Perturbative QCD at Colliders
(RHIC/LHC/JLab/EIC)

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MIT

Long Range Plan Joint Town Hall Meetings on QCD
Temple University, PA
September 2014

Orthogonal to other speakers (mostly)

Look to the future first, and (mostly) discuss past work that makes future ideas viable (one measure of importance).

Many things are left out (sorry!)

Outline

- Factorization for Colliders   LHC, RHIC, JLab, Fermilab,…, EIC, …

  Non-perturbative and Perturbative
- Precision Theory, needed for PDFs, Strong Coupling, …
- Hadronization: single parton, multi-parton & multi-hadron
- New Hadronic probes for quarks and gluons in Jets
- Rapidity and Q^2 Evolution, TMDPDFs
- Form Factors for 2-photon contributions
- Factorization Violation
- Conclusion

Non-perturbative Factorization:

parton distributions

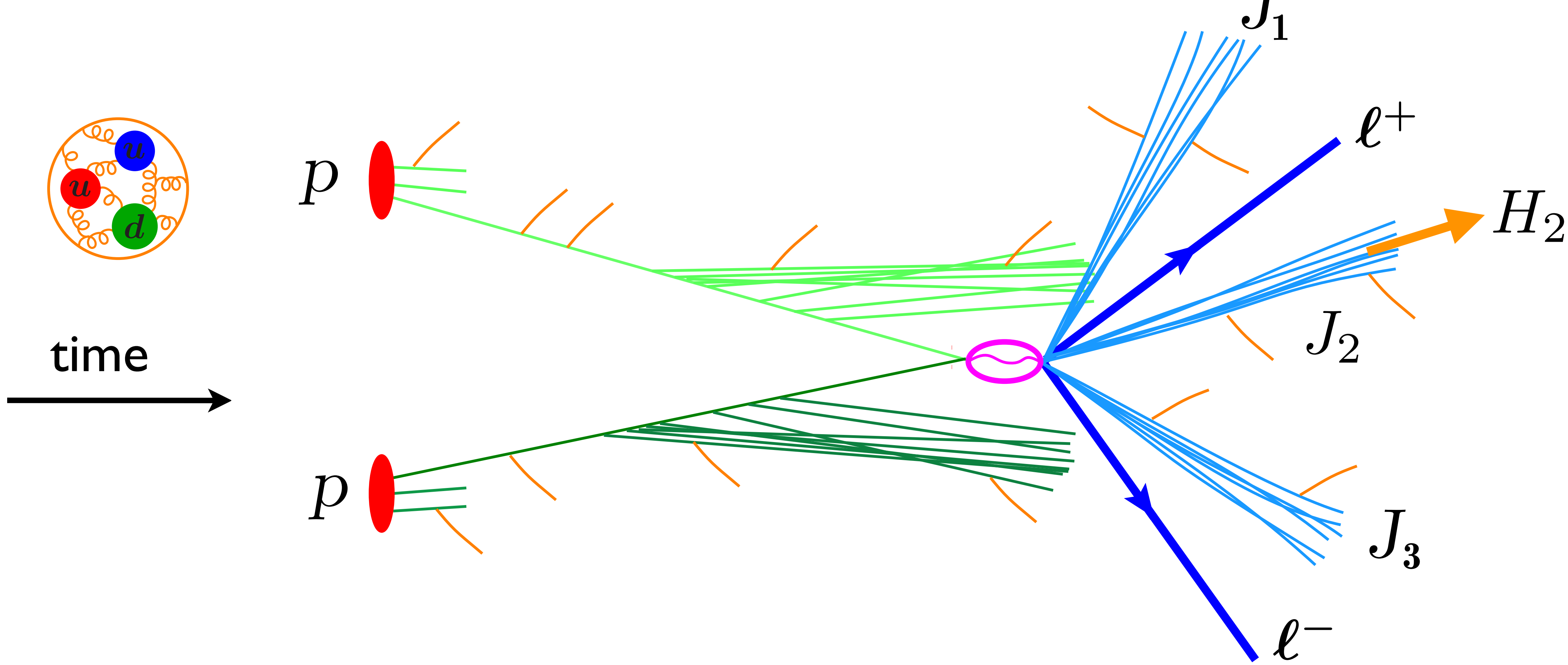
hadronization:

$$d\sigma = f_a f_b \otimes \hat{\sigma} \otimes F$$

fragmentation fns.,
soft hadronization, ...
(often with QFT operators)

universal hadronic dynamics
via
universal hadronic functions

perturbative cross section



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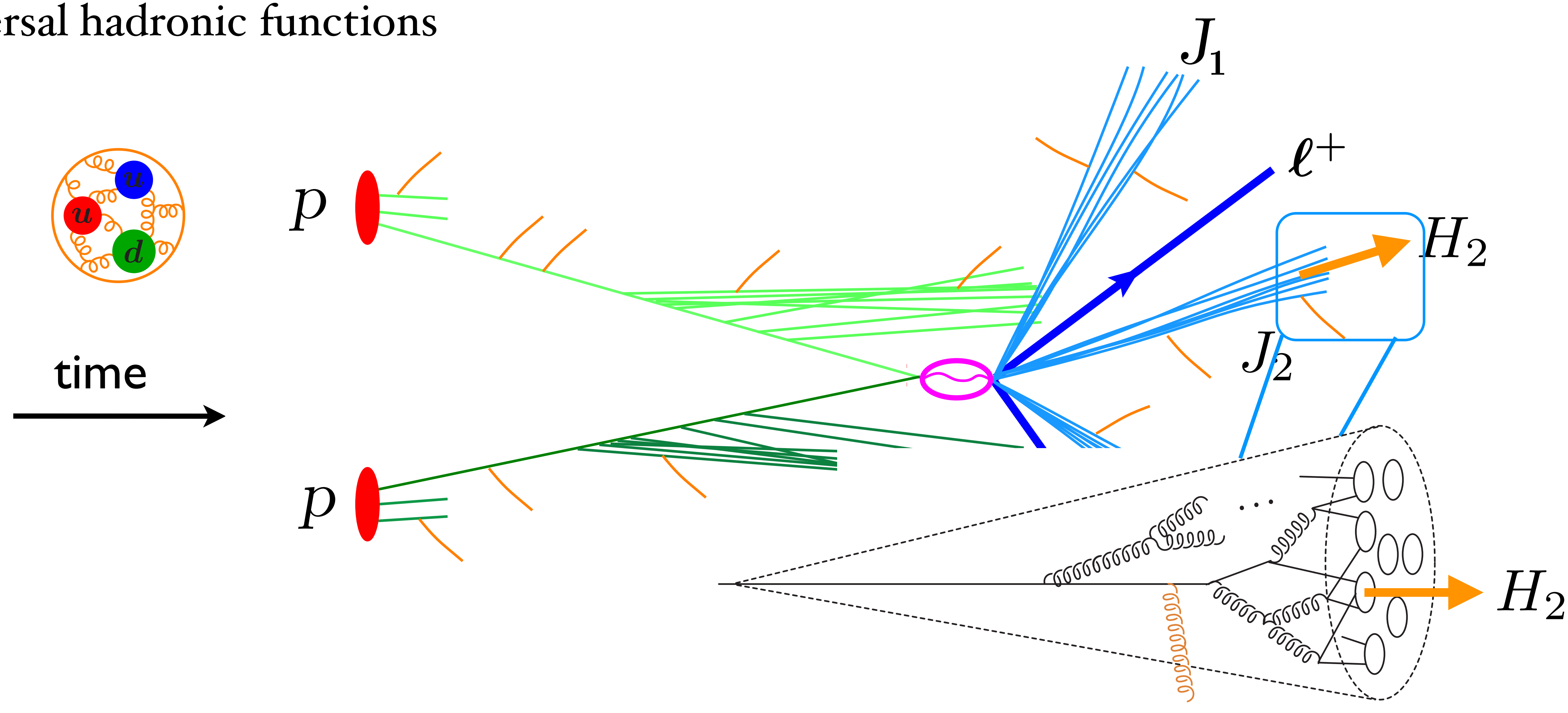


Perturbative QCD Results:

fixed order:

$$\hat{\sigma} = \sigma_0 \left[1 + \alpha_s + \alpha_s^2 + \ldots \right]$$
$$= \mathrm{LO} + \mathrm{NLO} + \mathrm{NNLO} + \ldots$$

resummation of large (double) logs: $L = \log(\ldots)$

$\log\left(\frac{\Lambda_{\rm QCD}}{Q}\right)$, $\log\left(\frac{p_T}{Q}\right)$, ...

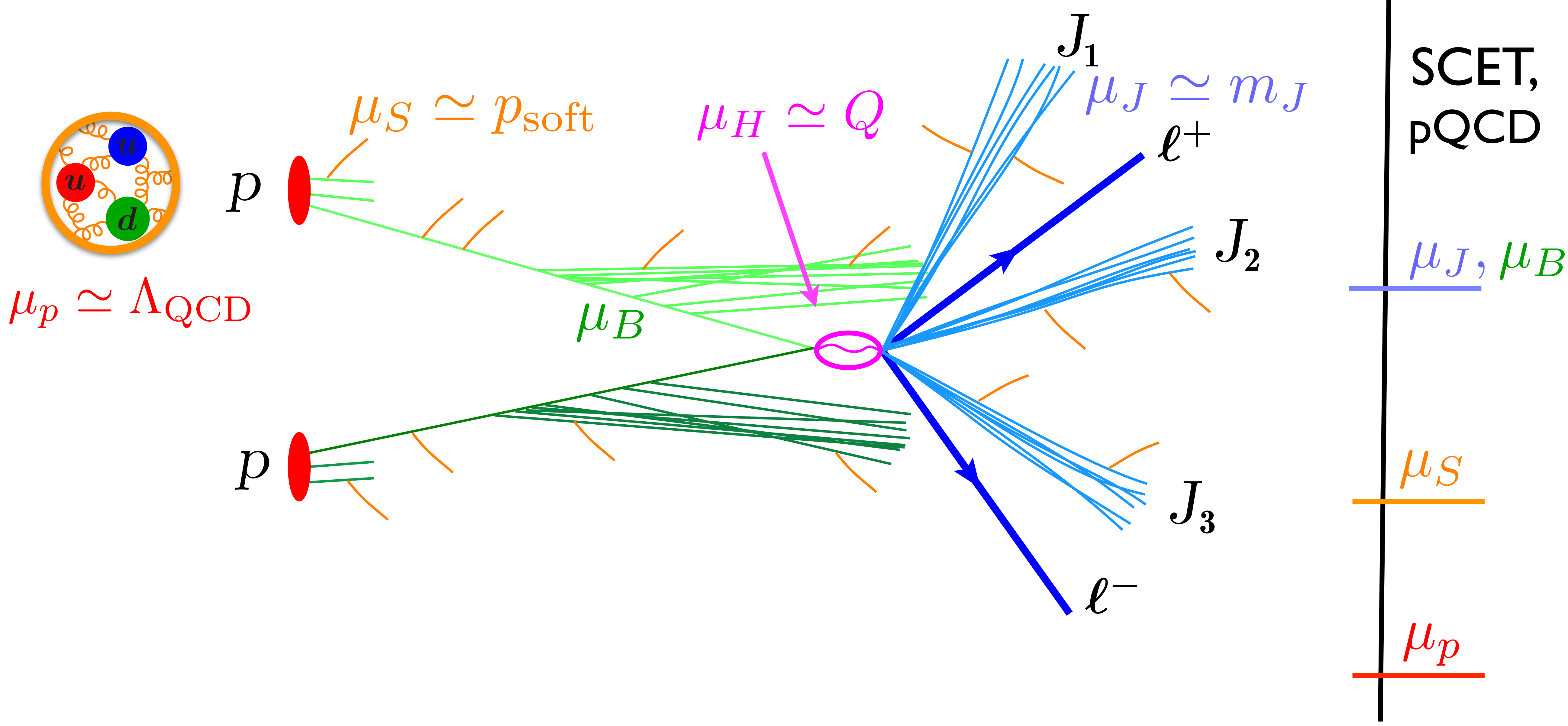
$$\ln \hat{\sigma}(y) = \sum_k L(\alpha_s L)^k + \sum_k (\alpha_s L)^k + \sum_k \alpha_s (\alpha_s L)^k + \sum_k \alpha_s^2 (\alpha_s L)^k + \ldots$$
$$= \mathrm{LL} + \mathrm{NLL} + \mathrm{NNLL} + \mathrm{N^3LL} + \ldots$$

Perturbative Factorization: for multi-scale problems with fixed # jets

	beam	hard	jet	pert. soft

$$\hat{\sigma}_{\rm fact} = \mathcal{I}_a \mathcal{I}_b \otimes H \otimes \prod_i J_i \otimes S$$

μ_B	μ_H	μ_J	μ_S



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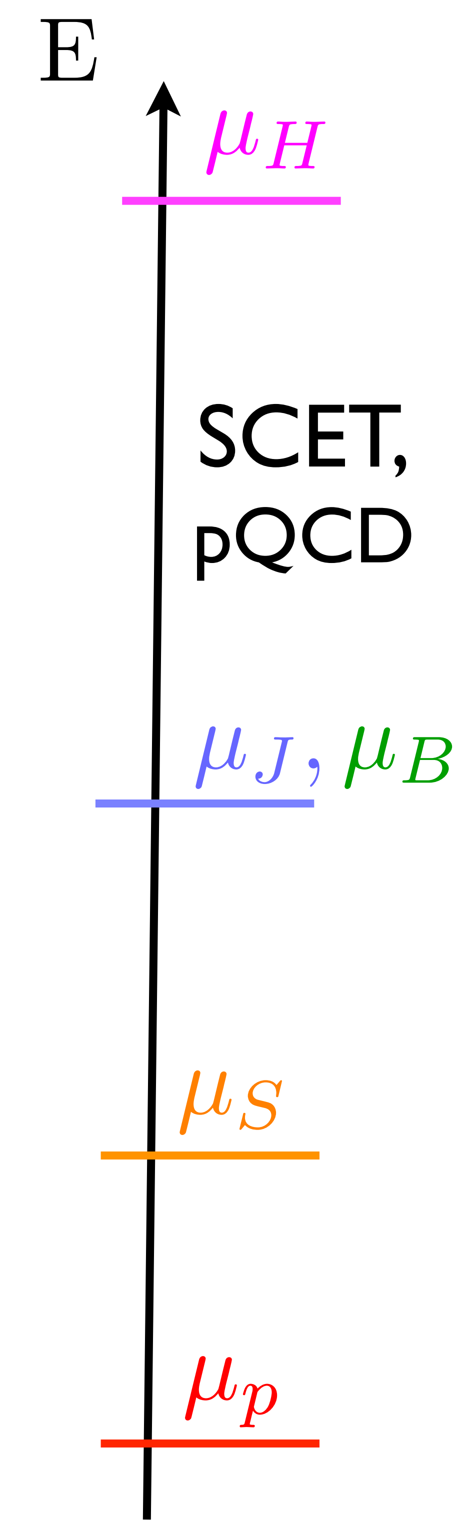


Perturbative Universality

- H determined by hard process, independent of jet radius, etc.
- J_i , $\mathcal{I}_{a,b}$ splitting and virtual effects for parton i, encode jet dynamics, independent of H — universal collinear dynamics

  eg. universal perturbative components for a TMDPDF
- S soft radiation, all partons contribute, eikonal Feynman rules

  universal soft dynamics

Scale dependence $\longleftrightarrow$ RGE sums up logarithms $\log\left(\frac{\mu_H}{\mu_S}\right), \ldots$

Inclusive Jets

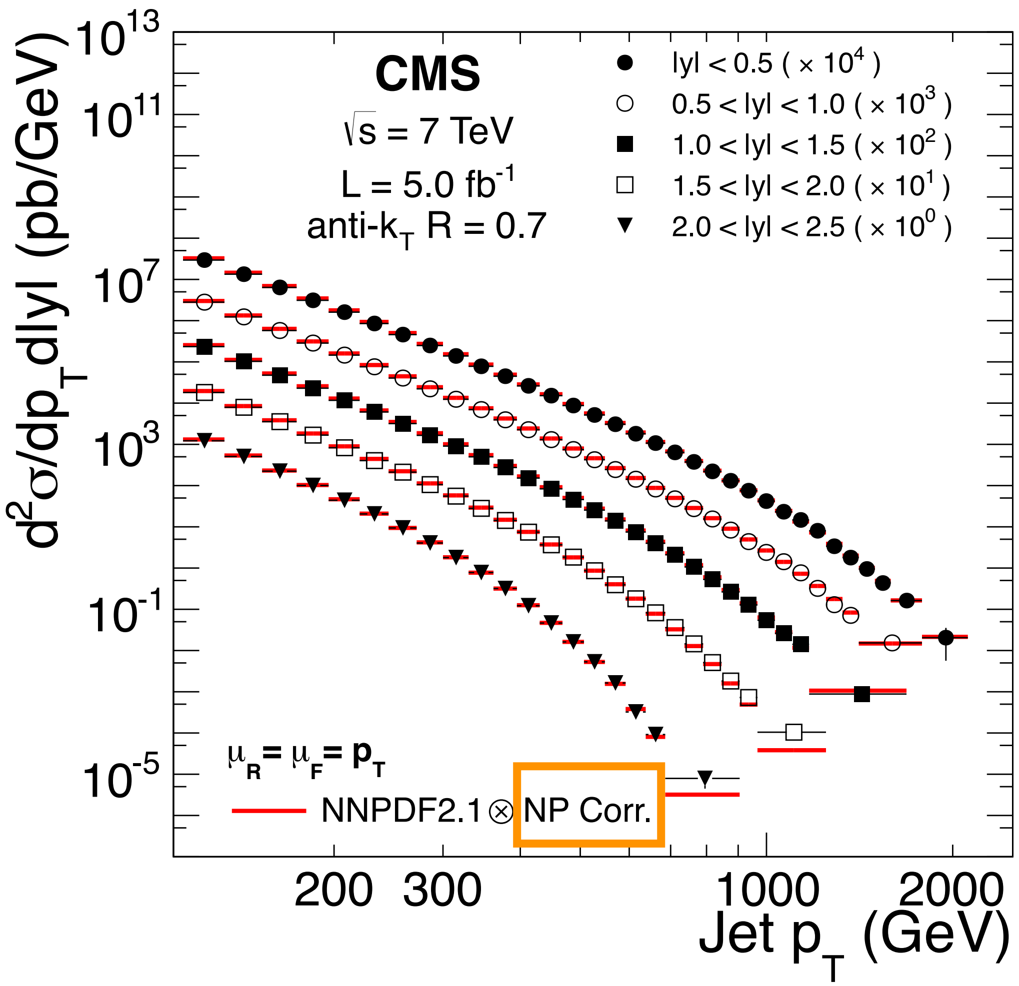
$$d\sigma = f_a f_b \otimes \hat{\sigma}_{\mathrm{NLO}} \otimes F$$

NNPDF | NLOJet++ (Z.Nagy) | Pythia/ Herwig

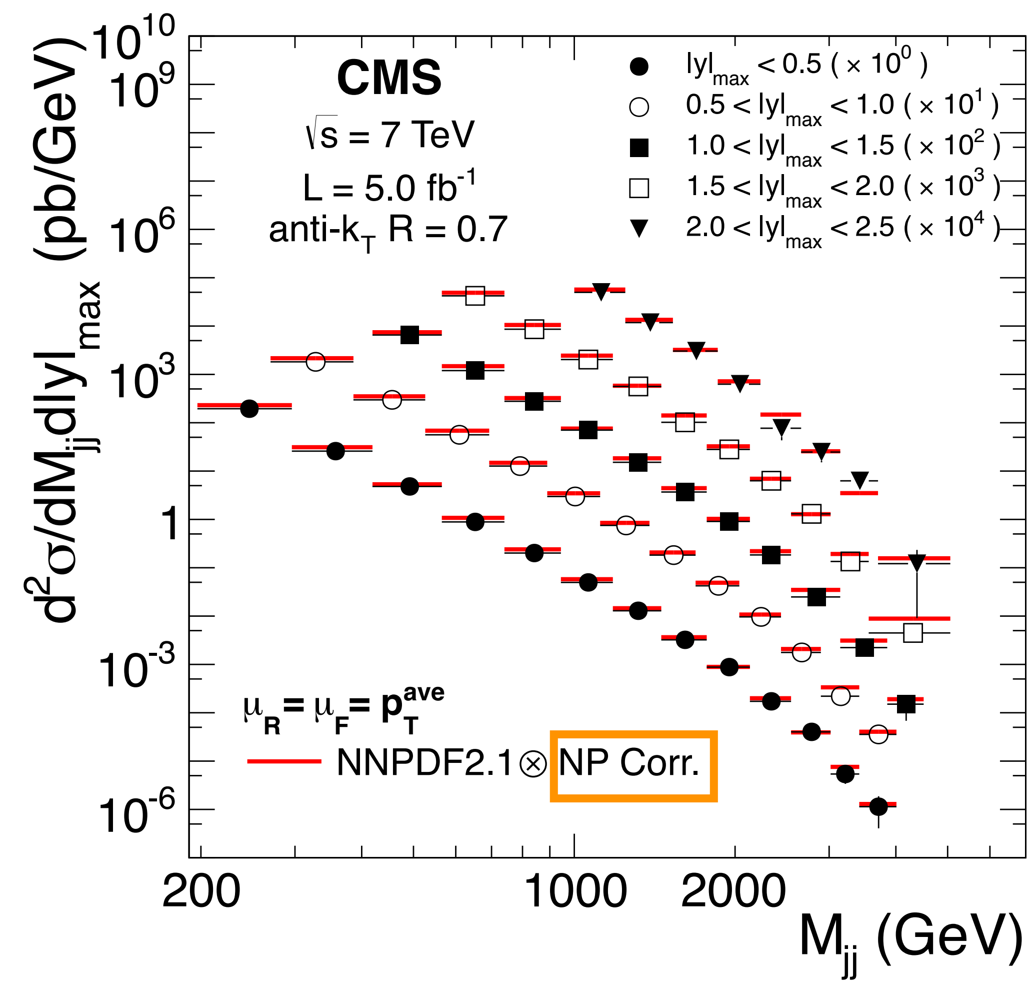
agreement with QCD over many orders of magnitude up to 2 TeV

uncertainty: $\leq 30\%$ | $5\% - 10\%$, 40% (large y) | $1\% - 20\%$

$pp \to \mathrm{jet} + X$



$pp \to \mathrm{dijets}$



CMS, arXiv:1212.6660

State of the Art Fixed Order pQCD:

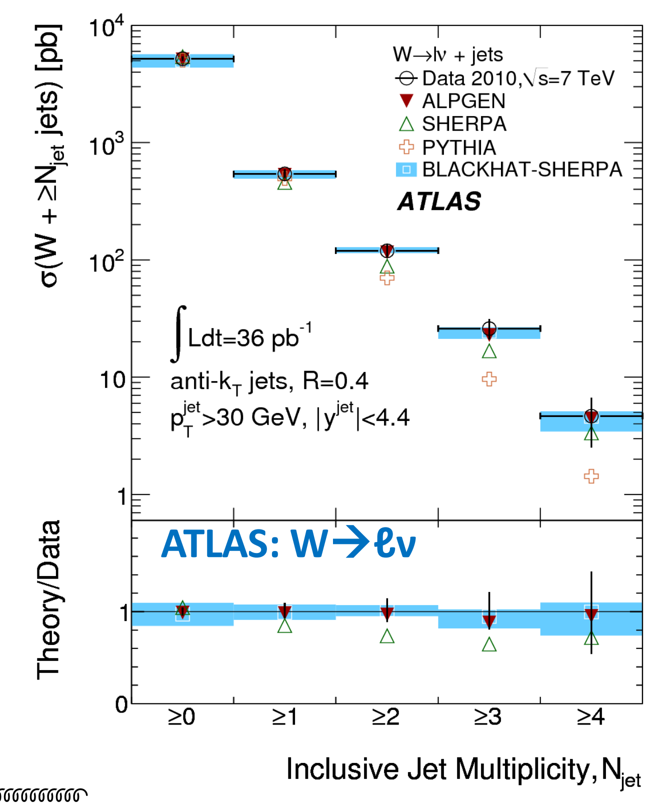
smaller uncertainty

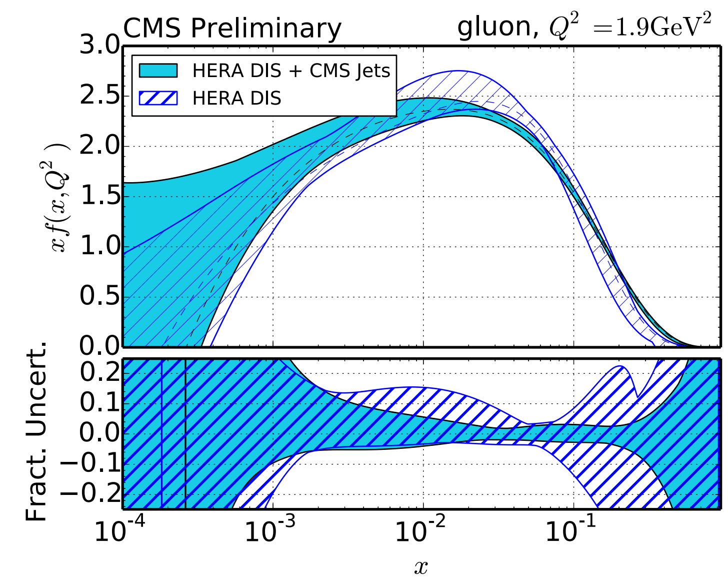
better PDFs

$e^+e^- \rightarrow$ jets: $\mathcal{O}(\alpha_s^3)$ Gerhmann-De Ridder, Gehrmann, Glover, Heinrich; Weinzierl

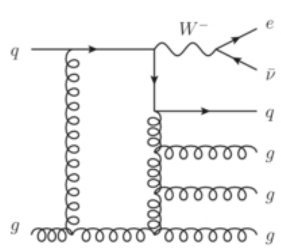
DIS: $\mathcal{O}(\alpha_s^3)$ NNLL evolution

Moch, Vermaseren, Vogt; , ...





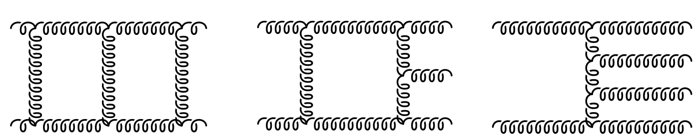
pp, ep(jets): mostly NLO (lots of legs!)



Blackhat collab., Rocket collab., ...

NNLO frontier

$gg \rightarrow gg$



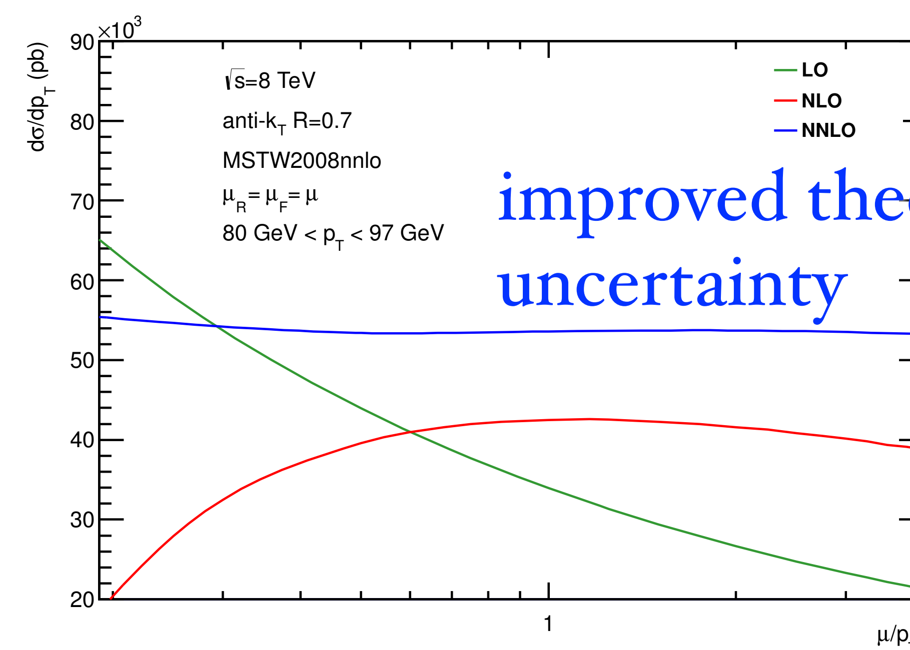
(C. Anastasiou, E.W.N. Glover, C. Oleari, M. Tejeida-Yeomans; Z. Bern, L. Dixon, A. De Freitas)

(Z. Kunszt, A. Signer, Z. Trocsanyi)

Gehrmann-De Ridder, Gehrmann, Glover, Pires arXiv:1301.7310

$pp \rightarrow t\bar{t}$ Czakon, Fiedler, Mitov, arXiv:1301.7310

$gg \rightarrow H + 1$-jet Boughezal, Caola, Melnikov, Petriello, Schulze arXiv:1302.6216



improved theory uncertainty

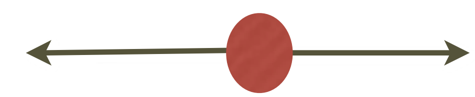
High Precision from event shapes

Lots of them! Few examples:

2 jets

$\tau \longrightarrow 0$

$C \longrightarrow 0$

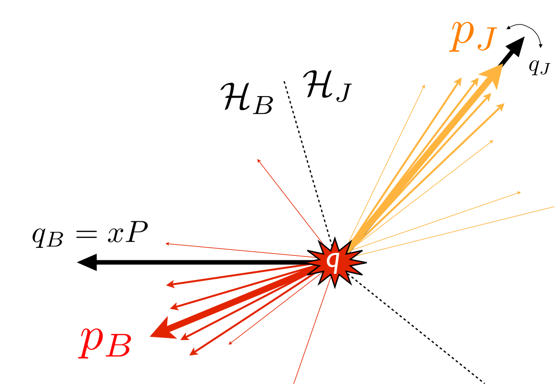


- Thrust $$\tau = 1 - \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum |\vec{p}_i\,|}$$

- C-parameter $$C = \frac{3}{2} \frac{\sum_{i,j} |\vec{p}_i||\vec{p}_j| \sin^2(\theta_{ij})}{(\sum_i |\vec{p}_i|)^2}$$

- DIS Thrust & 1-jettiness (relevant for EIC)

$$\tau^{\text{DIS}} = 1 - \frac{2}{Q} \sum_{i \in \mathcal{H}_J} |\vec{p}_i \cdot \vec{n}| \,, \qquad \tau_1 = \frac{2}{Q^2} \sum_i \min\{q_B \cdot p_i, q_J \cdot p_i\}$$



axes: q_B(beam), q_J(jet)

Dasgupta, Salam; IS, Tackmann, Waalewijn; Kang, Mantry, Qiu

Strong Coupling

Becher & Schwartz
Abbate et.al.

$e^+e^- \to$ jets:

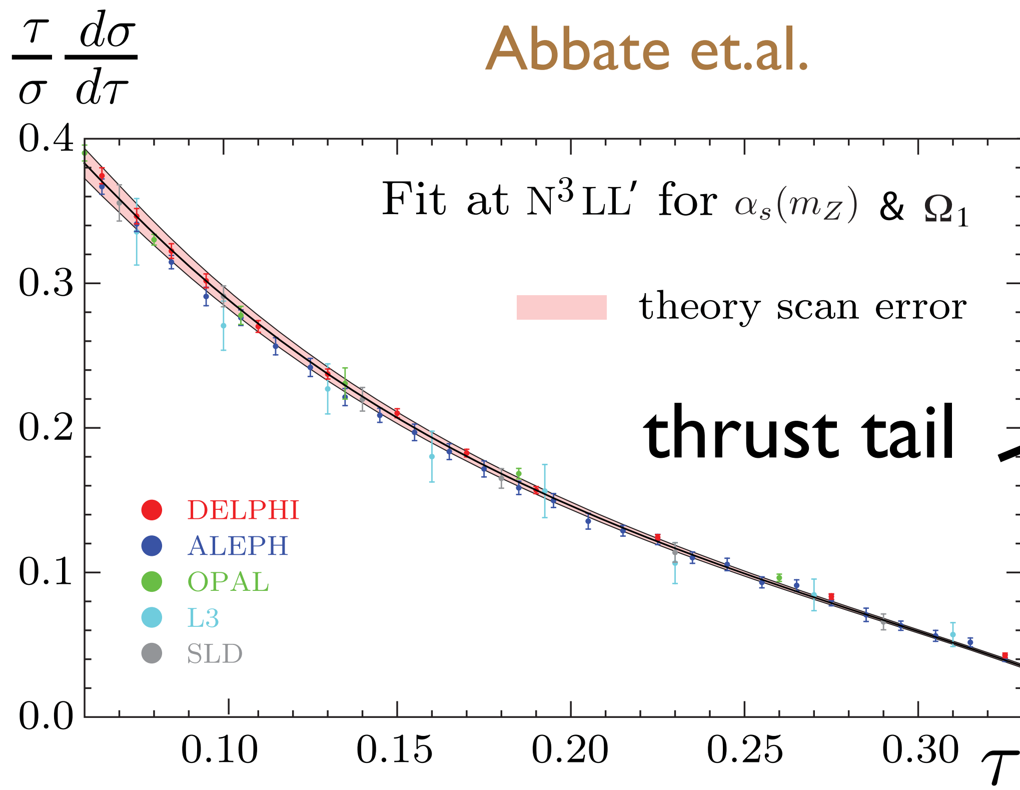
N^{3}LL + $\mathcal{O}(\alpha_s^3)$

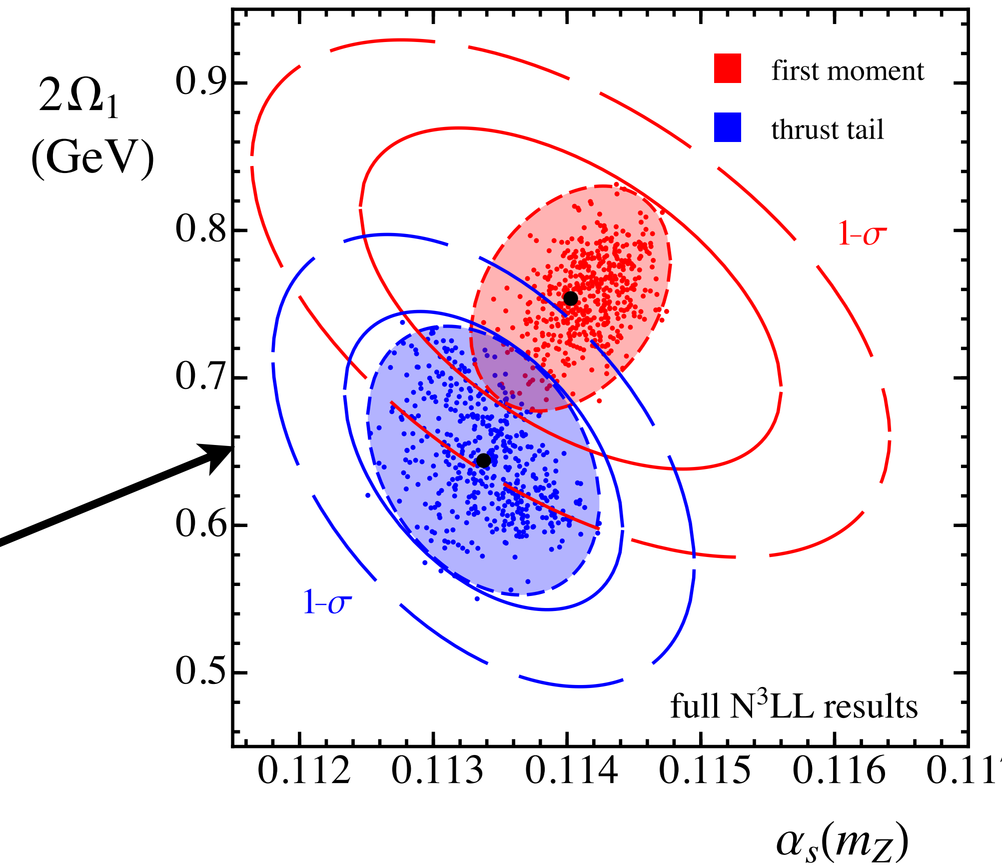
power corrections

renormalon subtractions

QED   b-mass

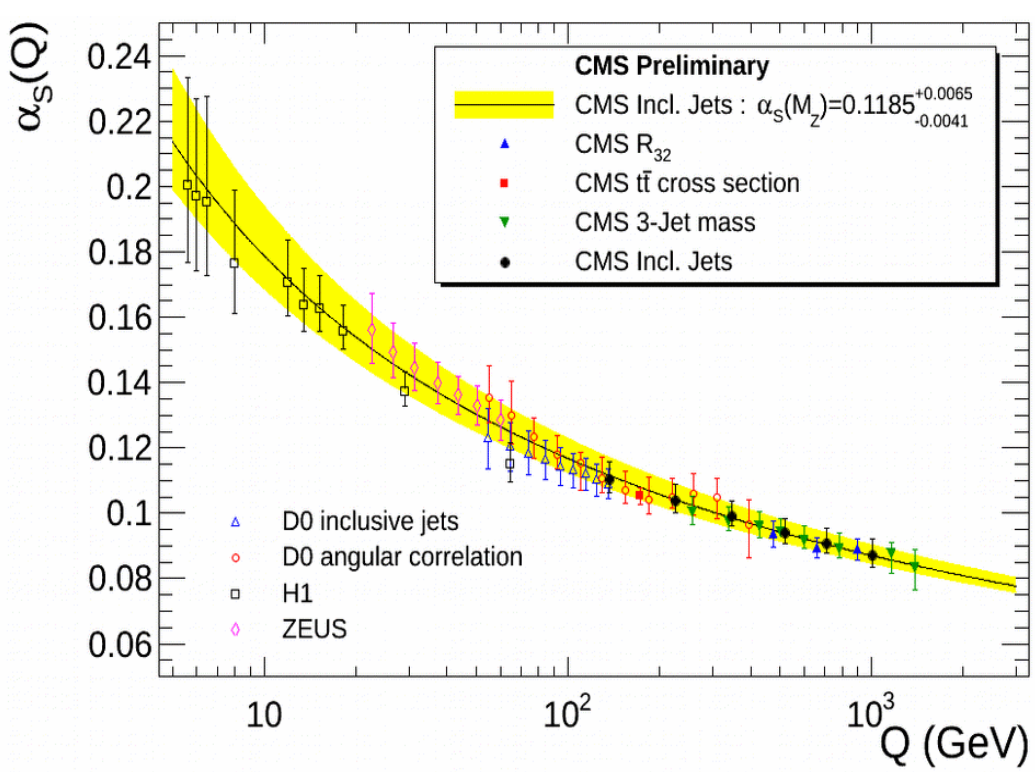
global fit





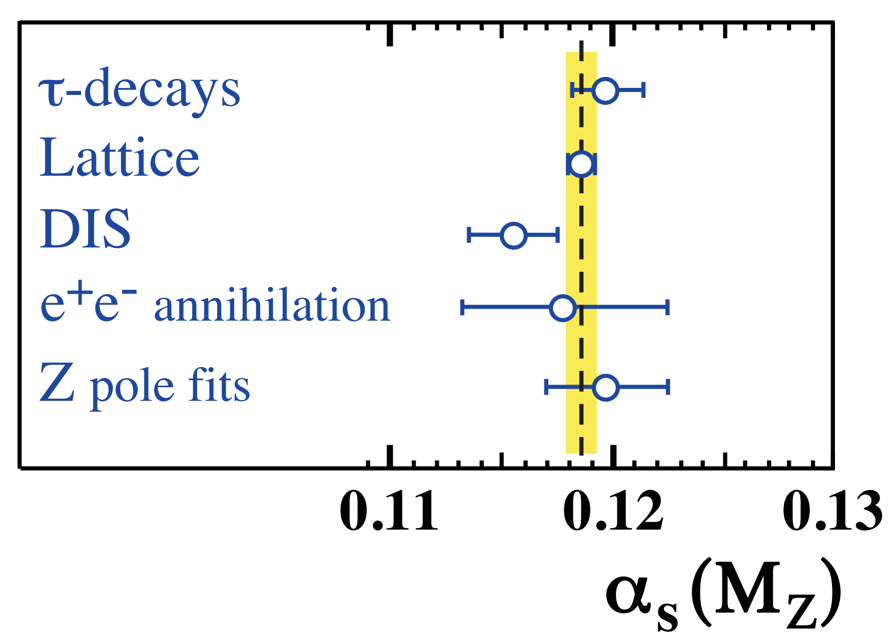
$pp \to$ jets:

$$\alpha_S(M_Z) = 0.1185 \pm 0.0019\,(\text{exp.}) \pm 0.0028\,(\text{PDF}) \pm 0.0004\,(\text{NP})^{+0.0055}_{-0.0022}\,(\text{scale})$$



PDG(2013)=Lattice(HPQCD):

$$\alpha_S(M_Z) = 0.1184 \pm 0.0007$$



Strong Coupling (Future @ EIC)

C. Glasman [1110.0016]

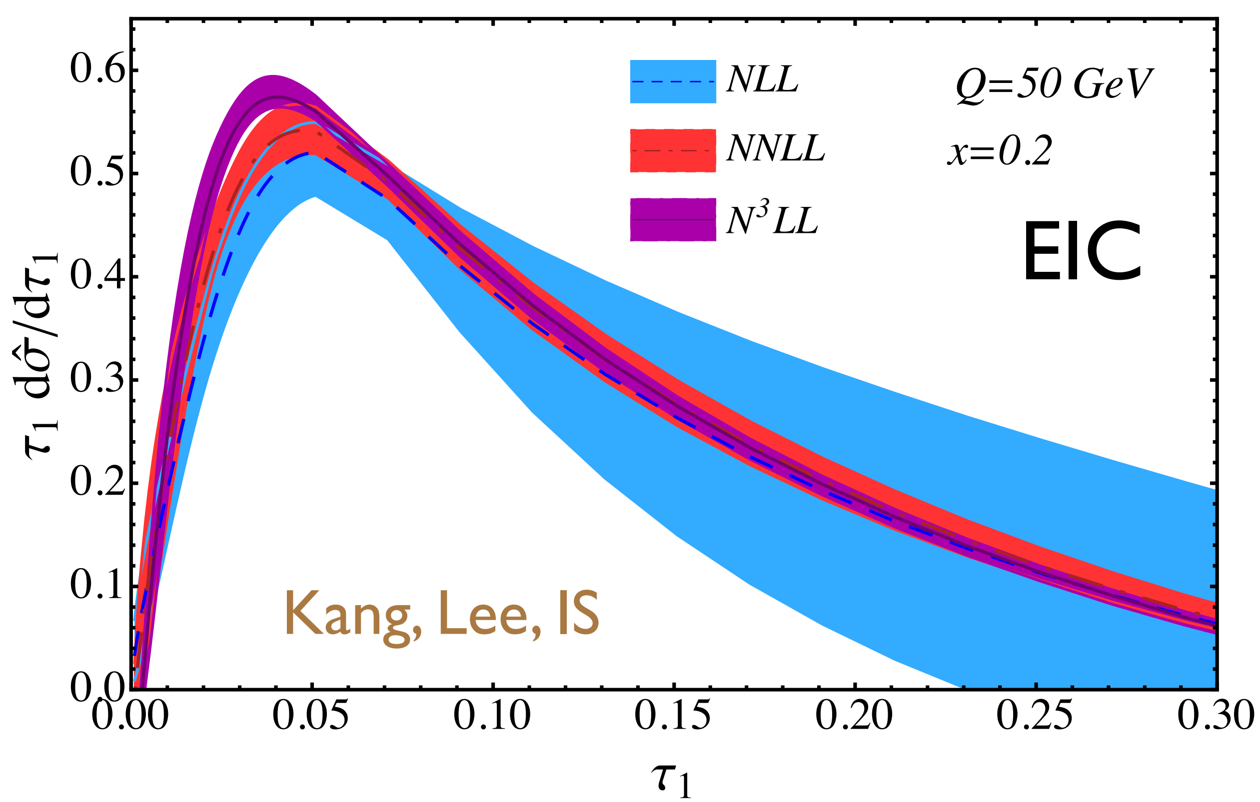
First Hera:

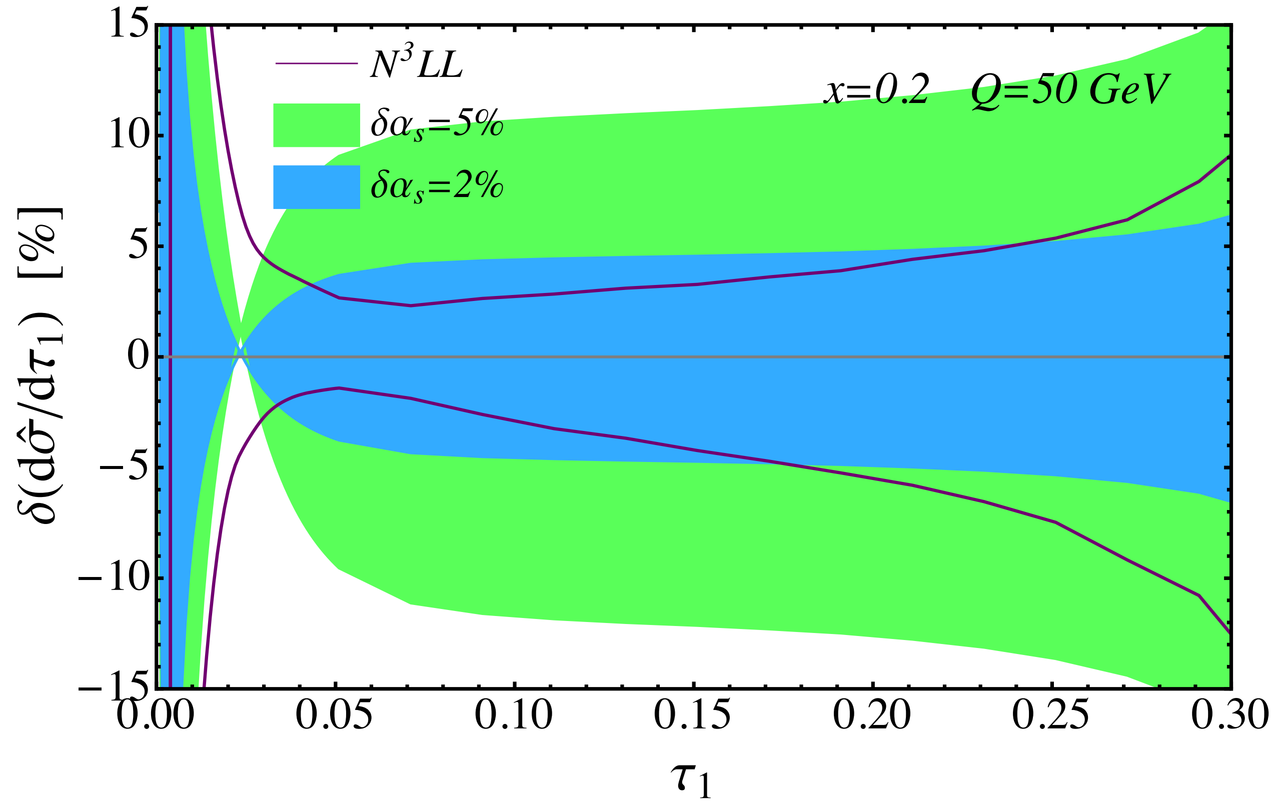
uncertainty dominated by theory

Process	Collab.	Value	Exp.	Th.	Total	(%)
(1) Inc. jets at low Q^2	H1	0.1180	0.0018	$^{+0.0124}_{-0.0093}$	$^{+0.0125}_{-0.0095}$	$^{+10.6}_{-8.1}$
(2) Dijets at low Q^2	H1	0.1155	0.0018	$^{+0.0124}_{-0.0093}$	$^{+0.0125}_{-0.0095}$	$^{+10.8}_{-8.2}$
(3) Trijets at low Q^2	H1	0.1170	0.0017	$^{+0.0091}_{-0.0073}$	$^{+0.0093}_{-0.0075}$	$^{+7.9}_{-6.4}$
(4) Combined low Q^2	H1	0.1160	0.0014	$^{+0.0094}_{-0.0079}$	$^{+0.0095}_{-0.0080}$	$^{+8.2}_{-6.9}$
(5) Trijet/dijet at low Q^2	H1	0.1215	0.0032	$^{+0.0067}_{-0.0059}$	$^{+0.0074}_{-0.0067}$	$^{+6.1}_{-5.5}$
(6) Inc. jets at medium Q^2	H1	0.1195	0.0010	$^{+0.0052}_{-0.0040}$	$^{+0.0053}_{-0.0041}$	$^{+4.4}_{-3.4}$
(7) Dijets at medium Q^2	H1	0.1155	0.0009	$^{+0.0045}_{-0.0035}$	$^{+0.0046}_{-0.0036}$	$^{+4.0}_{-3.1}$
(8) Trijets at medium Q^2	H1	0.1172	0.0013	+0.0053	+0.0055	+4.7

Precision Event Shapes:

DIS thrust $\delta\alpha_s < 2\%$





Hadronization

Hadronization

- Single Parton Fragmentation functions (covered elsewhere)

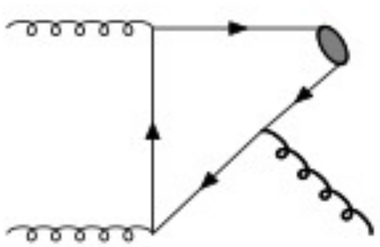
  → Key measurements for current and future NP program

- Double Parton Fragmentation functions

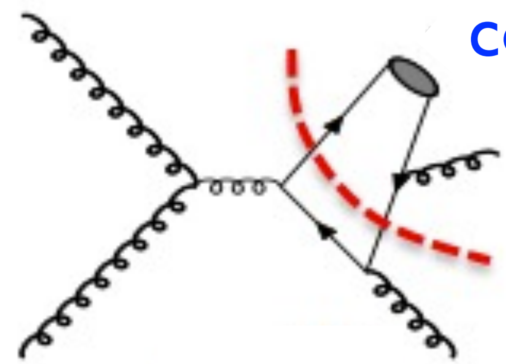
Ma, Qiu, Sterman, Kang
Fleming, Leibovich, Mehen

$J/\psi(c\bar{c}), \Upsilon(b\bar{b})$ production

NRQCD: color singlet and octet production

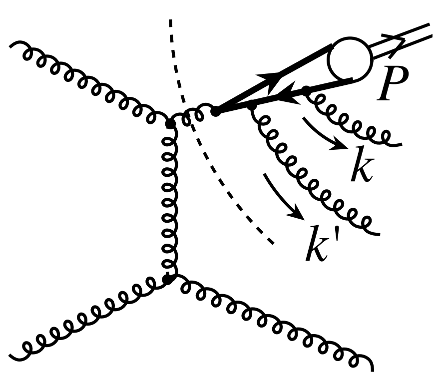


$$\frac{d\hat{\sigma}^{LO}}{dp_T^2} \sim \frac{\alpha_s^3(p_T)m_Q^4}{p_T^8}$$



color singlet

$$\frac{d\hat{\sigma}^{NLO}}{dp_T^2} \sim \frac{\alpha_s^4(p_T)m_Q^2}{p_T^6}$$



color octet

$$\frac{d\hat{\sigma}^{\rm NNLO}}{dp_T^2} \sim \frac{\alpha_s^5(p_T)}{p_T^4}$$

$\frac{m_Q}{p_T}$ versus α_s expansions

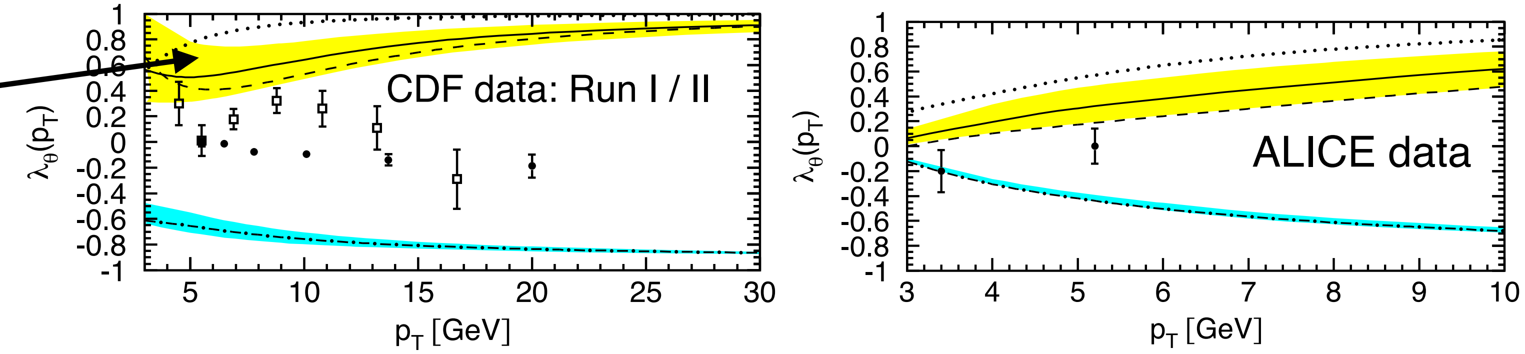
$$\frac{d\sigma}{dp_T^2} = d\hat{\sigma}_{AB\to iX} \otimes D_{H/i} + d\hat{\sigma}_{AB\to Q\bar{Q}X} \otimes \mathcal{D}_{H/Q\bar{Q}} + \dots$$

color octet   color singlet

D's calculable via constant NRQCD matrix elts.

Polarization Puzzle
(using Global NRQCD fit)

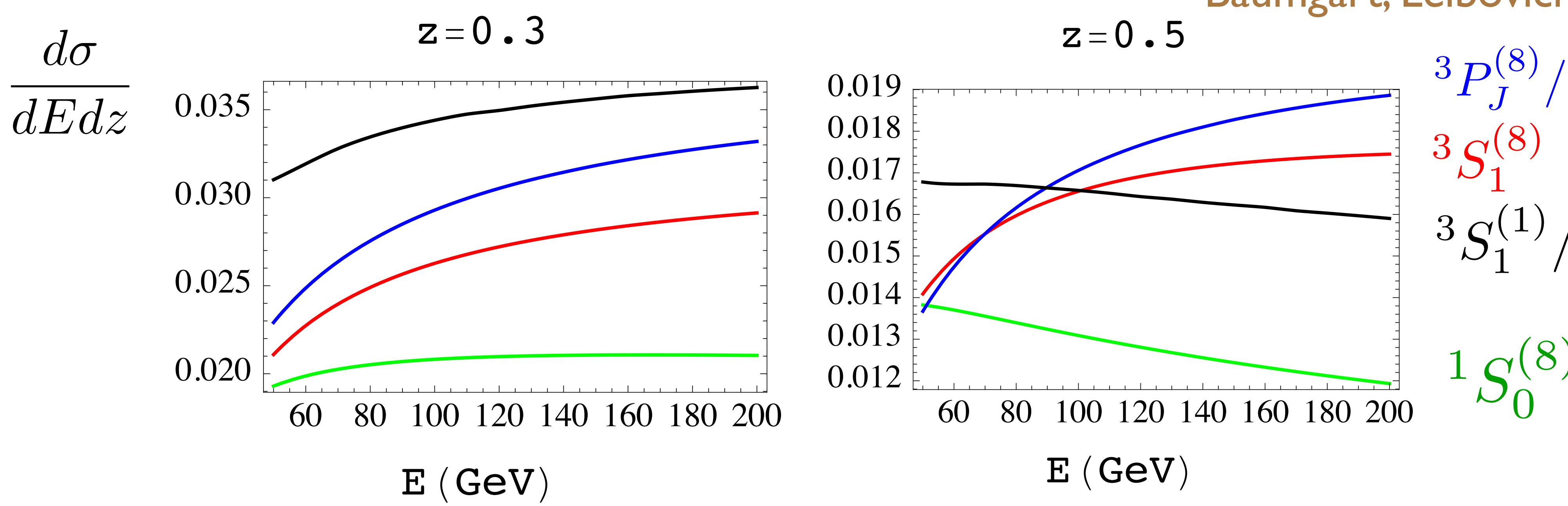
Butenschoen, Kniehl



- Global Fit and J/ψ polarization puzzle prefer <u>different</u> values of NRQCD matrix elements   Chao et.al.; Bodwin et.al.

- Measure the energy E of the Jet in which the J/ψ fragments.

Baumgart, Leibovich, Mehen, Rothstein



(with global fit norms)

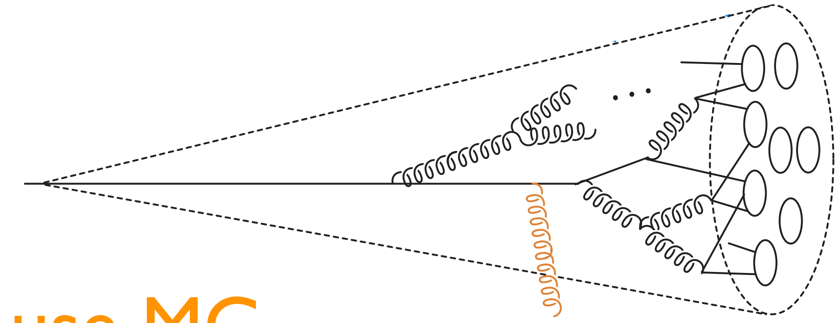
Polarization puzzle prefers a dominant $^1S_0^{(8)}$, so …

Test this by measuring E dependence of the cross section for $z \gtrsim 0.5$

<u>More General Point</u>: we learn interesting things by measuring the properties of the jet environment in which the fragmentation takes place.

(see also Liu's talk, Jet-Sivers & Jet-Collins at EIC)

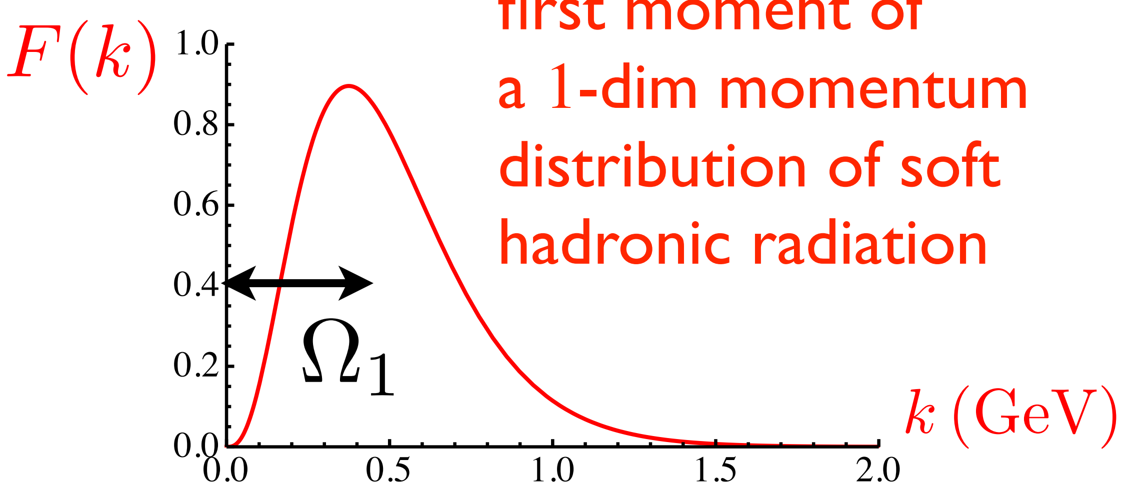
Hadronization

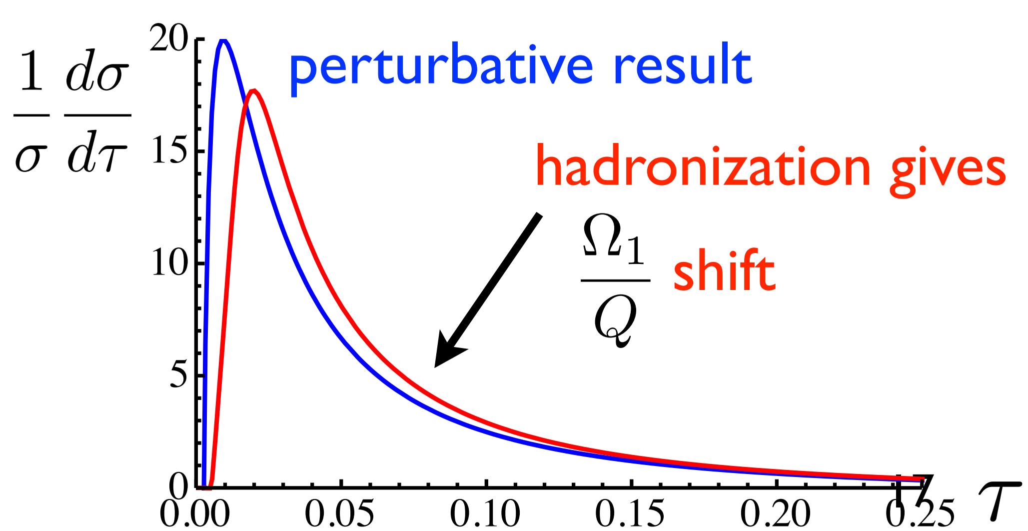


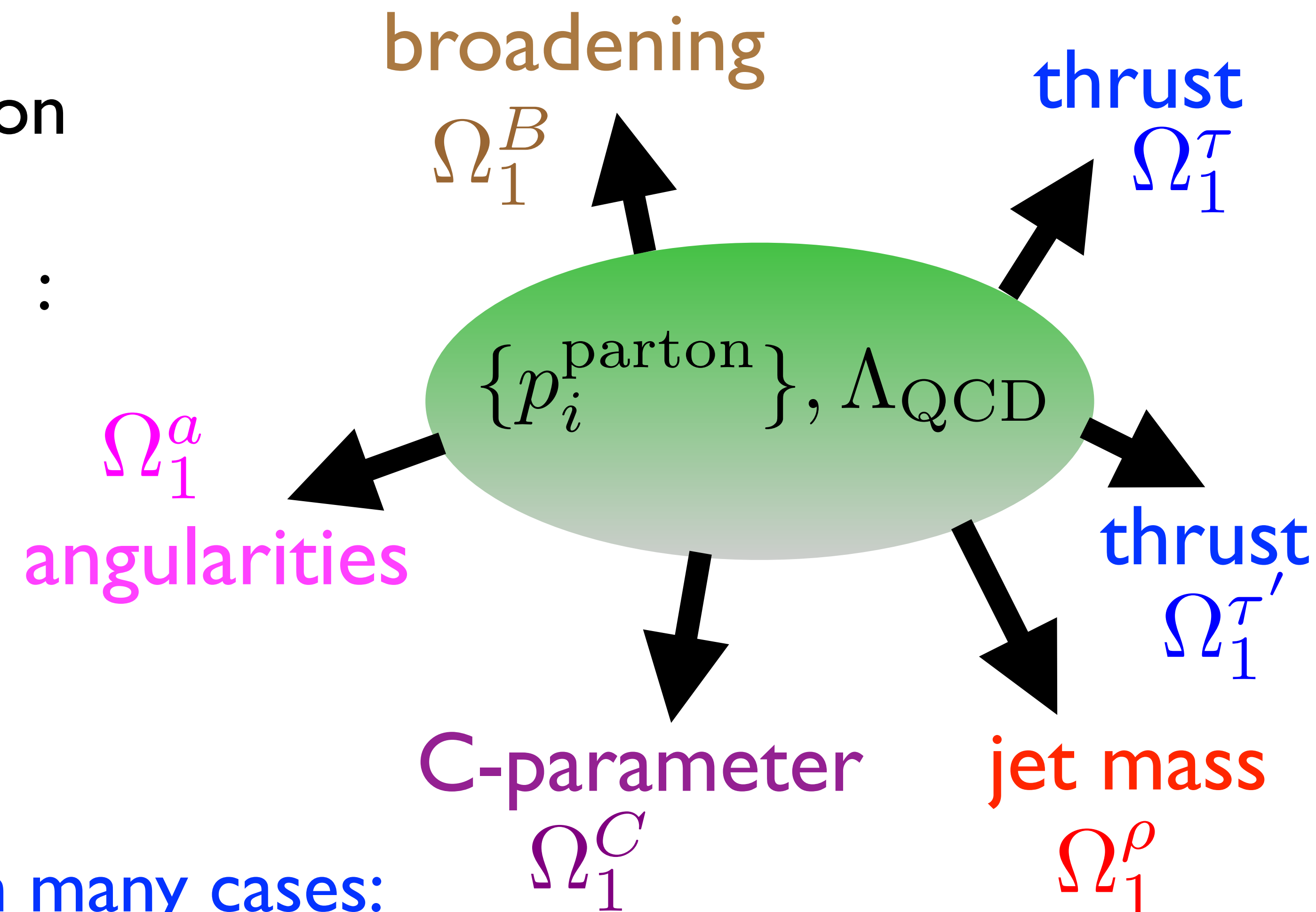
- Collective Hadronization of partons in a Jet

In general a complicated map: $\{p_i^{\text{parton}}\}, \Lambda_{\text{QCD}} \overset{\text{use MC}}{\Longrightarrow} \{p_j^{\text{hadron}}\}$

Test our understanding of hadronization with more inclusive measurements
e = event shapes in $(e^+e^-, \underline{e^-p}, \underline{e^-\text{-Ion}})$:







In many cases:

$$\frac{\Omega_1^i}{\Omega_1^j} = \text{calculable via QFT}$$

but does depend on treatment of hadron masses

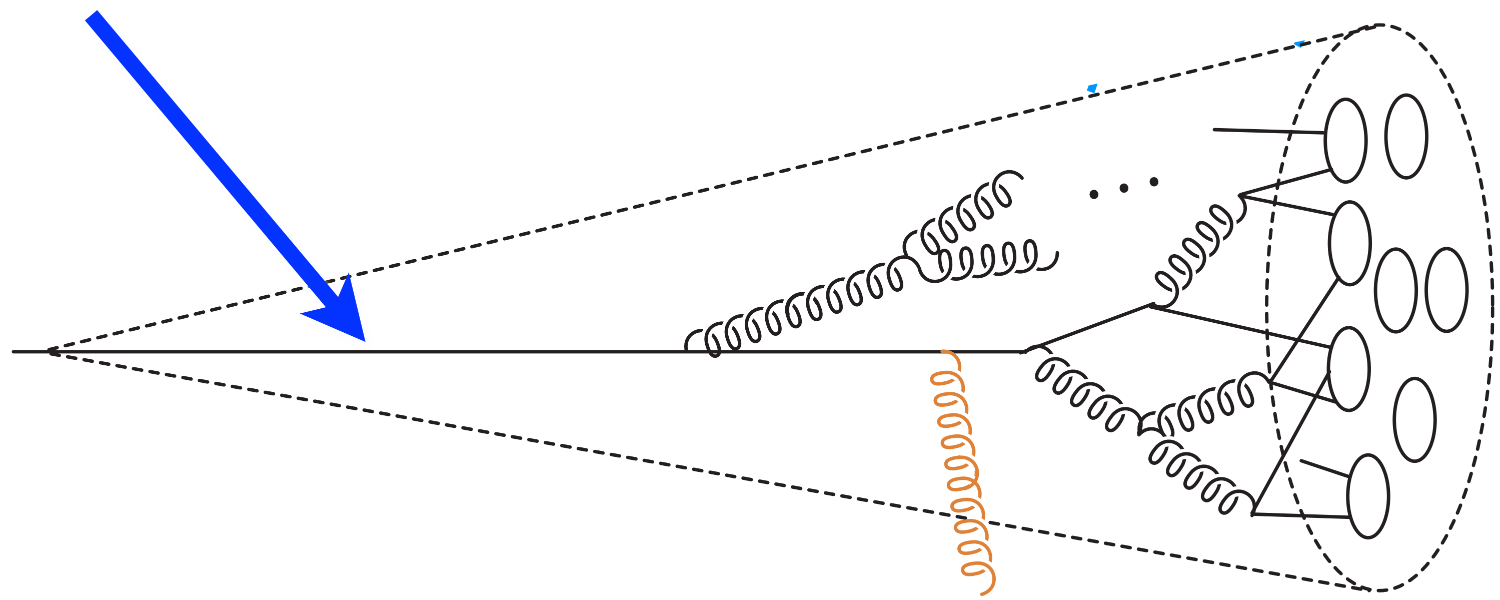
Dokshitzer, Webber, Wicke, Salam, Akhoury, Zakarhov, Korchemsky, Movilla et.al., **Lee, Sterman,** Mateu et.al.

$$\Omega_1 = \langle 0|Y_{\bar{n}} Y_n \delta(\cdots) Y_n^\dagger Y_{\bar{n}}^\dagger|0\rangle$$

Jet Substructure

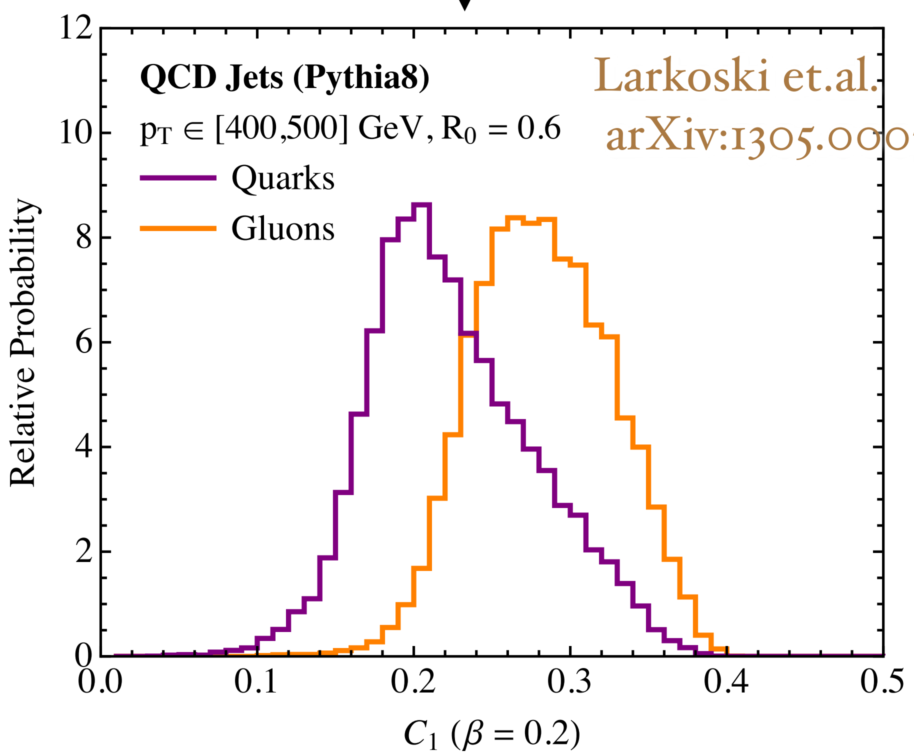
Jet Substructure

- Measure the quantum numbers of the hard parton that produces a jet?



Quarks versus Gluons? Electric Charge?

↓ tough, but maybe



Larkoski et.al.
arXiv:1305.0007

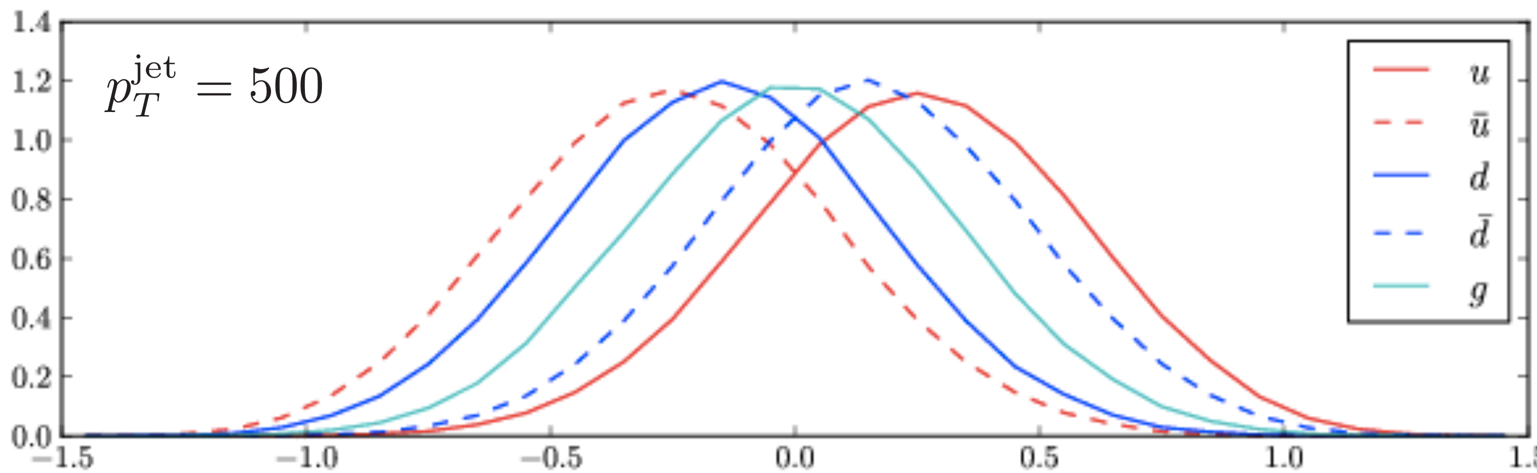
Jet Charge

p_T-weighted: $\mathcal{Q}^i_\kappa = \frac{1}{(p_T^{\rm jet})^\kappa} \sum_{j \in {\rm jet}} Q_j (p_T^j)^\kappa$

$-\frac{2}{3}, -\frac{1}{3}, 0, \frac{1}{3}, \frac{2}{3}$

κ=0.5

Krohn,Lin,Schwartz, Waalewijn: arXiv:1209.2421



Mean:

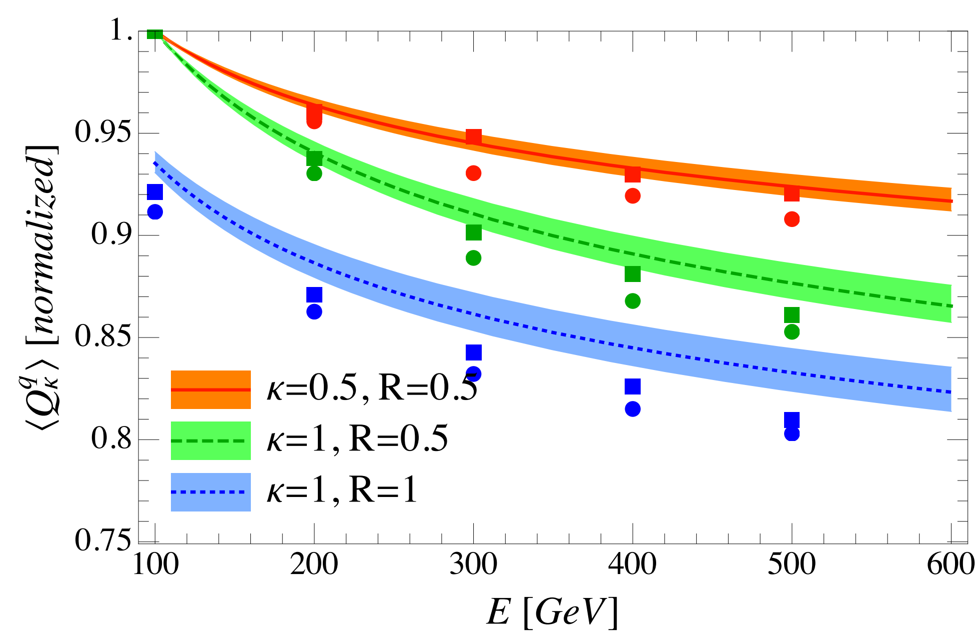
$$\langle Q^q_\kappa \rangle = \tilde{\mathcal{J}}_{qq}(ER, \kappa, \mu = ER) \sum_h Q_h \tilde{D}^h_q(\kappa, \mu = ER)$$

Some properties are calculable

jet energy E & jet radius R

Involves moment of frag. functions

$$\tilde{D}^h_q(\kappa, \mu) = \int_0^1 dx\, x^\kappa D^h_q(x, \mu)$$



Pythia:

■ d-quarks

● u-quarks

What about measurements of only charged tracks?

traditional view: a) not infrared safe, b) using pQCD is very tough

True **False**

nonperturbative
Track Functions: $T_i(z, \mu)$ parton i with momentum p_i hadronizes to charged hadrons with total momentum zp_i

Chang, Procura, Thaler, Waalewijn arXiv:1303.6637

all hadrons

$$\frac{\mathrm{d}\sigma}{\mathrm{d}e} = \sum_N \int \mathrm{d}\Pi_N \, \frac{\mathrm{d}\sigma_N}{\mathrm{d}\Pi_N} \, \delta[e - \hat{e}(\{p_i^\mu\})]$$

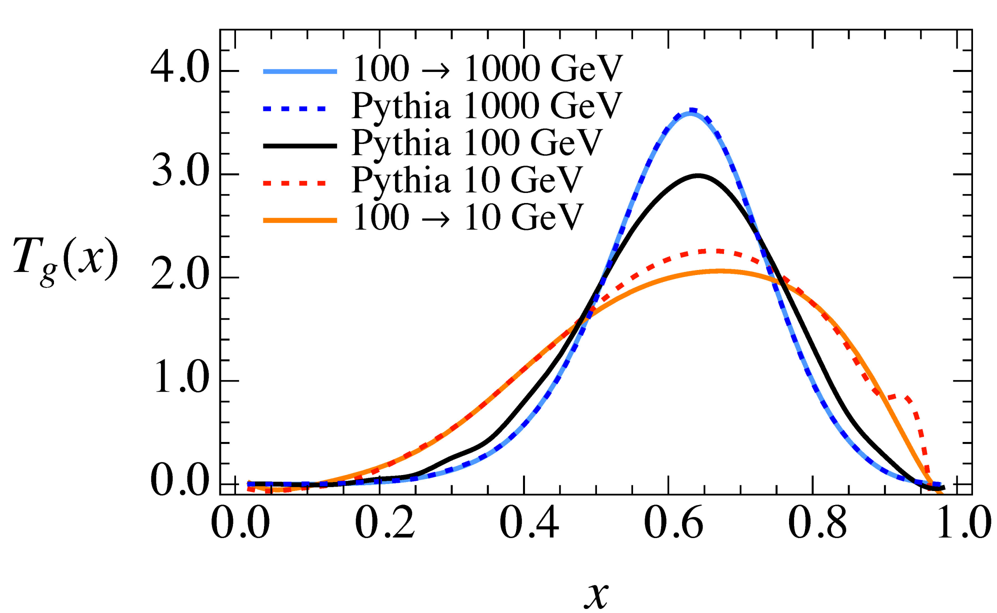
→

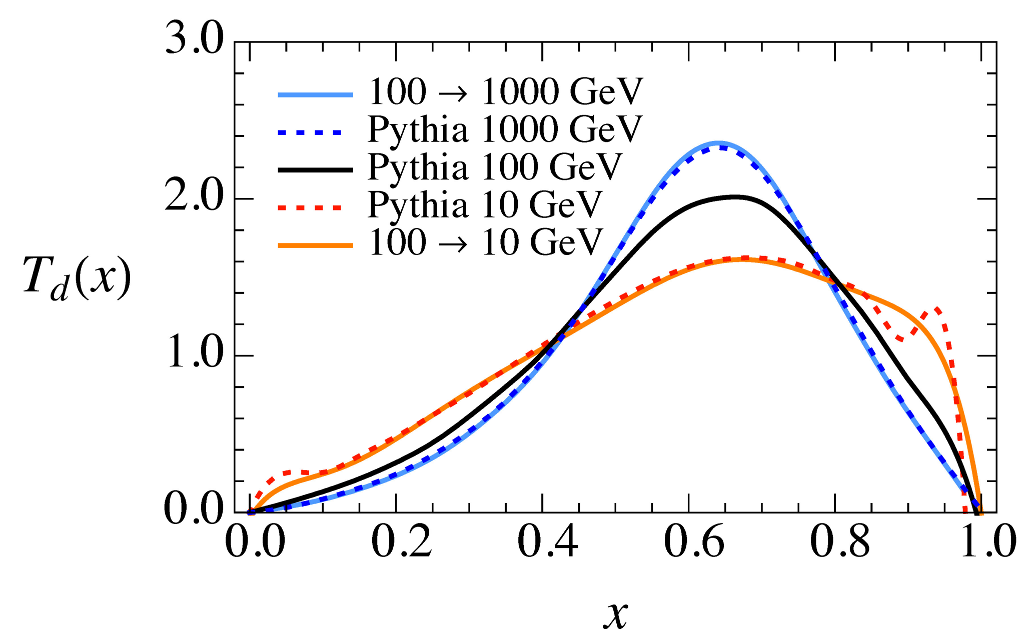
charged hadrons

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\bar{e}} = \sum_N \int \mathrm{d}\Pi_N \, \frac{\mathrm{d}\bar{\sigma}_N}{\mathrm{d}\Pi_N} \int \prod_{i=1}^{N} \mathrm{d}x_i \, T_i(x_i) \, \delta[\bar{e} - \hat{e}(\{x_i p_i^\mu\})]$$

absorbs IR div.

nonlinear evolution equation





$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} T_i(x, \mu) = \frac{1}{2} \sum_{j,k} \int \mathrm{d}z \, \mathrm{d}x_1 \, \mathrm{d}x_2 \, \frac{\alpha_s(\mu)}{\pi} P_{i \to jk}(z) \; T_j(x_1, \mu) T_k(x_2, \mu) \, \delta[x - z x_1 - (1-z) x_2]$$

agrees with parton shower

Cross Fertilization with Jets in Medium

- Many of the systematics for "Cold" Jets also play a role for Jets in Medium

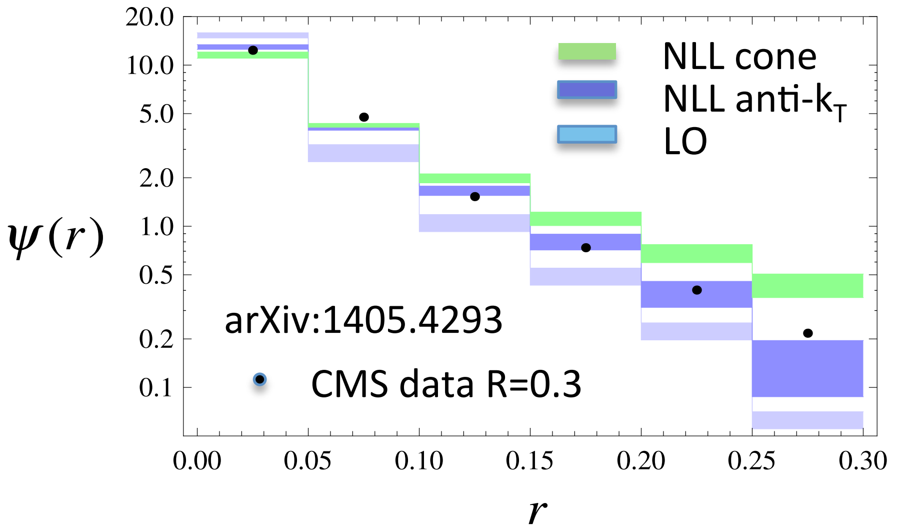
  factorization?

  key observables? key distributions?

  calculable vs. measurable vs. useful?

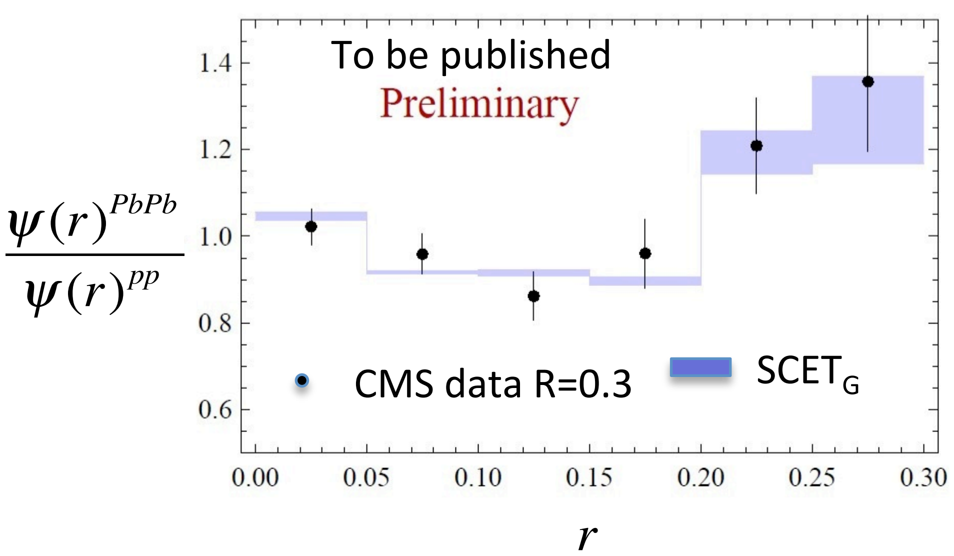
eg. "Cold and Hot" jet shapes

Chien, Vitev



- In high energy nuclear collisions $SCET_G$ (with medium interactions) is being developed to allow for systematic improvements in the precision of in-medium jet calculations. This builds on the strong base of work done with "cold jets".

  Idilbi, Majumder; D'Eramo, Liu, Rajagopal; Ovanesyan, Vitev; ...



Likely to have useful applications to heavy ion physics and phases of QCD matter.

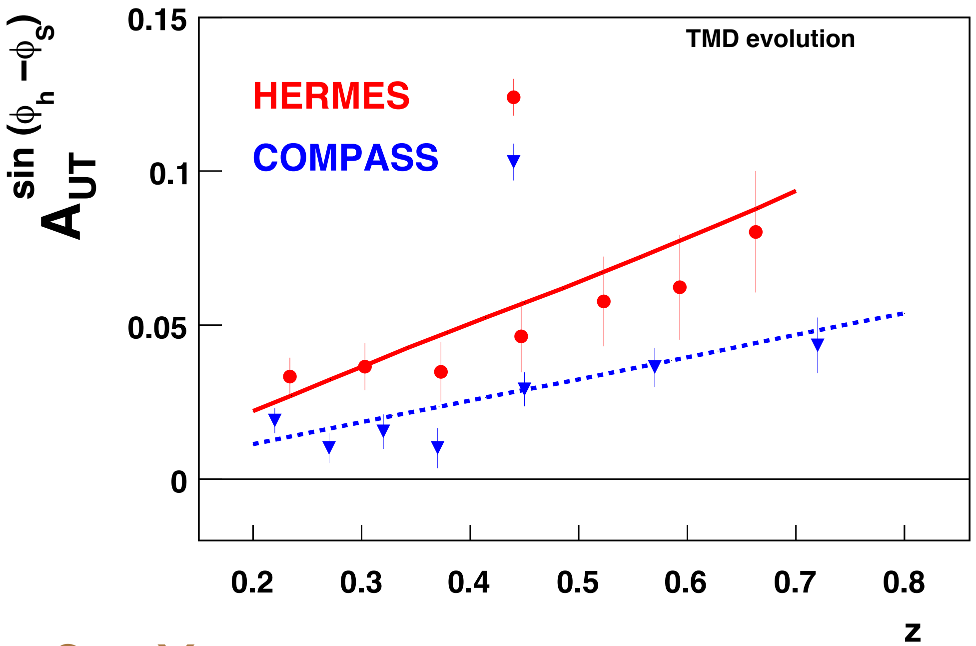
TMDPDF Evolution

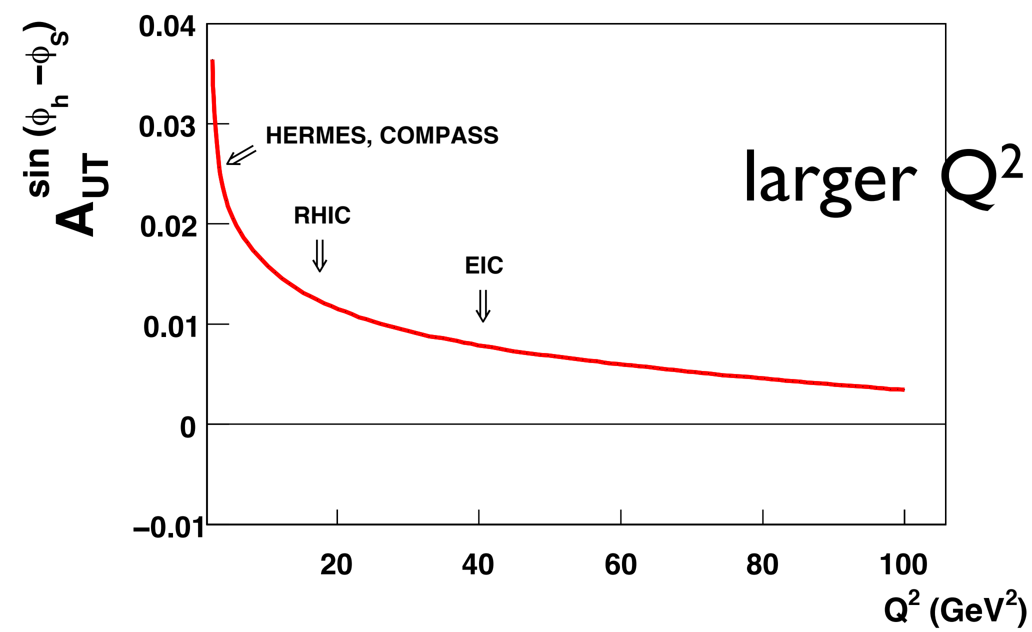
Q^2 dependence

Important for JLab, RHIC, EIC, …

See Qiu's talk

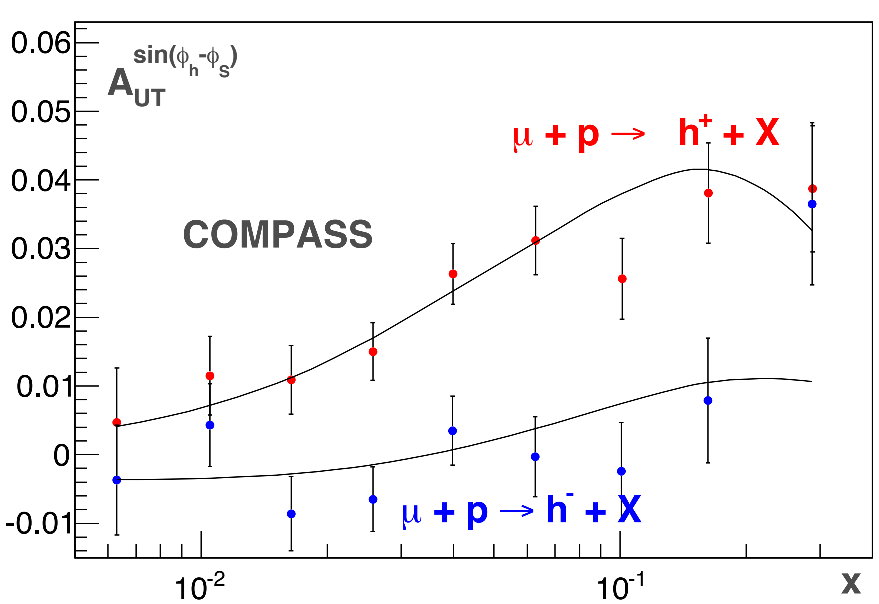
Aybat, Prokudin, Rogers

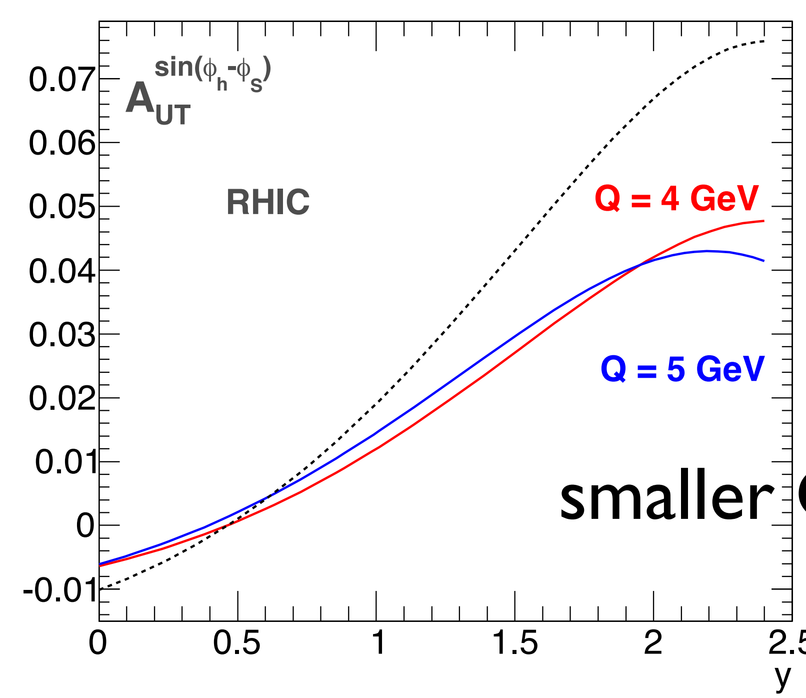




larger Q^2 dependence

Sun, Yuan;

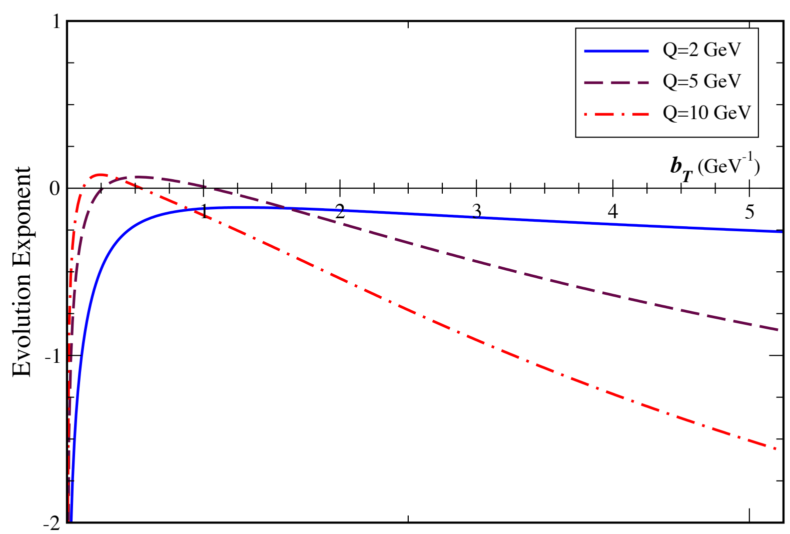




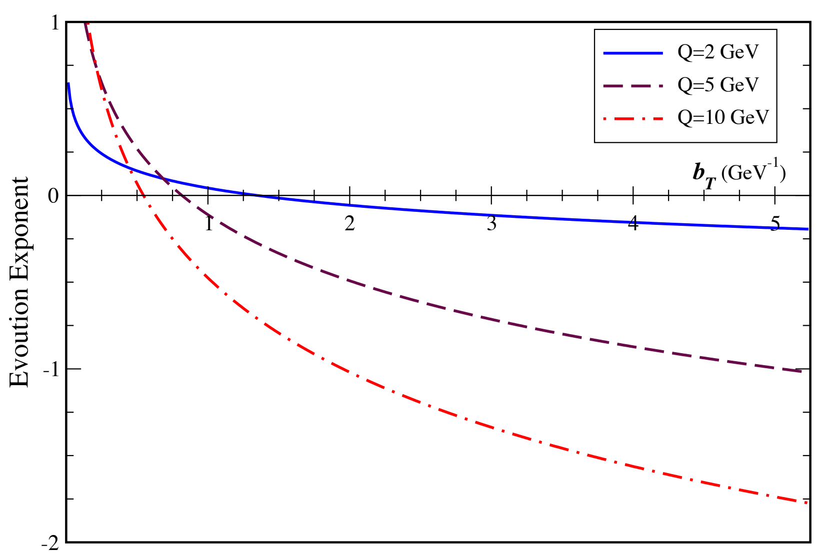
smaller Q^2 dependence

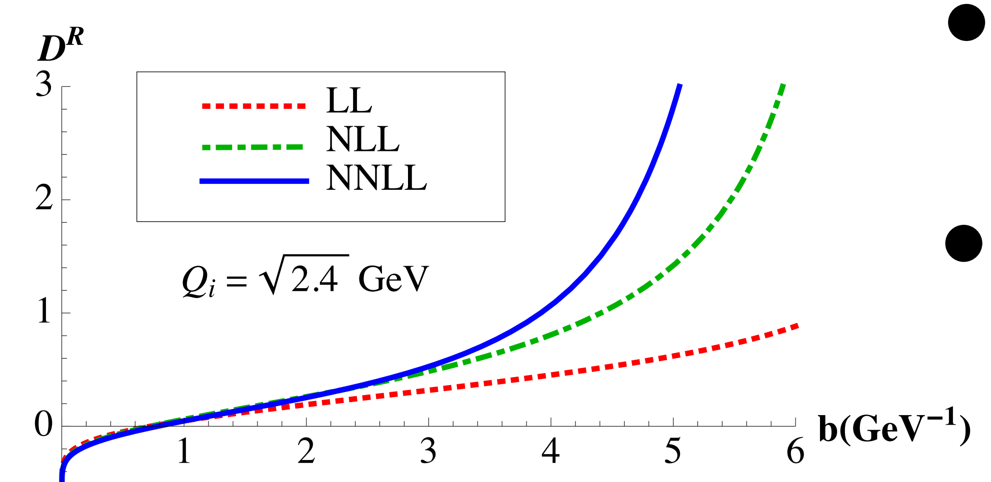
TMDPDF Evolution

Collins TMD-Evolution including $g_K(b_T; b_{max})$



Sun-Yuan Evolution





EISS group, convergence

Recent discussions

Collins; Aybat, Prokudin, Rogers; Aidala et.al.
Sun, Yuan;
Echevarria, Idilbi, Schaefer, Scimemi

- Consistent definitions, agreement on anom.dim. eqtns.

$$F(x, b, \mu_f, \zeta_f) = U(b, \mu_f, \zeta_f, \mu_i, \zeta_i) F(x, b, \mu_i, \zeta_i)$$

$$\frac{\partial}{\partial \ln \zeta} U(b, \mu, \zeta, \mu_i, \zeta_i) = -K(b, \mu) \;, \quad \frac{d}{d \ln \mu} \ln U(b, \mu, \zeta, \mu_i, \zeta_i) = \gamma_F(\alpha_s, \zeta/\mu) \;, \quad U(b, \mu, \zeta, \mu, \zeta) = 1$$

$$\frac{d}{d \ln \mu} K(b, \mu) = \Gamma_K(\alpha_s)$$

same for SIDIS, DY, e^+e^-

Need: $K(b, \mu_i) = K^{\rm pert}(b, \mu_i, \tilde{b}) + K^{\rm NP}(b, \mu_i, \tilde{b})$

$b \lesssim \tilde{b}$ $\qquad$ $b \gtrsim \tilde{b}$

definition of $\tilde{b}$ defines scheme to split perturbative and nonperturbative parts.

- Theorists responsible for: "scheme"/definitions, consistency, perturbative stability, Fourier Trnsfm.

- More Experimental Data: Measure F(p_T) at low scales. Measuring universal $K^{\rm NP}(p_T)$

needed for strength of evolution with Q

2 Photon Form Factors

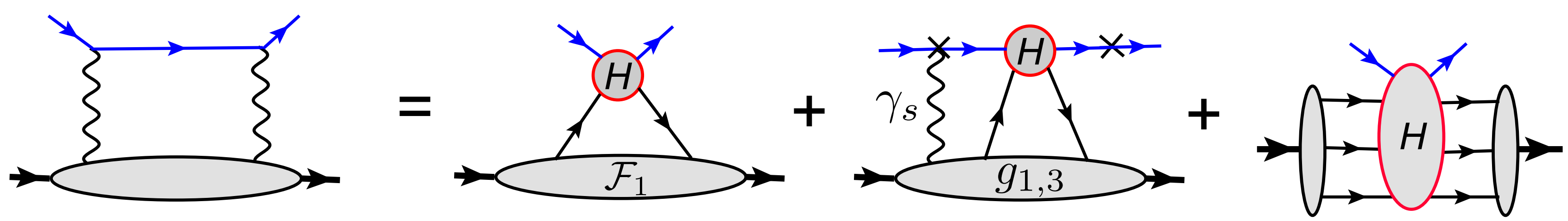
Kivel & Vanderhaeghen arXiv:1212.0683

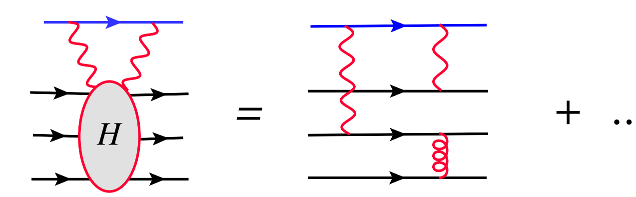
$$s \sim -t \sim -u \gg \Lambda^2$$

$$A_{ep} - A_{ep}^{\gamma} \equiv A_{ep}^{\gamma\gamma} = \frac{e^2}{Q^2}\bar{u}(k')\gamma^\mu u(k)\;\bar{N}(p')\left[\gamma^\mu \delta\tilde{G}_M(\varepsilon, Q^2) - \frac{P^\mu}{m}\delta\tilde{F}_2(\varepsilon, Q^2) + \frac{P^\mu}{m^2}\not{K}\;\tilde{F}_3(\varepsilon, Q^2)\right]N(p)$$

approach based on partons & factorization in SCET

$$\varepsilon = \frac{(s-u)^2 + t(4m^2 - t)}{(s-u)^2 - t(4m^2 - t)}$$





soft form factors   hard scattering

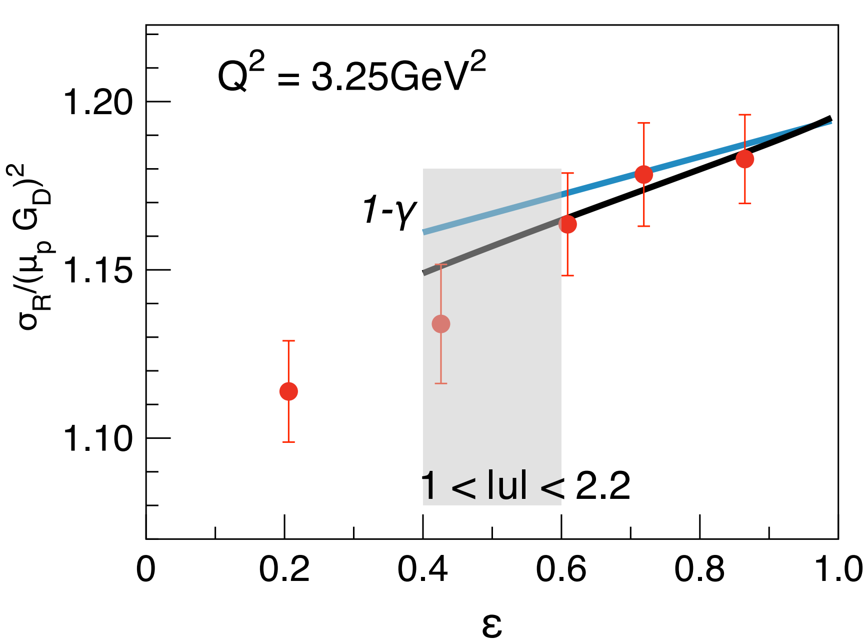
$$\delta\tilde{G}_M^{2\gamma}(\varepsilon, Q^2) = \delta\tilde{G}_M^{(s)}(\varepsilon, Q^2) + \delta\tilde{G}_M^{(h)}(\varepsilon, Q^2),$$
$$\tilde{F}_3(\varepsilon, Q^2) = \tilde{F}_3^{(s)}(\varepsilon, Q^2) + \tilde{F}_3^{(h)}(\varepsilon, Q^2),$$
$$\delta\tilde{F}_2^{2\gamma}(\varepsilon, Q^2) = \delta\tilde{F}_2^{(s)}(\varepsilon, Q^2) + \delta\tilde{F}_2^{(h)}(\varepsilon, Q^2),$$

$$\delta\tilde{F}_2^{(s)}(\varepsilon, Q^2) = \left[\delta\tilde{F}_2^{(s)}\right]_{\rm subl} + \frac{\alpha}{\pi}\frac{4m^2}{Q^2}\left[g_1 + C_M\mathcal{F}_1 + \frac{\nu}{s}\{C_3\mathcal{F}_1 + g_3\}\right]$$

$$F_3^{(h)} = \mathbf{\Psi}(x_i) * H_3(z, Q^2;\; x_i, y_i) * \mathbf{\Psi}(y_i),$$
$$\delta\tilde{G}_M^{(h)} = \mathbf{\Psi}(x_i) * H_M(z, Q^2;\; x_i, y_i) * \mathbf{\Psi}(y_i),$$

hadron distributions

3 soft form factors in EFT: $\mathcal{F}_1(Q)$ extracted by factorizing wide angle Compton scattering and using data (here ε dependence is calculable)



$g_{1,3}(z, Q^2)$ use models

$$z = -t/s$$

Factorization Violation

- Examples of factorization violation are known for TMD factorization in hadro-production of nearly back-to-back hadrons

$$H_1 + H_2 \to H_3 + H_4 + X$$

Bomhof, Mulders, Pijlman
Collins, Qiu

issues: uniqueness of Wilson line operators (not just a sign flip),
Glauber non-cancellations (required to factor hadrons)

- Can we generally characterize theoretically what processes violate factorization? Can we characterize factorization violations experimentally?

- Theory work in this direction is in progress in the SCET community. Operators have been derived to accommodate Glauber Exchange in SCET, without double counting anything. This goes beyond having Glauber's for a background medium. Interesting connections to small x, Reggeization, BFKL, …

(see eg. Fleming)

Summary

- Any requests for desperately needed higher order perturbative QCD calculations? eg. higher order jet cross sections for PDFs
- Event shape variables for precision jet physics at EIC (eg. strong coupling). Optimal jet shapes for ions? for jets in medium?
- Fertile directions for probing hadronization: double parton distributions and collective hadronization in jets at RHIC/EIC/LHC

$$\Omega_1 = \langle 0| Y_{\bar{n}} Y_n \delta(\cdots) Y_n^\dagger Y_{\bar{n}}^\dagger |0\rangle$$

- Looking inside jets: Jet Charge, Track Functions, Jet Shapes, …
- TMDPDFs and 2-photon Form Factors: crucial places for further fertile interactions between theory and experiment
- Future: Envision stronger connections in theory for both Cold and Hot QCD, and for Hard Scattering and Small-x communities