EXPLORING THE INTERIOR OF THE NUCLEON WITH TRANSVERSE MOMENTUM DEPENDENT PARTON DISTRIBUTIONS (TMDS)

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3DSPIN
MAPPING THE PROTON IN 3D

European Research Council

INFN Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DI PAVIA

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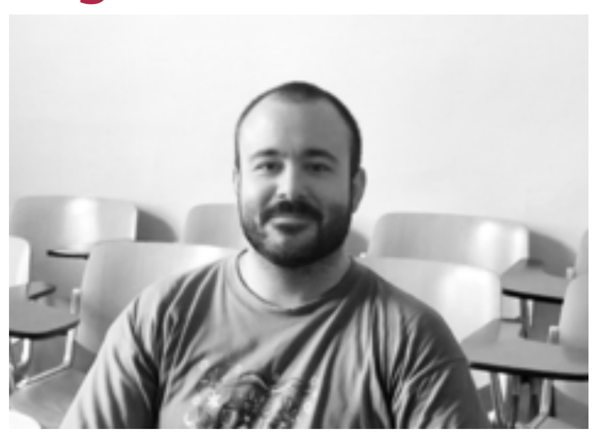

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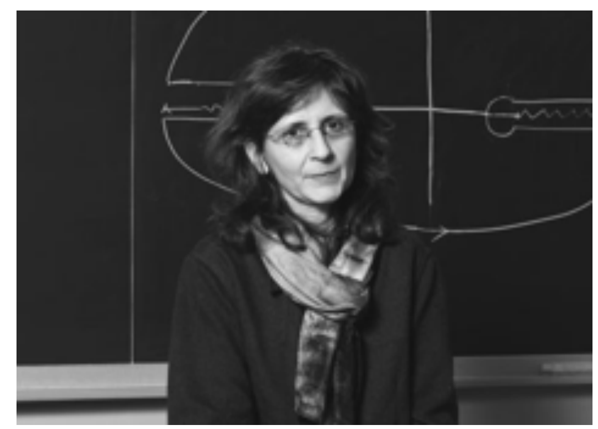

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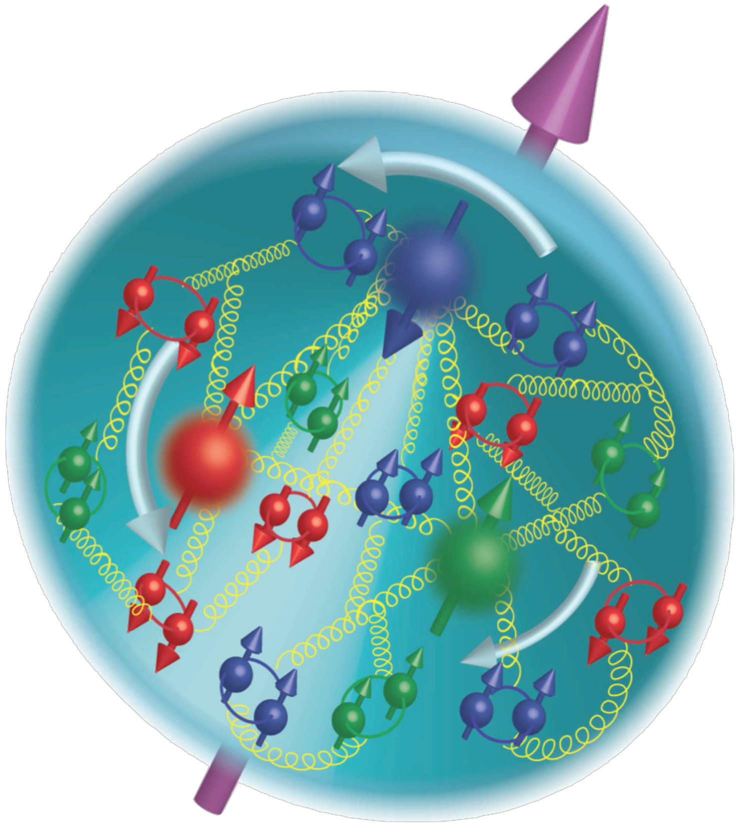
Cristian Pisano

Marco Radici

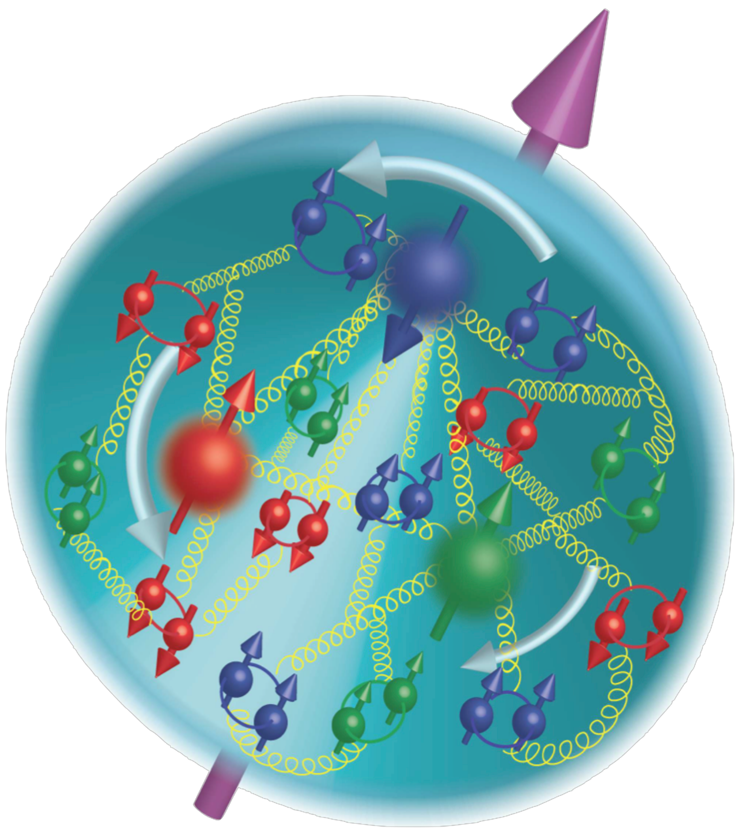
Simone Rodini

WHY IS IT INTERESTING TO MAP THE NUCLEON?



WHY IS IT INTERESTING TO MAP THE NUCLEON?

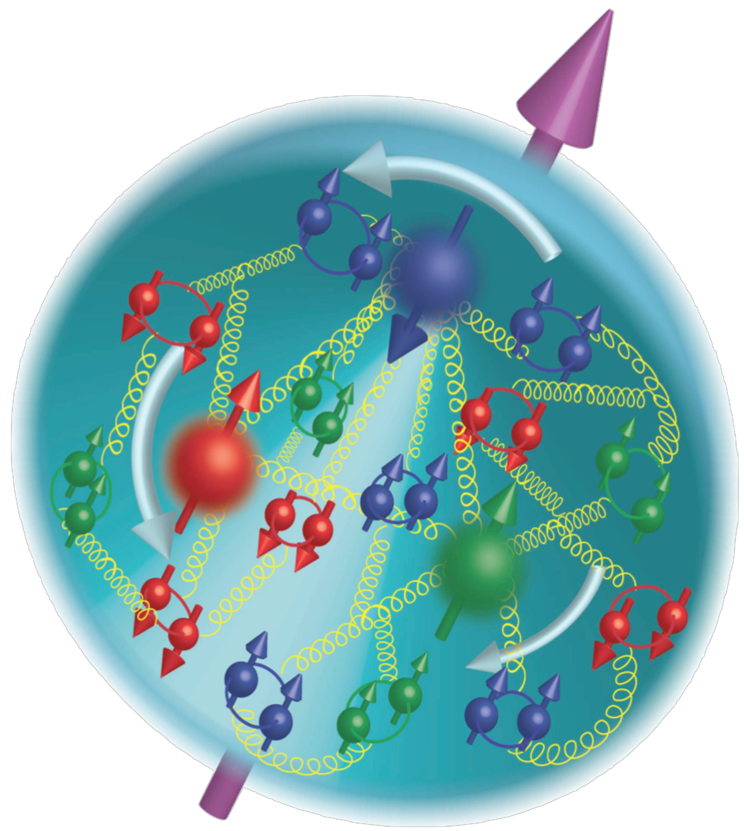
$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \overline{\psi}_q (i \not\partial - g \not A + m) \psi_q - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$



Check predictions

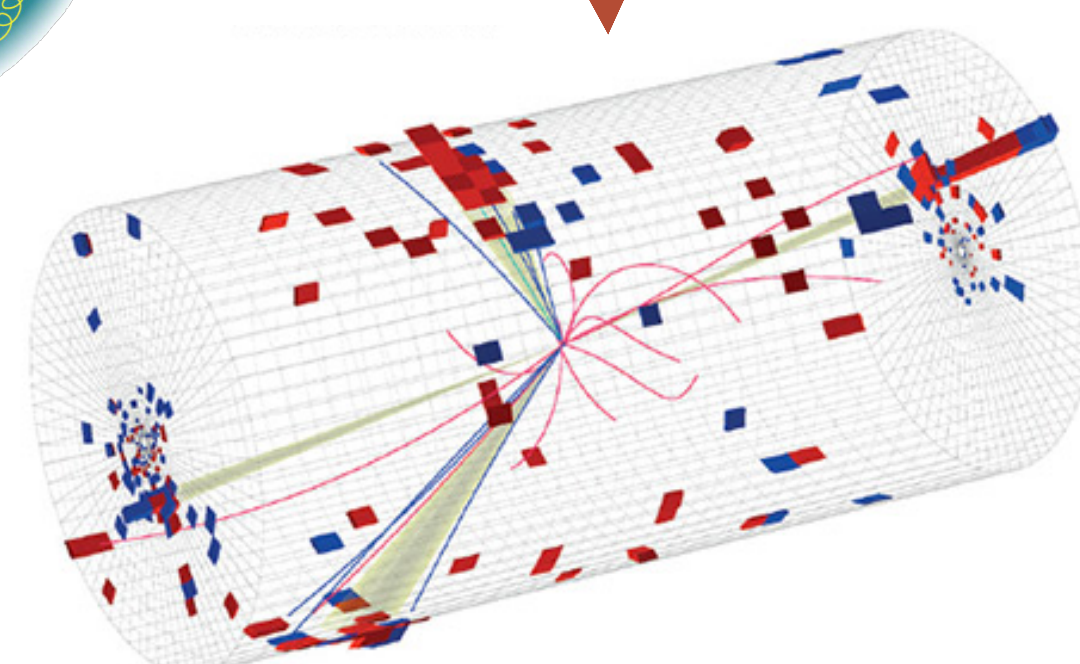
WHY IS IT INTERESTING TO MAP THE NUCLEON?

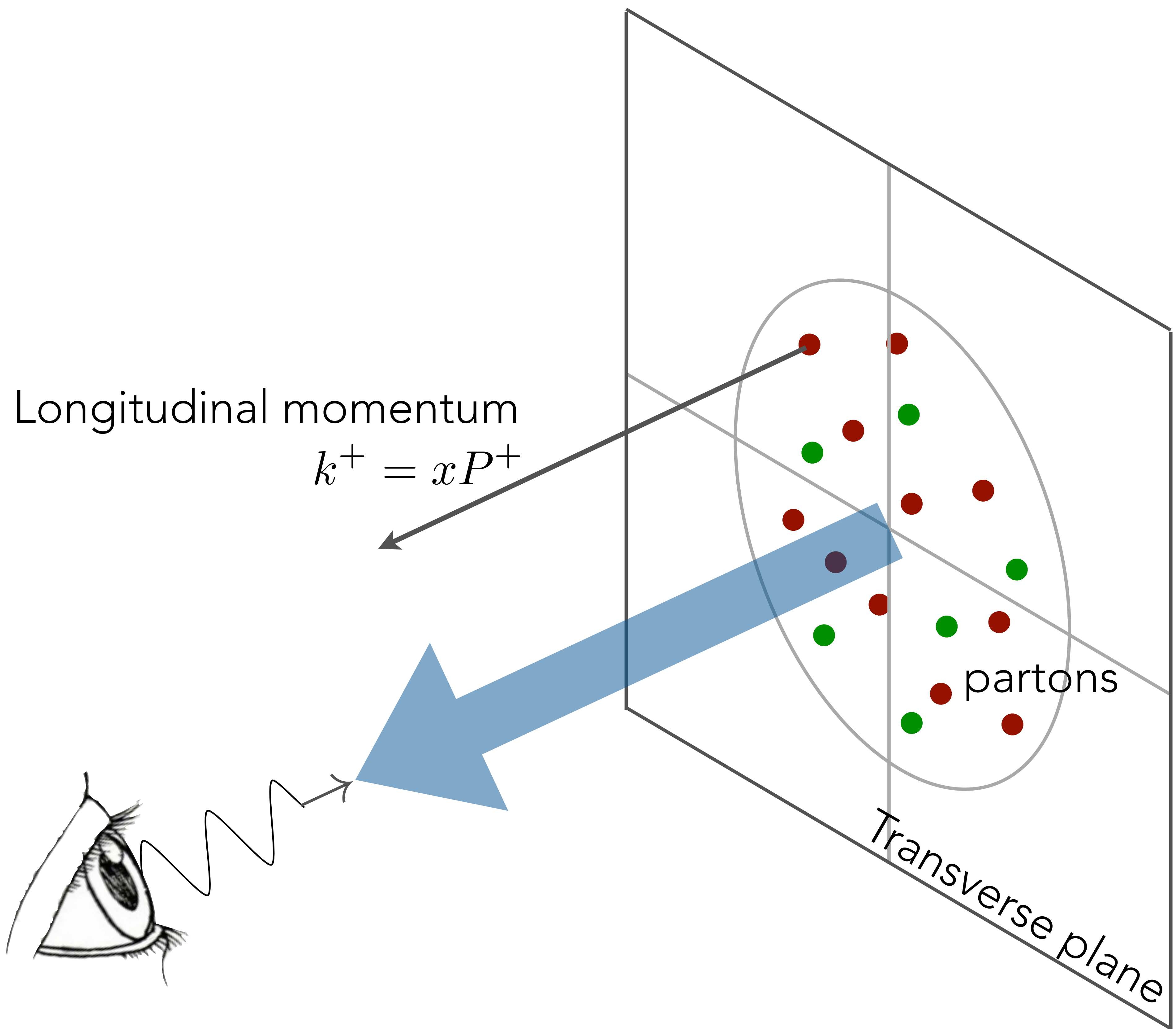
$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \overline{\psi}_q (i\,\partial\!\!\!/ - g\,A\!\!\!/ + m)\psi_q - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$



Make predictions

Check predictions



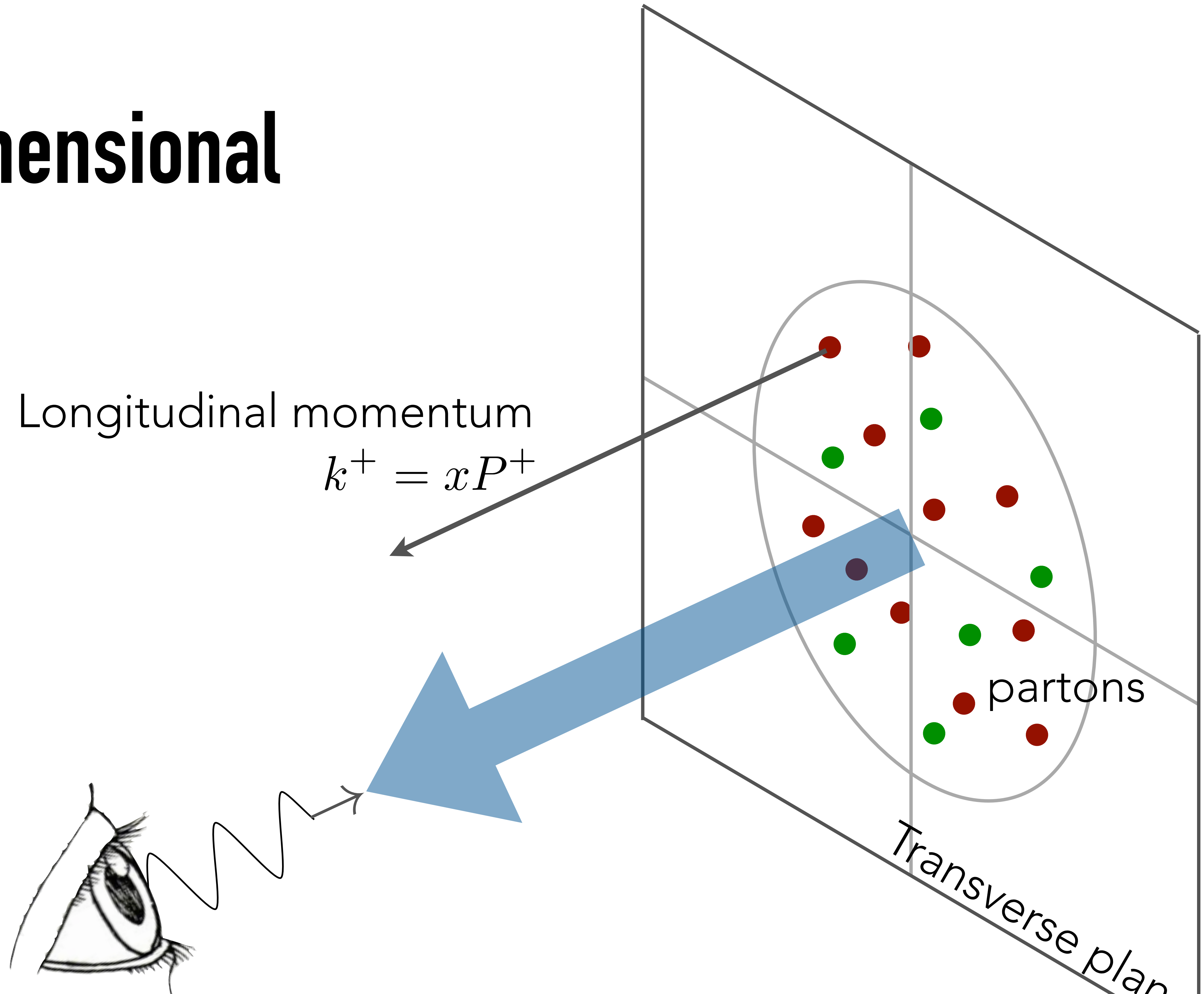


Longitudinal momentum
$k^+ = xP^+$
partons
Transverse plane

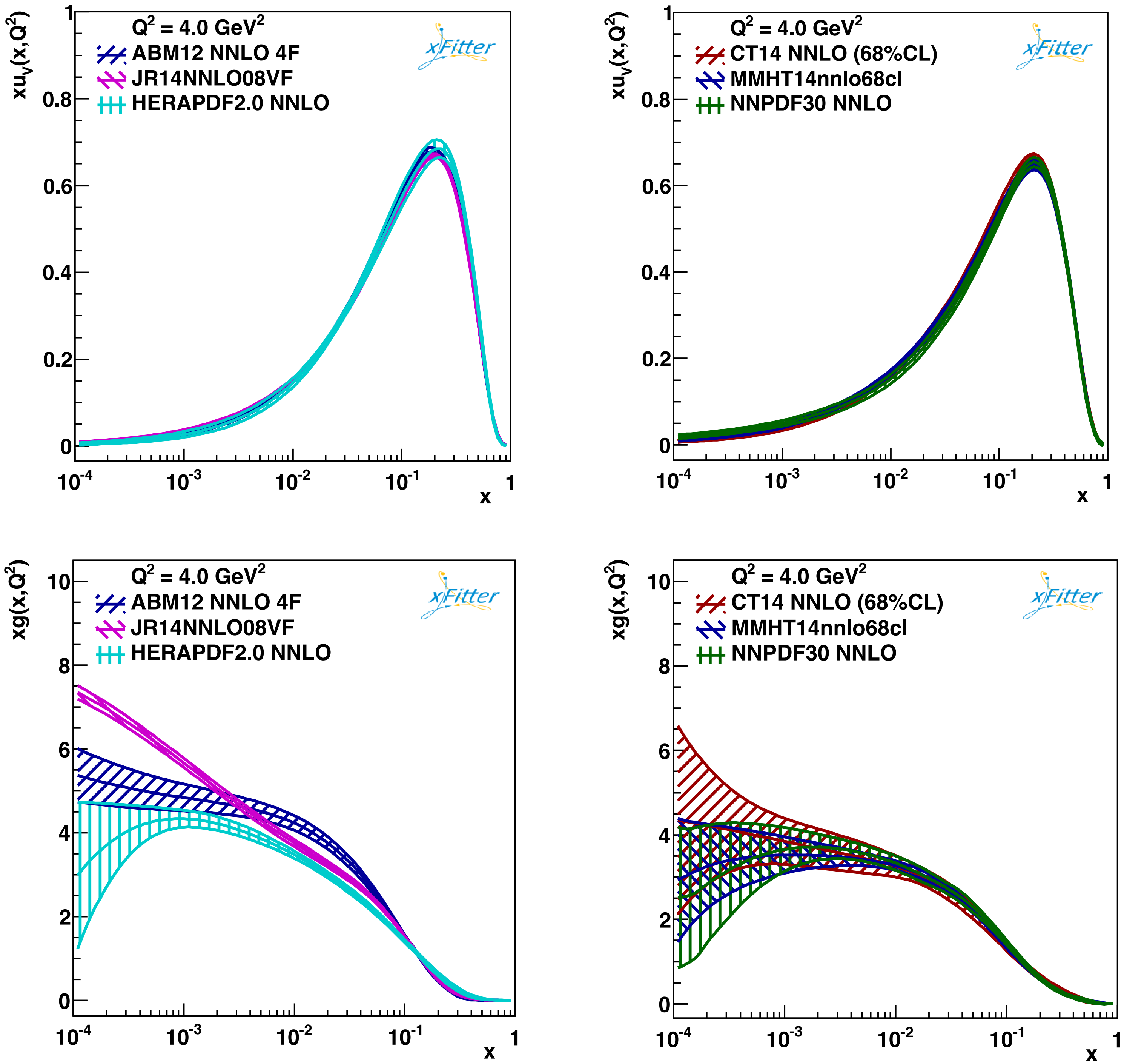
Parton Distribution Functions

$f(x)$

1 dimensional



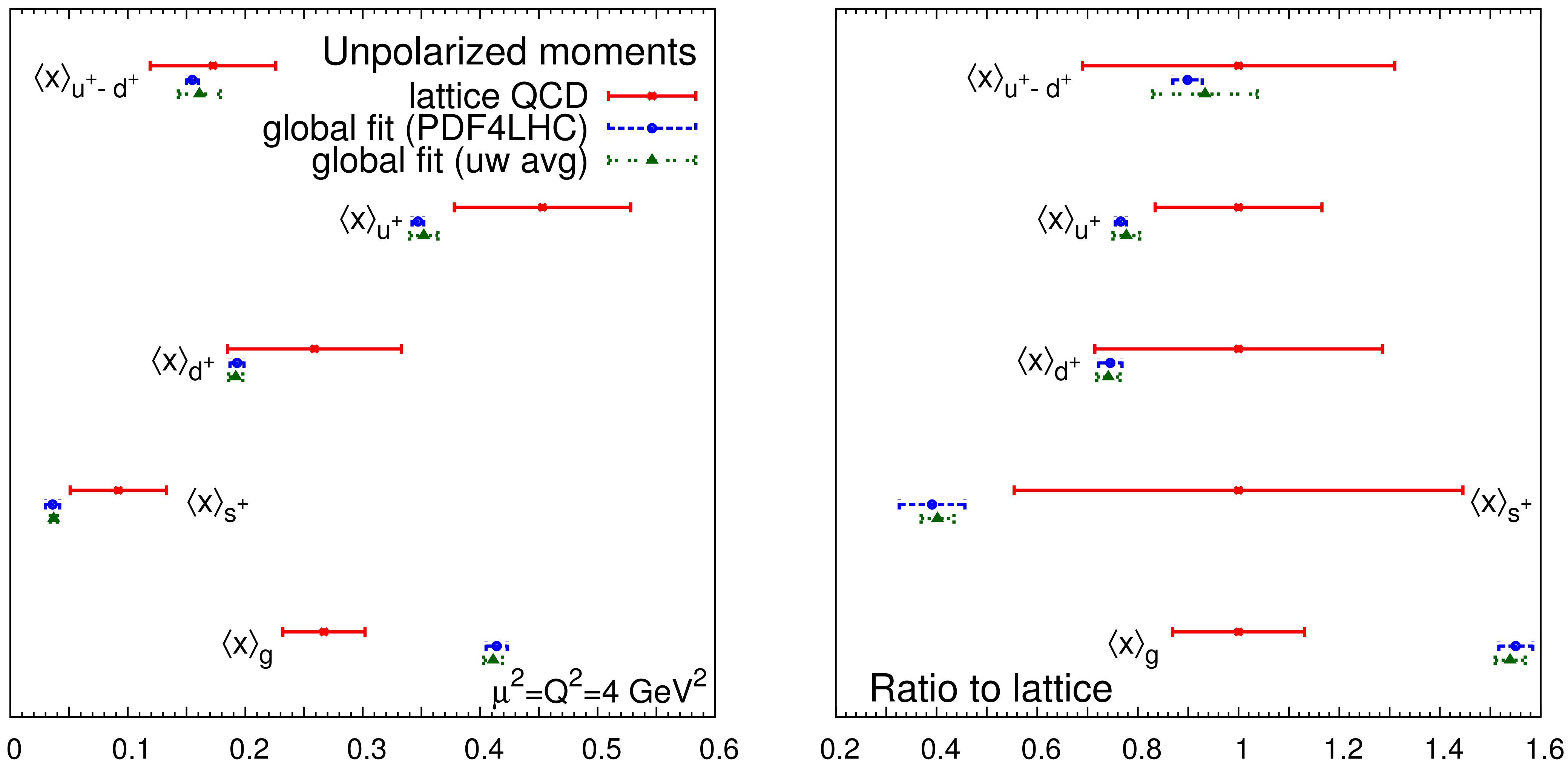
STANDARD PARTON DISTRIBUTION FUNCTIONS



Standard collinear PDFs describe the distribution of partons in one dimension in momentum space. They are extracted through global fits

Accardi et al., arXiv:1603.08906

UNPOLARIZED PDF MOMENTS AND LATTICE QCD

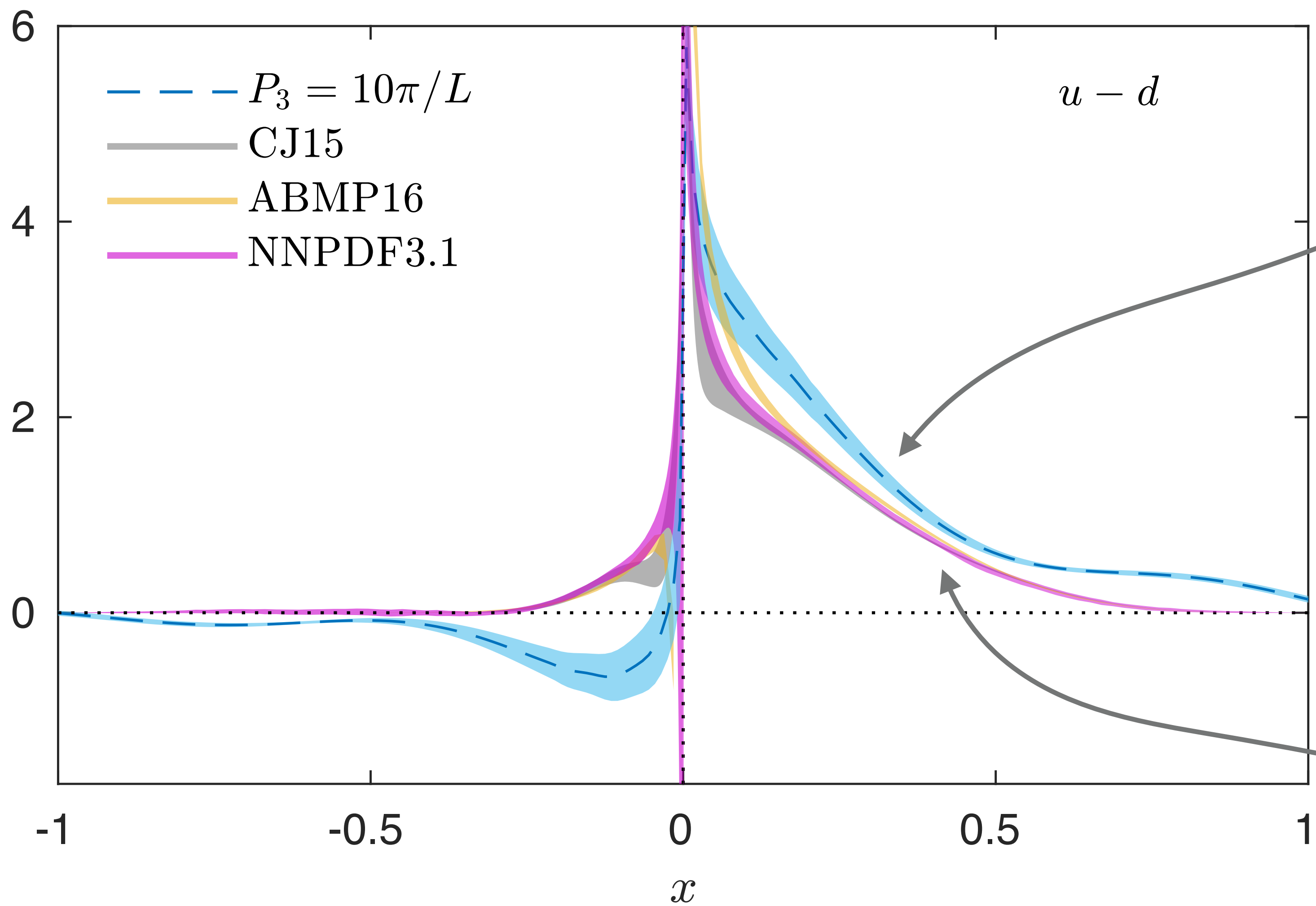


PDFLattice White Paper, arXiv:1711.07916

Fair agreement, but not perfect

FULL UNPOLARIZED PDF AND LATTICE QCD

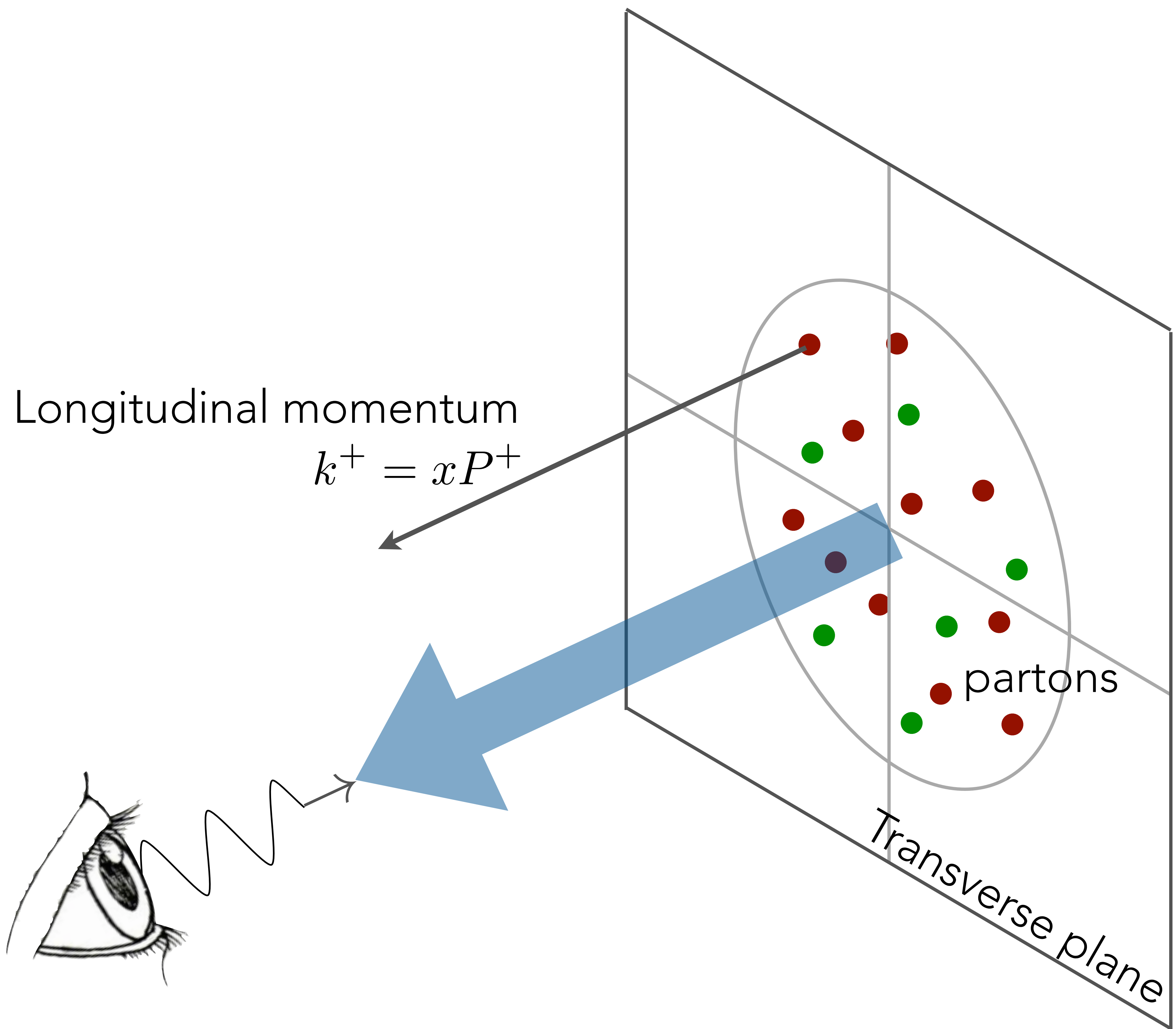
Alexandrou, Cichy, Constantinou, Hadjiyiannakou, Jansen, Scapellato, Steffens, arXiv:1902.00587

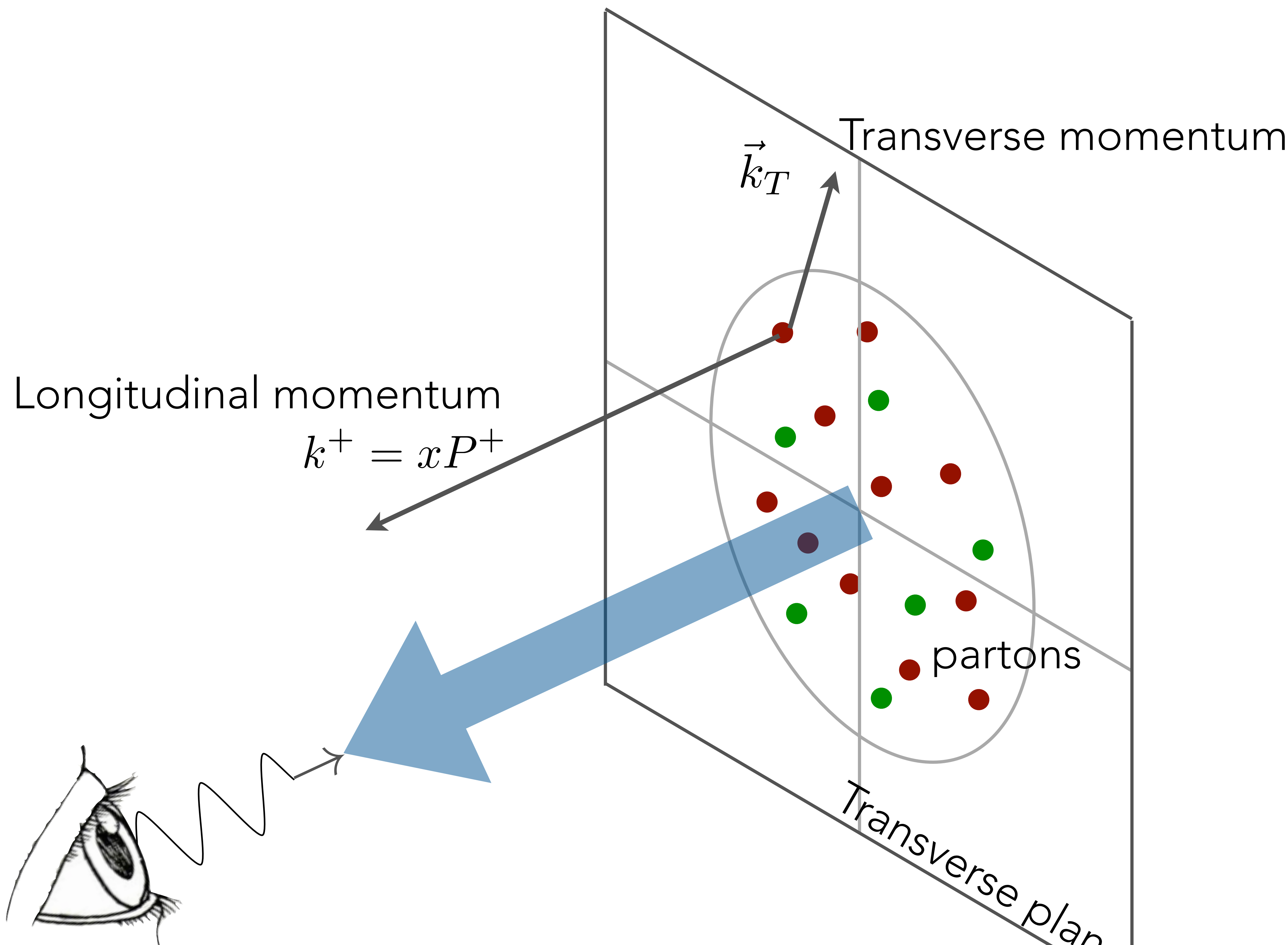


lattice calculation (quasi-PDF approach)

global fits

antiquarks quarks

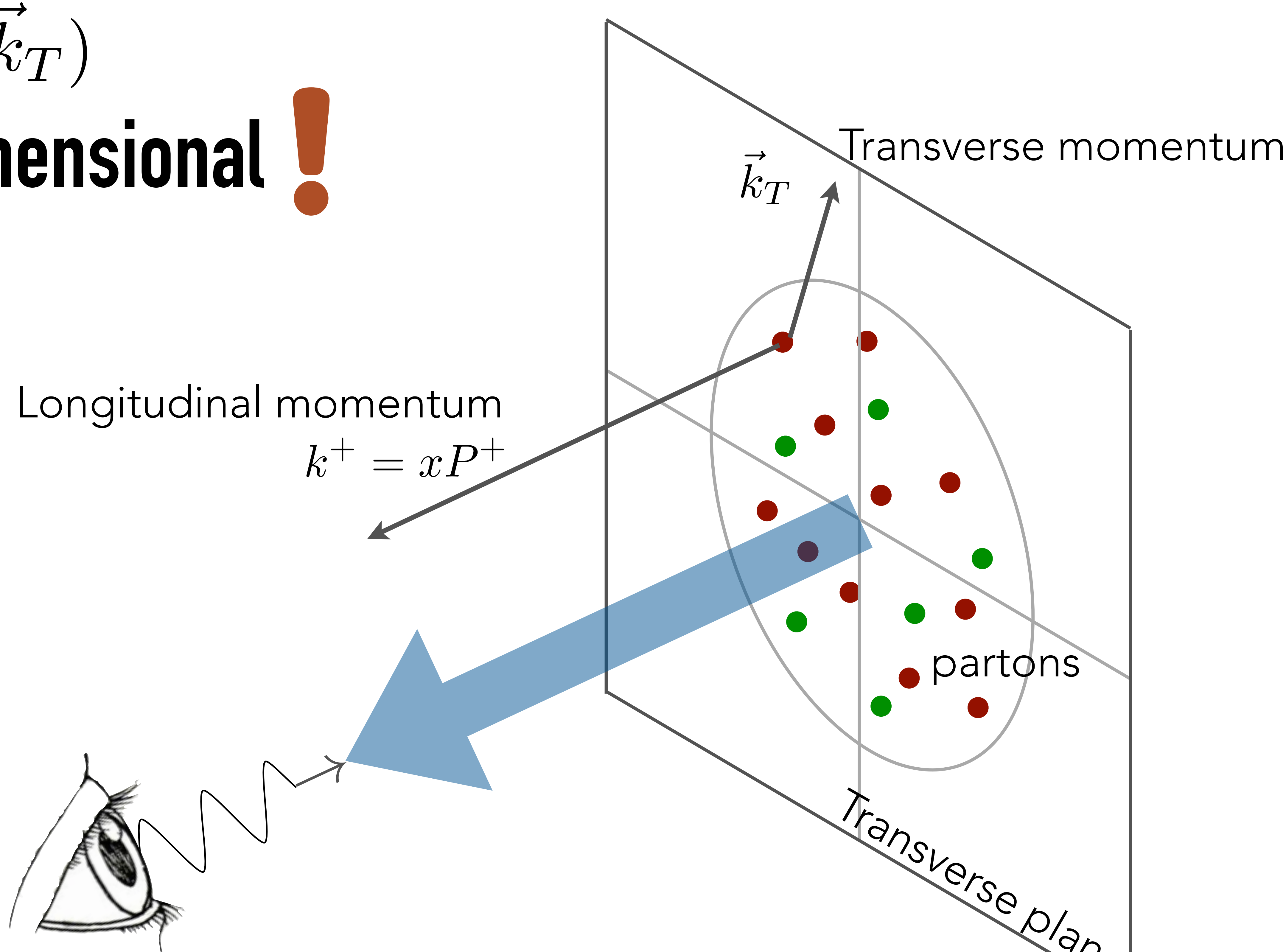

Longitudinal momentum
$k^+ = xP^+$
partons
Transverse plane


Transverse momentum
$\vec{k}_T$
Longitudinal momentum
$k^+ = xP^+$
partons
Transverse plane

Transverse-Momentum Distributions

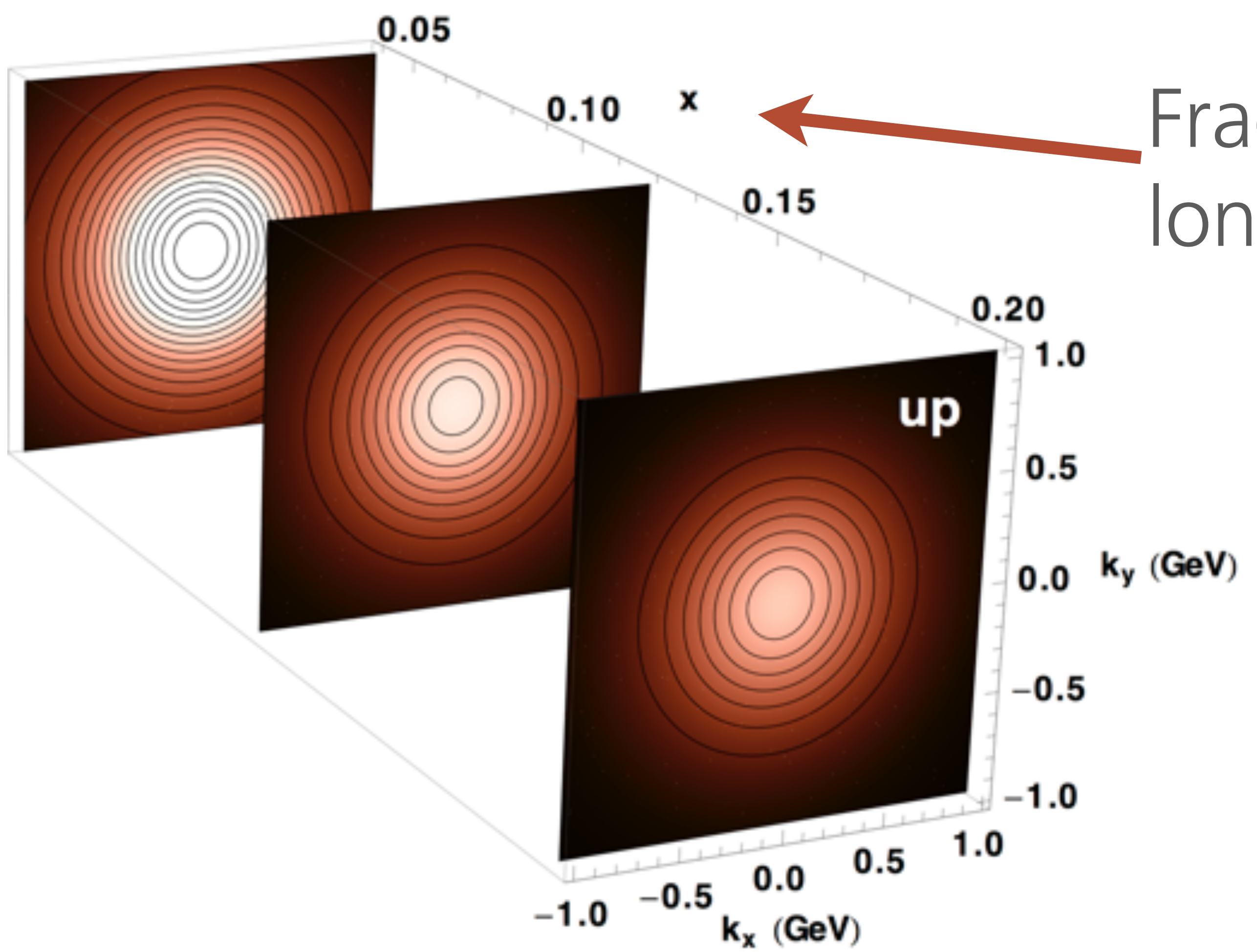
$f(x, \vec{k}_T)$

3 dimensional !



TRANSVERSE MOMENTUM DISTRIBUTIONS

TMDs describe the distribution of partons in three dimensions in momentum space. They also have to be extracted through global fits.



Fraction of longitudinal momentum

Transverse momentum

TRANSVERSE MOMENTUM DISTRIBUTIONS

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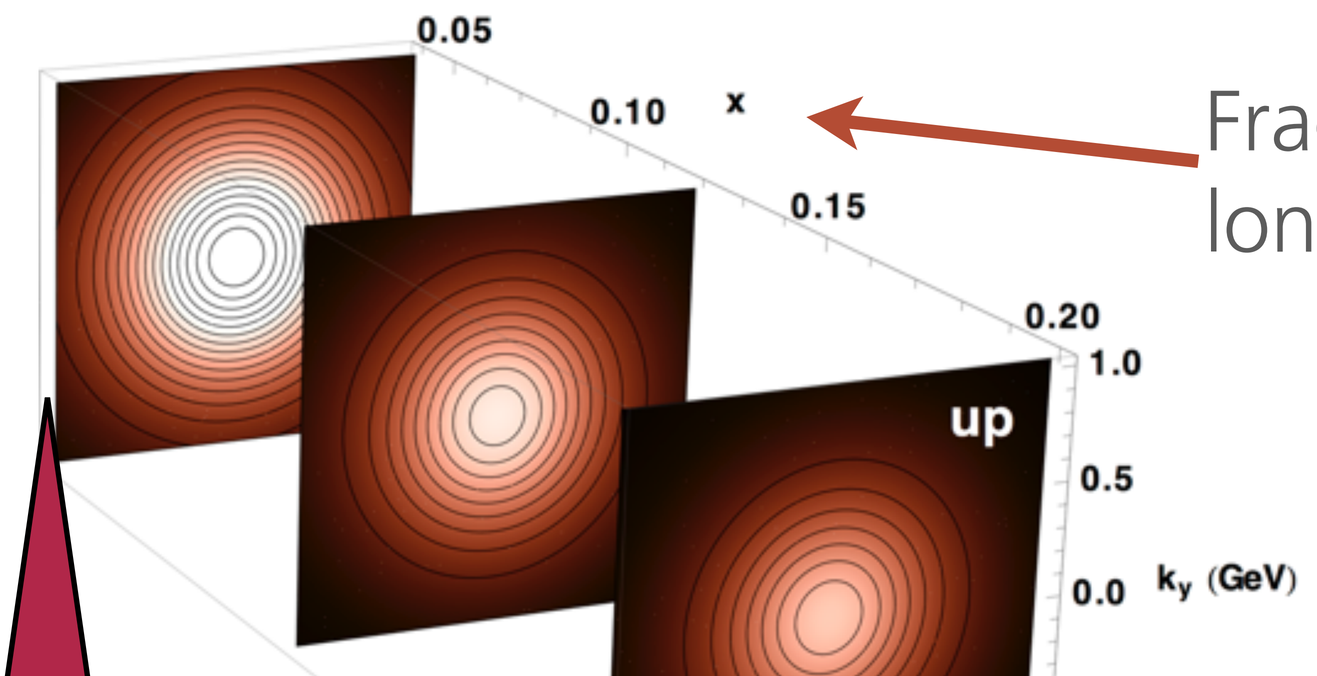


Fraction of longitudinal momentum

How "wide" is the distribution?
Is there a difference between flavors?
Does it get wider at low x?

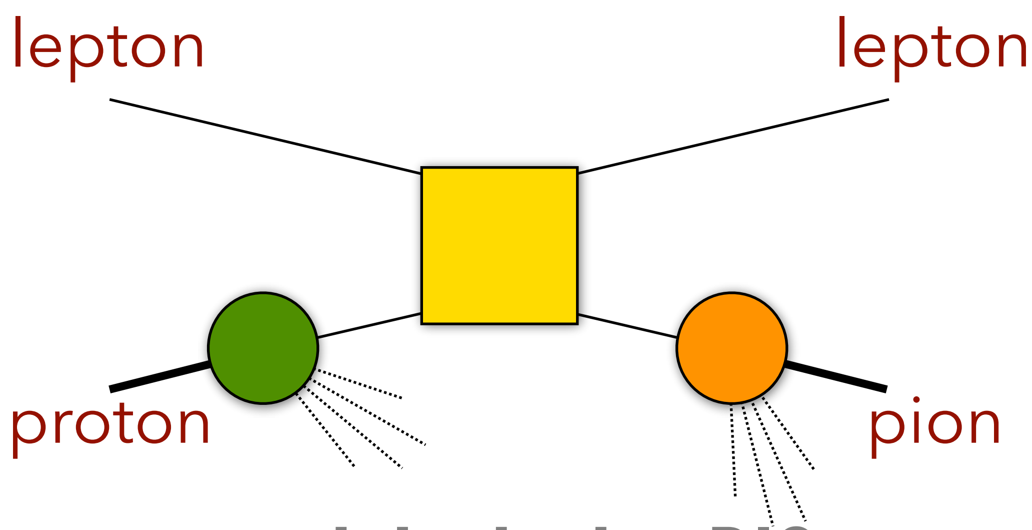
momentum

UNPOLARISED QUARK TMDS

UNPOLARISED QUARK TMDS

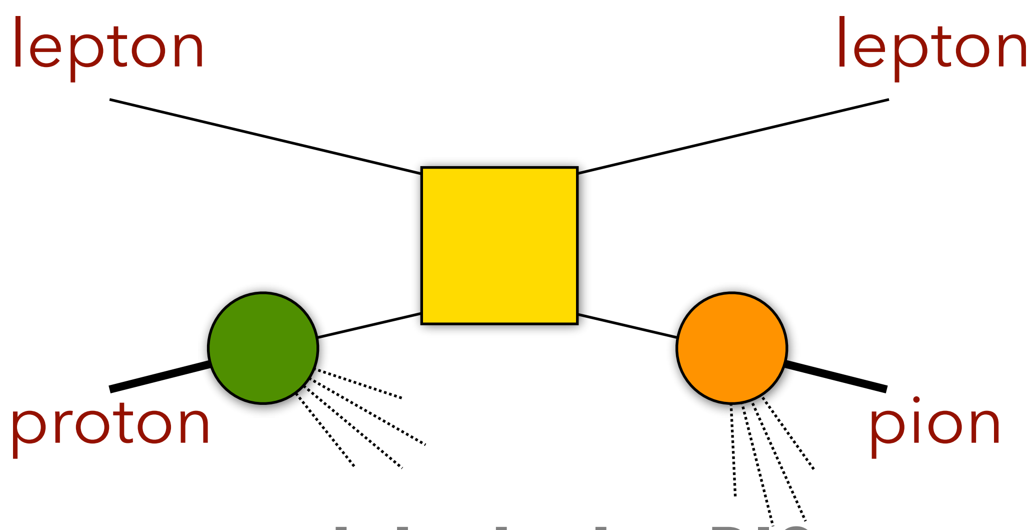
see talk by M. Radici for polarized ones

FACTORIZATION AND UNIVERSALITY

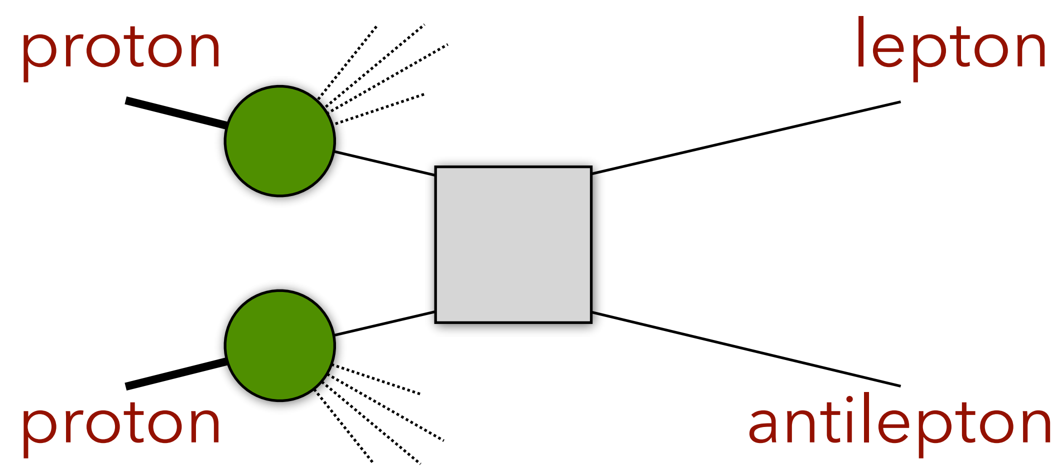


semi-inclusive DIS

FACTORIZATION AND UNIVERSALITY

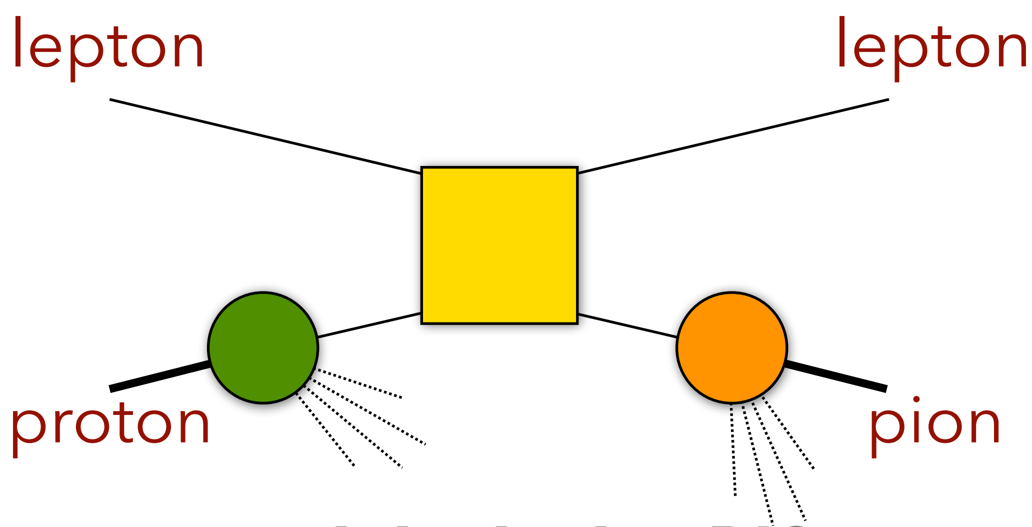


semi-inclusive DIS



Drell-Yan

FACTORIZATION AND UNIVERSALITY



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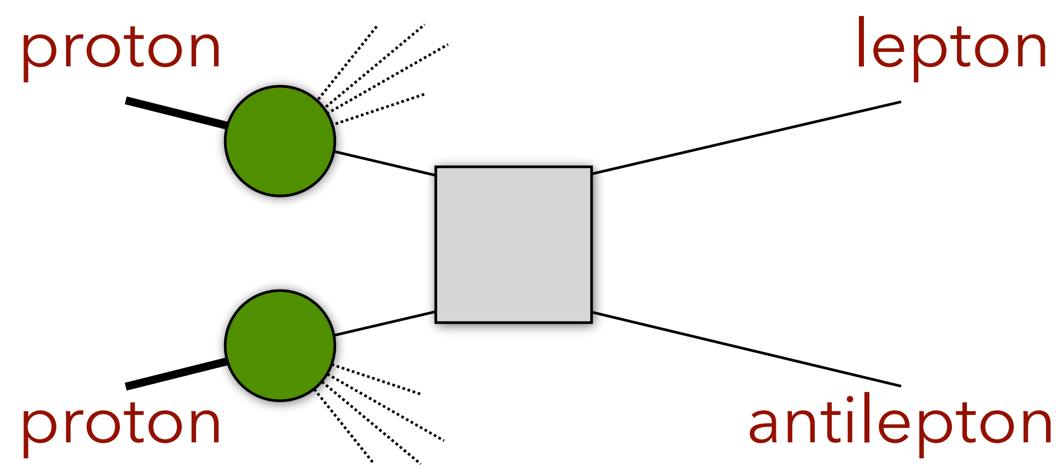
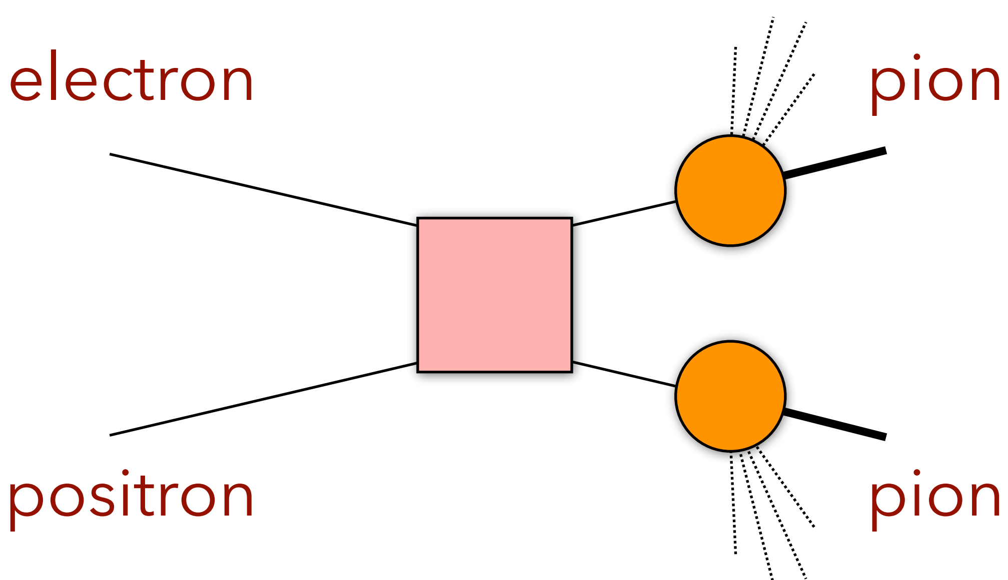
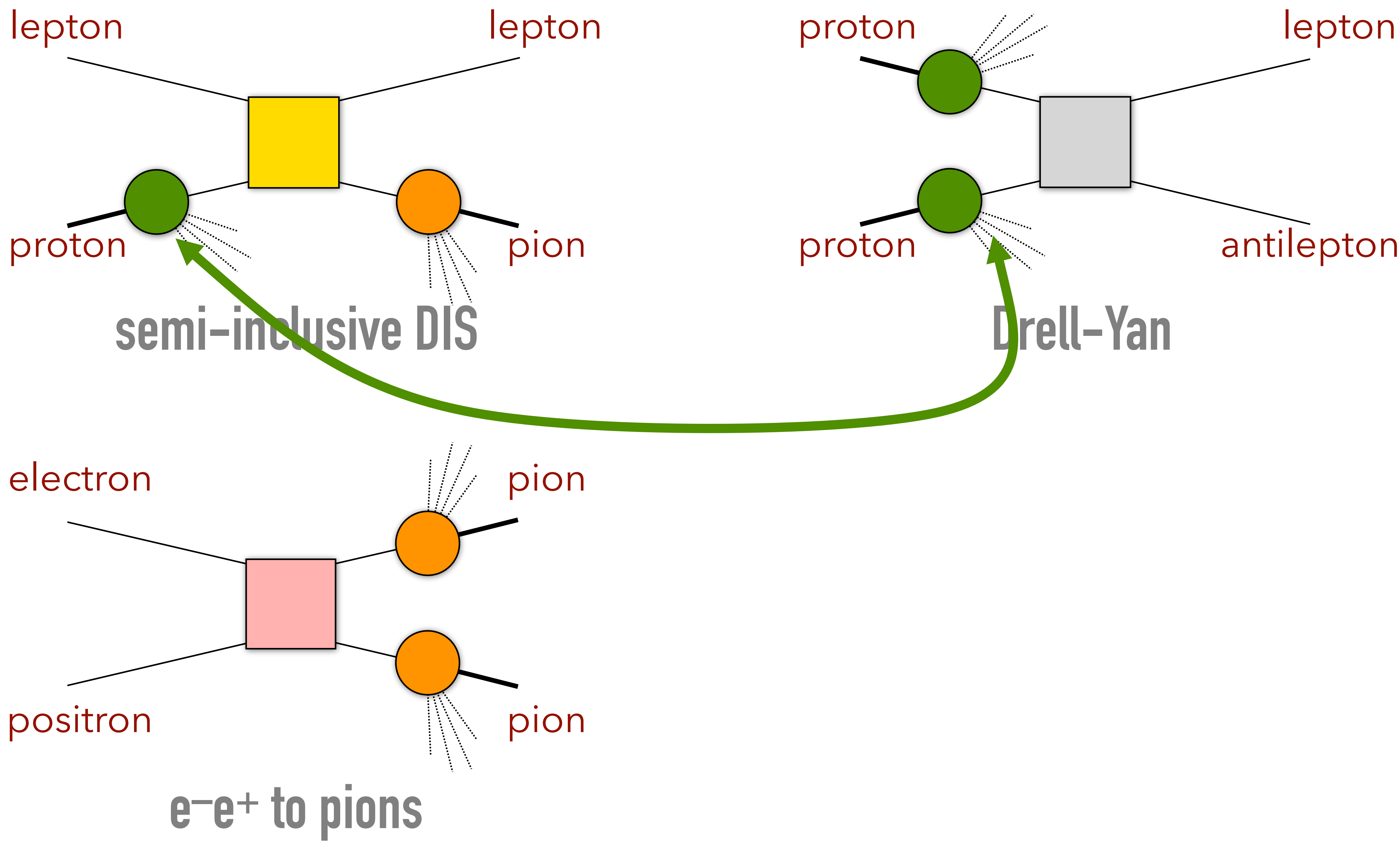


Drell-Yan



e⁻e⁺ to pions

FACTORIZATION AND UNIVERSALITY



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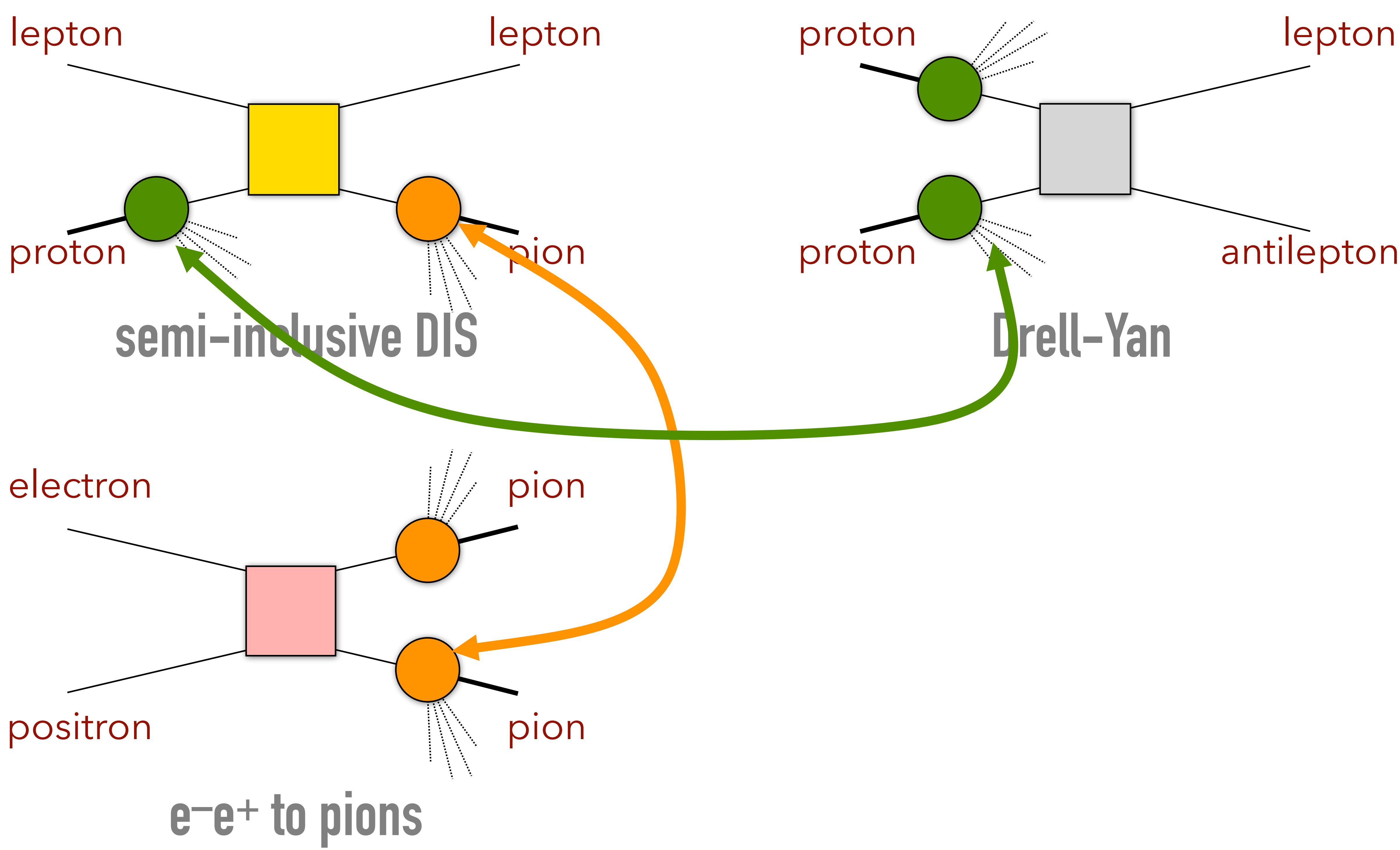

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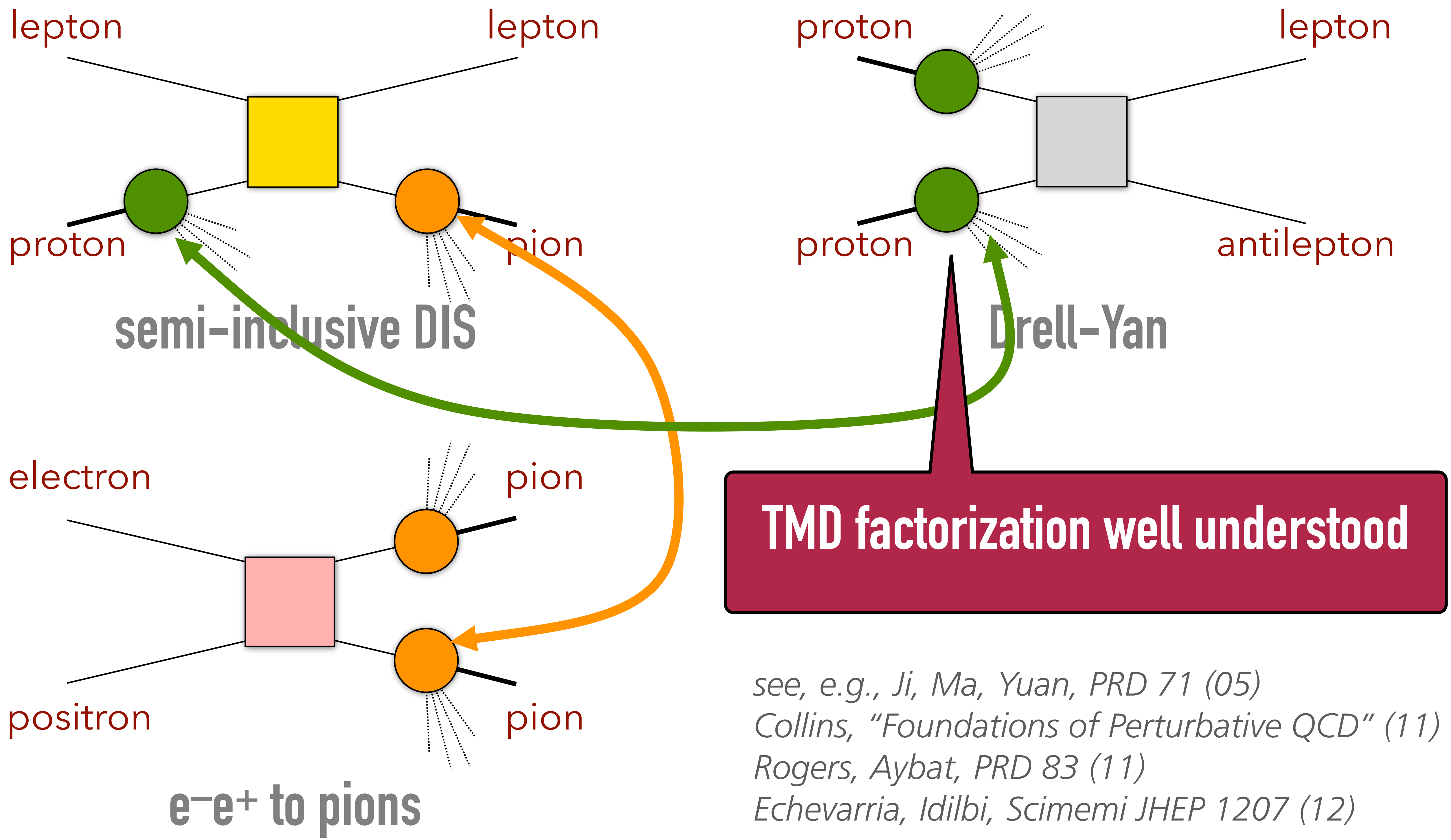
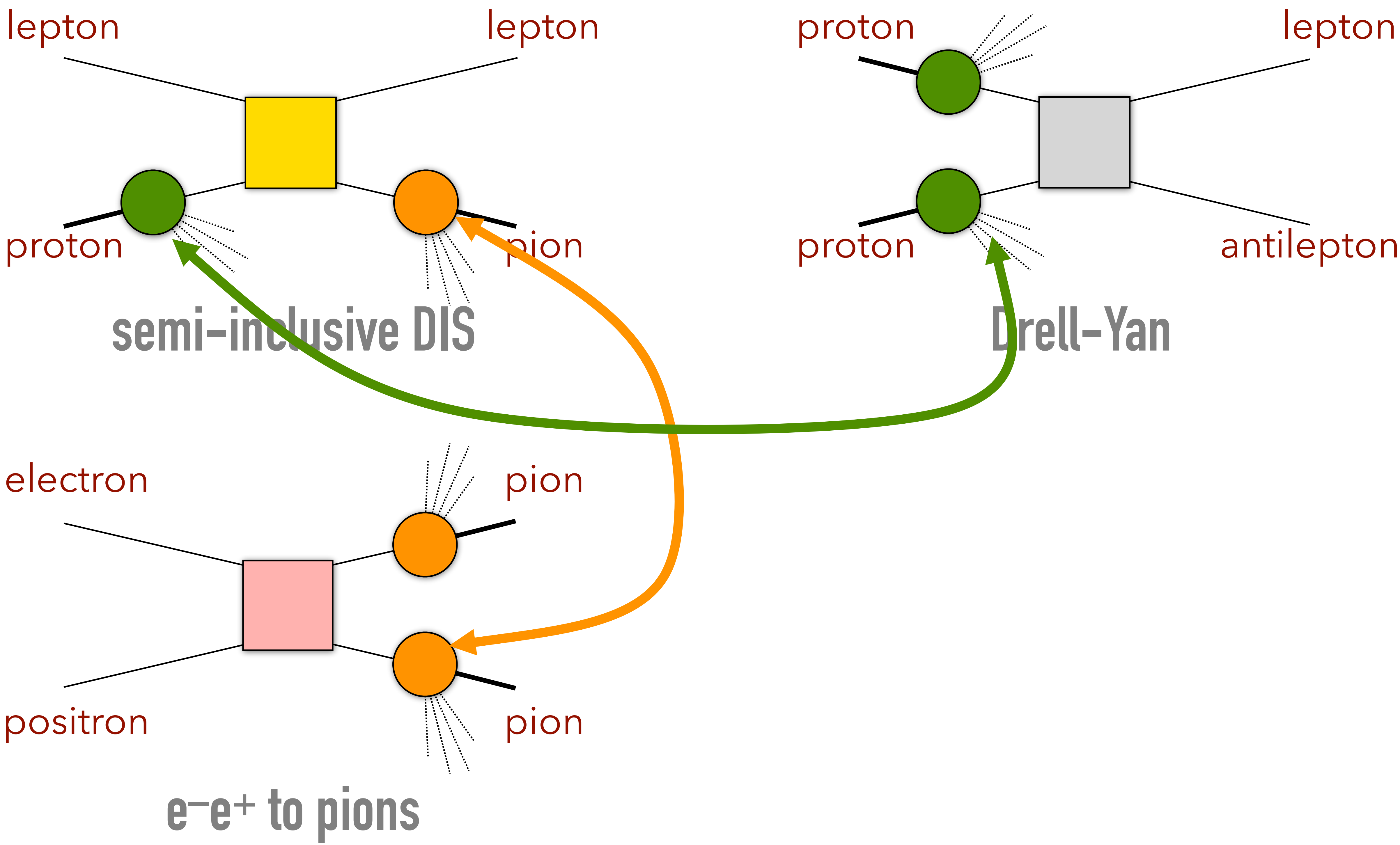


see, e.g., Ji, Ma, Yuan, PRD 71 (05)
Collins, "Foundations of Perturbative QCD" (11)
Rogers, Aybat, PRD 83 (11)
Echevarria, Idilbi, Scimemi JHEP 1207 (12)

FACTORIZATION AND UNIVERSALITY



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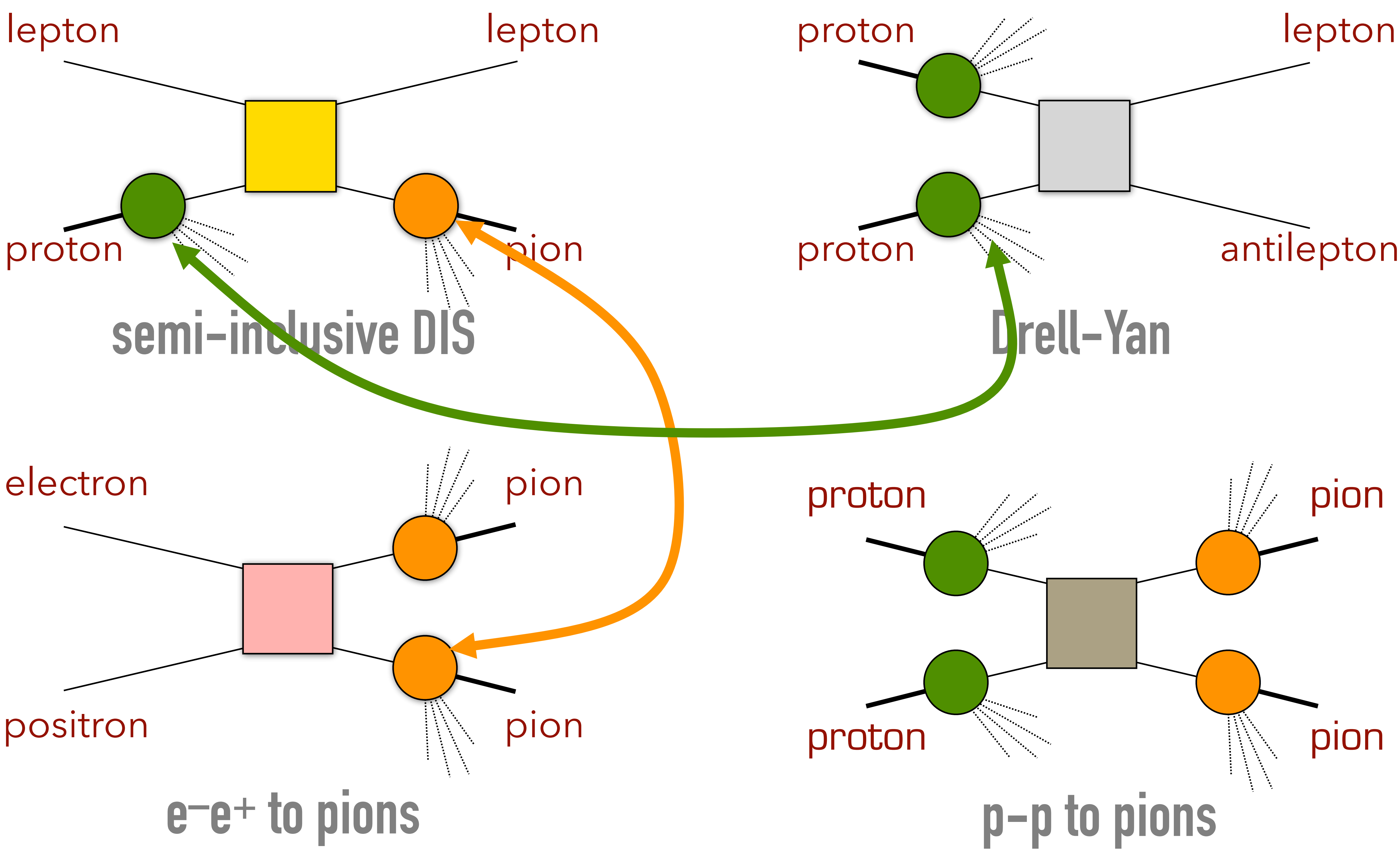

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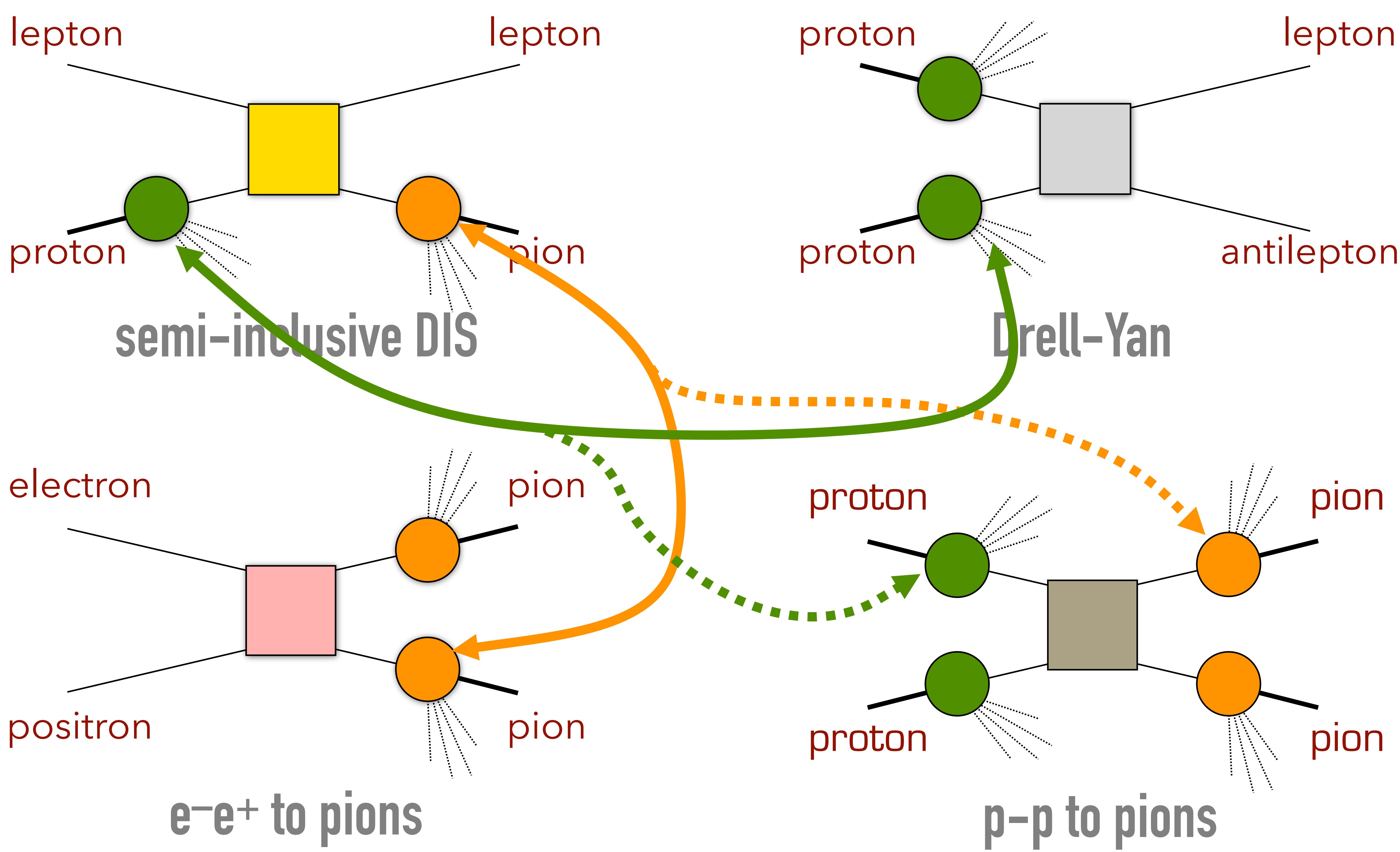

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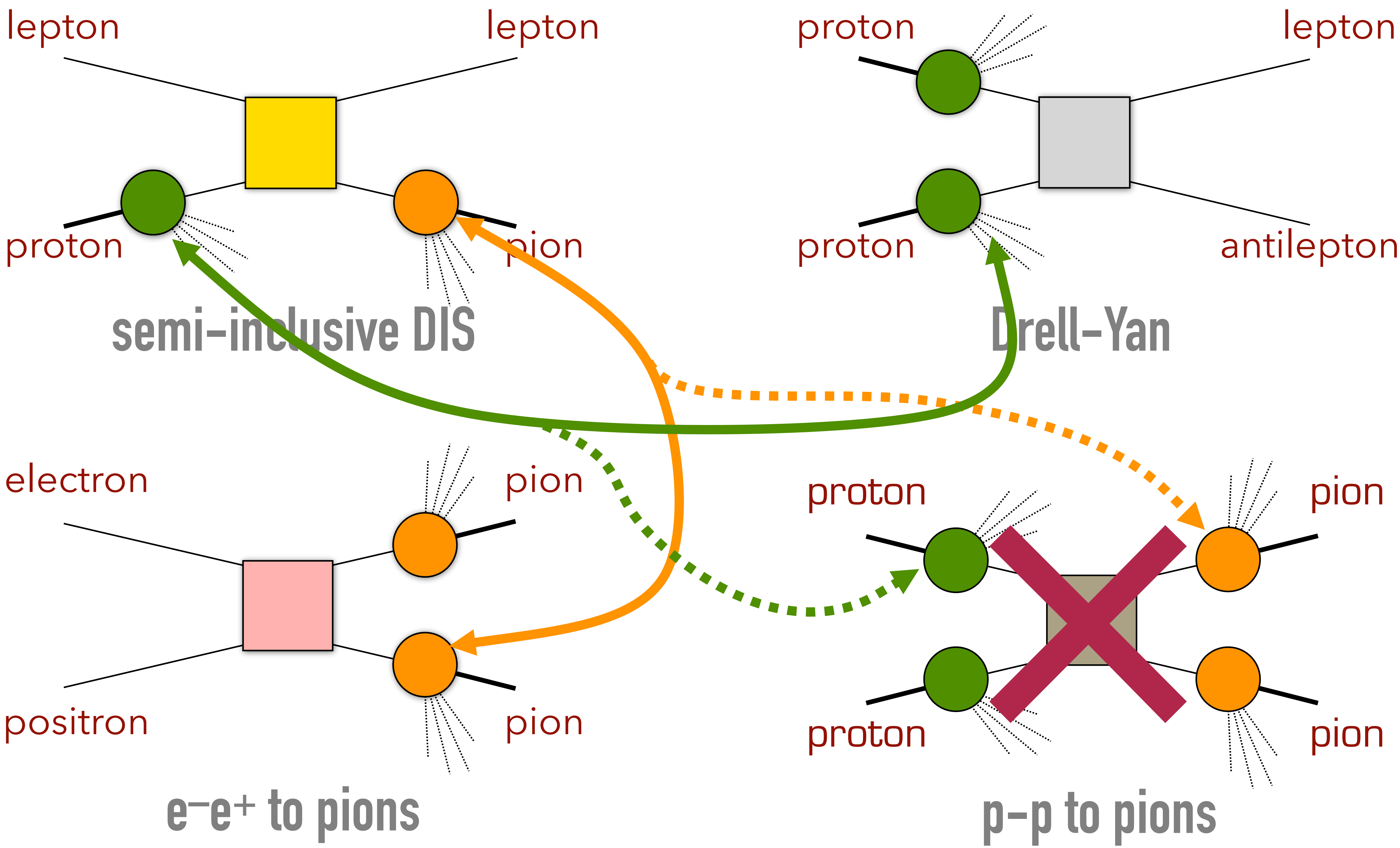
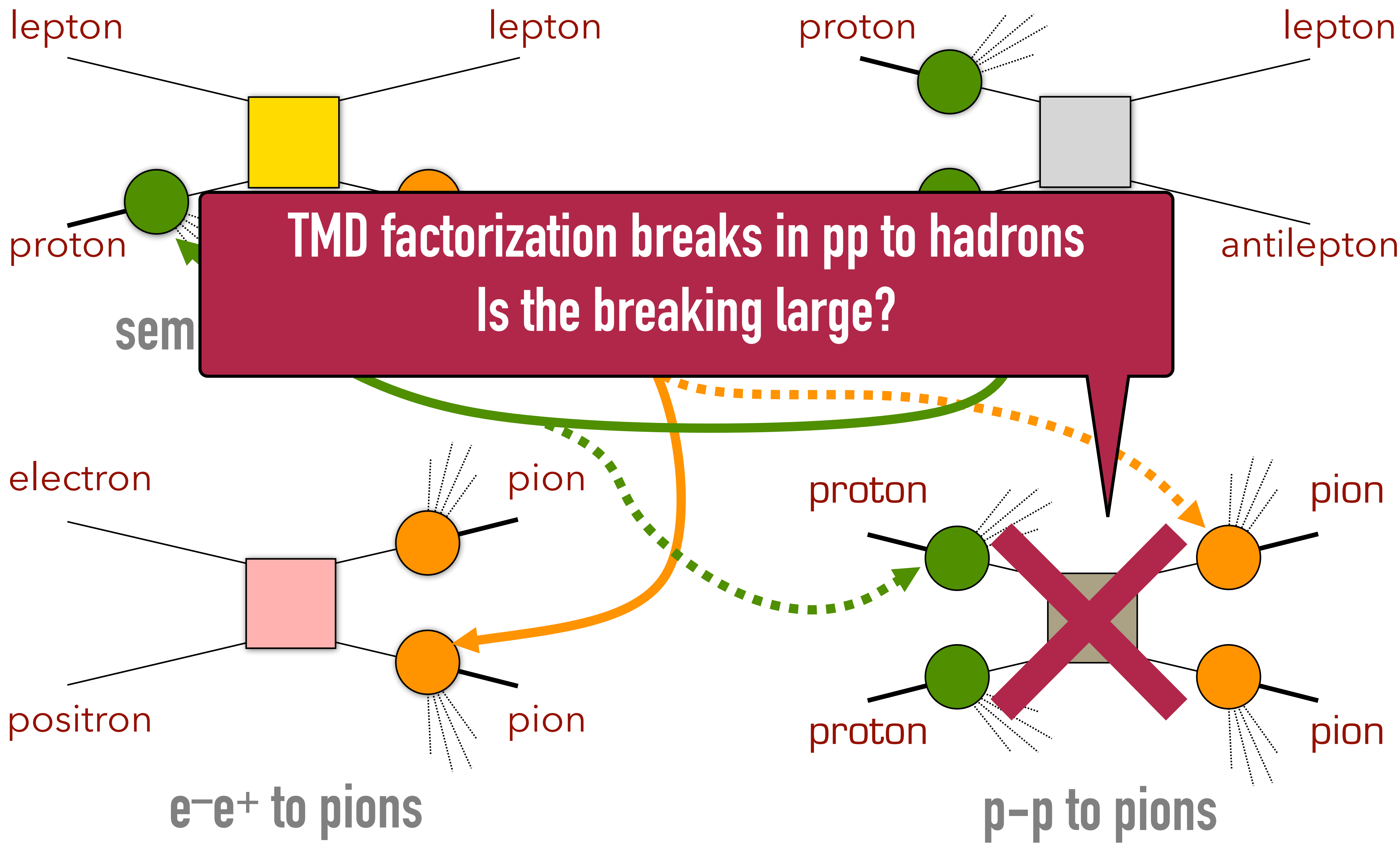


see, e.g., Rogers, Mulders, PRD81 (10)

Buffing, Kang, Lee, Liu, arXiv:1812.07549

FACTORIZATION AND UNIVERSALITY



see, e.g., Rogers, Mulders, PRD81 (10)

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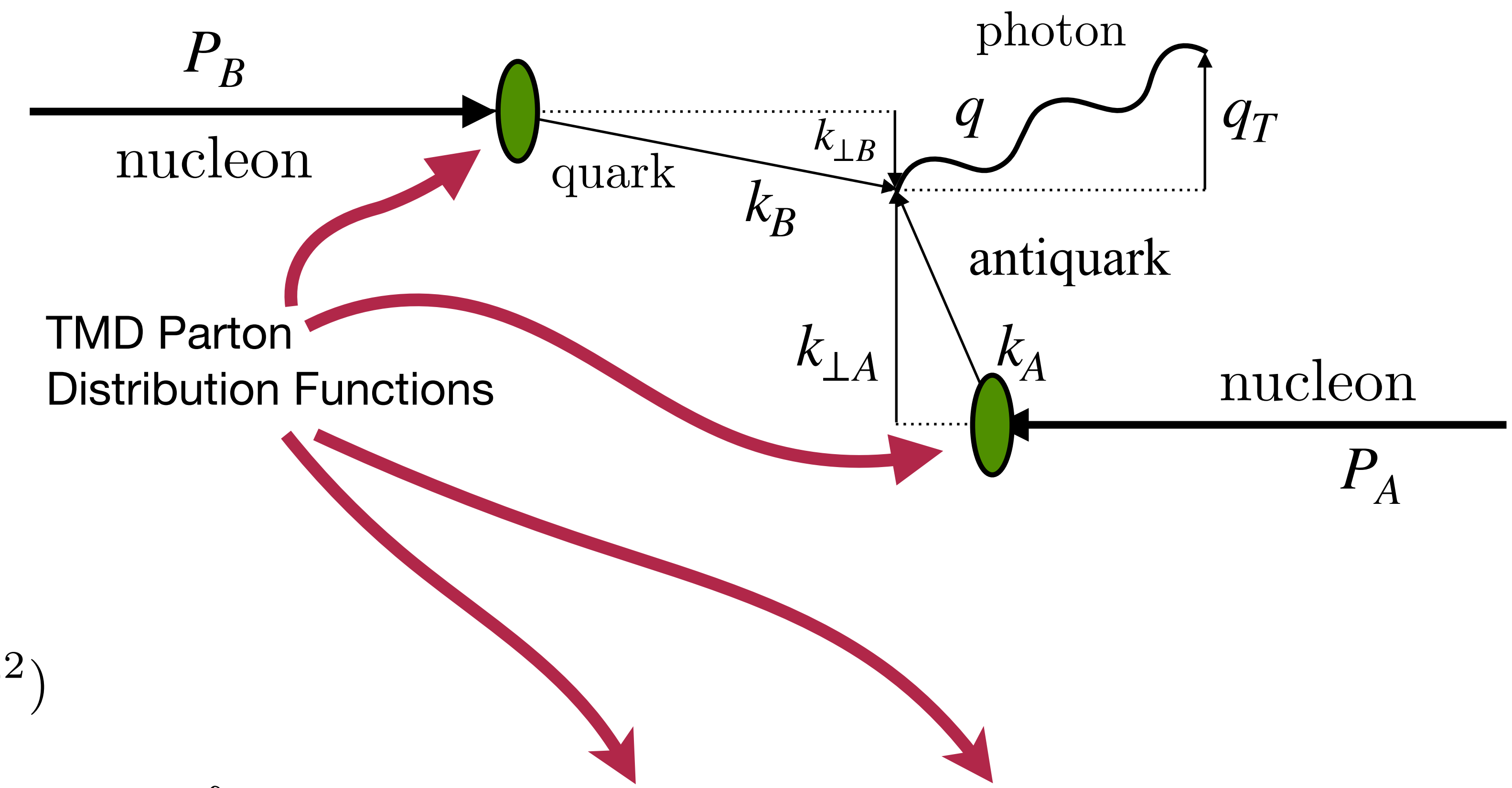
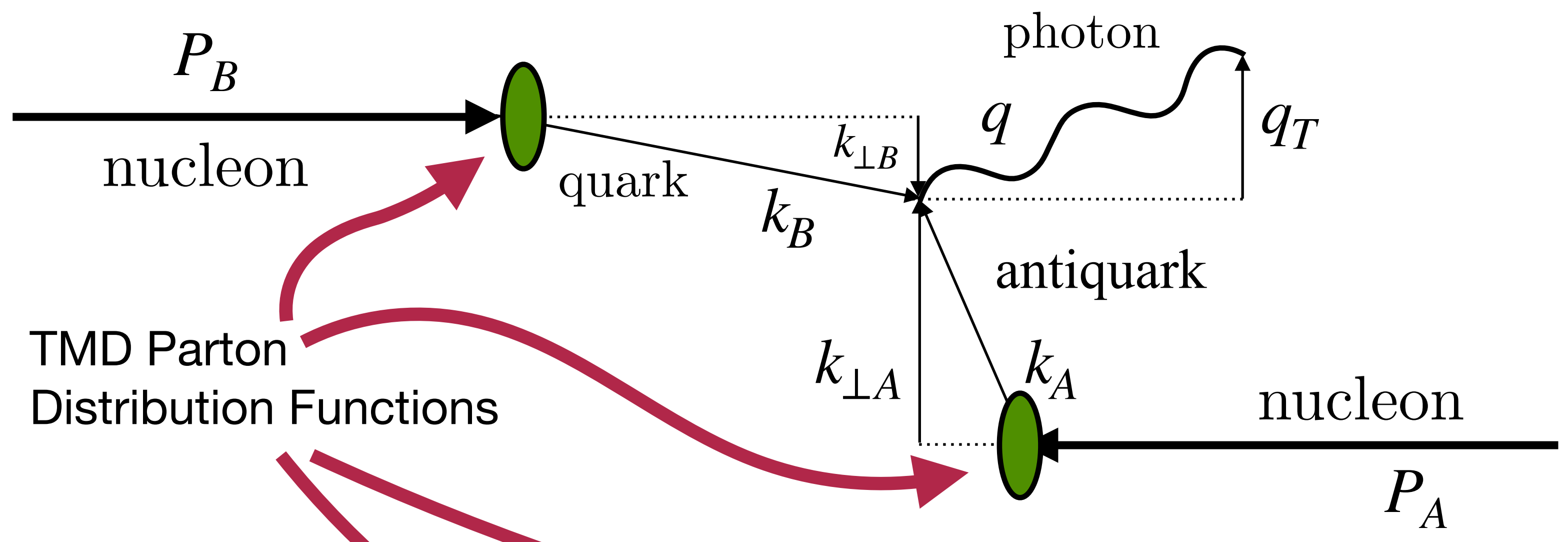
TMDS IN DRELL-YAN PROCESSES



$$F^1_{UU}(x_A, x_B, \boldsymbol{q}_T^2, Q^2)$$

$$\approx \sum_q \mathcal{H}^{1q}_{UU}(Q^2,\mu^2) \int d^2\boldsymbol{k}_{\perp A}\, d^2\boldsymbol{k}_{\perp B}\, f_1^q\big(x_A, \boldsymbol{k}^2_{\perp A};\mu^2\big)\, f_1^{\bar{q}}\big(x_B, \boldsymbol{k}^2_{\perp B};\mu^2\big)\, \delta^{(2)}\big(\boldsymbol{k}_{\perp A} - \boldsymbol{q}_T + \boldsymbol{k}_{\perp B}\big)$$

TMDS IN DRELL–YAN PROCESSES

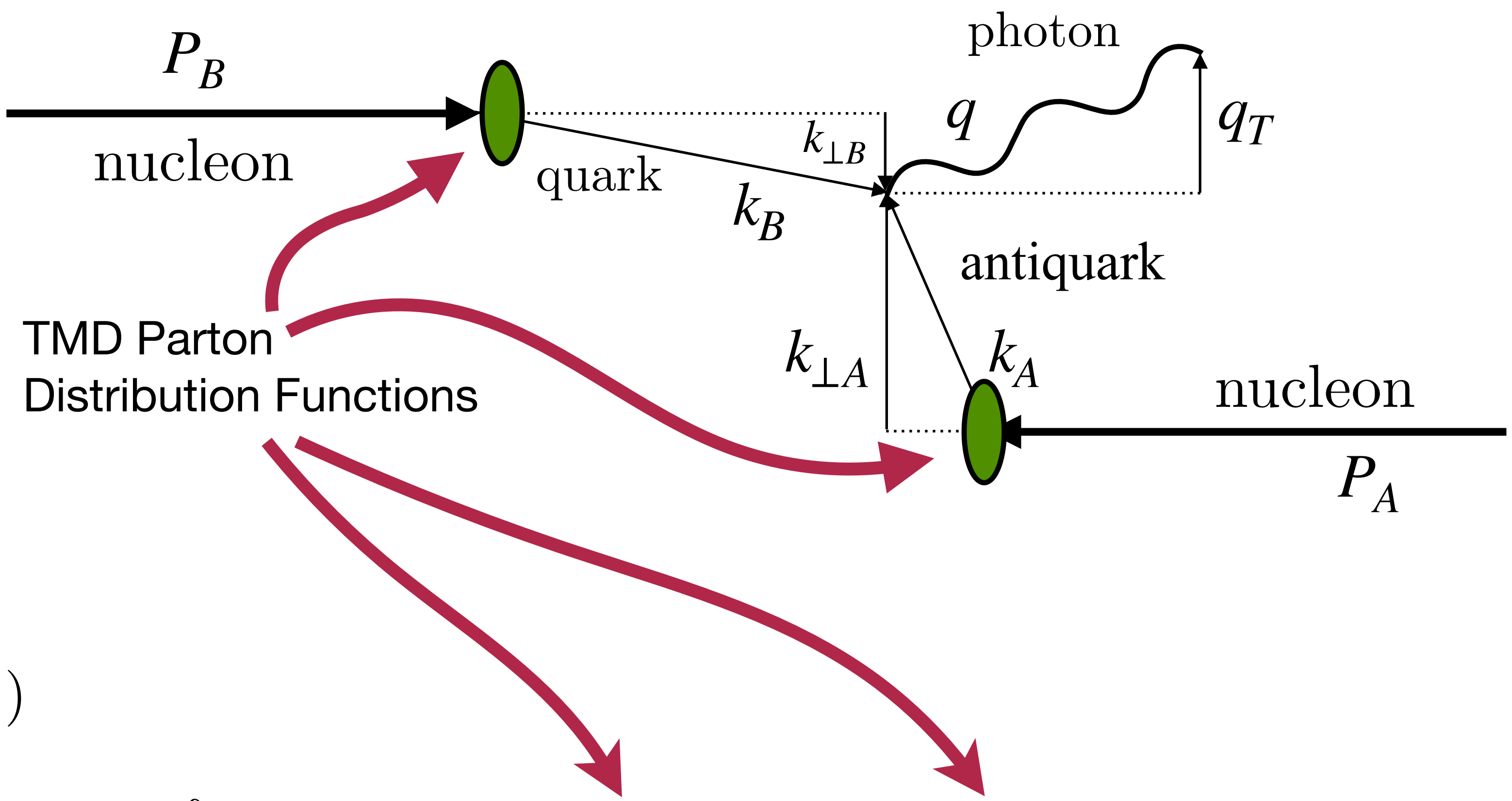


$$F_{UU}^{1}(x_A, x_B, \boldsymbol{q}_T^2, Q^2)$$

$$\approx \sum_q \mathcal{H}_{UU}^{1q}(Q^2, \mu^2) \int d^2\boldsymbol{k}_{\perp A}\, d^2\boldsymbol{k}_{\perp B}\, f_1^q\big(x_A, \boldsymbol{k}_{\perp A}^2; \mu^2\big)\, f_1^{\bar{q}}\big(x_B, \boldsymbol{k}_{\perp B}^2; \mu^2\big)\, \delta^{(2)}\big(\boldsymbol{k}_{\perp A} - \boldsymbol{q}_T + \boldsymbol{k}_{\perp B}\big)$$

At small transverse momentum, the dominant part is given by TMDs.

TMDS IN DRELL-YAN PROCESSES



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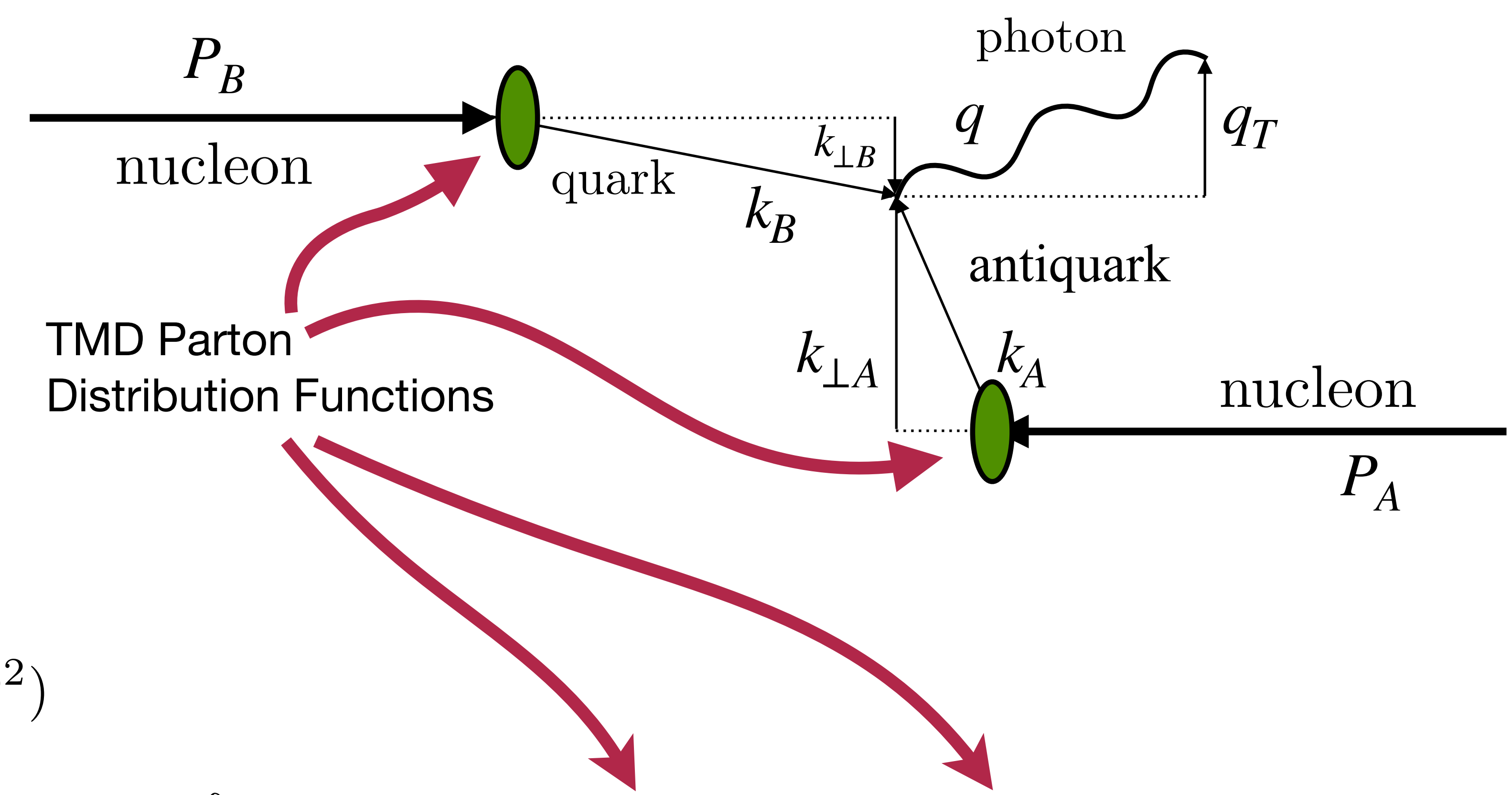
$$= \sum_q \mathcal{H}^{1q}_{UU}(Q^2,\mu^2) \int db_T b_T J_0(b_T|\boldsymbol{q}_T|) \hat{f}_1^q(x_A, b_T^2;\mu^2)\, \hat{f}_1^{\bar{q}}(x_B, b_T^2;\mu^2)$$

At small transverse momentum, the dominant part is given by TMDs.

The analysis of is usually done in Fourier-transformed space

TMDS IN DRELL-YAN PROCESSES



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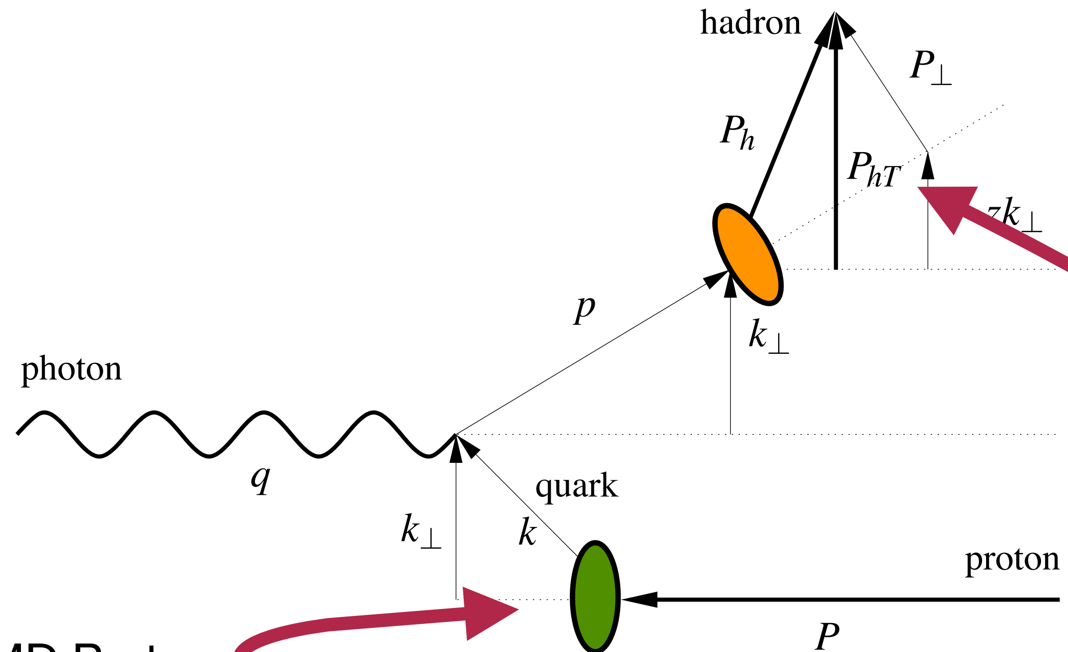
At small transverse momentum, the dominant part is given by TMDs.

The analysis of is usually done in Fourier-transformed space

TMDs formally depend on two scales, but usually they are set to be equal.

TMDS IN SEMI-INCLUSIVE DIS



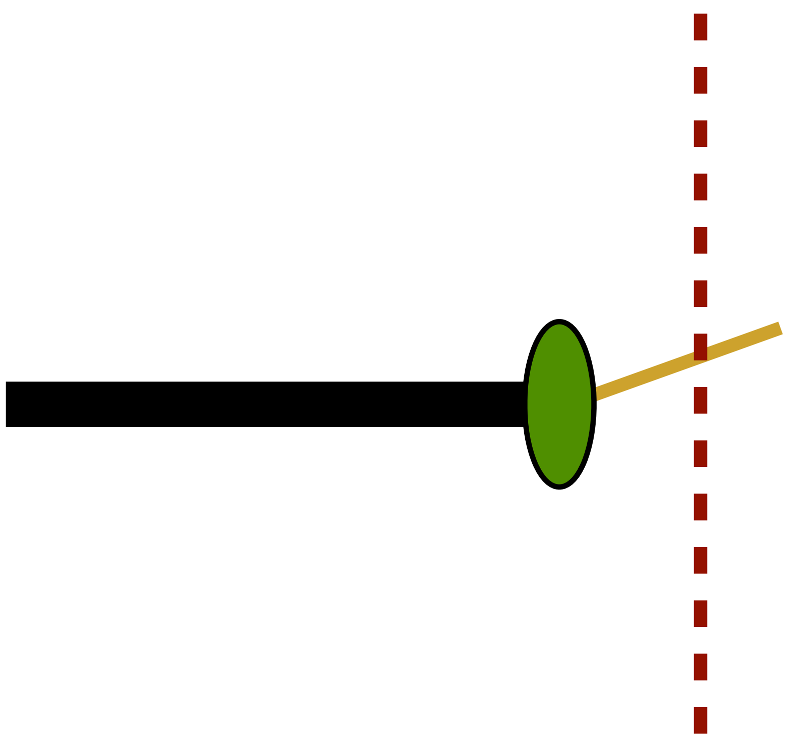
TMD Parton
Distribution Functions

TMD Parton
Fragmentation Functions

$$
\begin{aligned}
&F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2, Q^2) \\
&\quad = x \sum_q \mathcal{H}^q_{UU,T}(Q^2, \mu^2) \int d^2\boldsymbol{k}_\perp\, d^2\boldsymbol{P}_\perp\, f_1^a(x, \boldsymbol{k}_\perp^2; \mu^2)\, D_1^{a\to h}(z, \boldsymbol{P}_\perp^2; \mu^2)\, \delta(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp) \\
&\quad = x \sum_a \mathcal{H}^q_{UU,T}(Q^2, \mu^2) \int db_T b_T J_0(b_T |\boldsymbol{P}_{h\perp}|) \hat{f}_1^q(x, z^2 b_\perp^2; \mu^2)\, \hat{D}_1^{a\to h}(z, b_\perp^2; \mu^2)
\end{aligned}
$$

DIFFERENT CONTRIBUTIONS TO TRANSVERSE MOMENTUM

"intrinsic"
transverse
momentum

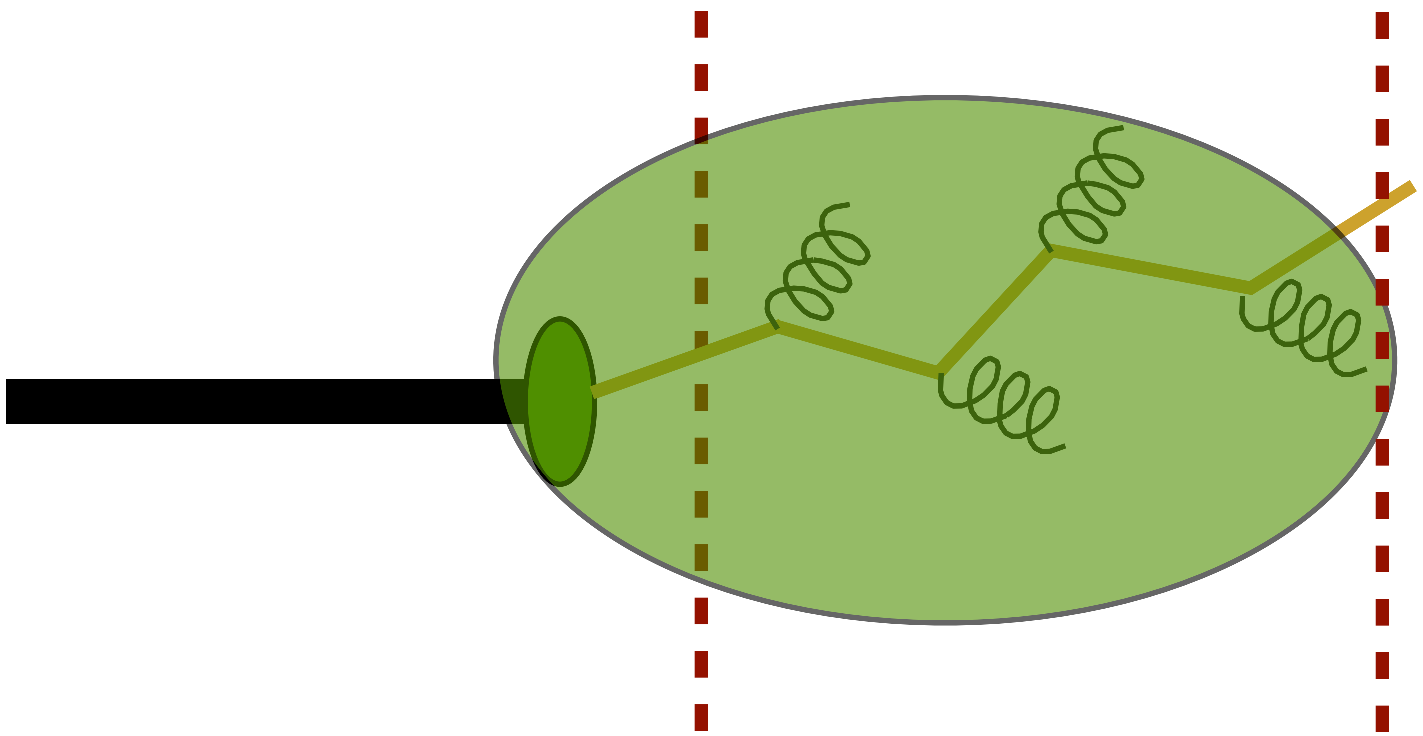


$$|k_\perp| \sim \Lambda_{\mathrm{QCD}}$$

DIFFERENT CONTRIBUTIONS TO TRANSVERSE MOMENTUM

"intrinsic" transverse momentum

soft and collinear gluon radiation



$|k_\perp| \sim \Lambda_{\mathrm{QCD}}$

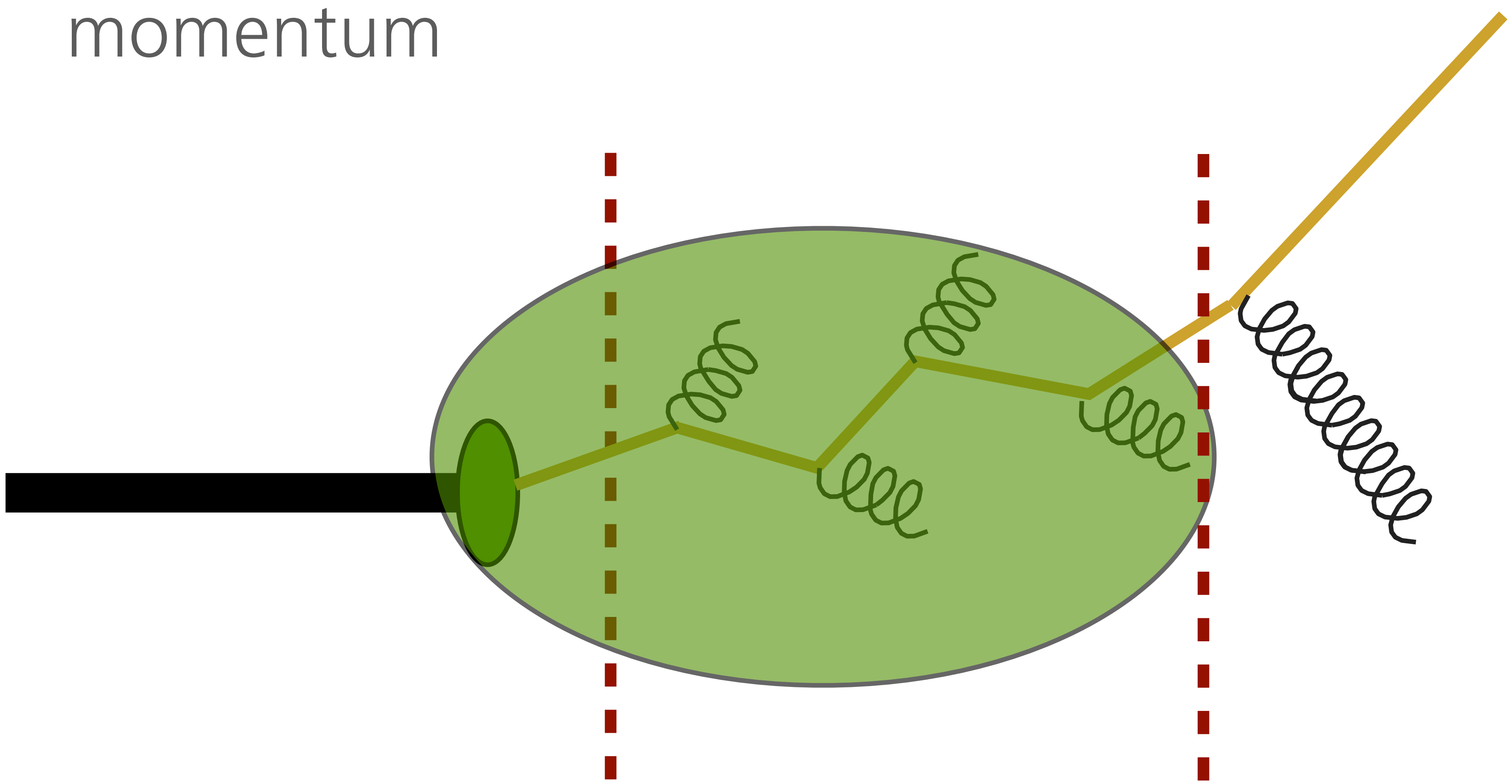
$|k_\perp| \ll Q$

DIFFERENT CONTRIBUTIONS TO TRANSVERSE MOMENTUM

"intrinsic" transverse momentum

soft and collinear gluon radiation

hard gluon radiation (not in TMD region)



$|k_\perp| \sim \Lambda_{\mathrm{QCD}}$

$|k_\perp| \ll Q$

$|k_\perp| \sim Q$

TMD FACTORIZATION

$$\hat{f}_1^q(x, b_T; \mu^2) = \int d^2\boldsymbol{k}_\perp e^{i\boldsymbol{b}_T\cdot\boldsymbol{k}_\perp} f_1^q(x, \boldsymbol{k}_\perp^2; \mu^2)$$

see, e.g., Rogers, Aybat, PRD 83 (11),
Collins, "Foundations of Perturbative QCD" (11)

other possible schemes, e.g.,
Laenen, Sterman, Vogelsang, PRL 84 (00)
Bozzi, Catani, De Florian, Grazzini, NPB737 (06)
Echevarria, Idilbi, Schaefer, Scimemi, EPJ C73 (13)

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$$\hat{f}_1^q(x, b_T; \mu^2) = \sum_i \big(C_{qi} \otimes f_1^i\big)(x, b_*; \mu_b) e^{\tilde{S}(b_*;\mu_b,\mu)} e^{g_K(b_T)\ln\frac{\mu}{\mu_0}} \hat{f}_{\mathrm{NP}}^q(x, b_T)$$

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$$\mu_b = \frac{2e^{-\gamma_E}}{b_*}$$

see, e.g., Rogers, Aybat, PRD 83 (11),
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TMD FACTORIZATION

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perturbative Sudakov form factor

$$\hat{f}_1^q(x, b_T; \mu^2) = \sum_i \left(C_{qi} \otimes f_1^i\right)(x, b_*; \mu_b) e^{\tilde{S}(b_*;\mu_b,\mu)} e^{g_K(b_T)\ln\frac{\mu}{\mu_0}} \hat{f}_{\mathrm{NP}}^q(x, b_T)$$

$$\mu_b = \frac{2e^{-\gamma_E}}{b_*}$$

collinear PDF

matching coefficients (perturbative)

nonperturbative part of evolution

nonperturbative part of TMD

see, e.g., Rogers, Aybat, PRD 83 (11),
Collins, "Foundations of Perturbative QCD" (11)

other possible schemes, e.g.,
Laenen, Sterman, Vogelsang, PRL 84 (00)
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Echevarria, Idilbi, Schaefer, Scimemi, EPJ C73 (13)

LOGARITHMIC ACCURACY

Sudakov form factor

LL $\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right)$

LOGARITHMIC ACCURACY

Sudakov form factor

LL $\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right)$

NLL $\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right), \quad \alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$

LOGARITHMIC ACCURACY

	Sudakov form factor	matching coeff.
LL	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right)$	C^0
NLL	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right), \quad \alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$	C^0

LOGARITHMIC ACCURACY

	Sudakov form factor	matching coeff.
LL	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right)$	C^0
NLL	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right), \quad \alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$	C^0
NLL′	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right), \quad \alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$	$\left(C^0 + \alpha_S C^1\right)$

LOGARITHMIC ACCURACY

	Sudakov form factor	matching coeff.
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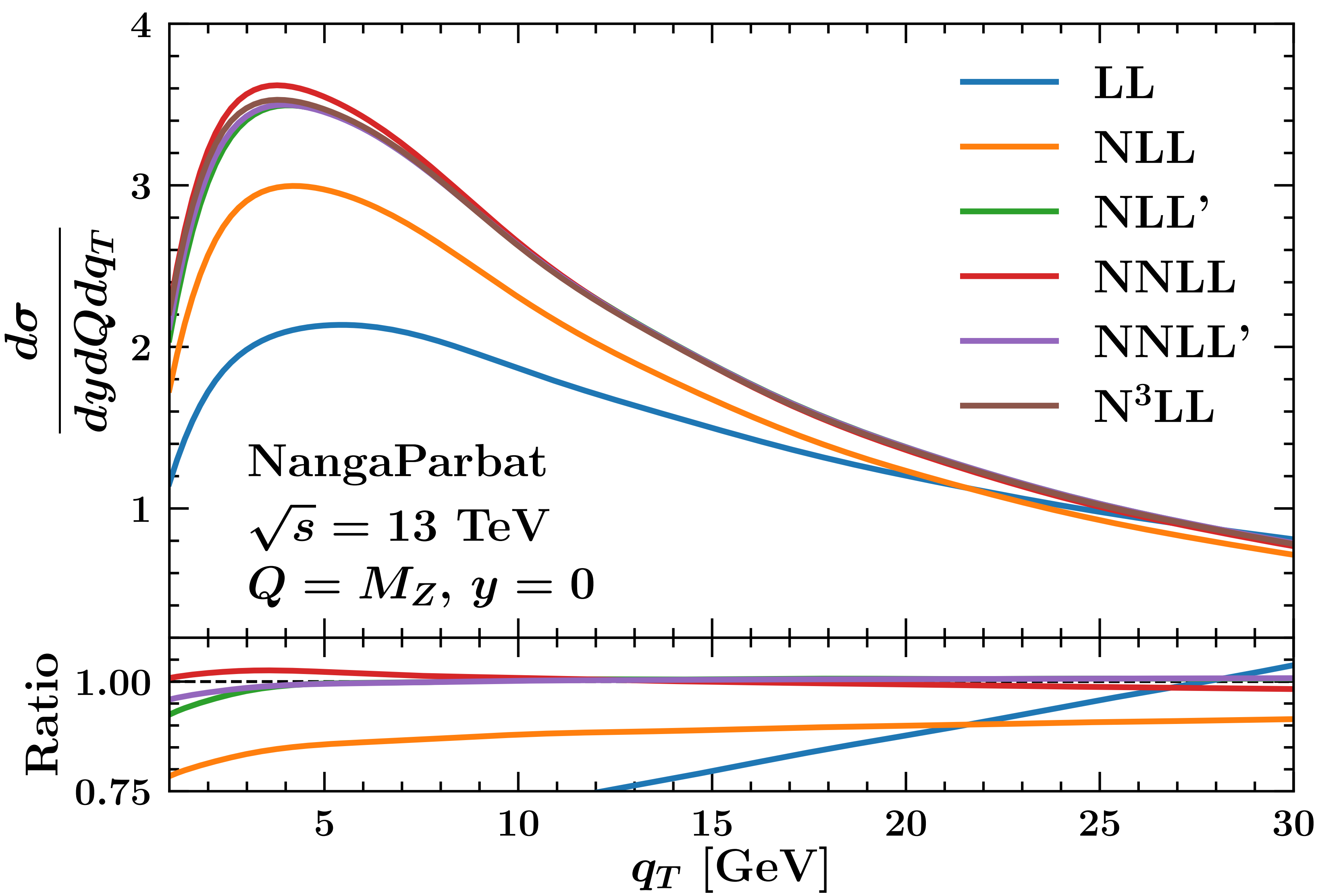
NLL′	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right), \quad \alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$	$\left(C^0 + \alpha_S C^1\right)$

the difference between the two is NNLL $\quad \alpha_S^n \ln^{2n-2}\left(\frac{Q^2}{\mu_b^2}\right)$

COMPARISON OF DIFFERENT ORDERS

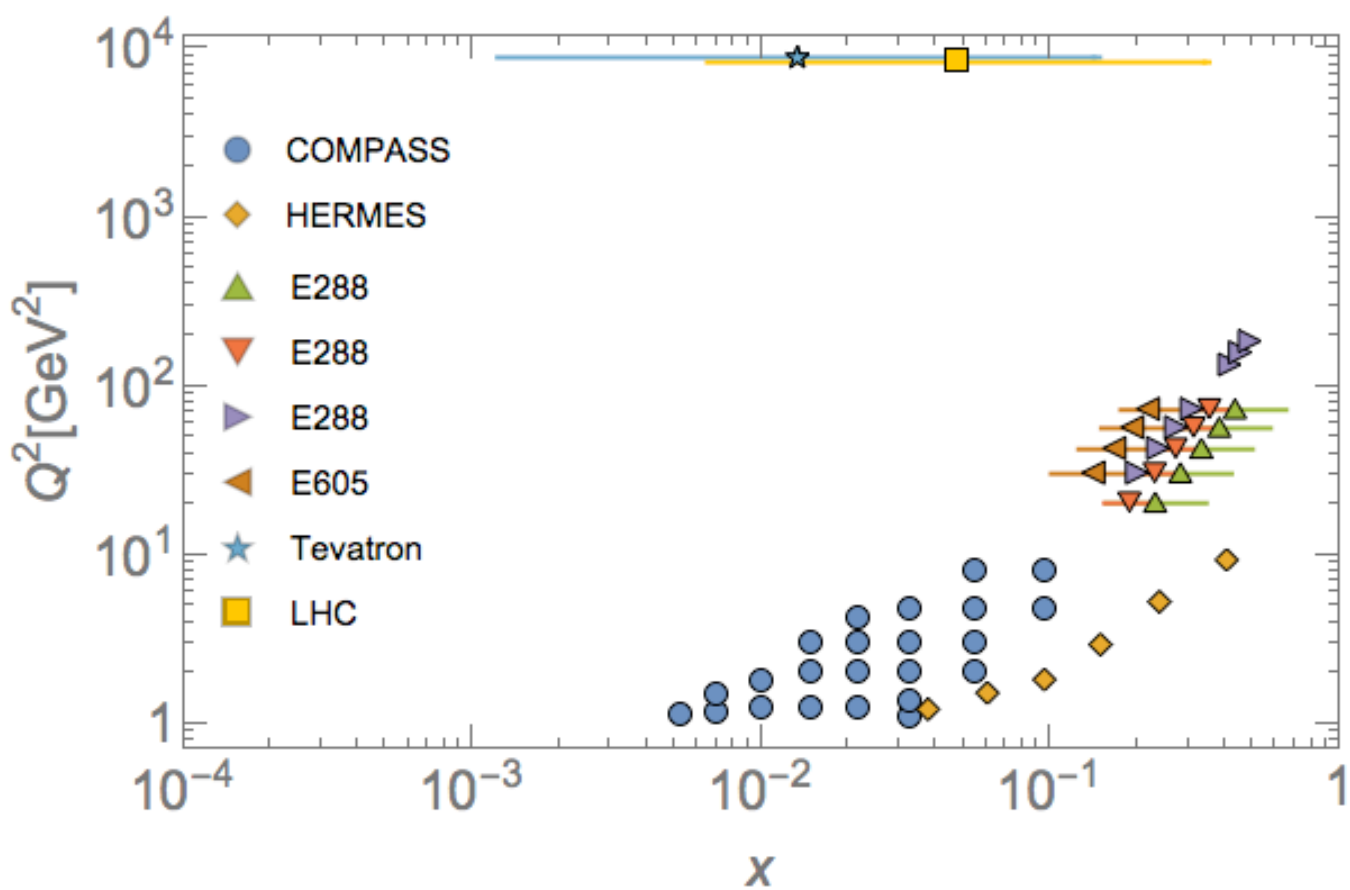
V. Bertone's talk at LHC EW WG General Meeting, Dec 2019
https://indico.cern.ch/event/849342/



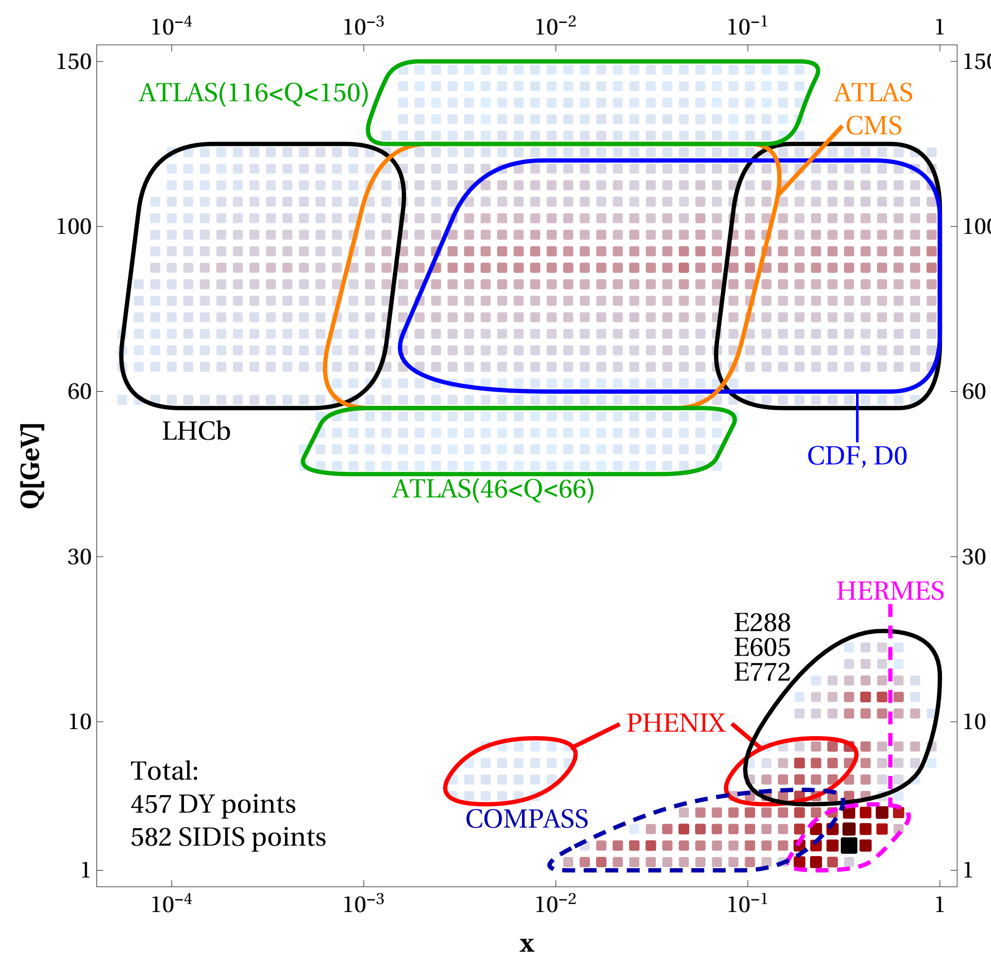
RECENT TMD FITS OF UNPOLARIZED DATA

	Framework	HERMES	COMPASS	DY	Z production	N of points	χ^2/N_{points}
Pavia 2017 arXiv:1703.10157	NLL	✔	✔	✔	✔	8059	1.55
SV 2017 arXiv:1706.01473	NNLL′	✘	✘	✔	✔	309	1.23
BSV 2019 arXiv:1902.08474	NNLL′	✘	✘	✔	✔	457	1.17
SV 2019 arXiv:1912.06532	NNLL′	✔	✔	✔	✔	1039	1.06
Pavia 2019 arXiv:1912.07550	N^3LL	✘	✘	✔	✔	353	1.02

x–Q² COVERAGE

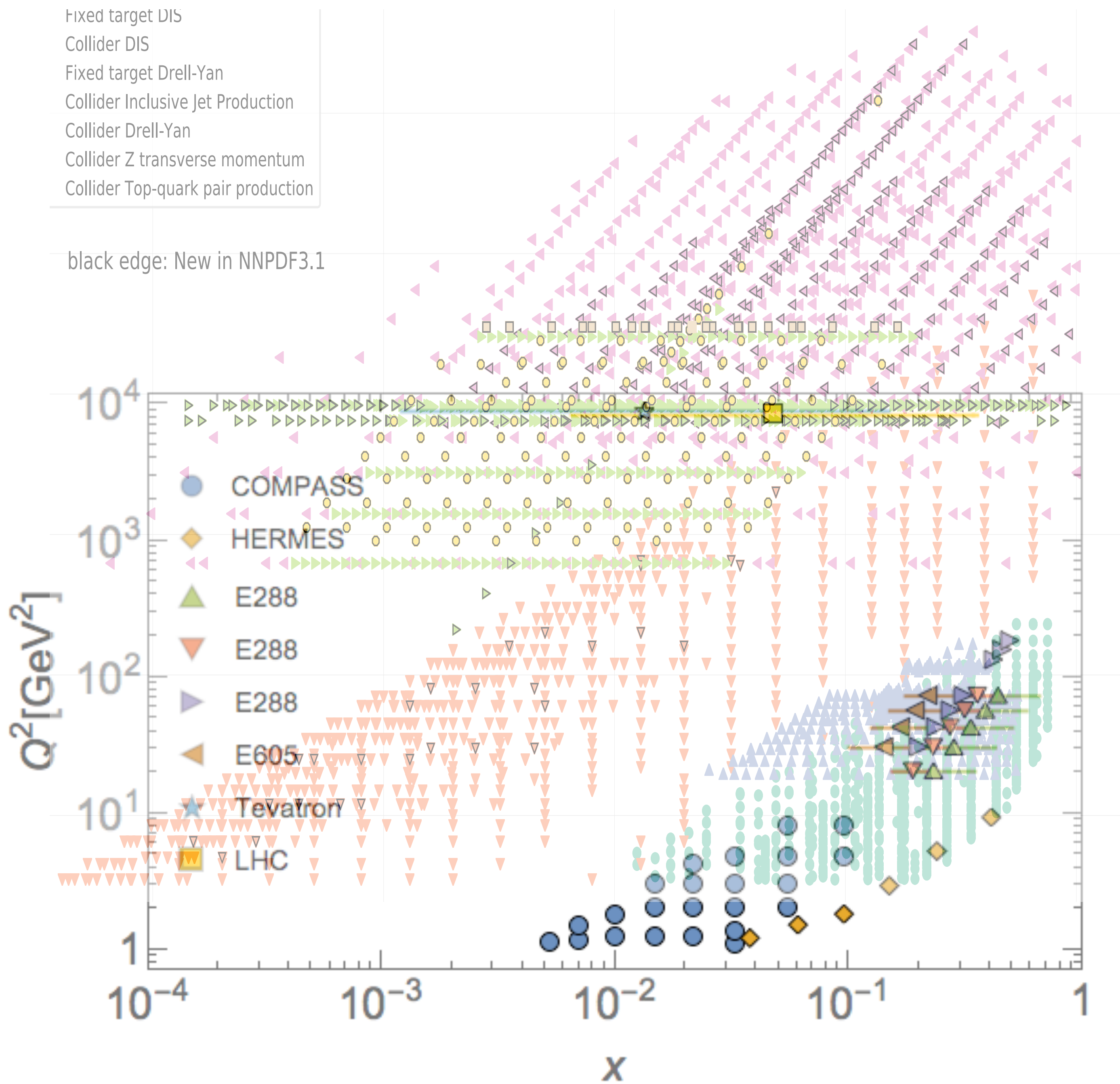


Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

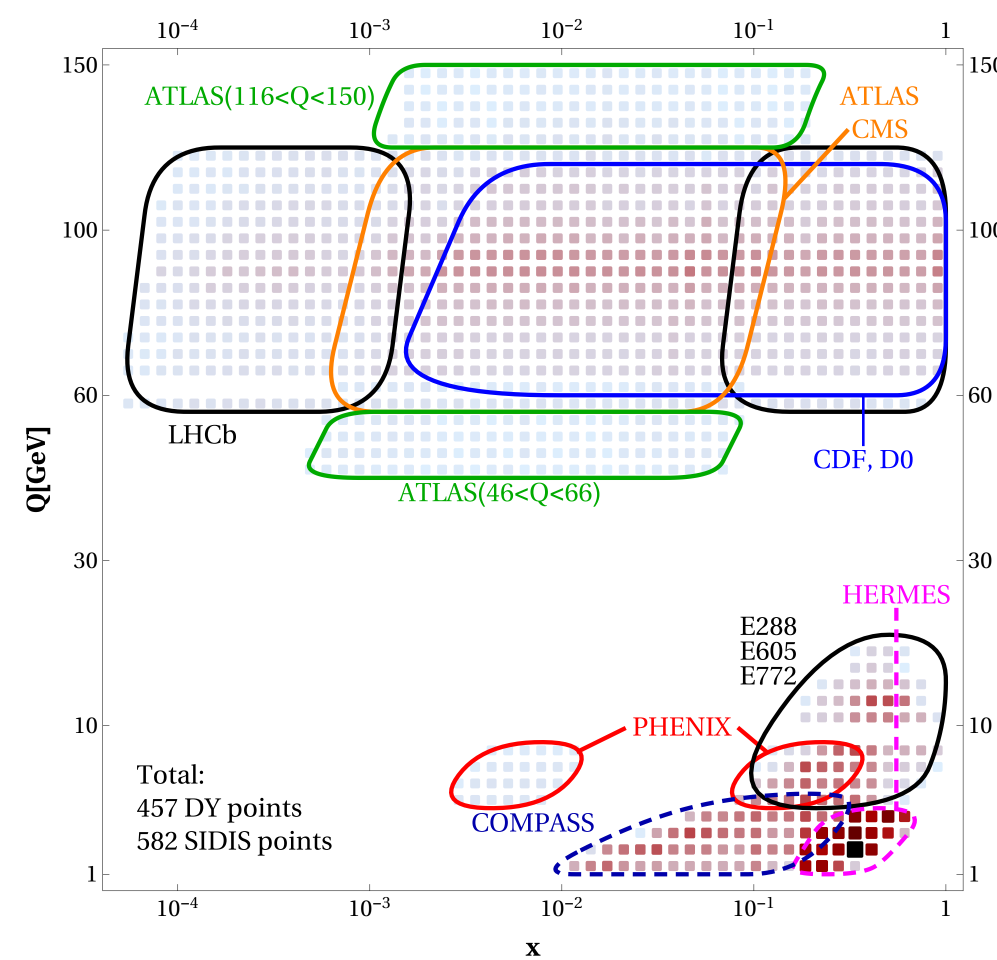


Scimemi, Vladimirov, arXiv:1912.06532

x–Q² COVERAGE

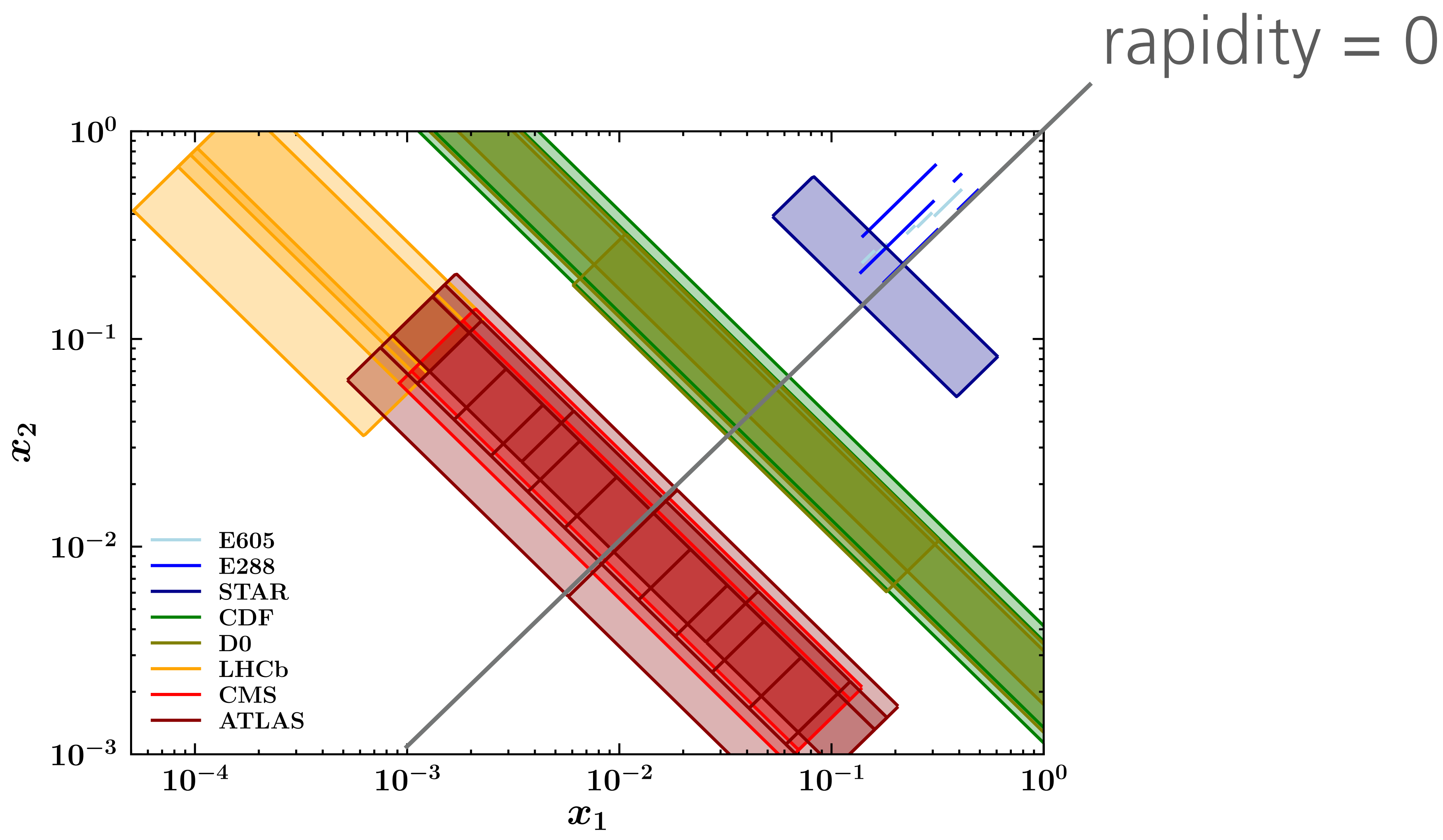


Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157



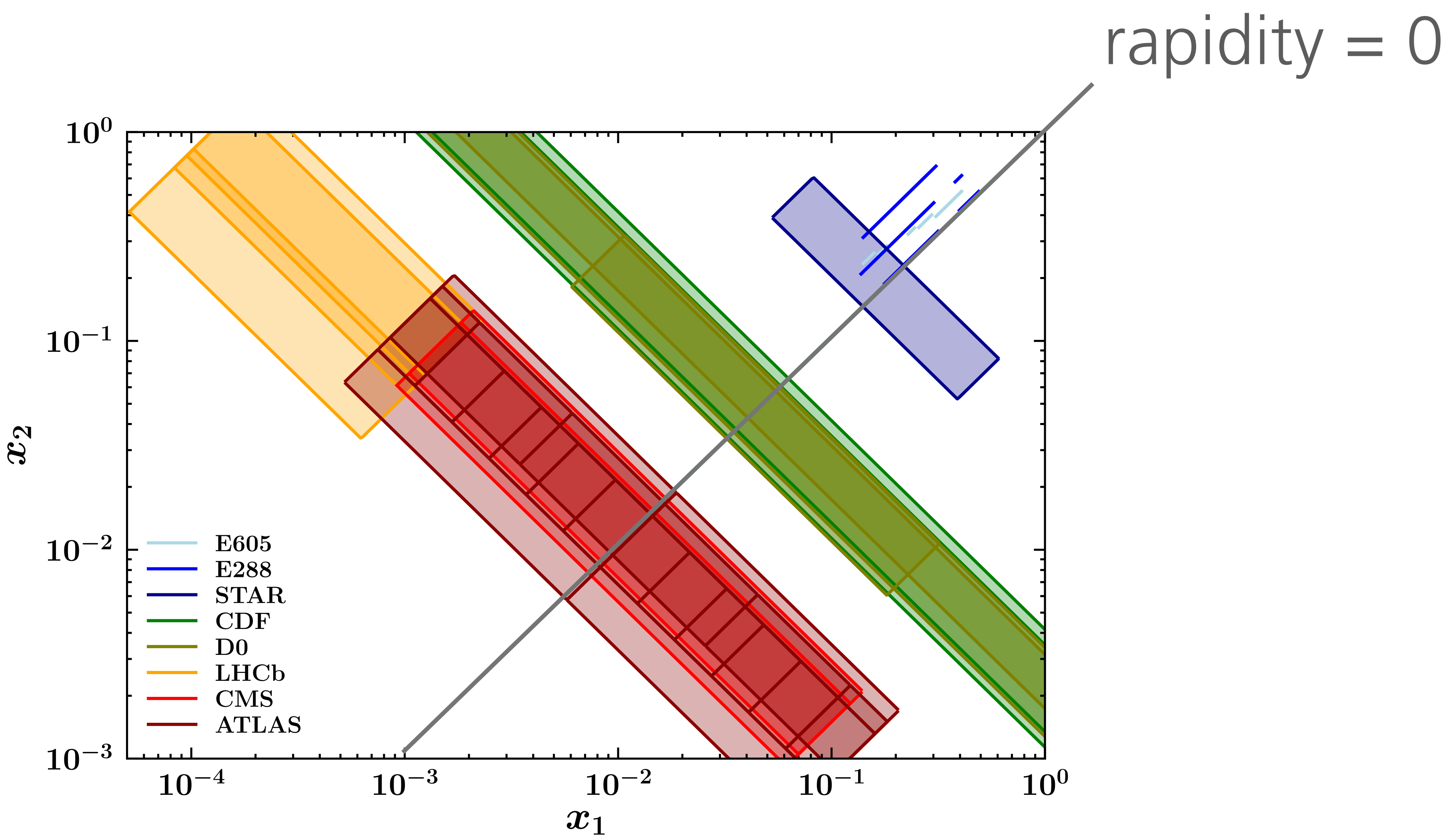
Scimemi, Vladimirov, arXiv:1912.06532

x_1 x_2 COVERAGE



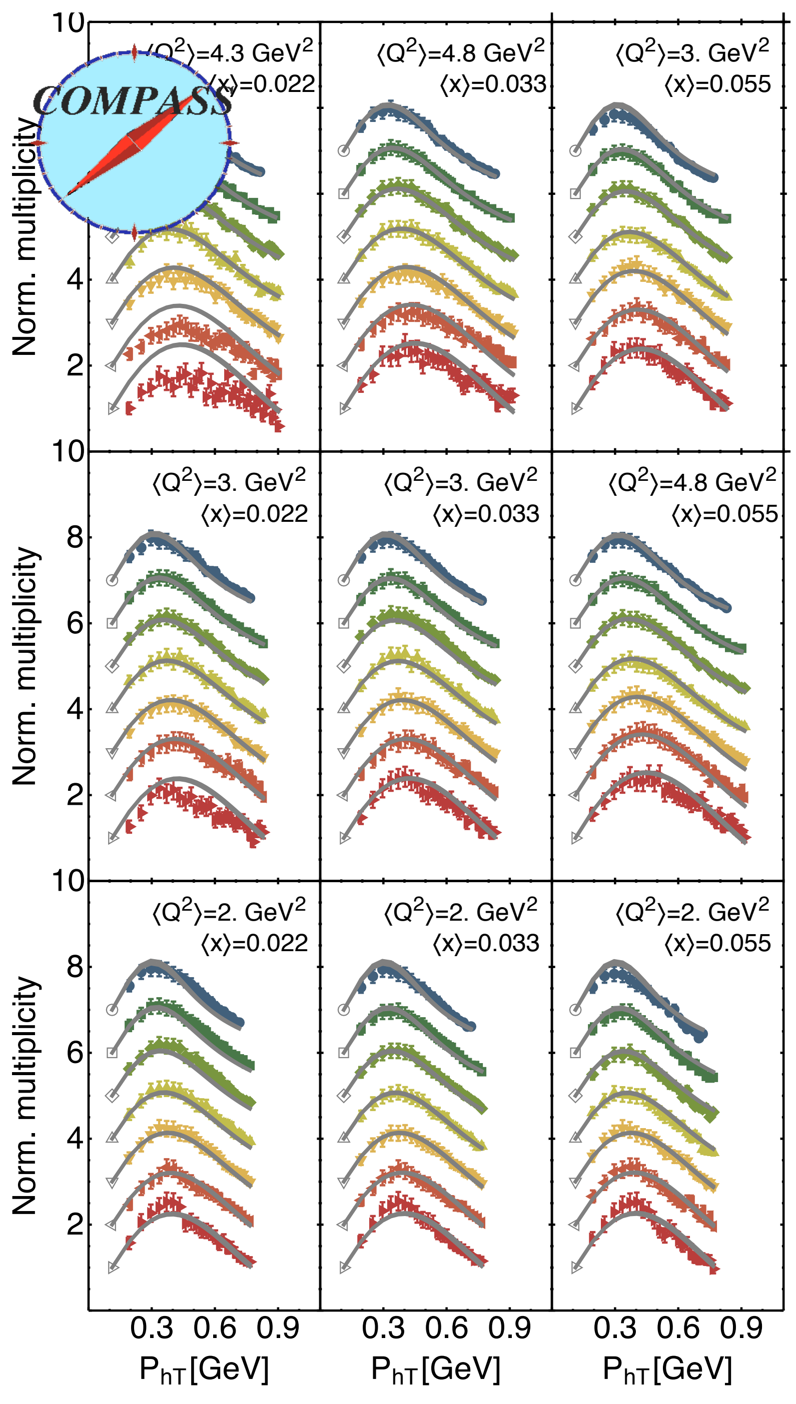
x_1 x_2 COVERAGE

Bacchetta, Bertone, Bissolotti, Bozzi, Delcarro, Piacenza, Radici, arXiv:1912.07550



THE PAVIA17 EXTRACTION

SIDIS



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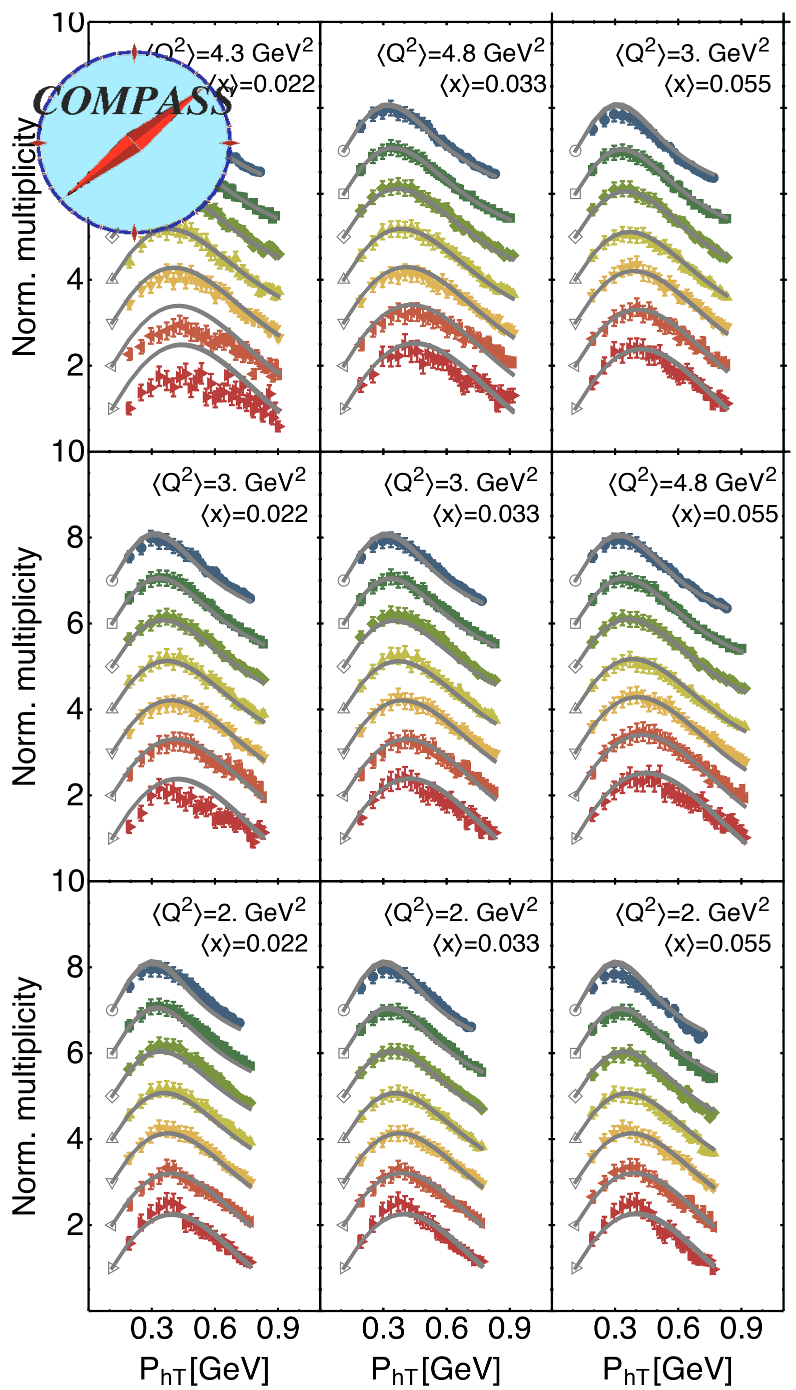
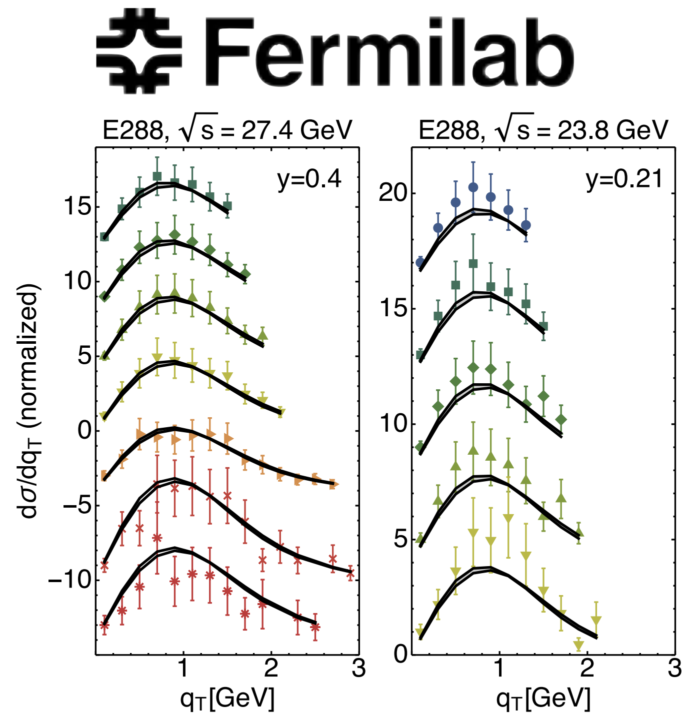


Drell-Yan



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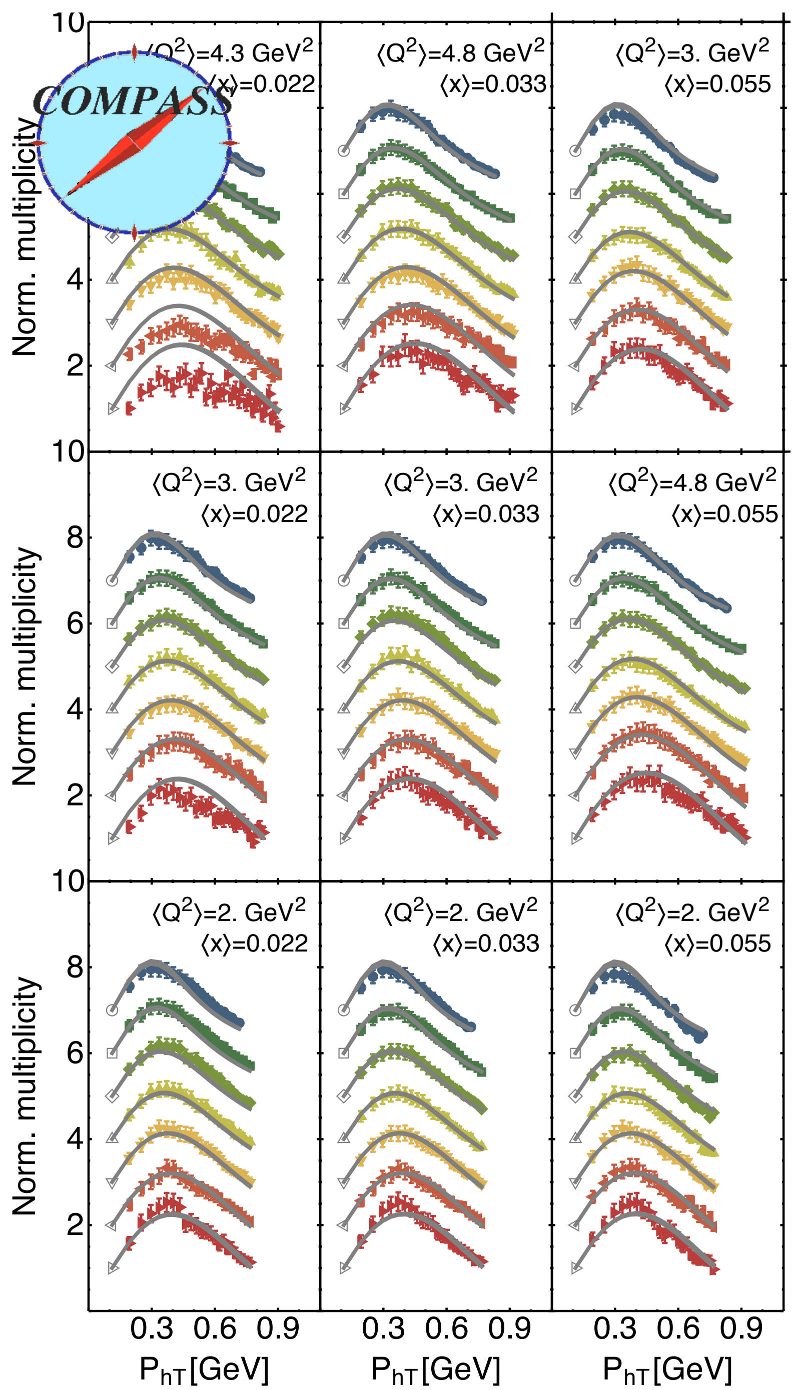
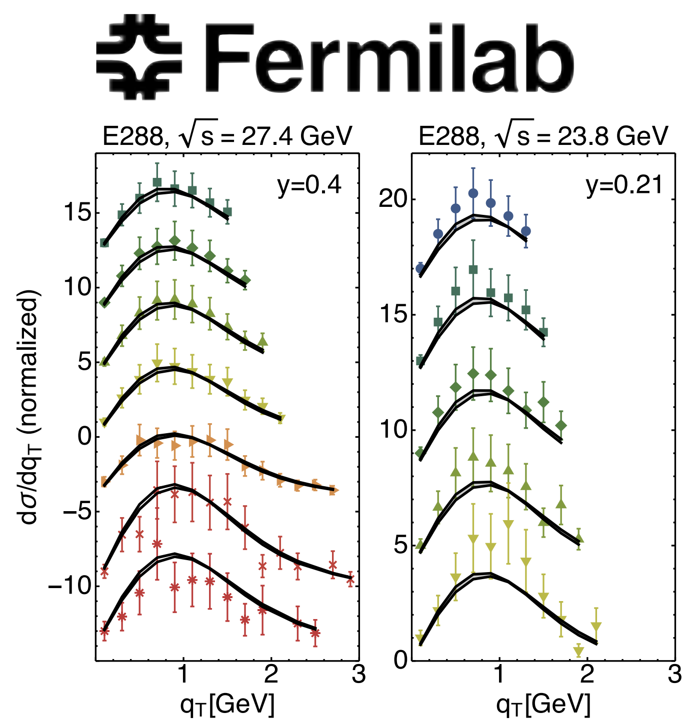
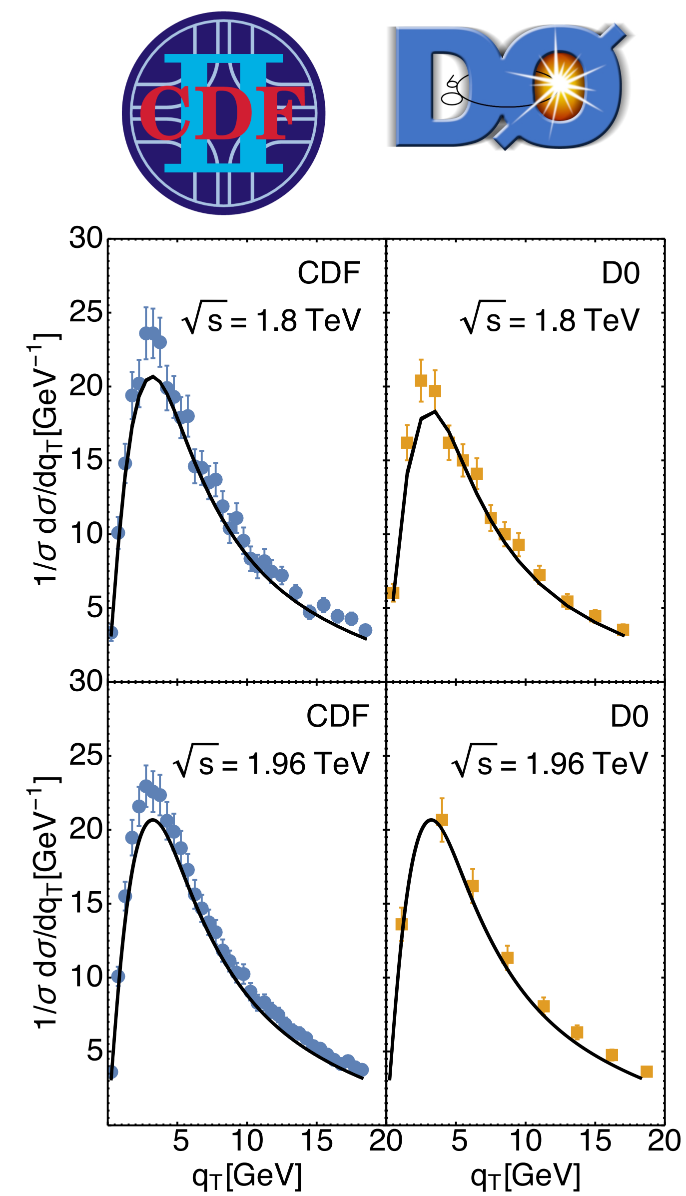


Drell-Yan



Z production



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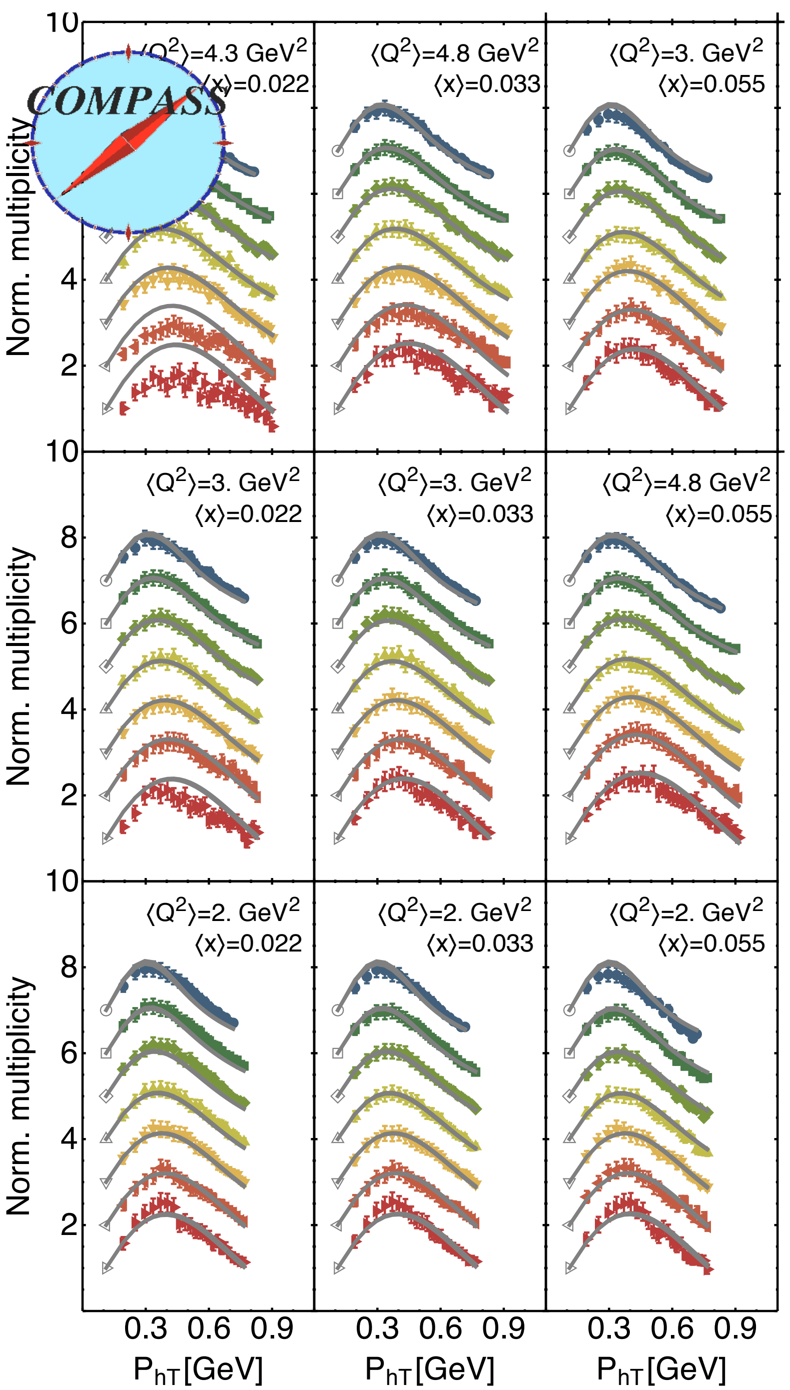
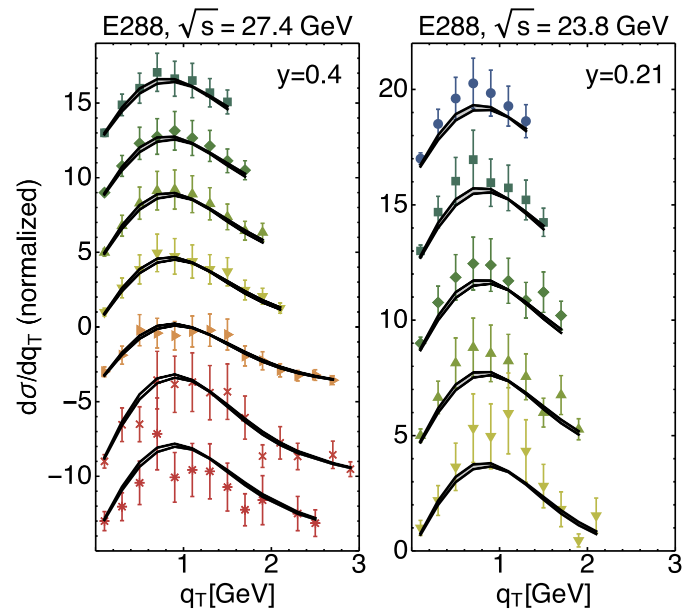
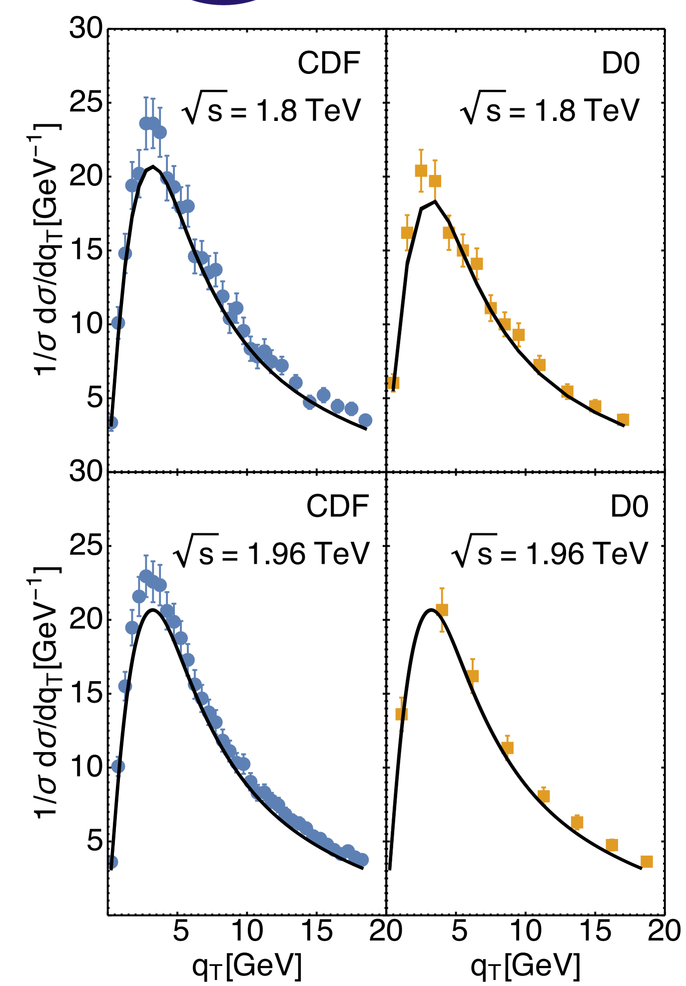


Drell-Yan

Fermilab



Z production



Number of data points: 8059

Global χ^2/dof = 1.55

Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

THE PAVIA17 EXTRACTION

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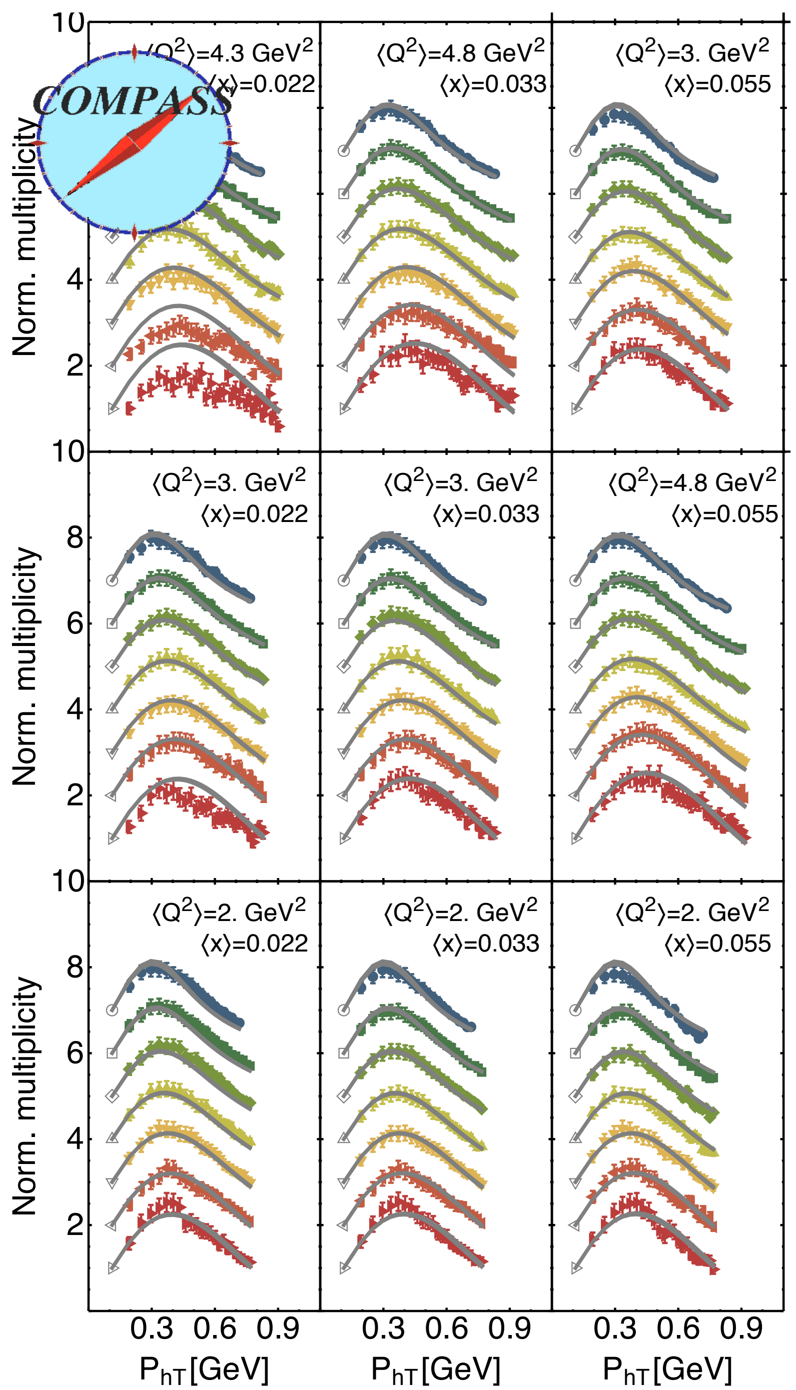
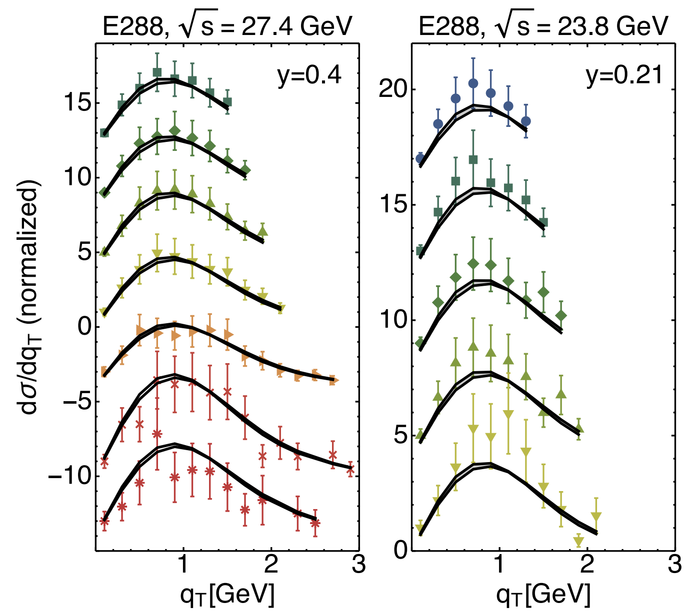


Drell-Yan

Fermilab



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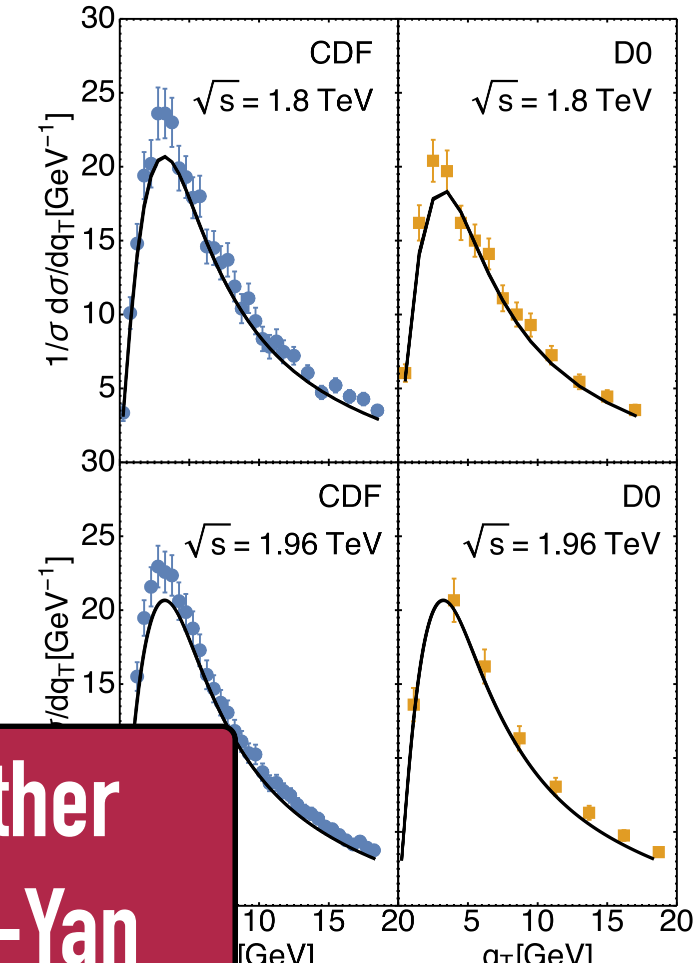

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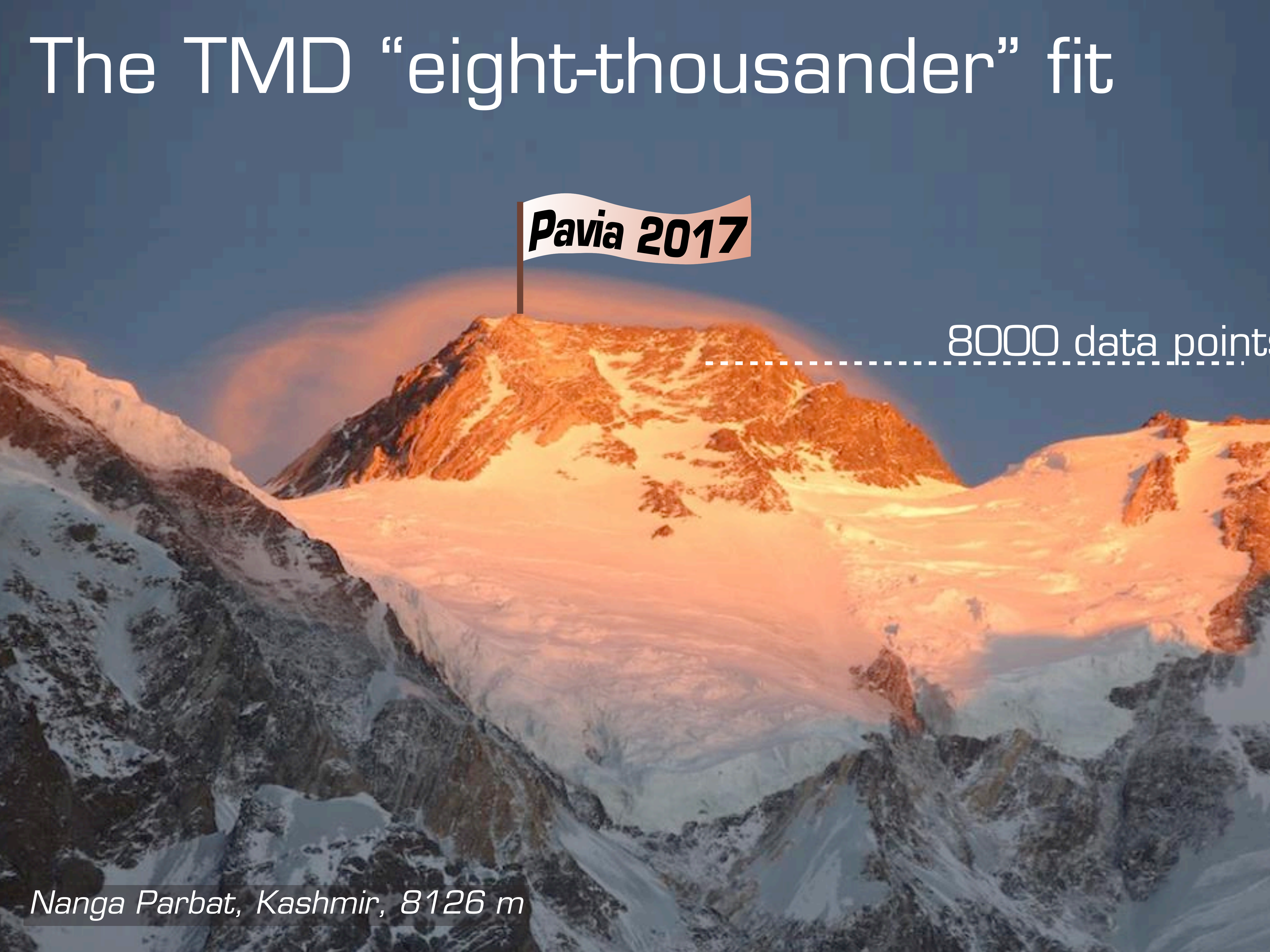
Pavia17: first fit putting together semi-inclusive DIS and Drell-Yan

Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

The TMD “eight-thousander” fit

Nanga Parbat, Kashmir, 8126 m

The TMD "eight-thousander" fit



Nanga Parbat, Kashmir, 8126 m

PV17 – RESULTING TMDS

expression in b_T space

$$\hat{f}_{\mathrm{NP}}(x, b_T) = e^{-g_1(x)\frac{b_T^2}{4}}\left(1 - \frac{\lambda g_1^2(x)}{1+\lambda g_1(x)}\frac{b_T^2}{4}\right)$$

PV17 – RESULTING TMDS

Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

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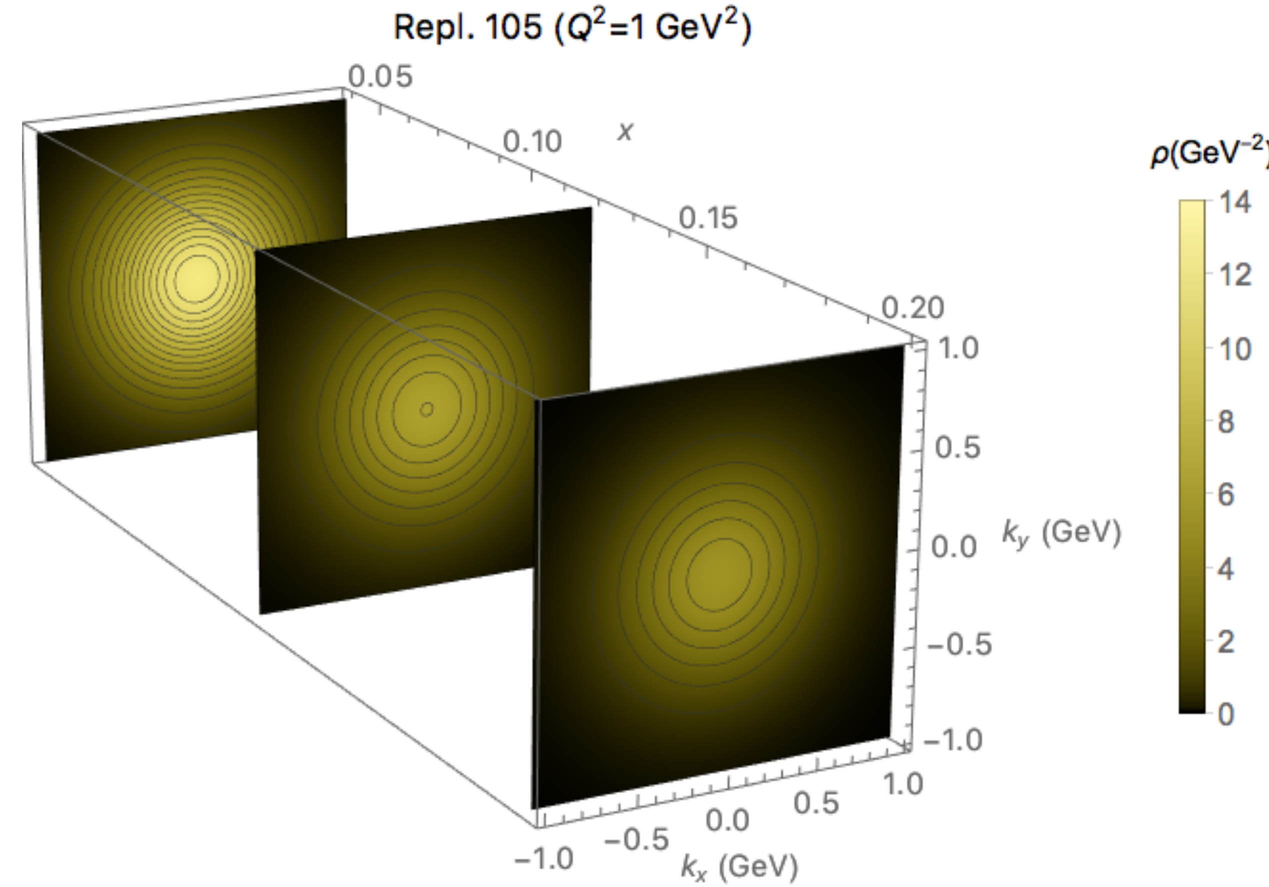
plot in $k_\perp$ space



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Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

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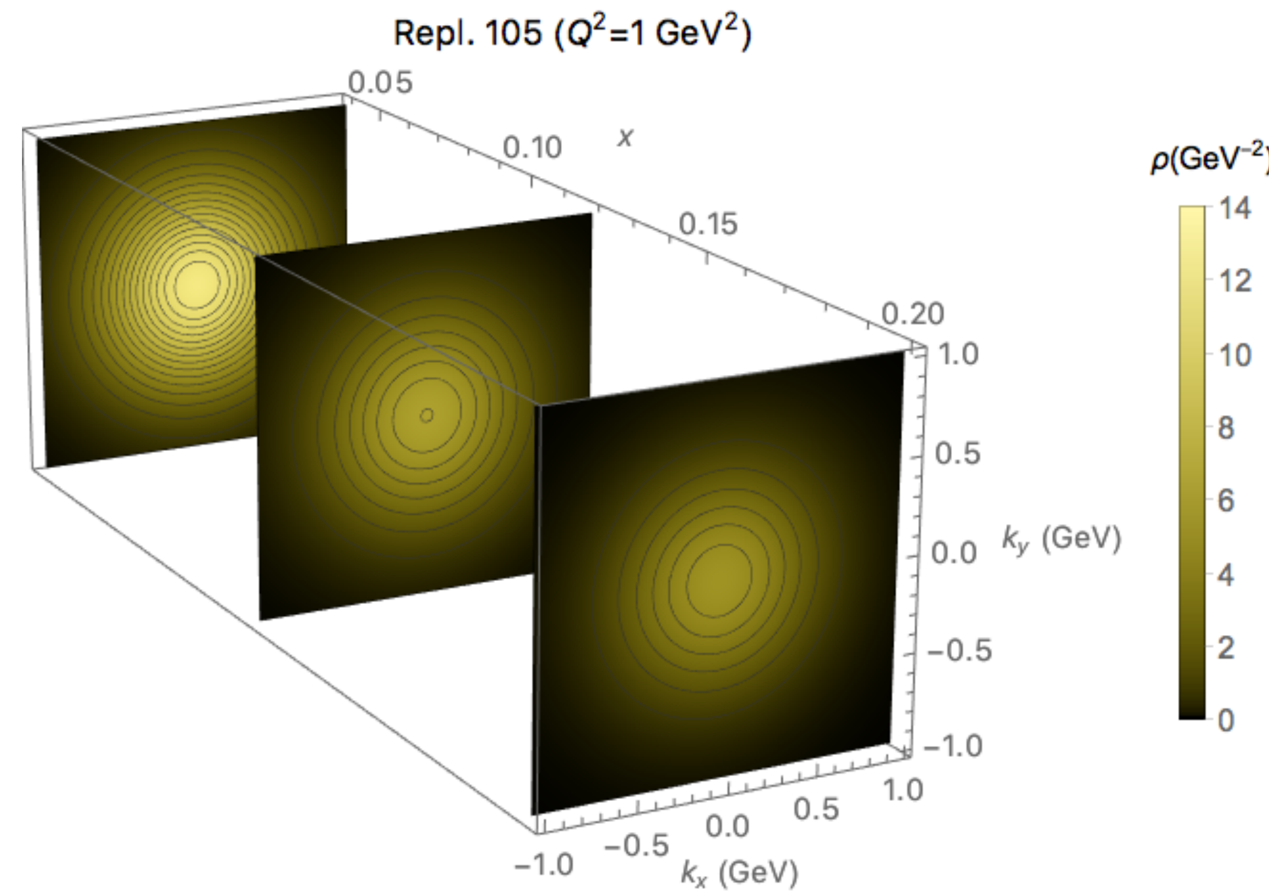
- Guassian + weighted Gaussian

plot in $k_\perp$ space



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- Guassian + weighted Gaussian
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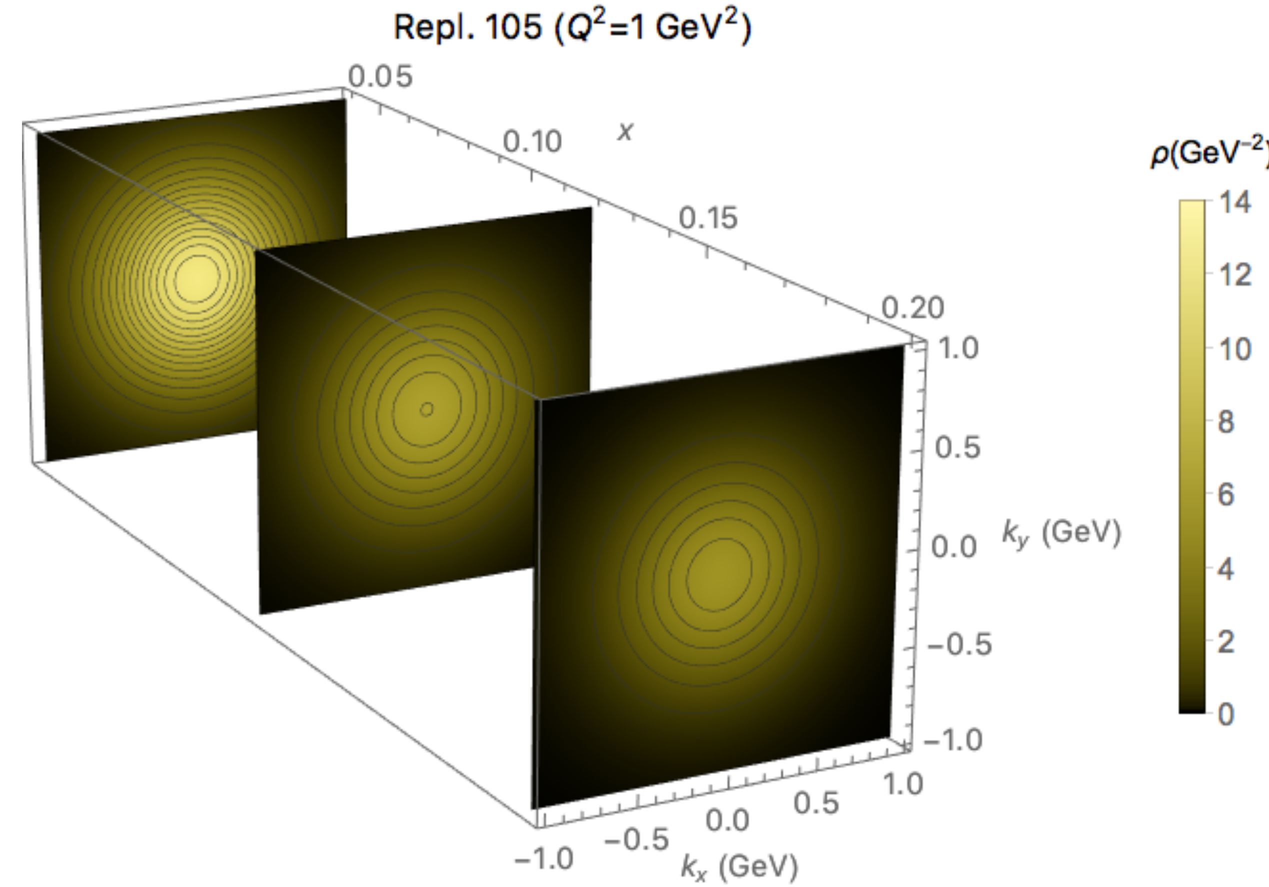

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- Guassian + weighted Gaussian
- nontrivial x dependence
- no flavor dependence

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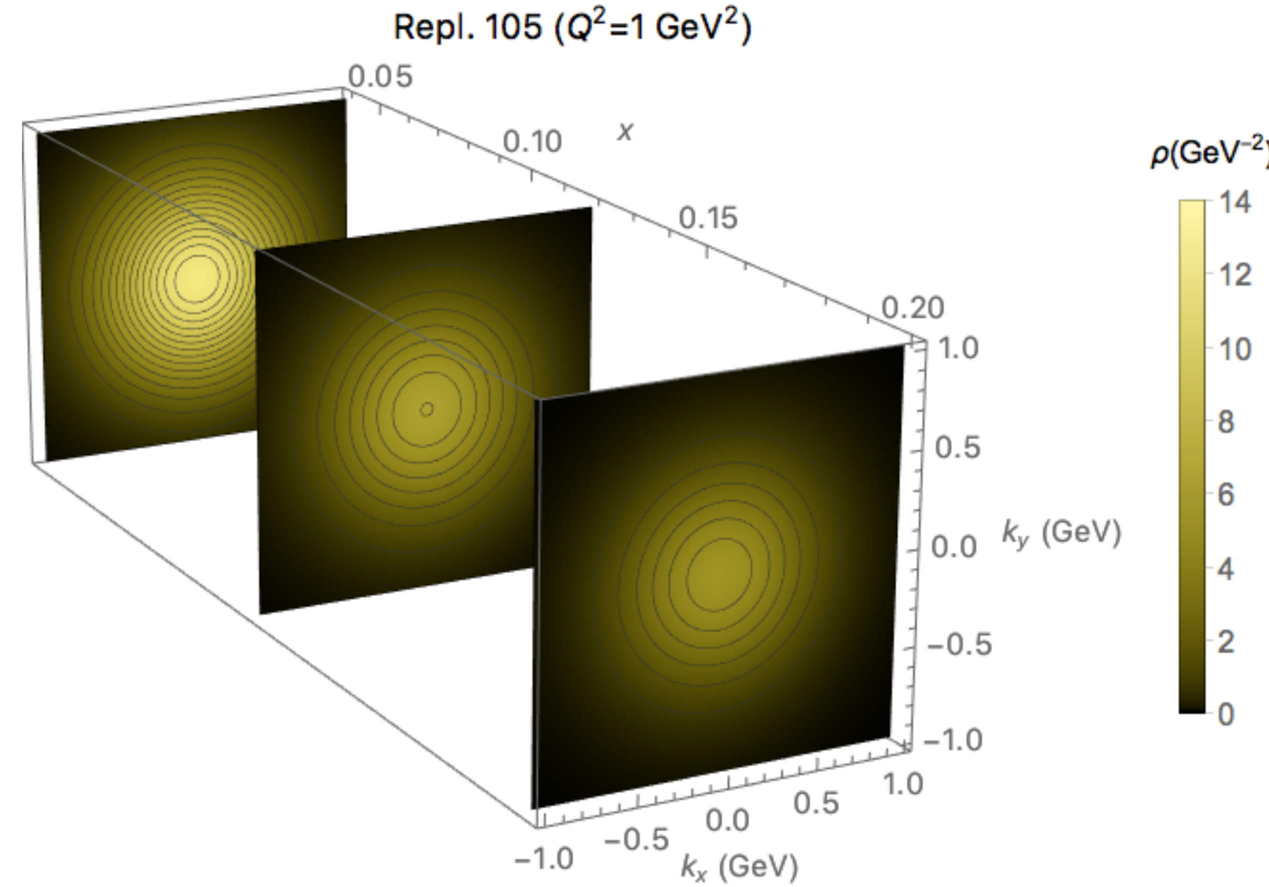

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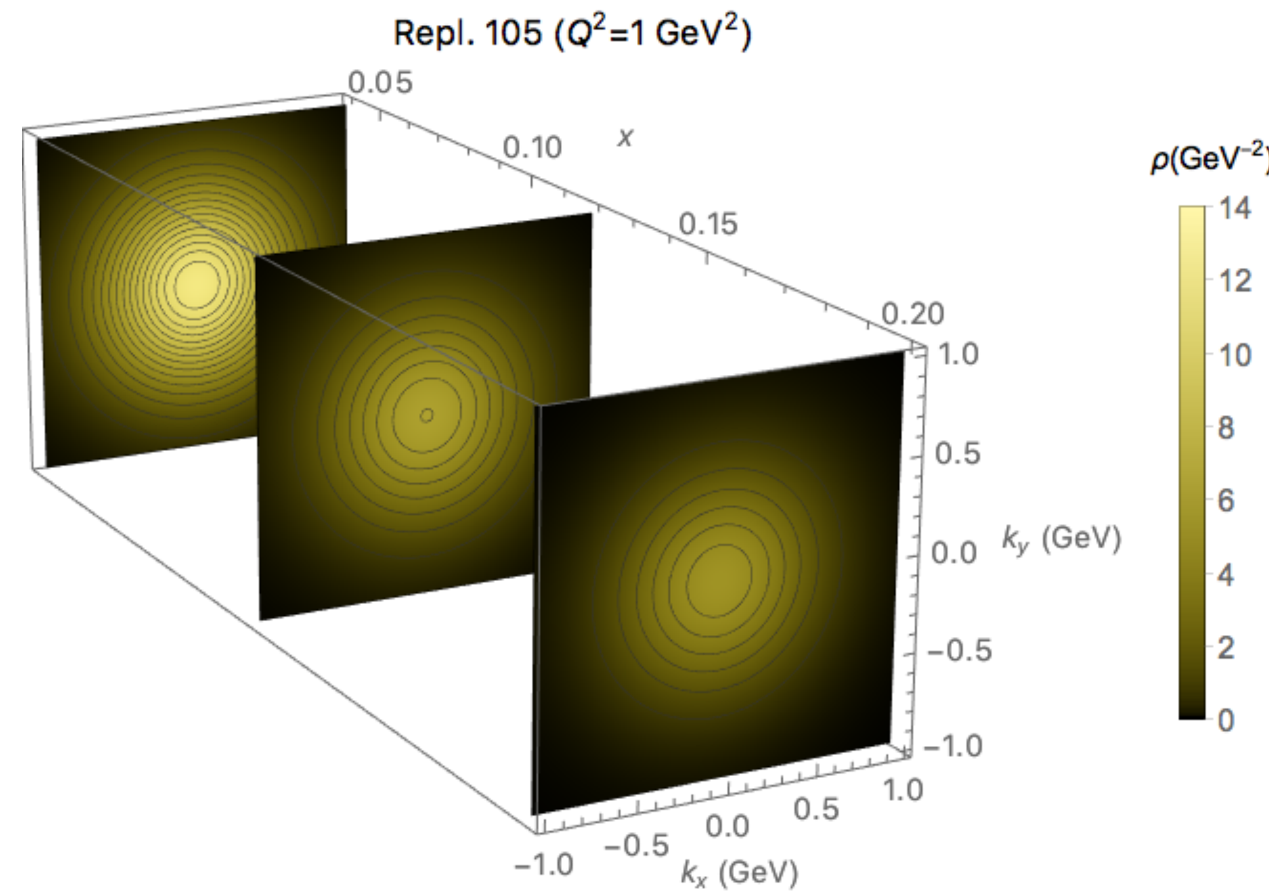
$$g_K(b_T) = -\frac{g_2}{2}b_T^2$$ Guassian

plot in $k_\perp$ space



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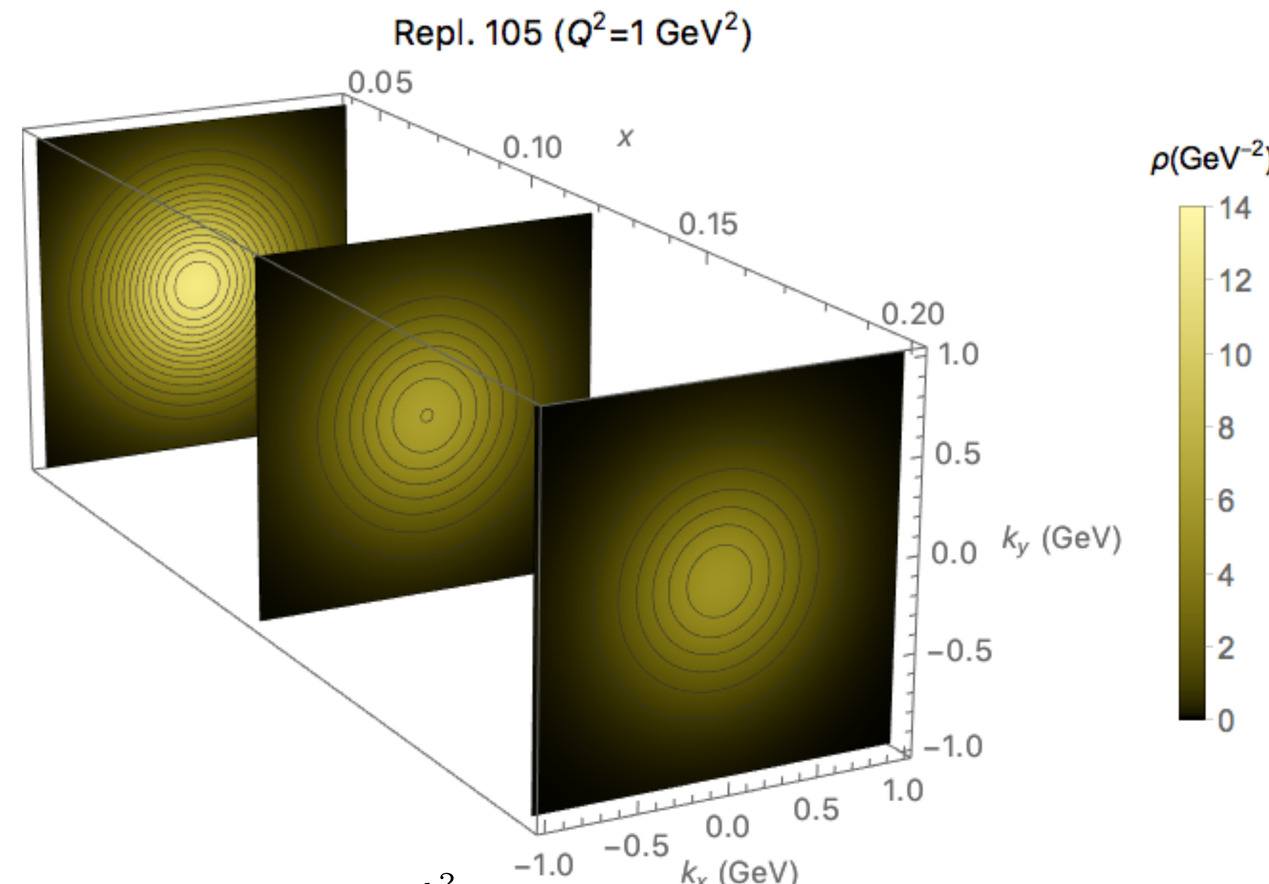
- no flavor dependence

plot in $k_\perp$ space



$$g_K(b_T) = -\frac{g_2}{2} b_T^2$$ Guassian

$$\hat{D}_{\mathrm{NP}}(z, b_T) = \frac{g_3(z)\ e^{-g_3(z)\frac{b_T^2}{4z^2}} + (\lambda_F/z^2) g_4^2(z) \left(1 - g_4(z)\frac{b_T^2}{4z^2}\right)\ e^{-g_4^2(z)\frac{b_T^2}{4z^2}}}{z^2\left(g_3(z) + (\lambda_F/z^2) g_4^2(z)\right)}$$

TMD Frag. Func.

PV17 – RESULTING TMDS

Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

expression in b_T space

$$\hat{f}_{\rm NP}(x, b_T) = e^{-g_1(x)\frac{b_T^2}{4}}\left(1 - \frac{\lambda g_1^2(x)}{1+\lambda g_1(x)}\frac{b_T^2}{4}\right)$$

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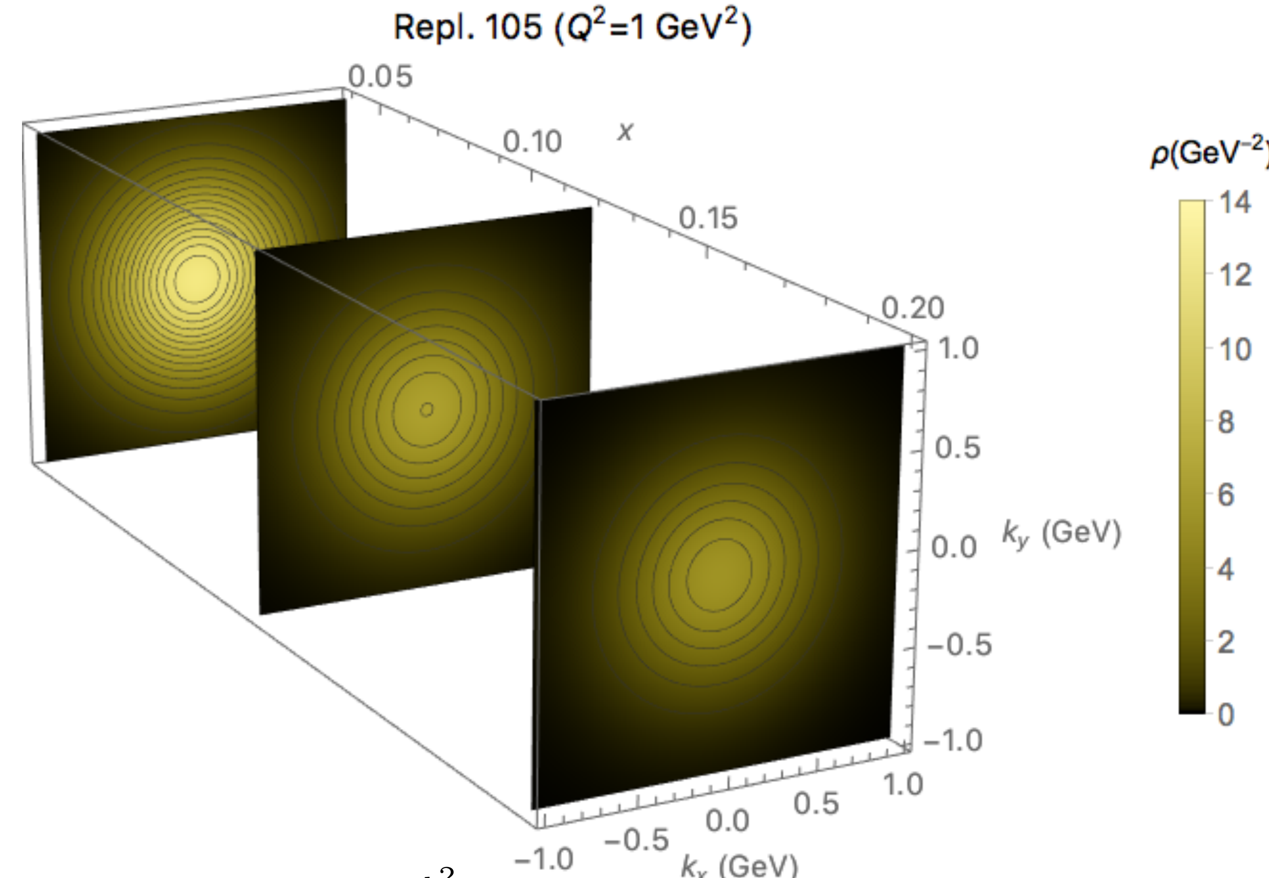
- no flavor dependence

$$g_K(b_T) = -\frac{g_2}{2} b_T^2$$ Guassian

plot in $k_\perp$ space



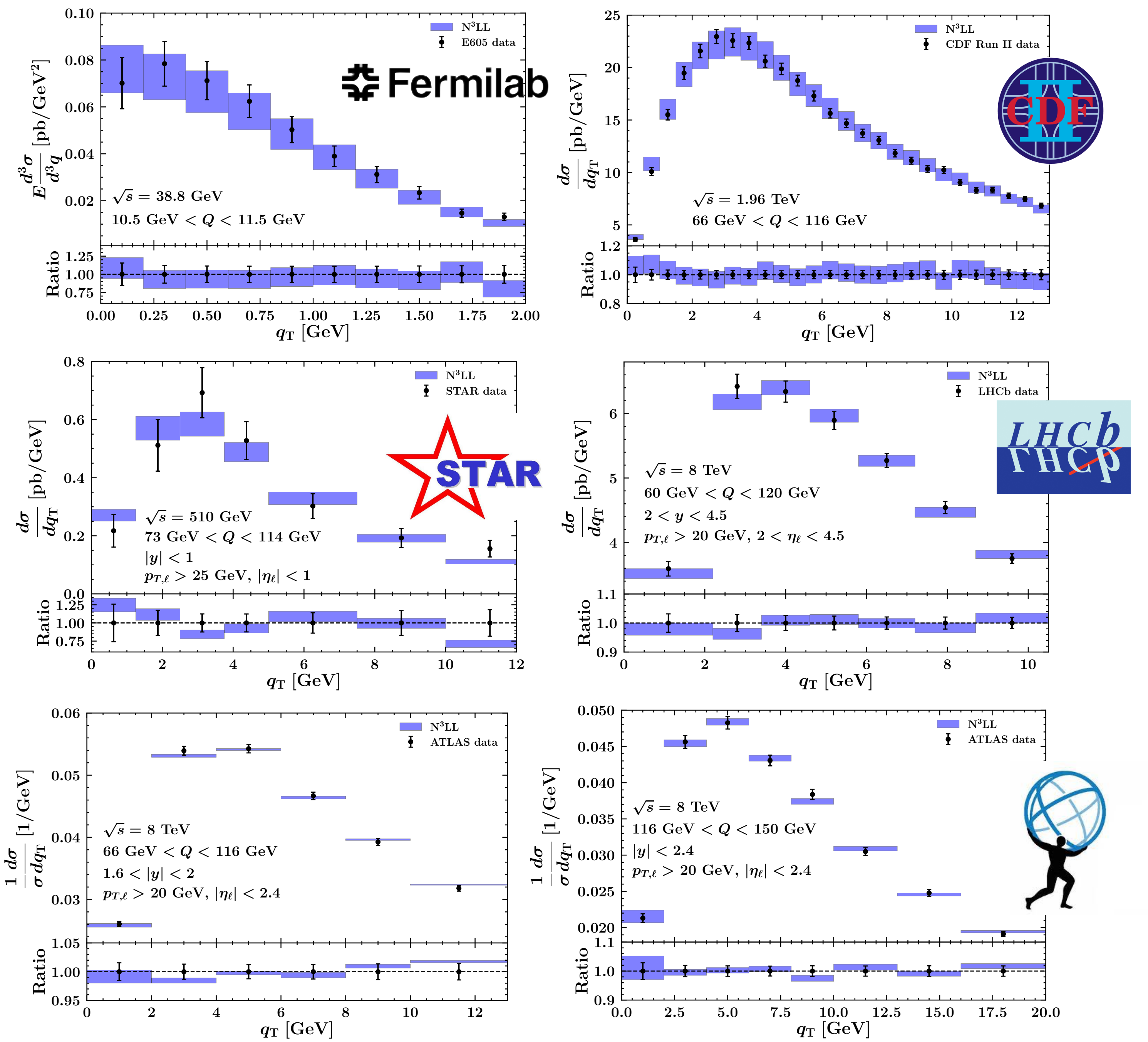
$$\hat{D}_{\rm NP}(z, b_T) = \frac{g_3(z)\; e^{-g_3(z)\frac{b_T^2}{4z^2}} + (\lambda_F/z^2) g_4^2(z)\left(1 - g_4(z)\frac{b_T^2}{4z^2}\right)\; e^{-g_4^2(z)\frac{b_T^2}{4z^2}}}{z^2\left(g_3(z) + (\lambda_F/z^2) g_4^2(z)\right)}$$

TMD Frag. Func.

11 free parameters

THE PAVIA19 EXTRACTION

Bacchetta, Bertone, Bissolotti, Bozzi, Delcarro, Piacenza, Radici, arXiv:1912.07550



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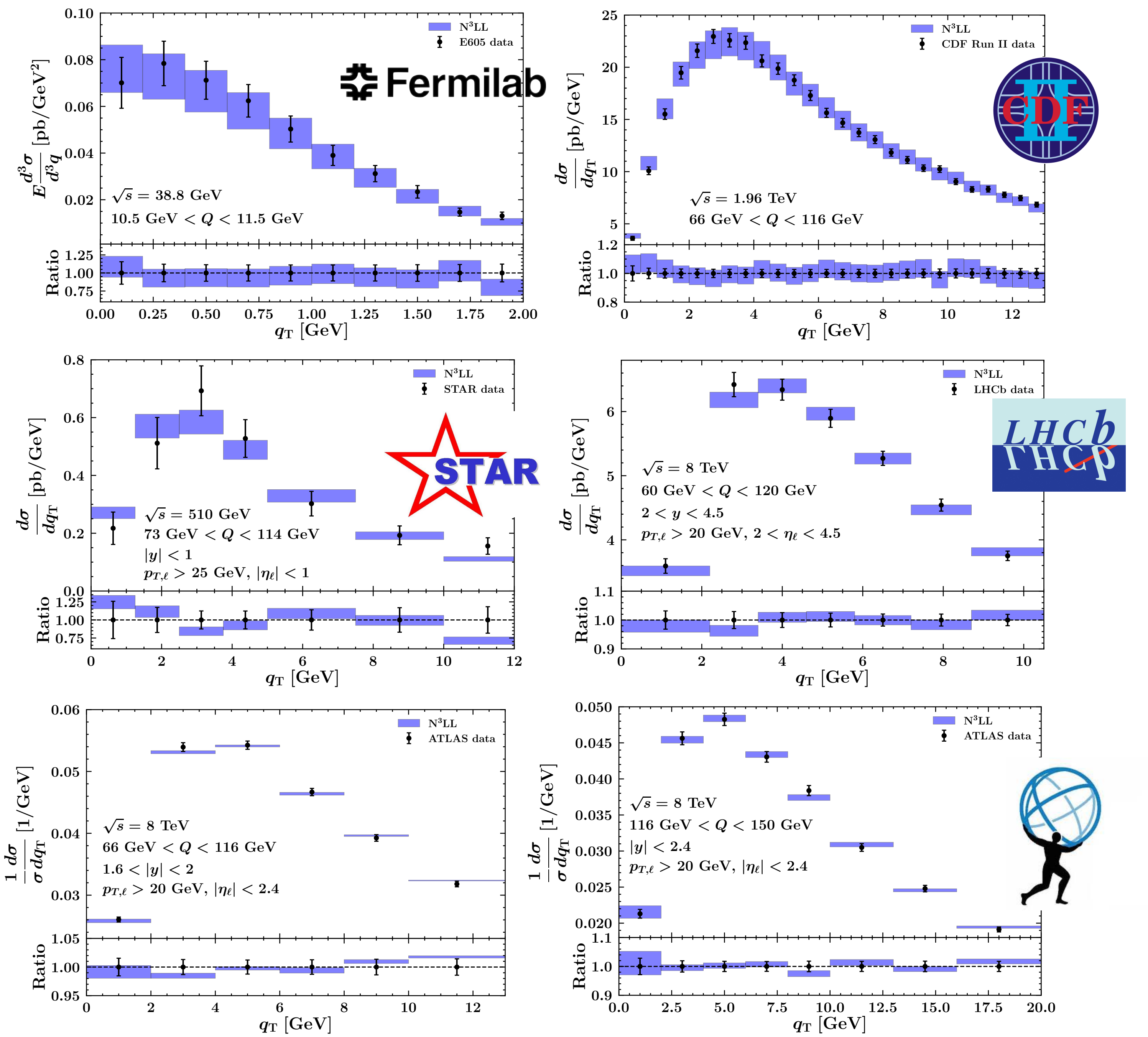
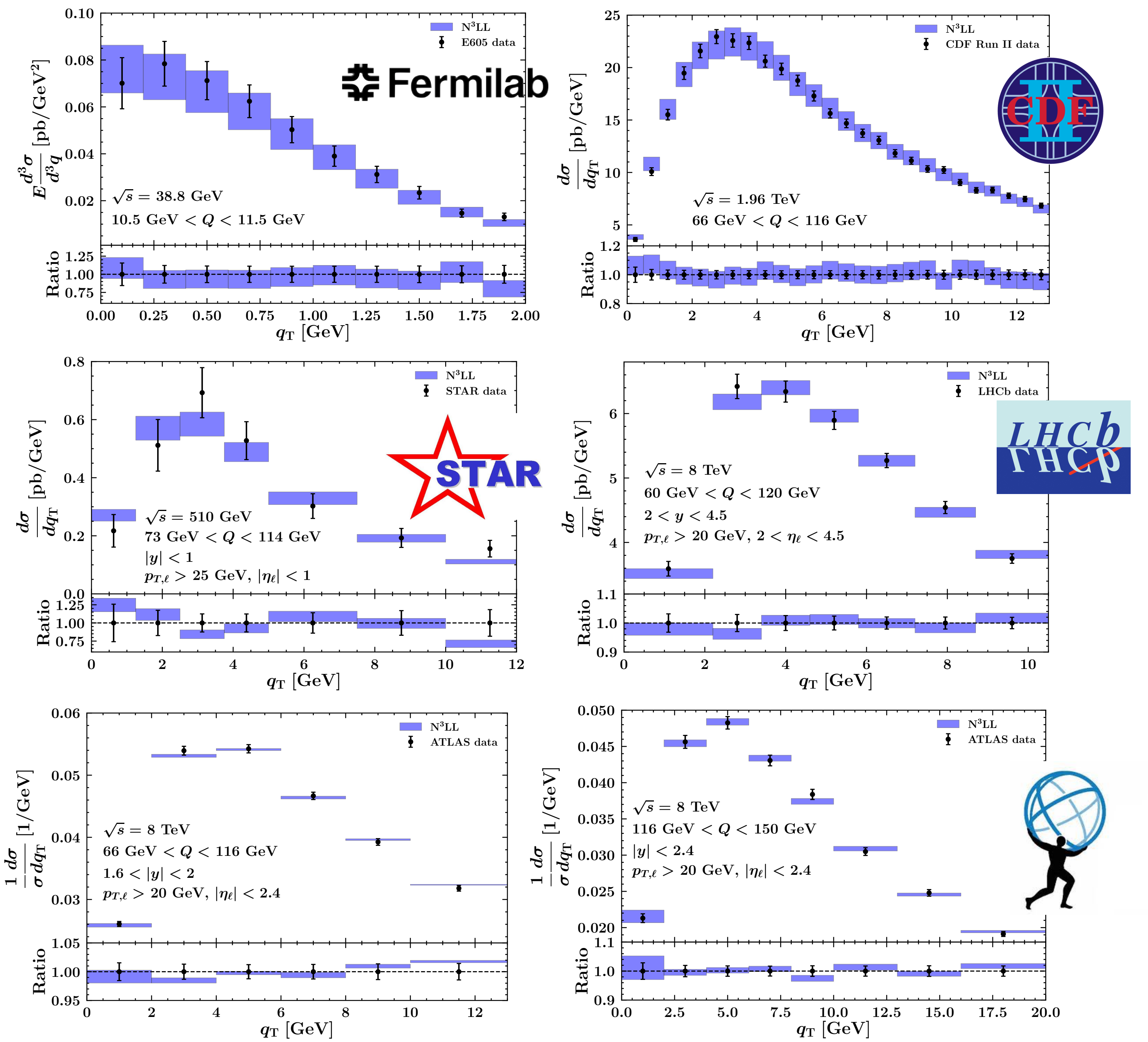
Bacchetta, Bertone, Bissolotti, Bozzi, Delcarro, Piacenza, Radici, arXiv:1912.07550



Data selection: $q_T/Q < 0.2$

THE PAVIA19 EXTRACTION

Bacchetta, Bertone, Bissolotti, Bozzi, Delcarro, Piacenza, Radici, arXiv:1912.07550



Data selection: $q_T/Q < 0.2$

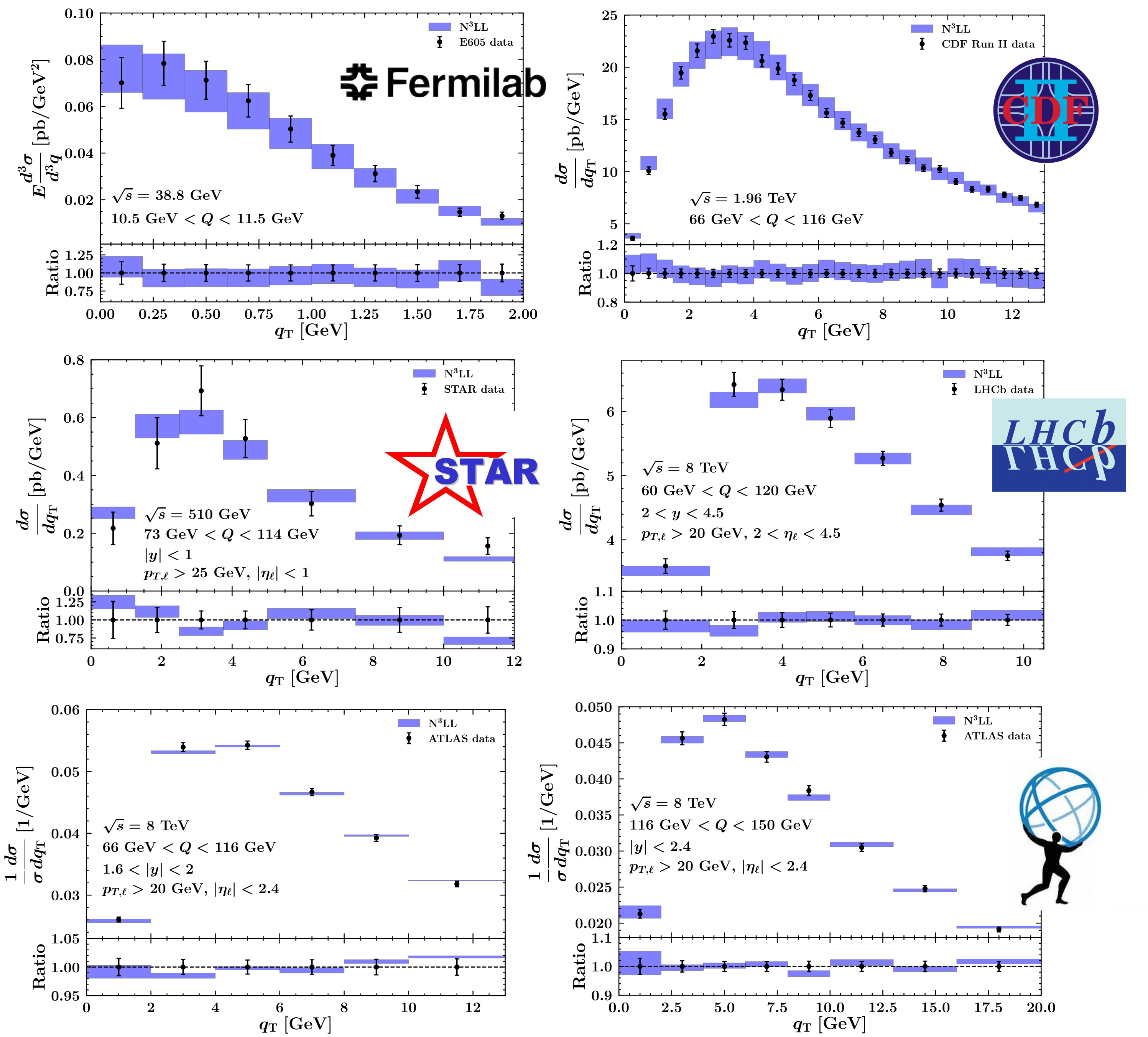
Number of data points: 353

The TMD "Varzi" fit

Varzi, province of Pavia, Italy, 400

PV19 – DATA COMPARISION

Bacchetta, Bertone, Bissolotti, Bozzi, Delcarro, Piacenza, Radici, arXiv:1912.07550



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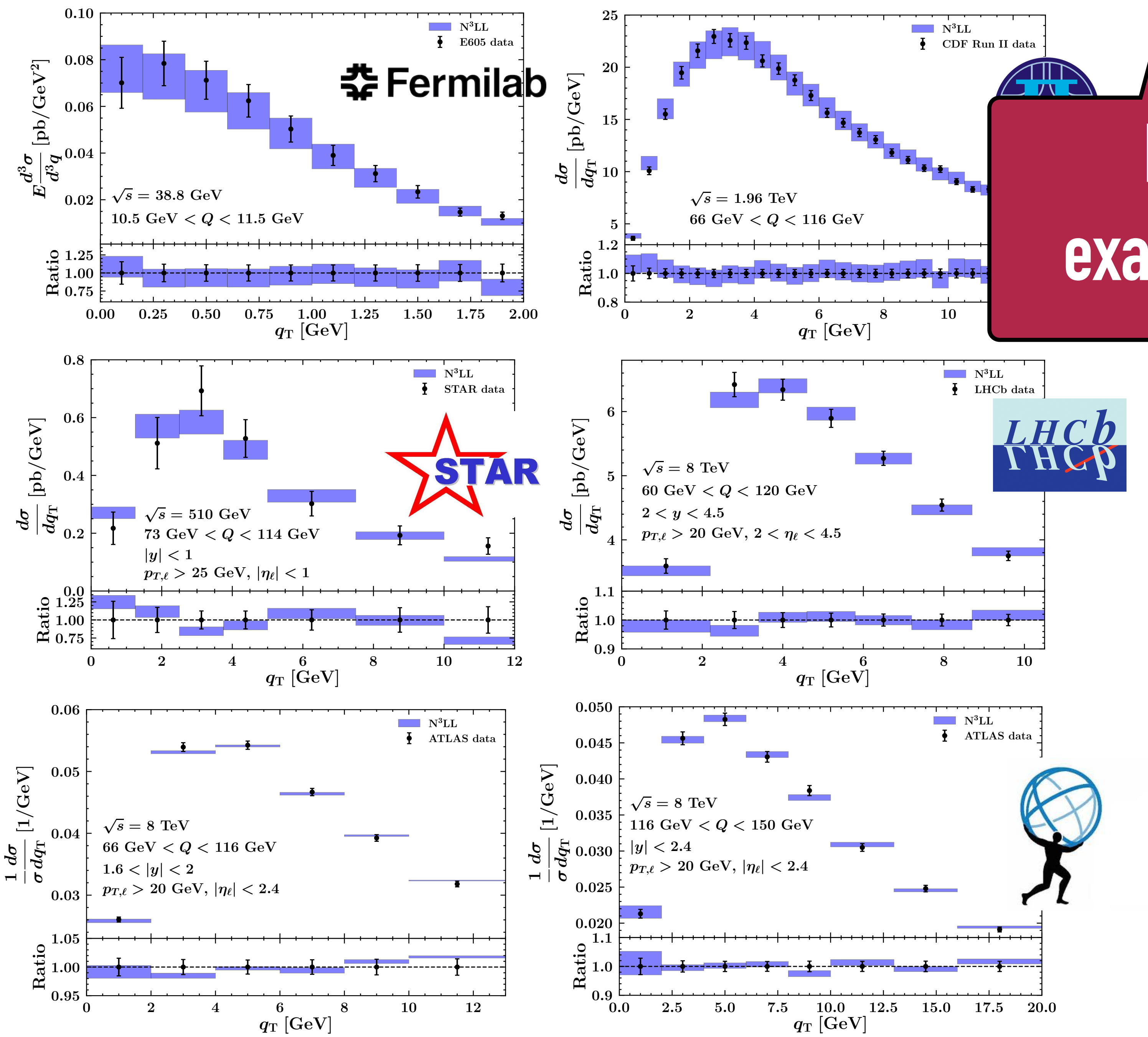

Pavia19: first DY fit at N³LL, exactly reproduces normalization

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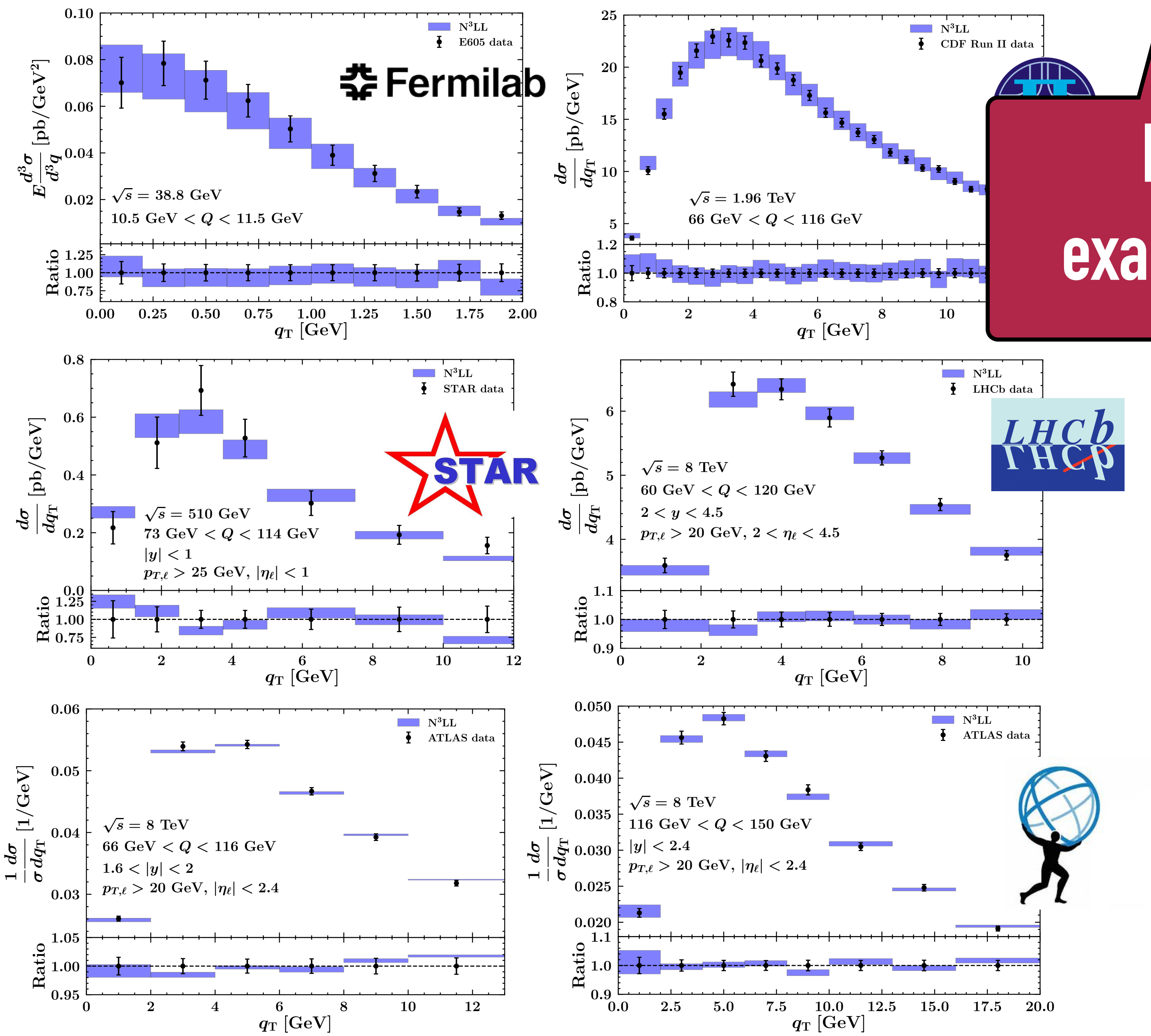

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Global χ^2/dof = 1.02

PV19 – RESULTING TMDS

expression in b_T space

$$f_{\rm NP}(x, b_T, \zeta) = \left[\frac{1-\lambda}{1 + g_1(x) \frac{b_T^2}{4}} + \lambda \exp\left(-g_{1B}(x) \frac{b_T^2}{4} \right) \right]$$

$$\times \; \exp\left[-\left(g_2 + g_{2B} b_T^2 \right) \ln\left(\frac{\zeta}{Q_0^2} \right) \frac{b_T^2}{4} \right] \; ,$$

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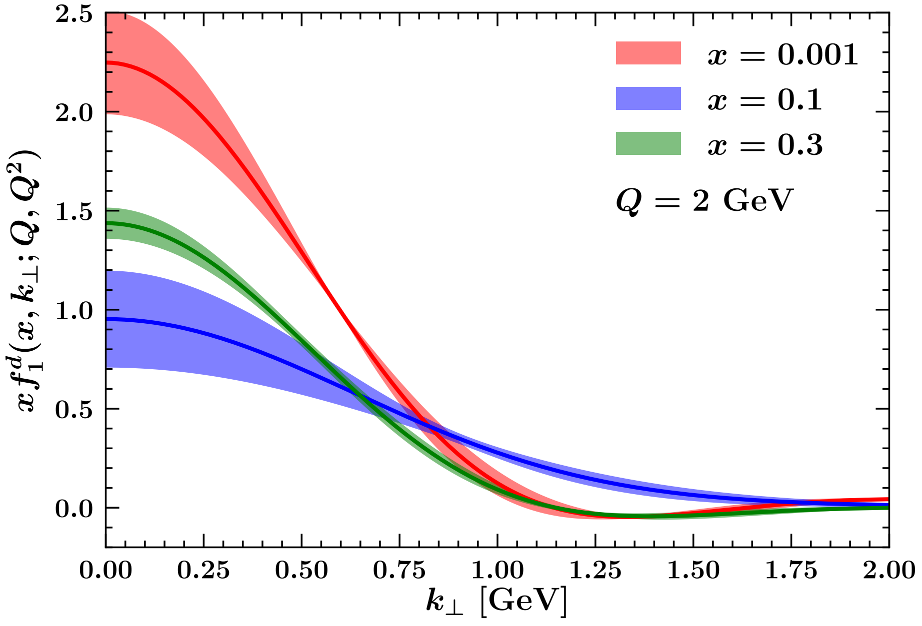
plot in $k_\perp$ space



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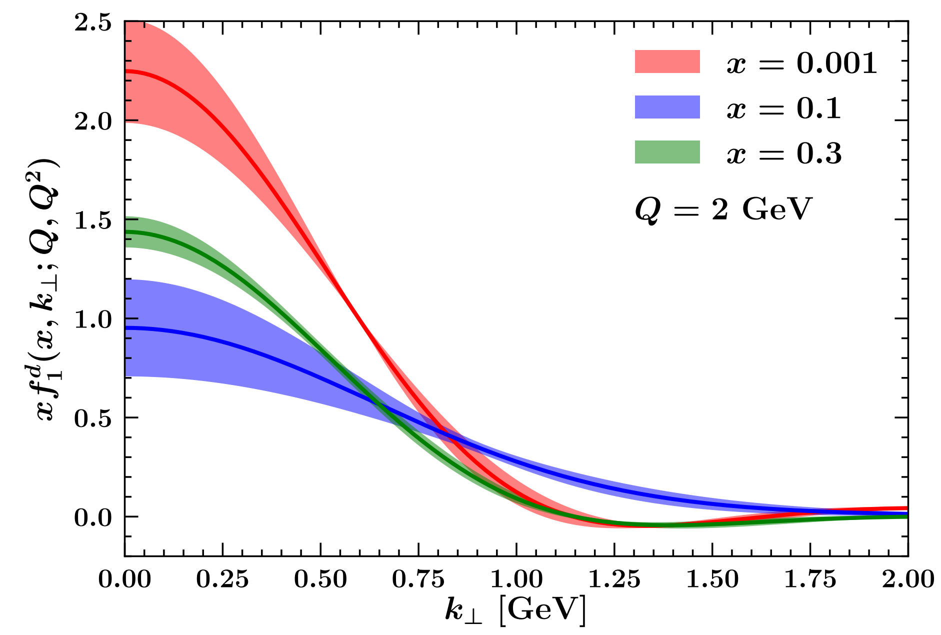
$$\times \exp\left[-\left(g_2 + g_{2B} b_T^2\right) \ln\left(\frac{\zeta}{Q_0^2}\right)\frac{b_T^2}{4}\right] ,$$

- q-Guassian + Gaussian

plot in $k_\perp$ space



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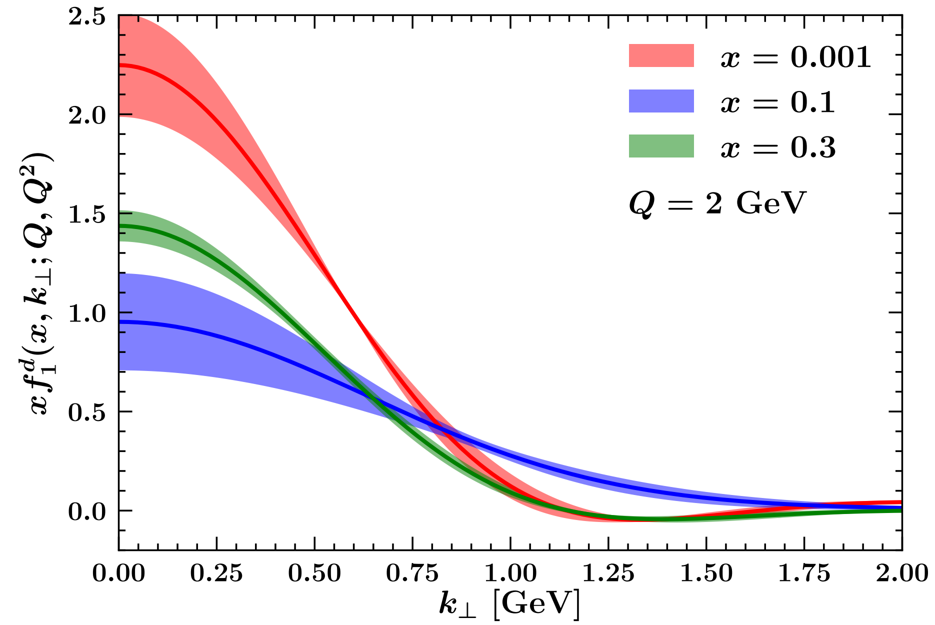
- q-Guassian + Gaussian
- nontrivial x dependence

plot in $k_\perp$ space



PV19 – RESULTING TMDS

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$$\times \ \exp\left[- \left(g_2 + g_{2B} b_T^2 \right) \ln\left(\frac{\zeta}{Q_0^2} \right) \frac{b_T^2}{4} \right] \ ,$$

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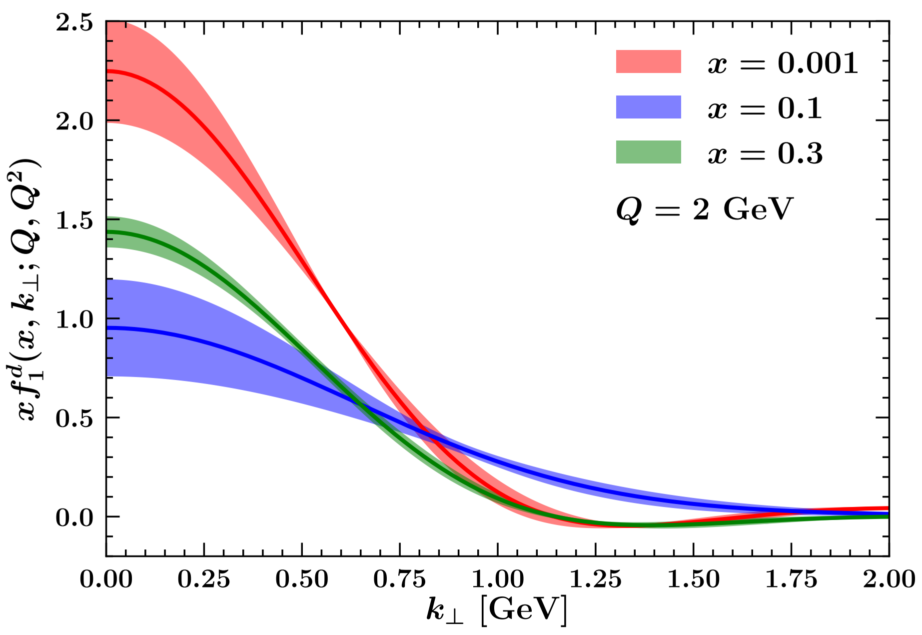

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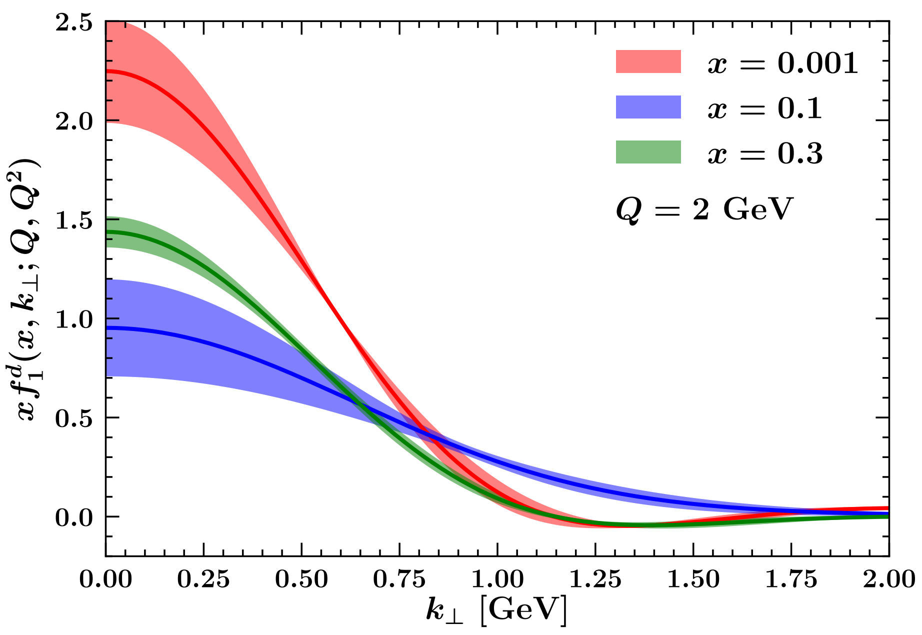
$$\times\ \exp\left[-\left(g_2 + g_{2B} b_T^2\right)\ln\left(\frac{\zeta}{Q_0^2}\right)\frac{b_T^2}{4}\right]\ ,$$

- q-Guassian + Gaussian
- nontrivial x dependence
- no flavor dependence
- non-Gaussian nonperturbative TMD evolution

plot in $k_\perp$ space



PV19 – RESULTING TMDS

expression in b_T space

$$f_{\mathrm{NP}}(x, b_T, \zeta) = \left[\frac{1-\lambda}{1 + g_1(x) \frac{b_T^2}{4}} + \lambda \exp\left(-g_{1B}(x) \frac{b_T^2}{4} \right) \right]$$

$$\times \exp\left[-\left(g_2 + g_{2B} b_T^2 \right) \ln\left(\frac{\zeta}{Q_0^2} \right) \frac{b_T^2}{4} \right] ,$$

- q-Guassian + Gaussian
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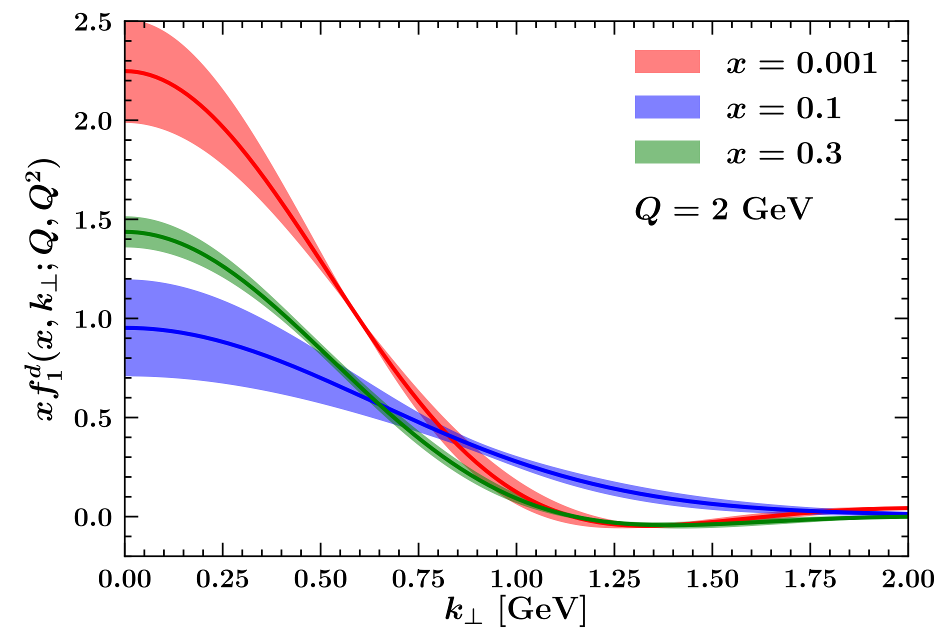
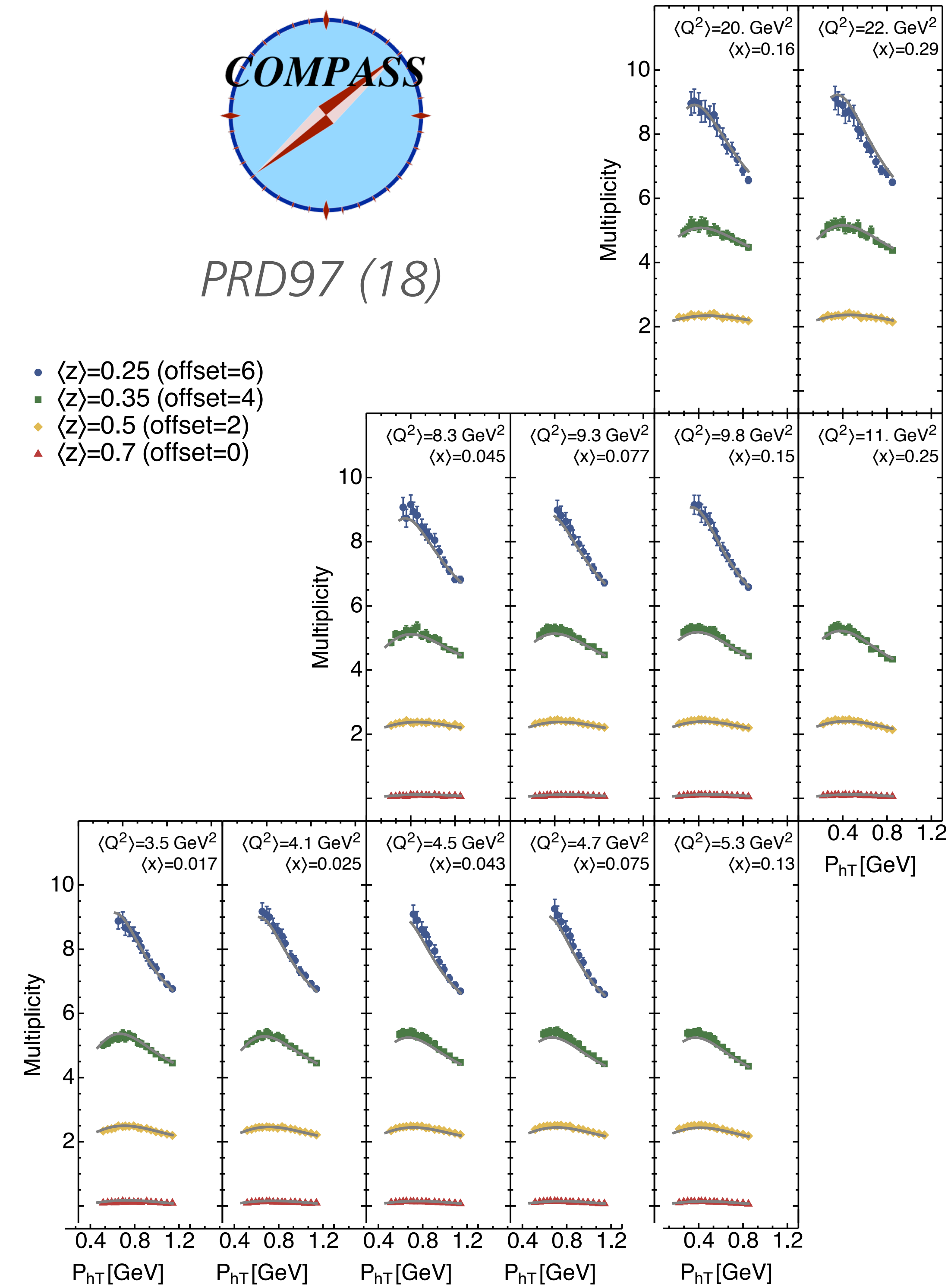


9 free parameters

PROBLEMS WITH SIDIS NORMALIZATION

PRD97 (18)



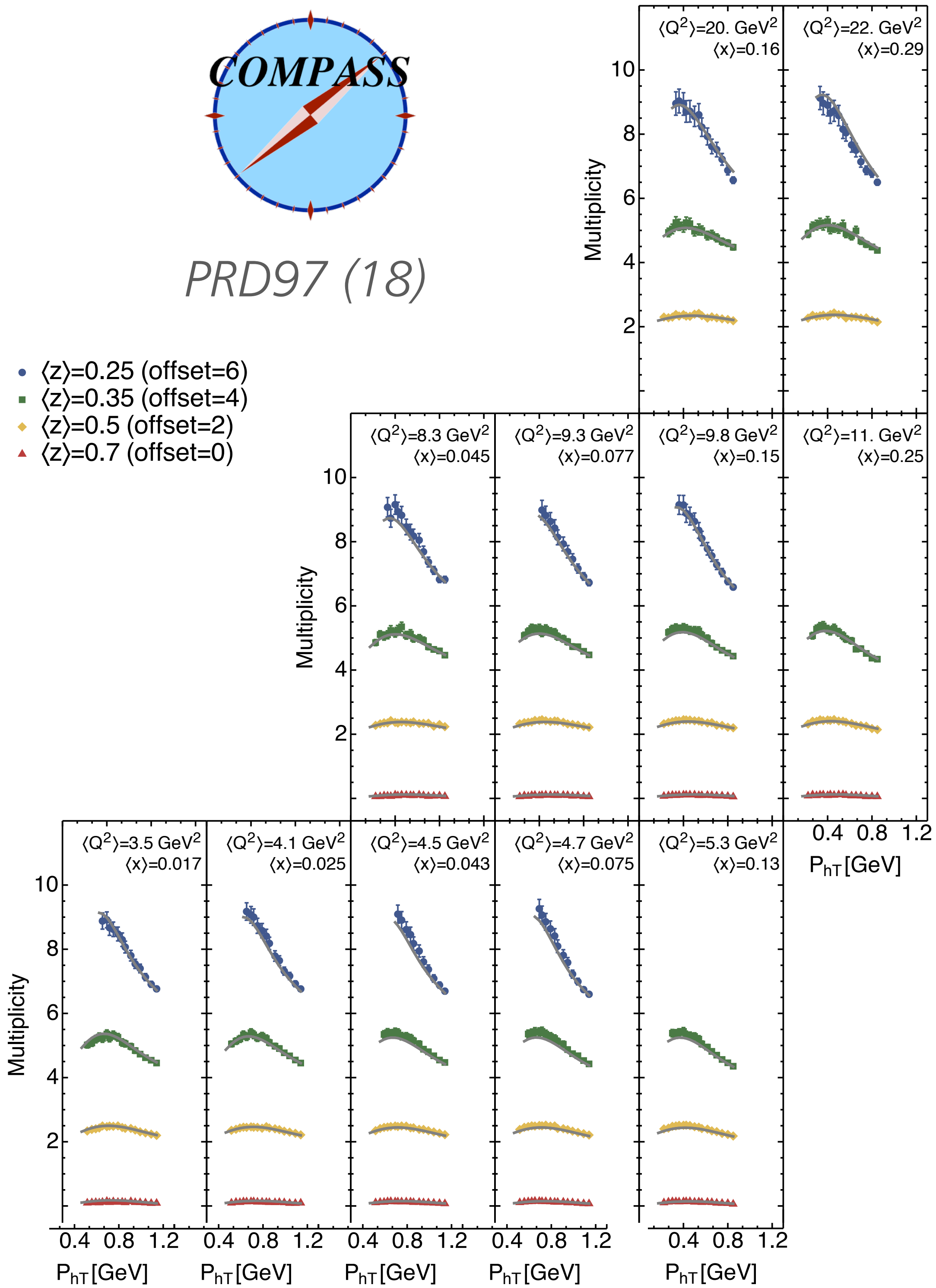
from F. Piacenza's PhD thesis

PROBLEMS WITH SIDIS NORMALIZATION

Comparing the PV17 extraction with the new COMPASS data, without normalization factors, at NLL the agreement is very good

COMPASS

PRD97 (18)



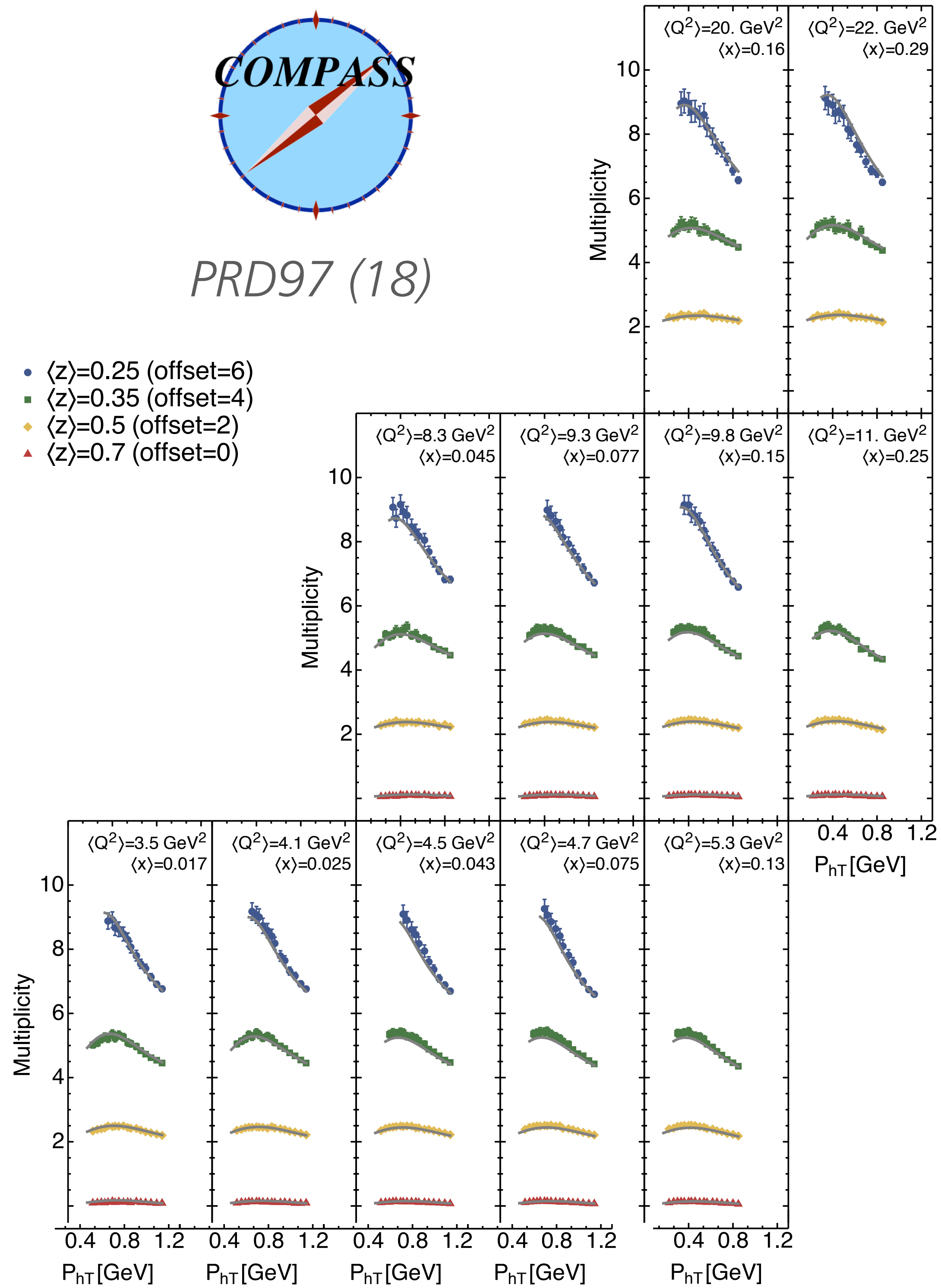
from F. Piacenza's PhD thesis

PROBLEMS WITH SIDIS NORMALIZATION

Comparing the PV17 extraction with the new COMPASS data, without normalization factors, at NLL the agreement is very good

Going to NLL' or NNLL the situation dramatically worsens!

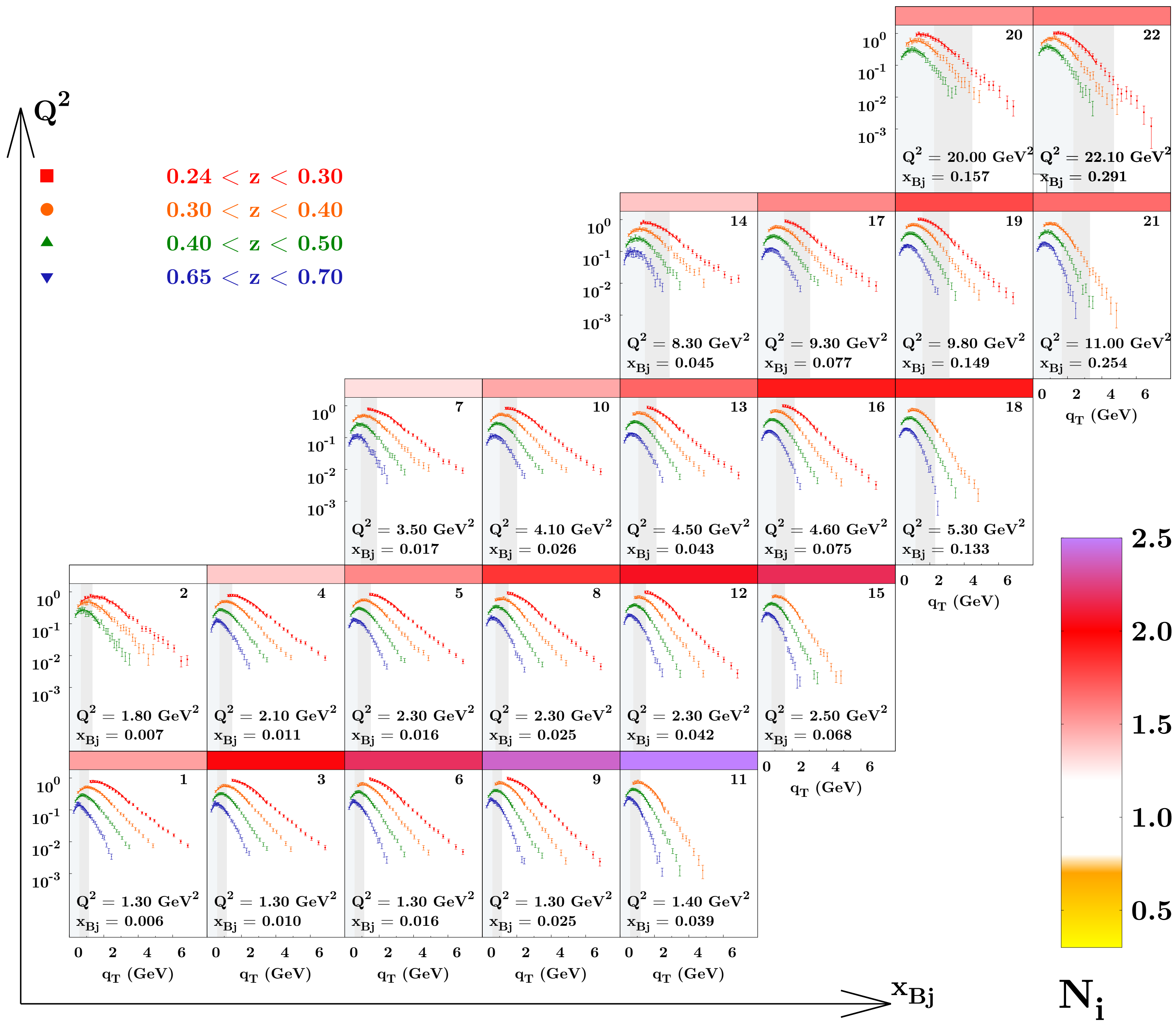
PRD97 (18)



from F. Piacenza's PhD thesis

PROBLEMS WITH SIDIS NORMALIZATION

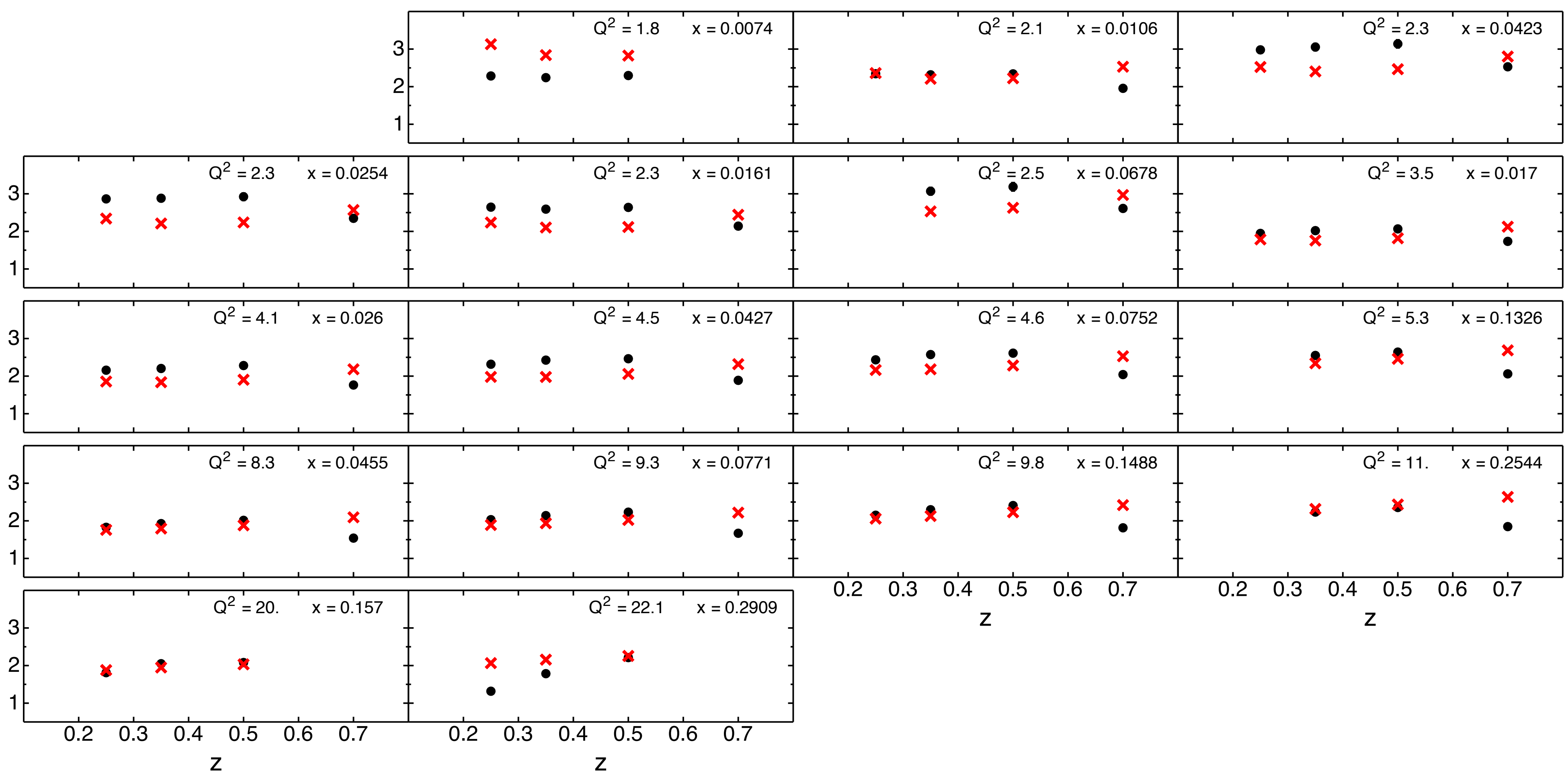
talk by O. Gonzalez at DIS2019



Torino's group also confirmed that large normalisation factors have to be introduced to describe COMPASS data

PROBLEMS WITH SIDIS NORMALIZATION

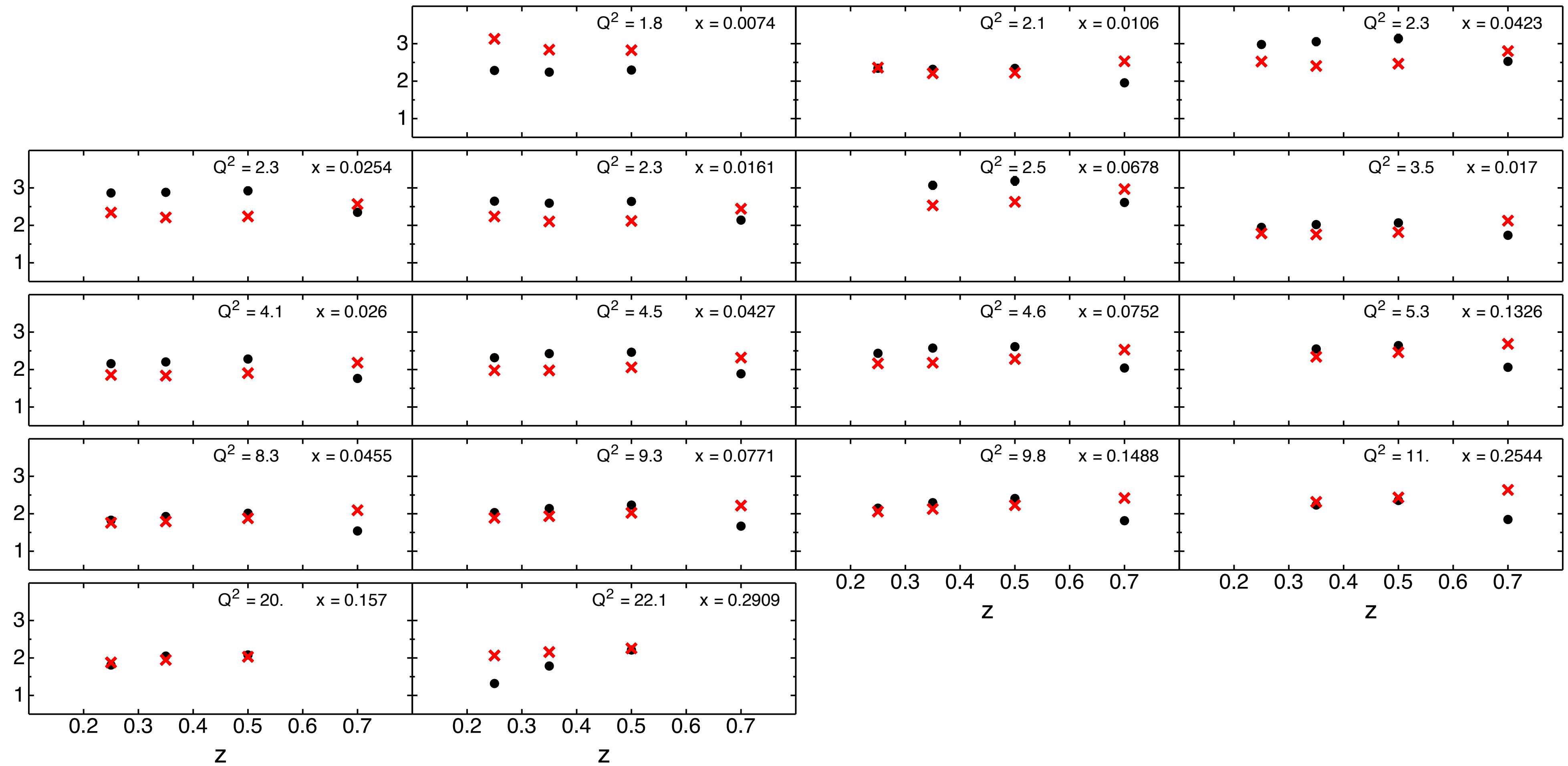
from F. Piacenza's PhD thesis



Black dots: large normalisation factors
required to fit COMPASS multiplicities at NLL'

PROBLEMS WITH SIDIS NORMALIZATION

from F. Piacenza's PhD thesis

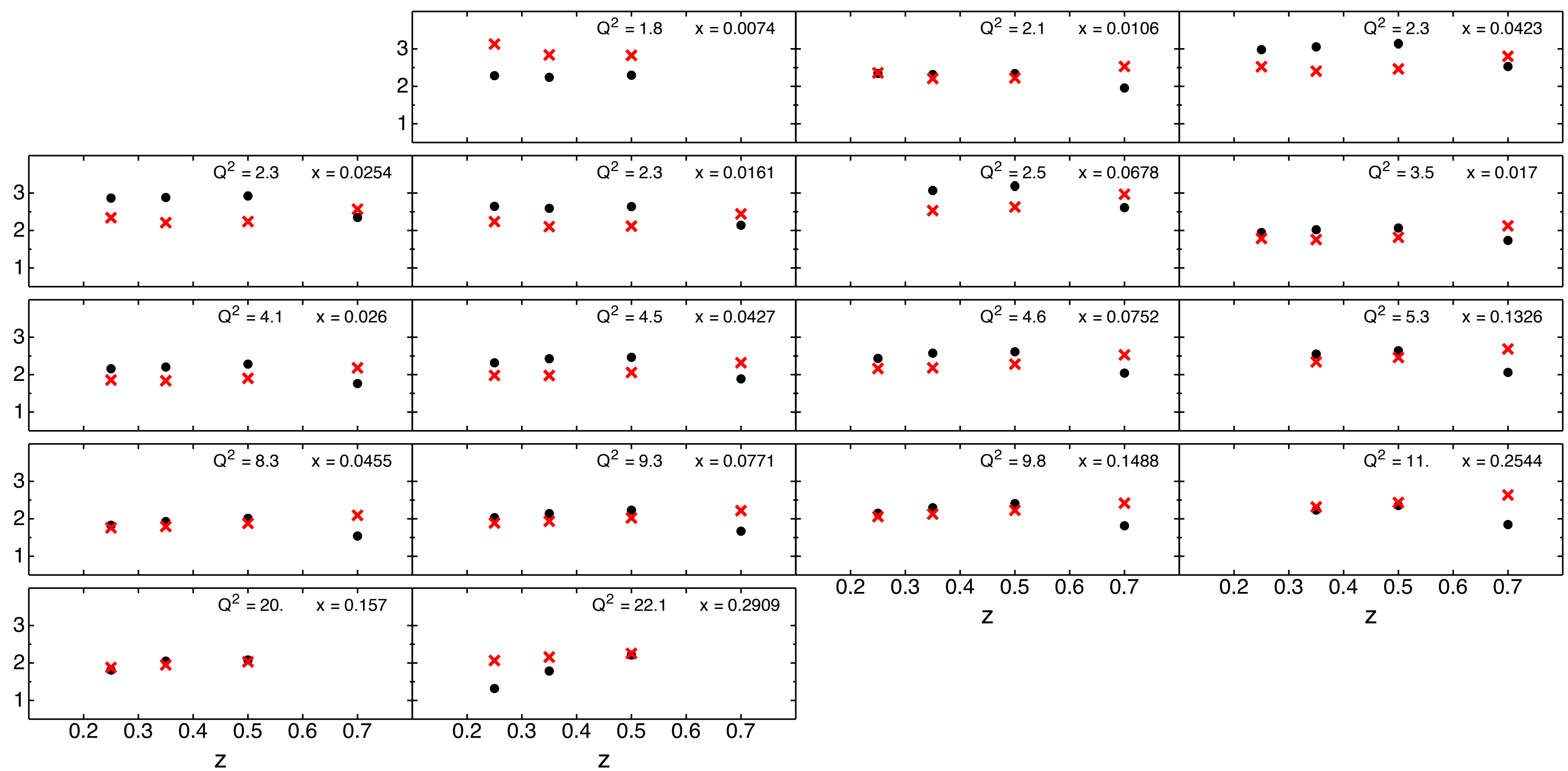


Black dots: large normalisation factors required to fit COMPASS multiplicities at NLL'

BAD

PROBLEMS WITH SIDIS NORMALIZATION

from F. Piacenza's PhD thesis



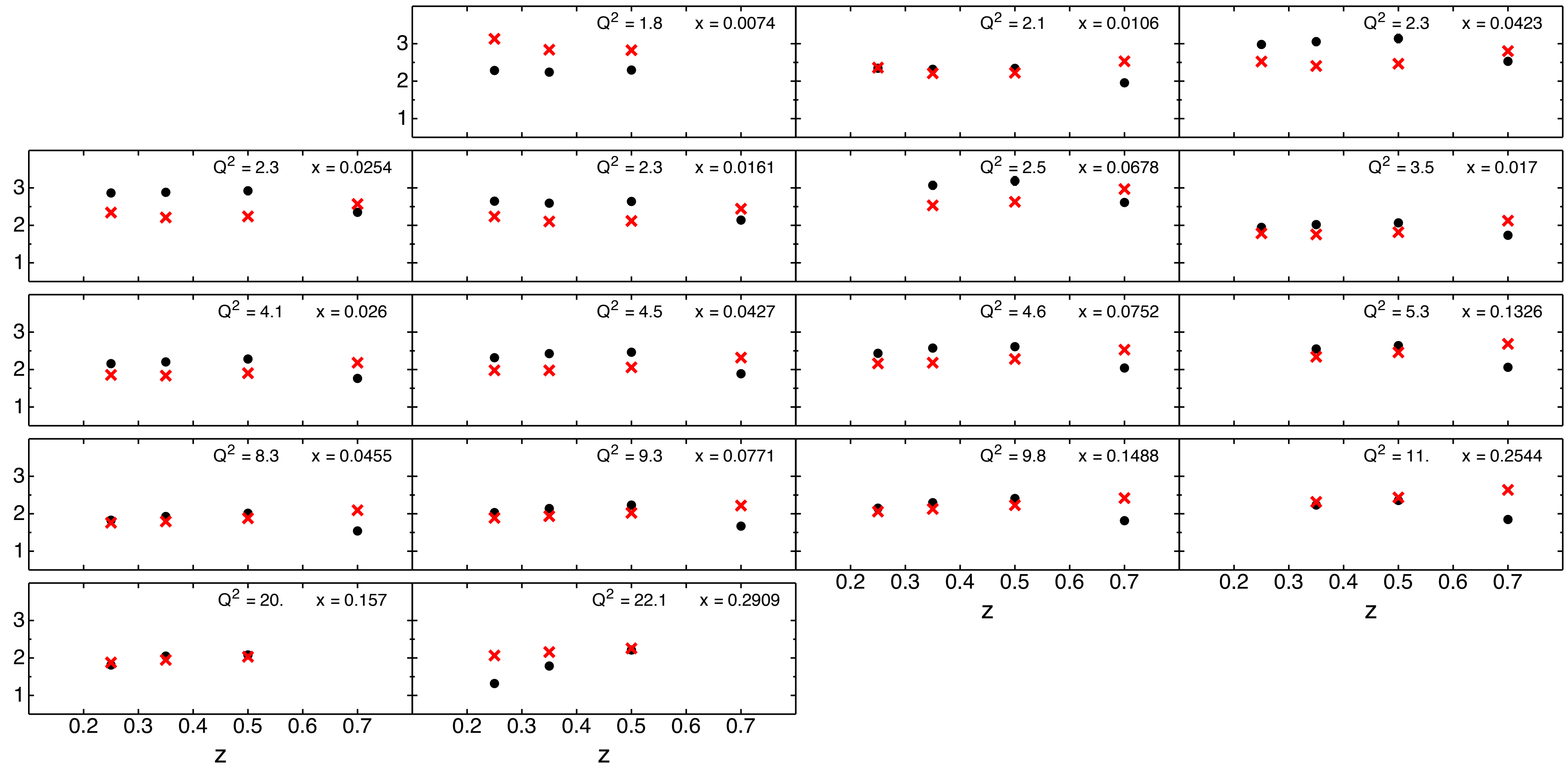
Black dots: large normalisation factors required to fit COMPASS multiplicities at NLL'

BAD

Red dots: ratio between collinear formula and integral of TMD part at order α_S

PROBLEMS WITH SIDIS NORMALIZATION

from F. Piacenza's PhD thesis



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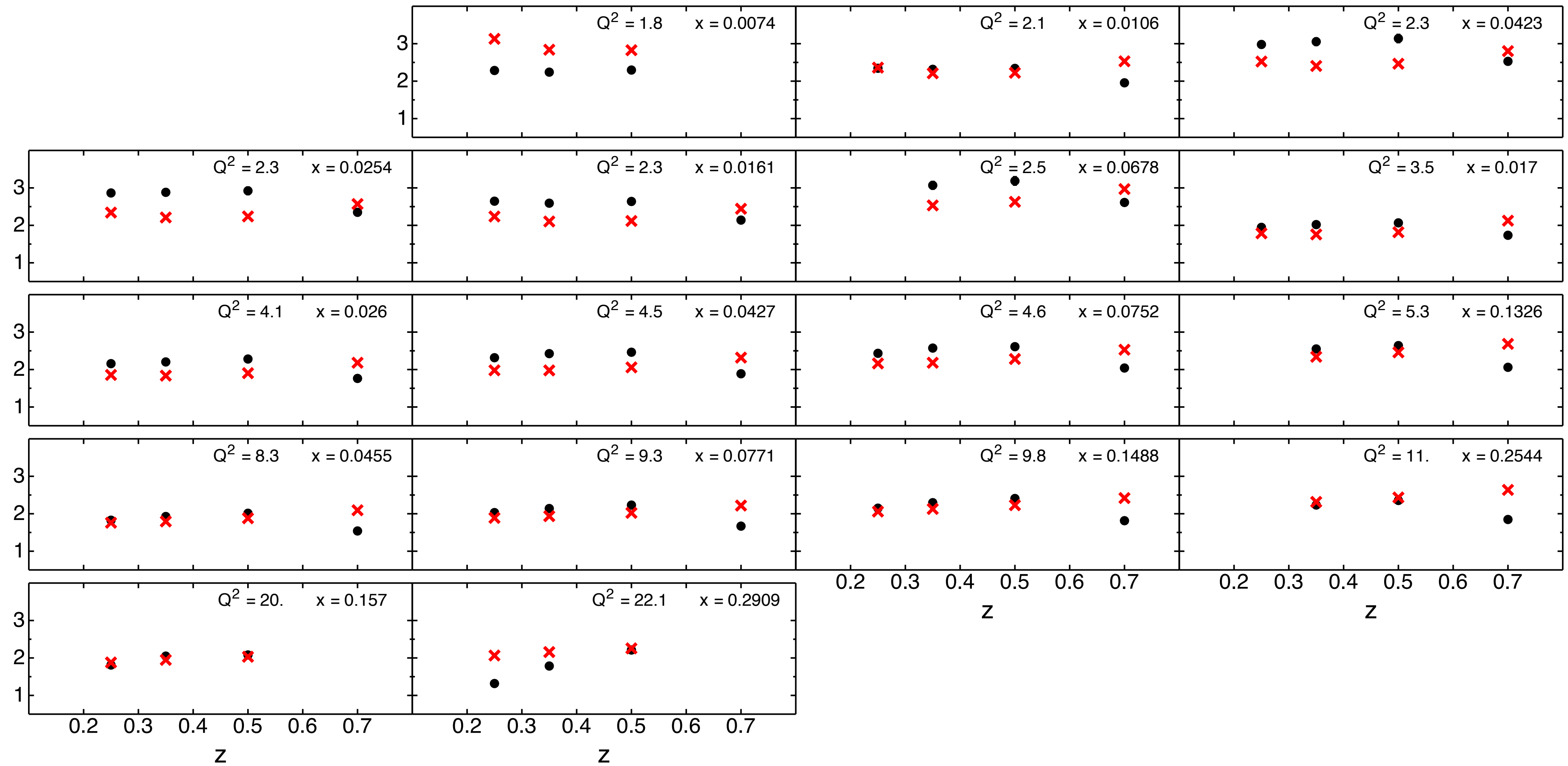

Black dots: large normalisation factors required to fit COMPASS multiplicities at NLL'

BAD

Black and red dots are similar

Red dots: ratio between collinear formula and integral of TMD part at order α_S

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PROBLEMS WITH SIDIS NORMALIZATION

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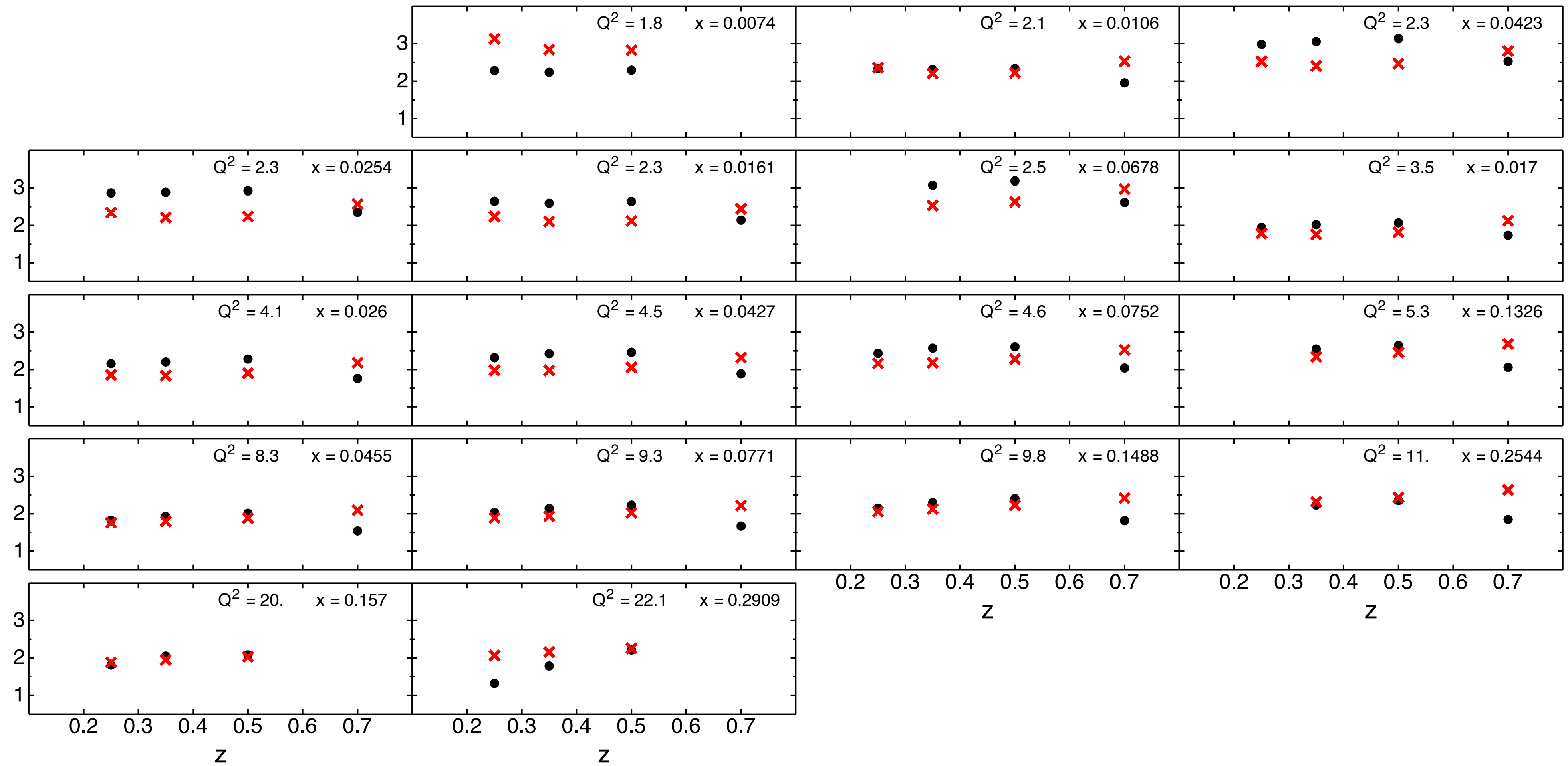

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BAD

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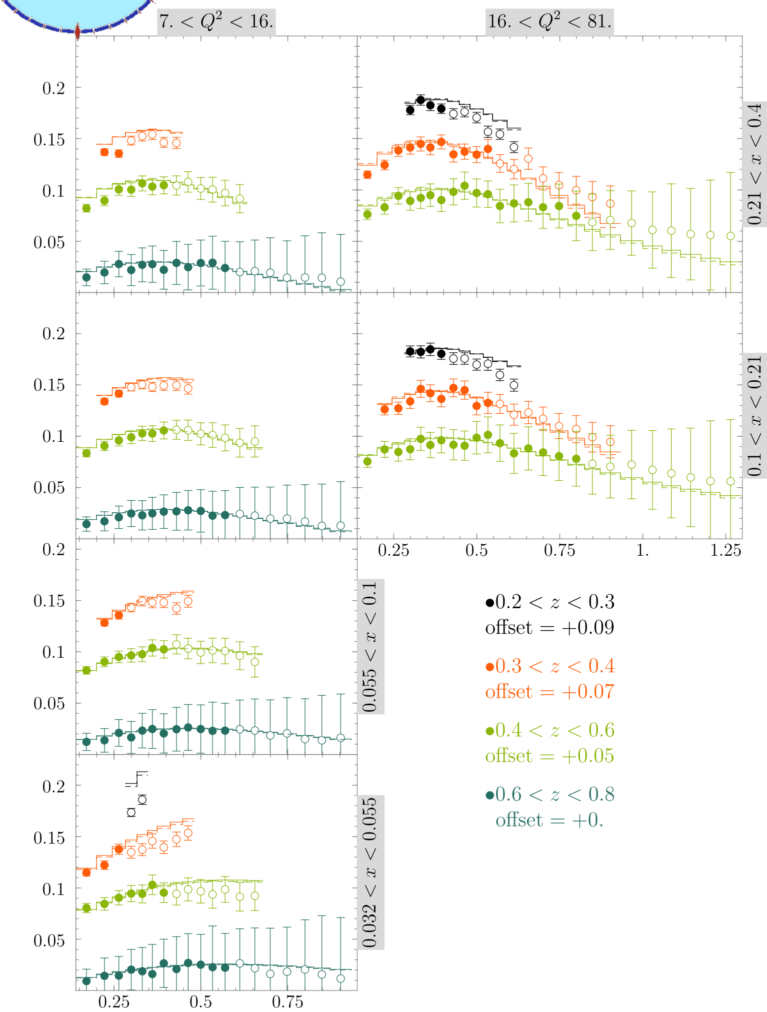
GOOD?

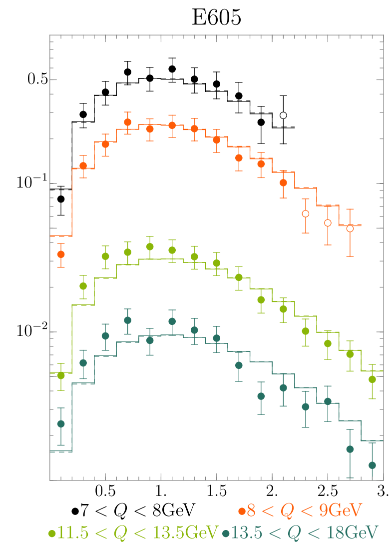
THE SCIMEMI-VLADIMIROV 19 EXTRACTION

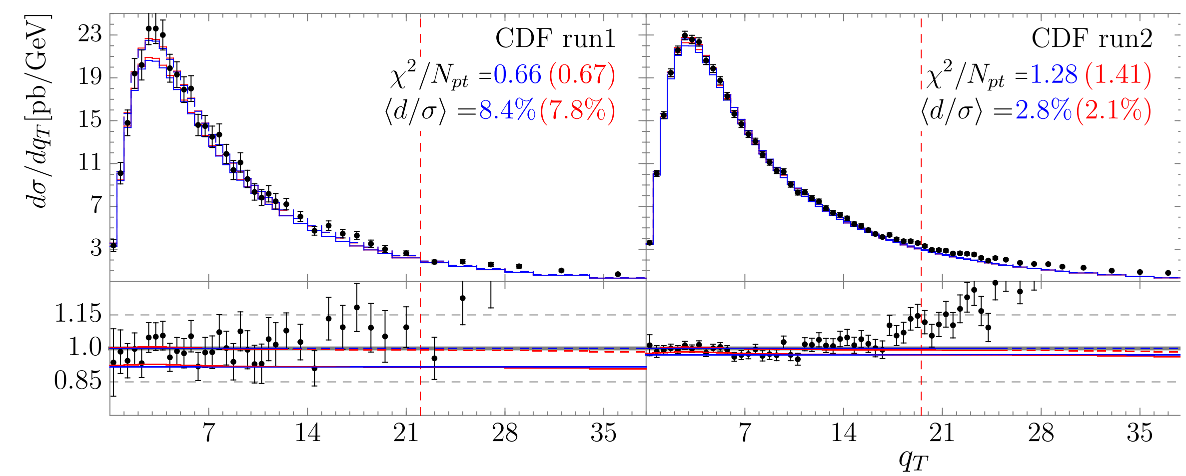
Scimemi, Vladimirov, arXiv:1912.06532

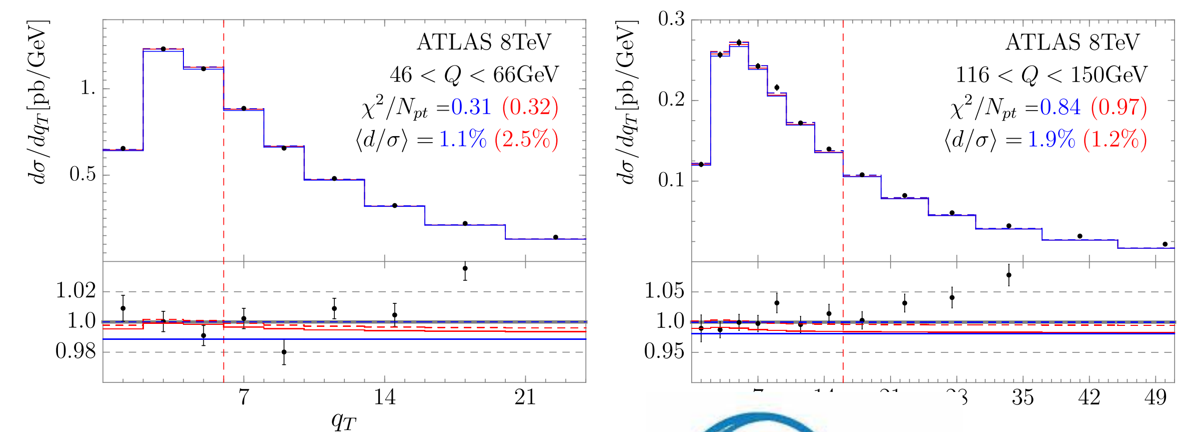
$z^2 \times M(z, p_T)$

$d \to h^+$









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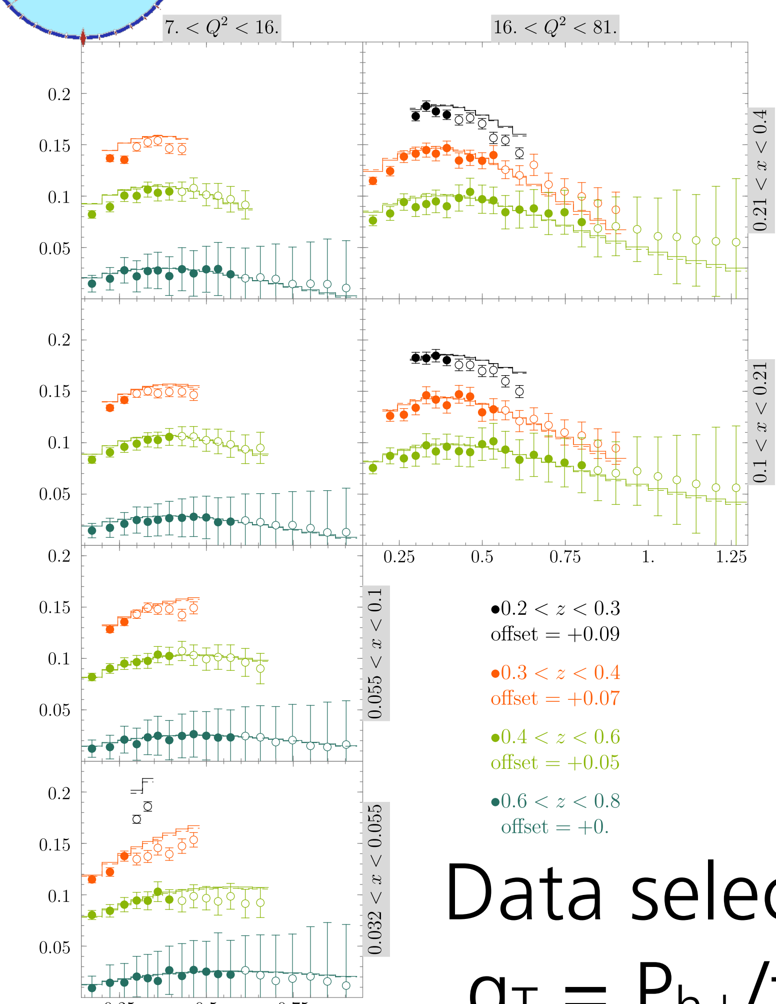
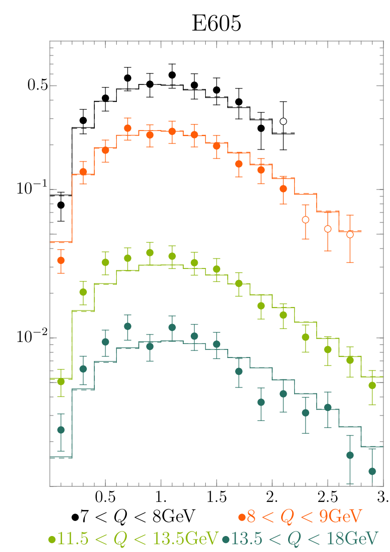
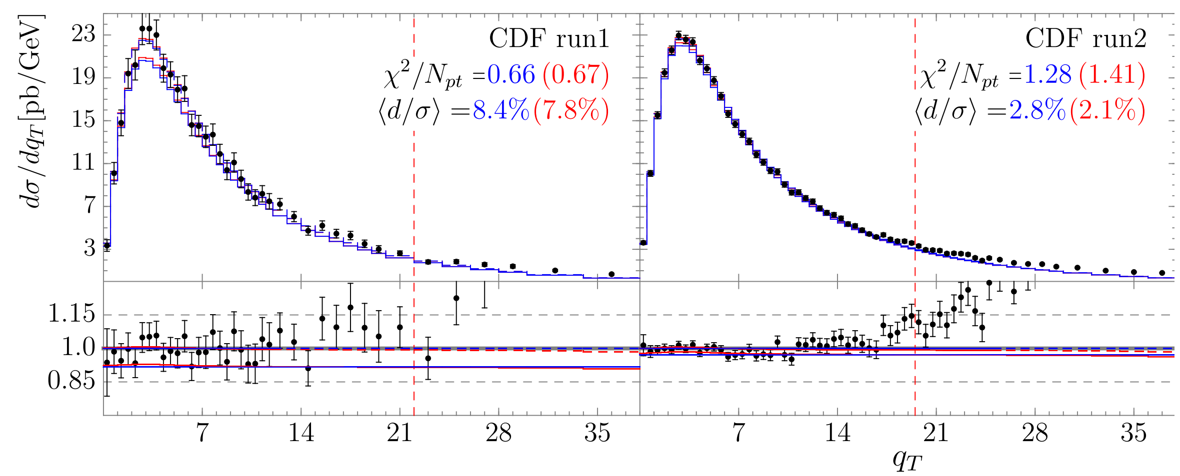
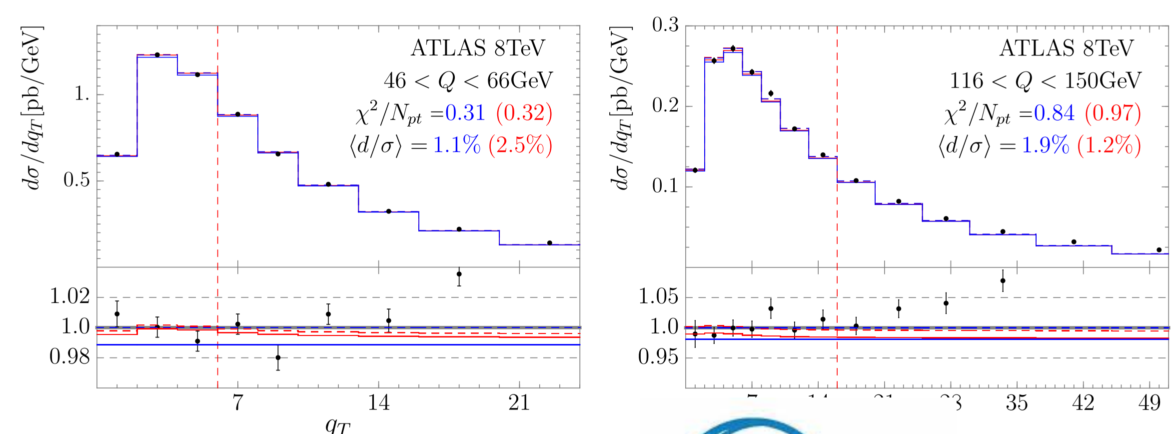








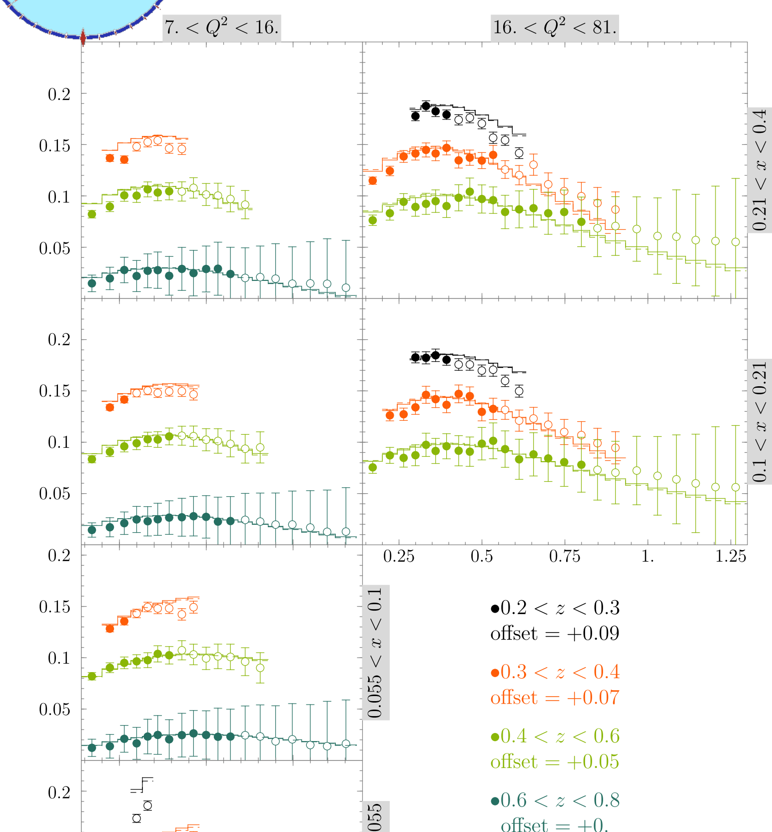
Data selection:

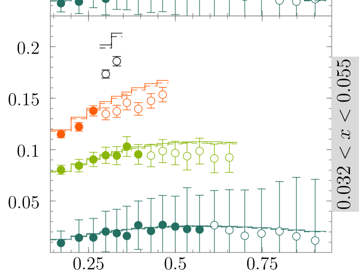
$q_T = P_{h\perp}/z < 0.25\, Q$

THE SCIMEMI-VLADIMIROV 19 EXTRACTION

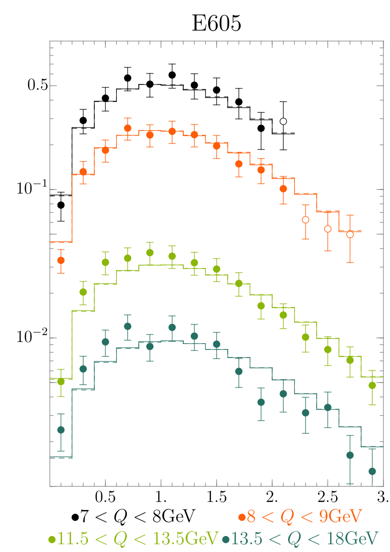
Scimemi, Vladimirov, arXiv:1912.06532

COMPASS $z^2 \times M(z, p_T)$ $d \to h^+$

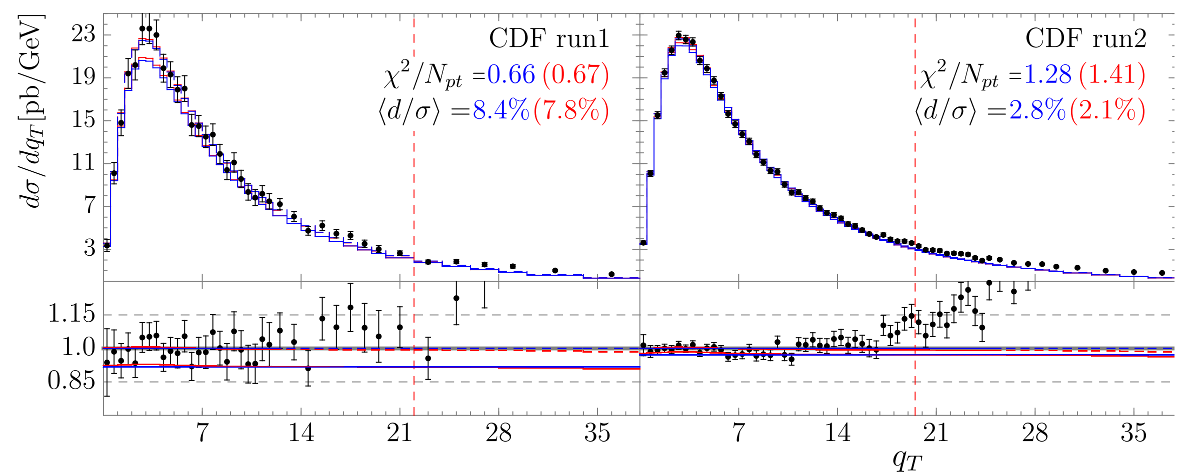


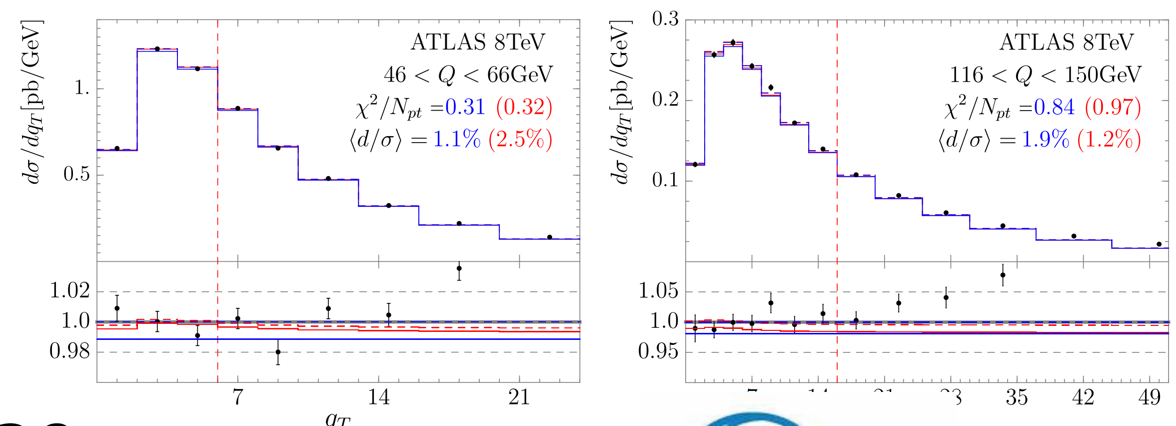


Fermilab



CDF





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$q_T = P_{h\perp}/z < 0.25\ Q$

Number of data points: 1039

Global χ^2/dof = 1.06

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Scimemi, Vladimirov, arXiv:1912.06532

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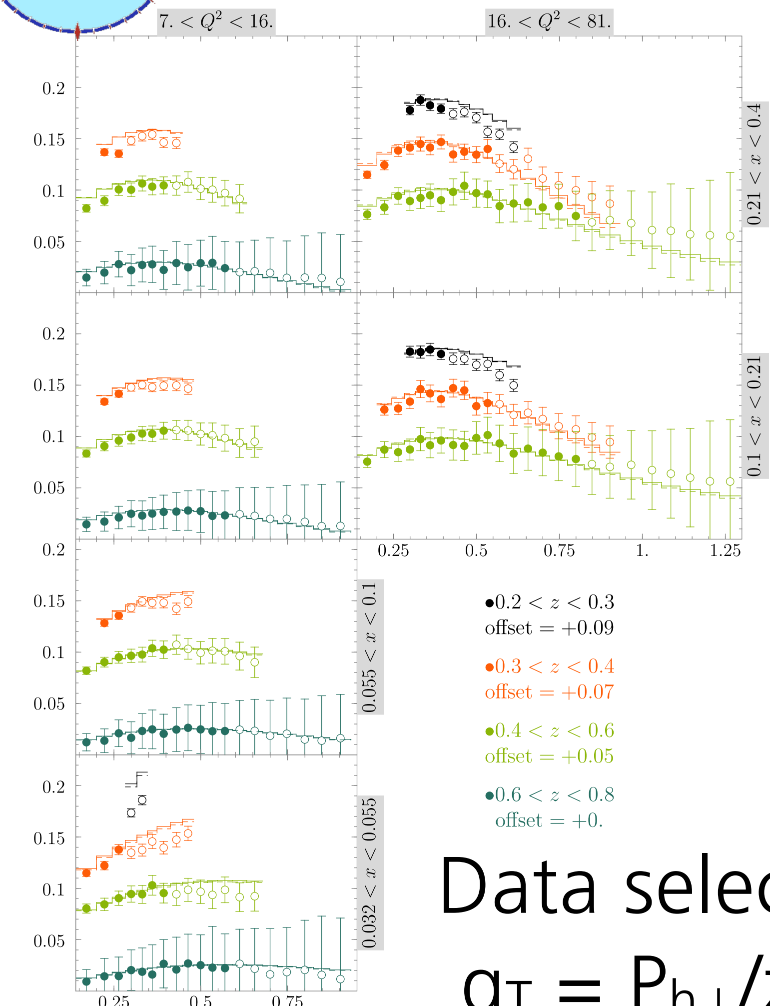

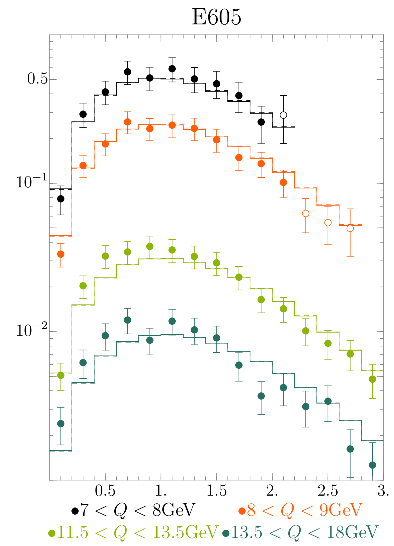

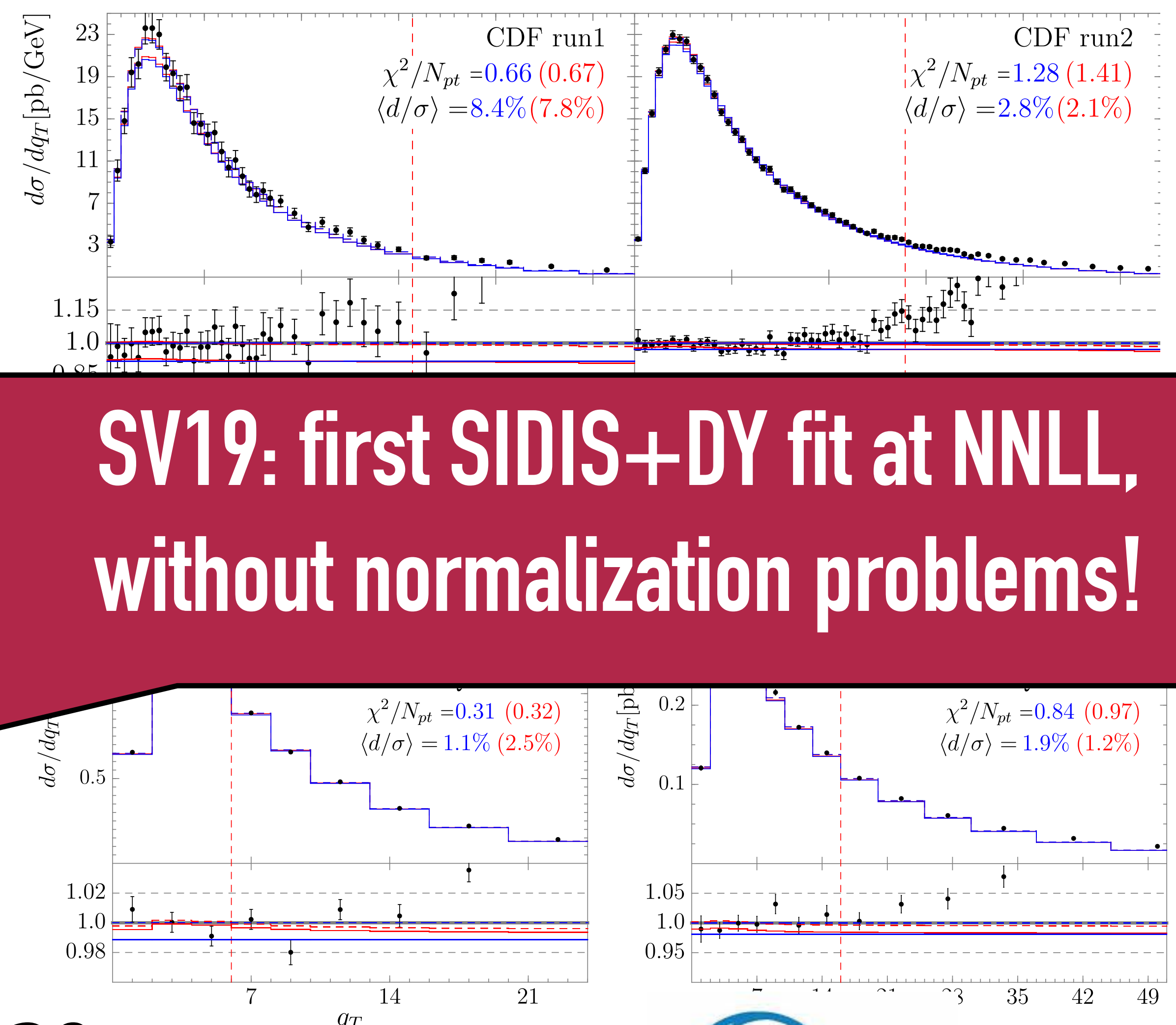

SV19: first SIDIS+DY fit at NNLL, without normalization problems!

Data selection:

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Number of data points: 1039

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SV19 – RESULTING TMDS

Scimemi, Vladimirov, arXiv:1912.06532

expression in b_T space

$$f_{NP}(x,b) = \exp\left(-\frac{\lambda_1(1-x)+\lambda_2 x + x(1-x)\lambda_5}{\sqrt{1+\lambda_3 x^{\lambda_4}\boldsymbol{b}^2}}\boldsymbol{b}^2\right)$$

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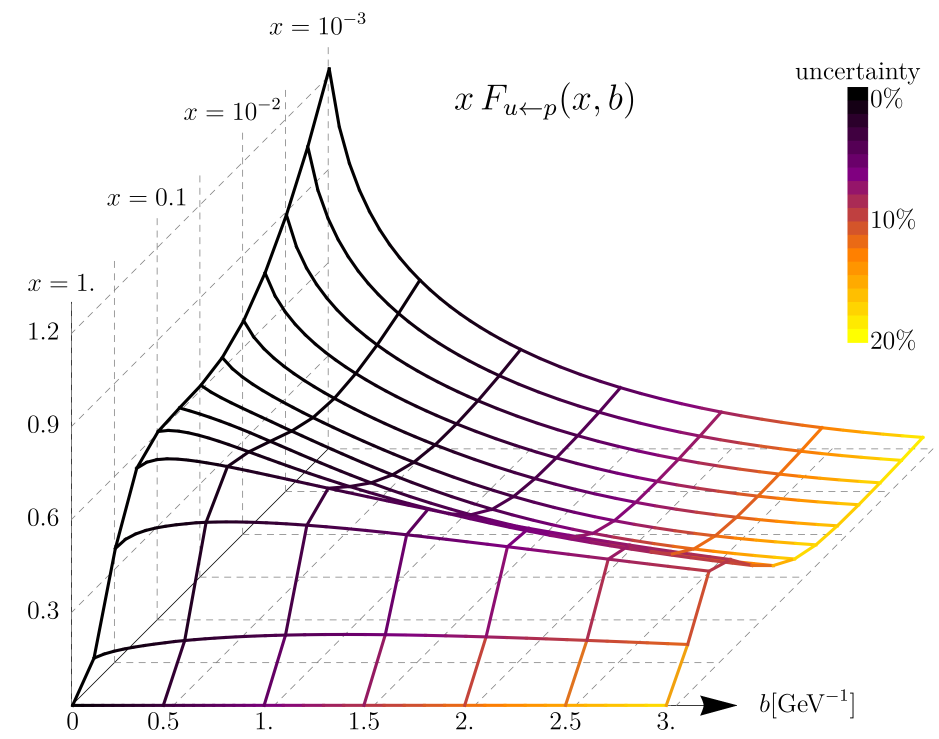
plot in b_T space



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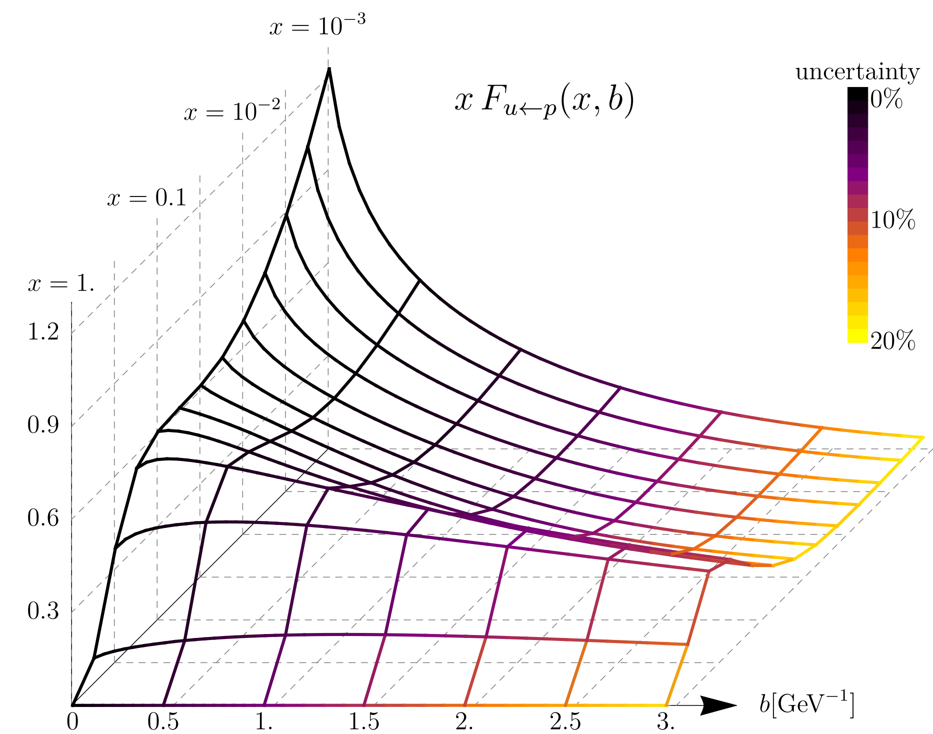
- Guassian at low b_T, exponential at high b_T

plot in b_T space



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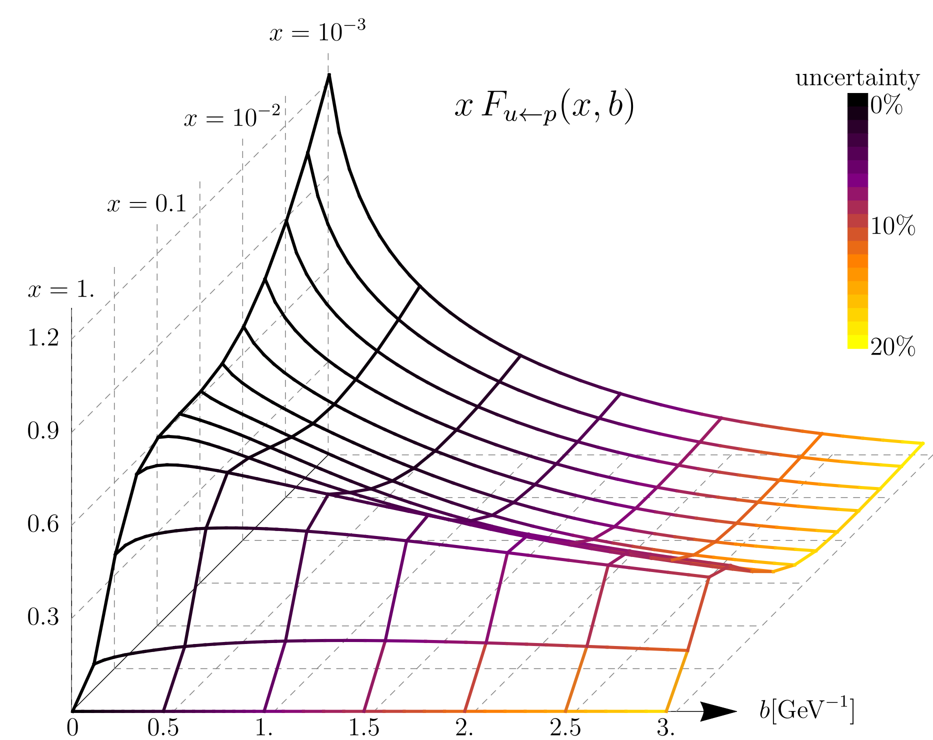
- nontrivial x dependence

plot in b_T space



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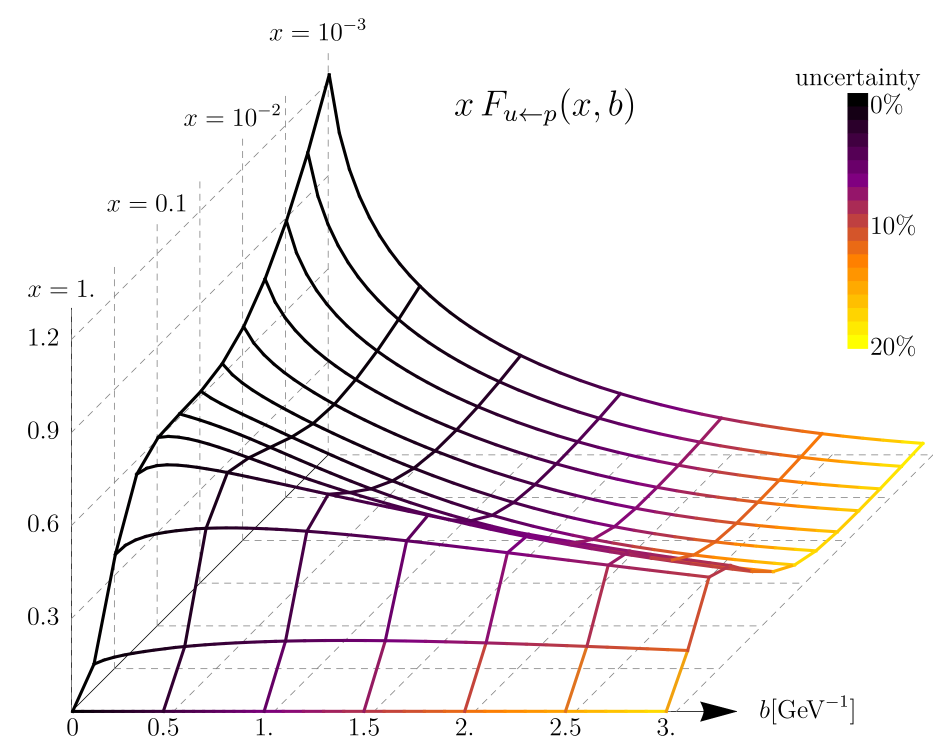

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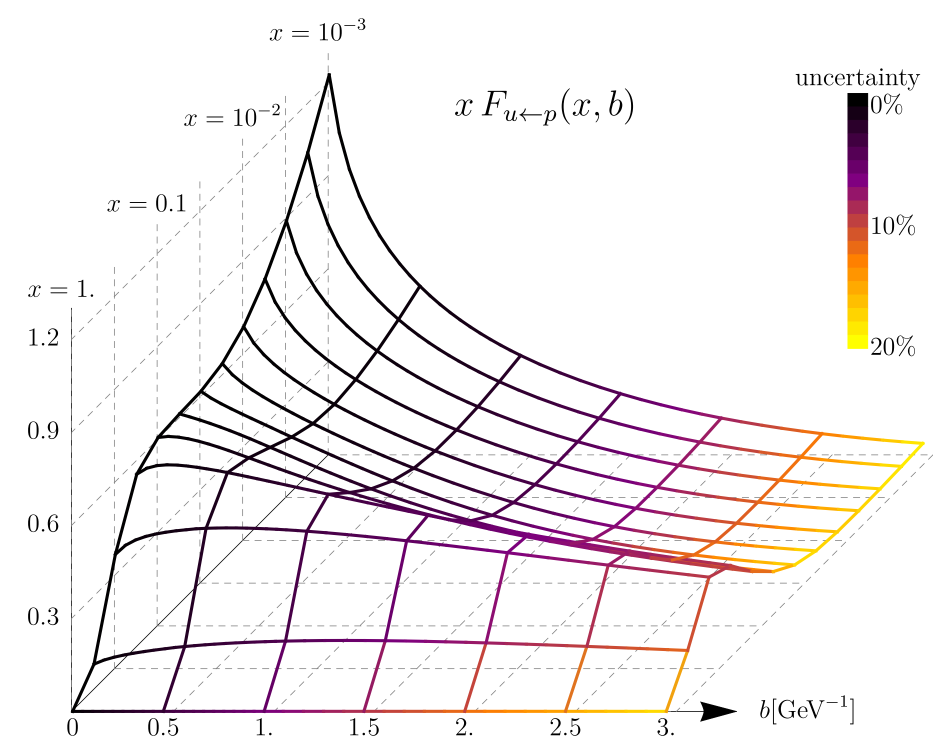
- Guassian at low b_T, exponential at high b_T
- nontrivial x dependence
- no flavor dependence
- Rapidity anomalous dimension
  (related to nonperturbative TMD evolution)

$$\mathcal{D}(\mu,b) = \mathcal{D}_{\text{resum}}(\mu, b^*(b)) + c_0 b b^*(b),$$

plot in b_T space



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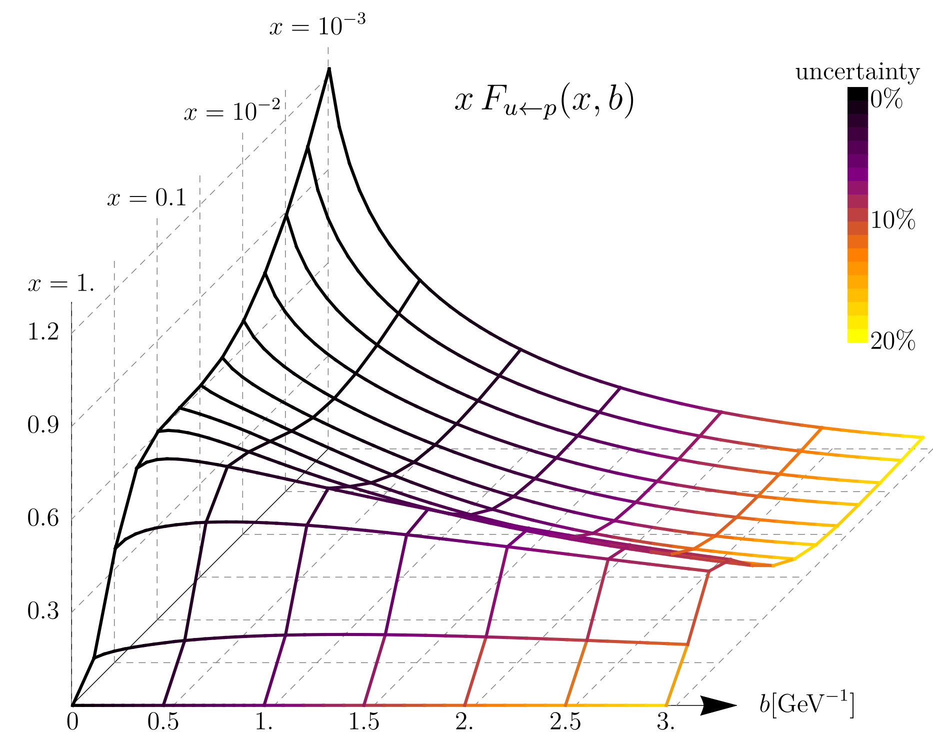
plot in b_T space



$$D_{NP}(x,b) = \exp\left(-\frac{\eta_1 z + \eta_2(1-z)}{\sqrt{1+\eta_3(\boldsymbol{b}/z)^2}}\frac{\boldsymbol{b}^2}{z^2}\right)\left(1+\eta_4\frac{\boldsymbol{b}^2}{z^2}\right)$$

TMD Frag. Func.

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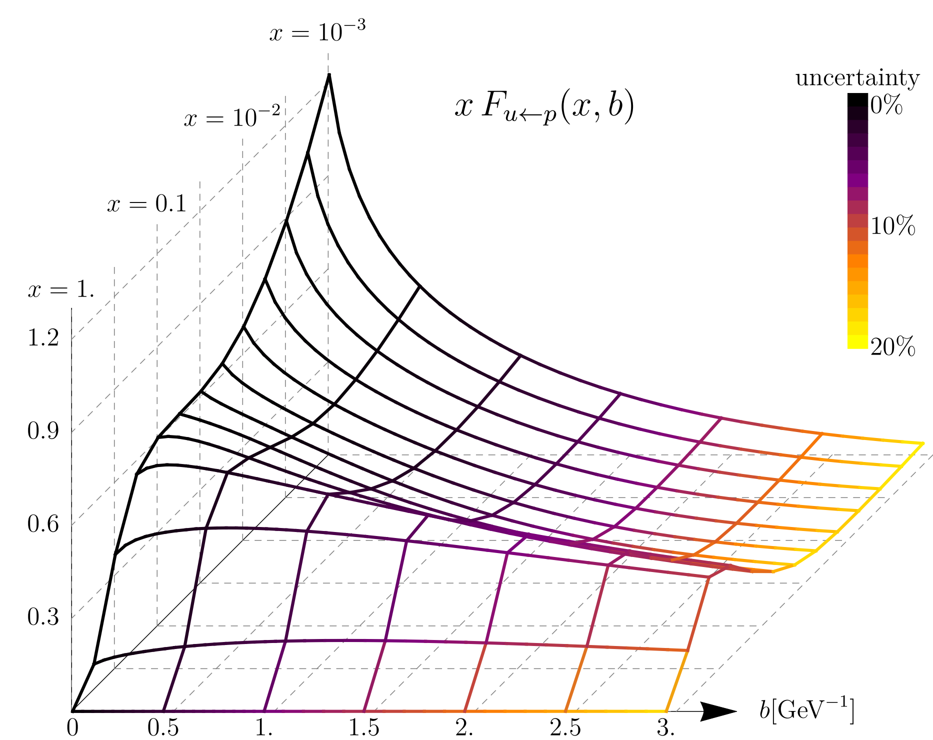
plot in b_T space



TMD Frag. Func.

11 free parameters

GENERAL CONSIDERATIONS

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- Not easy to perform direct comparison due to different formalisms employed

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- In all extractions, simple Gaussians are not sufficient

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GENERAL CONSIDERATIONS

- Not easy to perform direct comparison due to different formalisms employed
- In all extractions, simple Gaussians are not sufficient
- Nontrivial x-dependence is required
- No flavor dependence is needed for the moment (note however that some flavor dependence is already generated by the collinear PDFs)

AVAILABLE TOOLS: NANGA PARBAT

https://github.com/vbertone/NangaParbat

Nanga Parbat: a TMD fitting framework

Nanga Parbat is a fitting framework aimed at the determination of the non-perturbative component of TMD distributions.

Download

You can obtain NangaParbat directly from the github repository:

https://github.com/vbertone/NangaParbat/releases

For the last development branch you can clone the master code:

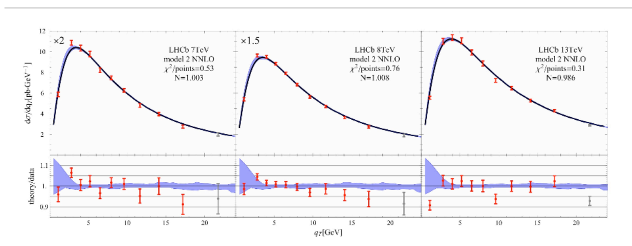
```
git clone git@github.com:vbertone/NangaParbat.git
```

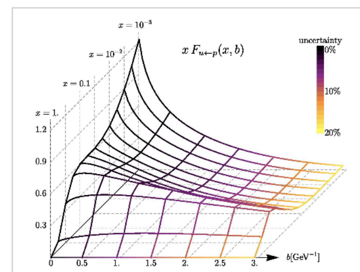
If you instead want to download a specific tag:

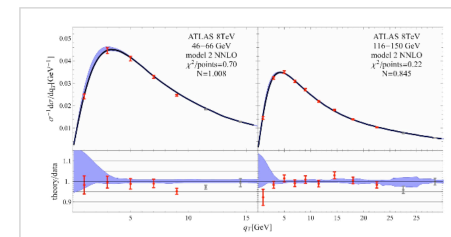
AVAILABLE TOOLS: ARTEMIDE

https://teorica.fis.ucm.es/artemide/

arTeMiDe







News

12 Dec 2019: Version 2.02 released (+manual update).

23 Feb 2019: Version 1.4 released (+manual update).

21 Jan 2019: Artemide now has a repository.

Archive of older links/news.

Articles, presentations & supplementary materials

Extra pictures for the paper arXiv:1902.08474

Seminar of A.Vladimirov in Pavia 2018 on TMD evolution.

Link to the text in Inspire.

Archive of older links/news.

Download

Recent version/release can be found in repository

About us & Contacts

If you have found mistakes, or have suggestions/questions, please, contact us.

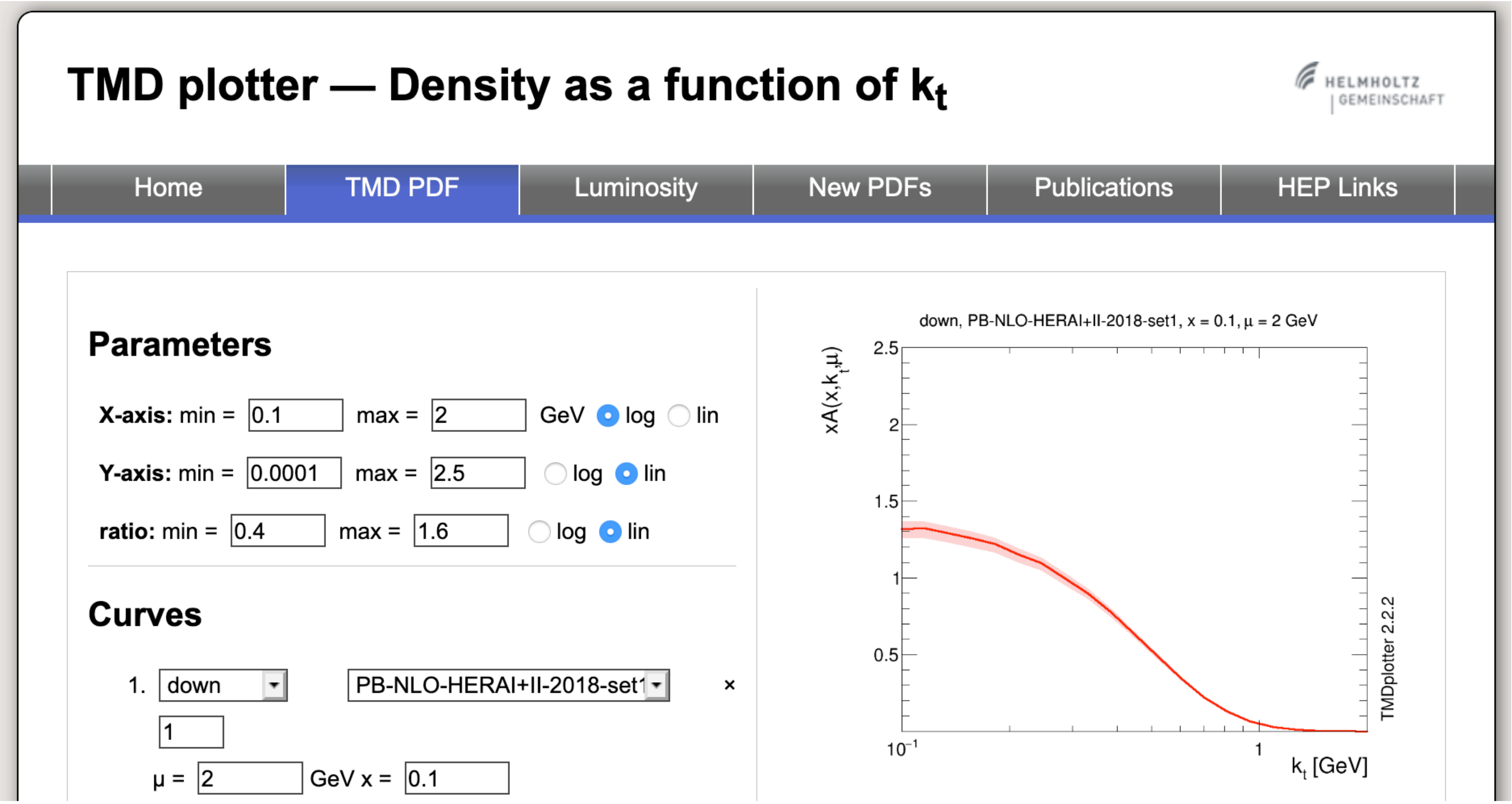
Some extra materials can be found on Alexey's web-page

Alexey Vladimirov Alexey.Vladimirov@physik.uni-regensburg.de

Ignazio Scimemi ignazios@fis.ucm.es

TMDLIB AND TMDPLOTTER

https://tmdlib.hepforge.org/



Soon more TMD parametrisation will be available

TOOLS USED FOR DRELL-YAN PREDICTIONS

V. Bertone's talk at LHC EW WG General Meeting, Dec 2019
https://indico.cern.ch/event/849342/

SCETlib [https://confluence.desy.de/display/scetlib]	SCET
CuTe [https://cute.hepforge.org]	SCET
DYRes/DYTURBO [https://gitlab.cern.ch/DYdevel/DYTURBO]	q_T-res.
ReSolve [https://github.com/fkhorad/reSolve]	q_T-res.
RadISH [https://arxiv.org/pdf/1705.09127.pdf]	PB
PB-TMD [https://arxiv.org/pdf/1906.00919.pdf]	PB
NangaParbat [https://github.com/vbertone/NangaParbat]	TMD
arTeMiDe [https://teorica.fis.ucm.es/artemide/]	TMD

TOOLS USED FOR DRELL-YAN PREDICTIONS

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https://indico.cern.ch/event/849342/

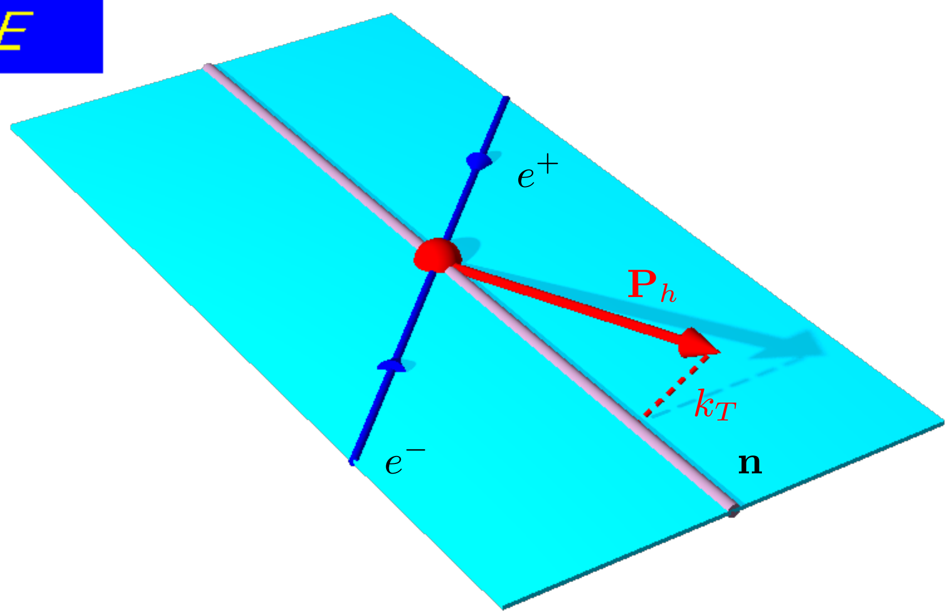
SCETlib [https://confluence.desy.de/display/scetlib]	SCET
CuTe [https://cute.hepforge.org]	SCET
DYRes/DYTURBO [https://gitlab.cern.ch/DYdevel/DYTURBO]	q_T-res.
ReSolve [https://github.com/fkhorad/reSolve]	q_T-res.
RadISH [https://arxiv.org/pdf/1705.09127.pdf]	PB
PB-TMD [https://arxiv.org/pdf/1906.00919.pdf]	PB
NangaParbat [https://github.com/vbertone/NangaParbat]	TMD
arTeMiDe [https://teorica.fis.ucm.es/artemide/]	TMD

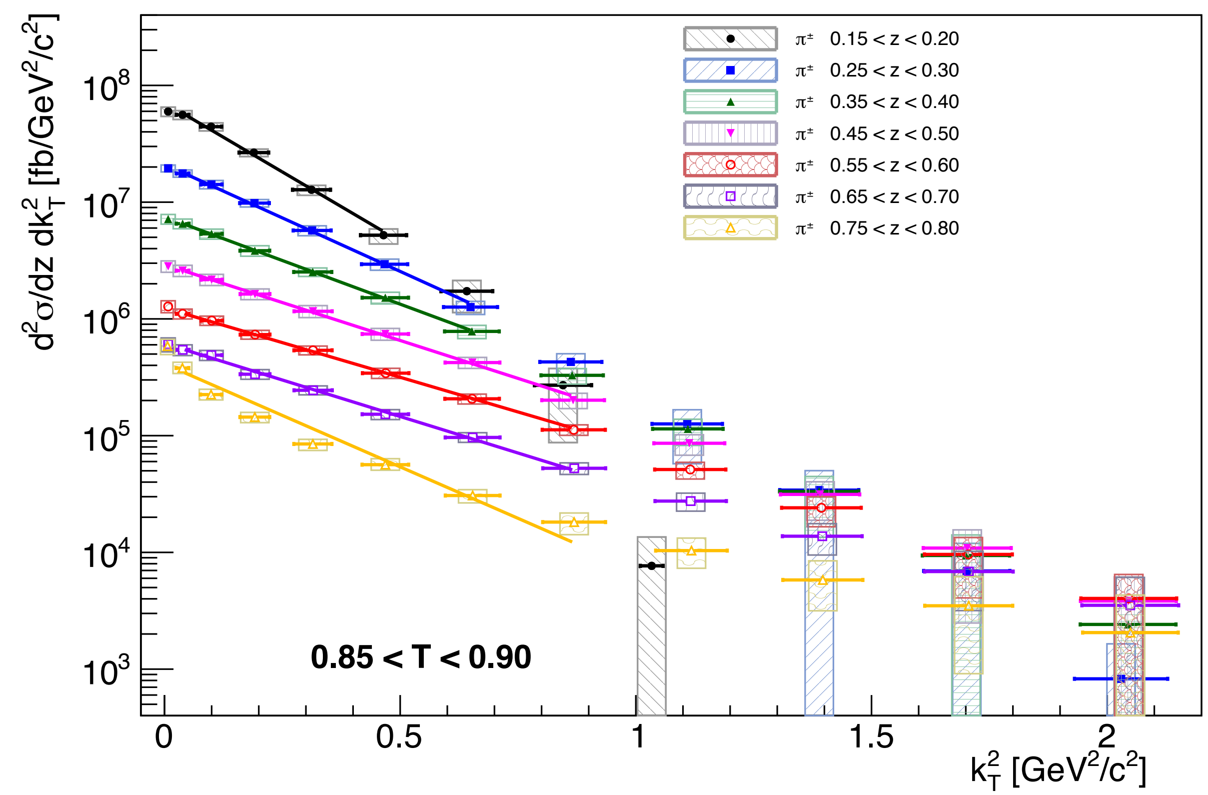
There is an entire industry of tools that make predictions for observables related to TMDs.
Most of them neglect SIDIS and the important effects coming from nonperturbative TMD components.

OPEN ISSUES

TRANSVERSE MOMENTUM IN FRAGMENTATION FUNCTIONS

Seidl et al., arXiv:1807.02101

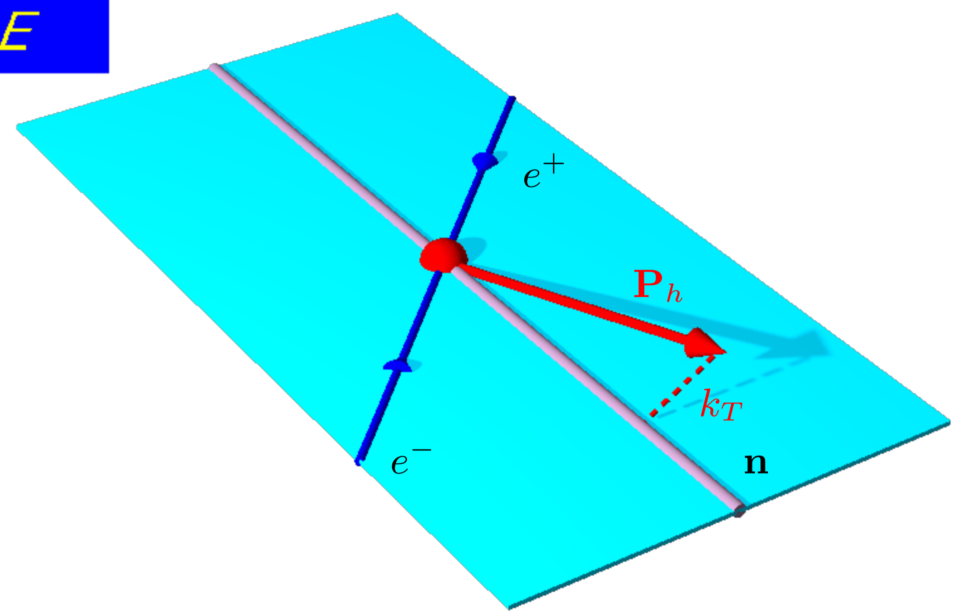


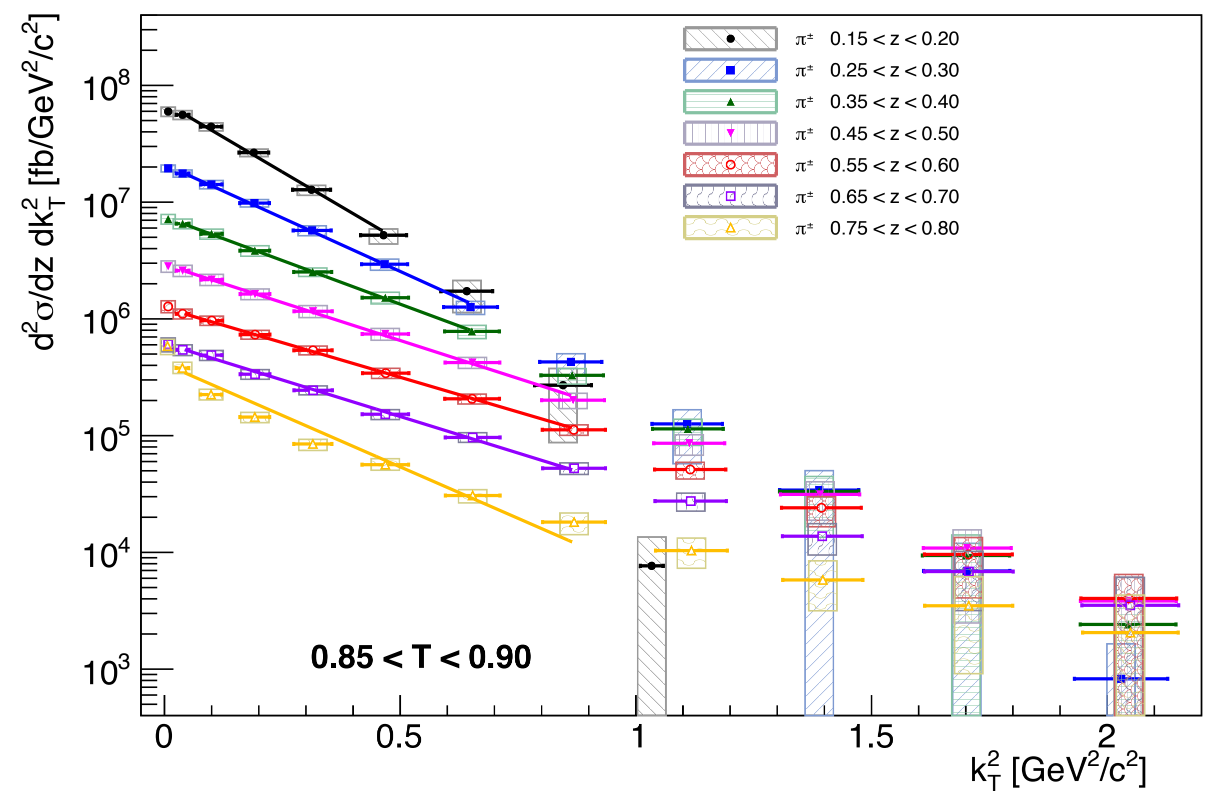


First direct measurement of TMD effects in fragmentation functions
Makes use of thrust axis: the formalism should take it into account

TRANSVERSE MOMENTUM IN FRAGMENTATION FUNCTIONS

Seidl et al., arXiv:1807.02101





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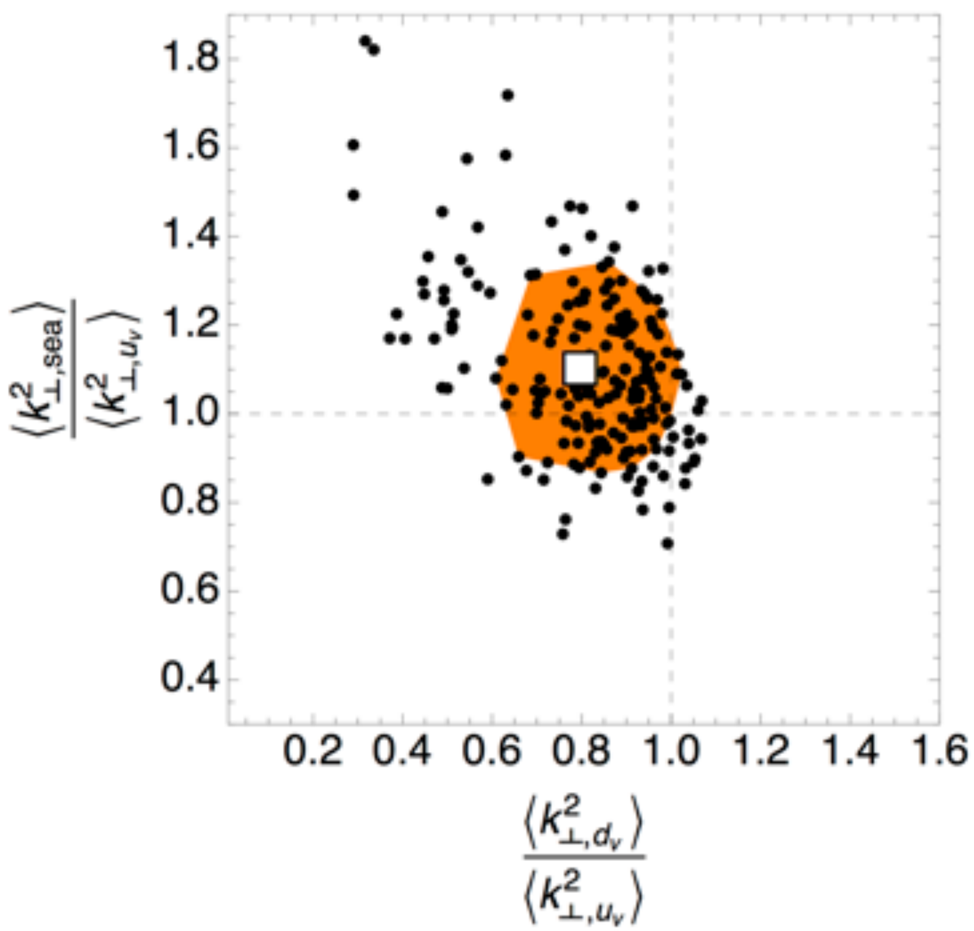
Parton-model attempt to extract TMDFFs: arXiv:1907.12294

FLAVOR DEPENDENCE OF TMDS

Signori, Bacchetta, Radici, Schnell JHEP 1311 (13)

Ratio of width of sea / width of up valence



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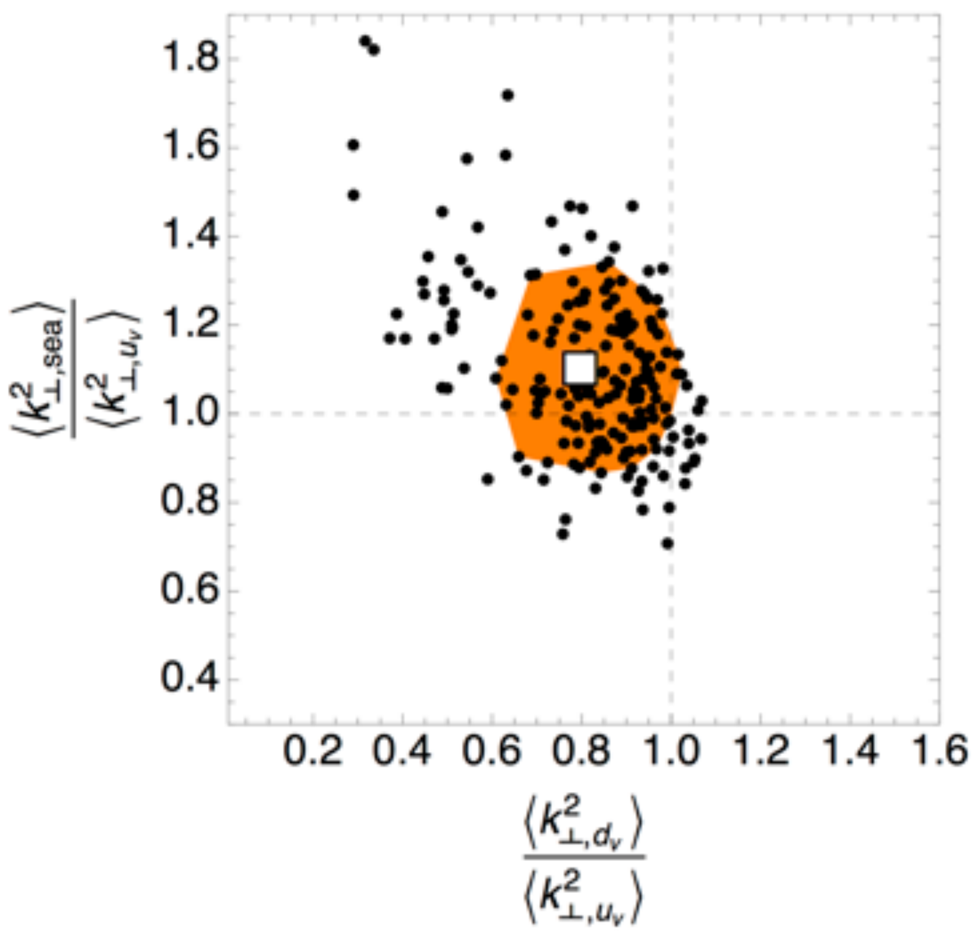

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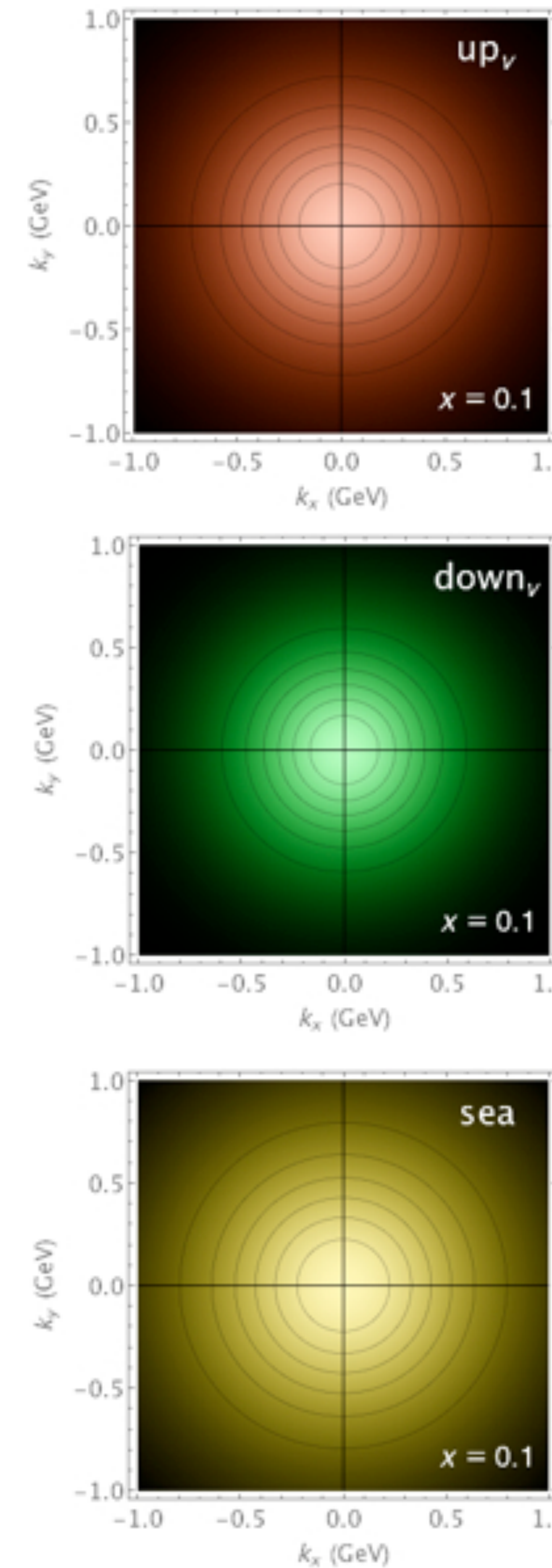

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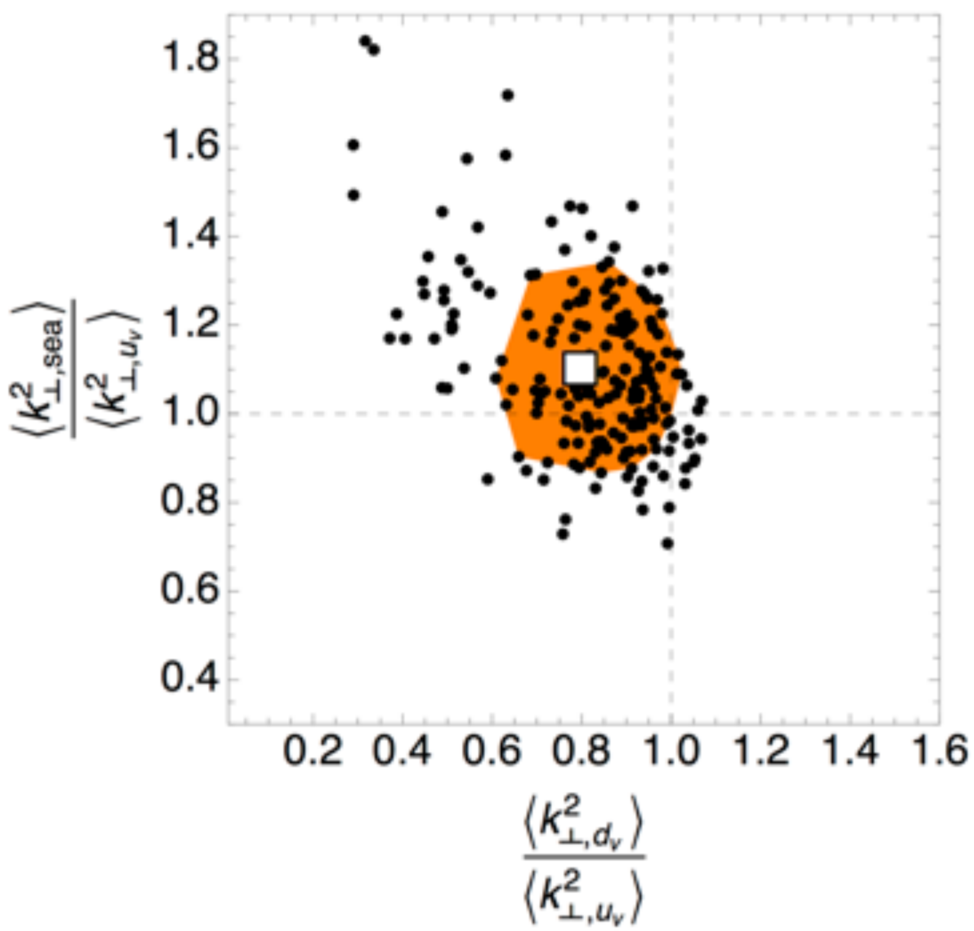

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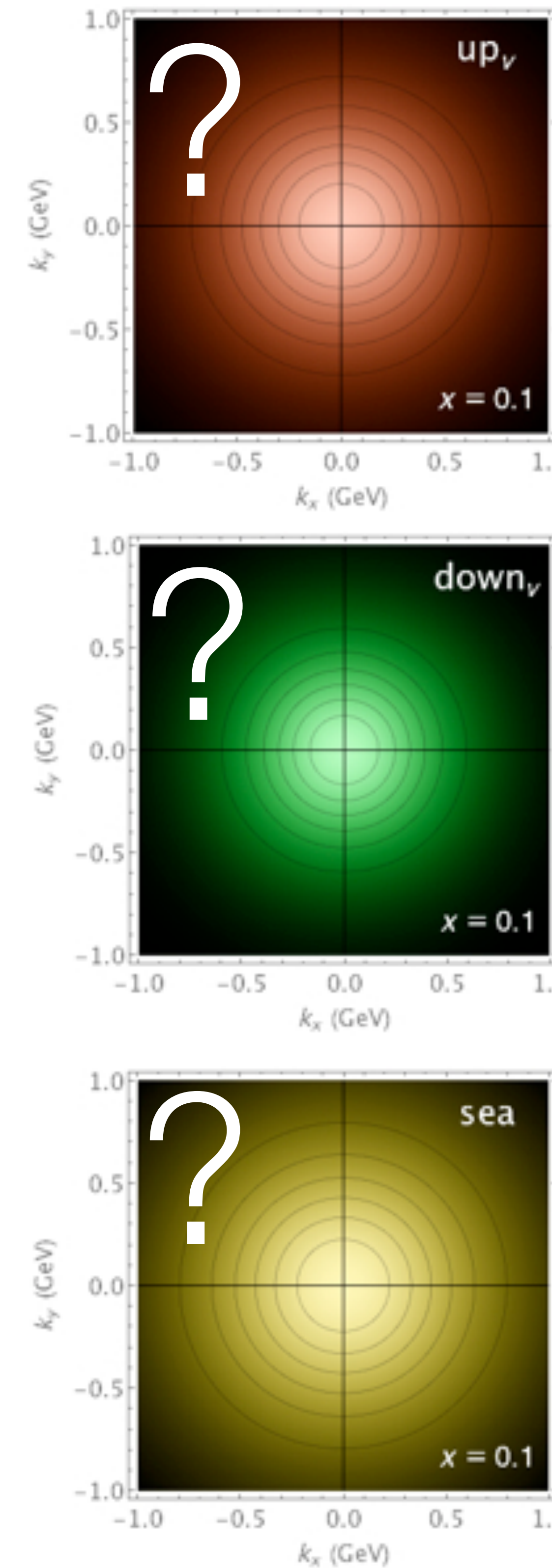

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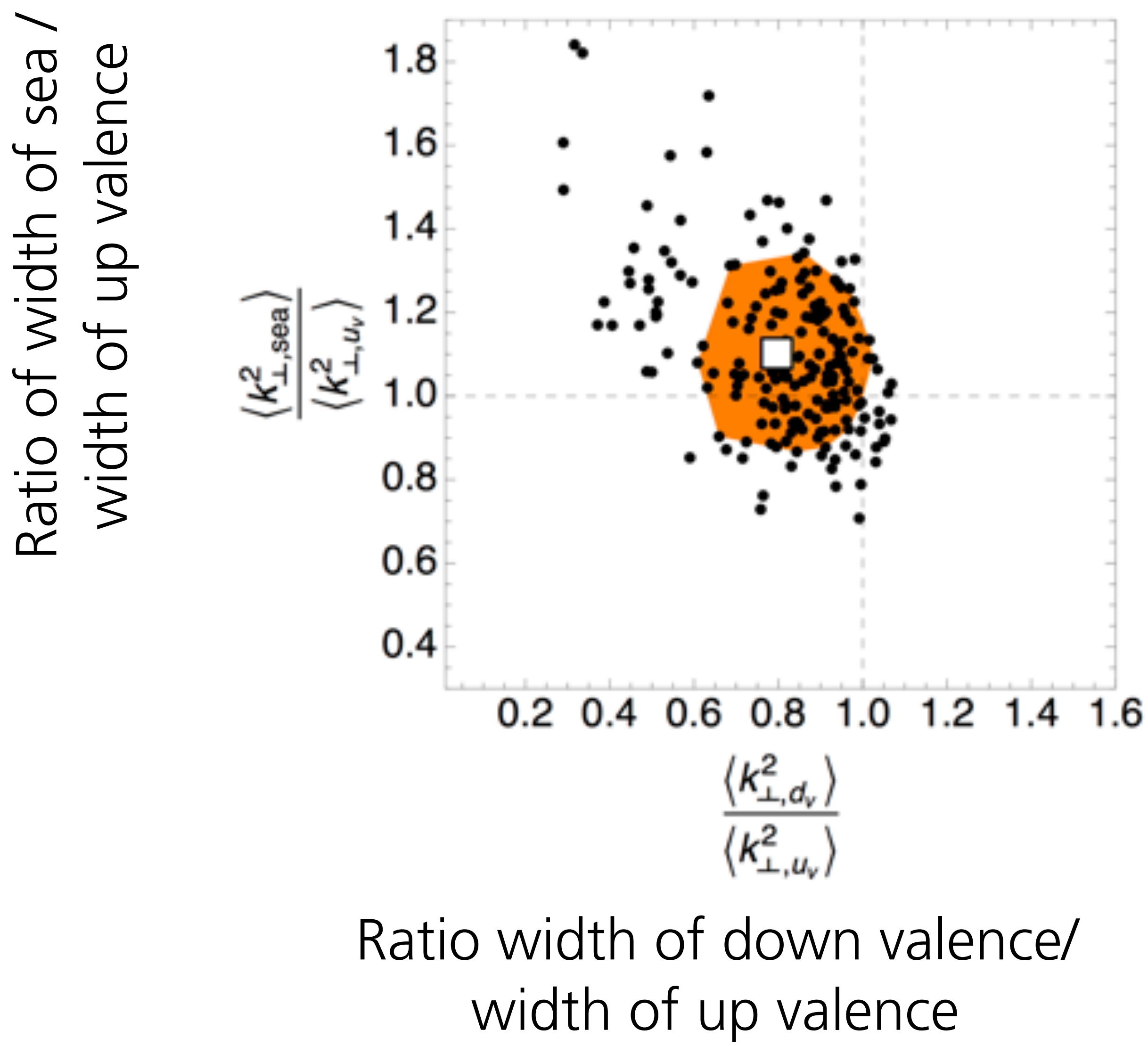
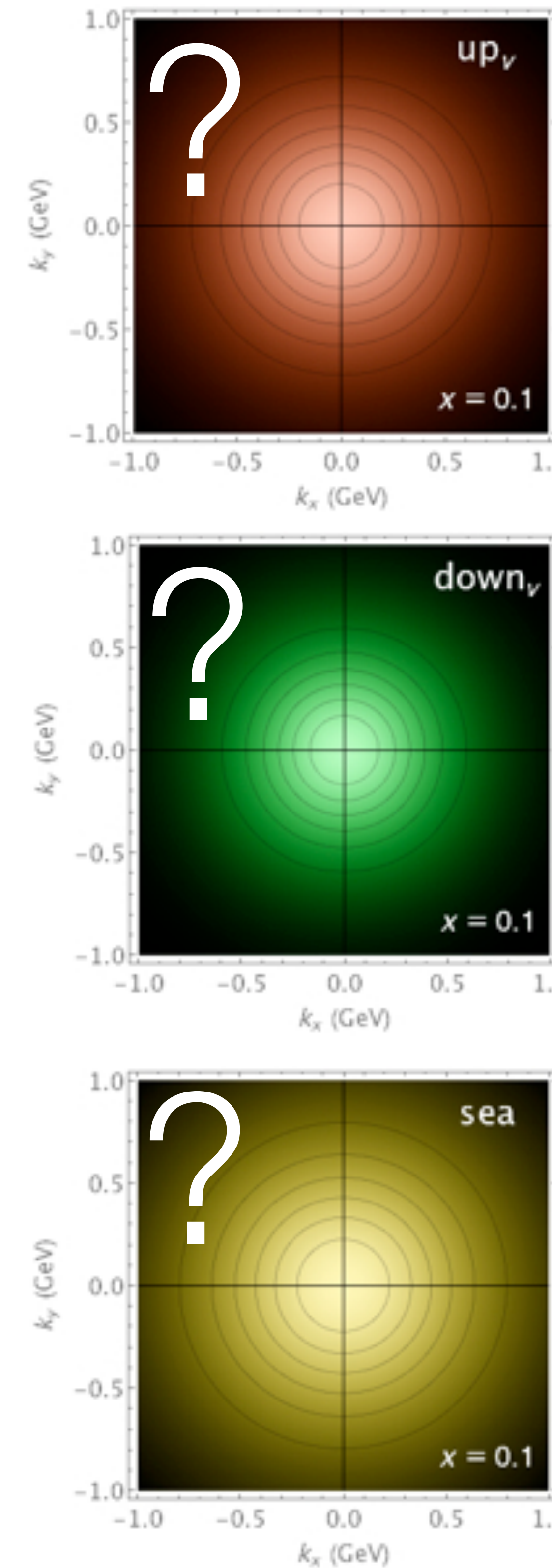
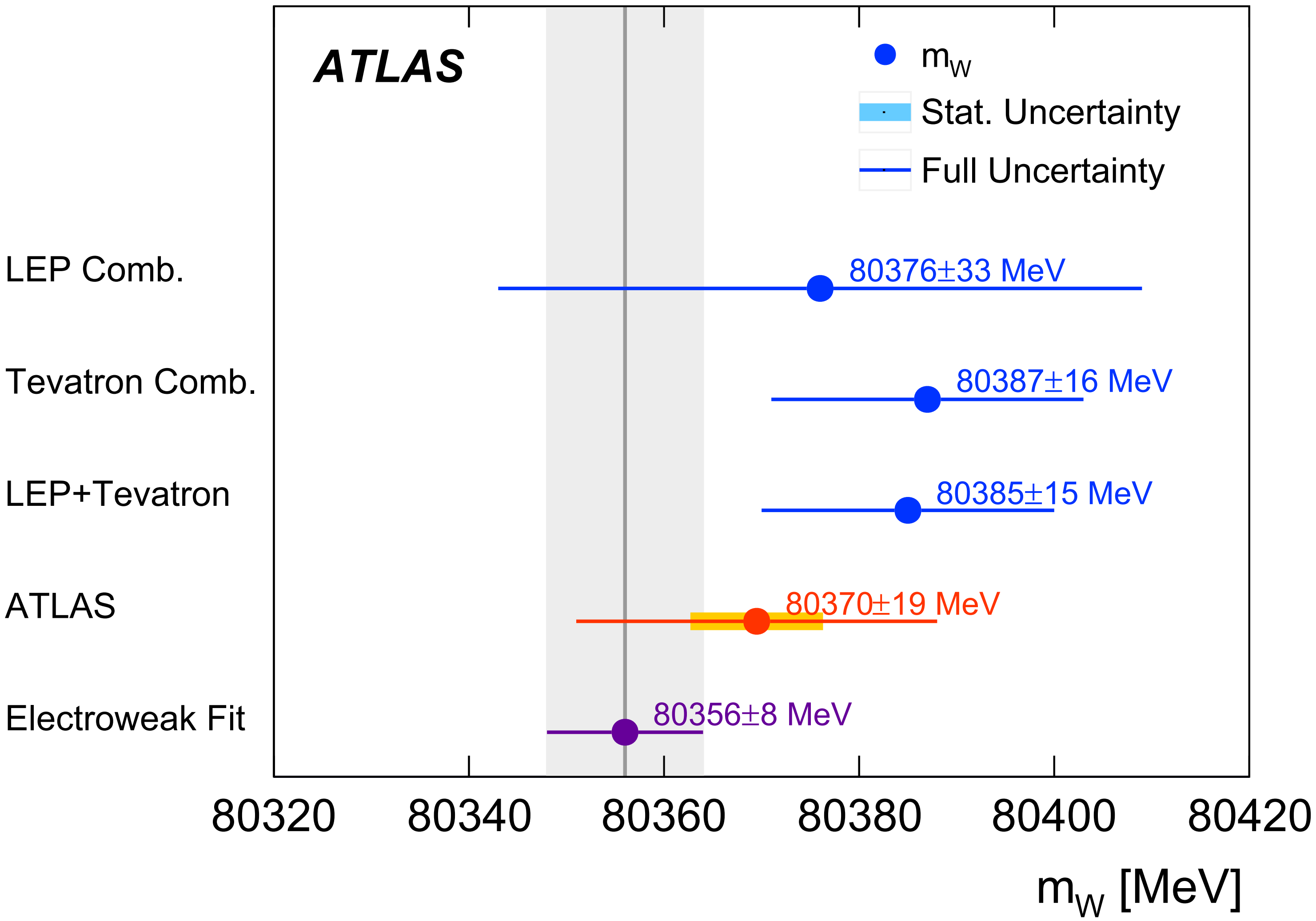




There is room for flavour dependence,
but we don't control it well

IMPACT ON W MASS DETERMINATION

ATLAS Collab. arXiv:1701.07240



$$\begin{aligned} m_W &= 80370 \pm 7\ (\text{stat.}) \pm 11\ (\text{exp. syst.}) \pm 14\ (\text{mod. syst.})\ \text{MeV} \\ &= 80370 \pm 19\ \text{MeV}, \end{aligned}$$

$$m_{W^+} - m_{W^-} = -29 \pm 28\ \text{MeV}.$$

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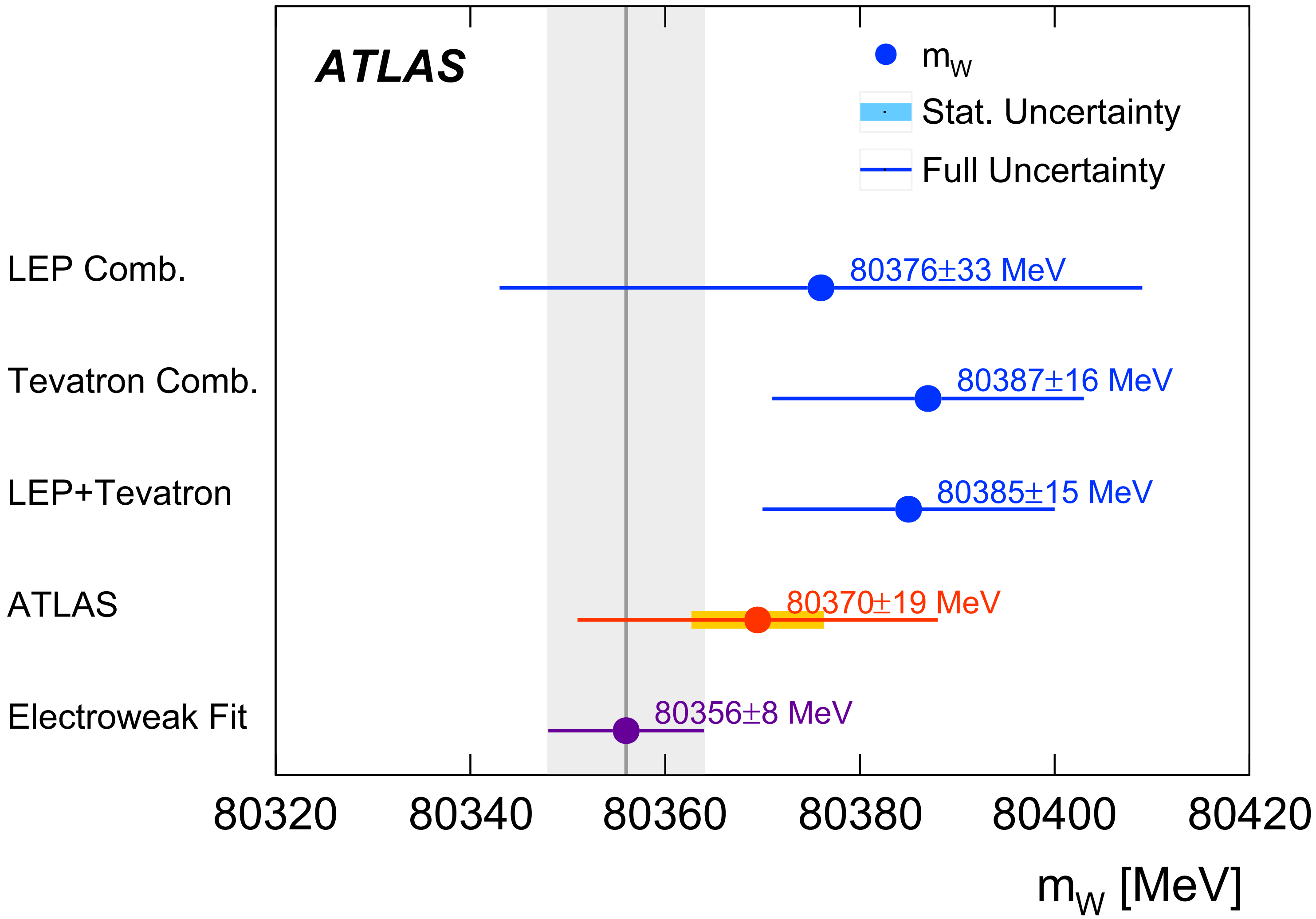

All analyses assume that TMDs are not flavor dependent.
What happens if they are?

$$
\begin{aligned}
m_W &= 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV} \\
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Try some judicious choices of flavour dependent widths and check

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Try some judicious choices of flavour dependent widths and check

Set	u_v	d_v	u_s	d_s	s
1	0.34	0.26	0.46	0.59	0.32
2	0.34	0.46	0.56	0.32	0.51
3	0.55	0.34	0.33	0.55	0.30
4	0.53	0.49	0.37	0.22	0.52
5	0.42	0.38	0.29	0.57	0.27

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narrow, medium, large
narrow, large, narrow
large, narrow, large
large, medium, narrow
medium, narrow, large

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	ΔM_{W+}		ΔM_{W-}	
Set	m_T	$p_{T\ell}$	m_T	$p_{T\ell}$
1	0	-1	-2	3
2	0	-6	-2	0
3	-1	9	-2	-4
4	0	0	-2	-4
5	0	4	-1	-3

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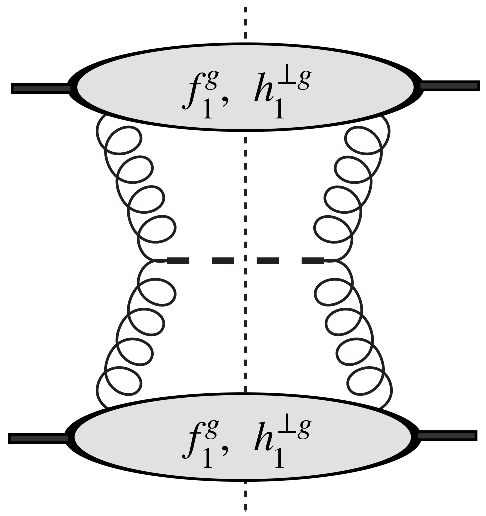
Not taking into account the flavour dependence of TMDs can lead to errors in the determination of the W mass

GLUON TMDS

Higgs production

Gutierrez-Reyes, Leal-Gomez, Scimemi, Vladimirov, arXiv:1907.03780



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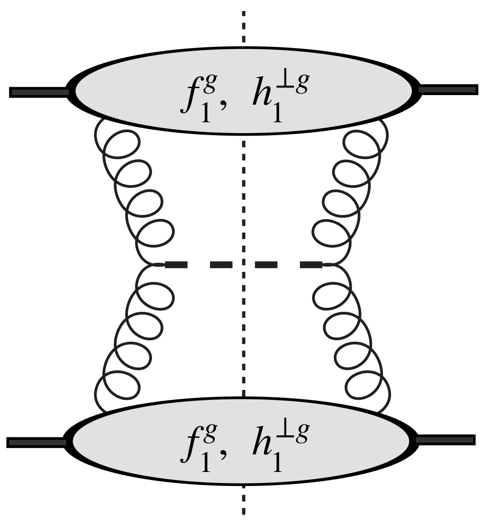
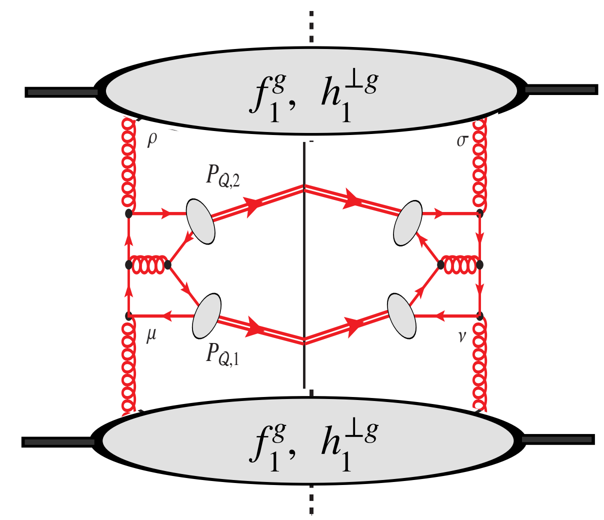


Quarkonium-pair production

Scarpa, Boer, Echevarria, Lansberg, Pisano, Schlegel, arXiv:1909.05769



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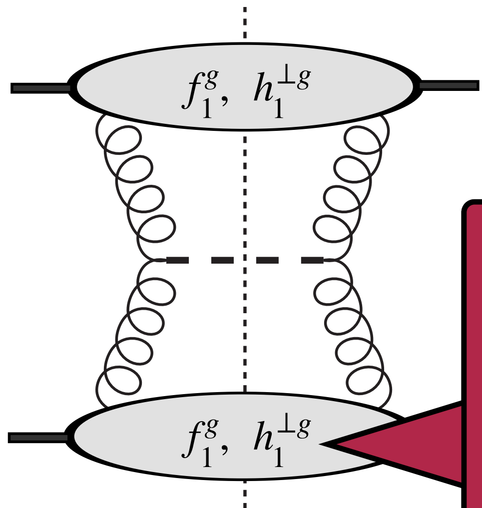

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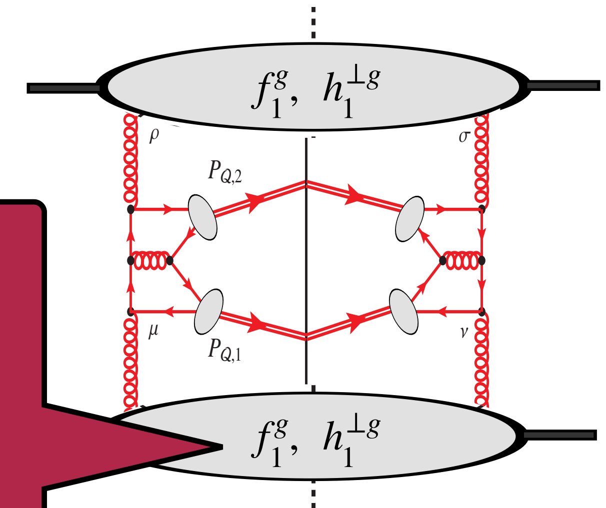

Also linearly polarized gluon TMD is involved!

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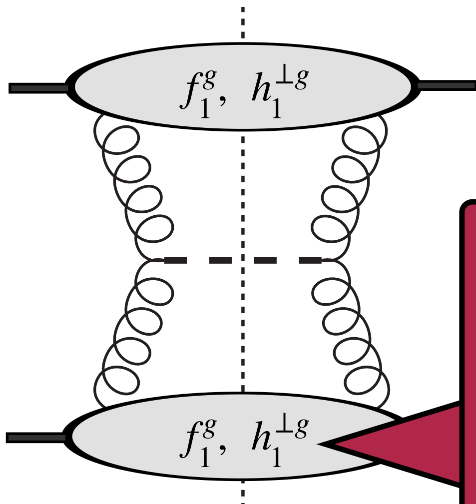

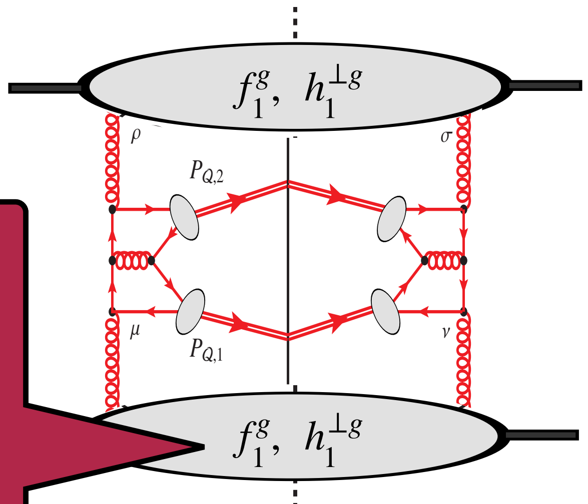

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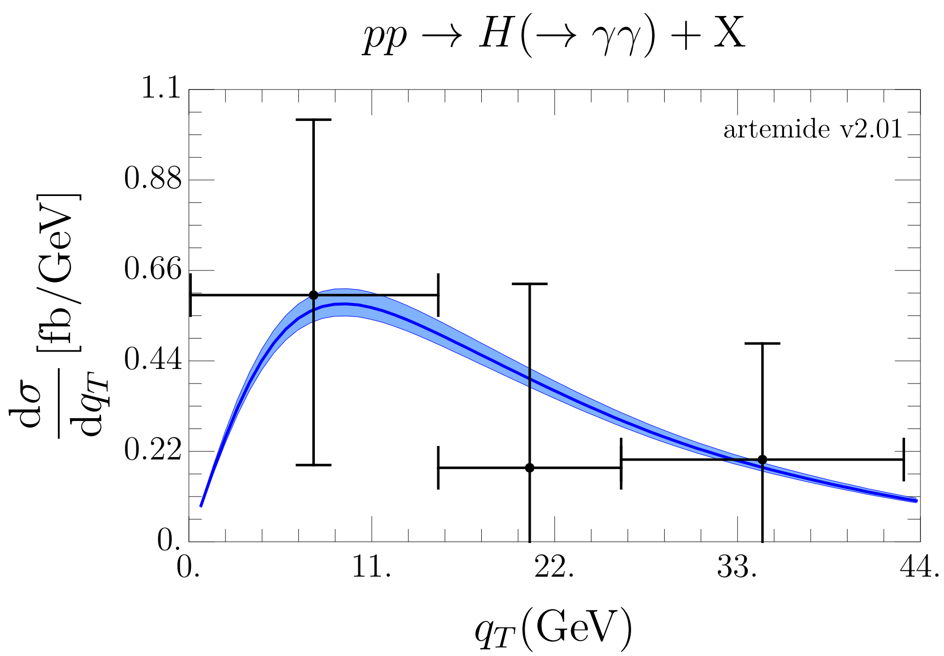

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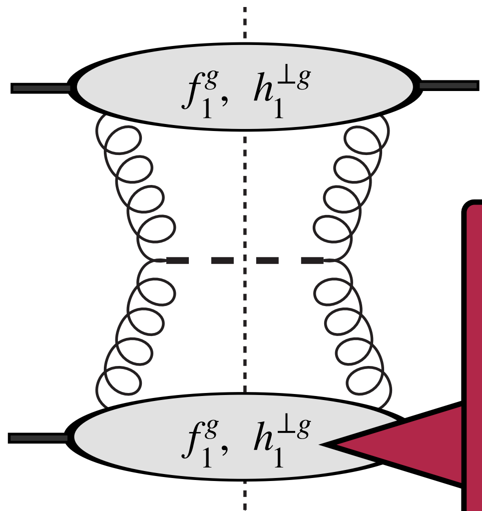

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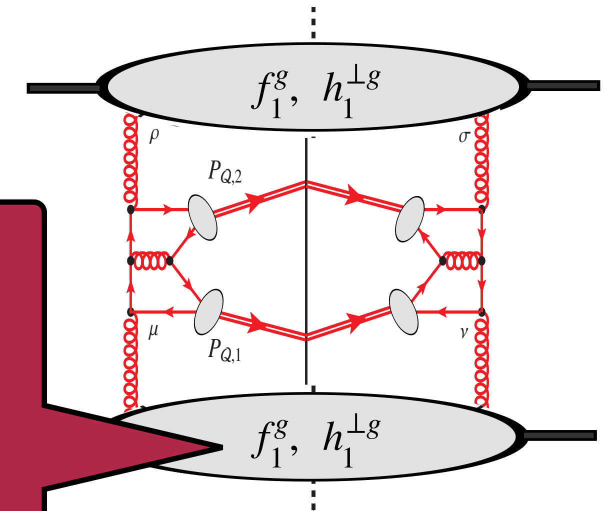

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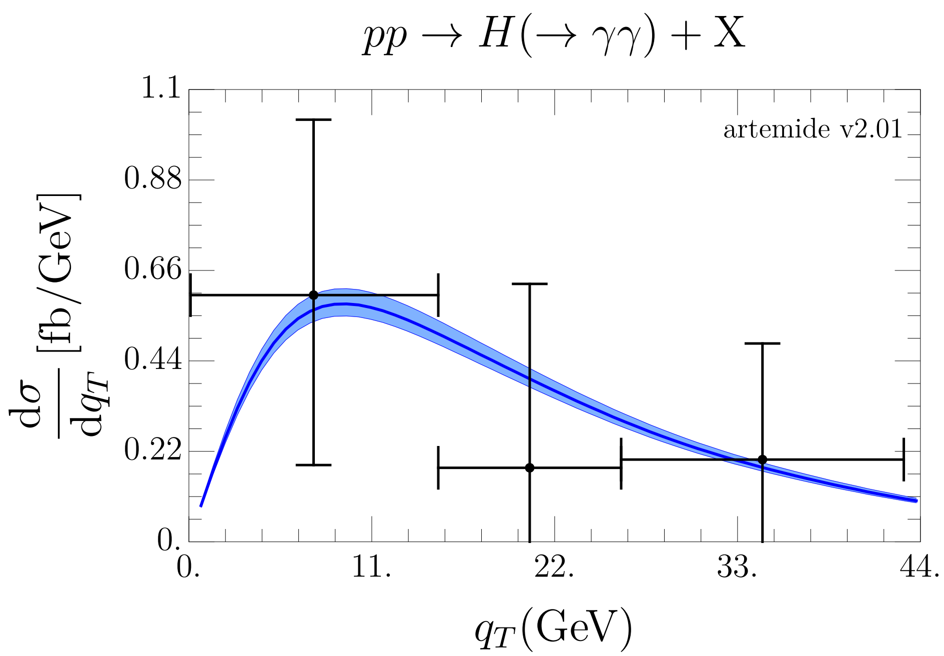

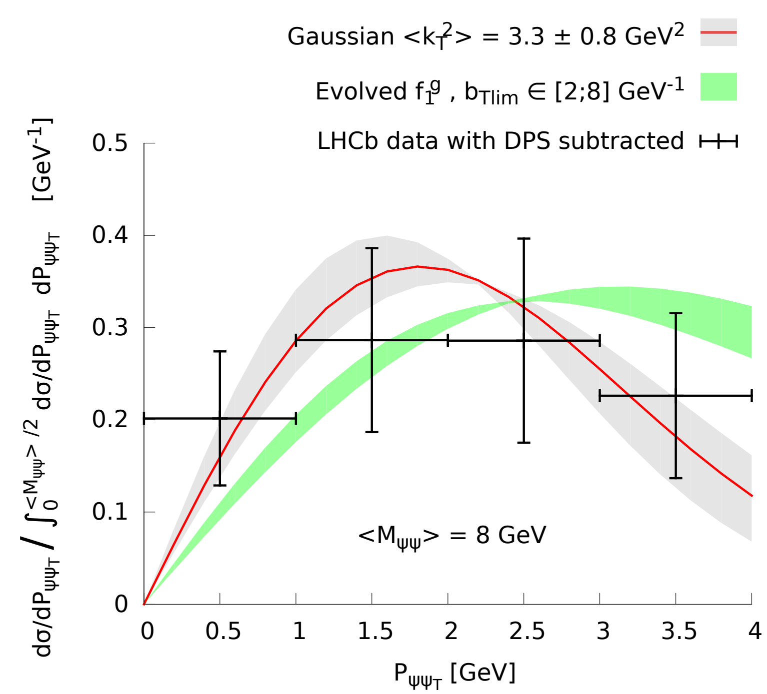

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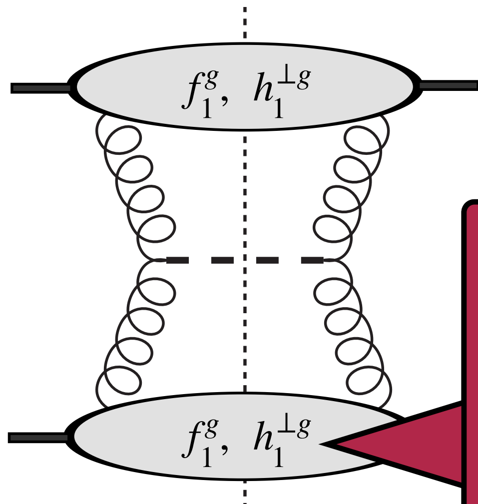

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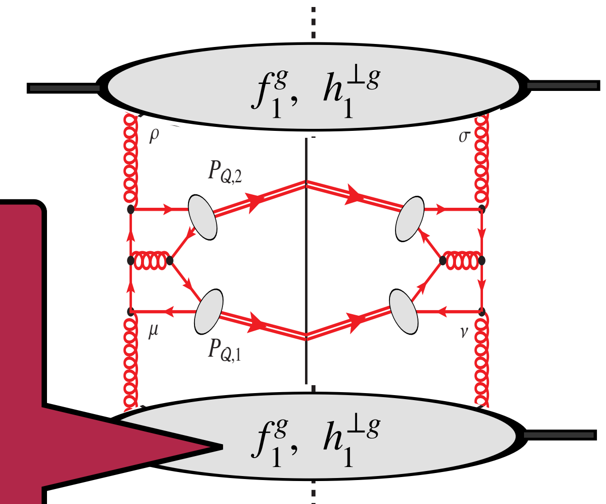

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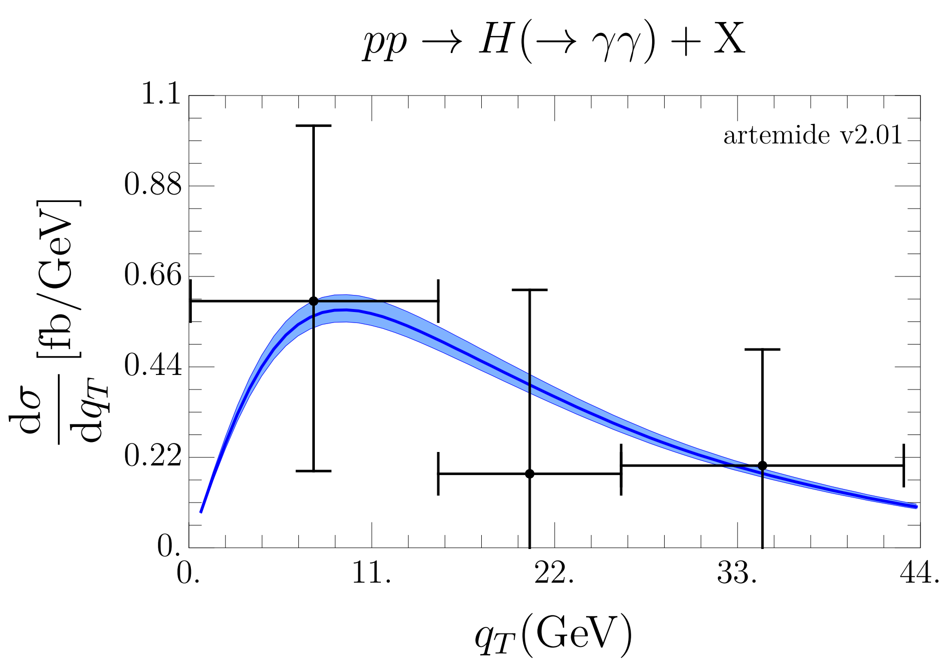
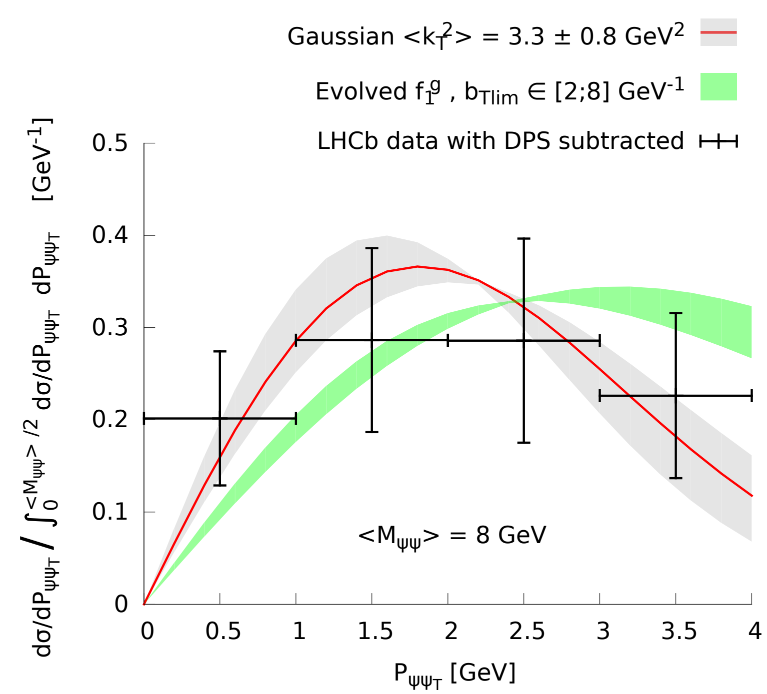
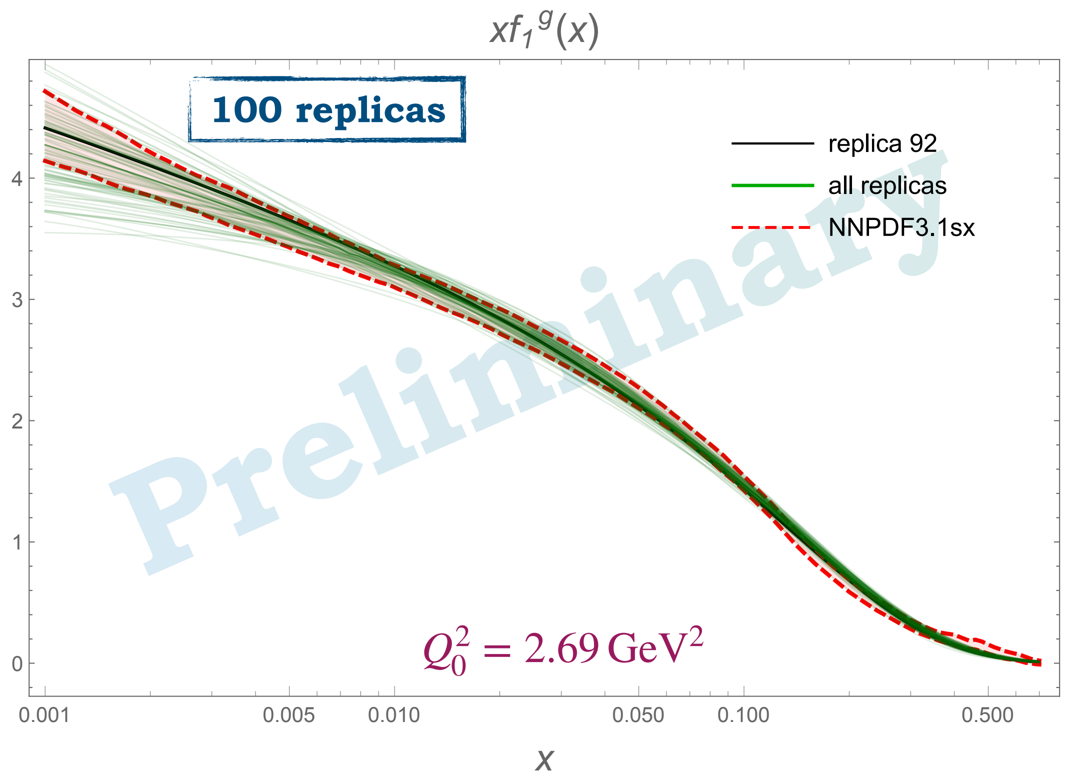




see also talk by Raj Kishore for other process

MODEL FOR GLUON TMDS



see talk by F. Celiberto at REF2019
https://agenda.infn.it/event/17749

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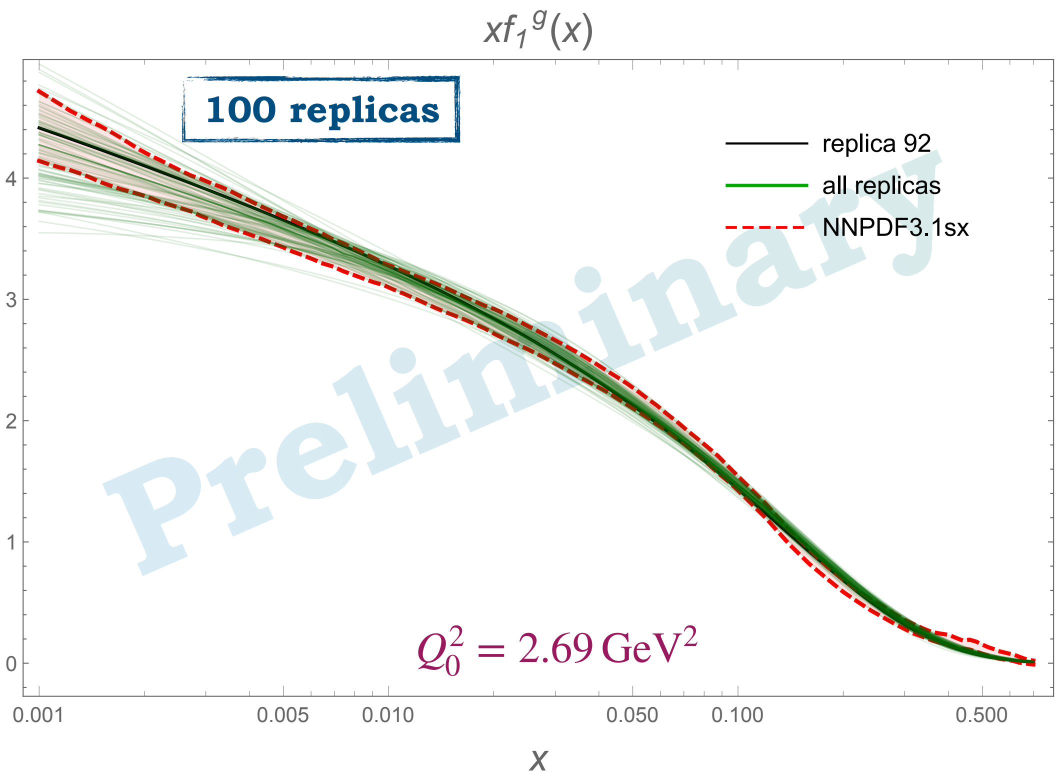

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Spectator model with spectral function

Reproduces collinear gluon PDFs

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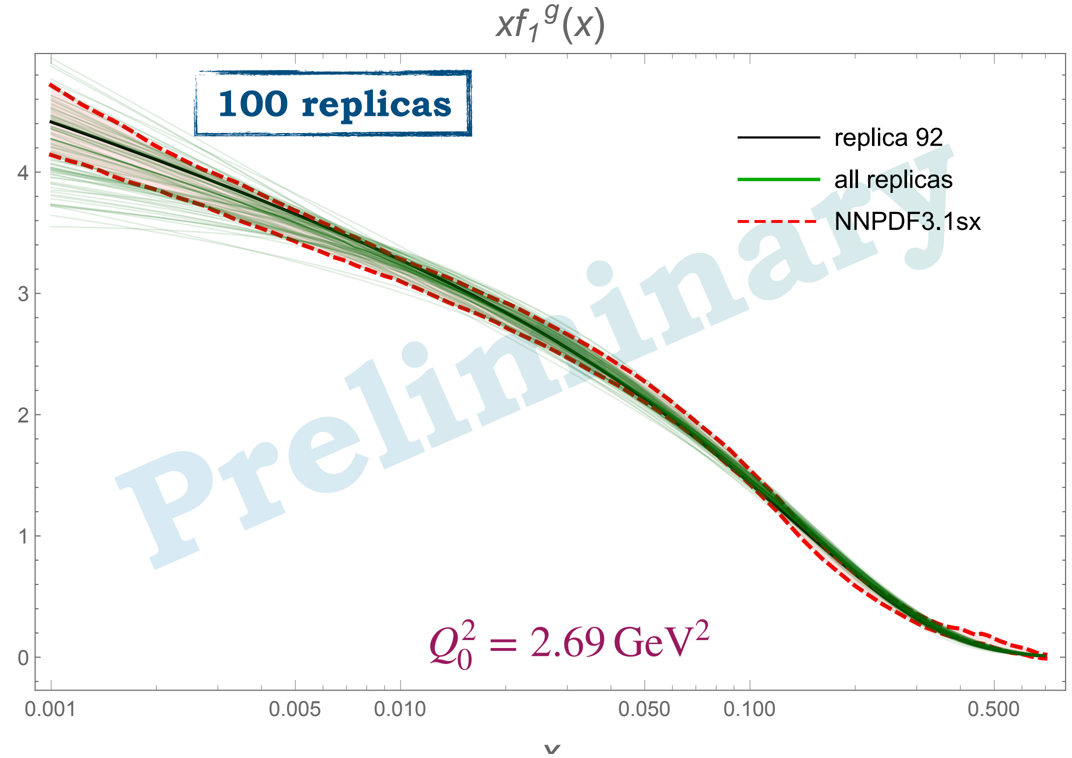

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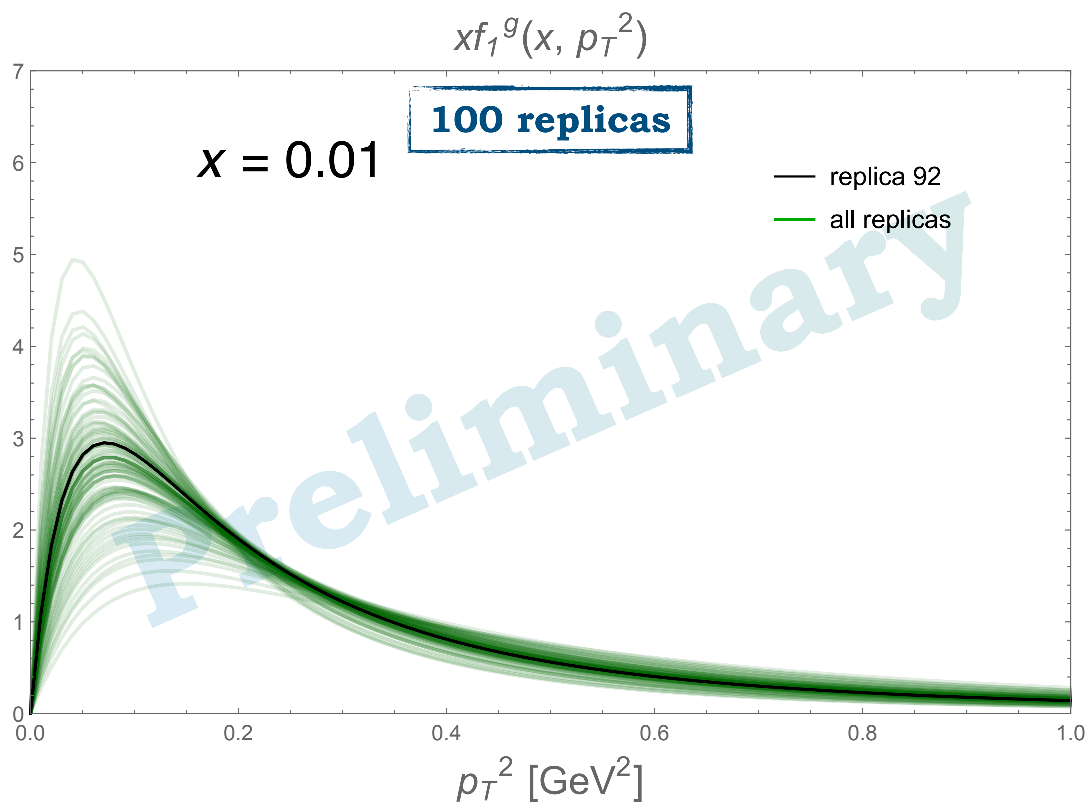
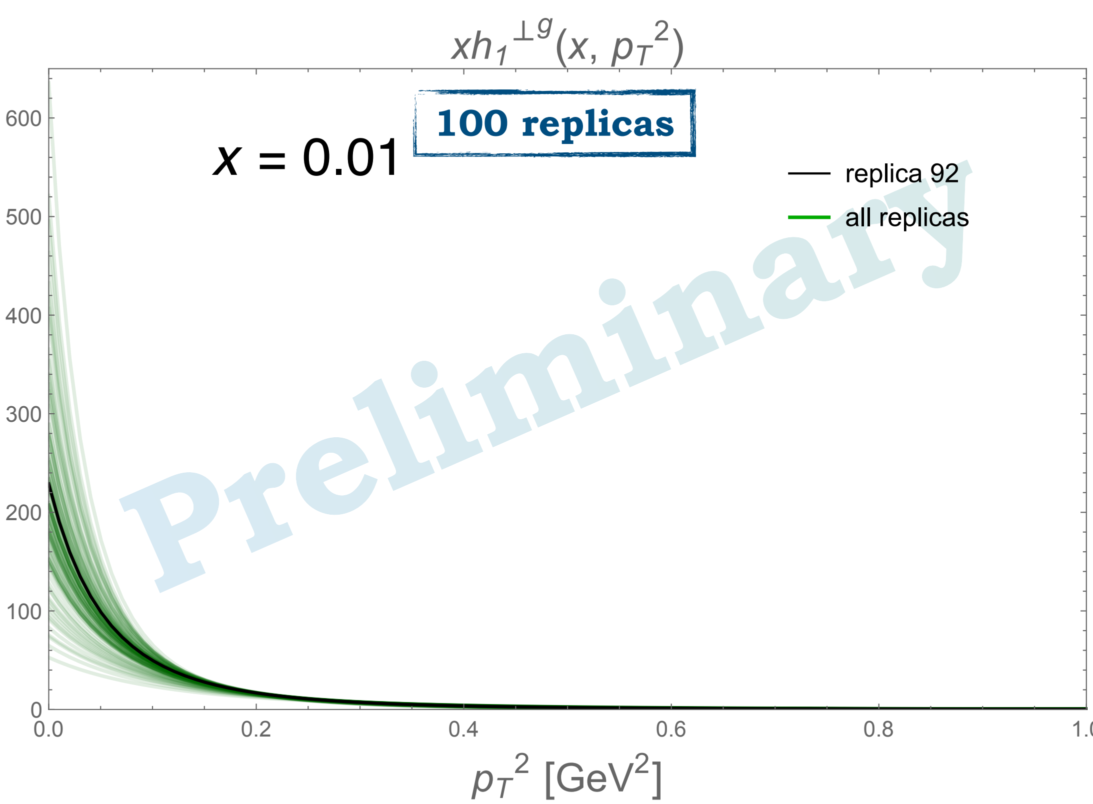
Spectator model with spectral function

Reproduces collinear gluon PDFs

Generates nontrivial and widely different TMDs

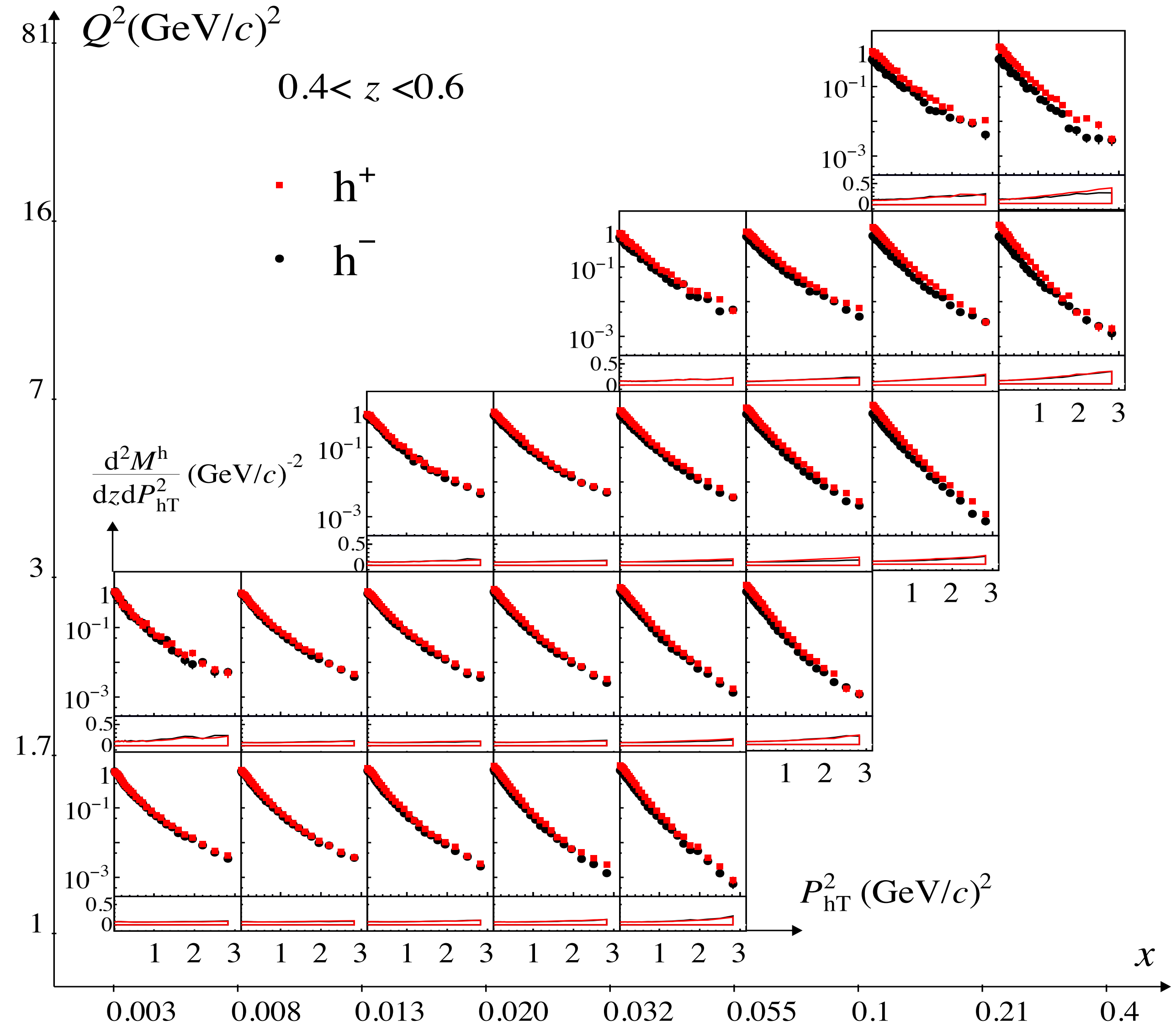




THE FUTURE

NEW DATA FROM COMPASS

Multidimesional binning



COMPASS Collab., arXiv:1709.07374

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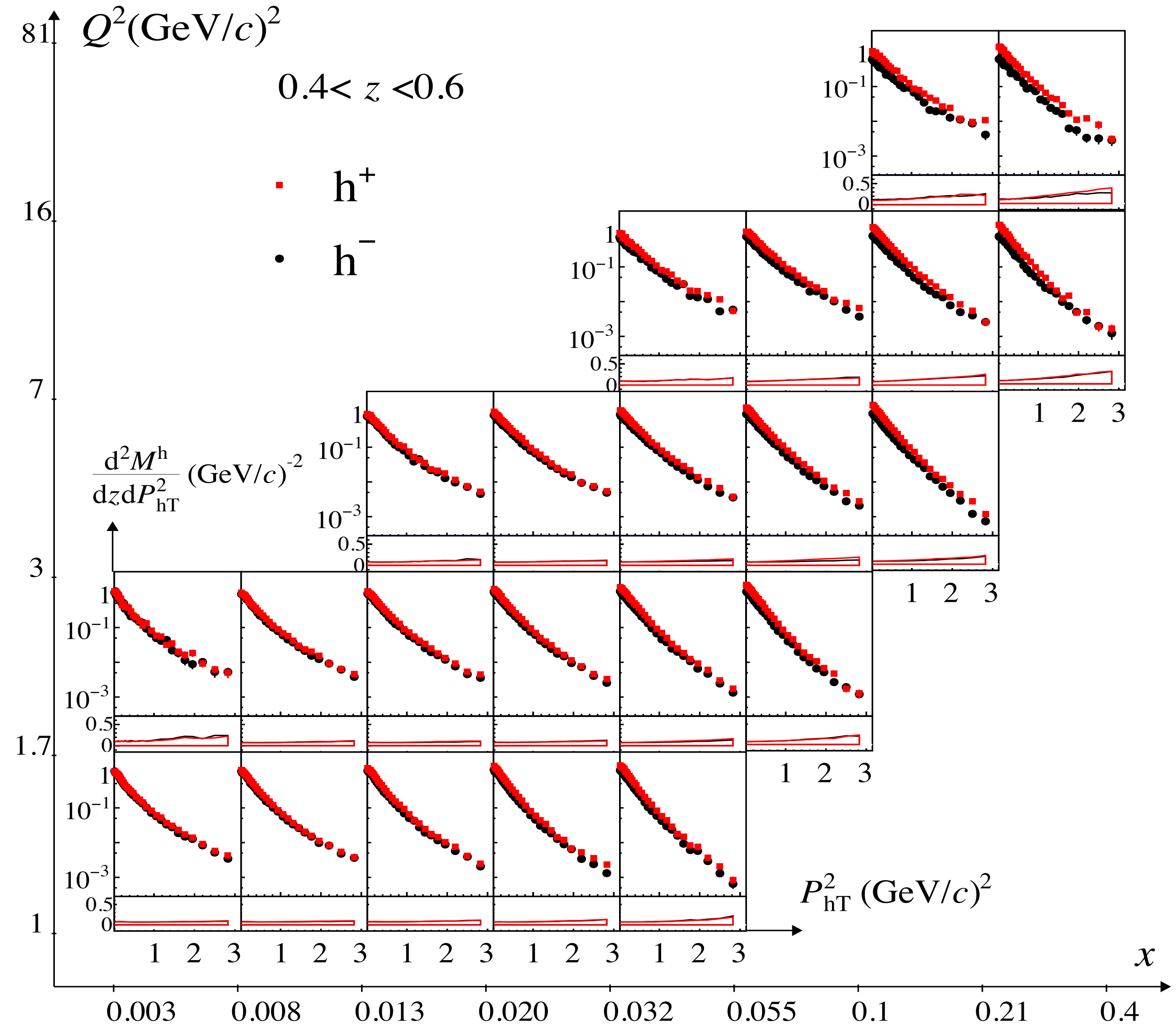
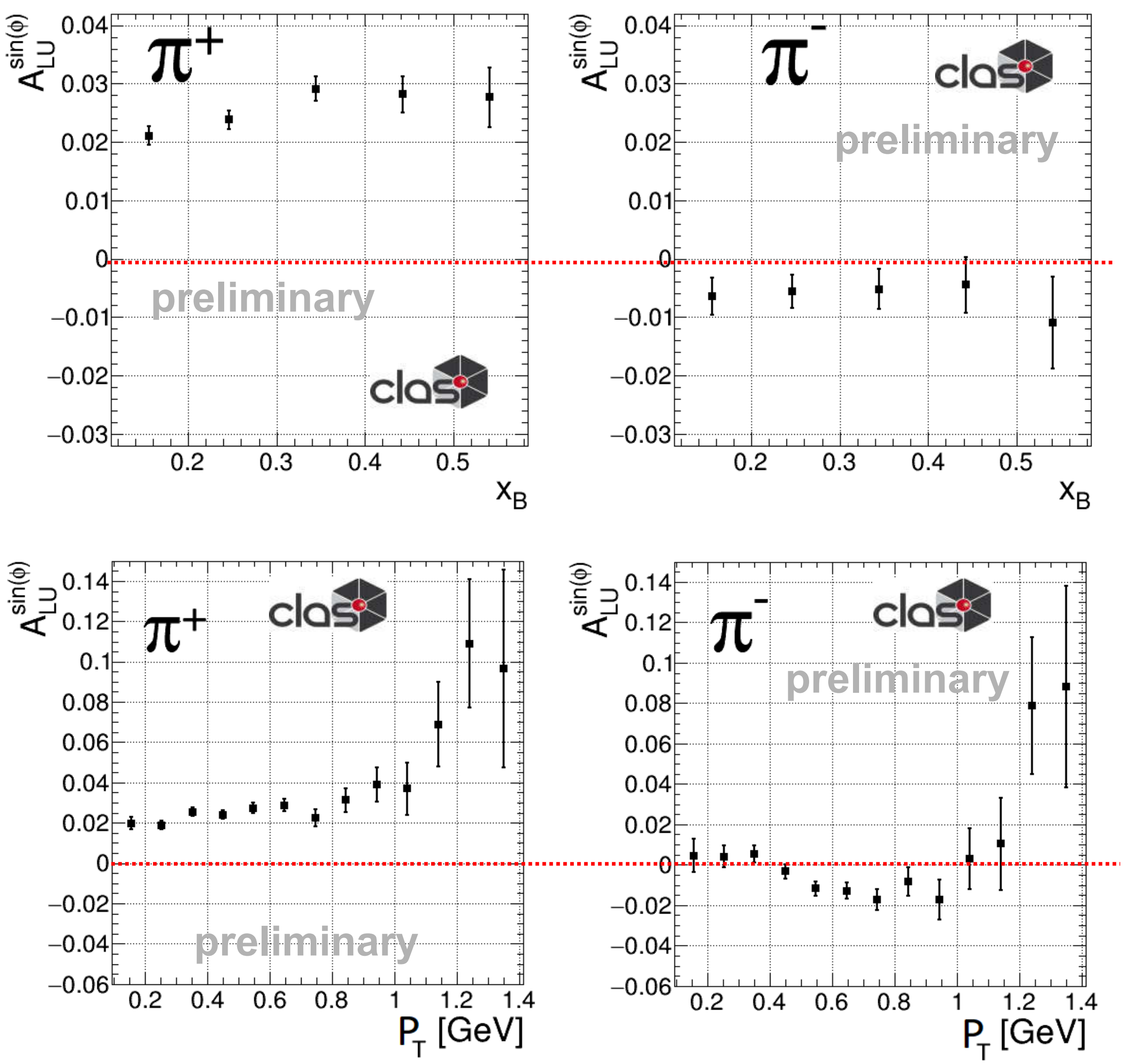


COMPASS Collab., arXiv:1709.07374

COMPASS is in "full swing" mode.
Proton-target data are also expected

FIRST JLAB PRELIMINARY DATA



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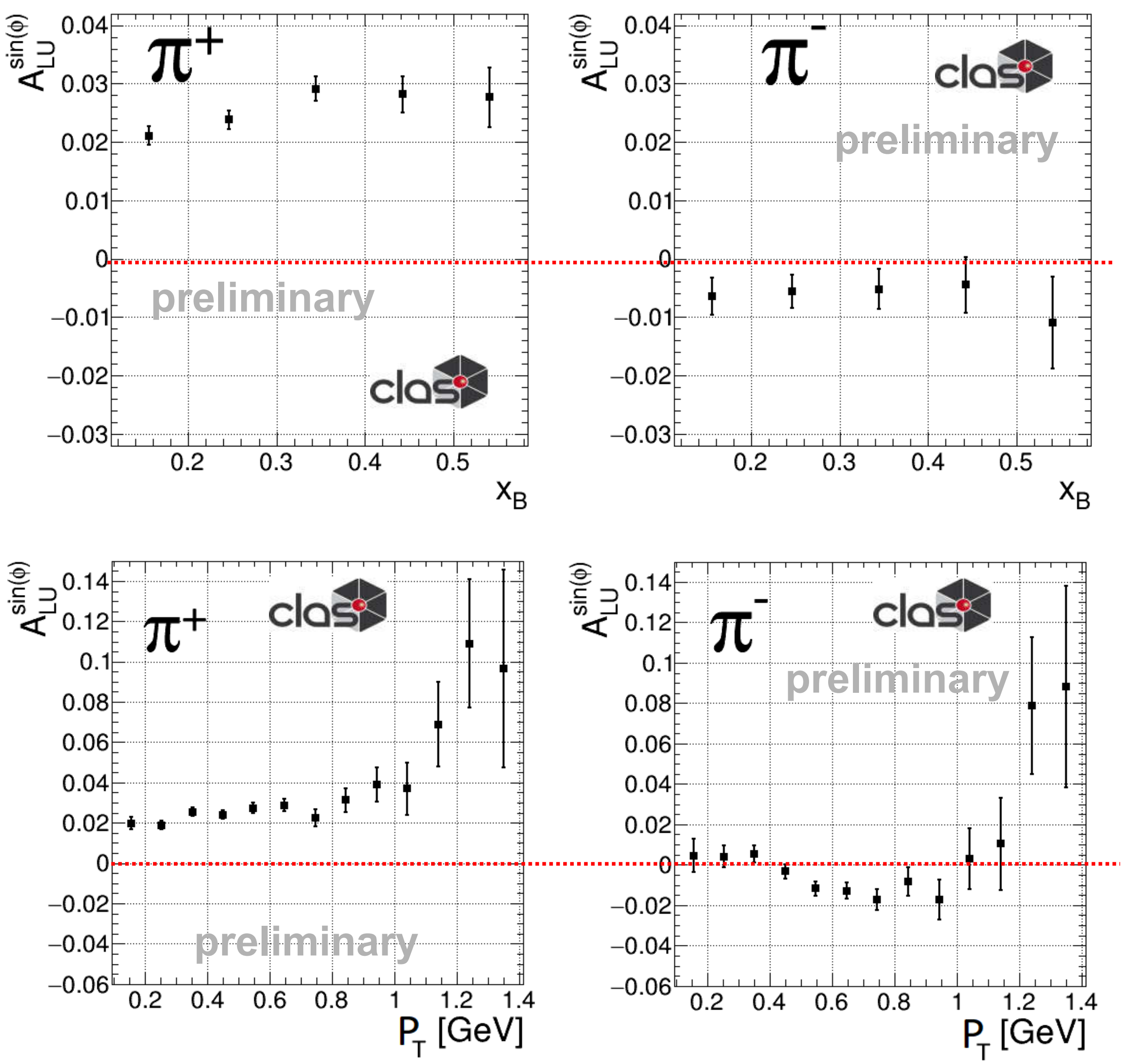

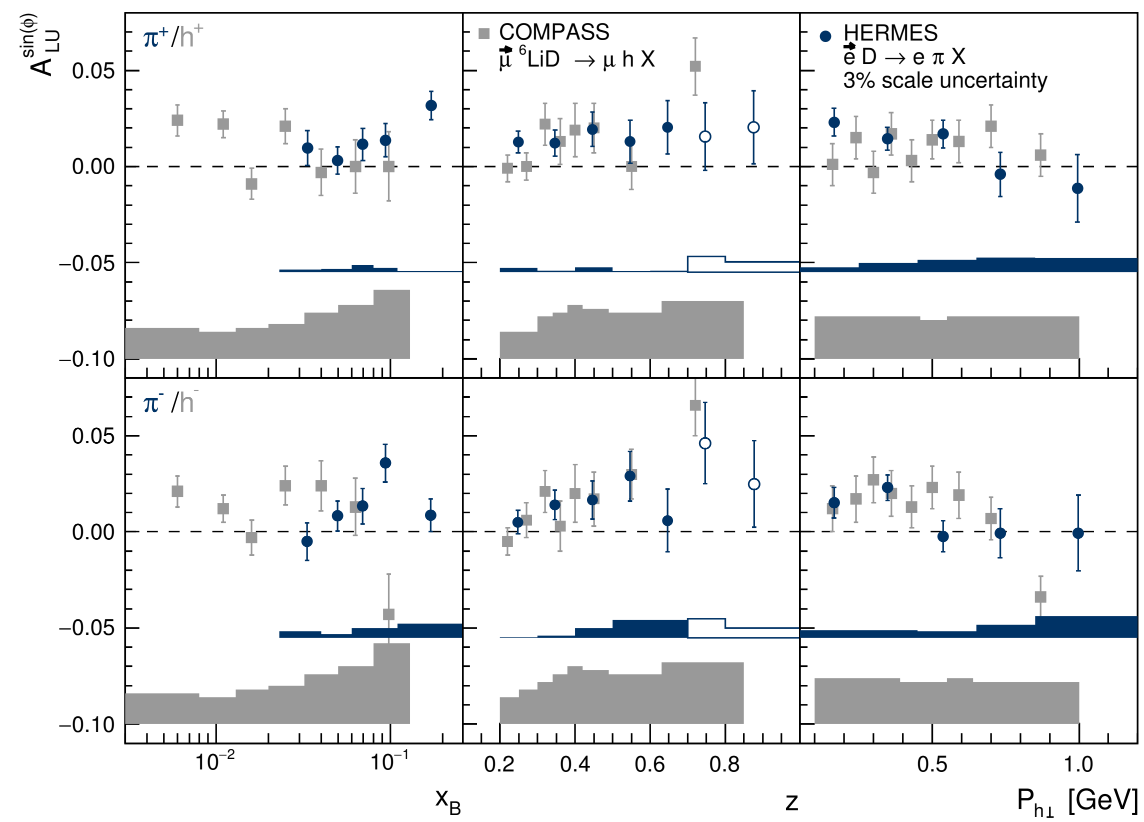

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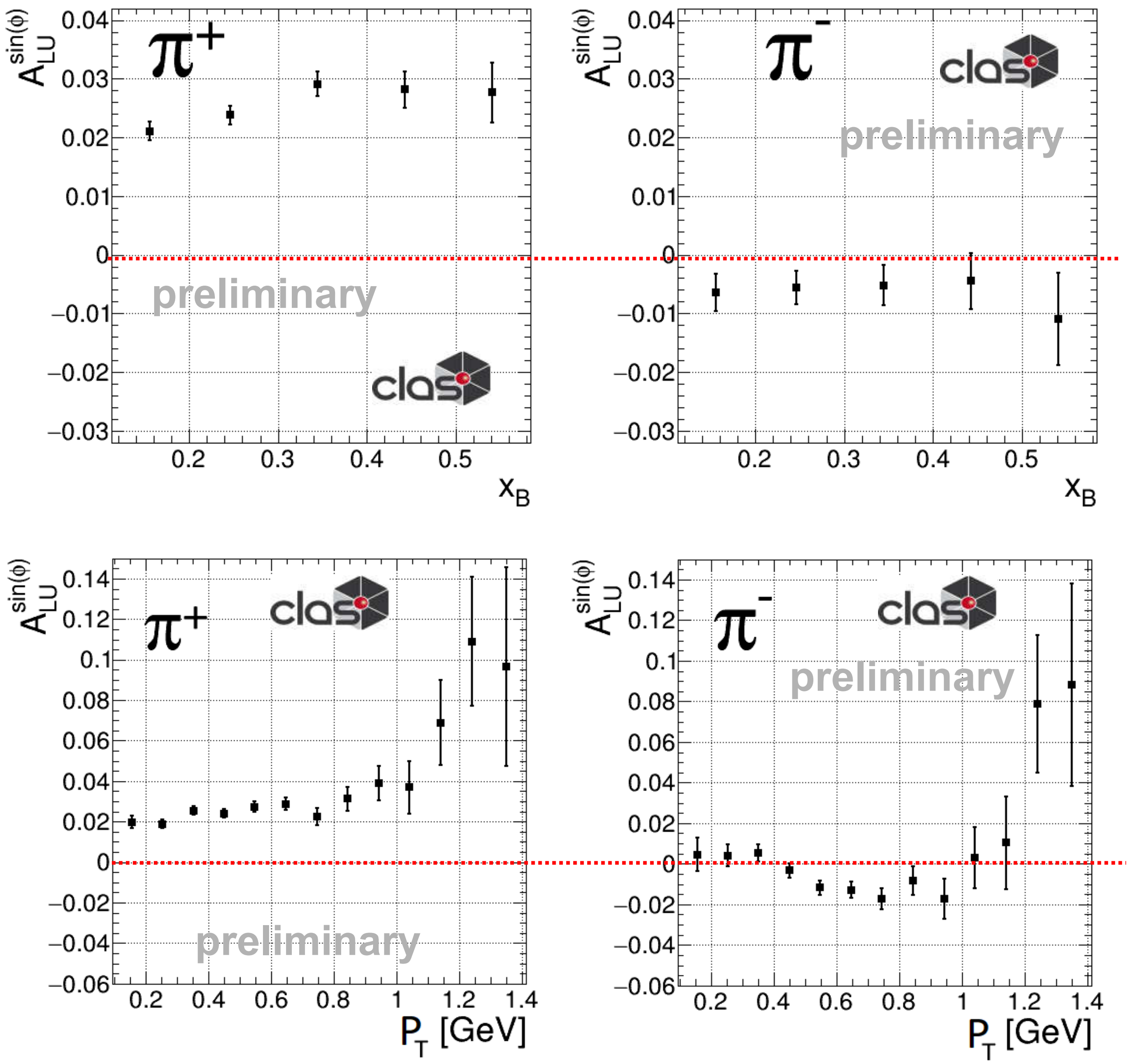

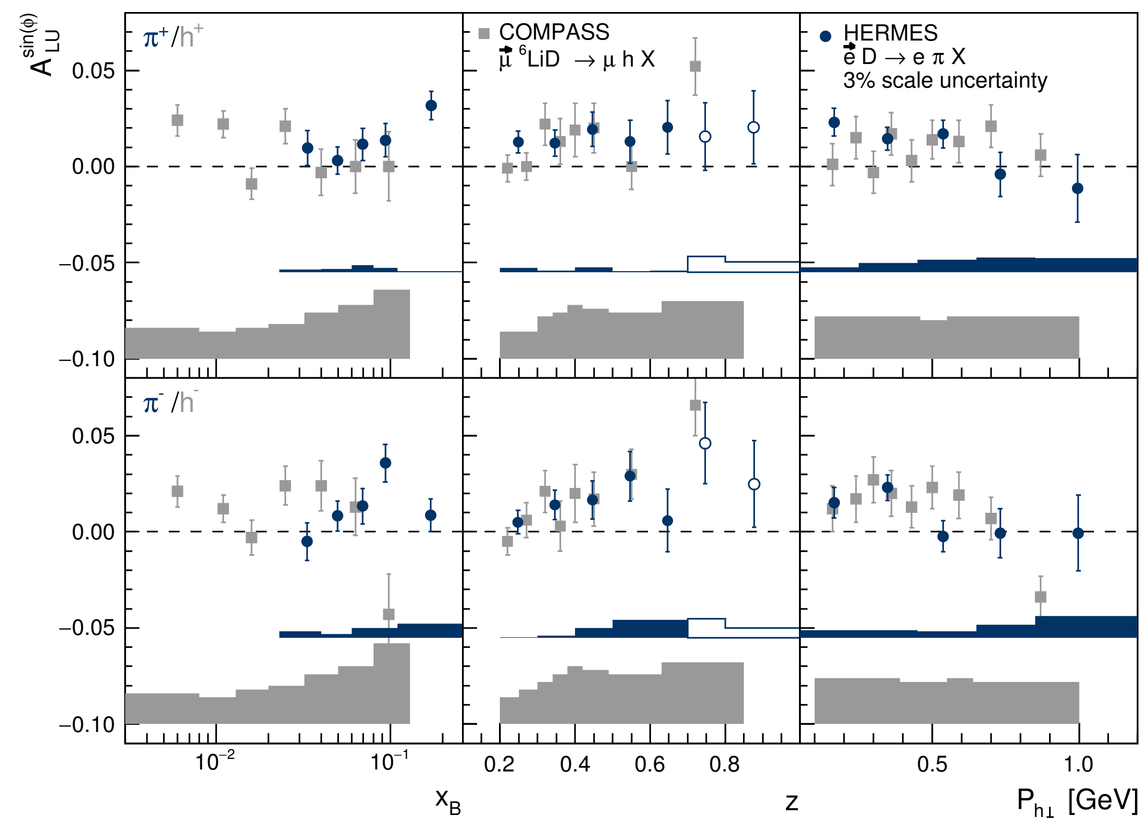

Only 2% of approved data taking

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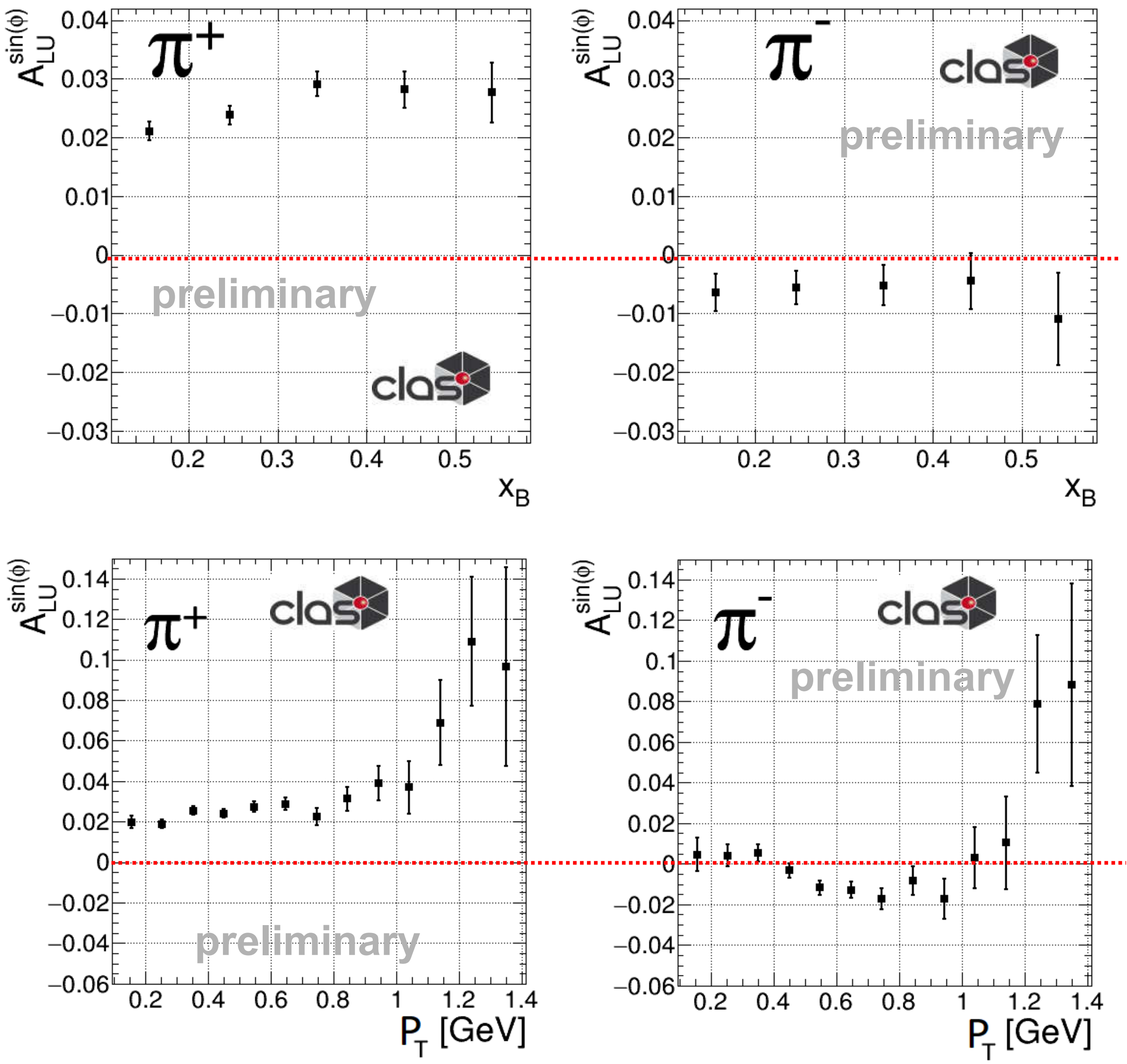

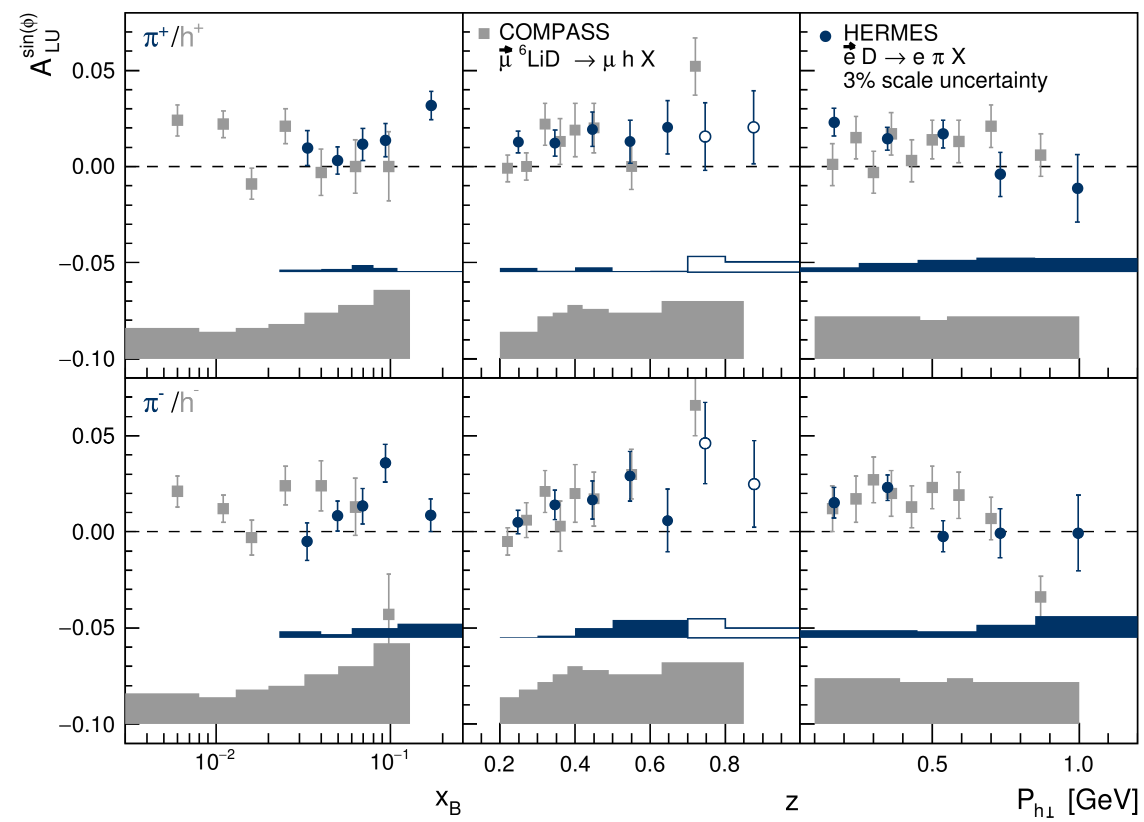

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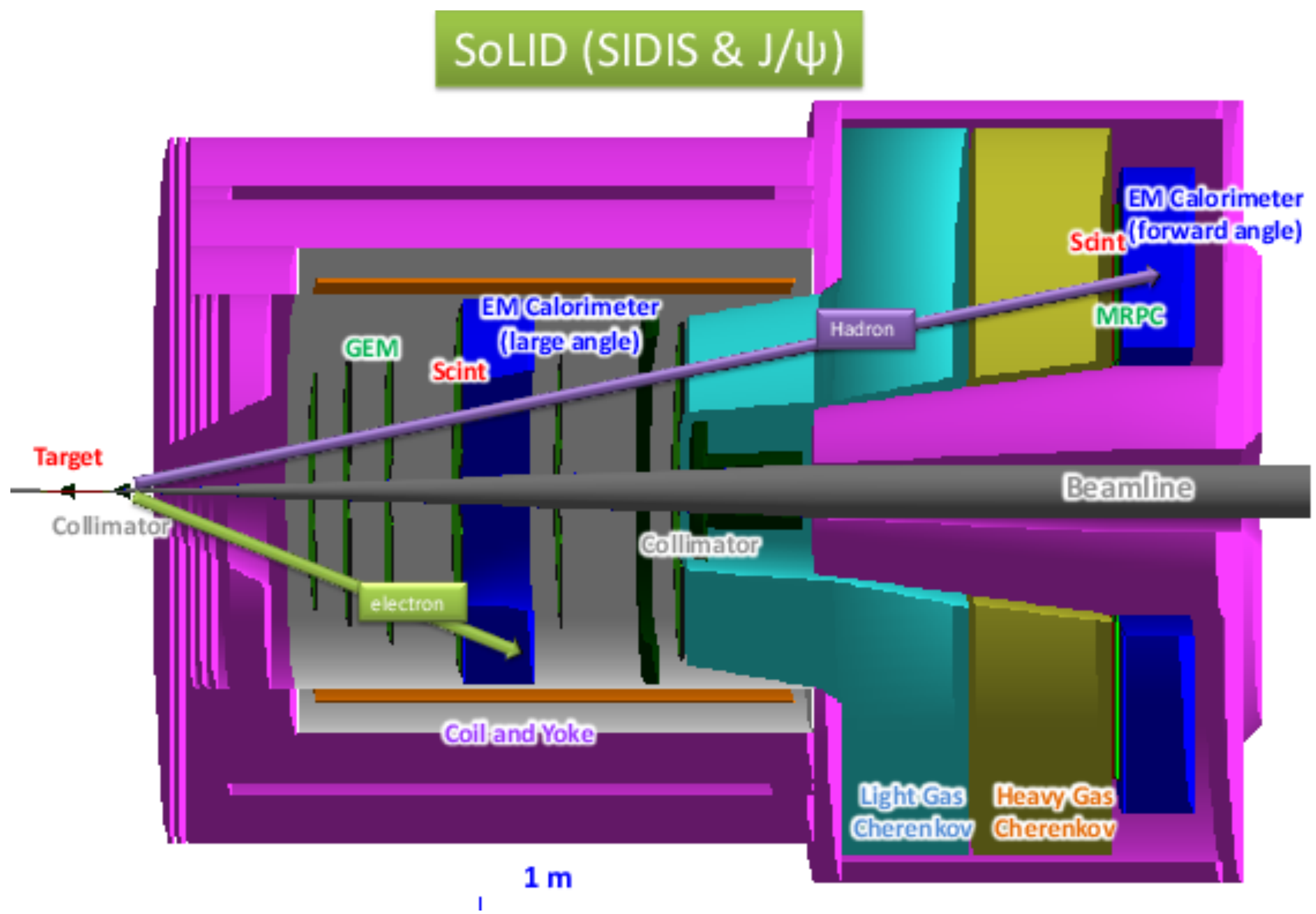
AWESOME!

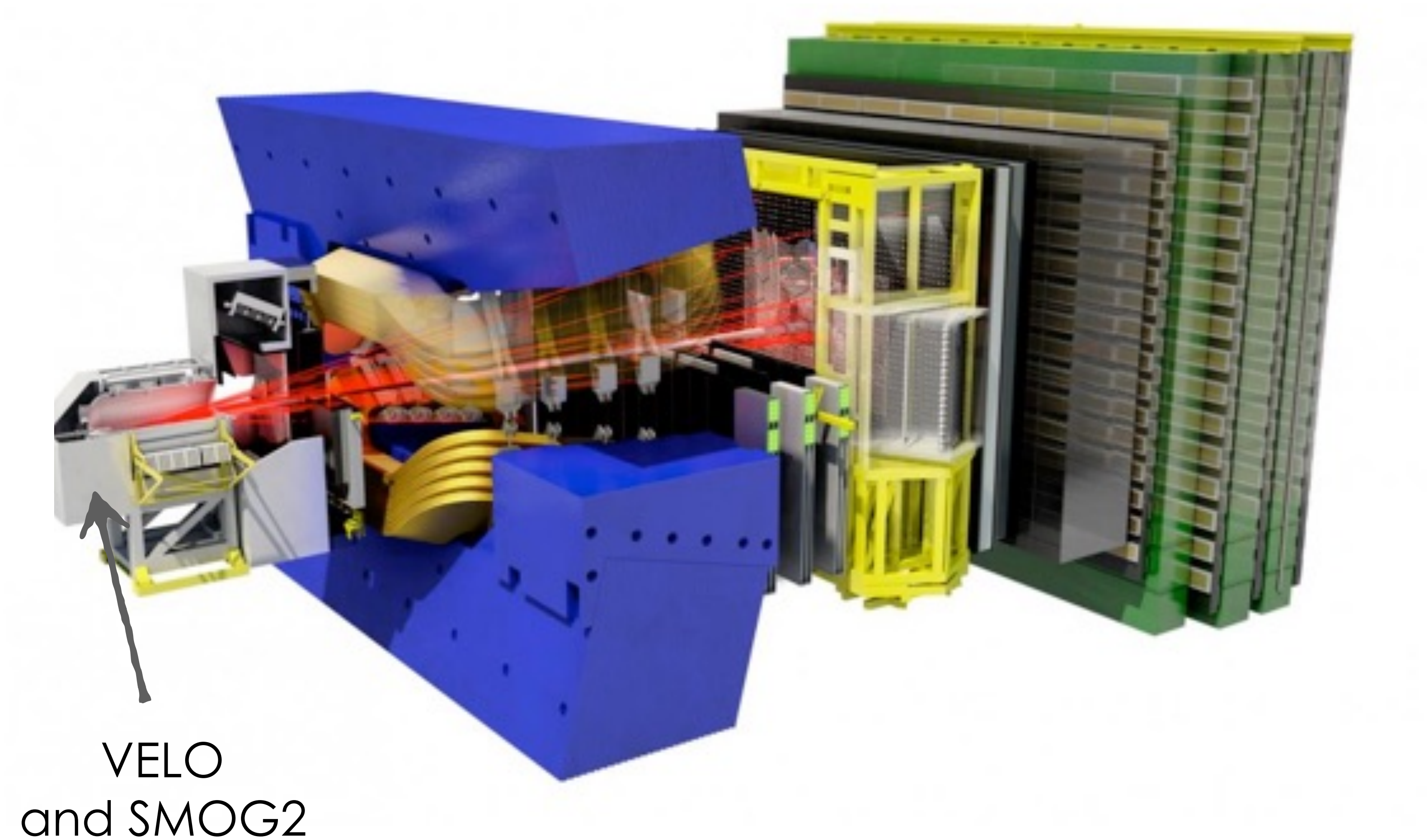
SOLID @ JLAB



SoLID (SIDIS & J/ψ)
EM Calorimeter
(forward angle)
Scint
MRPC
Hadron
EM Calorimeter
(large angle)
GEM
Scint
Target
Collimator
Beamline
Collimator
electron
Coil and Yoke
Light Gas
Cherenkov
Heavy Gas
Cherenkov
1 m

LHCb FIXED TARGET, INCLUDING POLARISATION

https://indico.cern.ch/event/755856/



LHCb FIXED TARGET, INCLUDING POLARISATION

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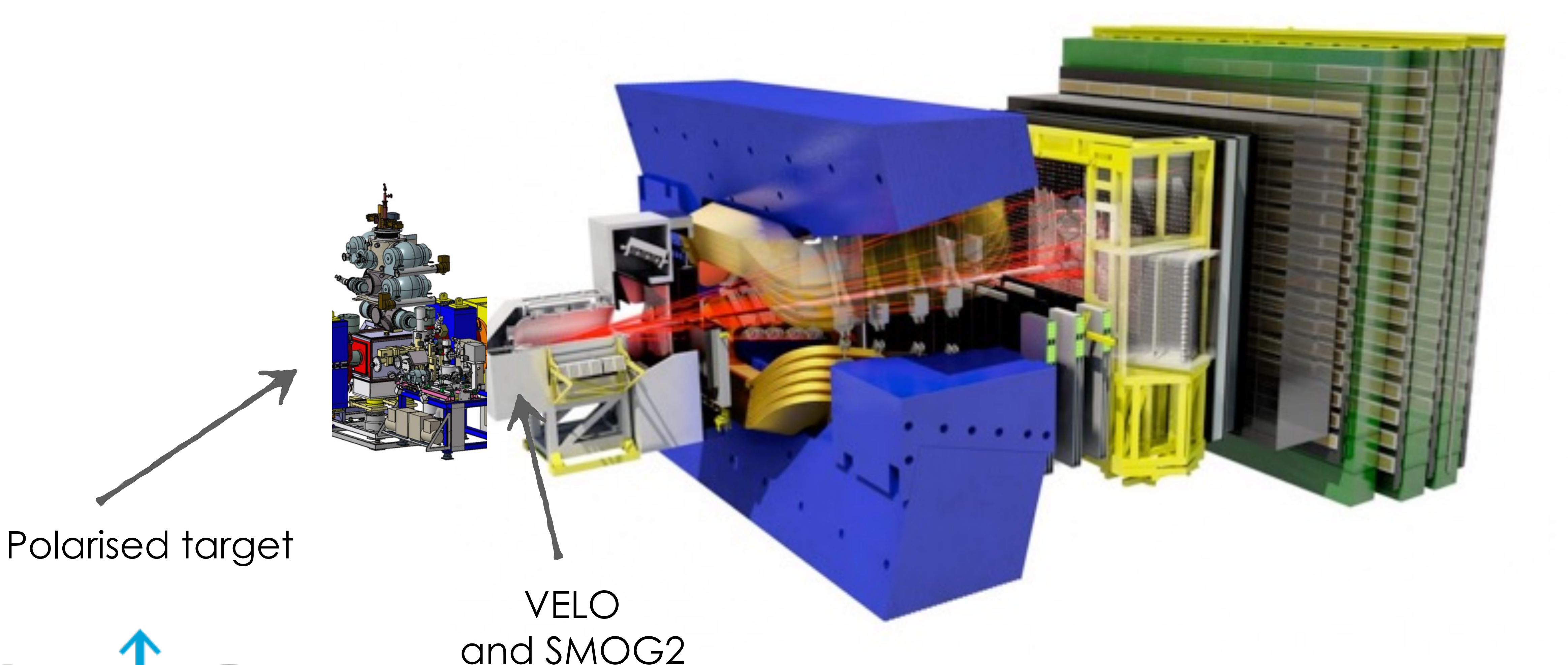

ALICE FIXED TARGET

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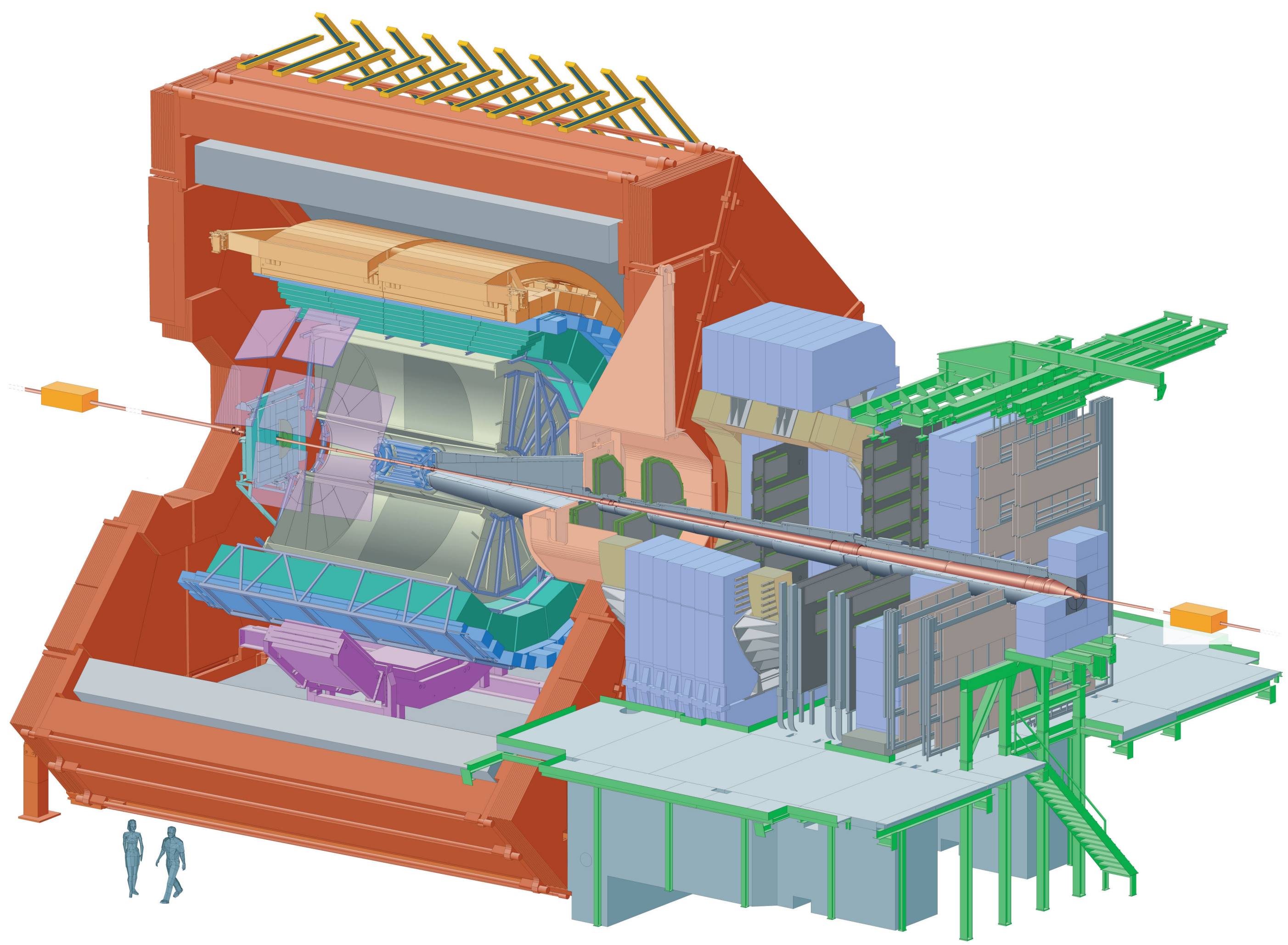

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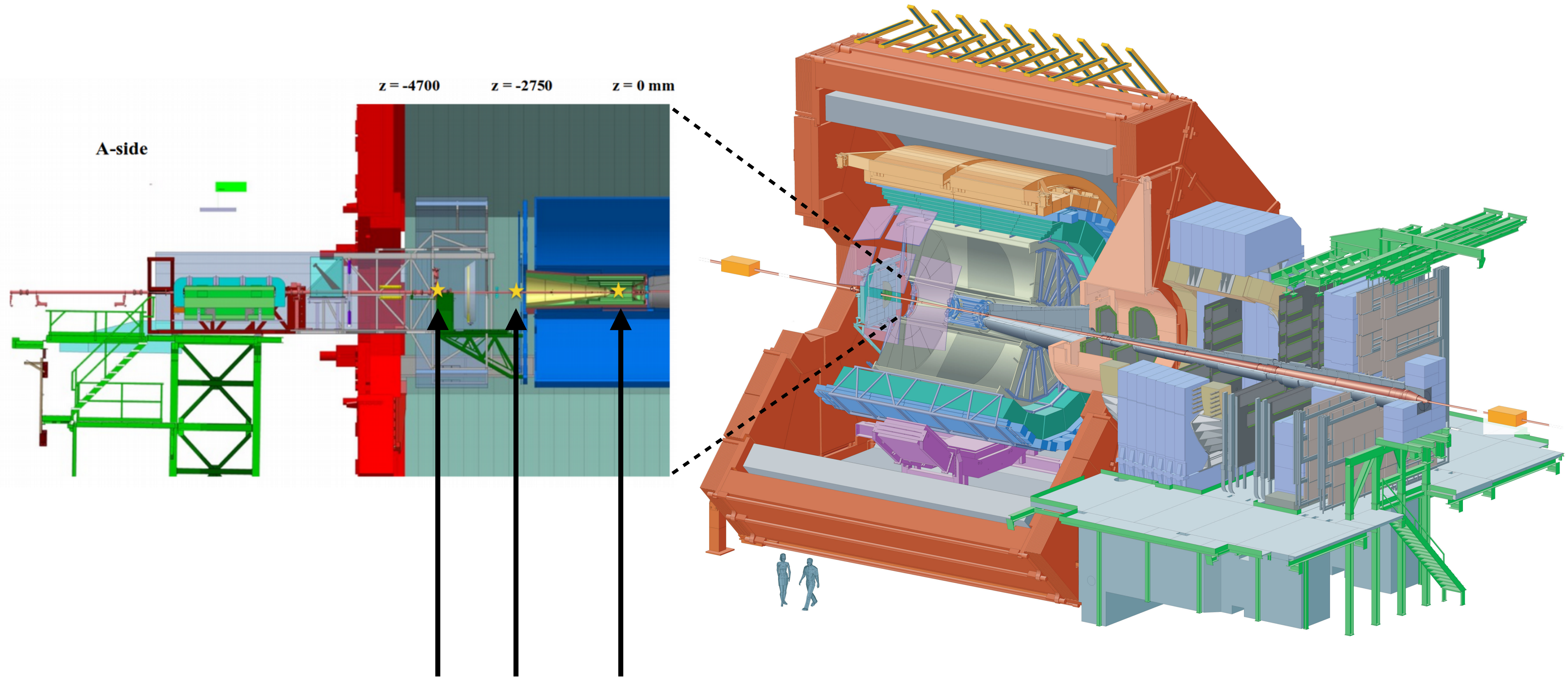
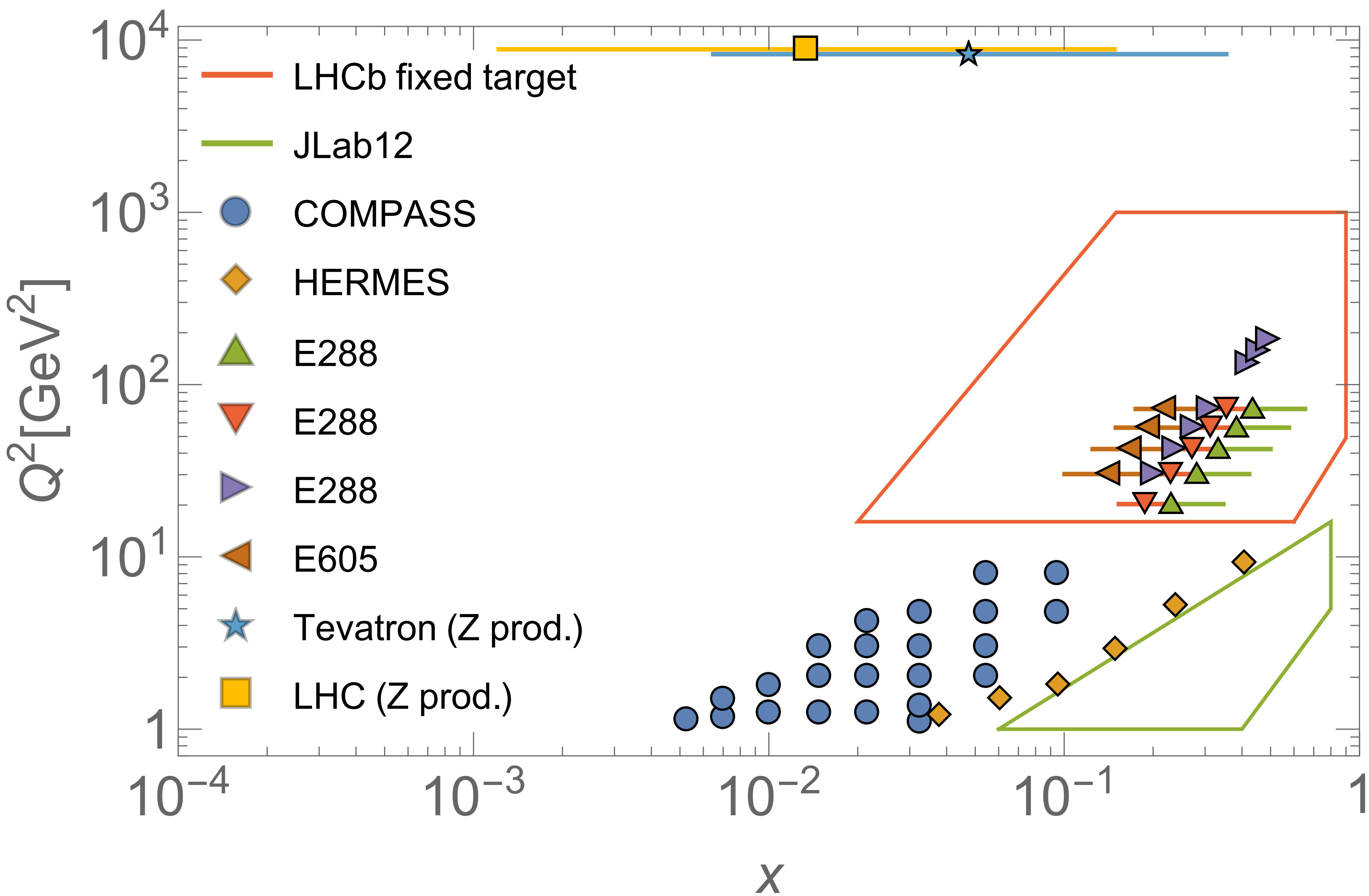


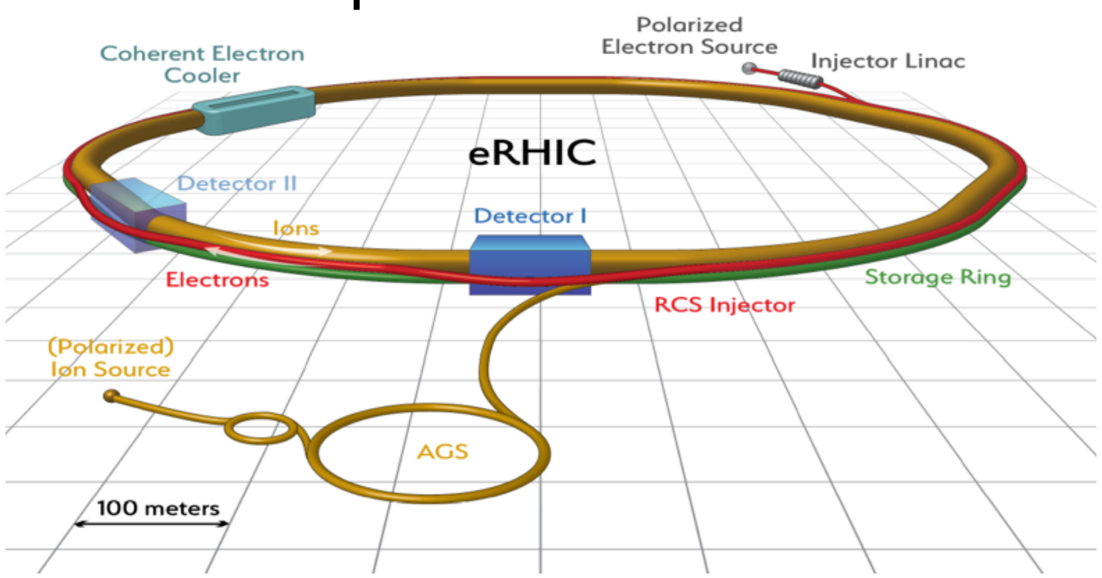
Possible fixed-target positioning

EXPECTED EXTENSION OF DATA RANGE

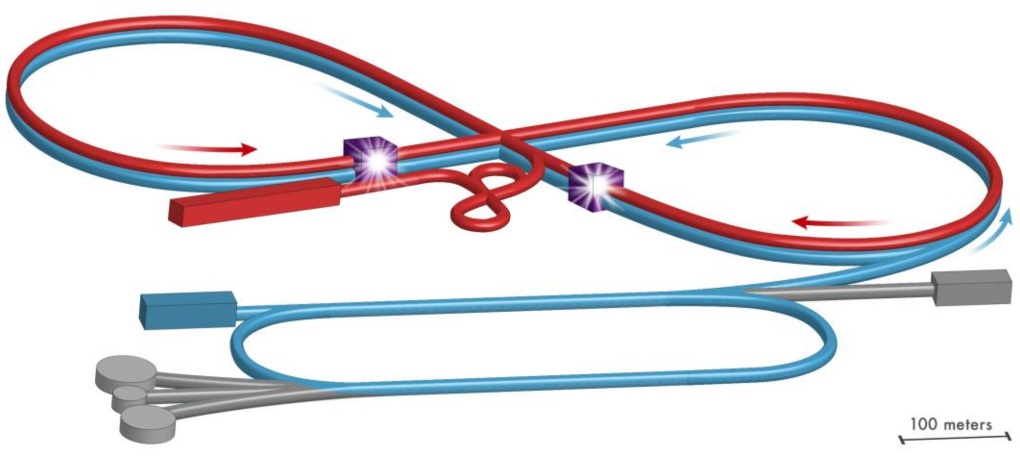


THE ELECTRON-ION COLLIDER PROJECT

BNL concept



JLab concept



- High luminosity: (10^{34} cm^{-2} s^{-1})
- Variable CM energy: 20-100 GeV
- Highly polarized beams
- Protons and other nuclei

25-29 May 2020
Almo Collegio Borromeo, Pavia, Italy
Europe/Rome timezone

- Overview
- Committees
- Timetable
- Registration
- Participant List
- Accommodation

Contacts

- transversity2020@unipv.it
- info@pragmacongressi.it
- +39 0382 309579

Transversity 2020 is the 6th international workshop on transverse polarization phenomena in hard processes, following those held in 2005 on Lake Como (Italy), 2008 in Ferrara (Italy), 2011 in Lošinj (Croatia), 2014 in Cagliari (Italy), and 2017 in Frascati (Italy)

The aim of the workshop is to provide an environment in which present theoretical and experimental knowledge in the field of transversity, transverse-momentum dependent distribution and fragmentation functions as well as generalised parton distribution functions will be presented and discussed in depth, together with new theoretical ideas and experimental perspectives. The workshop represents a valuable opportunity to gather the spin physics community, with a broad participation of theorists, as well as of experimentalists working in international collaborations at BEPC-II, BNL, CERN, DESY, KEK and Jefferson Lab (JLab), all deeply involved in this area of research. The workshop will also be a unique occasion for young researchers to form a detailed and up-to-date perspective on this fast-developing research field, and to present and discuss their own work and projects in a highly stimulating and reactive context.

UNIVERSITÀ DI PAVIA

3DSPIN MAPPING THE PROTON IN 3D

https://agenda.infn.it/e/transversity2020

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- Fragmentation functions need independent data
- Flavor dependence of TMDs still not well constrained
- We expect a steady flow of data coming up in the next years

BACKUP SLIDES

LOW-b_T MODIFICATIONS

$$\log\left(Q^2 b_T^2\right) \to \log\left(Q^2 b_T^2 + 1\right)$$

see, e.g., Bozzi, Catani, De Florian, Grazzini
hep-ph/0302104

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$$b_\mathrm{min} \equiv b_*(b_c(0)) = \frac{b_0}{C_5 Q}\sqrt{\frac{1}{1 + b_0^2/(C_5^2 Q^2 b_\mathrm{max}^2)}}$$

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- The justification is to recover the integrated result ("unitarity constraint")
- Modification at low b_T is allowed because resummed calculation is anyway unreliable there

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These are all choices that should be at some point checked/challenged

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$$\hat{f}_1^q(x, b_T; \mu^2) = \sum_i \left(C_{qi} \otimes f_1^i\right)(x, b_*; \mu_b) e^{\tilde{S}(b_*;\mu_b,\mu)} e^{g_K(b_T) \ln \frac{\mu}{\mu_0}} \hat{f}_{\mathrm{NP}}^q(x, b_T)$$

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EFFECTS OF b_* PRESCRIPTION

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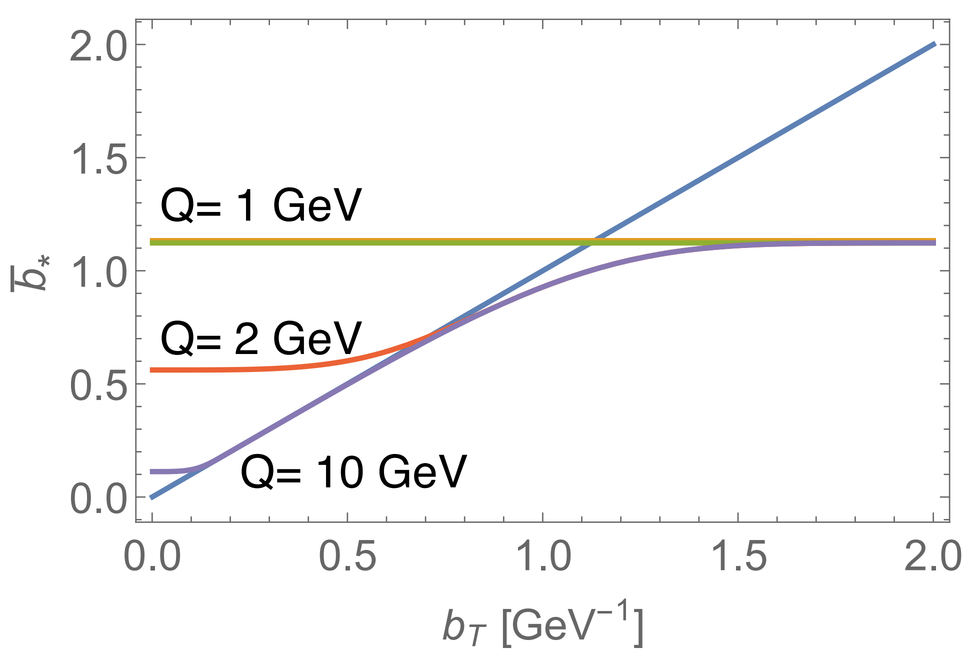

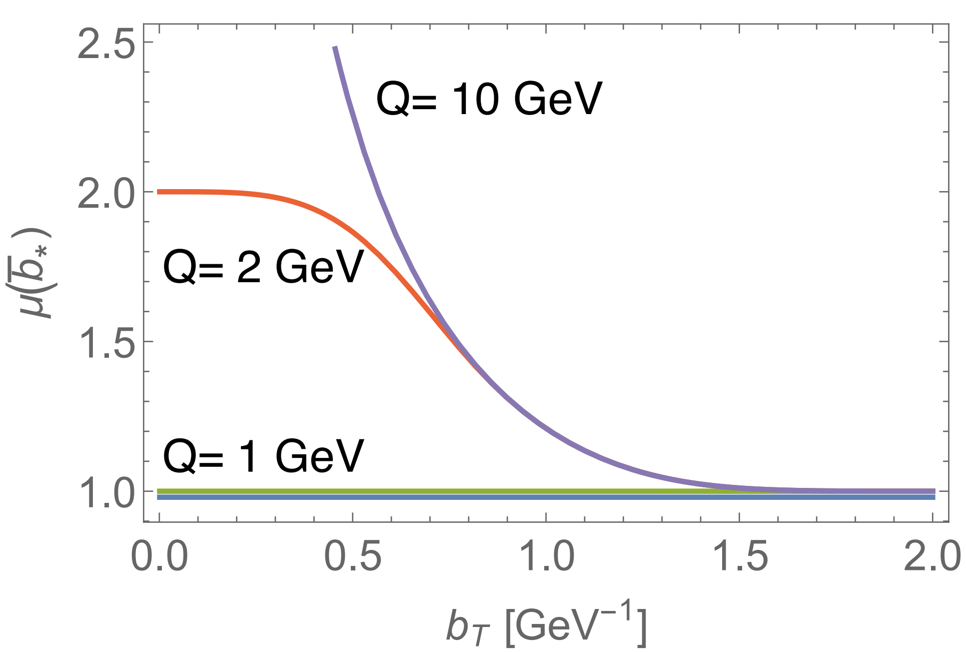

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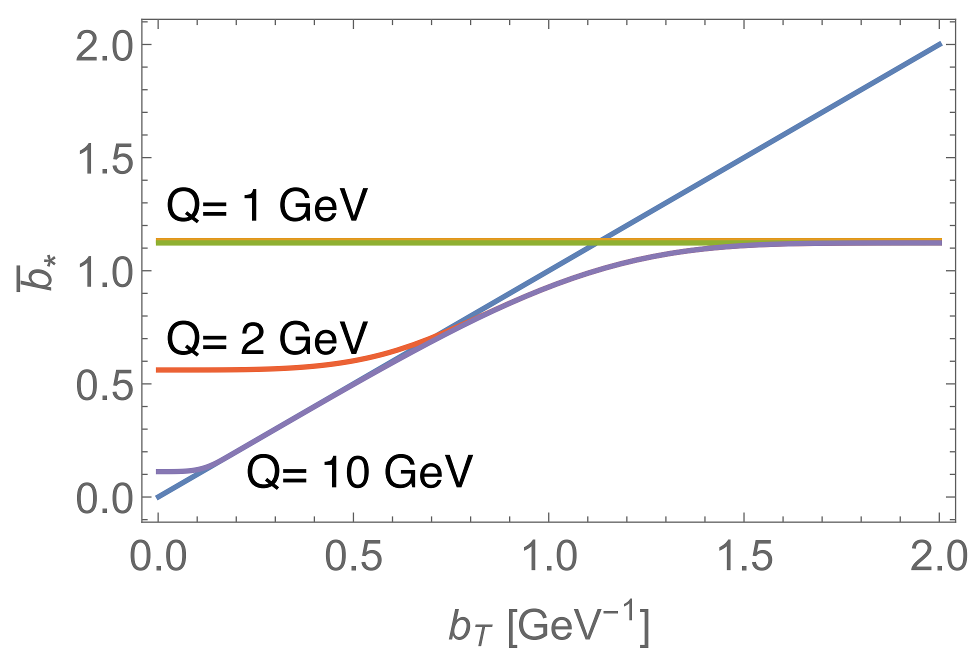

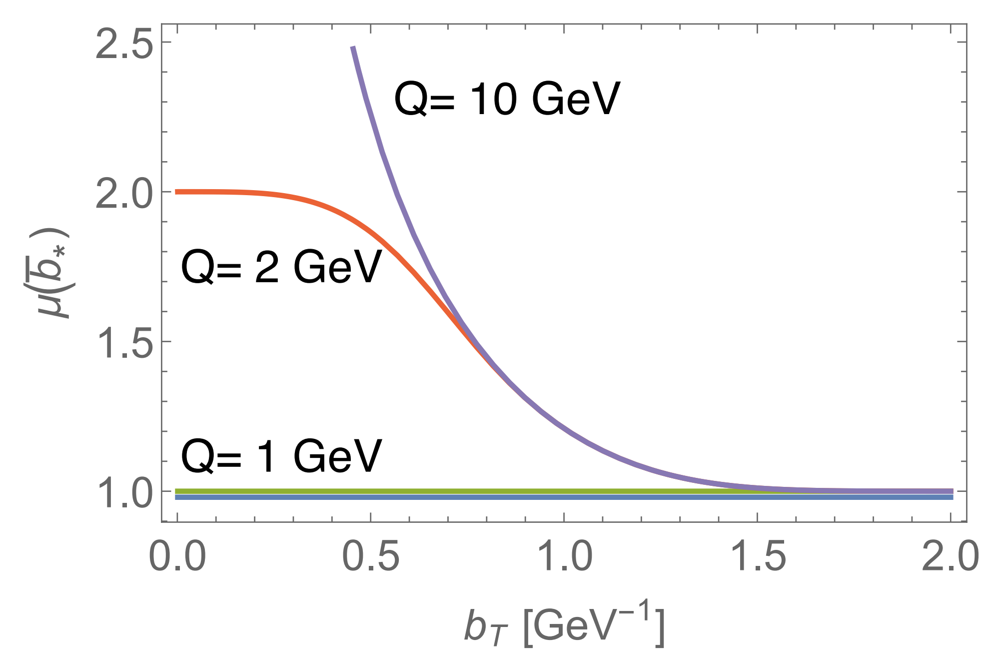

No significant effect at high Q, but large effect at low Q (inhibits perturbative contribution)

DATA SELECTION IN PAVIA 2017

$$Q^2 > 1.4 \text{ GeV}^2$$

$$0.2 < z < 0.7$$

$$P_{hT}, q_T < \text{Min}[0.2\ Q, 0.7\ Qz] + 0.5 \text{ GeV}$$

We checked also

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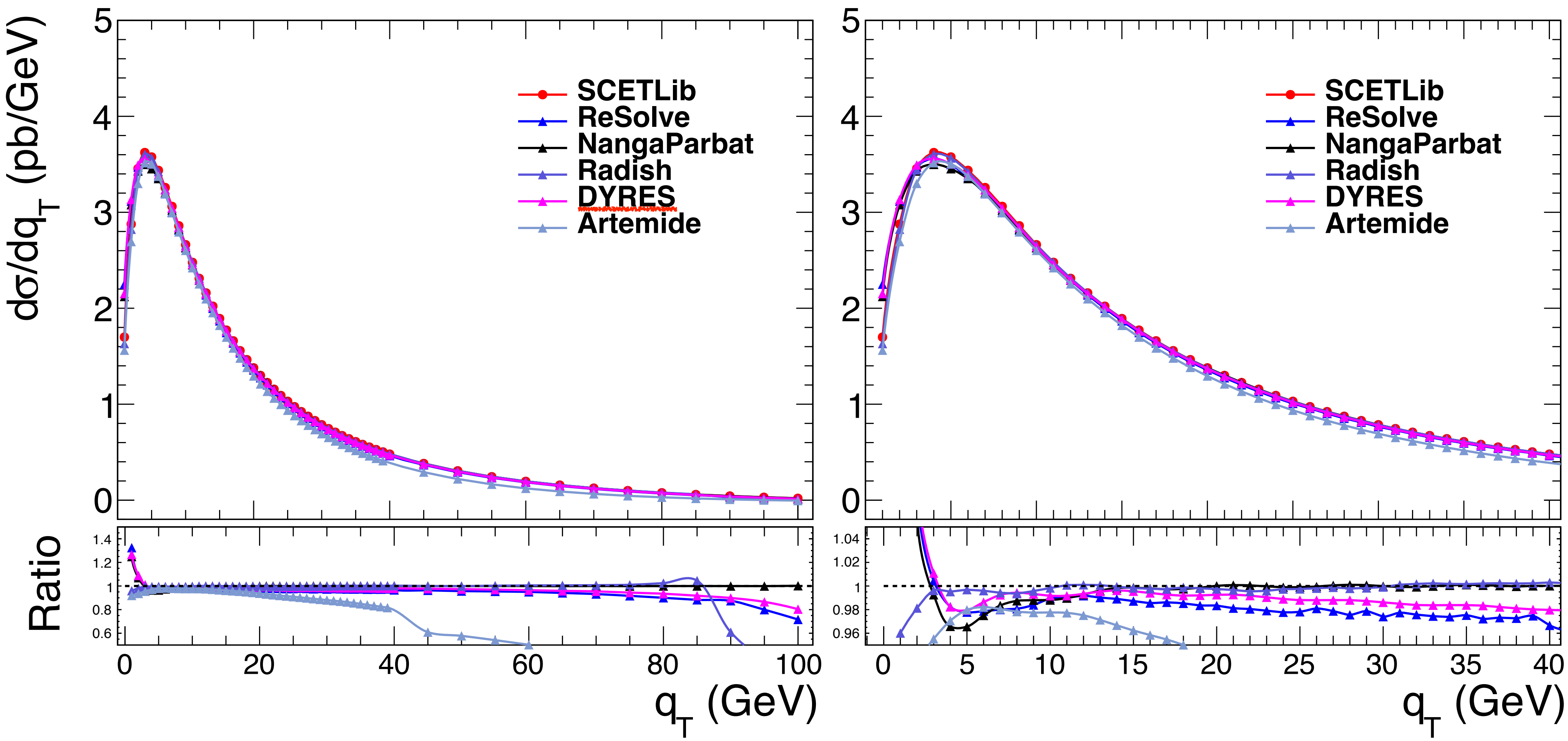
$P_{hT} < 0.2\,Qz$

Total number of data points: 477

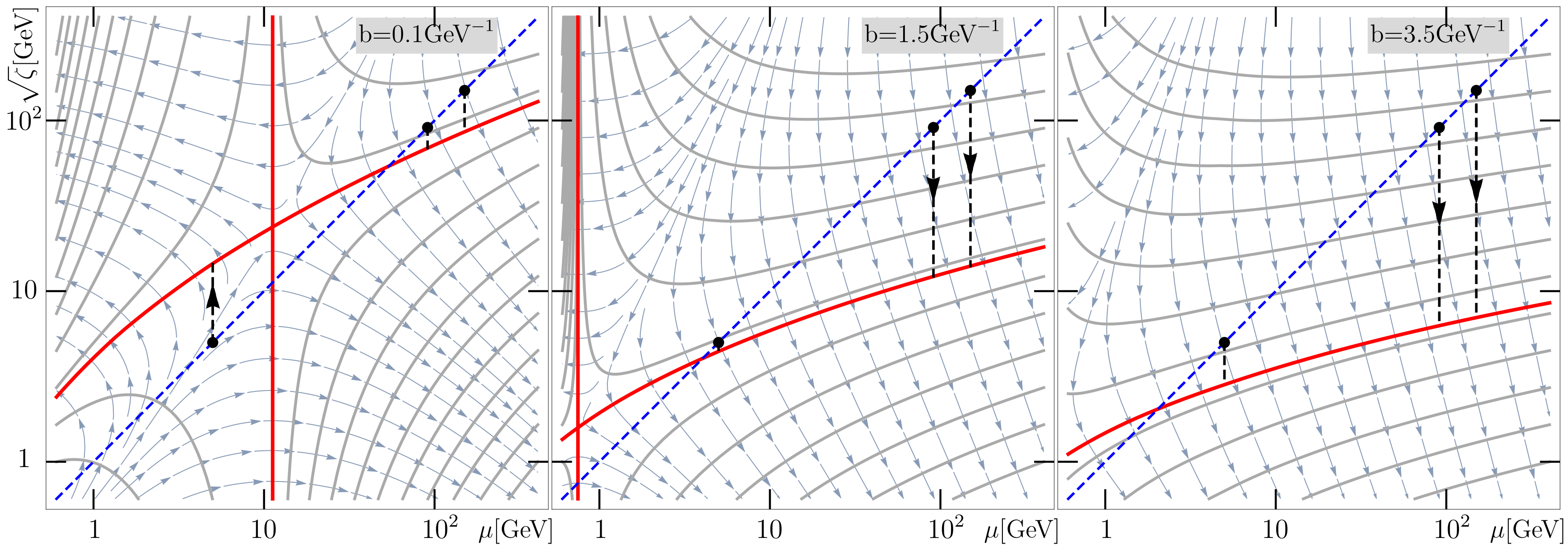
Total χ^2/dof = 1.02

BENCHMARKING OF DIFFERENT CODES

V. Bertone's talk at LHC EW WG General Meeting, Dec 2019
https://indico.cern.ch/event/849342/



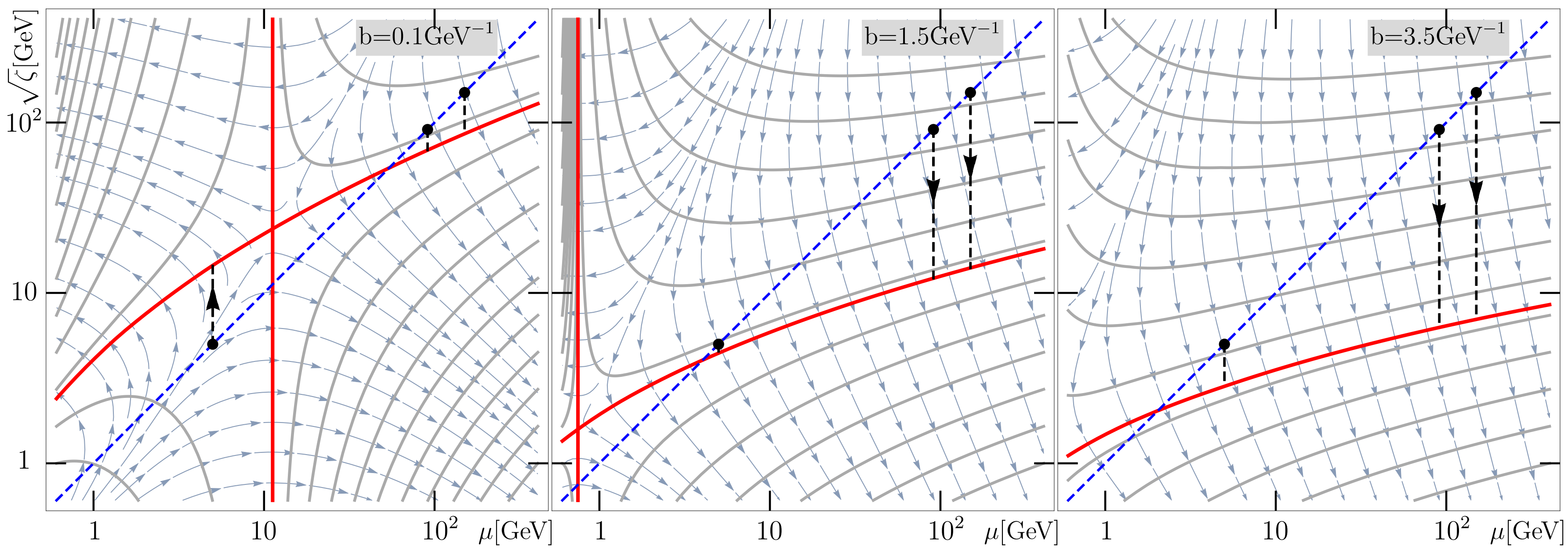
TMDS AND TWO-SCALE EVOLUTION



The ζ-prescription is equivalent to the popular CSS-scheme since it satisfies the same set of differential equations. Nonetheless, this equivalence is strict only within an all-order perturbation theory and it is numerically violated for any truncated series.

TMDS AND TWO-SCALE EVOLUTION

Scimemi, Vladimirov, arXiv:1912.06532



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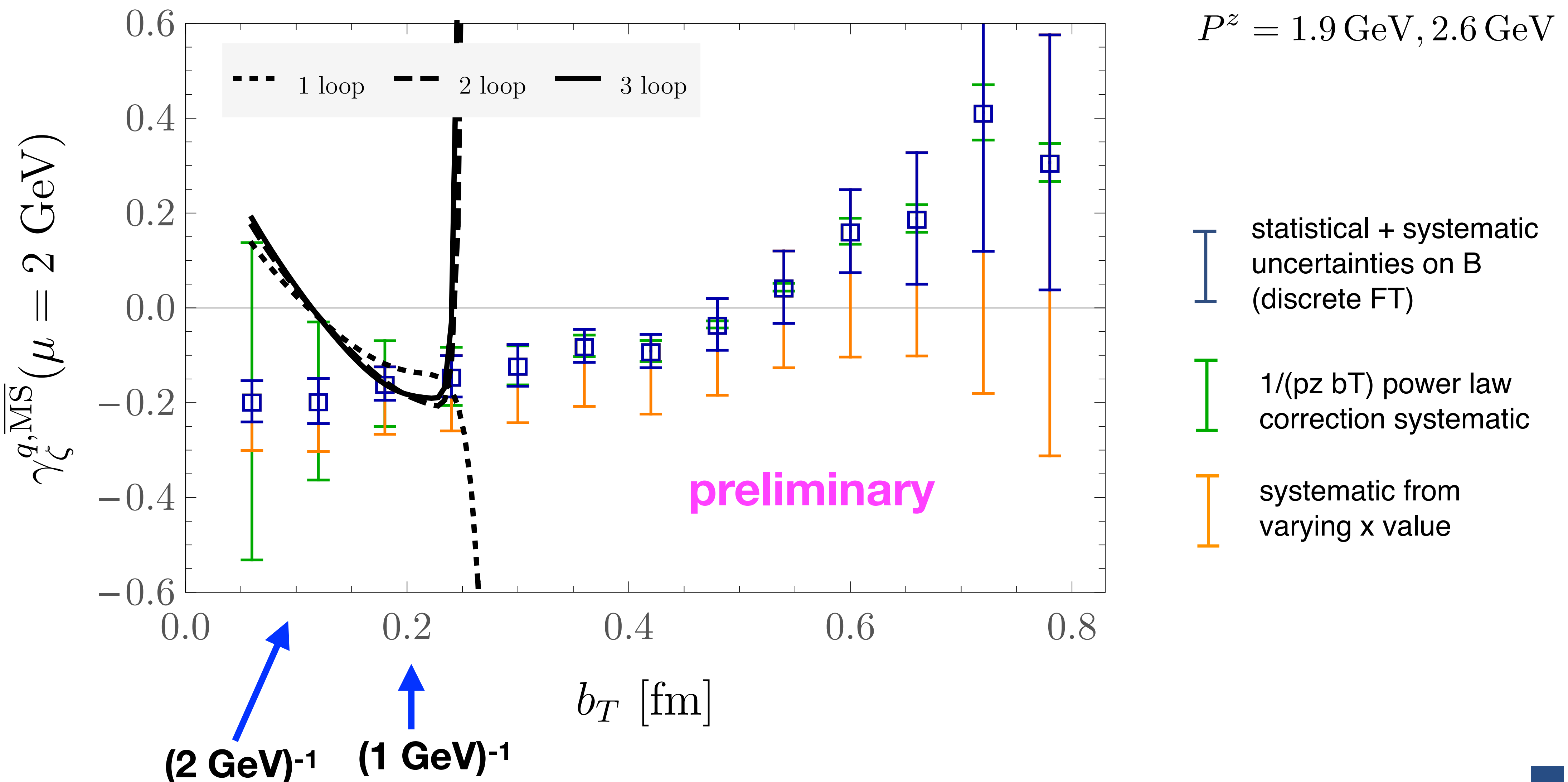
NONPERTURBATIVE TMD EVOLUTION FROM LATTICE

talk by I. Stewart at REF2019, work in progress with P. Shanahan, M. Wagman, Y. Zhao



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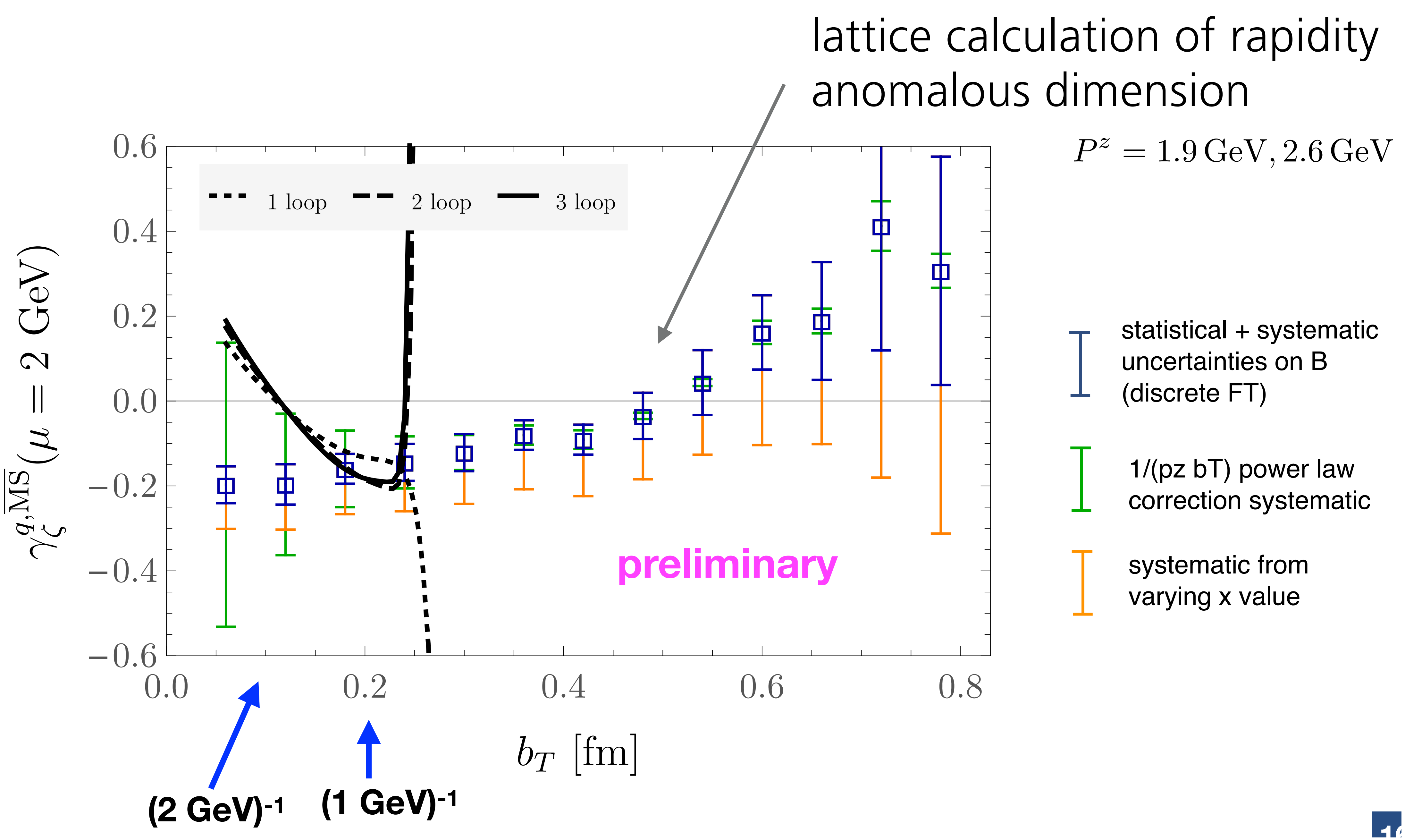

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