Scalar QCD

Axel Maas
with Tajdar Mufti

5th of September 2013
QCD TNT III
Trento
Italy

Scalar QCD

Bound States, Elementary Particles & Interaction Vertices

Axel Maas
with Tajdar Mufti

5th of September 2013
QCD TNT III
Trento
Italy

Why Scalar QCD?

- Only confinement – no chiral symmetry breaking
  - Confinement independent of Lorentz structure

Why Scalar QCD?

- Only confinement – no chiral symmetry breaking
  - Confinement independent of Lorentz structure
- Simple(r) tensor structures

Why Scalar QCD?

- Only confinement – no chiral symmetry breaking
  - Confinement independent of Lorentz structure
- Simple(r) tensor structures
- Rich bound state spectrum

Why Scalar QCD?

- Only confinement – no chiral symmetry breaking
  - Confinement independent of Lorentz structure
- Simple(r) tensor structures
- Rich bound state spectrum
- Cheap lattice simulations
  - Test case for functional equations

Why Scalar QCD?

- Only confinement – no chiral symmetry breaking
  - Confinement independent of Lorentz structure
- Simple(r) tensor structures
- Rich bound state spectrum
- Cheap lattice simulations
  - Test case for functional equations
- Limited by (possible) triviality
  - But triviality cutoff can be high enough

Scalar QCD

- Gauge theory

Scalar QCD

- Gauge theory

$$L = -\frac{1}{4} A^{a}_{\mu\nu} A^{\mu\nu}_{a}$$

$$A^{a}_{\mu\nu} = \partial_{\mu} A^{a}_{\nu} - \partial_{\nu} A^{a}_{\mu}$$

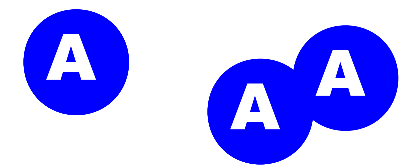
- Gluons A^{a}_{μ}

Scalar QCD

- Gauge theory

$$L = -\frac{1}{4} A^a_{\mu\nu} A^{\mu\nu}_a$$

$$A^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^a{}_{bc} A^b_\mu A^c_\nu$$



- Gluons A^a_μ

- Coupling g and some numbers f^{abc}

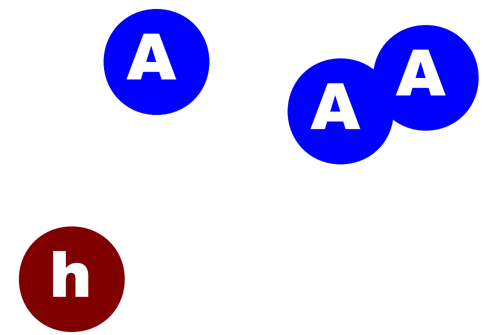
Scalar QCD

- Gauge theory

$$L = -\frac{1}{4} A^a_{\mu\nu} A^{\mu\nu}_a + \left(D^{ij}_\mu h^j \right)^+ D^\mu_{ik} h_k$$

$$A^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^a_{bc} A^b_\mu A^c_\nu$$

$$D^{ij}_\mu = \delta^{ij} \partial_\mu$$



- Gluons A^a_μ
- Scalar quarks h_i
- Coupling g and some numbers f^{abc}

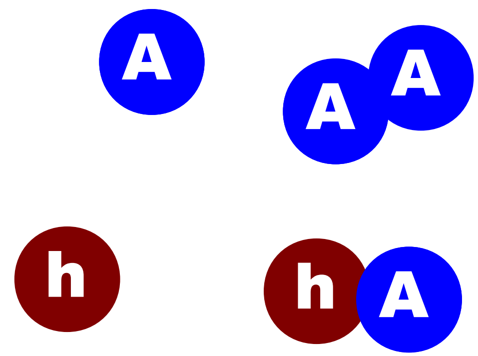
Scalar QCD

- Gauge theory

$$L = -\frac{1}{4} A^a_{\mu\nu} A^{\mu\nu}_a + \left(D^{ij}_\mu h^j \right)^+ D^\mu_{ik} h_k$$

$$A^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^a_{bc} A^b_\mu A^c_\nu$$

$$D^{ij}_\mu = \delta^{ij} \partial_\mu - ig A^a_\mu t^{ij}_a$$



- Gluons A^a_μ
- Scalar quarks h_i
- Coupling g and some numbers f^{abc} and t^{ij}_a
- Gauge group SU(2)

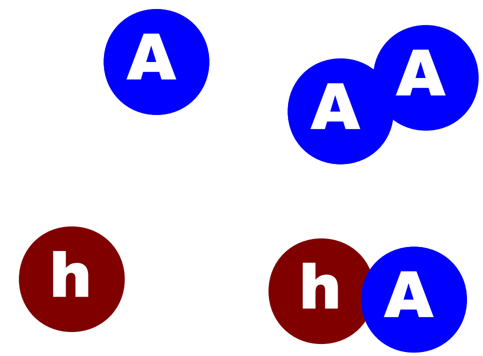
Scalar QCD

- Gauge theory

$$L = -\frac{1}{4} A^{a}_{\mu\nu} A^{\mu\nu}_{a} + \left(D^{ij}_{\mu} h^{j} \right)^{+} D^{\mu}_{ik} h_{k}$$

$$A^{a}_{\mu\nu} = \partial_{\mu} A^{a}_{\nu} - \partial_{\nu} A^{a}_{\mu} + g f^{a}_{\ bc} A^{b}_{\mu} A^{c}_{\nu}$$

$$D^{ij}_{\mu} = \delta^{ij} \partial_{\mu} - i g A^{a}_{\mu} t^{ij}_{a}$$



- Gluons A^{a}_{μ}
- Scalar quarks h_i
- Coupling g and some numbers f^{abc} and t^{ij}_{a}

- Gauge group SU(2)
- No 'baryon number'

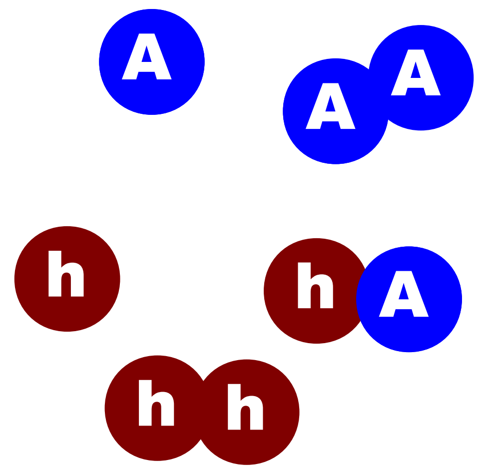
Scalar QCD

- Gauge theory

$$L = -\frac{1}{4} A^a_{\mu\nu} A^{\mu\nu}_a + \left(D^{ij}_\mu h^j\right)^+ D^\mu_{ik} h_k + \lambda\left(h^a h_a^+ - v^2\right)^2$$

$$A^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^a_{\ bc} A^b_\mu A^c_\nu$$

$$D^{ij}_\mu = \delta^{ij} \partial_\mu - i g A^a_\mu t^{ij}_a$$



- Gluons A^a_μ
- Scalar quarks h_i
- Couplings g, v, λ and some numbers f^{abc} and t_a^{ij}

- Gauge group SU(2)
- No 'baryon number'

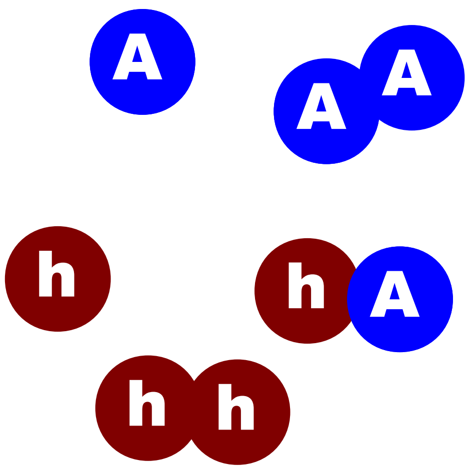
Scalar QCD

- Gauge theory

$$L = -\frac{1}{4} A^a_{\mu\nu} A_a^{\mu\nu} + \left(D^{ij}_\mu h^j\right)^+ D^\mu_{ik} h_k + \lambda\left(h^a h_a^+ - v^2\right)^2$$

$$A^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^a_{bc} A^b_\mu A^c_\nu$$

$$D^{ij}_\mu = \delta^{ij} \partial_\mu - ig A^a_\mu t^{ij}_a$$



- Gluons A^a_μ
- Scalar quarks h_i
- Couplings $g, v=0, \lambda=0$ and some numbers f^{abc} and t^{ij}_a
    - Scalar self-interaction set to zero
- Gauge group SU(2)
- No 'baryon number'

Symmetries

$$L = -\frac{1}{4} A^a_{\mu\nu} A^{\mu\nu}_a + \left(D^{ij}_\mu h^j \right)^+ D^\mu_{ik} h_k + \lambda \left(h^a h_a^+ - v^2 \right)^2$$

$$A^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^a{}_{bc} A^b_\mu A^c_\nu$$

$$D^{ij}_\mu = \delta^{ij} \partial_\mu - i g A^a_\mu t^{ij}_a$$

Symmetries

$$L = -\frac{1}{4} A^{a}_{\mu\nu} A^{\mu\nu}_{a} + \left(D^{ij}_{\mu} h^{j}\right)^{+} D^{\mu}_{ik} h_{k} + \lambda\left(h^{a} h_{a}^{+} - v^{2}\right)^{2}$$

$$A^{a}_{\mu\nu} = \partial_{\mu} A^{a}_{\nu} - \partial_{\nu} A^{a}_{\mu} + g f^{a}_{\ bc} A^{b}_{\mu} A^{c}_{\nu}$$

$$D^{ij}_{\mu} = \delta^{ij} \partial_{\mu} - ig A^{a}_{\mu} t^{ij}_{a}$$

- Local SU(2) gauge symmetry
  - Invariant under arbitrary gauge transformations $\phi^{a}(x)$

$$A^{a}_{\mu} \rightarrow A^{a}_{\mu} + \left(\delta^{a}_{b} \partial_{\mu} - g f^{a}_{\ bc} A^{c}_{\mu}\right) \phi^{b}$$

$$h_{i} \rightarrow h_{i} + g\, t^{ij}_{a} \phi^{a} h_{j}$$

Symmetries

$$L = -\frac{1}{4} A^{a}_{\mu\nu} A^{\mu\nu}_{a} + \left(D^{ij}_{\mu} h^{j} \right)^{+} D^{\mu}_{ik} h_{k} + \lambda \left(h^{a} h^{+}_{a} - v^{2} \right)^{2}$$

$$A^{a}_{\mu\nu} = \partial_{\mu} A^{a}_{\nu} - \partial_{\nu} A^{a}_{\mu} + g f^{a}_{bc} A^{b}_{\mu} A^{c}_{\nu}$$

$$D^{ij}_{\mu} = \delta^{ij} \partial_{\mu} - i g A^{a}_{\mu} t^{ij}_{a}$$

- Local SU(2) gauge symmetry
  - Invariant under arbitrary gauge transformations $\phi^{a}(x)$

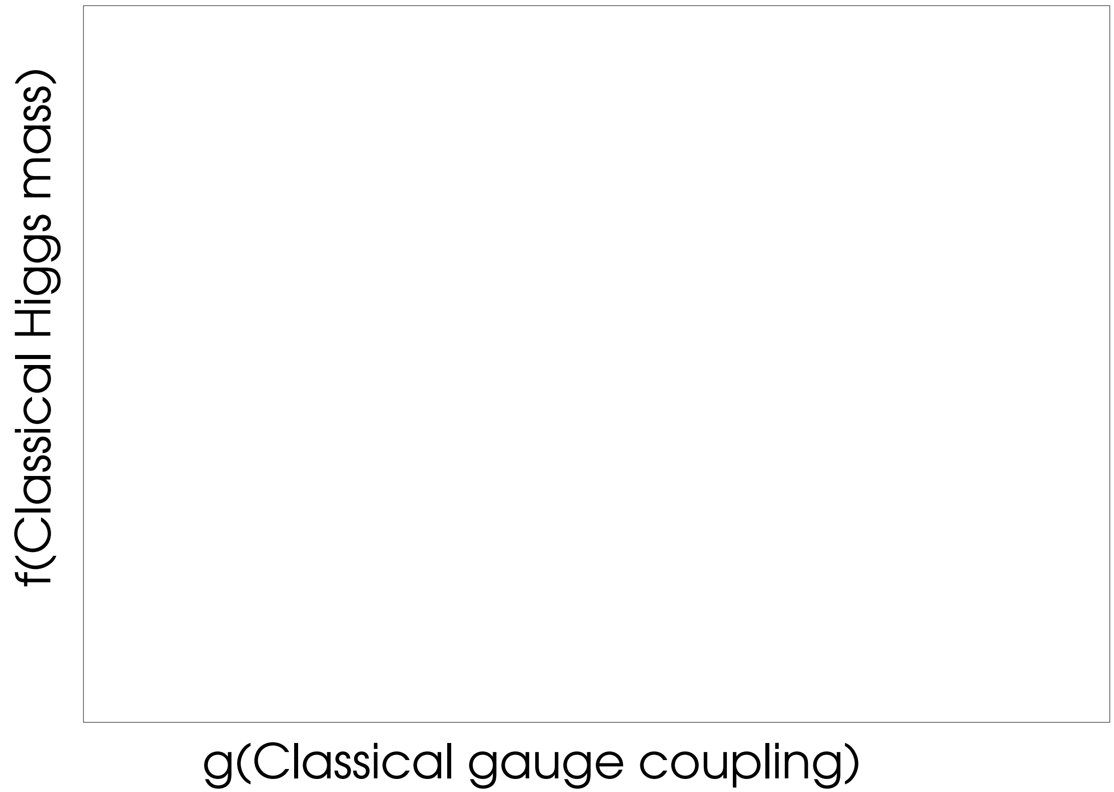
$$A^{a}_{\mu} \rightarrow A^{a}_{\mu} + \left(\delta^{a}_{b} \partial_{\mu} - g f^{a}_{bc} A^{c}_{\mu} \right) \phi^{b} \qquad h_{i} \rightarrow h_{i} + g\, t^{ij}_{a} \phi^{a} h_{j}$$

- Global SU(2) quark flavor symmetry
  - Acts as right-transformation on the quark field only

$$A^{a}_{\mu} \rightarrow A^{a}_{\mu} \qquad h_{i} \rightarrow h_{i} + a^{ij} h_{j} + b^{ij} h^{*}_{j}$$

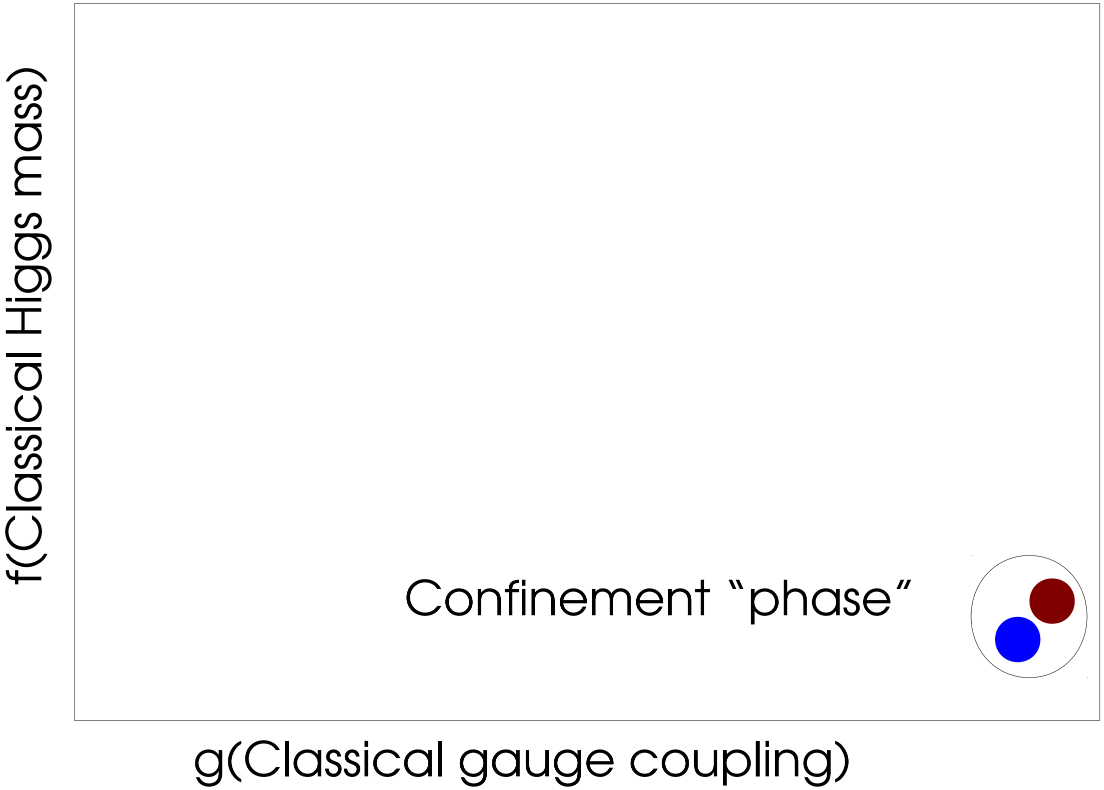
QCD-like vs. Higgs-like

[Fradkin & Shenker PRD'79
Caudy & Greensite PRD'07]



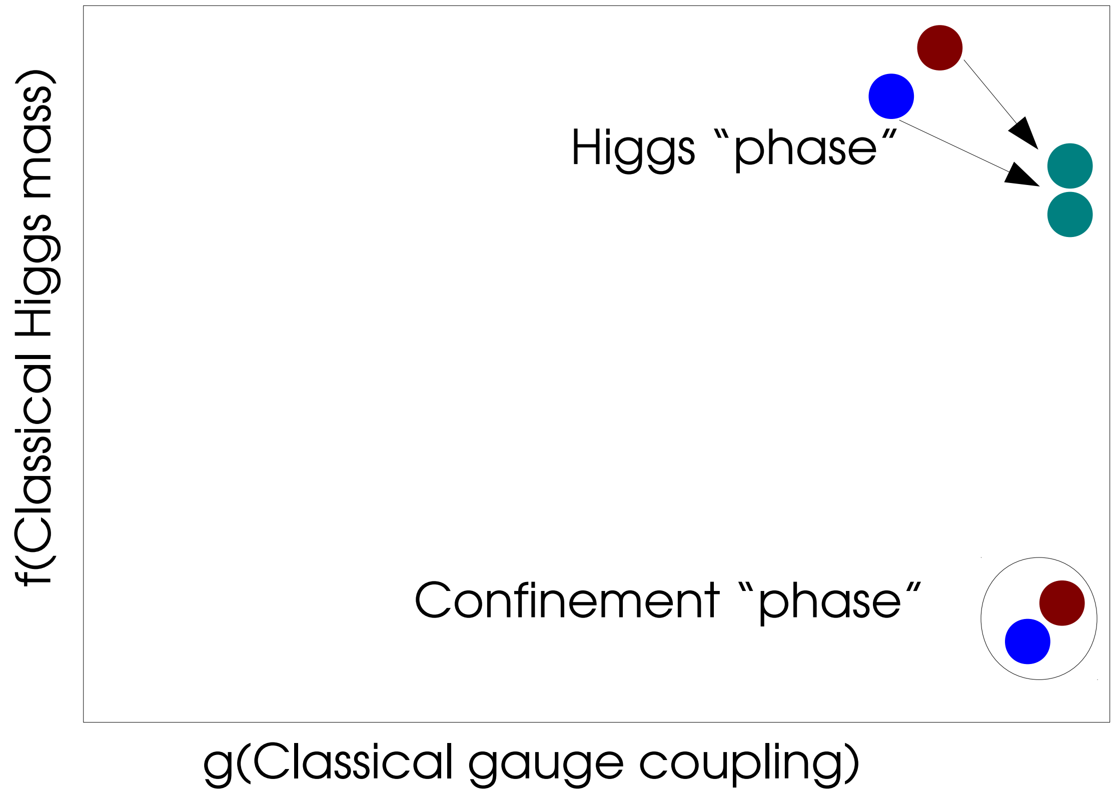
QCD-like vs. Higgs-like

[Fradkin & Shenker PRD'79
Caudy & Greensite PRD'07]



QCD-like vs. Higgs-like

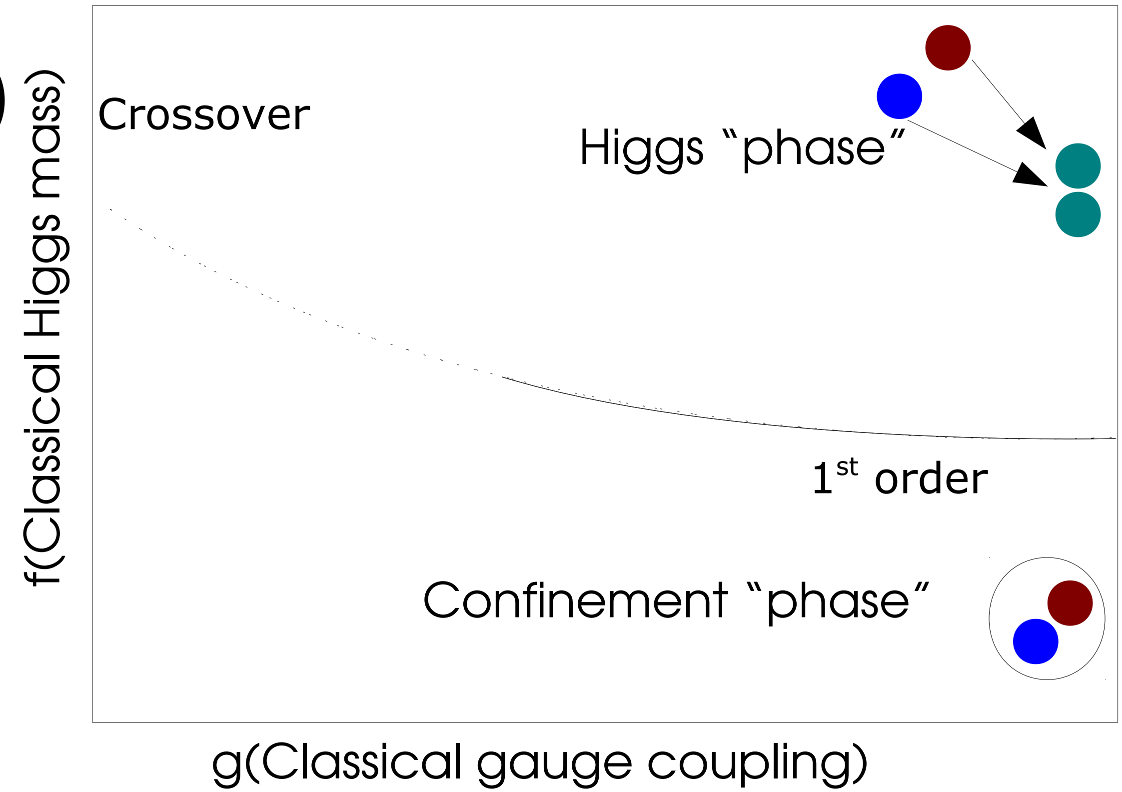
[Fradkin & Shenker PRD'79
Caudy & Greensite PRD'07]



QCD-like vs. Higgs-like

[Fradkin & Shenker PRD'79
Caudy & Greensite PRD'07]

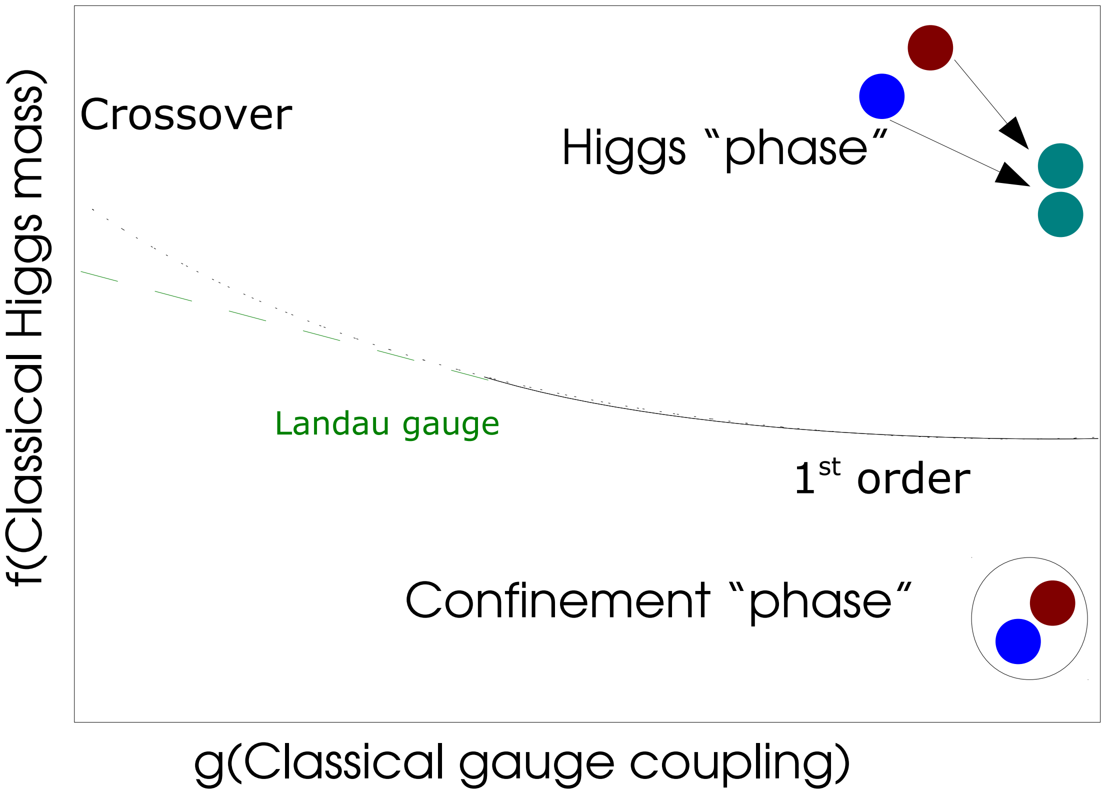
- (Lattice-regularized) phase diagram continuous



QCD-like vs. Higgs-like

[Fradkin & Shenker PRD'79
Caudy & Greensite PRD'07]

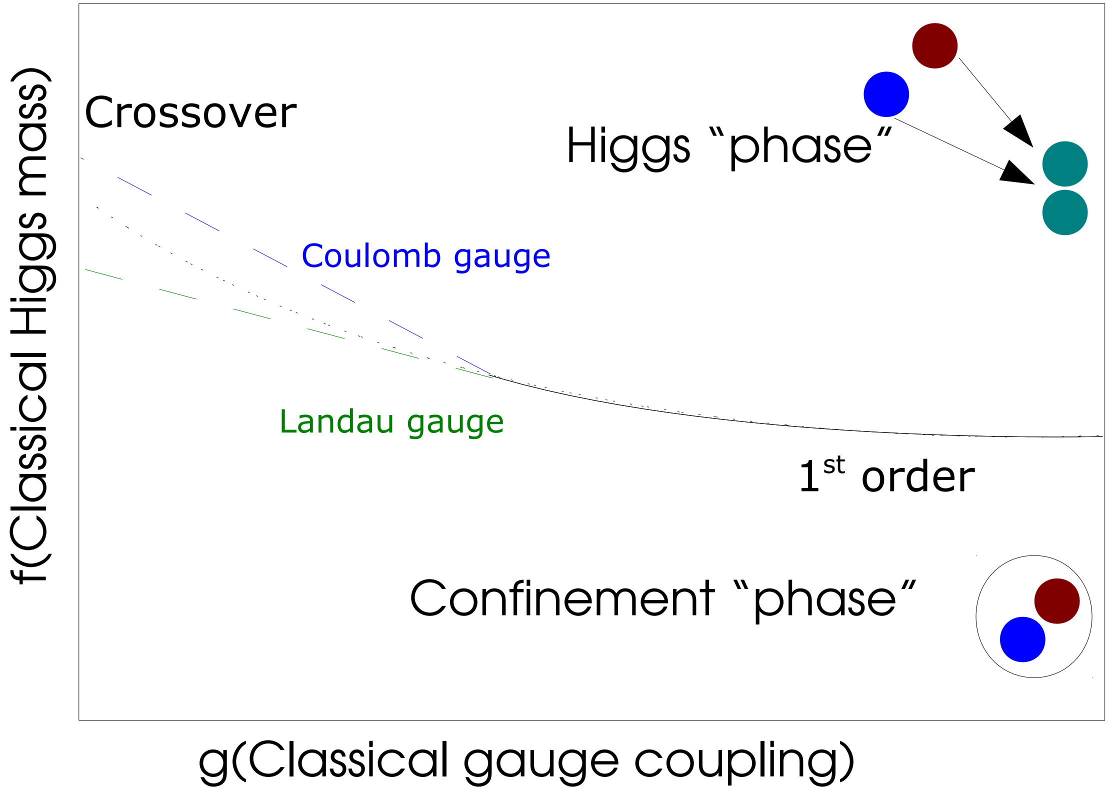
- (Lattice-regularized) phase diagram continuous
  - Separation only in fixed gauges



QCD-like vs. Higgs-like

[Fradkin & Shenker PRD'79
Caudy & Greensite PRD'07]

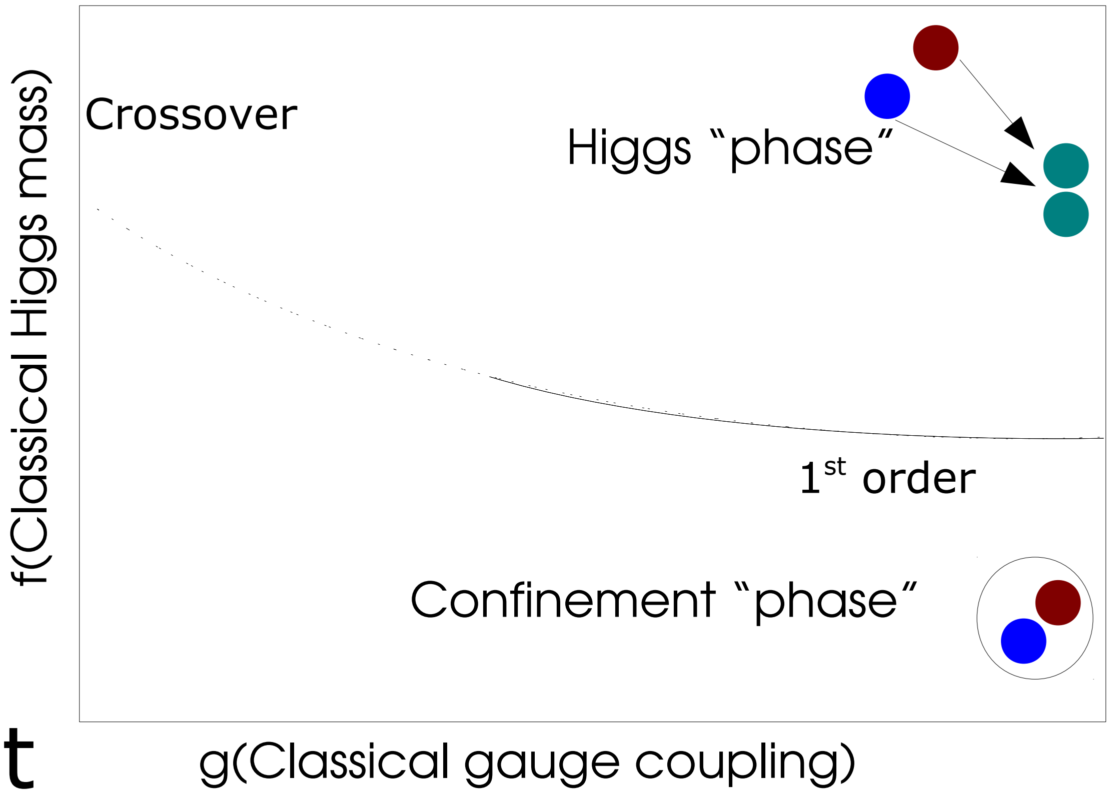
- (Lattice-regularized) phase diagram continuous
  - Separation only in fixed gauges



QCD-like vs. Higgs-like

[Fradkin & Shenker PRD'79
Caudy & Greensite PRD'07]

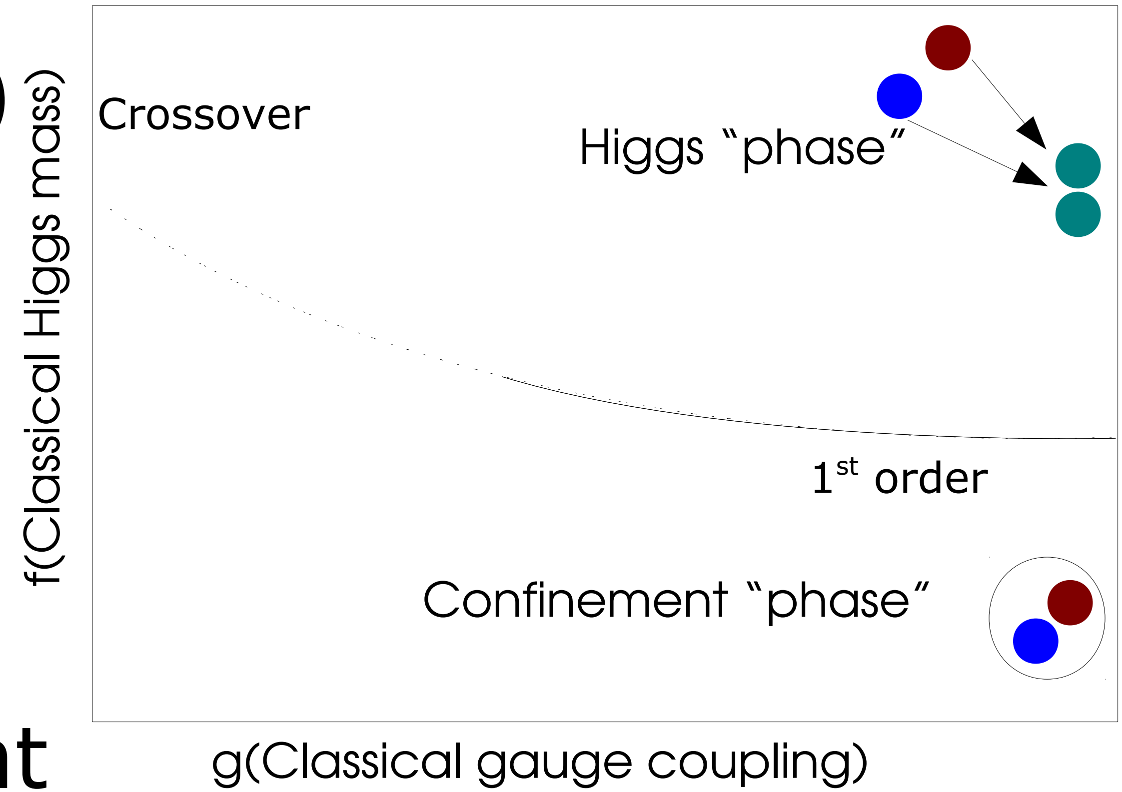
- (Lattice-regularized) phase diagram continuous
  - Separation only in fixed gauges
- Same physical state space in confinement and Higgs pseudo-phases, irrespective of couplings



QCD-like vs. Higgs-like

[Fradkin & Shenker PRD'79
Caudy & Greensite PRD'07]

- (Lattice-regularized) phase diagram continuous
  - Separation only in fixed gauges



- Same physical state space in confinement and Higgs pseudo-phases, irrespective of couplings
  - Asymptotic states depend on whether ground states for given J^{PC}_{F} are stable

Non-aligned gauges

[Maas, MPLA'12]

- Explicit charge direction inconvenient beyond perturbation theory

Non-aligned gauges

[Maas, MPLA'12]

- Explicit charge direction inconvenient beyond perturbation theory
- Define a gauge without preferred direction

Non-aligned gauges

[Maas, MPLA'12]

- Explicit charge direction inconvenient beyond perturbation theory
- Define a gauge without preferred direction
  - Local part fixed to Landau gauge by $\partial^{\mu} A_{\mu}^{a} = 0$
    - Gribov-Singer ambiguity fixed by minimal prescription
    - Introduces usual Faddeev-Popov ghosts

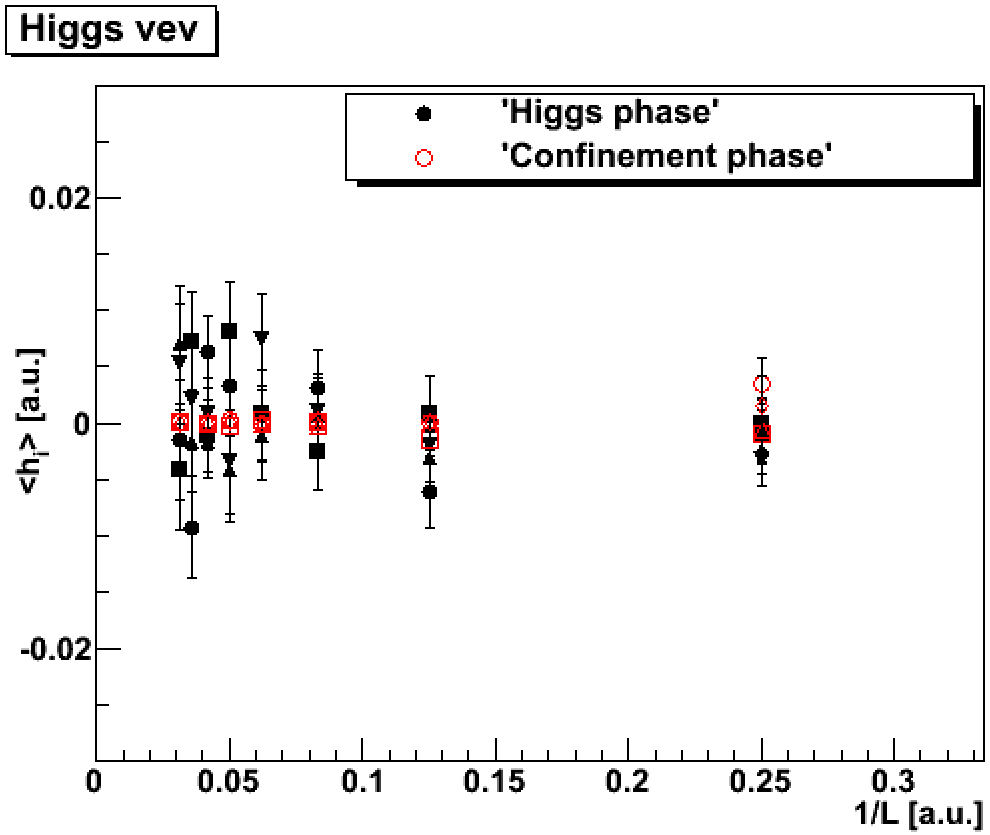
Non-aligned gauges

[Maas, MPLA'12]

- Explicit charge direction inconvenient beyond perturbation theory
- Define a gauge without preferred direction
  - Local part fixed to Landau gauge by $\partial^\mu A_\mu^a = 0$
    - Gribov-Singer ambiguity fixed by minimal prescription
    - Introduces usual Faddeev-Popov ghosts
  - Global part fixed by $\langle h \rangle = 0$
    - Aligned Landau gauges also possible

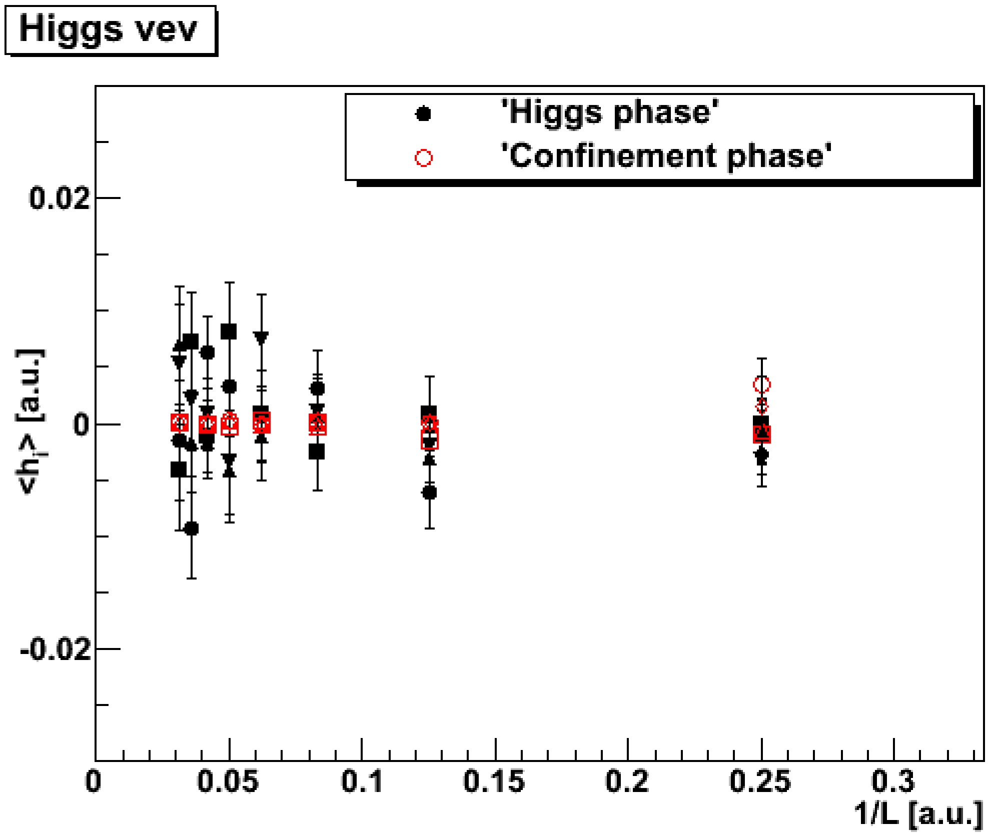
Differentiating phases

[Maas, MPLA'12,
Caudy & Greensite'07]



Differentiating phases

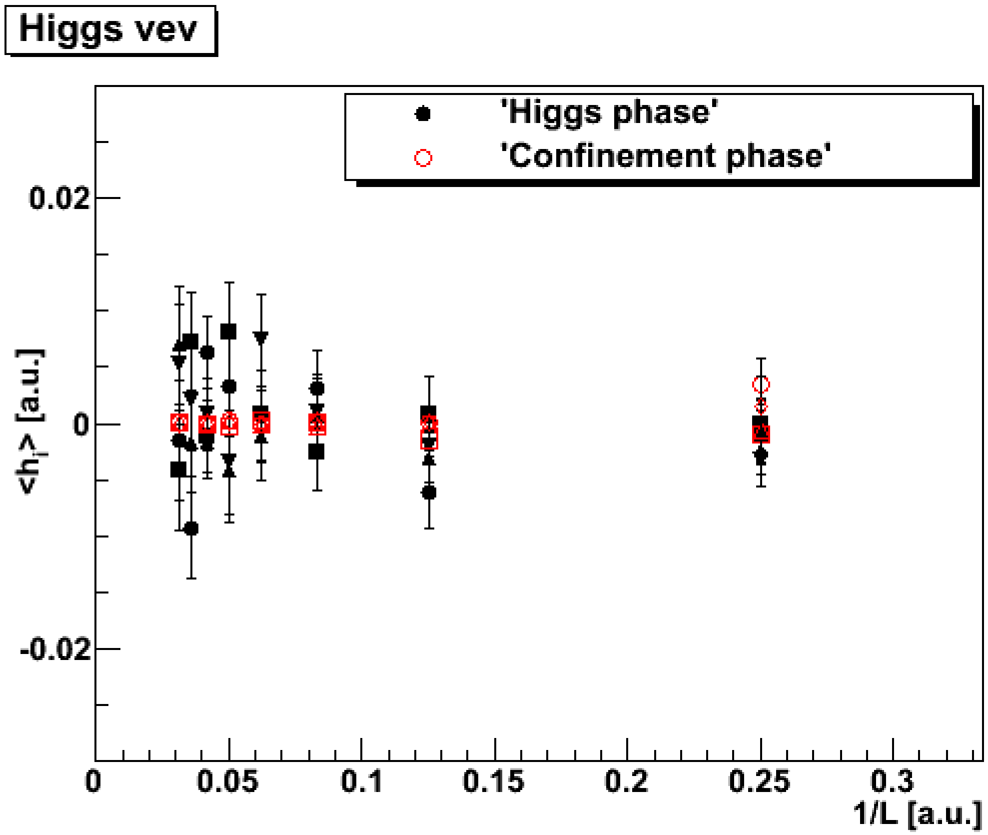
[Maas, MPLA'12,
Caudy & Greensite'07]

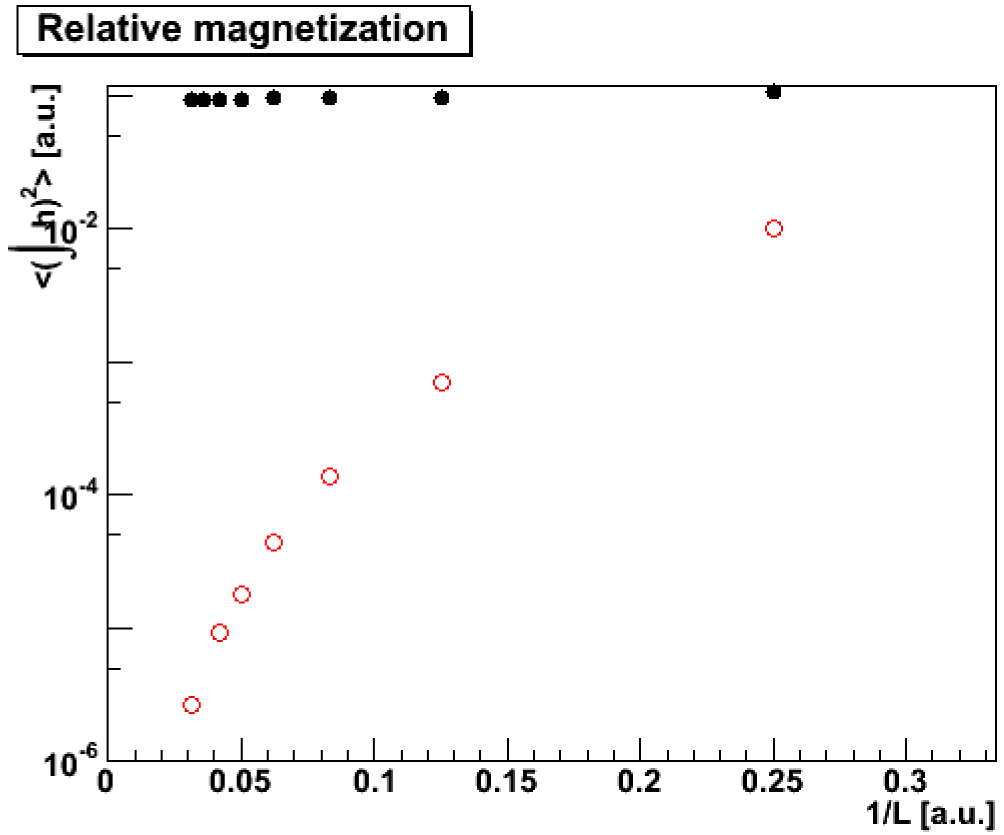


- How to distinguish phases?

Differentiating phases

[Maas, MPLA'12,
Caudy & Greensite'07]

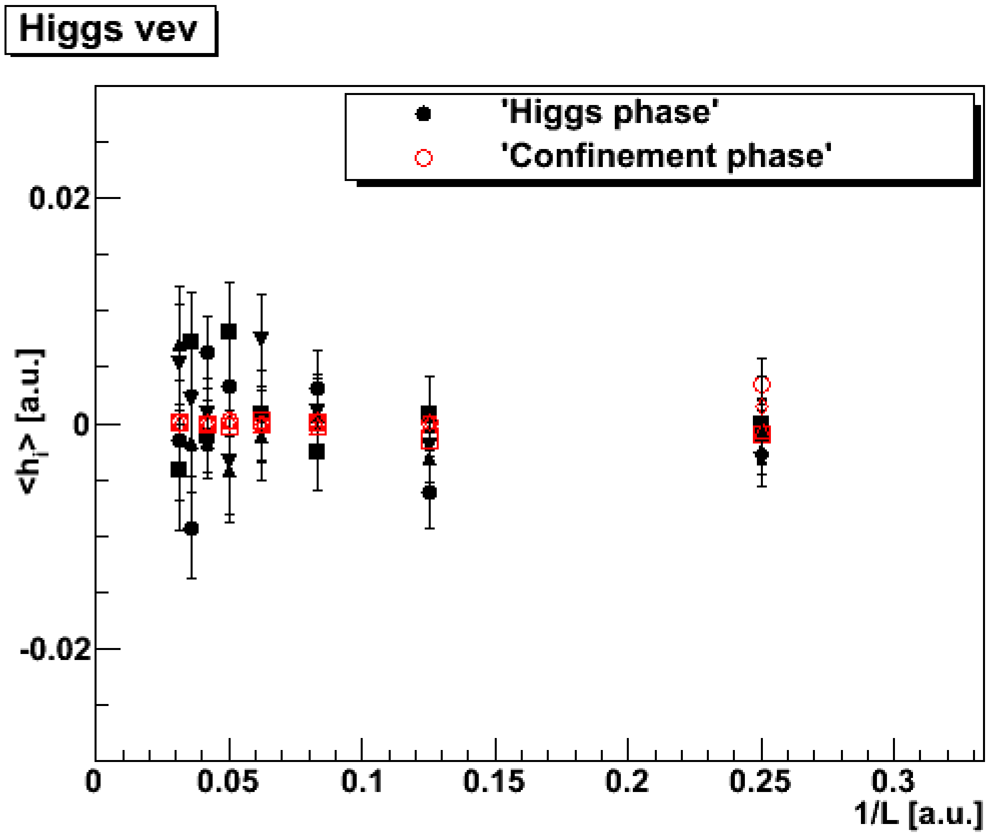




- How to distinguish phases?
- Relative orientation $\langle \int hdx \int hdy \rangle$
  - $\int hdx$ is the magnetization

Differentiating phases

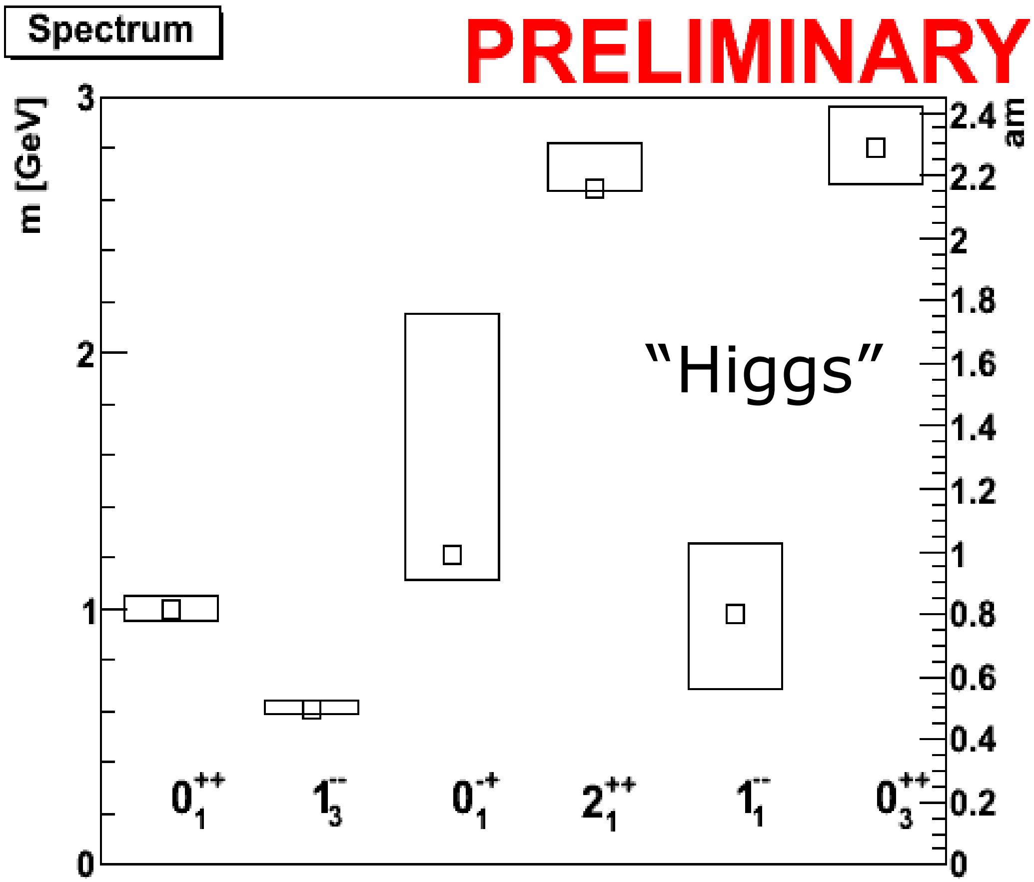
[Maas, MPLA'12, Caudy & Greensite'07]



- How to distinguish phases?
- Relative orientation $\langle \int hdx \int hdy \rangle$
    - $\int hdx$ is the magnetization
- But not so important anyway...

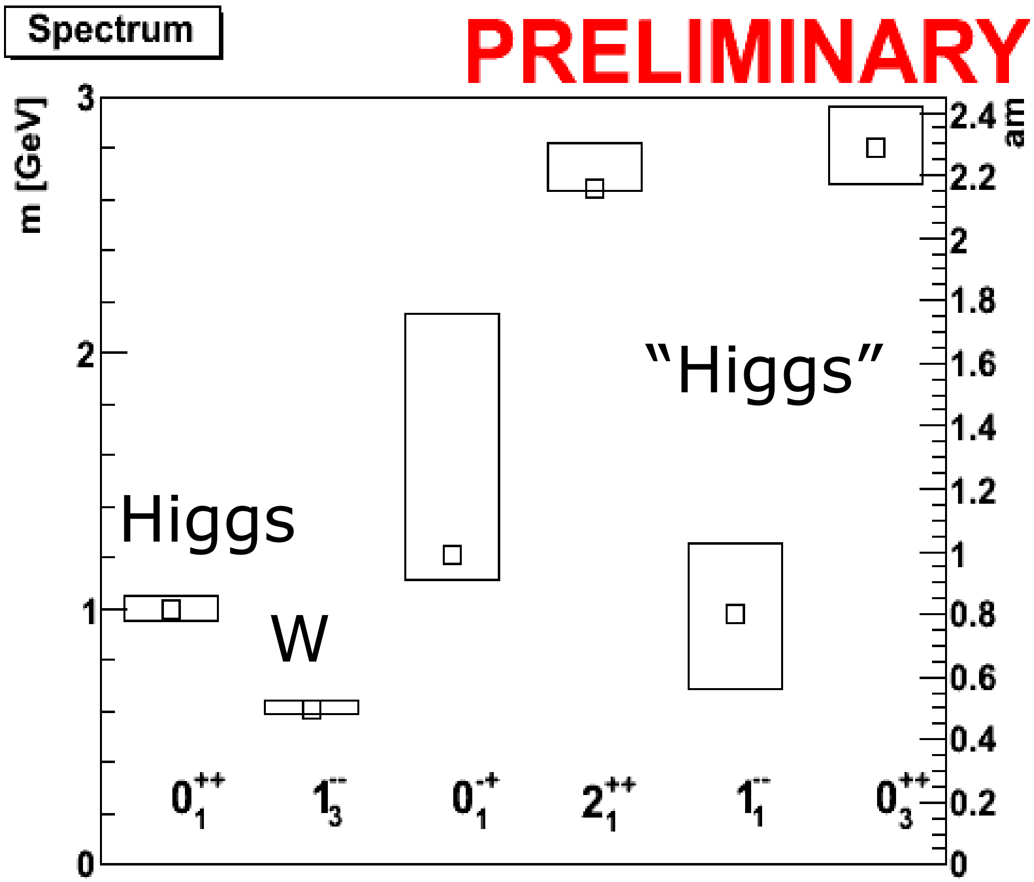
Typical spectra

[Maas, Mufti PoS'12, unpublished]



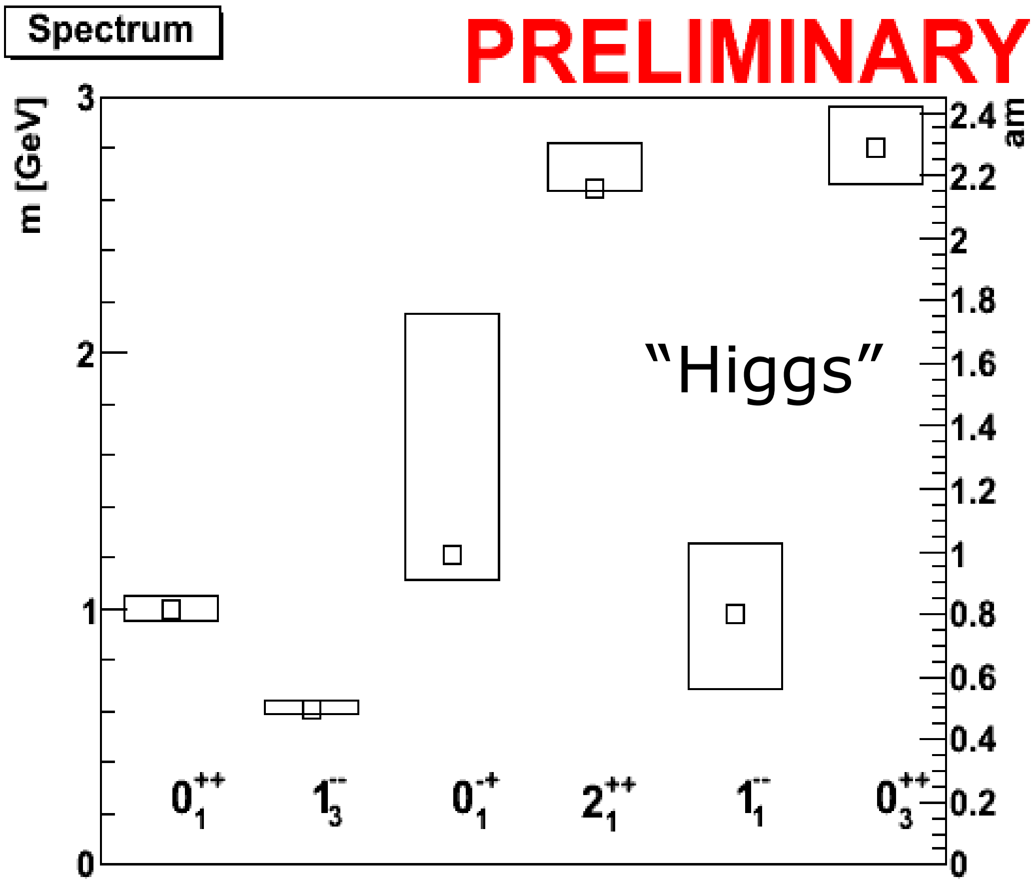
Typical spectra

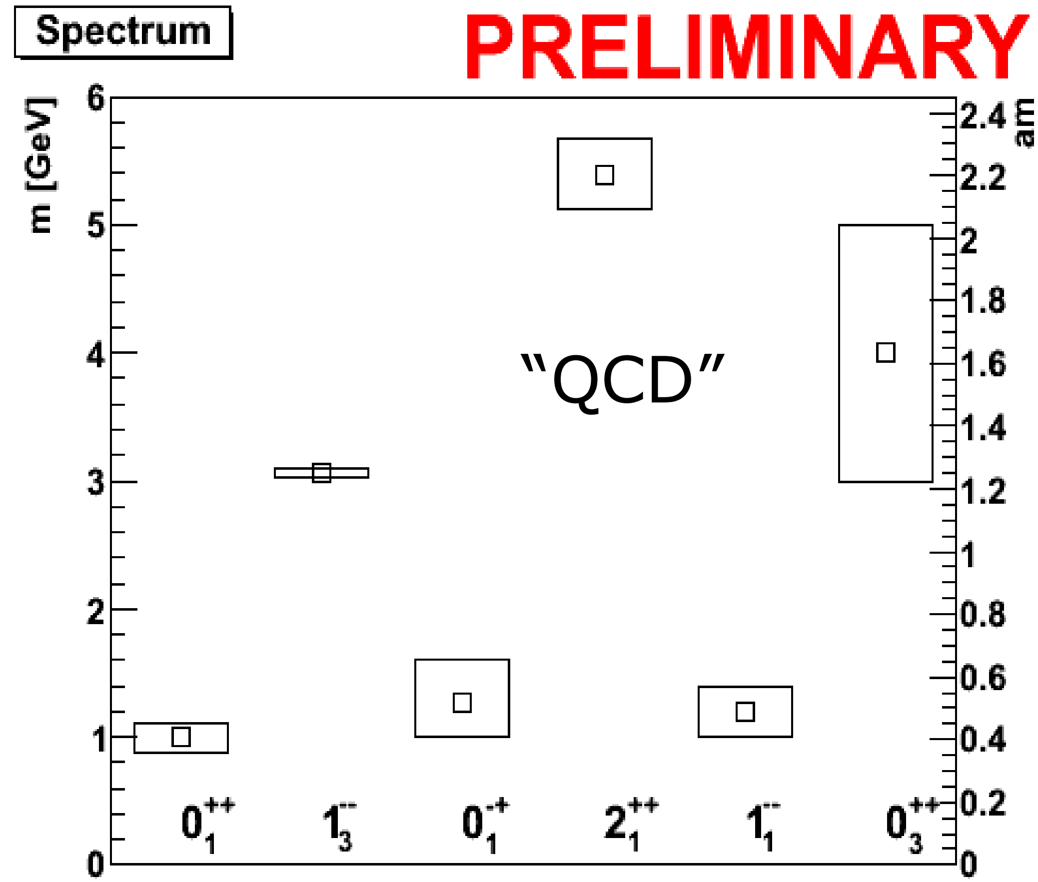
[Maas, Mufti PoS'12, unpublished, Maas MPLA'13]



Typical spectra

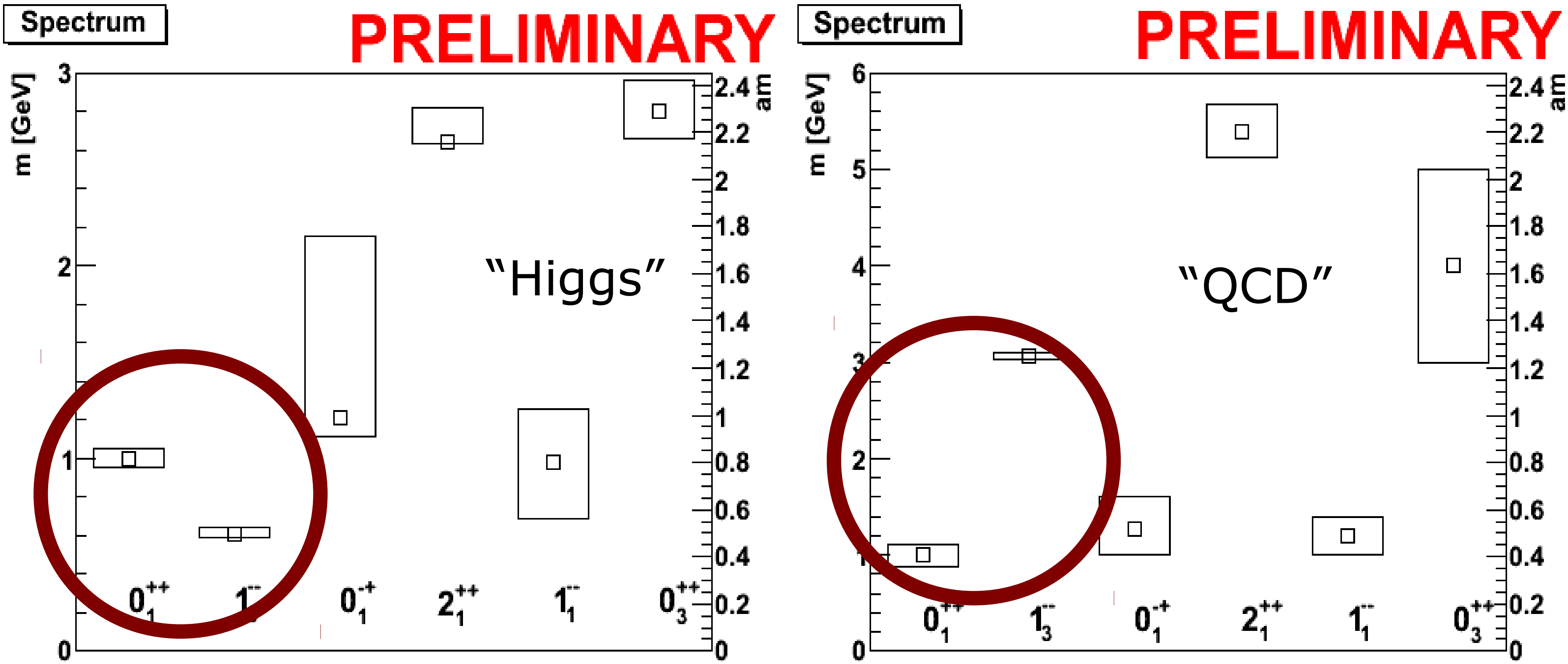
[Maas, Mufti PoS'12, unpublished]





Typical spectra

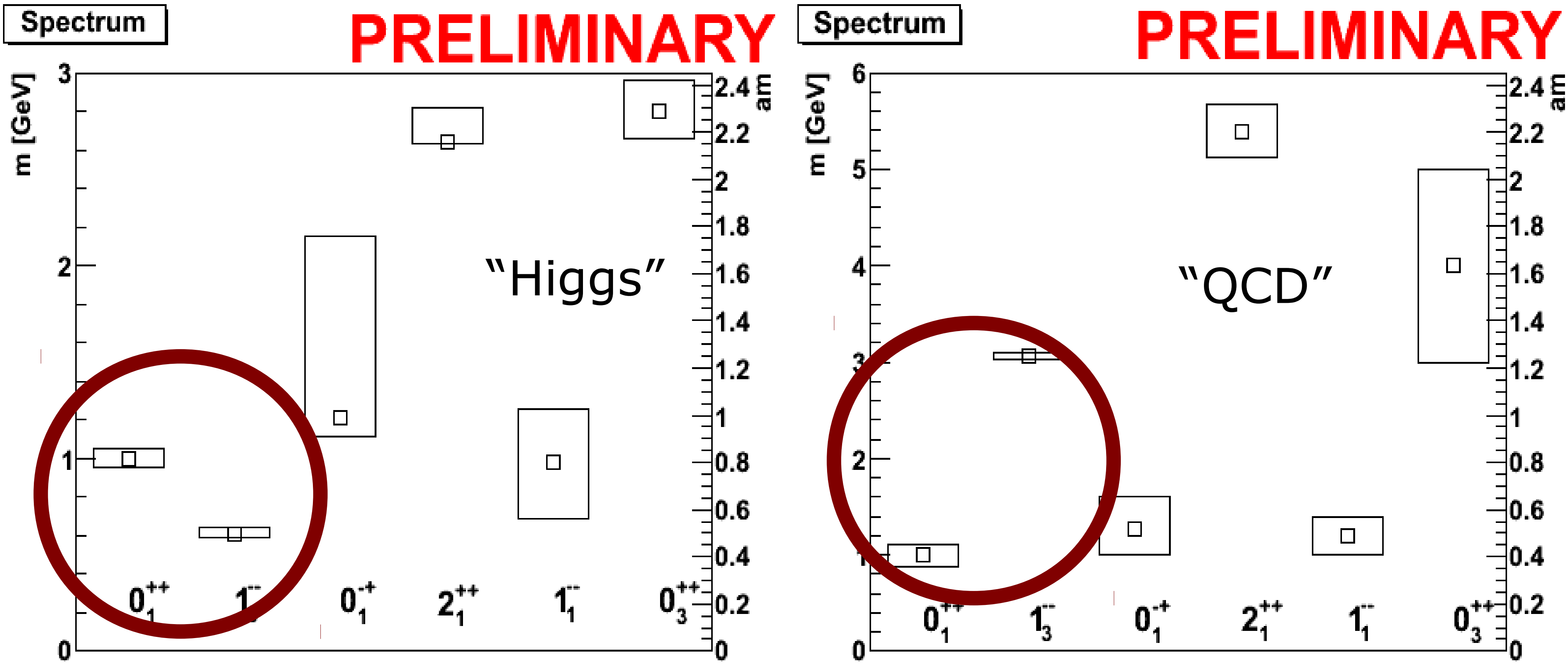
[Maas, Mufti PoS'12, unpublished]



- Rather different low-lying spectra
  - 0^{++} lighter in (Landau gauge) QCD-like region
  - 1^{--} lighter in (Landau gauge) Higgs-like region

Typical spectra

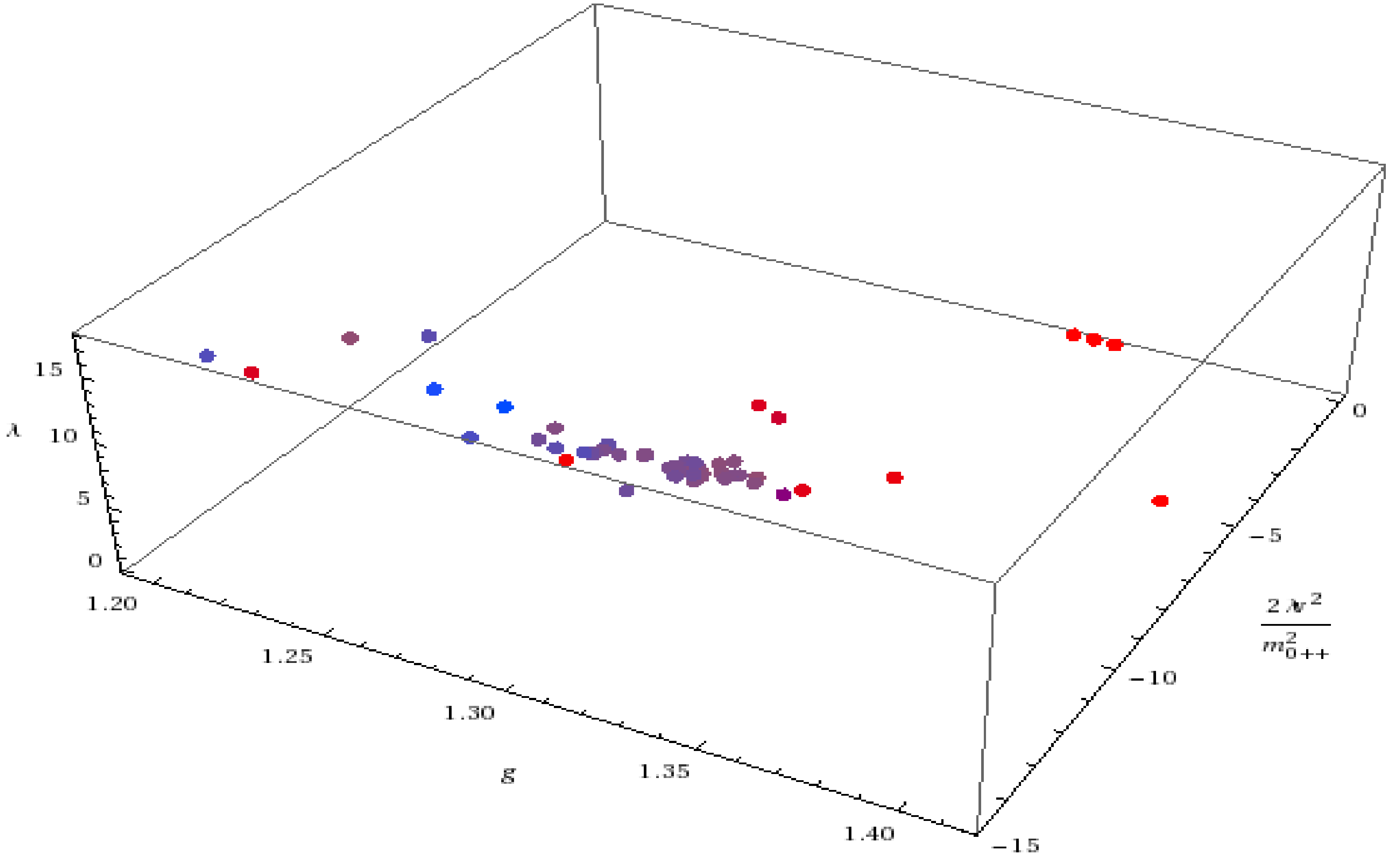
[Maas, Mufti PoS'12, unpublished]



- Rather different low-lying spectra
  - 0^{++} lighter in (Landau gauge) QCD-like region
  - 1^{--} lighter in (Landau gauge) Higgs-like region
- Use as operational definition of phase

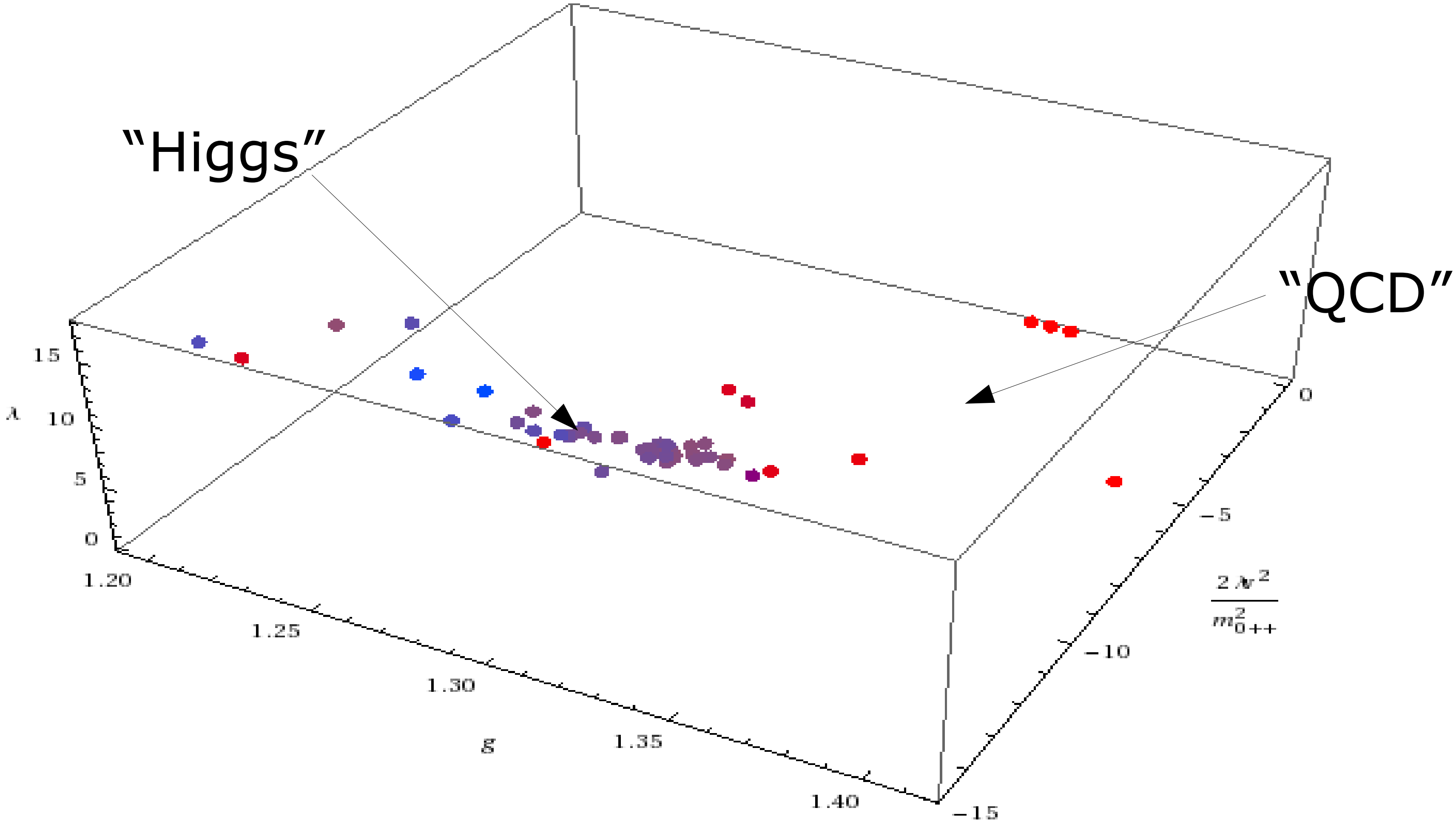
Phase diagram

[Maas, Mufti, unpublished]



Phase diagram

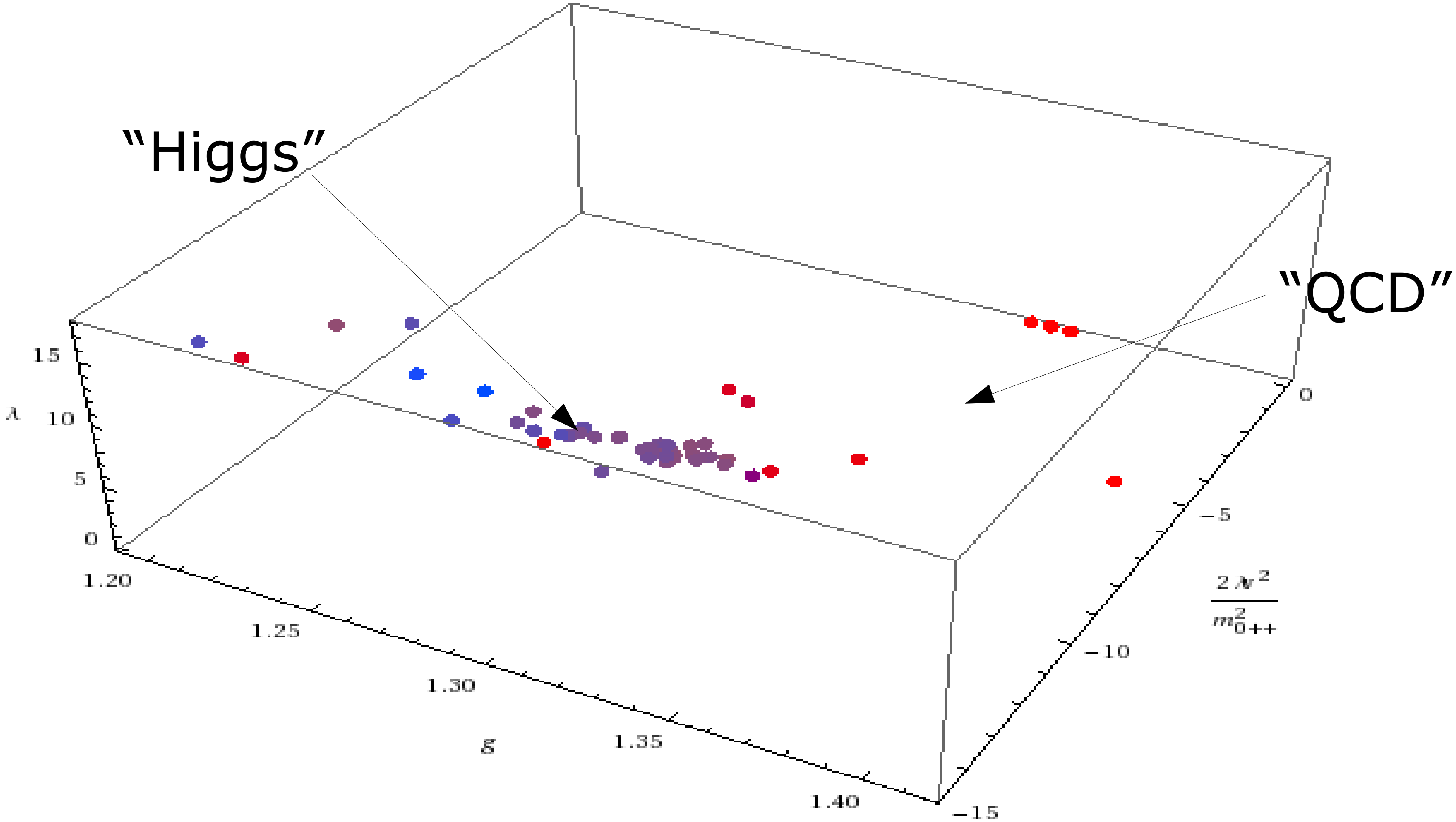
[Maas, Mufti, unpublished]



- Complicated real phase diagram

Phase diagram

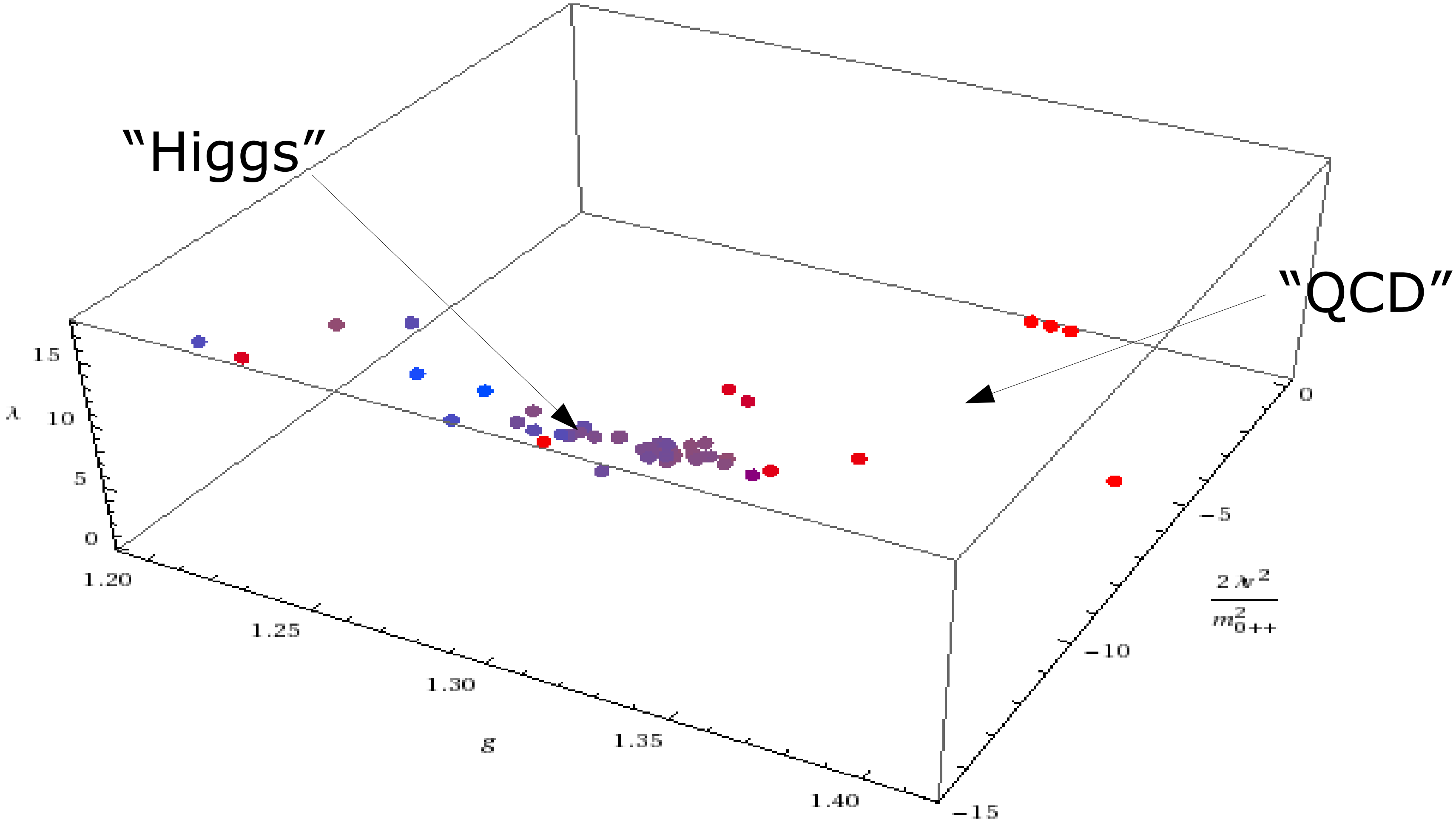
[Maas, Mufti, unpublished]



- Complicated real phase diagram
- QCD-like behavior even for negative bare mass

Phase diagram

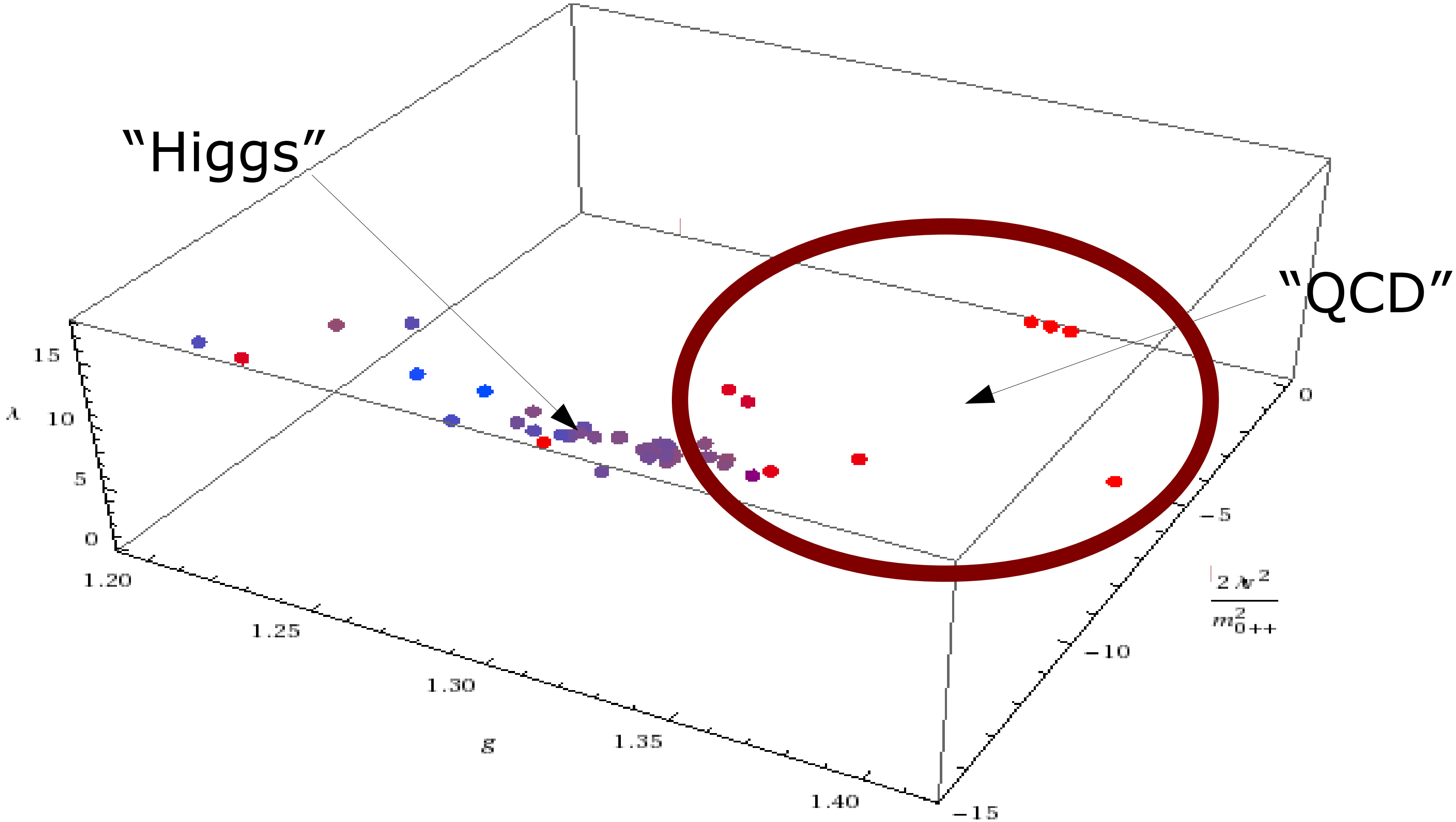
[Maas, Mufti, unpublished]



- Complicated real phase diagram
- QCD-like behavior even for negative bare mass
- Similar bare couplings for both physic types

Phase diagram

[Maas, Mufti, unpublished]



- Complicated real phase diagram
- QCD-like behavior even for negative bare mass
- Similar bare couplings for both physic types

Propagators

- 3 propagators

Propagators

- 3 propagators
  - Gluon $D^{ab}_{\mu\nu}(x-y) = \ <A^a_\mu(x) A^b_\nu(y)>$

Propagators

- 3 propagators
  - Gluon $D^{ab}_{\mu\nu}(x-y) = \ <A^a_\mu(x) A^b_\nu(y)>$
    - 1 scalar dressing function $D_{\mu\nu}(p) = (\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}) D(p)$

Propagators

- 3 propagators
  - Gluon $D_{\mu\nu}^{ab}(x-y) = \langle A_\mu^a(x) A_\nu^b(y) \rangle$
    - 1 scalar dressing function $D_{\mu\nu}(p) = (\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}) D(p)$
  - Ghost $D_G^{ab}(x-y) = \langle \bar{c}^a(x) c^b(y) \rangle$

Propagators

- 3 propagators
  - Gluon $D_{\mu\nu}^{ab}(x-y)= \langle A_\mu^a(x)A_\nu^b(y)\rangle$
    - 1 scalar dressing function $D_{\mu\nu}(p)=(\delta_{\mu\nu}-\frac{p_\mu p_\nu}{p^2})D(p)$
  - Ghost $D_G^{ab}(x-y)= \langle \bar{c}^a(x)c^b(y)\rangle$
    - Negative semi-definite $-D_G(p)$

Propagators

- 3 propagators
  - Gluon $D_{\mu\nu}^{ab}(x-y) = \langle A_\mu^a(x) A_\nu^b(y) \rangle$
    - 1 scalar dressing function $D_{\mu\nu}(p) = \left(\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}\right) D(p)$
  - Ghost $D_G^{ab}(x-y) = \langle \bar{c}^a(x) c^b(y) \rangle$
    - Negative semi-definite $-D_G(p)$
  - Both renormalize multiplicatively

Propagators

- 3 propagators
  - Gluon $D_{\mu\nu}^{ab}(x-y)= <A_\mu^a(x)A_\nu^b(y)>$
    - 1 scalar dressing function $D_{\mu\nu}(p)=(\delta_{\mu\nu}-\frac{p_\mu p_\nu}{p^2})D(p)$
  - Ghost $D_G^{ab}(x-y)= <\bar{c}^a(x)c^b(y)>$
    - Negative semi-definite $-D_G(p)$
  - Both renormalize multiplicatively
  - Scalar $D_H^{ij}(x-y)= <h^i(x)h^{j+}(y)>$

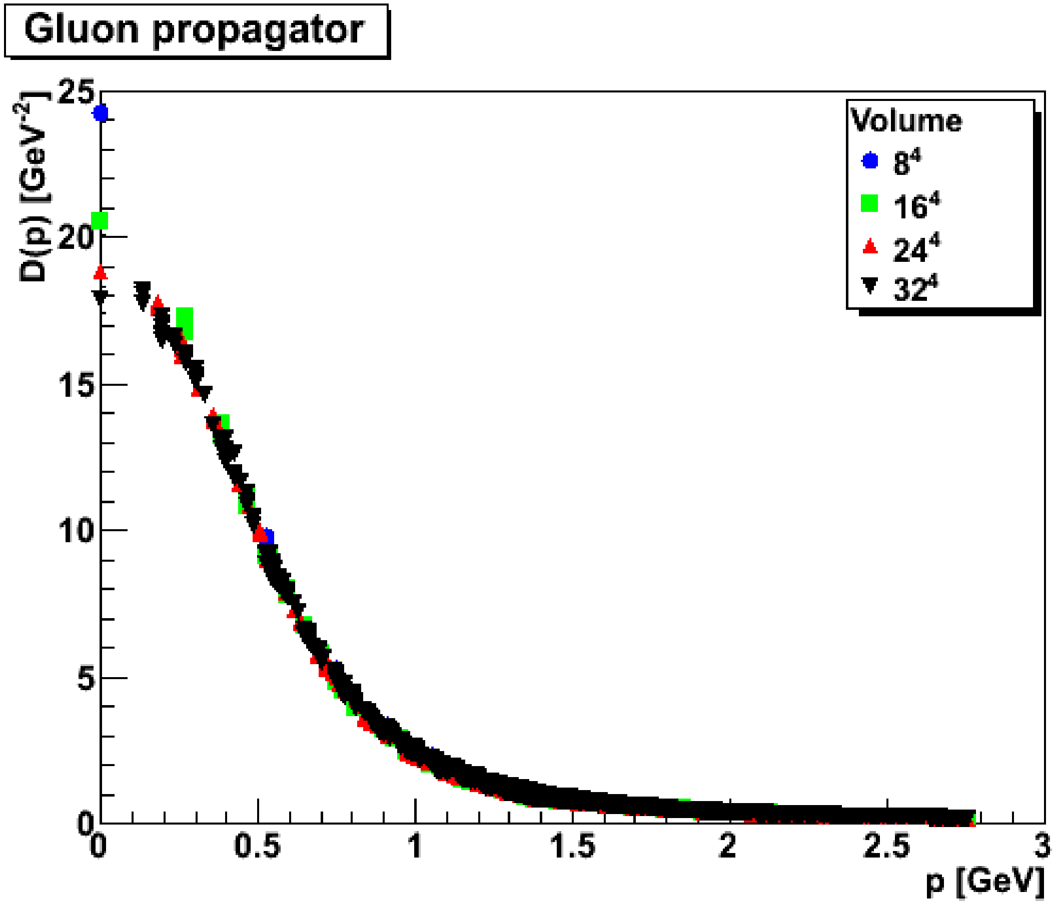
Propagators

- 3 propagators
  - Gluon $D^{ab}_{\mu\nu}(x-y) = <A^a_\mu(x) A^b_\nu(y)>$
    - 1 scalar dressing function $D_{\mu\nu}(p) = (\delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2}) D(p)$
  - Ghost $D^{ab}_G(x-y) = <\bar{c}^a(x) c^b(y)>$
    - Negative semi-definite $-D_G(p)$
  - Both renormalize multiplicatively
  - Scalar $D^{ij}_H(x-y) = <h^i(x) h^{j+}(y)>$
    - Requires more complicated renormalization

$$D_H(\mu) = D^{tl}_H(\mu)$$
$$D_H(\mu)' = D^{tl}_H(\mu)'$$
$$D^{tl}_H(p) = 1/(p^2 + m_r^2)$$
$$\mu = m_r$$

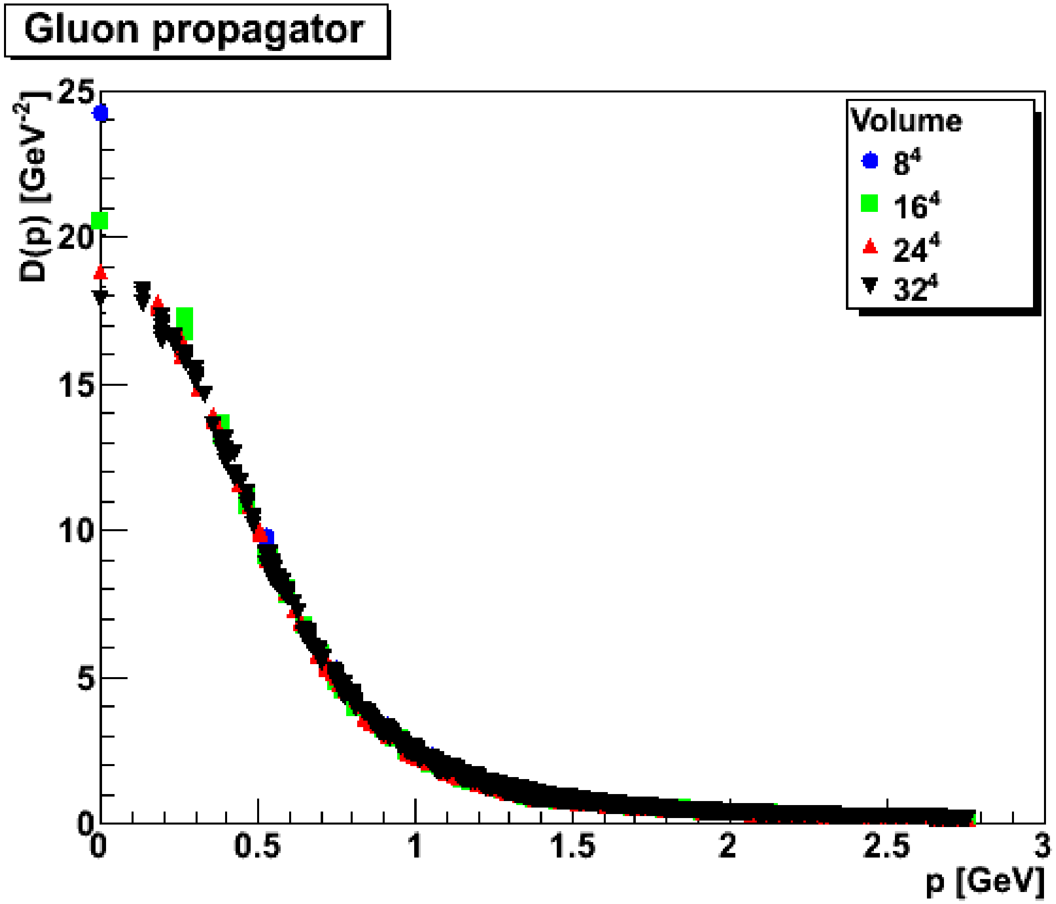
Gluon propagator

[Maas, EPJC'11
Maas, Mufti PoS'12, unpublished]



Gluon propagator

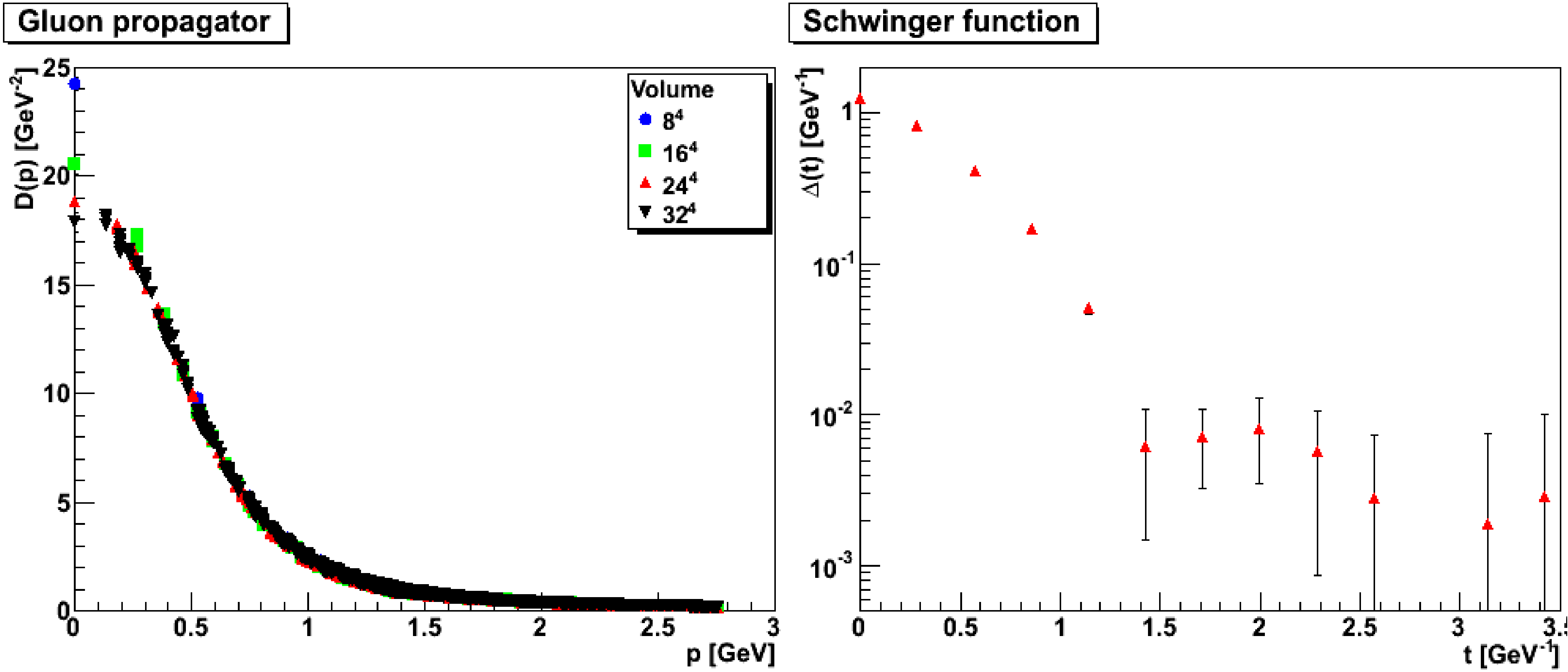
[Maas, EPJC'11
Maas, Mufti PoS'12, unpublished]



- Significantly volume-dependent
- Decoupling-type

Gluon propagator

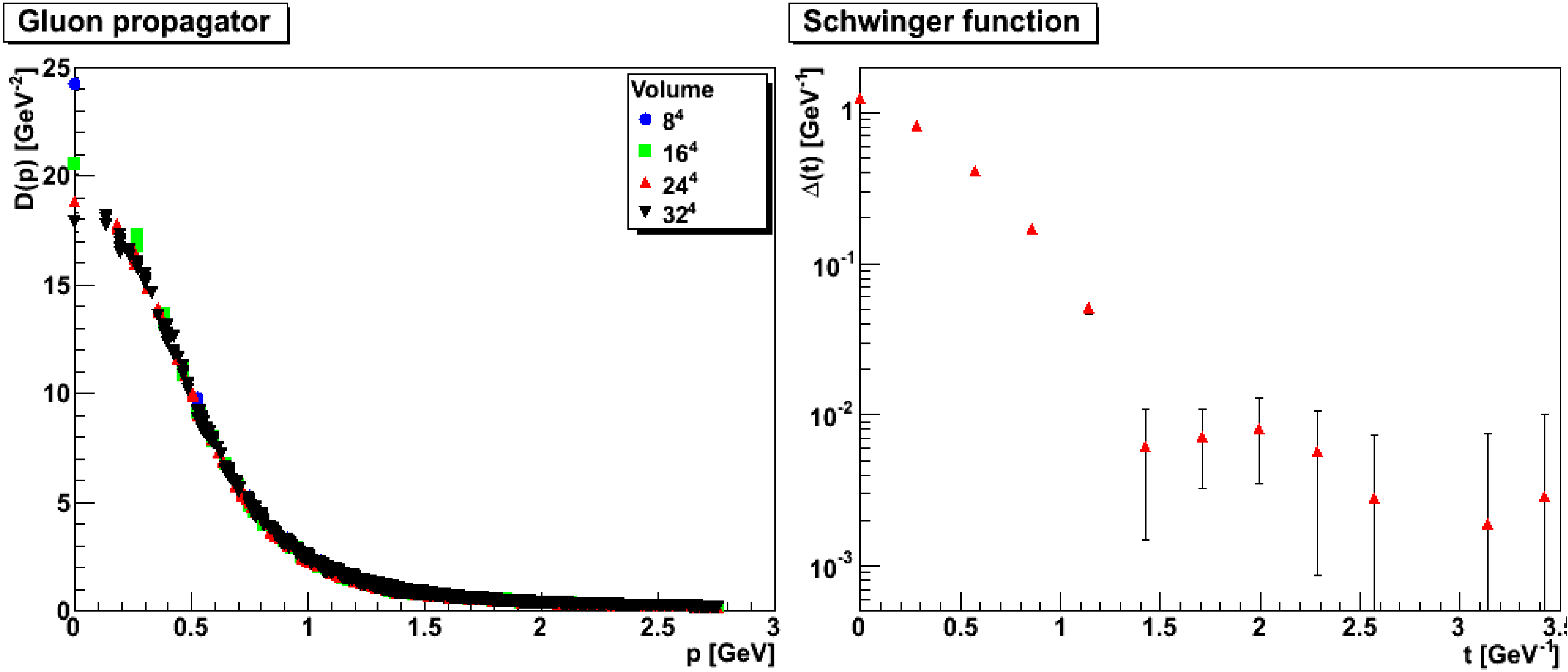
[Maas, EPJC'11
Maas, Mufti PoS'12, unpublished]



- Significantly volume-dependent
- Decoupling-type
- Positivity violating

Gluon propagator

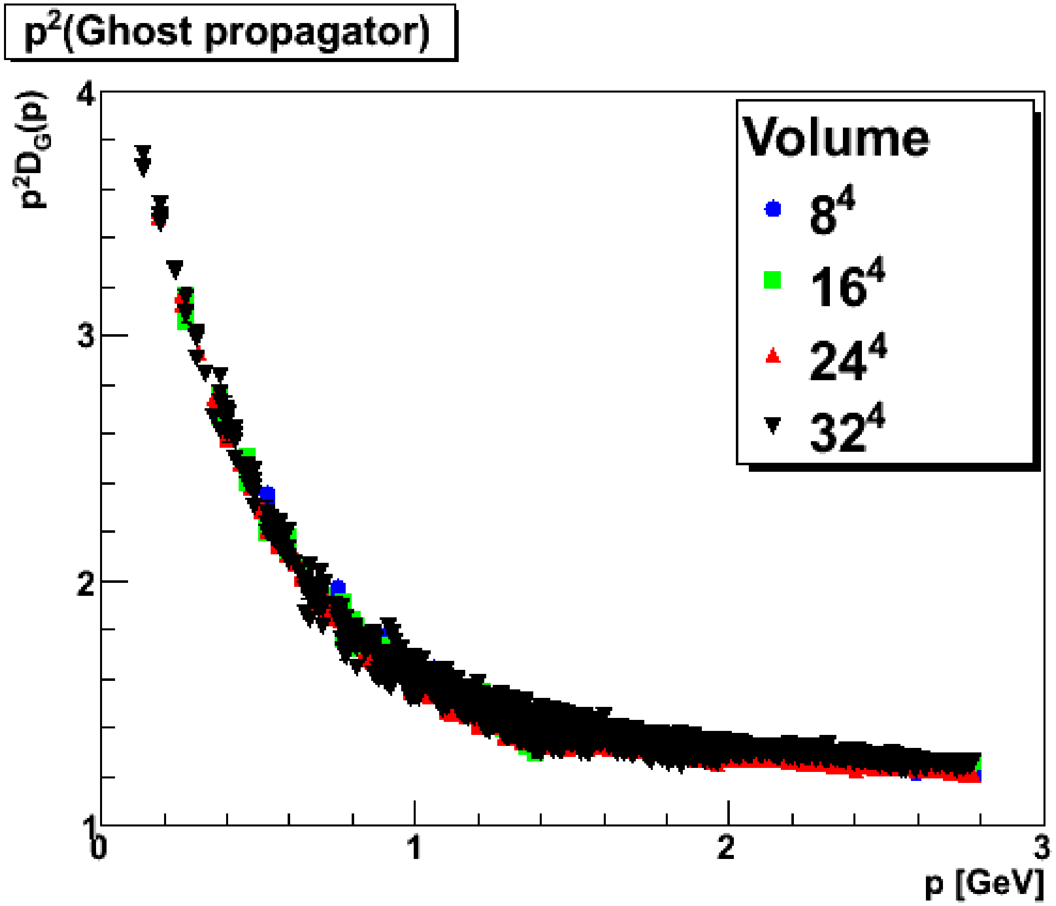
[Maas, EPJC'11
Maas, Mufti PoS'12, unpublished]



- Significantly volume-dependent
- Decoupling-type
- Positivity violating
- Little impact when changing scalar sector

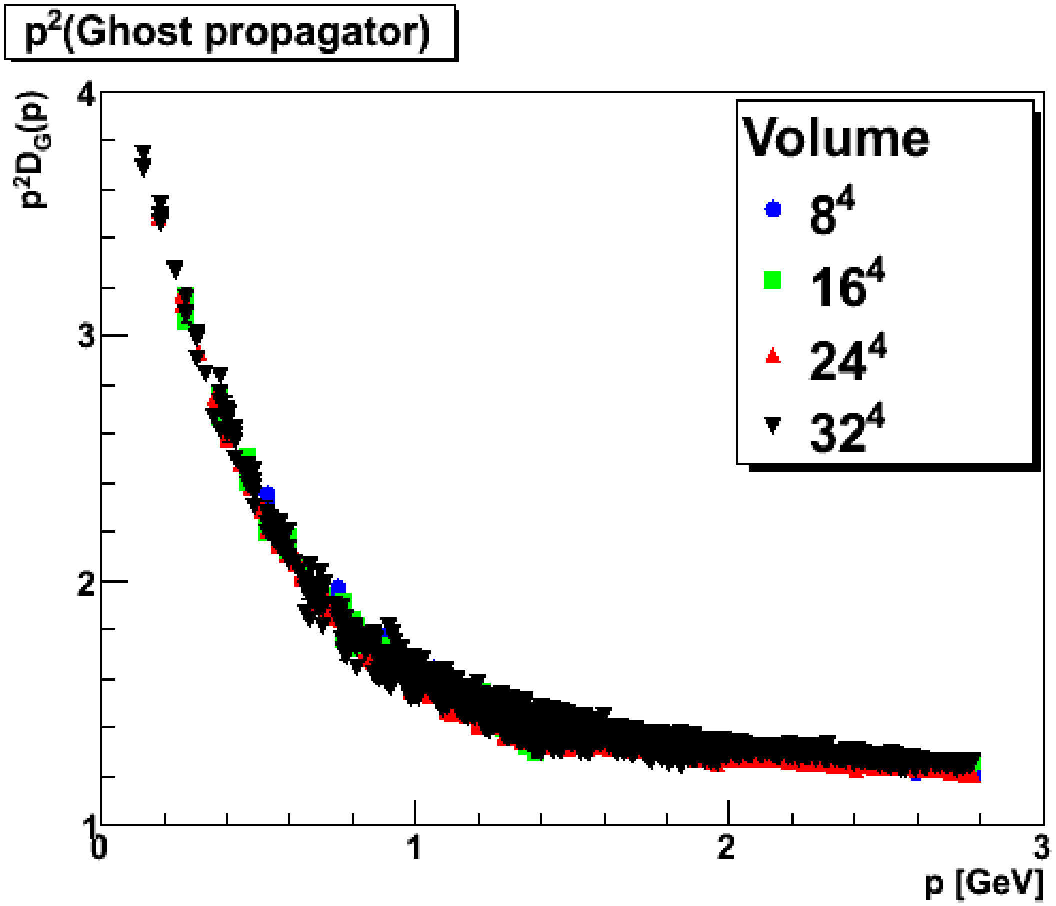
Ghost propagator

[Maas, EPJC'11
Maas, Mufti PoS'12, unpublished]



Ghost propagator

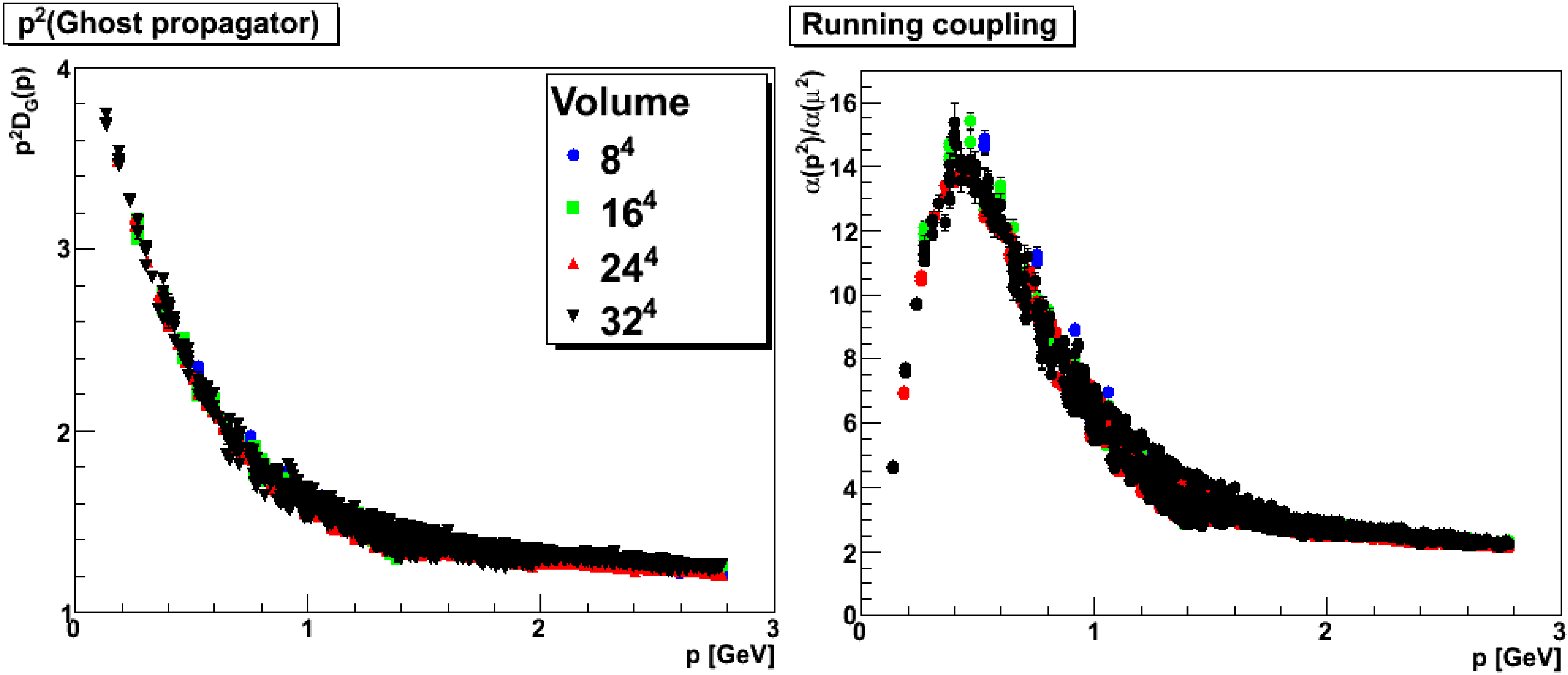
[Maas, EPJC'11
Maas, Mufti PoS'12, unpublished]



- Infrared enhanced
  - But likely not divergent

Ghost propagator

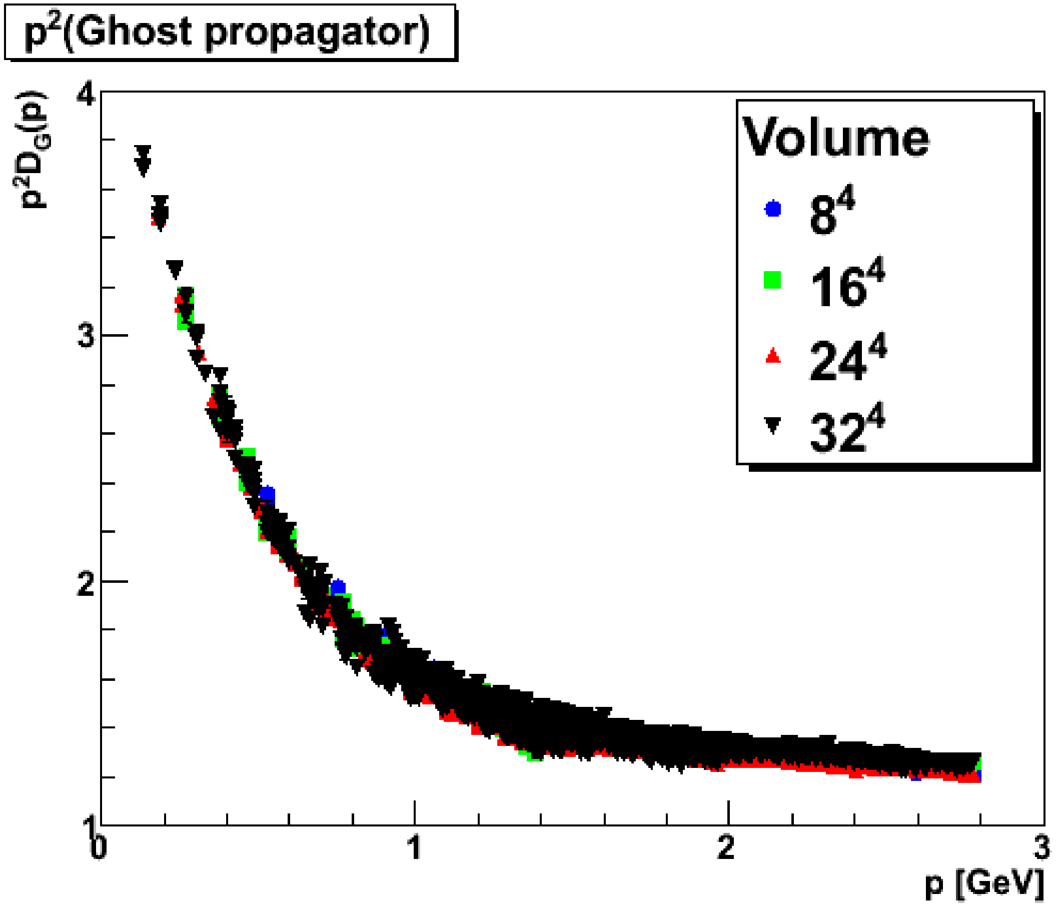
[Maas, EPJC'11
Maas, Mufti PoS'12, unpublished]

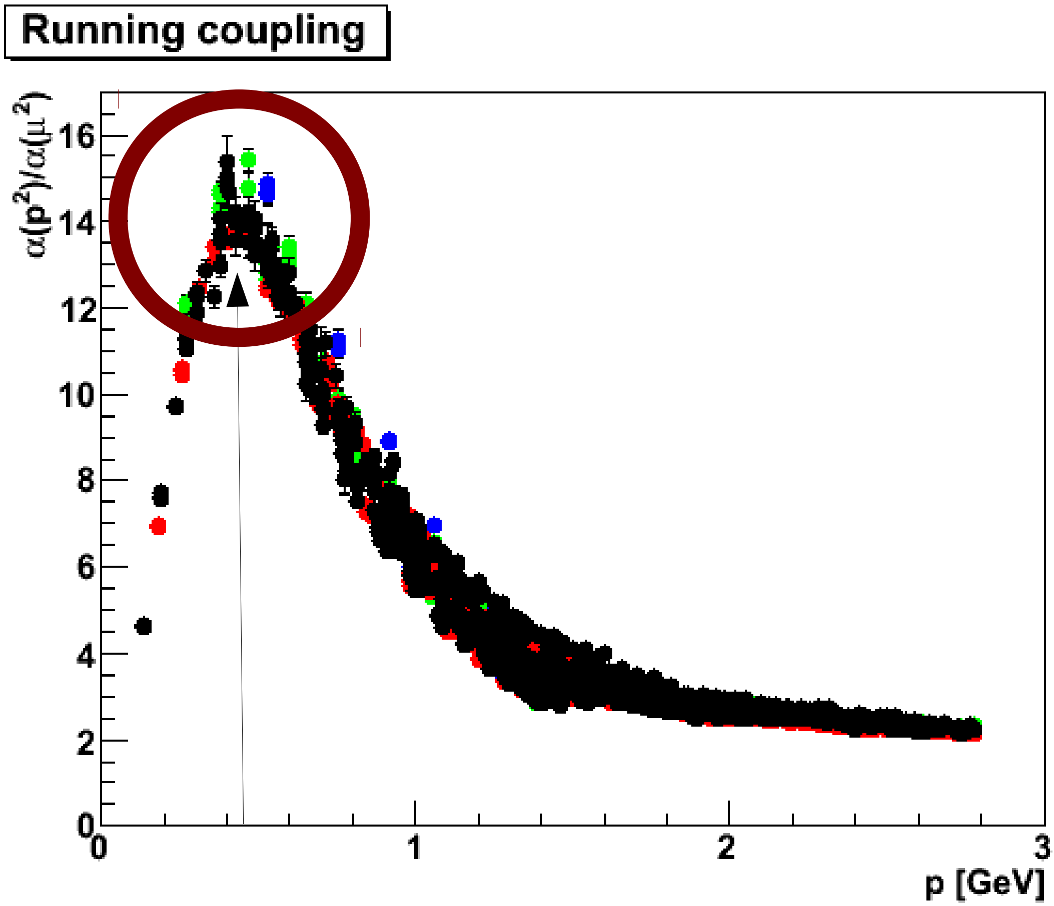


- Infrared enhanced
  - But likely not divergent
- Derive a running coupling from $p^6 D_G{}^2 D$

Ghost propagator

[Maas, EPJC'11
Maas, Mufti PoS'12, unpublished]

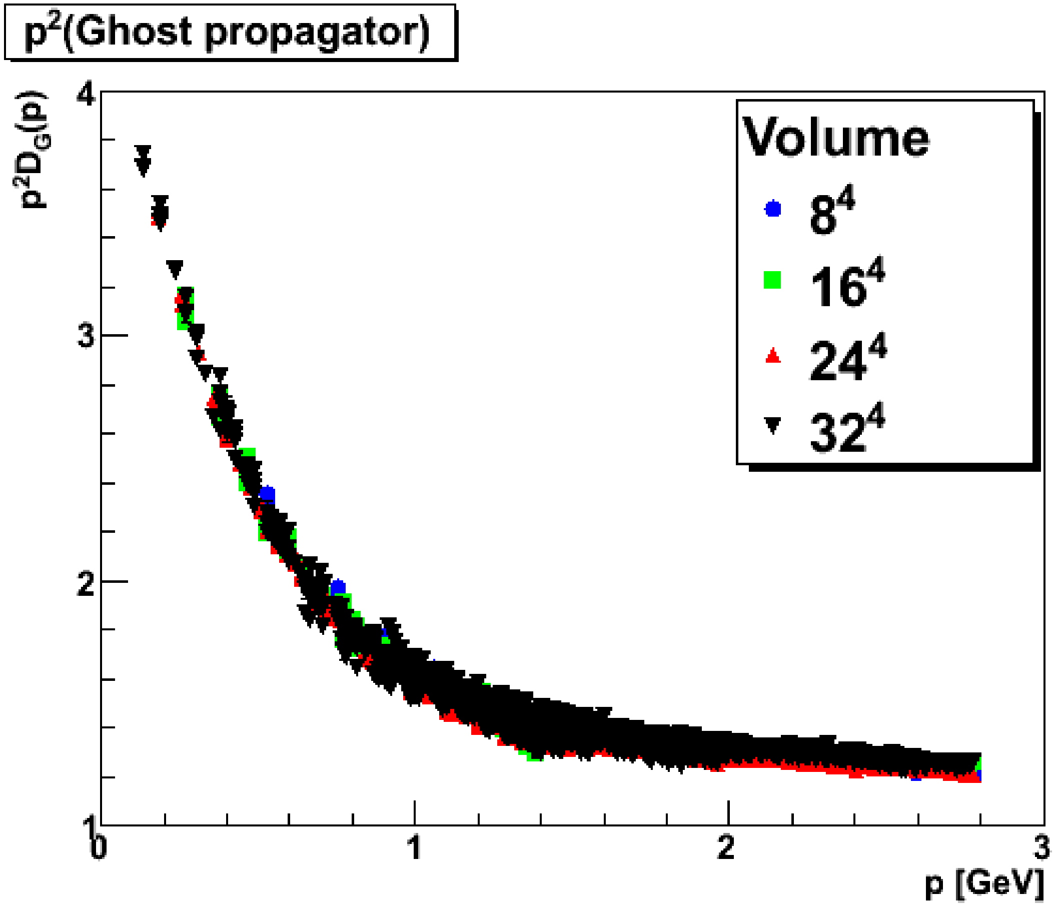


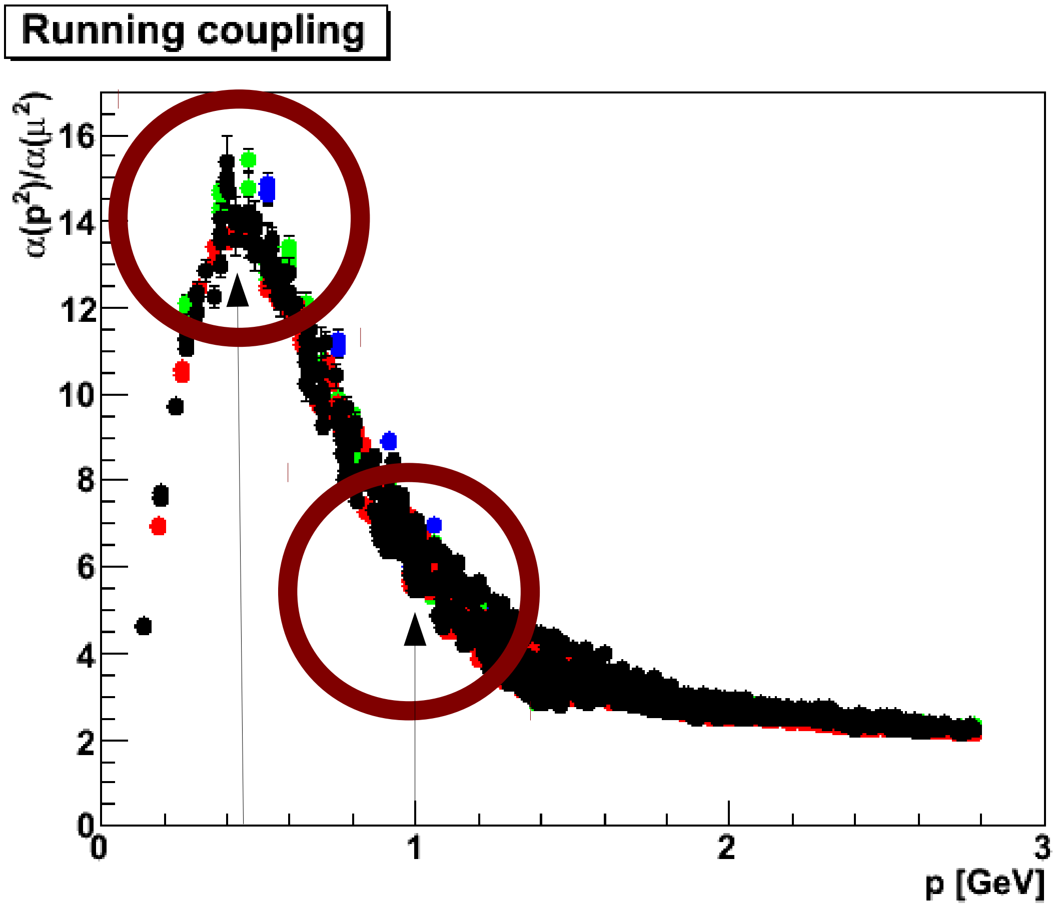


- Infrared enhanced
  - But likely not divergent
- Derive a running coupling from $p^6D_G{}^2D$

Ghost propagator

[Maas, EPJC'11
Maas, Mufti PoS'12, unpublished]

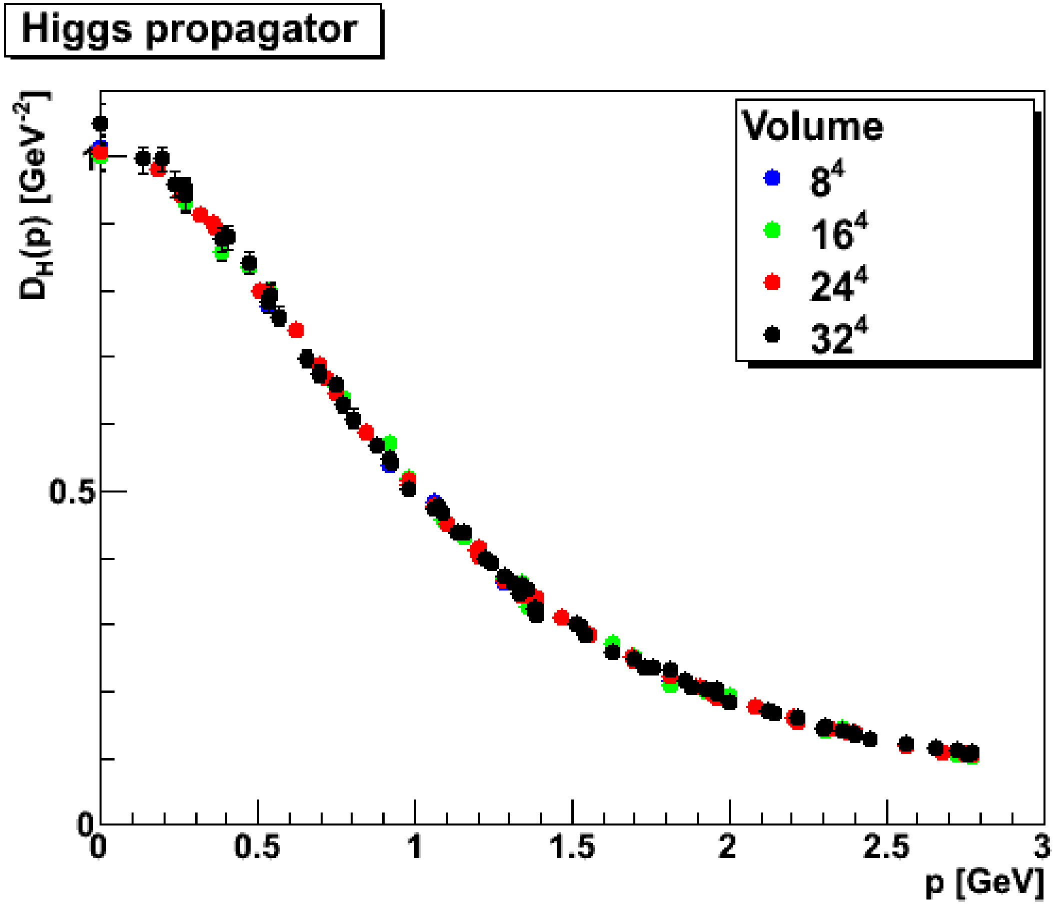




- Infrared enhanced
  - But likely not divergent
- Derive a running coupling from $p^6 D_G^2 D$
  - Not strongest at lowest bound state masses

Scalar quark propagator

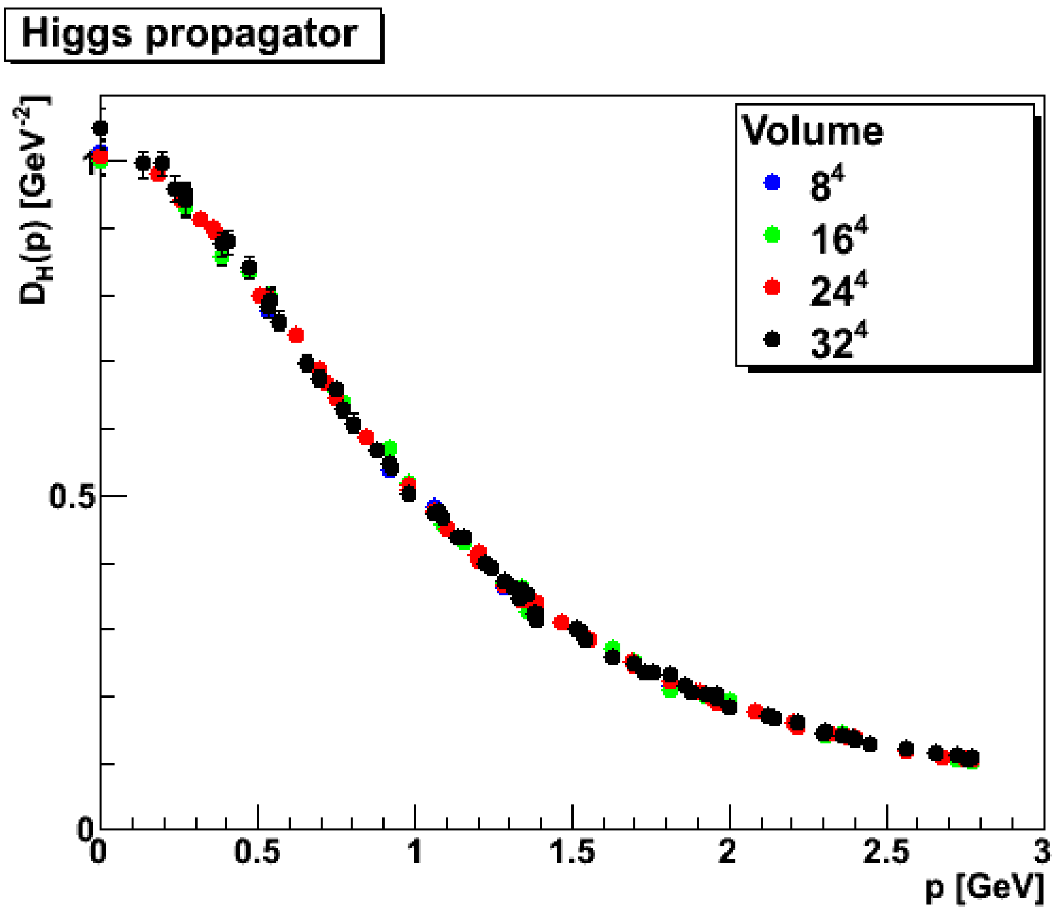
[Maas, EPJC'11
Maas, Mufti PoS'12, unpublished]



m_r=1 GeV

Scalar quark propagator

[Maas, EPJC'11
Maas, Mufti PoS'12, unpublished]

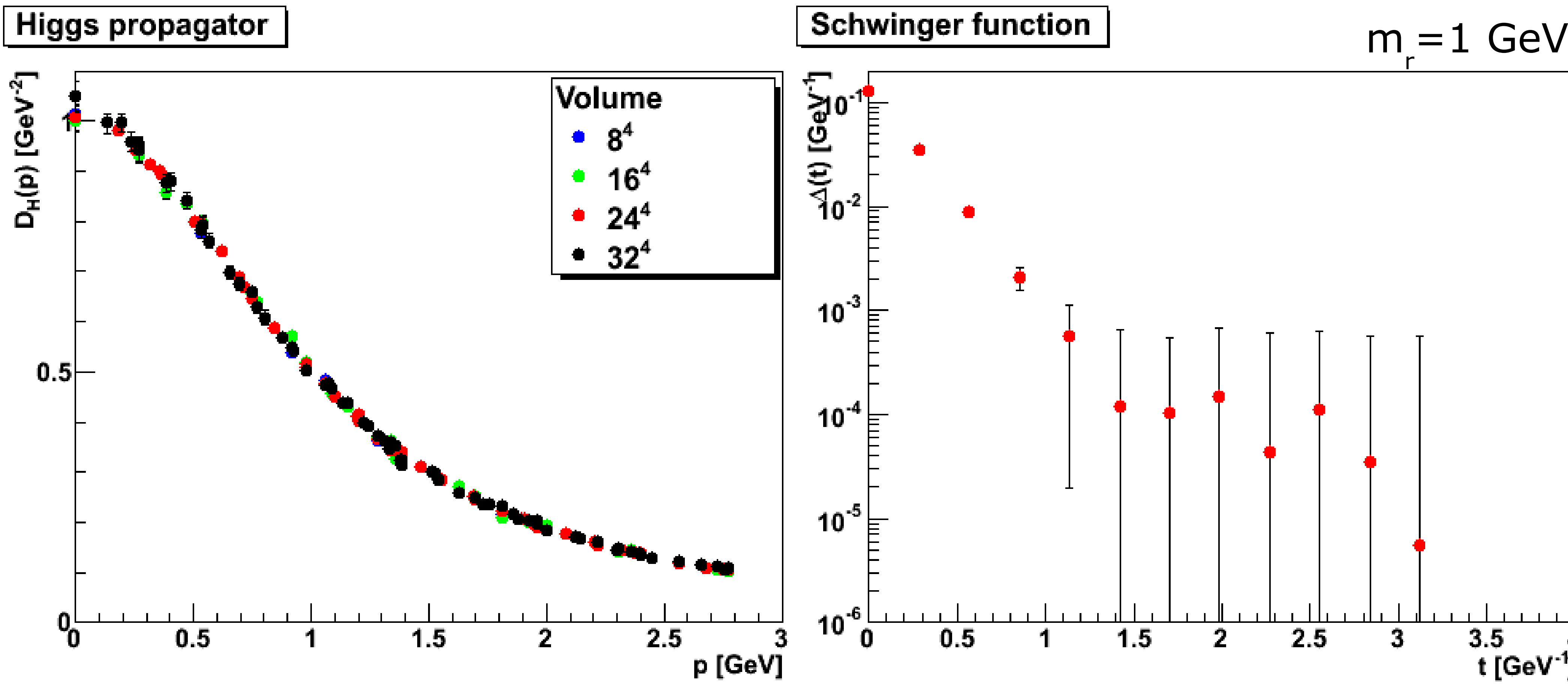


m_r=1 GeV

- Requires mass renormalization
  - Tree-level mass zero: "Mass generation"

Scalar quark propagator

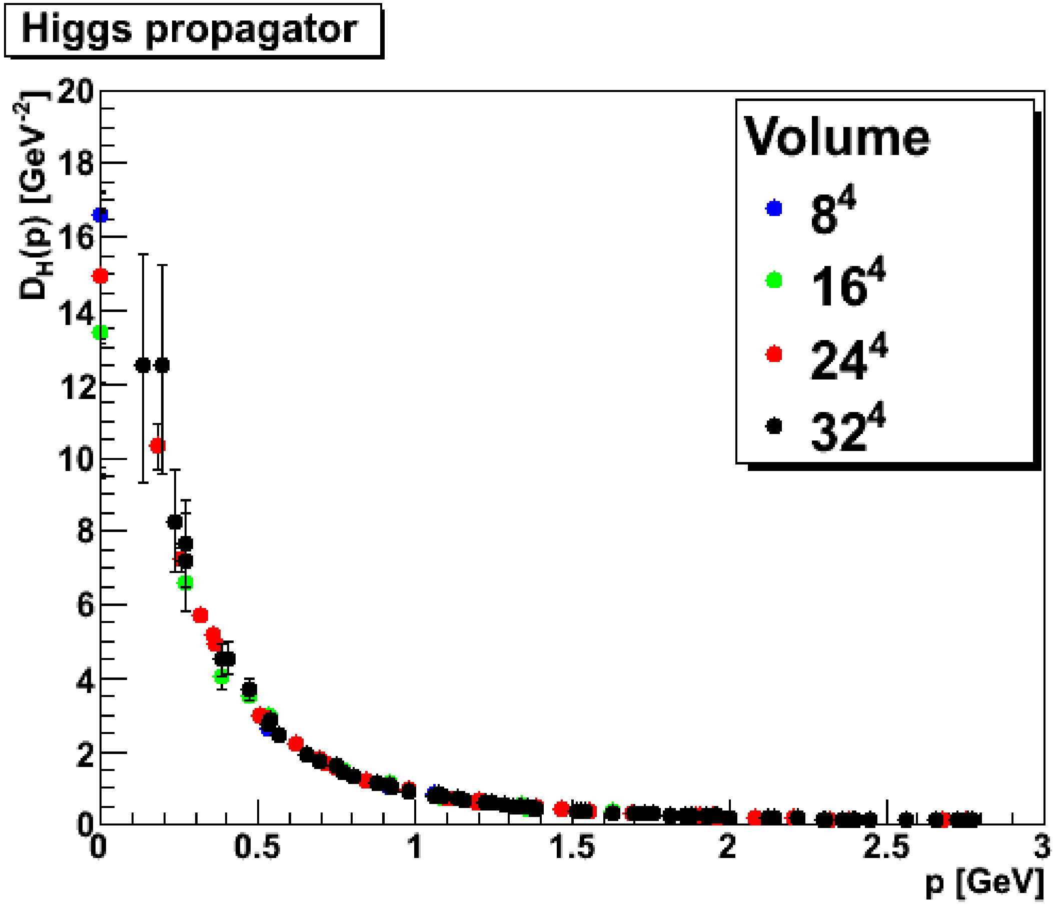
[Maas, EPJC'11
Maas, Mufti PoS'12, unpublished]

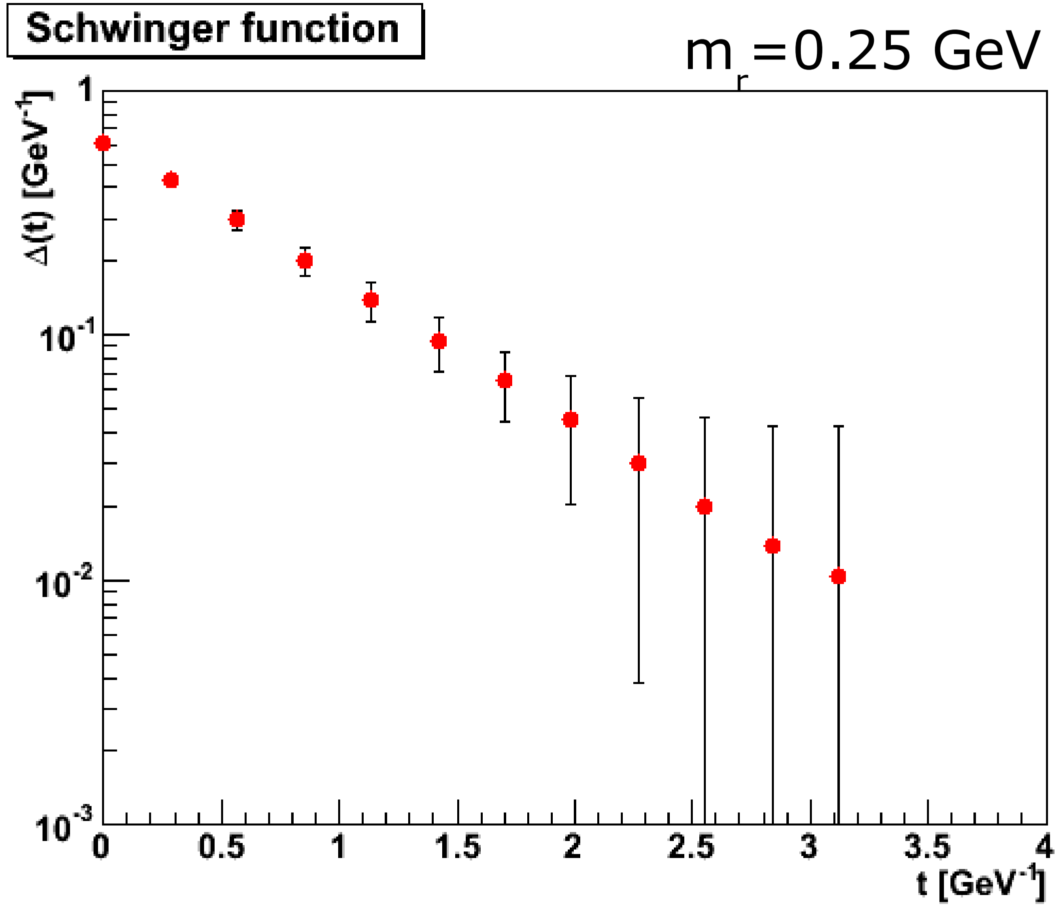


- Requires mass renormalization
  - Tree-level mass zero: “Mass generation”
- No sign (yet) of positivity violation

Scalar quark propagator

[Maas, EPJC'11
Maas, Mufti PoS'12, unpublished]





- Requires mass renormalization
  - Tree-level mass zero: “Mass generation”
- No sign (yet) of positivity violation

Vertices

Vertices

- Three 3-point vertices
  - 4-point vertices too expensive

Vertices

[Cucchieri, Maas, Mendes, PRD'06,'08
Maas, Mufti PoS'12, unpublished]

- Three 3-point vertices
  - 4-point vertices too expensive
  - Ghost-gluon vertex $<A_\mu^a c^b \bar{c}^c> = D_{\mu\nu}^{ad} D_G^{be} D_G^{cf} \Gamma_\nu^{def}$

Vertices

[Cucchieri, Maas, Mendes, PRD'06,'08
Maas, Mufti PoS'12, unpublished]

- Three 3-point vertices
  - 4-point vertices too expensive
  - Ghost-gluon vertex $<A_\mu^a c^b \bar{c}^c> = D_{\mu\nu}^{ad} D_G^{be} D_G^{cf} \Gamma_\nu^{def}$

$$G^{Ac\bar{c}} = \Gamma^{tl} < A c \bar{c} > / \left(\Gamma^{tl} D D_G D_G \Gamma^{tl} \right)$$

Vertices

[Cucchieri, Maas, Mendes, PRD'06,'08
Maas, Mufti PoS'12, unpublished]

- Three 3-point vertices
  - 4-point vertices too expensive
  - Ghost-gluon vertex $<A_\mu^a c^b \bar{c}^c> = D_{\mu\nu}^{ad} D_G^{be} D_G^{cf} \Gamma_\nu^{def}$

    $G^{Ac\bar{c}} = \Gamma^{tl} < A c \bar{c} > / \left(\Gamma^{tl} D D_G D_G \Gamma^{tl} \right)$
  - 3-gluon vertex $<A_\mu^a A_\nu^b A_\rho^c> = D_{\mu\alpha}^{ad} D_{\nu\beta}^{be} D_{\rho\gamma}^{cf} \Gamma_{\alpha\beta\gamma}^{def}$

    $G^{A^3} = \Gamma^{tl} < AAA > / \left(\Gamma^{tl} DDD \Gamma^{tl} \right)$

Vertices

[Cucchieri, Maas, Mendes, PRD'06,'08
Maas, Mufti PoS'12, unpublished]

- Three 3-point vertices
  - 4-point vertices too expensive
  - Ghost-gluon vertex $<A_\mu^a c^b \bar{c}^c> = D_{\mu\nu}^{ad} D_G^{be} D_G^{cf} \Gamma_\nu^{def}$

    $G^{Ac\bar{c}} = \Gamma^{tl} < A c \bar{c} > / \left(\Gamma^{tl} D D_G D_G \Gamma^{tl} \right)$
  - 3-gluon vertex $<A_\mu^a A_\nu^b A_\rho^c> = D_{\mu\alpha}^{ad} D_{\nu\beta}^{be} D_{\rho\gamma}^{cf} \Gamma_{\alpha\beta\gamma}^{def}$

    $G^{A^3} = \Gamma^{tl} < AAA > / \left(\Gamma^{tl} DDD \Gamma^{tl} \right)$
  - Scalar-gluon vertex $<A_\mu^a h^i h^{j\,+}> = D_{\mu\nu}^{ad} D_H^{ik} D_G^{jm} \Gamma_\nu^{dkm}$

    $G^{Ahh^+} = \Gamma^{tl} < A h h^+ > / \left(\Gamma^{tl} D D_H D_H \Gamma^{tl} \right)$

Vertices

[Cucchieri, Maas, Mendes, PRD'06,'08
Maas, Mufti PoS'12, unpublished]

- Three 3-point vertices
  - 4-point vertices too expensive
  - Ghost-gluon vertex $< A_\mu^a c^b \bar{c}^c > = D_{\mu\nu}^{ad} D_G^{be} D_G^{cf} \Gamma_\nu^{def}$

    $G^{Ac\bar{c}} = \Gamma^{tl} < A c \bar{c} > / \left(\Gamma^{tl} D D_G D_G \Gamma^{tl} \right)$
  - 3-gluon vertex $< A_\mu^a A_\nu^b A_\rho^c > = D_{\mu\alpha}^{ad} D_{\nu\beta}^{be} D_{\rho\gamma}^{cf} \Gamma_{\alpha\beta\gamma}^{def}$

    $G^{A^3} = \Gamma^{tl} < AAA > / \left(\Gamma^{tl} DDD \Gamma^{tl} \right)$
  - Scalar-gluon vertex $< A_\mu^a h^i t_F h^{j+} > = D_{\mu\nu}^{ad} D_H^{ik} D_G^{jm} \Gamma_\nu^{dkm}$

    $G^{Ahh^+} = \Gamma^{tl} < A h t_F h^+ > / \left(\Gamma^{tl} D D_H D_H \Gamma^{tl} \right)$
    - t_F makes vertex flavor-conserving
    - Flavor-violating vertex vanishes
      - Flavor conserved

Vertices

[Cucchieri, Maas, Mendes, PRD'06,'08
Maas, Mufti PoS'12, unpublished]

- Three 3-point vertices
  - 4-point vertices too expensive
  - Ghost-gluon vertex $<A_\mu^a c^b \bar{c}^c> = D_{\mu\nu}^{ad} D_G^{be} D_G^{cf} \Gamma_\nu^{def}$

    $G^{Ac\bar{c}} = \Gamma^{tl} < A c \bar{c} > / \left(\Gamma^{tl} D D_G D_G \Gamma^{tl} \right)$
  - 3-gluon vertex $<A_\mu^a A_\nu^b A_\rho^c> = D_{\mu\alpha}^{ad} D_{\nu\beta}^{be} D_{\rho\gamma}^{cf} \Gamma_{\alpha\beta\gamma}^{def}$

    $G^{A^3} = \Gamma^{tl} < AAA > / \left(\Gamma^{tl} DDD \Gamma^{tl} \right)$
  - Scalar-gluon vertex $<A_\mu^a h^i t_F h^{j\,+}> = D_{\mu\nu}^{ad} D_H^{ik} D_G^{jm} \Gamma_\nu^{dkm}$

    $G^{Ahh^+} = \Gamma^{tl} < A h t_F h^+ > / \left(\Gamma^{tl} D D_H D_H \Gamma^{tl} \right)$
- Two momentum configurations

Vertices

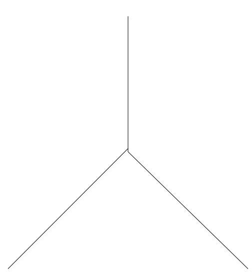
[Cucchieri, Maas, Mendes, PRD'06,'08
Maas, Mufti PoS'12, unpublished]

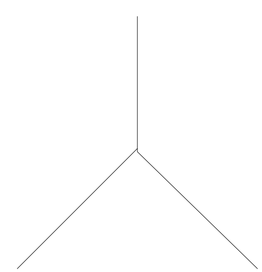
- Three 3-point vertices
  - 4-point vertices too expensive
  - Ghost-gluon vertex $<A_\mu^a c^b \bar{c}^c> \; = D_{\mu\nu}^{ad} D_G^{be} D_G^{cf} \Gamma_\nu^{def}$

    $G^{Ac\bar{c}} = \Gamma^{tl} < A c \bar{c} > \; / \left(\Gamma^{tl} D D_G D_G \Gamma^{tl} \right)$
  - 3-gluon vertex $<A_\mu^a A_\nu^b A_\rho^c> \; = \; D_{\mu\alpha}^{ad} D_{\nu\beta}^{be} D_{\rho\gamma}^{cf} \Gamma_{\alpha\beta\gamma}^{def}$

    $G^{A^3} = \Gamma^{tl} < AAA > \; / \left(\Gamma^{tl} DDD \Gamma^{tl} \right)$
  - Scalar-gluon vertex $<A_\mu^a h^i t_F h^{j\,+}> \; = D_{\mu\nu}^{ad} D_H^{ik} D_G^{jm} \Gamma_\nu^{dkm}$

    $G^{Ahh^+} = \Gamma^{tl} < A h t_F h^+ > \; / \left(\Gamma^{tl} D D_H D_H \Gamma^{tl} \right)$
- Two momentum configurations





Vertices

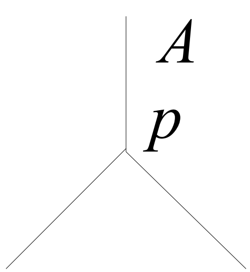
[Cucchieri, Maas, Mendes, PRD'06,'08
Maas, Mufti PoS'12, unpublished]

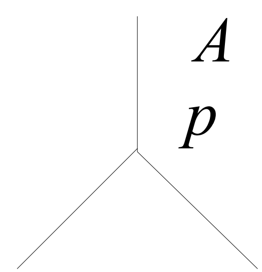
- Three 3-point vertices
  - 4-point vertices too expensive
  - Ghost-gluon vertex $<A_\mu^a c^b \bar{c}^c> = D_{\mu\nu}^{ad} D_G^{be} D_G^{cf} \Gamma_\nu^{def}$

    $G^{Ac\bar{c}} = \Gamma^{tl} <A c \bar{c}> / \left(\Gamma^{tl} D D_G D_G \Gamma^{tl}\right)$
  - 3-gluon vertex $<A_\mu^a A_\nu^b A_\rho^c> = D_{\mu\alpha}^{ad} D_{\nu\beta}^{be} D_{\rho\gamma}^{cf} \Gamma_{\alpha\beta\gamma}^{def}$

    $G^{A^3} = \Gamma^{tl} <AAA> / \left(\Gamma^{tl} DDD \Gamma^{tl}\right)$
  - Scalar-gluon vertex $<A_\mu^a h^i t_F h^{j\,+}> = D_{\mu\nu}^{ad} D_H^{ik} D_G^{jm} \Gamma_\nu^{dkm}$

    $G^{Ahh^+} = \Gamma^{tl} <A h t_F h^+> / \left(\Gamma^{tl} D D_H D_H \Gamma^{tl}\right)$
- Two momentum configurations





Vertices

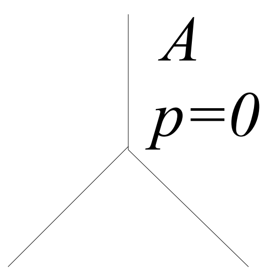
[Cucchieri, Maas, Mendes, PRD'06,'08
Maas, Mufti PoS'12, unpublished]

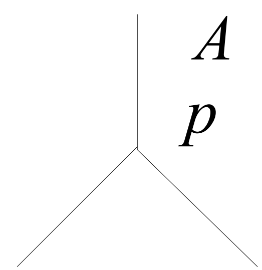
- Three 3-point vertices
  - 4-point vertices too expensive
  - Ghost-gluon vertex $<A_\mu^a c^b \bar{c}^c> \; = D_{\mu\nu}^{ad} D_G^{be} D_G^{cf} \Gamma_\nu^{def}$

    $G^{Ac\bar{c}} = \Gamma^{tl} < A c \bar{c} > \; / \left(\Gamma^{tl} D D_G D_G \Gamma^{tl} \right)$
  - 3-gluon vertex $<A_\mu^a A_\nu^b A_\rho^c> \; = \; D_{\mu\alpha}^{ad} D_{\nu\beta}^{be} D_{\rho\gamma}^{cf} \Gamma_{\alpha\beta\gamma}^{def}$

    $G^{A^3} = \Gamma^{tl} < AAA > \; / \left(\Gamma^{tl} DDD \Gamma^{tl} \right)$
  - Scalar-gluon vertex $<A_\mu^a h^i t_F h^{j\,+} > \; = D_{\mu\nu}^{ad} D_H^{ik} D_G^{jm} \Gamma_\nu^{dkm}$

    $G^{Ahh^+} = \Gamma^{tl} < A h t_F h^+ > \; / \left(\Gamma^{tl} D D_H D_H \Gamma^{tl} \right)$
- Two momentum configurations





Vertices

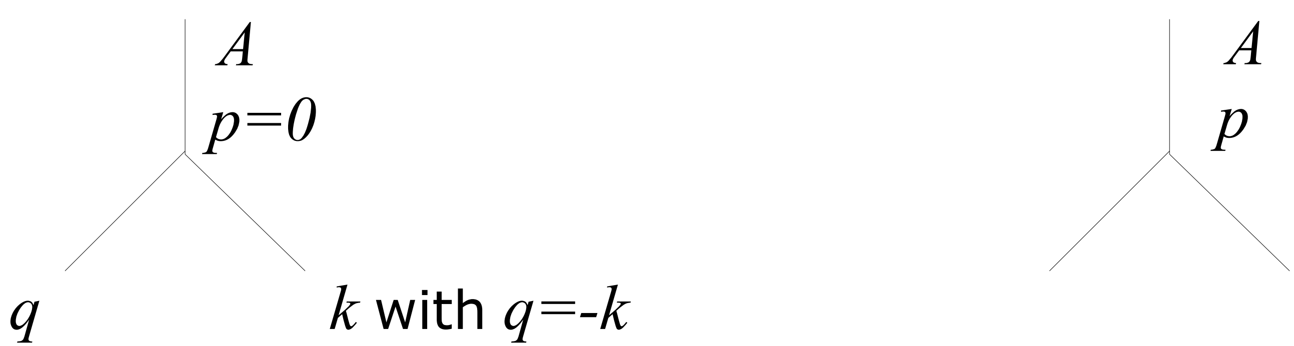
[Cucchieri, Maas, Mendes, PRD'06,'08
Maas, Mufti PoS'12, unpublished]

- Three 3-point vertices
  - 4-point vertices too expensive
  - Ghost-gluon vertex $<A_\mu^a c^b \bar{c}^c> = D_{\mu\nu}^{ad} D_G^{be} D_G^{cf} \Gamma_\nu^{def}$

    $G^{Ac\bar{c}} = \Gamma^{tl} < A c \bar{c} > /\left(\Gamma^{tl} D D_G D_G \Gamma^{tl}\right)$
  - 3-gluon vertex $<A_\mu^a A_\nu^b A_\rho^c> = D_{\mu\alpha}^{ad} D_{\nu\beta}^{be} D_{\rho\gamma}^{cf} \Gamma_{\alpha\beta\gamma}^{def}$

    $G^{A^3} = \Gamma^{tl} < AAA > /\left(\Gamma^{tl} DDD \Gamma^{tl}\right)$
  - Scalar-gluon vertex $<A_\mu^a h^i t_F h^{j\,+}> = D_{\mu\nu}^{ad} D_H^{ik} D_G^{jm} \Gamma_\nu^{dkm}$

    $G^{Ahh^+} = \Gamma^{tl} < A h t_F h^+ > /\left(\Gamma^{tl} D D_H D_H \Gamma^{tl}\right)$
- Two momentum configurations



Vertices

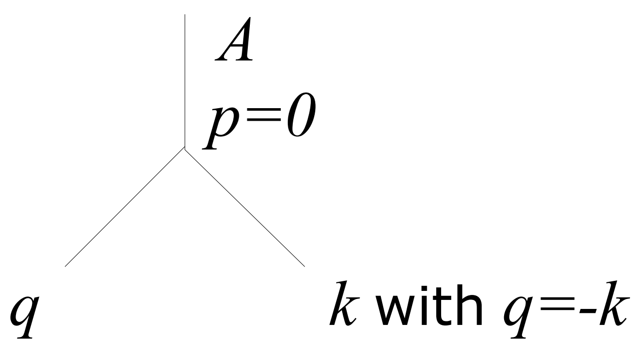
[Cucchieri, Maas, Mendes, PRD'06,'08
Maas, Mufti PoS'12, unpublished]

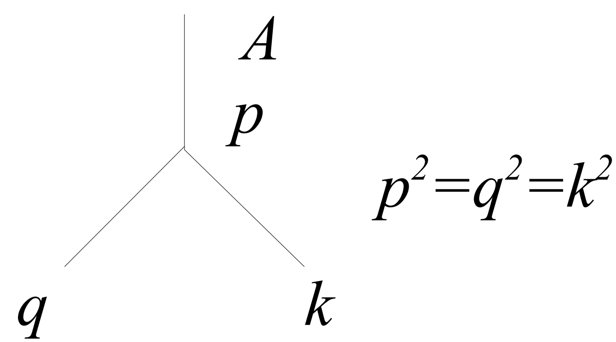
- Three 3-point vertices
  - 4-point vertices too expensive
  - Ghost-gluon vertex $<A_\mu^a c^b \bar{c}^c> = D_{\mu\nu}^{ad} D_G^{be} D_G^{cf} \Gamma_\nu^{def}$

    $G^{Ac\bar{c}} = \Gamma^{tl} < A c \bar{c} > / \left(\Gamma^{tl} D D_G D_G \Gamma^{tl} \right)$
  - 3-gluon vertex $<A_\mu^a A_\nu^b A_\rho^c> = D_{\mu\alpha}^{ad} D_{\nu\beta}^{be} D_{\rho\gamma}^{cf} \Gamma_{\alpha\beta\gamma}^{def}$

    $G^{A^3} = \Gamma^{tl} < AAA > / \left(\Gamma^{tl} DDD \Gamma^{tl} \right)$
  - Scalar-gluon vertex $<A_\mu^a h^i t_F h^{j\,+}> = D_{\mu\nu}^{ad} D_H^{ik} D_G^{jm} \Gamma_\nu^{dkm}$

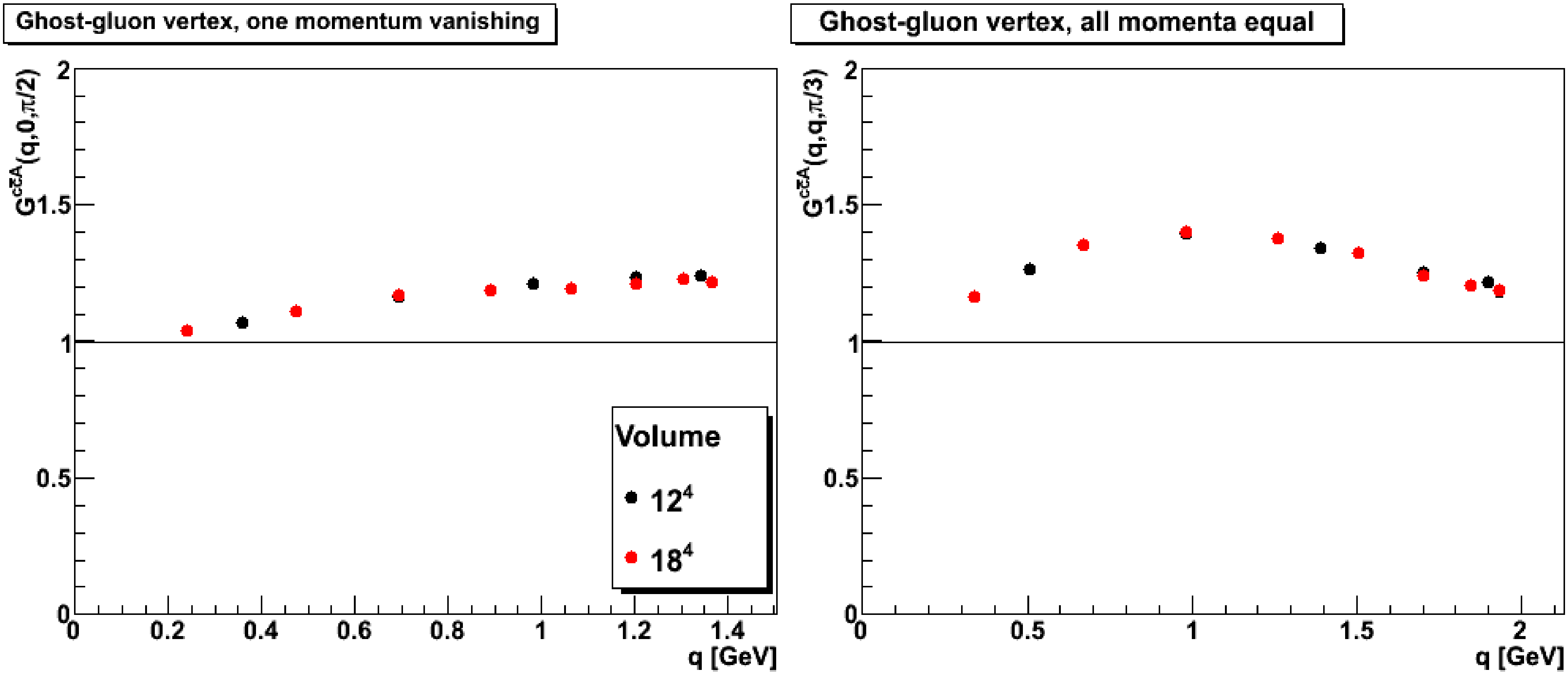
    $G^{Ahh^+} = \Gamma^{tl} < A h t_F h^+ > / \left(\Gamma^{tl} D D_H D_H \Gamma^{tl} \right)$
- Two momentum configurations





Ghost-gluon vertex

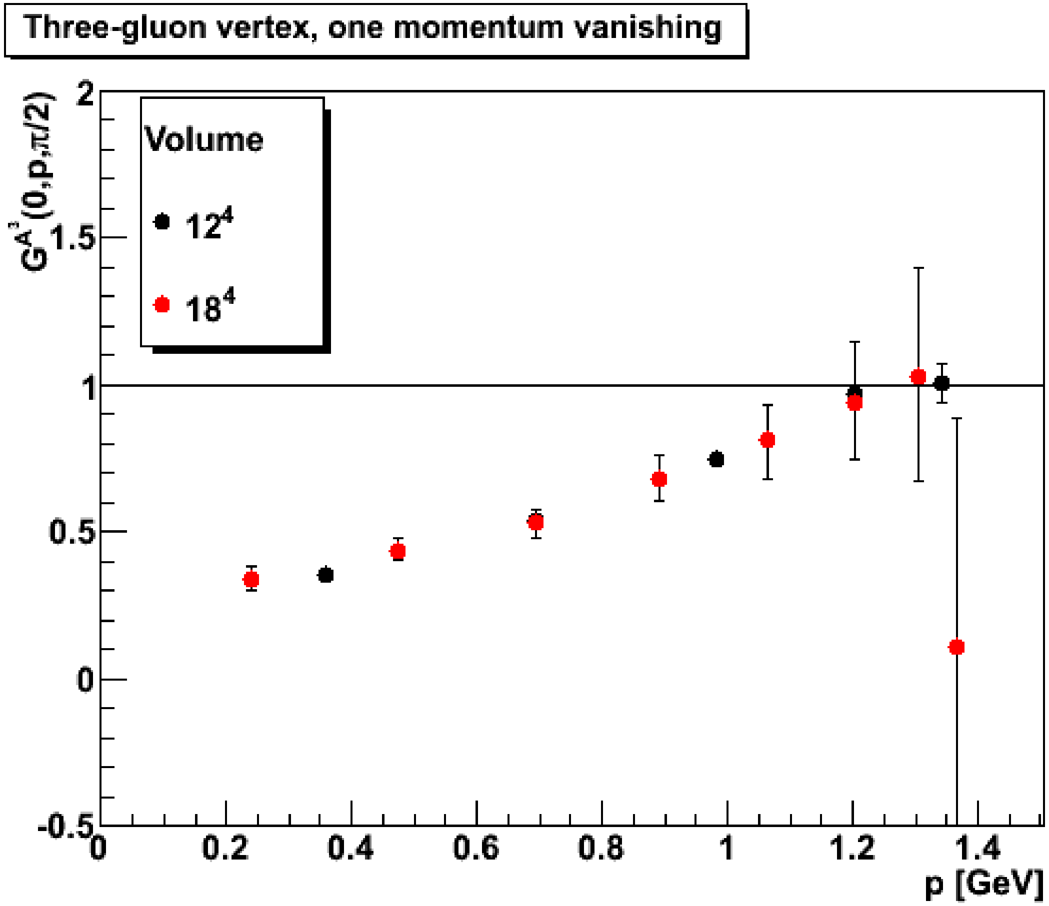
[Maas, Mufti PoS'12, unpublished]

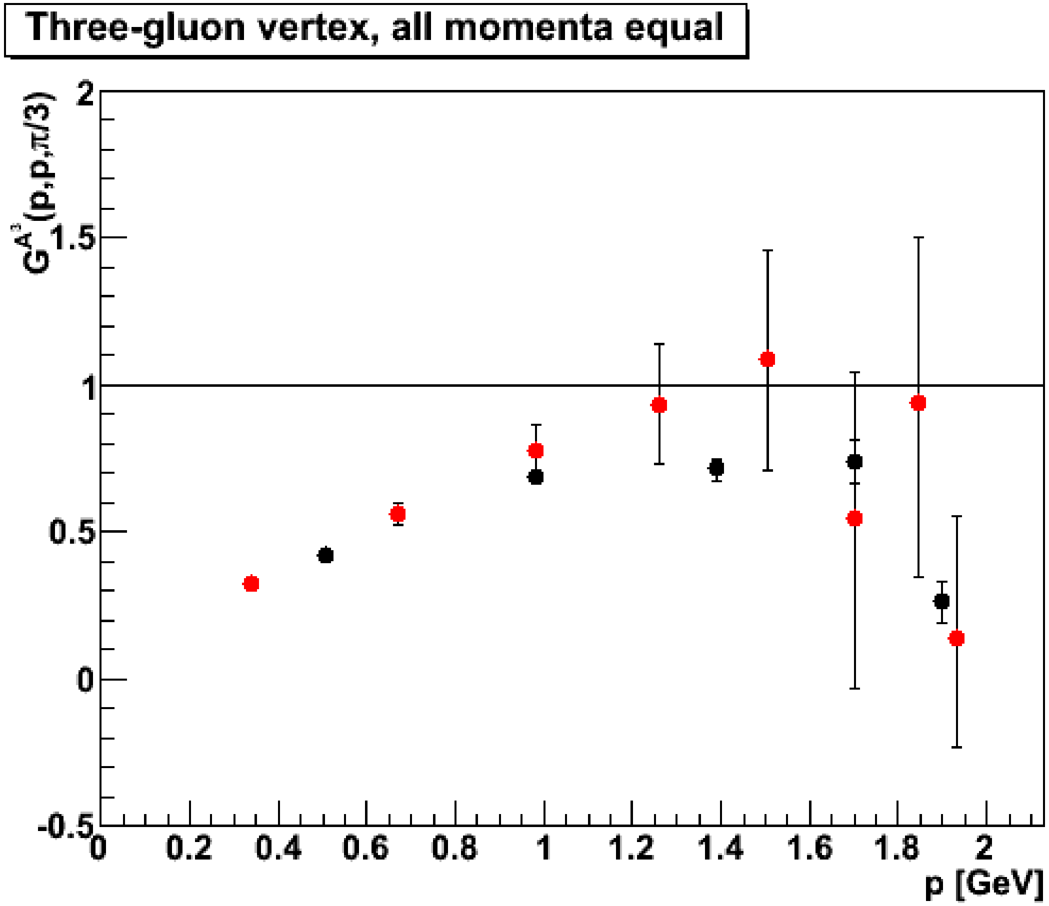


- Only small deviations from tree-level
  - Like in Yang-Mills theory
  - Strongest effect at bound state mass scale

3-gluon vertex

[Maas, Mufti PoS'12, unpublished]

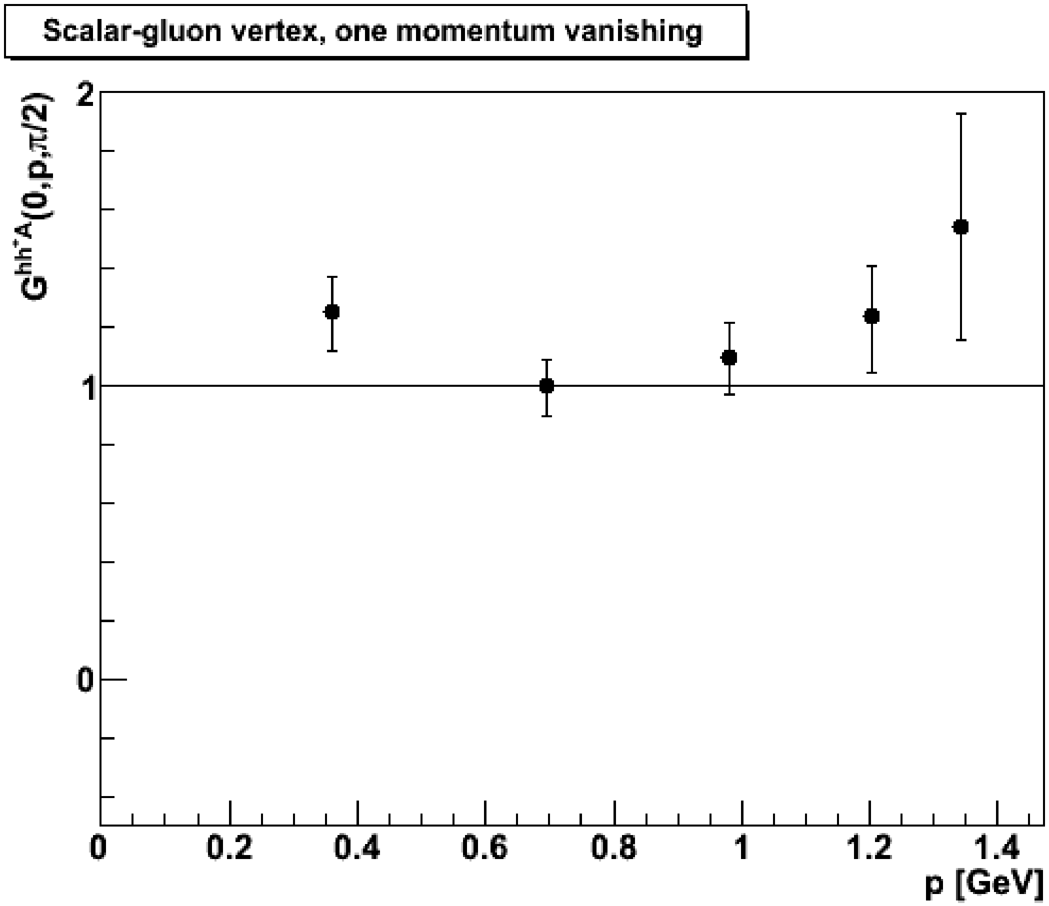


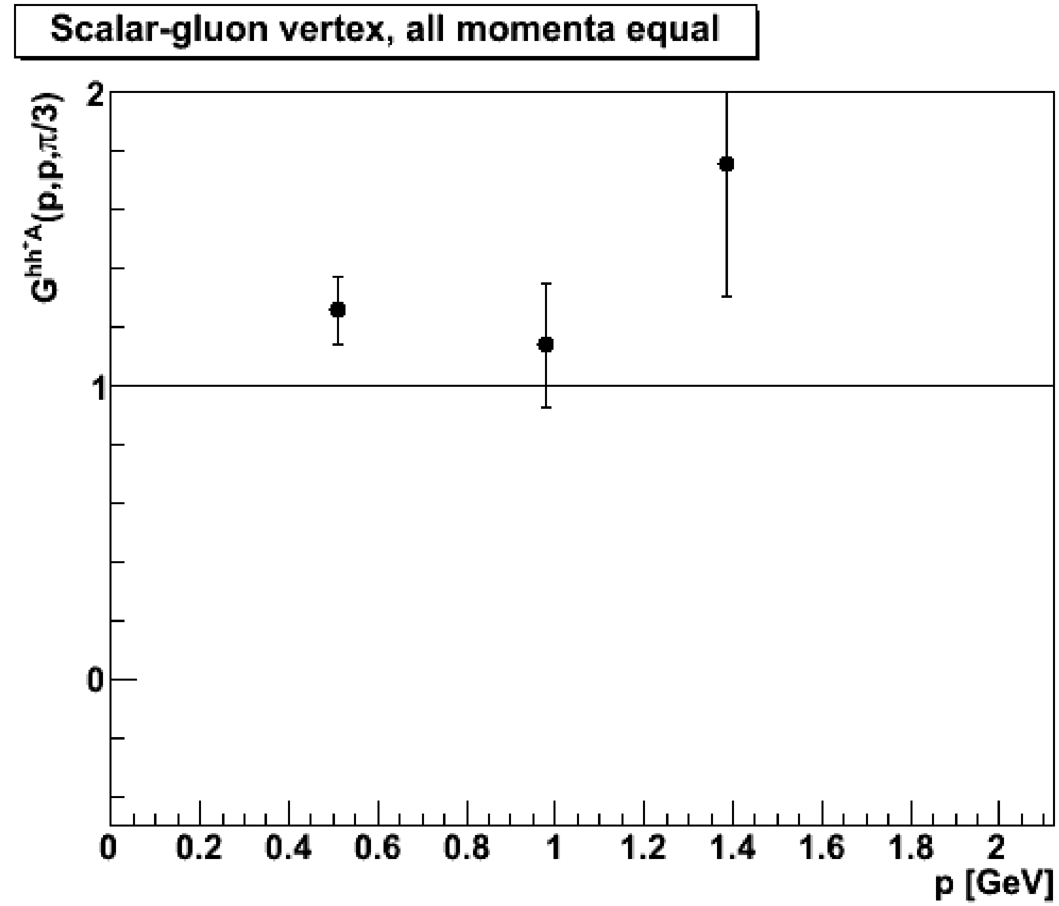


- Infrared suppressed
  - Sets in at bound state mass scale
  - Absence of (supposed) sign change of Yang-Mills theory at small momenta?

Scalar-gluon vertex

[Maas, Mufti PoS'12, unpublished]

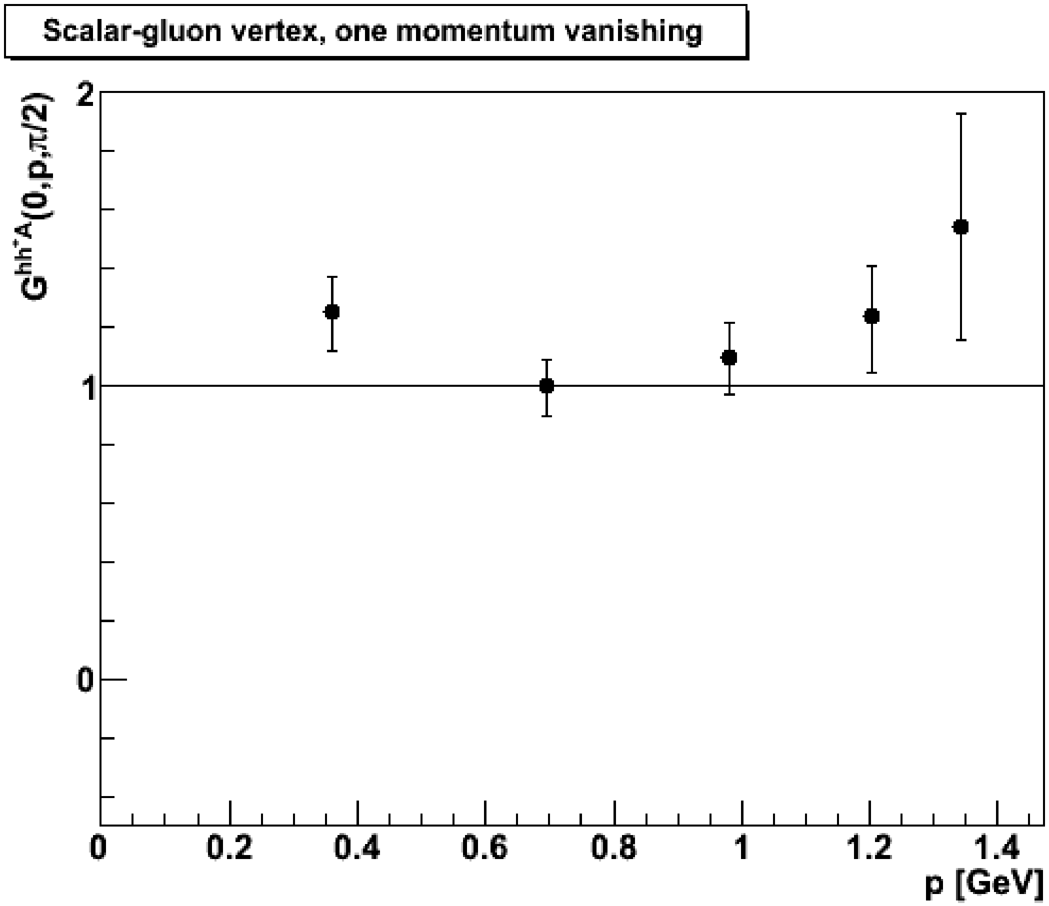


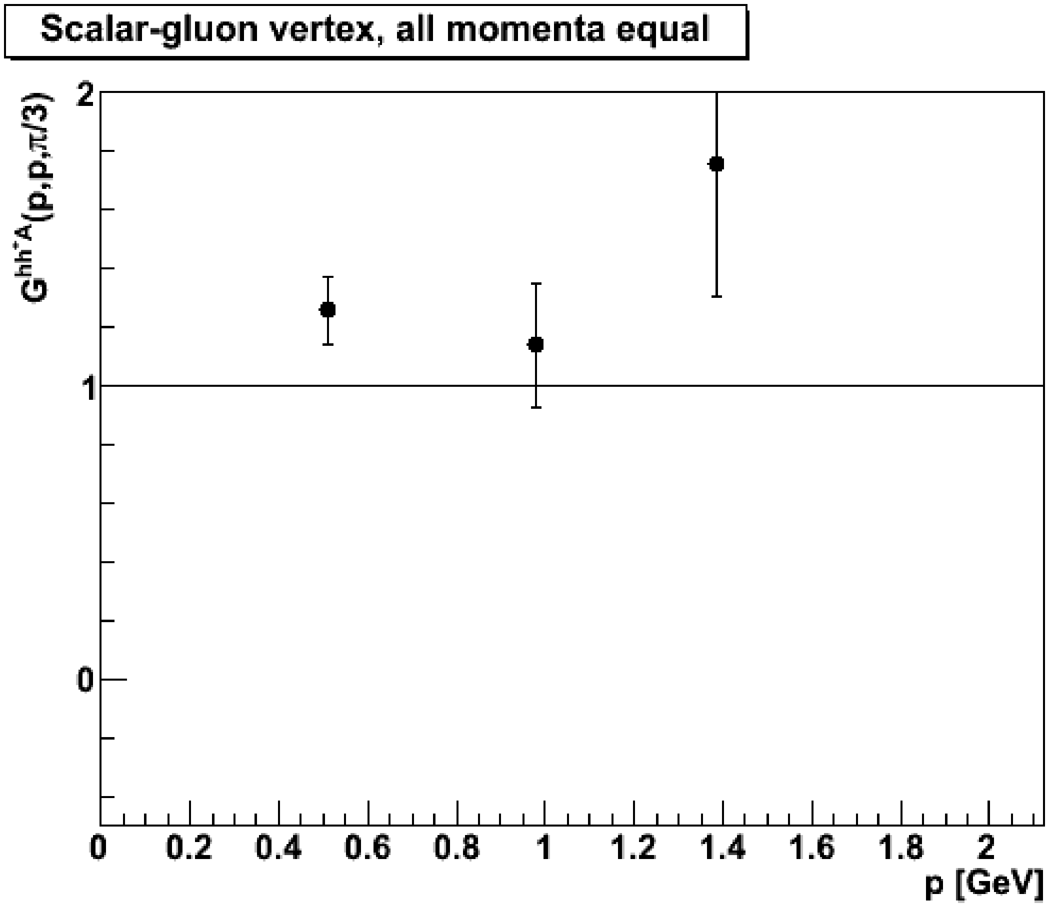


- Essentially tree-level
    - No indications for infrared effects (yet?)

Scalar-gluon vertex

[Maas, Mufti PoS'12, unpublished]

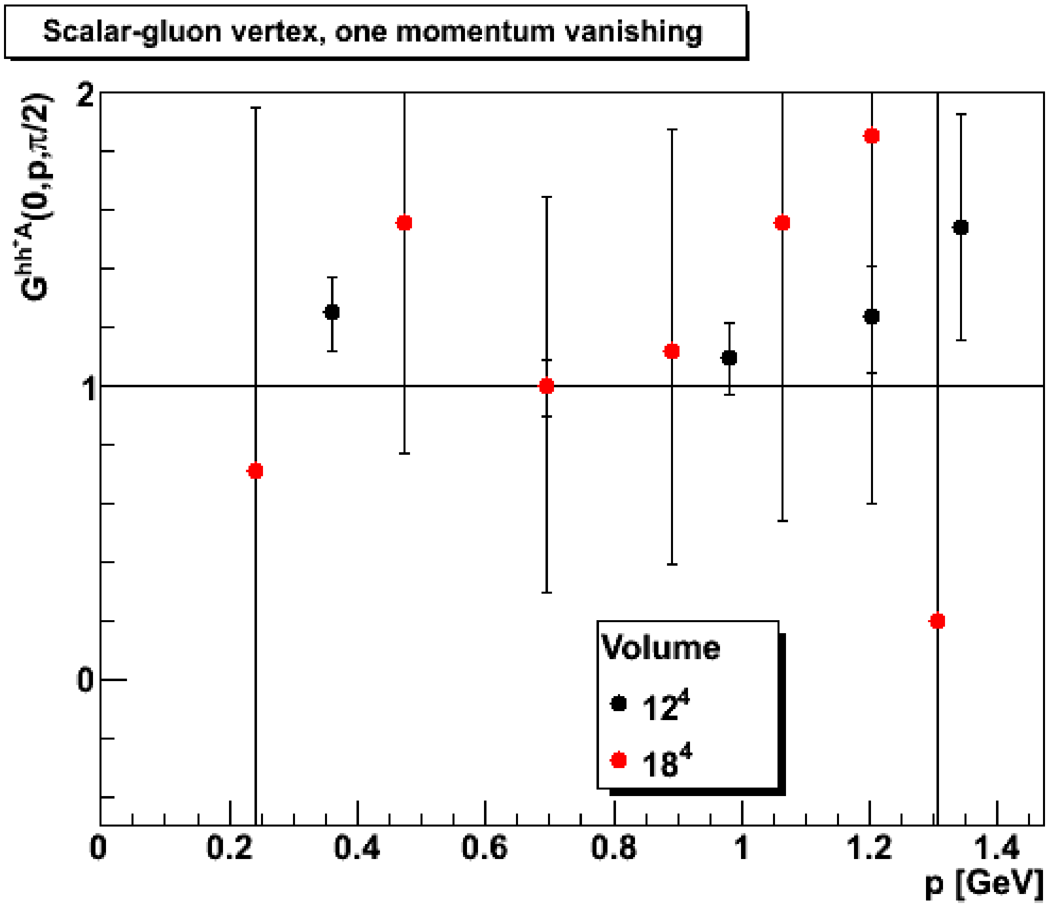


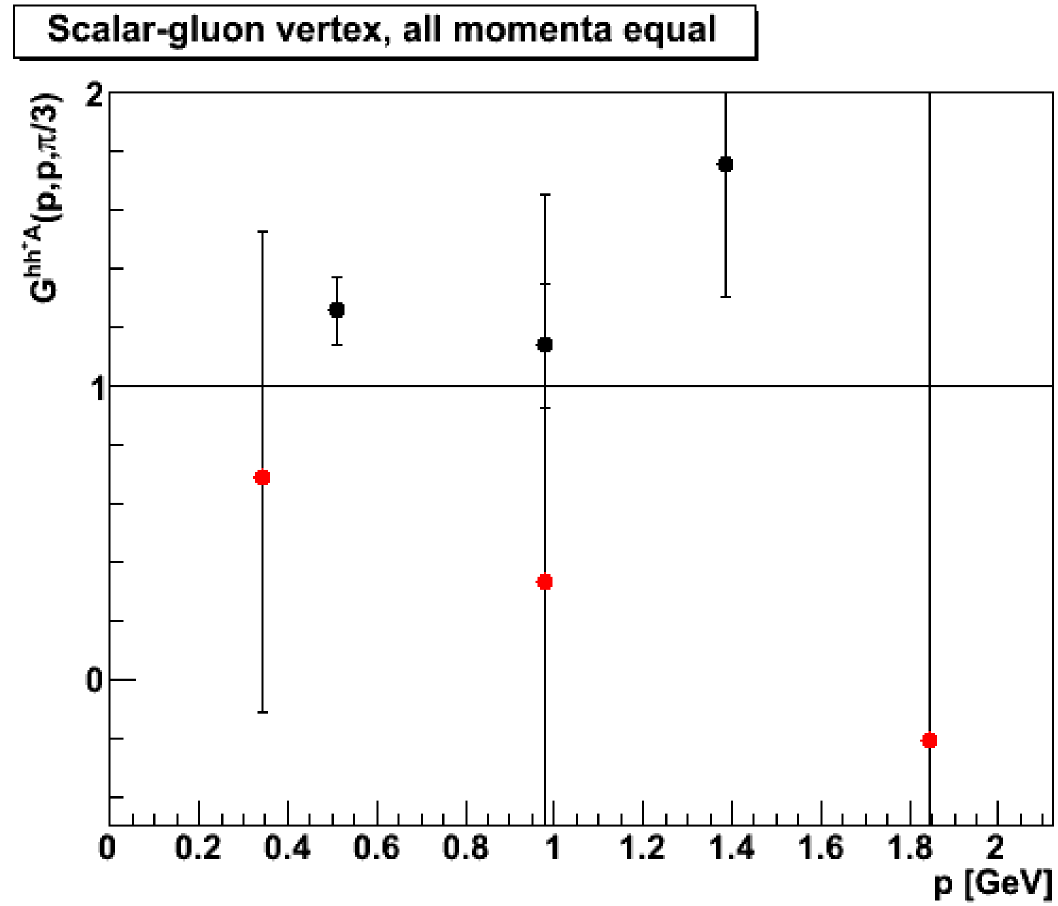


- Essentially tree-level
  - No indications for infrared effects (yet?)
- Different than a (pseudo-)confining 1-gluon exchange
- As in the quenched case [Maas, PoS'11, unpublished]

Scalar-gluon vertex

[Maas, Mufti PoS'12, unpublished]





- Essentially tree-level
  - No indications for infrared effects (yet?)
- Different than a (pseudo-)confining 1-gluon exchange
- As in the quenched case [Maas, PoS'11, unpublished]

Summary

- Scalar QCD a role model for QCD
  - Scalar theory simpler...

Summary

- Scalar QCD a role model for QCD
  - Scalar theory simpler...
  - ...but distinction to Higgs-like physics complicated

Summary

- Scalar QCD a role model for QCD
  - Scalar theory simpler...
  - ...but distinction to Higgs-like physics complicated
  - Test case for functional methods

Summary

- Scalar QCD a role model for QCD
  - Scalar theory simpler...
  - ...but distinction to Higgs-like physics complicated
  - Test case for functional methods
- Propagators in QCD-like region similar to Yang-Mills theory

Summary

- Scalar QCD a role model for QCD
  - Scalar theory simpler...
  - ...but distinction to Higgs-like physics complicated
  - Test case for functional methods
- Propagators in QCD-like region similar to Yang-Mills theory
  - Positivity violating gluon
  - Scalar quark not obviously positivity violating

Summary

- Scalar QCD a role model for QCD
  - Scalar theory simpler...
  - ...but distinction to Higgs-like physics complicated
  - Test case for functional methods
- Propagators in QCD-like region similar to Yang-Mills theory
  - Positivity violating gluon
  - Scalar quark not obviously positivity violating
- Vertices Yang-Mills-like

Summary

- Scalar QCD a role model for QCD
  - Scalar theory simpler...
  - ...but distinction to Higgs-like physics complicated
  - Test case for functional methods
- Propagators in QCD-like region similar to Yang-Mills theory
  - Positivity violating gluon
  - Scalar quark not obviously positivity violating
- Vertices Yang-Mills-like
  - No infrared effects in the scalar-gluon vertex

Summary

- Scalar QCD a role model for QCD
  - Scalar theory simpler...
  - ...but distinction to Higgs-like physics complicated
  - Test case for functional methods
- Propagators in QCD-like region similar to Yang-Mills theory
  - Positivity violating gluon
  - Scalar quark not obviously positivity violating
- Vertices Yang-Mills-like
  - No infrared effects in the scalar-gluon vertex
- So far...no obvious confinement