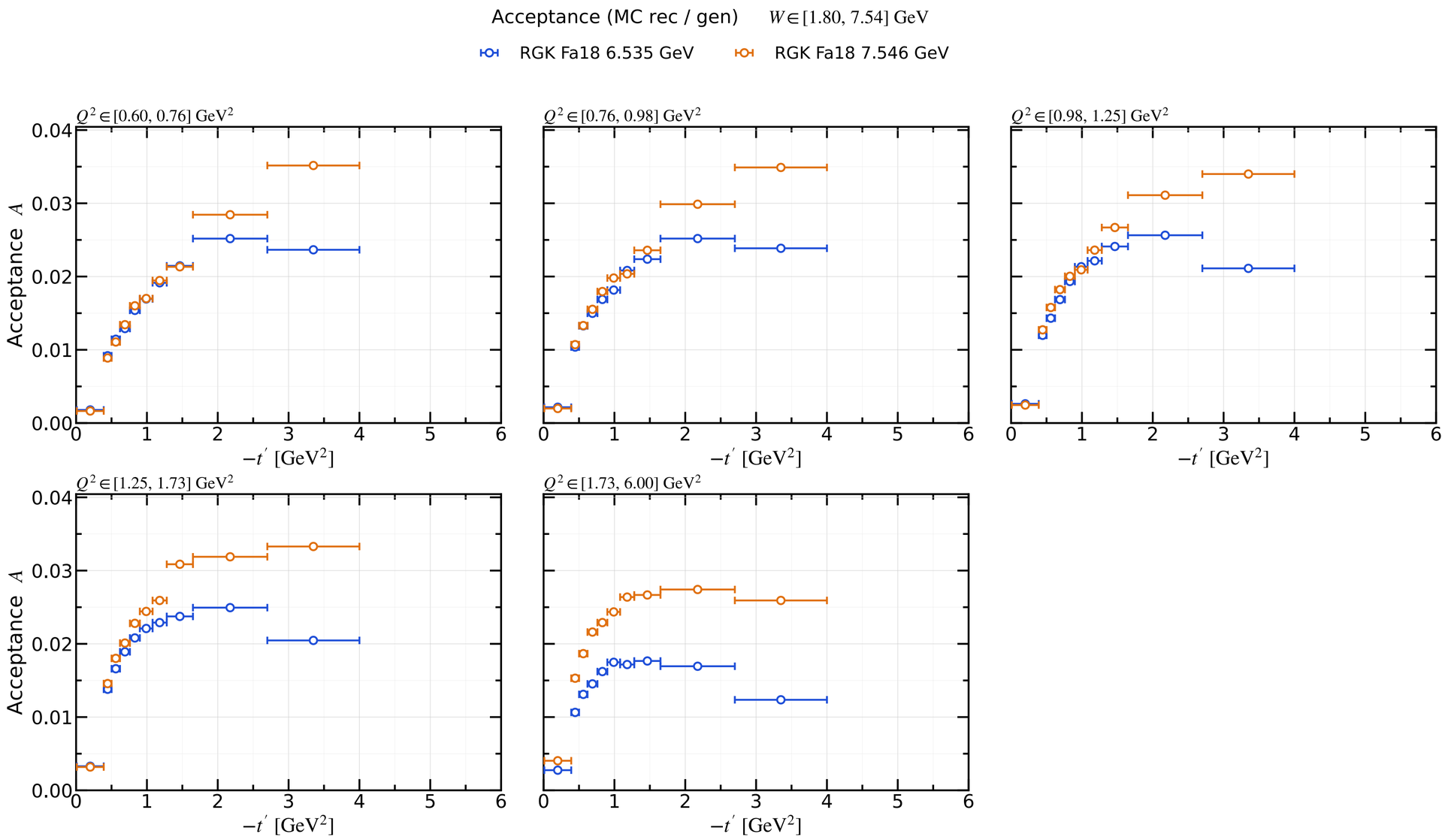
Virtual Photon Flux correction: RGK

- Each kinematics point carry virtual photon flux correction

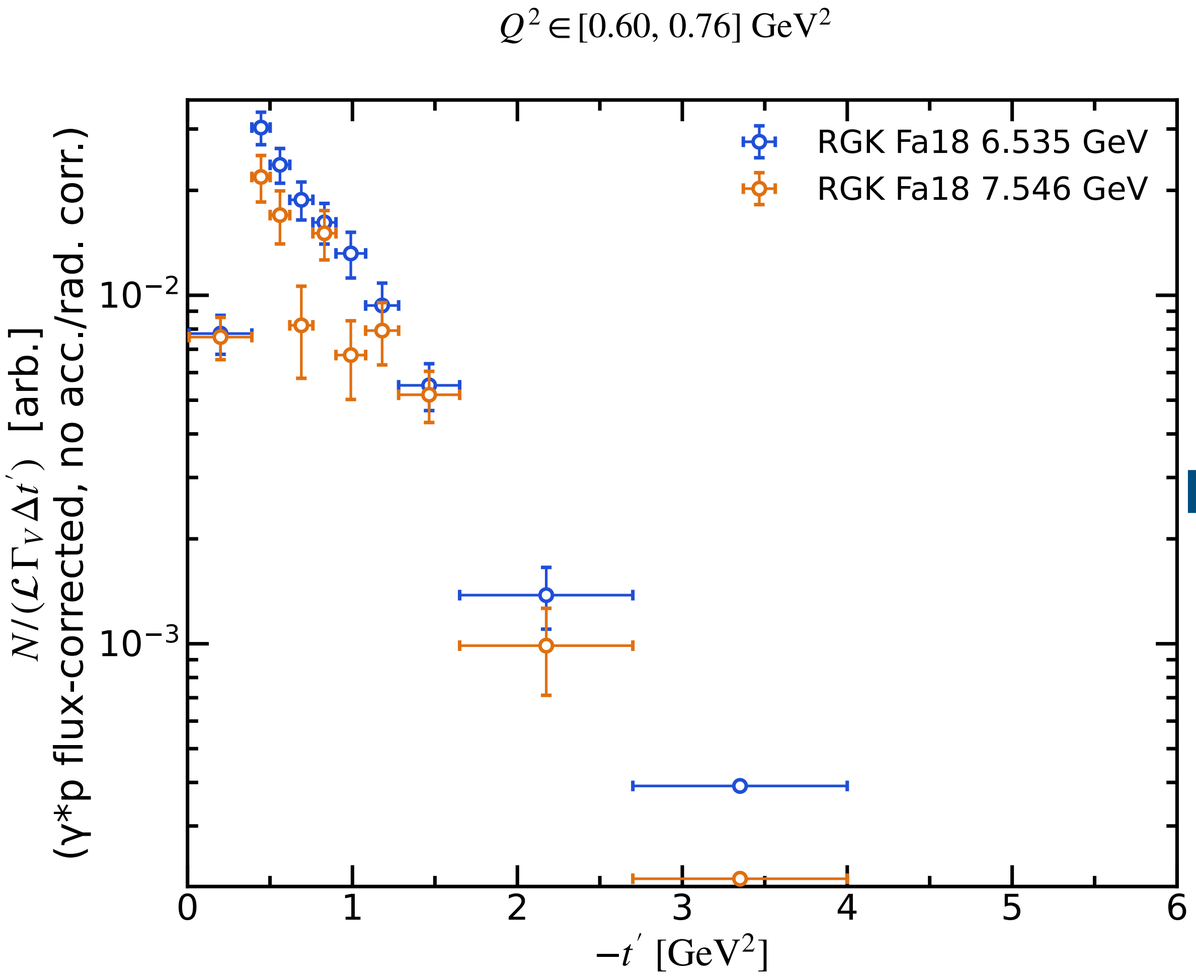


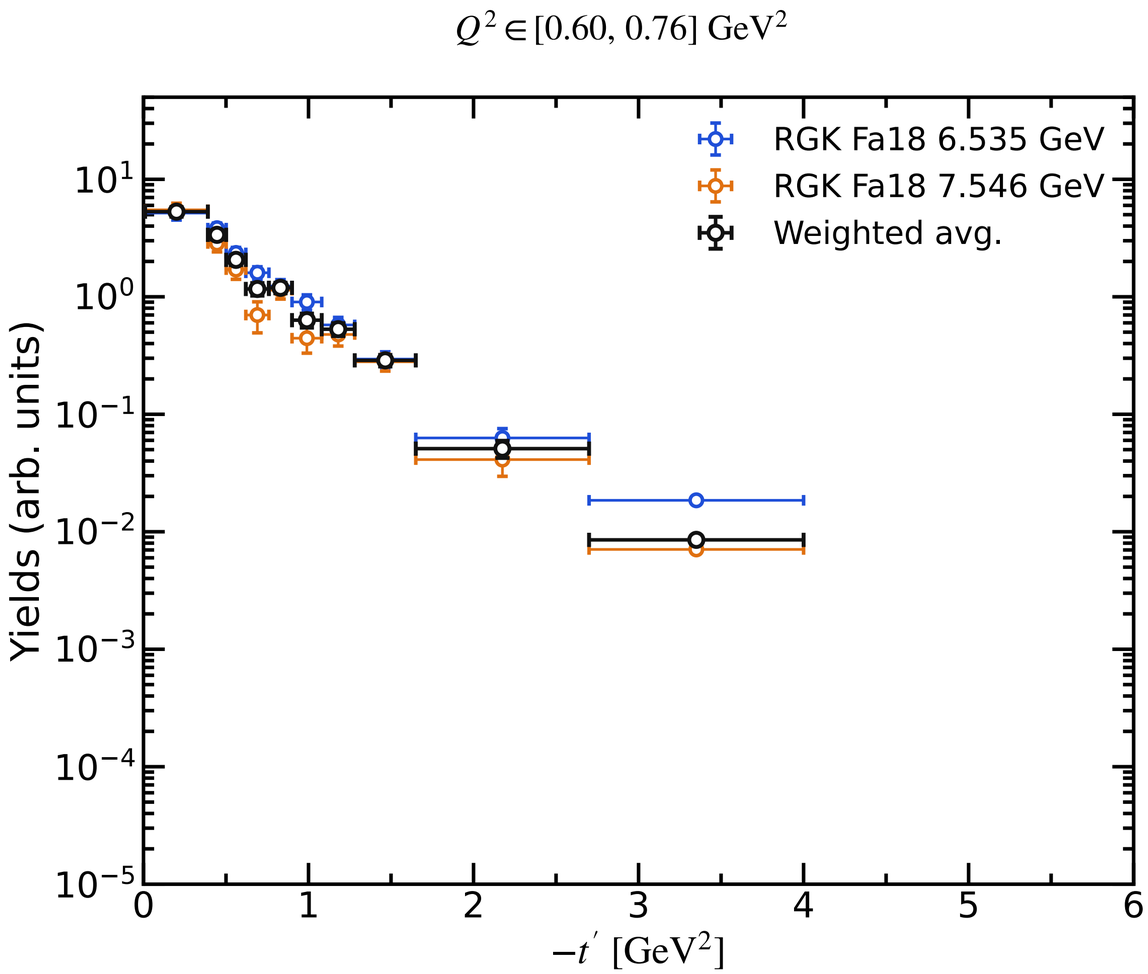
Detector acceptance effects RGK

- **Without** the efficiency for background merging corrections!



Impact of acceptance correction





Acceptance impacted by the SDMEs

- Non-flat decay angle affects the acceptance of the cross-section for vector meson

