

Some aspects of QCD measurements at the CEPC

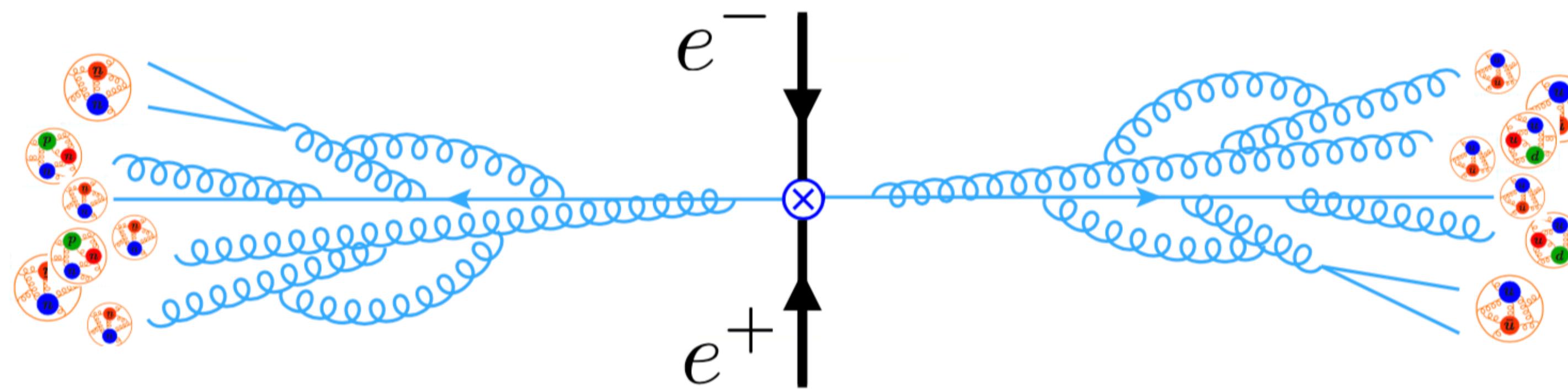
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第十三届全国粒子物理学术会议
山东青岛，2021年8月16-20日

$$\mathcal{L}_{\text{QCD}} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu} + \text{theta term}$$

Deceptively simple Lagrangian, with astonishingly rich phenomena.



In high energy e^+e^- collider we have access to QCD through $q\bar{q}$ production and subsequent bremsstrahlung.

There is no need to TEST QCD as the correct theory of strong interaction.

With a new e^+e^- collider, we should aim for precision QCD measurements, and **exploration of new phenomena in QCD**.

Outline for this talk

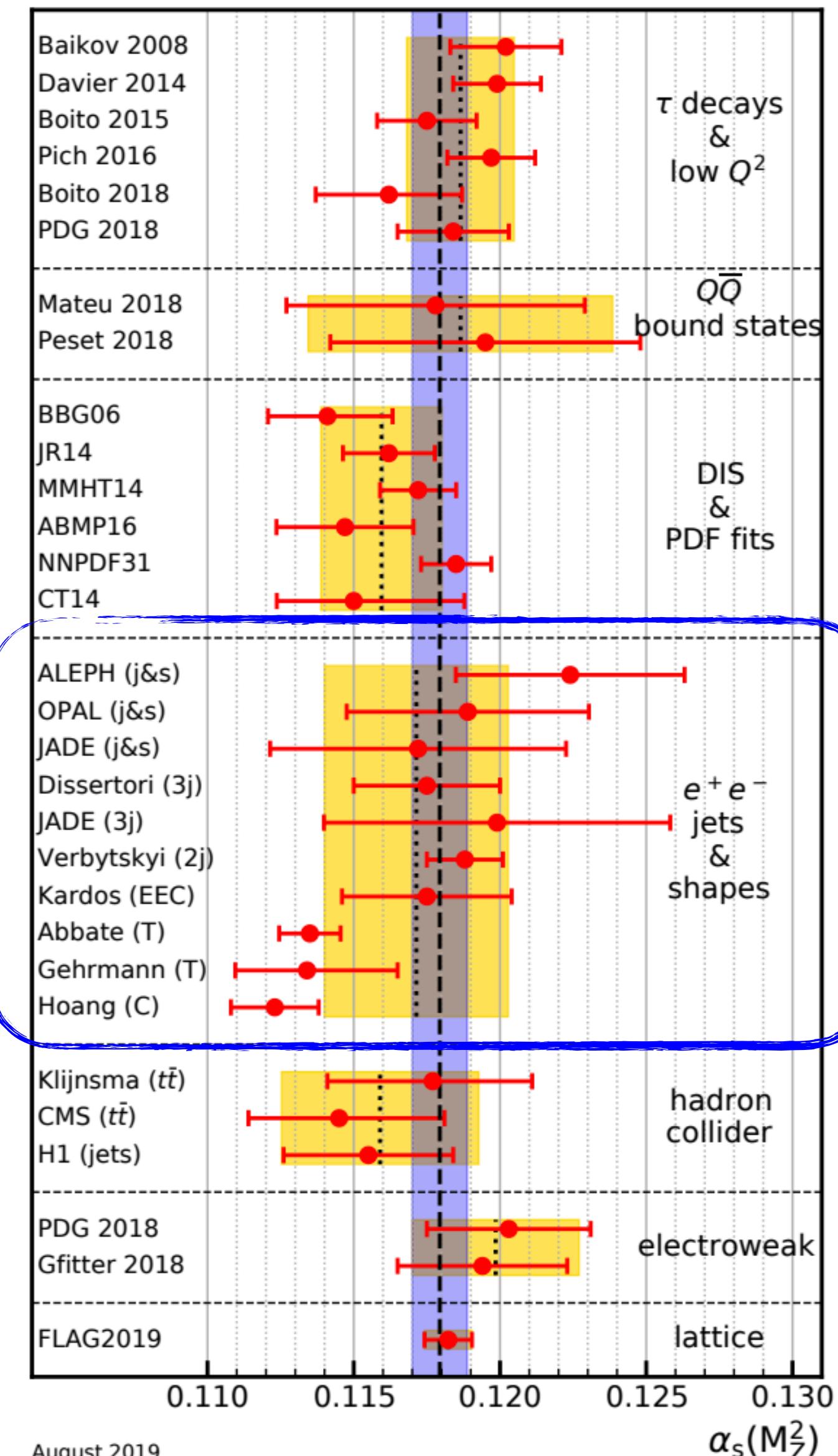
- How to achieve the ultimate precision for alphaS at the CEPC ?
- Can we see gluon spin interference at the CEPC ??
- How to observe entanglement from non-global observables at the CEPC ???
- Can we quantitatively understand hadronization ????

Disclaimer #1: this is not a review talk, many important subjects are not covered due to time restriction and the speaker's ignorance.

Disclaimer #2: there is probably no definite answer to the questions above. Opportunities for future studies.

- How to achieve the ultimate precision for alphaS at the CEPC ?

The legacy of LEP



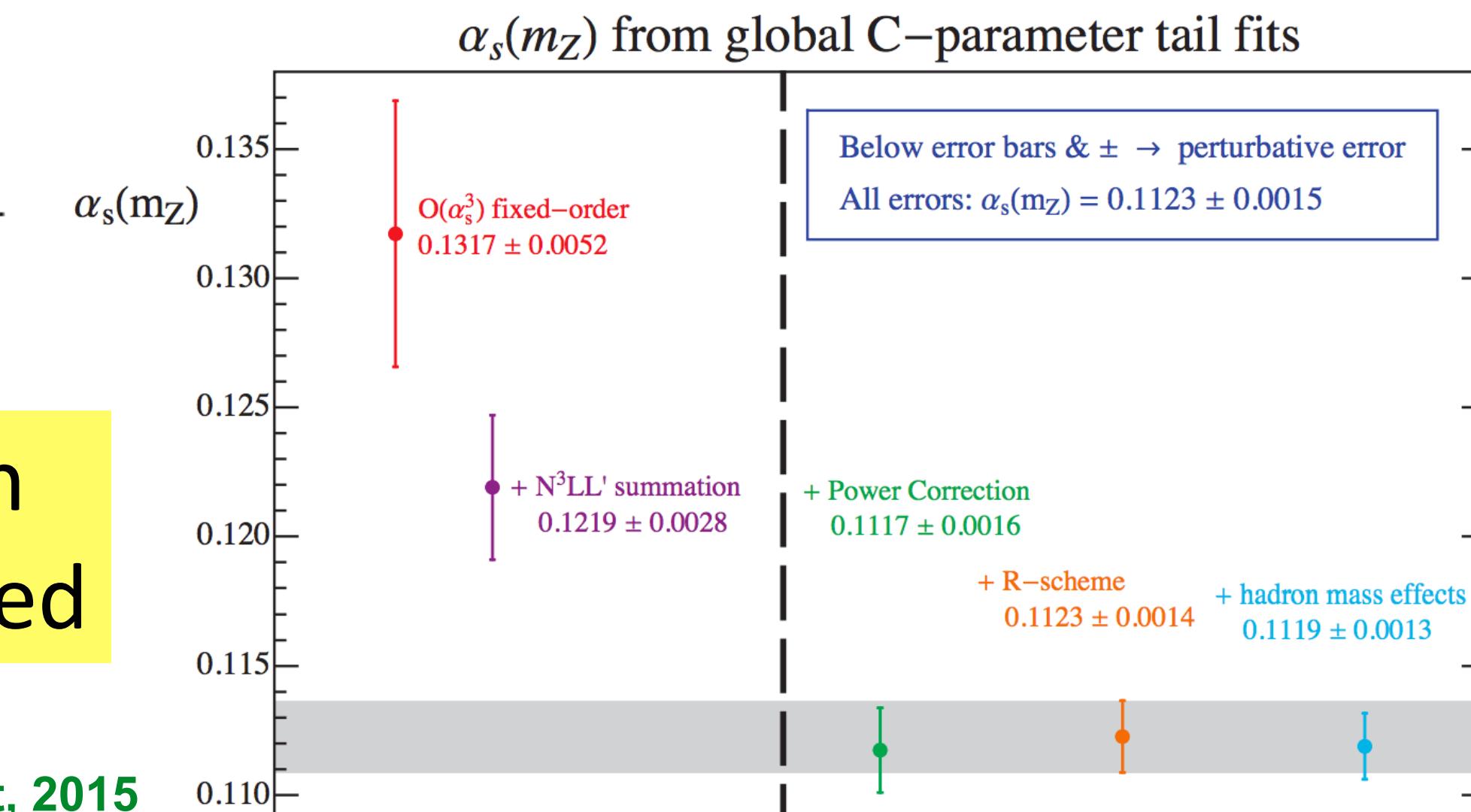
- LEP provided the largest data set and the closest to world average determination so far.
- But also notable outliers in most accurate calculations

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

Theory hadronization uncertainties dominated

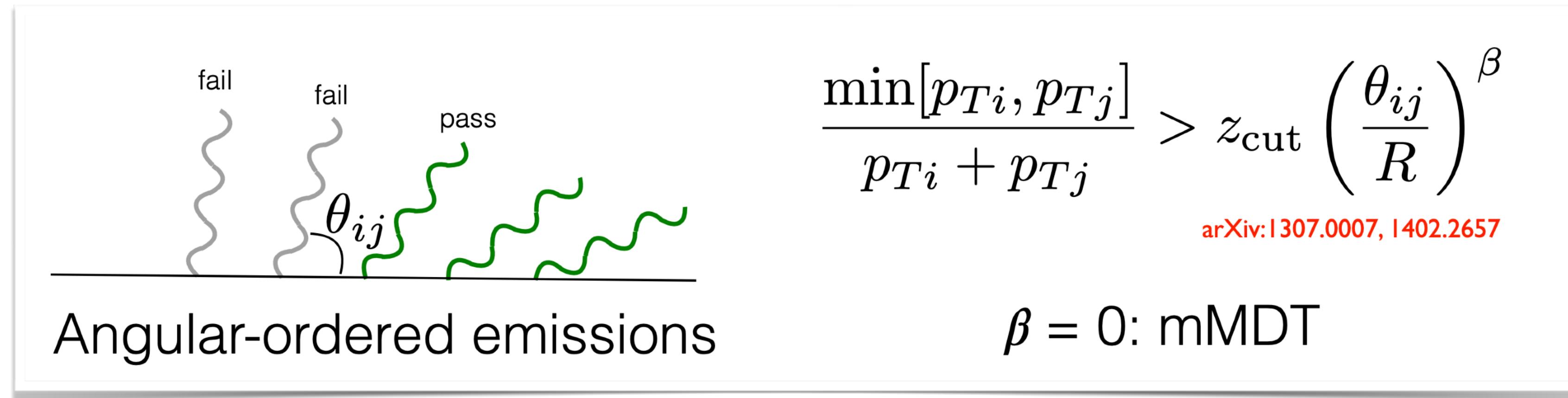
Hoang, Kolodrubetz, Mateu, Stewart, 2015

see also recent study: Luisoni, Monni, Salam, 2012.00622

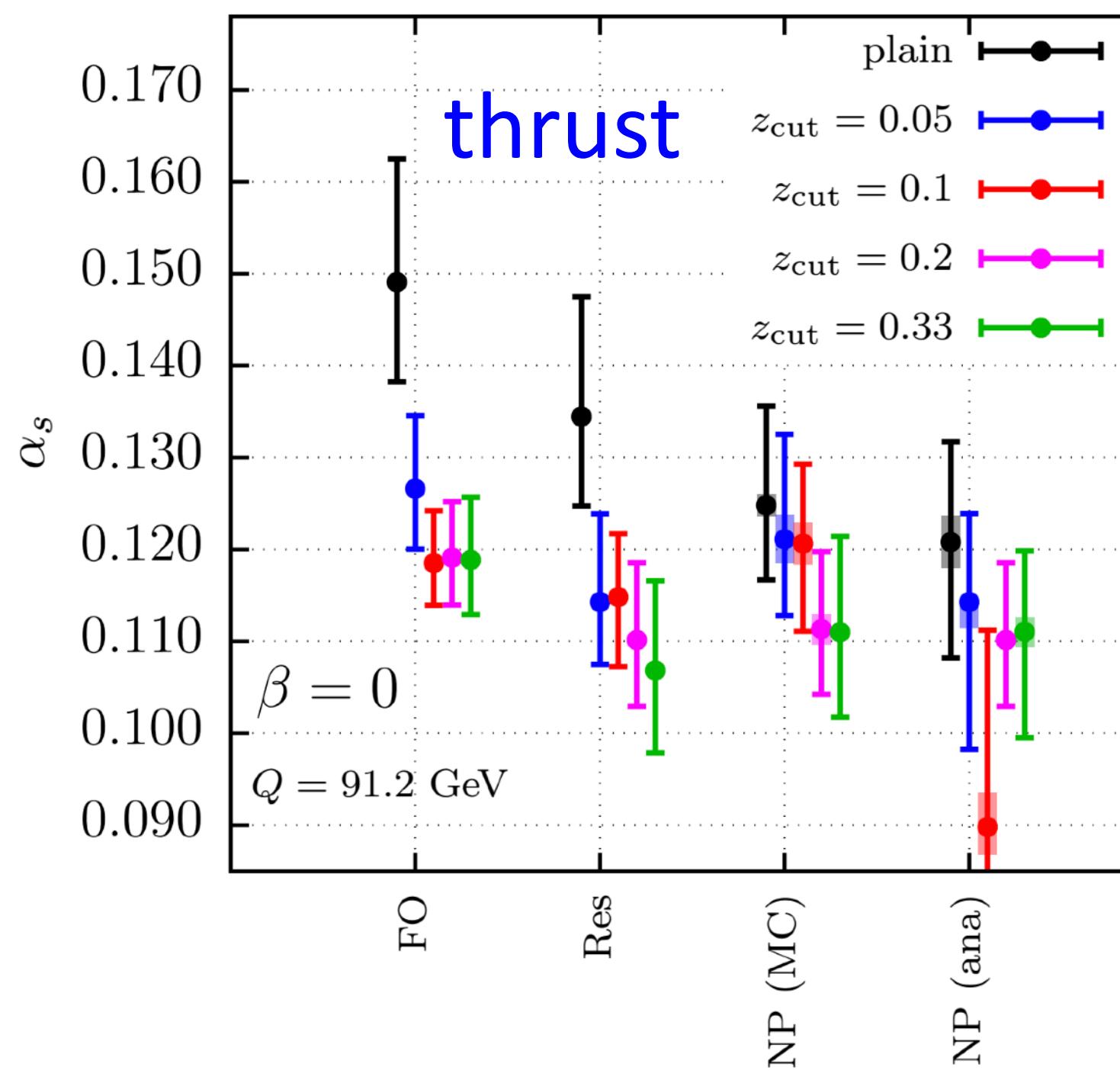


- Looking ahead to the future, can theorists come up with new ideas to solve this decade-long challenge?
 - soft-drop observables (new)
 - Energy correlators (old but with new understanding)

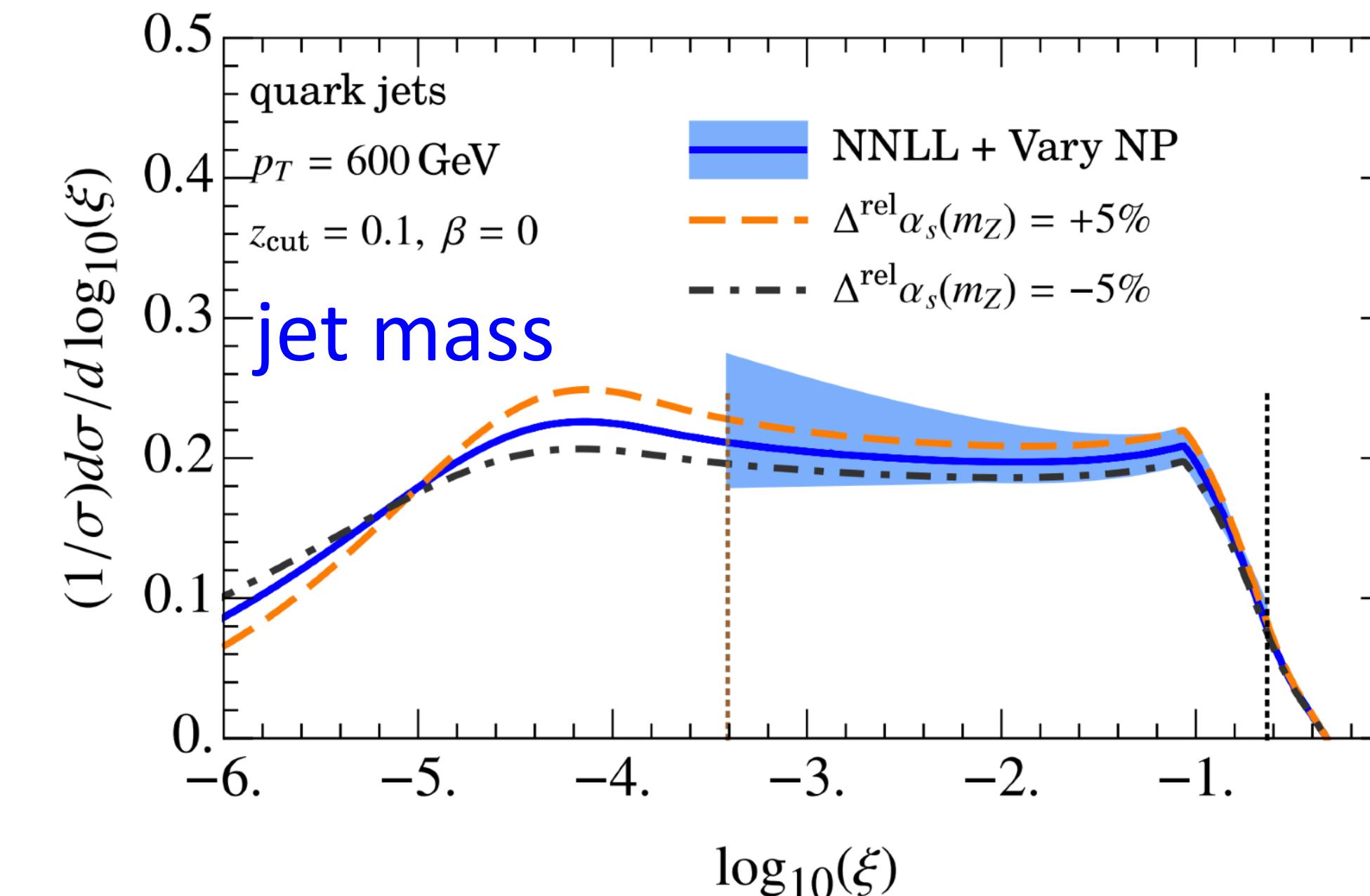
Precision soft-drop observables



credit: Larkoski



Marzani et al., 1906.10504

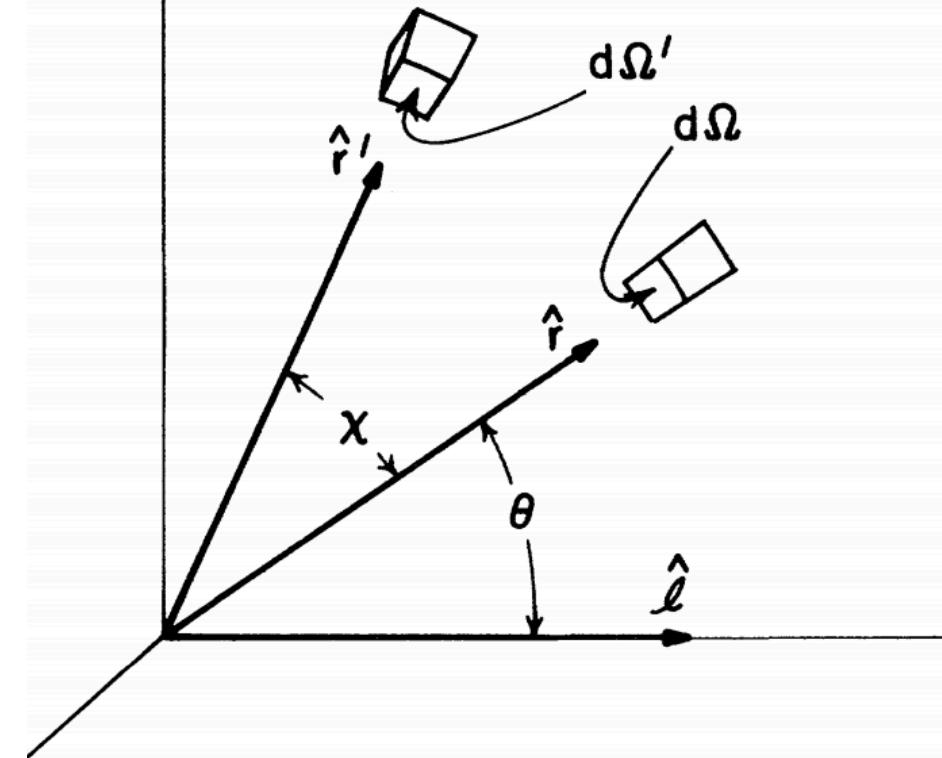


Honnefoss, Pathak, Schwartz, Stewart, Boost 2021

- For jet mass, sensitivity to α_s is retained for un-normalized distribution.
- Theory precision is very important here!

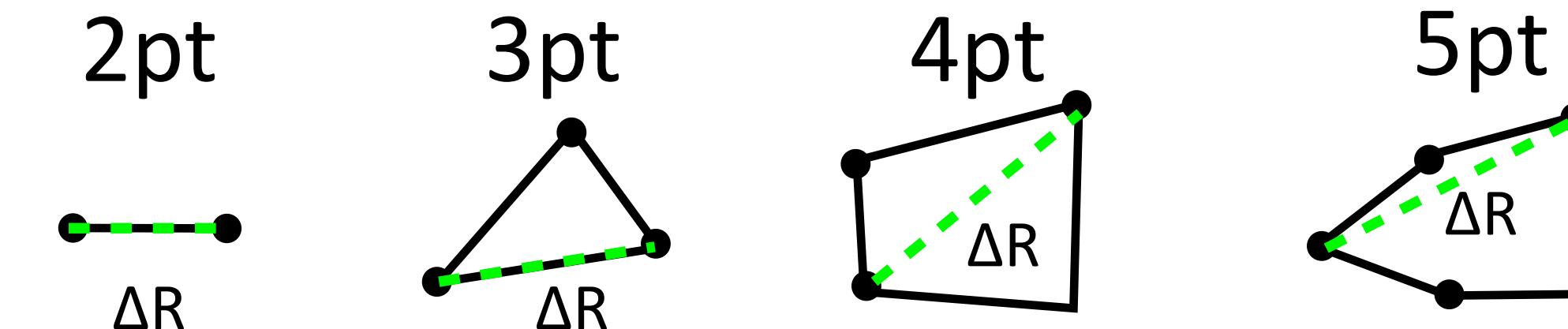
Energy correlators

Basham, Brown, Ellis, Love, 1978



$$\text{EEC}(\chi) = \frac{1}{N} \sum_{\text{events}}^N \sum_{i,j}^{N_{\text{particles}}} \frac{E_i E_j}{E_{\text{tot}}^2} \left(\frac{1}{\Delta\chi} \int_{\chi - \Delta\frac{\chi}{2}}^{\chi + \Delta\frac{\chi}{2}} \delta(\chi' - \chi_{ij}) d\chi' \right)$$

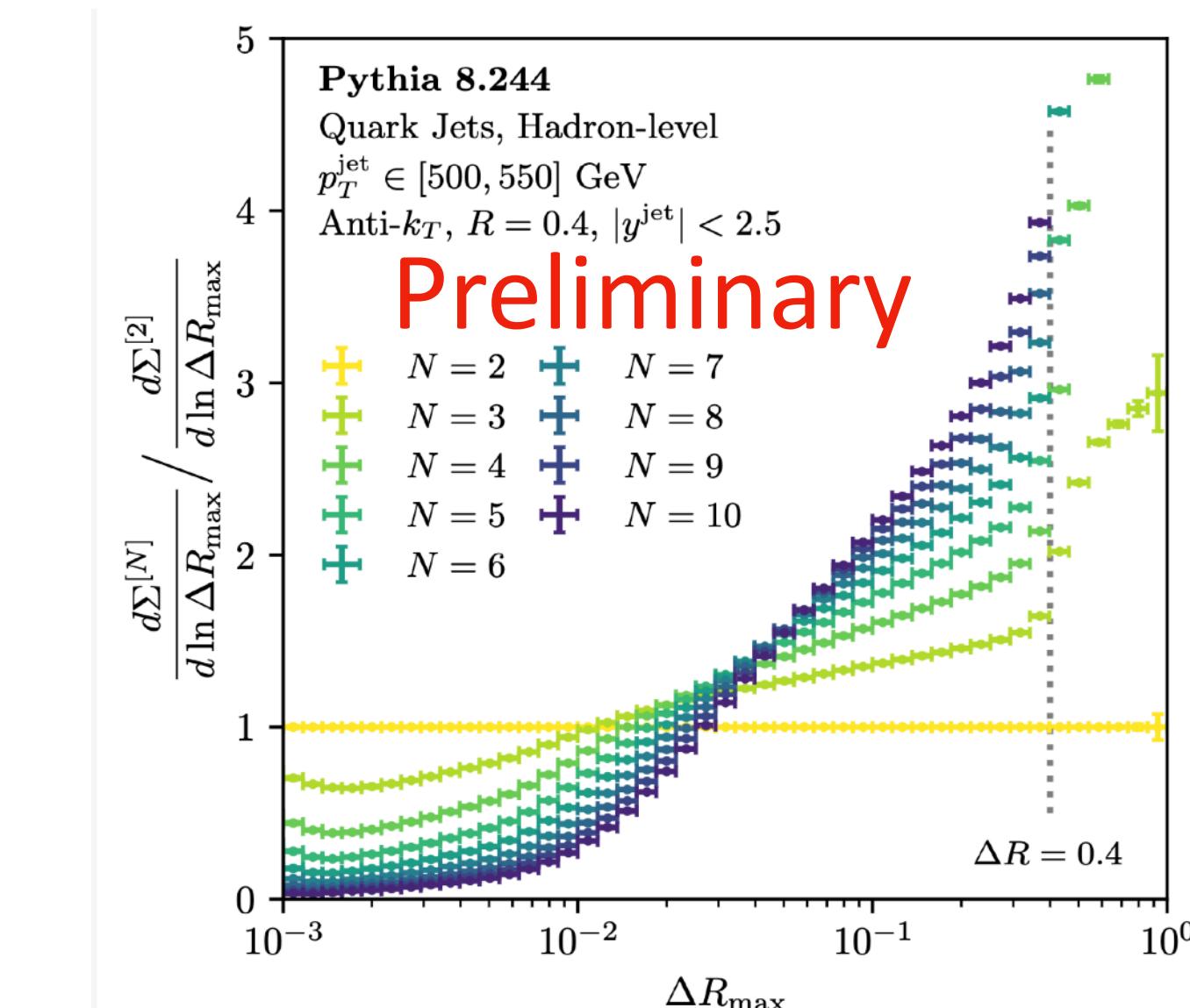
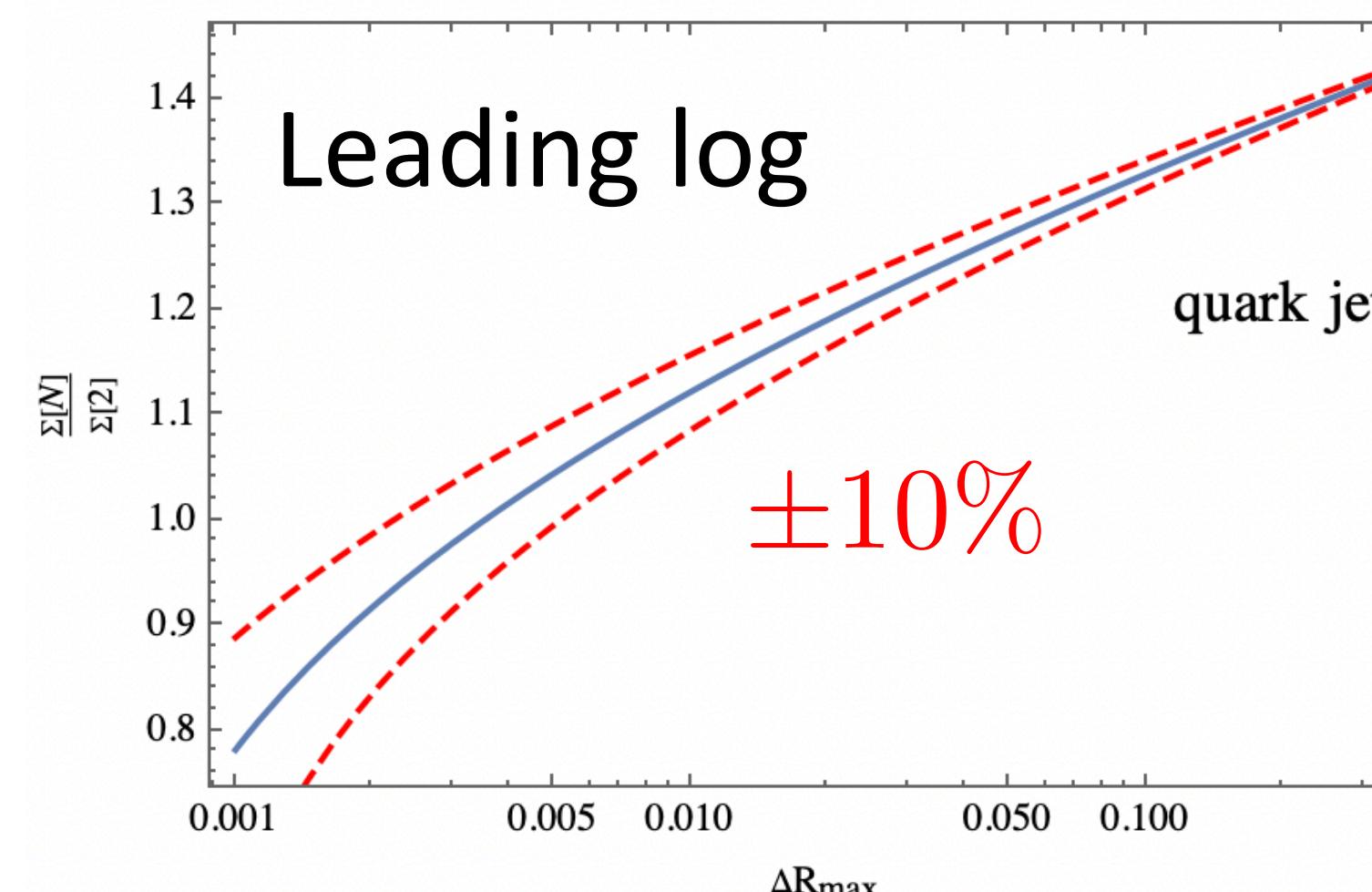
Generalizable to multiple point: H. Chen, Moult, X.Y. Zhang, HXZ, 2004.11381



$$\begin{aligned} \frac{3\text{-point}}{2\text{-point}} &= \frac{\text{3-point diagram}}{\text{2-point diagram}} \\ &= (\Delta R)^{\gamma(J=4) - \gamma(J=3)} \end{aligned}$$

(ΔR)^{γ(J=4) - γ(J=3)}

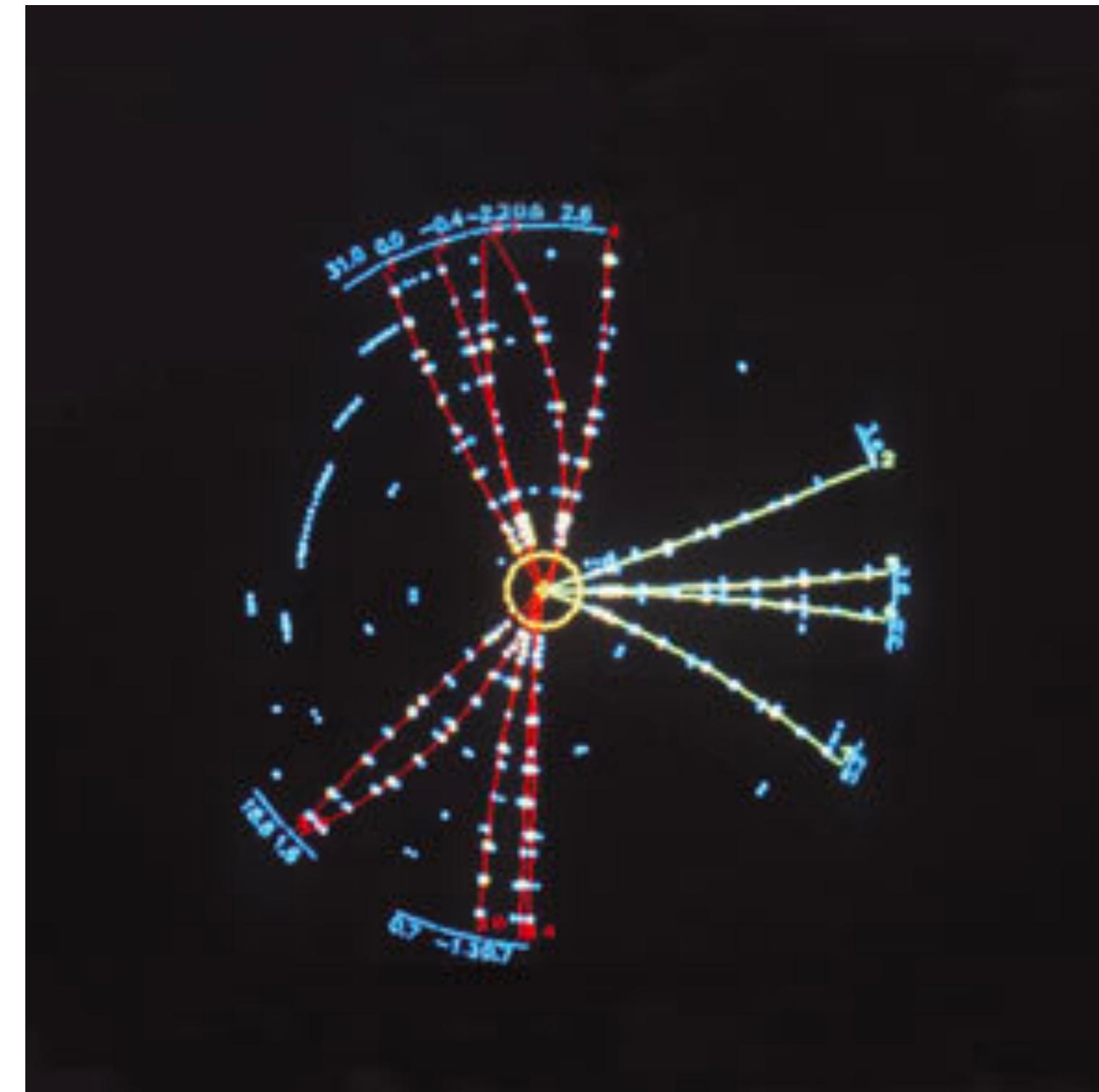
direct sensitive to α_s



Moult, Patrick, Thaler, HXZ, in preparation

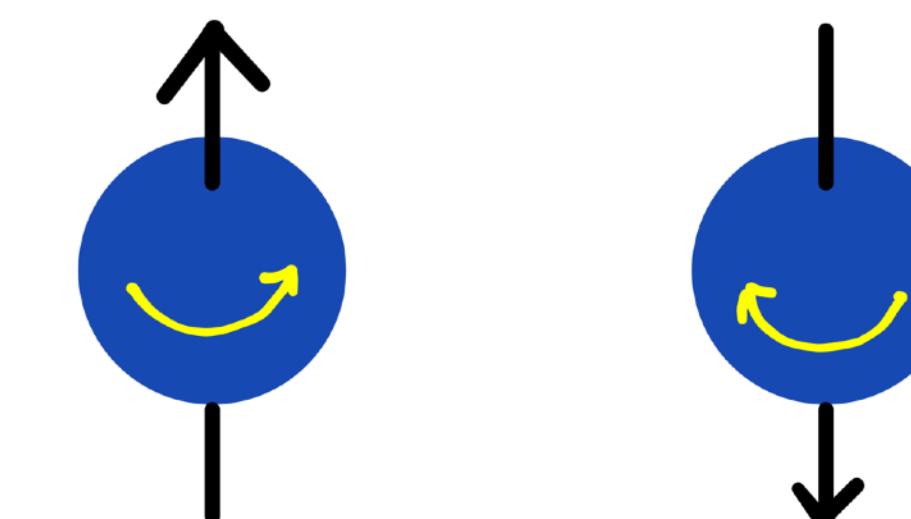
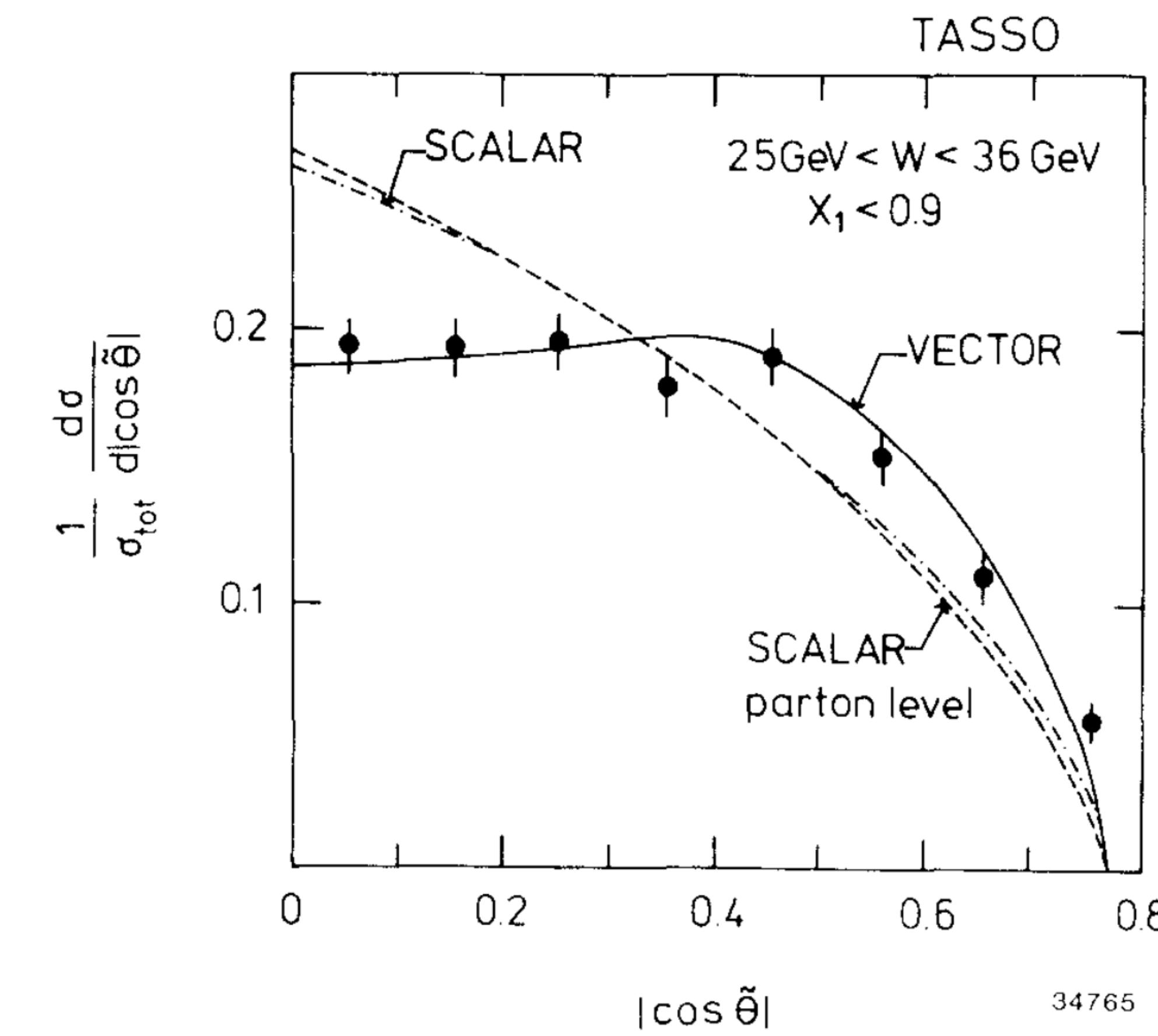
- Can we see gluon spin interference at the CEPC ??

42 years of Gluon discovery



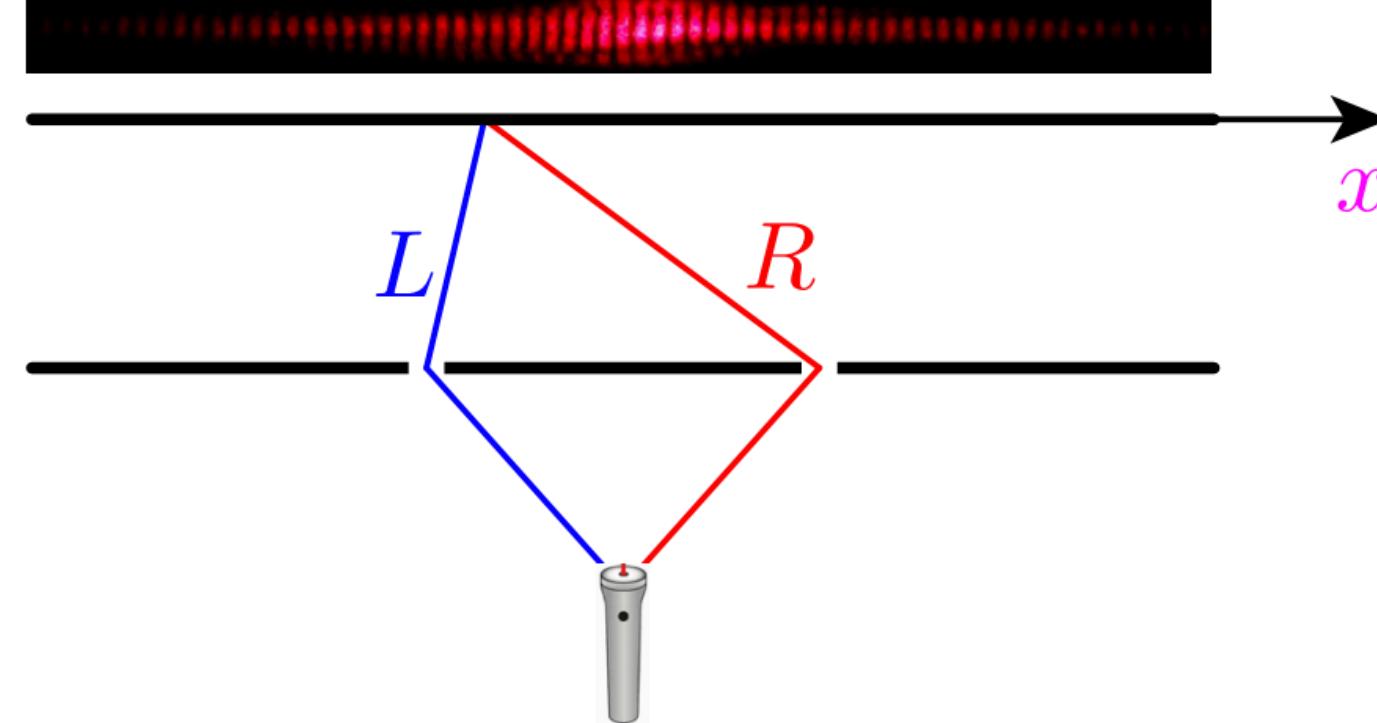
PETRA, 1979, S.L. Wu et al.

Just like a spin 1 photon with 8 color.
But does gluon interference with itself ?

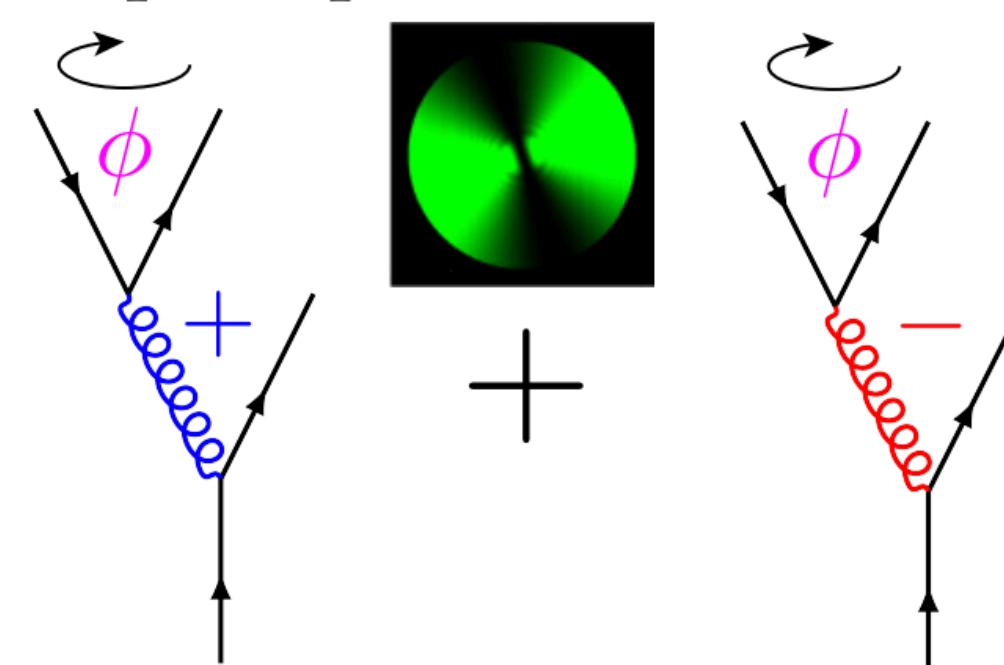


A spin double slit experiment for gluon

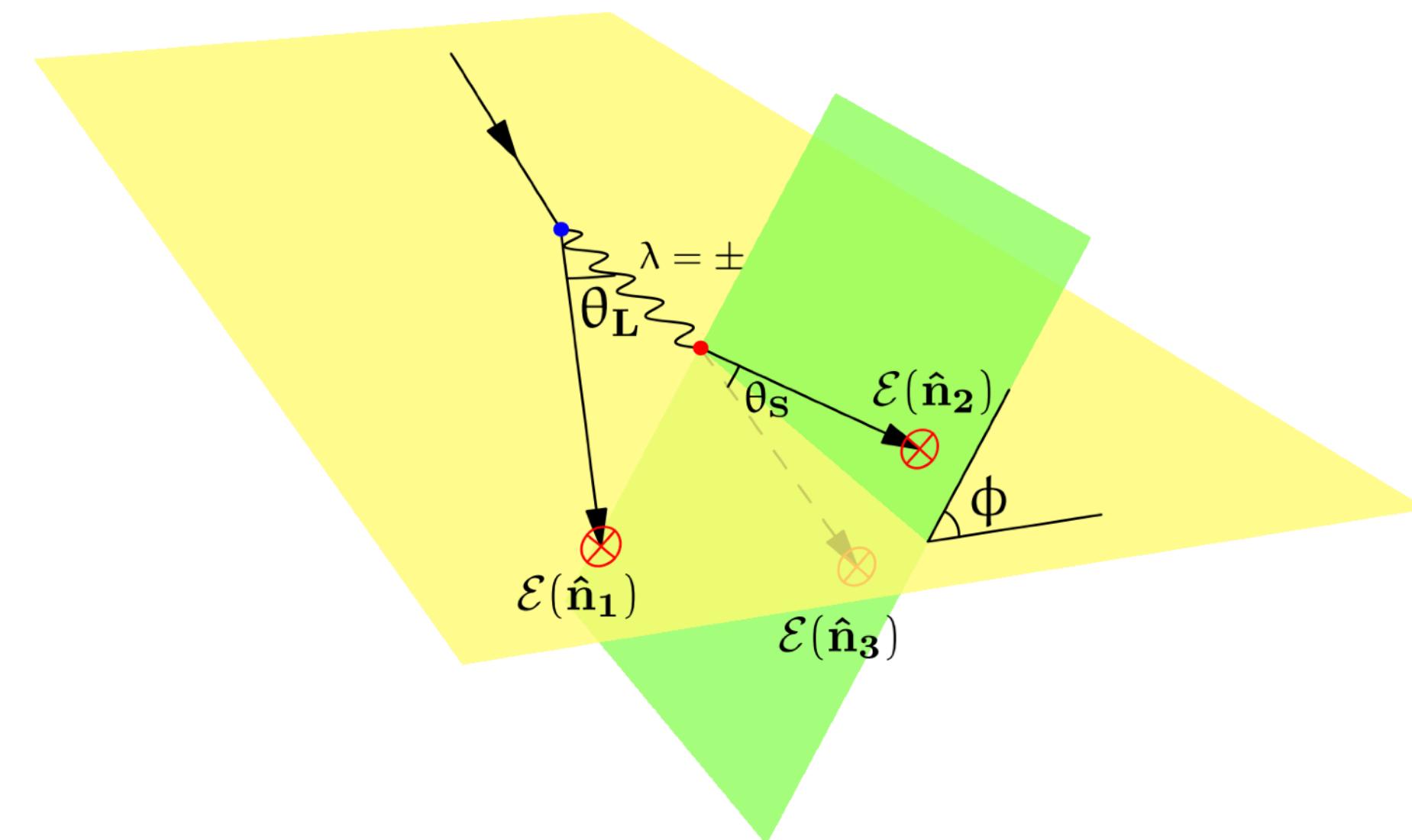
Position Space Double Slit



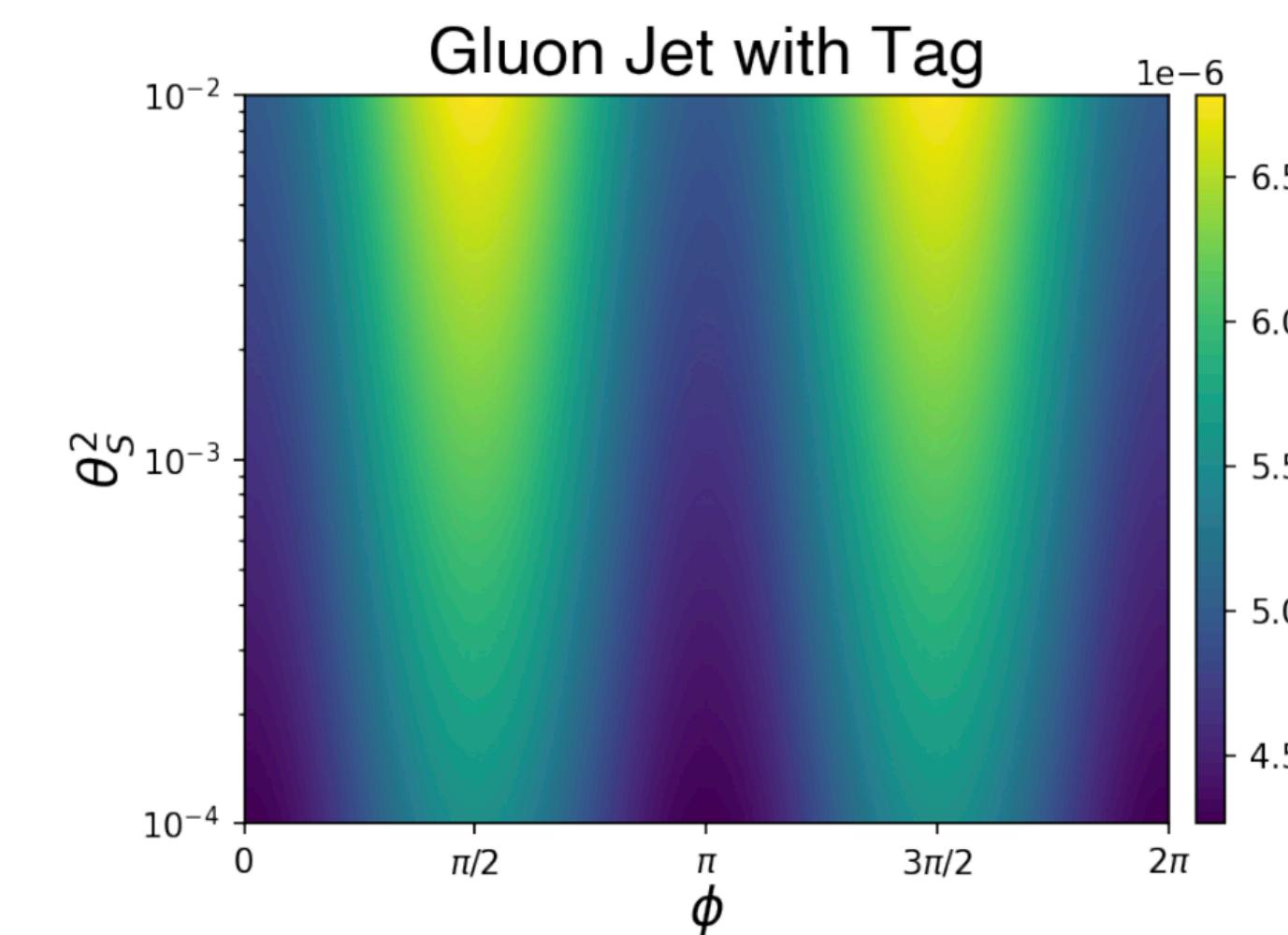
Spin Space Double Slit



EEE_C



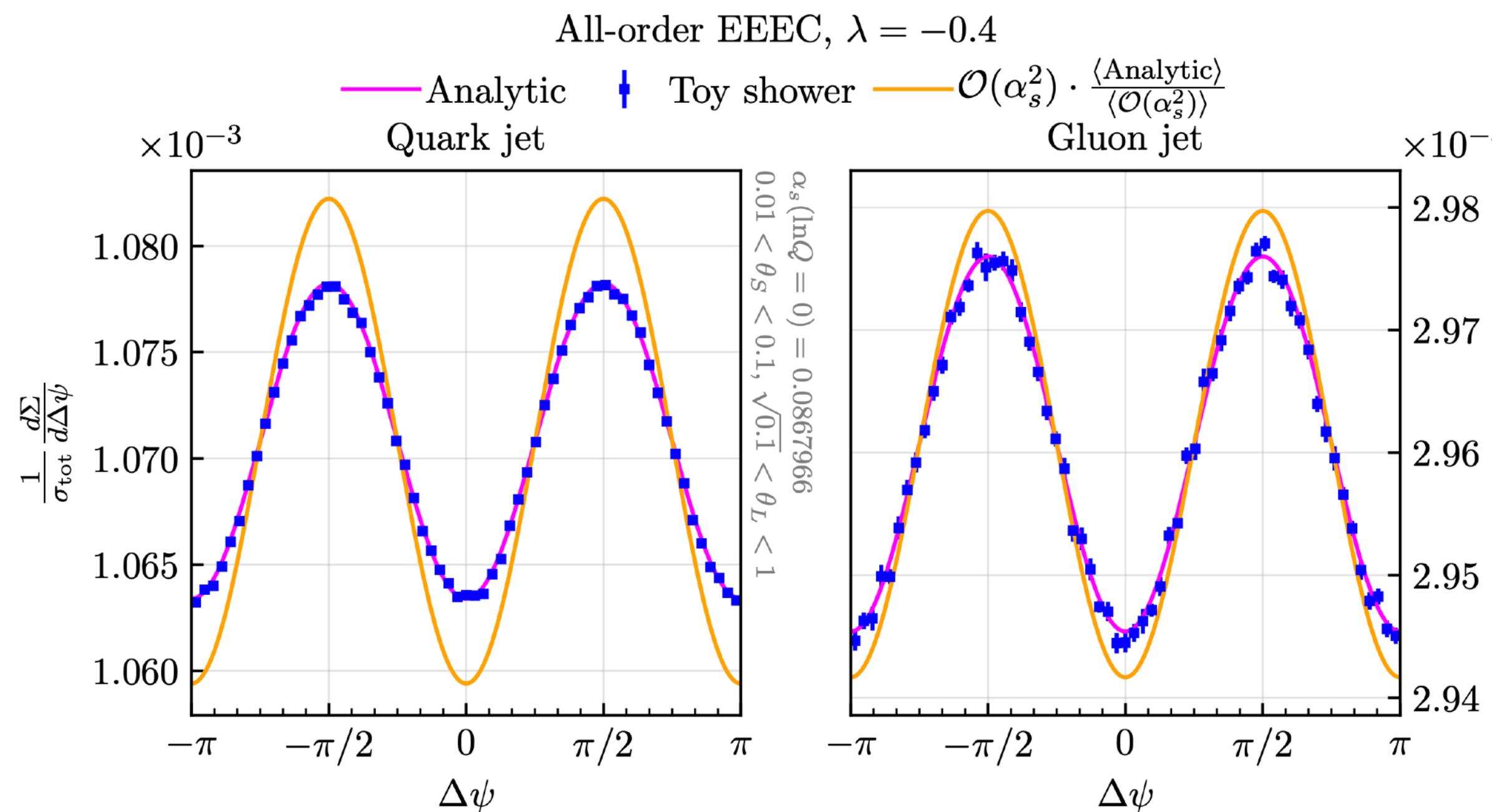
H. Chen, Moult, HXZ, 2011.02492



Requires better understanding of gluon->bb splitting

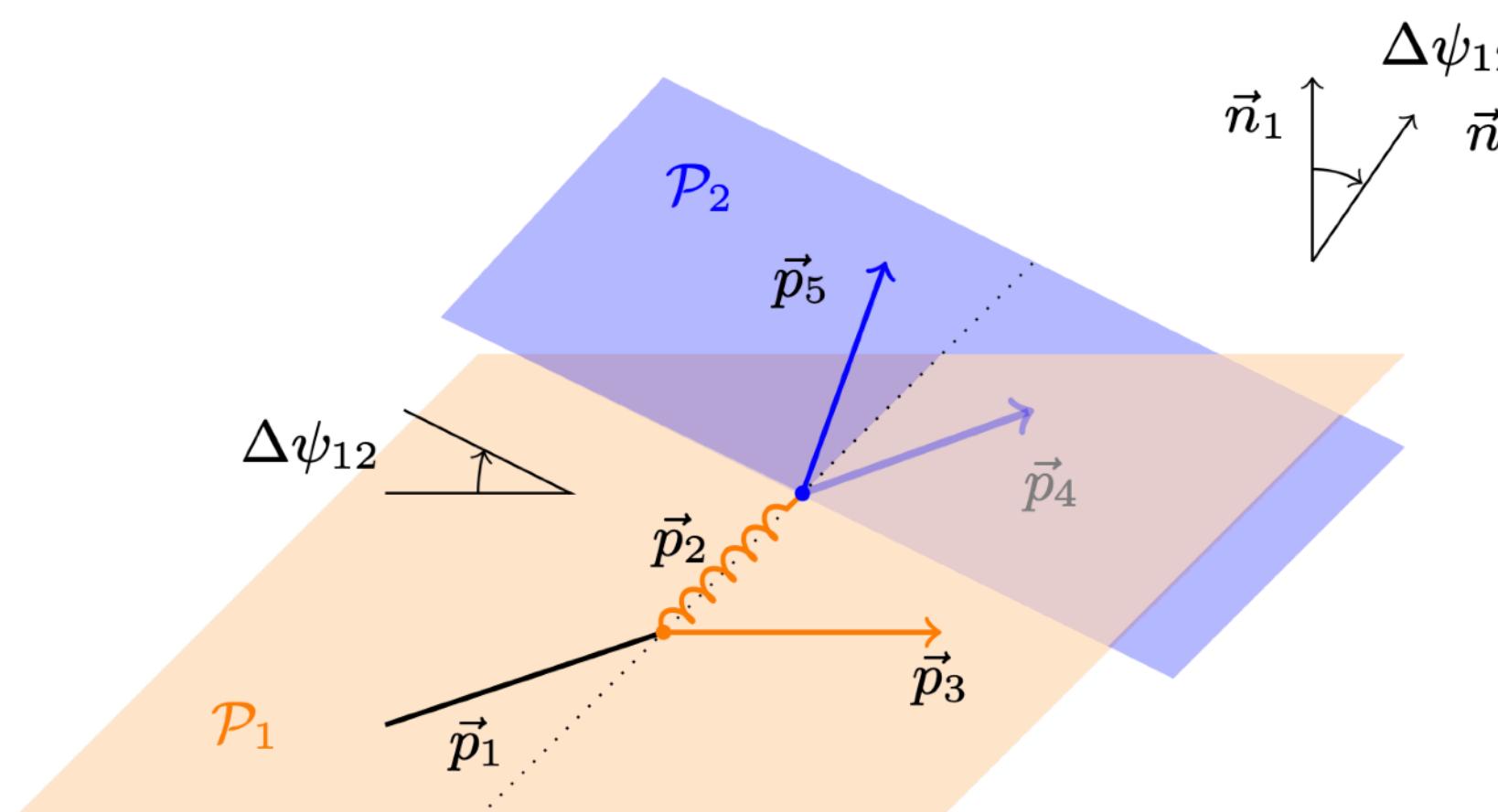
A step towards Bell-type experiment with gluon

Spin interference through parton shower

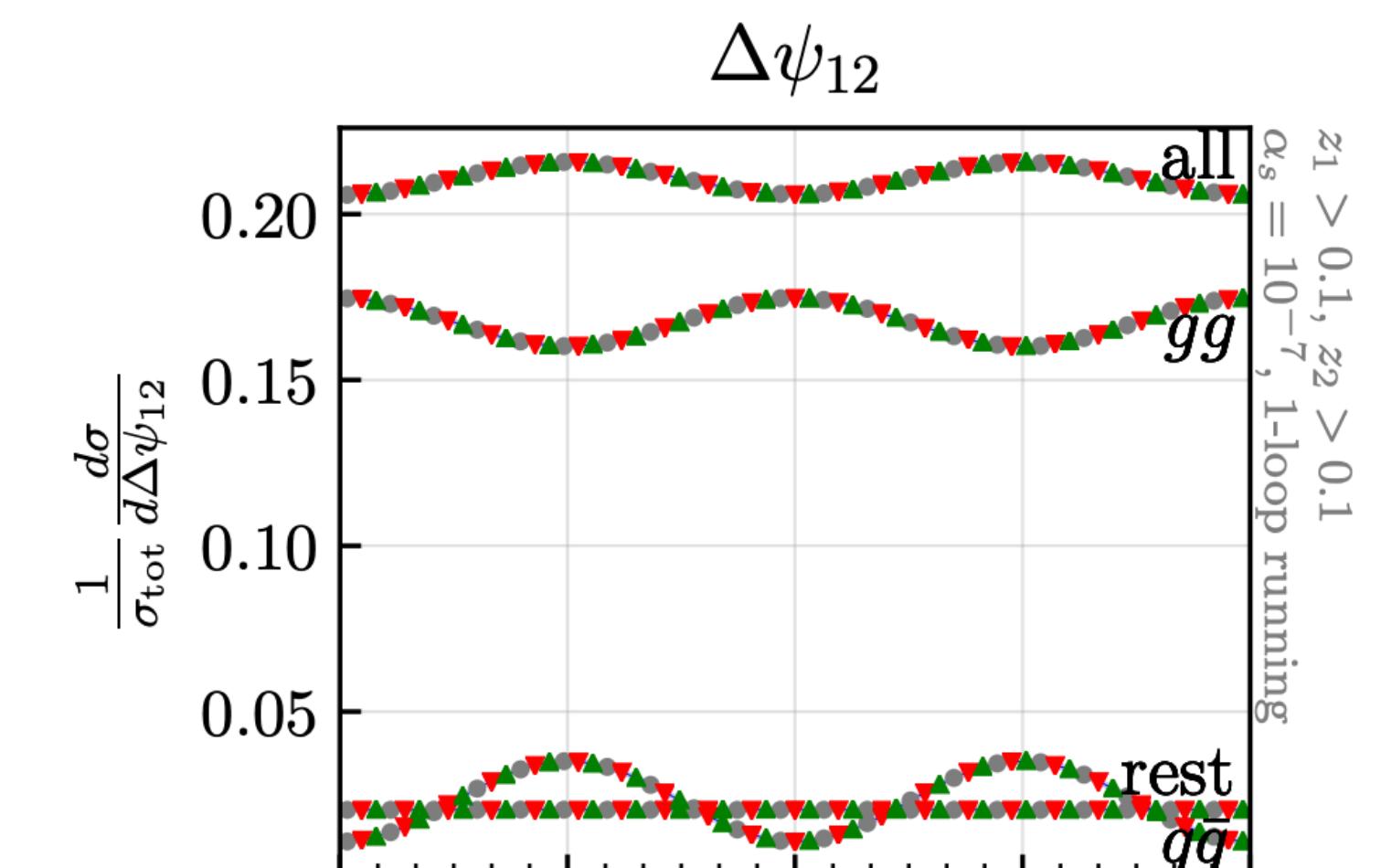


Karlberg, Salam, Scyboz, Verheyen, 2103.16526
 PanScale shower v.s. analytic resummation
 H. Chen, Moult, HXZ, 2011.02492
 Excellent agreement validate the shower implementation of spin correlation
 Also leads to promising new observable

- (Re-)cluster jet with C/A
- Find highest- k_t branching with $z_1 > z_{1,\text{cut}} \rightarrow$ plane 1
- Follow the softest branch
- Find highest- k_t branching with $z_2 > z_{2,\text{cut}} \rightarrow$ plane 2
- Compute $\Delta\psi$ between two planes



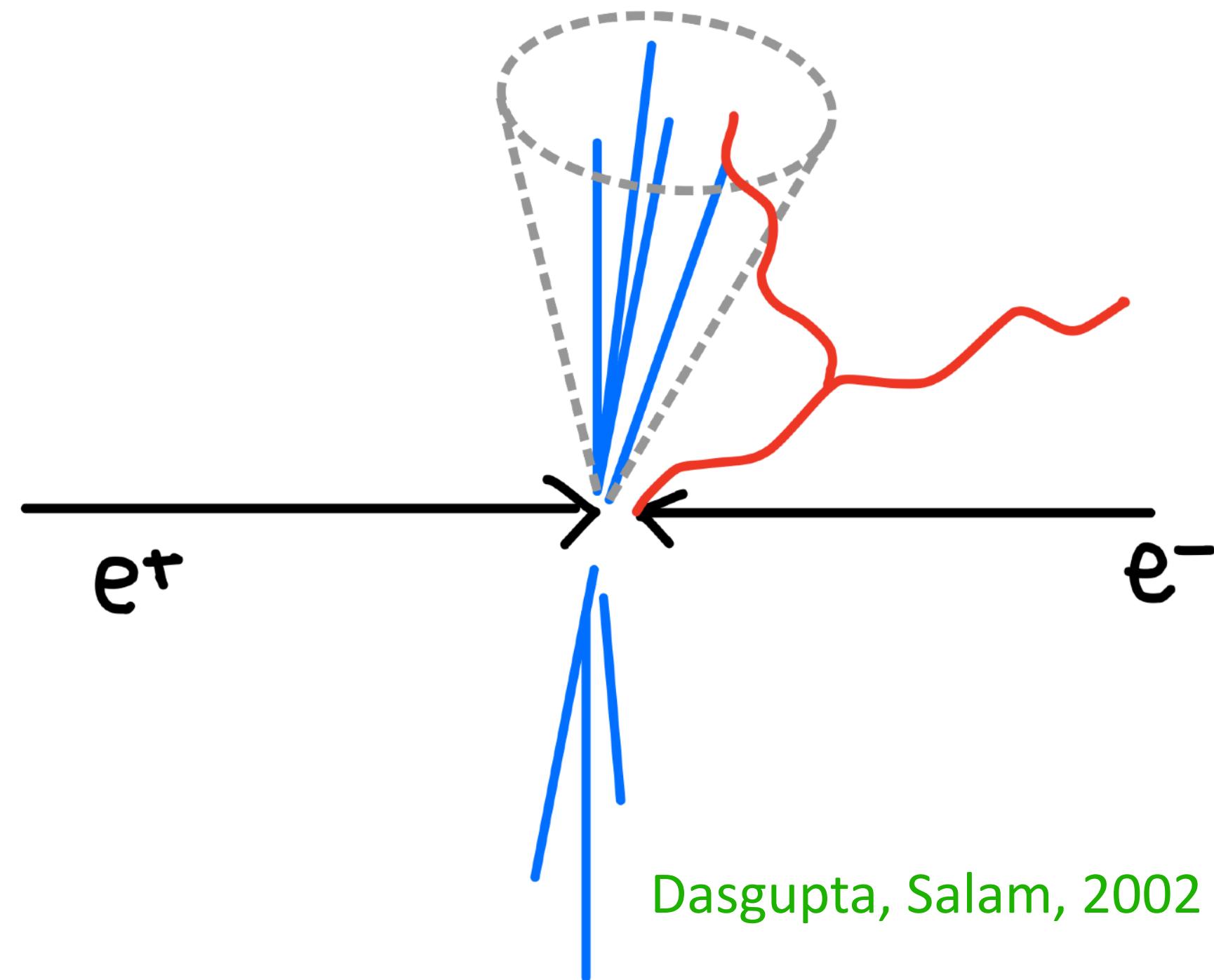
Spin correlation in Lund plane



Karlberg, Salam, Scyboz, Verheyen, 2103.16526

- How to observe entanglement from non-global observables at the CEPC ???

Non-global logarithms



Banfi-Marchesini-Smye equation

$$\partial_L G_{ab}(L) \int \frac{d\Omega_j}{4\pi} \frac{n_a \cdot n_b}{(n_a \cdot n_j)(n_b \cdot n_j)} \left\{ \theta_{\text{cone}}(j) G_{aj}(L) G_{jb}(L) - G_{ab}(L) \right\}$$

Formally analogous to Balitsky-Kovchegov equation,
small-x physics in jet?

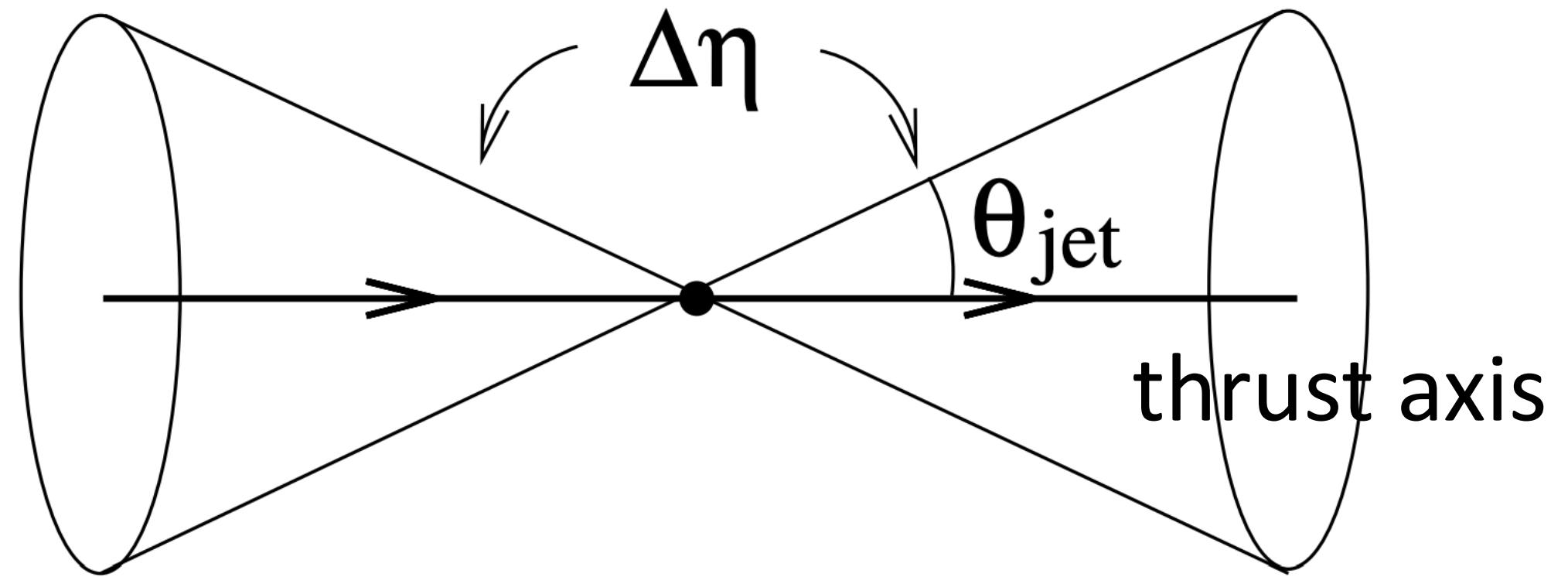
Unlike BK, perturbative boundary condition. Can be
solved iteratively in alphaS:

single log $g_{n\bar{n}}(L) = 1 - \frac{\pi^2}{24} L^2 + \frac{\zeta(3)}{12} L^3 + \frac{\pi^4}{34560} L^4 + \left(-\frac{\pi^2 \zeta(3)}{360} + \frac{17\zeta(5)}{480} \right) L^5 + \dots$

Entanglement between in and out region

- Theoretically very interesting effects. But experimentally has never been confirmed.
- Requires: single logarithmic observables; absent of or well-controlled global logarithms; not contaminated by non-perturbative effects.

Example: Rapidity gap in e+e-



$$\Sigma(v) \simeq 1 + \left(\frac{\alpha_s}{2\pi}\right) \left(\mathcal{H}_2^{(1)} - 4C_F \int [dk] w_{12}^{(0)}(k) \Theta_{in}(k) \Theta(v(k) - v) \Theta(Q - k_t) + \mathcal{H}_3^{(1)} \otimes \mathbb{1} \right)$$

$$- 4C_F \left(\frac{\alpha_s}{2\pi}\right)^2 \int [dk] w_{12}^{(0)}(k) \Theta_{in}(k) \Theta(v(k) - v) \Theta(k_t - Q) \left(K^{(1)} - 4\pi\beta_0 \ln \frac{k_t}{Q} \right)$$

$$+ 8C_F^2 \left(\frac{\alpha_s}{2\pi}\right)^2 \left(\int [dk] w_{12}^{(0)}(k) \Theta_{in}(k) \Theta(v(k) - v) \Theta(Q - k_t) \right)^2$$

$$- 8C_F \left(\frac{\alpha_s}{2\pi}\right)^2 \int [dk_a] \int [dk_b] \left[C_A \left(\bar{w}_{12}^{(gg)}(k_a, k_b) + \bar{w}_{12}^{(gg)}(k_b, k_a) \right) \right.$$

$$\left. + n_f \left(\bar{w}_{12}^{(q\bar{q})}(k_a, k_b) + \bar{w}_{12}^{(q\bar{q})}(k_b, k_a) \right) \right] \quad (6.19)$$

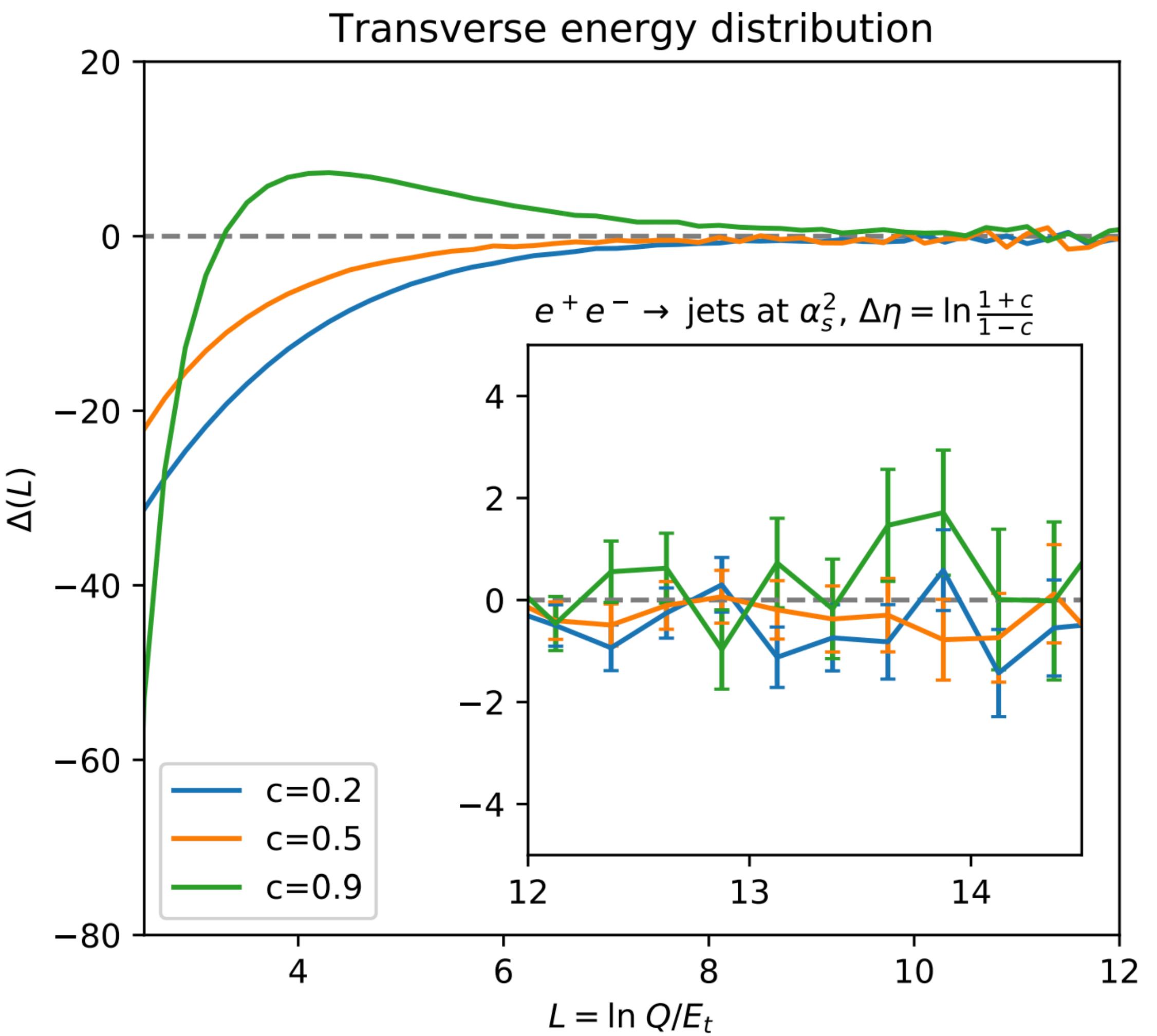
$$\times \Theta(Q - k_{t(ab)}) \Theta(k_{ta} - k_{tb}) \left\{ \Theta_{out}(k_{(ab)}) [\Theta_{in}(k_a) \Theta_{out}(k_b) \Theta(v(k_a) - v) \right.$$

$$\left. + \Theta_{out}(k_a) \Theta_{in}(k_b) \Theta(v(k_b) - v)] - \Theta_{in}(k_{(ab)}) \Theta_{out}(k_a) \Theta_{out}(k_b) \Theta(v(k_{(ab)}) - v) \right\}$$

$$- 2 \left(\frac{\alpha_s}{2\pi}\right)^2 \int [dk] \Theta_{in}(k) \Theta(v(k) - v) \Theta(Q - k_t)$$

$$\times \left[2C_F \mathcal{H}_2^{(1)} w_{12}^{(0)}(k) + \mathcal{H}_3^{(1)} \otimes \left(C_A (w_{13}^{(0)}(k) + w_{32}^{(0)}(k)) + (2C_F - C_A) w_{12}(k) \right) \right].$$

Banfi, Dreyer, Monni, 2104.06416
 See also: Caron-Huot, 1501.03754
 Becher, Neubert, Rothen, D.Y. Shao, 1508.06645
 Larkoski, Moult, Neill, 1501.04596



- Can we quantitatively understand hadronization ???

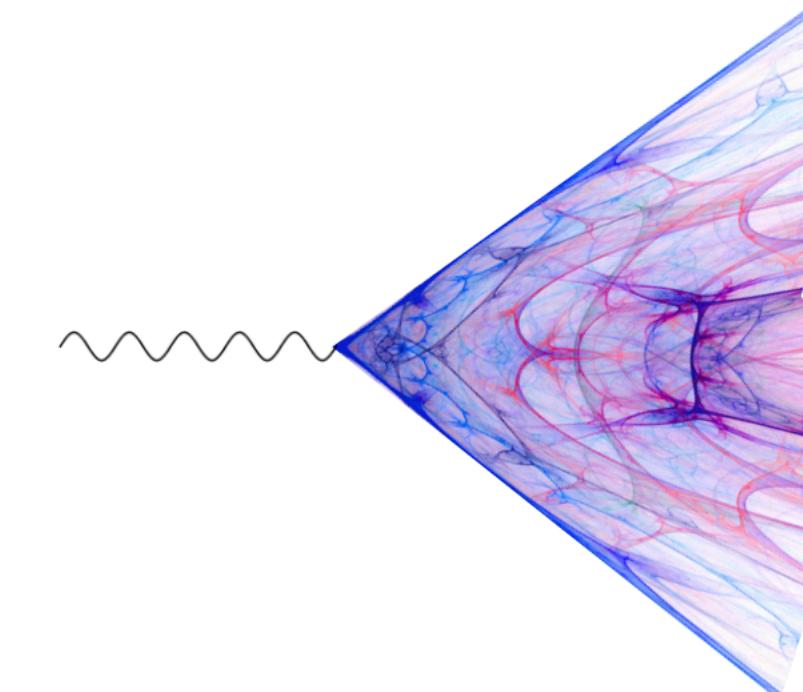
What is hadronization ?

谢去病

山东大学

Hadronization

- 高能碰撞必先产生各种夸克。
- 夸克如何强子化成各种各样的强子？
- 强子化过程不仅出现于任何高能反应，而且是与夸克禁闭、QCD真空结构等一系列重大理论问题直接相关的非微扰QCD过程。——其研究是当代物理中一个基本又艰巨课题



Confinement in QCD remains a fundamental and unsolved problem.

Affects all final states with jets: fragmentation uncertainties, colour reconnections, ...

+ interesting (stringy) physics in its own right

What does that mean for experiments?

Relative momentum kicks of order $\Lambda_{\text{QCD}} \sim 100 \text{ MeV}$ must be well resolved

Must be able to tell which hadrons are which (strangeness, baryon number, spin) ➤ PID

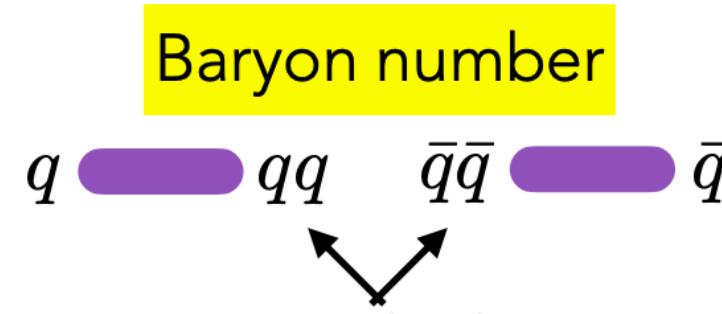
+ good coverage to tell how global/local conservation laws are acting

credit: Peter Skands

Real time quantum evolution, can not be simulated on Euclidean lattice. Only a real collider can provides clues to the BIG QUESTION!

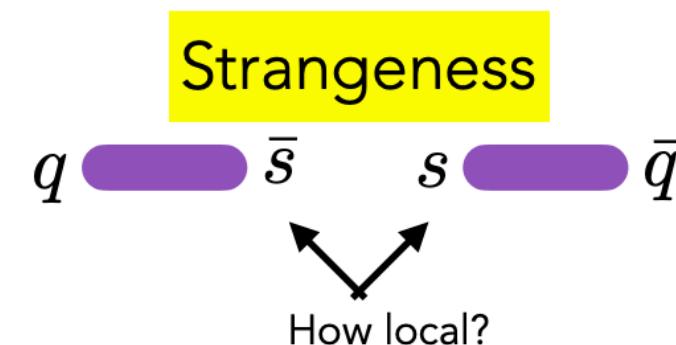
Conservation law and generalized fragmentation

QCD **conserves** baryon number, strangeness, and momentum



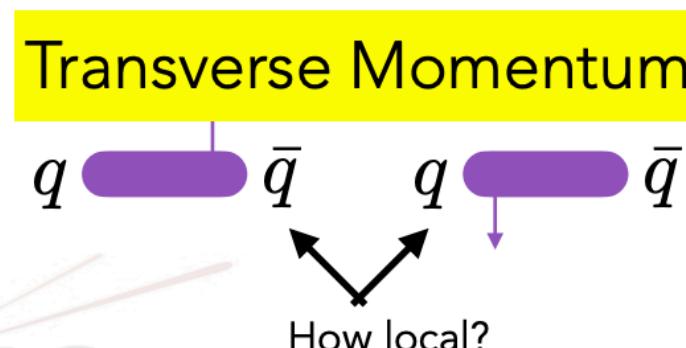
→ Particle Correlations

E.g., **how far** from a baryon (or a strange particle) do you have to go before you find an anti-baryon (anti-strange)?



Must be able to tell **which hadrons are which** (strangeness, baryon number, spin) ➤ **PID**

credit: Peter Skands



Relative **momentum kicks** of order Λ_{QCD} ~ **100 MeV** must be well resolved

Track function evolution beyond LO: mesh very well with energy correlators!

Y.B. Li, Moult, van Velzen, Waalewijn, HXZ, 2108.01674

$$\frac{d}{d \ln \mu^2} T_g(2) = -\gamma_{gg}^{(1)}(3) T_g(2) + \sum_q \left(-2\gamma_{qg}^{(1)}(3) \right) T_q(2) + \left[C_A^2 \left(-8\zeta_3 + \frac{2158}{675} + \frac{26\pi^2}{45} \right) - \frac{4}{9} C_A n_f T_F \right] T_g(1) T_g(1) + \dots ,$$

$$\begin{aligned} \frac{d}{d \ln \mu^2} T_g(3) &= -\gamma_{gg}^{(1)}(4) T_g(3) + \sum_q \left(-2\gamma_{qg}^{(1)}(4) \right) T_q(3) + \left[C_A^2 \left(24\zeta_3 + \frac{767263}{4500} - \frac{278\pi^2}{15} \right) - \frac{2}{3} C_A n_f T_F \right] T_g(2) T_g(1) \\ &\quad + \sum_q \left[C_A T_F \left(\frac{23051}{1125} - \frac{28}{15}\pi^2 \right) - C_F T_F \frac{28}{15} \right] T_g(1) T_q(1) T_q(1) + \dots . \end{aligned}$$

How to incorporate correlation effects in fragmentation model?

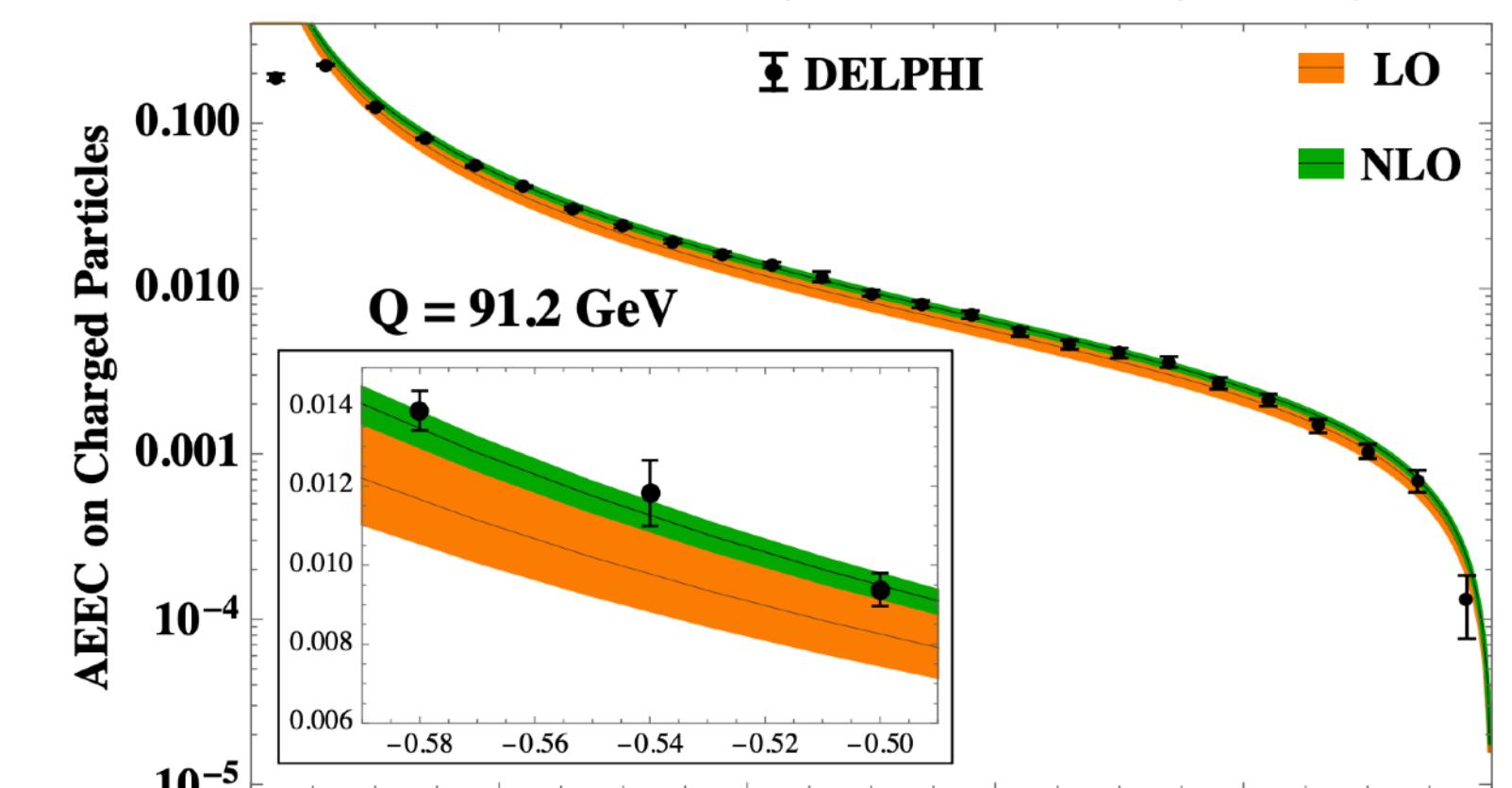
Track function evolution

Chang, Procura, Thaler, Waalewijn, 1303.6637

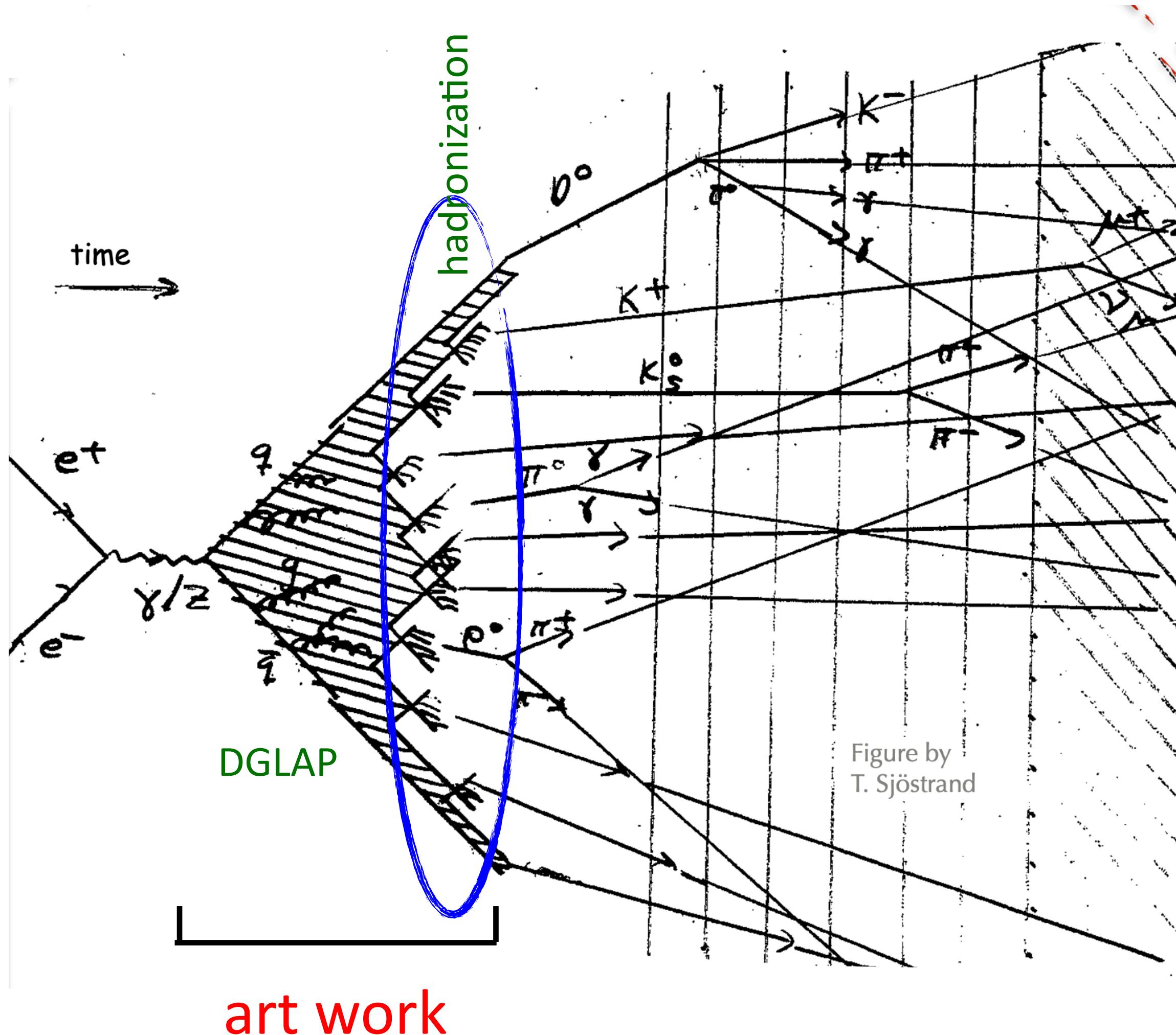
LO evolution: already highly nonlinear

$$\begin{aligned} \frac{d}{d \ln \mu^2} T_i(x, \mu) &= a_s(\mu) \sum_{j,k} \int dz dx_1 dx_2 P_{i \rightarrow jk}^{(0)}(z_1, z_2) \delta(1 - z_1 - z_2) \\ &\quad \times T_j(x_1, \mu) T_k(x_2, \mu) \delta[x - z_1 x_1 - z_2 x_2] . \end{aligned}$$

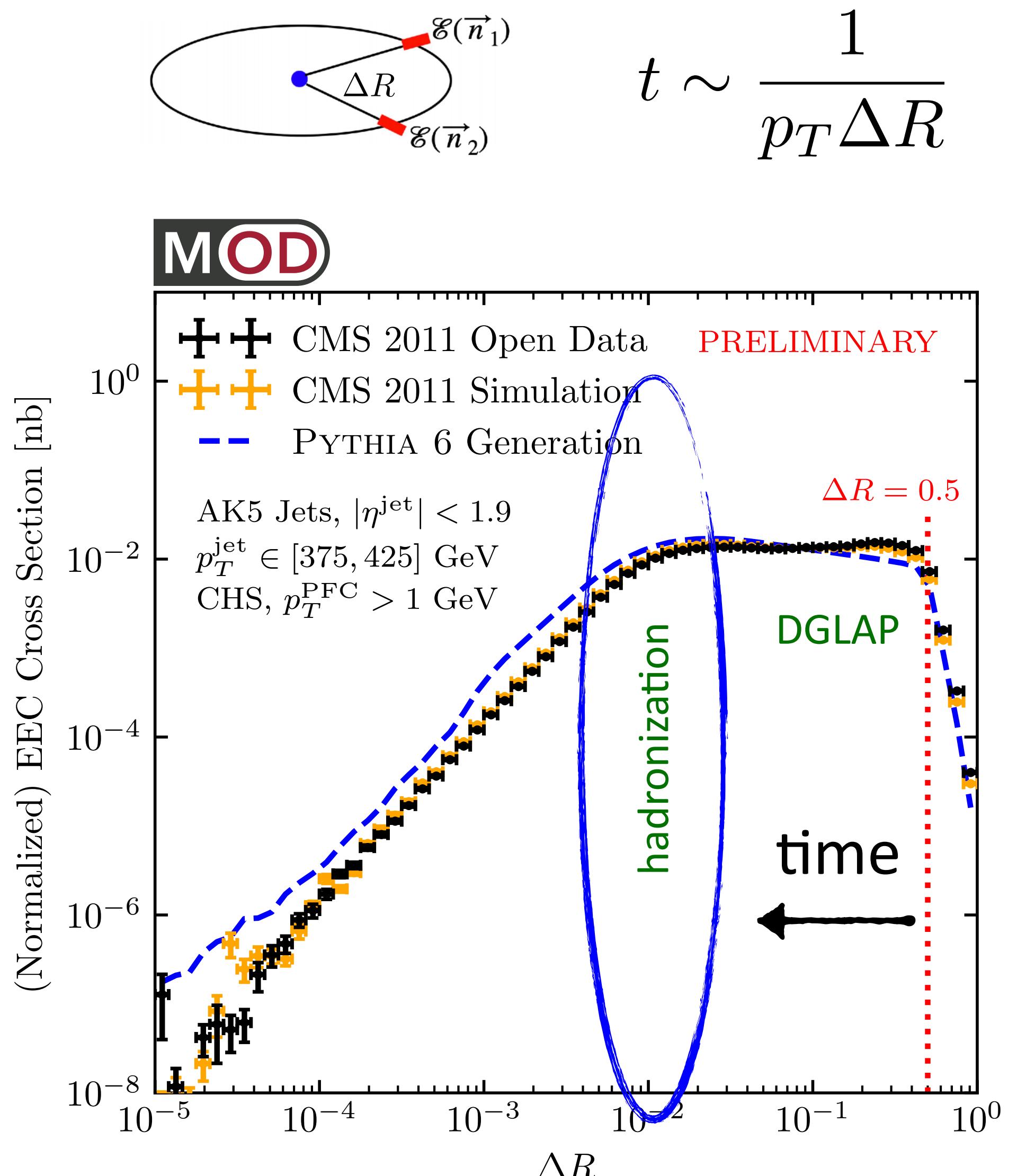
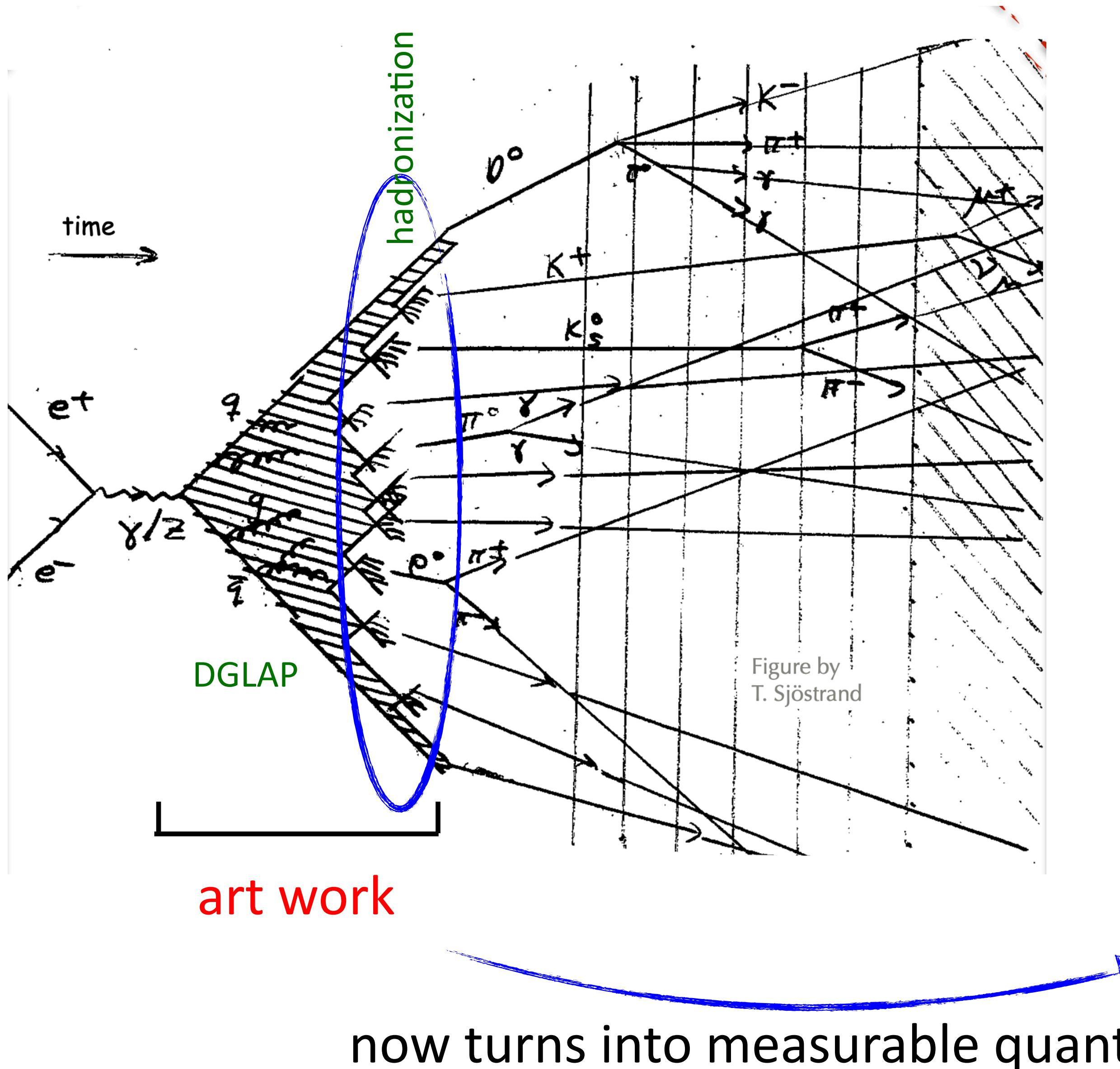
- AEEC($\cos \chi$) = EEC($\cos \chi$) - EEC($-\cos \chi$), $\cos \chi \leq 0$



Decoding the time evolution of jets



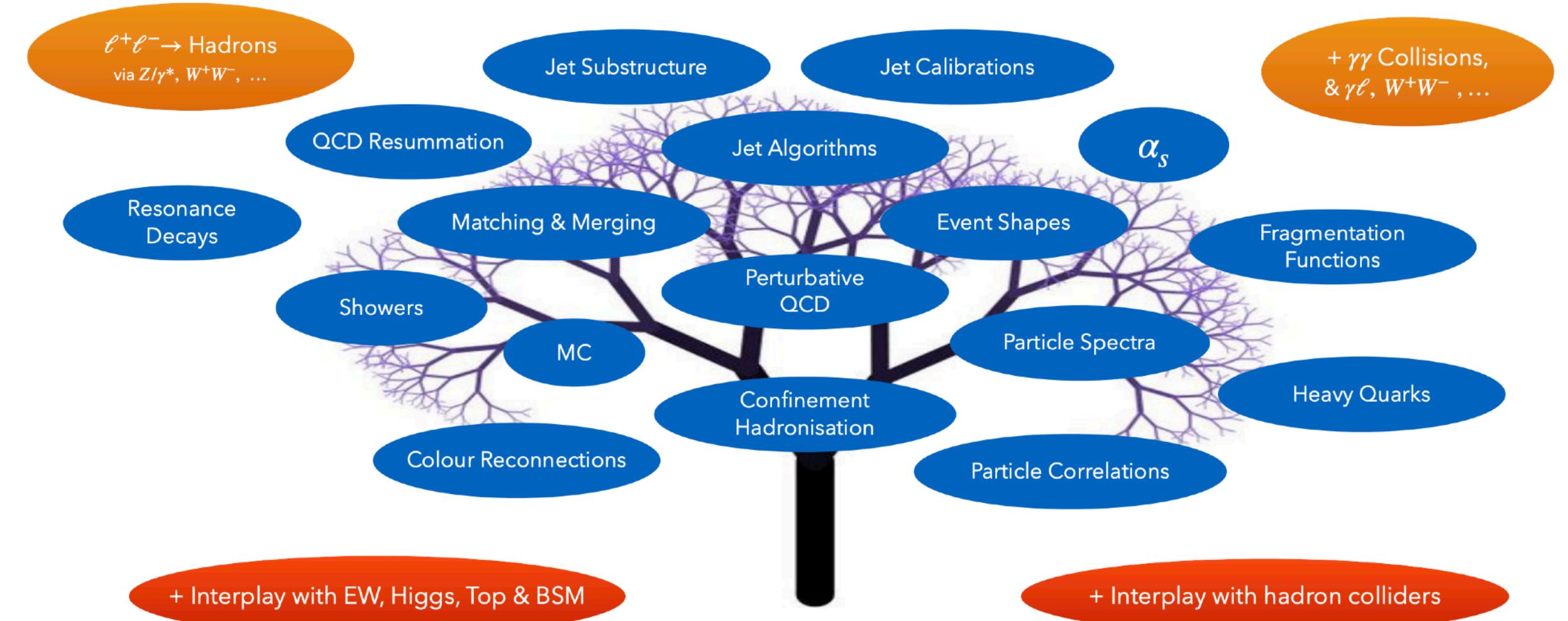
Decoding the time evolution of jets



Moult, Patrick, Thaler, HXZ, in preparation

Summary

- QCD at e+e- colliders remain exciting
- New potential for ultimate precision
- Novel QCD phenomena awaiting discovery
- Deep theory puzzle calls for new data



credit: Peter Skands