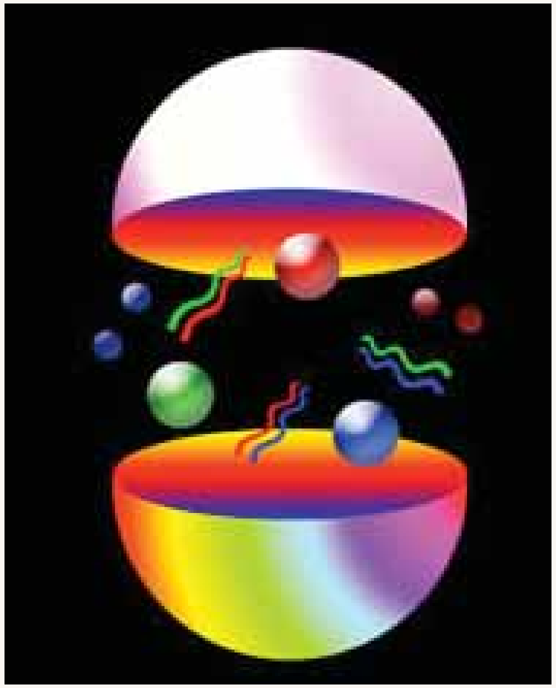
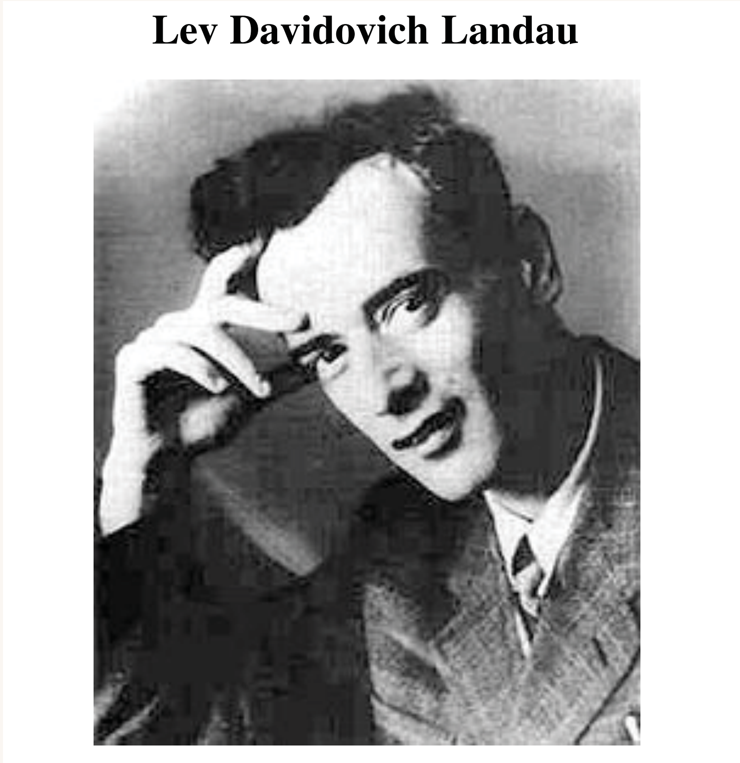
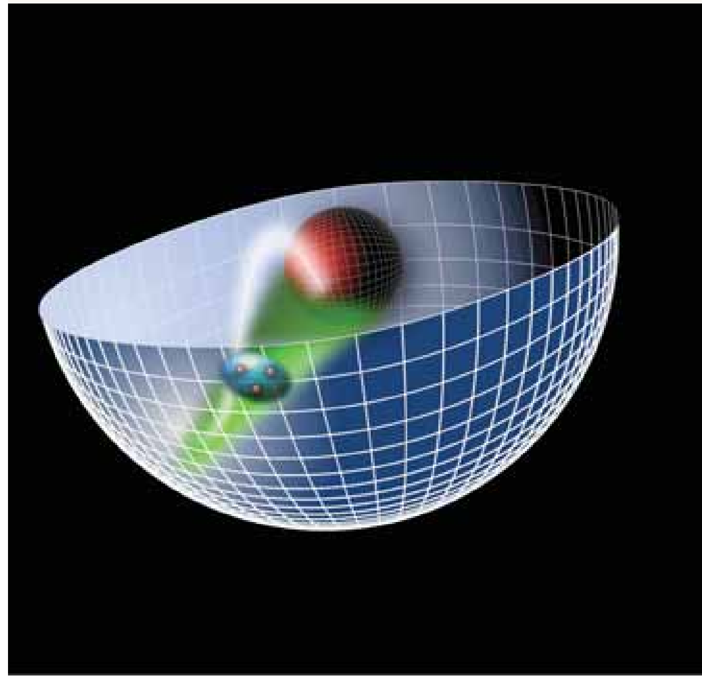
AdS/CFT and Hadronic Physics on the Light Front







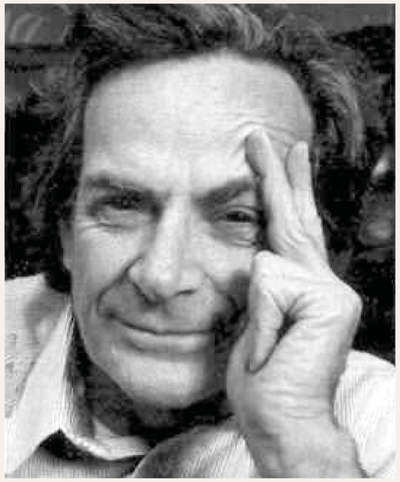
Stan Brodsky SLAC/IPPP

Landau Memorial Meeting Moscow June 20, 2008

Landau's Impact

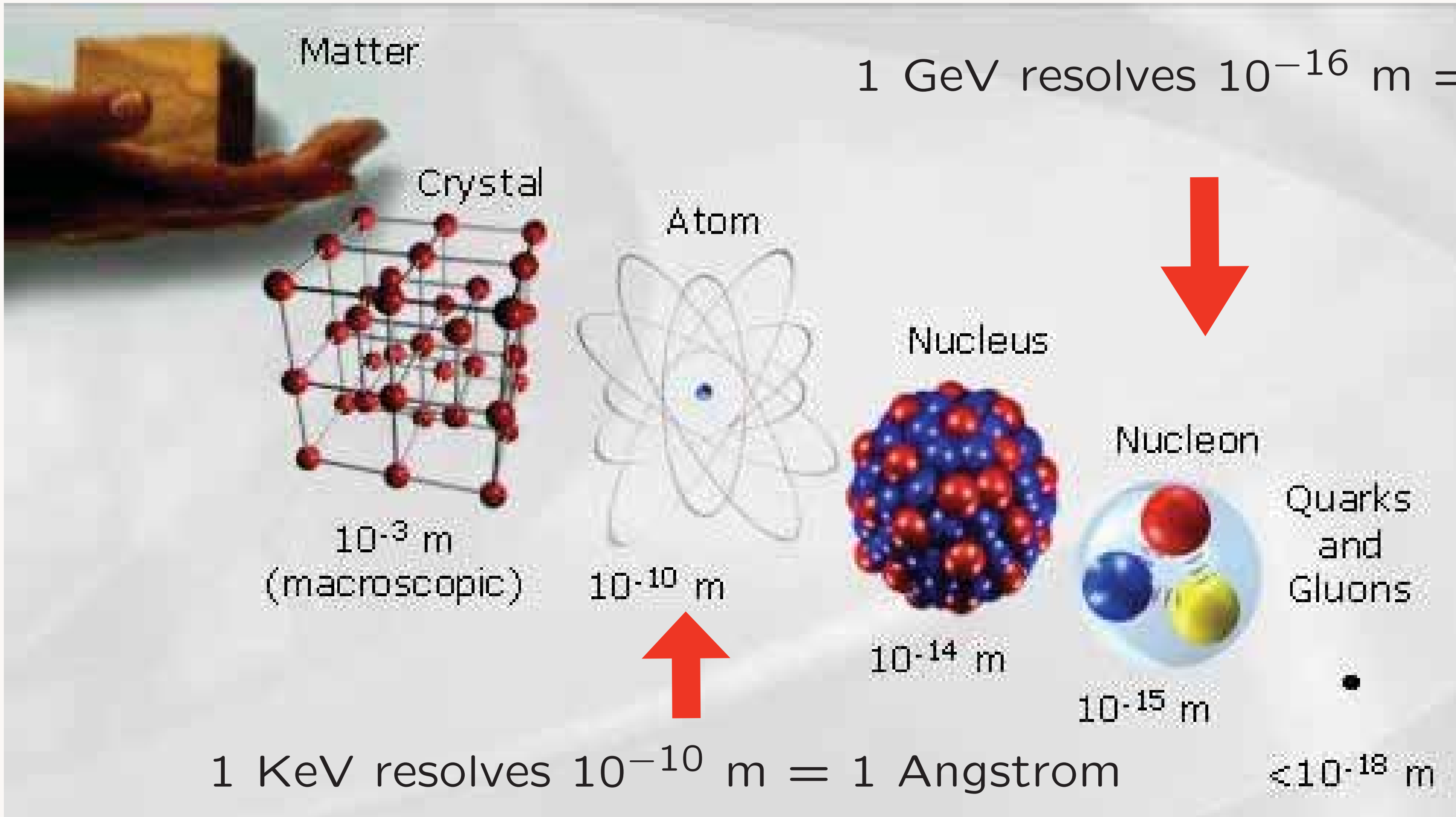
- **International Influence throughout Atomic, Nuclear, Electroweak, High Energy Physics**
- **Fundamentals of Quantum Field Theory**
- **CP Invariance, Neutrino Physics**
- **Renormalization theory, Landau Singularity**
- **Remarkable Students, Legacy of Russian Schools**

Physical Intuition!



Searching for the Ultimate Constituents

1 GeV resolves 10^{-16} m = 0.1 fm



1 KeV resolves 10^{-10} m = 1 Angstrom

Electrons, Quarks, and Gluons may be truly pointlike!

1 TeV resolves 10^{-19} m = 0.0001 fm

THE PERIODIC TABLE

Particles like the electron (fermions, spin 1/2)

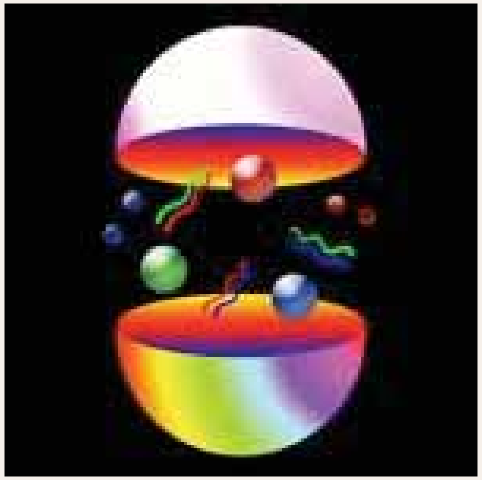
Leptons		Quarks (each in 3 "colors")	
e 0.511 MeV	ν_e < 0.000003	d 7	u 3
μ 106	ν_μ < 0.2	s 120	c 1200
τ 1777	ν_τ < 20	b 4300	t 175,000
-1	0	$-1/3$	$2/3$ ← charge

Particles like the photon (bosons, spin 1)

γ 0	photon	"electromagnetism"
g 0	gluon (8 "colors")	"strong interaction"
$W^\pm$ 80,420	Z^0 91,188	"weak interaction"

The World of Quarks and Gluons:

- Quarks and Gluons: Fundamental constituents of hadrons and nuclei



- Remarkable and novel properties of *Quantum Chromodynamics (QCD)*
- New Insights from higher space-time dimensions: Holography: AdS/CFT

QCD Lagrangian

gluon dynamics

quark kinetic energy + quark-gluon dynamics

mass term

$$L_{QCD} = -\frac{1}{4g^2} Tr(G^{\mu\nu} G_{\mu\nu}) + \sum_{f=1}^{n_f} i \bar{\Psi}_f D_\mu \gamma^\mu \Psi_f + \sum_{f=1}^{n_f} m_f \bar{\Psi}_f \Psi_f$$

QCD color charge

field strength tensor

covariant derivative

quark field

Yang-Mills Gauge Principle: Invariance under Color Rotation and Phase Change at Every Point of Space and Time

Dimensionless Coupling

Renormalizable

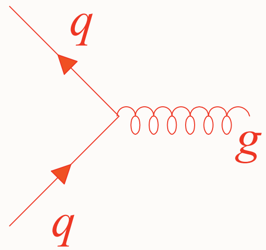
Asymptotic Freedom

Color Confinement

QCD

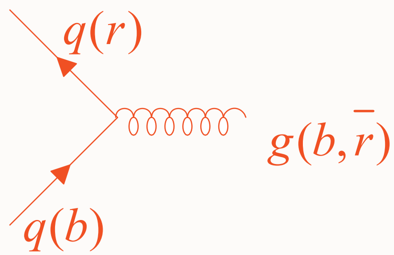
Fundamental Couplings

Only quarks and gluons involve basic vertices: Quark-gluon vertex



Similar to QED

More exactly



Gluon vertices

colored particles couple to gluons

QCD Lagrangian

gluon dynamics · quark kinetic energy + quark-gluon dynamics · mass term

$$L_{QCD} = -\frac{1}{4g^2} Tr(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{nf} i\, \overline{\psi_f}\, D_\mu \gamma^\mu \psi_f + \sum_{f=1}^{nf} m_f\, \overline{\psi_f}\, \psi_f$$

QCD color charge · field strength tensor · covariant derivative · quark field

$[C_F = \frac{N_C^2-1}{2N_C}]$

$\lim N_C \to 0$ at fixed $\alpha = C_F \alpha_s, n_\ell = n_F / C_F$

Analytic limit of QCD: Abelian Gauge Theory

QCD → QED

Huet, sjb

QED: Underlies Atomic Physics, Molecular Physics, Chemistry, Electromagnetic Interactions ...

QCD: Underlies Hadron Physics, Nuclear Physics,

Theoretical Tools:

- Feynman diagrams and perturbation theory, evolution equations
- Bethe Salpeter and Dyson-Schwinger Equations
- Lattice Gauge Theory
- Discretized Light-Front Quantization
- AdS/CFT !

Given the elementary gauge theory interactions, all fundamental processes described in principle!

Example from QED:

Electron gyromagnetic moment - ratio of spin precession frequency to Larmor frequency in a magnetic field

$\frac{1}{2}g_e = 1.001\ 159\ 652\ 201(30)$ QED prediction (Kinoshita, et al.)

$\frac{1}{2}g_e = 1.001\ 159\ 652\ 193(10)$ Measurement (Dehmelt, et al.)

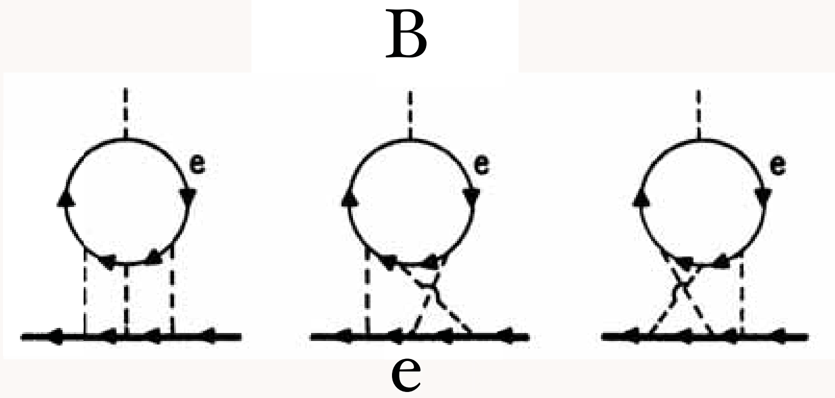
$\frac{1}{2}g_e = 1.001\ 159\ 652\ 180\ 85\ [0.76\ ppt]$

Dirac: $g_e \equiv 2$ Measurement (Gabrielse, et al.)

QED provides an asymptotic series relating g and α,

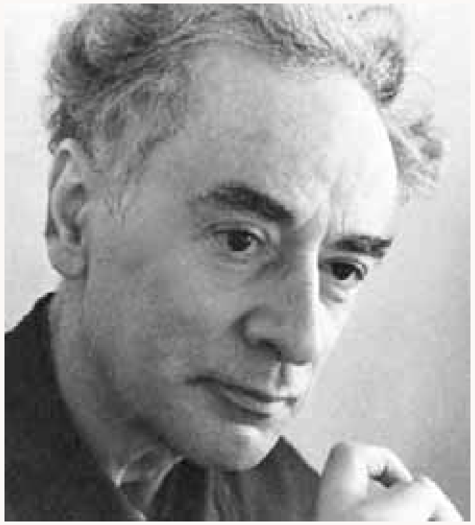
$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + \ldots$$
$$+ a_{\mu\tau} + a_{\mathrm{hadronic}} + a_{\mathrm{weak}},$$

Light-by-Light Scattering Contribution to C_6

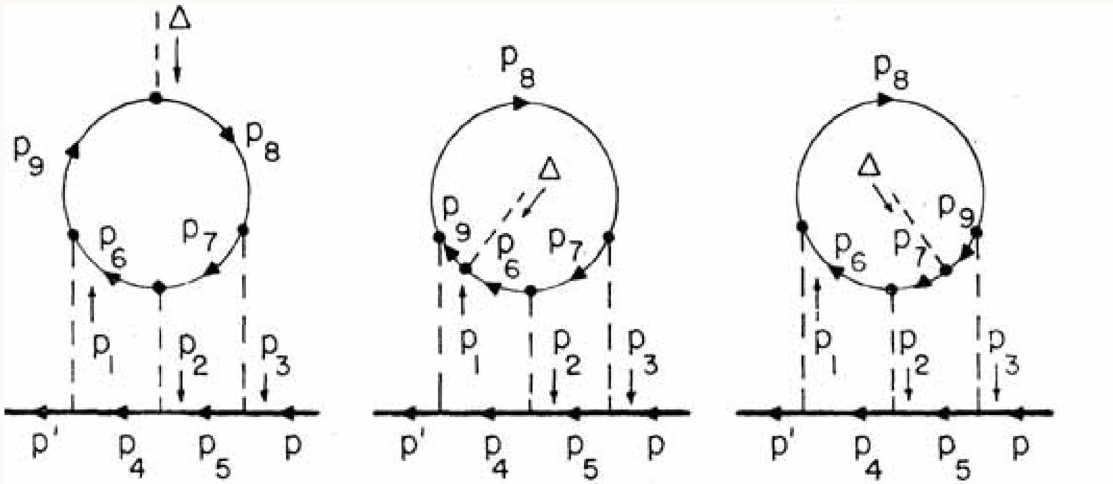


$$\alpha^{-1} = 137.035\,999\,710\,(90)\,(33)\,[0.66\ \mathrm{ppb}][0.24\ \mathrm{ppb}],$$
$$= 137.035\,999\,710\,(96)\,[0.70\ \mathrm{ppb}].$$

G. Gabrielse, D. Hanneke, T. Kinoshita, M. Nio, and B. Odom, Phys. Rev. Lett. **97**, 030802 (2006).



In 1959 Landau and Bjorken developed,
independently and simultaneously,
the analogy of Feynman graphs
to electrical circuit theory
and the use of Kirchhoff's laws
to analyze their singularity structure



Light-by-light contribution to
the muon and electron anomalous magnetic moments

Aldins, Dufner, Kinoshita, sjb

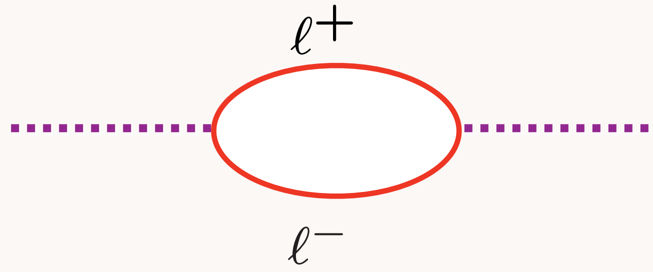
Electron-Electron Scattering in QED

$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$

$$\alpha(t) = \frac{\alpha(0)}{1 - \Pi(t)}$$

Gell Mann-Low Effective Charge

QED One-Loop Vacuum Polarization



$t = -Q^2 < 0$

(t spacelike)

$$\Pi(Q^2) = \frac{\alpha(0)}{3\pi}\left[\frac{5}{3} - \frac{4m^2}{Q^2} - \left(1 - \frac{2m^2}{Q^2}\right)\sqrt{1 + \frac{4m^2}{Q^2}}\log\frac{1+\sqrt{1+\frac{4m^2}{Q^2}}}{\left|1-\sqrt{1+\frac{4m^2}{Q^2}}\right|}\right]$$

Analytically continue to timelike t: Complex

$$\Pi(Q^2) = \frac{\alpha(0)}{15\pi}\frac{Q^2}{m^2}$$ $Q^2 << 4M^2$ **Serber-Uehling**

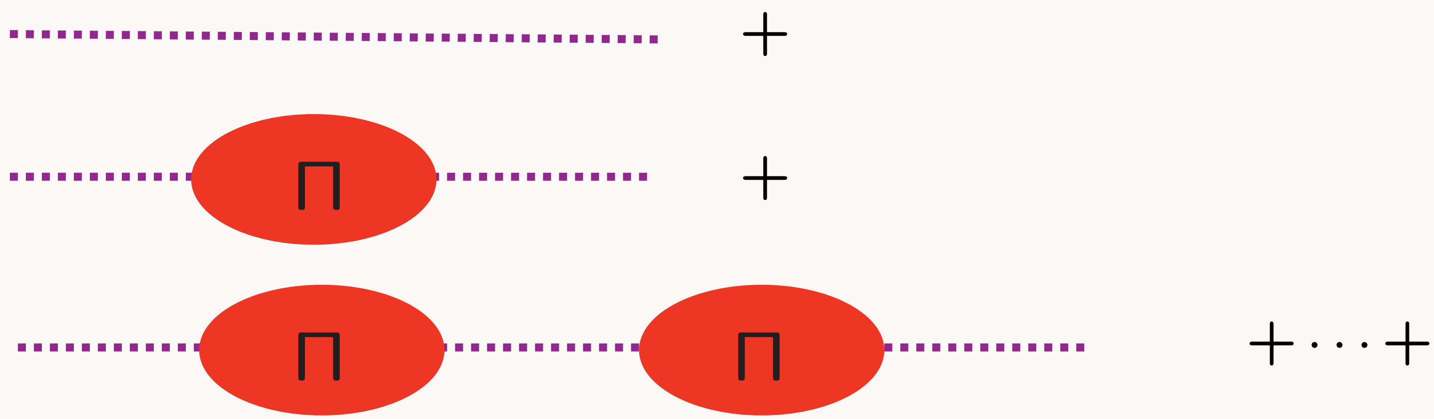
$$\Pi(Q^2) = \frac{\alpha(0)}{3\pi}\frac{\log Q^2}{m^2}$$ $Q^2 >> 4M^2$ **Landau Pole**

$$\beta = \frac{d(\frac{\alpha}{4\pi})}{d\log Q^2} = \frac{4}{3}\left(\frac{\alpha}{4\pi}\right)^2 n_\ell > 0$$

QED Effective Charge

$$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$$

All-orders lepton loop corrections to dressed photon propagator



$$\alpha(t) = \frac{\alpha(t_0)}{1-\Pi(t,t_0)} \qquad \Pi(t,t_0) = \frac{\Pi(t)-\Pi(t_0)}{1-\Pi(t_0)}$$

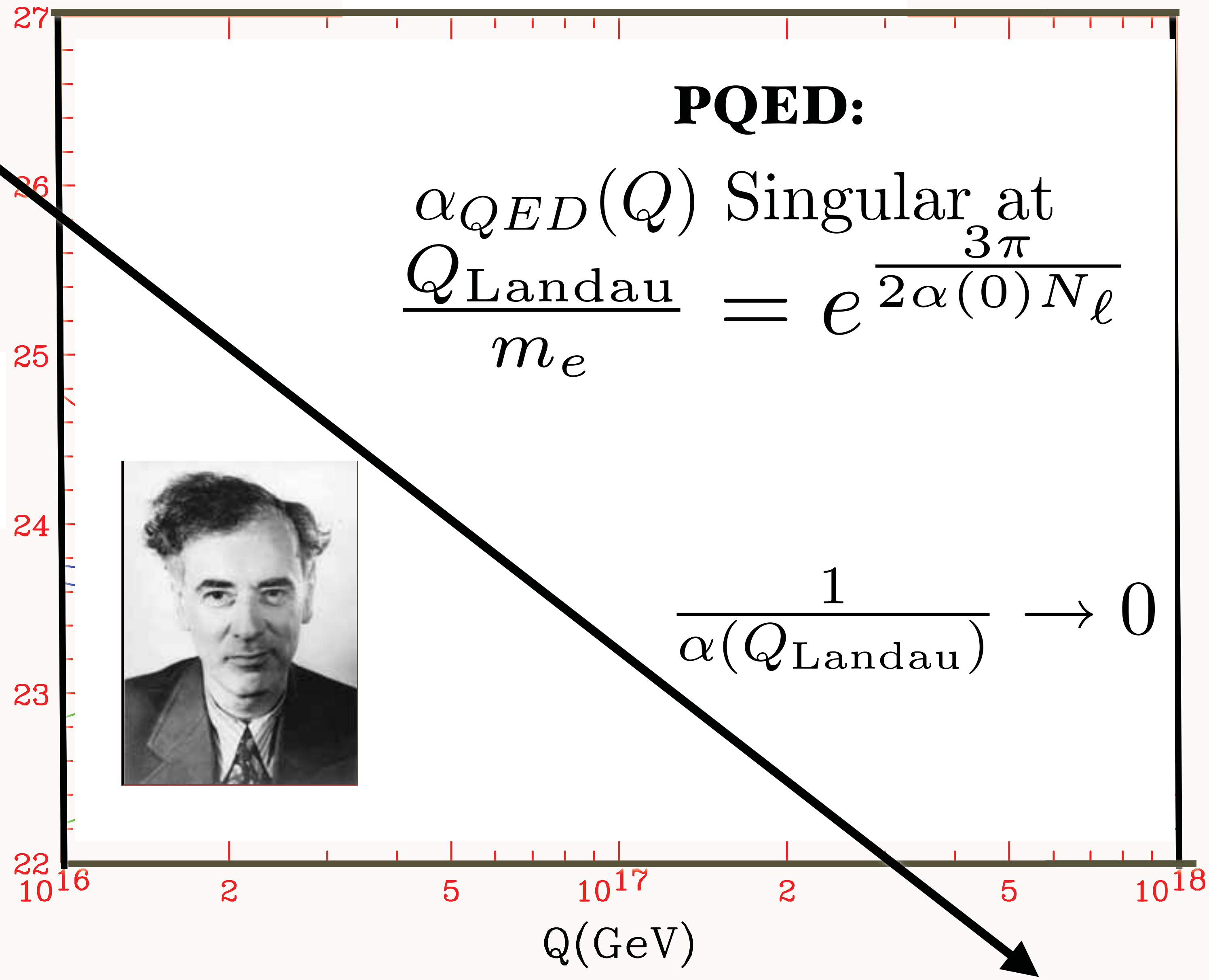
Initial scale t_0 is arbitrary -- Variation gives RGE Equations

Physical renormalization scale t never arbitrary

$\frac{1}{\alpha(0)} = 137.035999084(51)[0.37\text{ppb}]$

Landau Pole

$$\frac{1}{\alpha_{\rm QED}(Q)}$$



PQED:

$\alpha_{QED}(Q)$ Singular at

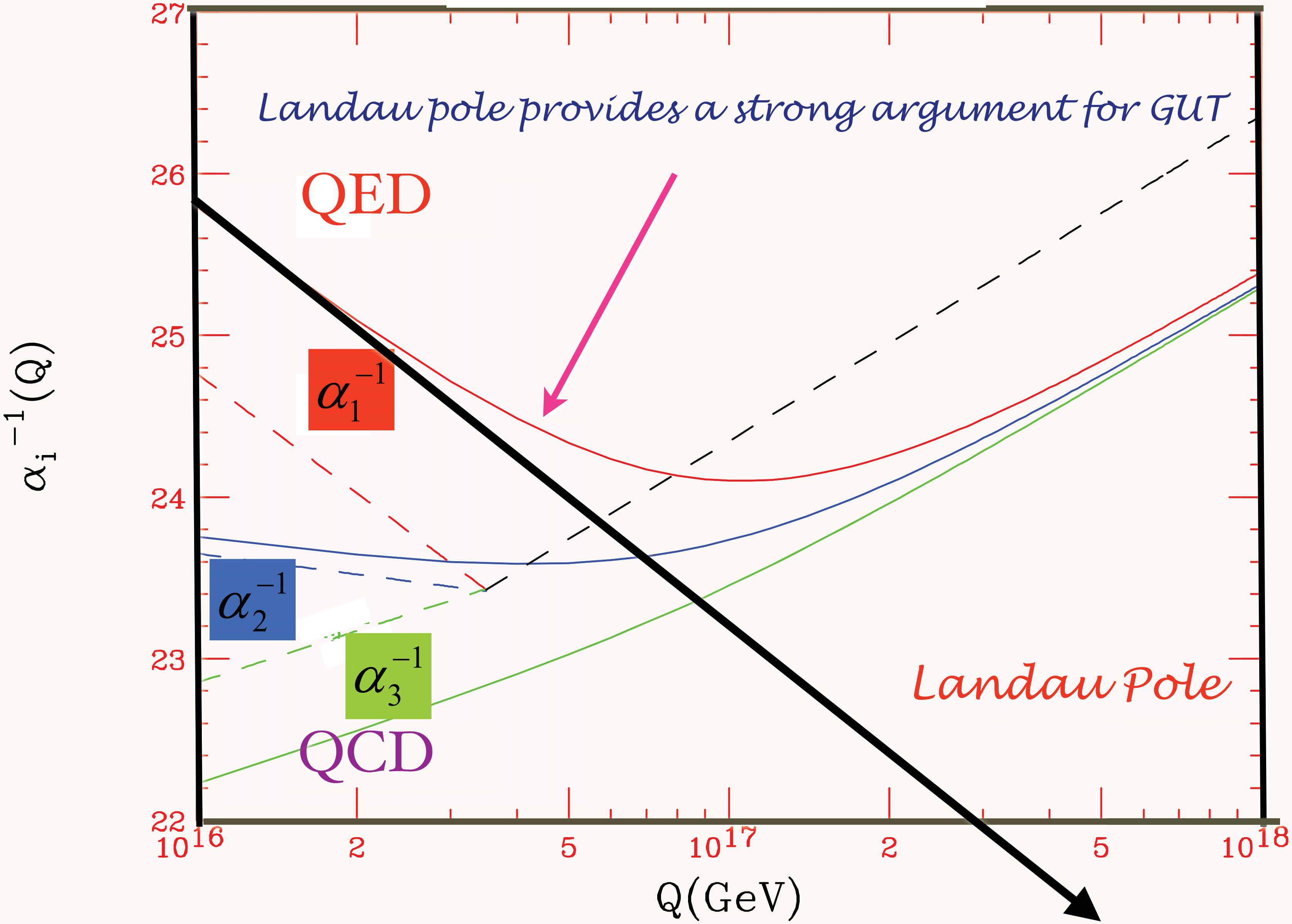
$$\frac{Q_{\rm Landau}}{m_e} = e^{\frac{3\pi}{2\alpha(0)N_\ell}}$$

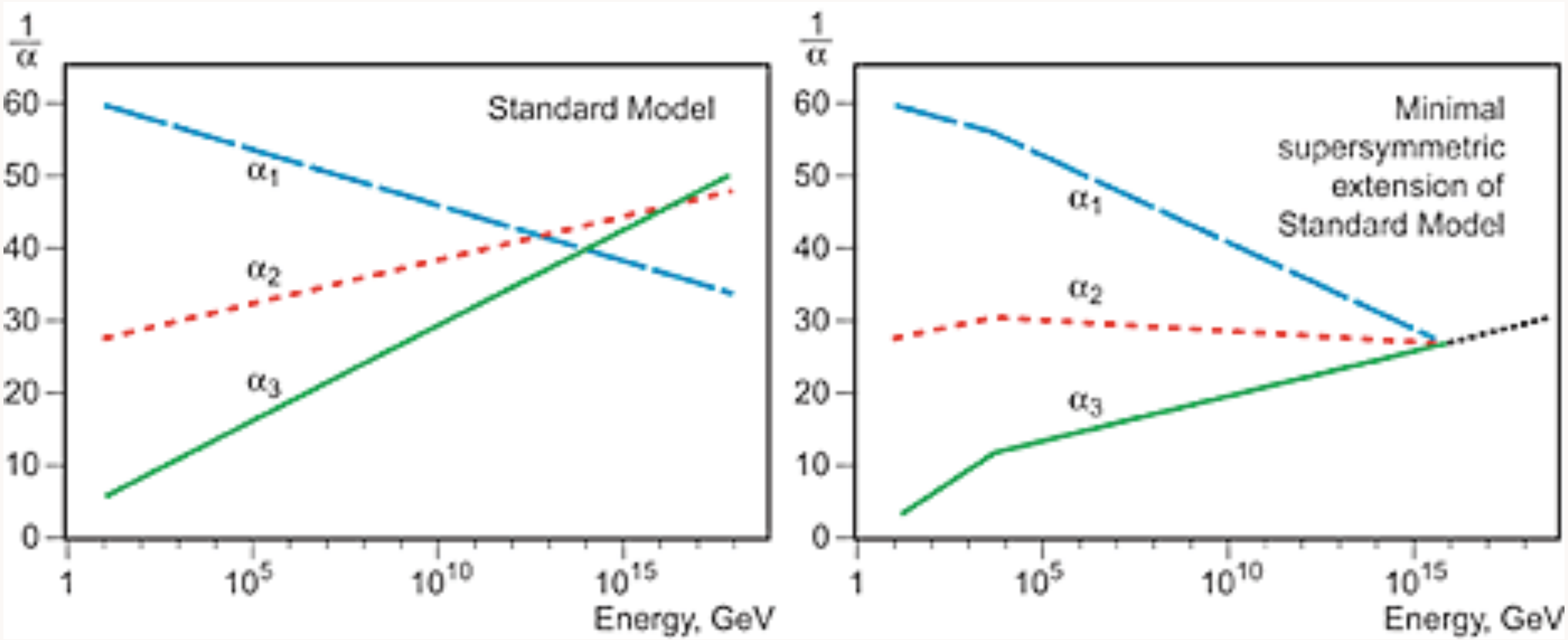
$$\frac{1}{\alpha(Q_{\rm Landau})} \to 0$$

Supersymmetric SU(5)

Coupling Unification

M. Binger, sjb

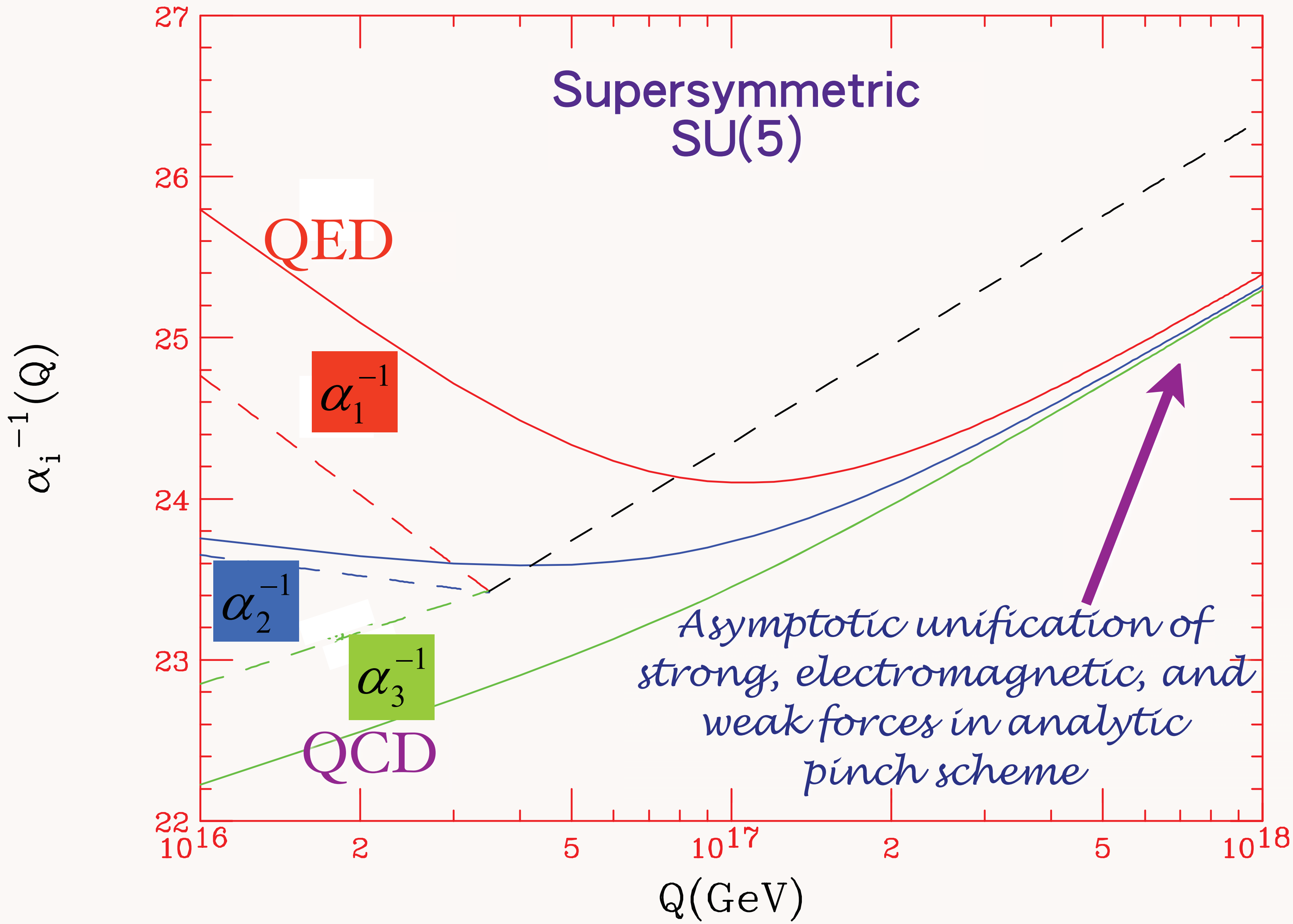




Coupling Unification in Nonanalytic $\overline{ms}$ Scheme

Analytic Coupling Unification

Binger, sjb



Lesson from QED:

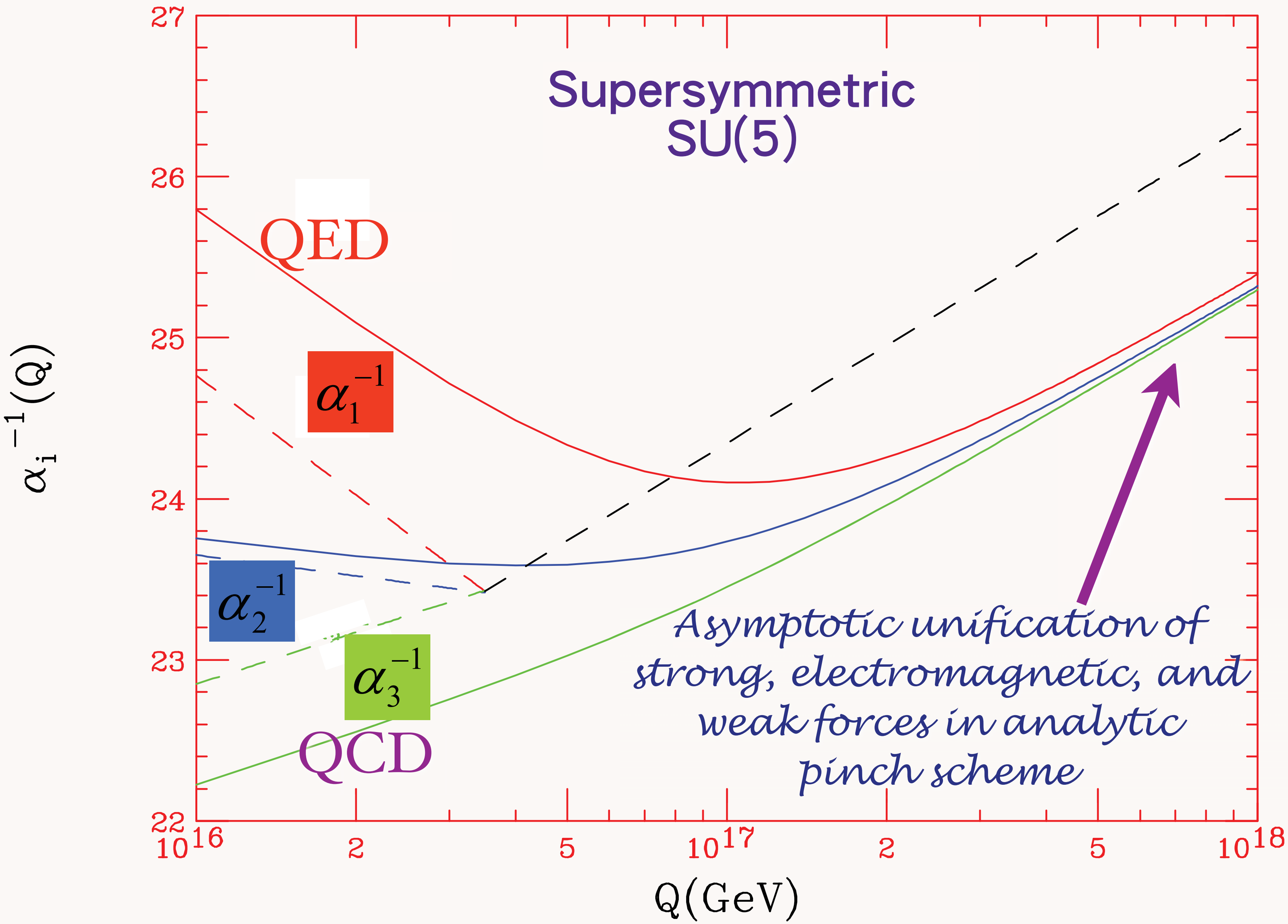
Use Physical Scheme to Characterize QCD Coupling

- Use Physical Observable to define QCD coupling
- No Renormalization Scale Ambiguity
- Analytic: Smooth behavior as one crosses new quark threshold
- New perspective on grand unification

Binger, Sjb

Analytic Coupling Unification

Binger, sjb



Lesson from QED:
Relate Observables to Each Other

- Eliminate intermediate scheme
- No scale ambiguity
- Transitive!
- Commensurate Scale Relations
- Example: Generalized Crewther Relation

$$R_{e^+e^-}(Q^2) \equiv 3 \sum_{\text{flavors}} e_q{}^2 \left[1 + \frac{\alpha_R(Q)}{\pi} \right].$$

$$\int_0^1 dx \left[g_1^{ep}(x, Q^2) - g_1^{en}(x, Q^2) \right] \equiv \frac{1}{3} \left| \frac{g_A}{g_V} \right| \left[1 - \frac{\alpha_{g_1}(Q)}{\pi} \right]$$

$$\frac{\alpha_R(Q)}{\pi} = \frac{\alpha_{\overline{MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^2 \left[\left(\frac{41}{8} - \frac{11}{3}\zeta_3\right) C_A - \frac{1}{8}C_F + \left(-\frac{11}{12} + \frac{2}{3}\zeta_3\right) f\right]$$

$$+ \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{90445}{2592} - \frac{2737}{108}\zeta_3 - \frac{55}{18}\zeta_5 - \frac{121}{432}\pi^2\right) C_A^2 + \left(-\frac{127}{48} - \frac{143}{12}\zeta_3 + \frac{55}{3}\zeta_5\right) C_A C_F - \frac{23}{32}C_F^2\right.$$

$$+ \left[\left(-\frac{970}{81} + \frac{224}{27}\zeta_3 + \frac{5}{9}\zeta_5 + \frac{11}{108}\pi^2\right) C_A + \left(-\frac{29}{96} + \frac{19}{6}\zeta_3 - \frac{10}{3}\zeta_5\right) C_F\right] f$$

$$\left. + \left(\frac{151}{162} - \frac{19}{27}\zeta_3 - \frac{1}{108}\pi^2\right) f^2 + \left(\frac{11}{144} - \frac{1}{6}\zeta_3\right) \frac{d^{abc}d^{abc}}{C_F d(R)} \frac{\left(\sum_f Q_f\right)^2}{\sum_f Q_f^2}\right\}.$$

$$\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_{\overline{MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^2 \left[\frac{23}{12}C_A - \frac{7}{8}C_F - \frac{1}{3}f\right]$$

$$+ \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{5437}{648} - \frac{55}{18}\zeta_5\right) C_A^2 + \left(-\frac{1241}{432} + \frac{11}{9}\zeta_3\right) C_A C_F + \frac{1}{32}C_F^2\right.$$

$$\left. + \left[\left(-\frac{3535}{1296} - \frac{1}{2}\zeta_3 + \frac{5}{9}\zeta_5\right) C_A + \left(\frac{133}{864} + \frac{5}{18}\zeta_3\right) C_F\right] f + \frac{115}{648}f^2\right\}.$$

Eliminate MSbar, Find Amazing Simplification

$$R_{e^+e^-}(Q^2) \equiv 3 \sum_{\text{flavors}} e_q{}^2 \left[1 + \frac{\alpha_R(Q)}{\pi}\right].$$

$$\int_0^1 dx \left[g_1^{ep}(x,Q^2) - g_1^{en}(x,Q^2)\right] \equiv \frac{1}{3}\left|\frac{g_A}{g_V}\right| \left[1 - \frac{\alpha_{g_1}(Q)}{\pi}\right]$$

$$\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_R(Q^*)}{\pi} - \left(\frac{\alpha_R(Q^{**})}{\pi}\right)^2 + \left(\frac{\alpha_R(Q^{***})}{\pi}\right)^3$$

Geometric Series in Conformal QCD

Generalized Crewther Relation

Lu, Kataev, Gabadadze, Sjb

Lu, Kataev, Gabadadze, Sjb

Generalized Crewther Relation

$$[1+\frac{\alpha_R(s^*)}{\pi}][1-\frac{\alpha_{g_1}(q^2)}{\pi}]=1$$

$$\sqrt{s^*}\simeq 0.52Q$$

Conformal relation true to all orders in perturbation theory

No radiative corrections to axial anomaly

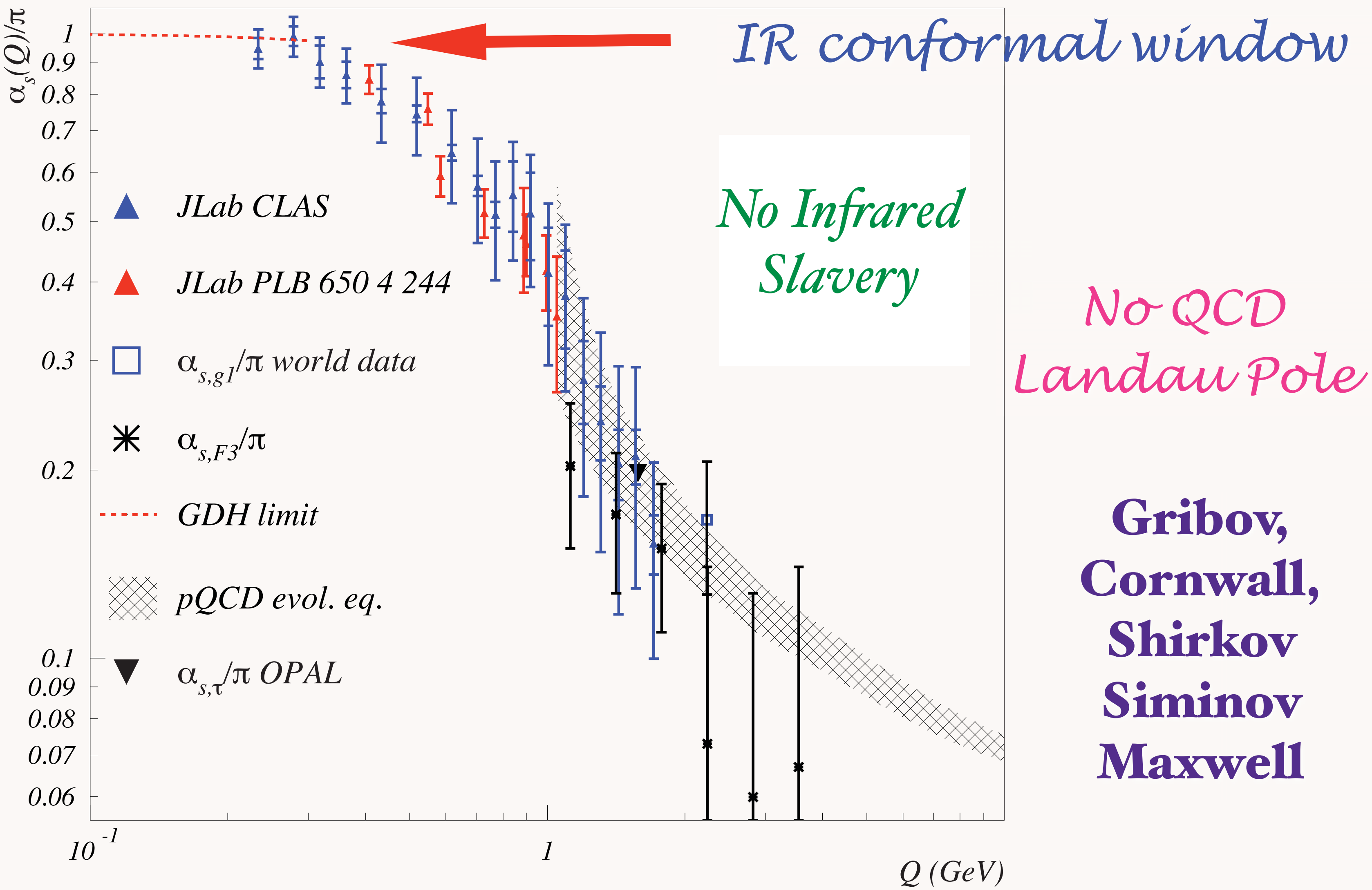
Nonconformal terms set relative scales (BLM)

Analytic matching at quark thresholds

No renormalization scale ambiguity!

Deur, Korsch, et al: Effective Charge from Bjorken Sum Rule

$$\Gamma_{bj}^{p-n}(Q^2) \equiv \frac{g_A}{6}\left[1 - \frac{\alpha_s^{g_1}(Q^2)}{\pi}\right]$$



Gribov, Cornwall, Shirkov Siminov Maxwell

Lesson from QED:

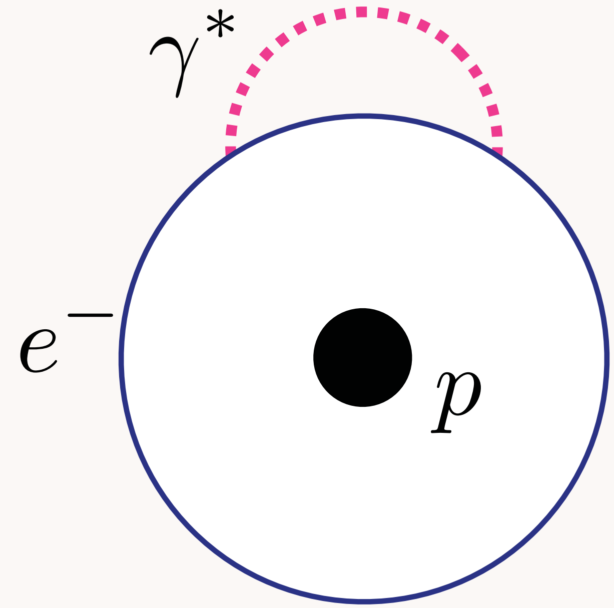
Lamb Shift in Hydrogen

$$\Delta E \sim \alpha (Z\alpha)^4 \ln (Z\alpha)^2 m_e$$

Bethe Log

$$\lambda < \frac{1}{Z\alpha m_e}$$

$$k > Z\alpha m_e$$



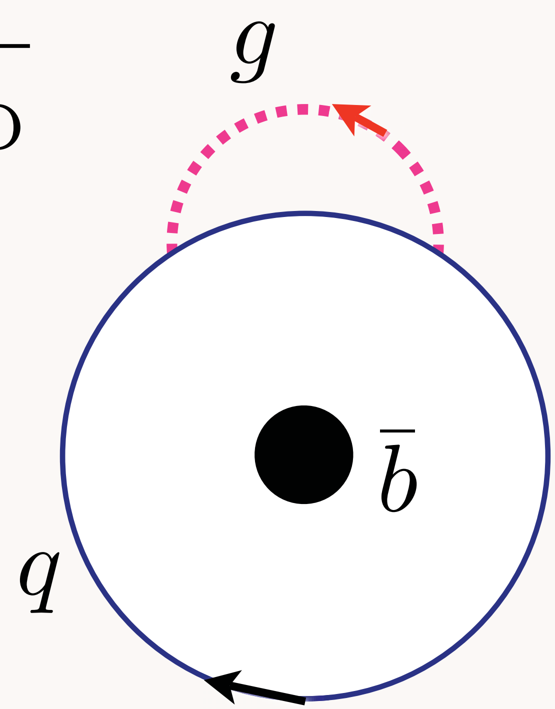
Maximum wavelength of bound electron

Infrared divergence of free electron propagator removed because of atomic binding

Lesson from QED and Lamb Shift:

maximum wavelength of bound quarks and gluons

$$k > \frac{1}{\Lambda_{QCD}} \qquad \lambda < \Lambda_{QCD}$$



B-Meson

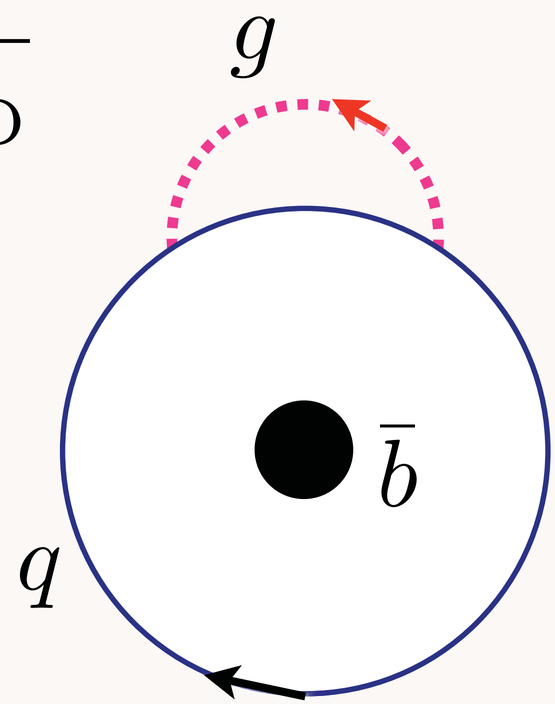
Shrock, sjb

gluon and quark propagators cutoff in IR because of color confinement

Lesson from QED and Lamb Shift:

maximum wavelength of bound quarks and gluons

$$k > \frac{1}{\Lambda_{\rm QCD}} \qquad \lambda < \Lambda_{\rm QCD}$$



B-Meson

Shrock, sjb

Use Dyson-Schwinger Equation for bound-state quark propagator: find confined condensate

$$< \bar b | \bar q q | \bar b > \text{ not } < 0 | \bar q q | 0 >$$

Lesson from QED and Lamb Shift:

Consequences of Maximum Quark and Gluon Wavelength

- Infrared integrations regulated by confinement
- Infrared fixed point of QCD coupling

$$\alpha_s(Q^2) \text{ finite}, \beta \to 0 \text{ at small } Q^2$$

- Bound state quark and gluon Dyson-Schwinger Equation
- Quark and Gluon Condensates exist within hadrons

Shrock, sjb

Determinations of the vacuum Gluon Condensate

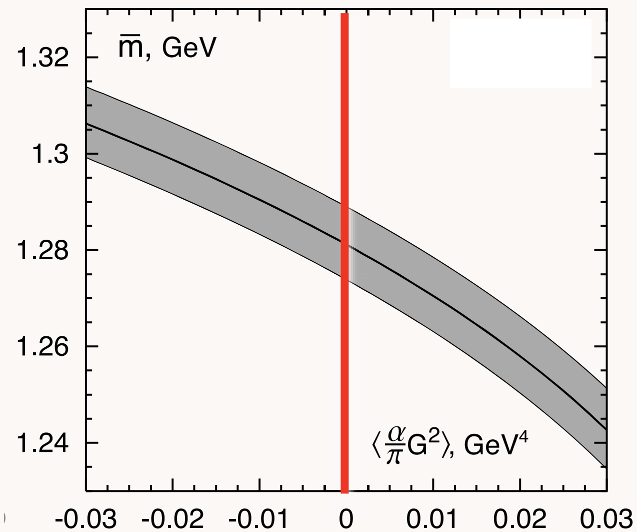
$$< 0|\frac{\alpha_s}{\pi} G^2|0 > [\mathrm{GeV}^4]$$

-0.005 ± 0.003 from τ decay. Davier et al.

$+0.006 \pm 0.012$ from τ decay. Geshkenbein, Ioffe, Zyablyuk

$+0.009 \pm 0.007$ from charmonium sum rules

Ioffe, Zyablyuk



Consistent with zero vacuum condensate

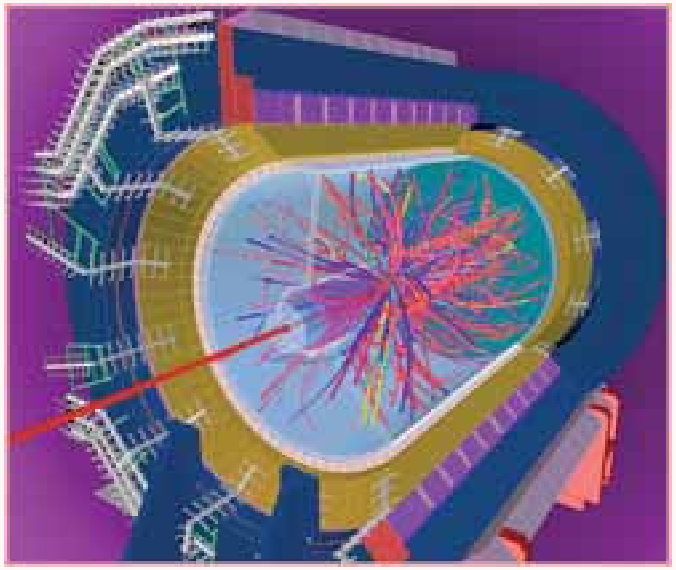
Quark and Gluon condensates reside within hadrons, not vacuum

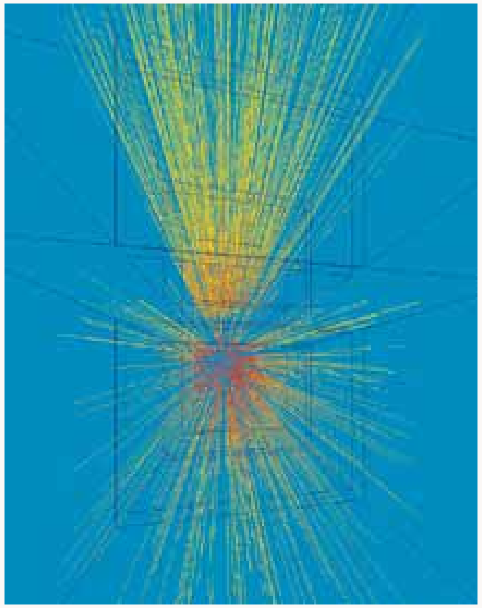
- Bound-State Dyson-Schwinger Equations
- Domain becomes infinite at zero pion mass
- Finite size phase transition
- Analogous to finite-size superconductor! M. Fisher
- Phase change observed at RHIC within a single-nucleus-nucleus collisions-- quark gluon plasma!
- Implications for cosmological constant -- reduction by 55 orders of magnitude!

"Confined QCD Condensates" Shrock, sjb

Collide Gold Nuclei Together

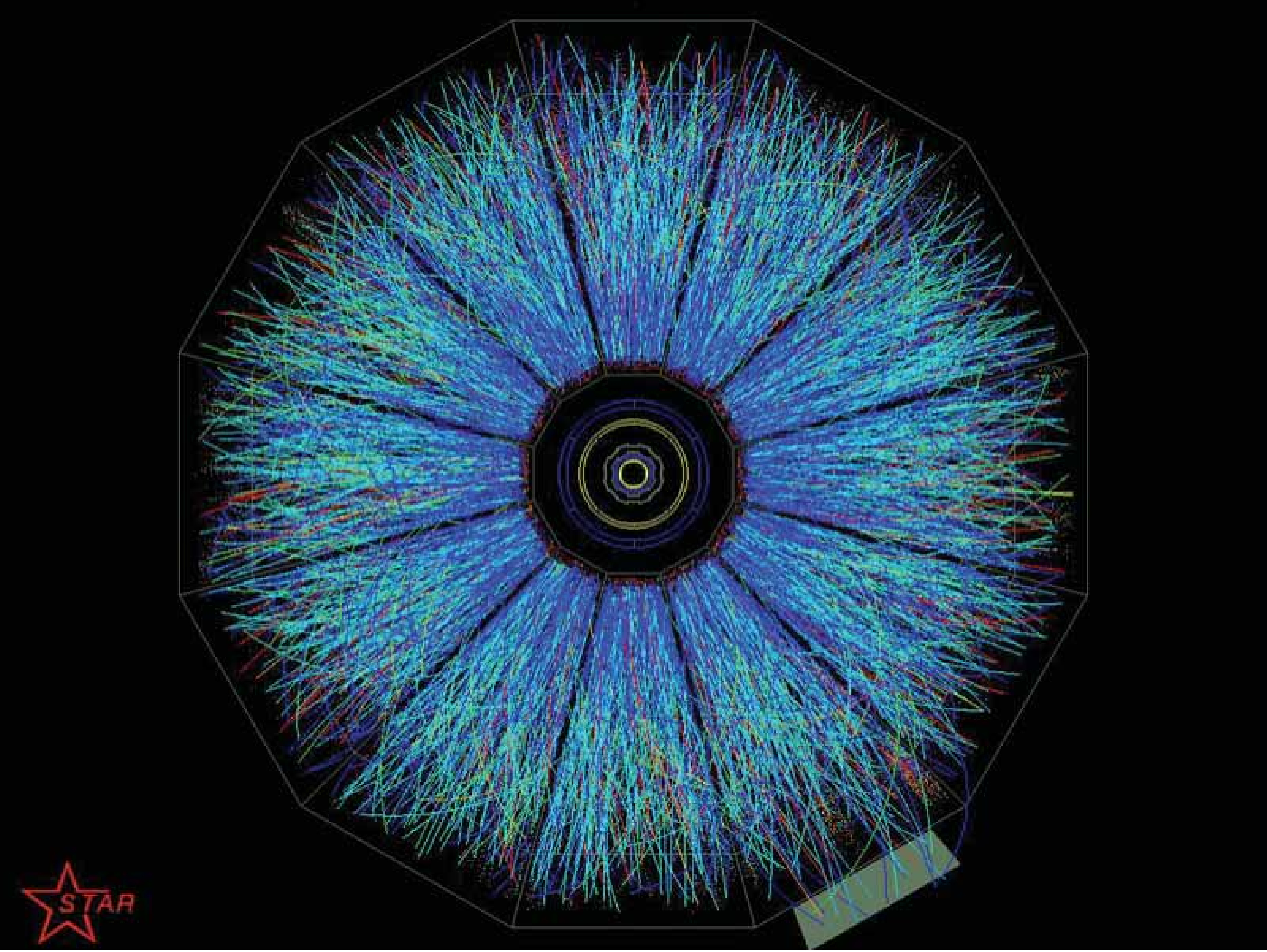
STAR Time-Projection Chamber at RHIC



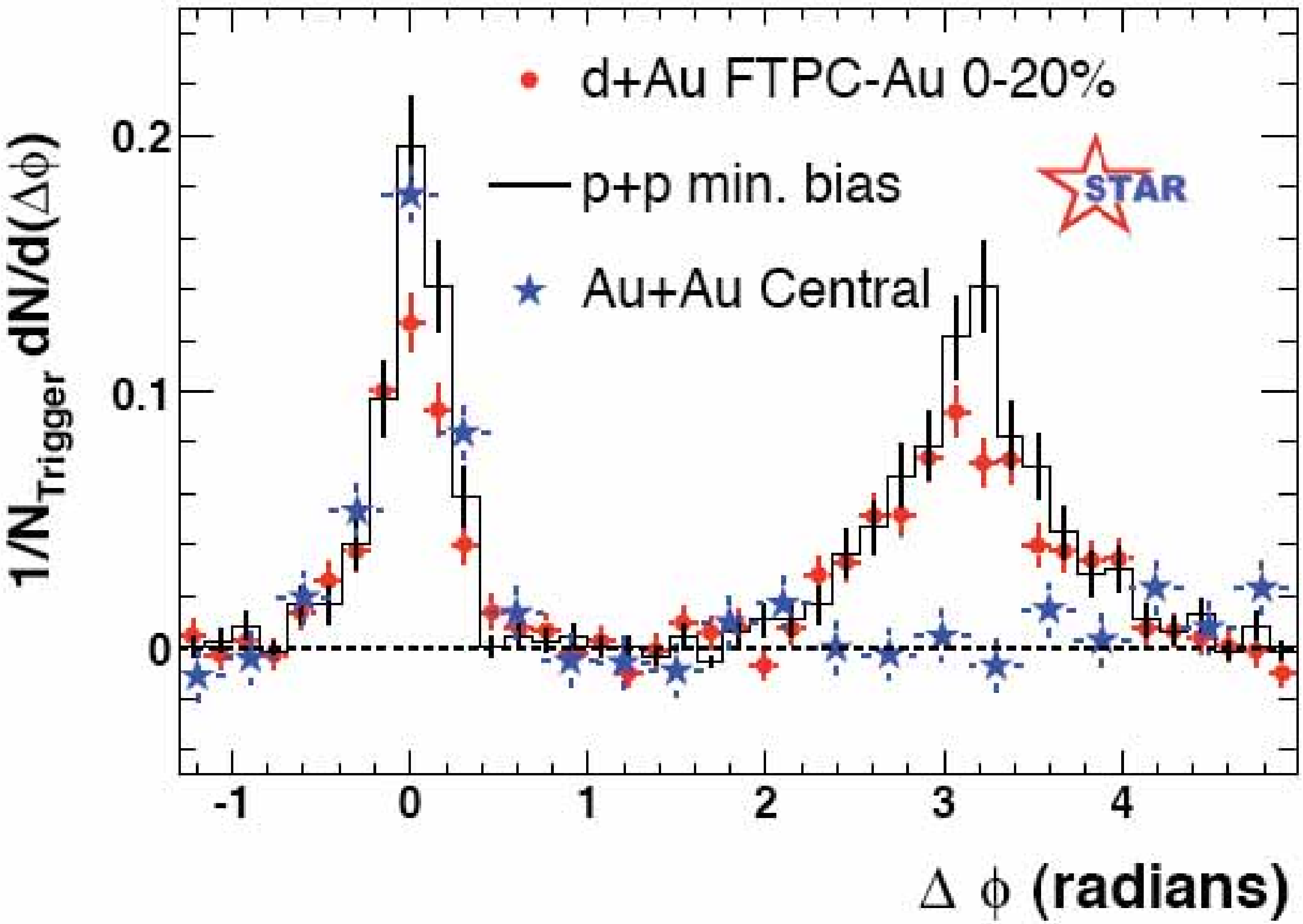


Produce thousands of particles in each collision

Evidence of Quark-Gluon Plasma


STAR

Away-side particles quenched in Au-Au Collisions

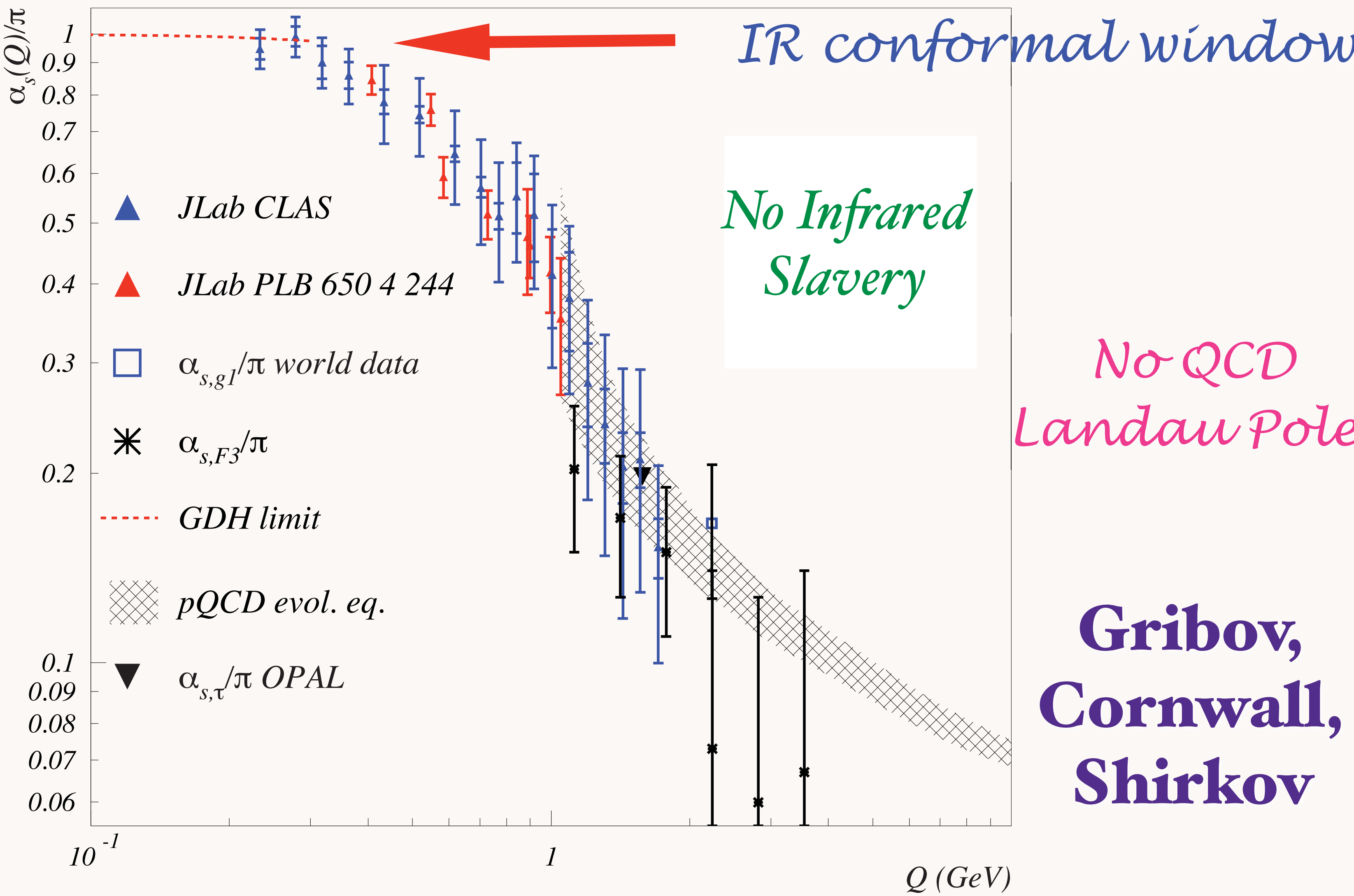


Gluon density 50 times more dense than cold nuclear matter !

Phase change within a single nucleus-nucleus collision

Deur, Korsch, et al: Effective Charge from Bjorken Sum Rule

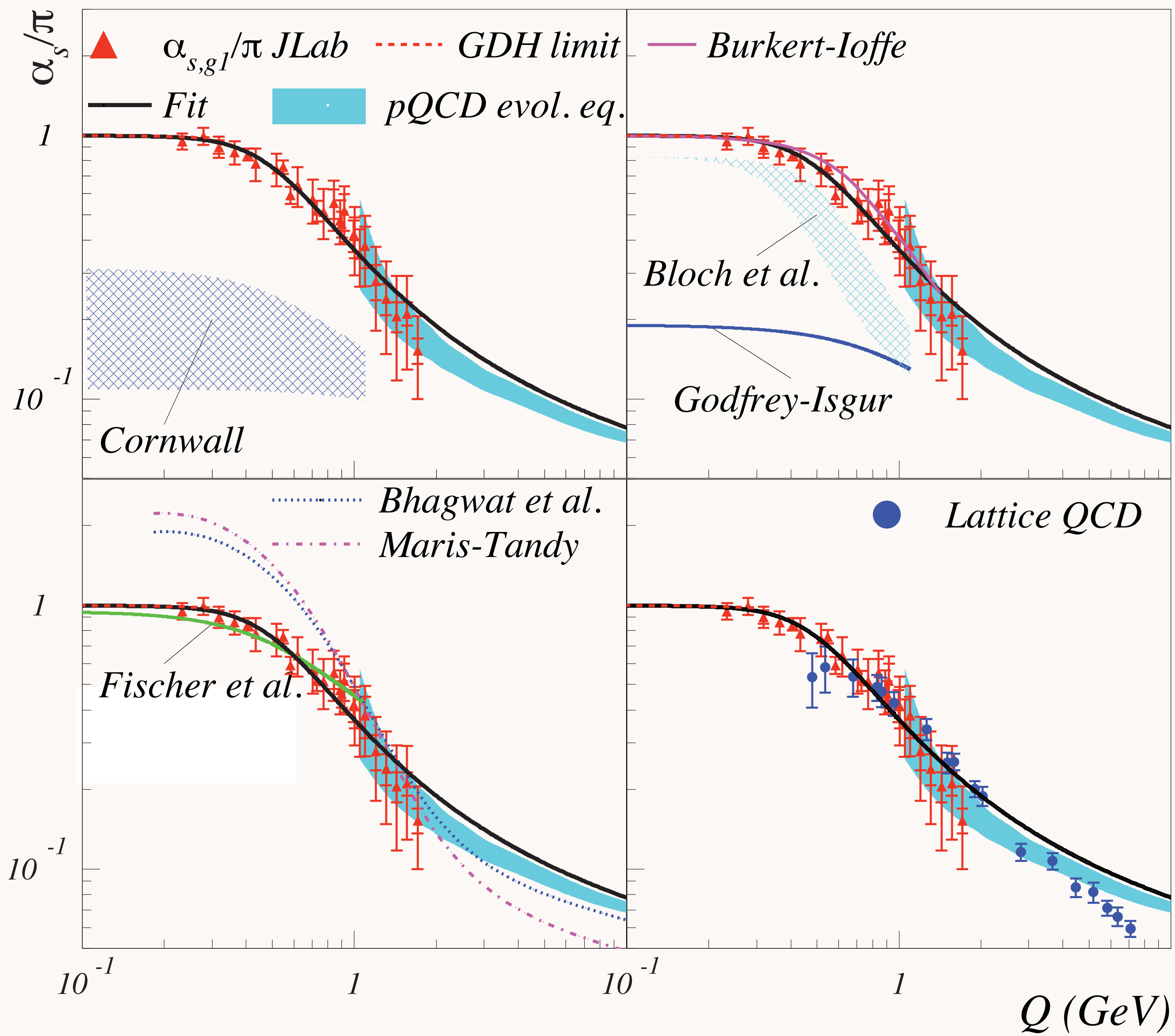
$$\Gamma_{bj}^{p-n}(Q^2) \equiv \frac{g_A}{6}\left[1 - \frac{\alpha_s^{g_1}(Q^2)}{\pi}\right]$$



No QCD Landau Pole!

Gribov, Cornwall, Shirkov

Deur, Korsch, et al.



IR Conformal Window for QCD

- *Dyson-Schwinger Analysis:* **QCD Coupling has IR Fixed Point**

- *Evidence from Lattice Gauge Theory*

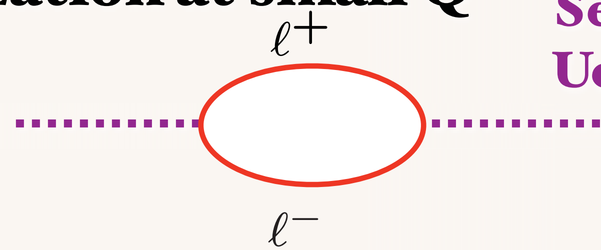
- Define coupling from observable: **indications of IR fixed point for QCD effective charges**

- **Confined gluons and quarks have maximum wavelength**

Shrock, de Teramond, sjb

- **Decoupling of QCD vacuum polarization at small Q²**

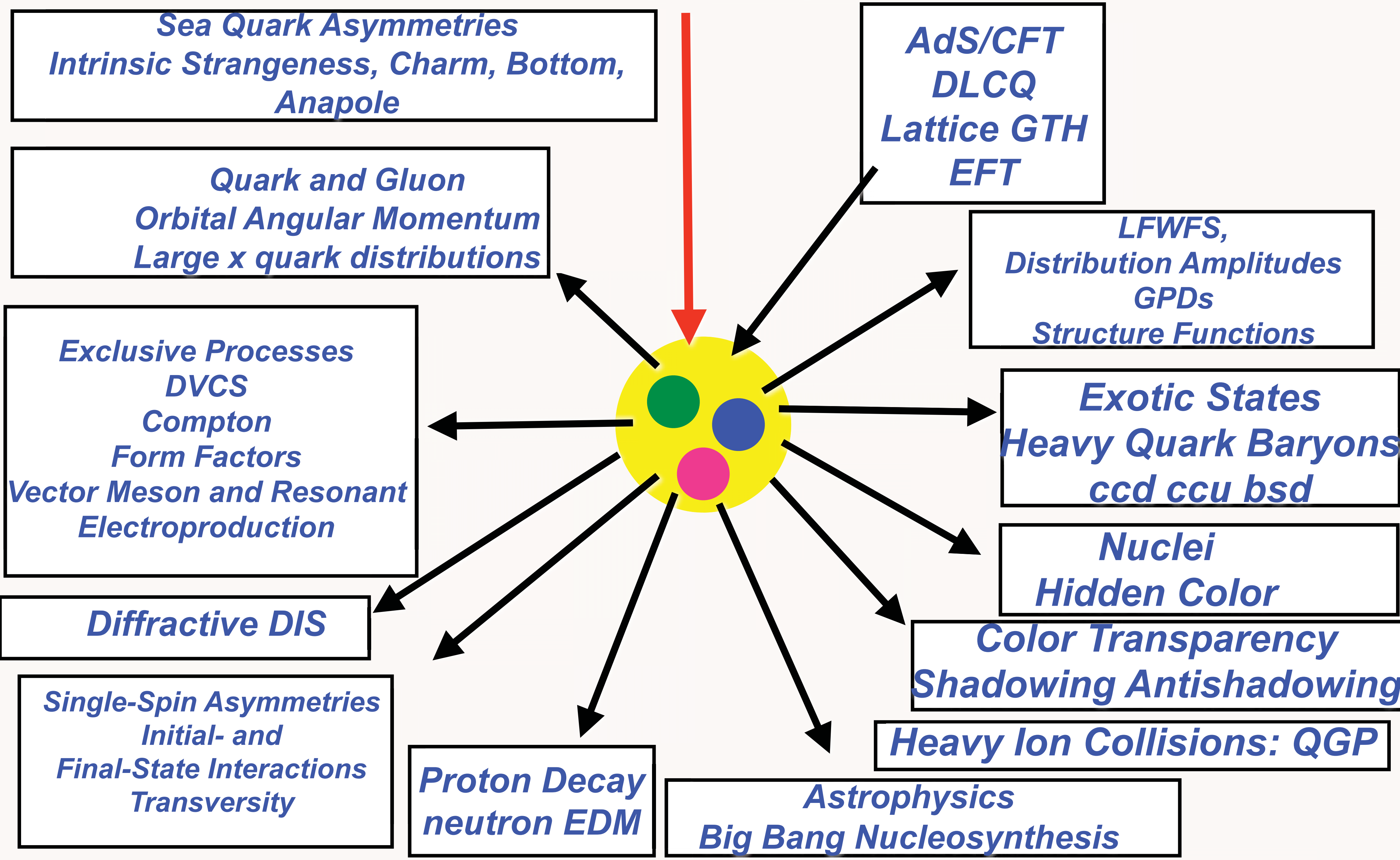
$$\Pi(Q^2) \to \frac{\alpha}{15\pi}\frac{Q^2}{m^2} \qquad Q^2 << 4m^2$$



Serber-Uehling

- **Justifies application of AdS/CFT in strong-coupling conformal window**

QCD Lagrangian



- Although we know the QCD Lagrangian, we have only begun to understand its remarkable properties and features.

- Novel QCD Phenomena: hidden color, color transparency, strangeness asymmetry, intrinsic charm, anomalous heavy quark phenomena, anomalous spin effects, single-spin asymmetries, odderon, diffractive deep inelastic scattering, dangling gluons, shadowing, antishadowing, QGP, CGL, ...

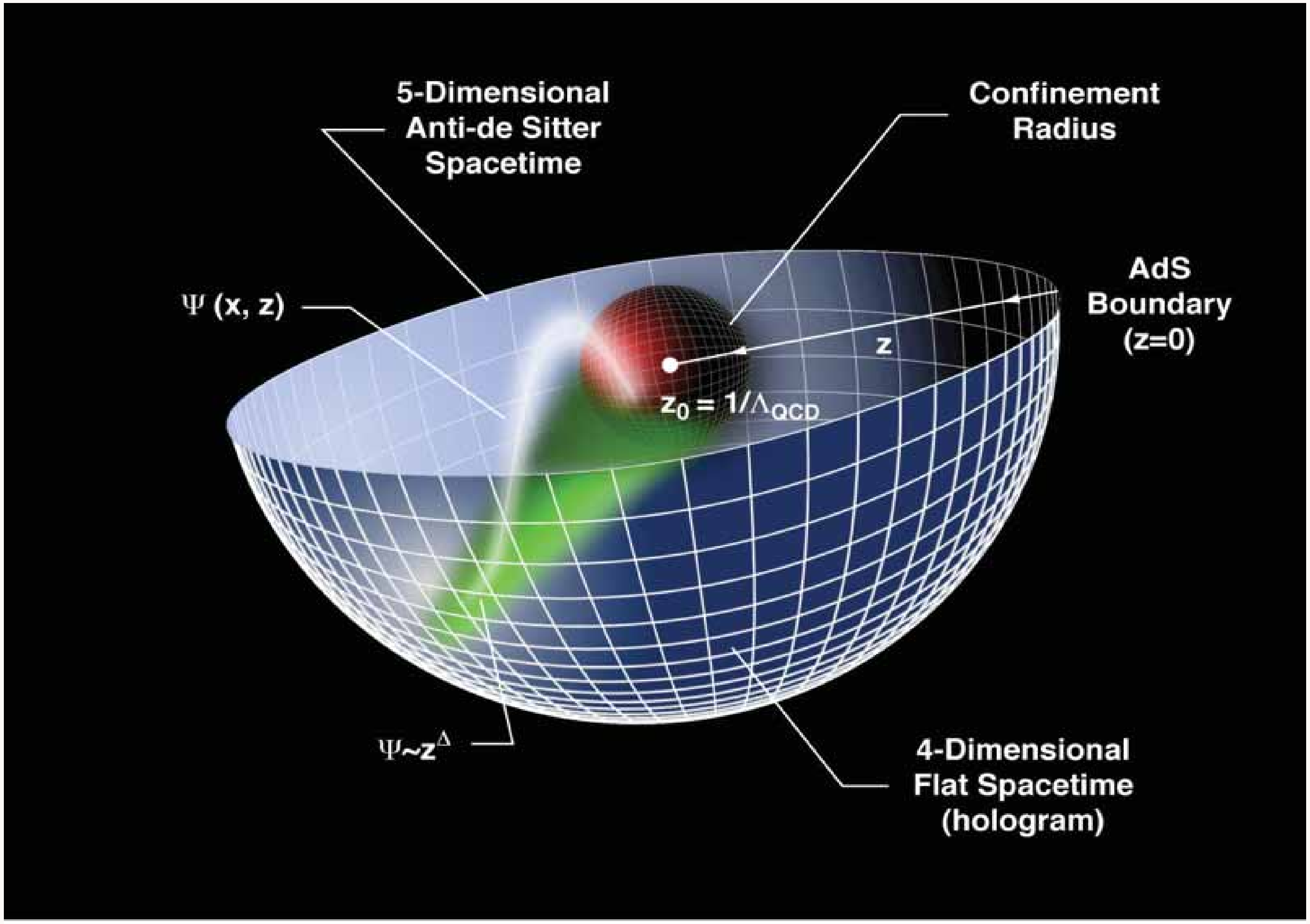
*Truth is stranger than fiction,
but it is because Fiction is
obliged to stick to possibilities.*

—Mark Twain

The World of Quarks and Gluons:

- Quarks and Gluons: Fundamental constituents of hadrons and nuclei
- Remarkable and novel properties of *Quantum Chromodynamics (QCD)*
- New Insights from higher space-time dimensions: Light-Front Holography: AdS/CFT

Applications of AdS/CFT to QCD



Changes in physical length scale mapped to evolution in the 5th dimension z

in collaboration with Guy de Teramond

Goal:

- **Use AdS/CFT to provide an approximate, covariant, and analytic model of hadron structure with confinement at large distances, conformal behavior at short distances**
- **Analogous to the Schrodinger Theory for Atomic Physics**
- *AdS/QCD Light-Front Holography*
- *Hadronic Spectra and Light-Front Wavefunctions*
- *Hadronization at the Amplitude Level*