# The challenge of femtometer scale physics

**Nobuo Sato**
ODU/JLab

QCD Evolution 19
**Argonne National Laboratory**

# Outline

1. A new perspective for MC event generators
2. Understanding the large $p_{\mathrm{T}}$ SIDIS spectrum
3. New developments to identify SIDIS regions

**Supported by:**
JLab LDRD19-13

## A new perspective for MC event generators

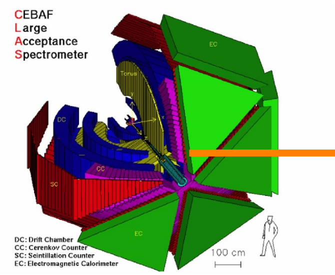
**QCD physicists** :

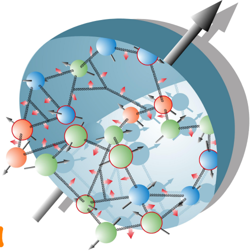
- W. Melnitchouk (JLab-theory)
- T. Liu (JLab-theory)
- NS (JLab/ODU-theory)
- R. E. McCleallan (JLab-theory)

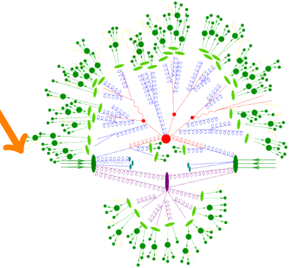
**Computer Scientists**:

- Y. Li (ODU)
- M. Kuchera (Davidson College)

# From detectors to partons





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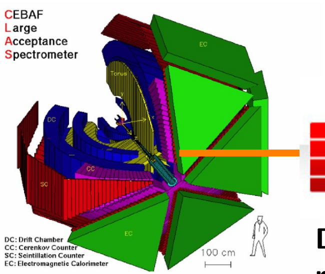
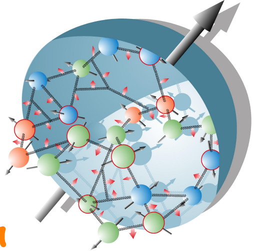
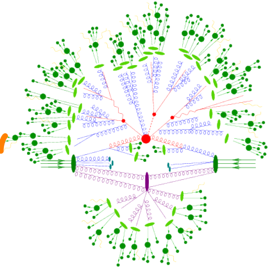



**Detector response**

**QED effects**

**QCD effects**





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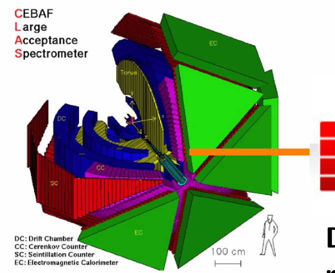


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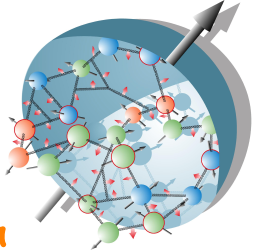

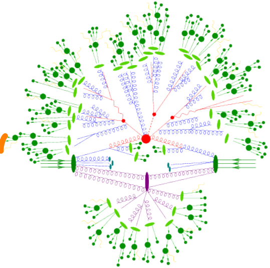

$$\sigma^{\mathrm{EXP}} = w^{\mathrm{DR}} \otimes w^{\mathrm{QED}} \otimes \sigma^{\mathrm{QCD}}$$

# A new perspective for MC event generators

- An empirical tool such that

$$\sigma^{\mathrm{EXP}} = w^{\mathrm{DR}} \otimes \sigma^{\mathrm{MCEG}}$$

$$\downarrow$$

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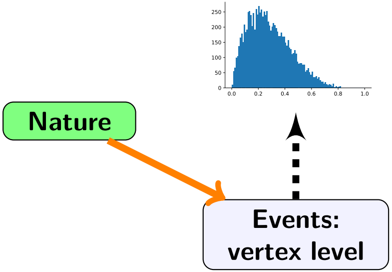
- Machine Learning based MCEG

# Empirically Trained Hadronic Event Regenerator (ETHER)



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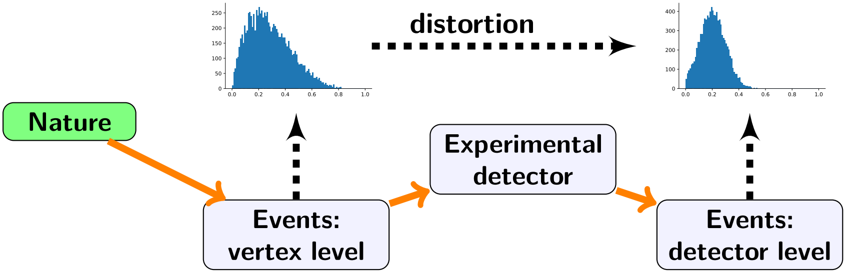

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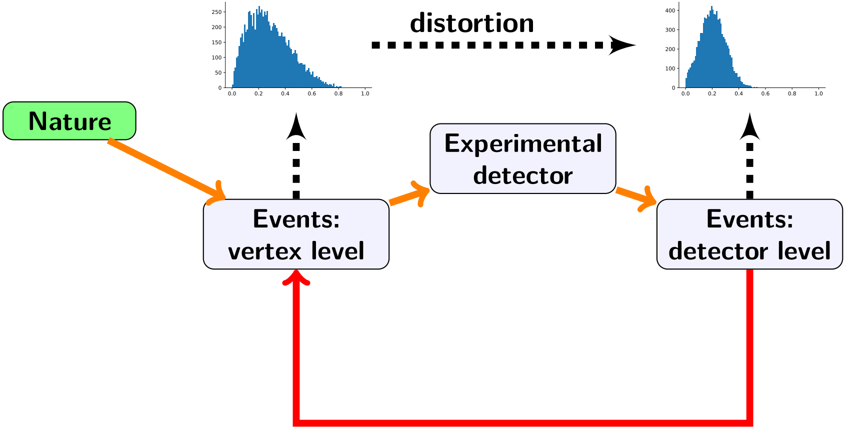


**Inverse problem $\rightarrow$ Model dependent**

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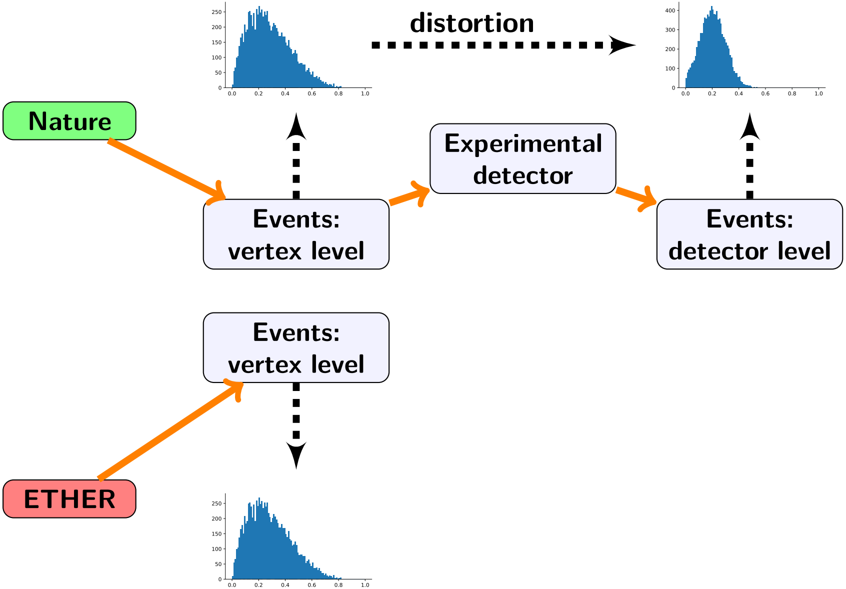

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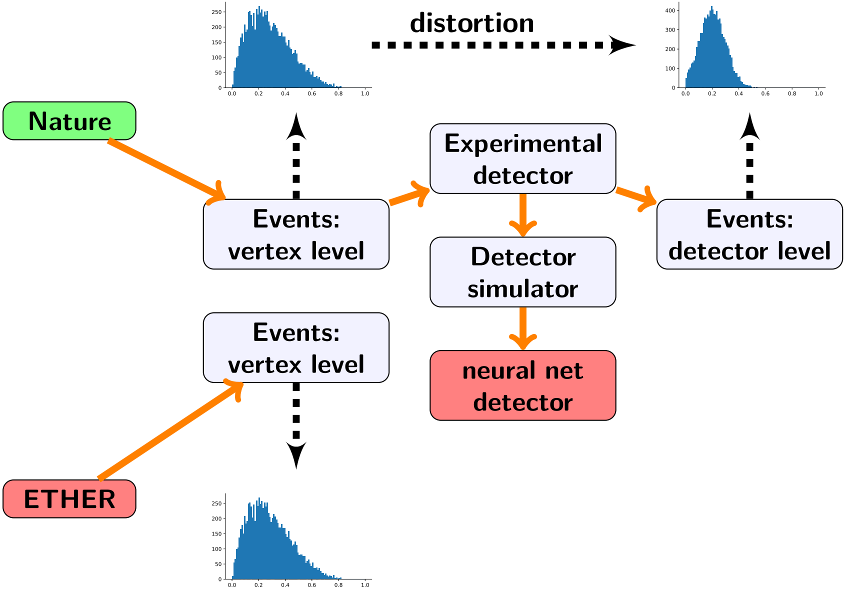

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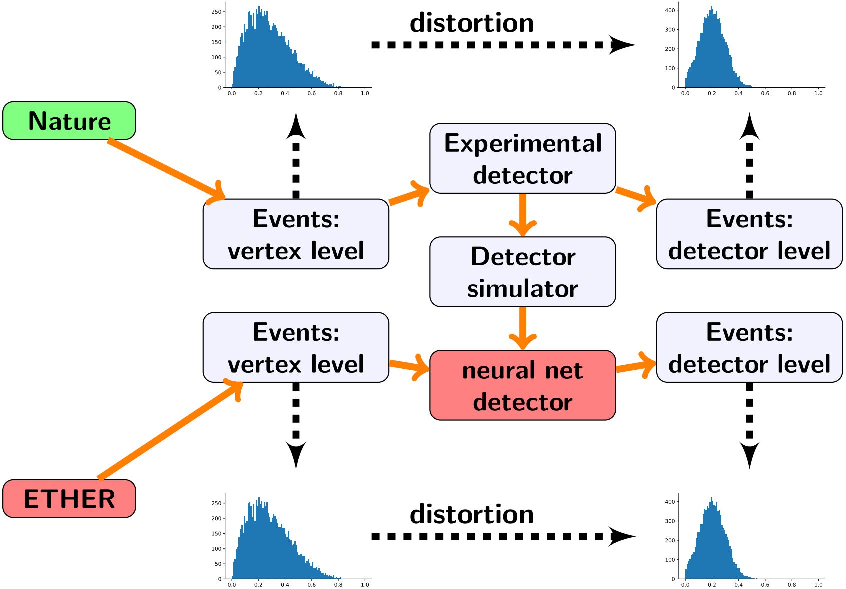

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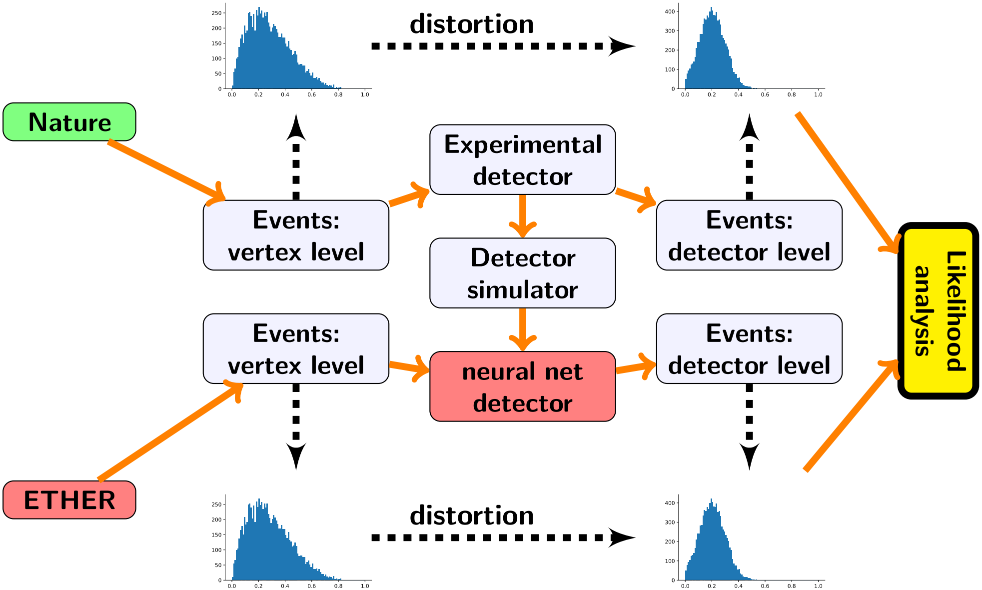

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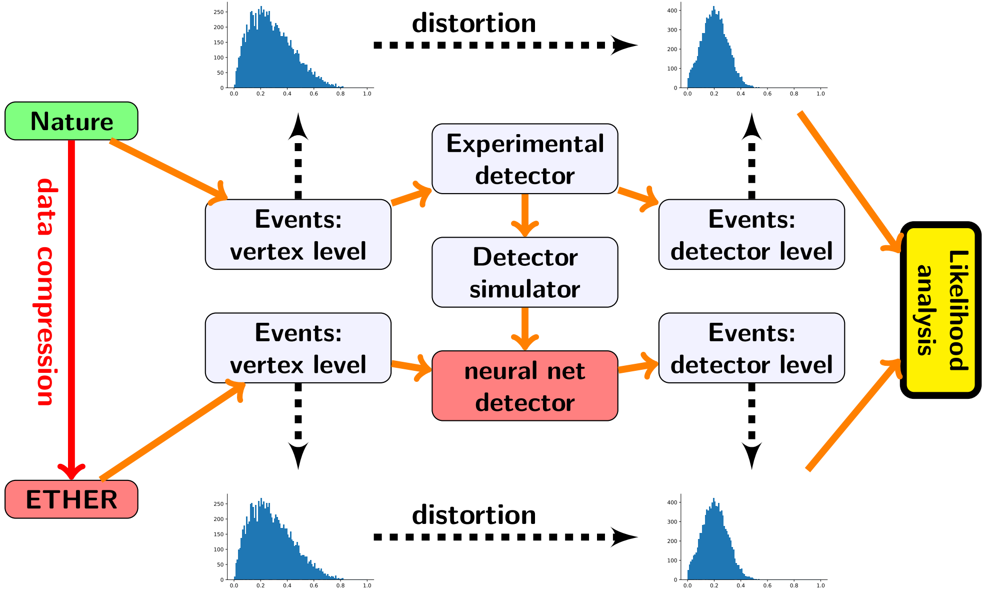

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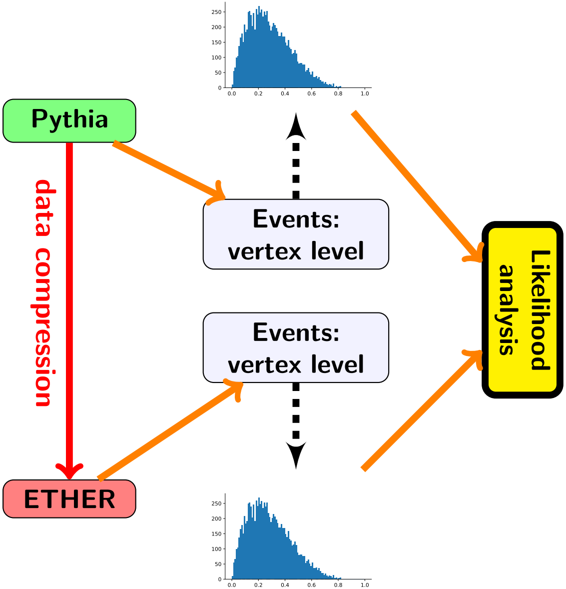

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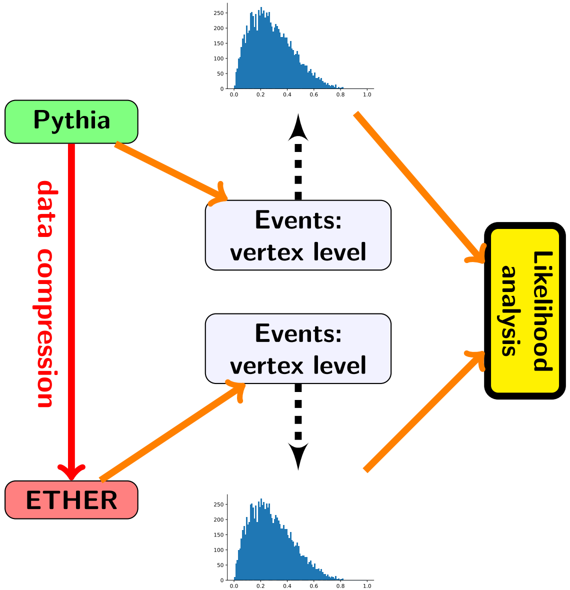



- **ML setup:** Generative adversarial network (GAN's)

- **Milestones**:
  - ✓ A setup for exclusive $l + p$ reaction
  - ✓ particles multiplicities
  - $\simeq$ $x_{\mathrm{bj}}$, $Q^2$,...

# Understanding the large $p_{\mathrm{T}}$ SIDIS spectrum

**Work based on**

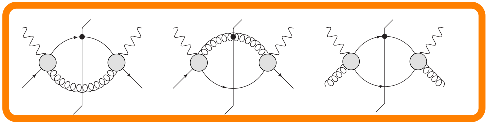
- Gonzalez-Hernandez, Rogers, NS, Wang ( PRD98 **2018** )
- Wang, Gonzalez-Hernandez, Rogers, NS ( arXiv:1903.01529 **2019** )

# SIDIS FO $O(\alpha_S^2)$ calculation completed! Wang, Gonzalez, Rogers, NS ('19)

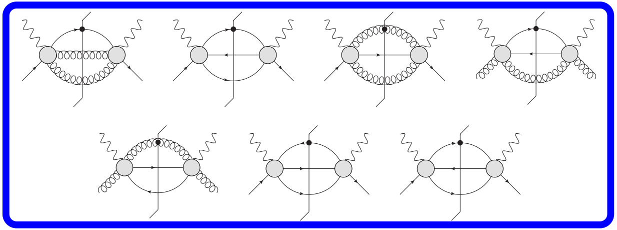
$$W^{\mu\nu}(P,q,P_H) = \int_{x-}^{1+} \frac{d\xi}{\xi} \int_{z-}^{1+} \frac{d\zeta}{\zeta^2} \hat{W}_{ij}^{\mu\nu}(q, x/\xi, z/\zeta) f_{i/P}(\xi) d_{H/j}(\zeta)$$

$$\{\mathrm{P}_g^{\mu\nu} \hat{W}_{\mu\nu}^{(N)}; \mathrm{P}_{PP}^{\mu\nu} \hat{W}_{\mu\nu}^{(N)}\} \equiv \frac{1}{(2\pi)^4} \int \{|M_g^{2\to N}|^2; |M_{pp}^{2\to N}|^2\}\, \mathrm{d}\Pi^{(N)} - \text{Subtractions}$$

**Born/Virtual**



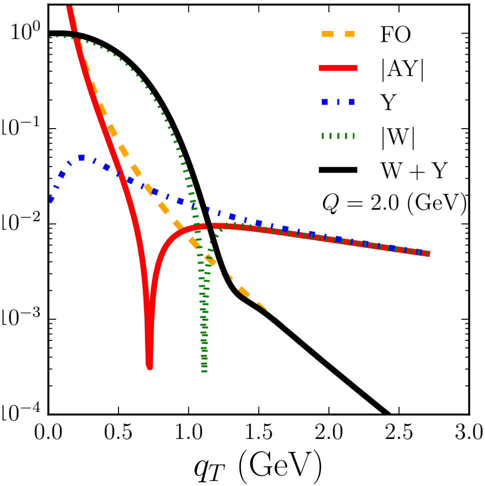
**Real**



- ✓ Generate all $2 \to 2$ and $2 \to 3$ squared amplitudes
- ✓ Evaluate $2 \to 2$ virtual graphs (Passarino-Veltman)
- ✓ Integrate 3-body PS analytically
- ✓ Check cancellation of IR poles
- ✓ Agreement within $20\%$ with Daleo's etal ('05)

# Why is this calculation relevant?

$$\frac{d\sigma}{dx dQ dz dq_T}$$



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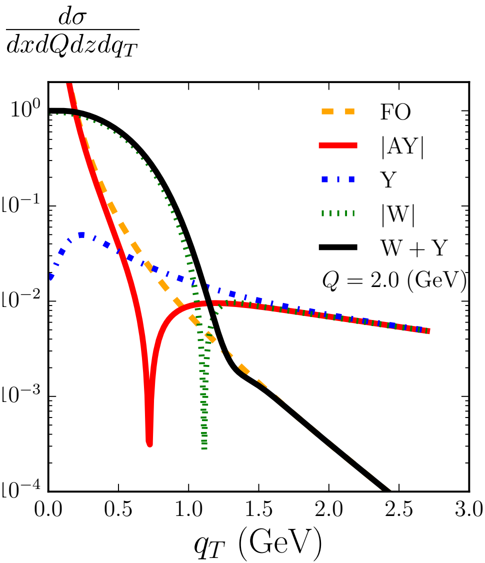


$$\mathrm{FO} = \sum_q e_q^2 \int_{\xi_{\min}}^{1} \frac{d\xi}{\xi - x} \, H(\xi) \; \boldsymbol{f}_q(\xi, \mu) \; \boldsymbol{d}_q(\zeta(\xi), \mu)$$
$$+ O(\alpha_S^2) + O(m^2/q^2)$$

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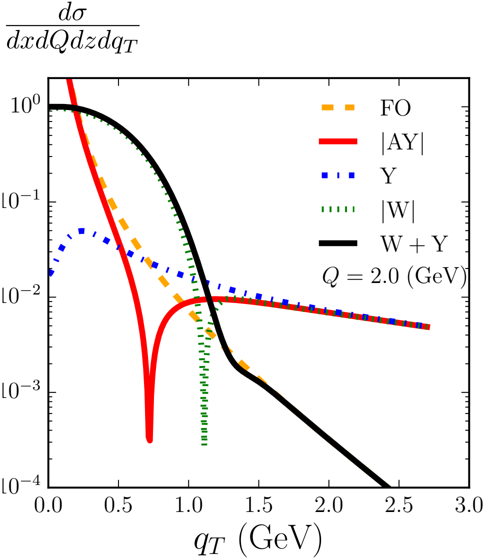


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$$\xi_{\min} = \frac{q_{\mathrm{T}}^2}{Q^2} \frac{xz}{1-z} + x$$

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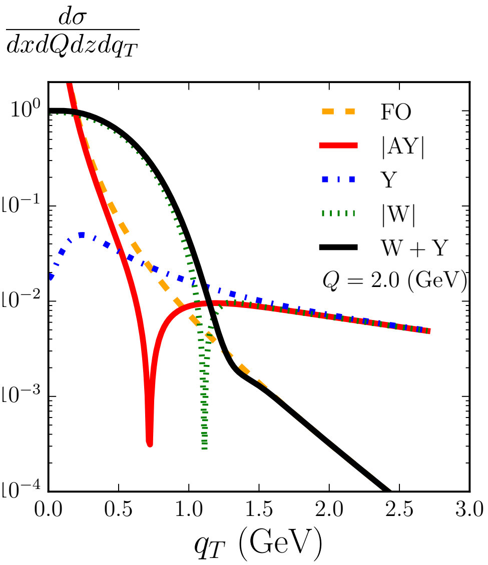


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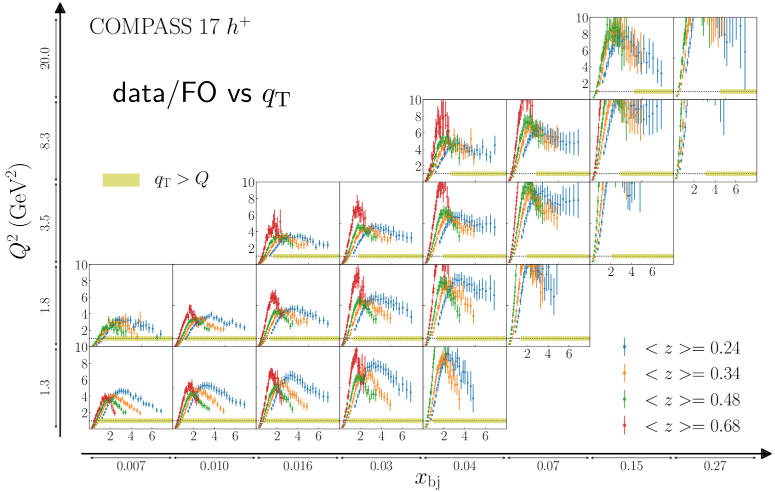
**Does it work?**

$$\mathrm{FO} = \sum_q e_q^2 \int_{\frac{q_T^2}{Q^2}\frac{xz}{1-z}+x}^{1} \frac{d\xi}{\xi - x}\; H(\xi)\; \boldsymbol{f}_q(\xi,\mu)\; \boldsymbol{d}_q(\zeta(\xi),\mu) + O(\alpha_S^2) + O(m^2/q^2)$$



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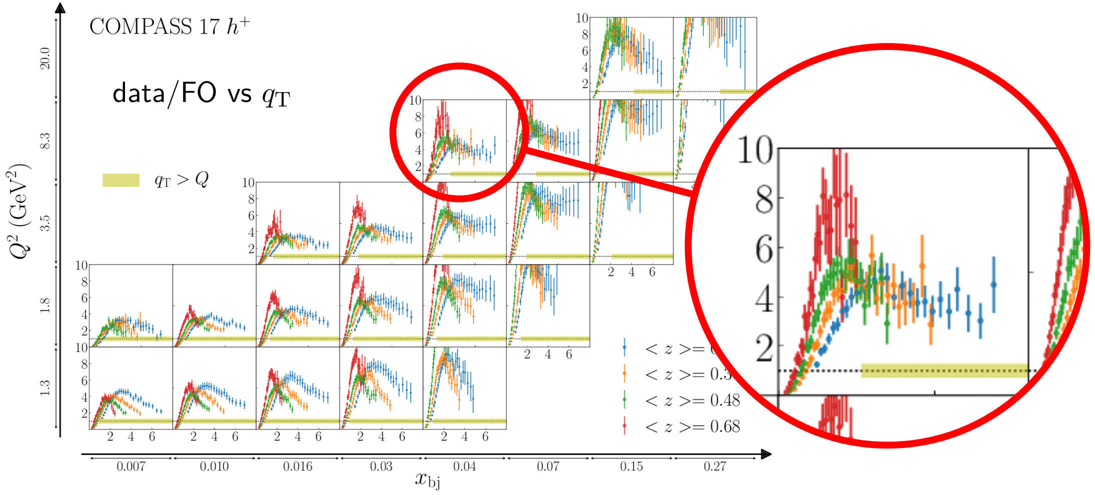
data/FO vs $q_T$



# What to do?

$$\mathrm{FO} = \sum_q e_q^2 \int_{\frac{q_\mathrm{T}^2}{Q^2}\frac{xz}{1-z}+x}^{1} \frac{d\xi}{\xi - x}\; H(\xi)\; \boldsymbol{f}_q(\xi,\mu)\; \boldsymbol{d}_q(\zeta(\xi),\mu) + O(\alpha_S^2) + O(m^2/q^2)$$

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1) Update FFs: use $q_\mathrm{T}$ integrated data

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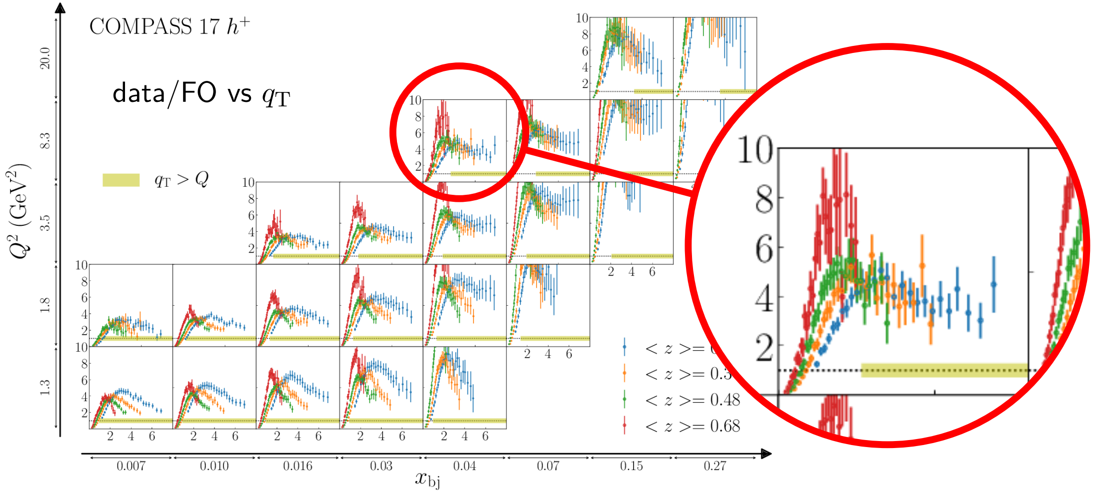
1) Update FFs: use $q_{\mathrm{T}}$ integrated data

2) Add $O(\alpha_S^2)$

$$\text{FO} = \sum_q e_q^2 \int_{\frac{q_T^2}{Q^2}\frac{xz}{1-z}+x}^{1} \frac{d\xi}{\xi - x}\; H(\xi)\; \boldsymbol{f}_q(\xi,\mu)\; \boldsymbol{d}_q(\zeta(\xi),\mu) + O(\alpha_S^2) + O(m^2/q^2)$$

data/FO vs $q_T$



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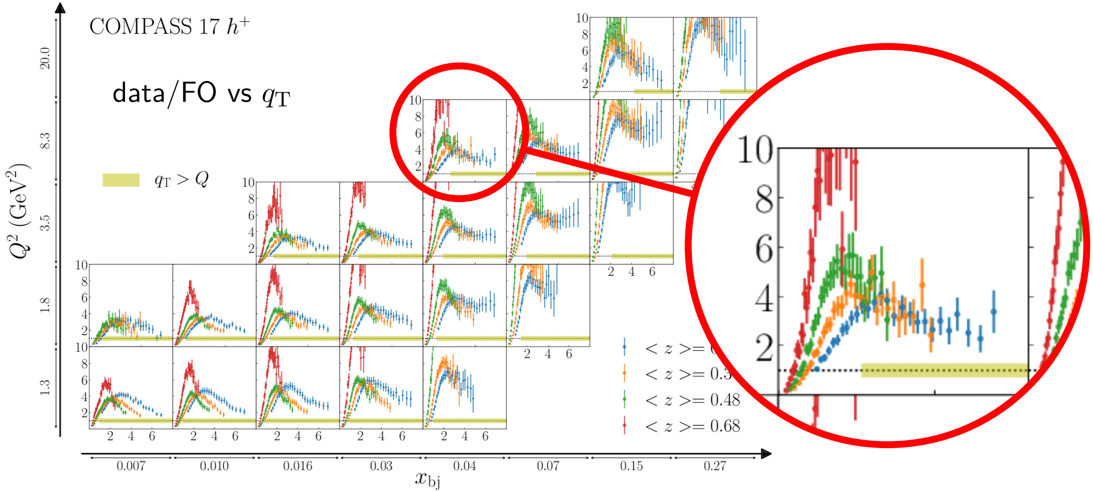

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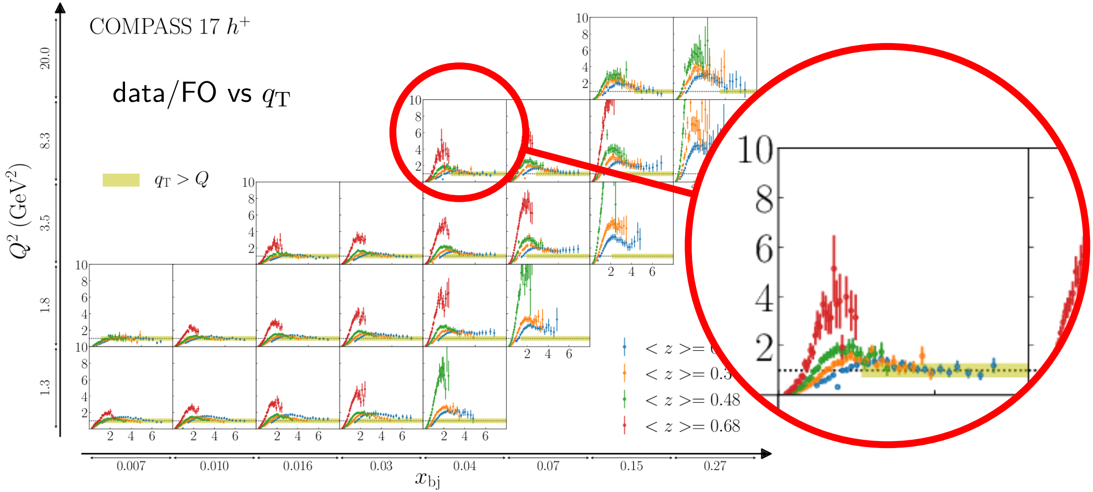

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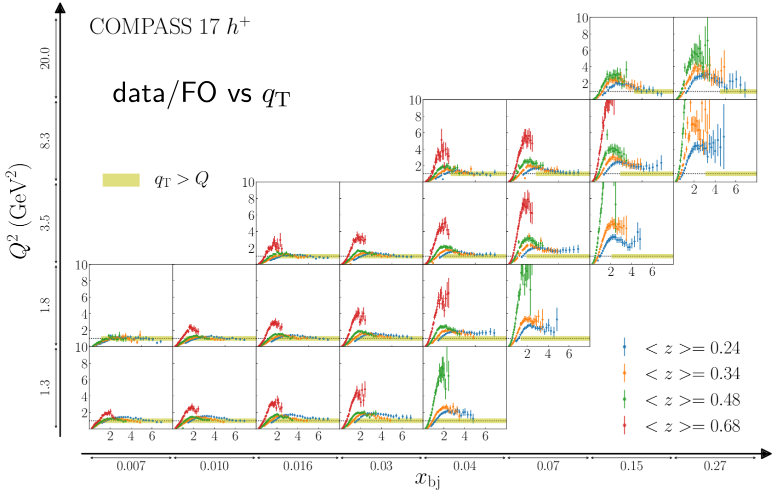
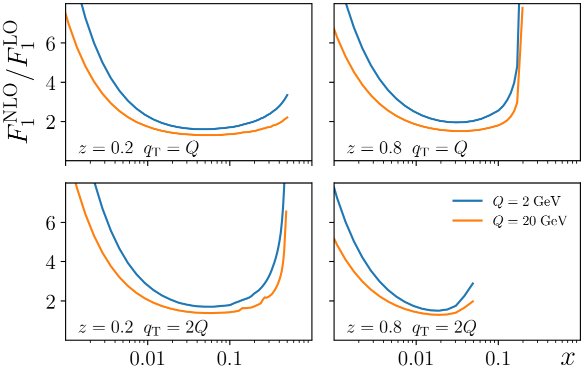
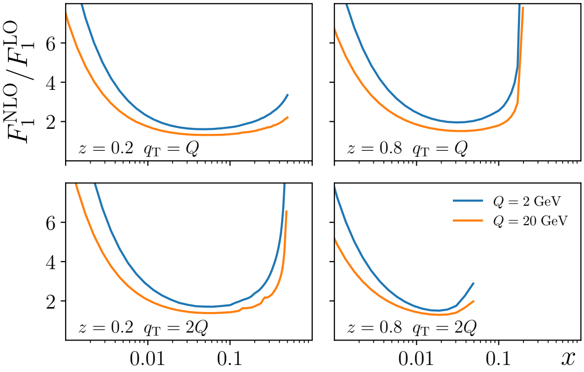



Issue at large $x$ remains




- Large threshold corrections
- The $x$ at the minimum can indicate where to expect large threshold corrections

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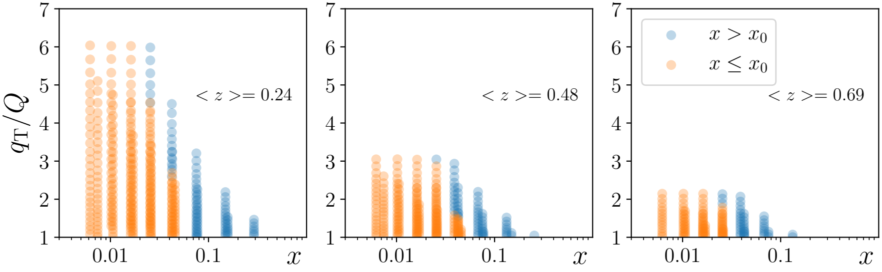
## COMPASS kinematics

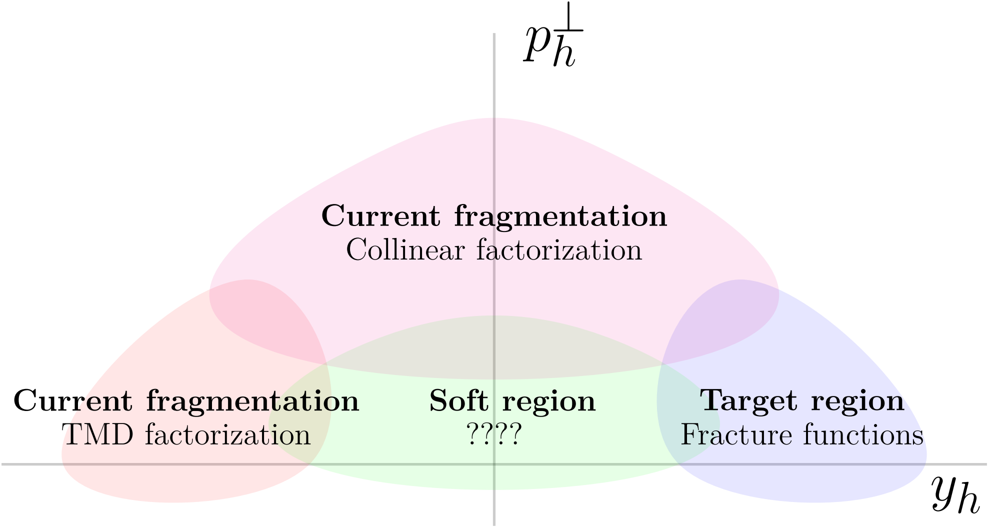


# New developments to identify SIDIS regions

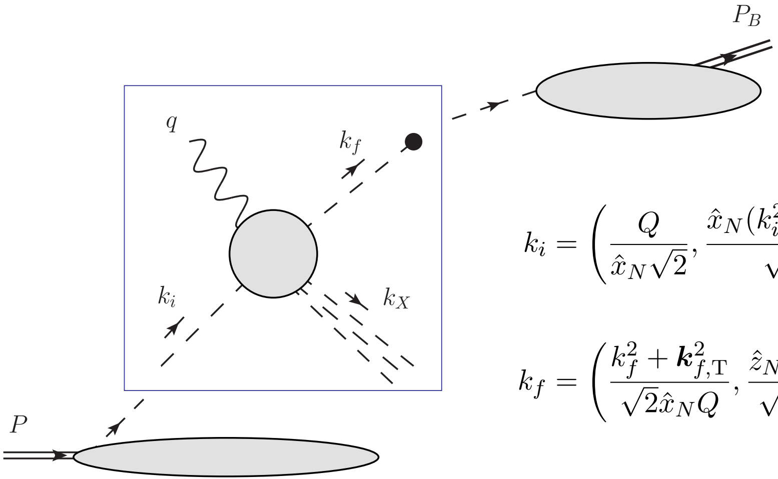
**Work based on**

- Boglione, Collins, Gamberg, Gonzalez-Hernandez, Rogers, NS
  ( PLB 766 **2017** )
- Boglione, Gamberg, Gordon, Gonzalez-Hernandez, Prokudin, Rogers, NS
  ( arXiv:1904.12882 )

# **SIDIS regions** (Breit frame kinematics)



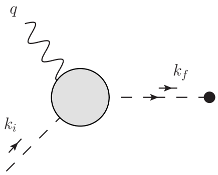
# SIDIS current region




$$k_i = \left( \frac{Q}{\hat{x}_N \sqrt{2}}, \frac{\hat{x}_N (k_i^2 + \boldsymbol{k}_{i,\mathrm{T}}^2)}{\sqrt{2} Q}, \boldsymbol{k}_{i,\mathrm{T}} \right)$$

$$k_f = \left( \frac{k_f^2 + \boldsymbol{k}_{f,\mathrm{T}}^2}{\sqrt{2} \hat{x}_N Q}, \frac{\hat{z}_N Q}{\sqrt{2}}, \boldsymbol{k}_{i,\mathrm{T}} \right)$$

# SIDIS in the current region




- For "current region" we must have

$$R_1 \equiv \frac{P_B \cdot k_f}{P_B \cdot k_i} \to \text{small}$$

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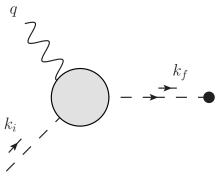
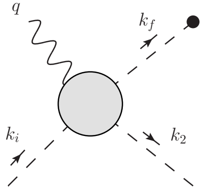
$$R_2 \equiv \frac{|(k_f - q)^2|}{Q^2} \simeq (1 - \hat{z}_N) + \hat{z}_N \frac{q_T^2}{Q^2}$$



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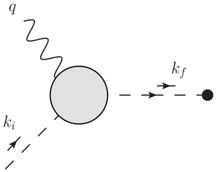


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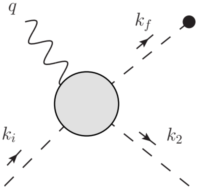
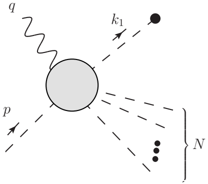


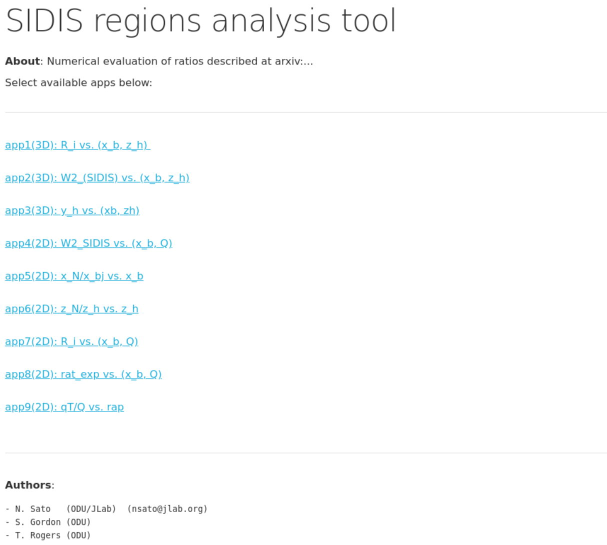

- Deviation from $2 \to 2$ kinematics

$$R_3 \equiv \frac{|k_X^2|}{Q^2}$$



# SIDIS regions web app

- https://sidis.herokuapp.com/
- feedback/questions are welcomed
- it might take few seconds to load be patient


SIDIS regions analysis tool

**About**: Numerical evaluation of ratios described at arxiv:...

Select available apps below:

app1(3D): R_i vs. (x_b, z_h)

app2(3D): W2_(SIDIS) vs. (x_b, z_h)

app3(3D): y_h vs. (xb, zh)

app4(2D): W2_SIDIS vs. (x_b, Q)

app5(2D): x_N/x_bj vs. x_b

app6(2D): z_N/z_h vs. z_h

app7(2D): R_i vs. (x_b, Q)

app8(2D): rat_exp vs. (x_b, Q)

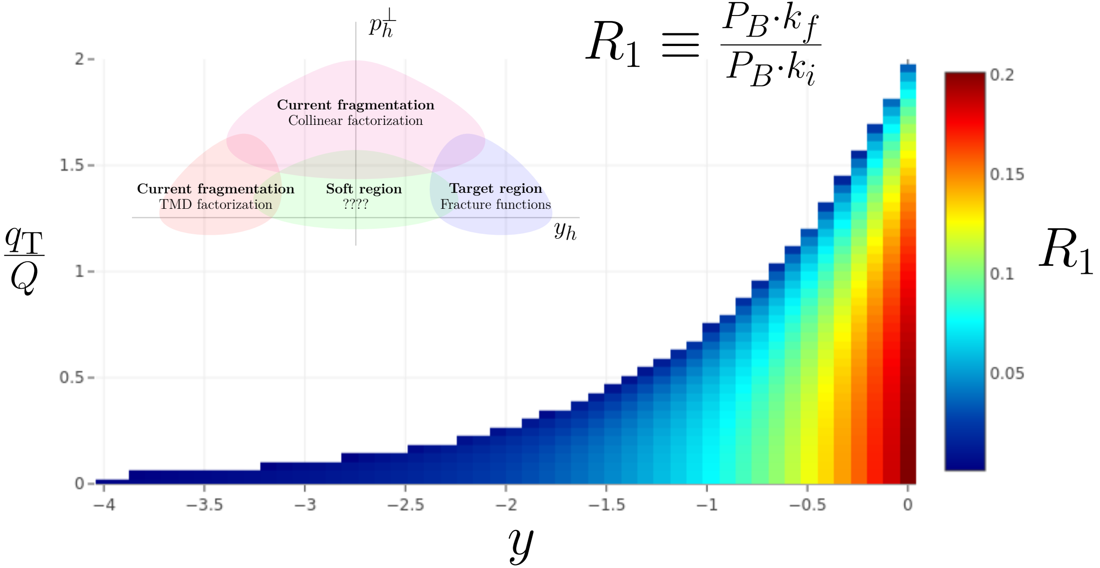
app9(2D): qT/Q vs. rap

**Authors**:

- N. Sato (ODU/JLab) (nsato@jlab.org)
- S. Gordon (ODU)
- T. Rogers (ODU)

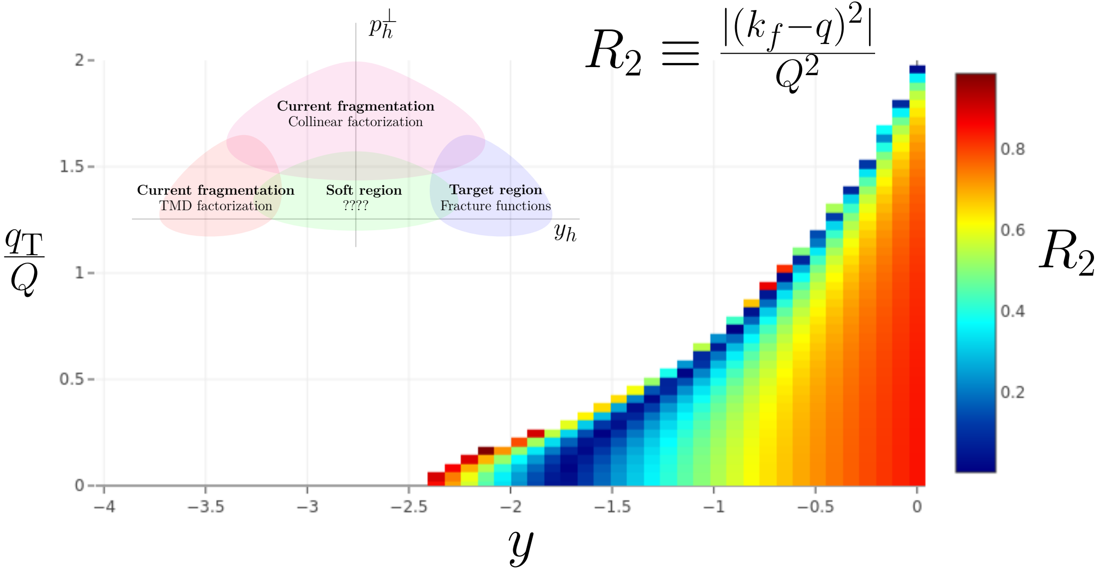
# example for pions

$$R_1 \equiv \frac{P_B \cdot k_f}{P_B \cdot k_i}$$



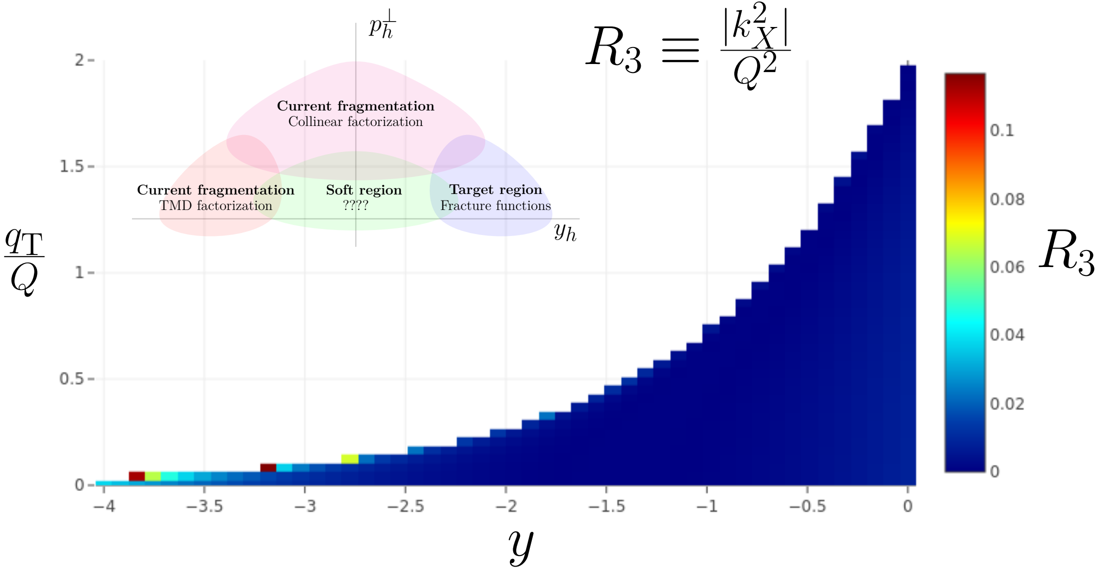
# example for pions

$$R_2 \equiv \frac{|(k_f - q)^2|}{Q^2}$$



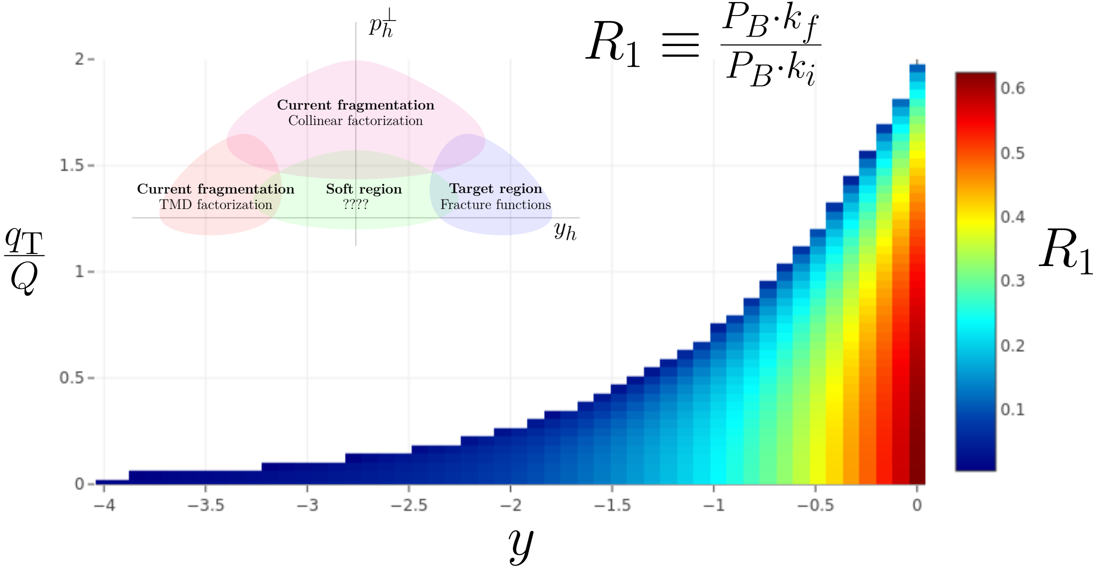
# example for pions

$$R_3 \equiv \frac{|k_X^2|}{Q^2}$$

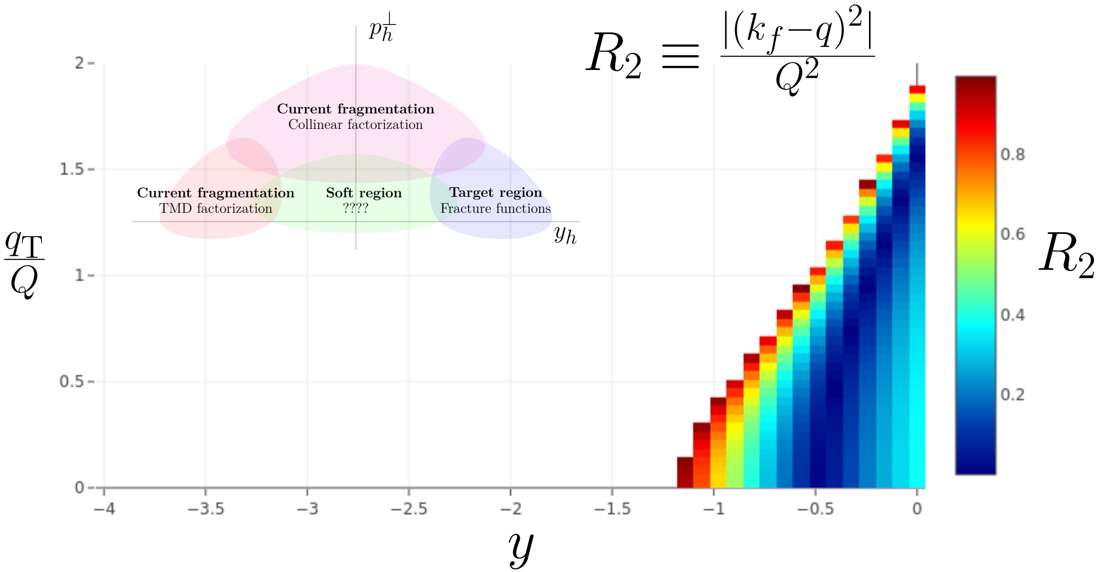


# example for kaons

$$R_1 \equiv \frac{P_B \cdot k_f}{P_B \cdot k_i}$$

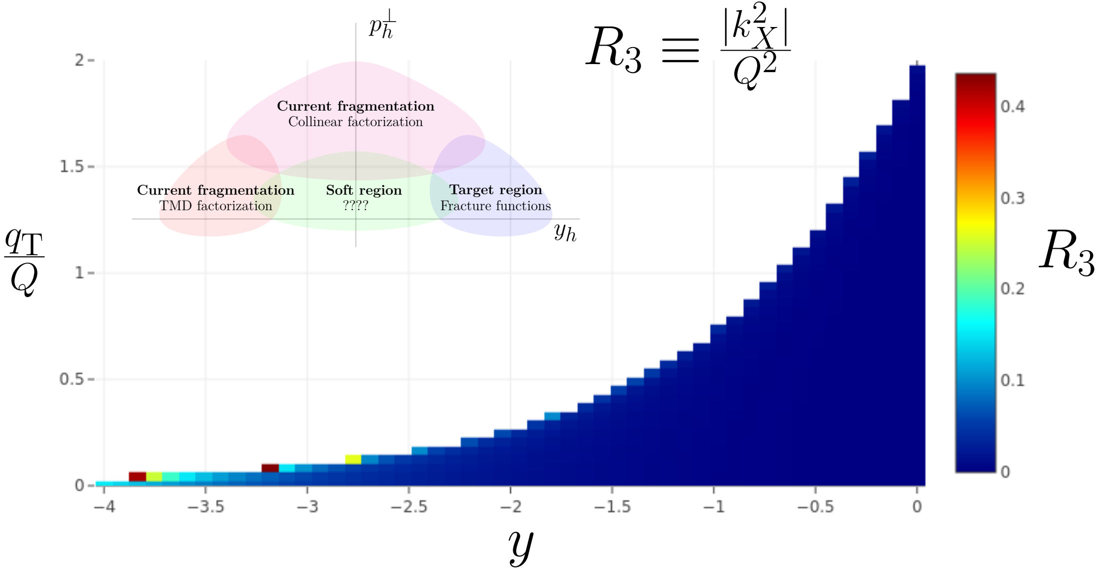


# example for kaons



# example for kaons

$$R_3 \equiv \frac{|k_X^2|}{Q^2}$$



# Using the ratios in phenomenology

- **Recall the Bayesian regression paradigm**

$$\mathcal{P}(\mathbf{a}|\text{data}) = \mathcal{L}(\mathbf{a},\text{data})\pi(\mathbf{a})$$

$$\text{E}[\mathcal{O}] = \int d^n a\ \mathcal{P}(\mathbf{a}|\text{data})\mathcal{O}(\mathbf{a})\,,$$

$$\text{V}[\mathcal{O}] = \int d^n a\ \mathcal{P}(\mathbf{a}|\text{data})\left(\mathcal{O}(\mathbf{a}) - \text{E}[\mathcal{O}]\right)^2$$

- **The likelihood**

$$\mathcal{L}(\mathbf{a},\text{data}) = \exp\left(-\frac{1}{2}\sum_i\left(\frac{\text{data}_i - \text{theory}_\text{i}(\mathbf{a})}{\delta\text{data}_i}\right)^2\right)$$

- **The priors**

$$\pi(\mathbf{a}) \propto \Pi_i\theta(a_i^{\text{min}} < a_i < a_i^{\text{max}})$$

# Using the ratios in phenomenology

- **IDEA: use $R_i$ as priors**

$$\pi(R_k) \propto \exp\left(-|R_k|^p\right)$$

- **The full prior becomes**

$$\pi(\mathbf{a}) \propto \Pi_i \theta(a_i^{\min} < a_i < a_i^{\max}) \times \Pi_j \exp\left(-\sum_{k=1,2,3} |R_k(\mathbf{a}, \mathbf{b}, \Omega_j)|^p\right) \times \pi(\mathbf{b})$$

$\rightarrow$ parameters $\mathbf{a}$ enter directly in TMD factorization

$\rightarrow$ parameters $\mathbf{b}$ are other parameters that characterize additional partonic d.o.f. (i.e. virtualities)

# Summary and outlook

- **A new perspective for MC event generators**
  - New ML based MCEG are getting built
  - ETHER at theory agnostic MCEG
  - Gaps between theory, experiment and computing are getting narrower

- **Understanding the large $p_{\mathrm{T}}$ SIDIS spectrum**
  - $O(\alpha_S^2)$ corrections are important to describe SIDIS at COMPASS
  - The large $x$ region receives large threshold corrections which can explain the difficulty to describe the data
  - Inclusion of SIDIS large $p_T$ data in PDFs/FFs analysis is required

- **New developments to identify SIDIS regions**
  - New tools to map SIDIS regions (web-app)
  - The indicators can be used as Bayesian priors for the regression in TMD phenomenology