Transverse Energy-Energy Correlators for TMD physics and reduction of uncertainties due to hadronization

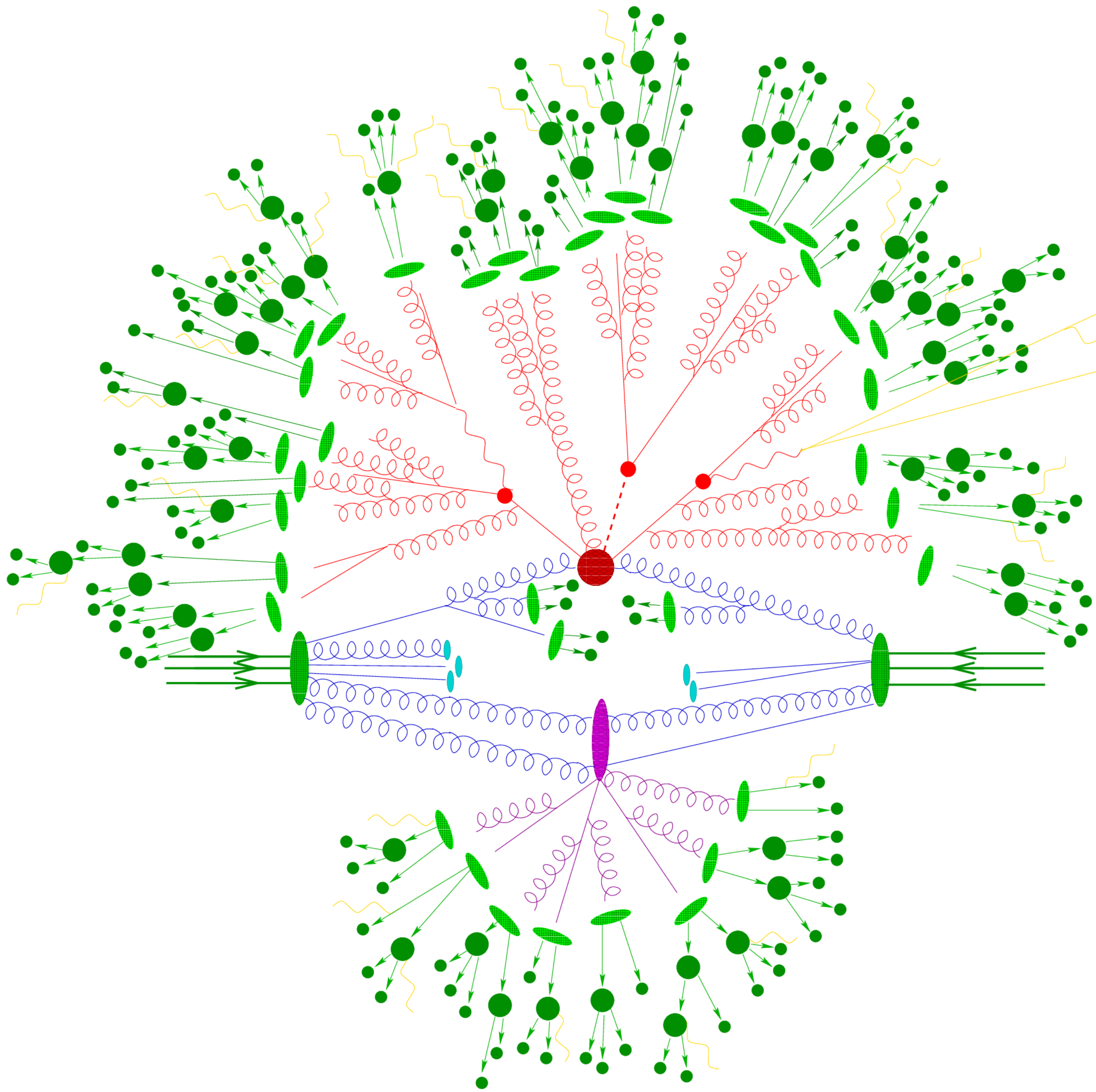
Los Alamos NATIONAL LABORATORY EST. 1943

Haitao Li

HTL, Ivan Vitev, Feng Yuan, HuaXing Zhu, YuJiao Zhu, in preparation

EIC workshop, temple
03-20-2019

Event at Colliders



Event shape observables, which measure the flow of radiation in a scattering event.

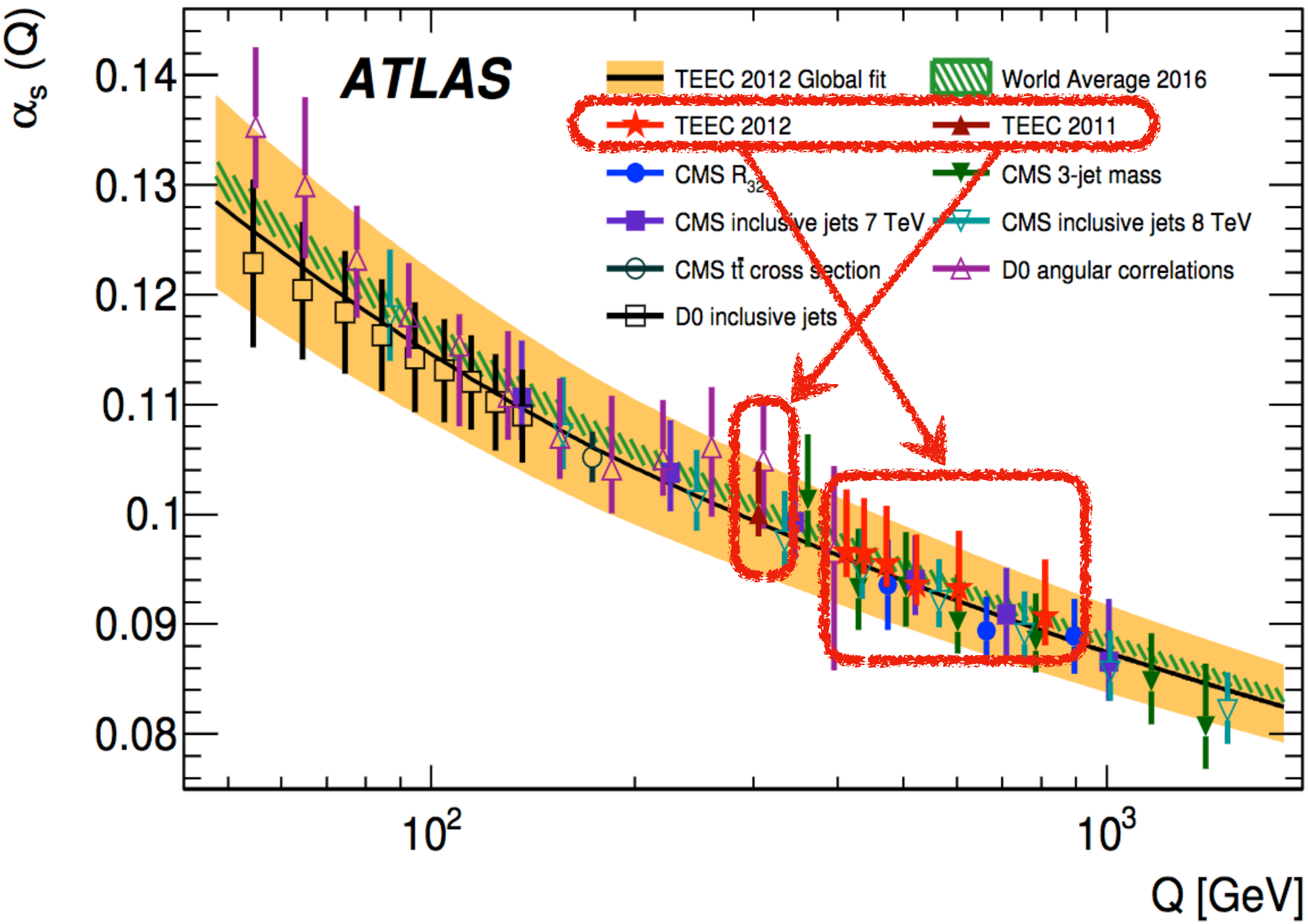
Thrust
N-jettiness
Transverse Thrust …

each radiation along with the QCD coupling at different scales

I will talk about TEEC which can be studied in

- ☑ lepton+lepton collisions
- ☑ lepton+proton collisions
- ☑ proton+proton collisions

TEEC at hadronic colliders



$$\alpha_s(m_Z) = 0.1162 \pm 0.0011\,(\text{exp.})\,\boxed{{}^{+0.0076}_{-0.0061}\,(\text{scale})} \pm 0.0018\,(\text{PDF}) \pm 0.0003\,(\text{NP}),$$

arXiv:1508.01579

TEEC at hadronic colliders

TRANSVERSE ENERGY–ENERGY CORRELATIONS:
A TEST OF PERTURBATIVE QCD FOR THE PROTON–ANTIPROTON COLLIDER

A. ALI [1], E. PIETARINEN [2] and W.J. STIRLING
CERN, Geneva, Switzerland

electron-positron collider: Basham et al 1978
hadronic collider: Ali et al 1984

Received 28 February 1984

The energy–energy correlation function, and its associated asymmetry, has proved a powerful technique for quantitative tests of perturbative quantum chromodynamics in high energy e^+e^- annihilation. Here we present the natural analogue for the $\bar{p}p$ collider, constructed from the transverse energies and azimuthal angles of the final state hadrons. Leading order QCD predictions are calculated. We show how the correlation function provides a measure of three-jet production which depends only weakly on the parton structure functions, and should therefore allow a direct measurement of the QCD coupling constant α_S.

TEEC at hadronic colliders

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...relation function, and its associated asymmetry, has proved a powerful technique for quantita-
... for the $\bar{p}p$ ... logue ... order
QCD predi... ich de-
pends only ... oupling

weighted by Energy

$$\mathrm{EEC} = \sum_{a,b} \int d\sigma_{V\to a+b+X} \frac{2E_a E_b}{Q^2 \sigma_{\mathrm{tot}}} \delta(\cos(\theta_{ab}) - \cos(\chi))$$

weighted by E_T

$$\mathrm{TEEC} = \sum_{a,b} \int d\sigma_{pp\to a+b+X} \frac{2E_{T,a}E_{T,b}}{|\sum_i E_{T,i}|^2} \delta(\cos\phi_{ab} - \cos\phi)$$

- sum over all the jets for each event
- sum over all the particles for each event

- weighted cross section
- the soft radiation does not contribute directly to the observable at leading power
- soft gluon contributes only via recoil

TEEC at hadronic colliders

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The particle level TEEC exhibits a remarkable perturbative simplicity in the back-to-back limit

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observable

- **sum over all the jets for each event**
- **sum over all the particles for each event**

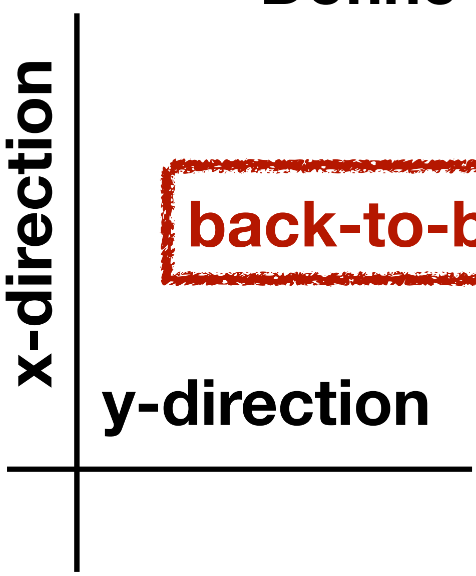
- **weighted cross section**
- **the soft radiation does not contribute directly to the observable at leading power**
- **soft gluon contributes only via recoil**

TEEC in DIS

Define scattering plane: x-z

azimuthal angle between final state hadrons and lepton

$$\mathrm{TEEC} = \sum_a \int d\sigma_{lp\to l+a+X} \frac{E_{T,l}E_{T,a}}{E_{T,l}\sum_i E_{T,i}} \delta(\cos\phi_{la} - \cos\phi)$$



back-to-back

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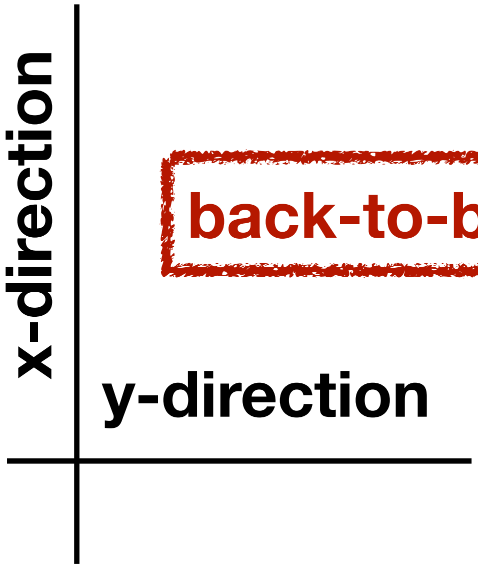

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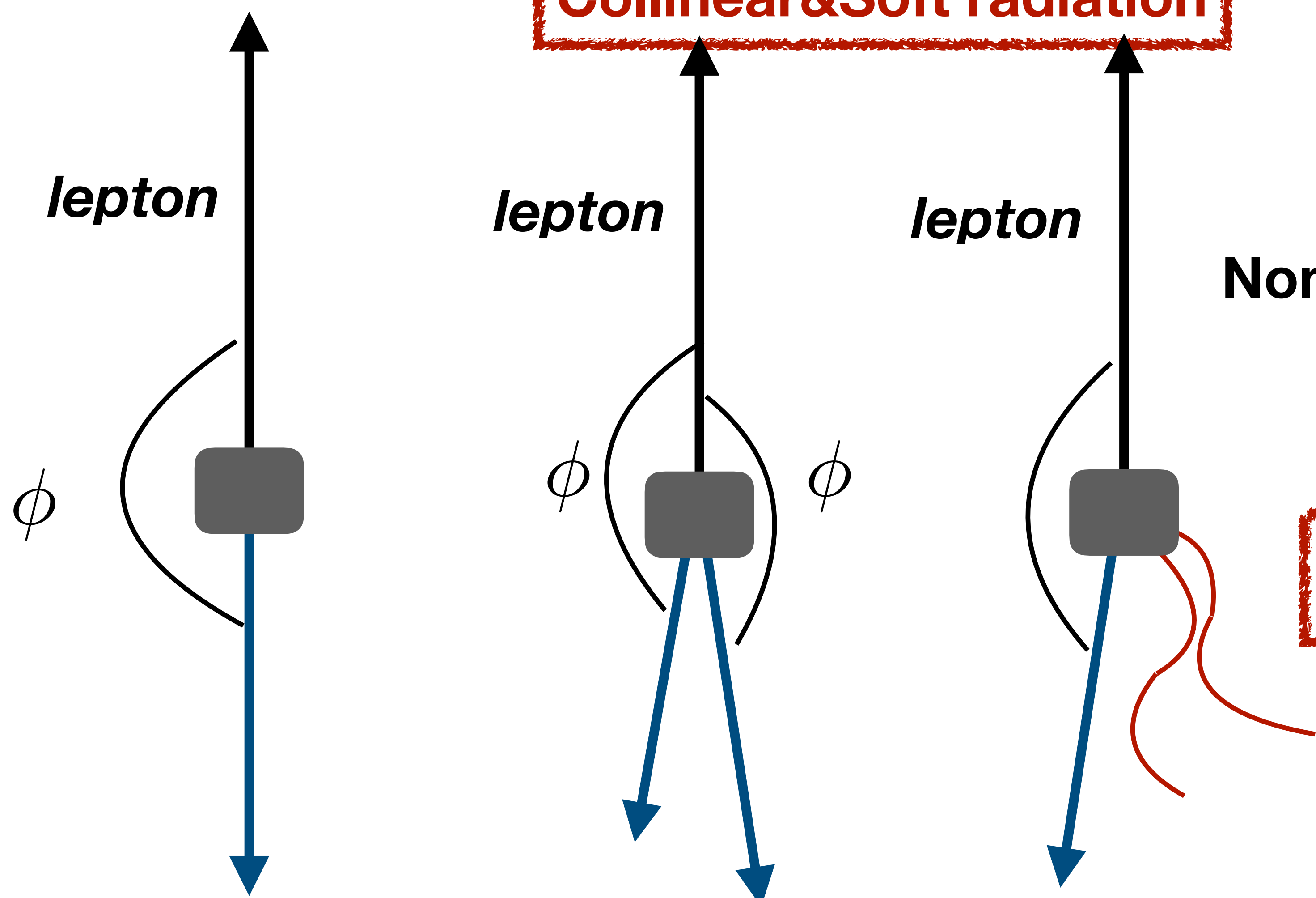
Collinear&Soft radiation



Non-zero momentum along y-direction

TMD Physics

$$\tau = \frac{1+\cos\phi}{2} \qquad \delta(\tau)$$

$$A\delta(\tau) + B\frac{1}{\tau} + C\frac{\ln\tau}{\tau}\cdots$$

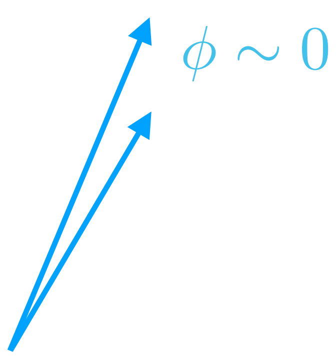
TEEC Definition

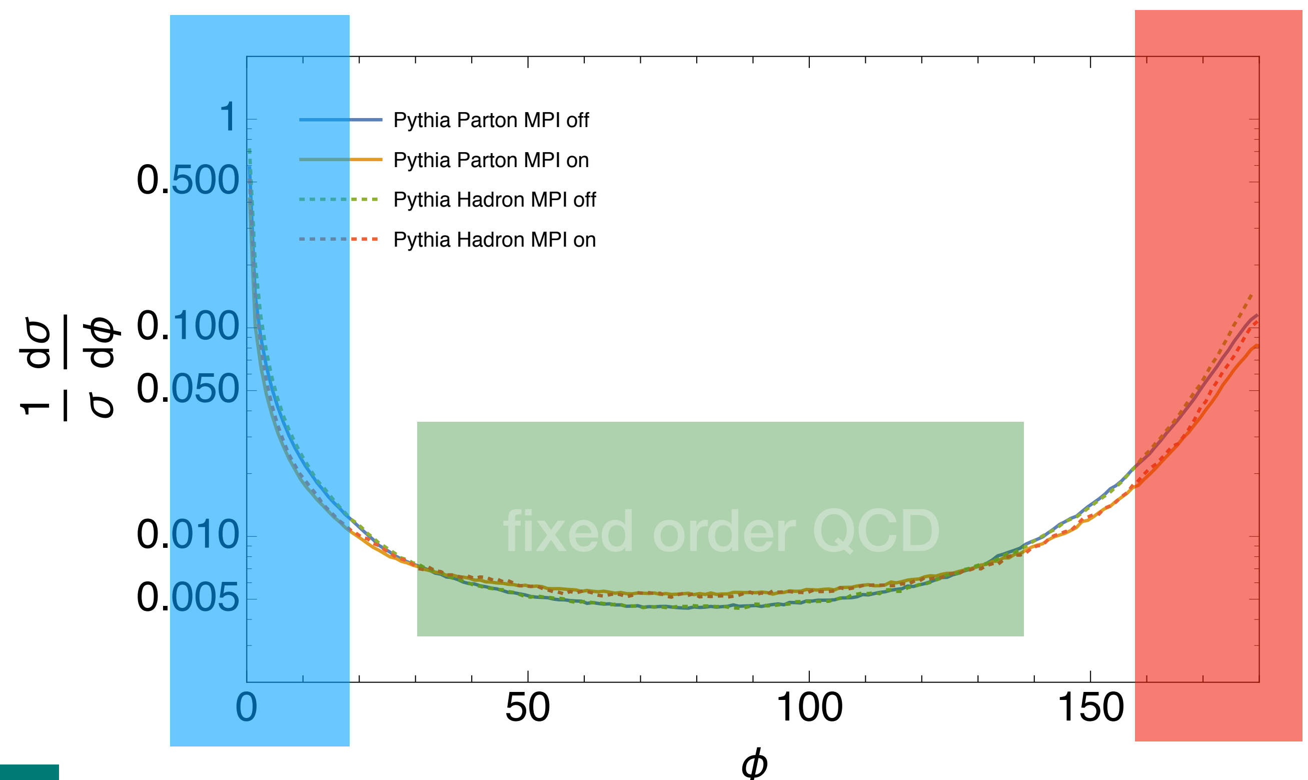
proton+proton

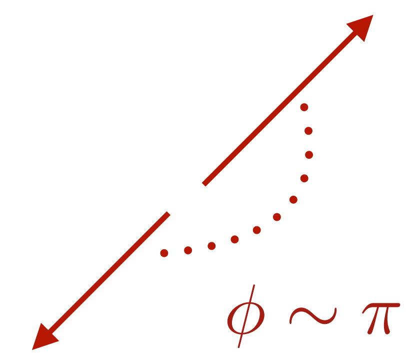
$$\mathrm{TEEC} = \sum_{a,b} \int d\sigma_{pp\to a+b+X} \frac{2E_{T,a}E_{T,b}}{|\sum_i E_{T,i}|^2} \delta(\cos\phi_{ab} - \cos\phi)$$

Collinear singularity $\cos\phi_{ab} \to 0$

Collinear and soft singularity $\cos\phi_{ab} \to -1$







proton+lepton

$$\mathrm{TEEC} = \sum_{a} \int d\sigma_{lp\to l+a+X} \frac{E_{T,a}}{P_{T,l}} \delta\left(\cos\phi_{la} - \cos\phi\right)$$

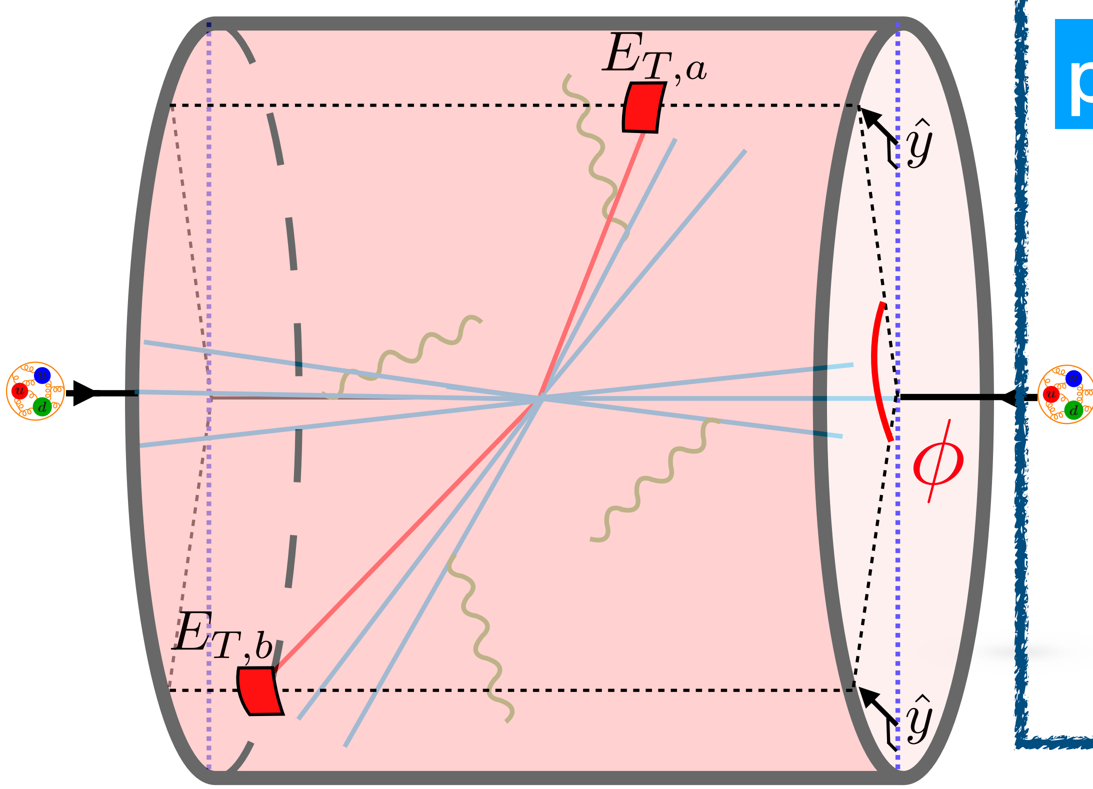
NO Collinear singularity when $\phi \to 0$

Back-to-back limit

Select events with a large hard scale

Define scattering plane: x-z

The back-to-back limit is defined as $\tau = \frac{1+\cos(\phi)}{2} \to 0$



proton+proton

Beam Functions

initial state collinear radiation

$$\frac{1+\cos\phi}{2} = \frac{\left(\frac{k_{3,y}}{\xi_3} + \frac{k_{4,y}}{\xi_4} + k_{1,y} + k_{2,y} - k_{s,y}\right)^2}{4P_T^2} + \dots$$

final state collinear radiation

soft-recoil

Jet Functions

Soft Functions

proton+lepton

$$\frac{1+\cos\phi}{2} = \frac{\left(\frac{k_{4,y}}{\xi_4} + k_{2,y} - k_{s,y}\right)^2}{4P_T^2} + \dots$$

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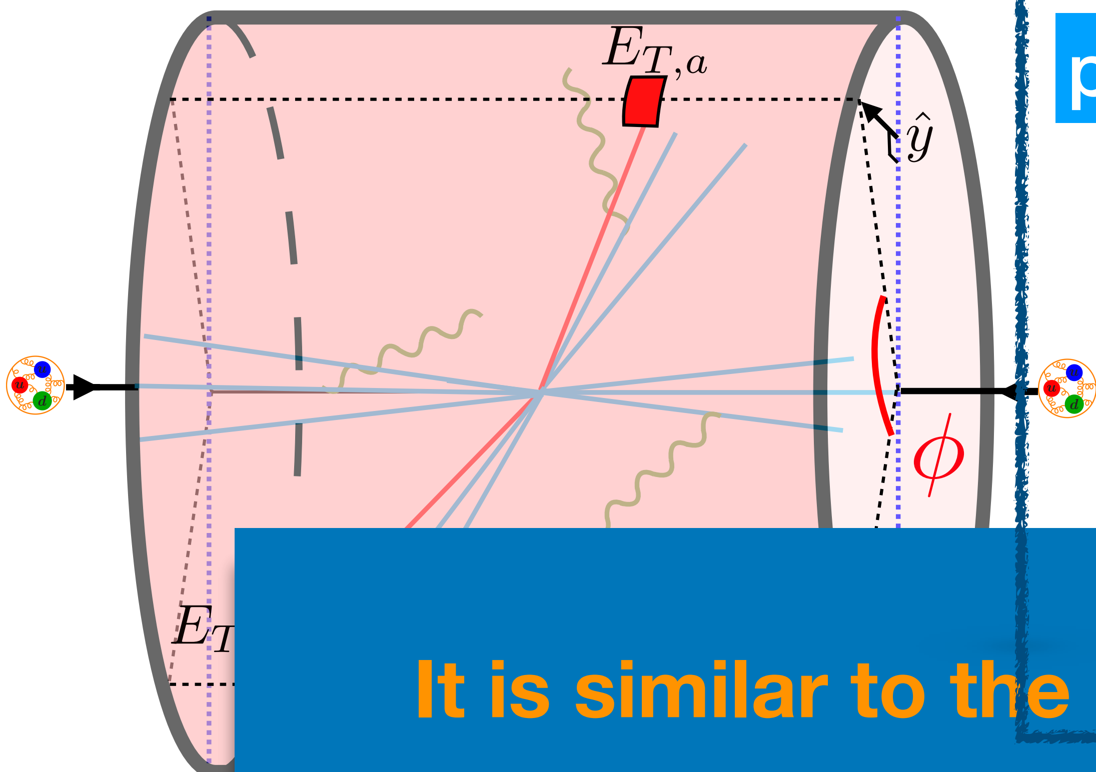

Beam Functions

proton+proton

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final state collinear radiation

soft-recoil

It is similar to the 1-dimensional TMD factorization

proton+lepton

$$\frac{1+\cos\phi}{2} = \frac{\left(\frac{k_{4,y}}{\xi_4}+k_{2,y}-k_{s,y}\right)^2}{4P_T^2}+\ldots$$

Factorization

proton+lepton

$$\frac{d\sigma^{(0)}}{d\tau} = \sum_f \int \frac{d\xi dQ^2}{\xi Q^2} Q_f^2 \sigma_0 \int \frac{db}{2\pi} e^{-2ib\sqrt{\tau}p_T} H(p_T, Q, \mu) S(b, Q, \mu, \nu) B_{f/N}(b, \xi, \mu, \nu) J_f(b, \mu, \nu)$$

Hard function know up to 3 loops

Beam Function

Soft function

Jet Function

Factorization

proton+lepton

$$\frac{d\sigma^{(0)}}{d\tau} = \sum_f \int \frac{d\xi dQ^2}{\xi Q^2} Q_f^2 \sigma_0 \int \frac{db}{2\pi} e^{-2ib\sqrt{\tau}p_T} H(p_T, Q, \mu) S(b, Q, \mu, \nu) B_{f/N}(b, \xi, \mu, \nu) J_f(b, \mu, \nu)$$

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Beam Function

Jet Function

Mixing between collinear and soft function depends on rapidity regulator

TMD PDFs

TMD FFs

Factorization

proton+lepton

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Hard function know up to 3 loops

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Jet Function

Mixing between collinear and soft function depends on rapidity regulator

TMD PDFs

TMD FFs

As TMD PDFs, TMD FFs can be matched onto collinear FFs

$$\mathscr{F}_{N/q}\left(z, b_\perp/z, \nu\right) = \sum_i \int_z^1 \frac{d\xi}{\xi} d_{N/i}(z/\xi) \mathscr{C}_{iq}\left(\xi, b_\perp/\xi, \nu\right)$$

Factorization

proton+lepton

$$\frac{d\sigma^{(0)}}{d\tau} = \sum_f \int \frac{d\xi dQ^2}{\xi Q^2} Q_f^2 \sigma_0 \int \frac{db}{2\pi} e^{-2ib\sqrt{\tau}p_T} H(p_T, Q, \mu) S(b, Q, \mu, \nu) B_{f/N}(b, \xi, \mu, \nu) J_f(b, \mu, \nu)$$

Hard function know up to 3 loops

Soft function

Beam Function

Jet Function

Mixing between collinear and soft function depends on rapidity regulator

$\underbrace{\text{Beam Function} \quad \text{Soft function}}_{\text{TMD PDFs}}$

$\underbrace{\text{Soft function} \quad \text{Jet Function}}_{\text{TMD FFs}}$

As TMD PDFs, TMD FFs can be matched onto collinear FFs

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The jet function is the second Mellin moment of the matching coefficients

$$J^q\left(b_\perp, \mu, \nu\right) = \sum_i \int_0^1 dx\, x \mathscr{C}_{iq}\left(x, b_\perp/x, \mu, \nu\right)$$

Factorization

lepton+lepton

$$\frac{d\sigma}{d\tau}=\frac{1}{2}\int d^2\vec{k}_\perp \int \frac{d^2\vec{b}_\perp}{(2\pi)^2} e^{-i\vec{b}_\perp\cdot\vec{k}_\perp} H(Q,\mu) J^q_{\mathrm{EEC}}\left(\vec{b}_\perp,\mu,\nu\right) J^{\bar{q}}_{\mathrm{EEC}}\left(\vec{b}_\perp,\mu,\nu\right) S_{\mathrm{EEC}}\left(\vec{b}_\perp,\mu,\nu\right)\delta\left(1-\tau-\frac{\vec{k}_\perp^2}{Q^2}\right)$$

proton+lepton

$$\frac{d\sigma^{(0)}}{d\tau}=\sum_f\int\frac{d\xi dQ^2}{\xi Q^2}Q_f^2\sigma_0\int\frac{db}{2\pi}e^{-2ib\sqrt{\tau}p_T}H(p_T,Q,\mu)S(b,Q,\mu,\nu)B_{f/N}(b,\xi,\mu,\nu)J_f(b,\mu,\nu)$$

proton+proton

$$\begin{aligned}\frac{d\sigma^{(0)}}{d\tau}=&\frac{1}{16\pi s^2\left(1+\delta_{f_5f_4}\right)\sqrt{\tau}}\sum_{\text{channels}}\frac{1}{N_{\text{init}}}\int\frac{dy_3dy_4p_Tdp_T^2}{\xi_1\xi_2}\int_{-\infty}^{\infty}\frac{db}{2\pi}e^{-2ib\sqrt{\tau}p_T}\\&\times\operatorname{tr}\left(\mathbf{H}^{f_1f_2\to f_3f_4}\left(p_T,y^*,\mu\right)\mathbf{S}\left(b,y^*,\mu,\nu\right)\right]B_{f_1/N_1}\left(b,\xi_1,\mu,\nu\right)B_{f_2/N_2}\left(b,\xi_2,\mu,\nu\right)J_{f_3}(b,\mu,\nu)J_{f_4}(b,\mu,\nu)\end{aligned}$$

Factorization

lepton+lepton

$$\frac{d\sigma}{d\tau} = \frac{1}{2}\int d^2\vec{k}_\perp \int \frac{d^2\vec{b}_\perp}{(2\pi)^2} e^{-i\vec{b}_\perp\cdot\vec{k}_\perp} H(Q,\mu) J^{q}_{\mathrm{EEC}}\left(\vec{b}_\perp,\mu,\nu\right) J^{\bar{q}}_{\mathrm{EEC}}\left(\vec{b}_\perp,\mu,\nu\right) S_{\mathrm{EEC}}\left(\vec{b}_\perp,\mu,\nu\right)\delta\left(1-\tau-\frac{\vec{k}_\perp^2}{Q^2}\right)$$

proton+lepton

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proton+proton

$$\frac{d\sigma^{(0)}}{d\tau} = \frac{1}{16\pi s^2\left(1+\delta_{f_5 f_4}\right)\sqrt{\tau}} \sum_{\text{channels}} \frac{1}{N_{\text{init}}} \int \frac{dy_3 dy_4 p_T dp_T^2}{\xi_1\xi_2} \int_{-\infty}^{\infty} \frac{db}{2\pi} e^{-2ib\sqrt{\tau}p_T}$$
$$\times\, \mathrm{tr}\left(\mathbf{H}^{f_1 f_2\to f_3 f_4}\left(p_T,y^*,\mu\right)\mathbf{S}\left(b,y^*,\mu,\nu\right)\right] B_{f_1/N_1}\left(b,\xi_1,\mu,\nu\right) B_{f_2/N_2}\left(b,\xi_2,\mu,\nu\right) J_{f_3}(b,\mu,\nu) J_{f_4}(b,\mu,\nu)$$

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Universality of QCD in the infrared regime

proto

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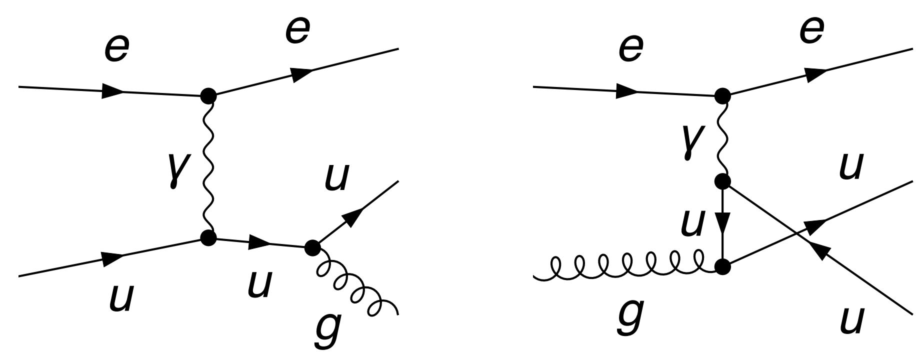
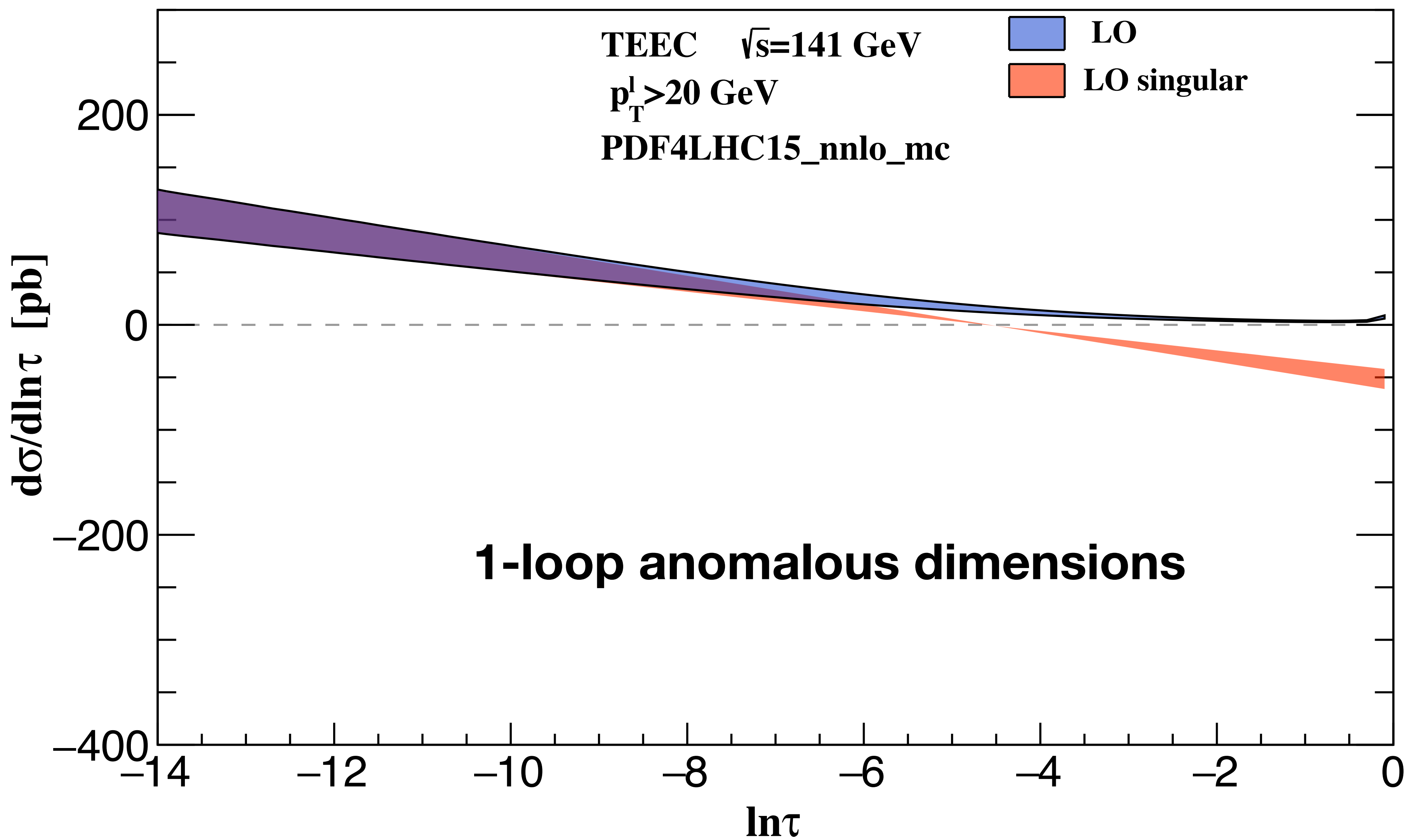
Fixed-order in DIS

The leading order process is





Cross-check with Full QCD predictions in the back-to-back limits

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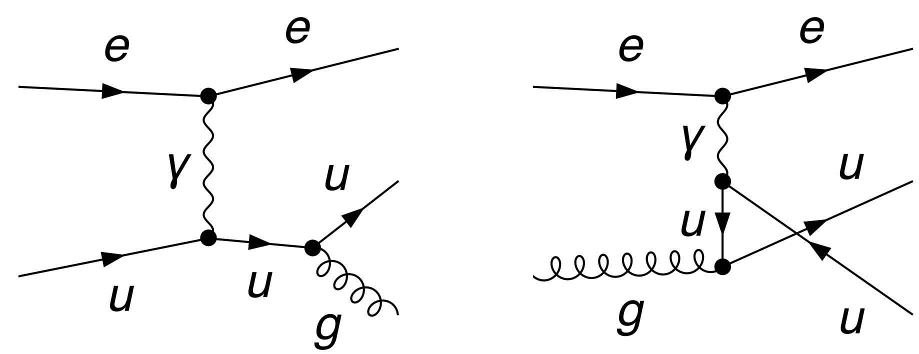

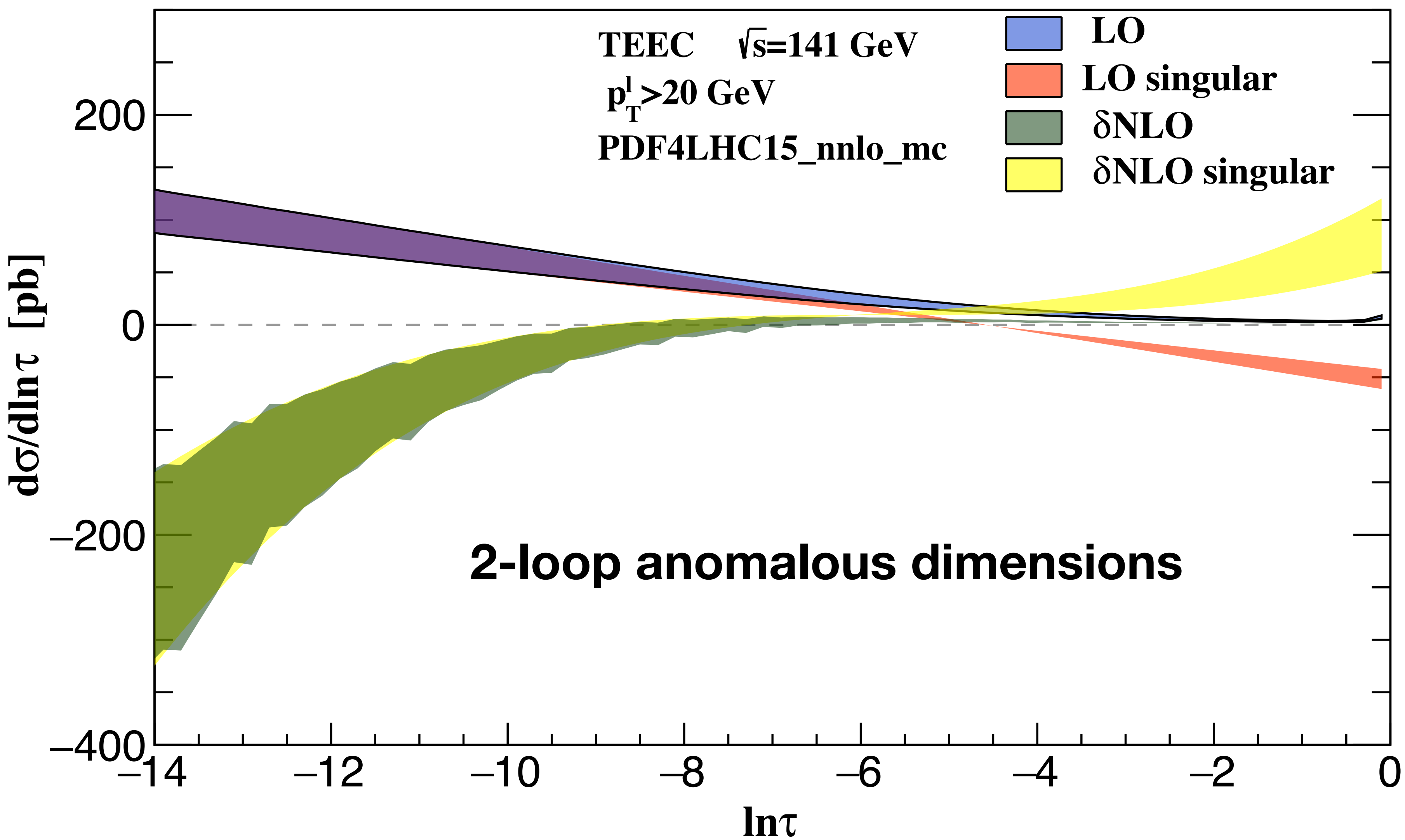

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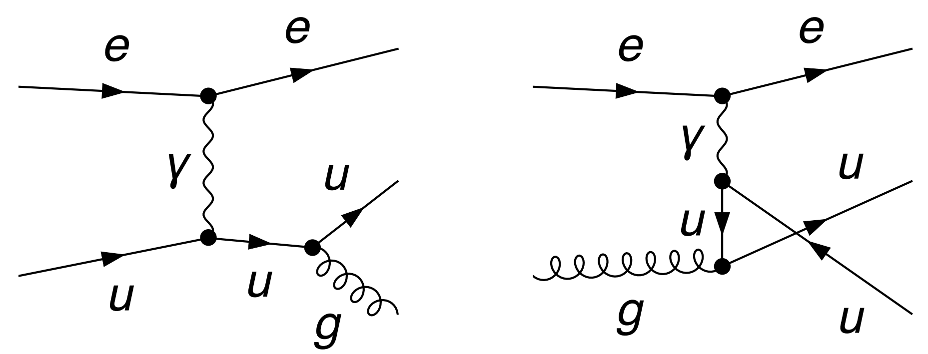

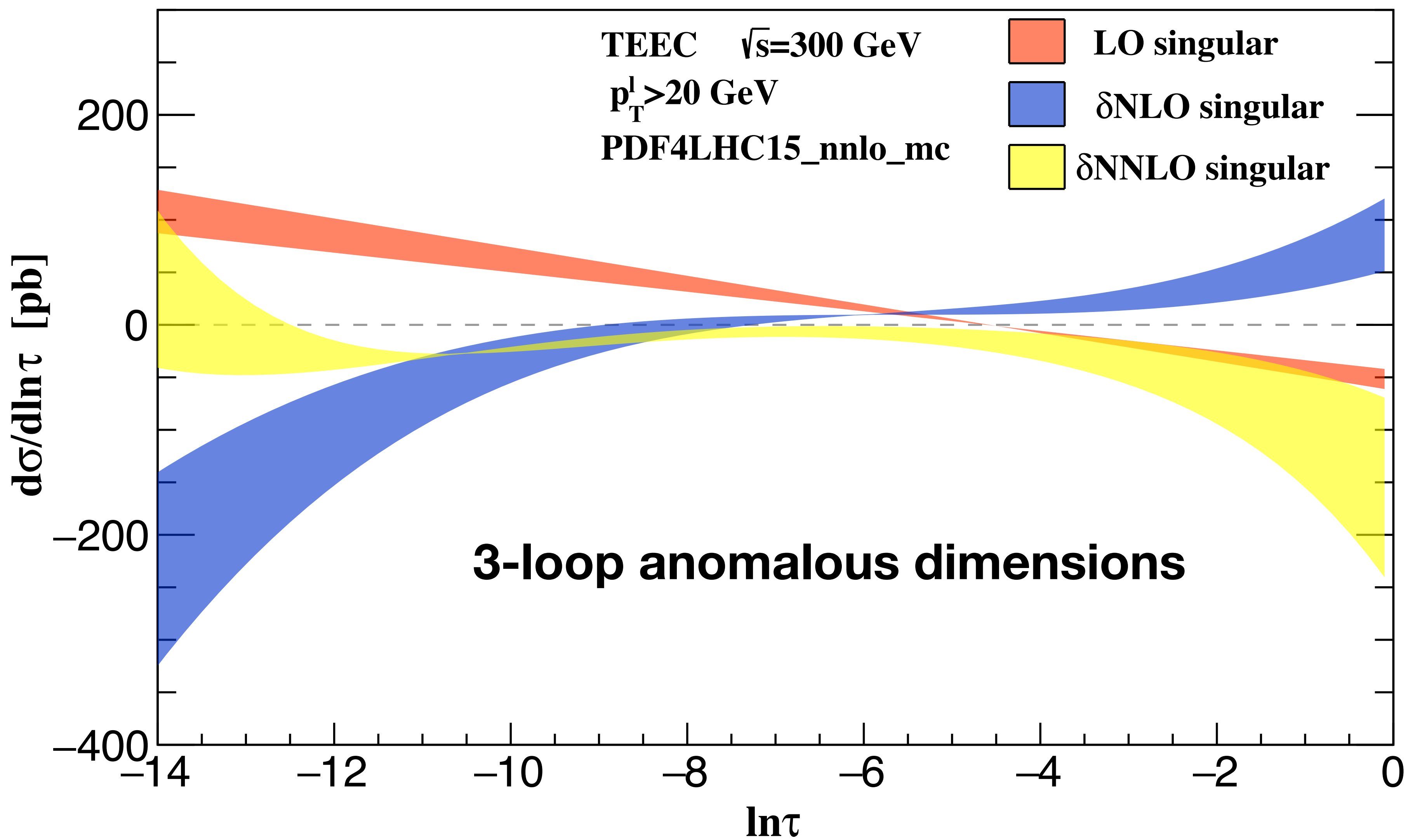

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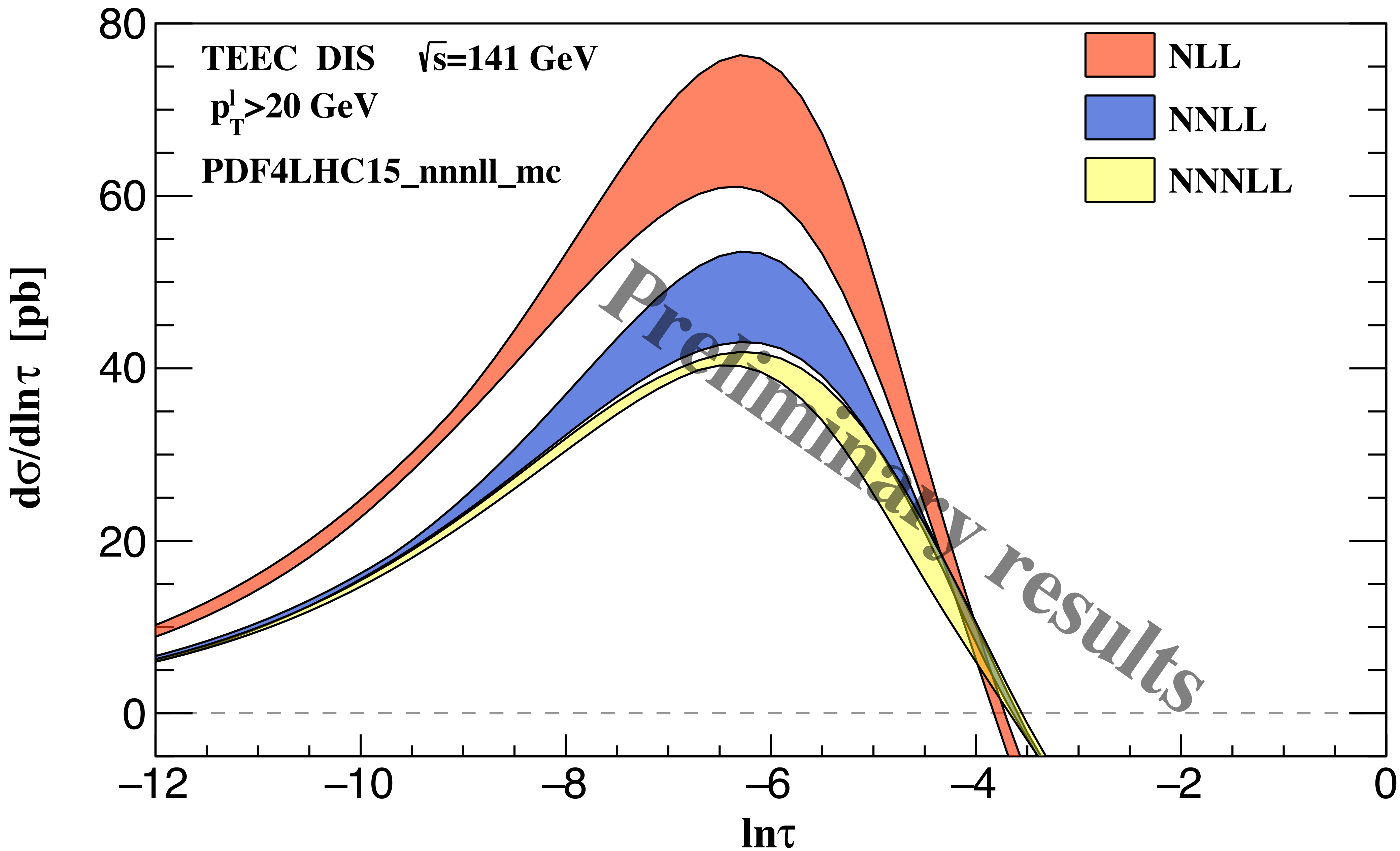
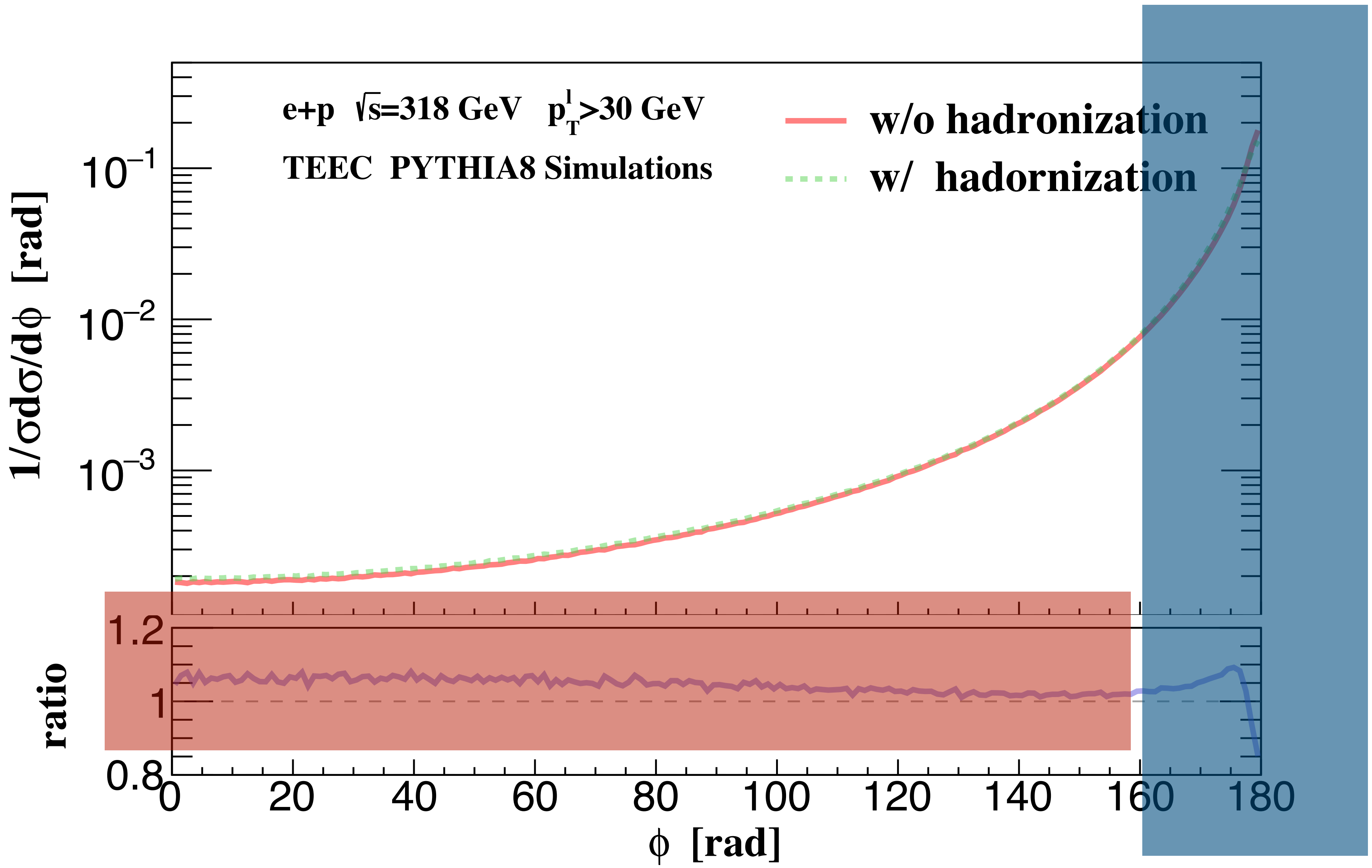
Resummation in DIS



The cross section converges when $\tau \to 0$
Reduction of scale uncertainties from NLL to NNNLL

Hadronization effects

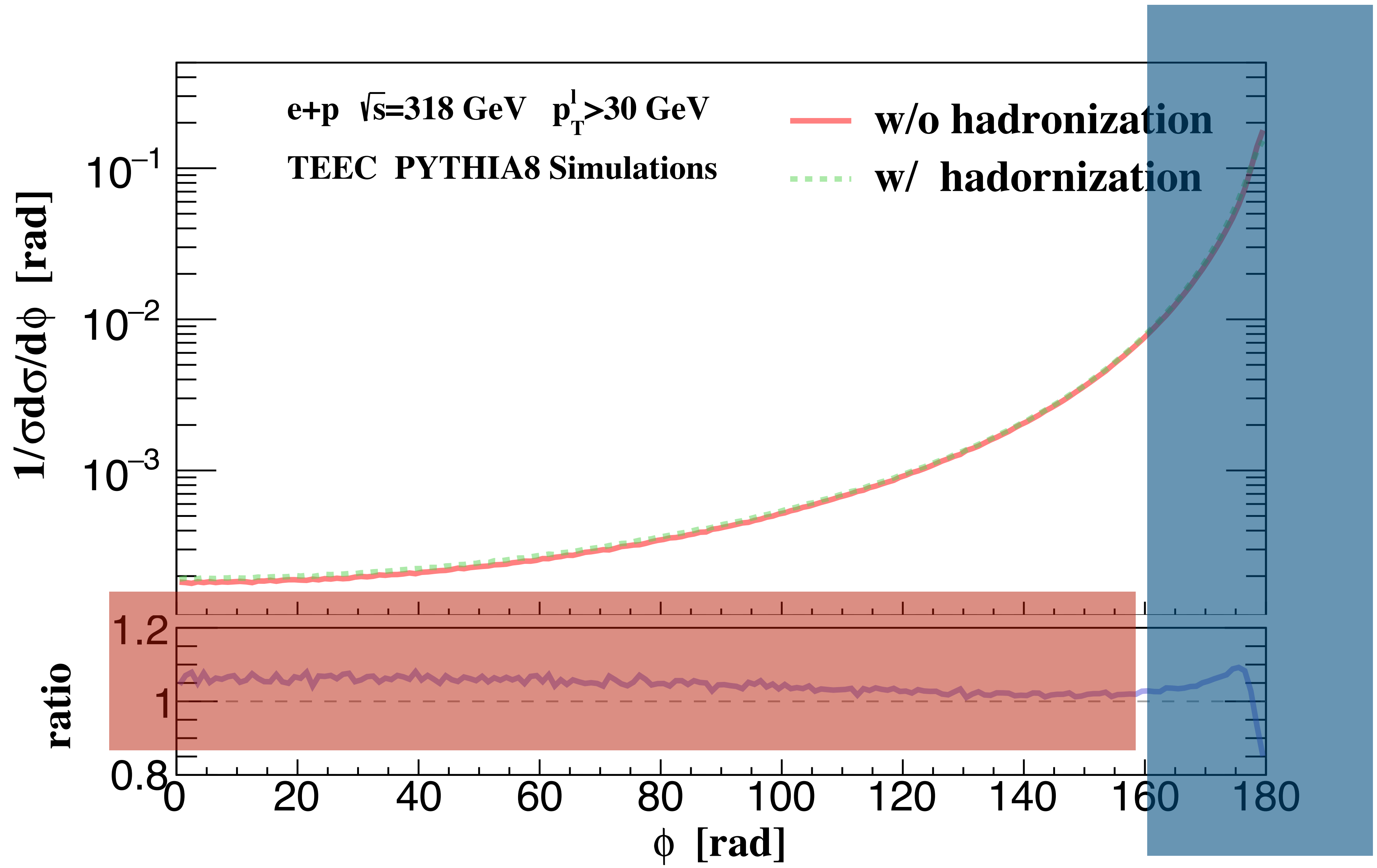


Small hadronization effects

Soft and Collinear radiations dominate

Hadronization effects is less than 20%

Hadronization effects



Small hadronization effects

Soft and Collinear radiations dominate

Hadronization effects is less than 20%

Precision prediction is dominated by perturbative QCD corrections

Comments on EIC TEEC

- sensitivity to non-perturbative effects
- be used to study the initial state nuclear effects
- It is feasible to study the polarized TMD PDFs

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For example:

Possible to construct using the medium-induced splitting kernels

Ovanesyan, Ringer, Vitev, 2016

Or $$\frac{d\sigma}{d\tau} \Longrightarrow \frac{d\sigma}{d\tau} \mathrm{e}^{-\frac{\hat{q} L b^2}{4}}$$

Liu , Ringer, Vogelsang , Yuan 2019

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$$F_{f/P^{\uparrow}}(x, k_T, S; \mu, \zeta_F) = F_{f/P}(x, k_T; \mu, \zeta_F) \boxed{- F_{1T}^{\perp f}(x, k_T; \mu, \zeta_F) \frac{\epsilon_{ij} k_T^i S^j}{M_p}}$$

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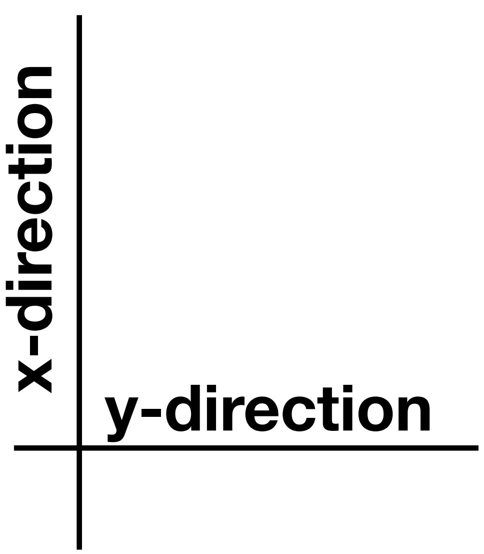
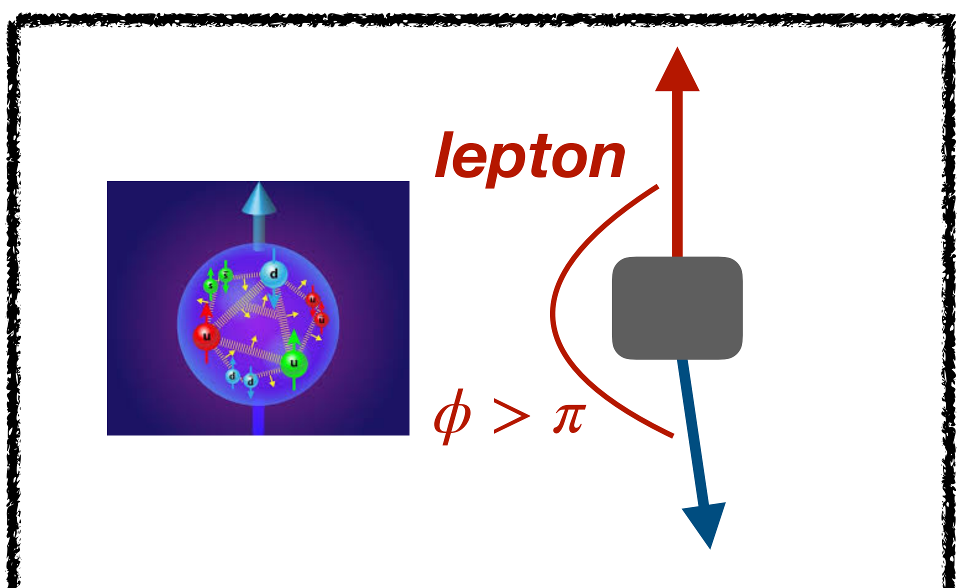
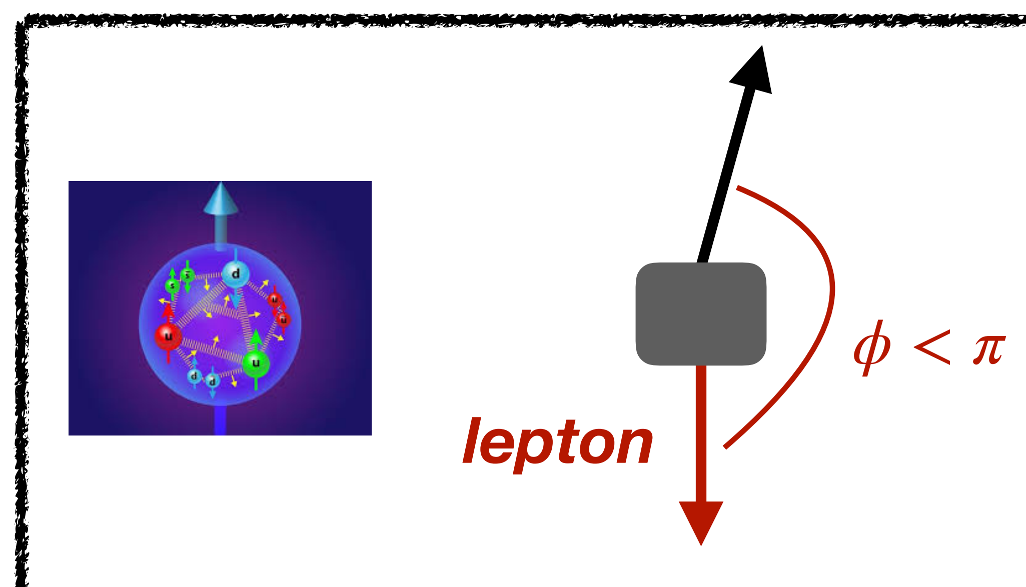
see Filippo Delcarro' talk

The difference between two configurations







4. Conclusion

- We study the TEEC in the framework of SCET.
- We present pQCD predictions for TEEC in proton+lepton collisions
- Resummation of this event shape is possible at N3LL
- **Open the avenue of precision event shape calculation and measurement at different types of colliders**
- **TEEC can be used to study the unpolarized and polarized TMD physics**

To-do list

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Thank you!