QCD Prospect for CEPC

Hua Xing Zhu
Zhejiang University

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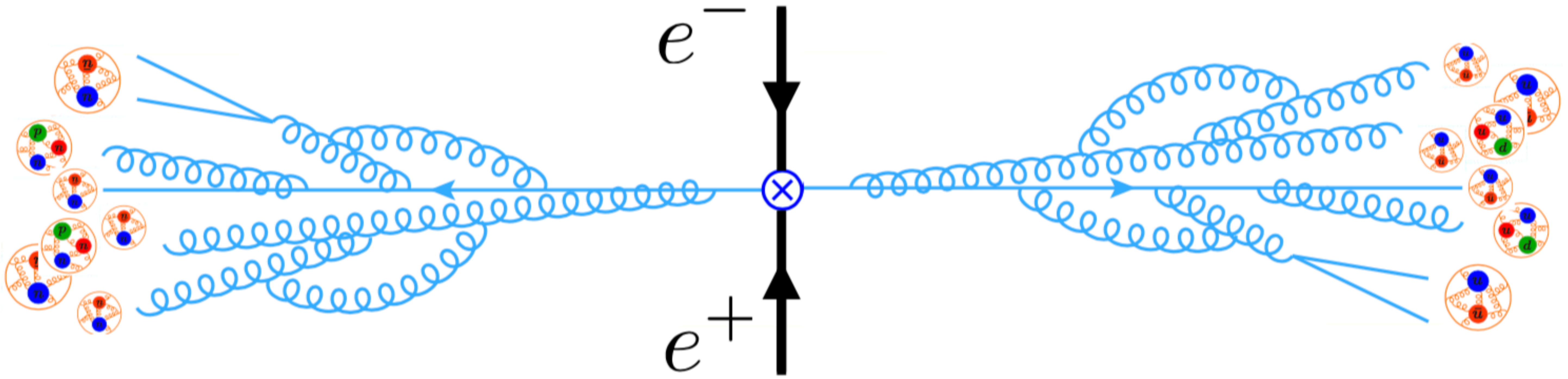
$$\mathcal{L}_{\rm QCD} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu} \quad + \text{ theta term}$$

Deceptively simple Lagrangian, with astonishingly rich phenomena.



In high energy e+e- collider we have access to QCD through qqbar production and subsequent bremsstrahlung.

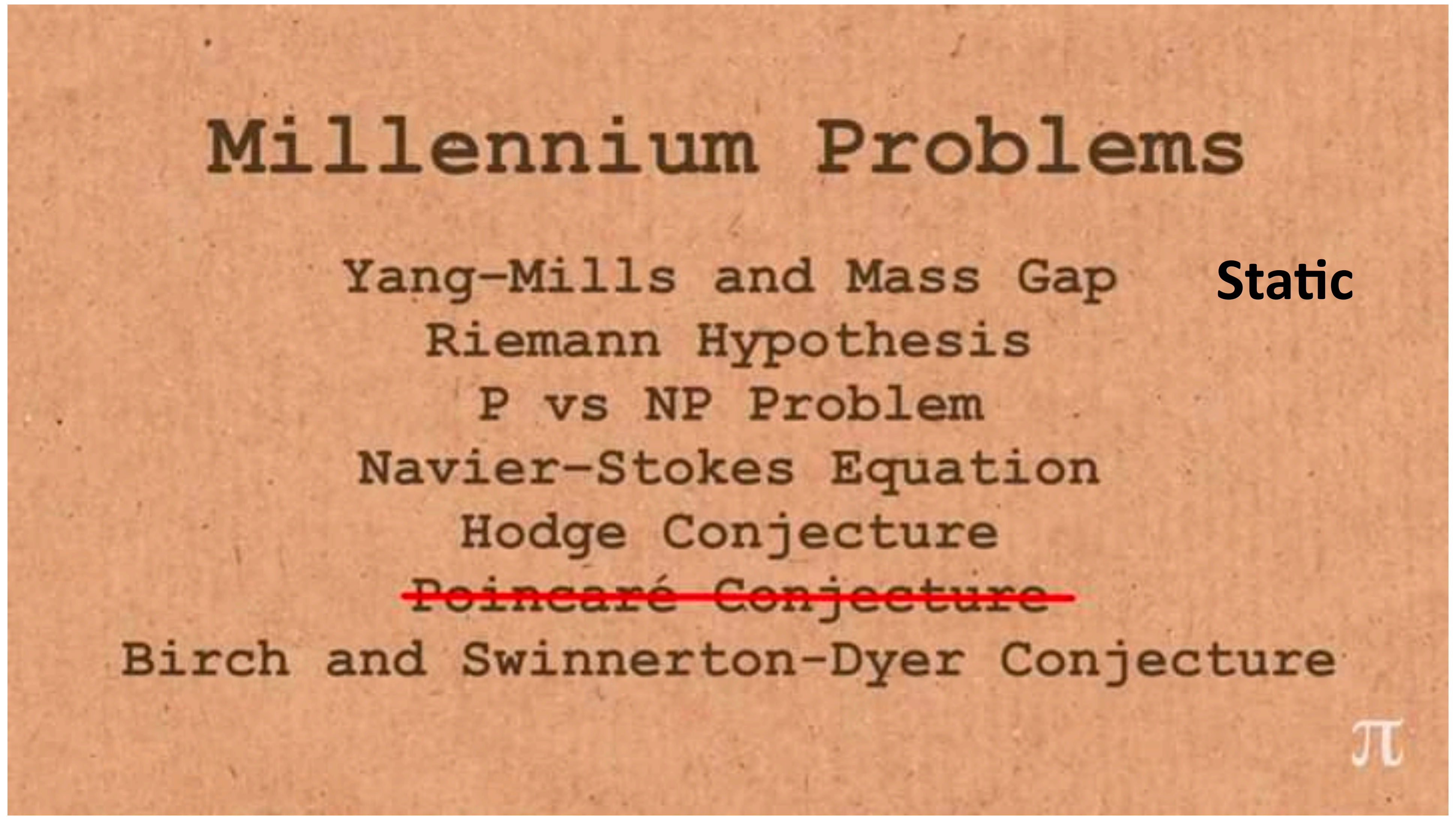
There is no need to TEST QCD as the correct theory of strong interaction.

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

We are far from fully understand QCD

It was often said that QCD is important because precision predictions from QCD is crucial for controlling the background estimate for BSM searches. True but probably not the foremost reason for studying QCD at high energy collider.

QCD (a strongly interacting quantum field theory) itself can justify the constructions of large colliders for its study.



Real time dynamics

谢去病

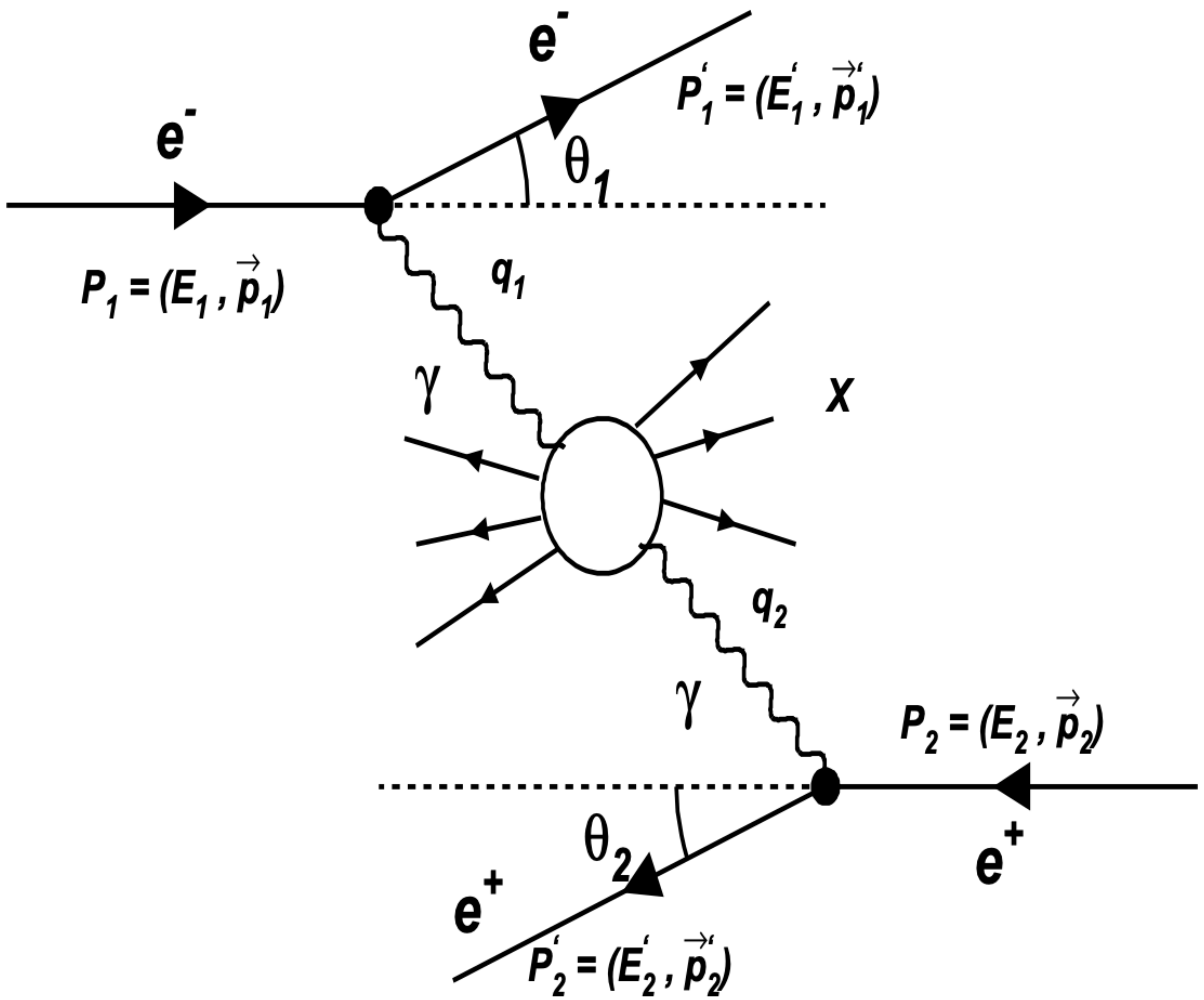
山东大学

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

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

CEPC is not just an e+e- collider

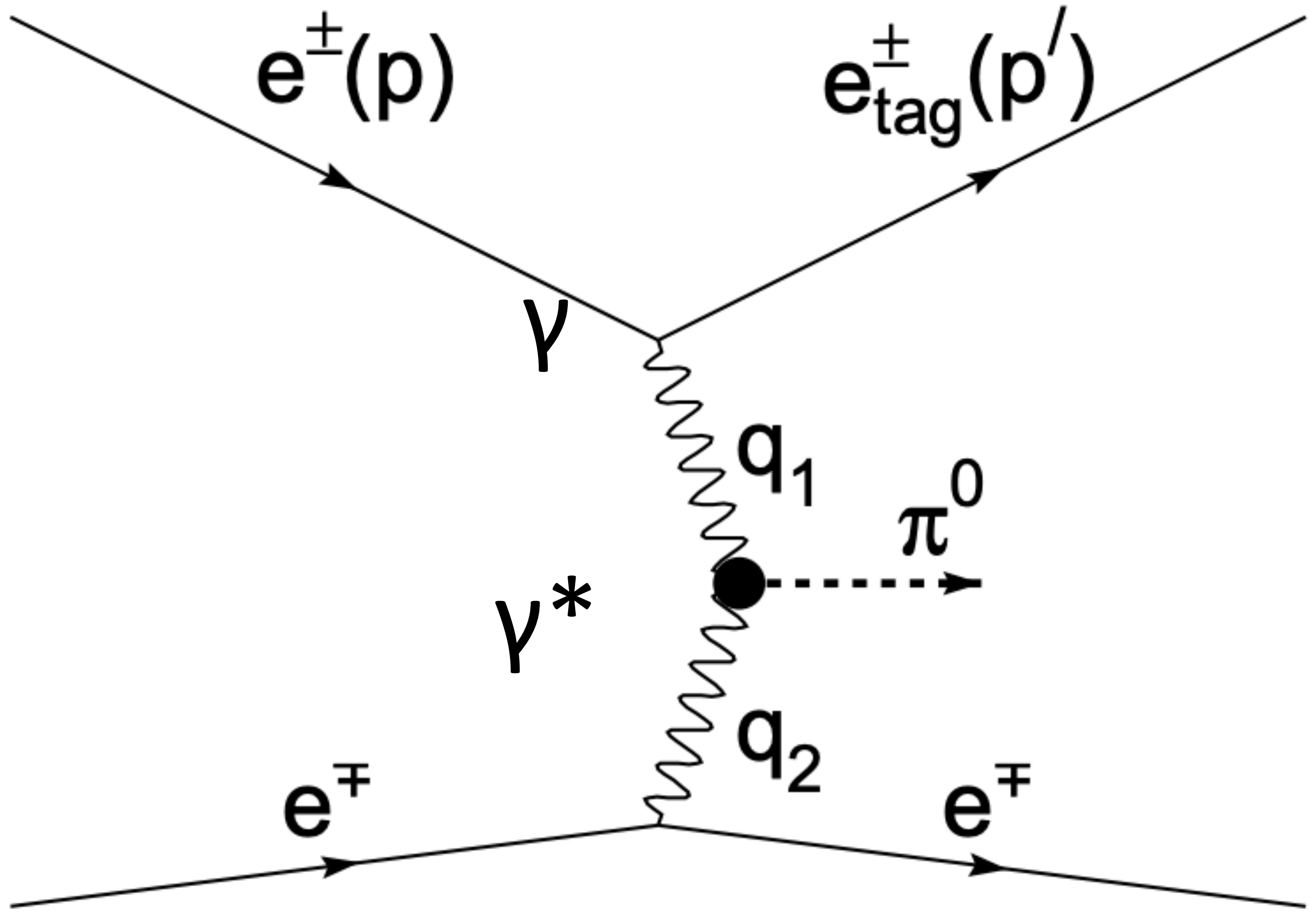


Wadhwa, hep-ex/9909001

- Resonance production
- Two photon total cross section
- Single particle and jet production
- Heavy quark production
- Lepton structure function (how bright is the electron)
- $\gamma^*\gamma^*$ collisions (clean test of BFKL)

Precision light-cone distribution

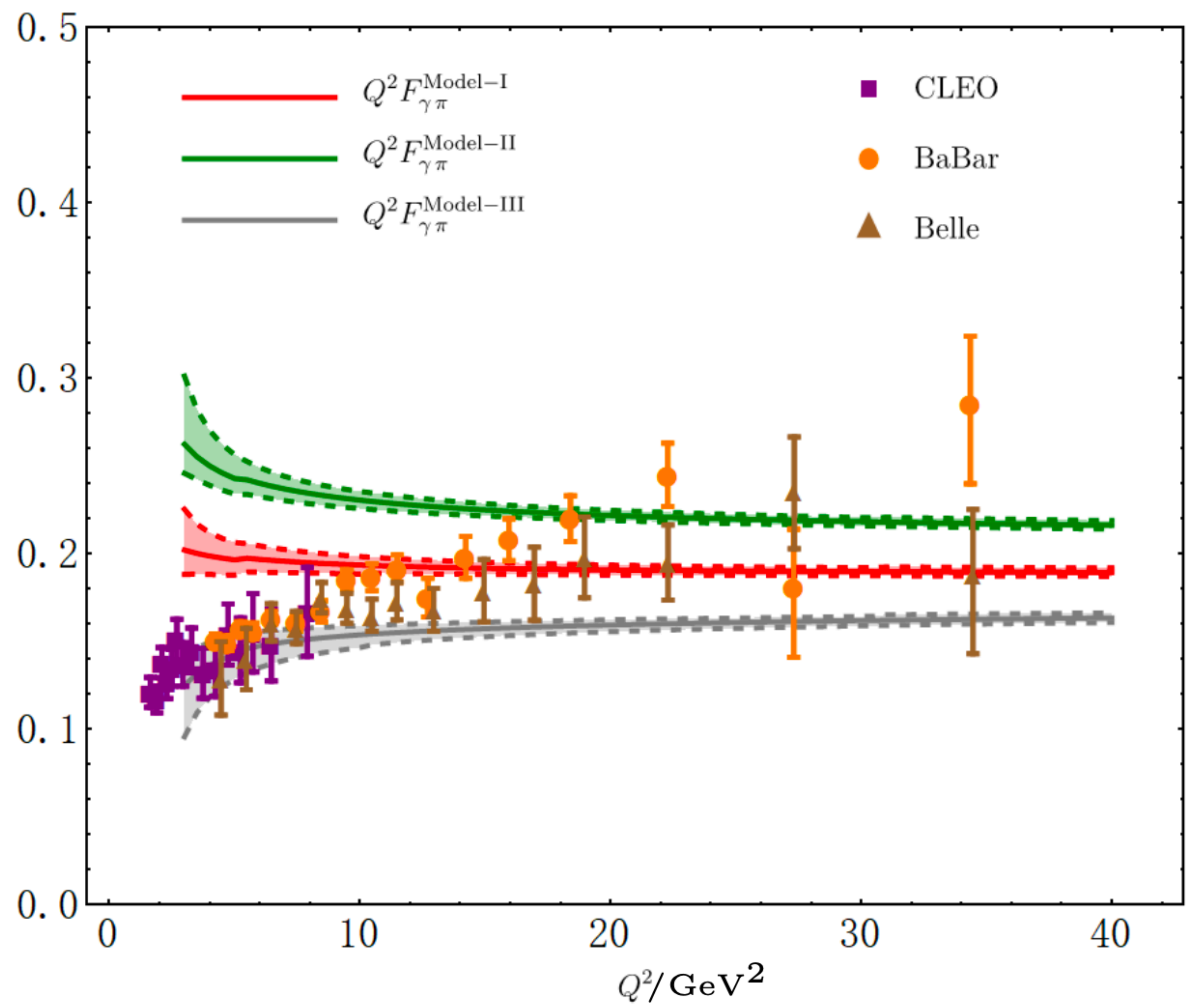
Ji Yao, Yu-ming Wang



$$\langle \pi^0(p) | j_\mu^{\rm em} | \gamma(p') \rangle = g_{\rm em}^2 \epsilon_{\mu\nu\alpha\beta} q^\alpha p^\beta \epsilon^\nu(p') F_{\gamma\pi}(Q^2)$$

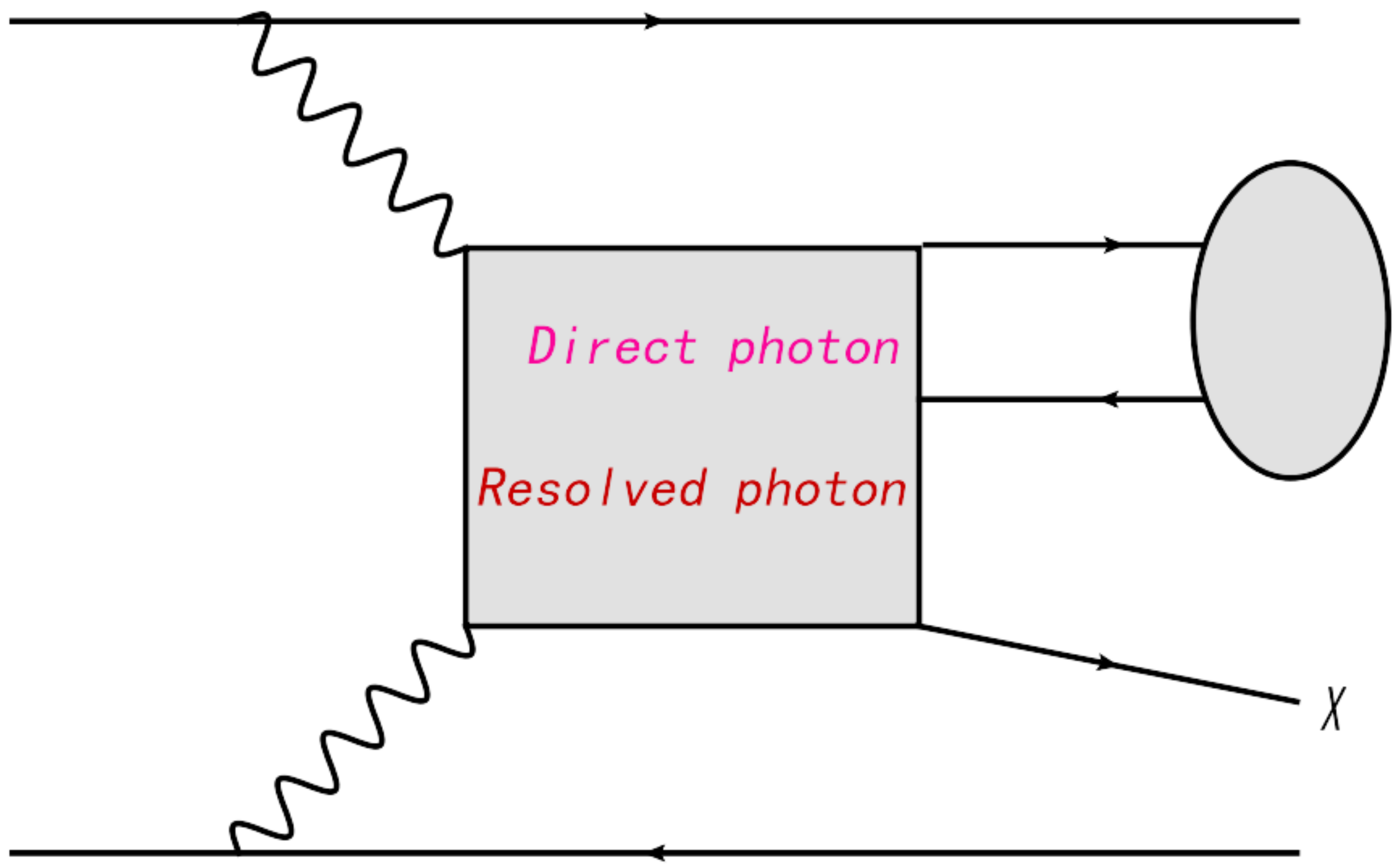
$$F_{\gamma\pi}^{\rm LP}(Q^2) = \frac{(e_u^2 - e_d^2) f_\pi}{\sqrt{2}\, Q^2} \int_0^1 dx\, T_2(x, Q^2, \mu_F)\, \phi_\pi(x, \mu_F)$$

$$F_{\gamma\pi}^{\rm asy}(Q^2,\mu_0) = \frac{(e_u^2 - e_d^2) f_\pi}{\sqrt{2} Q^2} \Big\{ 6 - 30 a_s C_F - a_s^2 C_F \Big[\beta_0 \left((31 + 12 L_0)\zeta_2 + 6\zeta_3 + 7 \right) + C_F \left(24(\zeta_2+\zeta_3) L_0 + 42\zeta_4 + 54\zeta_3 + 37\zeta_2 - \frac{85}{2} \right) - \frac{1}{N_c} (6\zeta_4 - 12\zeta_3 - 2\zeta_2 + 13) \Big] \Big\}$$

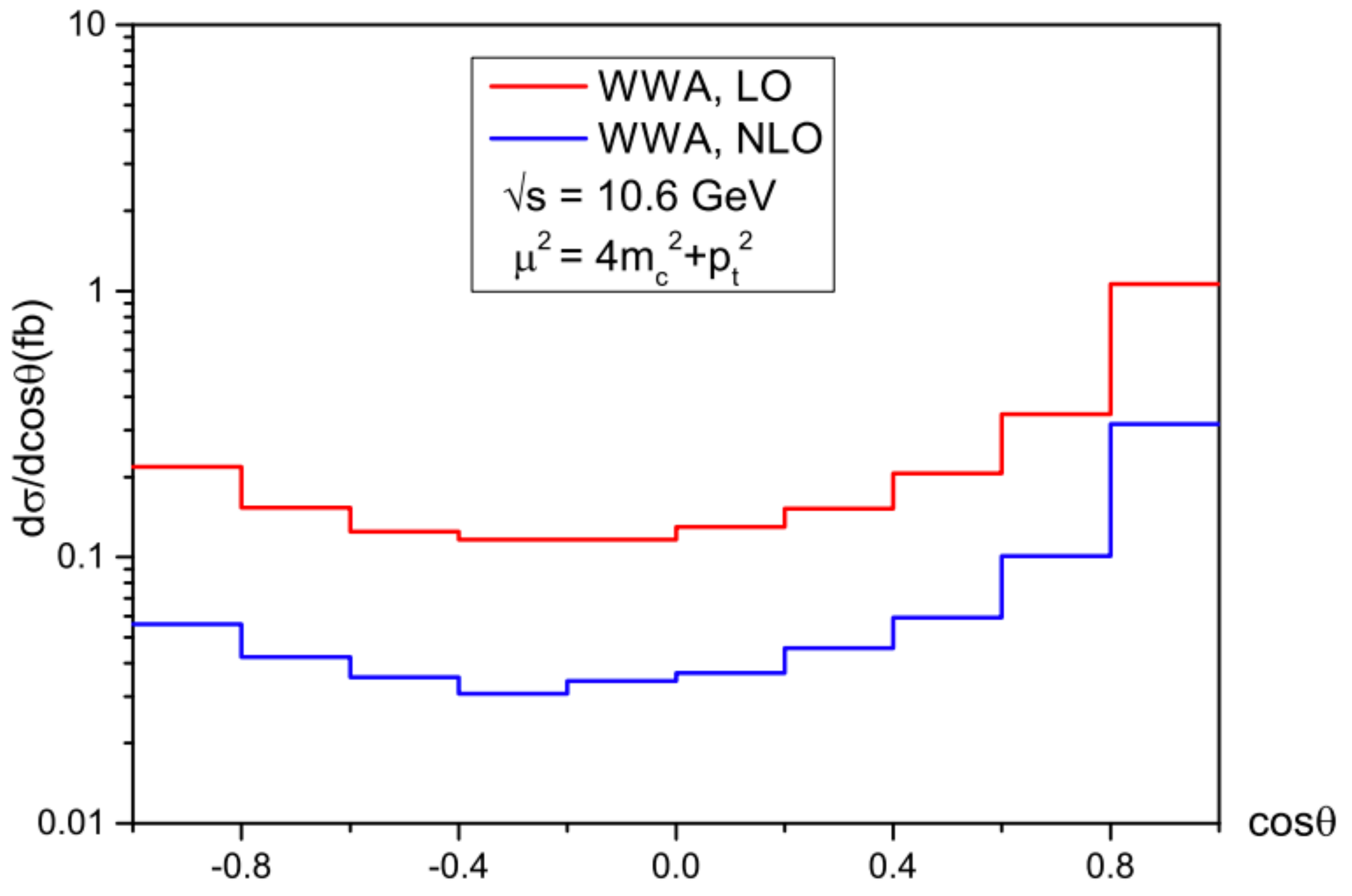


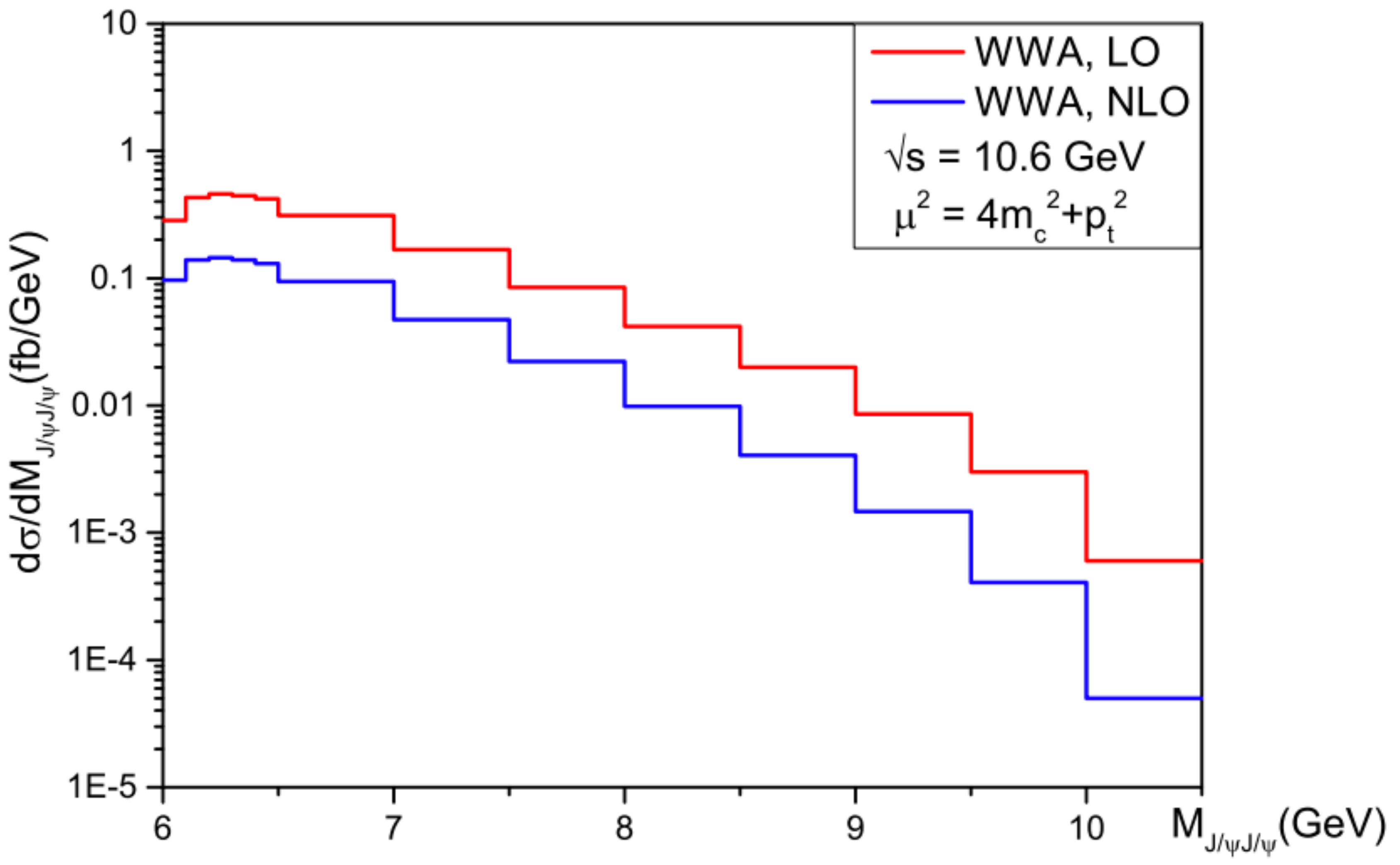
J/psi production

Cong-feng Qiao, Hao Yang

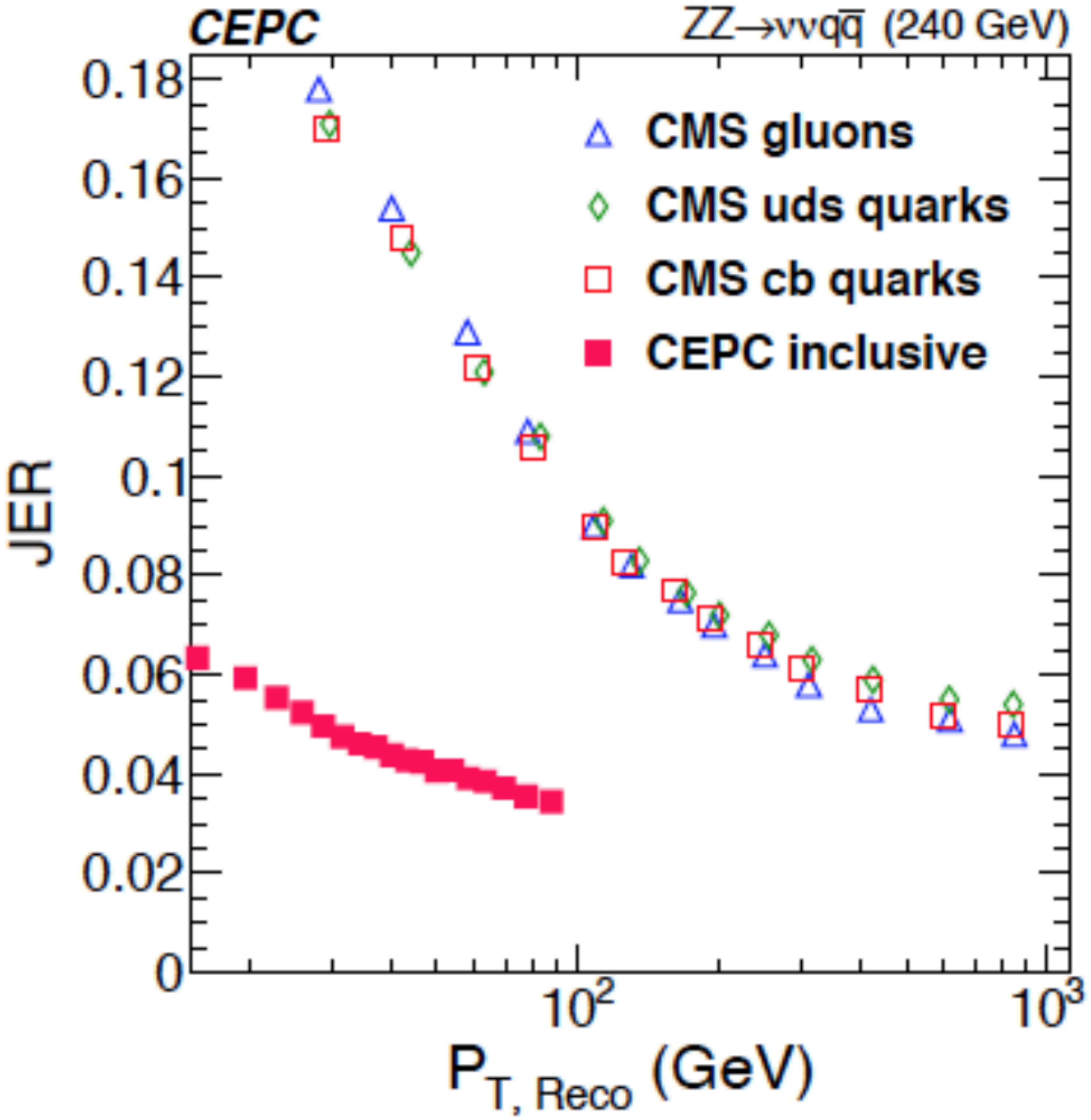


$\sqrt{s}$ (GeV)	$\sigma_{J/\psi J/\psi}$(fb)	$\sigma_{\eta_c\eta_c}$(fb)	$\sigma_{\Upsilon\Upsilon}$(ab)	$\sigma_{\eta_b\eta_b}$(ab)
SuperKEKB	0.154(0.527)	0.361(0.152)	—	—
250 (WWA)	1.28(4.78)	2.18(1.15)	2.20(4.33)	1.89(1.10)
250 (LBS)	0.645(2.76)	1.10(0.597)	12.4(25.7)	9.55(5.66)
500 (WWA)	1.69(6.34)	2.90(1.52)	3.29(6.44)	2.80(1.63)
500 (LBS)	0.161(0.706)	0.280(0.152)	3.22(6.69)	2.47(1.46)

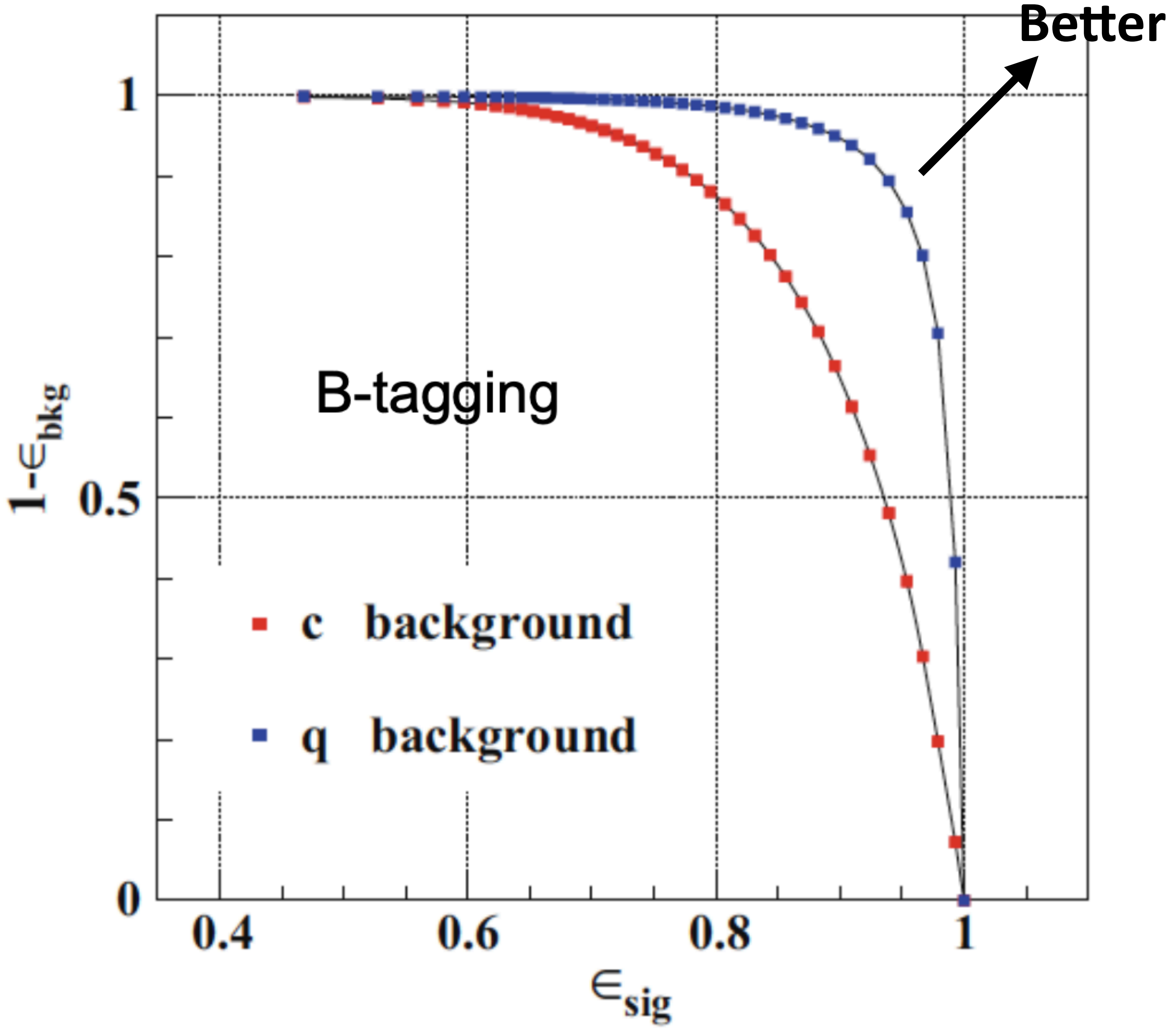


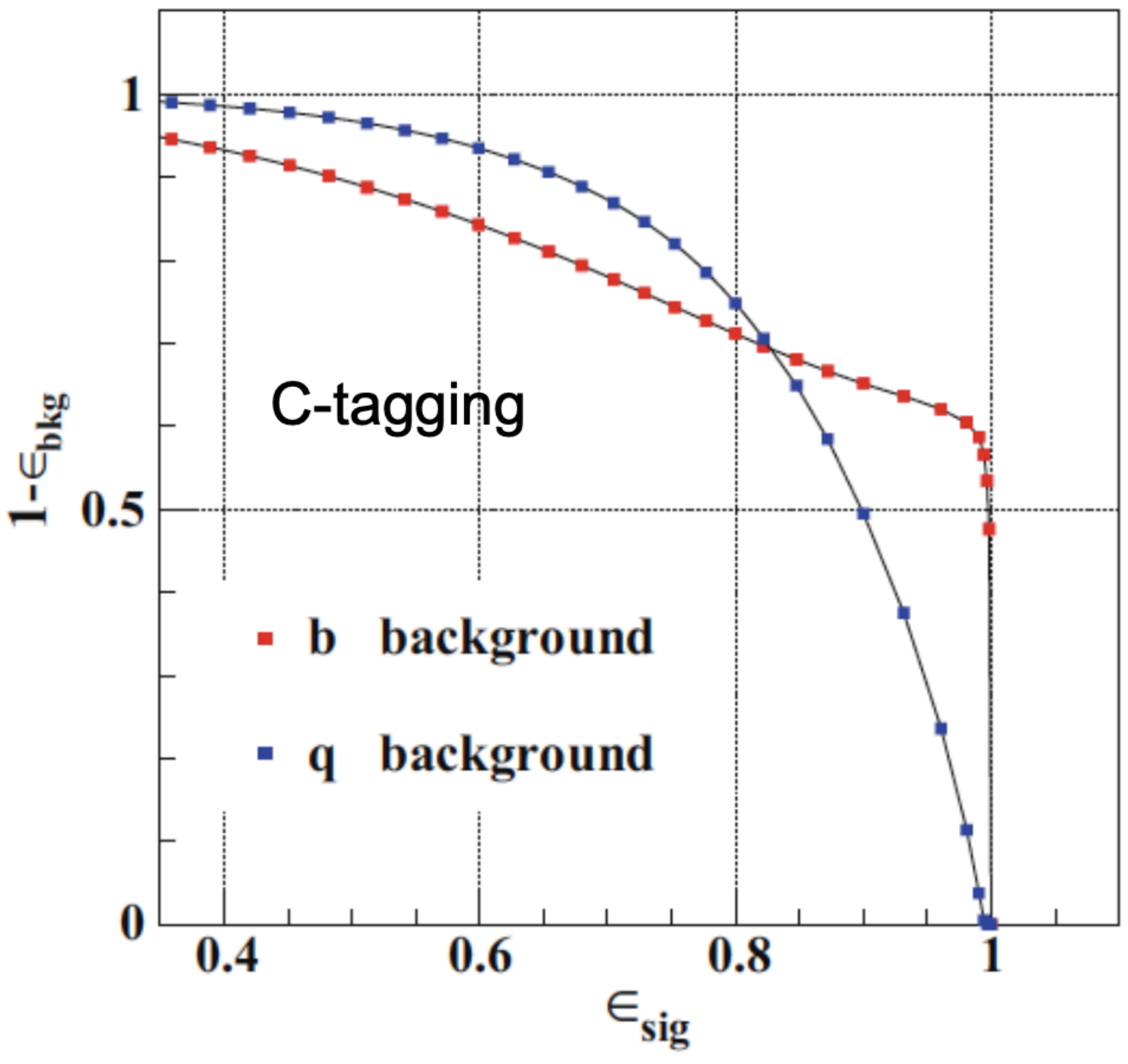


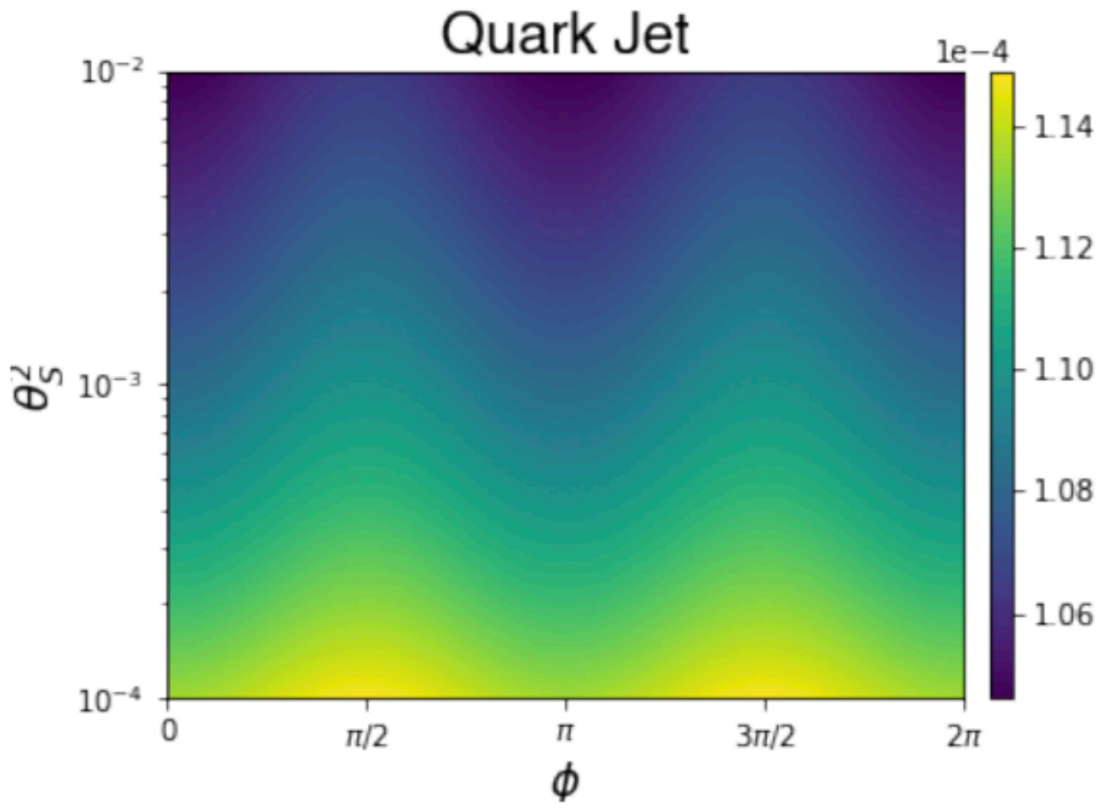
Jet calibration and flavor tagging

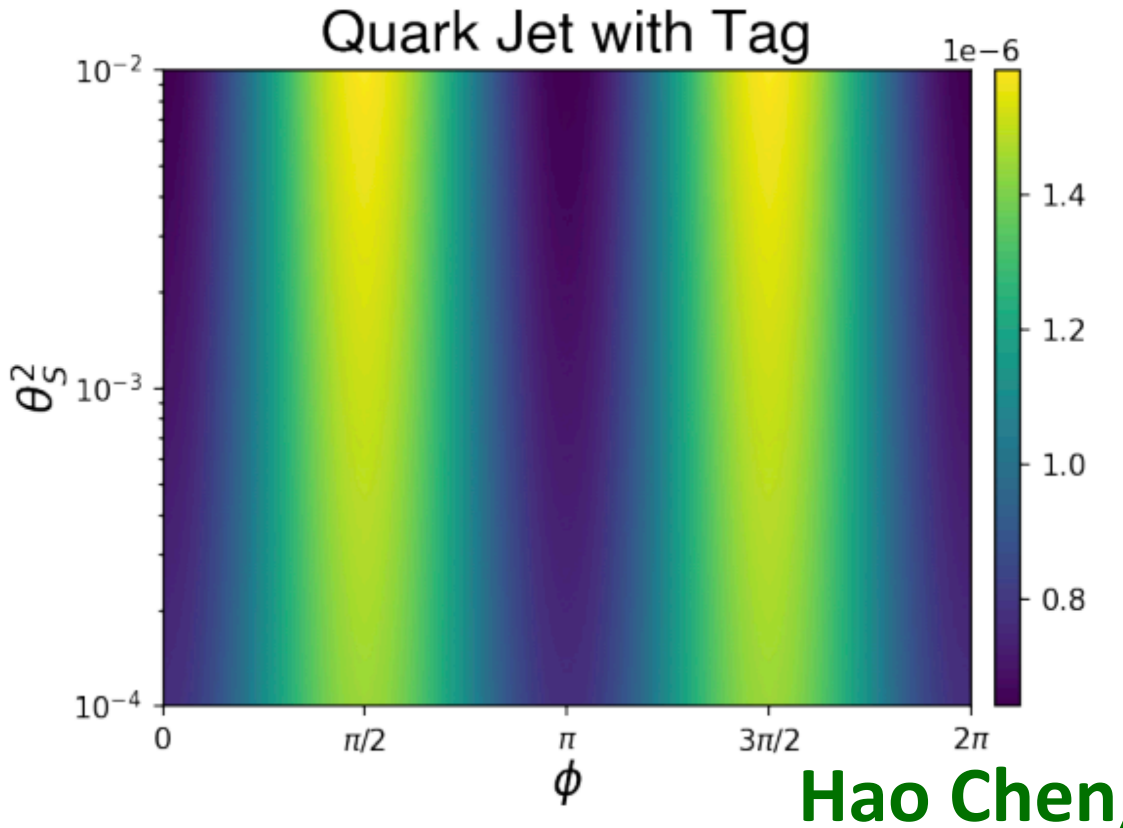


Manqi Ruan, CEPC 2021 workshop



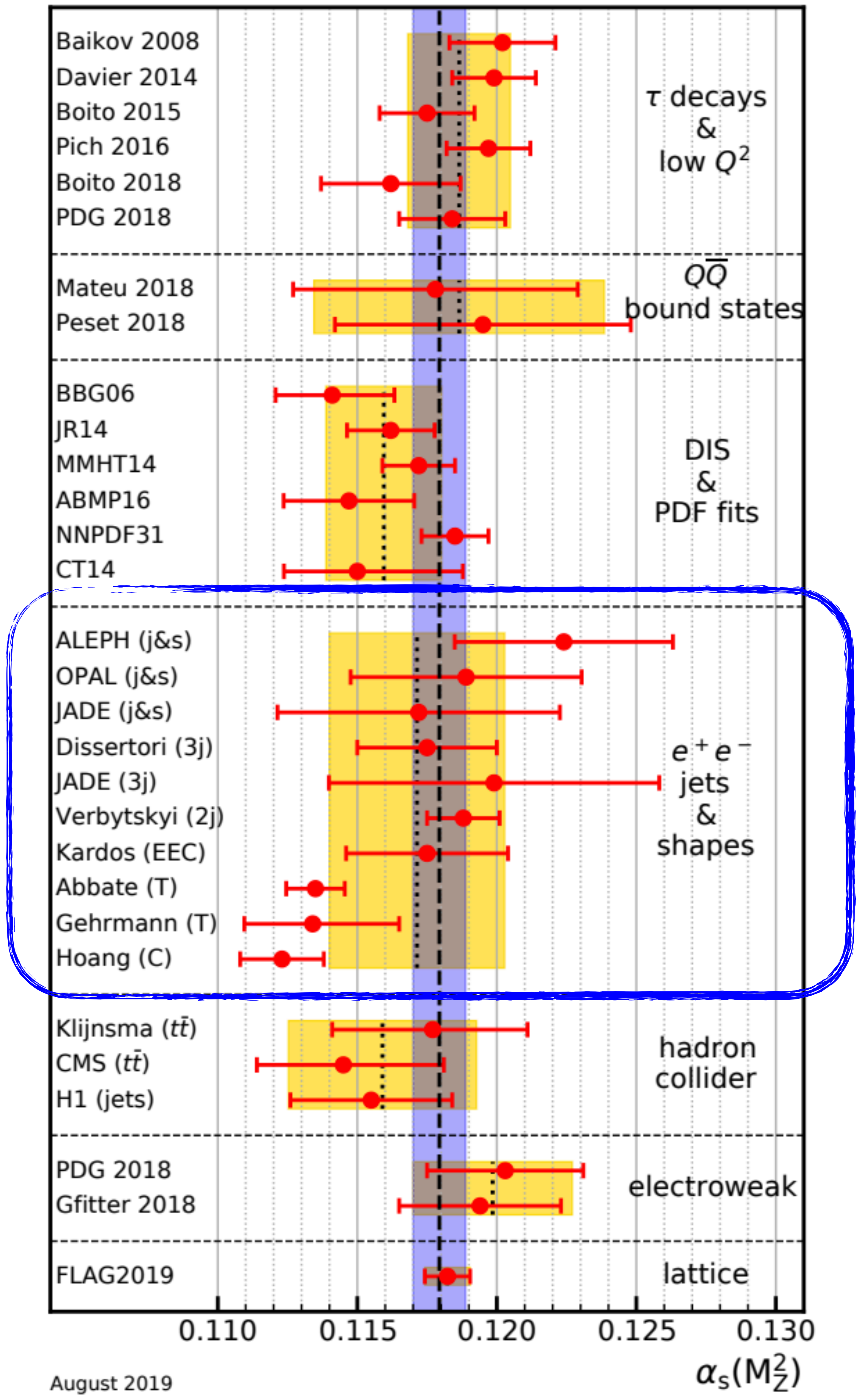






Hao Chen, I. Moult, HXZ

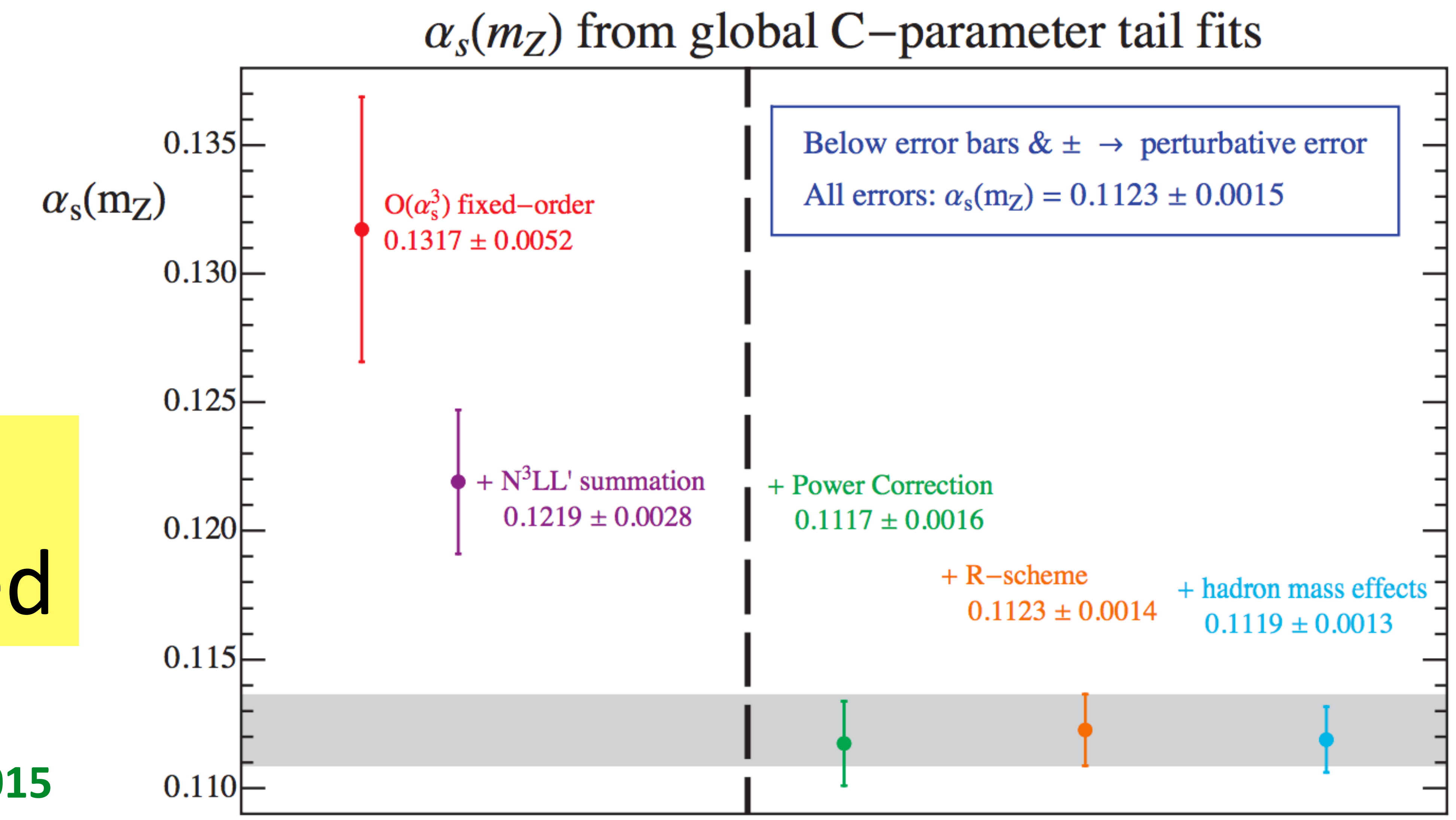
The legacy of LEP



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

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

Theory hadronization uncertainties dominated



Hoang, Kolodrubetz, Mateu, Stewart, 2015
see also recent study: Luisoni, Monni, Salam, 2012.00622

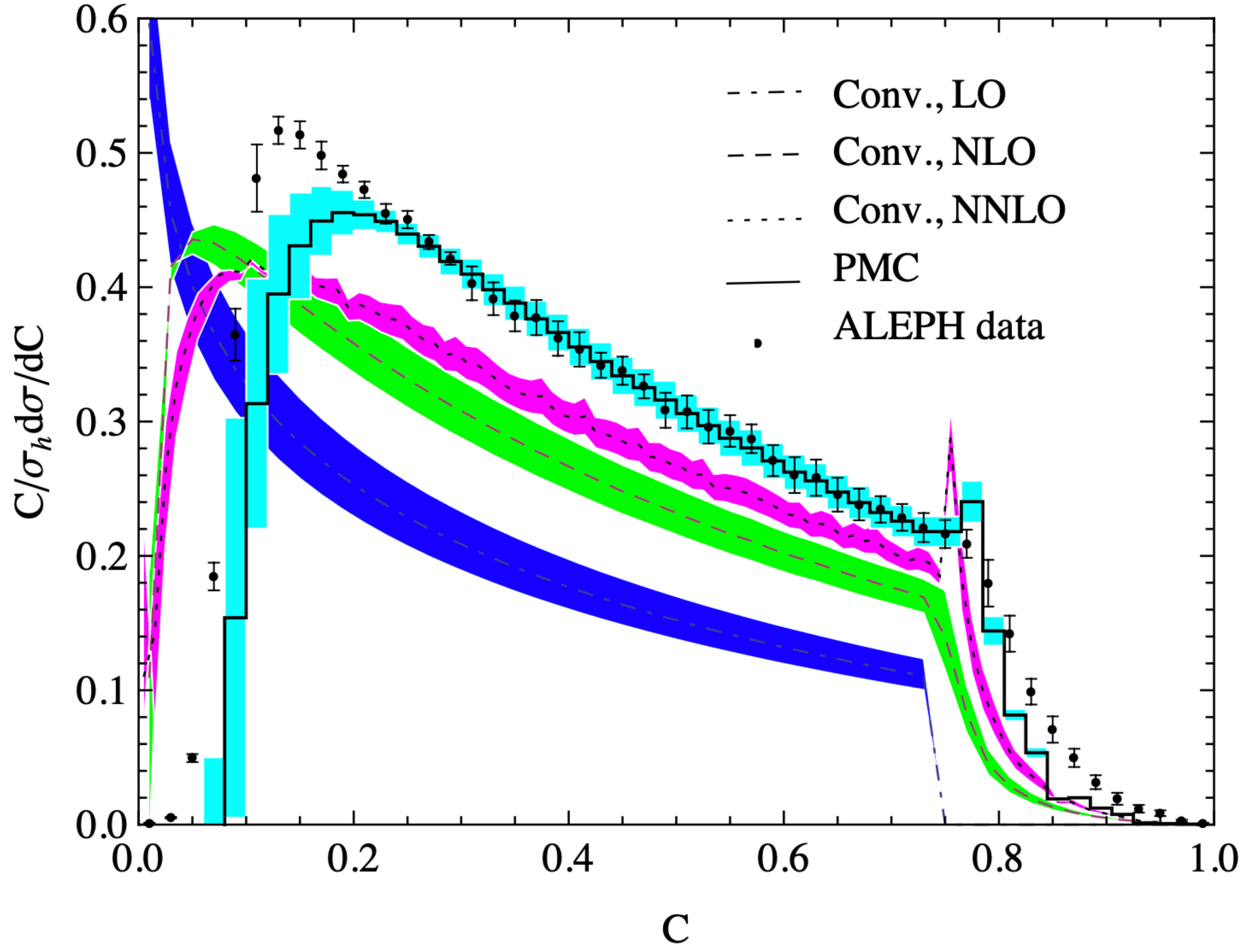
- Looking ahead to the future, can theorists come up with new ideas to solve this decade-long challenge?
  - Principle of maximal conformality
  - soft-drop observables

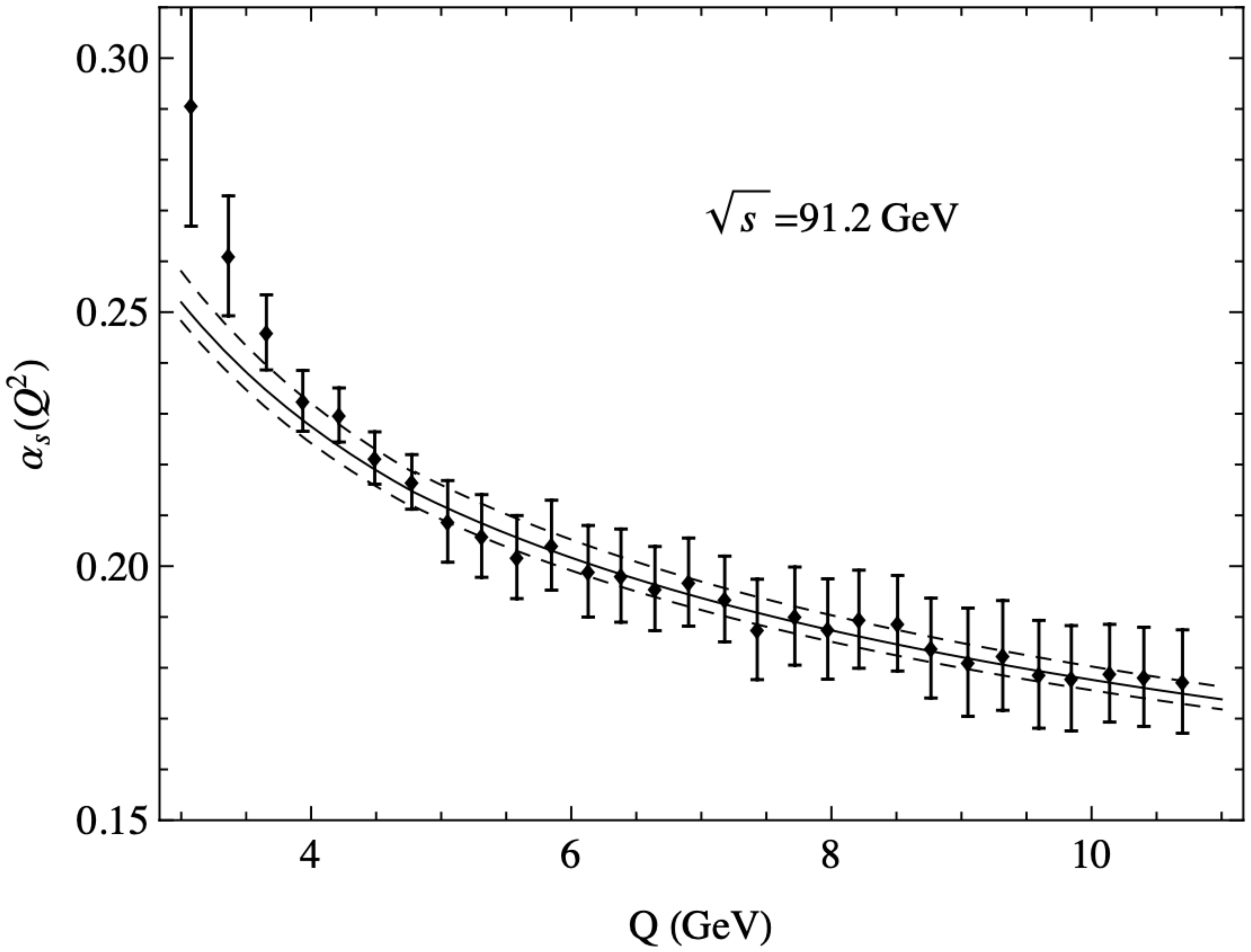
The principle of maximal conformality

Sheng-quan Wang, Xing-gang Wu, Jian-ming Shen, S. Brodsky

$$\sigma = \sigma_0 + \alpha_s(\mu_r)\sigma_1(\mu_r) + \alpha_s^2(\mu_r)\sigma_2(\mu_r) + \cdots$$

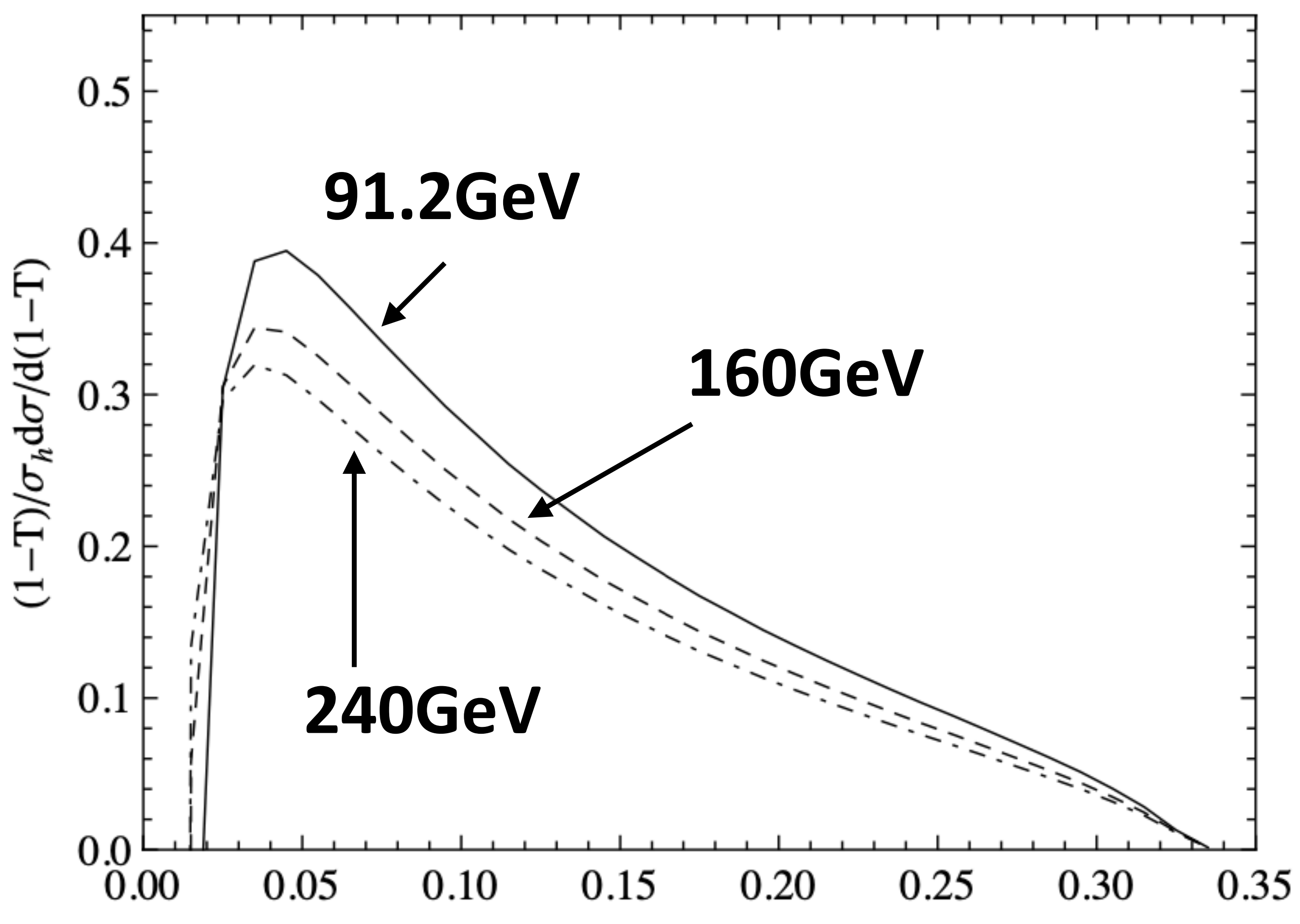
Contain beta dependent terms



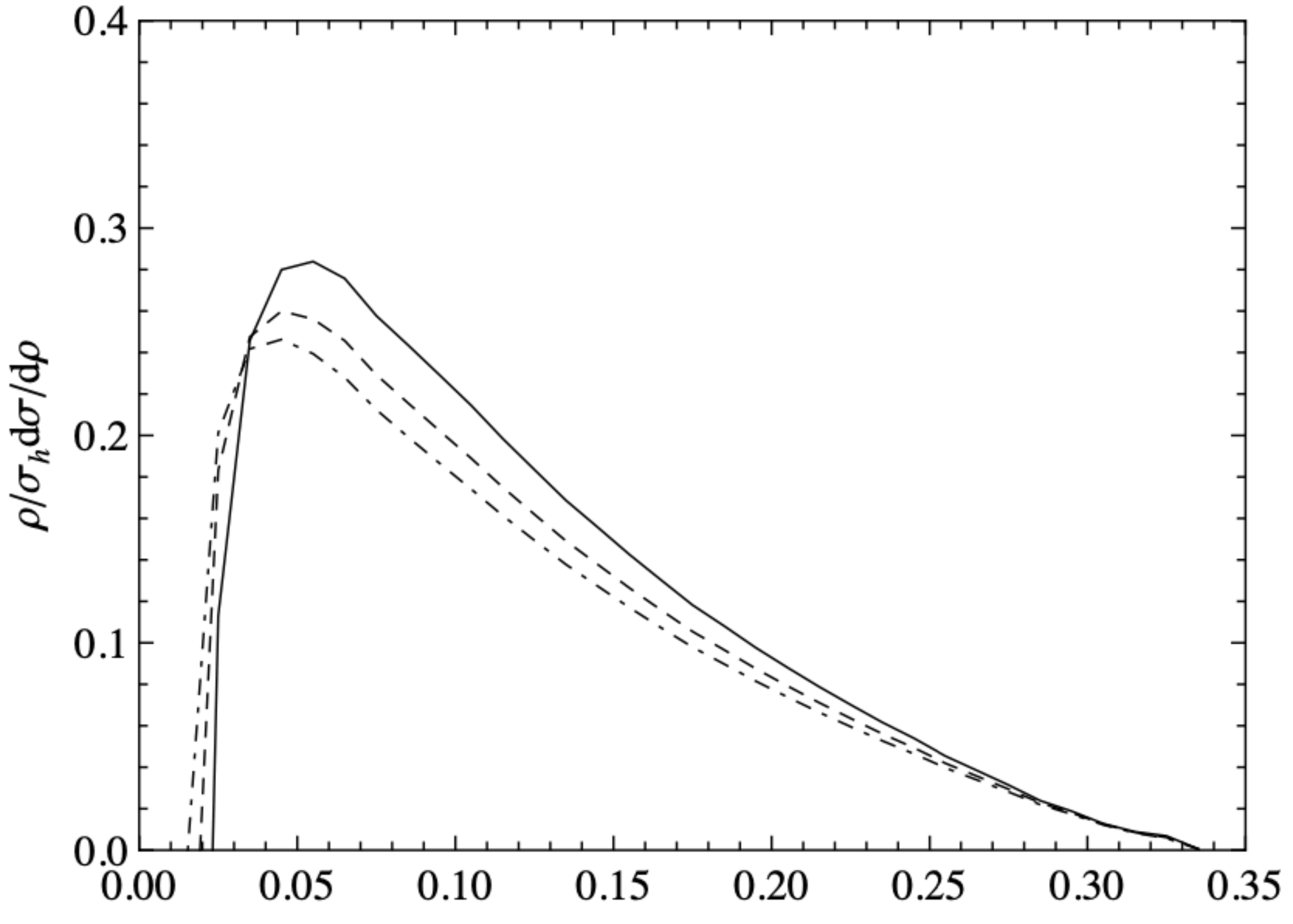


PMC predictions for CEPC energy

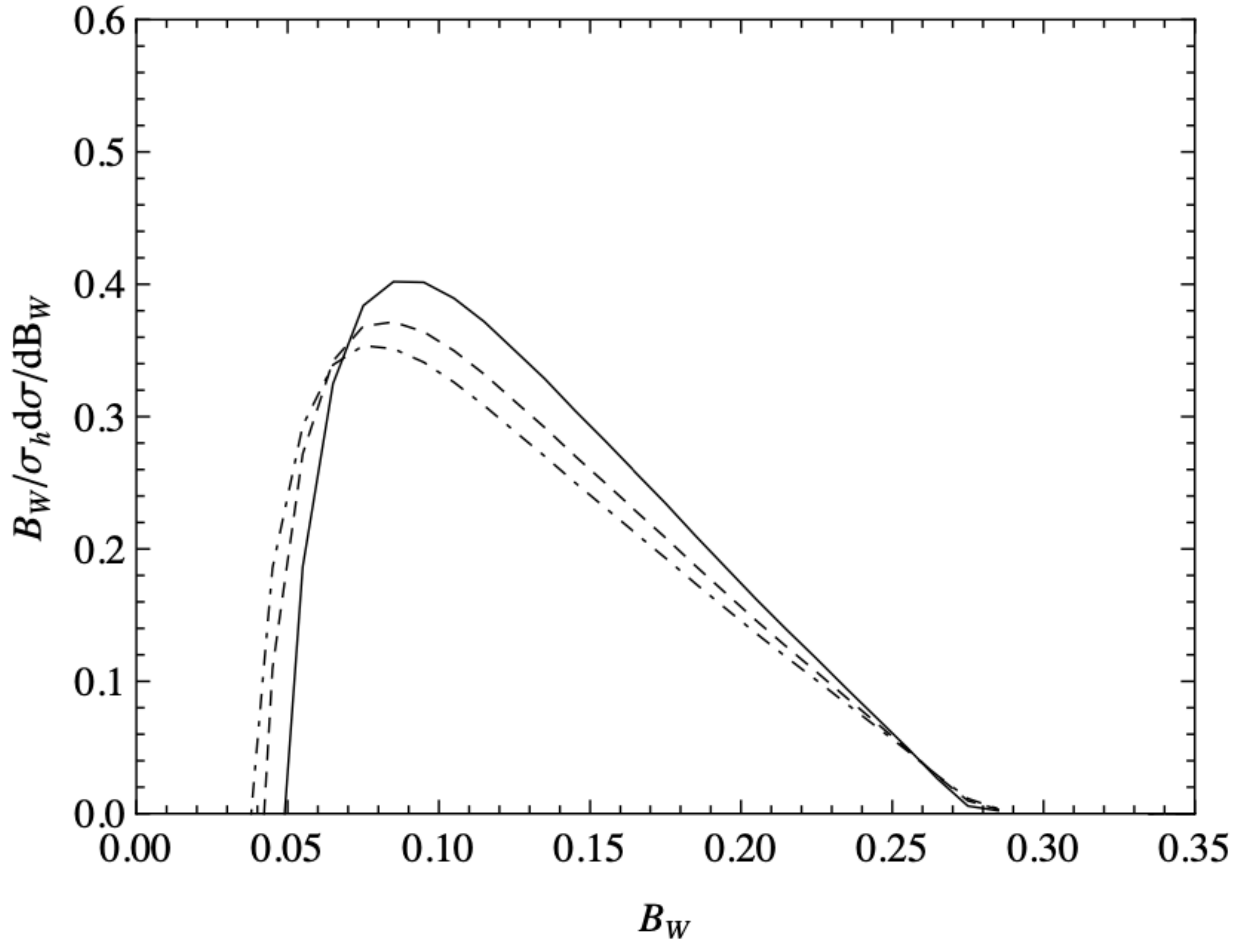
Sheng-quan Wang, Xing-gang Wu, Jian-ming Shen, S. Brodsky



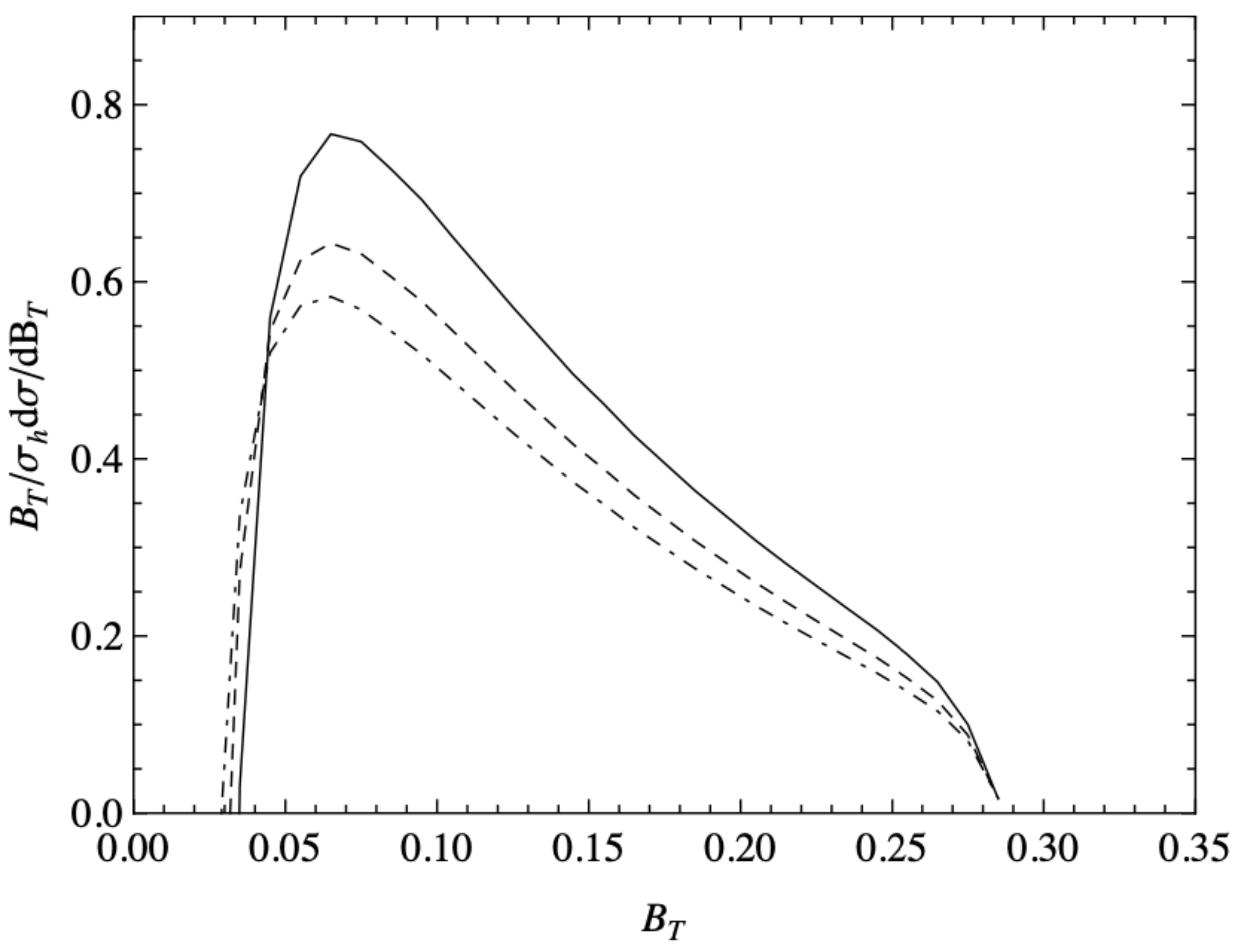
1−T **Thrust**



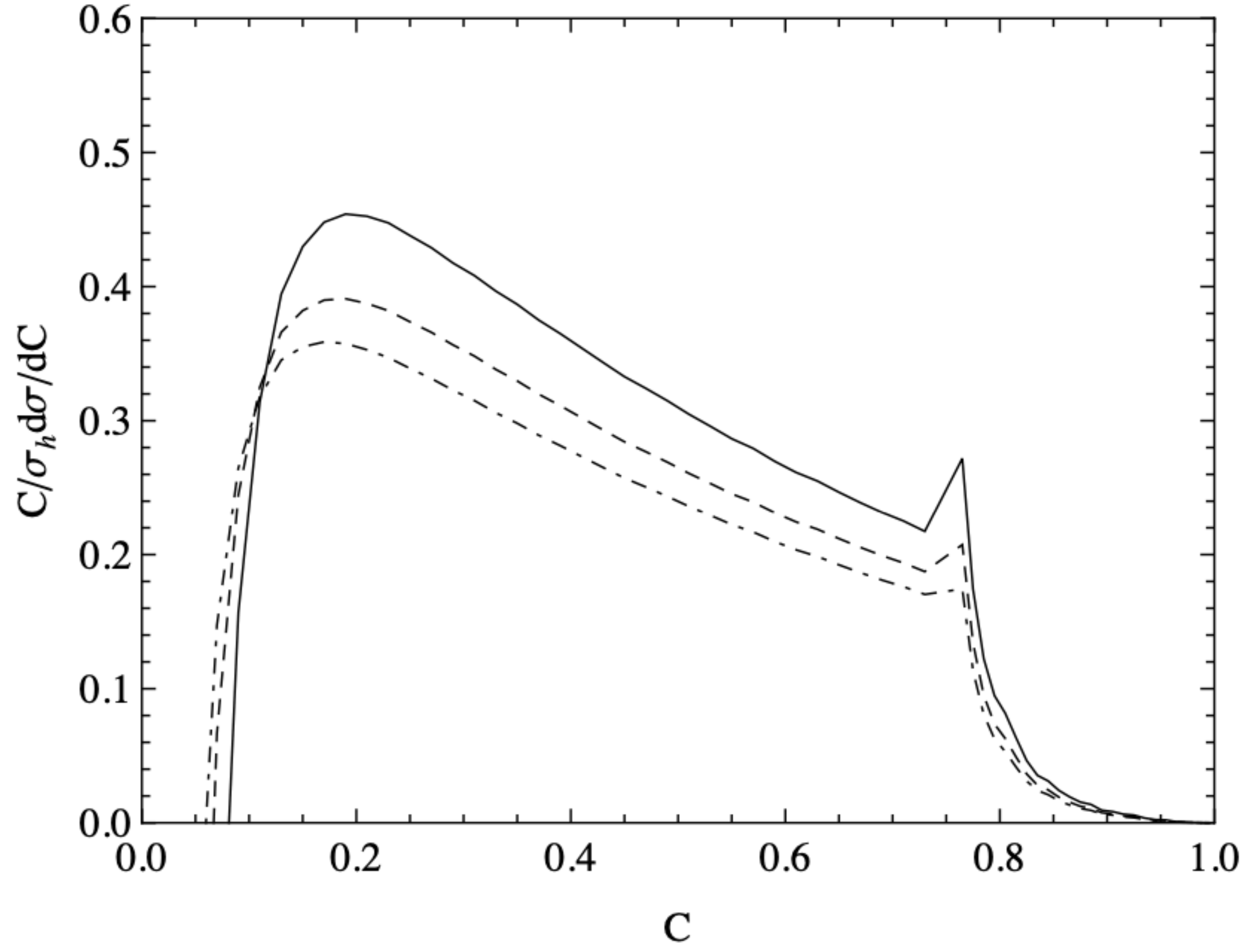
ρ **Heavy jet mass**



Wide jet broadening

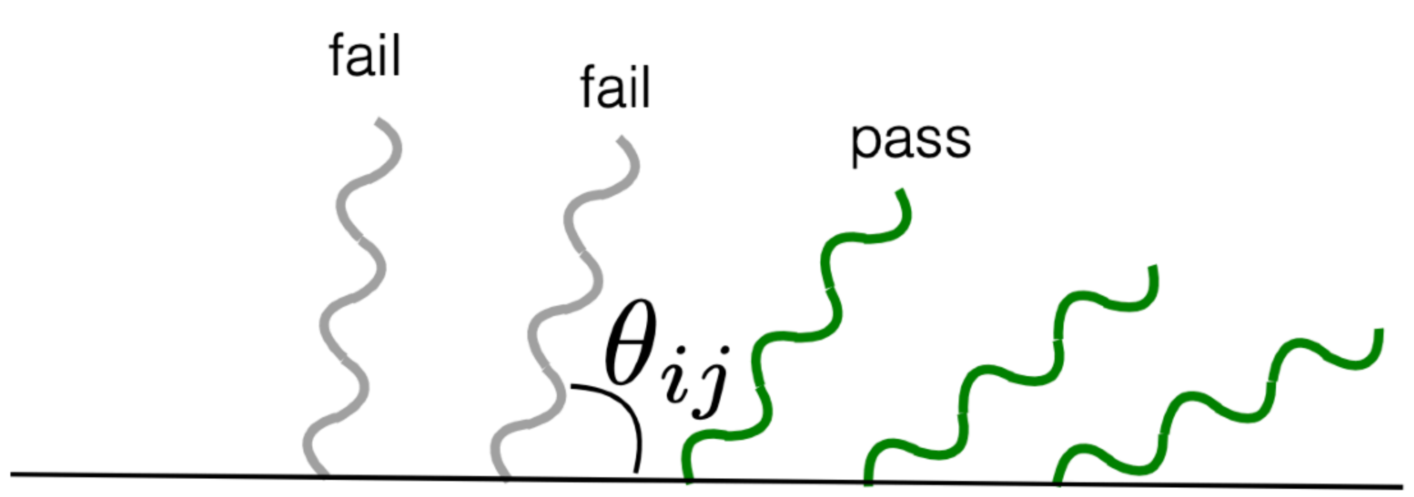


Total jet broadening



C parameter

Precision soft-drop observables



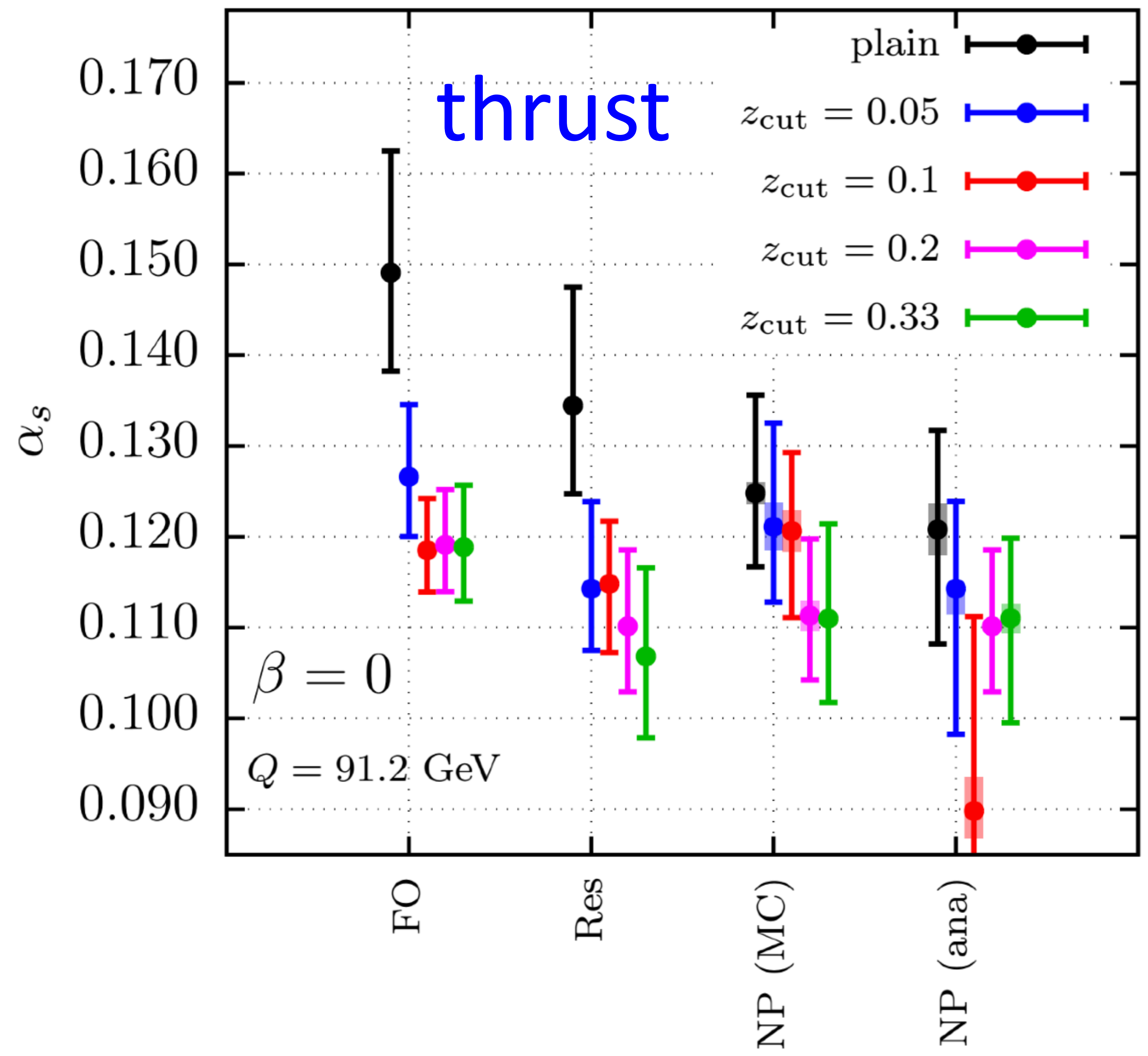
Angular-ordered emissions

$$\frac{\min[p_{Ti}, p_{Tj}]}{p_{Ti} + p_{Tj}} > z_{\mathrm{cut}} \left(\frac{\theta_{ij}}{R}\right)^{\beta}$$

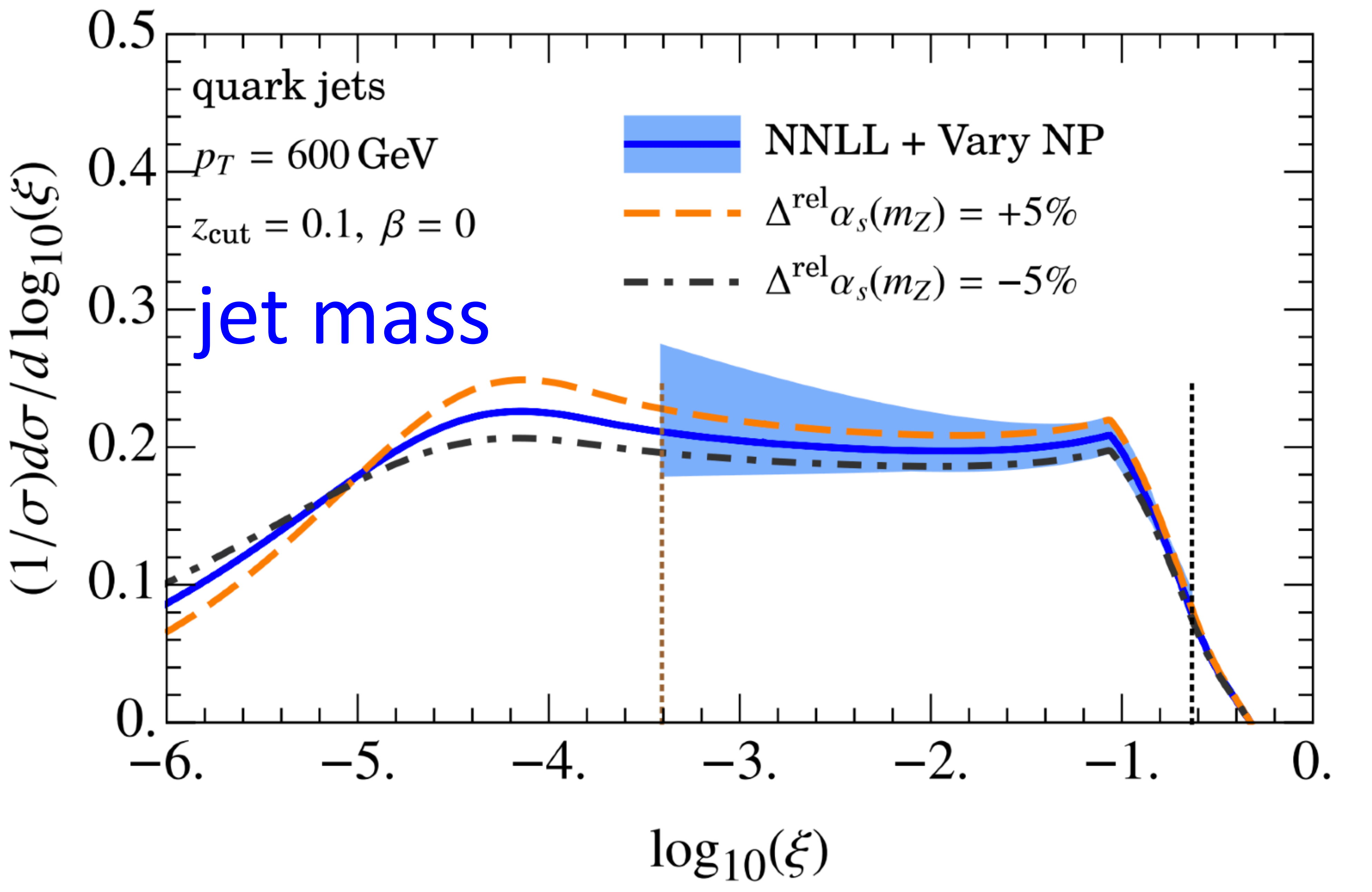
arXiv:1307.0007, 1402.2657

β = 0: mMDT

credit: Larkoski



Marzani et al., 1906.10504



Honnesdottir, Pathak, Schwartz, Stewart, Boost 2021

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

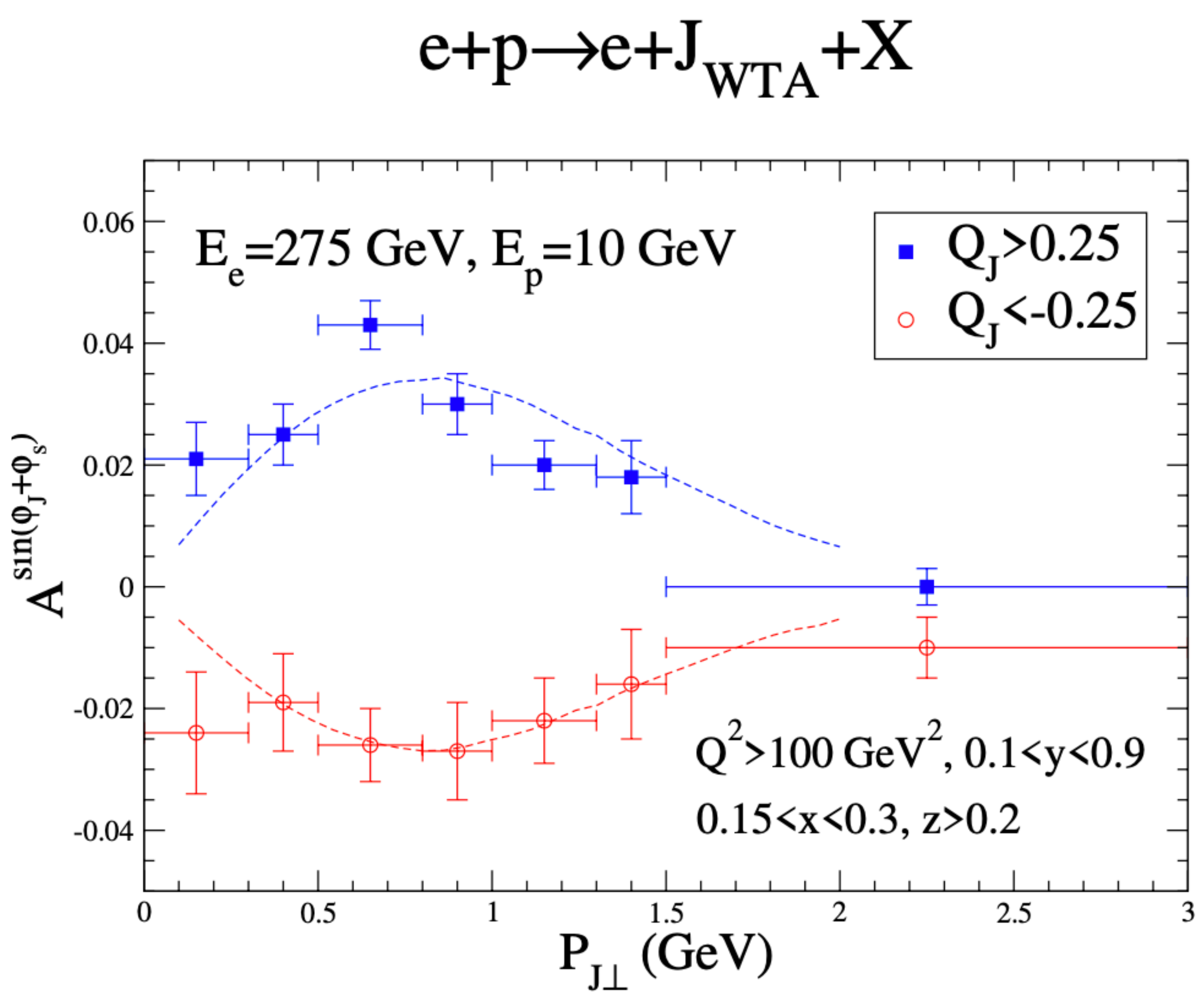
Time-reversal-odd jet function

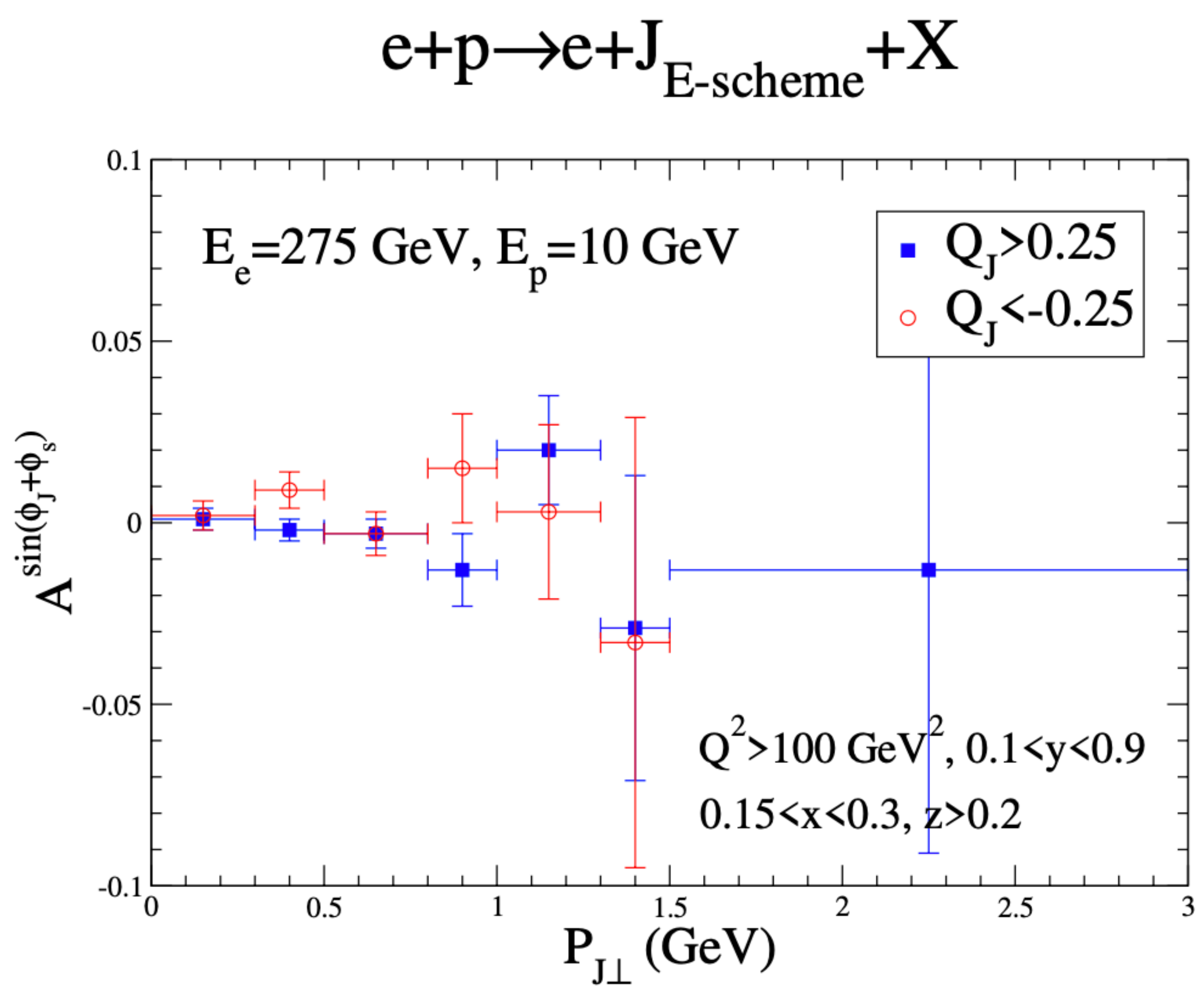
Lin Dai, Xiaohui Liu, Hong-xi Xing

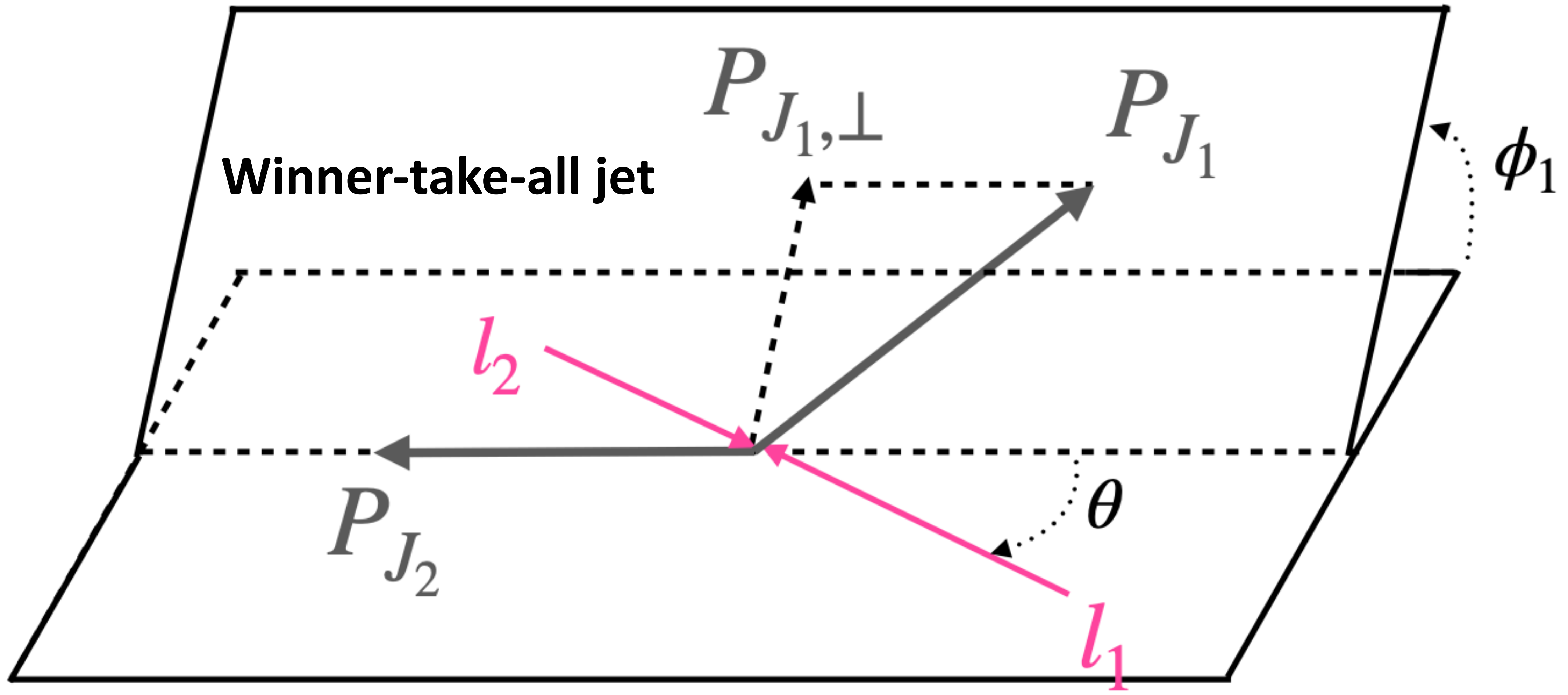
$$F_U = |\boldsymbol{q}_T| \sum_q e_q^2 \int \frac{d^2 b}{(2\pi)^2} e^{i\boldsymbol{q}_T\cdot\boldsymbol{b}} \tilde{J}_1^q(b^2)\tilde{J}_1^{\bar{q}}(b^2)\,,$$

$$F_T = |\boldsymbol{q}_T| \sum_q e_q^2 \int \frac{d^2 b}{(2\pi)^2} e^{i\boldsymbol{q}_T\cdot\boldsymbol{b}} \left(2\frac{q_T^i q_T^j}{|\boldsymbol{q}_T|^2} - \delta^{ij}\right) \partial_{b^i}\tilde{J}_T^q(b^2)\partial_{b^j}\tilde{J}_T^{\bar{q}}(b^2)\,,$$

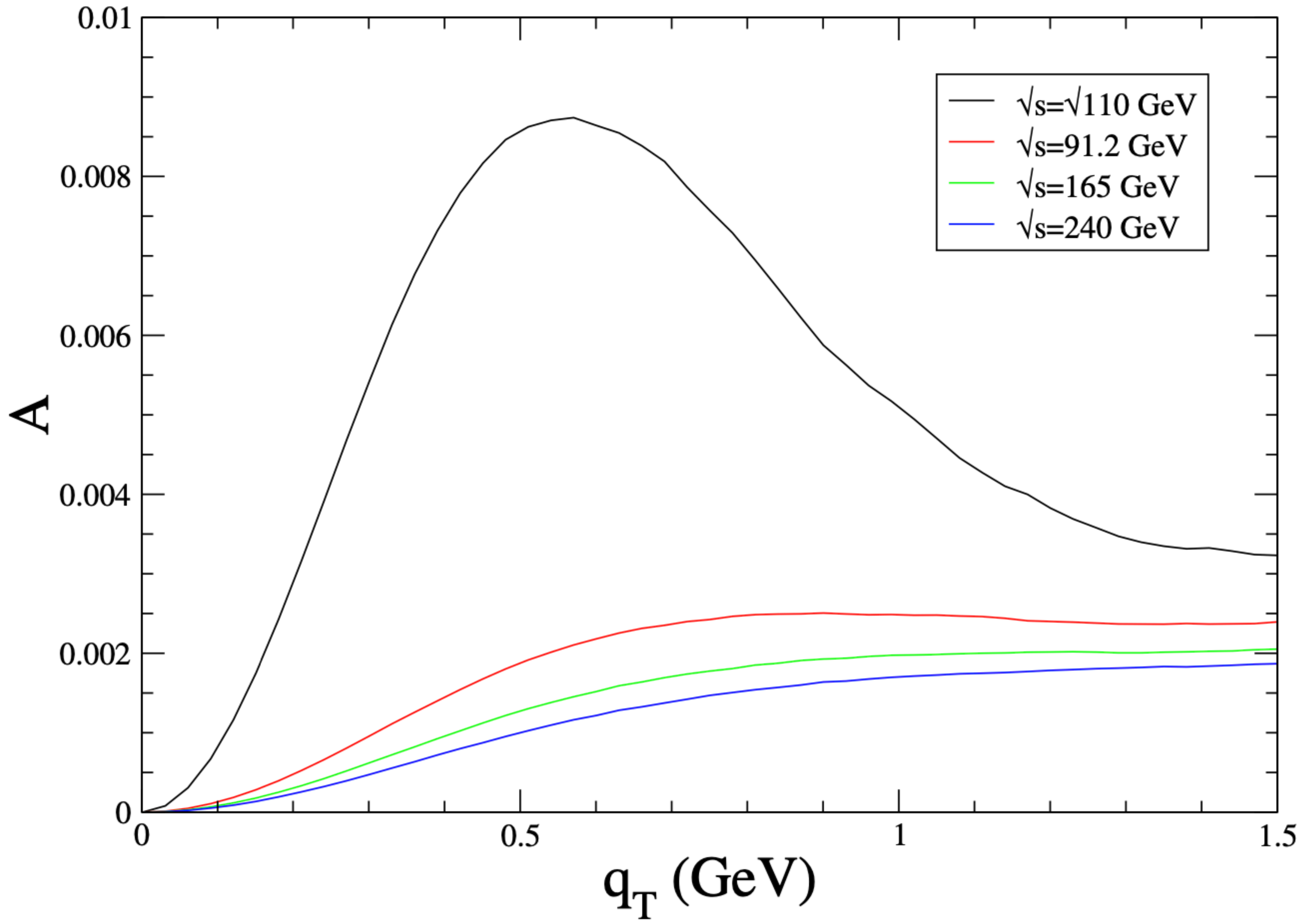
Linearly polarized gluon





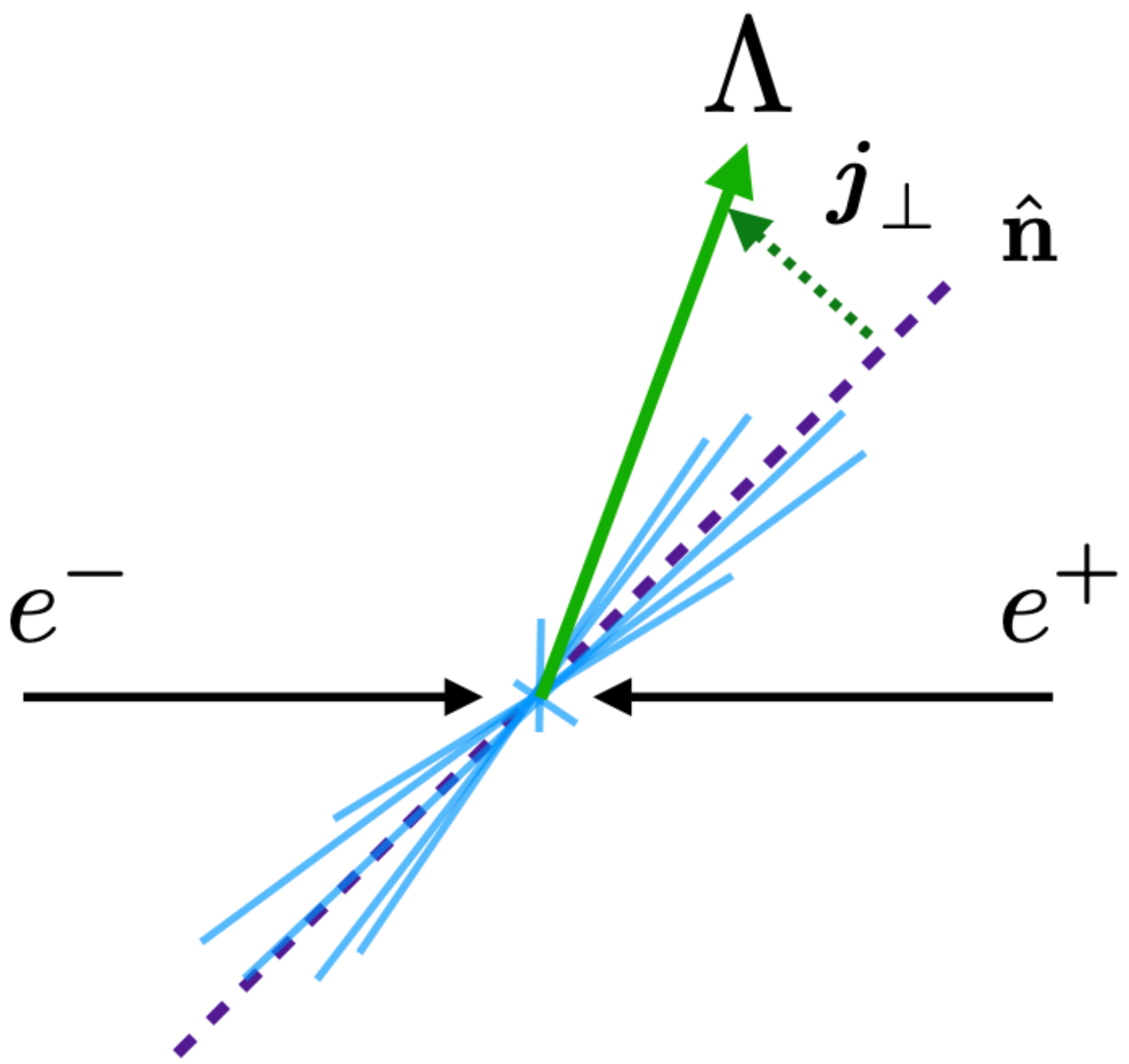


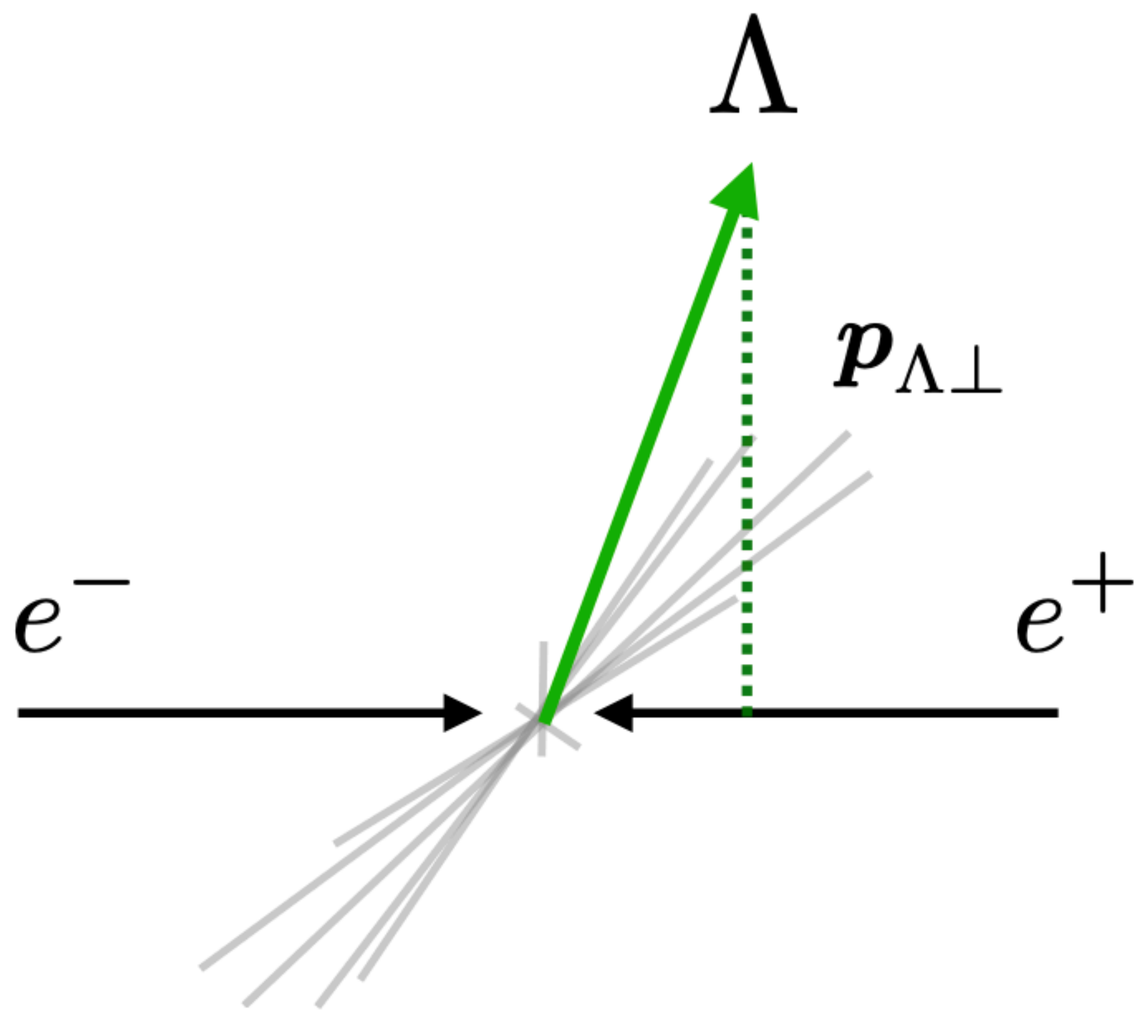
Azimuthal asymmetry

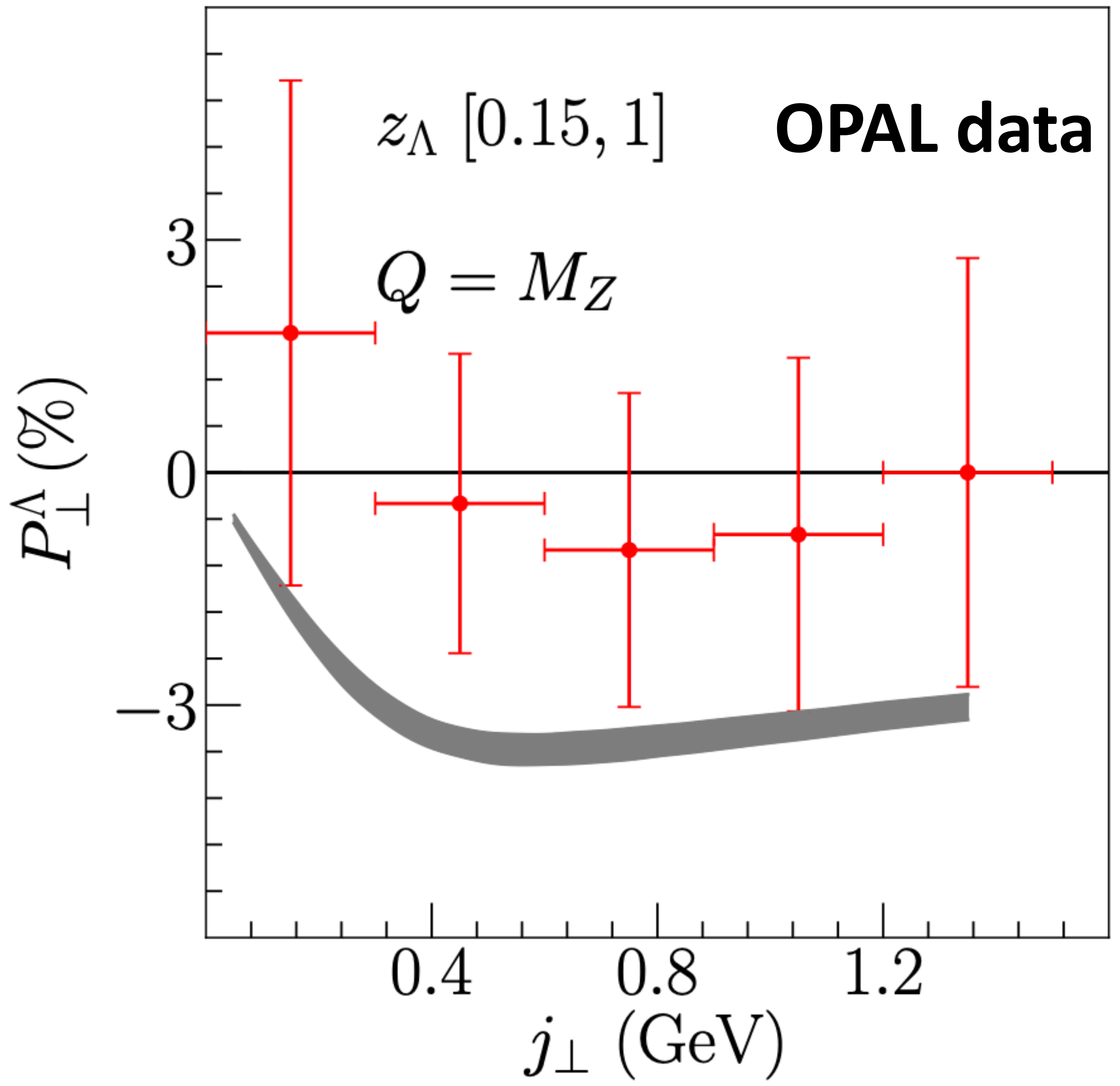


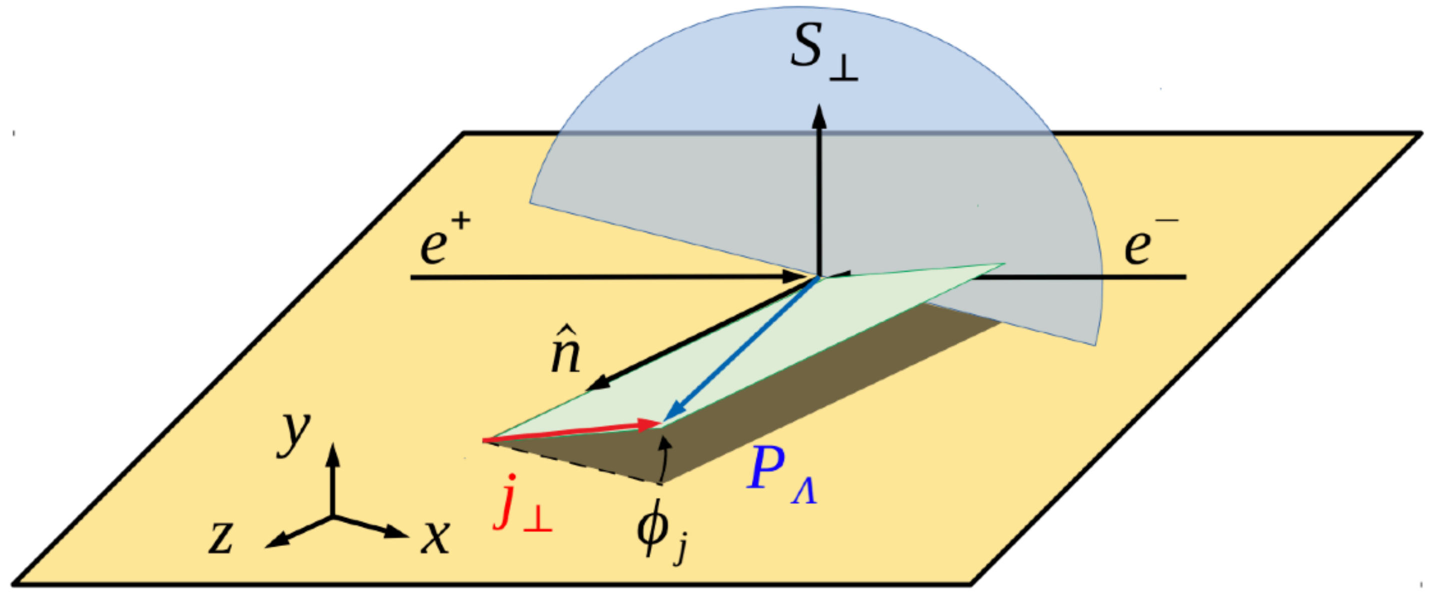
Transverse Λ polarization in e+e-

L. Gamberg, Zhong-bo Kang, Ding Yu Shao, J. Terry, Fanyi Zhao

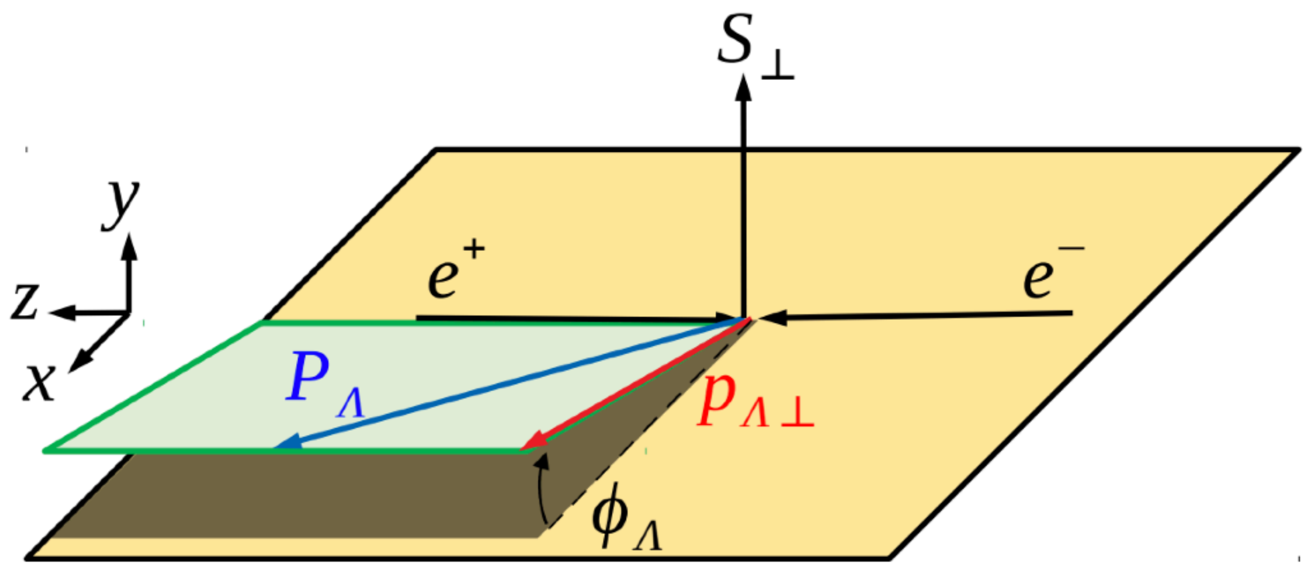




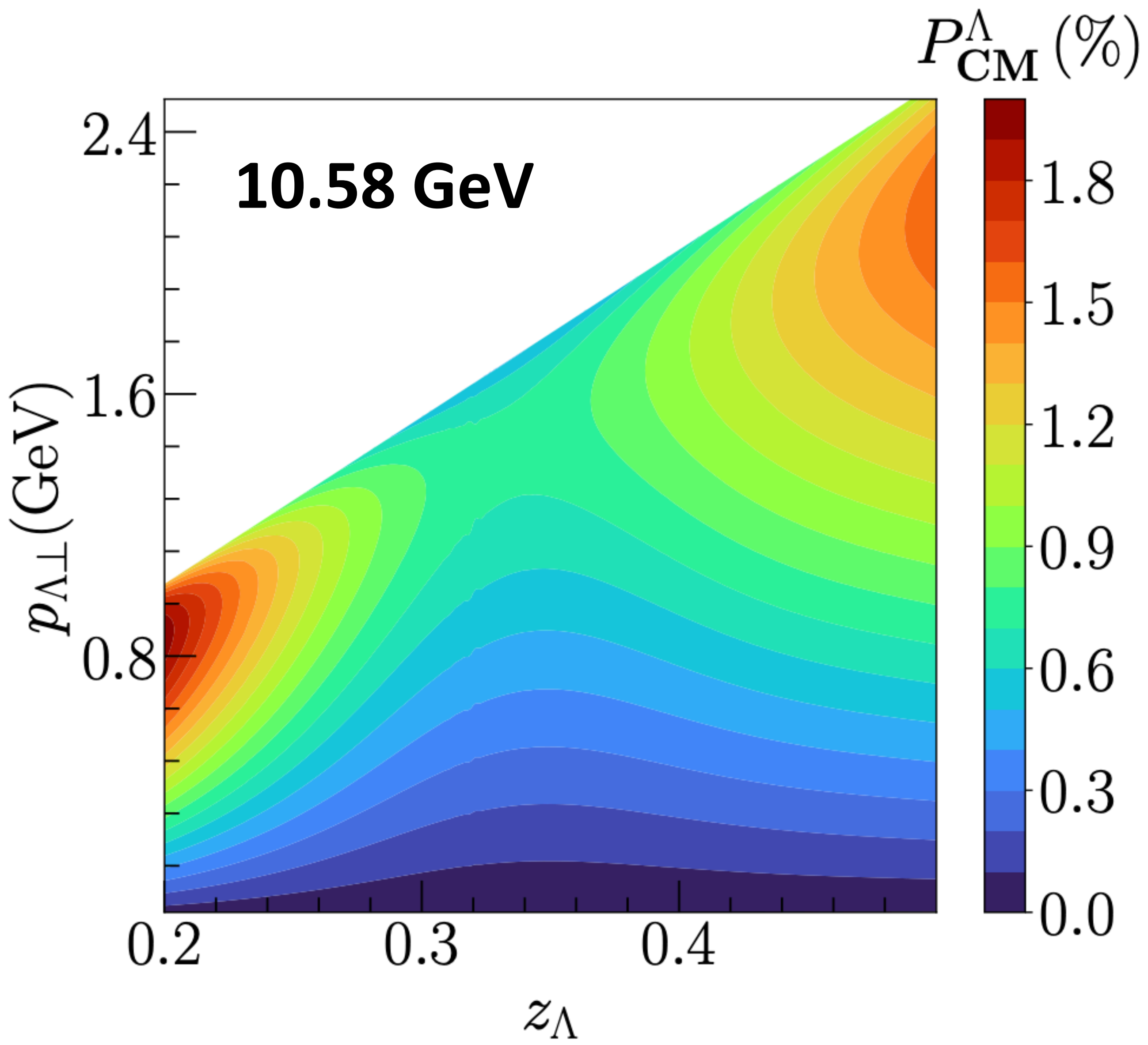


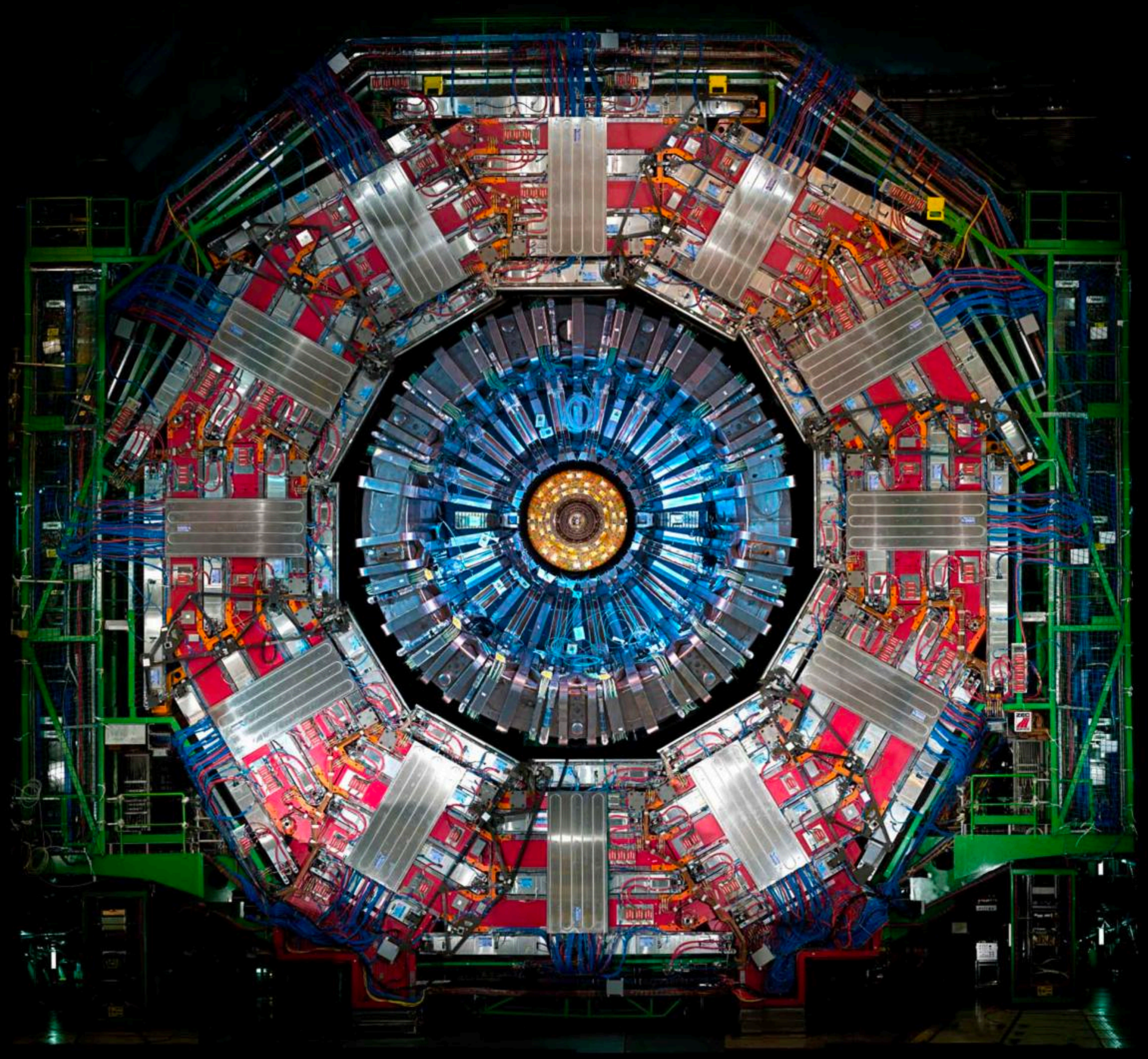


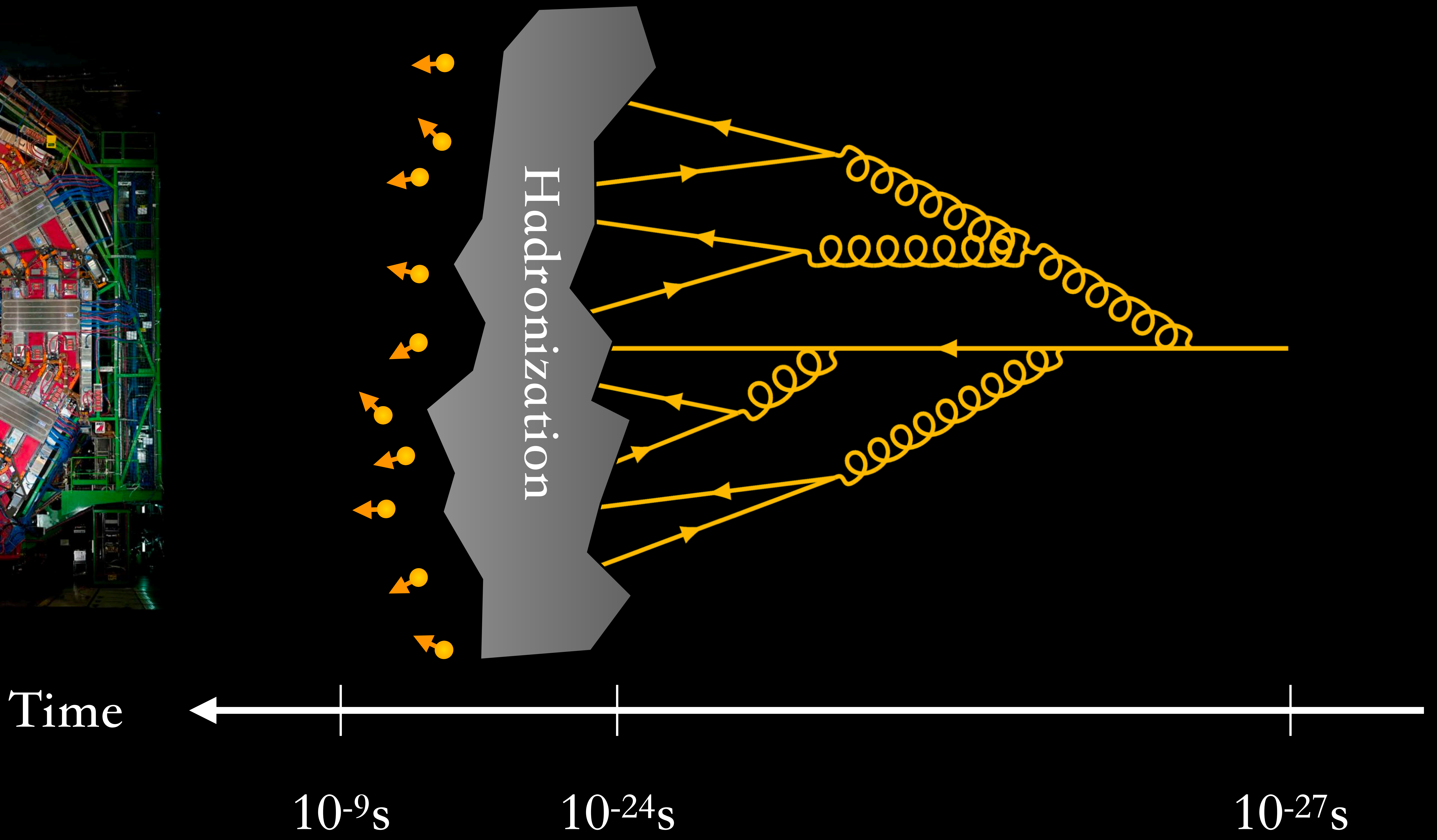
TMD polarization fragmentation

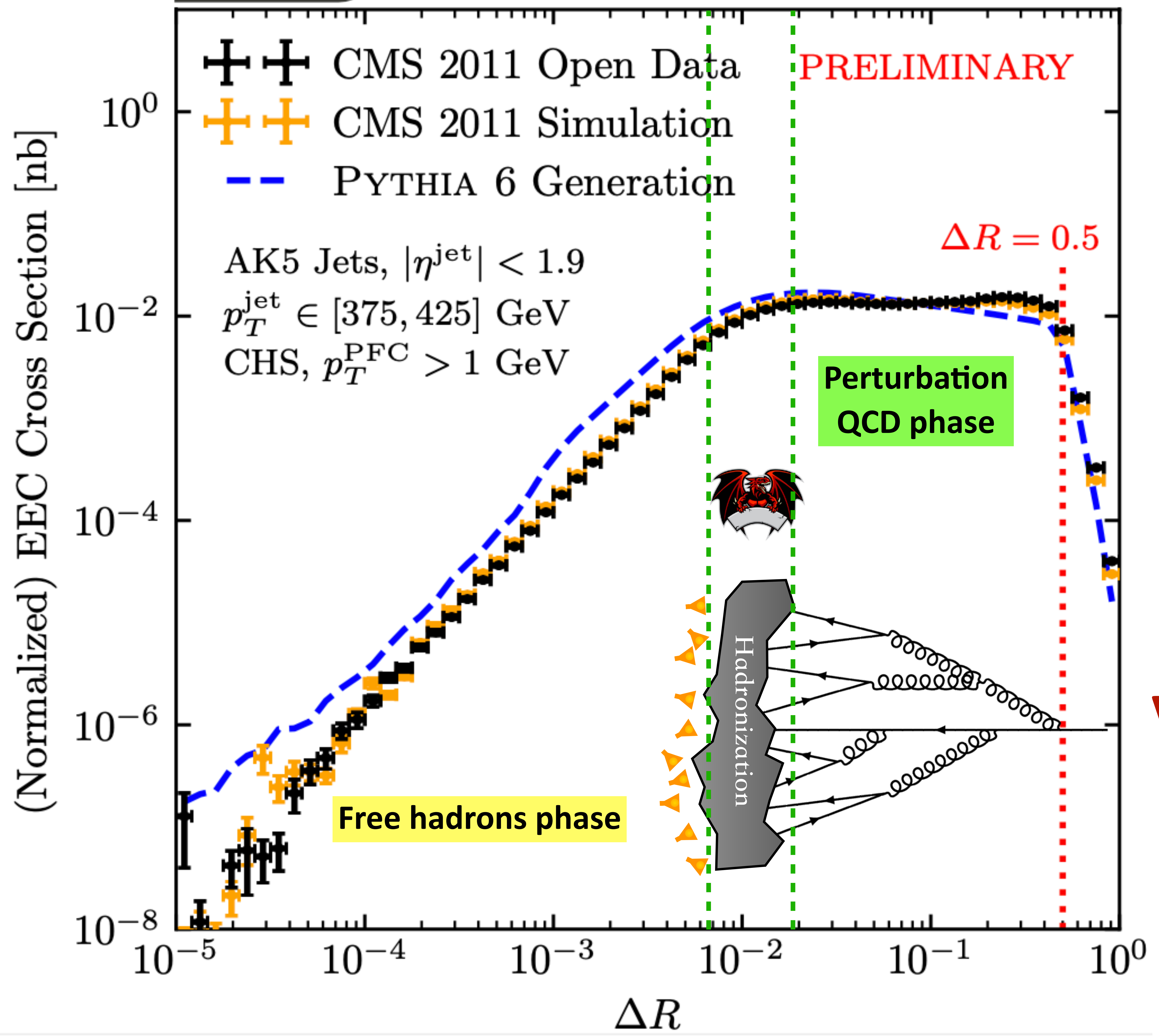


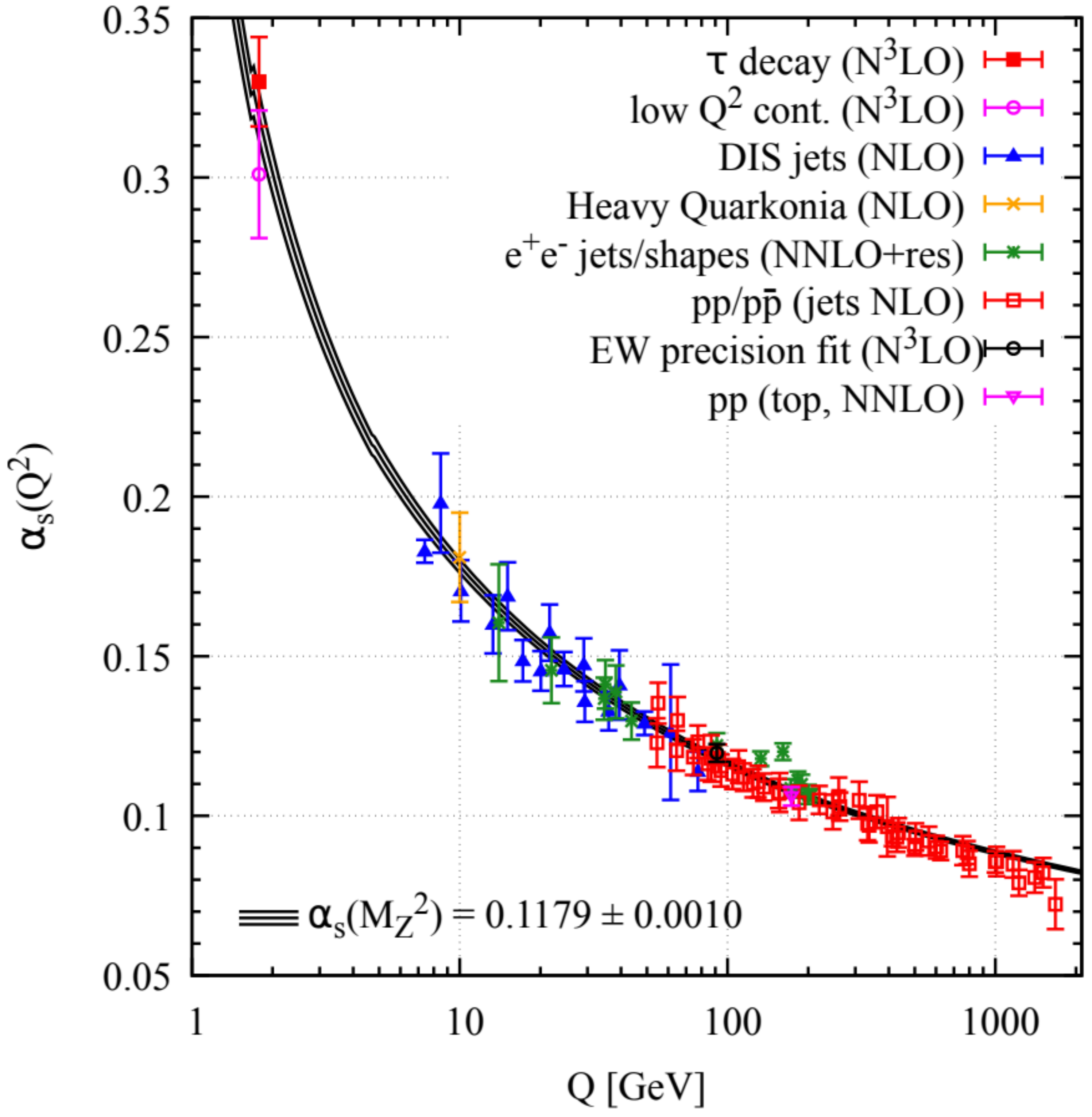
Collinear twist-3 fragmentation






Hadronization
Time
10-9s
10-24s
10-27s





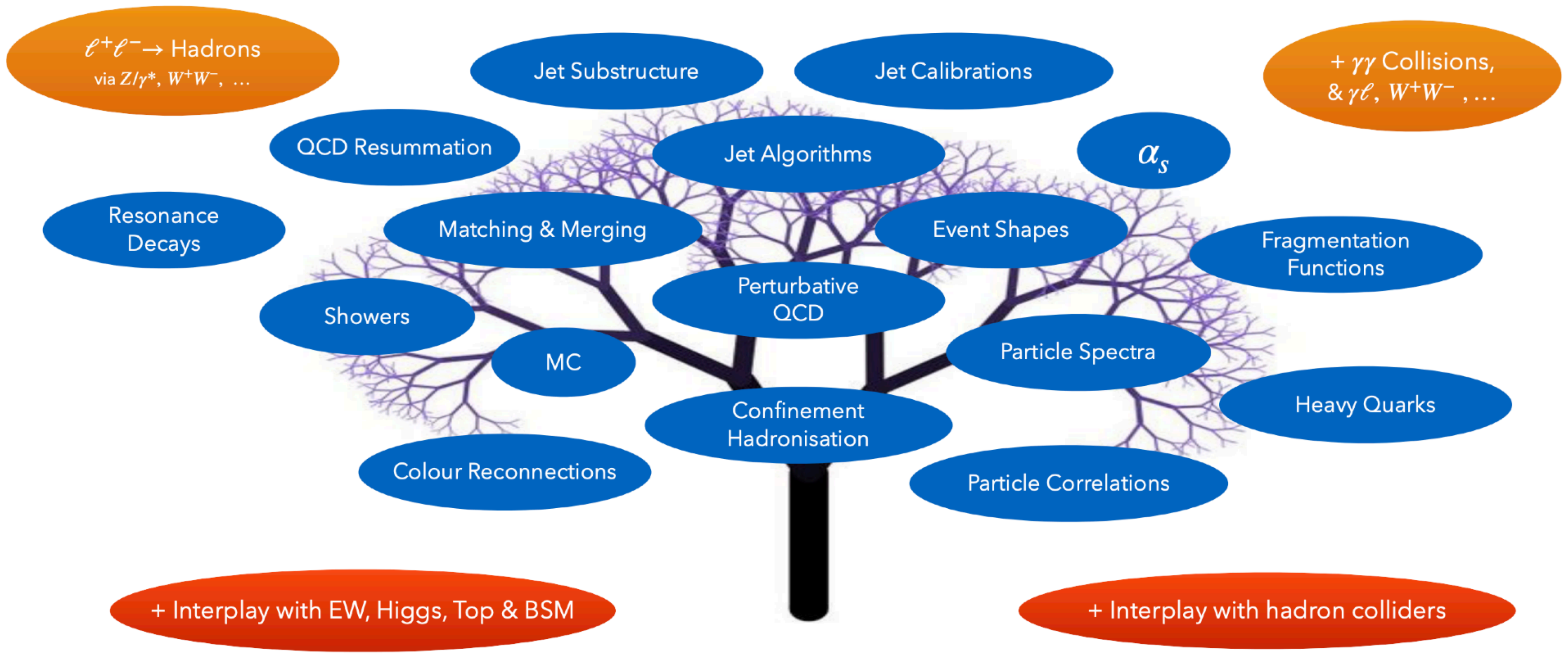
Visualization of evolution from parton to hadrons

Low energy
long distance

P. Komiske, I. Moult, J. Thaler, HXZ

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