Sudakov Logarithms from Double Lightcone OPE

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Based on arXiv: 2301.03616 with Hao Chen and Xinan Zhou

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Sudakov logarithms

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Summing Sudakov logarithms in $B \to X_s \gamma$ in effective field theory

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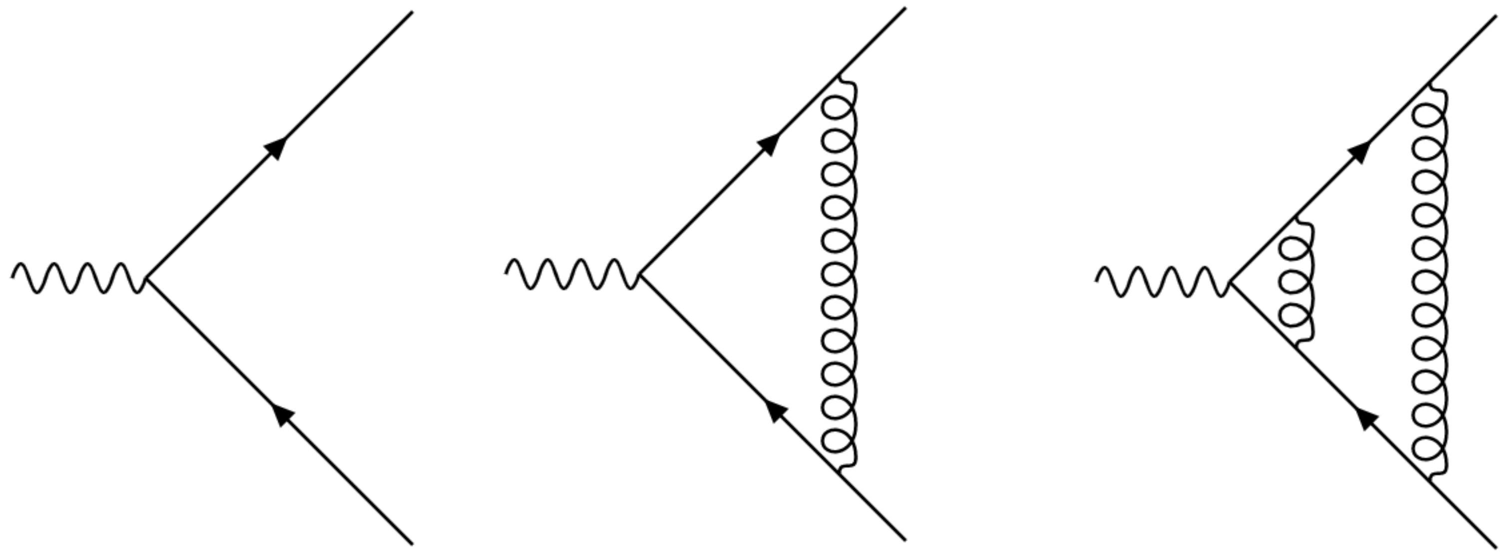
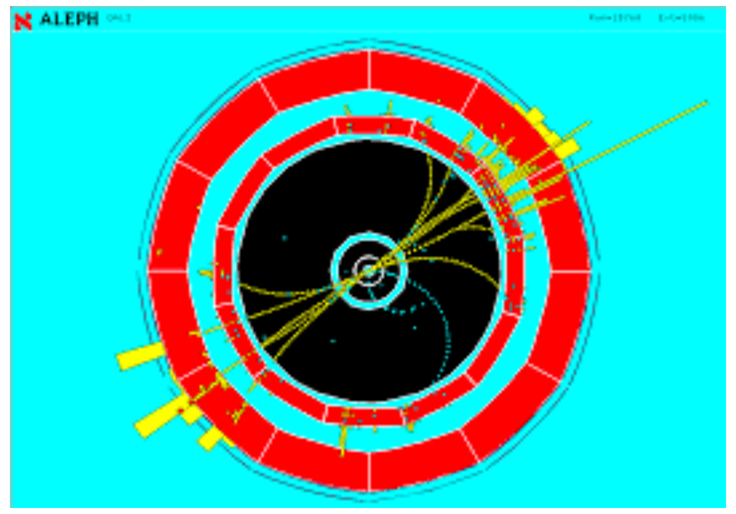




in massive form factor $\alpha^n \ln^{2n} \frac{Q^2}{m^2}$

in physical observable: $\alpha^n \frac{1}{\tau} \ln^{2n-1} \frac{1}{\tau}$

Sudakov logarithms are consequence of soft and collinear dynamics of massless gauge theory

Sudakov logarithms at NLP

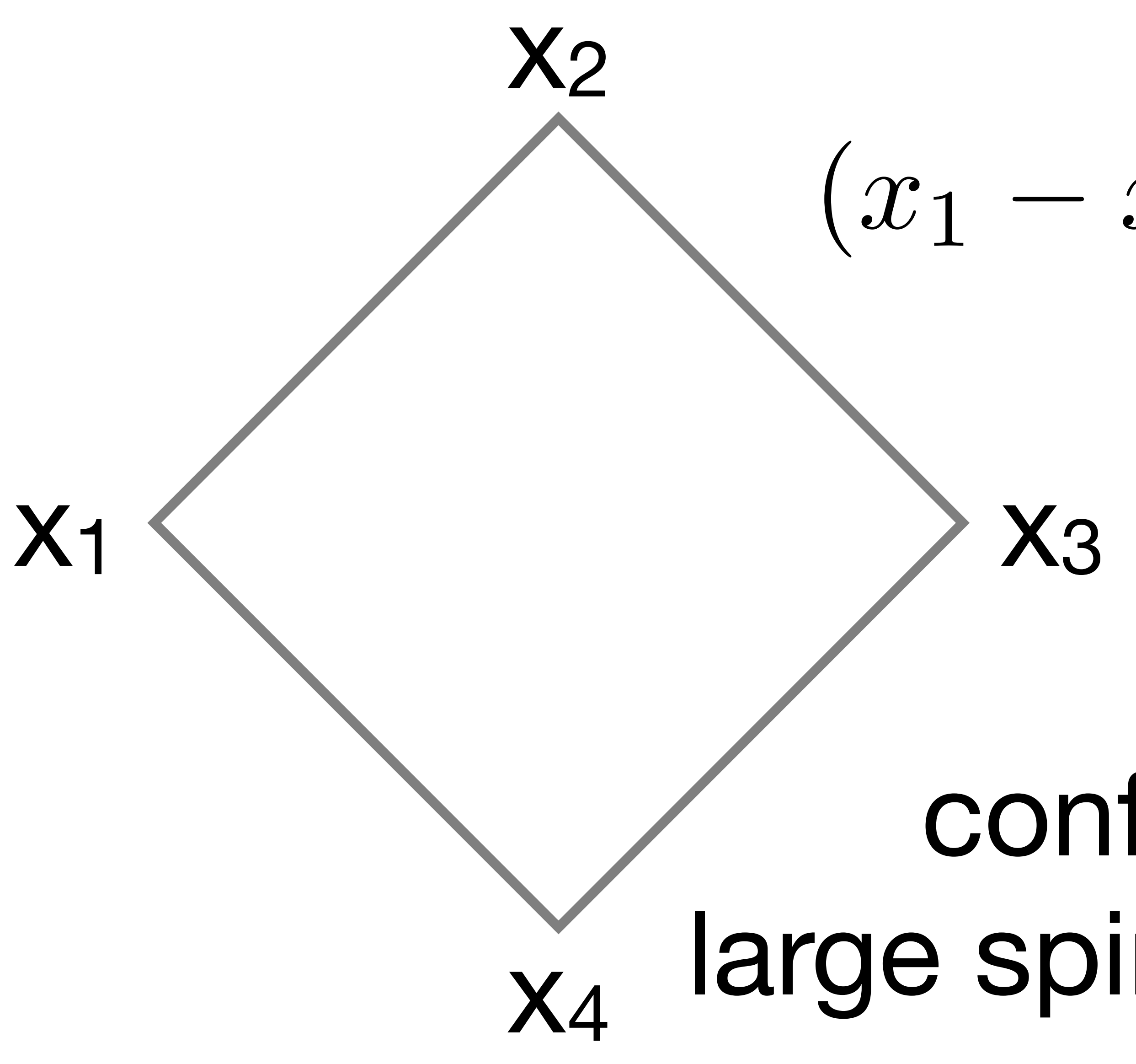
- Resummation Sudakov logarithms in collider processes at leading power is no longer a rocket science — thanks to SCET!
- The current frontiers is to go beyond leading power
  - Has practical applications: e.g. improving slicing methods such as qT subtraction and N-jettiness subtraction
  - Can guide parameterization for non-perturbative hadronization effects
  - Teach valuable lessons for QFT near lightcone in general

Bacchetta, Bahjat-Abbas, Beenakker, Beneke, Bonocore, Boughezal, Bozzi, Broggio, Buonocore, Camarda, Caola, Chapovsky, Cieri, Del Duca, Diehl, Ebert, Echevarria, Feige, Feldmann, Ferrario Ravasio, Ferrera, Gamberg, Gao, Garny, Goerke, Grazzini, Inglis-Whalen, Isgrò, Jaskiewicz, Kallweit, Kang, Kolodrubetz, Laenen, Limatola, Liu, Luisoni, Luke, Magnea, Mecaj, Melnikov, Melville, Michel, Monni, Moos, Moult, Nason, Neubert, Oleari, Petriello, Pirjol, Pisano, Prokudin, Radici, Rocco, Rothen, Rottoli, Roy, Salam, Schnubel, Scimemi, Shao, Sinninghe Damsté, Slade, Spourdalakis, Stewart, Szafron, Tackmann, Terry, Tramontano, Vernazza, Vita, Vladimirov, Wang, White, Wiesemann, Yan, Zhao, Zhu, van Beekveld, …

Sudakov logarithms double lightcone OPE

Introduce a new method to resum Sudakov logarithms (LP, NLP, and beyond)
based of operator production expansion

Double lightcone dominance

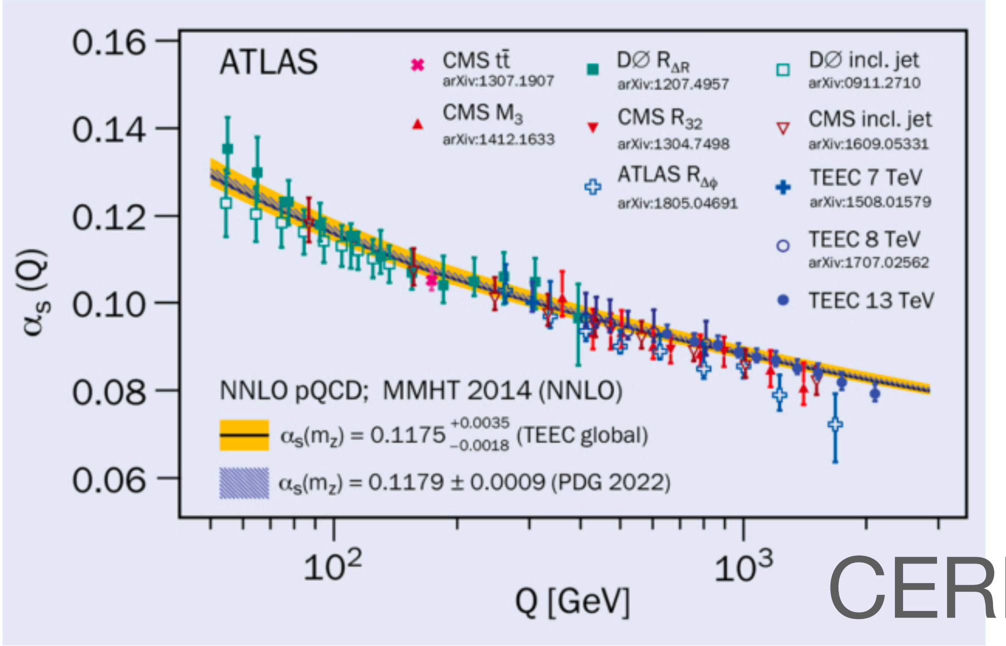


$$(x_1 - x_2)^2 \sim (x_2 - x_3)^2 \sim 0$$

conformal symmetry
large spin perturbation theory
analyticity in spin

Energy-Energy Correlator

Probably the simplest event shape
Measured at LEP at the LHC

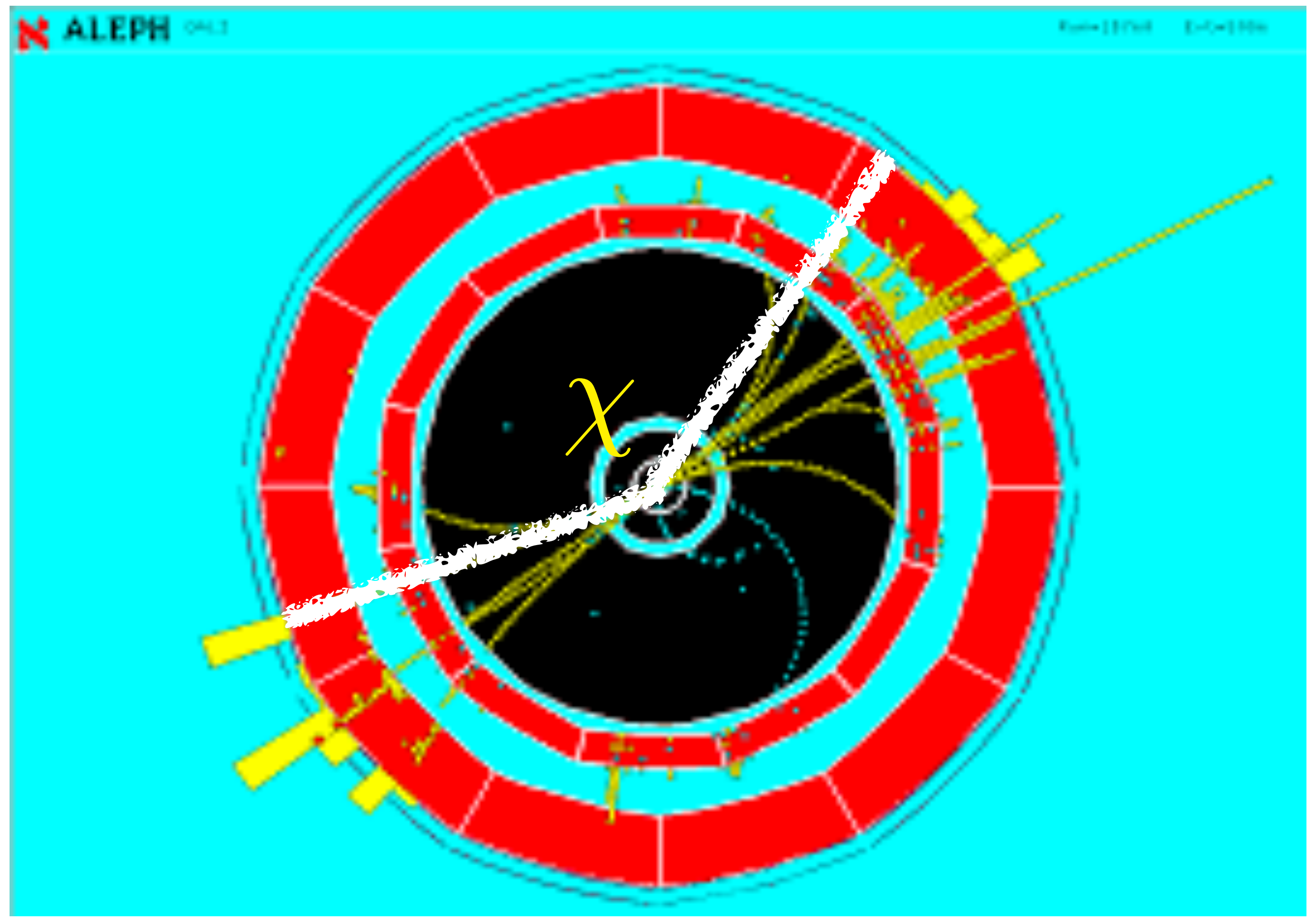


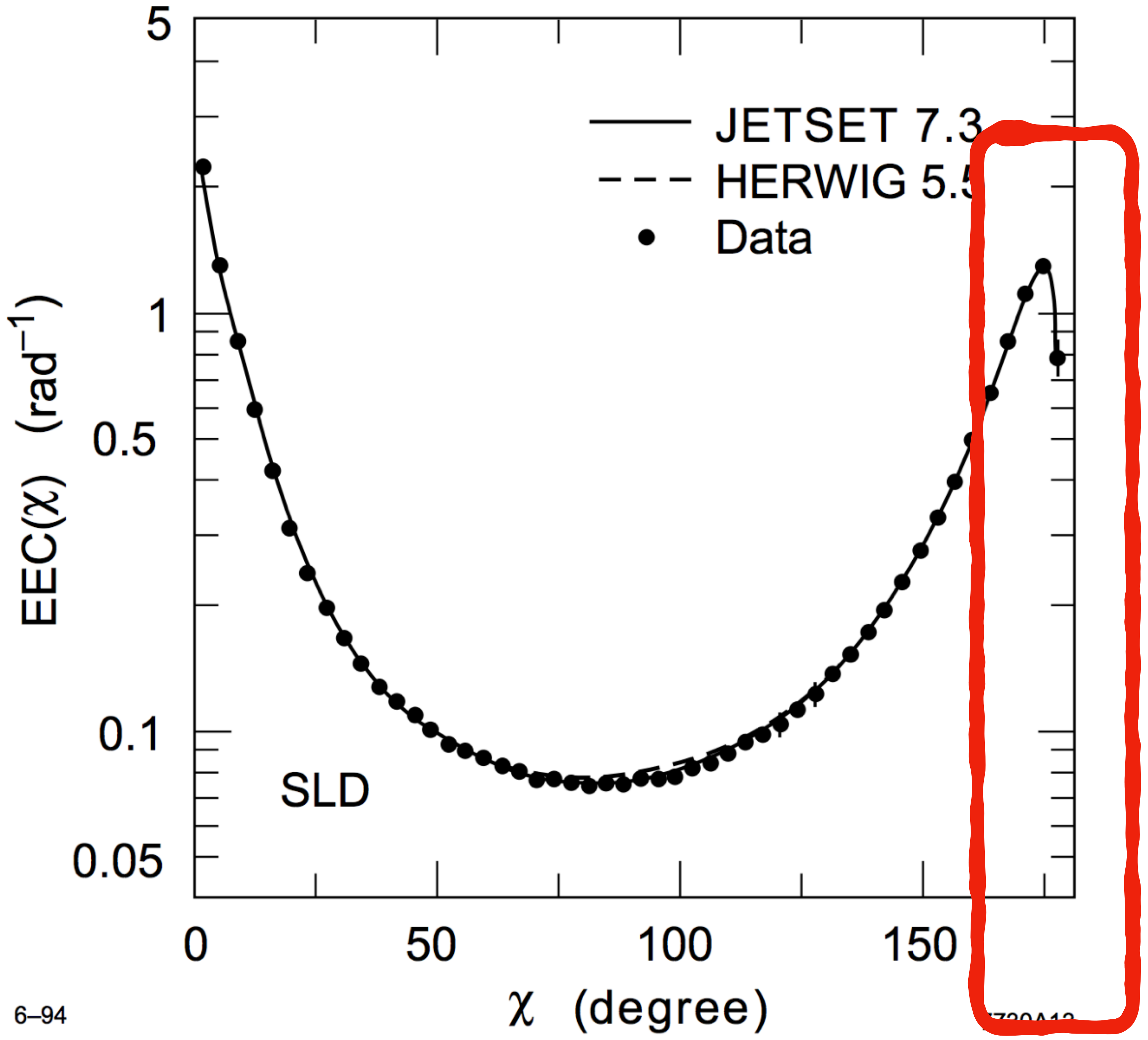
CERN courier 2023

Related to C/D parameter by moment
See talks by: Cao, Jaarsma, Lee

EEC in the back-to-back limit

Basham, Brown, Love, Ellis, 1978





$$\mathrm{EEC}(\chi) = \frac{1}{\sigma}\sum_{i,j}\int d\sigma_{e^+e^-\to i+j+X}\frac{E_iE_j}{Q^2}\delta(\cos\chi - \frac{\vec{p}_i\cdot\vec{p}_j}{|\vec{p}_i||\vec{p}_j|})$$

back-to-back limit: χ → π $\quad y = \frac{1+\cos\chi}{2}$

$$\mathrm{EEC}(y) \sim \sum_{n=1}^{\infty}\sum_{m=0}^{2n-1}\alpha_s^n\left(c_{n,m}\frac{\log^m y}{y} + d_{n,m}\log^m y\right)$$

$$\mathrm{EEC}(y)\Big|_{y\to 0} \sim H(Q,\mu)S(b,\mu,\nu)J_q(b,\mu,\nu)J_q(b,\mu,\nu)$$

TMD soft function

First moment of TMD fragmentation function

Collins, Soper, 1983
Moult, Zhu, 2018

A SCET-II problem!

Position space definition of EEC

EEC as Lorentizan Wightman correlation function of null-integrated opeartors

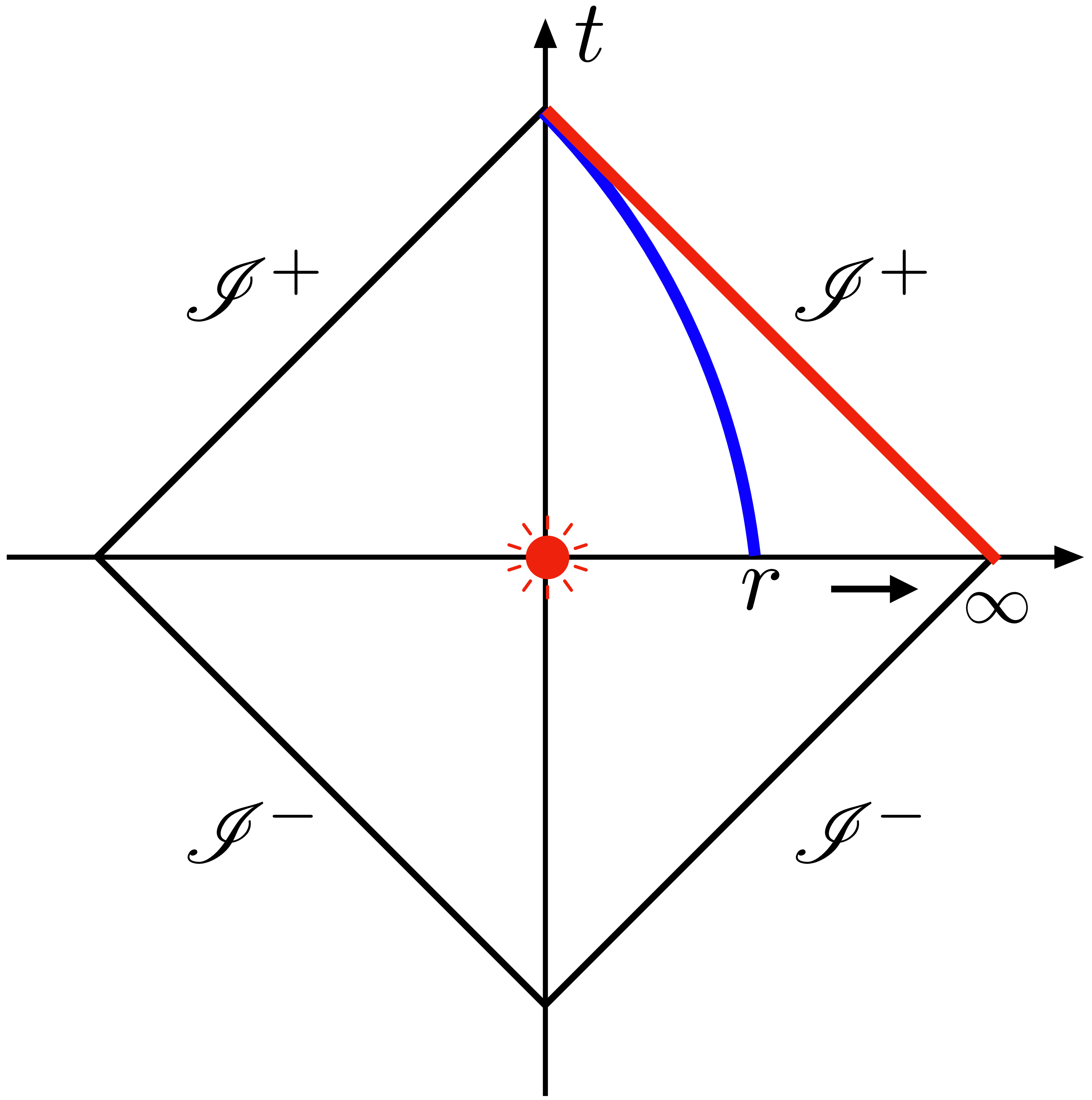
Belitsky, Hohenegger, Korchemsky, Sokatchev, Zhiboedov, 2013

$$\mathrm{EEC}(y) = \frac{8\pi^2}{q^2\sigma_0}\int d^4x\, e^{iq\cdot x_{13}}\langle J^\mu(x_1)\mathcal{E}(n_2)\mathcal{E}(n_4)J^\dagger_\mu(x_3)\rangle$$

Tkachov, 1995; Hofman, Maldacena 2008; Bauer, Fleming, Lee, Sterman, 2008

$$\mathcal{E}(n_i) = \int_{-\infty}^{\infty}\frac{d\,n_i\cdot x_i}{16}\lim_{\bar{n}_i x_i\to\infty}(\bar{n}_i\cdot x_i)^2 T_{\mu\nu}(x_i)\bar{n}_i^\mu\bar{n}_i^\nu$$

$$\mathcal{E}(n_i)|p\rangle = \omega|p\rangle\,, \qquad p^\mu = \omega n_i^\mu$$



Double lightcone dominance

Korchemsky 2019; Chen, Zhou, HXZ, 2023

$$\int d^4x_{13} e^{iq\cdot x_{13}} \quad + \text{ Light transformation } \quad \langle J_\mu(x_1) T^{\rho\sigma}(x_2) T^{\lambda\kappa}(x_4) J^\mu(x_3)\rangle$$

q: virtual photon momentum

$$x_1 = 0, \quad x_2 = (t_2, r\vec{n}_2), \quad x_4 = (t_4, r\vec{n}_4)$$

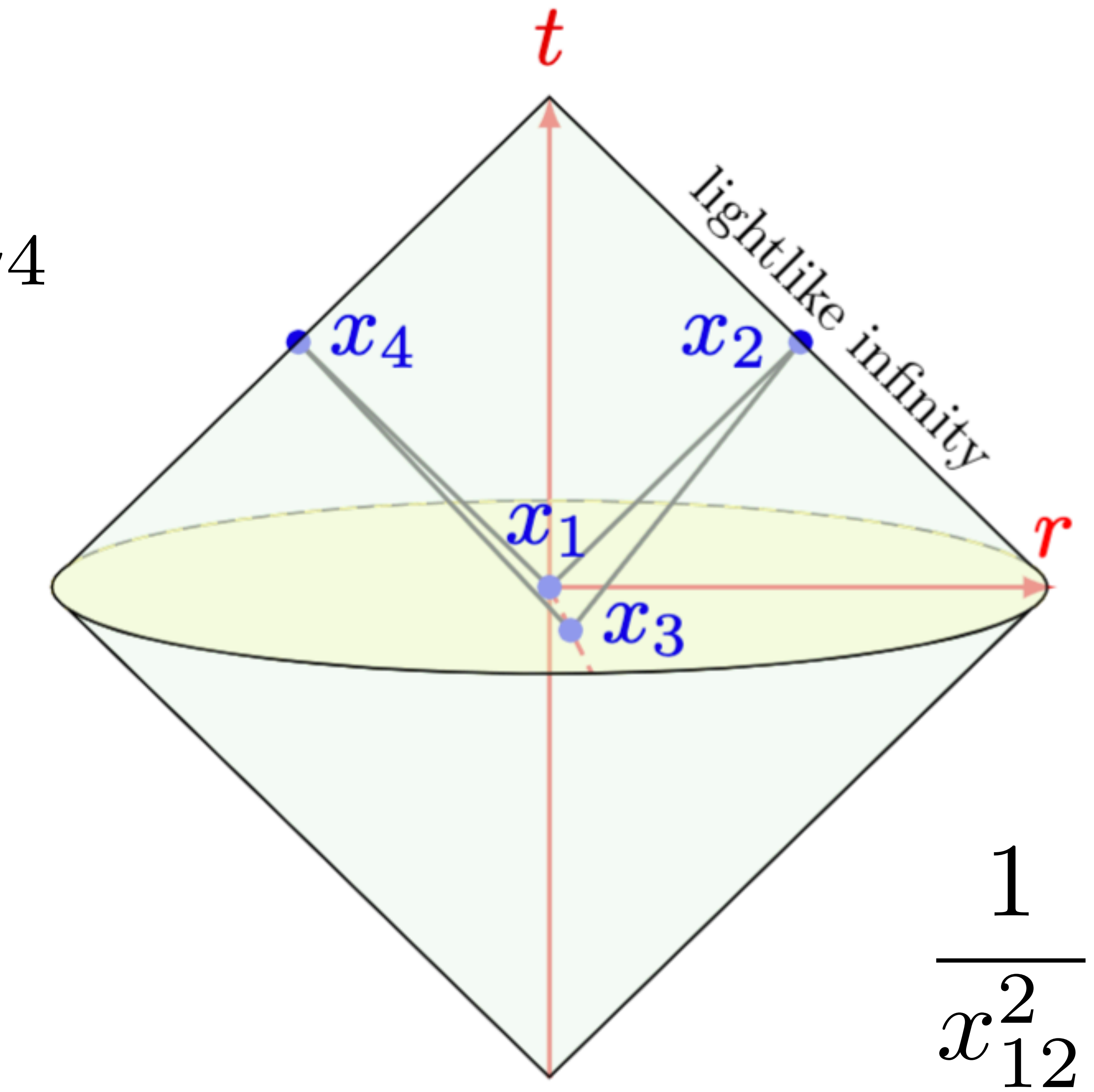
Where is the back-to-back limit in position space?

Choose a frame where detectors are exactly back-to-back $n_2 = \bar{n}_4$

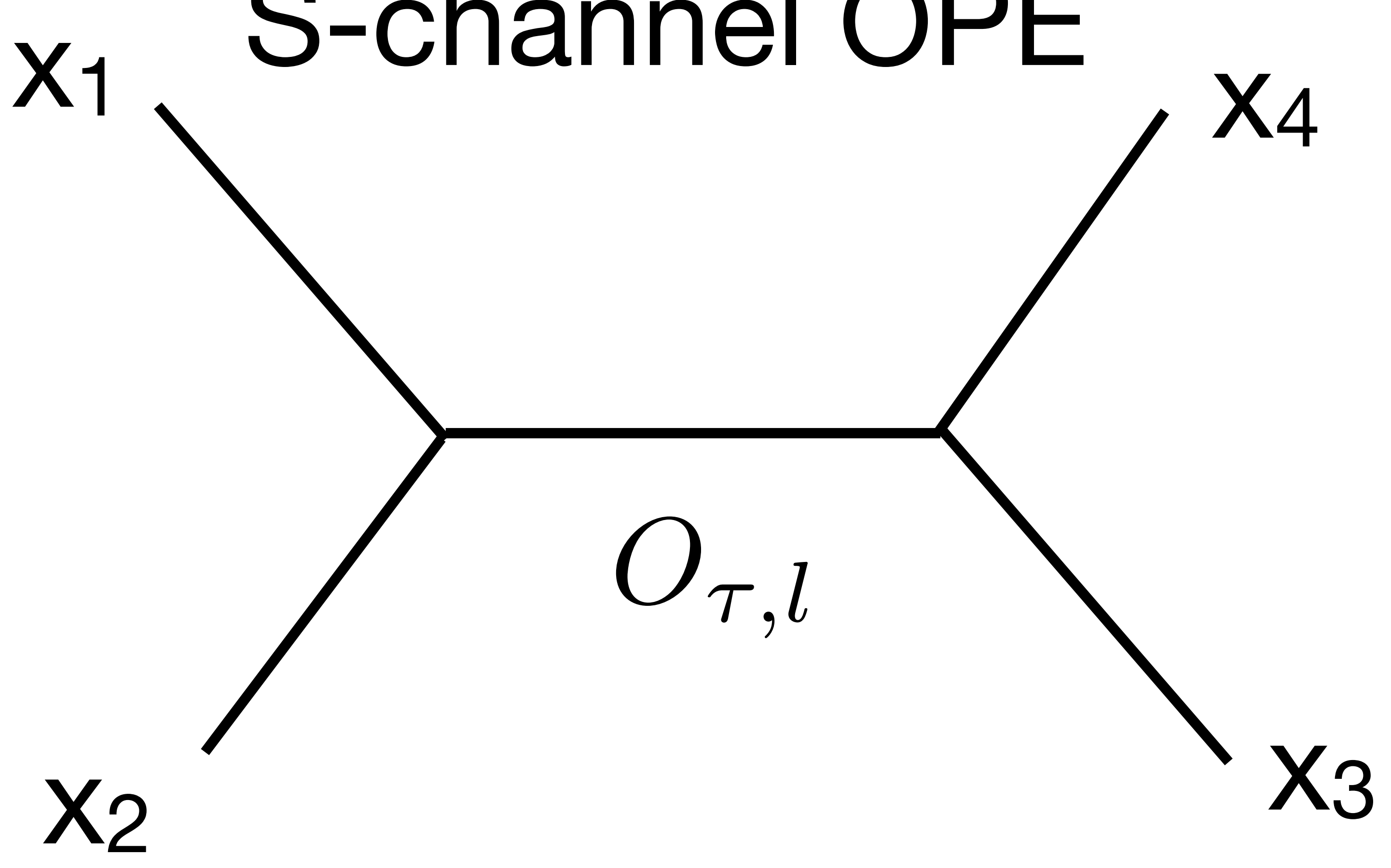
$$y \sim \frac{q_\perp^2}{q^2} \to 0$$

$$y \sim \frac{x_{13}^+ x_{13}^-}{x_{13}^2} \to 0$$

$$x_{12}^2,\ x_{23}^2 \ll x_{13}^2$$



S-channel OPE



dominated by $\dfrac{1}{x_{12}^2}$ → lightcone OPE twist expansion $\quad \tau = \Delta - l$

$\dfrac{1}{x_{23}^2}$ → requires sum over infinite operators with degenerate twist to reproduce

Concrete example: N=4 SYM

$$L = \mathrm{tr}\left\{-\frac{1}{2g^2}F_{\mu\nu}F^{\mu\nu} + \frac{\theta_I}{8\pi^2}F_{\mu\nu}\bar{F}^{\mu\nu} - i\bar{\lambda}^a\bar{\sigma}^\mu D_\mu \lambda_a - D_\mu X^i D^\mu X^i + gC_i^{ab}\lambda_a[X^i,\lambda_b] + g\bar{C}_{iab}\bar{\lambda}^a[X^i,\bar{\lambda}^b] + \frac{g^2}{2}[X^i,X^j]^2\right\},$$

A close cousin of QCD

superconformal sym. Korchemsky, Sokatchev, 2015

$$\langle \mathcal{O}(x_1)\mathcal{T}(x_2)\mathcal{T}(x_4)\mathcal{O}(x_3)\rangle_{\mathrm{dyn}} = \frac{1}{(2\pi)^4}\frac{x_{13}^4 x_{24}^4}{(x_{12}^2 x_{34}^2)^4}\mathcal{F}(u,v) \quad \Rightarrow \quad \langle \mathcal{O}(x_1)\mathcal{O}(x_2)\mathcal{O}(x_4)\mathcal{O}(x_3)\rangle_{\mathrm{dyn}} = \frac{1}{(2\pi)^4}\frac{x_{13}^4 x_{24}^4}{(x_{12}^2 x_{34}^2)^4}\mathcal{F}(u,v)$$

conformal cross ratio

$$u = \frac{x_{12}^2 x_{34}^2}{x_{13}^2 x_{24}^2} = z\bar{z}\,, \quad v = \frac{x_{23}^2 x_{14}^2}{x_{13}^2 x_{24}^2} = (1-z)(1-\bar{z})$$

double lightcone limit:

$$u \to 0, \quad v \to 0$$

$$\text{one loop} = \left[-\frac{1}{4}\log u \log v + 0\cdot\log(uv) + \cdots\right] - \left[\frac{1}{4}(u+v)\log u\log v + \frac{1}{2}(u\log u + v\log v) + \cdots\right] + \cdots,$$

$$\text{two loop} = \left[\frac{1}{16}\log^2 u\log^2 v + 0\cdot\log u\log v\log(uv) + \cdots\right] + \left[\frac{1}{8}(u+v)\log^2 u\log^2 v + \frac{3}{16}\log u\log v(u\log u + v\log v) + \frac{1}{8}\log u\log v(v\log u + u\log v) + \cdots\right] + \cdots,$$

$$\text{three loop} = \left[-\frac{1}{96}\log^3 u\log^3 v + 0\cdot\log^2 u\log^2 v\log(uv) + \cdots\right] - \left[\frac{1}{48}(u+v)\log^3 u\log^3 v\right.$$

light transform

$$\mathrm{EEC}^{(1)} = -\frac{1}{4y}\log y - \frac{1}{2}\log y + 0\cdot y^0 + \mathcal{O}(y)\,,$$

$$\mathrm{EEC}^{(2)} = \frac{1}{y}\left(\frac{\log^3 y}{8} + 0\cdot\log^2 y + \cdots\right) + \left(\frac{\log^3 y}{6} + \frac{3}{16}\log^2 y + \cdots\right) + \mathcal{O}(y)$$

$$\mathrm{EEC}^{(3)} = \frac{1}{y}\left(-\frac{\log^5 y}{32} + 0\cdot\log^4 y + \cdots\right) + \left(-\frac{3\log^5 y}{80} - \frac{\log^4 y}{12} + \cdots\right) + \mathcal{O}(y)\,.$$

Henn, Sokatchev, Yan, Zhiboedov, 2019

Drummond, Duhr, Eden, Helsop, Pennington, Smirnov, 2013

see also an expansion leading to different results in Moult, Vita, Yan, 2019

Double lightcone expansion

$$u = \frac{x_{12}^2 x_{34}^2}{x_{13}^2 x_{24}^2} = z\bar{z}\,, \quad v = \frac{x_{23}^2 x_{14}^2}{x_{13}^2 x_{24}^2} = (1-z)(1-\bar{z})$$

Sudakov limit in EEC → singularities in $u \to 0, \quad v \to 0$

collinear $u \to 0$ twist expansion. Power corrections computed by including higher twist operator

soft $v \to 0$ Large spin expansion. Power corrections computed by retaining 1/spin suppression terms

example: $\gamma_{2,\ell}^{(1)} = \log J_{6,\ell}^2 + 2\gamma_E + \frac{1}{3J_{6,\ell}^2} + \mathcal{O}(J_{6,\ell}^{-4})$

cusp anomalous dim.

normal anomalous dim.

large spin suppression

Crossing symmetry

$$u = \frac{x_{12}^2 x_{34}^2}{x_{13}^2 x_{24}^2} = z\bar{z}\,, \quad v = \frac{x_{23}^2 x_{14}^2}{x_{13}^2 x_{24}^2} = (1-z)(1-\bar{z})$$

$$\langle \mathcal{O}(x_1)\mathcal{O}(x_2)\mathcal{O}(x_4)\mathcal{O}(x_3)\rangle = \langle \mathcal{O}(x_3)\mathcal{O}(x_2)\mathcal{O}(x_4)\mathcal{O}(x_1)\rangle$$

$$u \leftrightarrow v$$

For a large part, twist suppression is determined by large spin suppression

$$\text{one loop} = \overbrace{\left[-\frac{1}{4}\log u \log v + 0\cdot\log(uv) + \cdots\right]}^{\text{Leading Power}} - \overbrace{\left[\boxed{\frac{1}{4}(u+v)\log u\log v} + \frac{1}{2}(u\log u + v\log v) + \cdots\right]}^{\text{Next-to-Leading Power}} + \cdots\,,$$

$$\text{two loop} = \left[\frac{1}{16}\log^2 u \log^2 v + 0\cdot\log u\log v\log(uv) + \cdots\right] + \left[\boxed{\frac{1}{8}(u+v)\log^2 u\log^2 v}\right.$$

$$\left. + \frac{3}{16}\log u\log v(u\log u + v\log v) + \frac{1}{8}\log u\log v(v\log u + u\log v) + \cdots\right] + \cdots\,,$$

$$\text{three loop} = \left[-\frac{1}{96}\log^3 u\log^3 v + 0\cdot\log^2 u\log^2 v\log(uv) + \cdots\right] - \left[\boxed{\frac{1}{48}(u+v)\log^3 u\log^3 v}\right.$$

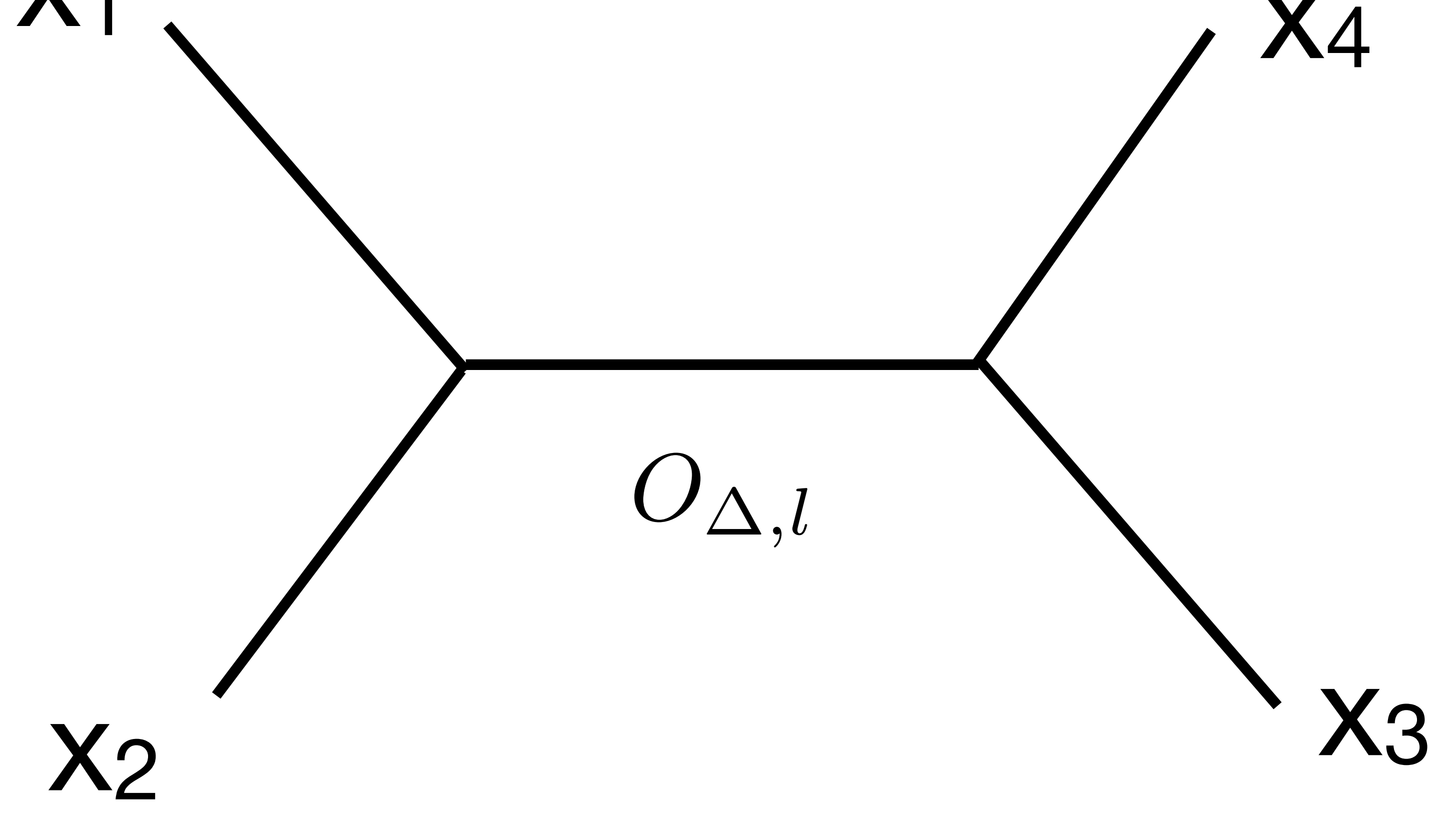
For leading and sub-leading log, we are left with large spin corrections

Conformal block expansion

$$\mathcal{F}(u,v) = \sum_{\Delta} \sum_{\text{even } \ell} a_{\tau,\ell} G_{\Delta+4,\ell}(u,v)$$

eigenfunction of conformal Casimir

S-channel OPE



Dolan, Osborn, 2001

$$G_{\Delta,\ell}(u,v) = \frac{z\bar{z}}{\bar{z}-z}\left[k_{\Delta-\ell-2}(z)k_{\Delta+\ell}(\bar{z}) - (z \leftrightarrow \bar{z})\right]$$

$$k_\beta(x) = x^{\beta/2}\,{}_2F_1(\beta/2,\beta/2,\beta;x)$$

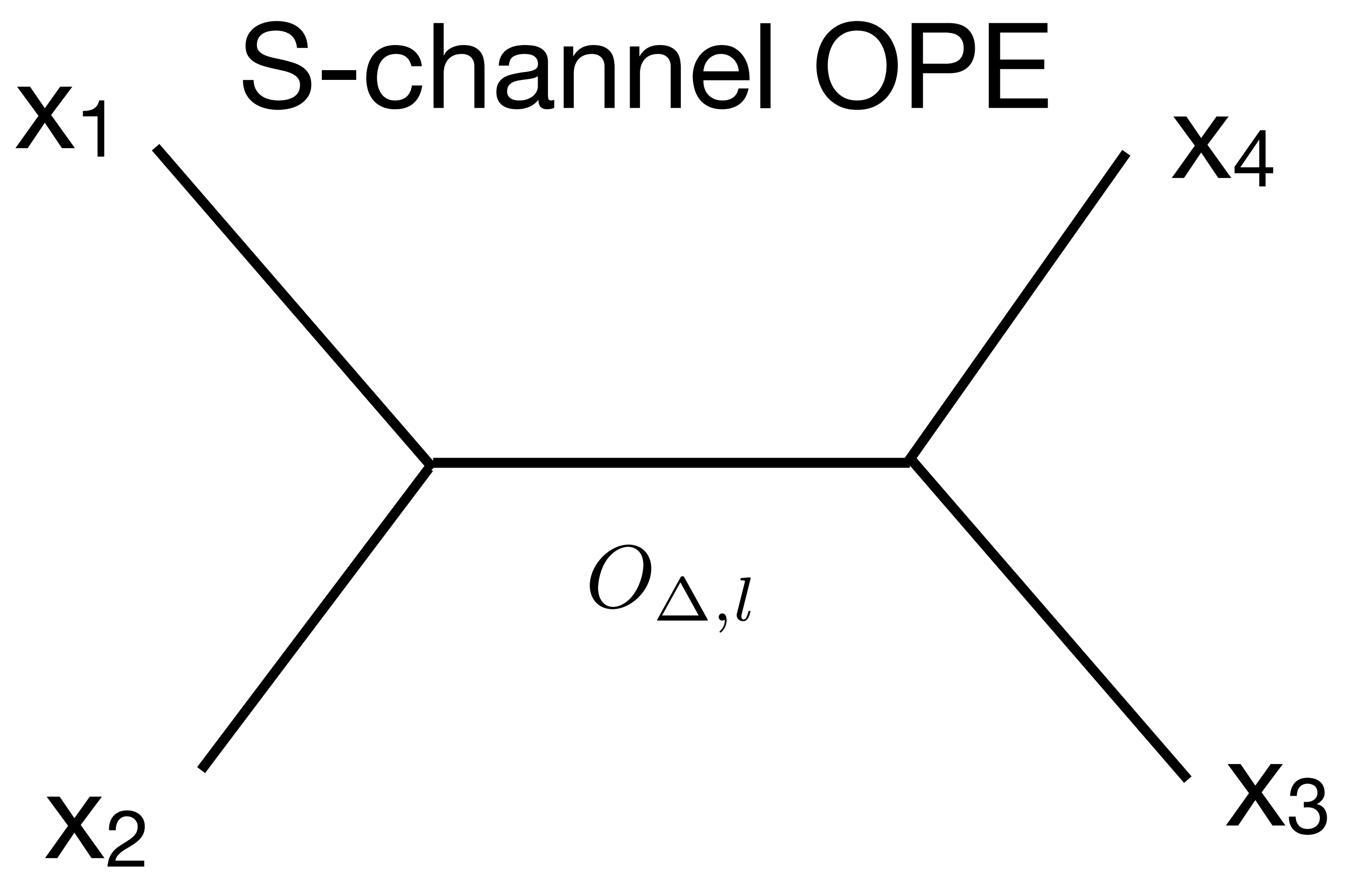
Leading twist expansion u->0 (z->0): $L_z = \log z$

$$\mathcal{F}^{(n)} = z^3 \sum_{\text{even } \ell} a^{(0)}_{2,\ell} \left\{ \frac{\left(\gamma^{(1)}_{2,\ell}\right)^n}{2^n n!} L_z^n + \frac{\left(\gamma^{(1)}_{2,\ell}\right)^{n-1} L_z^{n-1}}{2^{n-1}(n-1)!} \times \left[\frac{a^{(1)}_{2,\ell}}{a^{(0)}_{2,\ell}} + (n-1)\frac{\gamma^{(2)}_{2,\ell}}{\gamma^{(1)}_{2,\ell}} + \frac{\gamma^{(1)}_{2,\ell}\partial_\ell}{2} \right] \right\} k_{2\ell+6}(\bar{z}) + \cdots$$

Leading in u but including infinite powers in v (fixed by conformal symmetry)
Resumming large logarithms in v requires sum over infinite spin
Resumming Power corrections in v requires systematic expansion over large spin

Twist conformal block

$$\mathcal{F}(u,v)=\sum_{\Delta}\sum_{\text{even }\ell} a_{\tau,\ell}G_{\Delta+4,\ell}(u,v)$$



twist conformal block $H_{\tau=2}=\sum_{\text{even }\ell} a^{(0)}_{\tau,\ell}G_{\ell+6,\ell}(u,v)$

Alday, 2016

$$H^{(m,i)}_{\tau_0}(z,\bar z)=\sum_{\ell} a^{(0)}_{\tau_0,\ell}\frac{\log^i J^2_{\tilde\tau_0,\ell}}{J^{2m}_{\tilde\tau_0,\ell}}G_{\Delta+4,\ell}(z,\bar z)$$

$$J^2_{\tau,\ell}=(\ell+\frac{\tau}{2})(\ell+\frac{\tau}{2}-1)$$

$$\tilde\tau_0=\tau+4$$

Leading twist expansion u->0 (z->0):

$L_z=\log z$

$$k_\beta(x)=x^{\beta/2}\,{}_2F_1(\beta/2,\beta/2,\beta;x)$$

LL

$$\mathcal{F}^{(n)}=z^3\sum_{\text{even }\ell} a^{(0)}_{2,\ell}\left\{\boxed{\frac{\left(\gamma^{(1)}_{2,\ell}\right)^n}{2^n n!}L_z^n}+\frac{\left(\gamma^{(1)}_{2,\ell}\right)^{n-1}L_z^{n-1}}{2^{n-1}(n-1)!}\times\left[\frac{a^{(1)}_{2,\ell}}{a^{(0)}_{2,\ell}}+(n-1)\frac{\gamma^{(2)}_{2,\ell}}{\gamma^{(1)}_{2,\ell}}+\frac{\gamma^{(1)}_{2,\ell}\partial_\ell}{2}\right]\right\}k_{2\ell+6}(\bar z)+\cdots$$

$$=\frac{L_z^n}{n!}\sum_i\binom{n}{i}\boxed{\left[\frac{\gamma_E^{n-i}}{2^i}H_2^{(0,i)}+\frac{n-i}{3}\frac{\gamma_E^{n-1-i}}{2^{i+1}}H_2^{(1,i)}\right]}+\cdots$$

$$a^{(0)}_{2,\ell}=\frac{\Gamma(\ell+3)^2}{\Gamma(2\ell+5)},$$

$$\gamma^{(1)}_{2,\ell}=\log J^2_{6,\ell}+2\gamma_E+\frac{1}{3J^2_{6,\ell}}+\mathcal{O}(J^{-4}_{6,\ell})$$

Analyticity in spin

$$\mathcal{F}(u,v) = \sum_{\Delta} \sum_{\text{even } \ell} a_{\tau,\ell} G_{\Delta+4,\ell}(u,v)$$

$$\mathcal{C}_{\tilde{\tau}_0} G_{\Delta+4,\ell}(z,\bar{z}) = J^2_{\tilde{\tau}_0,\ell} G_{\Delta+4,\ell}(z,\bar{z})$$

$$\mathcal{C}_\tau = \mathcal{D}_2 + \frac{1}{4}\tau(2d-\tau-2)$$

$$\mathcal{D}_2 = z^2((1-z)\partial_z^2 - \partial_z) + \frac{(d-2)z\bar{z}}{z-\bar{z}}(1-z)\partial_z + (z \leftrightarrow \bar{z})$$

twist conformal block $H_{\tau=2} = \sum_{\text{even } \ell} a^{(0)}_{\tau,\ell} G_{\ell+6,\ell}(u,v)$

Alday, 2016

$$H^{(m,i)}_{\tau_0}(z,\bar{z}) = \sum_{\ell} a^{(0)}_{\tau_0,\ell} \frac{\log^i J^2_{\tilde{\tau}_0,\ell}}{J^{2m}_{\tilde{\tau}_0,\ell}} G_{\Delta+4,\ell}(z,\bar{z})$$

$$J^2_{\tau,\ell} = (\ell + \frac{\tau}{2})(\ell + \frac{\tau}{2} - 1)$$

$$\tilde{\tau}_0 = \tau + 4$$

$$\boxed{H^{(m,i)}_{\tau_0}(z,\bar{z}) = \mathcal{C}_{\tilde{\tau}_0} H^{(m+1,i)}_{\tau_0}(z,\bar{z})}$$

analytic continuation in m

$$H^{(m,0)}_{\tau_0}(z,\bar{z}) \quad \cdots \quad \boxed{H^{(-2,0)}_{\tau_0}(z,\bar{z})} \xleftarrow{\mathcal{C}_{\tilde{\tau}_0}} \boxed{H^{(-1,0)}_{\tau_0}(z,\bar{z})} \xleftarrow{\mathcal{C}_{\tilde{\tau}_0}} \boxed{H^{(0,0)}_{\tau_0}(z,\bar{z})} \quad H^{(0,i)}_{\tau_0}(z,\bar{z}) \quad H^{(1,i)}_{\tau_0}(z,\bar{z})$$

$$\bar{H}^{(m,0)}_2(\bar{z}) = \frac{1}{2}\epsilon^{m-1}\Gamma(1-m)^2 + \frac{1}{6}m\left(2m^2-6m+1\right)\epsilon^m\Gamma(-m)^2 + \frac{1}{180}(m-1)m(m+1)\left(20m^3-54m^2-35m+36\right)\epsilon^{m+1}\Gamma(-m-1)^2 + \cdots$$

$$\frac{\bar{z}^2(2-\bar{z})}{2(1-\bar{z})} + \bar{z}\log(1-\bar{z}) = \frac{1}{2\epsilon} + \text{regular terms}$$

$$1-\bar{z} = \epsilon$$

Alday, 2016
Henriksson, Lukowski, 2017

Resummation for local correlator

$$\mathcal{F}^{(n)}(z,\bar{z}) = z^3 \left\{ \frac{1}{n!}\log^n z \left[\frac{1}{\epsilon}\left(\frac{(-1)^n}{2^{n+1}}\log^n \epsilon + \cdots \right) + \left(\frac{(-1)^{n+1}}{2^{n+1}}\log^n \epsilon + \frac{(-1)^n n}{3\times 2^n}\log^{n-1}\epsilon + \cdots \right) + \cdots \right] \right.$$
$$+ \frac{\log^{n-1} z}{(n-1)!}\left[\frac{1}{\epsilon}\left(\frac{(-1)^n}{2^{n+1}}(n+1)\zeta_2 \log^{n-1}\epsilon - \frac{(-1)^n}{2^{n+1}} 3(n-1)\zeta_3 \log^{n-2}\epsilon + \cdots \right) \right.$$
$$\left.\left. + \left(\frac{(-1)^n}{2^{n+1}n}\log^n \epsilon + \frac{(-1)^{n+1}}{2^{n+1}}(n+1)\zeta_2 \log^{n-1}\epsilon + \cdots \right) \right] + \cdots \right\} + \mathcal{O}(z^4)$$

Agree with fixed-oder expansion (up to terms not enhanced by large spin)

$$\text{one loop} = \left[-\frac{1}{4}\log u \log v + 0\cdot \log(uv) + \cdots \right] - \left[\frac{1}{4}(u+v)\log u \log v + \frac{1}{2}(u\log u + v \log v) + \cdots \right] + \cdots\,,$$

$$\text{two loop} = \left[\frac{1}{16}\log^2 u \log^2 v + 0\cdot \log u \log v \log(uv) + \cdots \right] + \left[\frac{1}{8}(u+v)\log^2 u \log^2 v \right.$$
$$\left. + \frac{3}{16}\log u \log v (u \log u + v \log v) + \frac{1}{8}\log u \log v (v\log u + u \log v) + \cdots \right] + \cdots\,,$$

$$\text{three loop} = \left[-\frac{1}{96}\log^3 u \log^3 v + 0\cdot \log^2 u \log^2 v \log(uv) + \cdots \right] - \left[\frac{1}{48}(u+v)\log^3 u \log^3 v \right.$$

Resummation for EEC beyond leading power

$$\mathrm{EEC}(y) \sim \sum_{n=1}^{\infty} \sum_{m=0}^{2n-1} \alpha_s^n \left(c_{n,m} \frac{\log^m y}{y} + d_{n,m} \log^m y \right)$$

NLL: $m \geq 2n - 2$

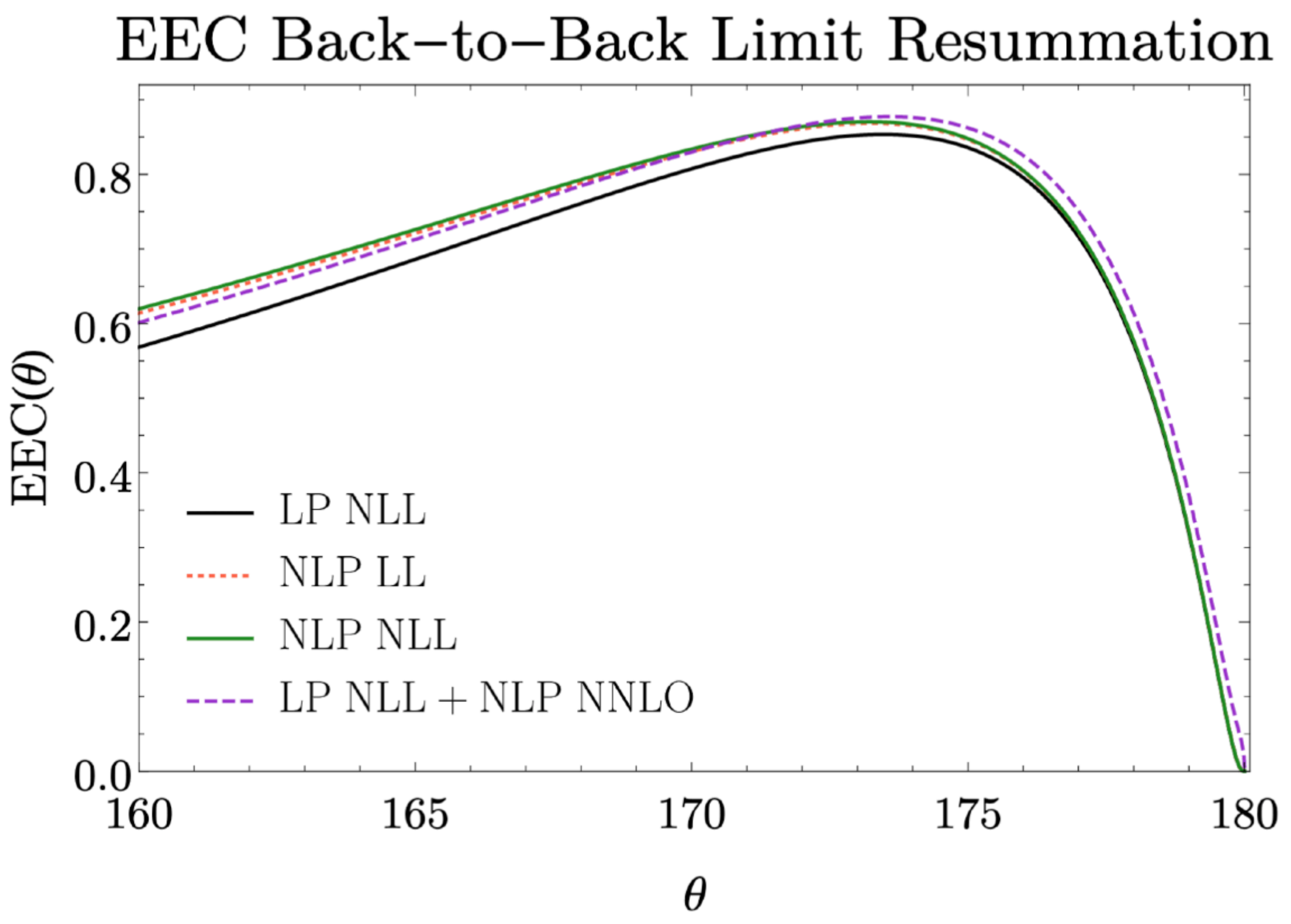
	Power Corrections		Perturbative Corrections	
	twist	large spin	LL	NLL
LP	2	$\mathcal{O}(\ell^0)$	$a_{2,\ell}^{(0)}, \gamma_{2,\ell}^{(1)}$	$a_{2,\ell}^{(1)}, \gamma_{2,\ell}^{(2)}$
NLP	2	$\mathcal{O}(\ell^{-2})$	$a_{2,\ell}^{(0)}, \gamma_{2,\ell}^{(1)}$	$a_{2,\ell}^{(1)}, \gamma_{2,\ell}^{(2)}$
	4	$\mathcal{O}(\ell^0)$	$a_{4,\ell}^{(0)}, \gamma_{4,\ell}^{(1)}$	$a_{4,\ell}^{(1)}, \gamma_{4,\ell}^{(2)}$

$$\mathrm{EEC}(y) = -\frac{aL_y e^{-\frac{aL_y^2}{2}}}{4y} - \frac{1}{4}\left[\sqrt{\frac{\pi}{2}}\sqrt{a}\,\mathrm{erf}\left(\sqrt{\frac{a}{2}}L_y\right) + aL_y e^{-\frac{aL_y^2}{2}}\right] + \frac{a}{48}(7aL_y^2 - 4)e^{-\frac{aL_y^2}{2}} + \frac{a}{12} + \cdots$$

$$\mathrm{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} dt$$

Discrepancy with NLP-LL prediction of Moult, Vita, Yan, 2019

$$\mathrm{EEC}^{(2)} = -\frac{\sqrt{2a\pi}}{2} e^{-x^2} \mathrm{erfi}\left[\sqrt{\frac{\Gamma_{\mathrm{cusp}}}{2}} \log y\right]$$



Summary

- A new method to resum Sudakov logarithms for EEC based on double lightcone expansion
    - conformal symmetry/large spin perturbation/analyticity in spin
- First LL and NLL resummation at NLP!
- Towards resummation in QCD (w.i.p.):
    - spinning conformal block
    - higher twist operators
    - running coupling
    - ……

Two distinct continents, SCET and CFT,
Each with their own story and history set,
Developed on their own, far apart,
But connected by an unexpected start.

EEC opened up the door,
To a world of possibilities, never seen before,
Bringing together what was once apart,
With newfound knowledge and a fresh start.

—chatGPT