TMDs and Large-x at the EIC

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2nd PSQ@EIC Meeting

20 July 2021

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Research supported by the
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- TMD PDFs from SIDIS Hadron and Dihadron Production
- Large-x Region and Experiment Overlaps → Low-y EIC
- Reconstruction at Low y
- Impact on p_T at Low y

TMD PDFs

Quark Polarization

Nucleon Polarization	U	L	T
U	Unpolarized PDF $f =$		Boer-Mulders $h_1^\perp =$ −
L		Helicity $g_{1L} =$ −	Kotzinian-Mulders Wormgear $h_{1L}^\perp =$ −
T	Sivers $f_{1T}^\perp =$ −	Kotzinian-Mulders Wormgear $g_{1T} =$ −	Transversity $h_{1T} =$ − Pretzelosity $h_{1T}^\perp =$ −

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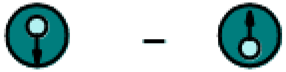
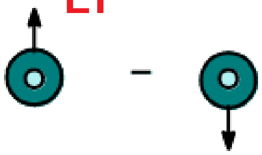
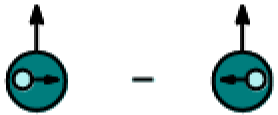
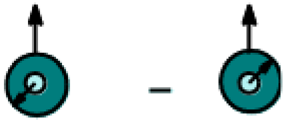
TMD PDFs

Quark Polarization

Nucleon Polarization	U	L	T
U	Unpolarized PDF f =		F_{UU} $h_1^\perp$ = 
L		Helicity g_{1L} =	F_{UL} $h_{1L}^\perp$ = 
T	F_{UT}, F_{LT} $f_{1T}^\perp$ = 	F_{UT}, F_{LT} g_{1T} = 	F_{UT} h_{1T} =  F_{UT} $h_{1T}^\perp$ = 

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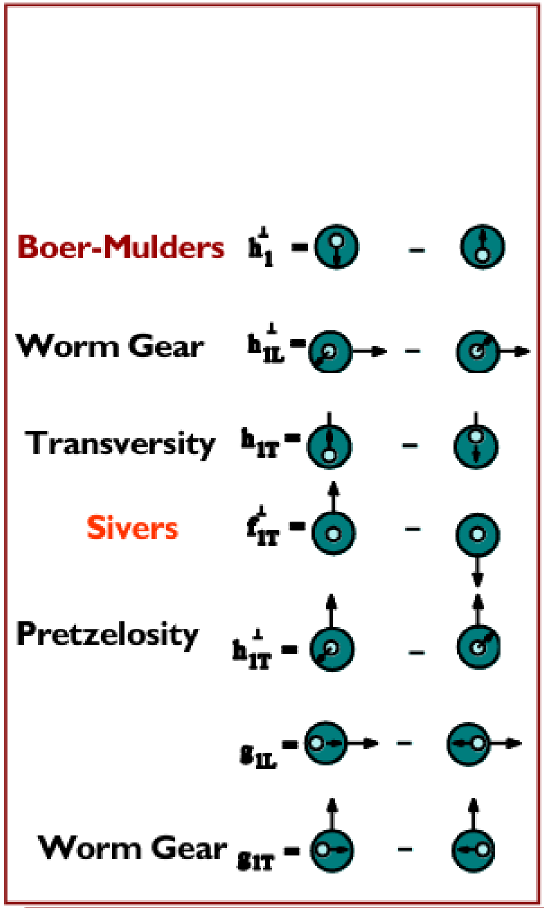
TMD PDFs — Single-hadron SIDIS — $ep \to ehX$



$$d^6\sigma = \frac{4\pi\alpha^2 s x}{Q^4} \times$$

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z, P_{h\perp}^2)$$

$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

Unpolarized

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z, P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

$$+\lambda_e|S_L| y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z, P_{h\perp}^2)$$

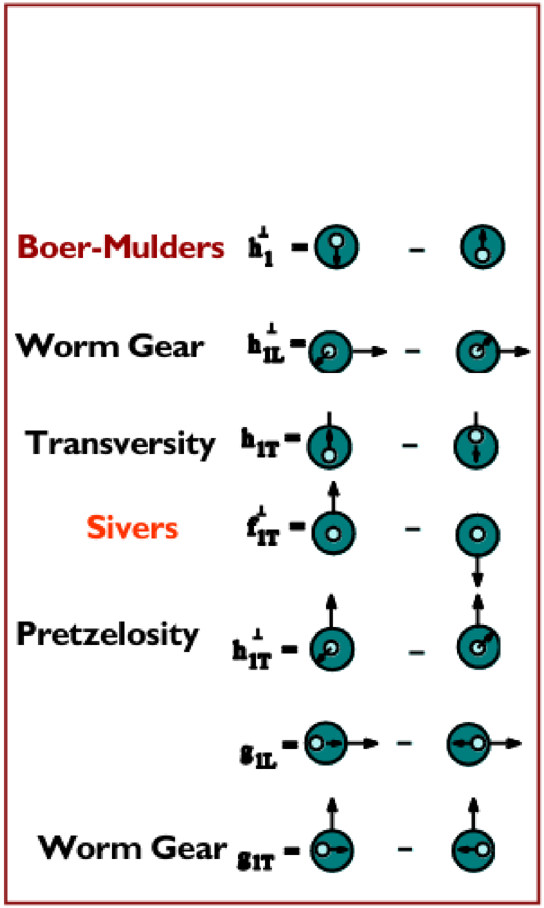
Polarized target

$$+\lambda_e|S_T| y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z, P_{h\perp}^2)\}$$

Polarzied beam and target

S_L and S_T: Target Polarizations; λe: Beam Polarization
x: momentum fraction carried by struck quark, z: fractional energy of hadron

TMD PDFs



Dihadron SIDIS $ep \rightarrow eh_1h_2X$

$$F_{UU}^{P_{\ell,m}\cos((2-m)\phi_h+m\phi_{R_\perp})} = -\mathcal{I}\left[\frac{|\boldsymbol{k}_T||\boldsymbol{p}_T|}{MM_h}\cos\left((m-2)\phi_h+\phi_k+(1-m)\phi_p\right)h_1^\perp H_1^{\perp|\ell,m\rangle}\right]$$

$$F_{UT}^{P_{\ell,m}\sin((1-m)\phi_h+m\phi_{R_\perp}+\phi_S)} = -\mathcal{I}\left[\frac{|\boldsymbol{p}_T|}{M_h}\cos\left((1-m)\left(\phi_p-\phi_h\right)\right)h_1 H_1^{\perp|\ell,m\rangle}\right]$$

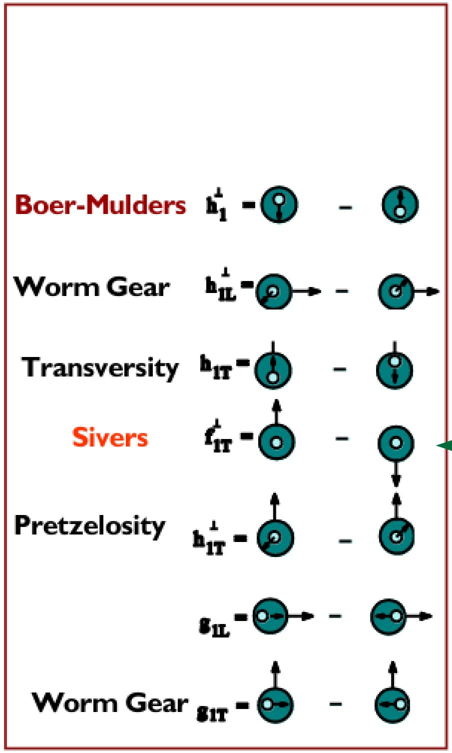
$$F_{UT,T}^{P_{\ell,m}\sin((1+m)\phi_h-m\phi_{R_\perp}-\phi_S)} = -\mathcal{I}\left[\frac{|\boldsymbol{k}_T|}{M}\cos\left(\phi_k+m\phi_p-(1+m)\phi_h\right)\times\left(f_{1T}^\perp D_1^{|\ell,m\rangle}+\mathrm{sign}[m]g_{1T}G_1^{|\ell,m\rangle}\right)\right]$$

+ many more

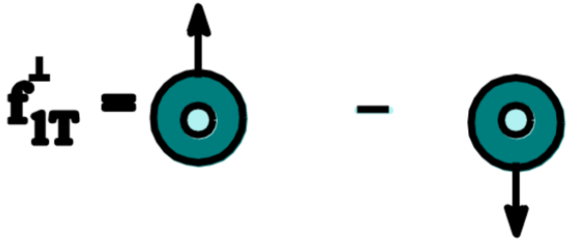
- Single hadron and dihadron measurements complementary
- Dihadron fragmentation functions → spin-momentum correlations in hadronization

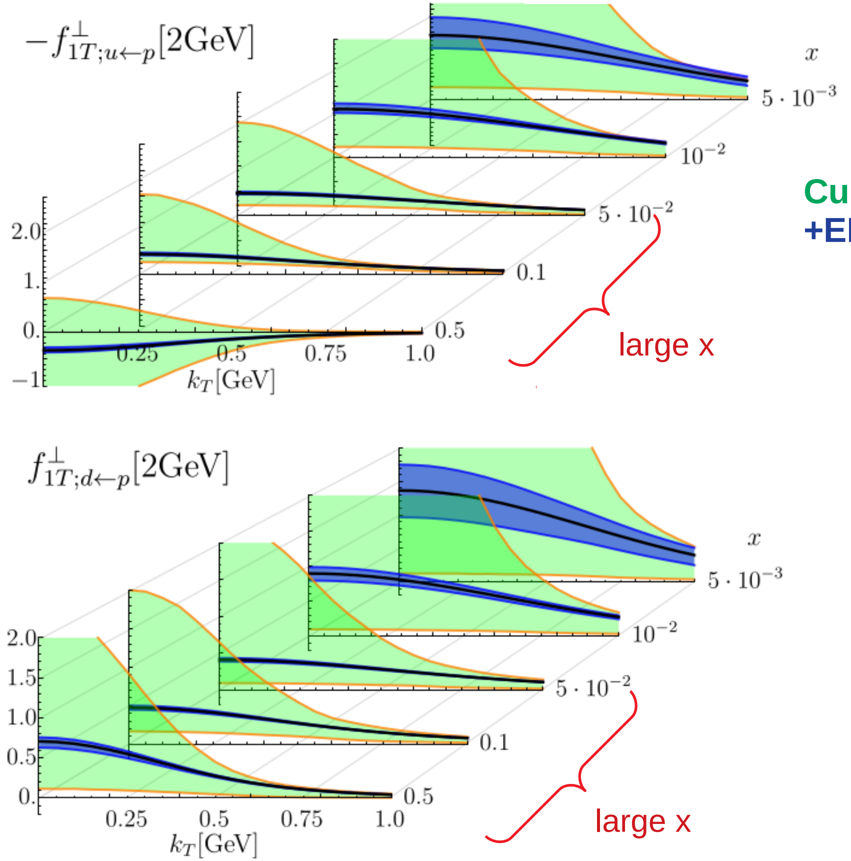
TMD PDFs

A_{UT} F_{UT} / F_{UU}



Impact on Sivers Function



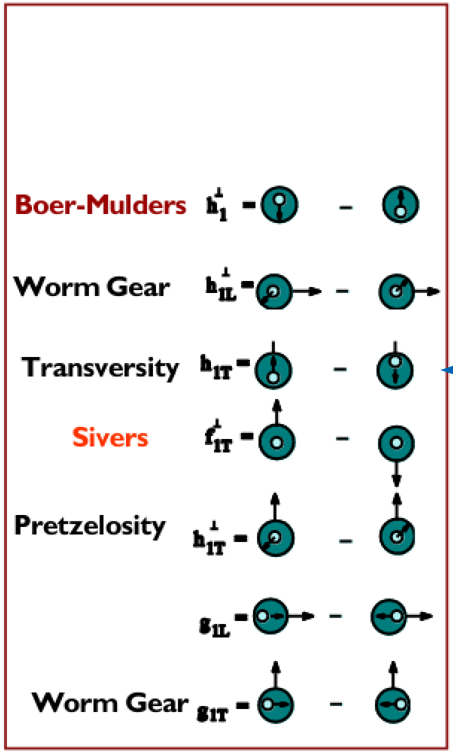


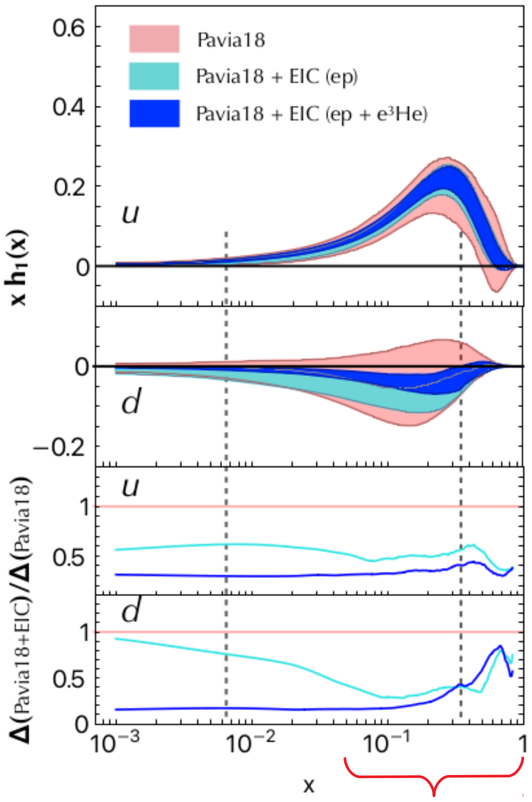
Current uncertainty
+EIC pseudodata

TMD PDFs

A_{UT} F_{UT} / F_{UU}

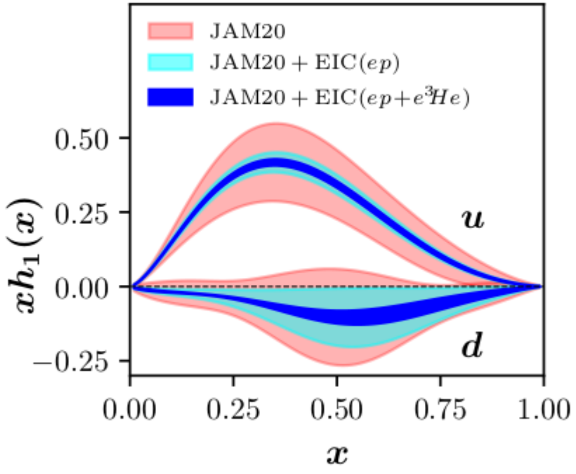
Transversity $h_{1T} =$ 





$Q^2 = 2.4\ GeV^2$

large x



$Q^2 = 4\ GeV^2$

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- **Large-x Region and Experiment Overlaps → Low-y EIC**
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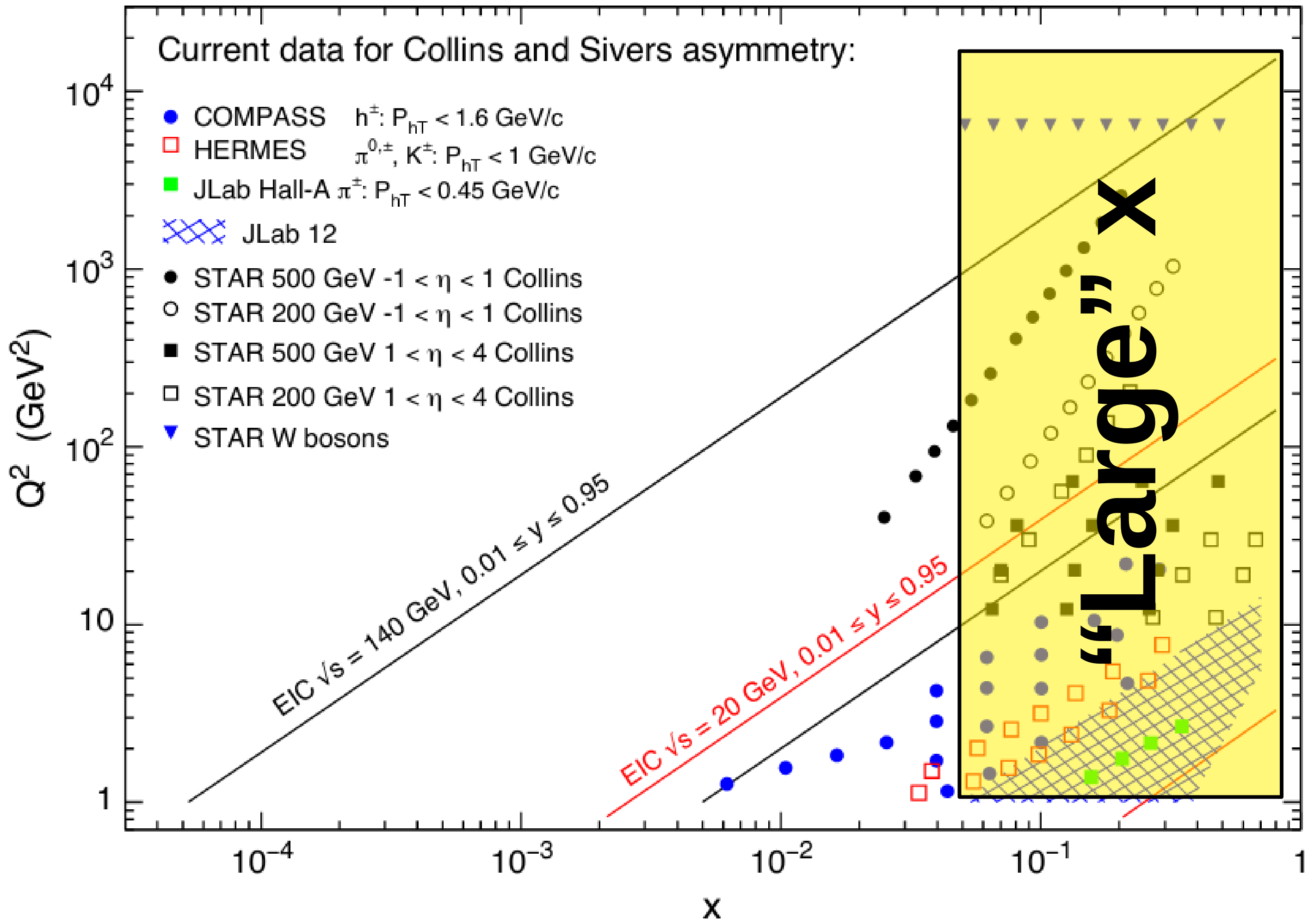
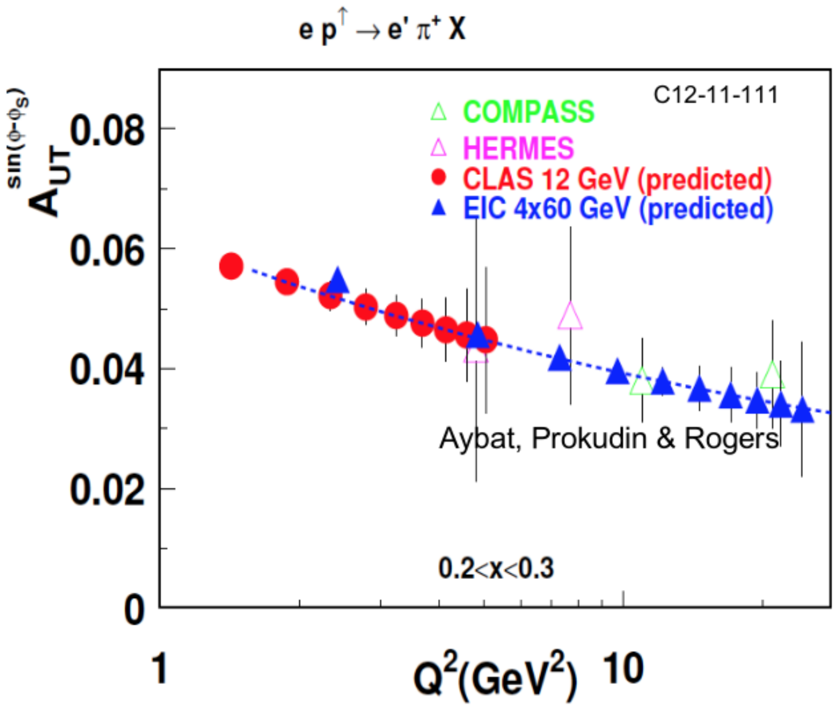
SIDIS Kinematic Coverage for Sivers and Collins



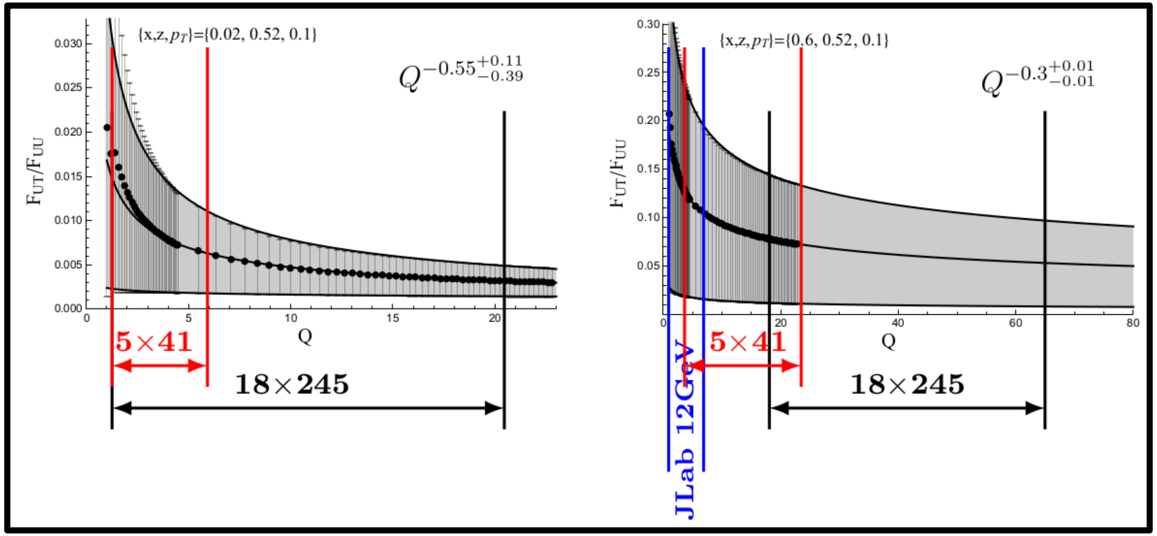
x > 0.05

Evolution



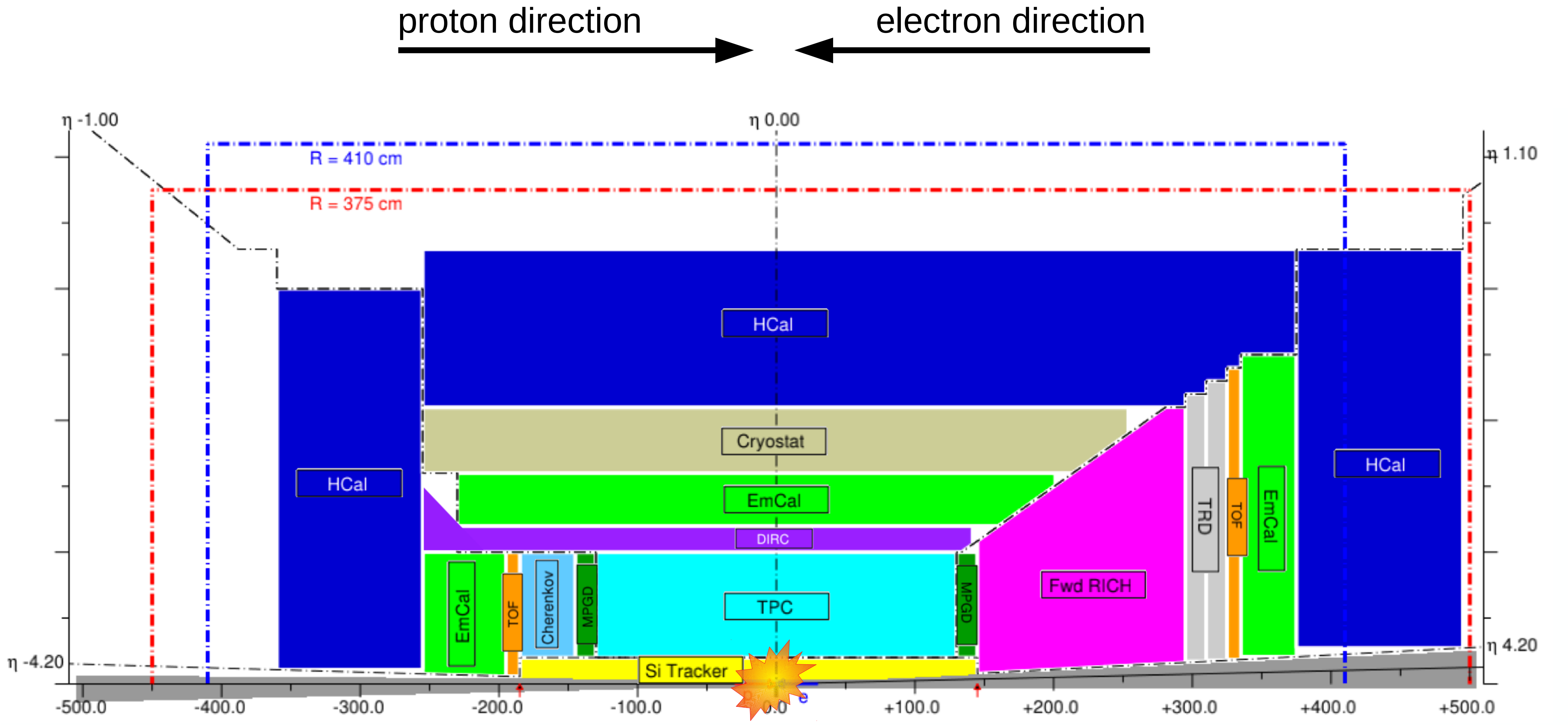
H. Avakian, REF2020, Dec 9

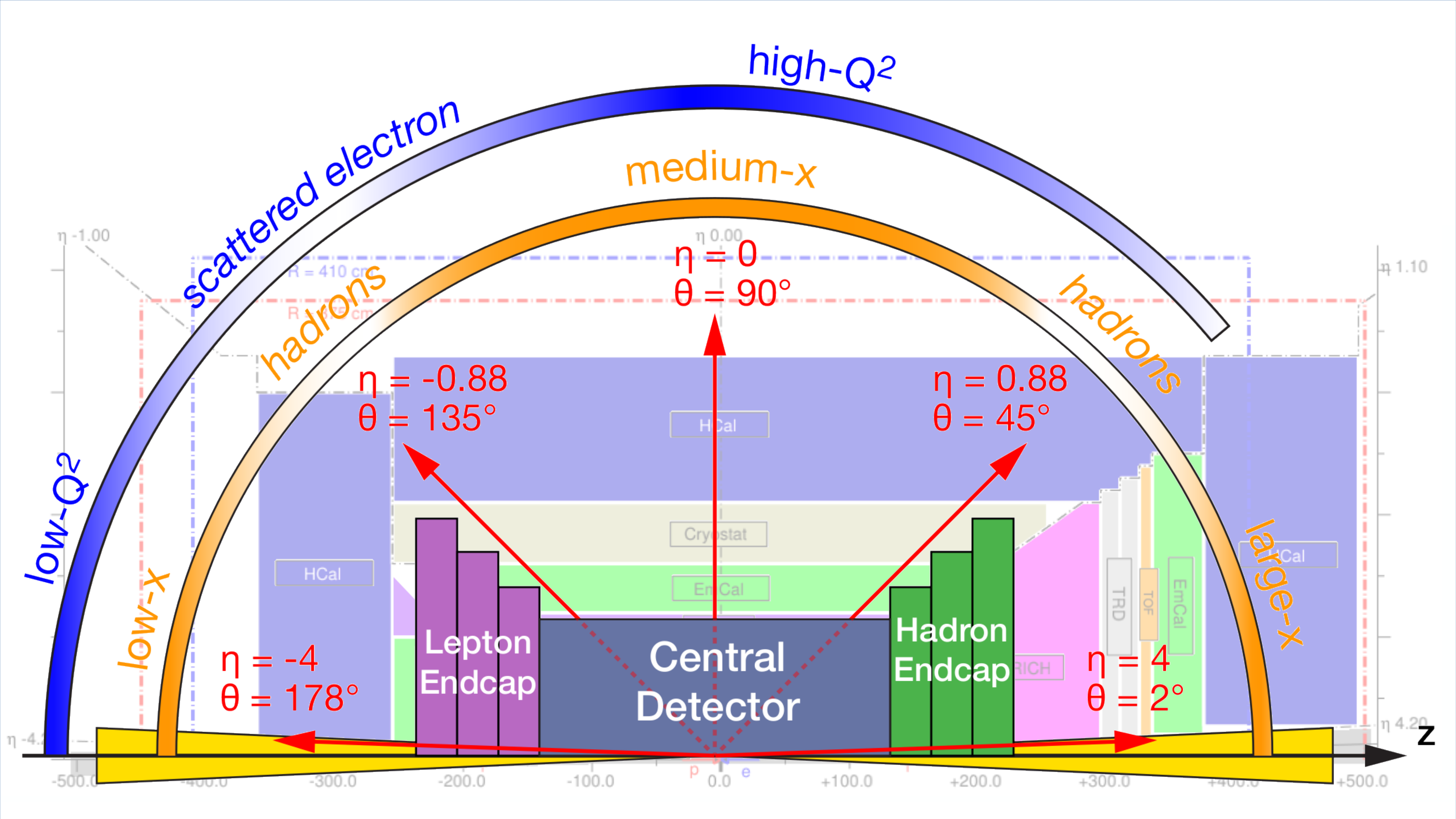
- Goal: measure asymmetries at large x ~ 10^{-1}
- Could go to large Q^2, but asymmetry may decrease as Q^2 increases; very high Q^2 would push above PID limits
- What are the limitations at small Q^2, large x?
- Ideal situation: (x,Q^2)-overlap data from JLab to EicC to EIC, but what do we need to do to get there?



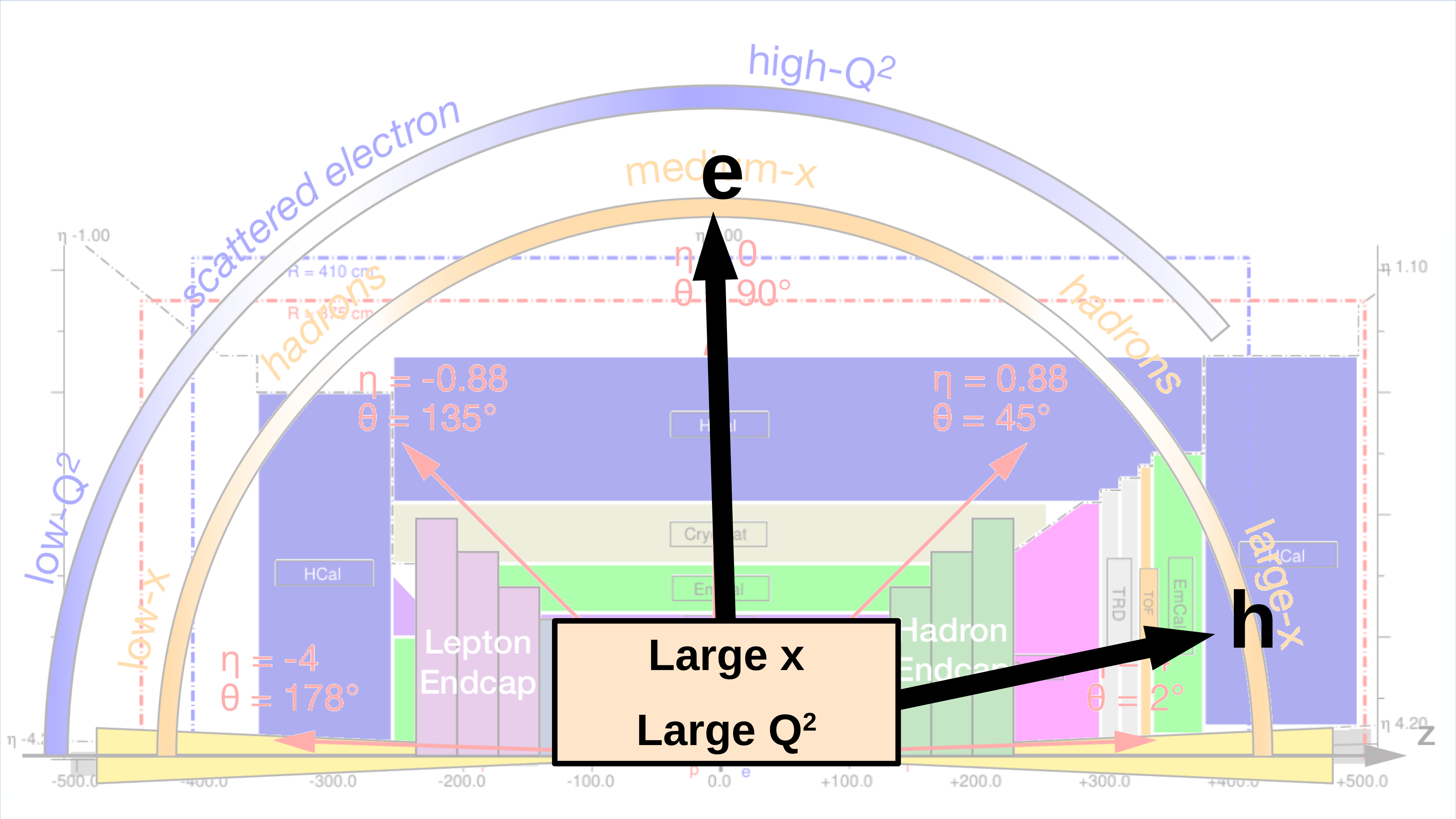
A. Vladimirov, IR2@EIC workshop, Mar 2021

EIC Yellow Report Design

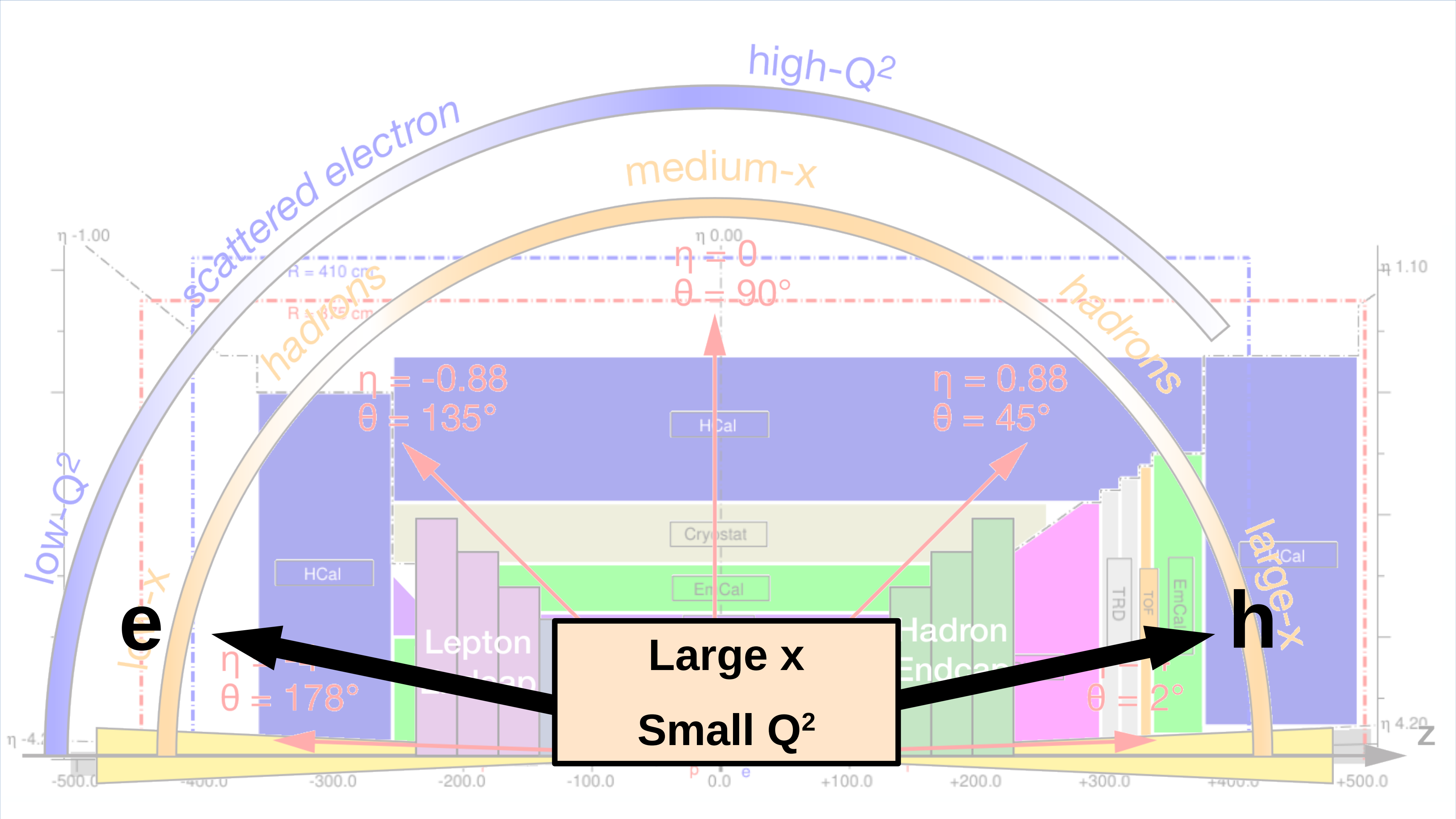




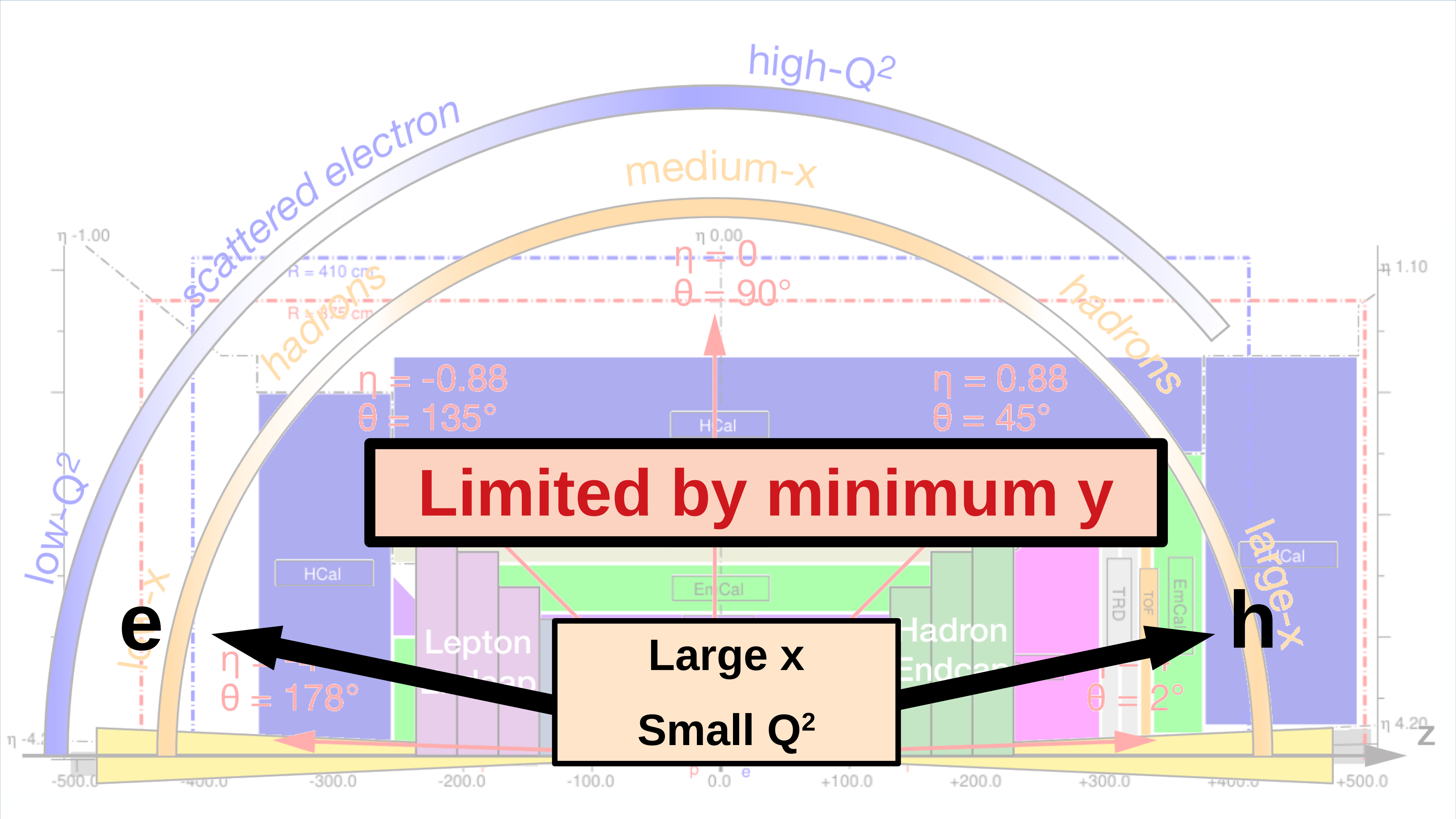
high-Q2
scattered electron
low-Q2
medium-x
hadrons
hadrons
low-x
large-x
η = 0
θ = 90°
η = -0.88
θ = 135°
η = 0.88
θ = 45°
η = -4
θ = 178°
η = 4
θ = 2°
Lepton Endcap
Central Detector
Hadron Endcap
HCal
Cryostat
EmCal
HCal
TRD
TOF
EmCal
RICH
z
-500.0
-400.0
-300.0
-200.0
-100.0
0.0
+100.0
+200.0
+300.0
+400.0
+500.0



high-Q²
scattered electron
medium-x
e
hadrons
hadrons
η = -0.88
θ = 135°
η = 0.88
θ = 45°
low-Q²
low-x
large-x
h
HCal
Lepton
Endcap
Hadron
Endcap
TRD
TOF
EmCal
η = -4
θ = 178°
θ = 2°
Large x
Large Q²
z
-500.0
-300.0
-200.0
-100.0
0.0
+100.0
+200.0
+300.0
+500.0

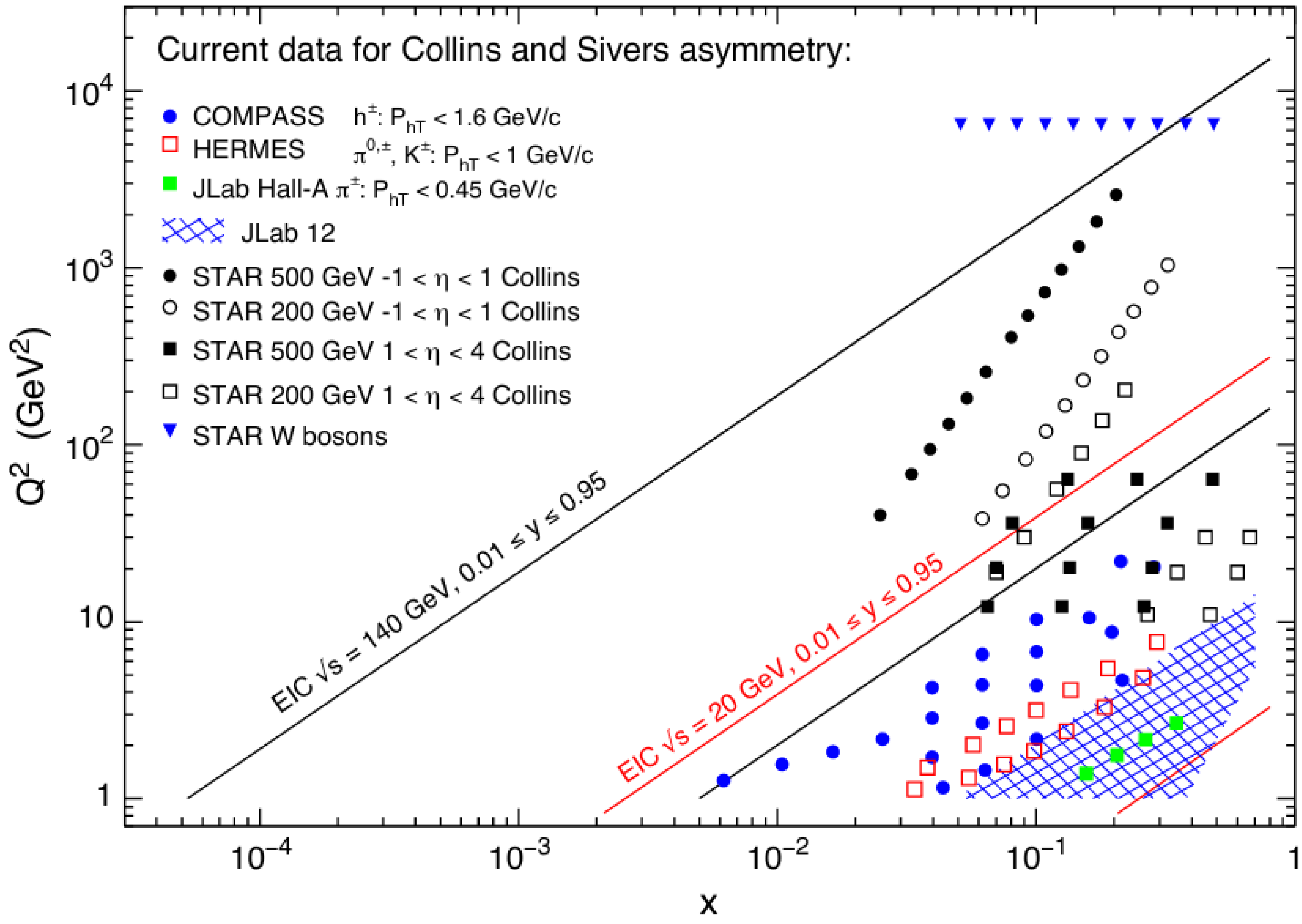


high-Q²
scattered electron
medium-x
hadrons
hadrons
low-Q²
large-x
η -1.00
η 0.00
η 1.10
η 4.20
R = 410 cm
η = 0
θ = 90°
η = -0.88
θ = 135°
η = 0.88
θ = 45°
HCal
HCal
HCal
Cryostat
EmCal
Lepton
Hadron
TRD
TOF
EmCal
θ = 178°
θ = 2°
e
h
Large x
Small Q²
z
-500.0
-300.0
-200.0
-100.0
0.0
+100.0
+200.0
+300.0
+500.0



high-Q²
scattered electron
medium-x
hadrons
hadrons
low-Q²
large-x
η -1.00
η 0.00
η 1.10
η 4.20
R = 410 cm
η = 0
θ = 90°
η = -0.88
θ = 135°
η = 0.88
θ = 45°
θ = 178°
θ = 2°
HCal
HCal
HCal
EmCal
EmCal
TRD
TOF
Lepton
Hadron
Limited by minimum y
e
h
Large x
Small Q²
z
-500.0
-400.0
-300.0
-200.0
-100.0
0.0
+100.0
+200.0
+300.0
+400.0
+500.0

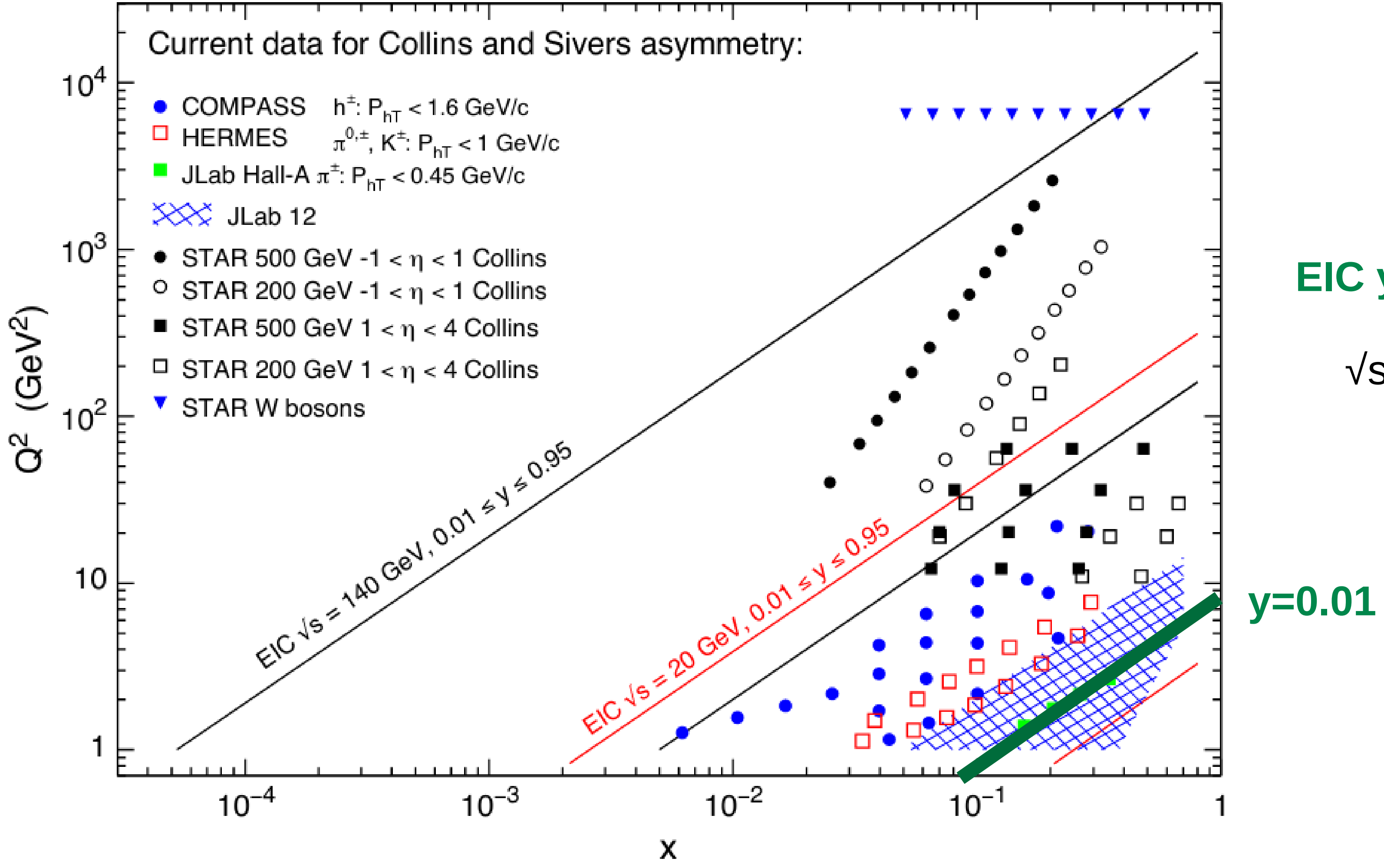
SIDIS Kinematic Coverage for Sivers and Collins



Nucleon rest frame:
$y = 1 - E_e'/E_e$

y contours
lines in (x, Q^2) plane

SIDIS Kinematic Coverage for Sivers and Collins

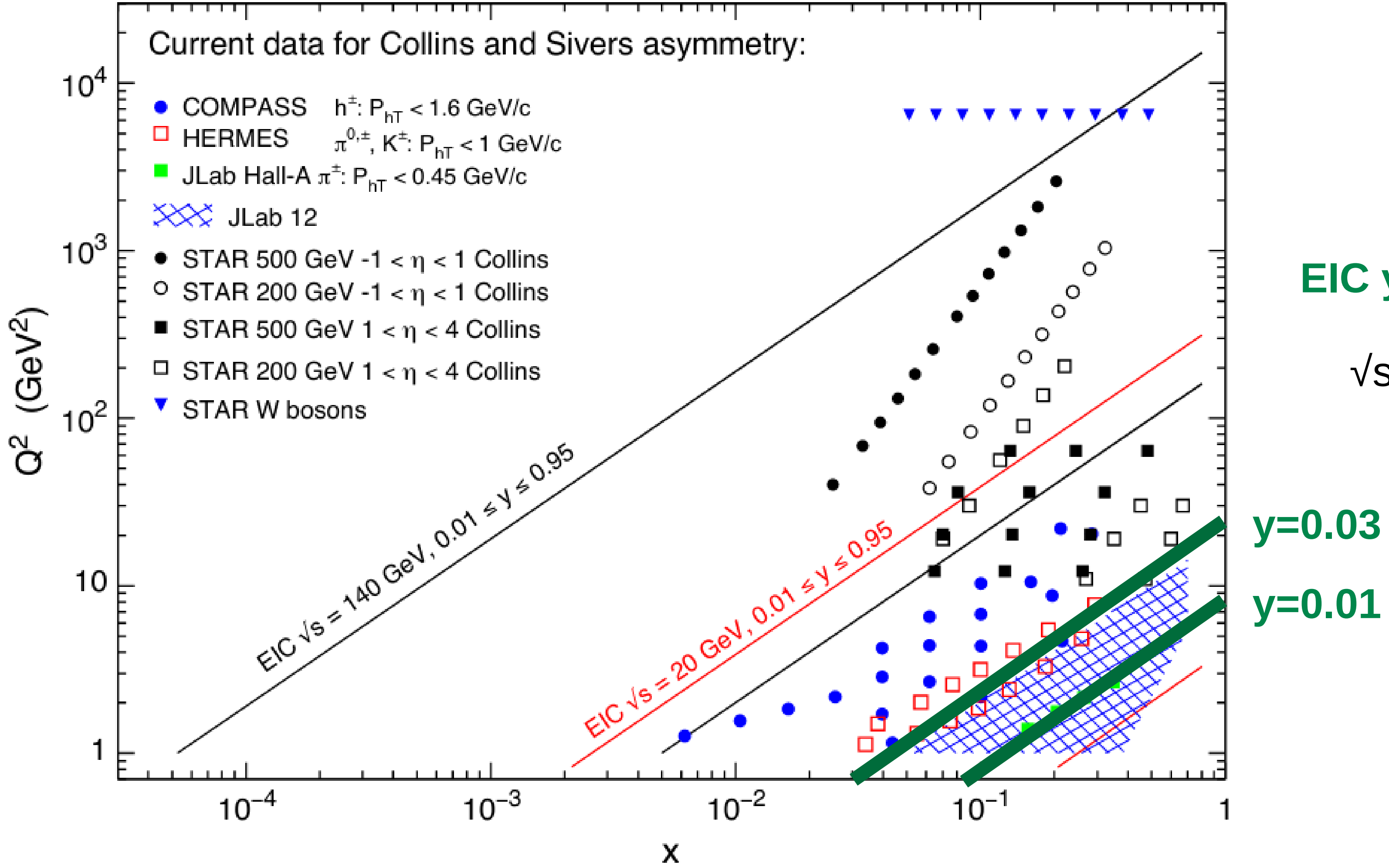


EIC y contours

5 x 41

$\sqrt{s} = 28.65$

SIDIS Kinematic Coverage for Sivers and Collins

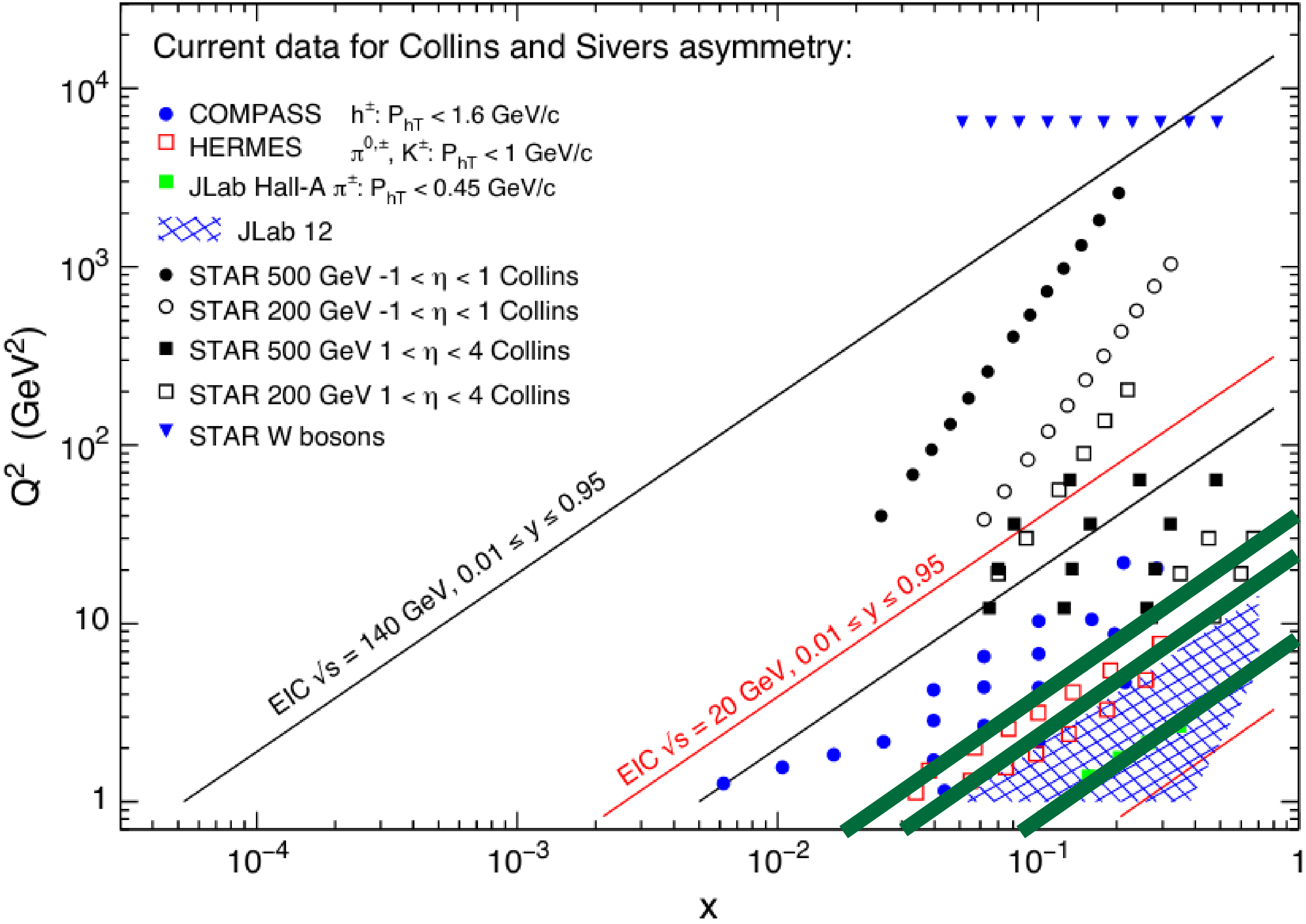


EIC y contours

5 x 41

$\sqrt{s} = 28.65$

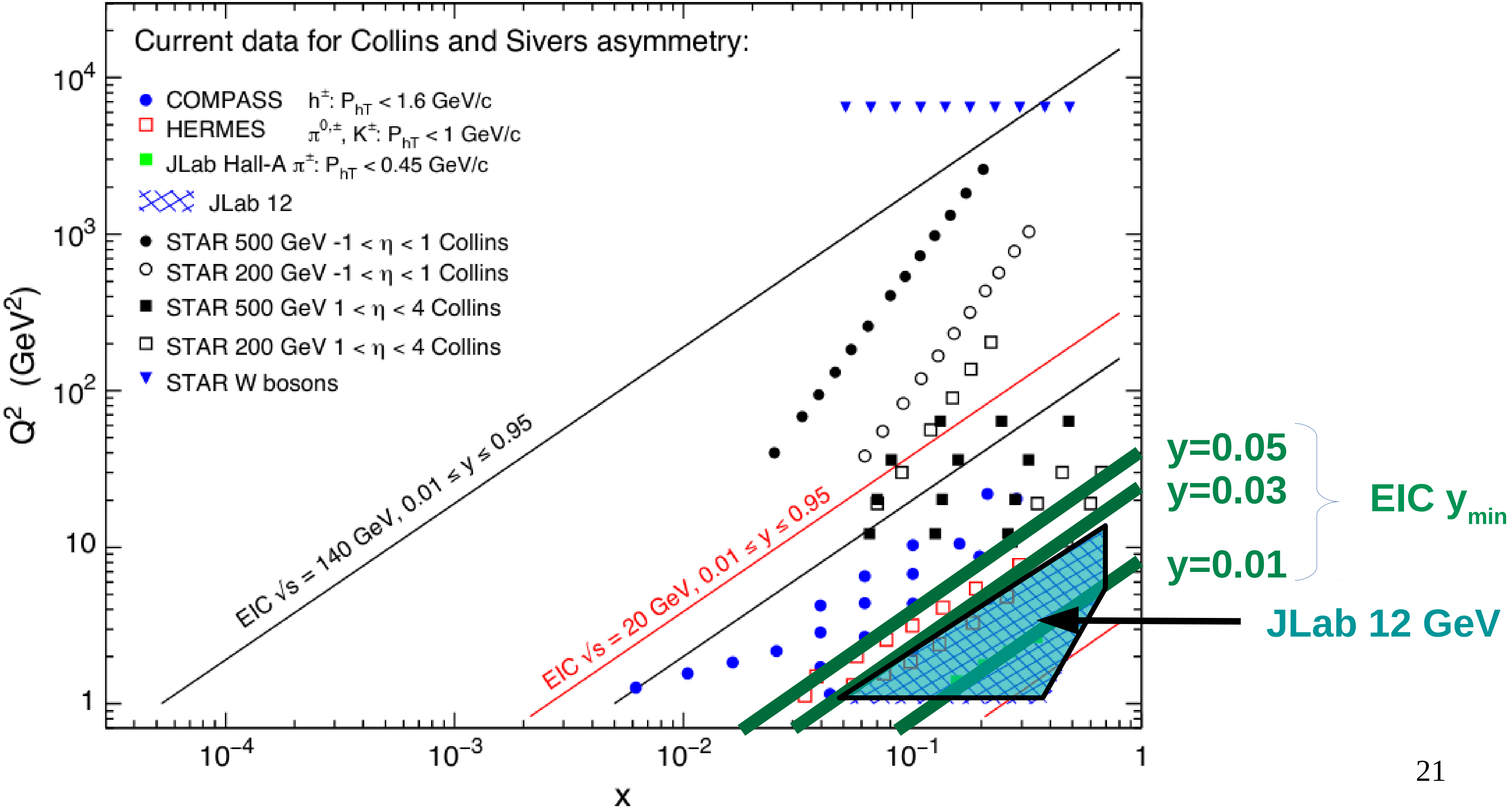
SIDIS Kinematic Coverage for Sivers and Collins



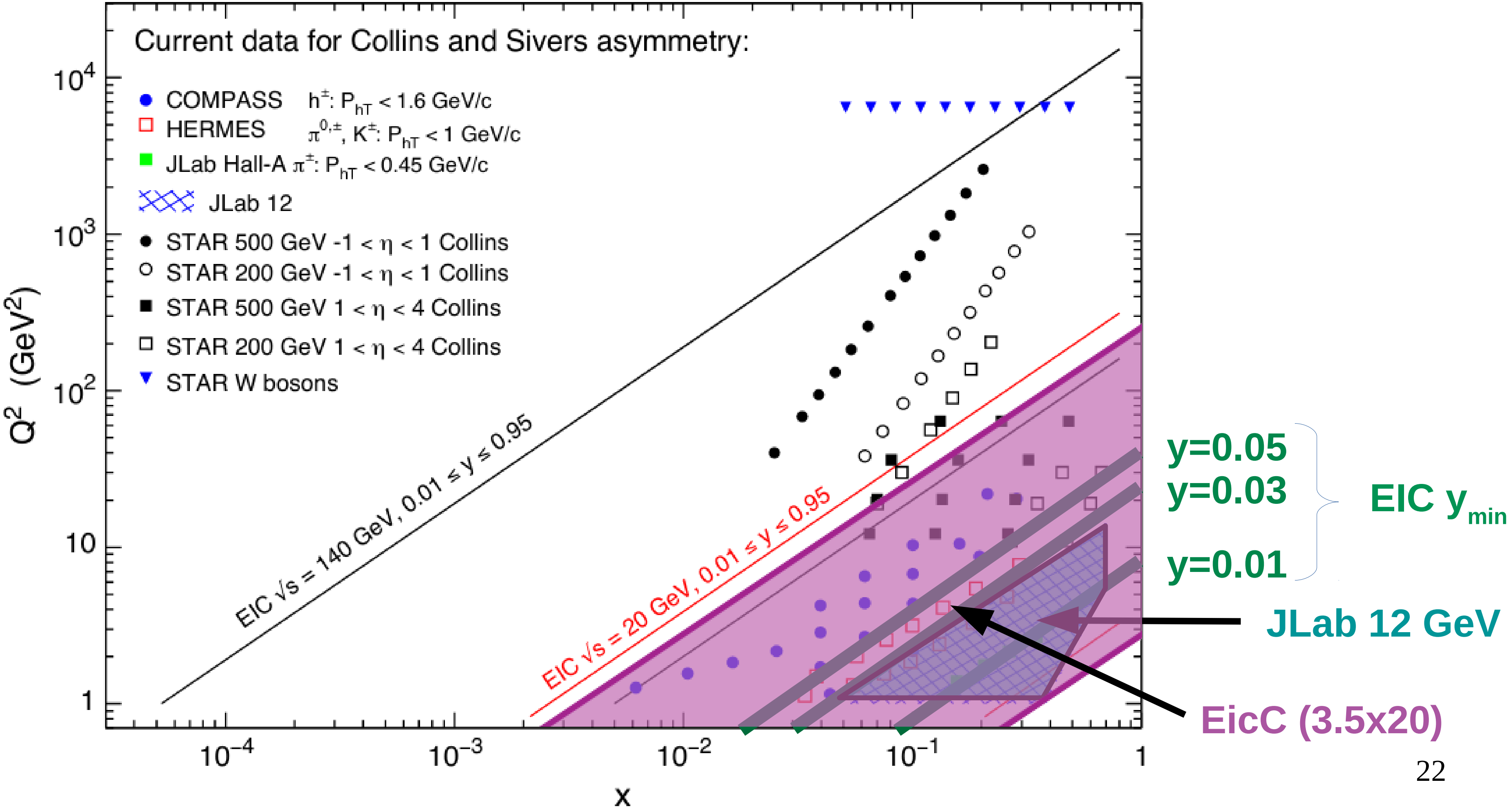
EIC y contours
5 x 41
√s = 28.65

y=0.05
y=0.03
y=0.01

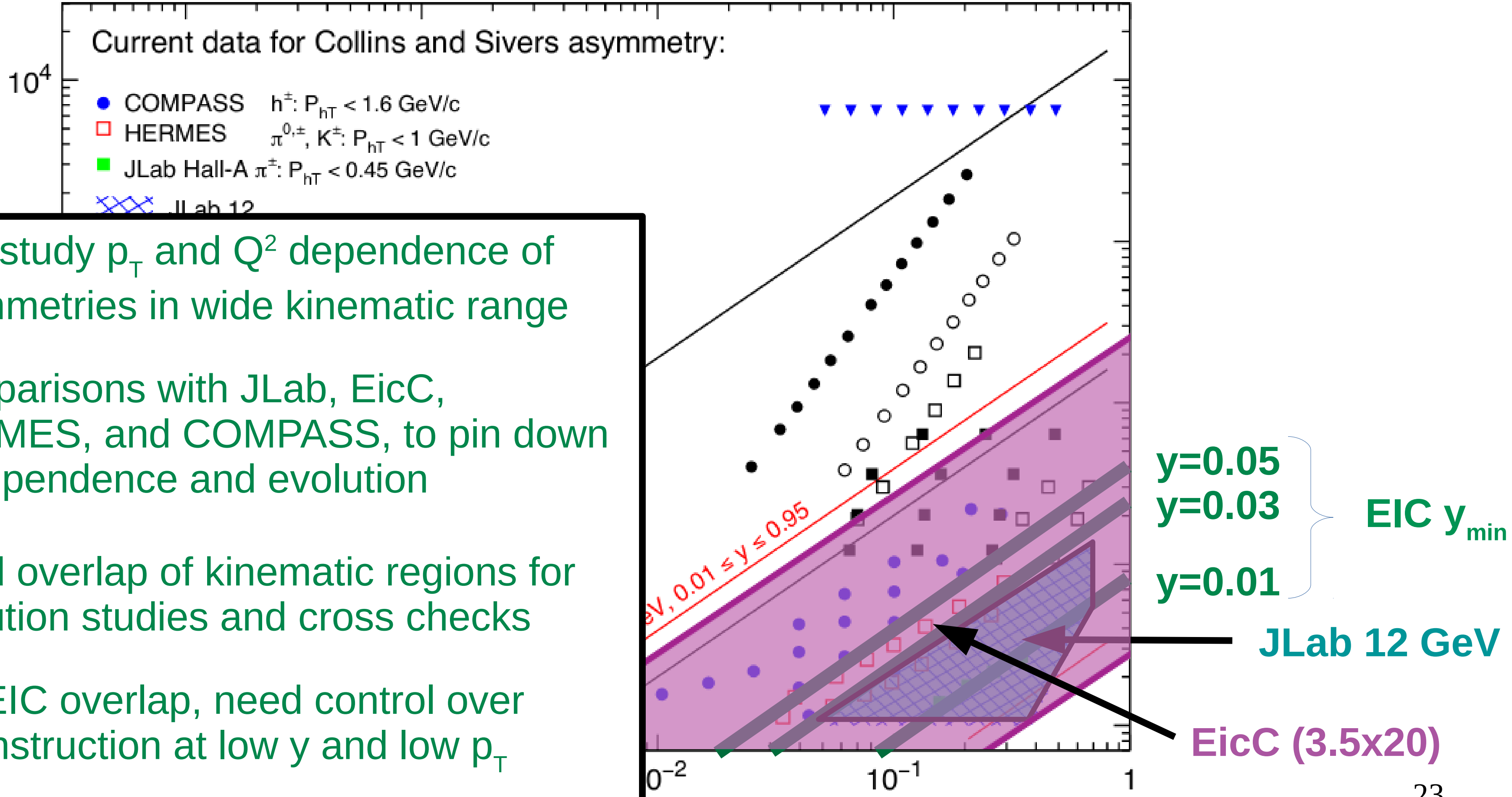
SIDIS Kinematic Coverage for Sivers and Collins



SIDIS Kinematic Coverage for Sivers and Collins

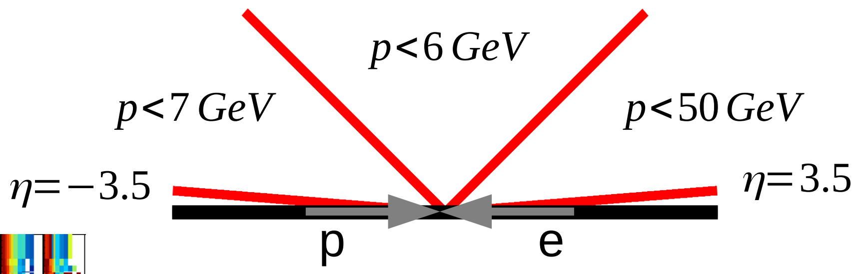


SIDIS Kinematic Coverage for Sivers and Collins

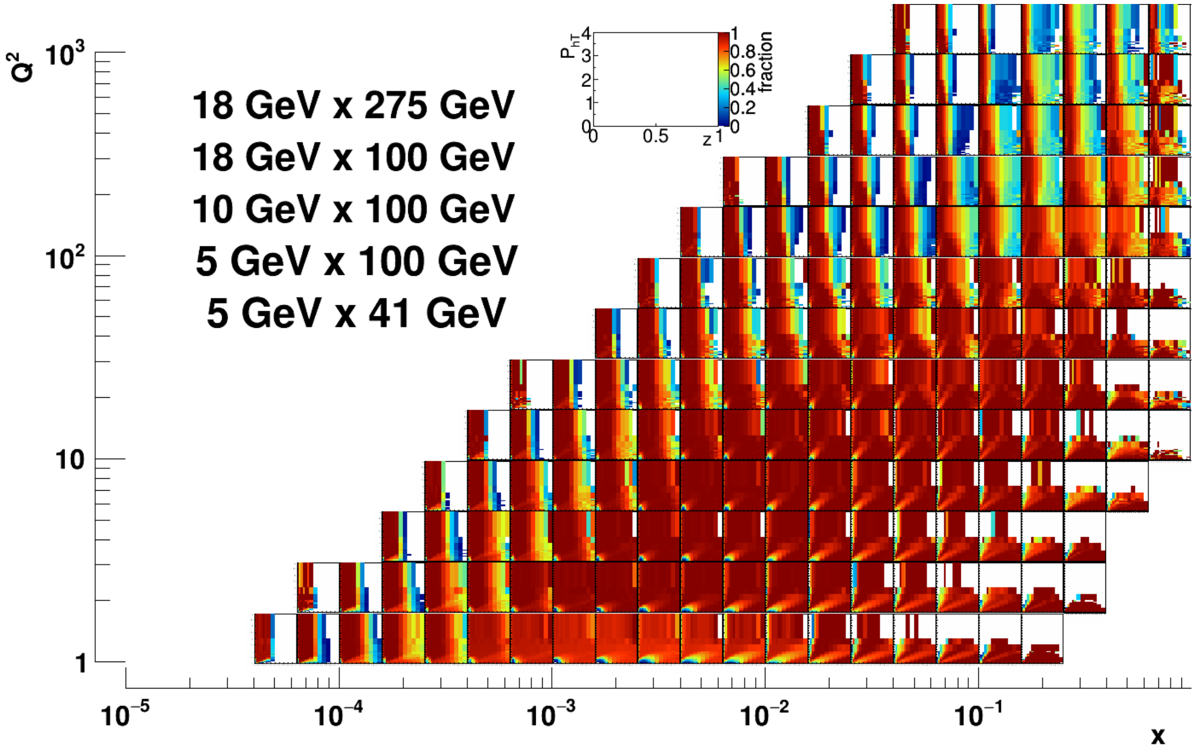


- EIC: study p_T and Q^2 dependence of asymmetries in wide kinematic range
- Comparisons with JLab, EicC, HERMES, and COMPASS, to pin down p_T dependence and evolution
- Need overlap of kinematic regions for evolution studies and cross checks
- For EIC overlap, need control over reconstruction at low y and low p_T

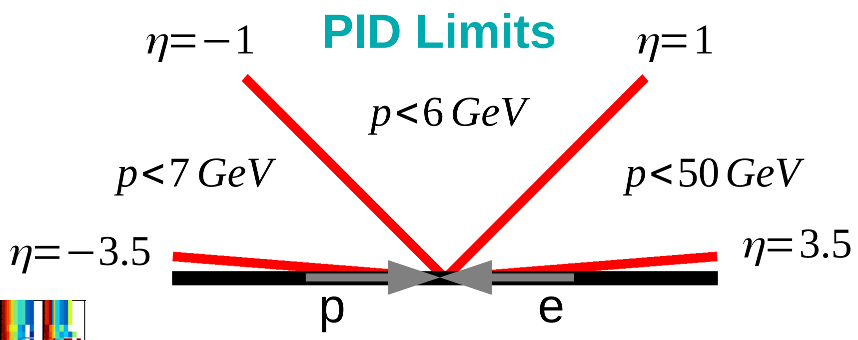
EIC Coverage Limits

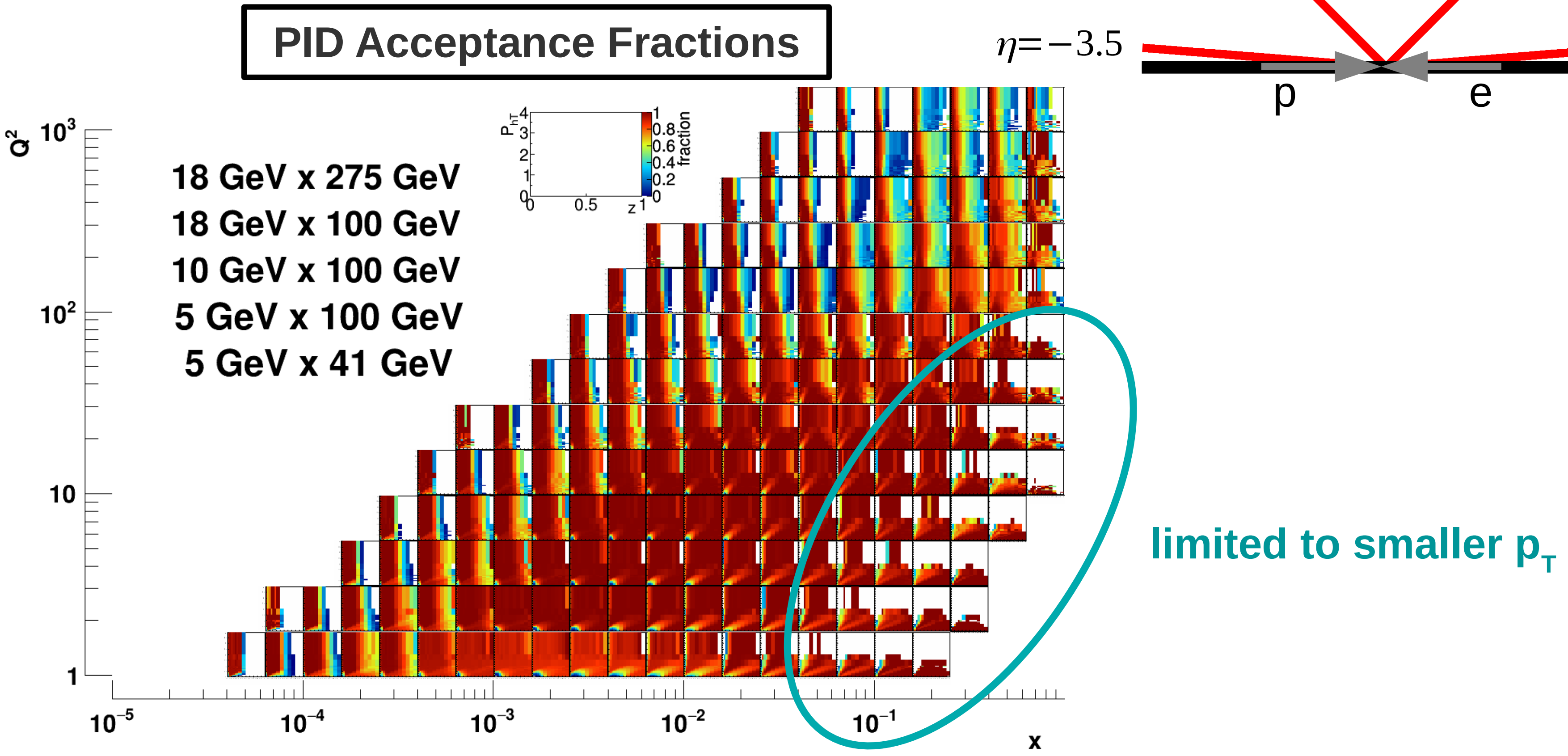


PID Acceptance Fractions

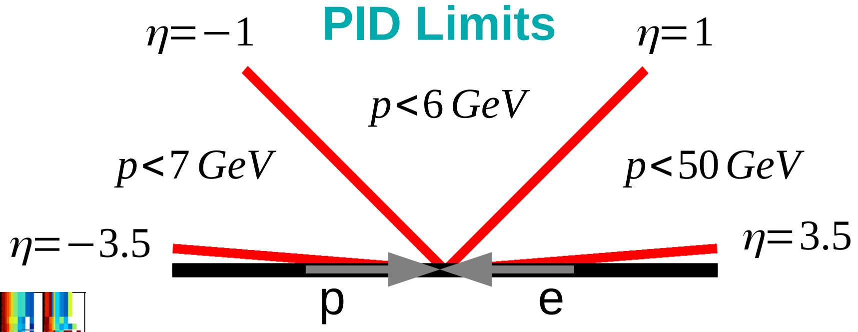


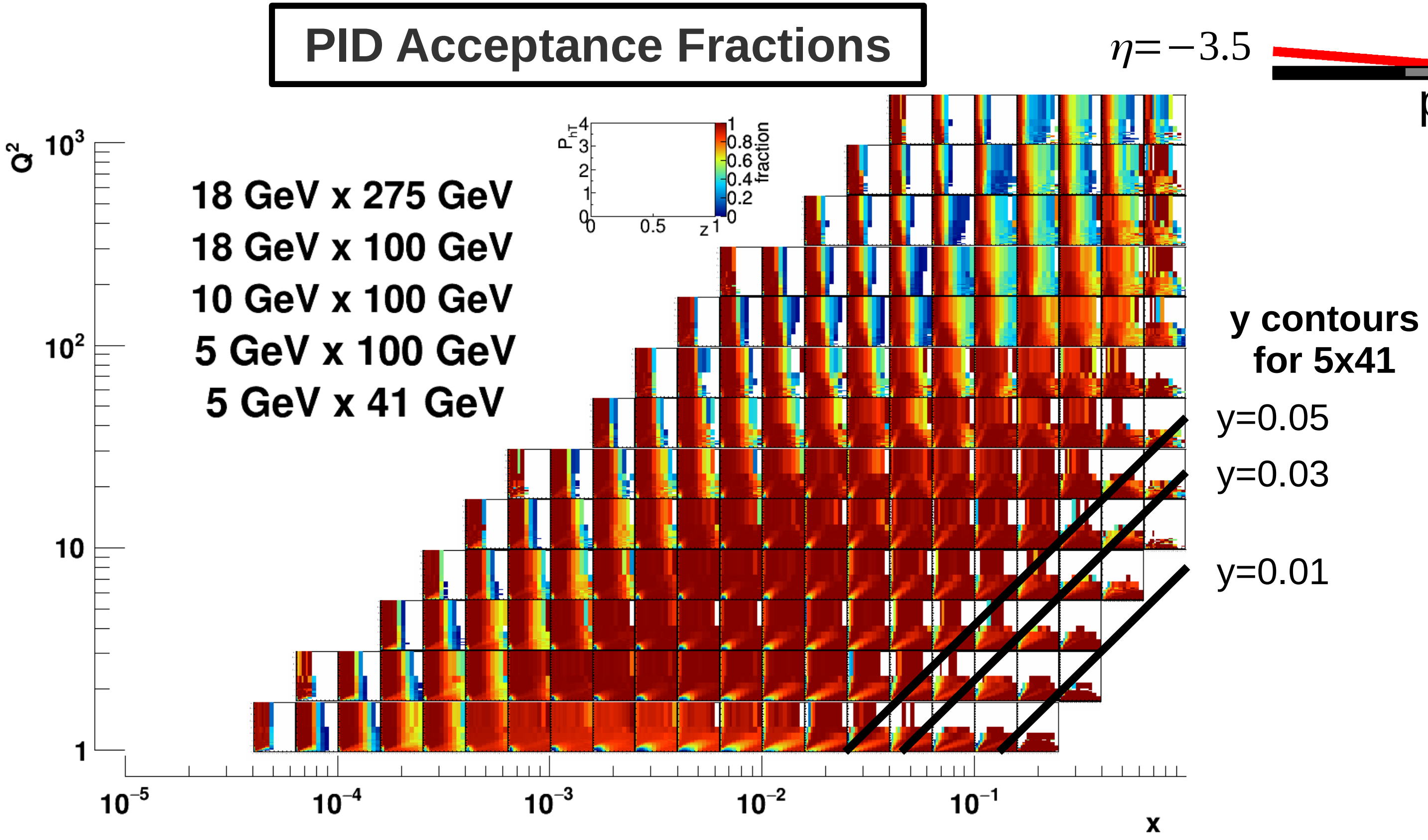
EIC Coverage Limits





EIC Coverage Limits





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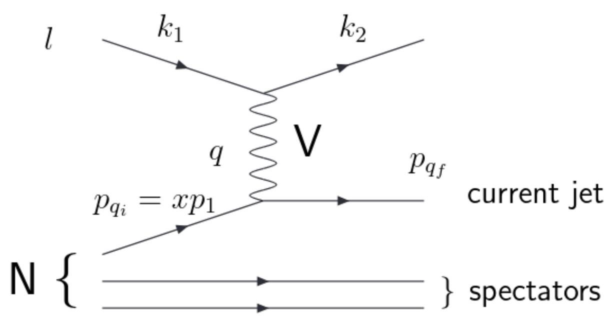
Kinematics Reconstruction Methods

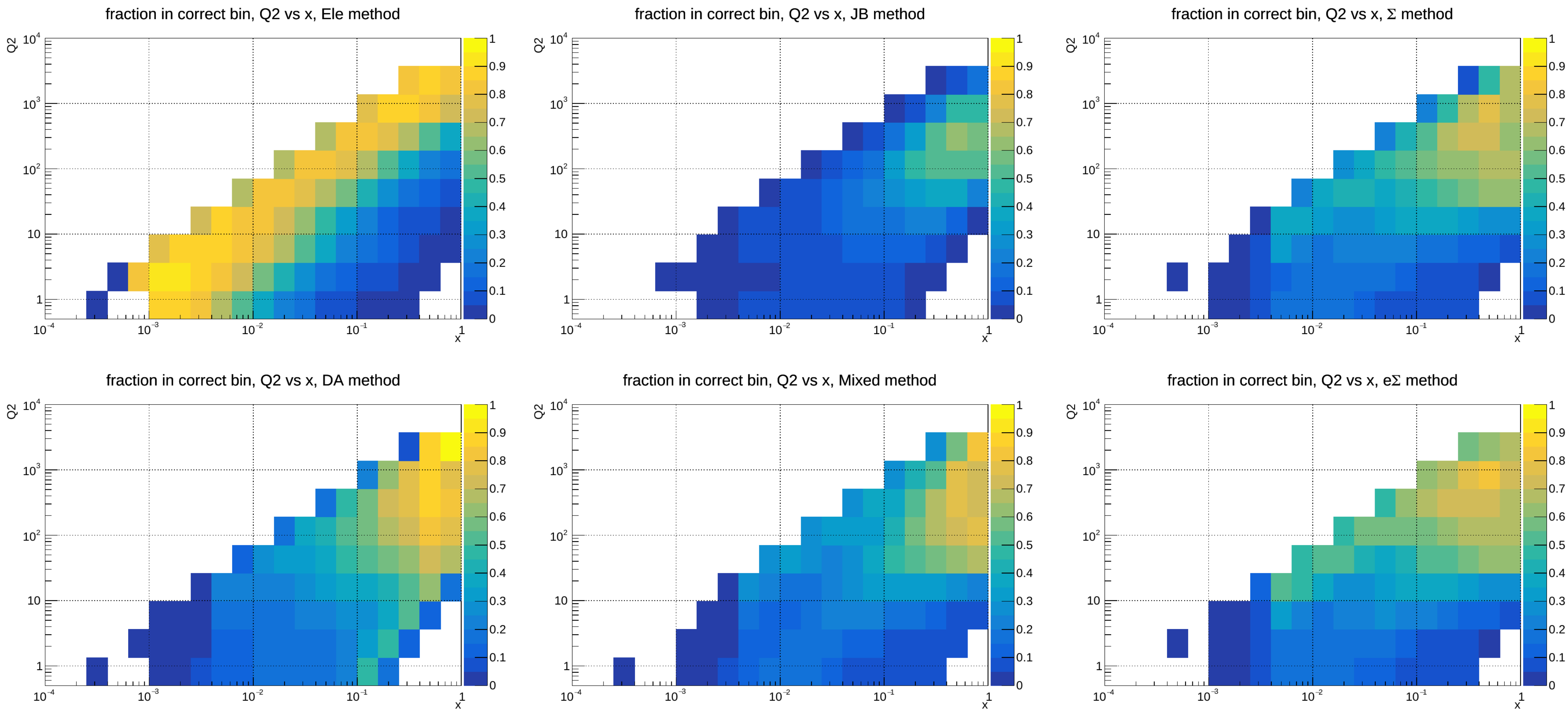


- SIDIS kinematics depends on what is used to reconstruct quantities such as x and Q^2
  - Scattered electron
  - Hadrons
  - Some mixture

i)	*Leptonic variables*	$q \equiv q_l = k_2 - k_1, \quad y_l = p_1.(k_1 - k_2)/p_1.k_1$
ii)	*Hadronic variables* [81]	$q \equiv q_h = p_2 - p_1, \quad y_l = p_1.(p_2 - p_1)/p_1.k_1$
iii)	*Jacquet-Blondel variables* [82]	$Q^2_{JB} = (\vec{p}_{2,\perp})^2/(1 - y_{JB}), \quad y_{JB} = \Sigma/(2E(k_1))$ $\Sigma = \sum_h (E_h - p_{h,z})$
iv)	*Mixed variables* [81]	$q = q_l, y_m = y_{JB}$
v)	*Double angle method* [83]	$Q^2_{DA} = \frac{4E(k_2)^2 \cos^2(\theta(k_2)/2)}{\sin^2(\theta(k_2)/2) + \sin(\theta(k_2)/2)\cos(\theta(k_2)/2)\tan(\theta(p_2)/2)},$ $y_{DA} = 1 - \frac{\sin(\theta(k_2)/2)}{\sin(\theta(k_2)/2) + \cos(\theta(k_2)/2)\tan(\theta(p_2)/2)},$
vi)	*θy method* [84]	$Q^2_{\theta y} = 4E(k_2)^2(1 - y_{JB})\frac{1 + \cos(\theta(k_2))}{1 - \cos(\theta(k_2))}, \quad y_{\theta y} = y_{JB}$
vii)	*Σ method* [85]	$Q^2_\Sigma = \frac{(\vec{k}_{2,\perp})^2}{1 - y_\Sigma}, \quad y_\Sigma = \frac{\Sigma}{\Sigma + E(k_2)[1 - \cos(\theta(k_2))]}$
viii)	*$e\Sigma$ method* [85]	$Q^2_{e\Sigma} = Q^2_l, \quad y_{e\Sigma} = \frac{Q^2_l}{s x_\Sigma}$

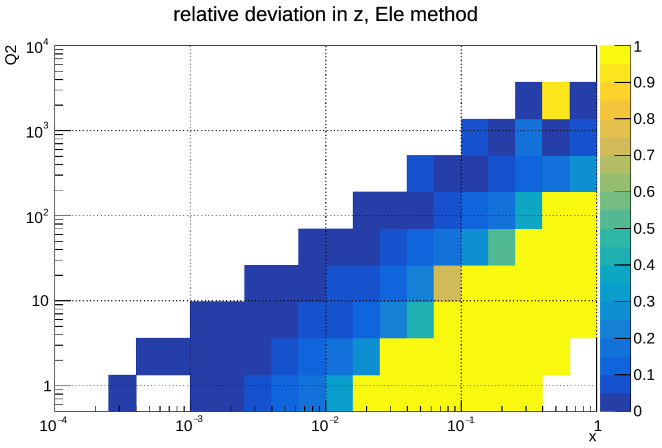
Prog.Part.Nucl.Phys. 69 (2013) 28-84, 1208.6087 [hep-ph]

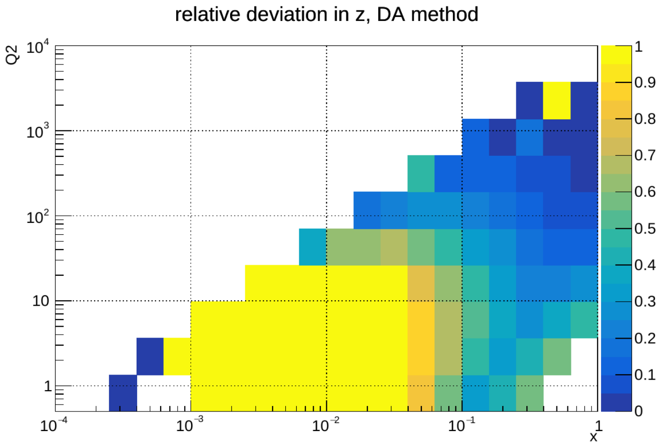
Fraction in correct bin (10x100)

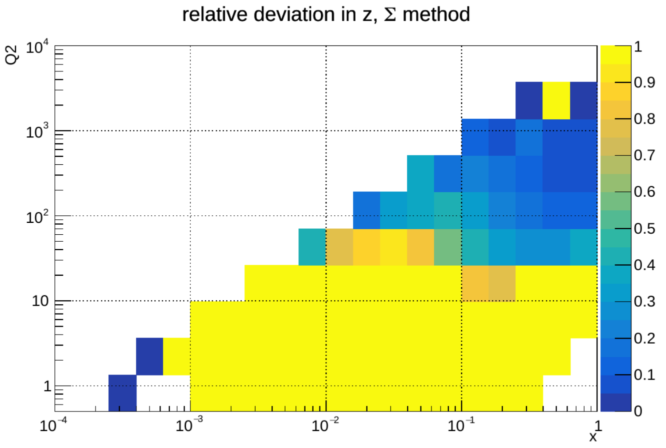


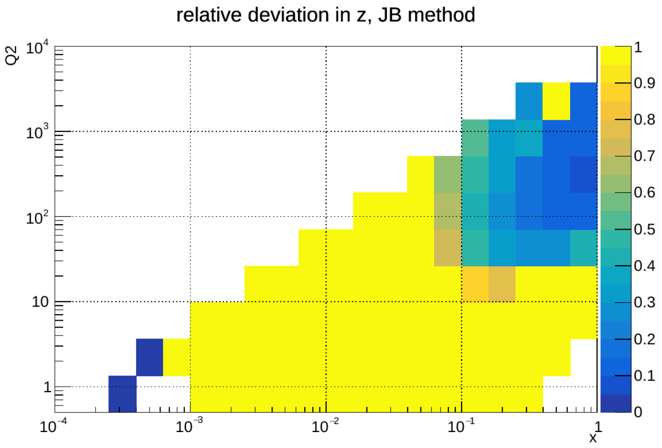
study from Connor Pecar

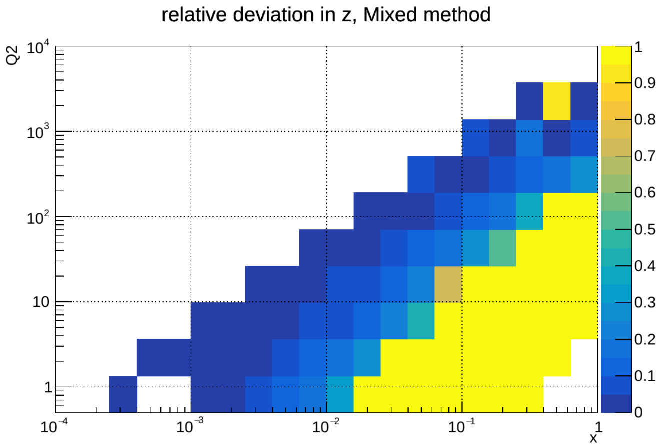
Relative Deviation in z (10x100)

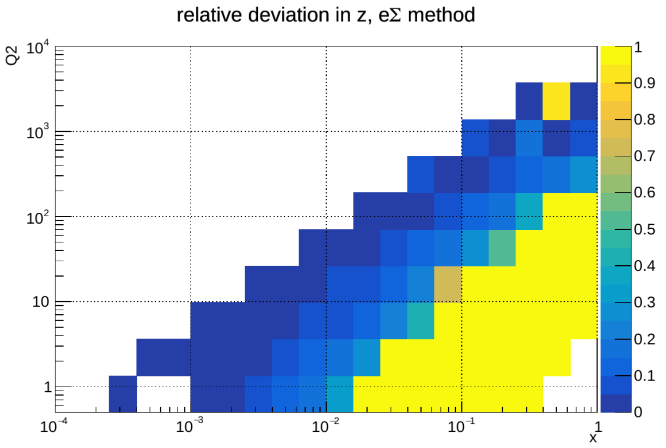






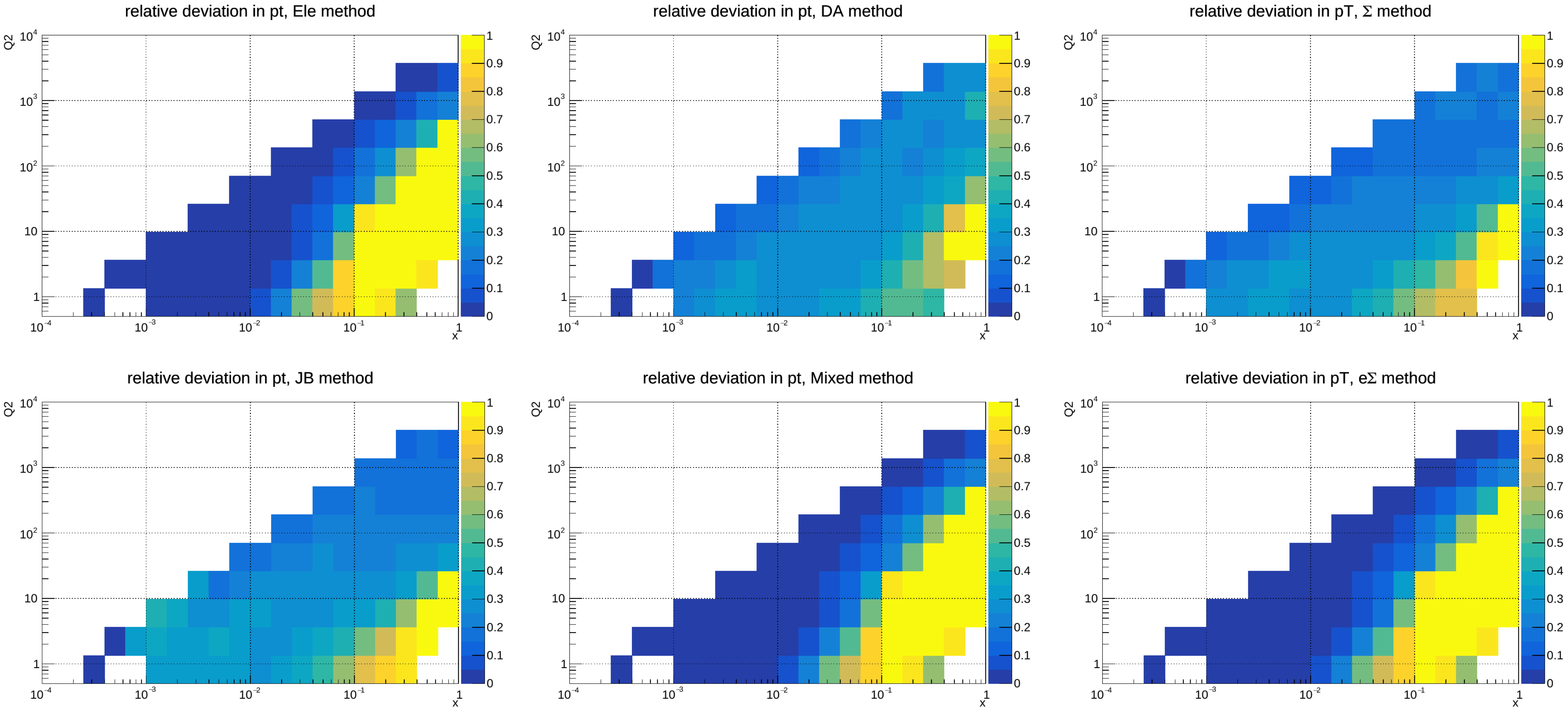






study from Connor Pecar

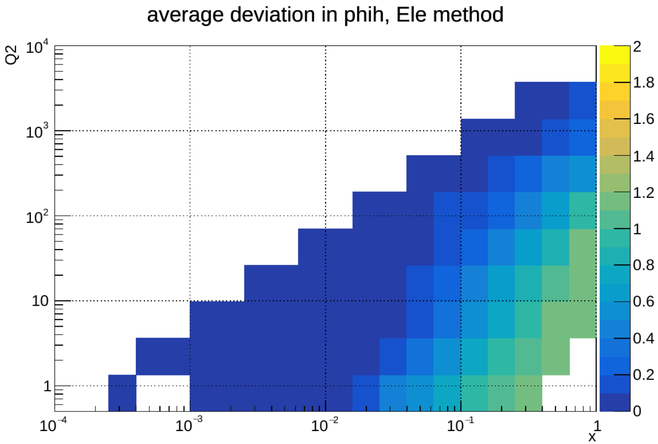
Relative Deviation in p_T (10x100)

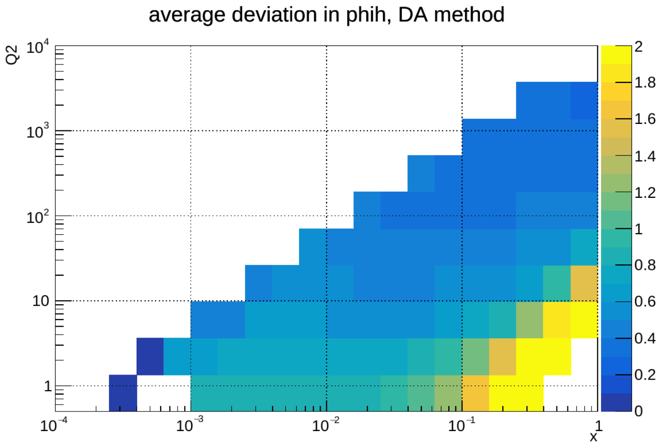


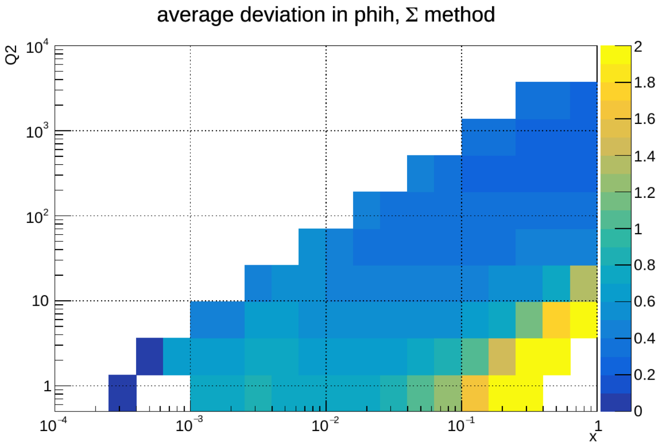
C. Dilks

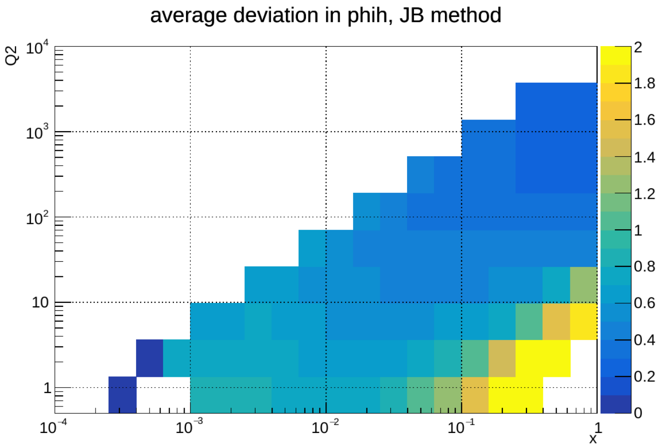
study from Connor Pecar

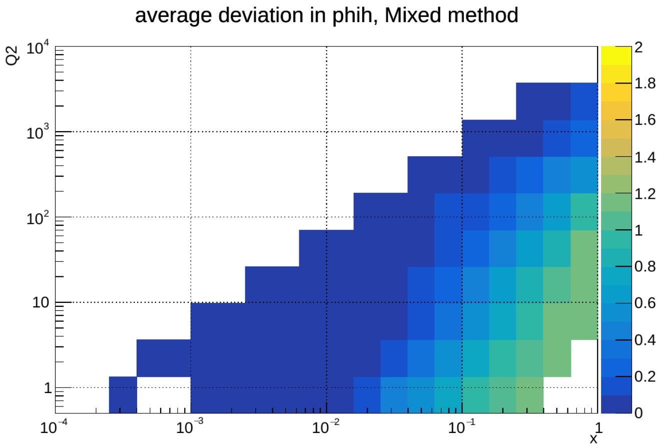
Average Deviation in ϕ_h (10x100)

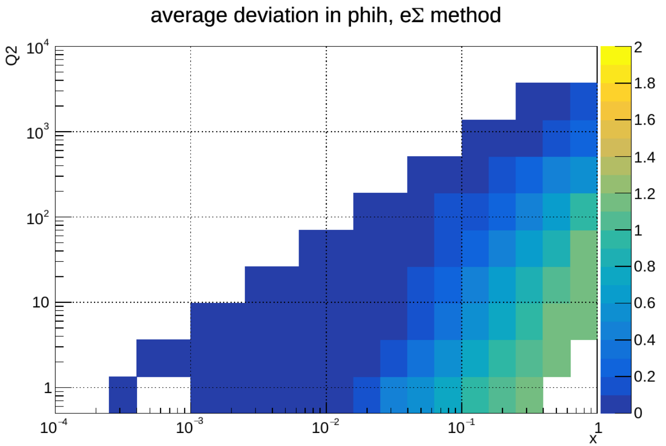












study from Connor Pecar

z and p_T Resolutions

$$0.4 \text{ GeV} < P_{hT} < 0.6 \text{ GeV},$$
$$0.4 < z < 0.5$$

0.05<y<0.95

*kinematics reconstructed from electron

z resolutions

EIC 5 × 41	x range				
Q^2 range(GeV^2)	0.0001–0.003	0.003–0.01	0.01–0.03	0.03–0.1	0.1–0.5
30–100	–	–	–	0.011	0.029
10–30	–	–	0.014	0.021	0.080
5–10	–	0.017	0.020	0.088	0.17
3–5	–	0.017	0.044	0.14	0.13
1–3	0.017	0.032	0.11	0.17	–

p_T resolutions

EIC 5 × 41	x range				
Q^2 range(GeV^2)	0.0001–0.003	0.003–0.01	0.01–0.03	0.03–0.1	0.1–0.5
30–100	–	–	–	0.030	0.15
10–30	–	–	0.022	0.059	0.24
5–10	–	0.021	0.040	0.17	0.34
3–5	–	0.025	0.069	0.21	0.29
1–3	0.021	0.035	0.11	0.19	–

study from Xiaqing Li

x Resolutions

$0.4 \text{ GeV} < P_{hT} < 0.6 \text{ GeV},$
$0.35 < z < 0.4$

Compare different y_{min} values

$0.01 < y < 0.95$	x range			
Q^2 range(GeV^2)	0.0001–0.01	0.01–0.03	0.03–0.1	0.1–0.5
10–100	–	0.0006	0.003	0.060
5–10	0.00018	0.0015	0.021	0.198
3–5	0.00039	0.0030	0.042	0.168
1–3	0.00072	0.0072	0.063	0.120

$0.05 < y < 0.95$	x range			
Q^2 range(GeV^2)	0.0001–0.01	0.01–0.03	0.03–0.1	0.1–0.5
10–100	–	0.0006	0.003	0.042
5–10	0.000018	0.0015	0.021	0.060
3–5	0.00039	0.0030	0.024	0.033
1–3	0.00066	0.0066	0.018	–

*kinematics reconstructed from electron

study from Xiaqing Li

Outline

- TMD PDFs from SIDIS Hadron and Dihadron Production
- Large-x Region and Experiment Overlaps → Low-y EIC
- Reconstruction at Low y
- **Impact on p_T at Low y**

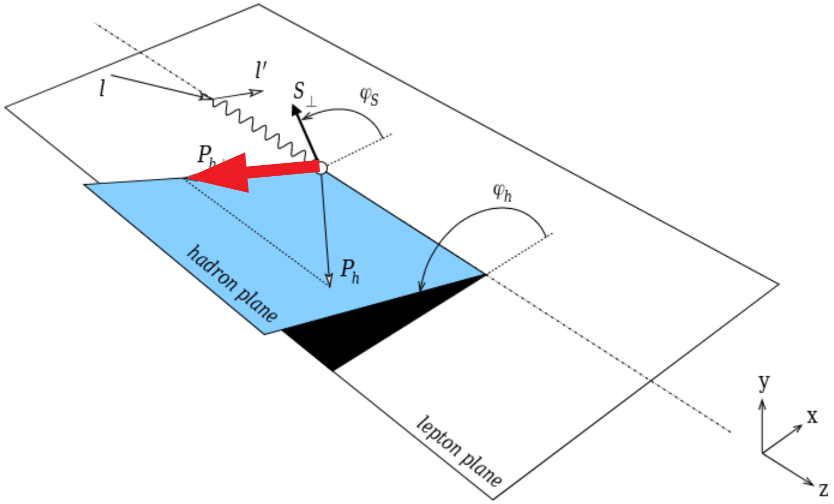
Goal: Explore low-y region (large x, small Q^2):
Vary minimum y limit, and check impact on p_T, $q_T = p_T/z$, and q_T/Q

- Event generation: 1M events from PythiaeRHIC (6), 5x41 GeV
- Fast simulation: EIC-smear (via ESCalate v1.1.0)
- Kinematics reconstruction: highest-E electron

note: some plots use notation p_{perp} or $p_\perp$; they denote the same as p_T:
the component of the pion momentum transverse to q, in the proton rest frame

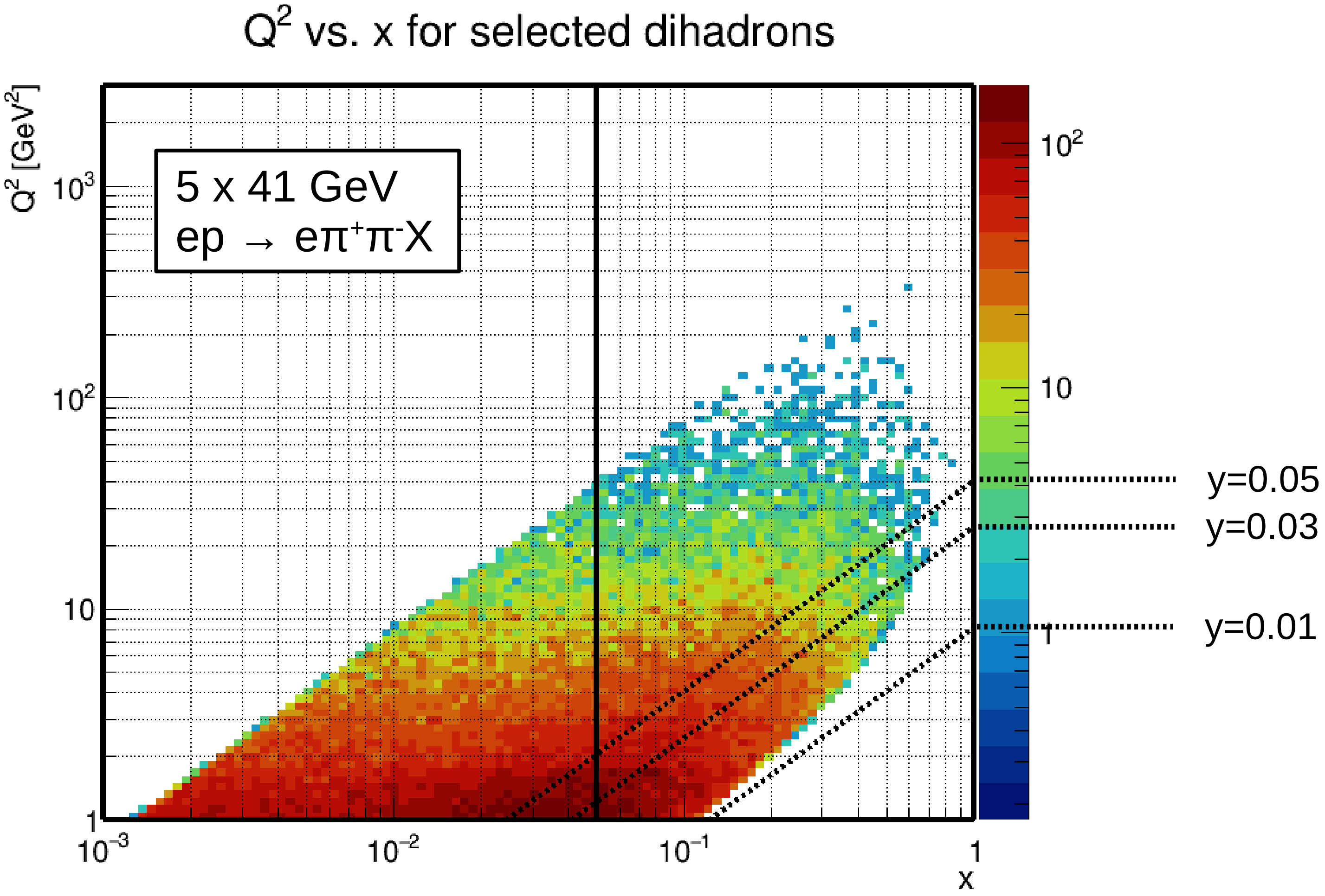
Event Selection Criteria

- $\pi+\pi-$ dihadron channel
- W > 3 GeV
- $y_{min} < y < 0.95$ (vary y_{min})
- $z_{pair} < 0.95$
- $z_{pion} > 0.2$ (effectively $z_{pair} > 0.4$)
- pion $p_{T\_lab} > 100$ MeV (tracking limit)
- pion $x_F > 0$
- $Q^2 > 1$ GeV^2 (generator level)

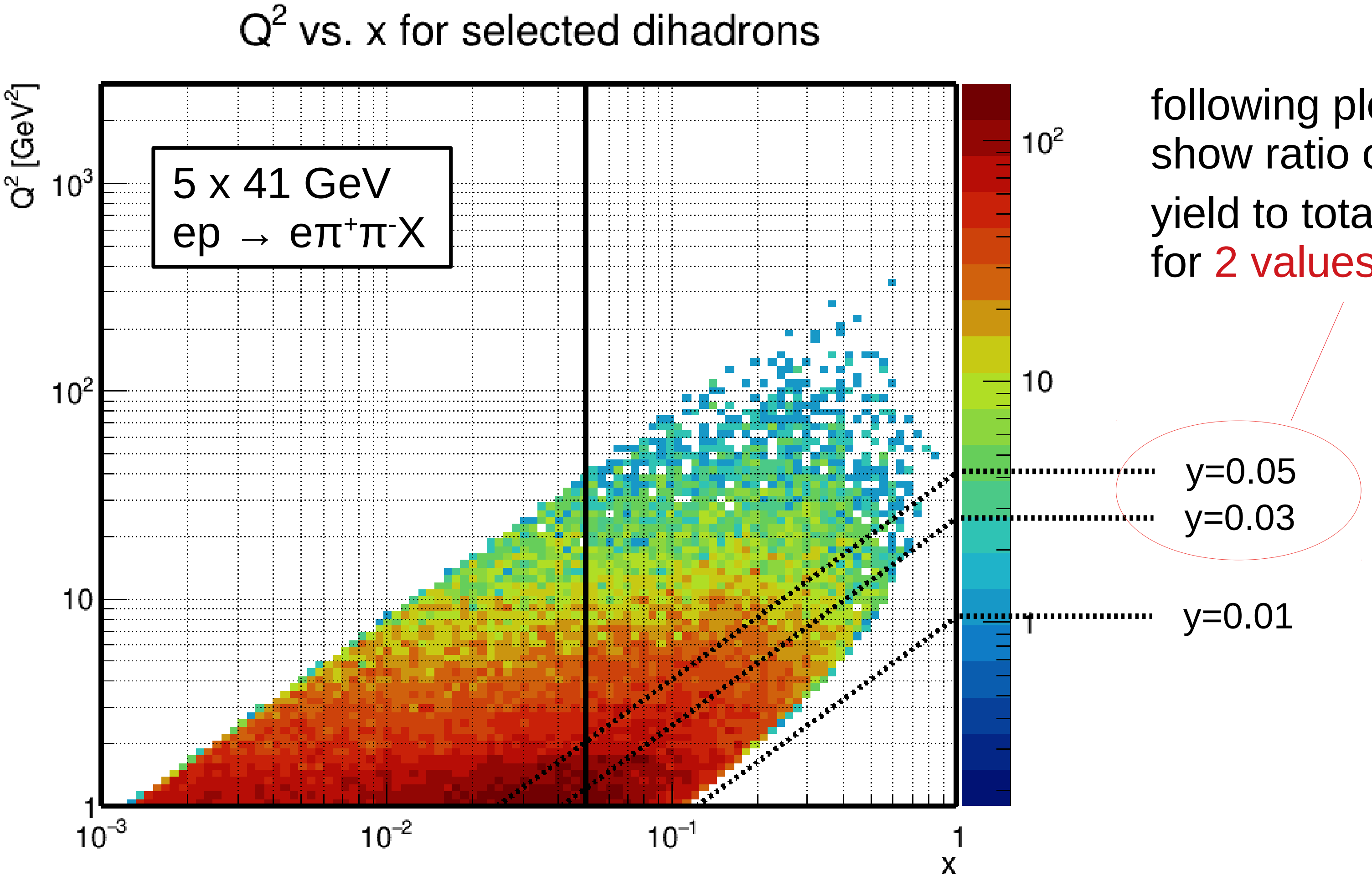


Large x:
x>0.05

Two z bins:
- 0.2 < z < 0.3
- 0.3 < z < 1



Q² vs. x for selected dihadrons
5 x 41 GeV
ep → eπ⁺π⁻X
Q² [GeV²]
10³
10²
10
1
10⁻³
10⁻²
10⁻¹
1
x
10²
10
1
y=0.05
y=0.03
y=0.01

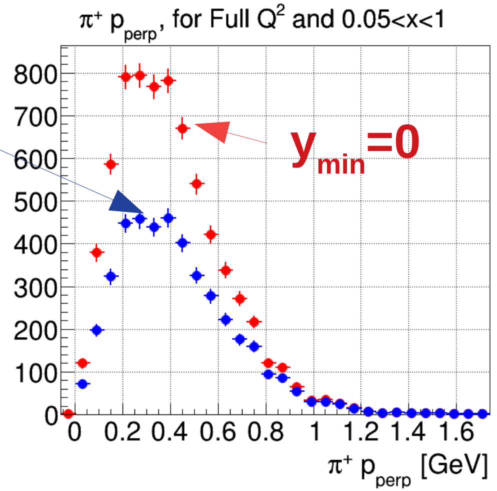


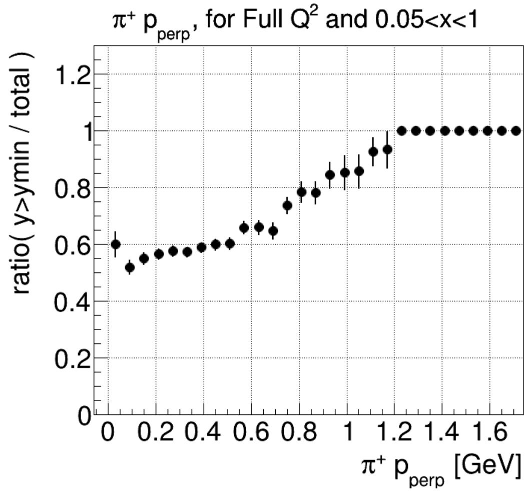
following plots show ratio of $y>y_{min}$ yield to total yield, for 2 values of y_{min}

p_T Distributions for varying y_{min} in 2 bins of z

y_{min} = 0.03

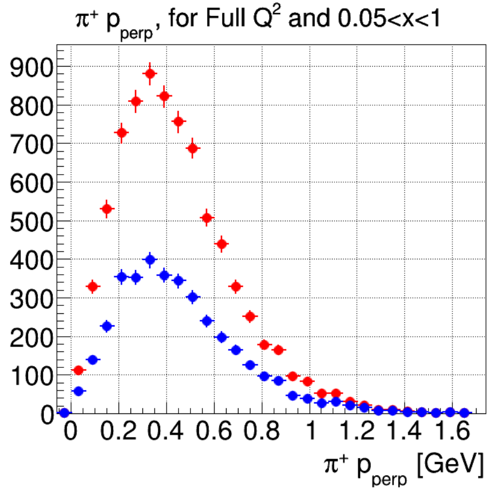
0.2 < z < 0.3

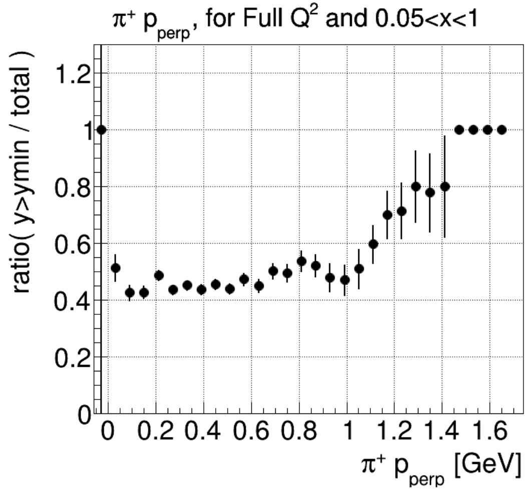




low p_T region has relatively larger suppression

0.3 < z < 1



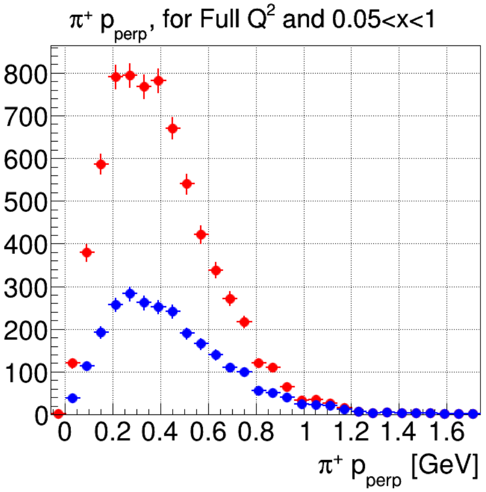


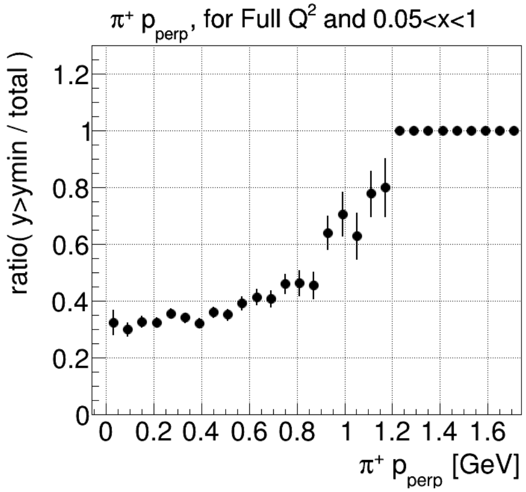
correlation between fragmenting particle and spin larger at high z, where suppression by y_{min} is worse

p_T Distributions for varying y_{min} in 2 bins of z

y_{min} = 0.05

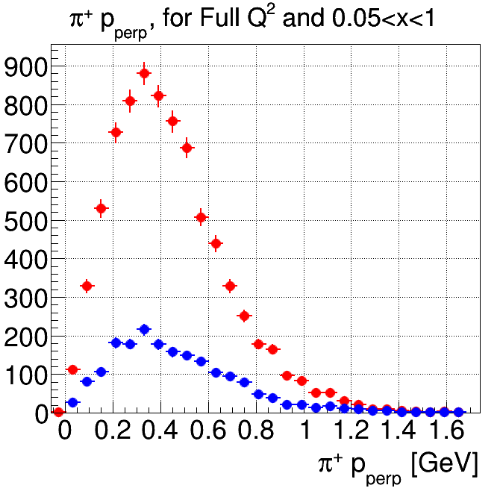
0.2 < z < 0.3

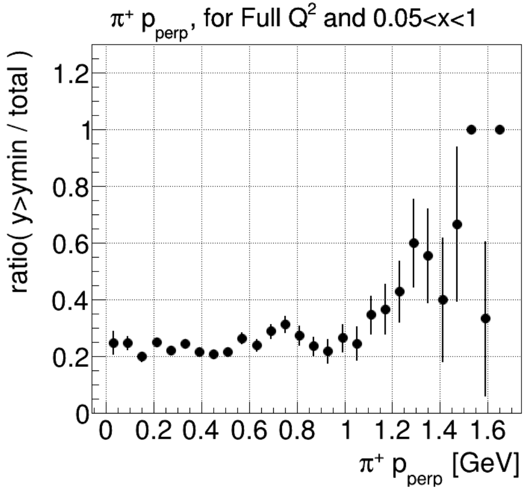




suppression worse at higher y_{min}, but similar relative trend

0.3 < z < 1



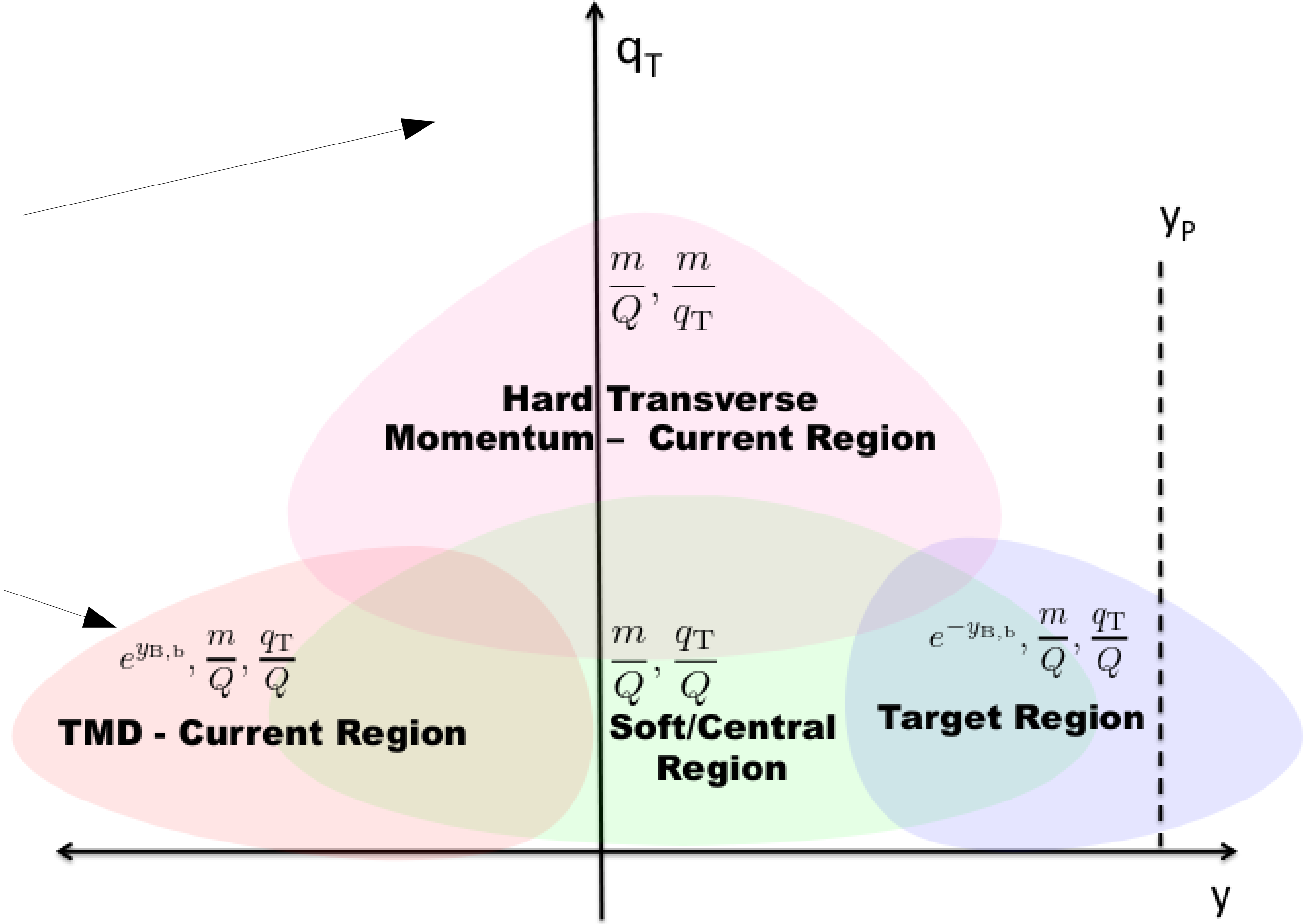


note: suppression trends for q_T look similar (see backup slides)

TMD Region Classification

high q_T/Q → collinear

low q_T/Q → TMD

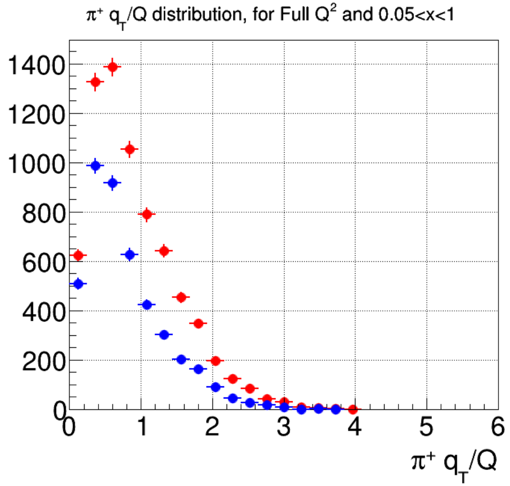


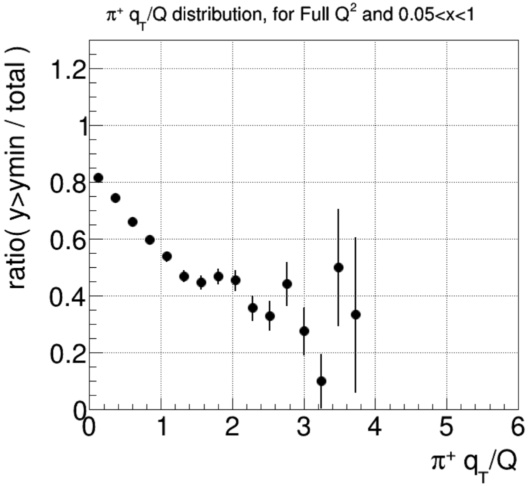
JHEP10(2019)122
1904.12882 [hep-ph]

q_T/Q Distributions for varying y_{min}

y_{min} = 0.03

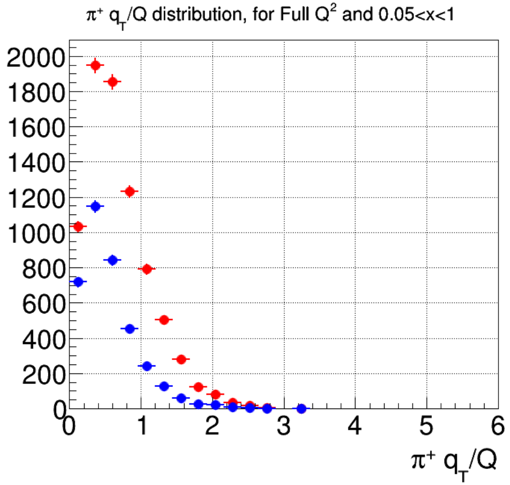
$0.2 < z < 0.3$

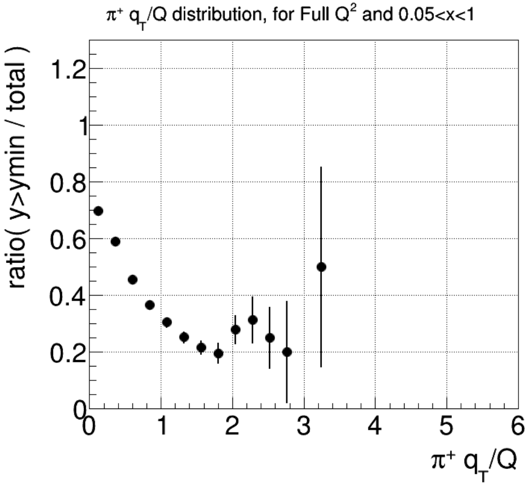




high q_T/Q is much more suppressed than low q_T/Q

$0.3 < z < 1$

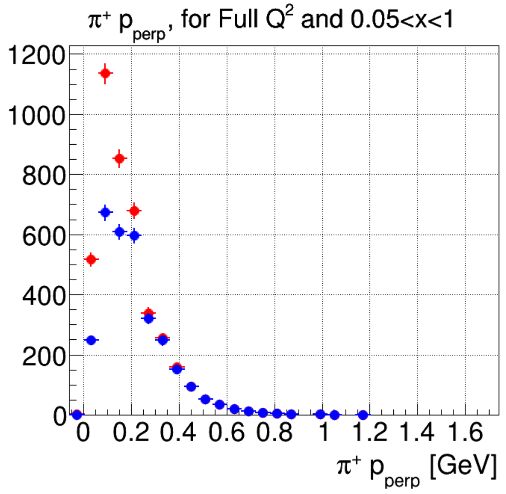


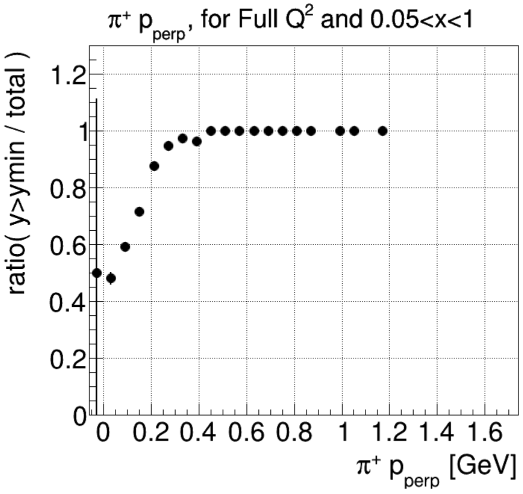


p_T Distributions for varying y_{min} in 2 bins of q_T/Q

y_{min} = 0.03

$q_T/Q < 0.25$

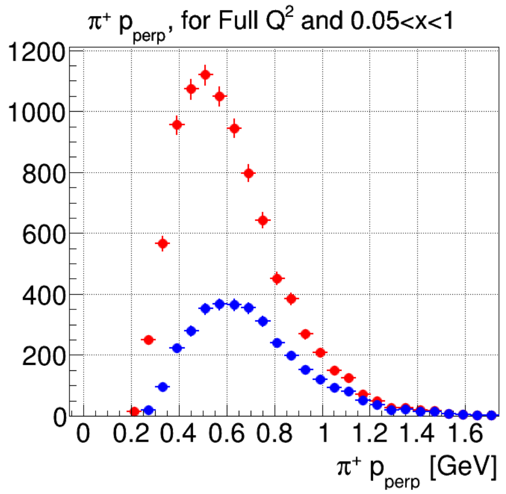


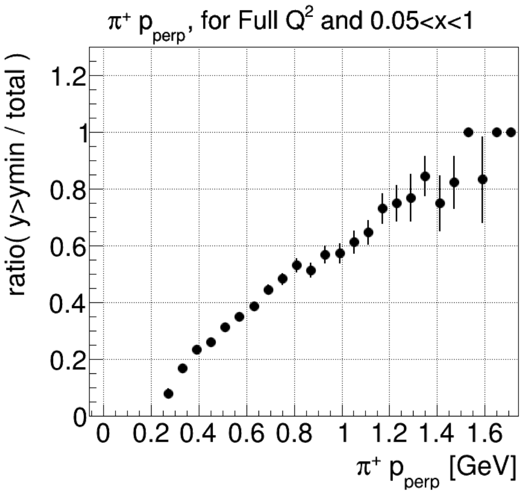


suppression localized to low p_T

(see backup slides for comparison with $q_T/Q<1$)

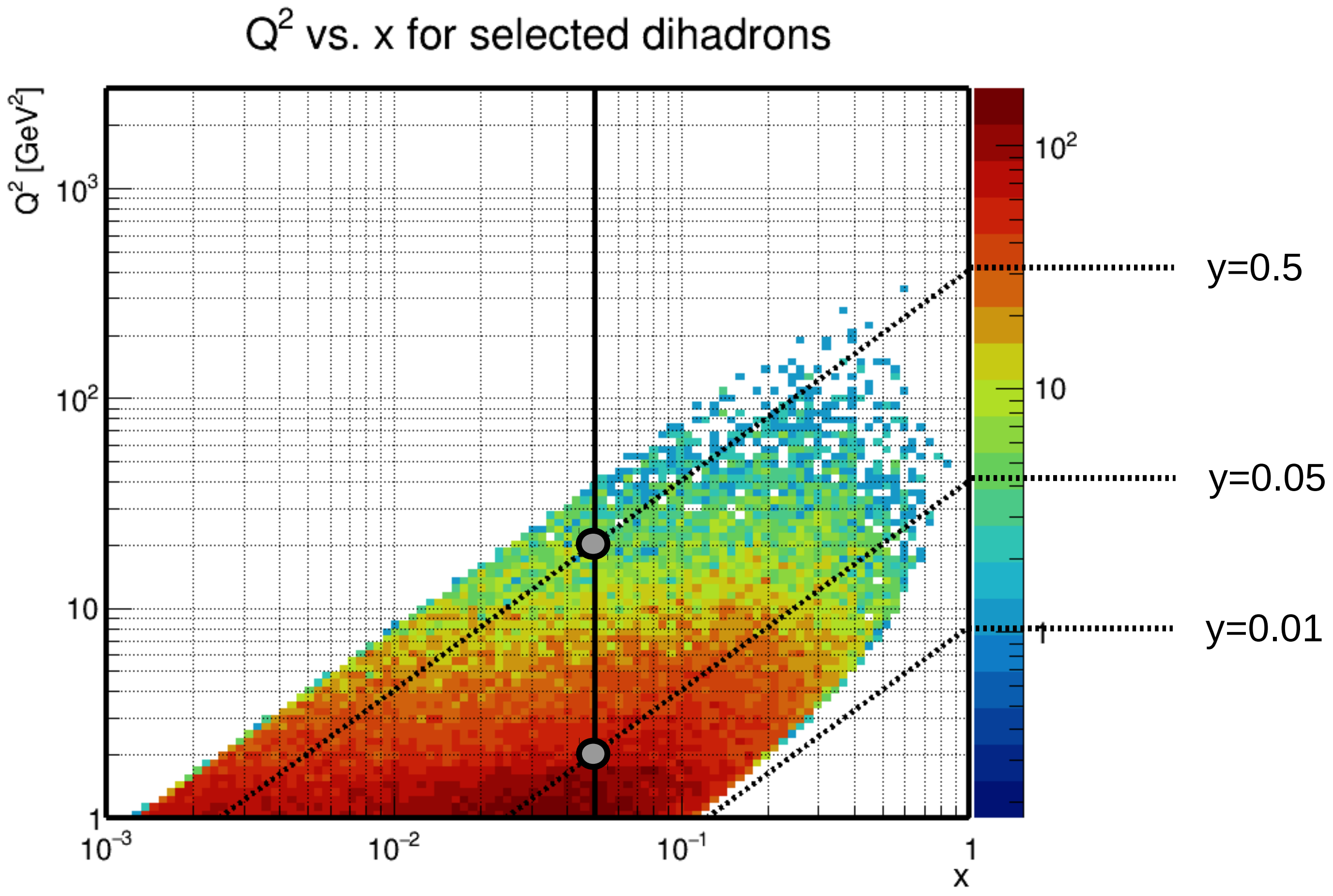
$q_T/Q > 1.0$



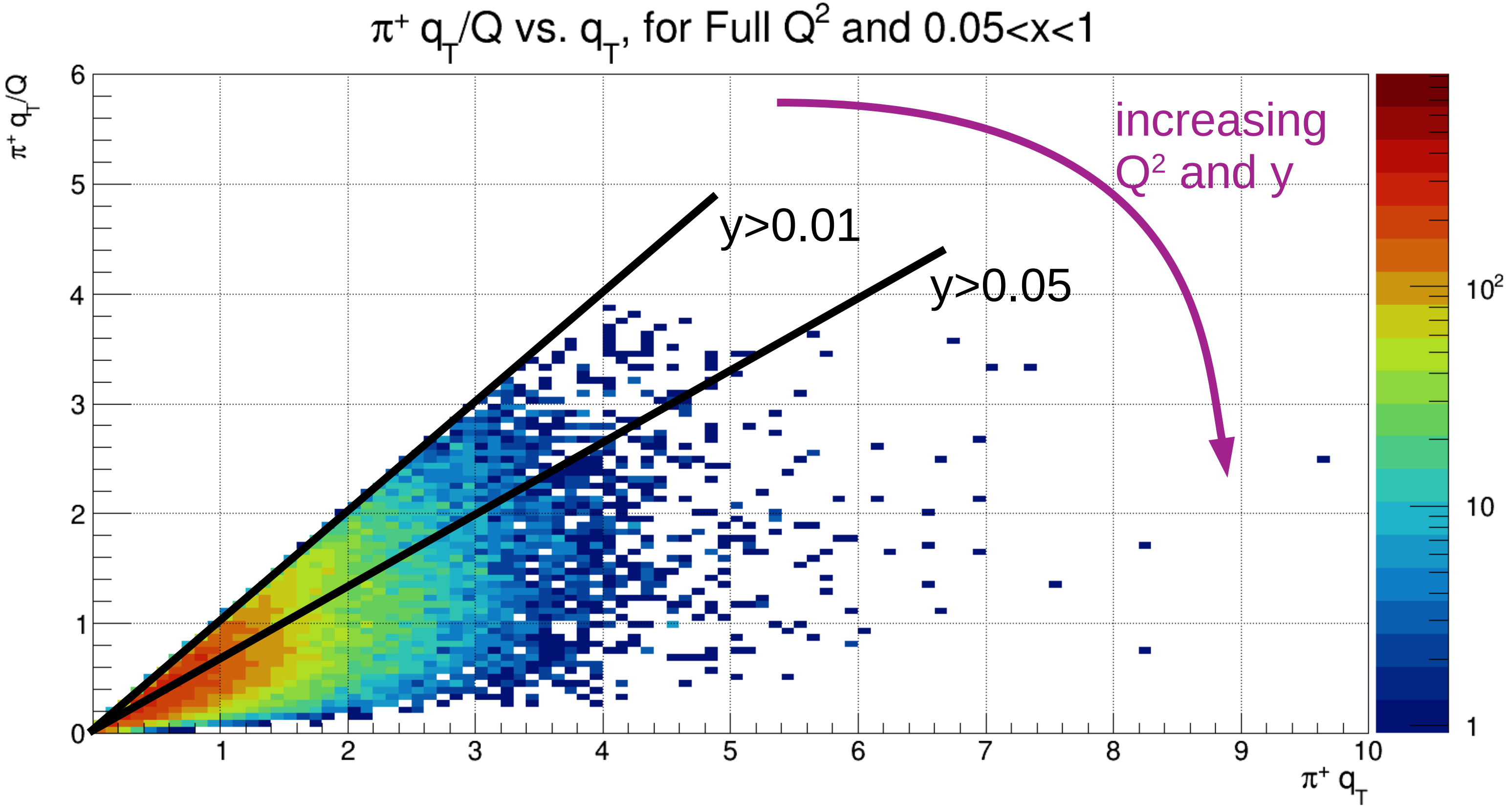


suppression worsens as p_T decreases

For x>0.05, as y_{min} increases, minimum Q^2 increases → imparts limits on q_T/Q

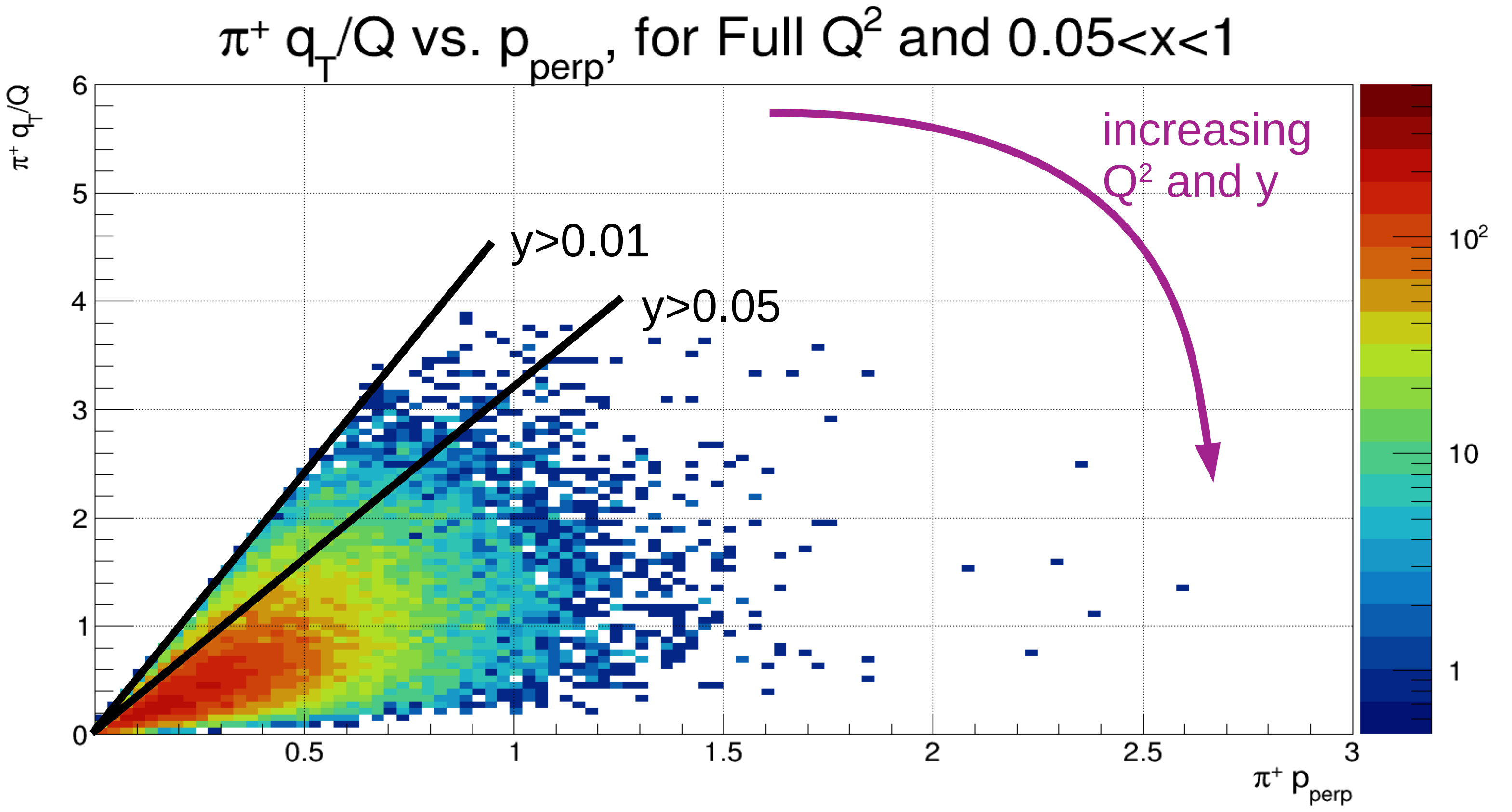


For $x>0.05$, as y_{min} increases, minimum Q^2 increases → imparts limits on q_T/Q



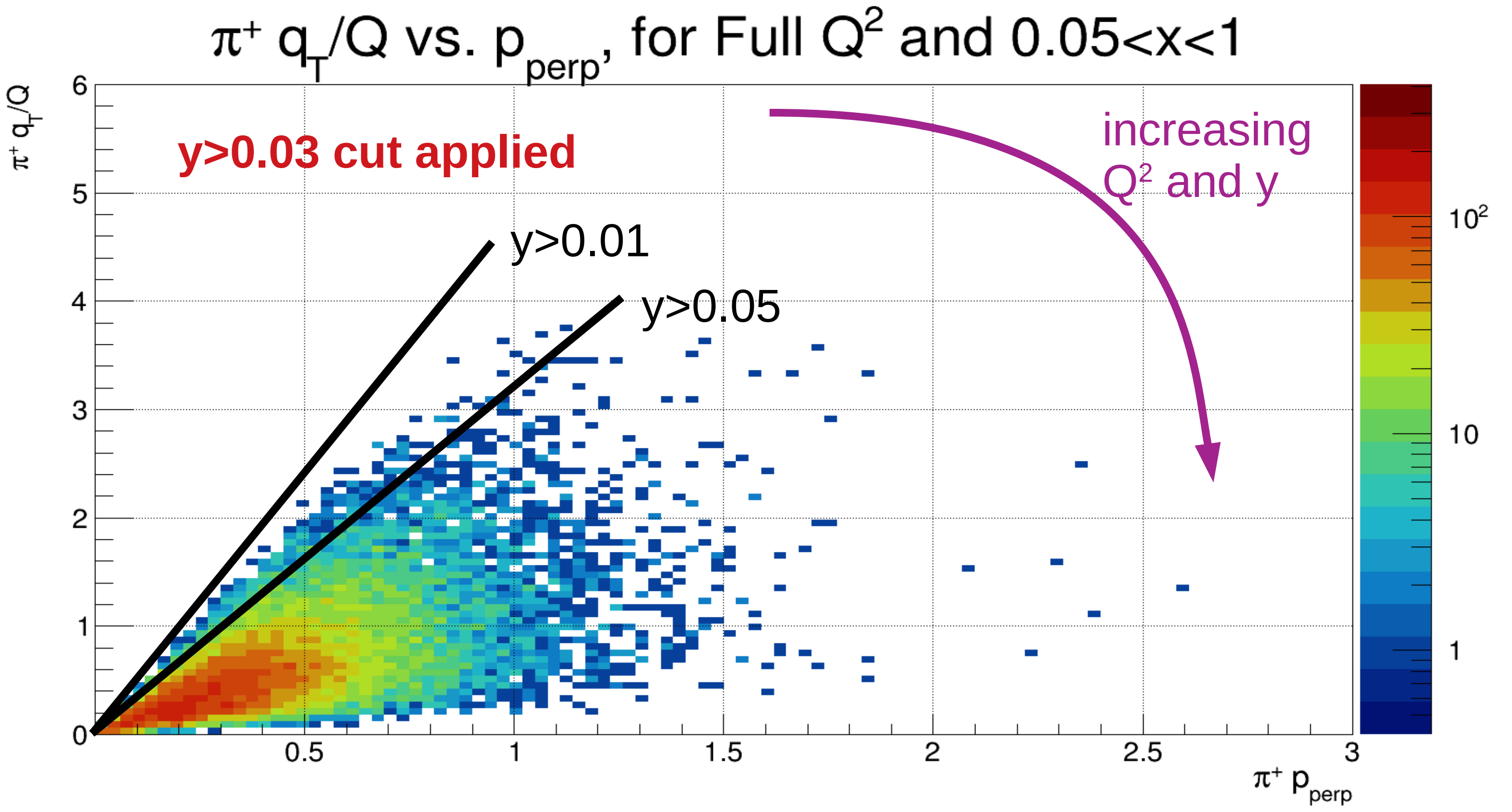
Similar story for q_T/Q vs p_T correlation

As y_{min} increases, relatively more low pT events are cut



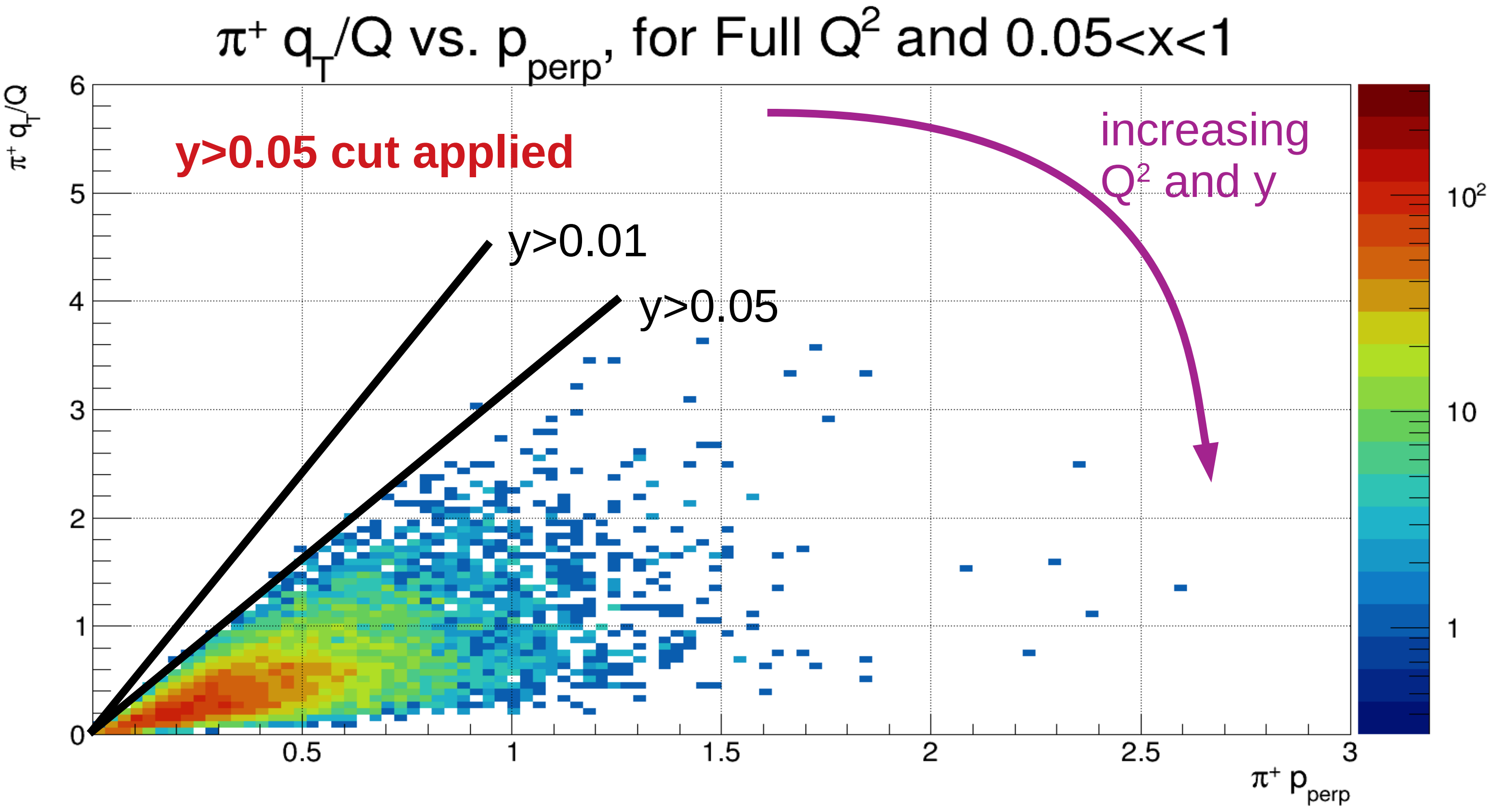
Similar story for q_T/Q vs p_T correlation

As y_{min} increases, relatively more low pT events are cut

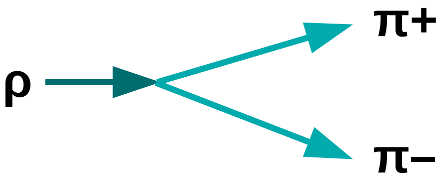


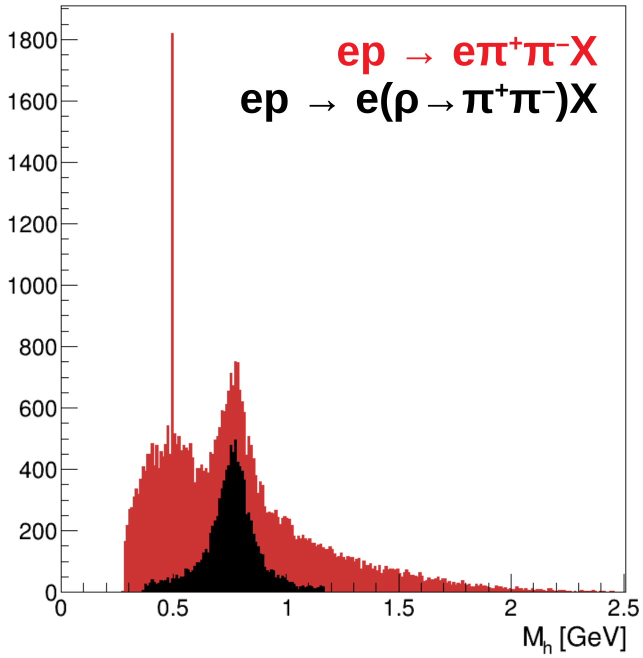
Similar story for q_T/Q vs p_T correlation

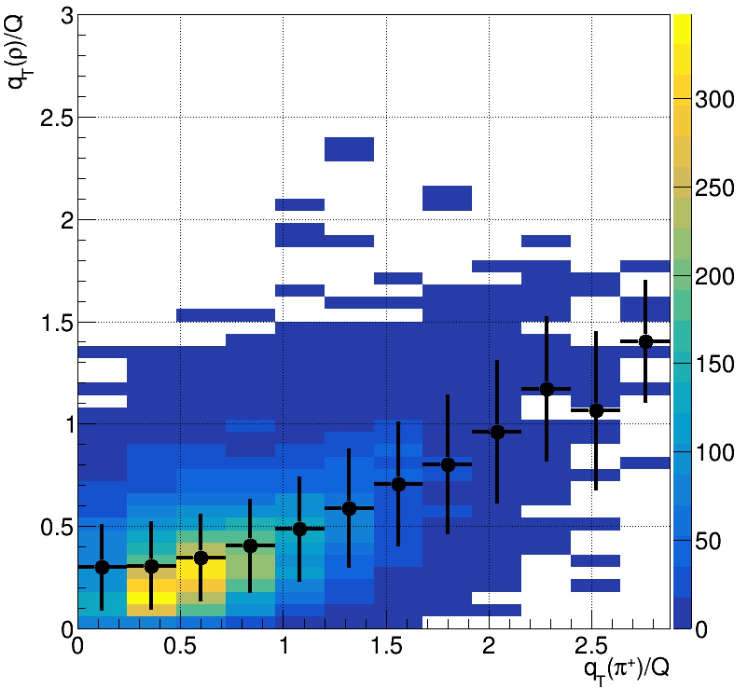
As y_{min} increases, relatively more low pT events are cut



Vector Meson Decays → Muddy the Waters for Interpretation

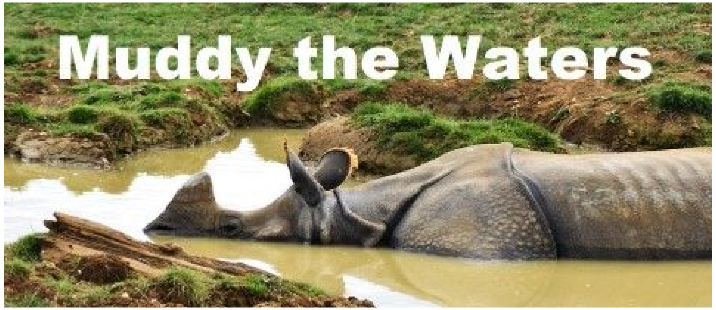






*** data not smeared!**

- Select $\rho \to \pi^+\pi^-$ dihadrons, and calculate q_T/Q using the ρ, vs. using the π^+
- Pion q_T/Q~1 could correspond to ρ-meson q_T/Q<<1
- VM decays can confuse TMD region classification
- Trend unaffected by y_{min} cuts



C. Dilks

Summary

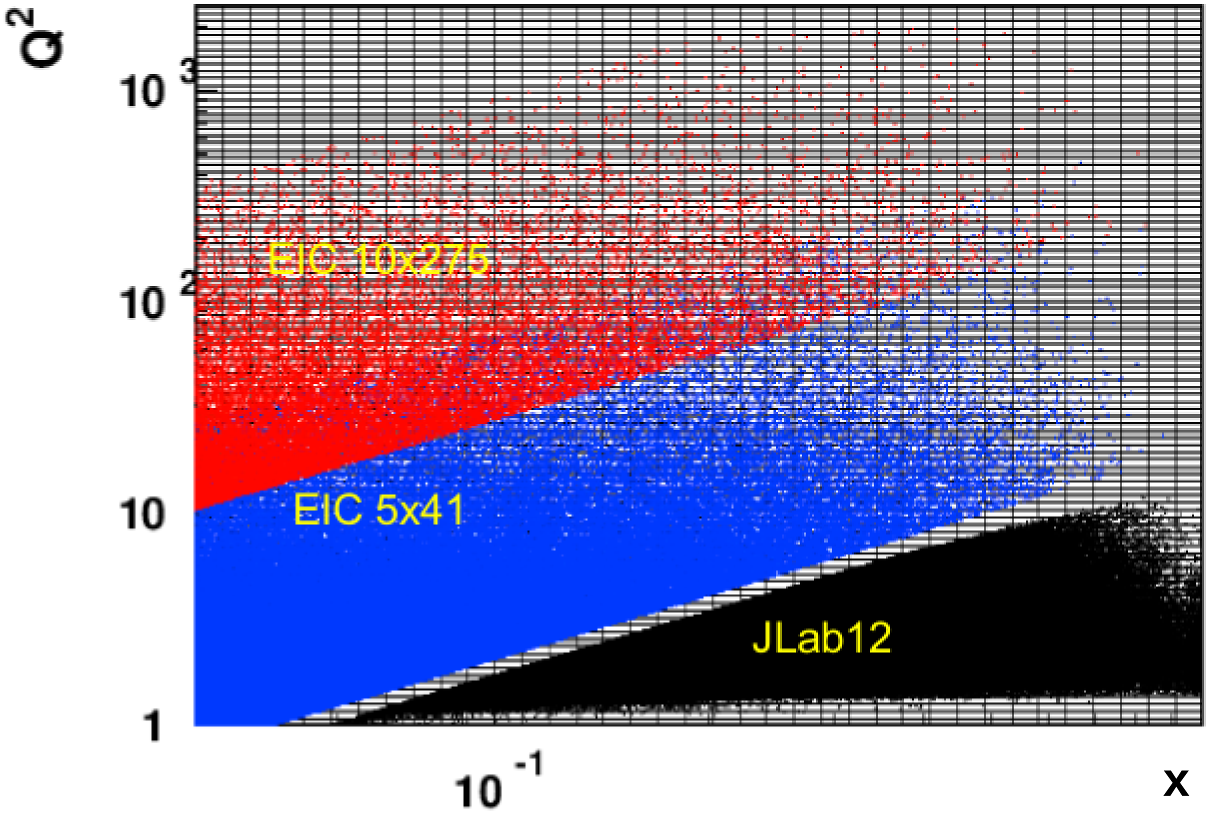
- **Interested in TMDs at large x (x>0.05), where spin-orbit correlations are likely relevant**
  - Large Q^2 may have smaller asymmetries
  - Better to look at small Q^2, where electron and hadron are detected at small scattering angles
  - Minimum y restricts phase space at large x and small Q^2

- **Overlap of experimental phase space vital for evolution studies, providing a more complete picture**
  - Limitations at low-y at the EIC:
    - Smaller p_T
    - Poorer resolutions (z, p_T, x)
  - Increasing minimum y causes:
    - Losses at small p_T and small q_T
    - Localized losses at small p_T for $q_T/Q<0.25$
    - Larger losses at large q_T/Q than at small q_T/Q
    - Increase minimum Q^2 (given x>0.05)

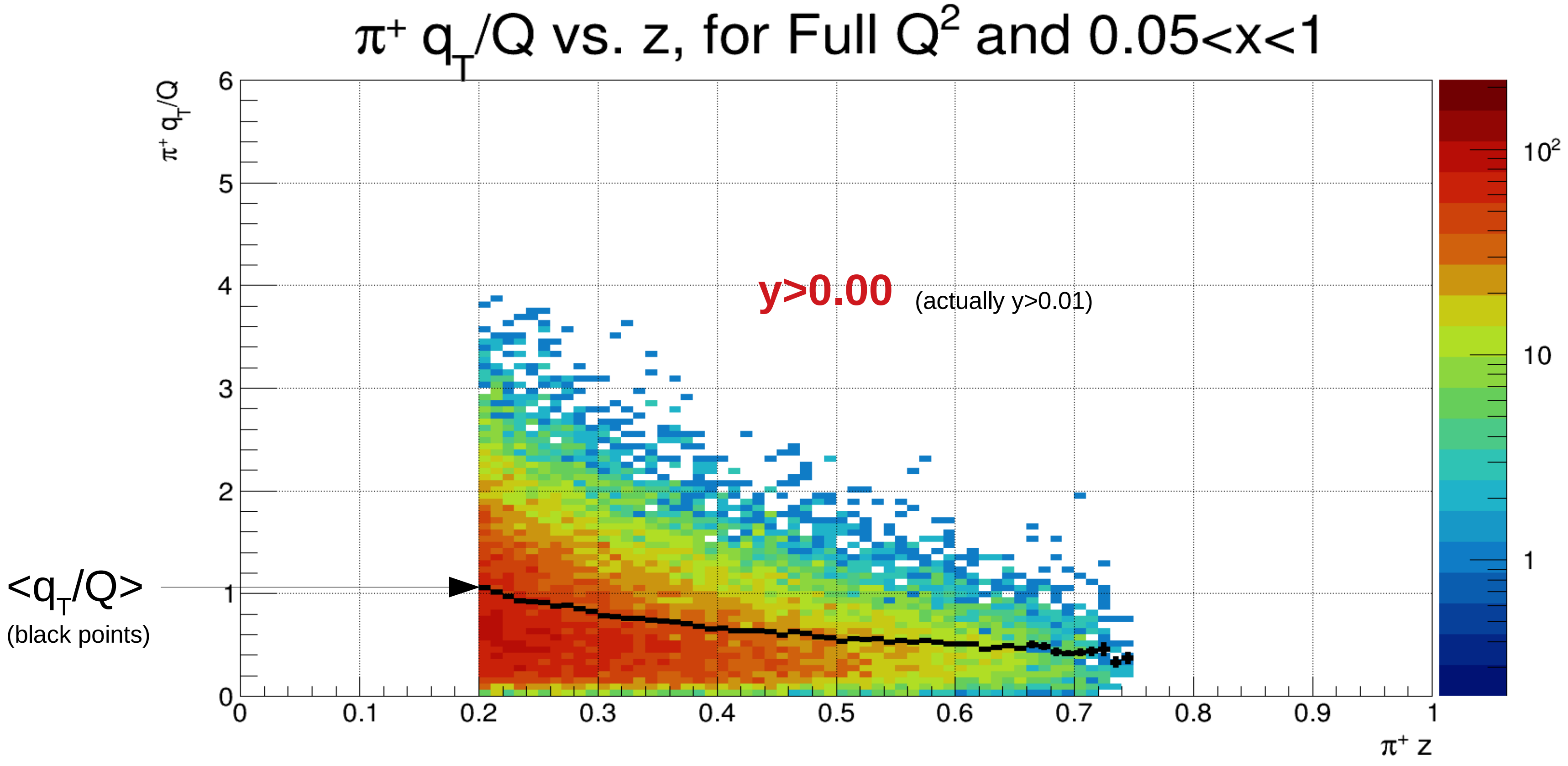
- **Vector mesons muddy the waters**
  - A pion with large $p_T/z/Q$, considered outside the TMD region, could come from a VM with small $p_T/z/Q$, well within the TMD region

backup

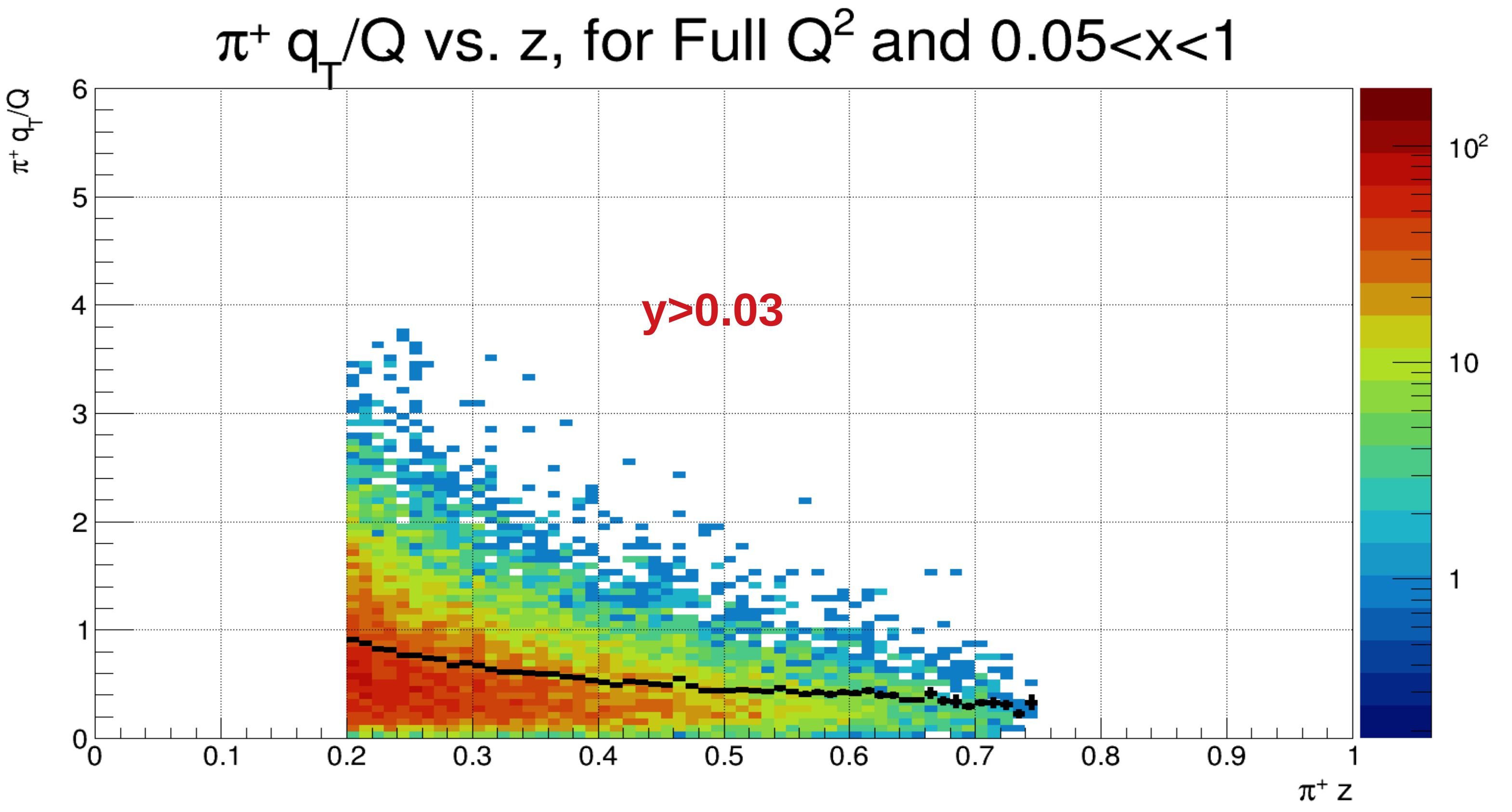
Kinematic Coverage for y > 0.025

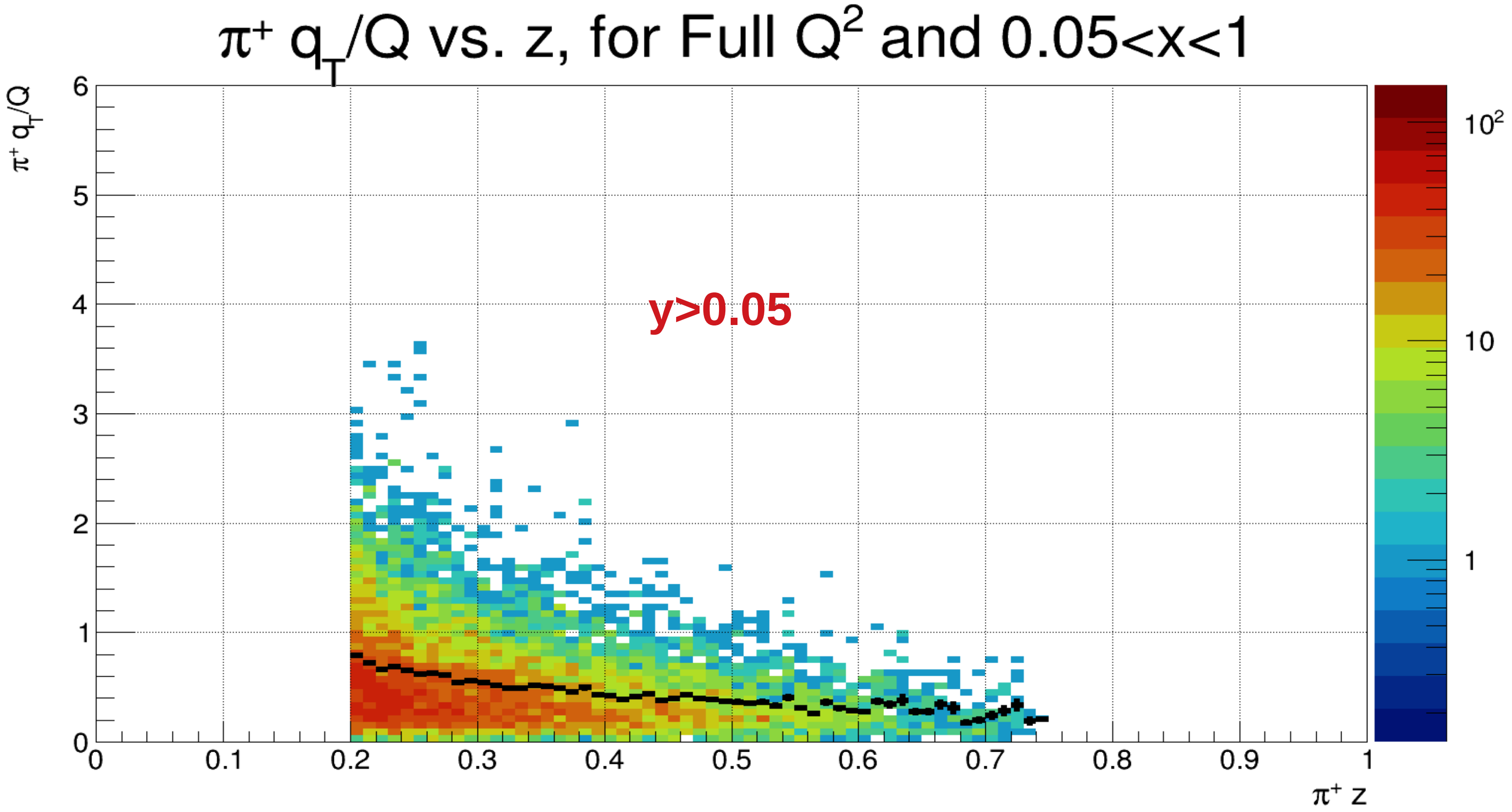


H. Avakian, REF2020, Dec 9



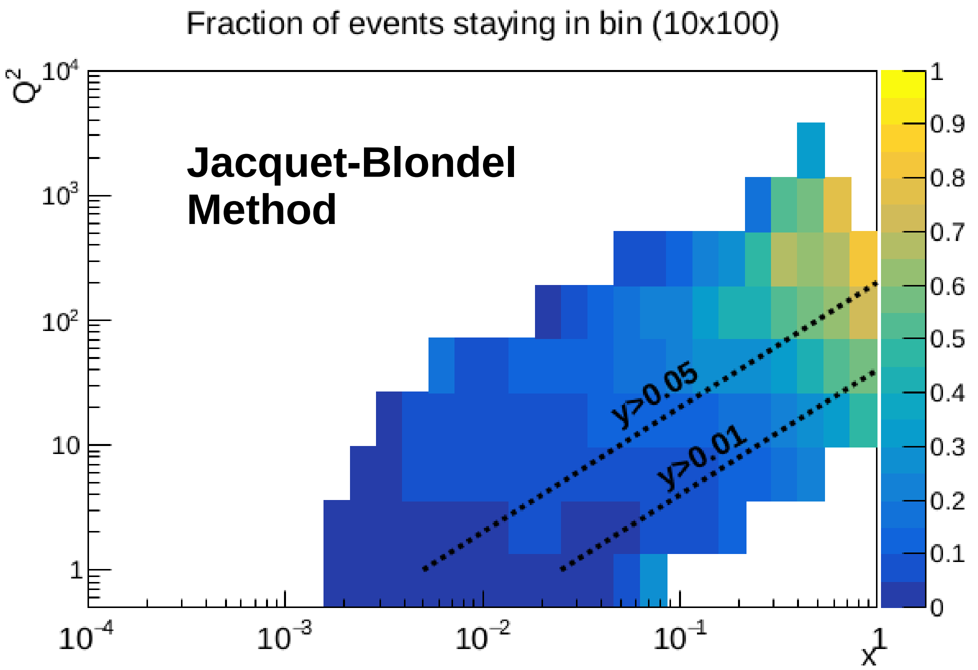
π⁺ q_T/Q vs. z, for Full Q² and 0.05<x<1
π⁺ q_T/Q
π⁺ z
y>0.00
(actually y>0.01)
<q_T/Q>
(black points)

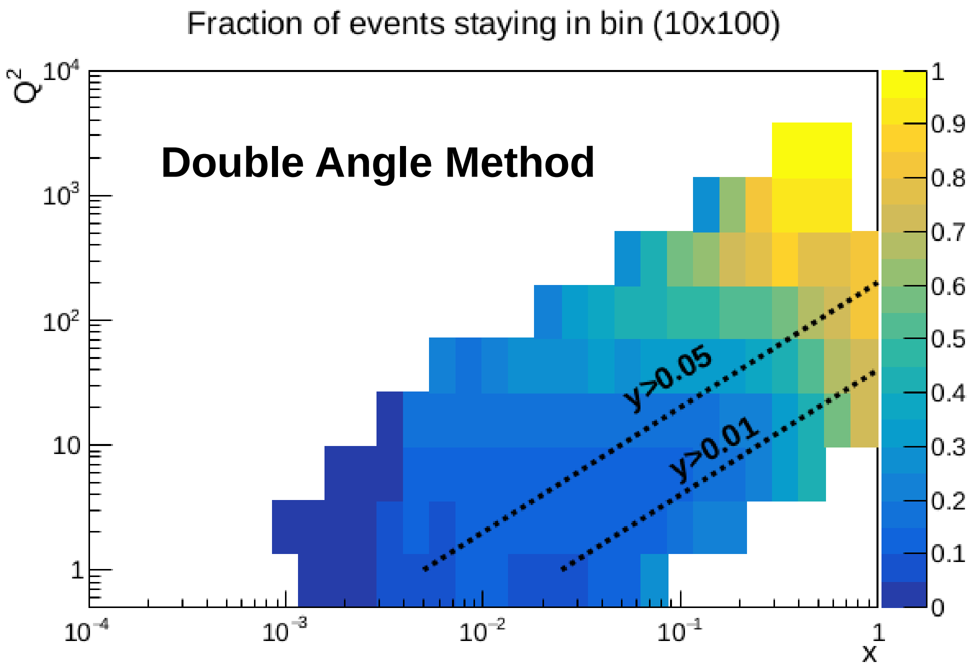

π^+ q_T/Q vs. z, for Full Q^2 and 0.05<x<1
π^+ q_T/Q
0
1
2
3
4
5
6
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
π^+ z
y>0.03
10^2
10
1



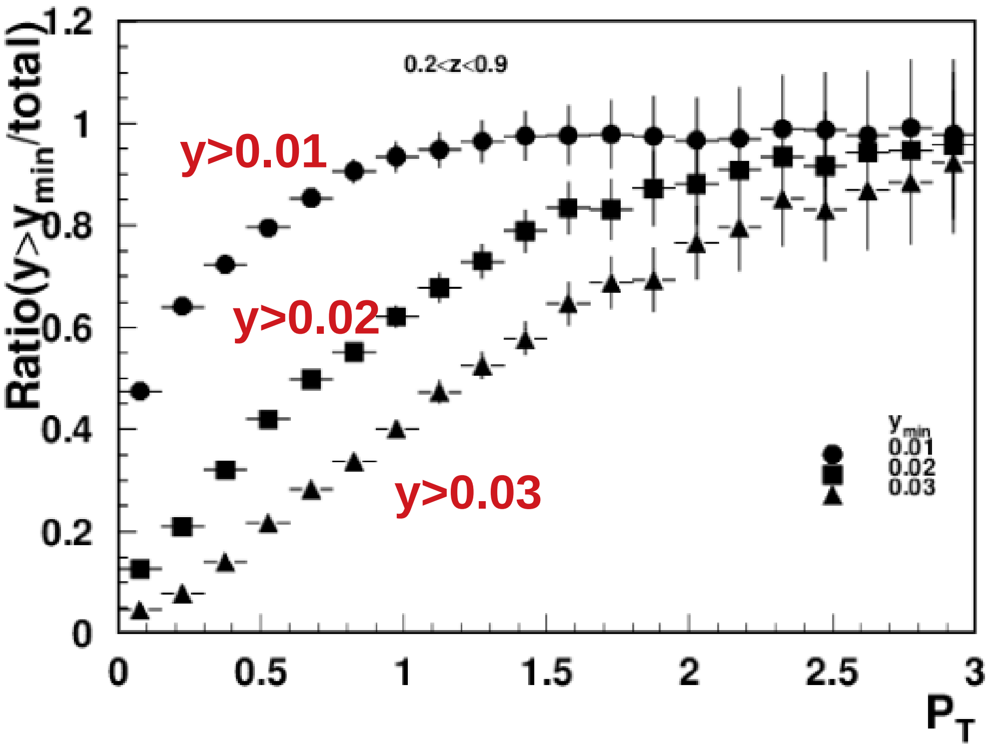
π+ qT/Q vs. z, for Full Q2 and 0.05<x<1
π+ qT/Q
6
5
4
3
2
1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
π+ z
y>0.05
10²
10
1

Kinematics Reconstruction Methods





Low Q^2 and large x kinematics in EIC: P_T-distributions



EIC 5x41
x>0.01

For large x(x>0.05) large y cuts can significantly change P_T-distributions

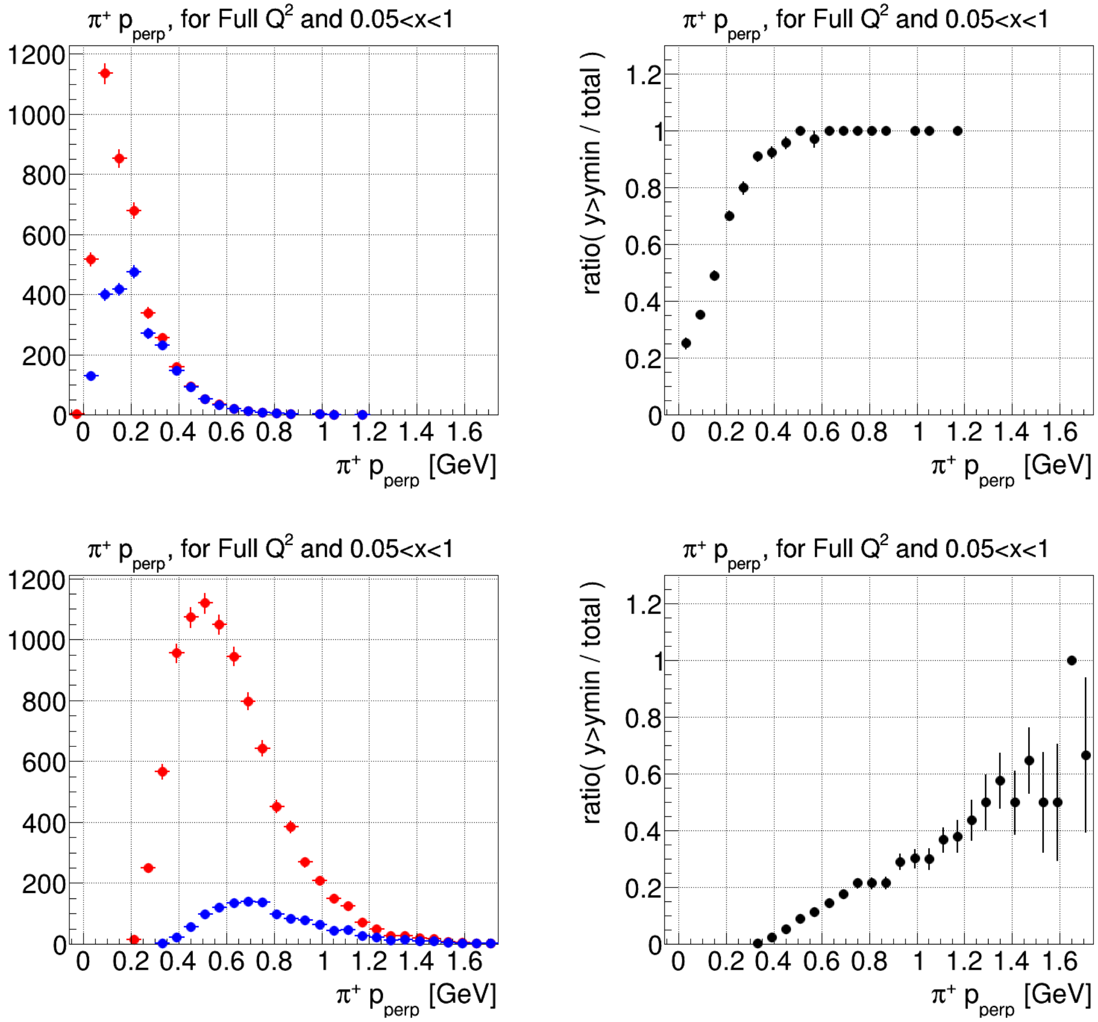
H. Avakian, REF2020, Dec 9

p_T Distributions for varying y_{min} in 2 bins of q_T/Q

y_{min} = 0.05

$q_T/Q < 0.25$

$q_T/Q > 1.0$

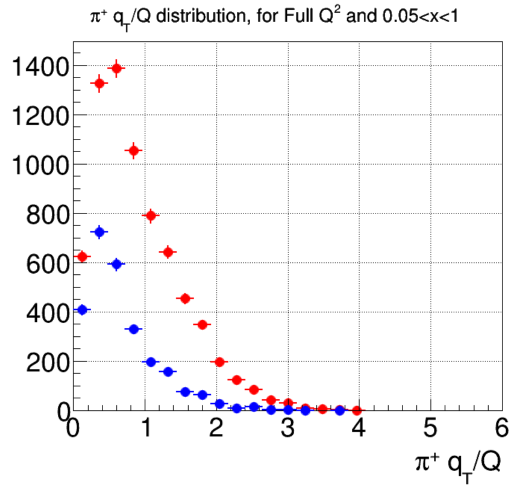


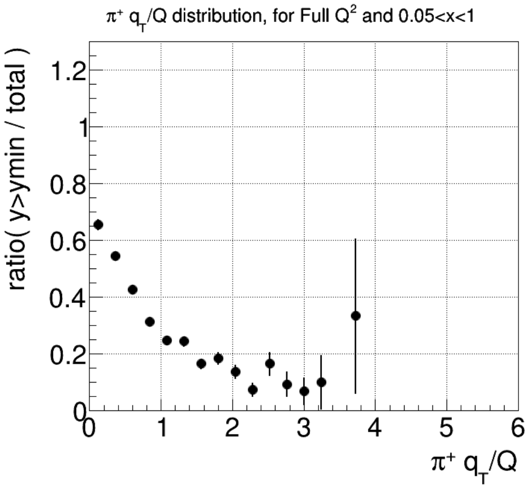
suppression worse at higher y_{min}, but similar relative trend

q_T/Q Distributions for varying y_{min}

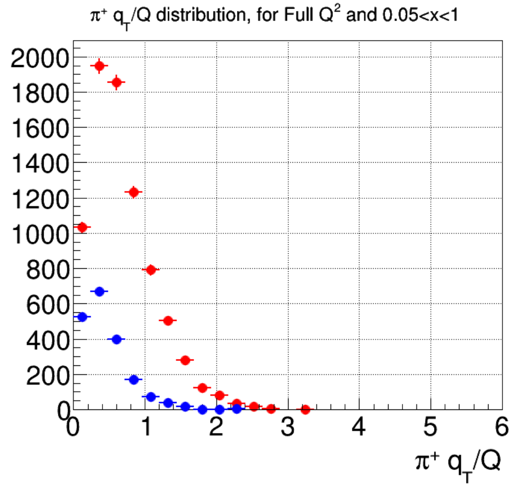
y_{min} = 0.05

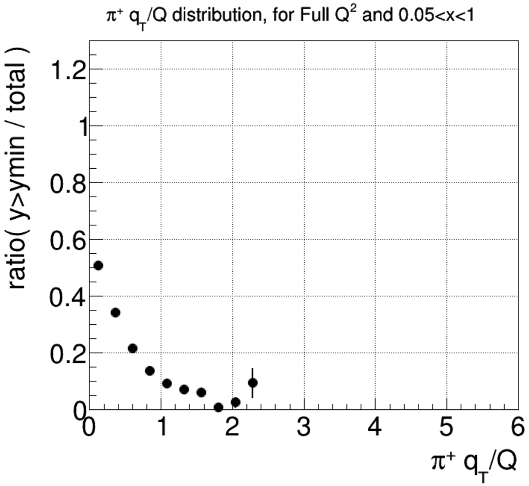
0.2 < z < 0.3





0.3 < z < 1



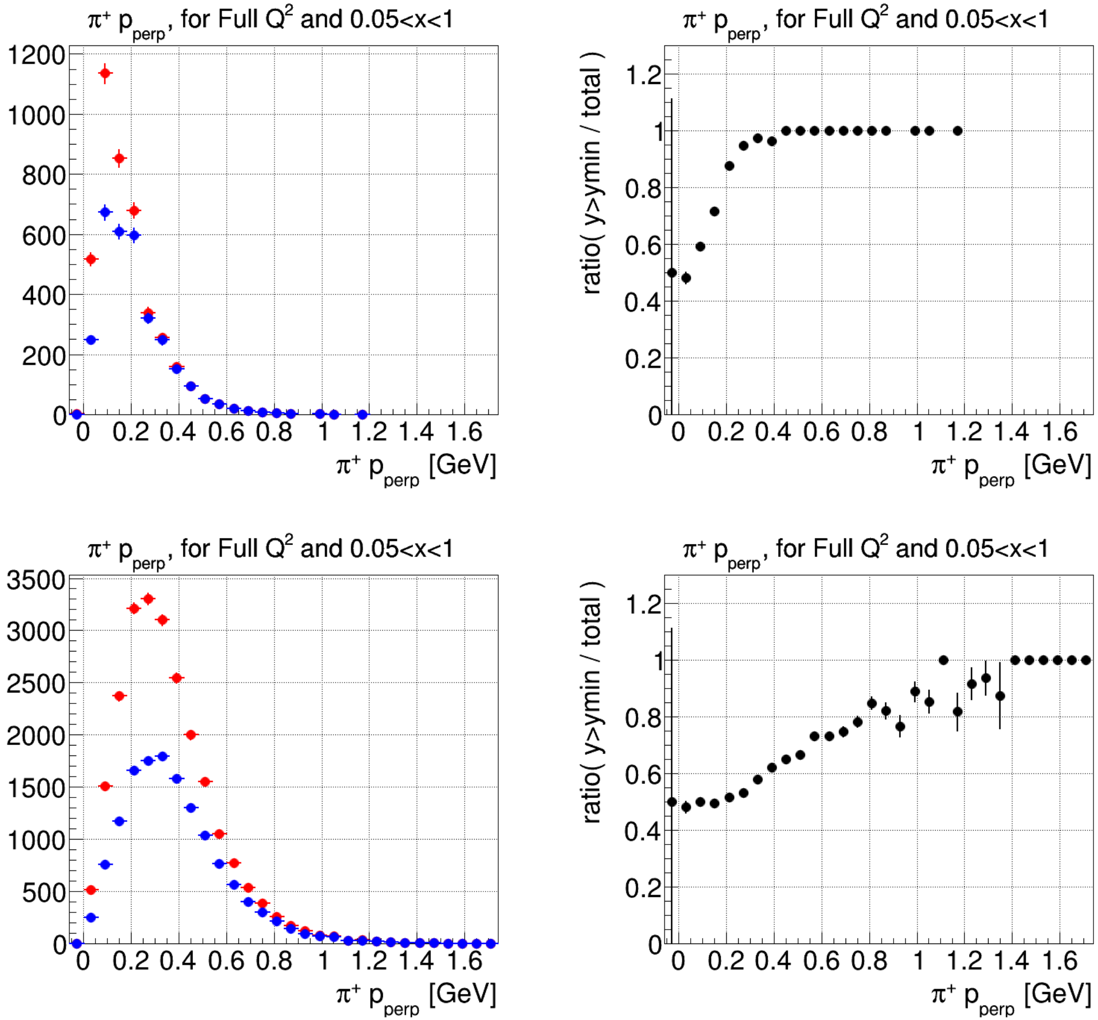


p_T Distributions for varying y_{min} in 2 bins of q_T/Q

$y_{min} = 0.03$

$q_T/Q < 0.25$

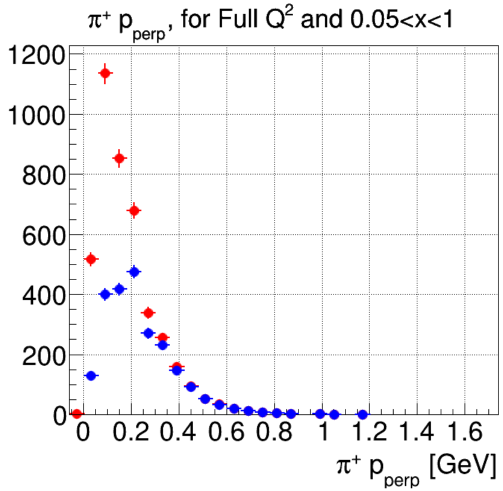
$q_T/Q < 1.0$

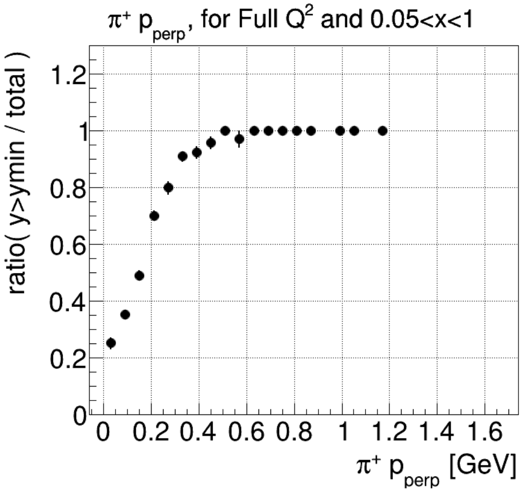


p_T Distributions for varying y_{min} in 2 bins of q_T/Q

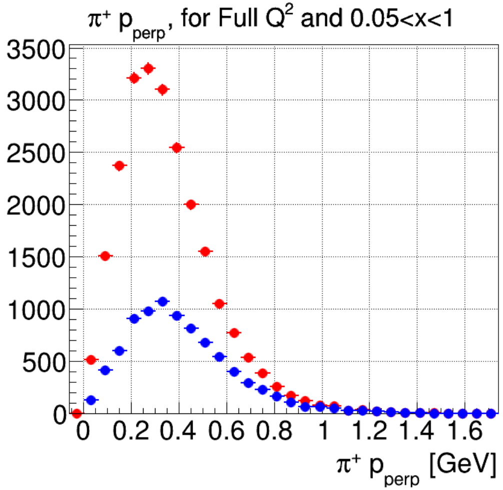
$y_{min} = 0.05$

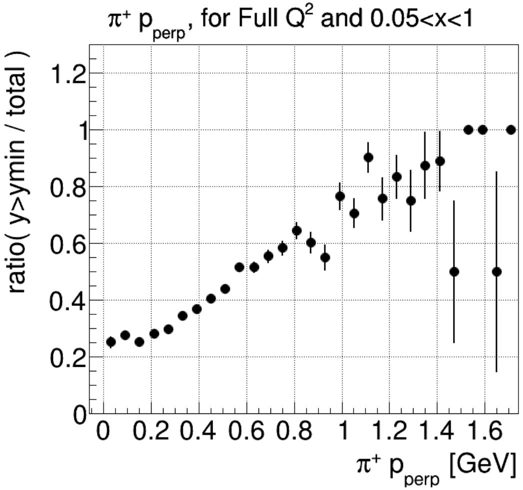
$q_T/Q < 0.25$





$q_T/Q < 1.0$

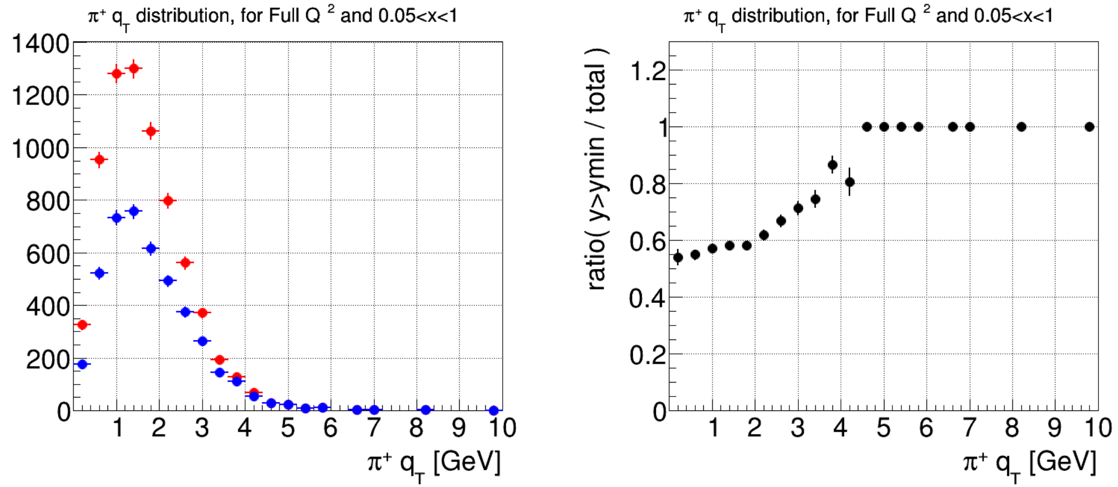




q_T Distributions for varying y_{min} in 2 bins of z

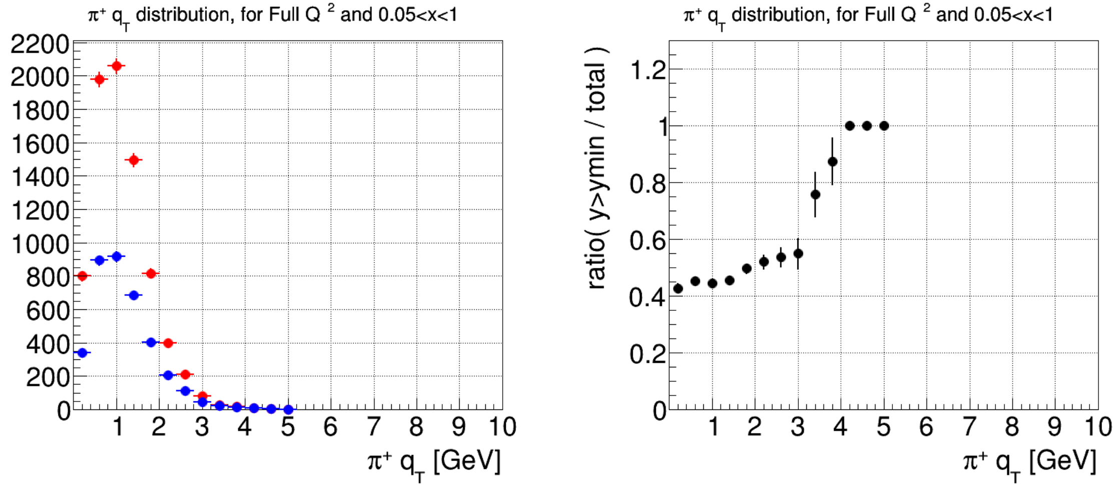
$y_{min} = 0.03$

0.2 < z < 0.3



similarly, low q_T has larger relative suppression

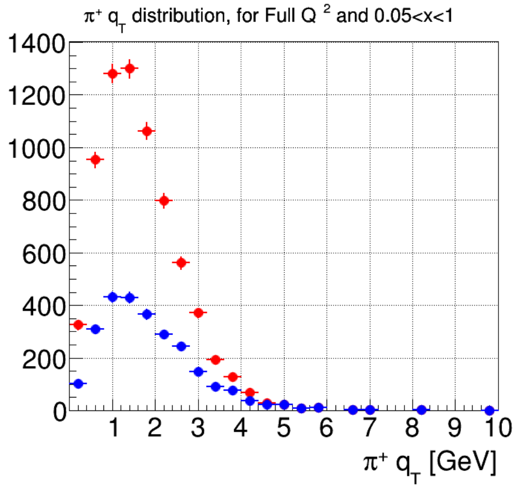
0.3 < z < 1

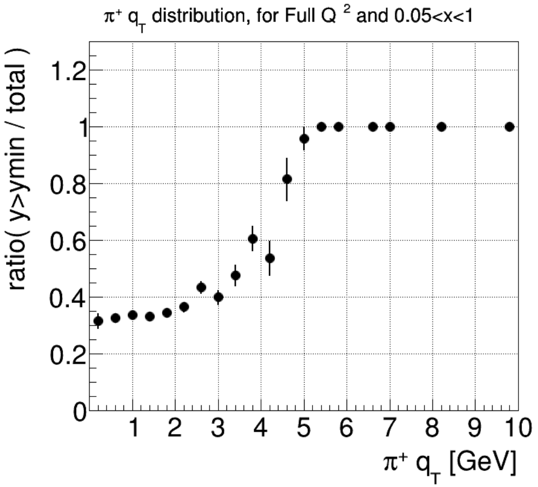


q_T Distributions for varying y_{min} in 2 bins of z

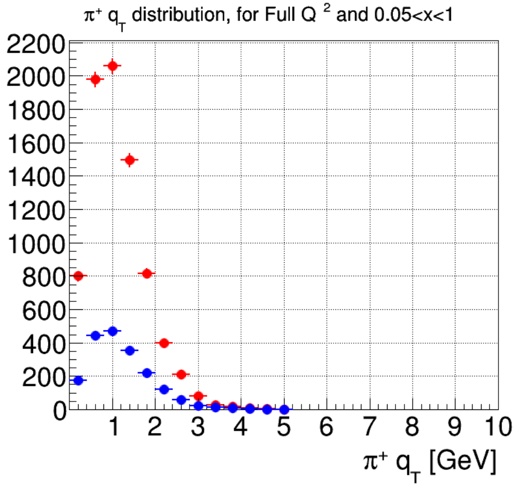
y_{min} = 0.05

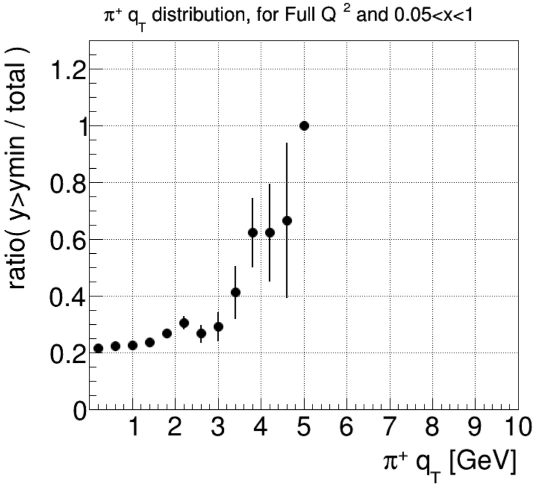
0.2 < z < 0.3



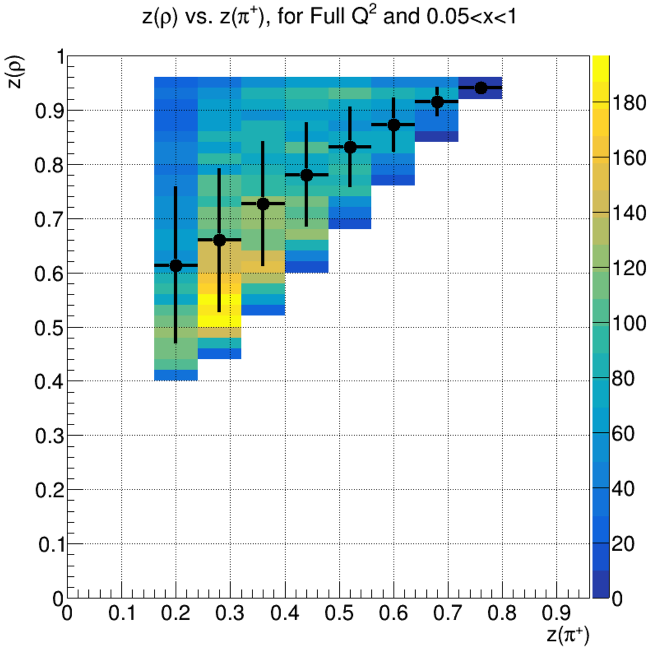


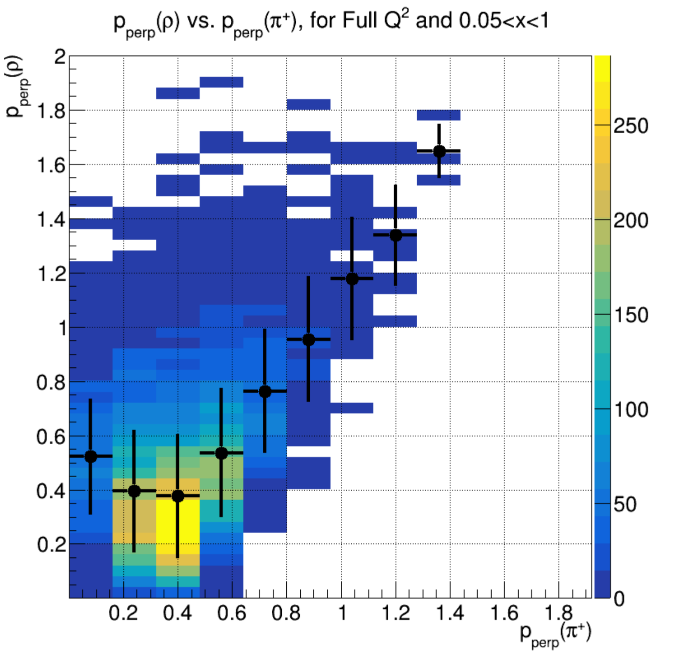
0.3 < z < 1

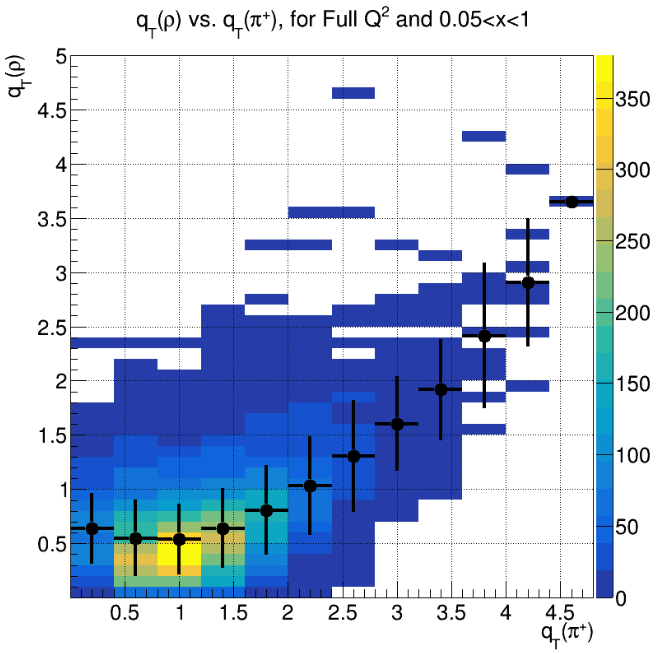




Vector Meson Decays → Muddy Waters for Interpretation







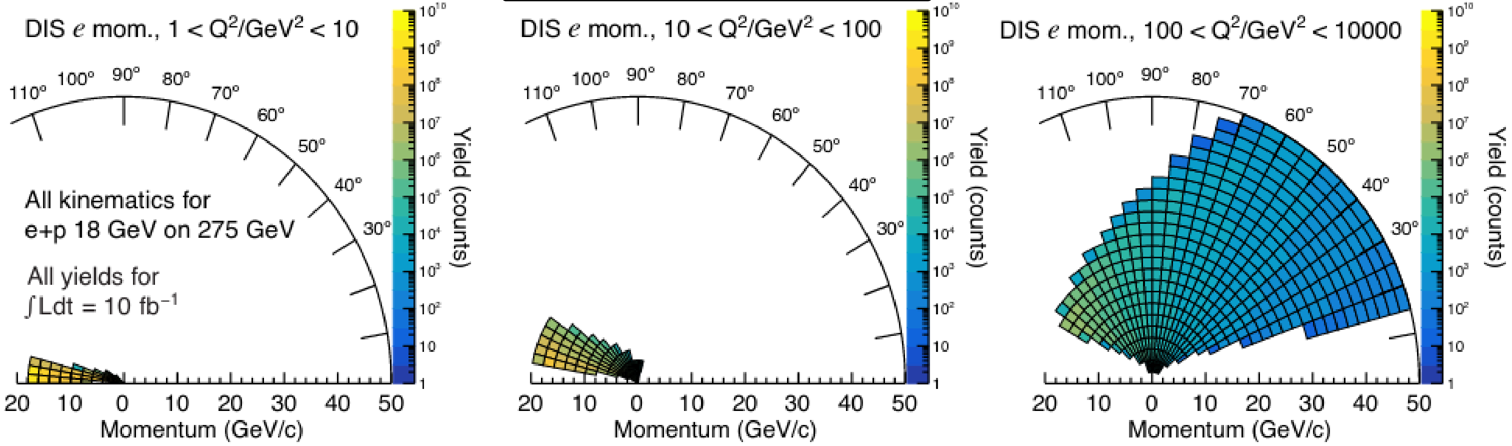
high-z ρ → small-z pion

p_Ts are somewhat similar

high-q_T pion from small-q_T ρ

DIS Electron

Low Q^2 | **High Q^2**



SIDIS Pion

Low x | **High x**