RANP 2013

Takeshi Kodama's Fest

$Z_c^+(3900)$ decay width from QCD sum rules

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Universidade de São Paulo

in coll. with J.M.Dias, F.S. Navarra & C.M. Zanetti

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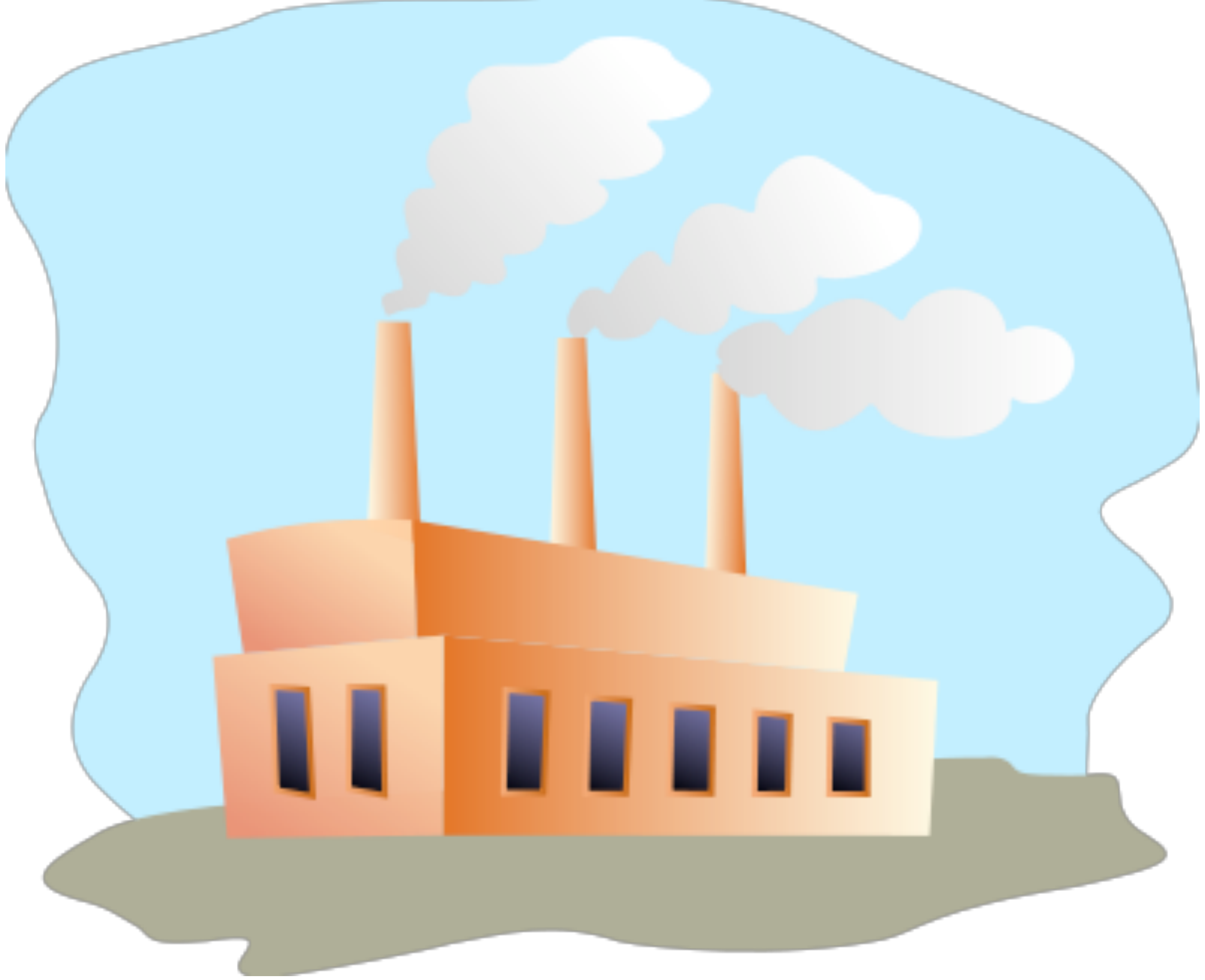
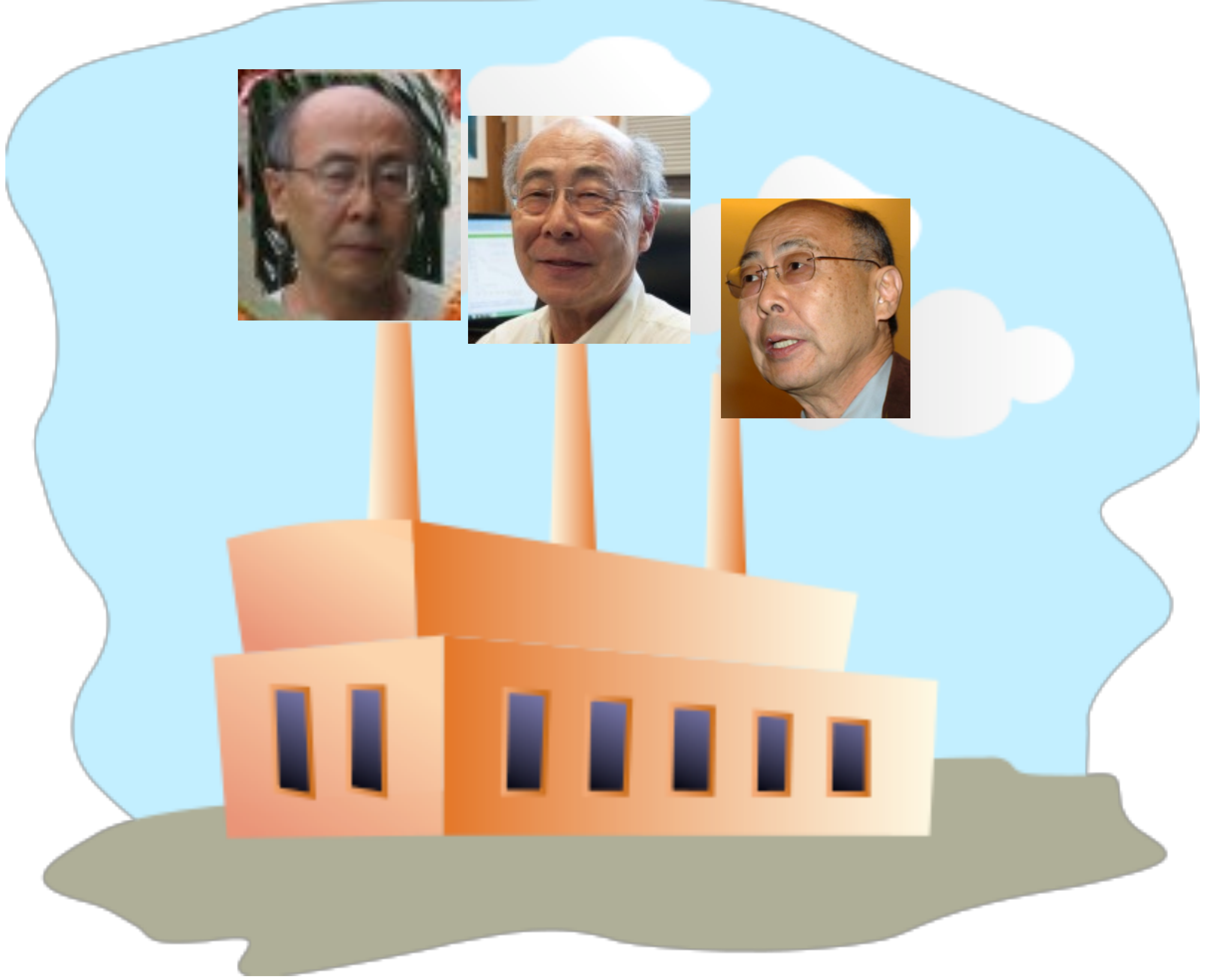
Some Charmonium states discovered at the B factories

X(3872) 2003	Y(4260) 2005	$Z^+(4430)$ 2007
Y(4360) 2006	Y(4660) 2007	$Z_1^+(4050)$ 2008
$Z_2^+(4250)$ 2008	Y(4140) 2009 $\gamma\gamma$	$Z_c^+(3900)$ 2013



B factories



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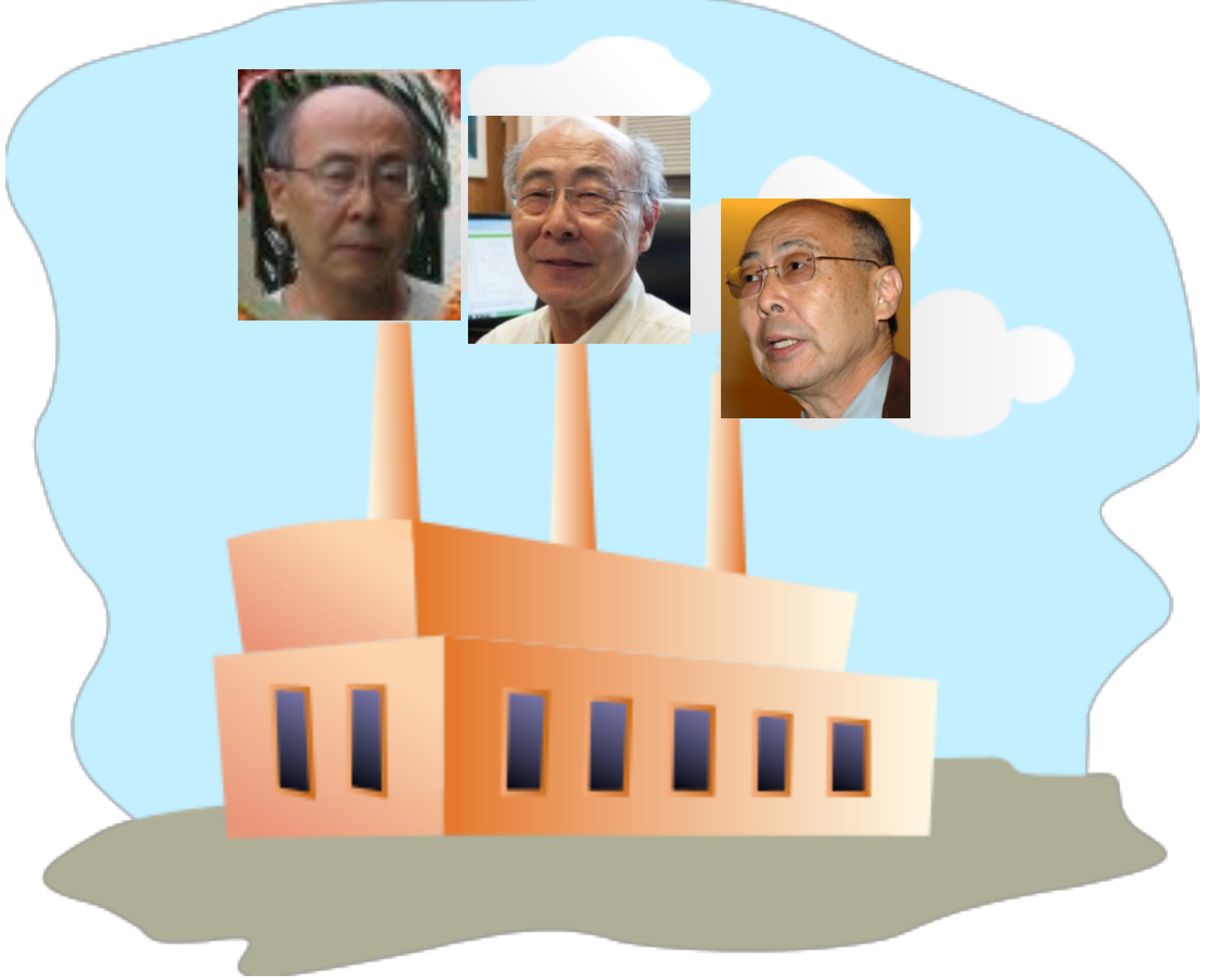
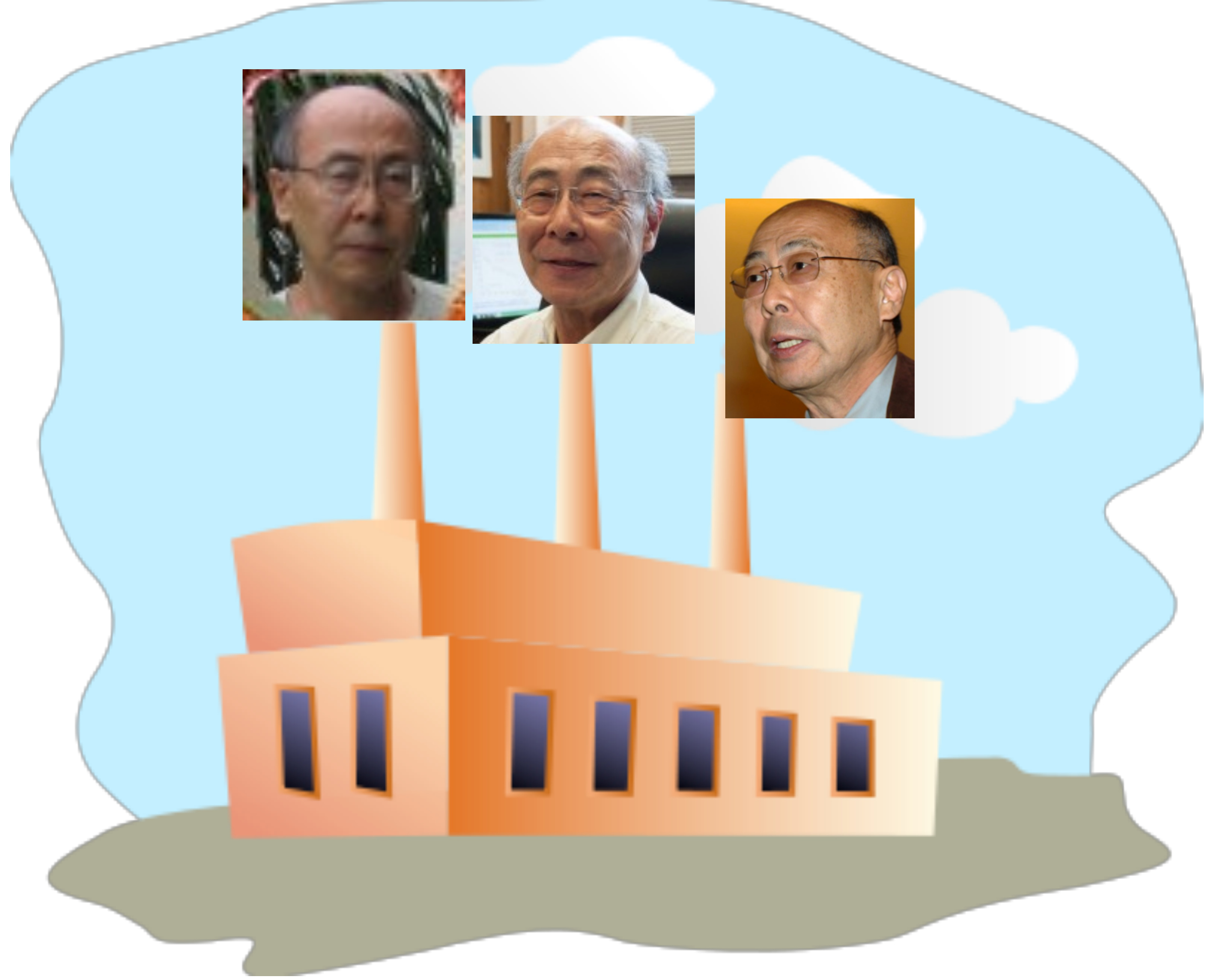


B factories

$e^+ e^-$ colliders with CM energy of 10.6 GeV

PEPII @ SLAC

KEKB @ KEK



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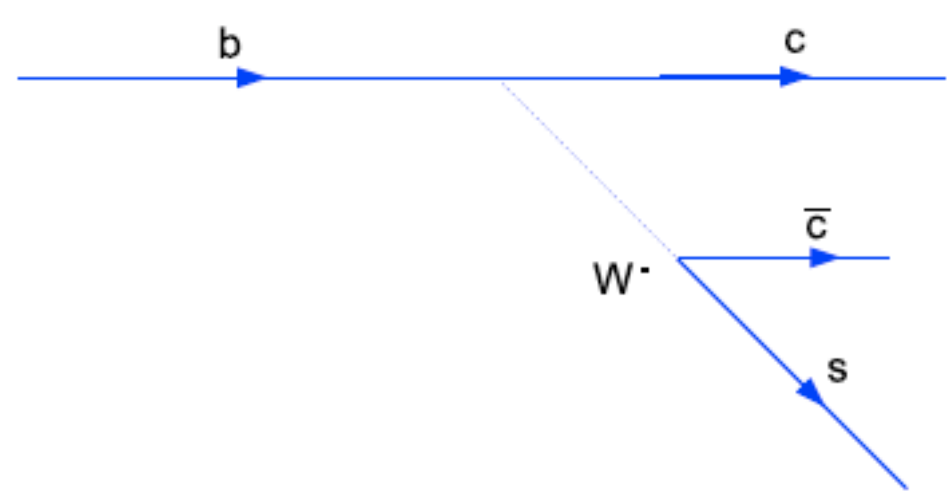
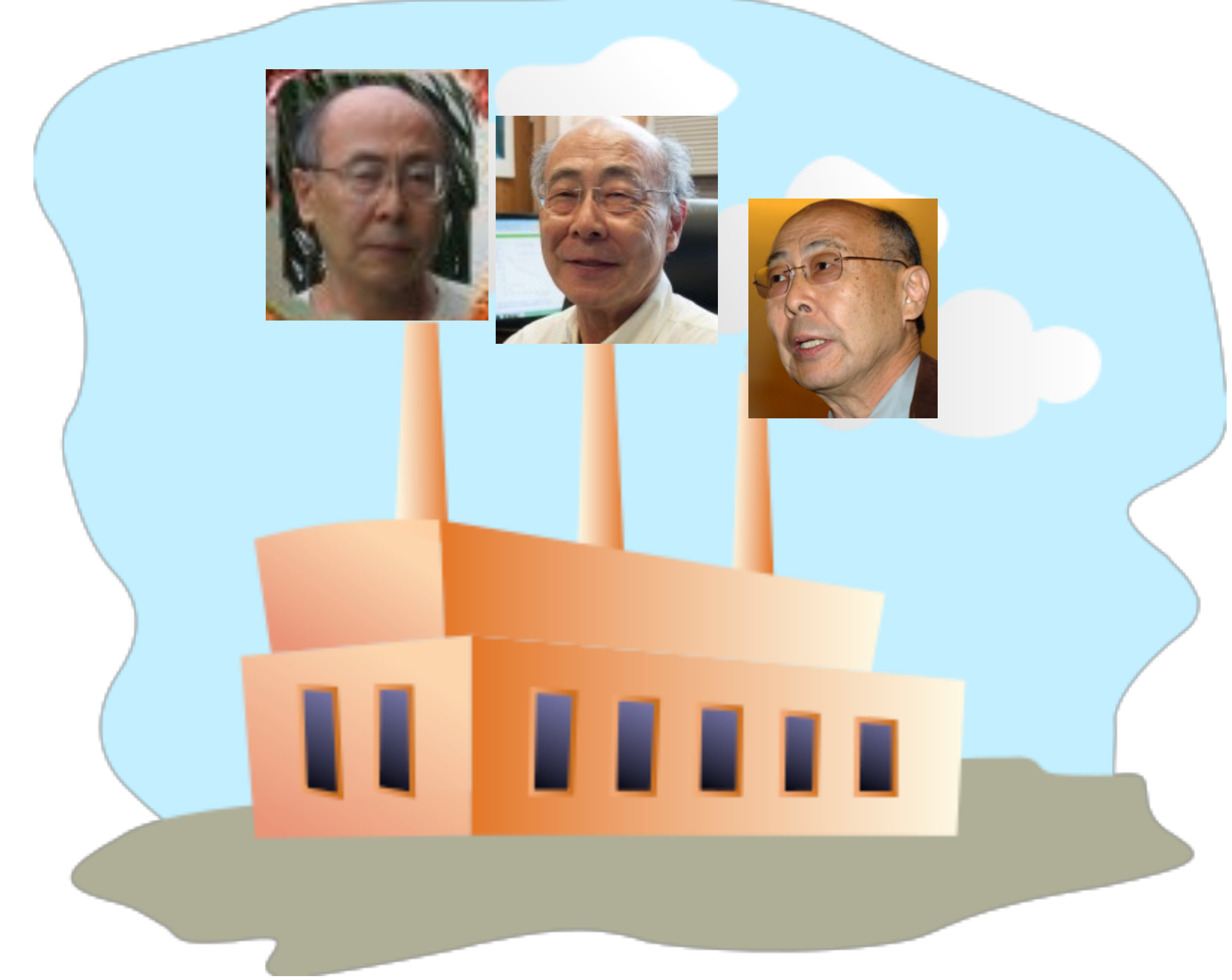
$$b \rightarrow W^- c :$$

50% of the times ➜

$$b \rightarrow c\bar{c}s$$





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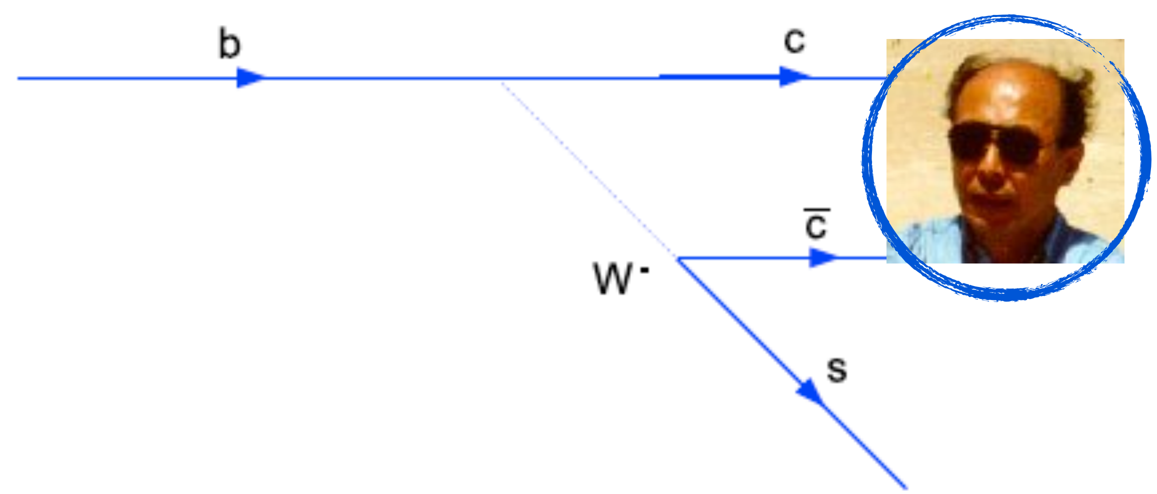

X(3872)	Y(4260)	$Z^+(4430)$
$\boldsymbol{B^\pm \to K^\pm (J/\psi \pi^+ \pi^-)}$	$e^+e^- \to \gamma_{IRS}(J/\psi\pi^+\pi^-)$	$\bar{B}^0 \to K^-(\psi'\pi^+)$
Y(4360)	Y(4660)	$Z_1^+(4050)$
$e^+e^- \to \gamma_{IRS}(\psi'\pi^+\pi^-)$	$e^+e^- \to \gamma_{IRS}(\psi'\pi^+\pi^-)$	$\bar{B}^0 \to K^-(\chi_{c1}\pi^+)$
$Z^+_2(4250)$	Y(4140)	$Z_c^+(3900)$
$\bar{B}^0 \to K^-(\chi_{c1}\pi^+)$	$B^+ \to K^+(\phi J/\psi)$	$Y(4260) \to (J/\psi\pi^+)\pi^-$

Common features

- All these states decay into J/ψ (ψ') ➔ they have a or $c\bar{c}$ pair in their quark components
- Their masses are not compatible with quark model calculations for charmonium states
- Absence of open charm production in their decays is inconsistent with $c\bar{c}$ interpretation
- Candidates for exotic (not quark-antiquark) states

X(3872)

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$$M(D^{*0}\bar{D}^0) = (3871 \pm 1)$$

X(3872): molecular $(D^{*0}\bar{D}^0 + \bar{D}^{*0}D^0)$ state (Swanson, Close, Voloshin, Wong ...)

Tornqwist (ZPC61(94)) predict a $\bar{D}D^*$ molecule with $J^{PC} = 0^{-+}$ or 1^{++}

Maiani et al. (PRD71 (05)) tetraquark $J^{PC} = 1^{++}$ state

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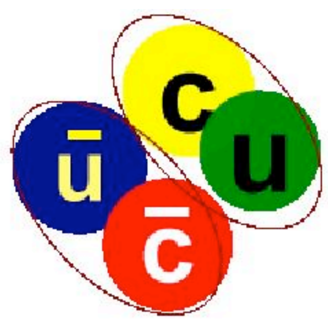
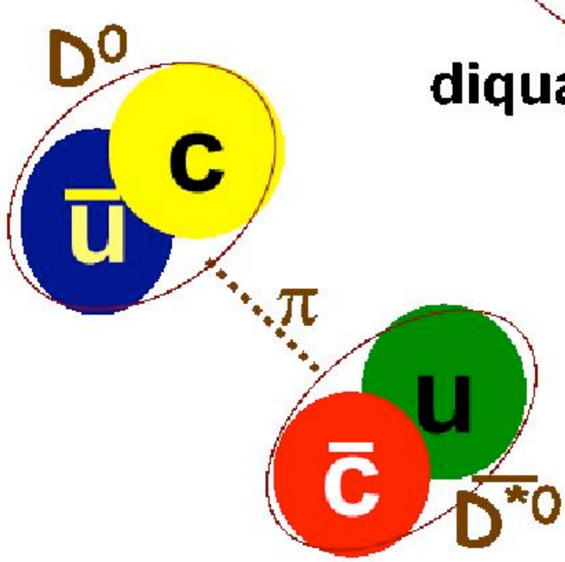


diquark-diantiquark



$D^0 - \overline{D}^{*0}$ "molecule"

molecular and tetraquark interpretations differ by the way quarks are organized in the state

$Z^+(4430)$

charged state ➡ not a $c\bar{c}$!

PRL100(08)142001

$Z^+(4430)$

charged state ➡ not a $c\bar{c}$!

PRL100(08)142001

arXiv:0905.2869

searched Z⁻(4430) in 4 decay modes:

no conclusive
evidence for the existence of $Z^+(4430)$ seen by Belle

$Z^+(4430)$

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PRL100(08)142001

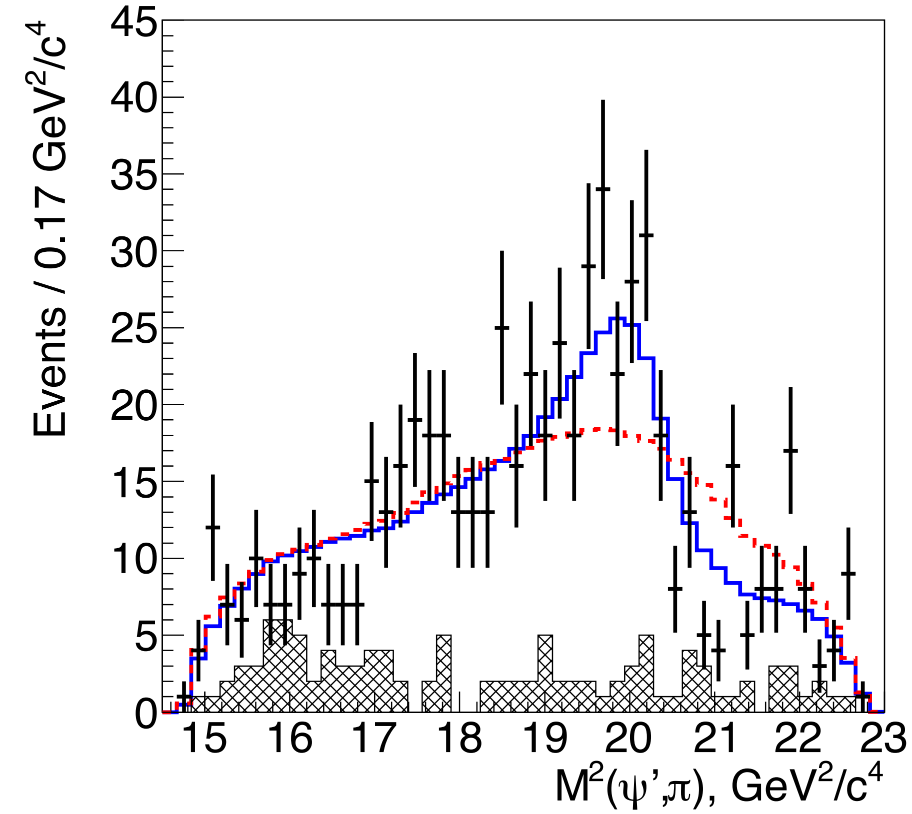
searched $Z^-(4430)$ in 4 decay modes:

arXiv:0905.2869

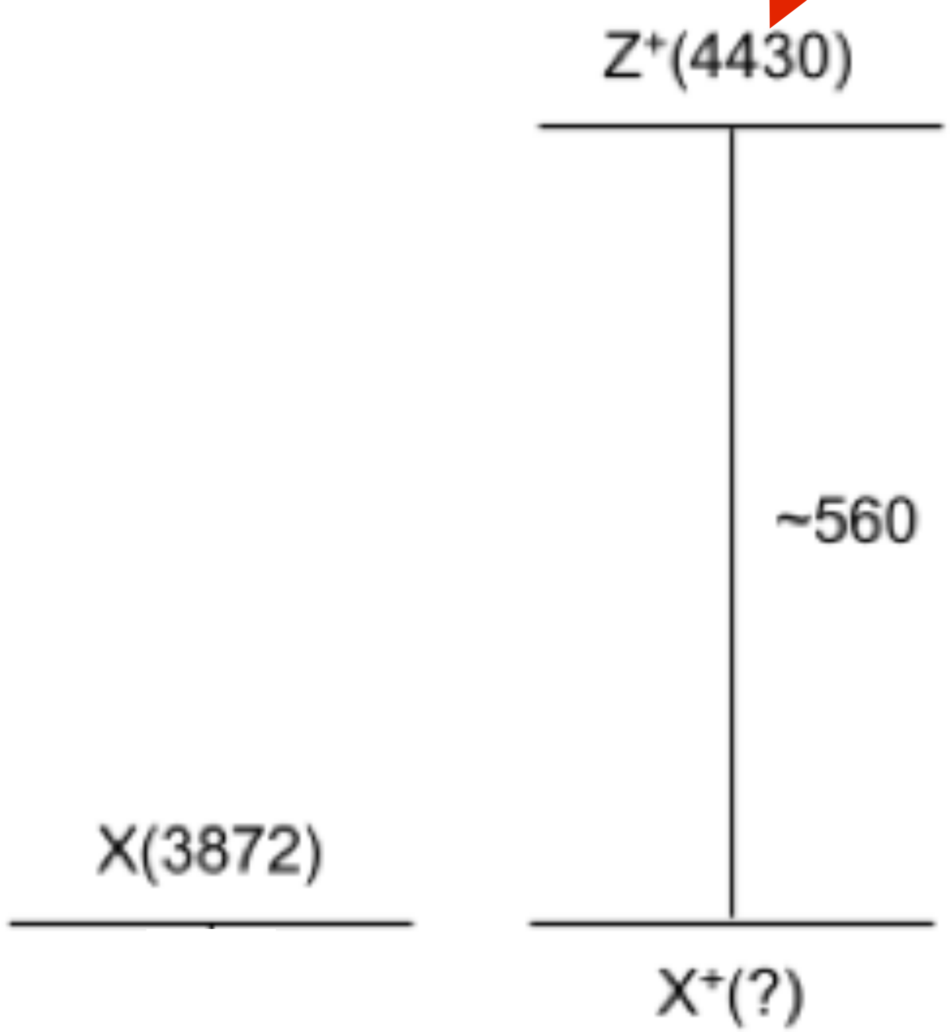
no conclusive evidence for the existence of $Z^+(4430)$ seen by Belle

arXiv:1306.4894

confirm the observation of $Z^+(4430)$ with $6.1\,\sigma$ and $J^+ = 1^+$



Maiani et al. (arXiv:0708.3997) : four-quark radial excitation of the 1^+ charged state (X(3872) partner)



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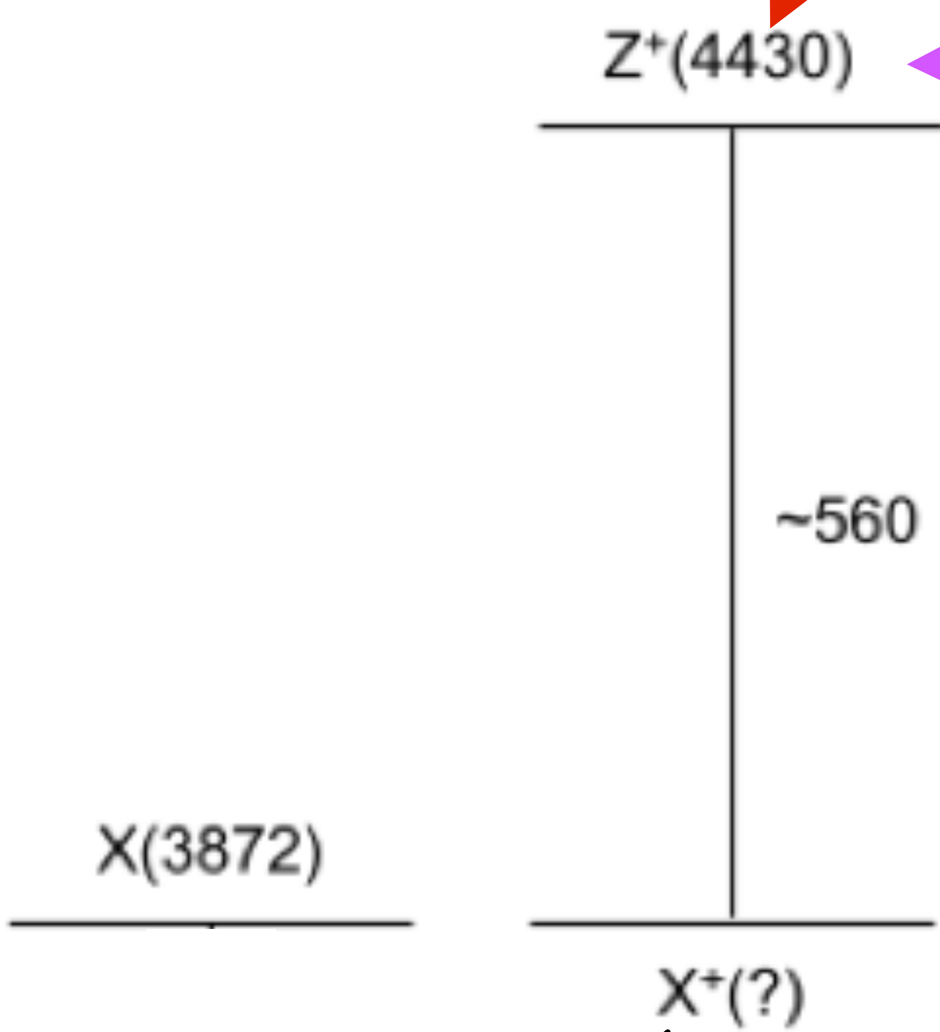
$Z^+(4430) \rightarrow \psi(2S)\pi^+$



should be seen in J/ψπ decay mode

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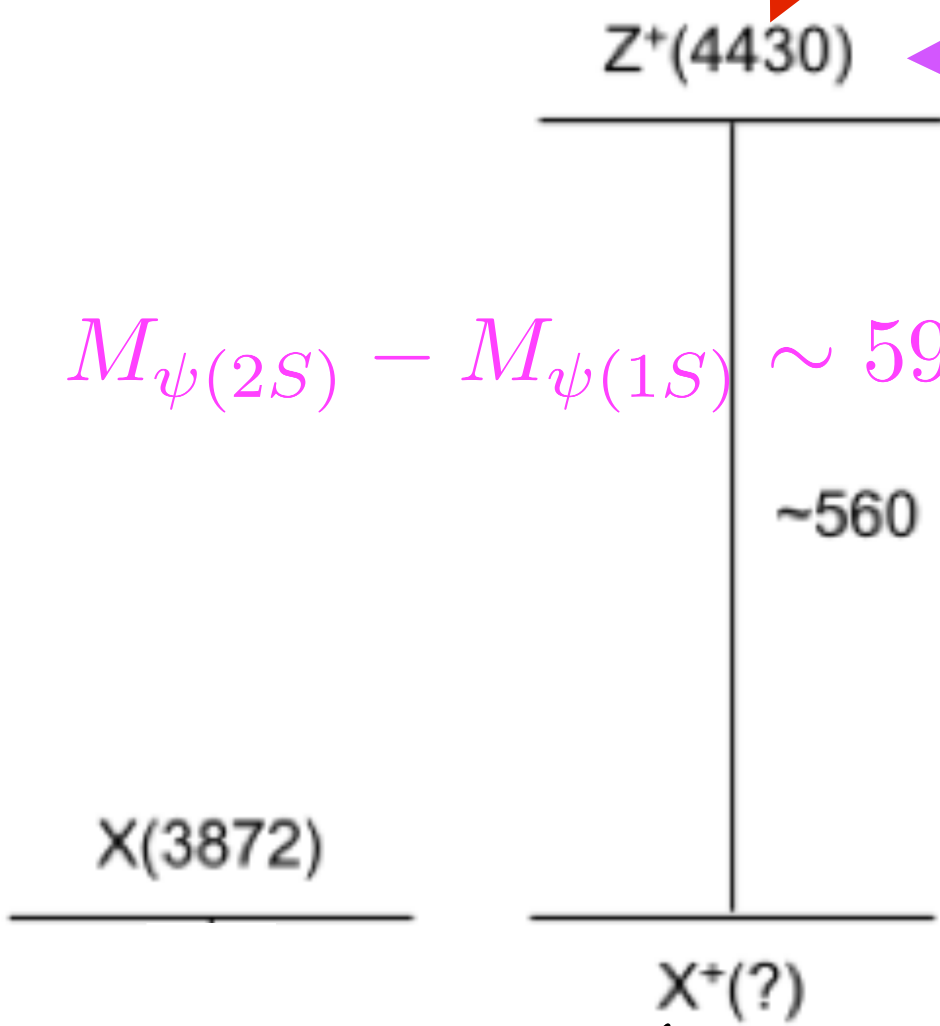

$$Z^+(4430) \to \psi(2S)\pi^+$$

$$M_{\psi(2S)} - M_{\psi(1S)} \sim 590 \text{ MeV} \sim M_{Z^+} - M_X$$

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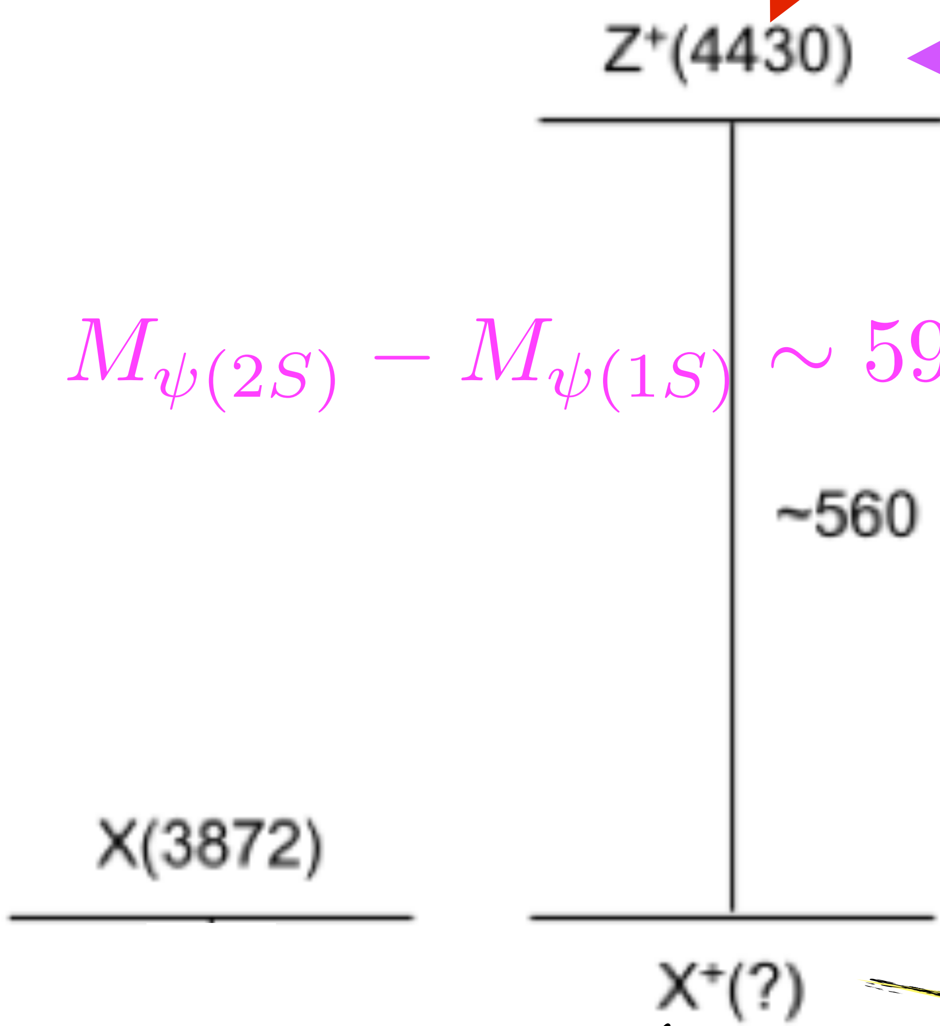

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who is the charged partner of X(3872)?

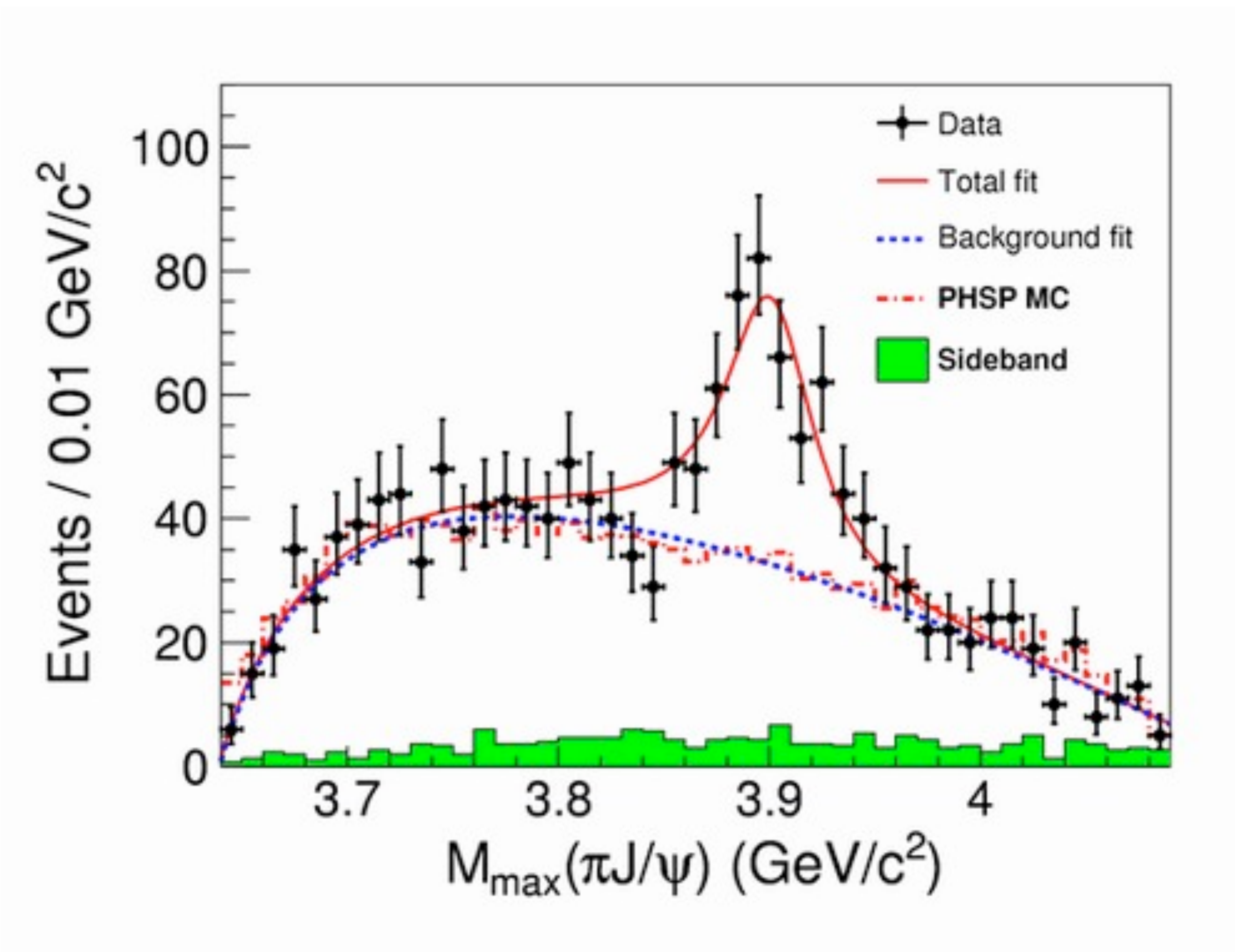
$Z_c^+(3900)$: most recent aquisition

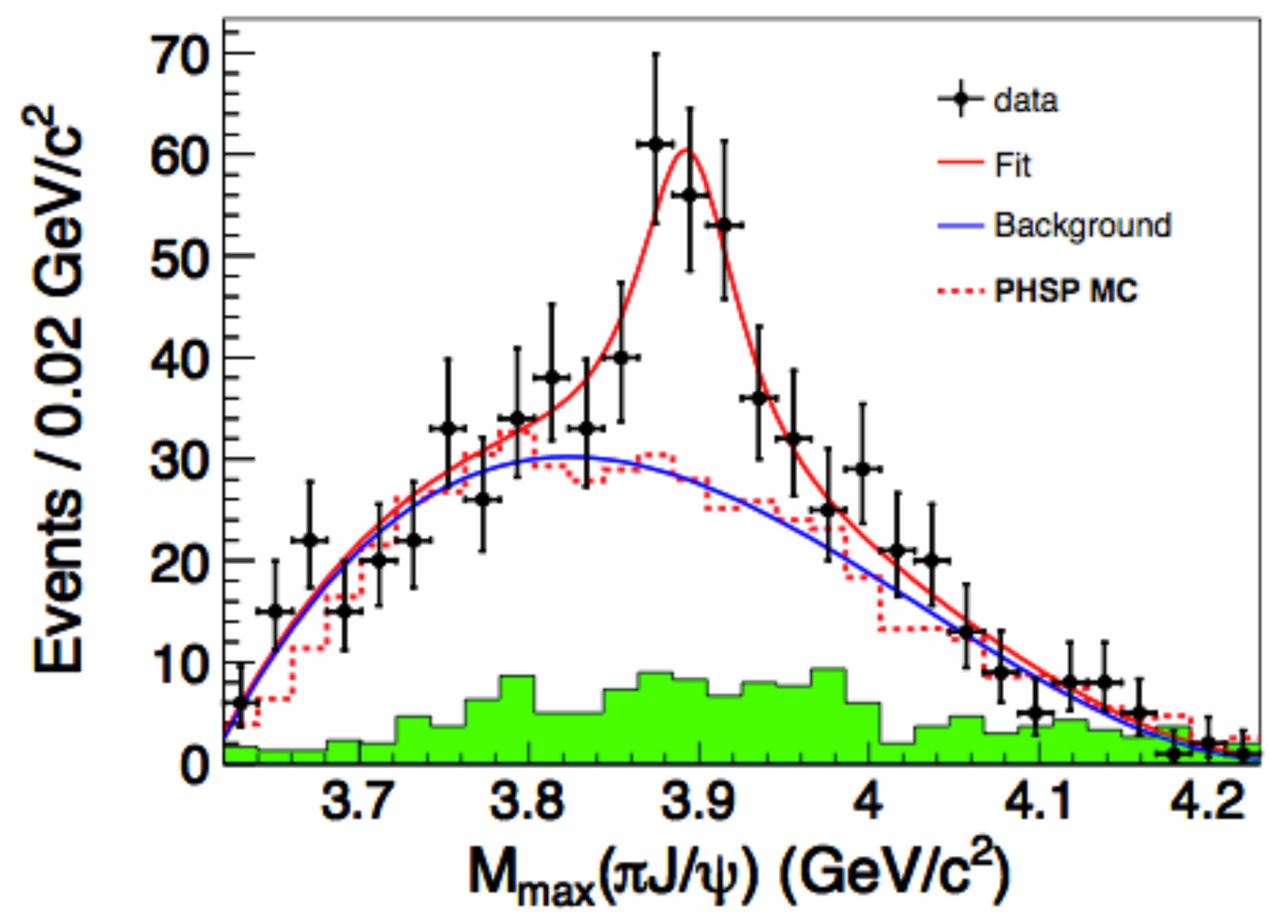
arXiv:1303.5949

arXiv:1304.0121

M = (3890±3.6±4.9) MeV
Γ = (46±10±20) MeV

M = (3894.5±6.6±4.5) MeV
Γ = (63±24±26) MeV





$$Y(4260) \to (J/\psi\pi^+)\pi^-$$

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BES III arXiv:1303.5949

BELLE arXiv:1304.0121

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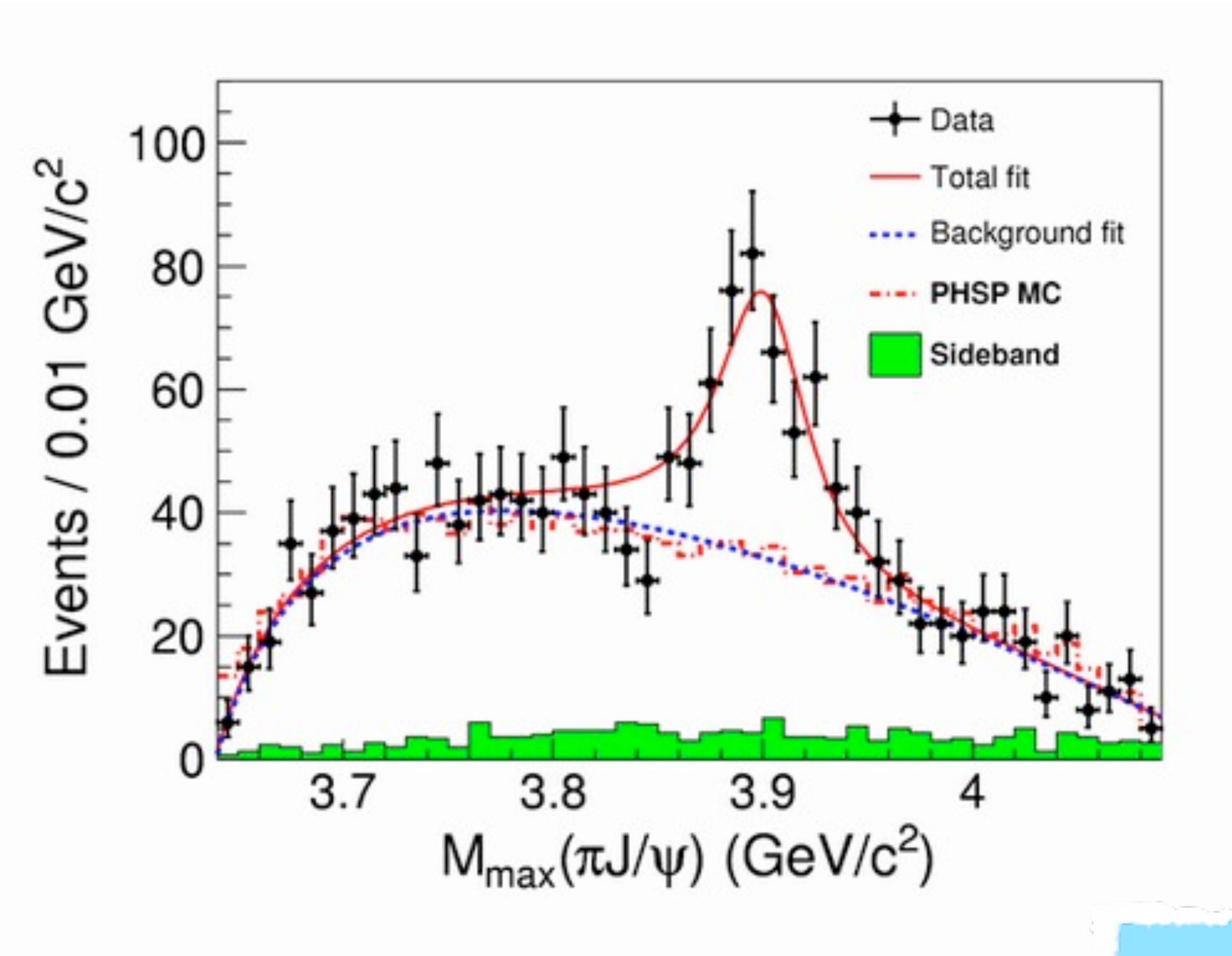

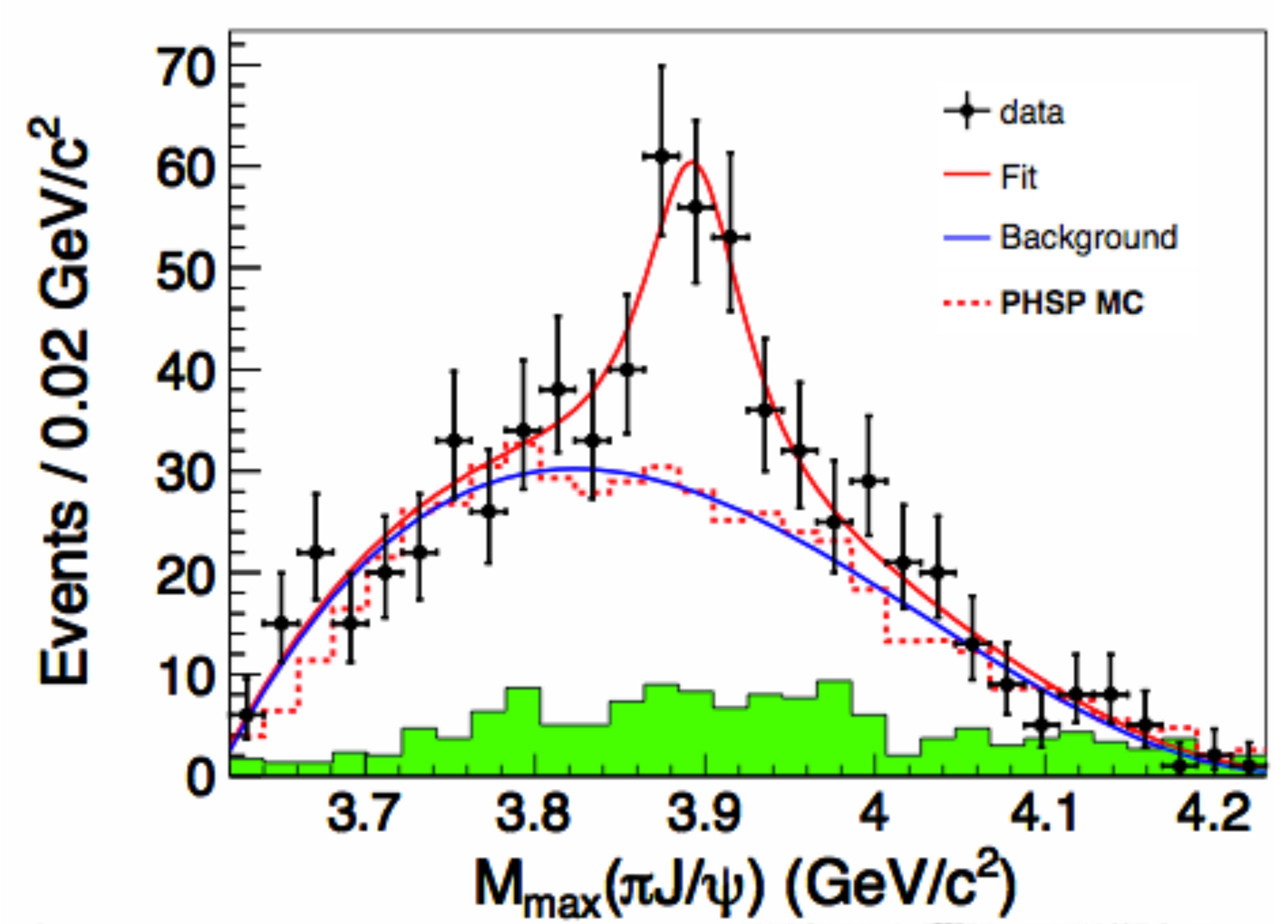

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$J^P = 1^+$ ➜ charged partner of the X(3872)

QCD Sum Rule

Fundamental Assumption: Principle of Duality

$$\boldsymbol{\Pi(q) = i \int d^4x \, e^{iq.x} \, \langle 0|T[j(x)j^\dagger(0)]|0\rangle}$$

Theoretical side

Phenomenological side

QCD Sum Rule

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Theoretical side Phenomenological side

Theoretical side

$$\Pi(q) = i\int d^4x\, e^{iq\cdot x}\langle 0|T[j(x)j^\dagger(0)|0\rangle \;= \sum_n C_n(Q^2)\hat{O}_n$$

Phenomenological side

$$\Pi(q^2) = -\int ds\,\frac{\rho(s)}{q^2 - s + i\epsilon} + \cdots$$

$$\rho(s) = \lambda^2 \delta(s - m^2) + \rho_{cont}(s)$$

$$\langle 0 | j | H \rangle = \lambda \qquad \rho_{cont}(s) = \rho^{OPE}(s)\Theta(s - s_0)$$

s_0: continuum parameter

$$\Pi^{phen}(Q^2) \leftrightarrow \Pi^{OPE}(Q^2) \Rightarrow \text{Borel transform}$$

$$\lambda^2 e^{-m^2/M^2} = \int_{s_{min}}^{s_0} ds \; e^{-s/M^2} \; \rho^{OPE}(s)$$

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Good Sum Rule ➡ Borel window such that:

- pole contribution > continuum contribution
- good OPE convergence
- good Borel stability

$$m^2 = \frac{\int_{s_{min}}^{s_0} ds\ e^{-s/M^2}\ s\ \rho^{OPE}(s)}{\int_{s_{min}}^{s_0} ds\ e^{-s/M^2}\ \rho^{OPE}(s)}$$

QCD sum rules calculation for $\boldsymbol{X(3872)}$

Matheus, Narison, MN, Richard: PRD75 (07)

$$j_\mu = \frac{i\epsilon_{abc}\epsilon_{dec}}{\sqrt{2}}[(q_a^T C\gamma_5 c_b)(\bar{q}_d\gamma_\mu C\bar{c}_e^T) + (q_a^T C\gamma_\mu c_b)(\bar{q}_d\gamma_5 C\bar{c}_e^T)]$$

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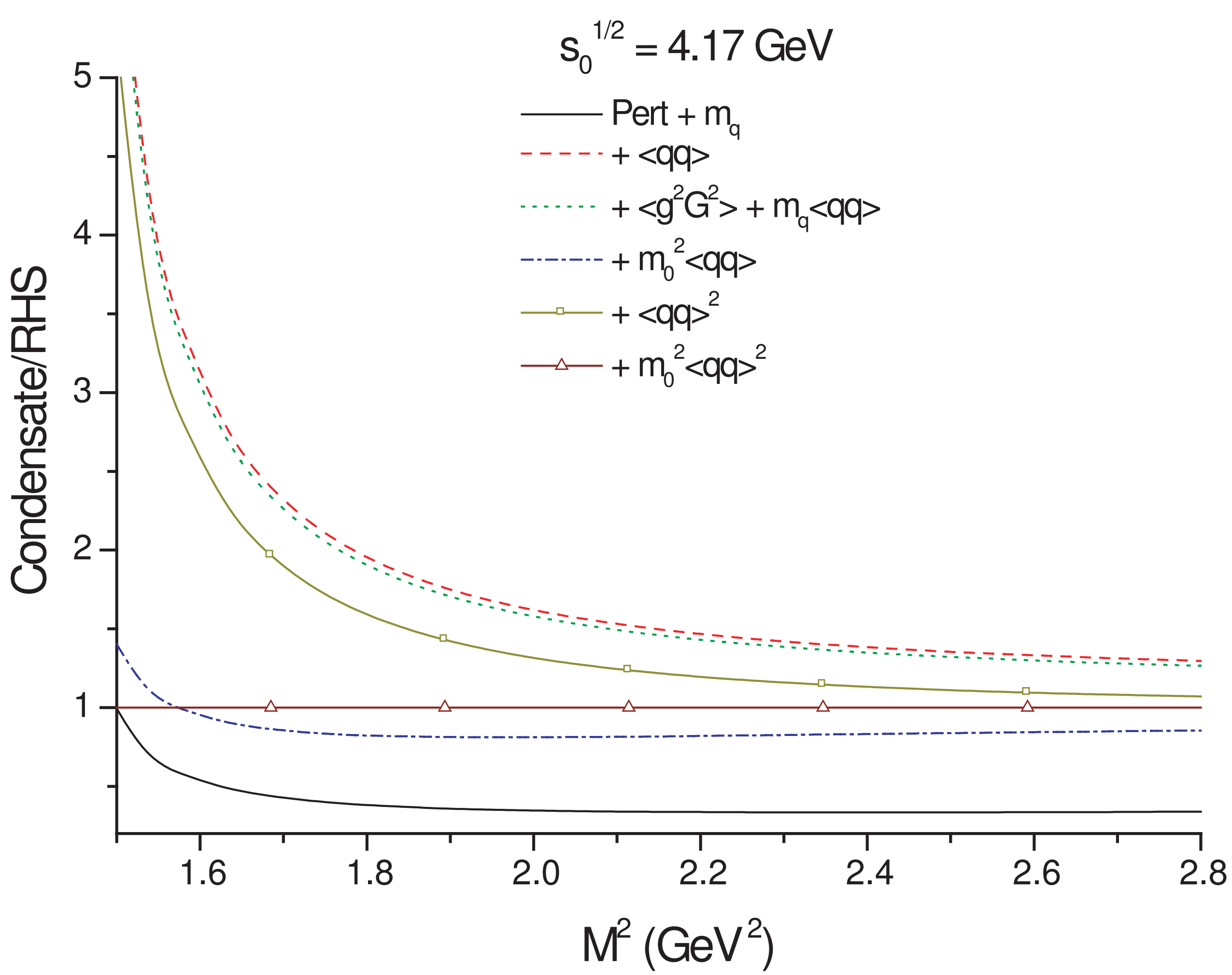

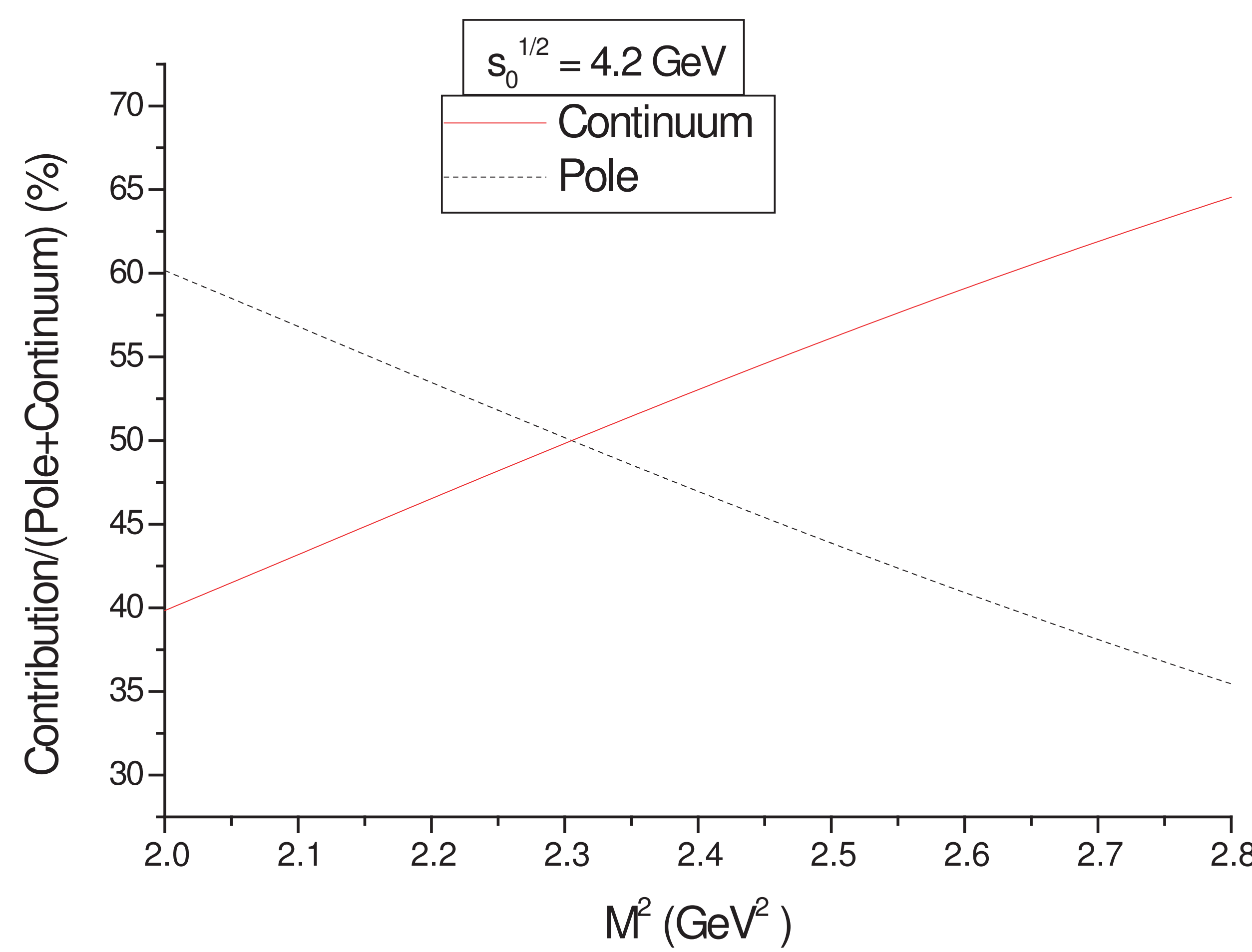

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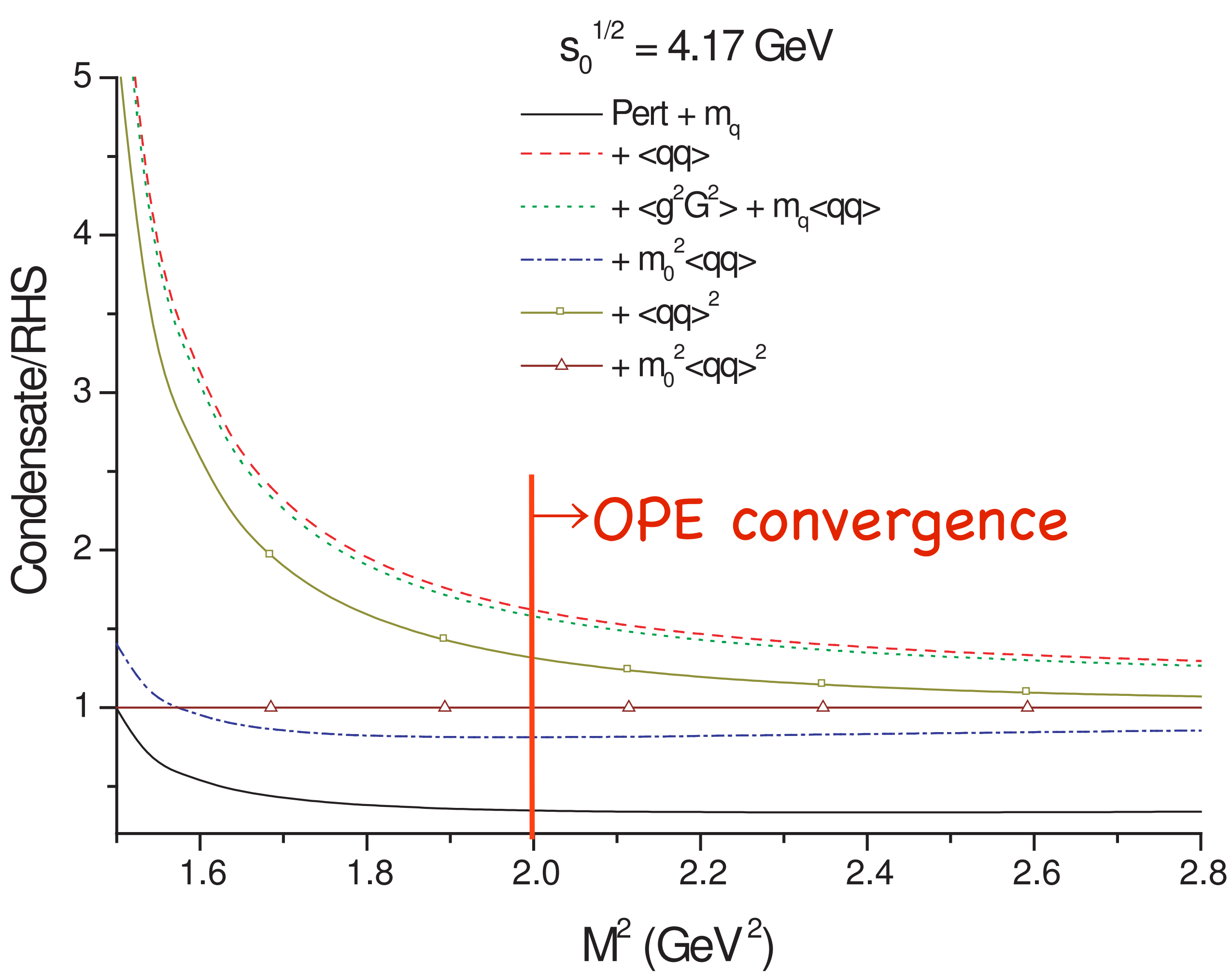

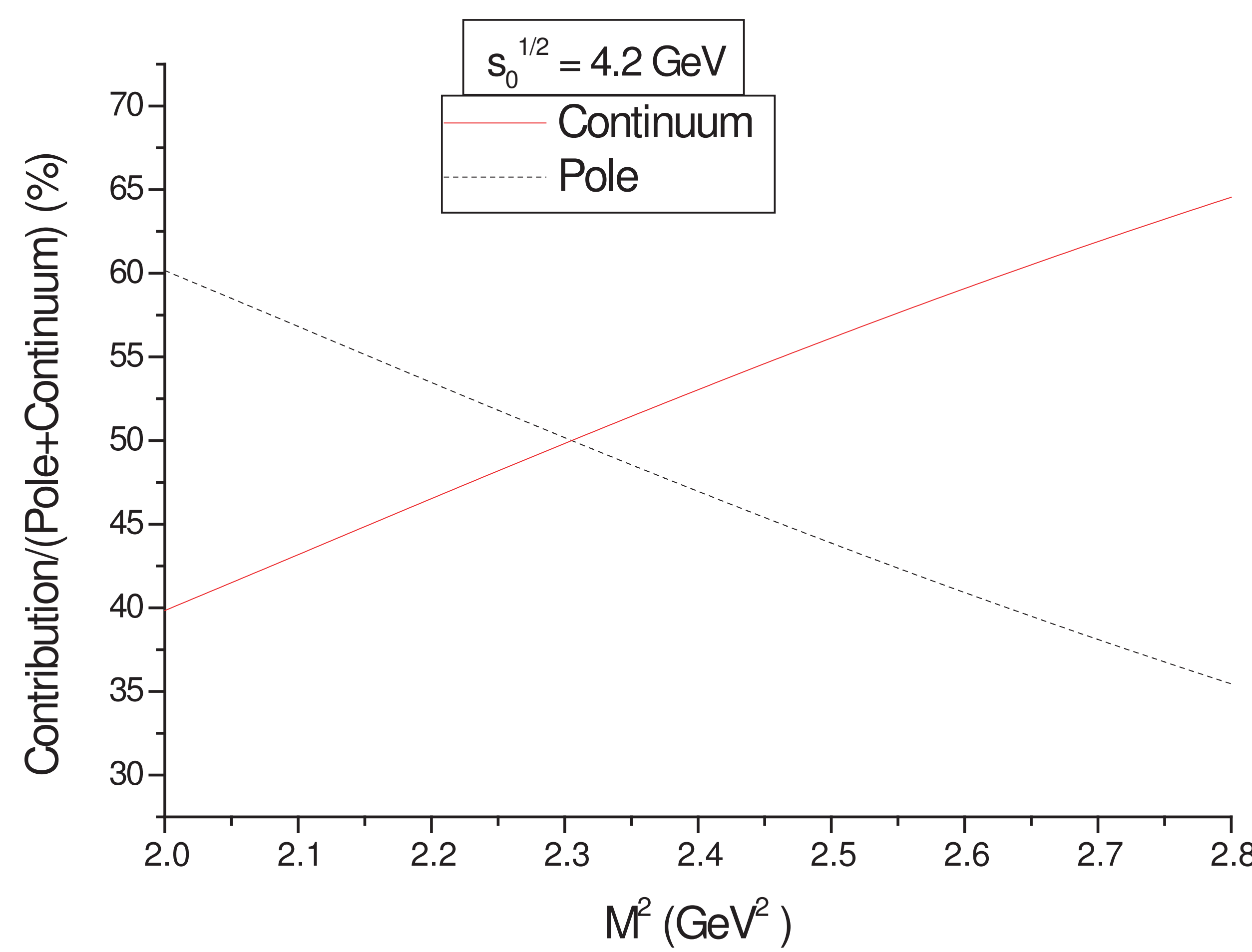

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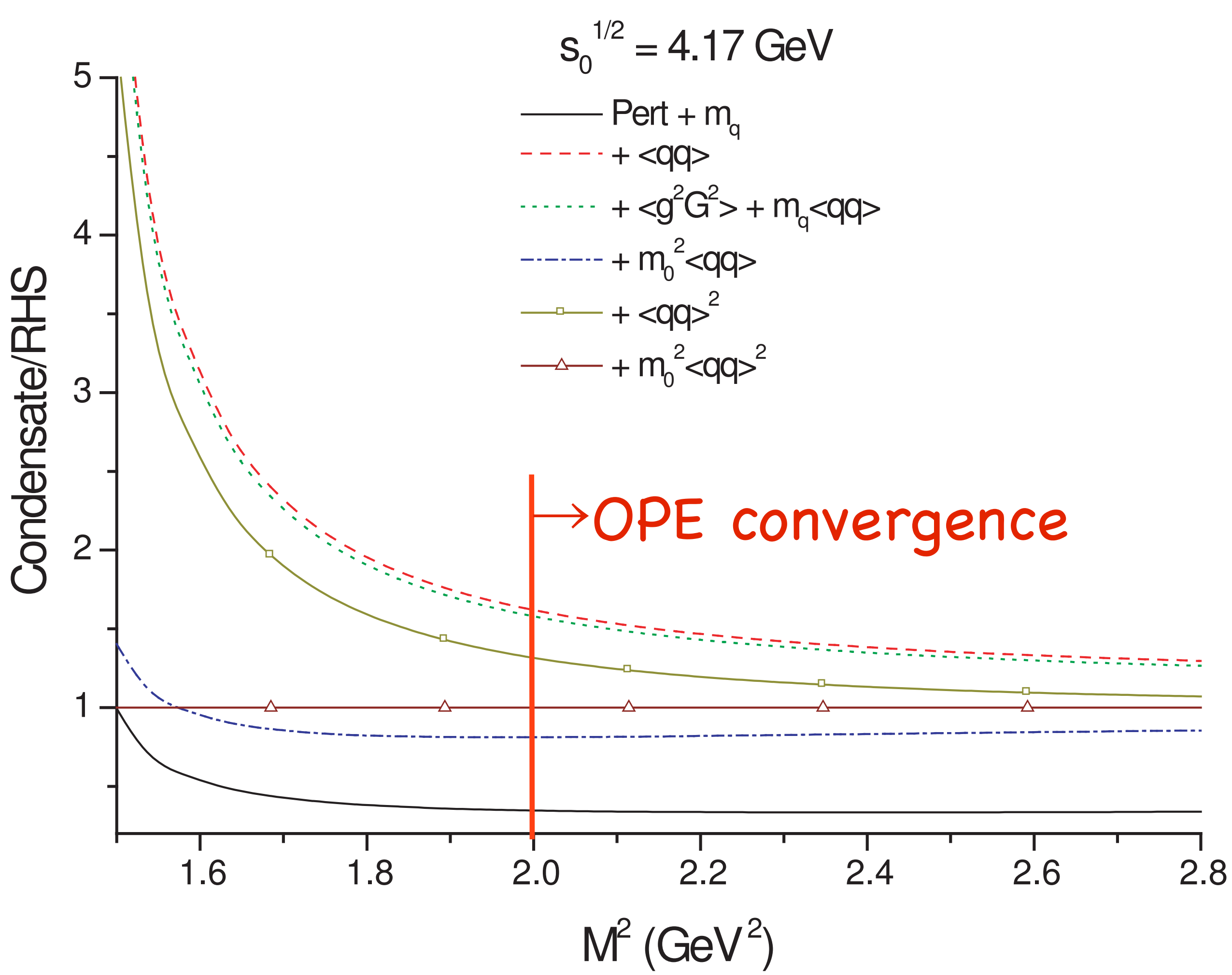
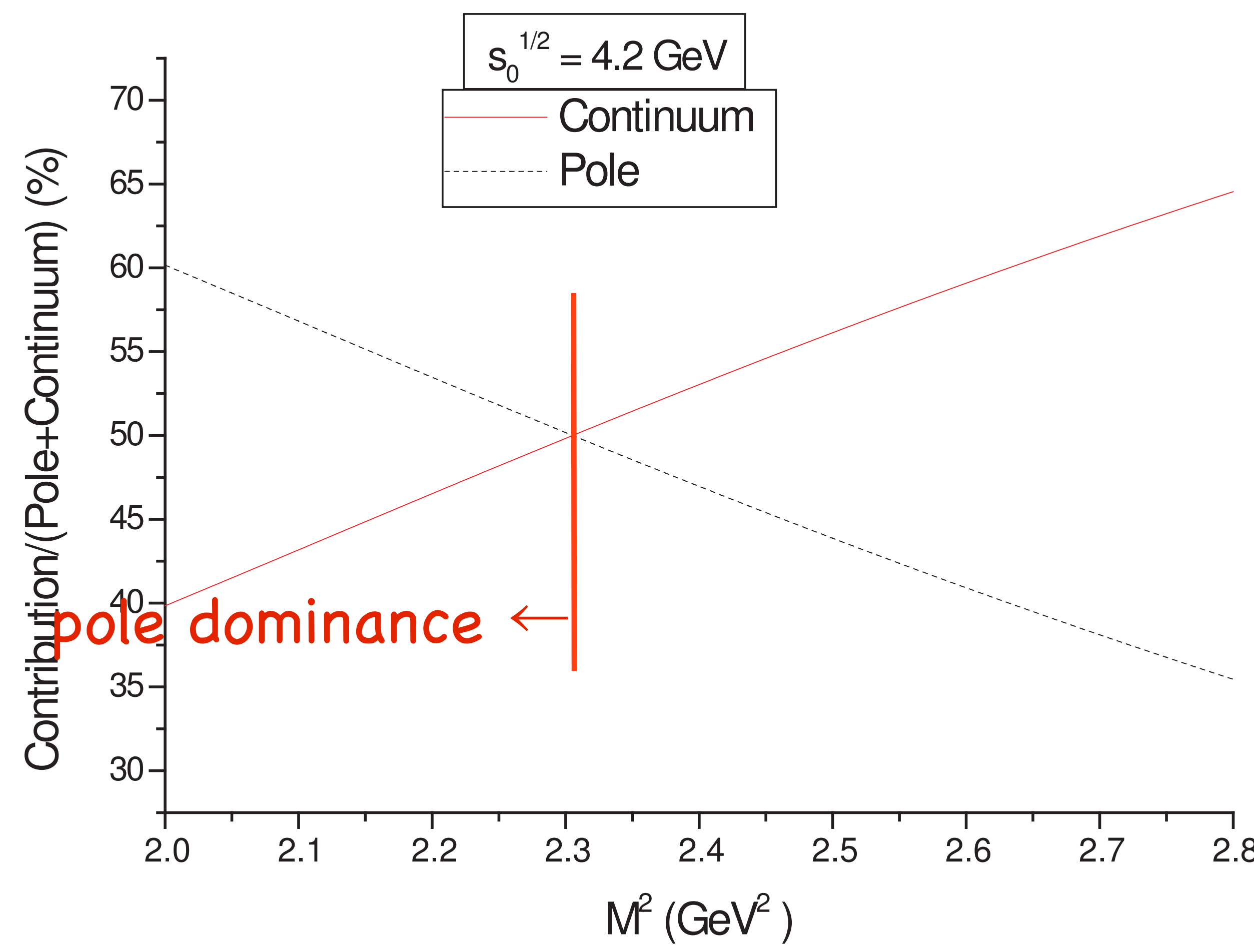
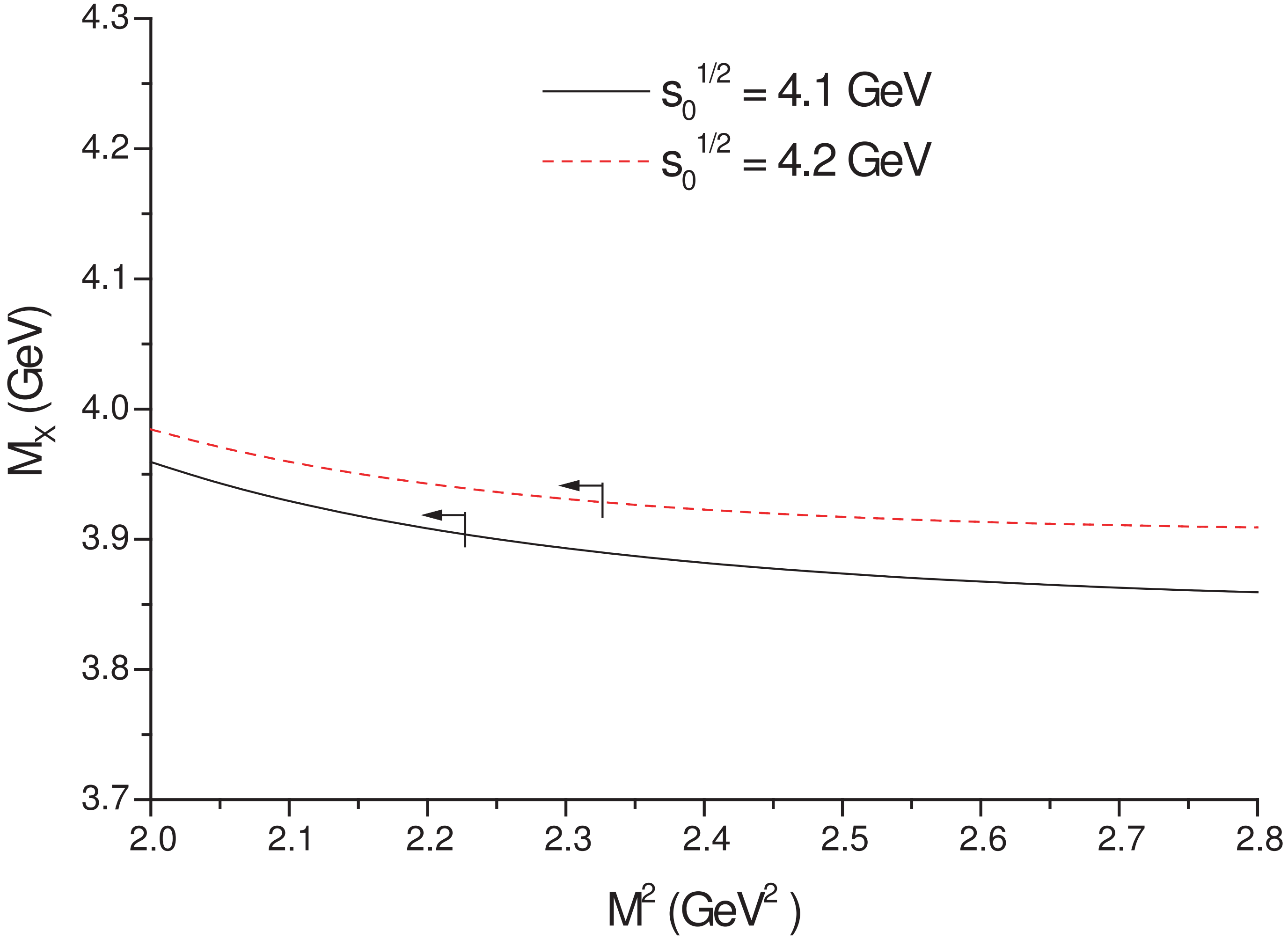
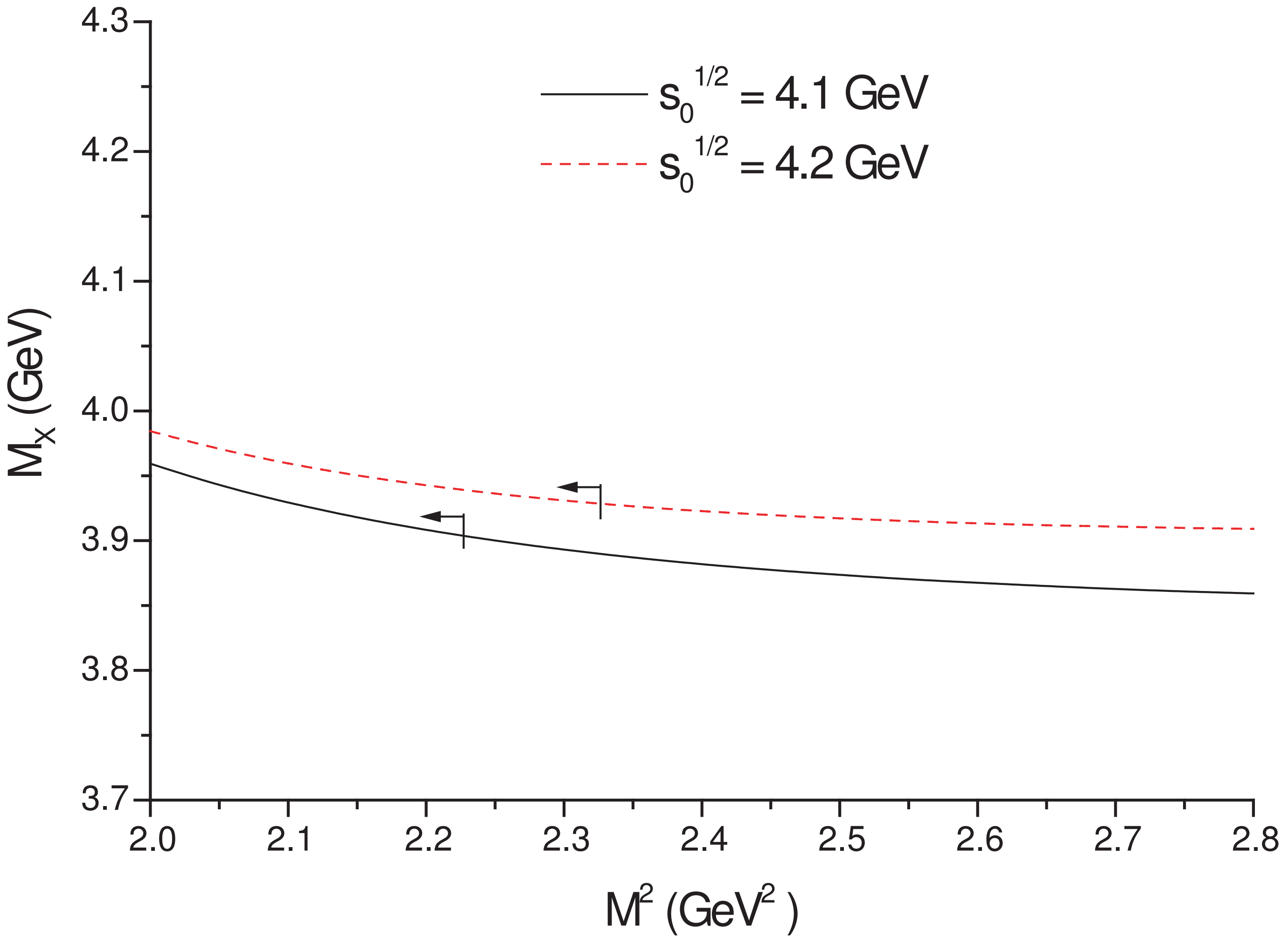






$$m_X = (3.92 \pm 0.13)\ \text{GeV}$$



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Lee, MN, Wiedner: $D^0 \bar{D}^{*0}$ molecular current (arXiv:0803.1168)

$$j_\mu^{(q,mol)}(x) = \frac{1}{\sqrt{2}}\Big[(\bar{q}_a(x)\gamma_5 c_a(x)\bar{c}_b(x)\gamma_\mu q_b(x)) - (\bar{q}_a(x)\gamma_\mu c_a(x)\bar{c}_b(x)\gamma_5 q_b(x)) \Big]$$

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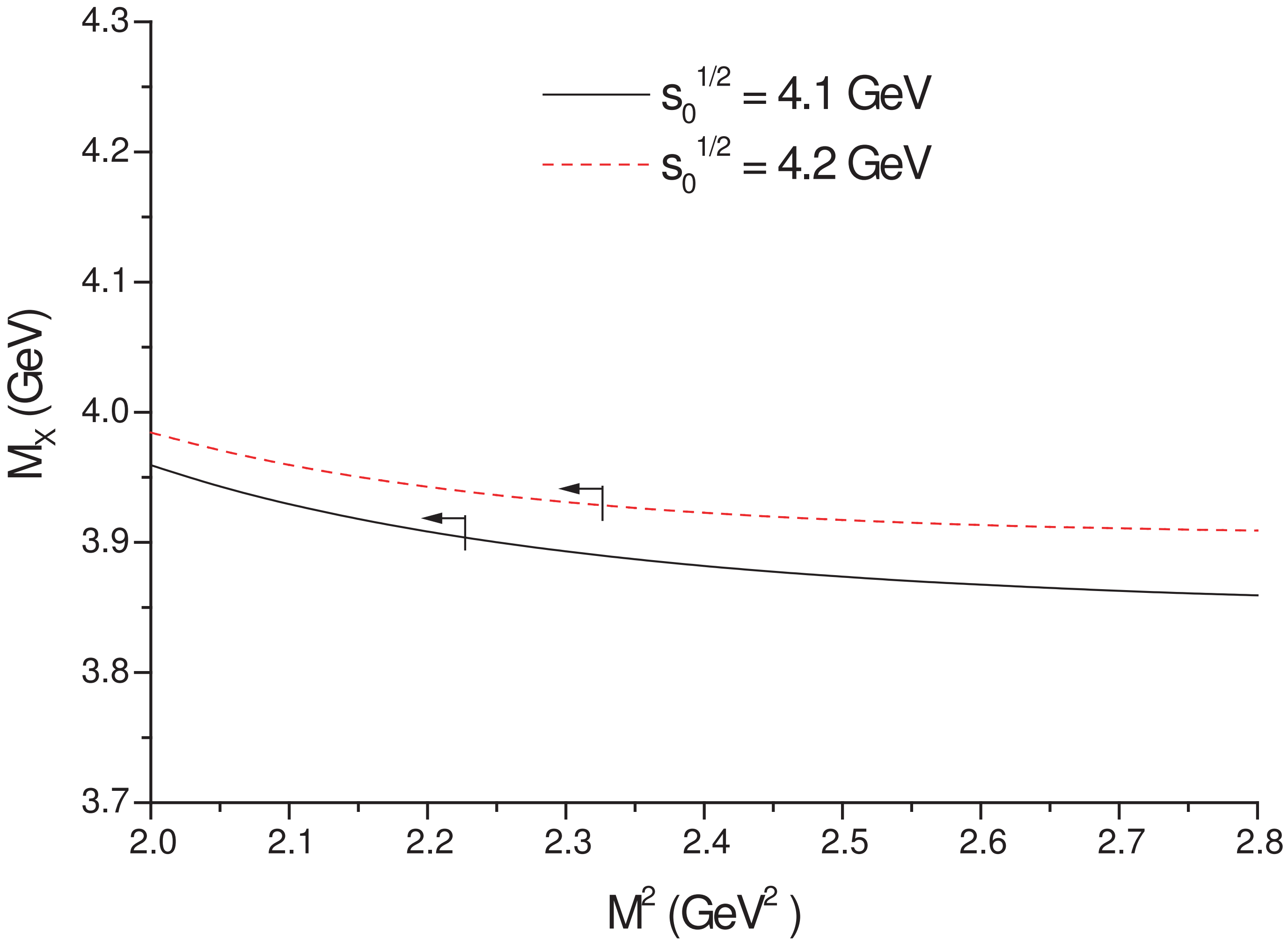

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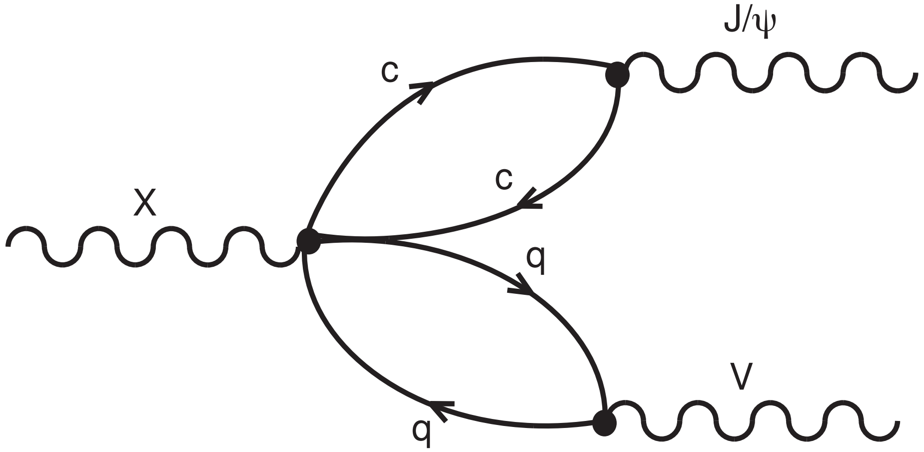
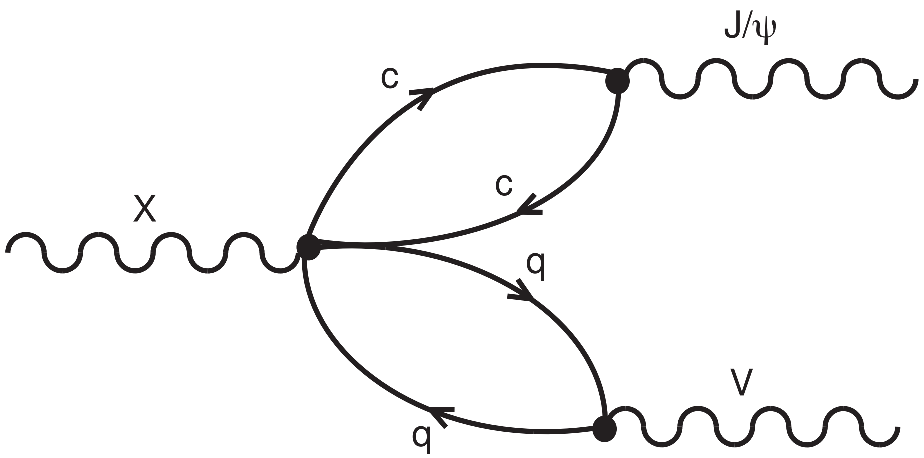
same mass is obtained for $Z_c^+(3900)$



Problem: decay width $X \to J/\psi\pi\pi$

~ 50 MeV (Navarra, MN, PLB639 (06)272)



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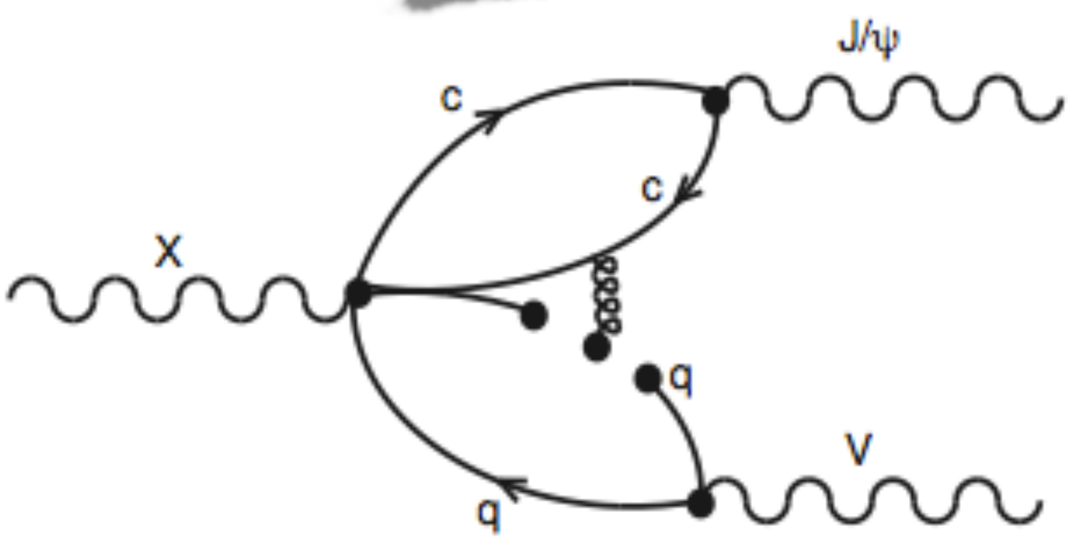
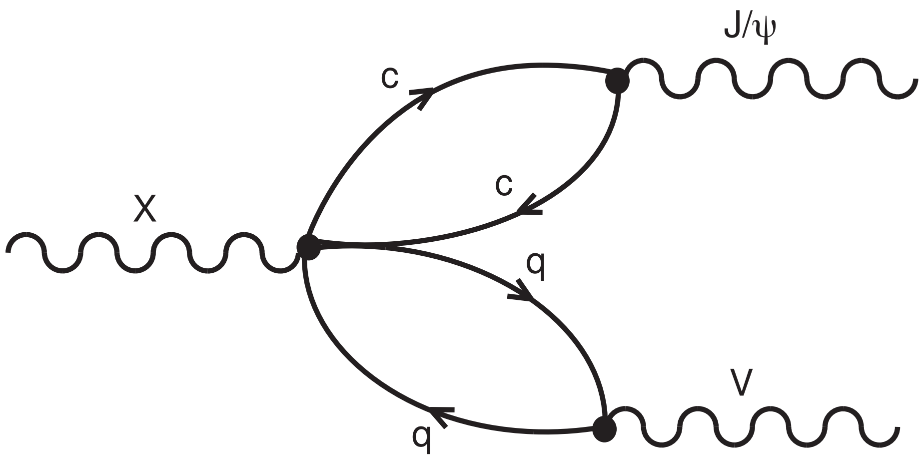
How to solve this problem?



If X(3872) is a genuine tetraquark state, only color-conected diagrams will contribute



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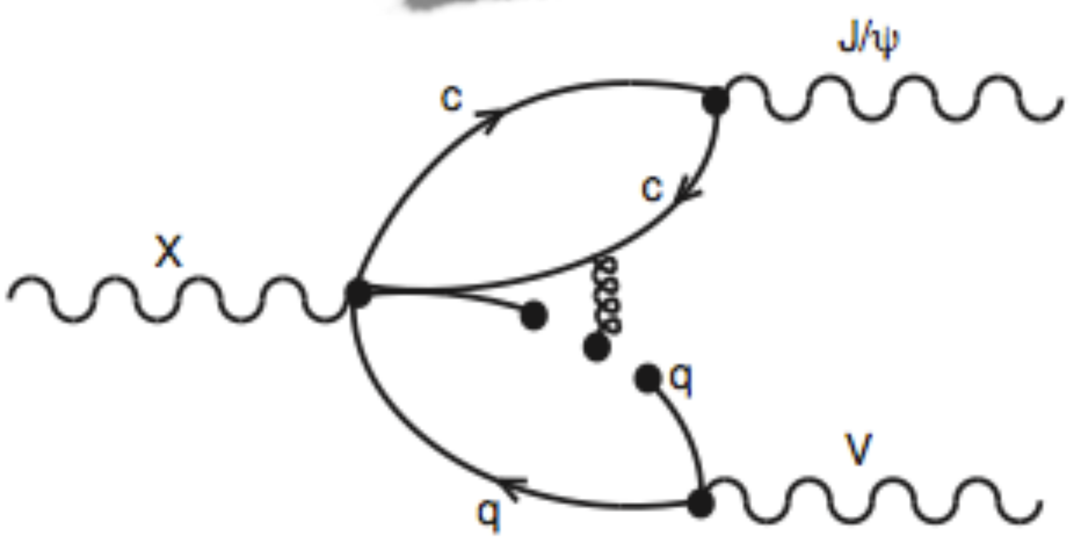

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$$\Gamma_{CC}(X \rightarrow J/\psi\ (n\pi)) = (0.7 \pm 0.2)\ \text{MeV}.$$

Navarra, MN, PLB639(06)272

Compatible with the experimental X(3872) width: Γ<2.3 MeV

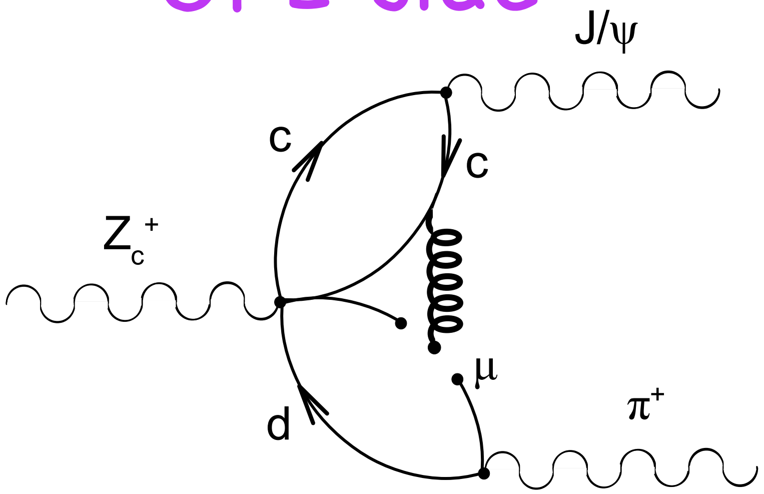
Decay width $Z^+ \to J/\psi\pi^+$

Dias, Navarra, MN, Zanetti
arXiv:1304.6433

$$\Pi_{\mu\nu\alpha}(p,p',q) = \int d^4x d^4y \; e^{ip'.x} \; e^{iq.y} \Pi_{\mu\nu\alpha}(x,y)$$

$$\Pi_{\mu\nu\alpha}(x,y) = \langle 0|T[j_\mu^\psi(x) j_{5\nu}^\pi(y) j_\alpha^\dagger(0)]|0\rangle$$

OPE side



Phen. side

$$\Pi^{(phen)}_{\mu\nu\alpha}(p,p',q) = \frac{\lambda_{Z_c} m_\psi f_\psi F_\pi \; g_{Z_c\psi\pi}(q^2) q_\nu}{(p^2 - m^2_{Z_c})(p'^2 - m^2_\psi)(q^2 - m^2_\pi)} \left(-g_{\mu\lambda} + \frac{p'_\mu p'_\lambda}{m^2_\psi}\right)\left(-g^\lambda_\alpha + \frac{p_\alpha p^\lambda}{m^2_{Z_c}}\right) + \cdots ,$$

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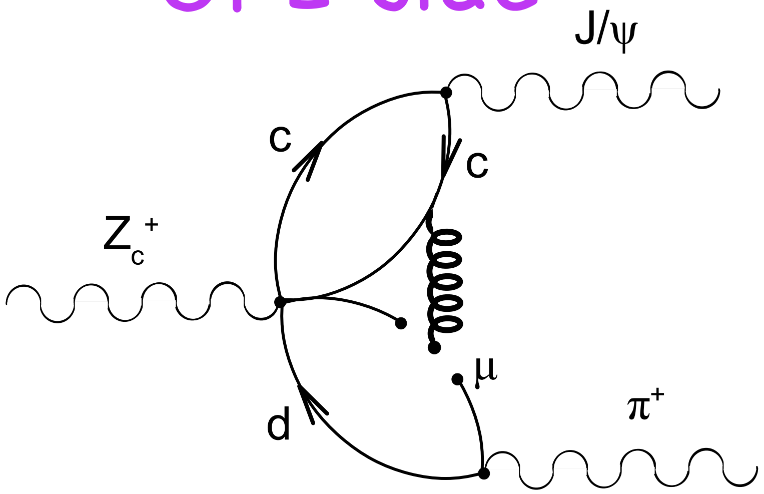

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coupling constant

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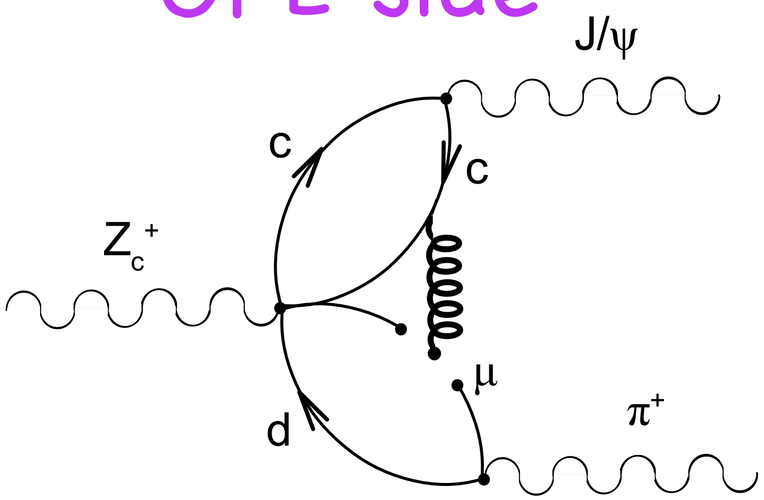
Dias, Navarra, MN, Zanetti
arXiv:1304.6433

$$\Pi_{\mu\nu\alpha}(p,p',q) = \int d^4x d^4y \; e^{ip'.x} \; e^{iq.y}\Pi_{\mu\nu\alpha}(x,y)$$

$$\Pi_{\mu\nu\alpha}(x,y) = \langle 0|T[j_\mu^\psi(x) j_{5\nu}^\pi(y) j_\alpha^\dagger(0)]|0\rangle$$

OPE side



Phen. side

$$\Pi_{\mu\nu\alpha}^{(phen)}(p,p',q) = \frac{\lambda_{Z_c} m_\psi f_\psi F_\pi \; g_{Z_c\psi\pi}(q^2) q_\nu}{(p^2 - m_{Z_c}^2)(p'^2 - m_\psi^2)(q^2 - m_\pi^2)}$$
$$\left(-g_{\mu\lambda} + \frac{p'_\mu p'_\lambda}{m_\psi^2}\right)\left(-g_\alpha^\lambda + \frac{p_\alpha p^\lambda}{m_{Z_c}^2}\right) + \cdots ,$$

$$\Gamma(Z_c^+(3900) \to J/\psi\pi^+) = \frac{p^*(m_{Z_c}, m_\psi, m_\pi)}{8\pi m_{Z_c}^2}$$
$$\times \frac{1}{3} g_{Z_c\psi\pi}^2 \left(3 + \frac{(p^*(m_{Z_c}, m_\psi, m_\pi))^2}{m_\psi^2}\right),$$

coupling constant

Phen. side:

$$A\left(e^{-m_\psi^2/M^2} - e^{-m_{Z_c}^2/M^2}\right) + B\ e^{-s_0/M^2}$$ with $$A = \frac{g_{Z_c\psi\pi}\lambda_{Z_c} f_\psi F_\pi\ (m_{Z_c}^2 + m_\psi^2)}{2m_{Z_c}^2 m_\psi (m_{Z_c}^2 - m_\psi^2)}$$

OPE side:

$$\frac{\langle \bar{q} g\sigma.Gq\rangle}{12\sqrt{2}\pi^2}\int_0^1 d\alpha\, e^{\frac{-m_c^2}{\alpha(1-\alpha)M^2}}$$

Phen. side:

$$A\left(e^{-m_\psi^2/M^2} - e^{-m_{Z_c}^2/M^2}\right) + B\, e^{-s_0/M^2}$$ with $$A = \frac{g_{Z_c\psi\pi}\lambda_{Z_c} f_\psi F_\pi\ (m_{Z_c}^2 + m_\psi^2)}{2m_{Z_c}^2 m_\psi (m_{Z_c}^2 - m_\psi^2)}$$

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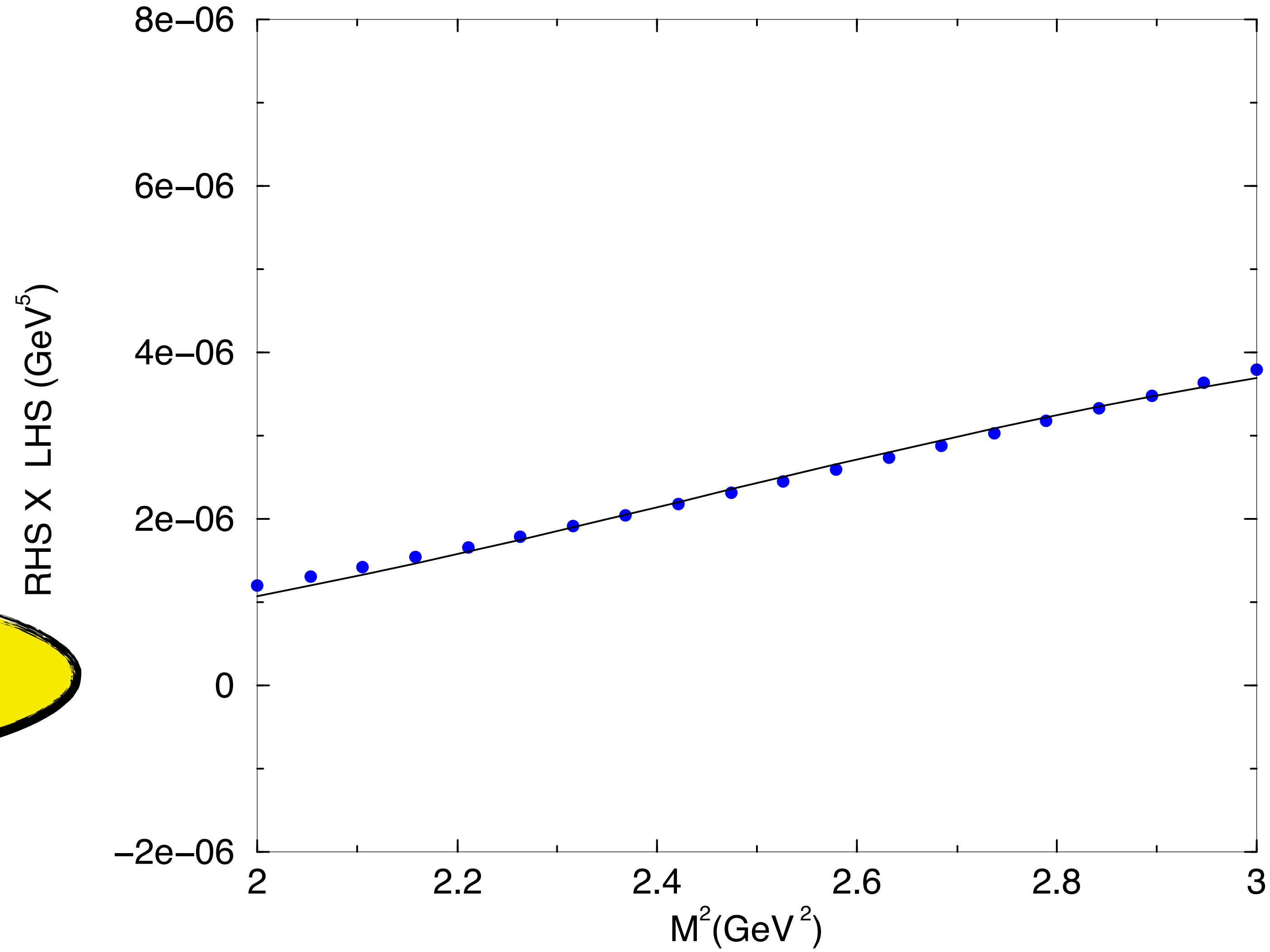


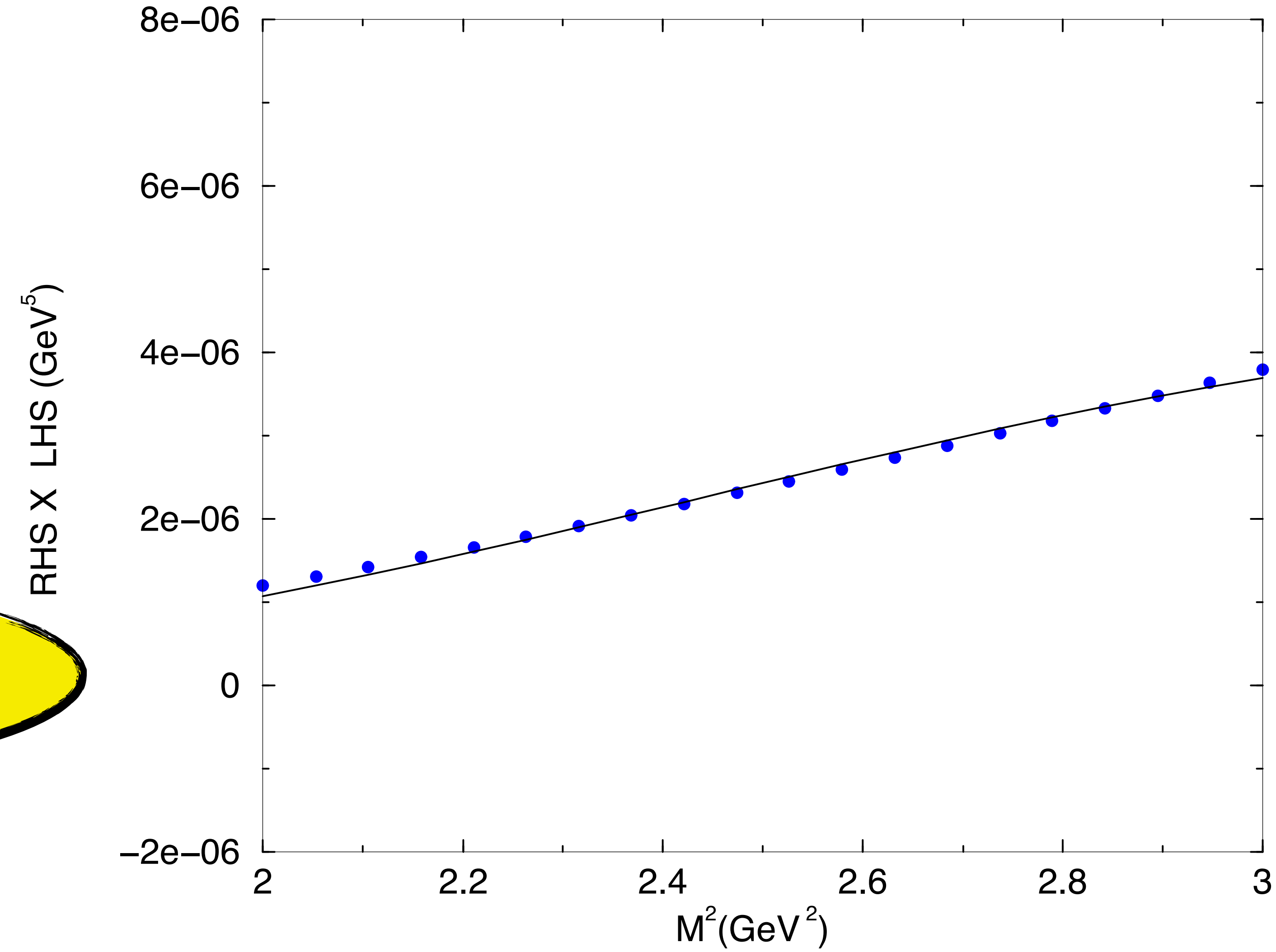
$$g_{Z_c\psi\pi} = (3.89 \pm 0.56)\ \ \mathrm{GeV}$$

Phen. side:

$$A\left(e^{-m_\psi^2/M^2} - e^{-m_{Z_c}^2/M^2}\right) + B\, e^{-s_0/M^2} \quad \text{with} \quad A = \frac{g_{Z_c\psi\pi}\lambda_{Z_c} f_\psi F_\pi\ (m_{Z_c}^2 + m_\psi^2)}{2m_{Z_c}^2 m_\psi (m_{Z_c}^2 - m_\psi^2)}$$

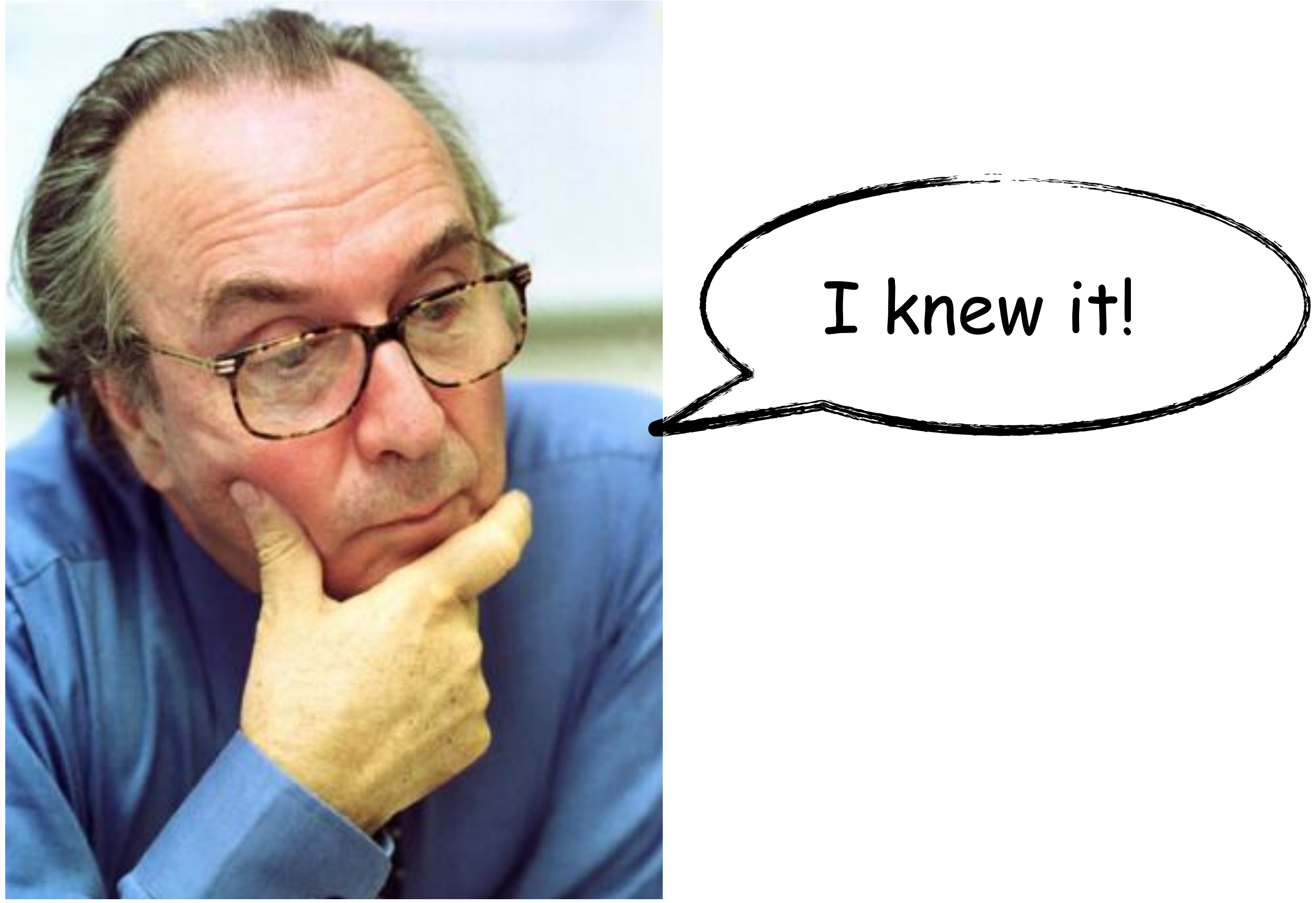
OPE side:

$$\frac{\langle \bar{q} g\sigma.Gq\rangle}{12\sqrt{2}\pi^2}\int_0^1 d\alpha\, e^{\frac{-m_c^2}{\alpha(1-\alpha)M^2}}$$



$$g_{Z_c\psi\pi} = (3.89 \pm 0.56)\ \text{GeV}$$

$$\Gamma(Z_c^+(3900) \to J/\psi\pi^+) = (29.1 \pm 8.2)\ \text{MeV}$$



L. Maiani et al.
arXiv:1303.6857

I knew it!

"We rely on a rough dimensional argument adopting $g \sim M_{Z_c^+} \sim 3.9\ \mathrm{GeV}$"

L. Maiani et al.
arXiv:1303.6857

1. $\Gamma(Z_c^+ \to J/\psi\ \pi^+) \approx 29\ \mathrm{MeV}$
2. $\Gamma(Z_c^+ \to \psi(2S)\ \pi^+) \approx 6\ \mathrm{MeV}$
3. $\Gamma(Z_c^+ \to \eta_c\ \rho^+) \approx 19\ \mathrm{MeV}$


Not good!

"You should do calculations, like my friends, instead of relying in rough dimensional arguments "

Decay width $Z^+ \to \eta_c \, \rho^+$

$$\Pi_{\mu\alpha}(p,p',q) = \int d^4x d^4y e^{ip'.x} e^{iqy} \, \Pi_{\mu\alpha}(x,y)$$

$$\Pi_{\mu\alpha}(x,y) = \langle 0|T[j_5^{\eta_c}(x) j_\mu^\rho j_\alpha^\dagger(0)]0\rangle$$

Phen. side: OPE side:

$$C\left(e^{-m_{\eta_c}^2/M^2} - e^{-m_{Z_c}^2/M^2}\right) + D\; e^{-s_0/M^2} = \frac{Q^2+m_\rho^2}{Q^2}\frac{m_c\langle\bar{q}g\sigma.Gq\rangle}{48\sqrt{2}\pi^2}\int_0^1 d\alpha \frac{e^{\frac{-m_c^2}{\alpha(1-\alpha)M^2}}}{\alpha(1-\alpha)}$$

Decay width $Z^+ \to \eta_c \, \rho^+$

$$\Pi_{\mu\alpha}(p,p',q) = \int d^4x d^4y e^{ip'.x} e^{iqy} \, \Pi_{\mu\alpha}(x,y)$$

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Phen. side: **OPE side:**

$$C\left(e^{-m_{\eta_c}^2/M^2} - e^{-m_{Z_c}^2/M^2}\right) + D\, e^{-s_0/M^2} = \frac{Q^2+m_\rho^2}{Q^2}\frac{m_c\langle\bar{q}g\sigma.Gq\rangle}{48\sqrt{2}\pi^2}\int_0^1 d\alpha \frac{e^{\frac{-m_c^2}{\alpha(1-\alpha)M^2}}}{\alpha(1-\alpha)}$$

$$C = \frac{g_{Z_c\eta_c\rho}(Q^2)\lambda_{Z_c} m_\rho f_\rho f_{\eta_c} m_{\eta_c}^2}{2m_c m_{Z_c}^2(m_{Z_c}^2 - m_{\eta_c}^2)}$$

Decay width $Z^+ \to \eta_c \rho^+$

$$\Pi_{\mu\alpha}(p,p',q) = \int d^4x d^4y e^{ip'.x} e^{iqy}\ \Pi_{\mu\alpha}(x,y)$$

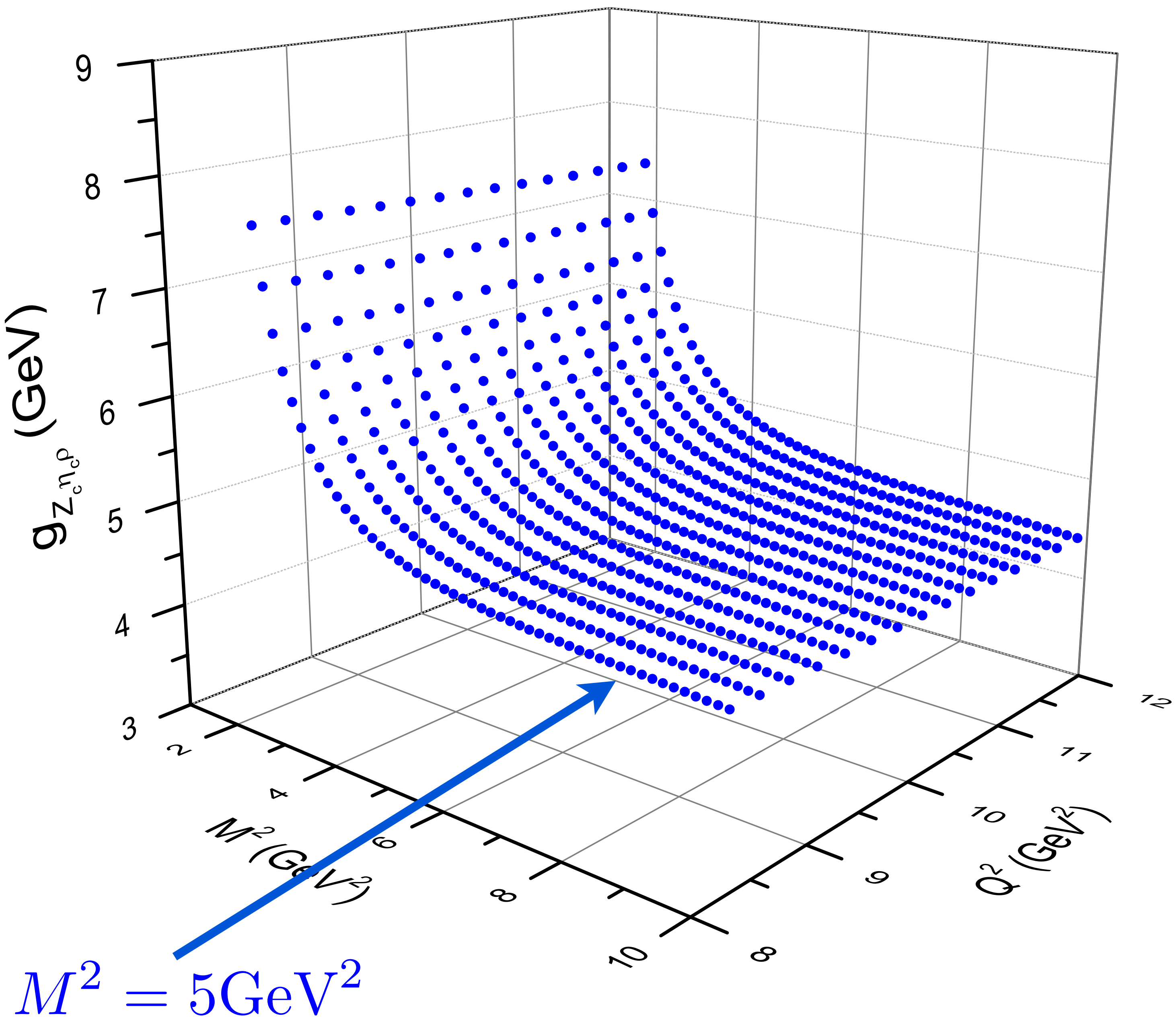
$$\Pi_{\mu\alpha}(x,y) = \langle 0|T[j_5^{\eta_c}(x) j_\mu^\rho j_\alpha^\dagger(0)]0\rangle$$

Phen. side: OPE side:

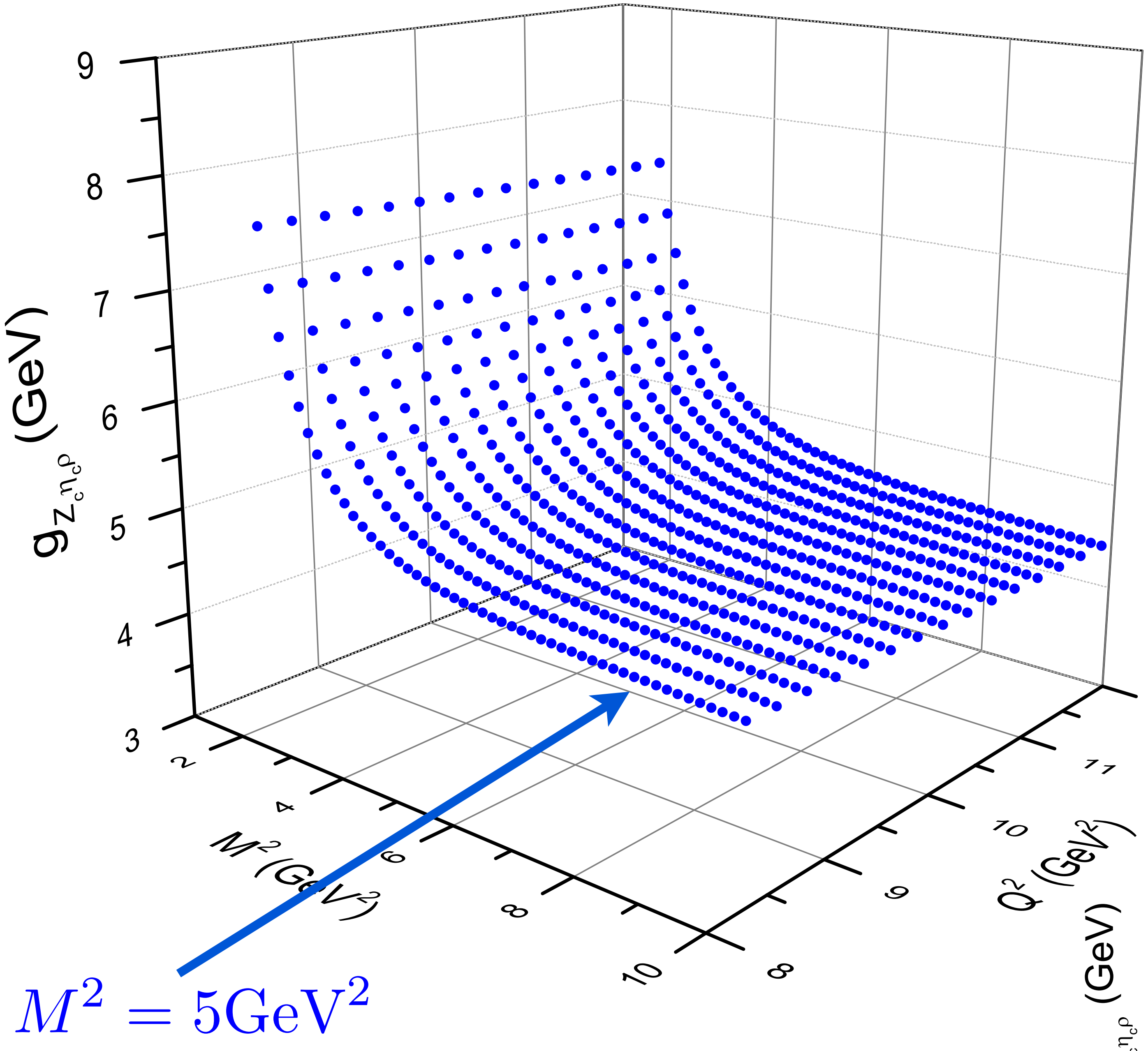
$$C\left(e^{-m_{\eta_c}^2/M^2} - e^{-m_{Z_c}^2/M^2}\right) + D\ e^{-s_0/M^2} = \frac{Q^2+m_\rho^2}{Q^2} \frac{m_c\langle\bar{q}g\sigma.Gq\rangle}{48\sqrt{2}\pi^2} \int_0^1 d\alpha \frac{e^{\frac{-m_c^2}{\alpha(1-\alpha)M^2}}}{\alpha(1-\alpha)}$$

form factor

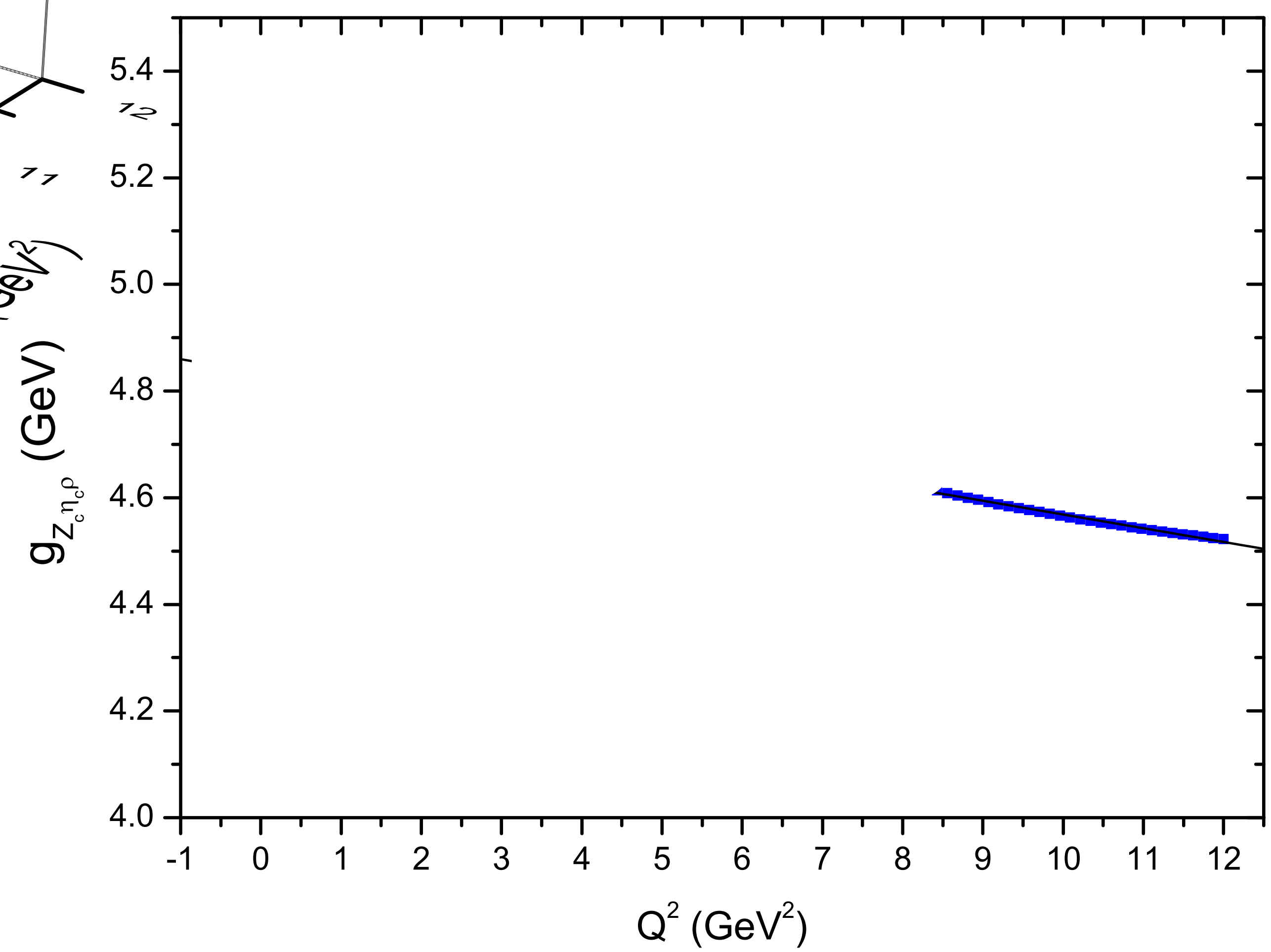
$$C = \frac{g_{Z_c\eta_c\rho}(Q^2)\lambda_{Z_c} m_\rho f_\rho f_{\eta_c} m_{\eta_c}^2}{2m_c m_{Z_c}^2(m_{Z_c}^2 - m_{\eta_c}^2)}$$



$g_{Z_c \eta_c \rho}$ (GeV)
M^2 (GeV^2)
Q^2 (GeV^2)
$M^2 = 5\mathrm{GeV}^2$

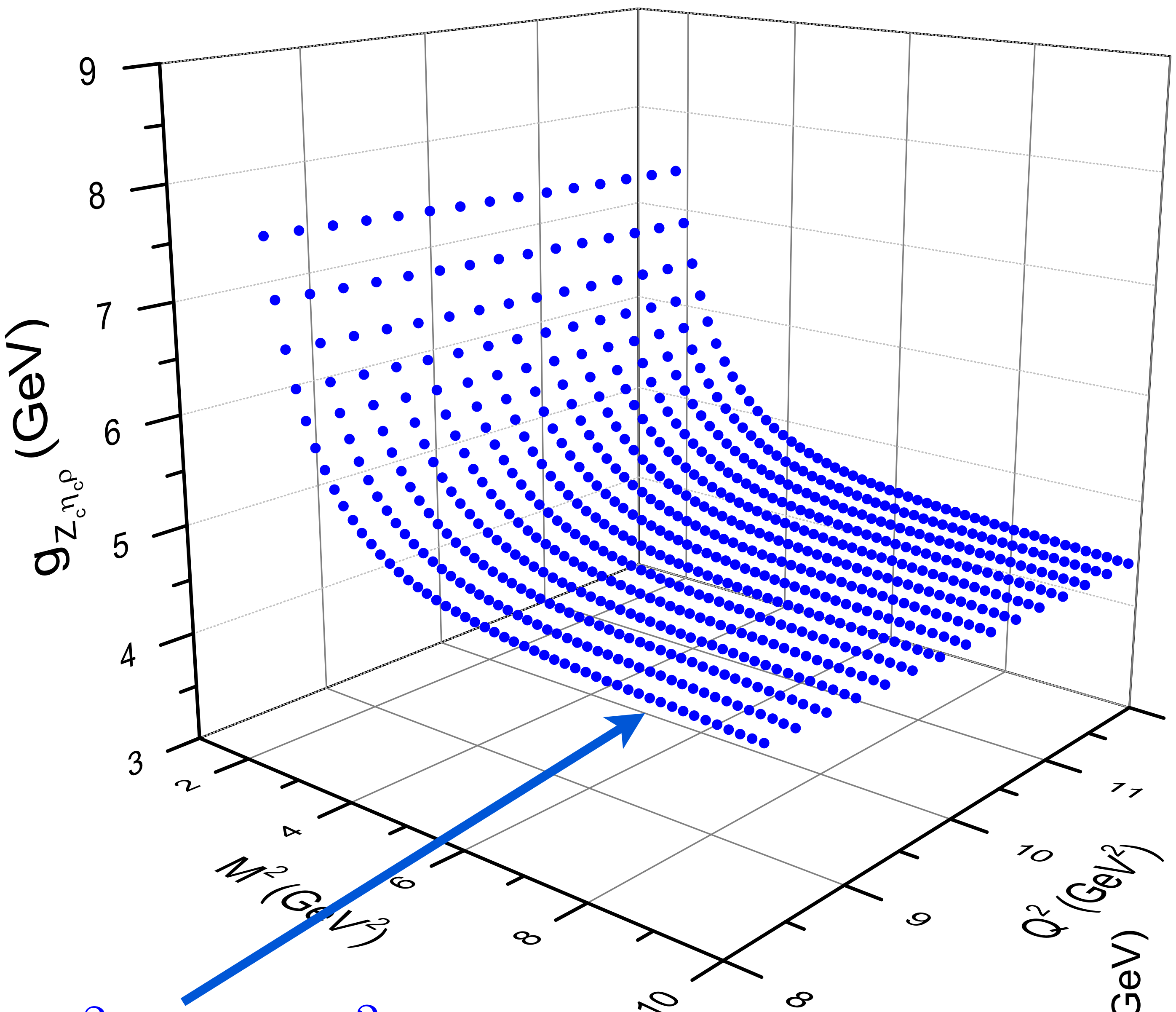


$g_{Z_c \eta_c \rho}$ (GeV)
M^2 (GeV^2)
Q^2 (GeV^2)
$M^2 = 5\mathrm{GeV}^2$



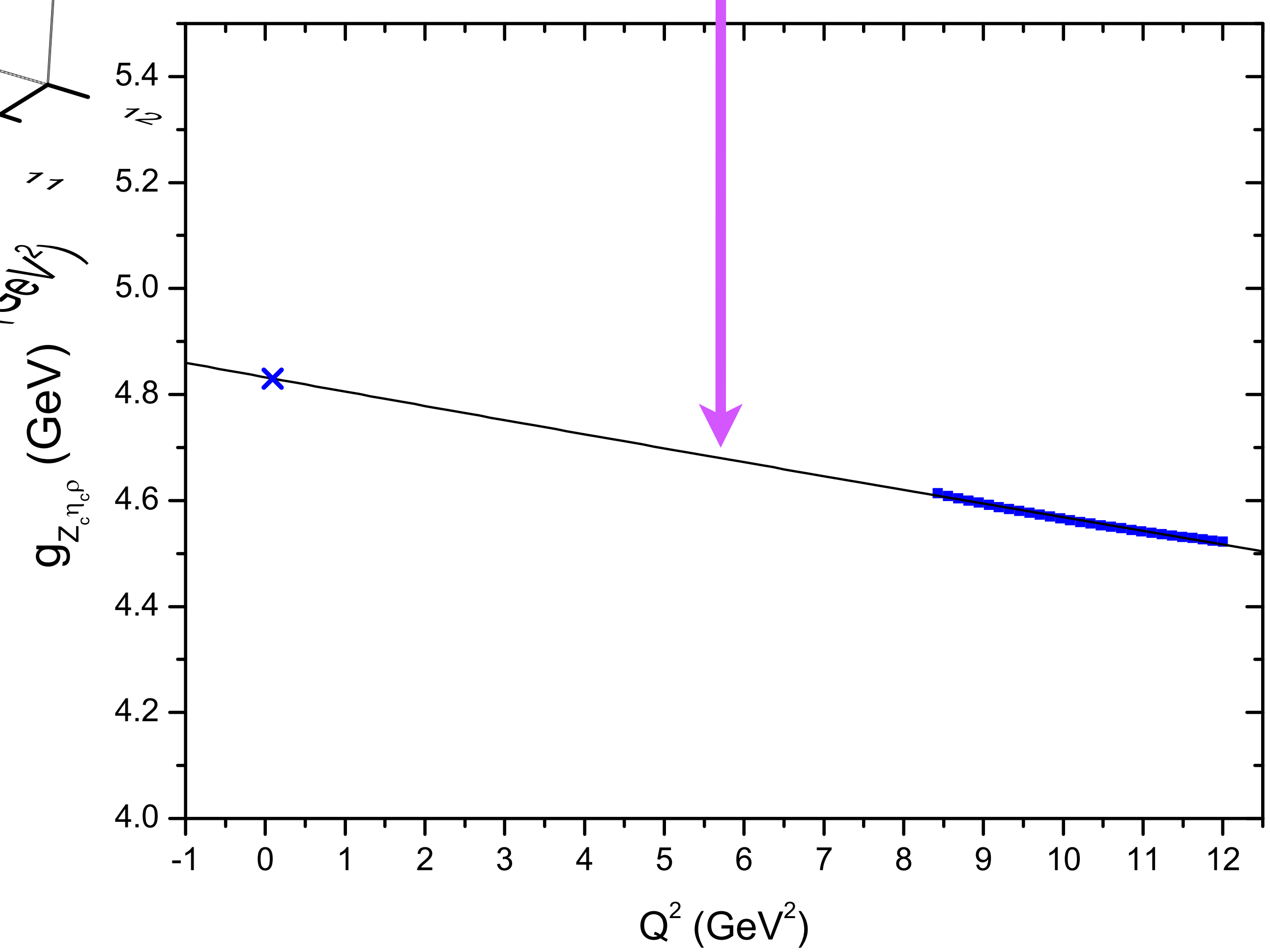
$g_{Z_c \eta_c \rho}$ (GeV)
Q^2 (GeV^2)

$$g_{Z_c\eta_c\rho}(Q^2) = g_1 e^{-g_2 Q^2}$$

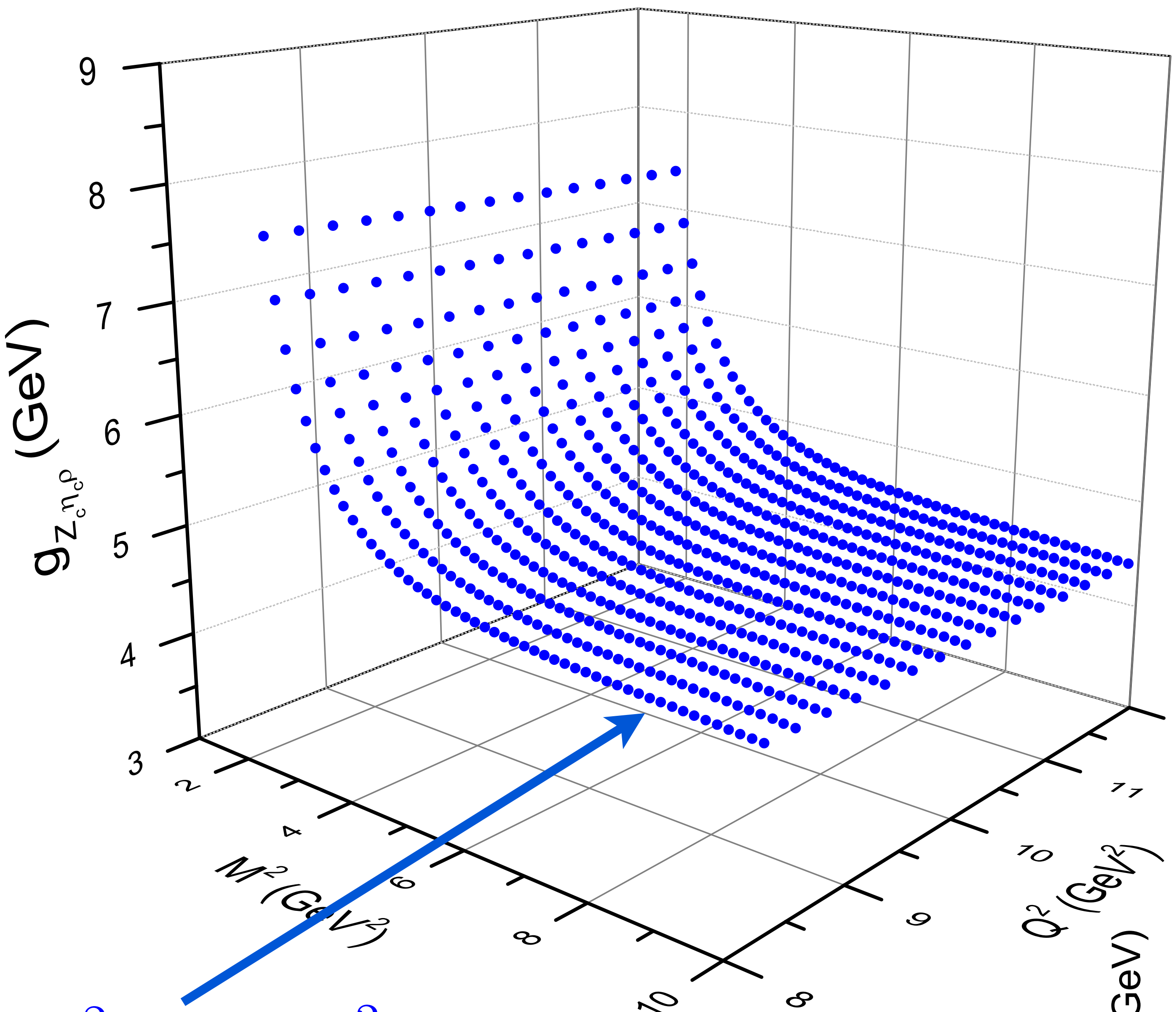


$M^2 = 5\mathrm{GeV}^2$

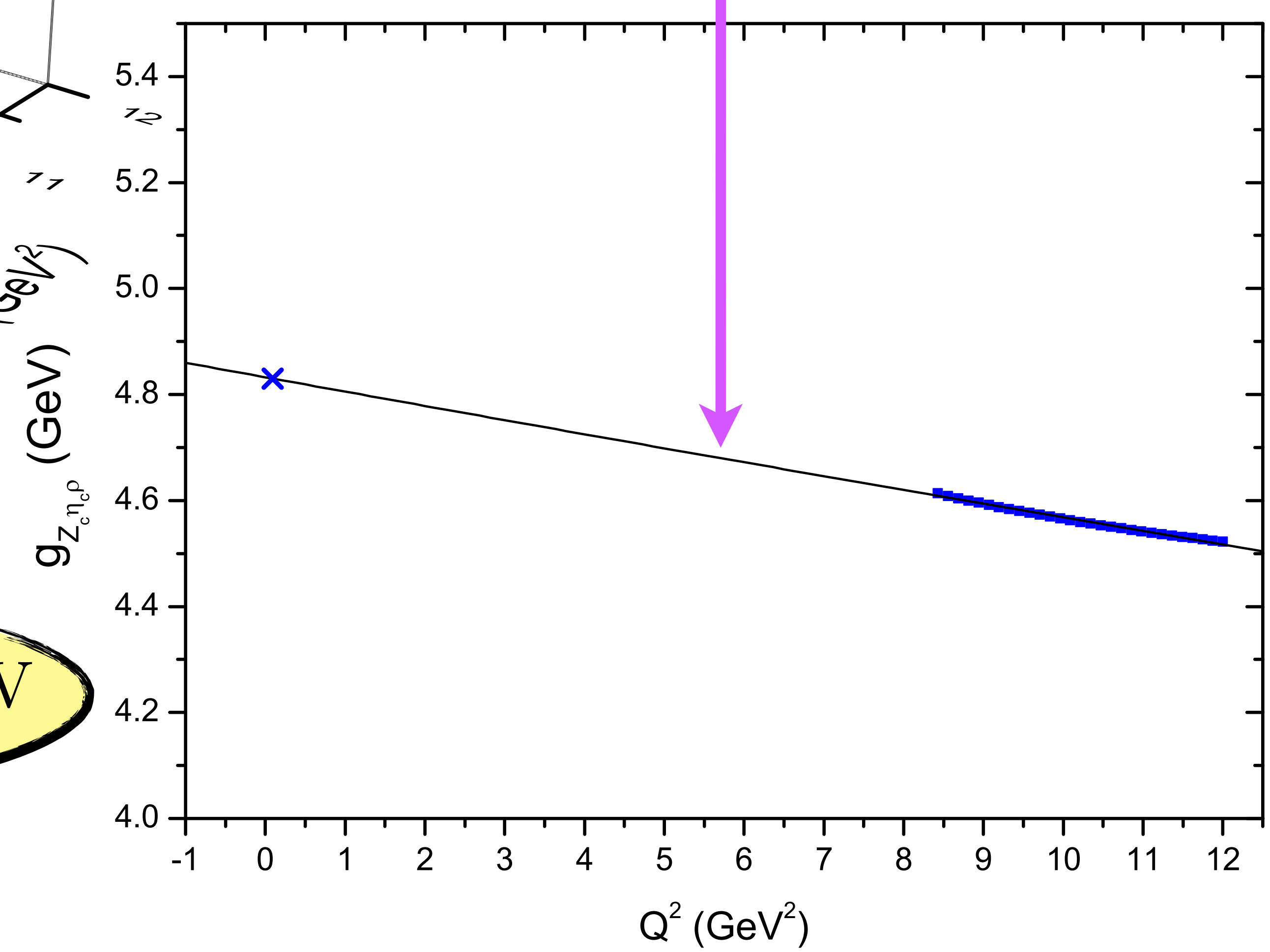
$g_1 = 4.83$ GeV, $g_2 = (5.6 \times 10^{-3})$ GeV^{-2}



$$g_{Z_c\eta_c\rho}(Q^2) = g_1 e^{-g_2 Q^2}$$

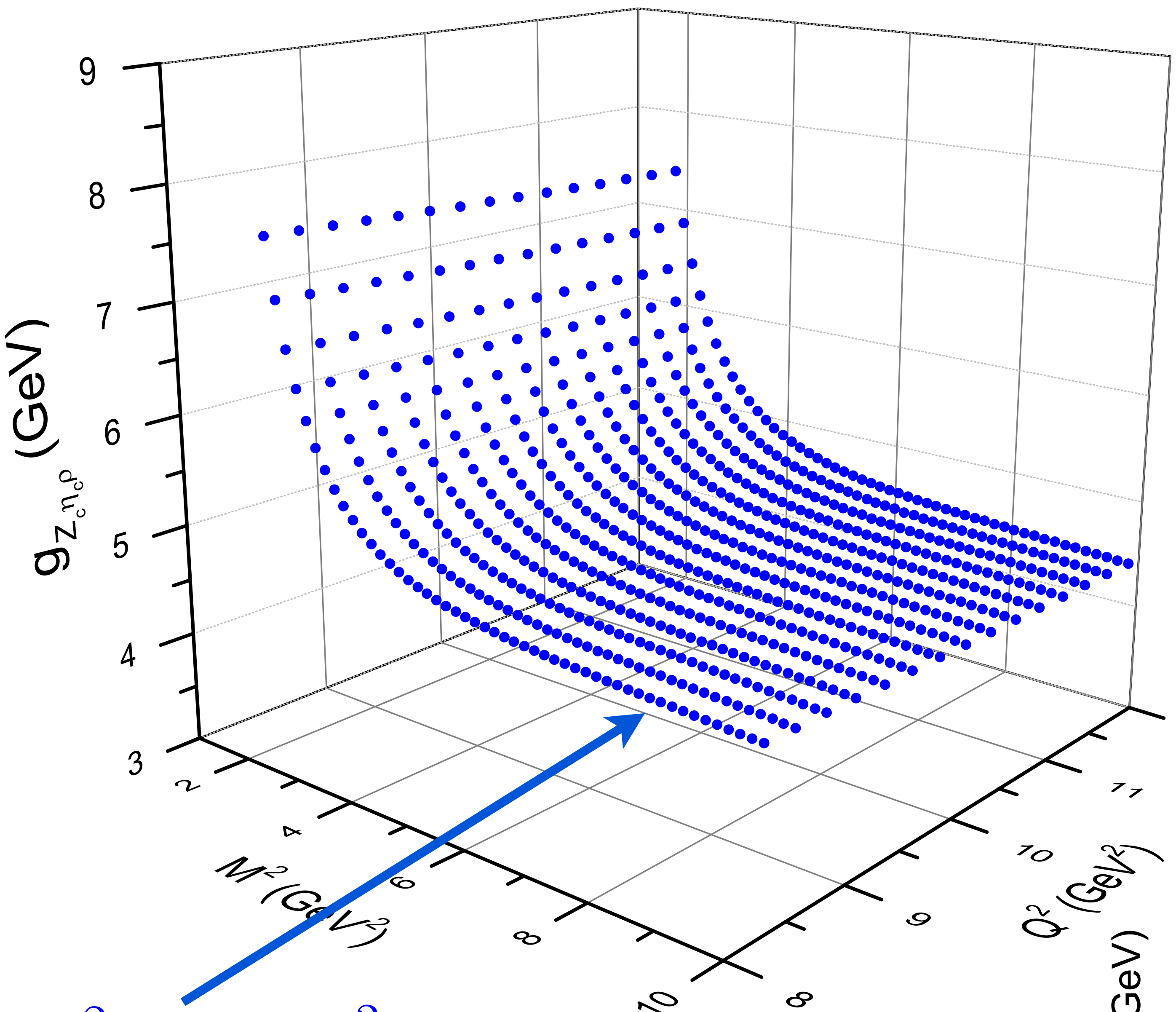


$$g_1 = 4.83 \text{ GeV}, \; g_2 = (5.6\times 10^{-3}) \text{ GeV}^{-2}$$



$$M^2 = 5\text{GeV}^2$$

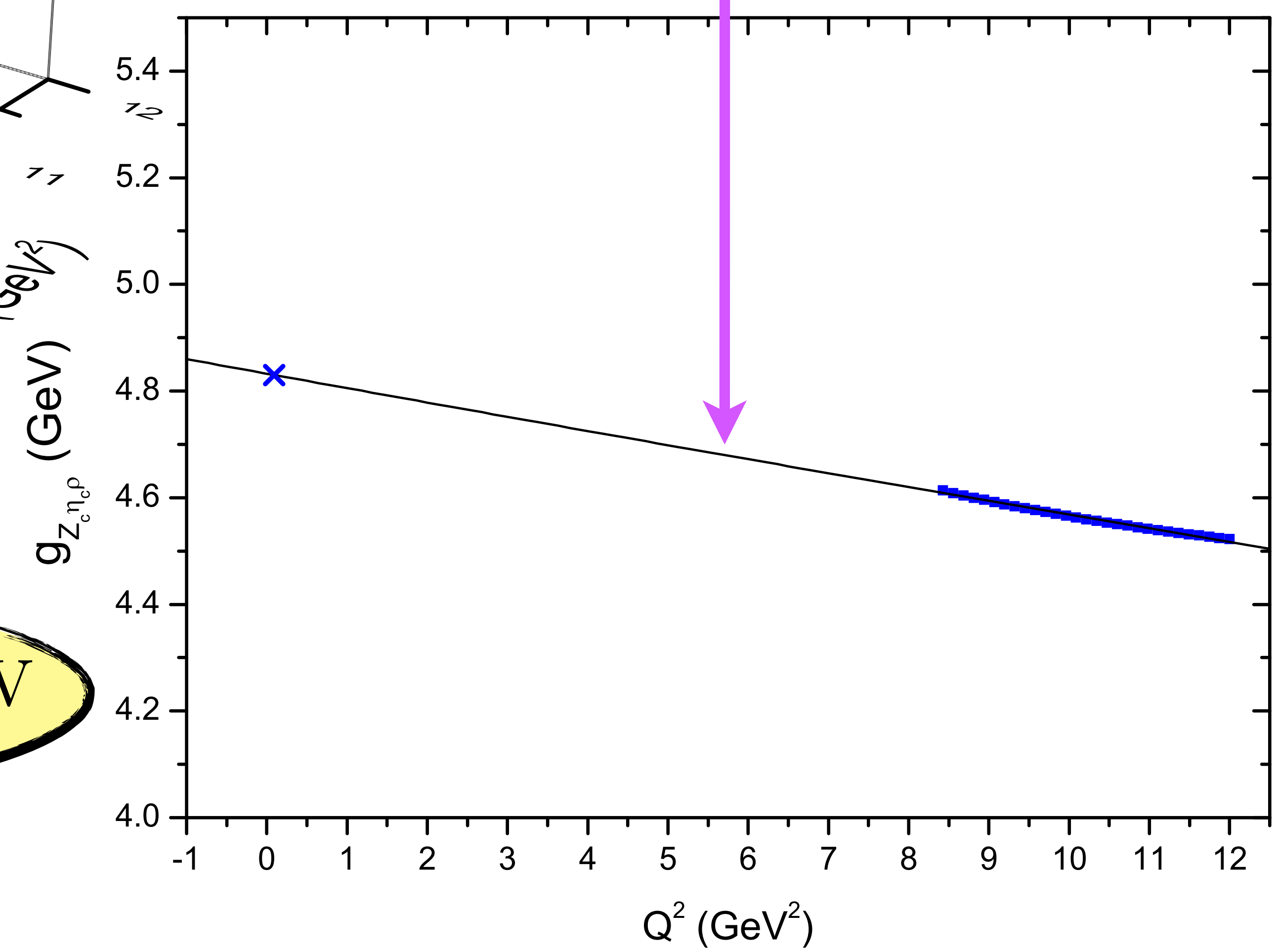
$$g_{Z_c\eta_c\rho} = g_{Z_c\eta_c\rho}(-m_\rho^2) = (4.85 \pm 0.81) \;\; \text{GeV}$$



$$g_{Z_c\eta_c\rho}(Q^2) = g_1 e^{-g_2 Q^2}$$

$$g_1 = 4.83\ \mathrm{GeV},\ \ g_2 = (5.6 \times 10^{-3})\ \mathrm{GeV}^{-2}$$

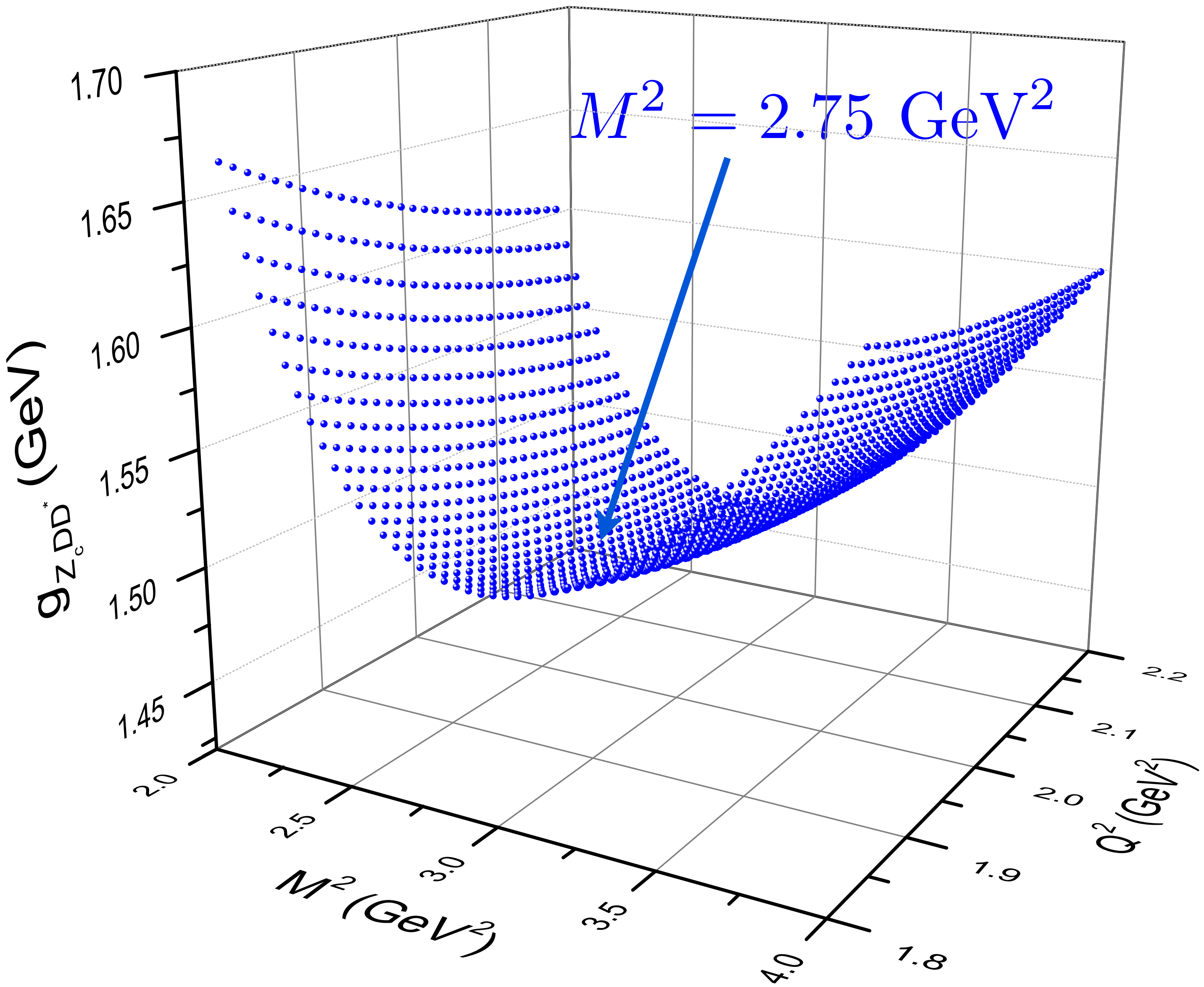
$M^2 = 5\mathrm{GeV}^2$



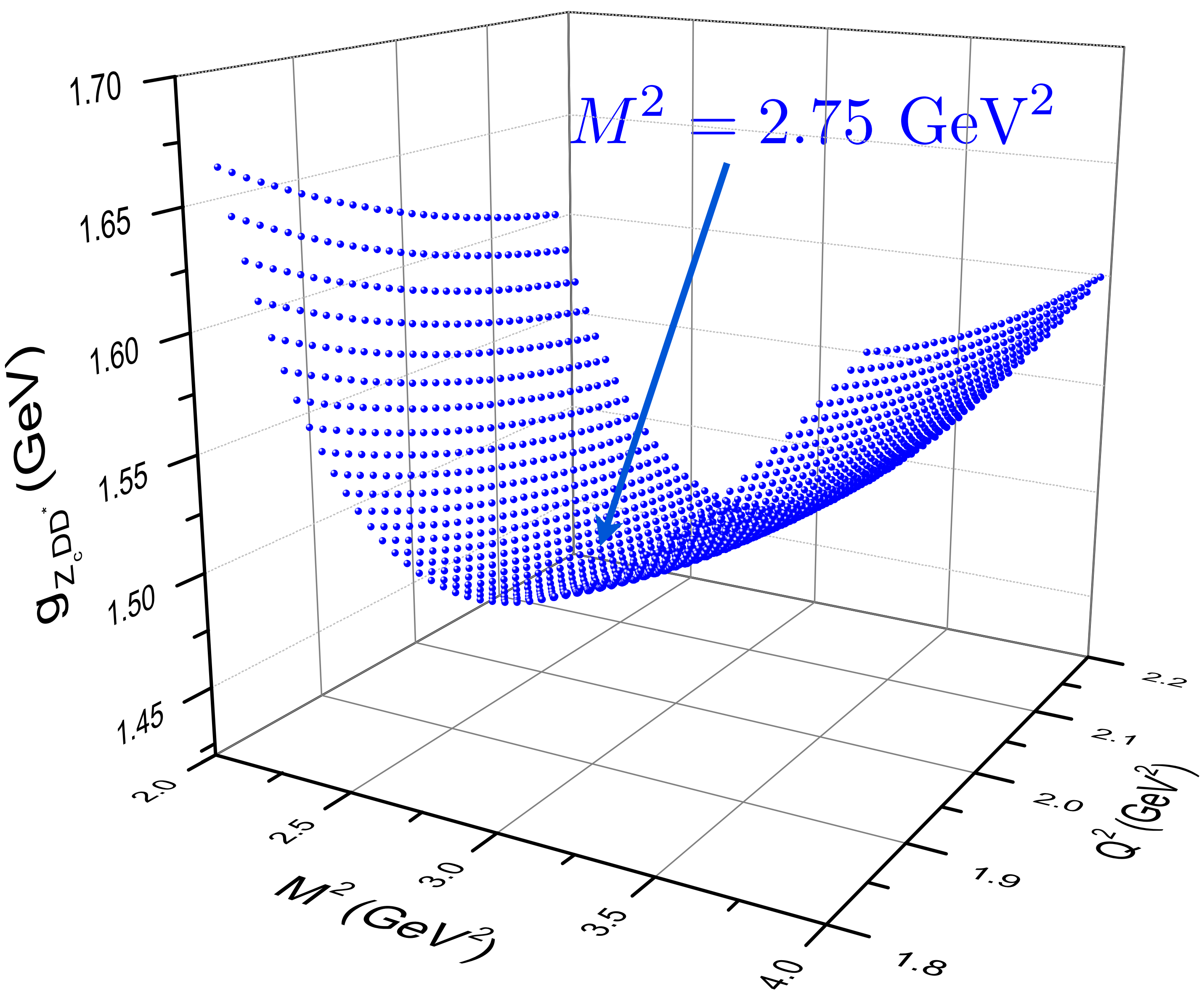
$$g_{Z_c\eta_c\rho} = g_{Z_c\eta_c\rho}(-m_\rho^2) = (4.85 \pm 0.81)\ \ \mathrm{GeV}$$

$$\Gamma(Z_c^+(3900) \to \eta_c\rho^+) = (27.5 \pm 8.5)\ \ \mathrm{MeV}.$$

Decay width $Z^+ \to D^* D^+$



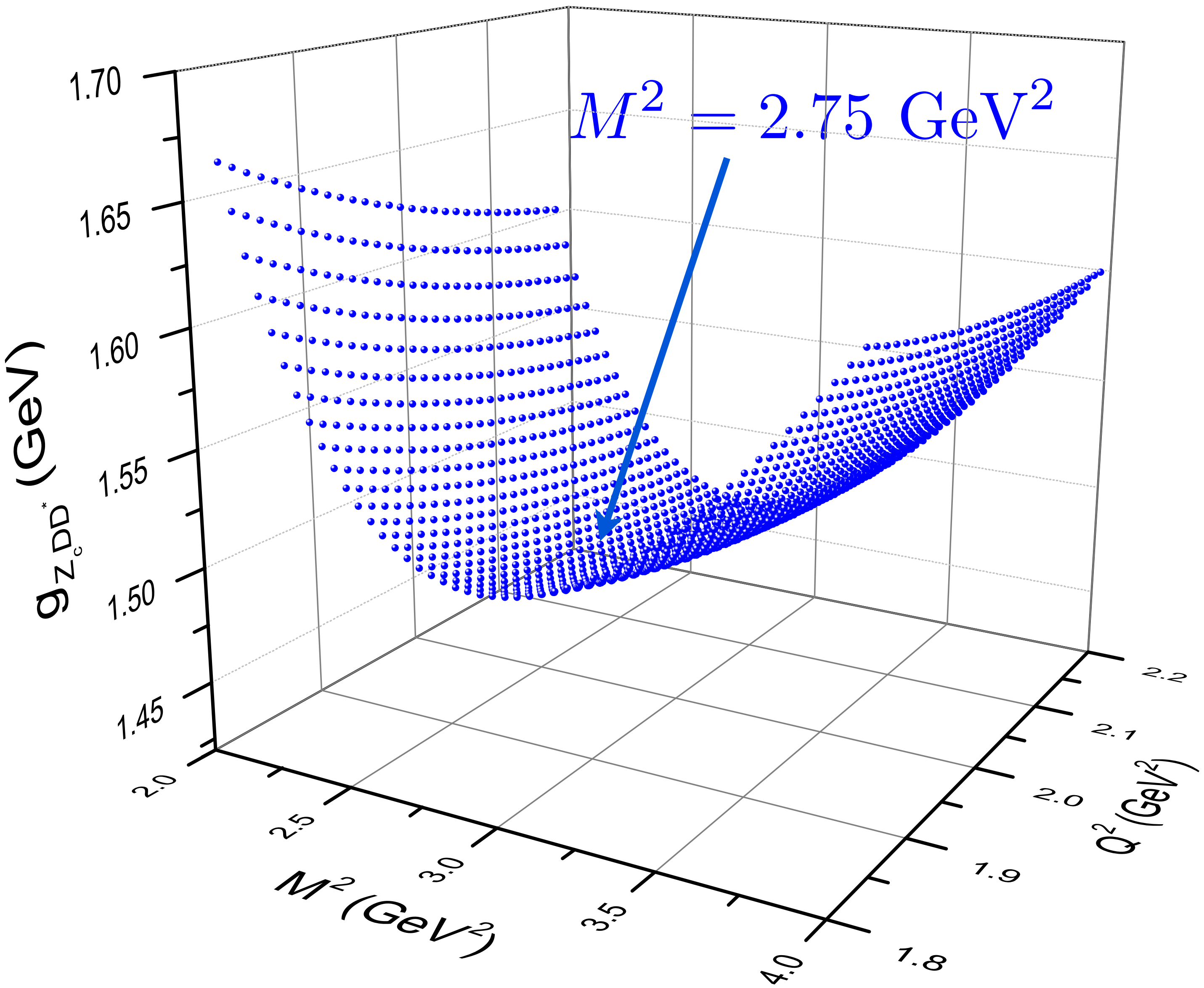
Decay width $Z^+ \rightarrow D^* D^+$



$$g_{Z_c D^* D}(Q^2) = 1.7e^{-0.08Q^2}$$

$$g_{Z_c D^* D}(Q^2 = -m_D^2) = (2.5 \pm 0.3)\ \mathrm{GeV}$$

Decay width $Z^+ \to D^* D^+$



$$g_{Z_c D^* D}(Q^2) = 1.7 e^{-0.08 Q^2}$$

$$g_{Z_c D^* D}(Q^2 = -m_D^2) = (2.5 \pm 0.3)\ \mathrm{GeV}$$

$$\Gamma(Z_c^+ \to D^+ \bar{D}^{*0}) = (3.2 \pm 0.7)\ \ \mathrm{MeV}$$

Vertex	coupling constant (GeV)	decay width (MeV)
$Z_c^+(3900)J/\psi\pi^+$	3.89 ± 0.56	29.1 ± 8.2
$Z_c^+(3900)\eta_c\rho^+$	4.85 ± 0.81	27.5 ± 8.5
$Z_c^+(3900)D^+\bar{D}^{*0}$	2.5 ± 0.3	3.2 ± 0.7
$Z_c^+(3900)\bar{D}^0 D^{*+}$	2.5 ± 0.3	3.2 ± 0.7

$$\Gamma_{Z_c^+} = (63 \pm 18)\ \mathrm{MeV}$$

Vertex	coupling constant (GeV)	decay width (MeV)
$Z_c^+(3900)J/\psi\pi^+$	3.89 ± 0.56	29.1 ± 8.2
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$Z_c^+(3900)D^+\bar{D}^{*0}$	2.5 ± 0.3	3.2 ± 0.7
$Z_c^+(3900)\bar{D}^0 D^{*+}$	2.5 ± 0.3	3.2 ± 0.7

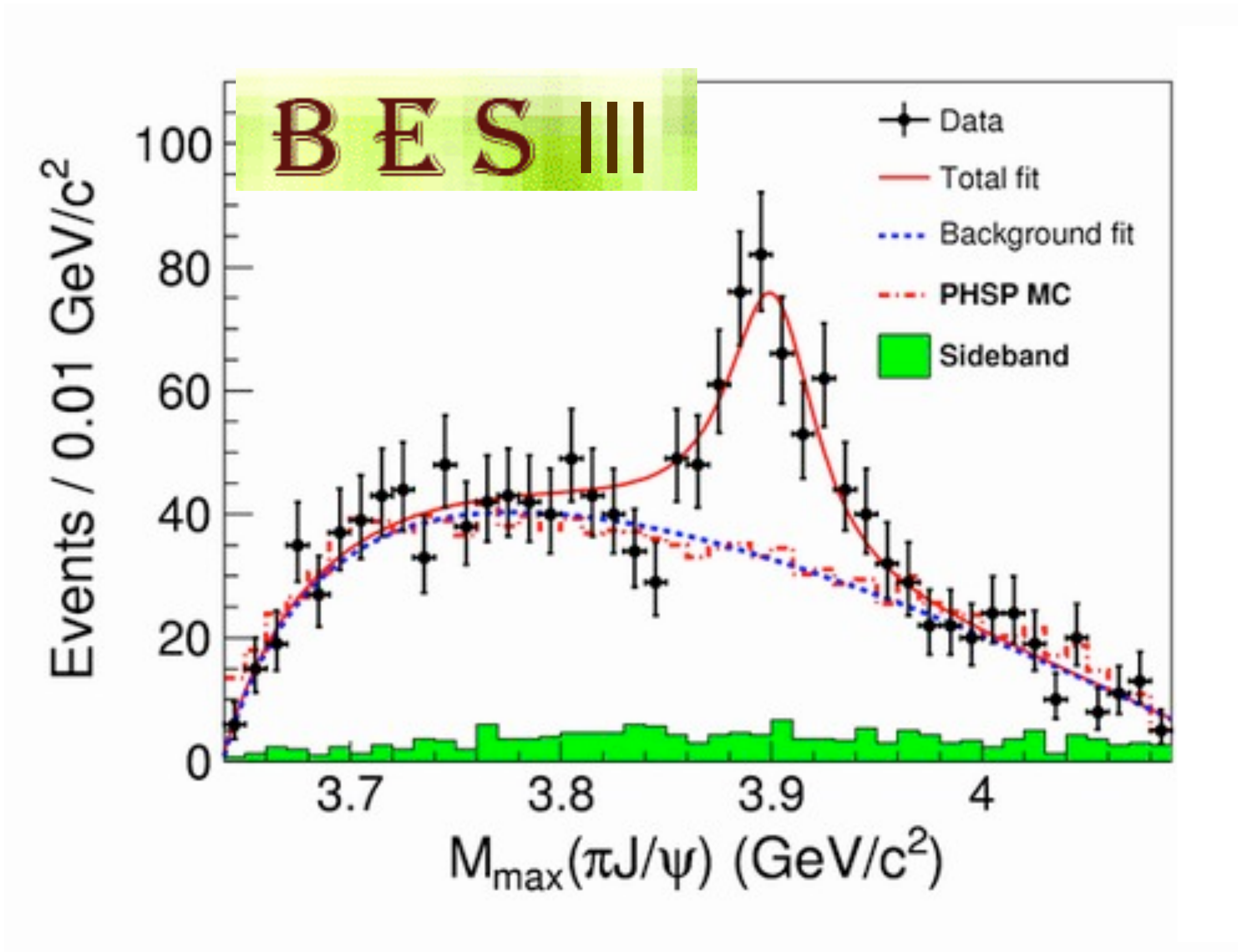
$$\Gamma_{Z_c^+} = (63 \pm 18)\ \text{MeV}$$

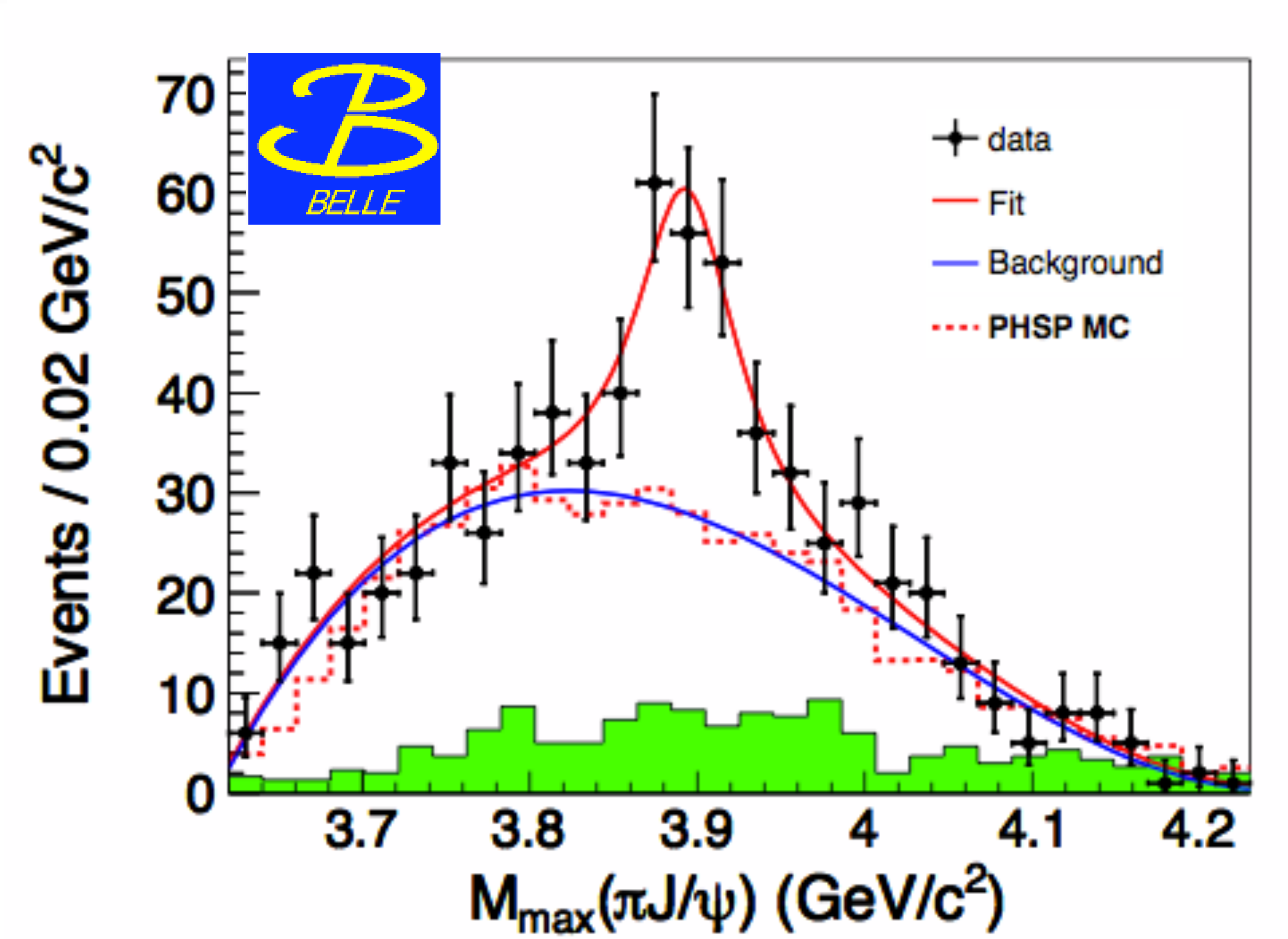
$$\Gamma_{Z_c^+}^{BESS} = (46 \pm 22)\ \text{MeV}$$

$$\Gamma_{Z_c^+}^{BELLE} = (63 \pm 35)\ \text{MeV}$$

Very good agreement

Conclusions





$Z_c^+(3900)$ ➜ $J^P = 1^+$ tetraquark state

➜ charged partner of the X(3872)

$$\Gamma_{Z_c^+} = (63 \pm 18)\ \text{MeV}$$





Conclusions II

- Lots of charmonia in the last 10 years, new bottomonia start to appear: a new spectroscopy?
  - Emerging consensus that X(3872) is a mixed charmonium-molecular state.
- Discovery of Y(4260), Y(4360) and Y(4660) represent an overpopulation of the 1^{--} charmonium states.
  - Absence of open charm production in the Y decay is inconsistent with $c\bar{c}$ interpretation
- Z^+ states, need confirmation, but only molecule or tetraquark interpretations are possible