INTERNATIONAL NUCLEAR PHYSICS CONFERENCE

ADELAIDE, AUSTRALIA
ADELAIDE CONVENTION CENTRE
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www.inpc2016.com

The $x^+(5568)$ from QCDSR

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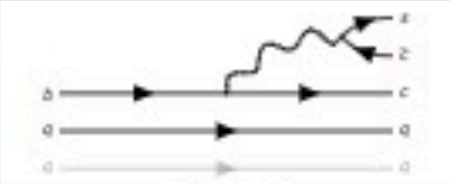
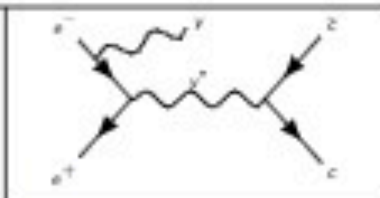
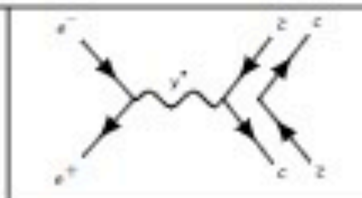
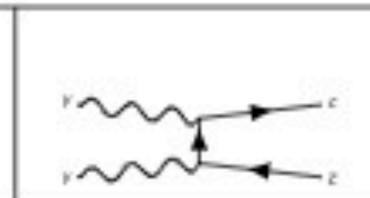
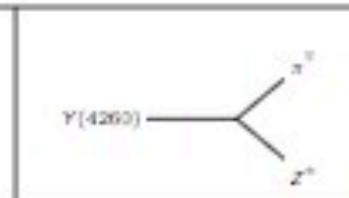
FORA
TEMER

Lots of X, Y and Z states observed by BaBar, Belle, BESIII, CDF, CLEOIII, CLEO-c, CMS, D0 and LHCb Collaborations

						$p\bar{p}$ incl.	pp incl.
$J/\psi\pi^+\pi^-$	X(3872)	Y(4260) Y(4008)				X(3872)	X(3872)
$\psi(2S)\pi^+\pi^-$		Y(4360) Y(4660)					
$\Lambda_c\bar{\Lambda}_c$		Y(4630)					
$\psi\gamma$	X(3872)						
$\chi_{c1}(1P)\gamma$	X(3832)						
$\chi_{c1}(1P)\omega$				Y(4220)			
$J/\psi\omega$	X(3872) Y(3940)			X(3915)			
$J/\psi\phi$	X(4140) X(4274) X(4500) X(4700)			X(4350)			
$J/\psi\pi$	Z(4430) Z(4200) Z(4240)				Z(3900)		
$\psi(2S)\pi$	Z(4430)						
$\chi_{c1}(1P)\pi$	Z(4051) Z(4248)						
$h_c(1P)\pi$					Z(4020)		
$D\bar{D}$				Z(3930)			
$D\bar{D}^*$	X(3872)		X(3940)		Z(3885)		
$D^*\bar{D}^*$			X(4160)		Z(4025)		
$J/\psi p$	$P_c(4380)$ $P_c(4430)$						
$B_s^0\pi$						X(5568)	-

many not confirmed states, many candidates for exotic states

Exotic States

Glueball

$[g]_8 \otimes [g]_8$

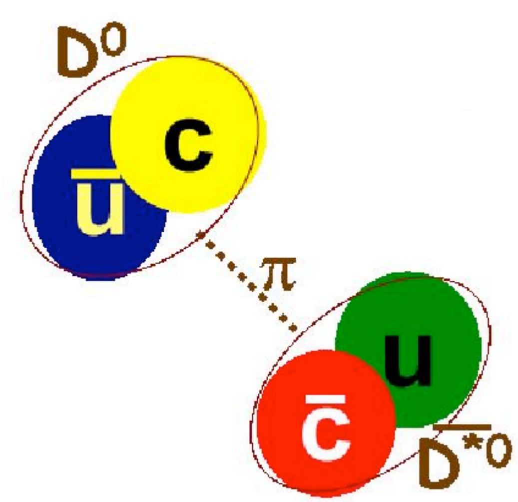
Hybrids $[q\bar{q}]_8 \otimes [g]_8$

Tetraquarks

$[qq]_{\bar{3}} \otimes [\bar{q}\bar{q}]_3, \quad [qq]_6 \otimes [\bar{q}\bar{q}]_{\bar{6}}, \quad [q\bar{q}]_8 \otimes [q\bar{q}]_8$

Molecules

$[q\bar{q}]_1 \otimes [q\bar{q}]_1, \quad [qqq]_1 \otimes [q\bar{q}]_1$



Pentaquarks

$\left[[qq]_{\bar{3}} \otimes [qq]_{\bar{3}}\right]_3 \otimes [\bar{q}]_{\bar{3}}, \quad \ldots$

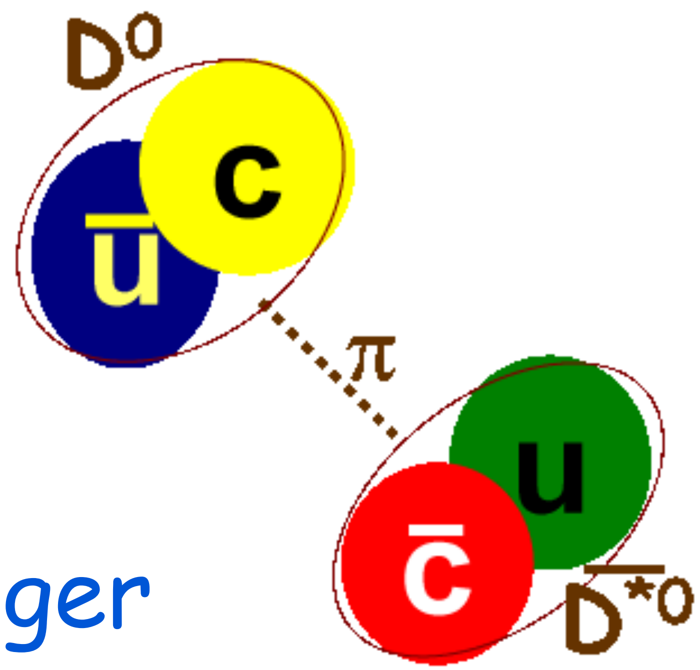
Up to now Belle, BaBar, BESIII, CLEO-c and LHCb reported 8 charged charmonium states

$Z^+(4430)$ 2007	$Z_1^+(4050)$ 2008	$Z_2^+(4250)$ 2008
$Z_c^+(3900)$ 2013	$Z_c^+(4025)$ 2013	$Z_c^+(4020)$ 2013
$Z_c^+(3885)$ 2013	$Z_c^+(4200)$ 2014	

possible structure: tetraquarks or molecules

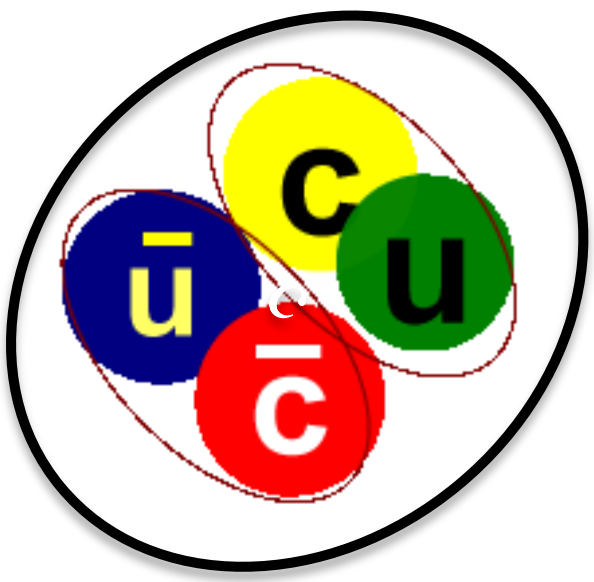
molecular and tetraquark interpretations differ by the way quarks are organized in the state

Meson molecule



state larger than normal mesons

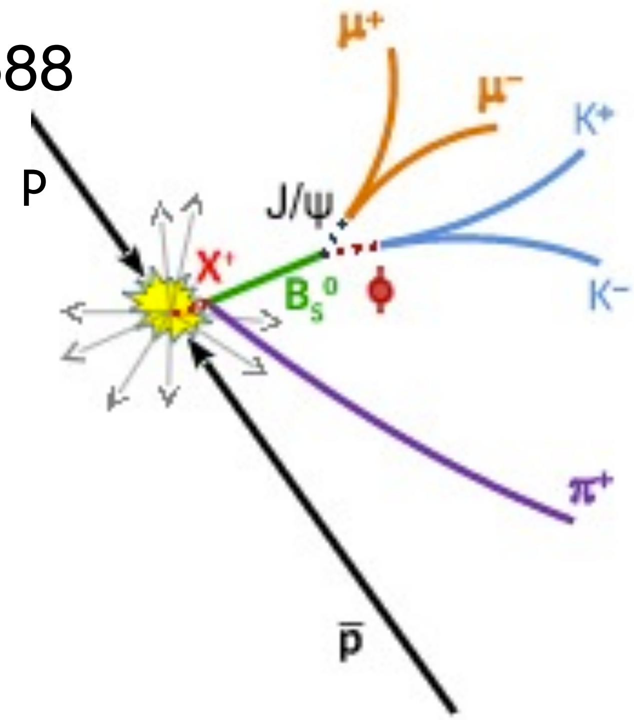
Tetraquark



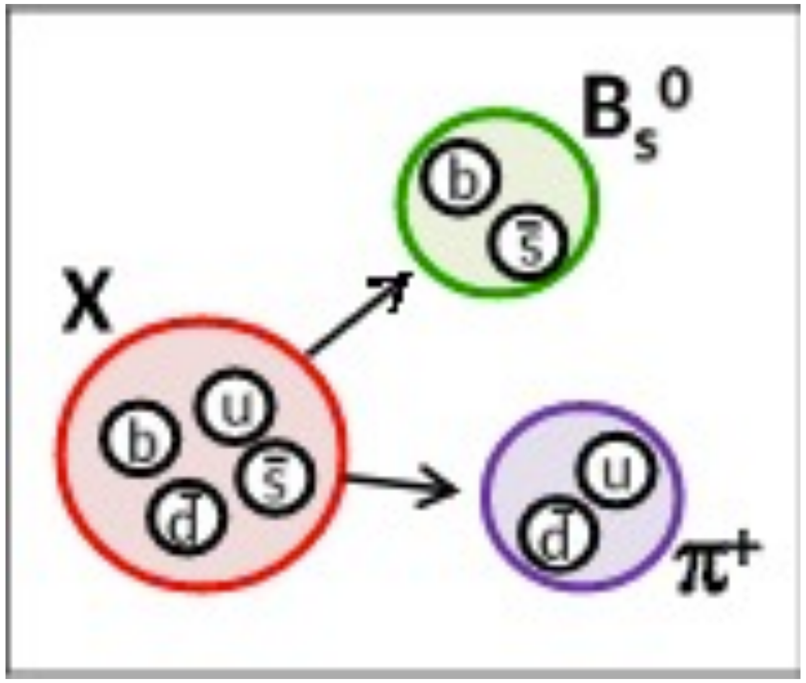
compact state

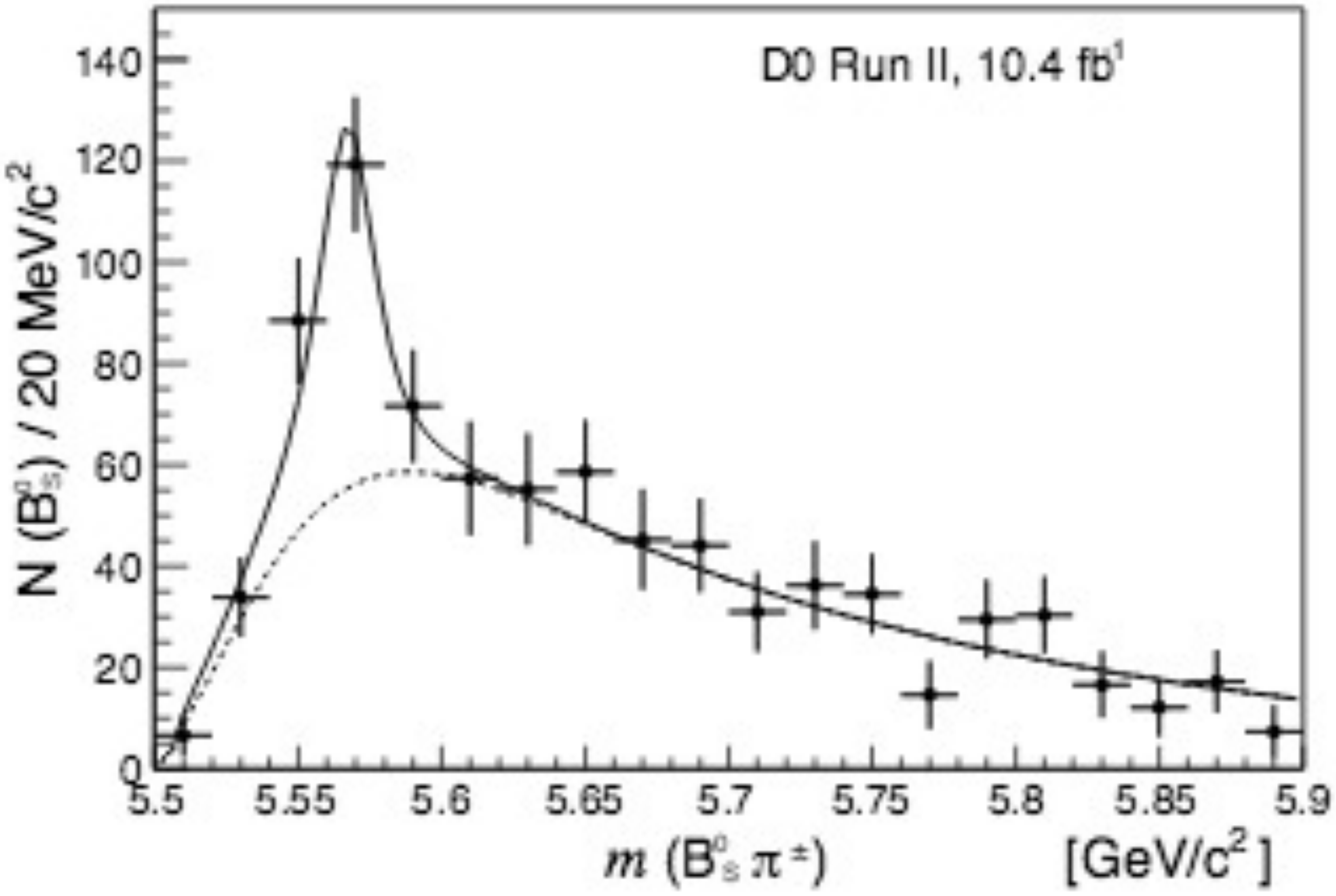
$X^{\pm}(5568)$: most recent acquisition

arXiv:1602.07588



$$X^{\pm}(5568) \to B_s^0 \pi^{\pm}$$





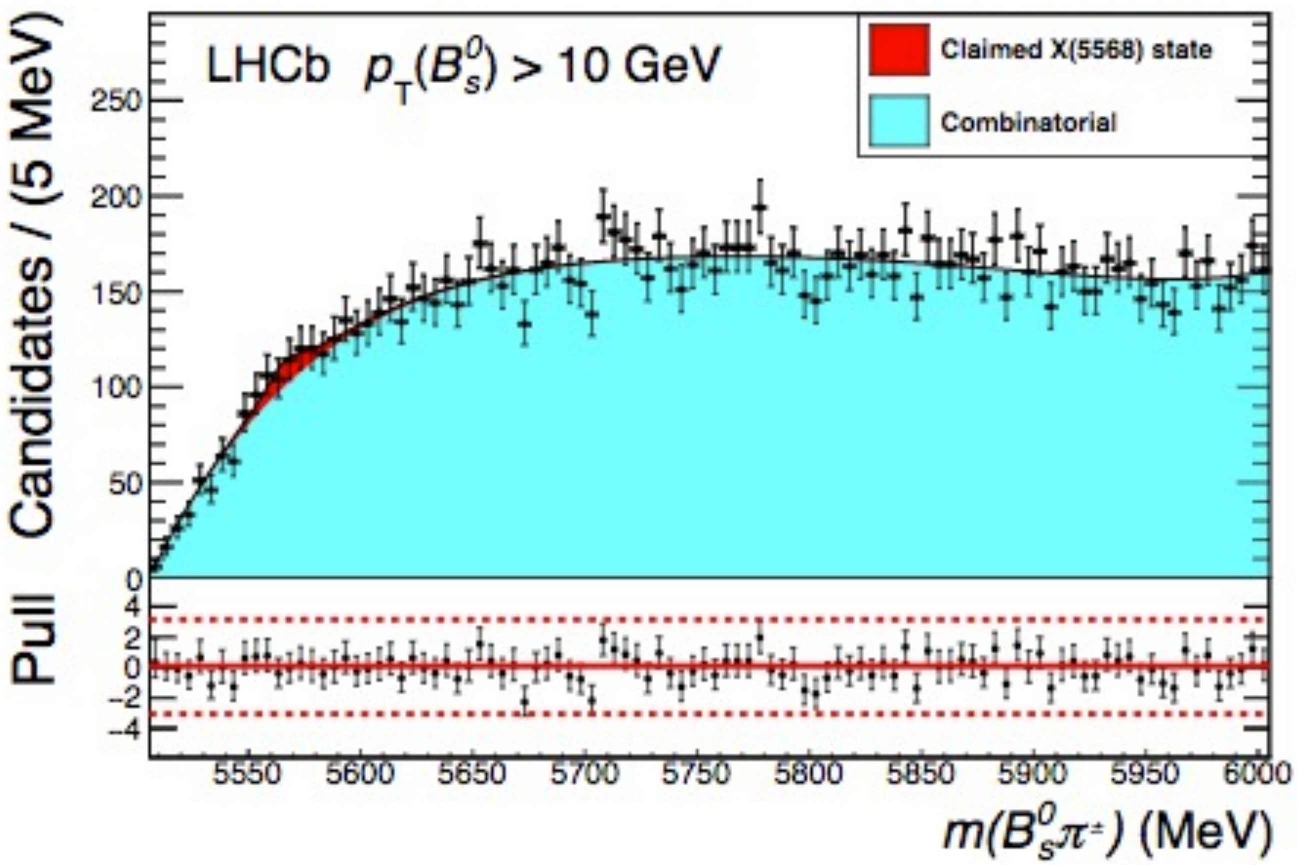
M = (5567.8±2.9±1.2) MeV

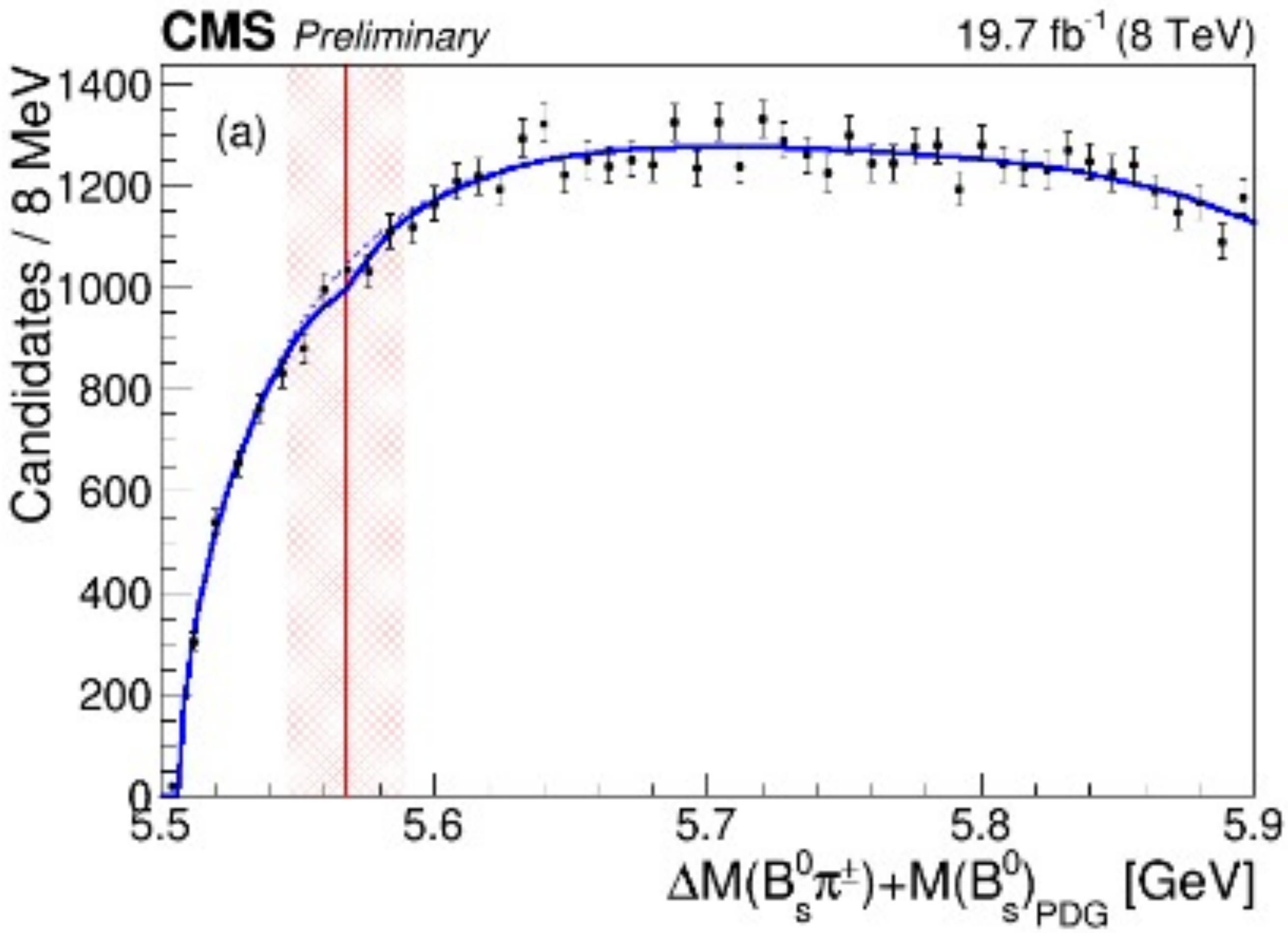
Γ = (21.9±6.4±3.5) MeV

stat. significance 5.1σ

LHCb and CMS: no structure is found from $B_s^0\ \pi^+$ from threshold up to 6000 MeV

arXiv:1608.00435



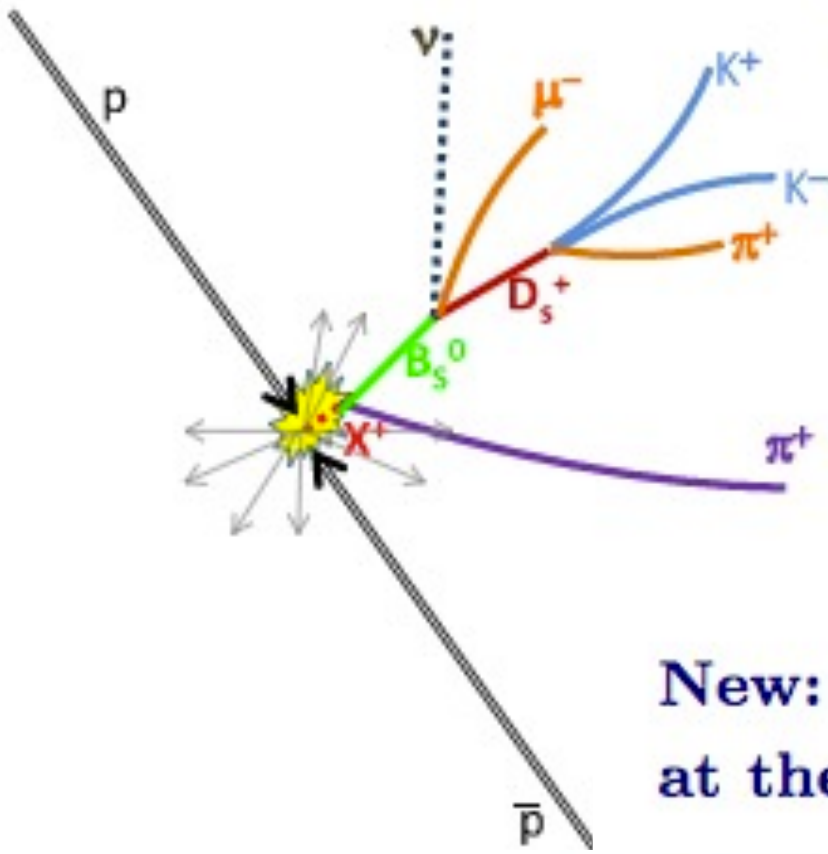


ICHEP2016 talk

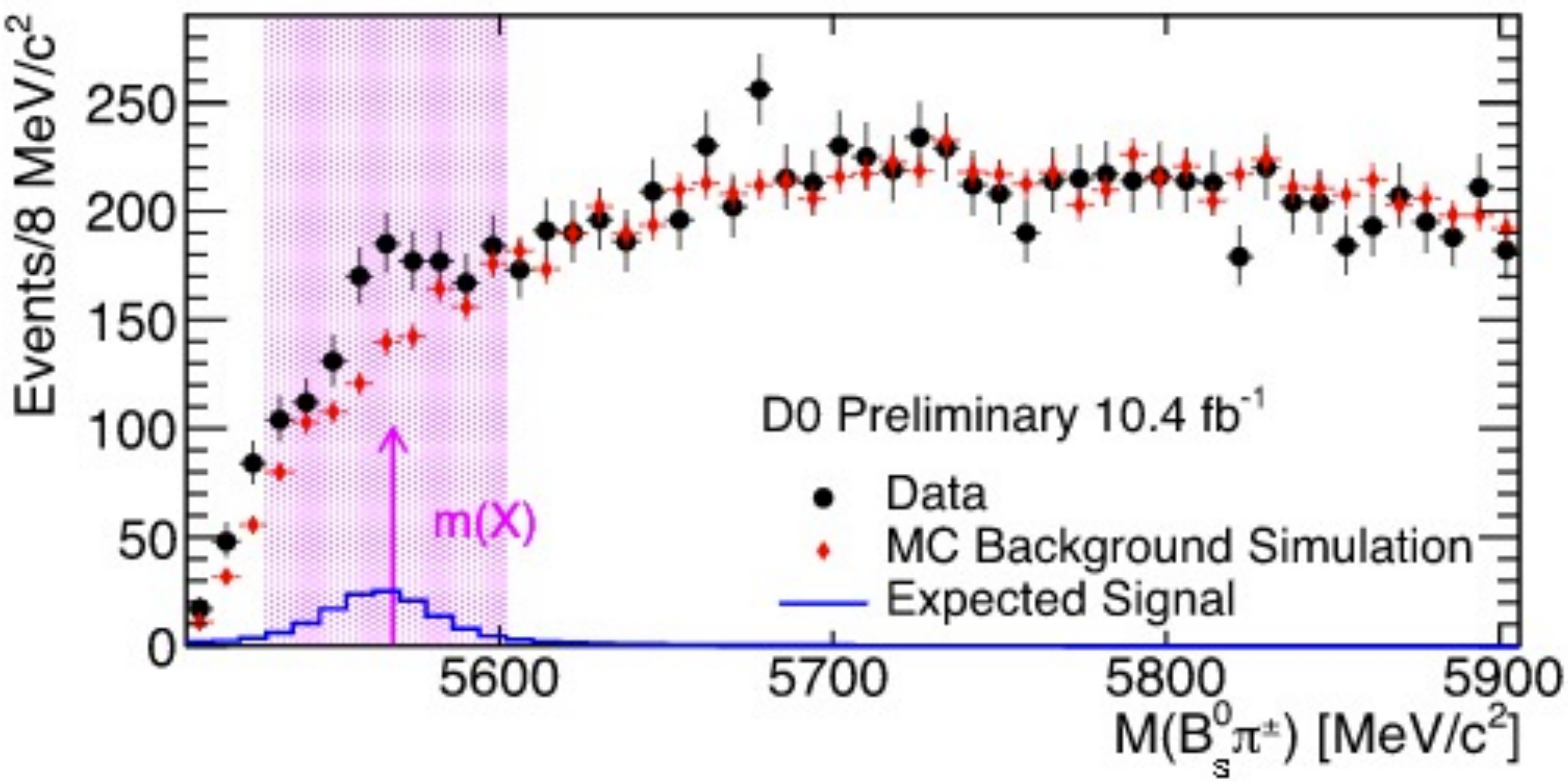
domingo, 11 de setembro de 16

New channel: $B_s^0\pi^\pm$, $B_s^0 \to D_s\mu\nu$

from D. Zieminska, ICHEP2016 talk



New: We see an enhancement in $m(B_s^0\pi^\pm)$ with $B_s^0 \to D_s\mu\nu$ at the same mass and at the expected width and rate.



Theoretical calculations

QCD sum rules: Agaev et al., arXiv:1602.08642; Chen et al., arXiv:1602.08916; Wang, arXiv:1602.08711; Chen et al., arXiv:1602.08916; Zanetti et al., arXiv:1602.09041; Agaev et al., arXiv:1603.00290; Dias et al., arXiv:1603.02249; Albuquerque et al., arXiv:1604.05566; ...

quark models: Wang & Zhu, arXiv:1602.08806; Liu et al., arXiv:1603.01131; Xiao & Chen, arXiv:1603.00228; Stancu, arXiv:1603.03322; Lu & Dong, arXiv:1603.06417; Chen & Ping, arXiv:1604.05615; Maiani et al., arXiv:1604.01731; ...

coupled channels: Albaladejo et al., arXiv:1603.09230

rescattering effects: Liu & Li., arXiv:1603.00708

more general arguments: Burns & Swanson, arXiv:1603.04366; Guo et al., arXiv:1603.06316

$X^{\pm}(5568)$

Tetraquark state

Agaev et al., arXiv:1602.08642; Chen et al., arXiv:1602.08916; Wang, arXiv:1602.08711; Tang & Qiao, arXiv:1603.04761

$B\bar{K}$ molecular state

Agaev et al., arXiv:1603.02708; Xiao & Chen, arXiv:1603.00228; Albaladejo et al., PLB757

mass not compatible with 4-q or mol.

Burns & Swanson, arXiv:1603.04366; Guo et al., arXiv:1603.06316; Zanetti et al., arXiv:1602.09041; Wang & Zhu, arXiv:1602.08806; Chen & Ping, arXiv:1604.05651; Maiani et al., arXiv:1604.01731; Lu & Dong, arXiv:1603.06417; Albuquerque et al., arXiv:1604.05566

Burns & Swanson (arXiv:1603.04366): could the signal be due to the fact that D0 detector cannot detect π^0 at low transverse momentum?

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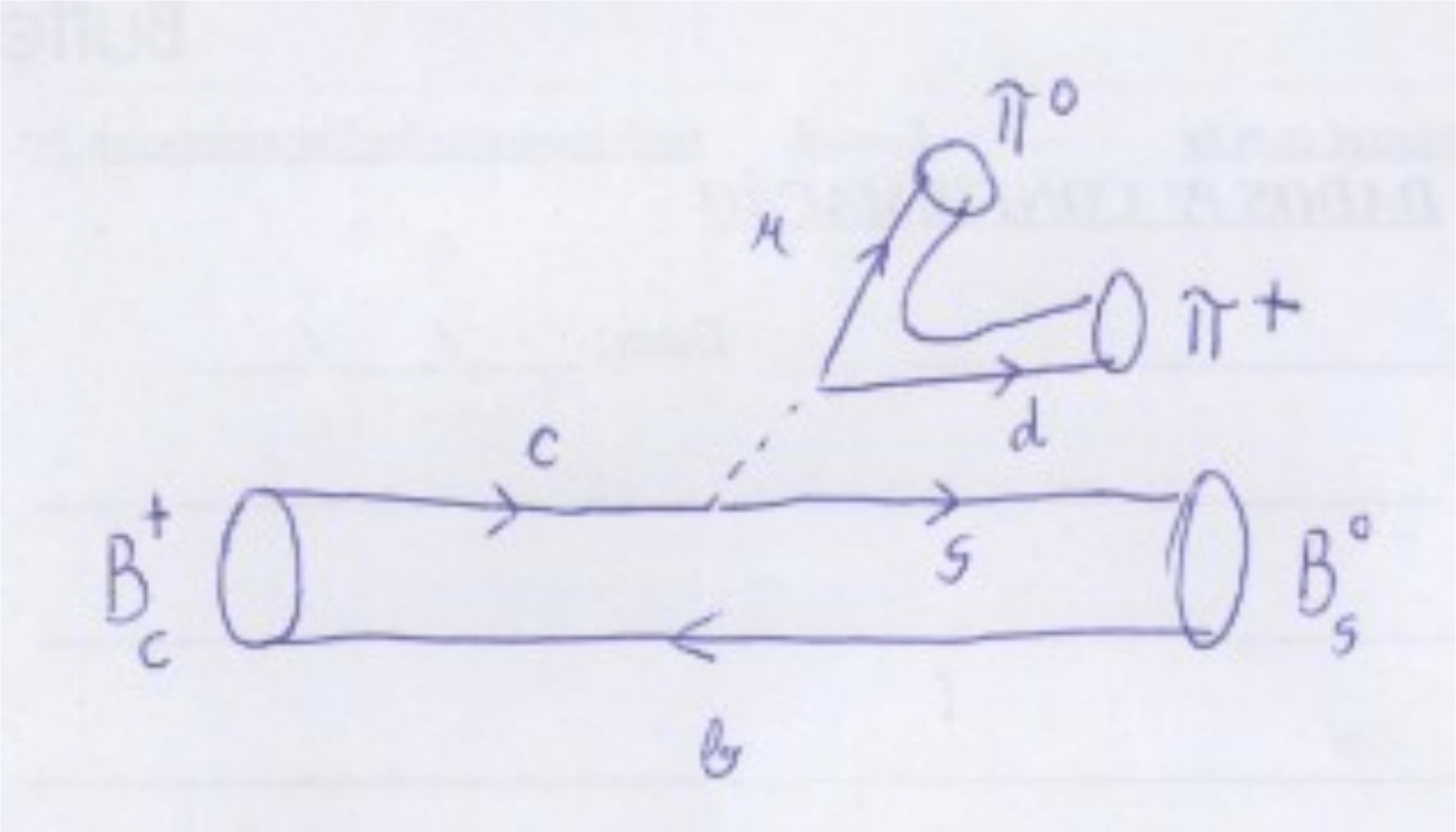
consider the weak decay: $B_c^+ \to B_s^0 \rho^+ \to B_s^0 \pi^+ [\pi^0]$



it naturally gives rise to a kink in the $B_s^0\pi^+$ spectrum near 5570 MeV

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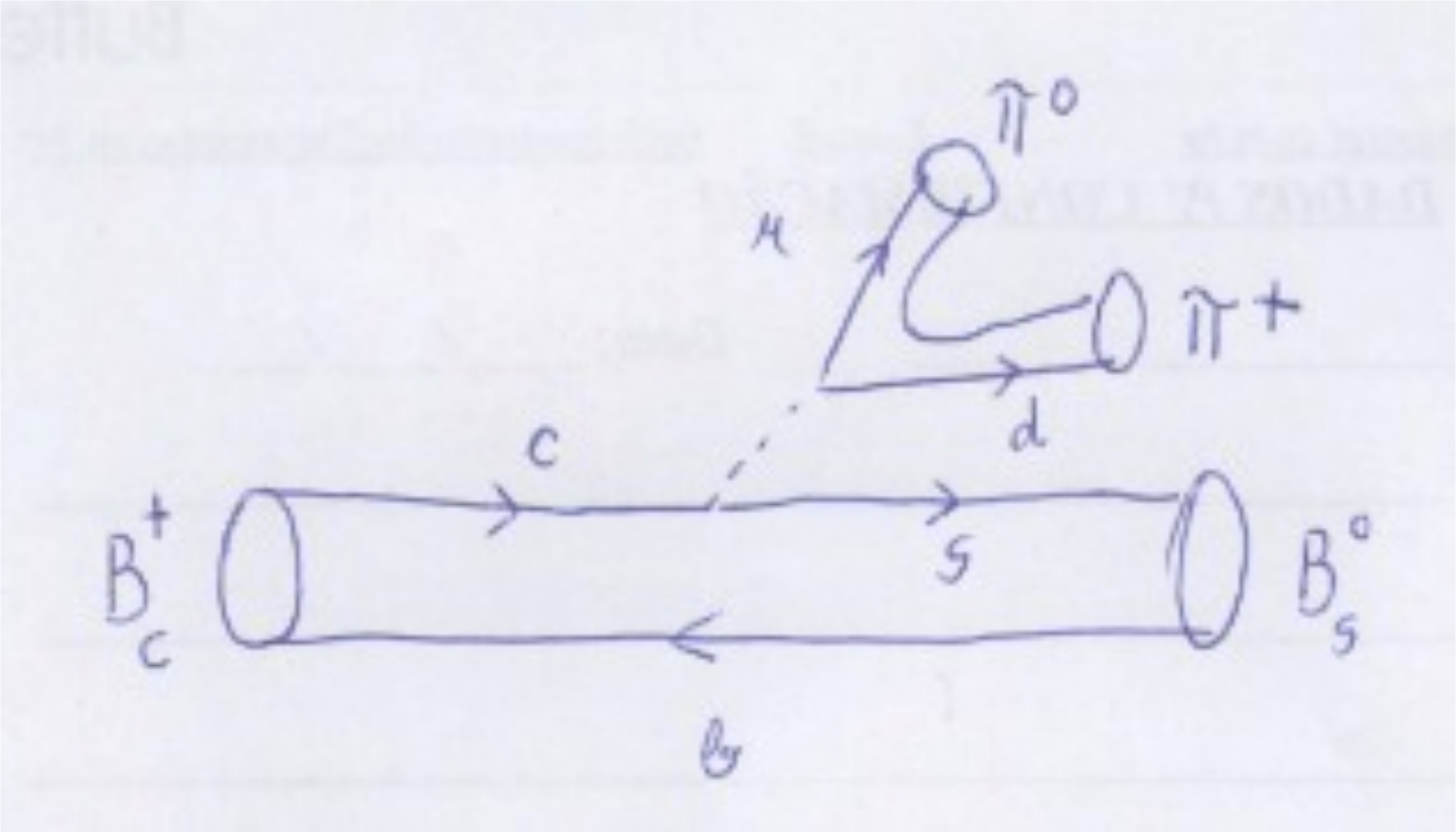

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What about LHCb and CMS detectors?

QCD Sum Rule

Fundamental Assumption: Principle of Duality

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

Theoretical side

quark level
quark and gluon
degrees of freedom

Wilson OPE

Phenomenological side

hadron level
hadron parameters
(masses, couplings,
form-factors,...)

dispersion relation

$$\Pi_i^{phen} \leftrightarrow \Pi_i^{OPE}$$

$$\Pi^{phen} = -\lambda^2 \frac{1}{m^2 - q^2} + continuum$$

$\lambda \Rightarrow$ coupling current-state

$$\Pi^{OPE}(q^2) = \int_{s_{min}}^{\infty} ds \; \frac{\rho^{OPE}(s)}{s - q^2}, \; \rho^{OPE}(s) = \frac{1}{\pi} Im[\Pi^{OPE}]$$

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$$continuum = \int_{s_0}^{\infty} ds \, \frac{\rho^{OPE}(s)}{s - q^2}$$

s_0: continuum parameter

$$\Pi^{phen}(Q^2) \leftrightarrow \Pi^{OPE}(Q^2)$$

valid at small Q^2

valid at large Q^2

To improve the matching $\Rightarrow$ Borel transform

Borel Transform $\left\{ \begin{array}{l} \text{eliminates subtraction terms} \\ \text{suppresses higher order condensates} \\ \text{increases importance pole contribution} \end{array} \right.$

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

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

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

Good Sum Rule ➡ Borel window such that:

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

OPE side: condensates
up to dimention 6

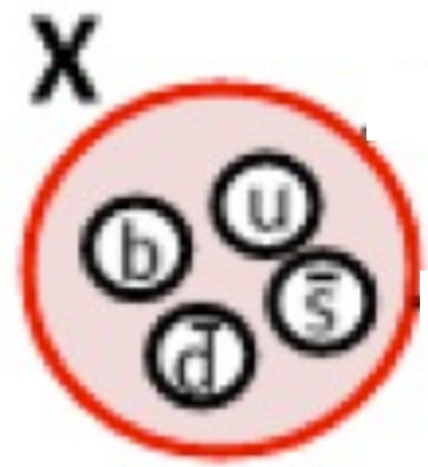
$\left\{ \begin{array}{l} \text{quark condensate} \\ \text{gluon condensate} \\ \text{mixed condensates} \\ \text{four-quark condensate.} \end{array} \right.$

QCDSR calculation for $X^+(5568)$ mass

Khemchandani, MN, Zanetti: arXiv:1602.09041

tetraquark current with $J^P = 0^+$

$$j_X = \varepsilon_{abc}\varepsilon_{dec}\left(u_a^T C\gamma_5 b_b\right)\left(\bar{d}_d\gamma_5 C\bar{s}_e^T\right)$$



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

$$\Pi(x) = f\left(S^u(x)S^d(-x)S^s(x)S^b(-x)\right)$$

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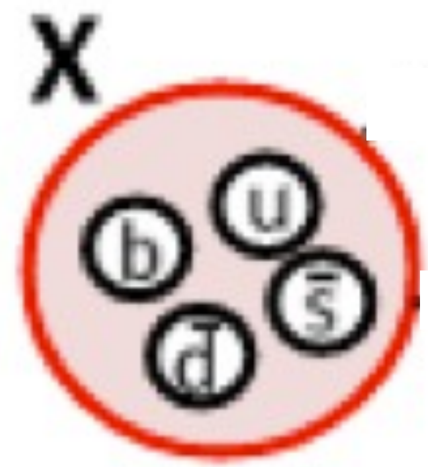

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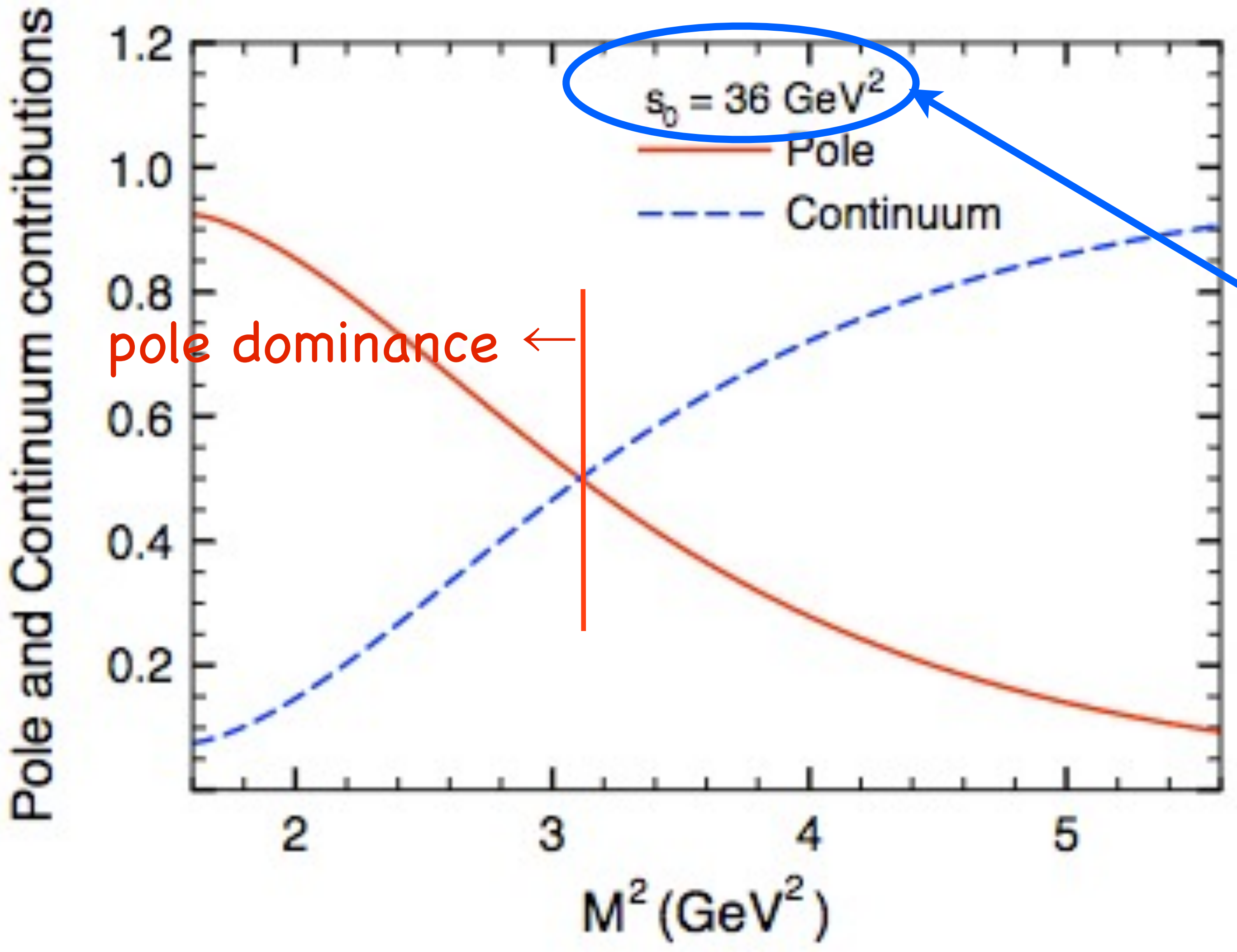
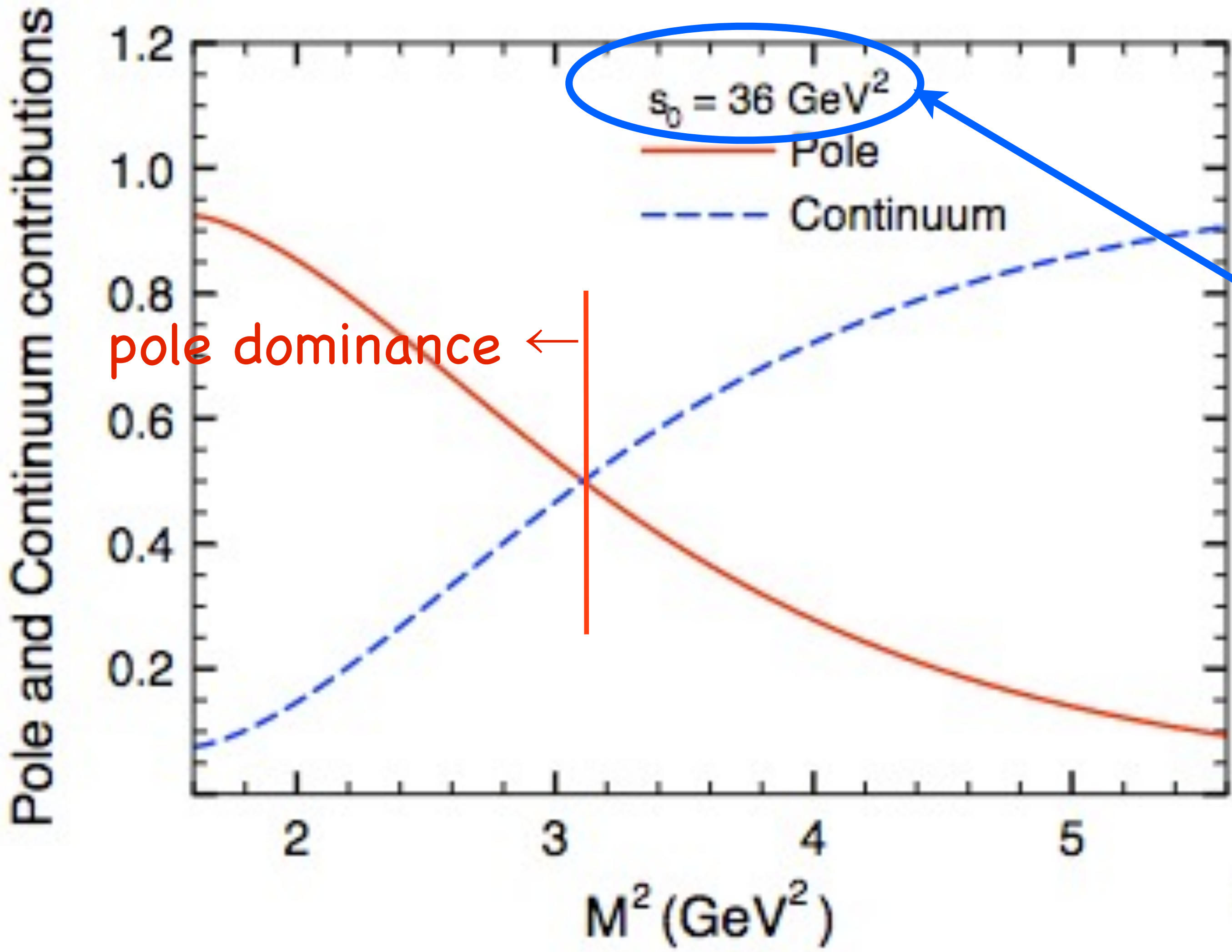
OPE for the quark propagator



Khemchandani, MN, Zanetti: arXiv:1602.09041

s_0? In general $s_0 = (m_X + 0.5\ \text{GeV})^2$



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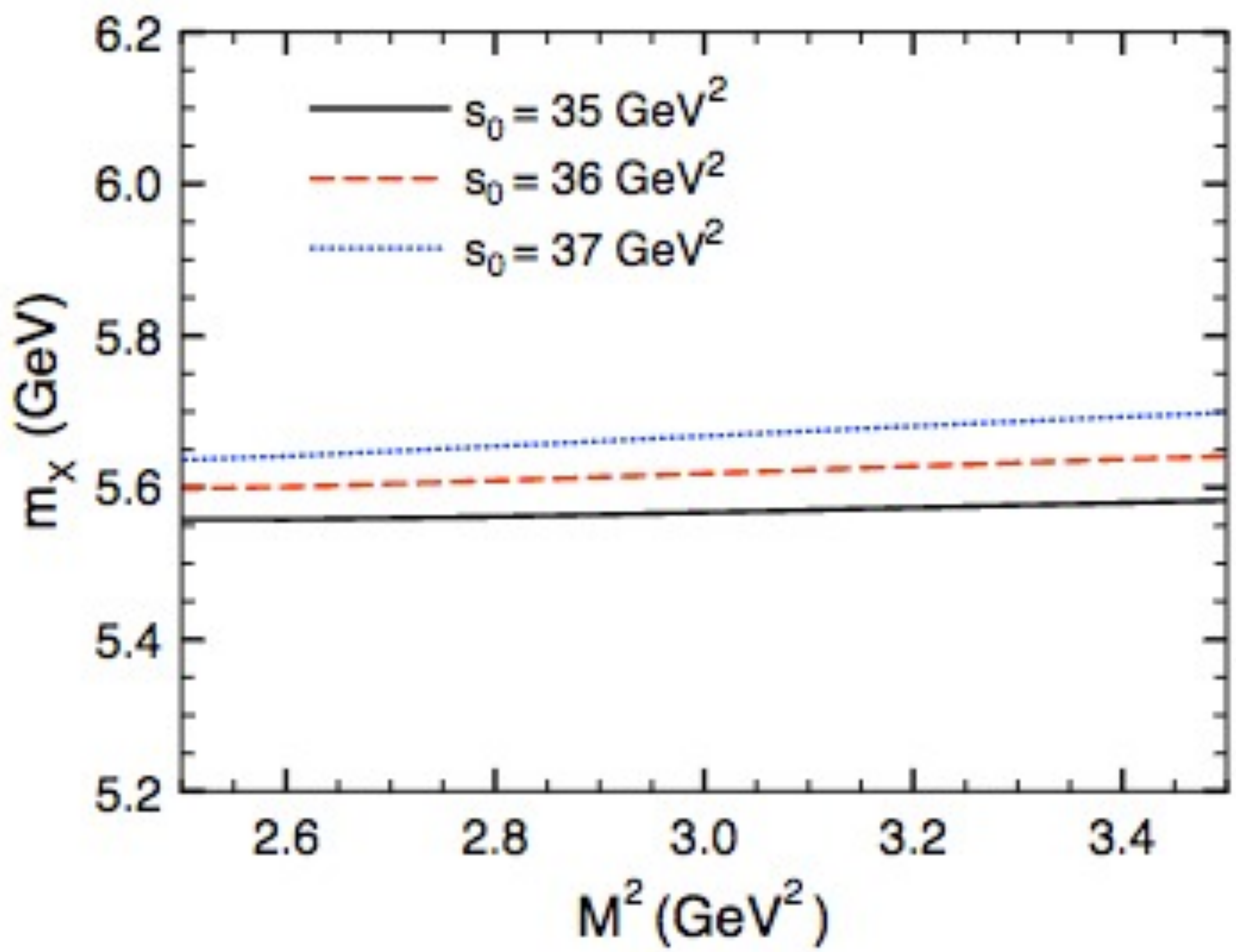
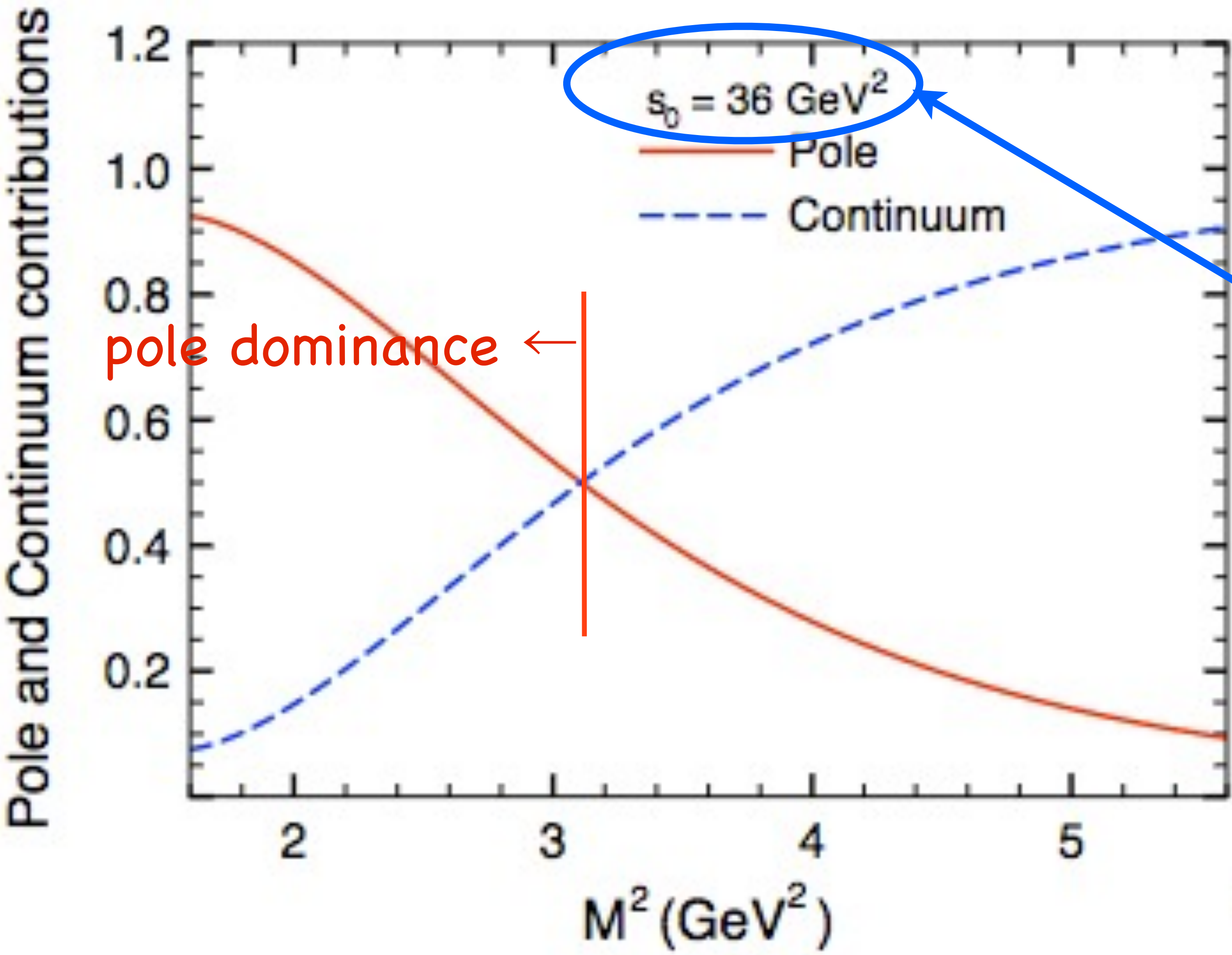


$m_X = (5.58 \pm 0.17)\,\mathrm{GeV}$



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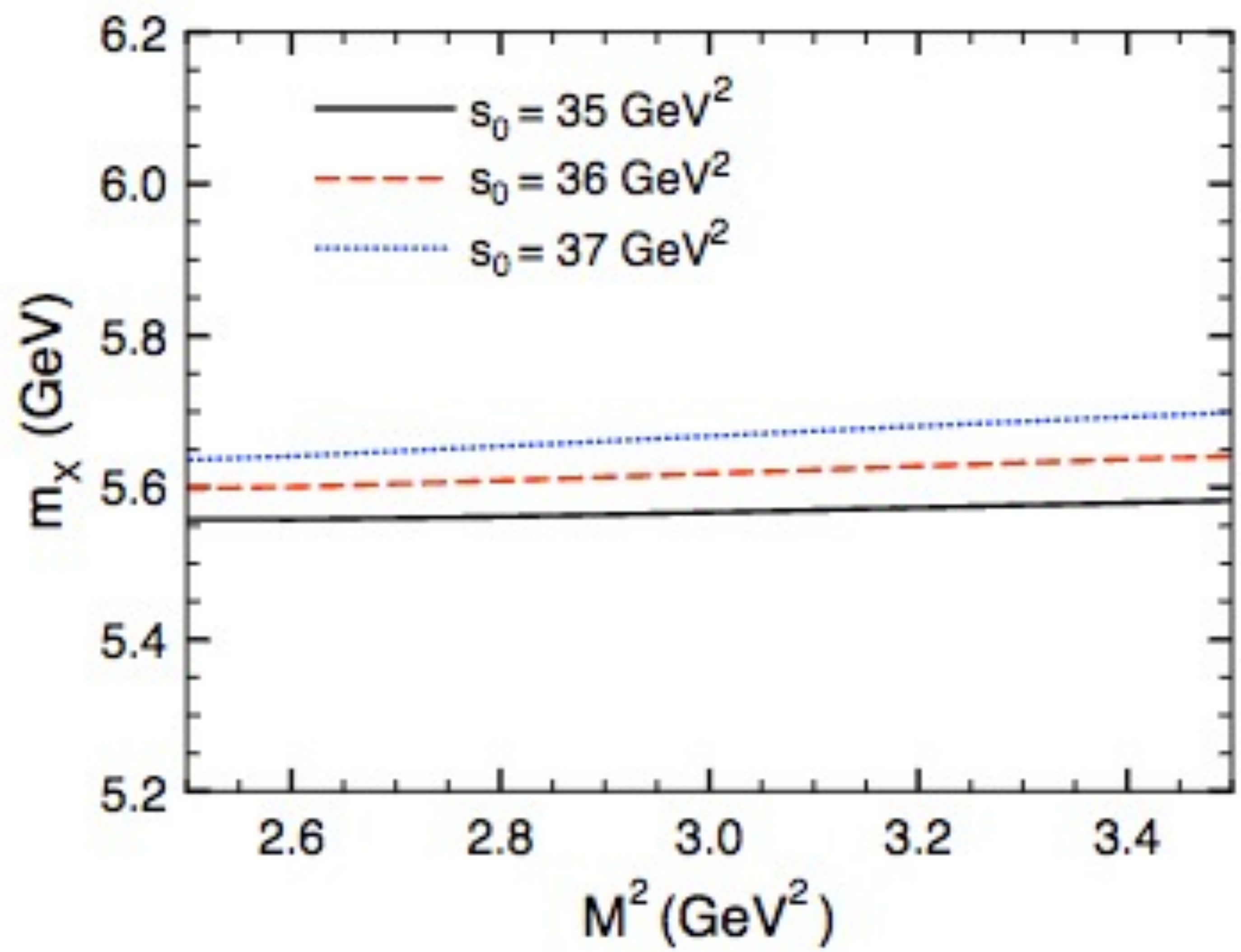

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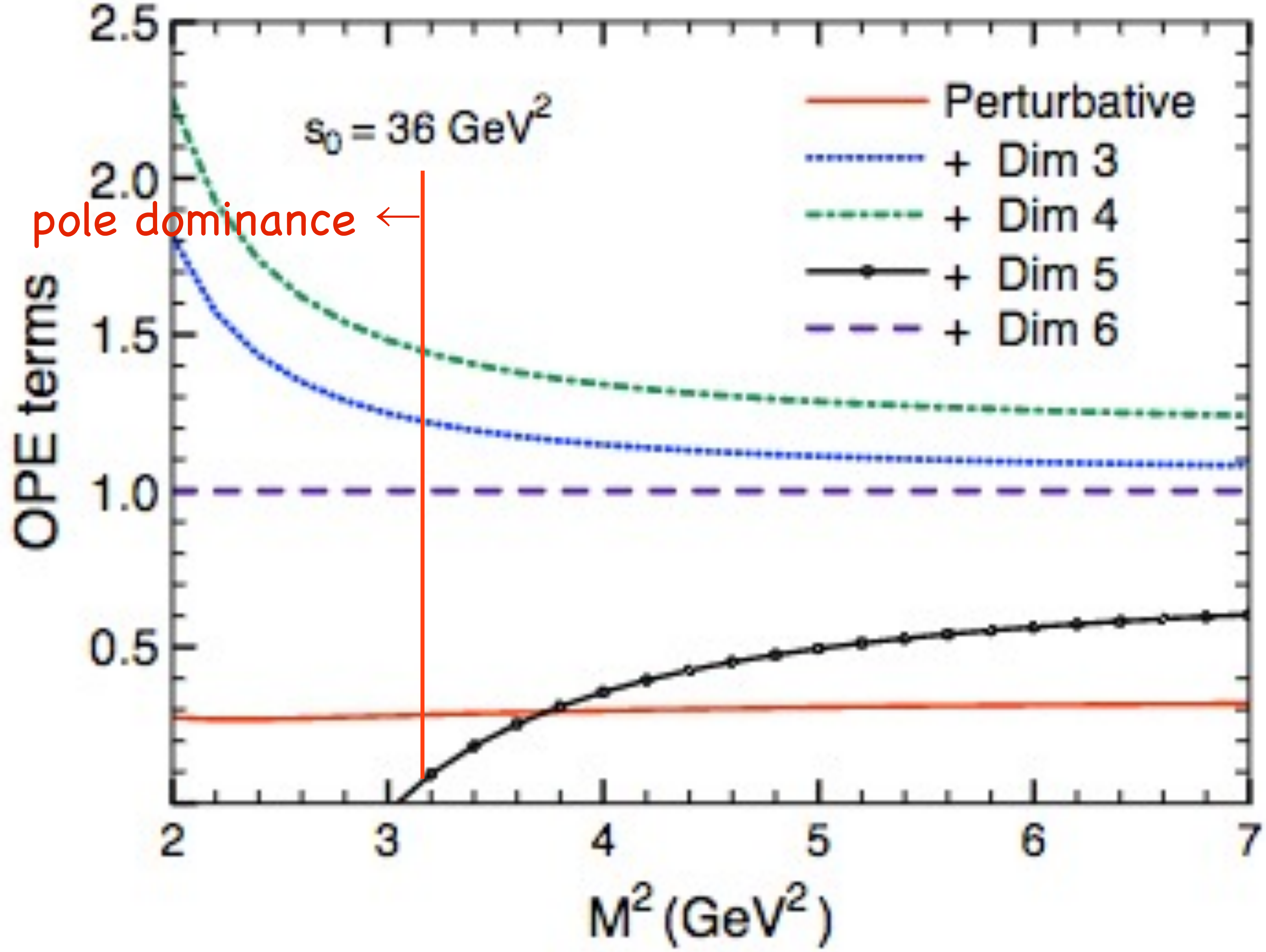
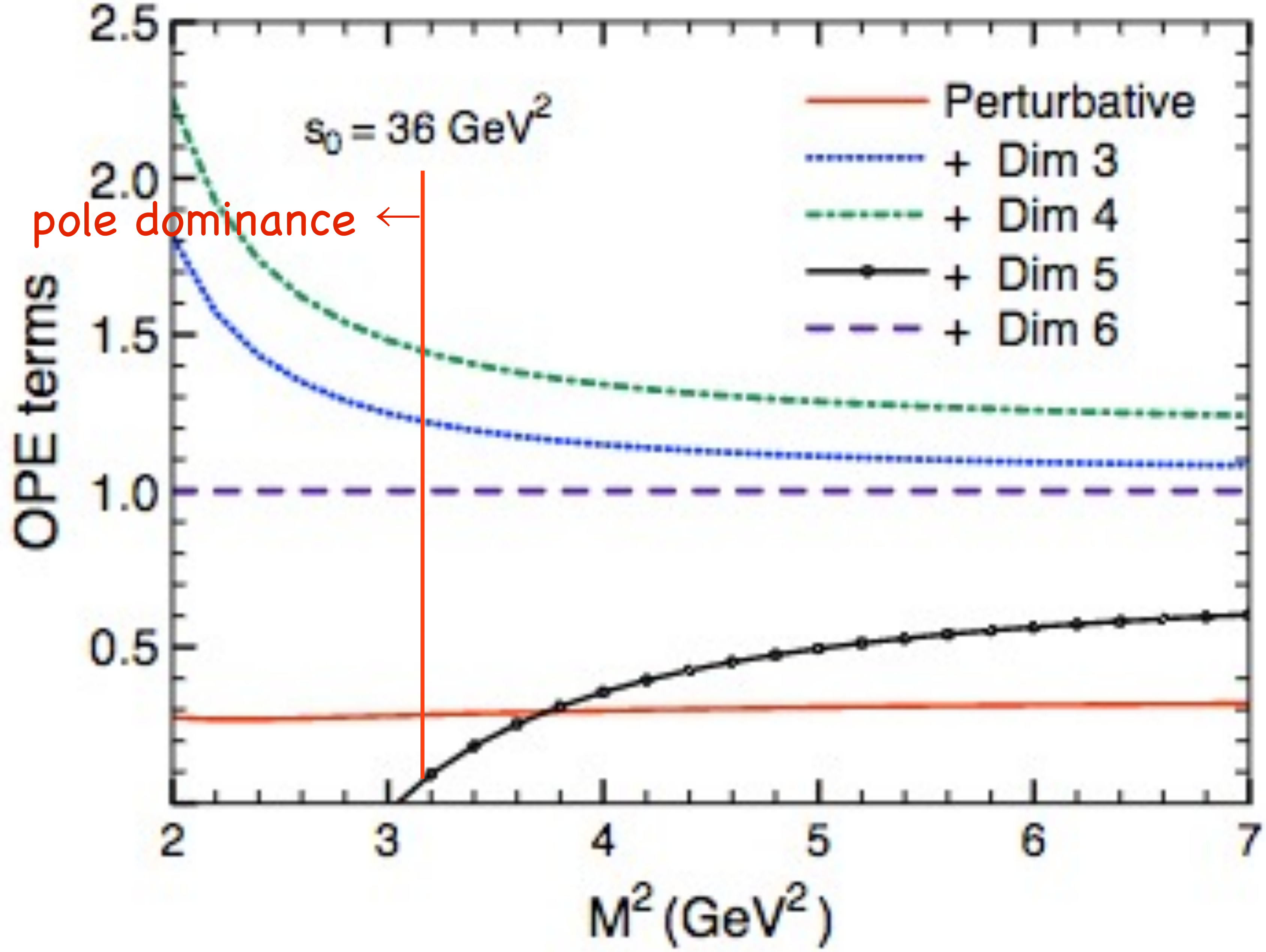
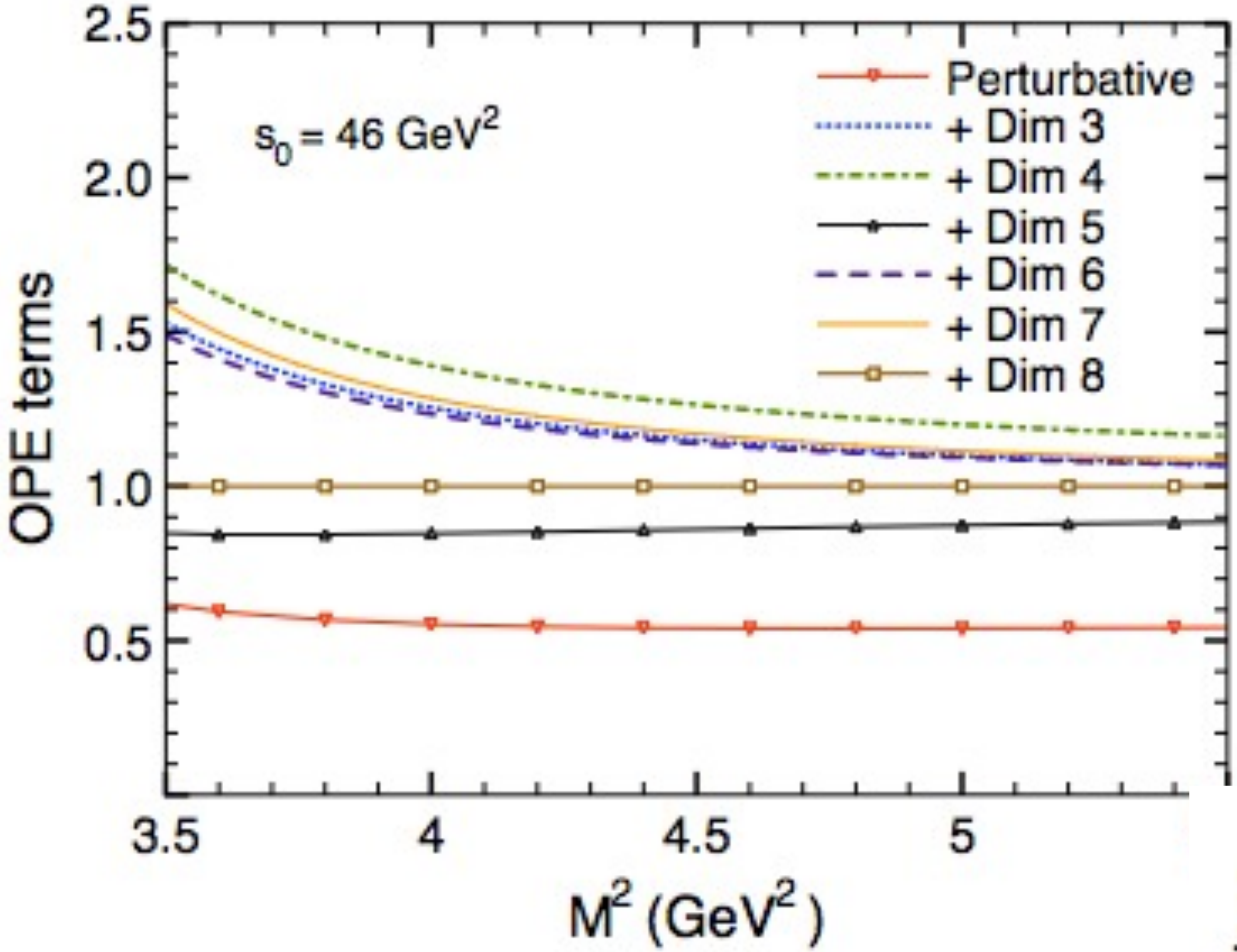
OPE convergence?



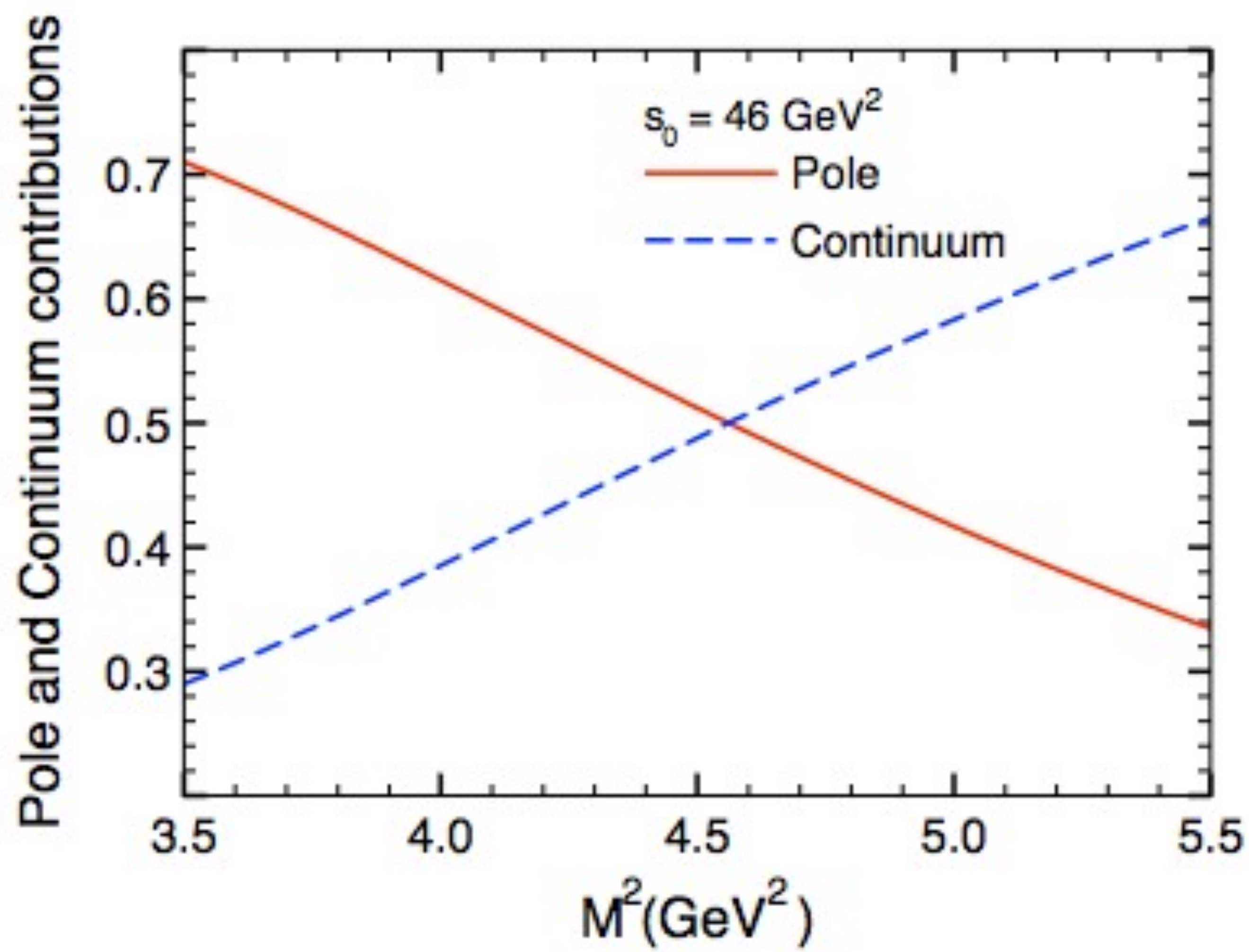
pole dominance
$s_0 = 36\ GeV^2$
Perturbative
+ Dim 3
+ Dim 4
+ Dim 5
+ Dim 6
OPE terms
$M^2\ (GeV^2)$



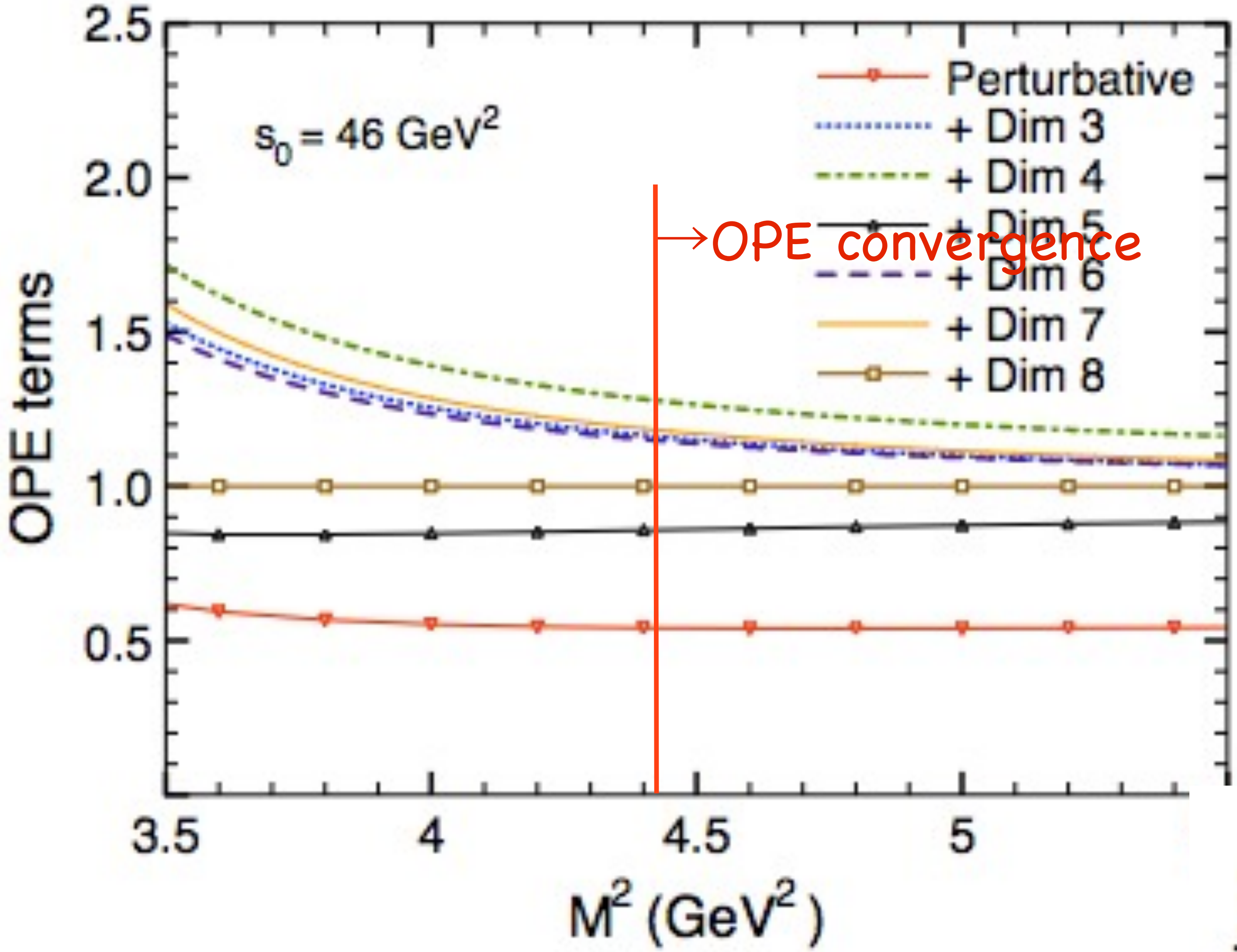
No OPE convergence for $s_0 < 46$ GeV^2



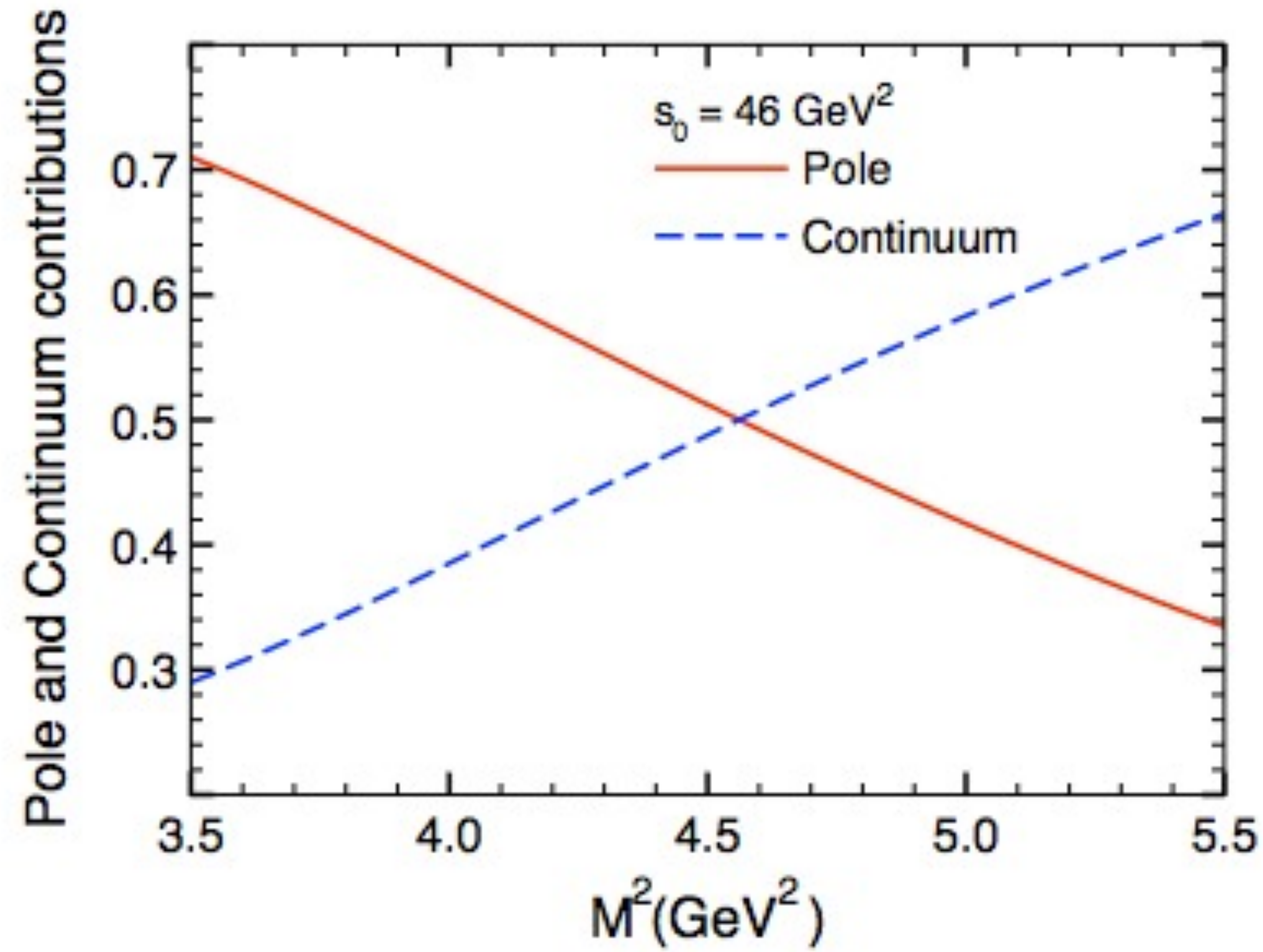
$s_0 = 46$ GeV^2
Perturbative
+ Dim 3
+ Dim 4
+ Dim 5
+ Dim 6
+ Dim 7
+ Dim 8
OPE terms
M^2 (GeV^2)



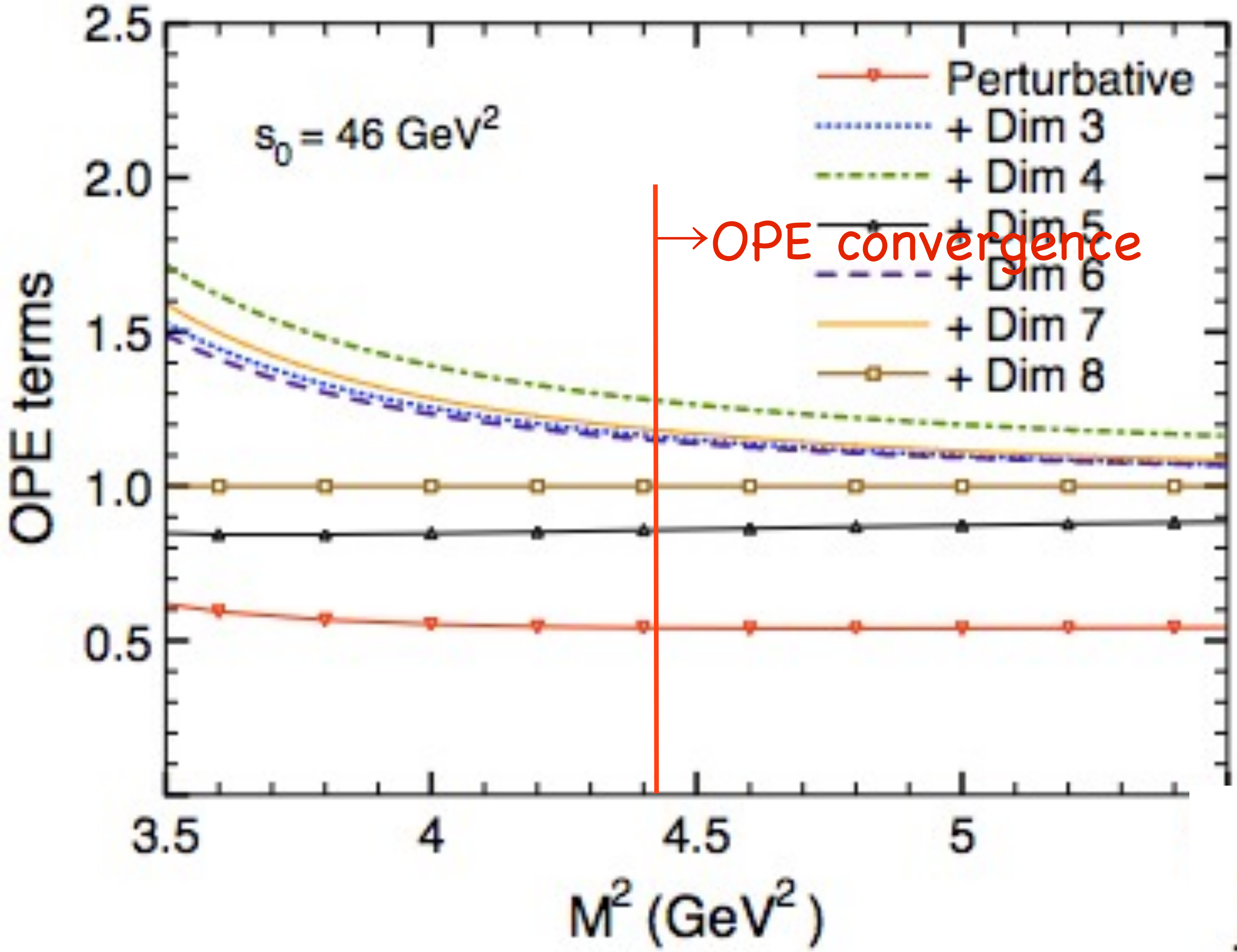
$s_0 = 46$ GeV^2
Pole
Continuum
Pole and Continuum contributions
M^2(GeV^2)



OPE terms
$s_0 = 46\ GeV^2$
Perturbative
+ Dim 3
+ Dim 4
+ Dim 5
+ Dim 6
+ Dim 7
+ Dim 8
OPE convergence
$M^2\ (GeV^2)$



Pole and Continuum contributions
$s_0 = 46\ GeV^2$
Pole
Continuum
$M^2(GeV^2)$



OPE terms
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+ Dim 3
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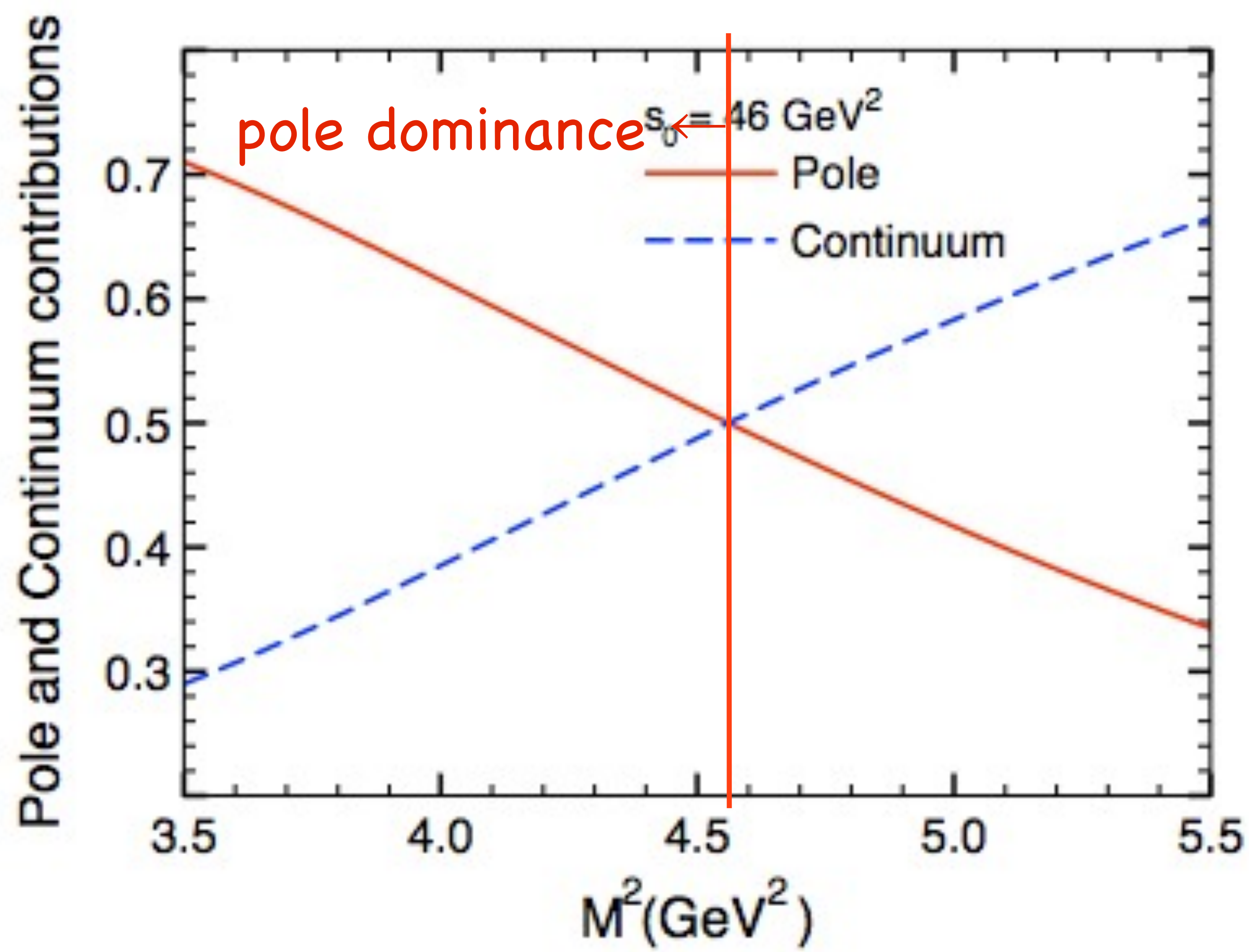
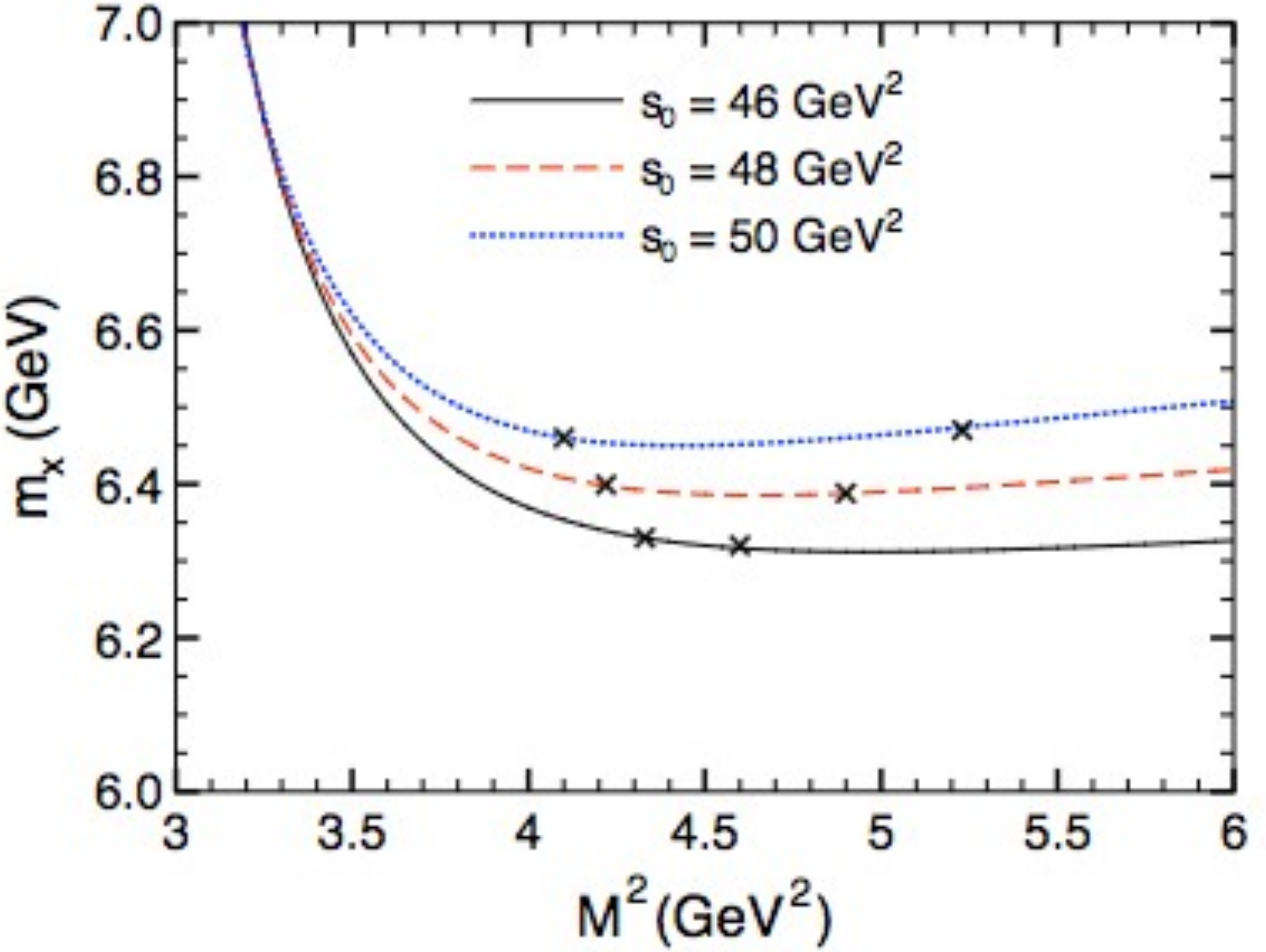
→OPE convergence
$M^2\ (GeV^2)$

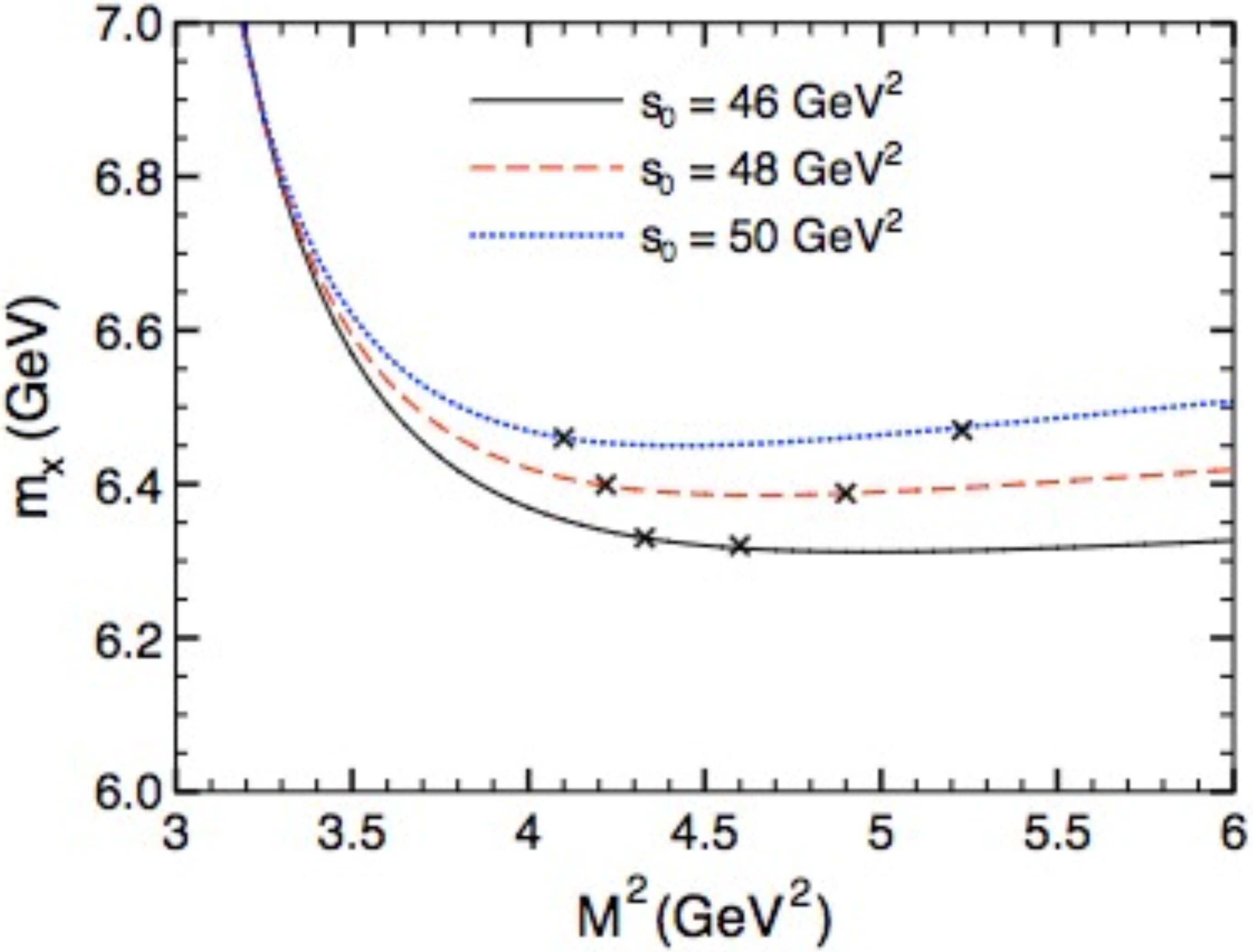


Pole and Continuum contributions
pole dominance←
$s_0 = 46\ GeV^2$
Pole
Continuum
$M^2(GeV^2)$



m_X=(6.39 ± 0.10)GeV

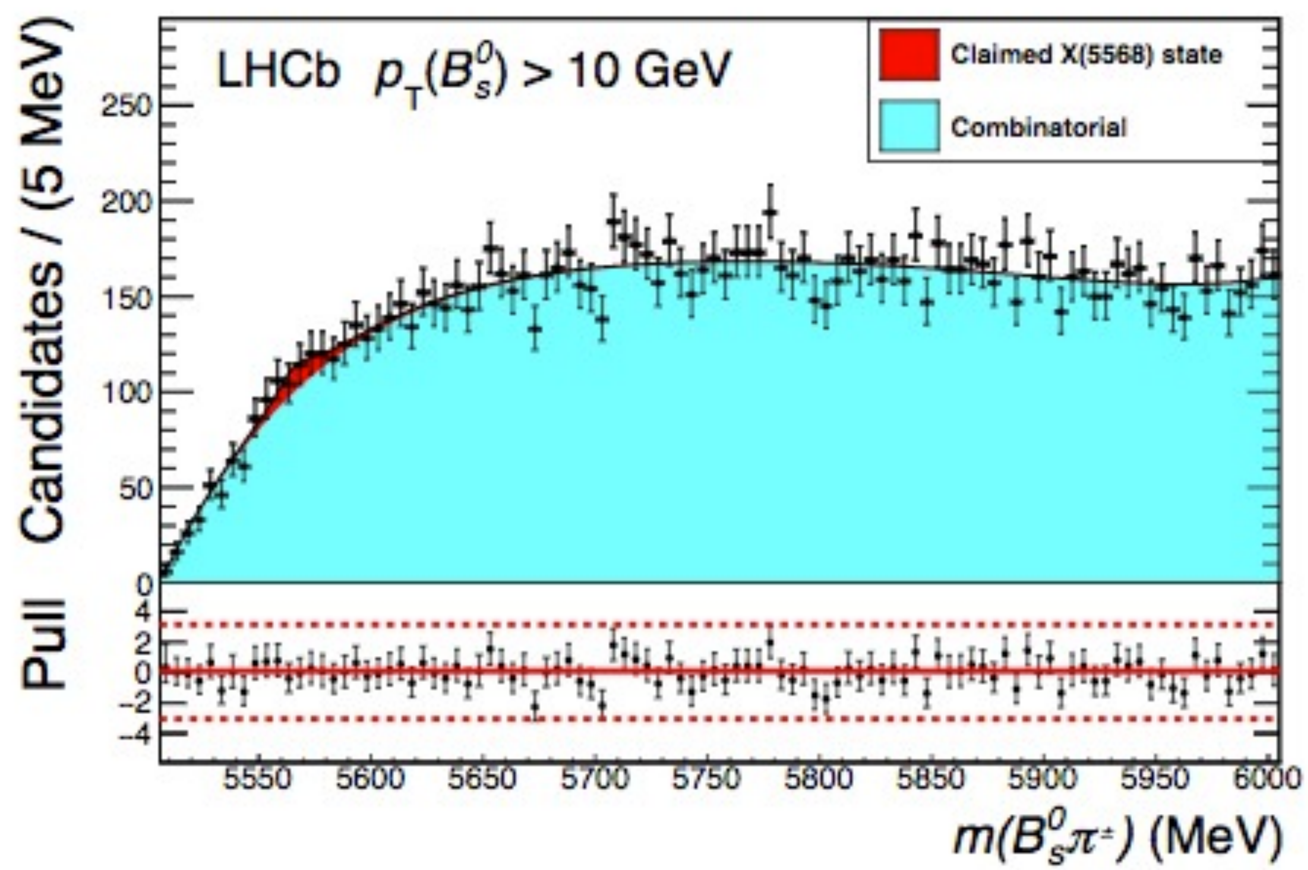
not compatible with X(5568) mass, but



m_X=(6.39 ± 0.10)GeV

not compatible with X(5568) mass, but

not excluded by LHCb data



Decay width $X^{\pm} \to B_s^0 \pi^{\pm}$

Dias, Khemchandani, Martínez Torres, MN, Zanetti: arXiv:1603.02249

$$\Gamma_\mu(p,p',q) = \int d^4x \int d^4y e^{ip'.x} e^{iq.y} \langle 0|T[j_{B_s^0}(x) j_{5\mu}^{\pi}(y) j_X^{\dagger}(0)]|0\rangle$$

$$j_{B_s^0} = i\bar{b}_a \gamma_5 s_a$$

$$j_{5\mu}^{\pi} = \bar{d}_a \gamma_\mu \gamma_5 u_a$$

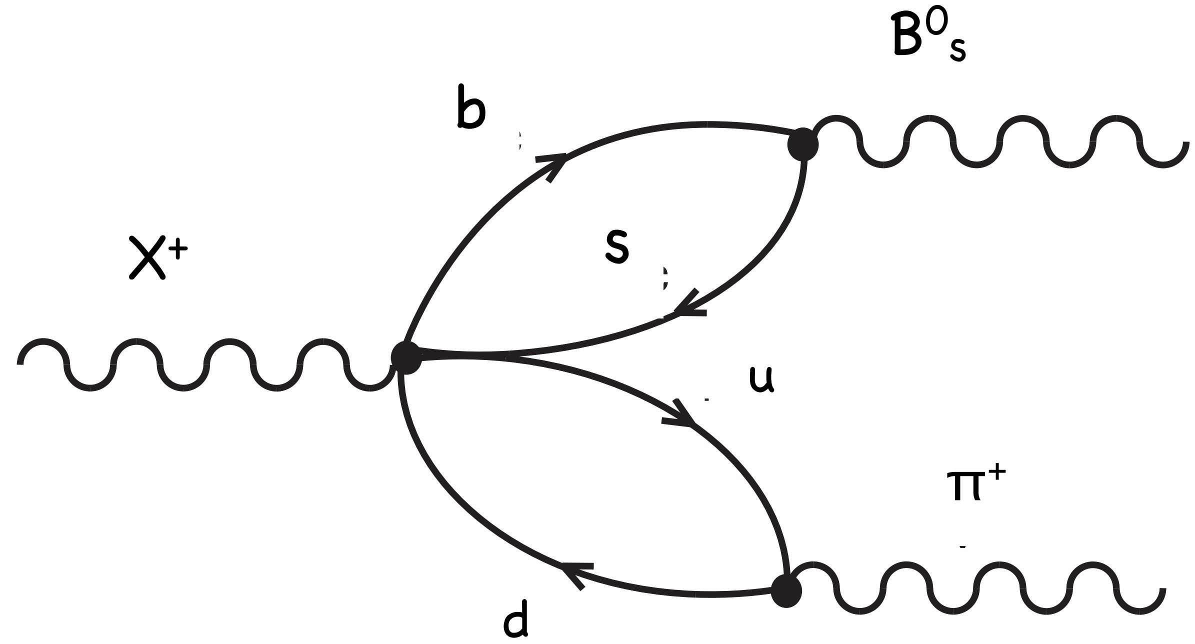
$$j_X = \varepsilon_{abc}\varepsilon_{dec} \left(u_a^T C\gamma_5 s_b\right) \left(\bar{b}_d \gamma_5 C \bar{d}_e^T\right)$$

Problem: due to Fierz transf. tetraquark currents can be written as a sum of molecular currents with trivial color configurations

$$j_X = \varepsilon_{abc}\varepsilon_{dec} \left(u_a^T C\gamma_5 s_b\right) \left(\bar{b}_d \gamma_5 C \bar{d}_e^T\right) \quad \} \text{ tetraquark}$$

$$= \sum_{\Gamma\ \Gamma'} g_{\Gamma\Gamma'} \left(\bar{b}_a\ \Gamma\ s_a\right) \left(\bar{d}_b\ \Gamma'\ u_b\right) \quad \} \text{ mesons}$$

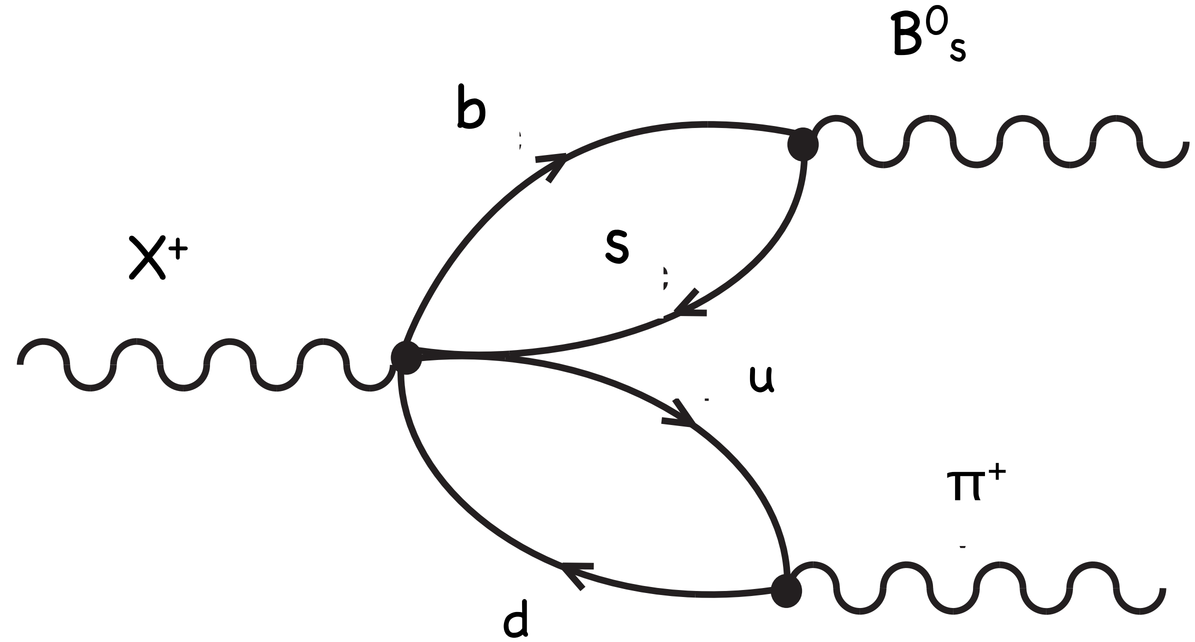
with mesonic currents the decay can proceed directly through the fall apart in its components



fall apart decays should not be possible with tetraquark currents with color entanglement

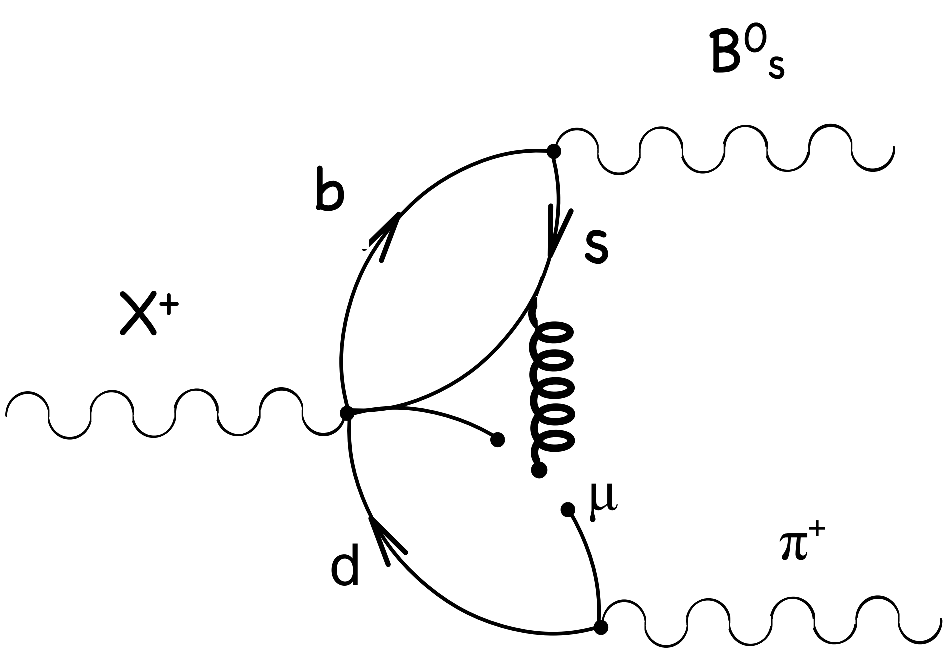
How to solve this problem?

with mesonic currents
the decay can proceed
directly through the fall
apart in its components



fall apart decays should not be possible with tetraquark currents with color entanglement

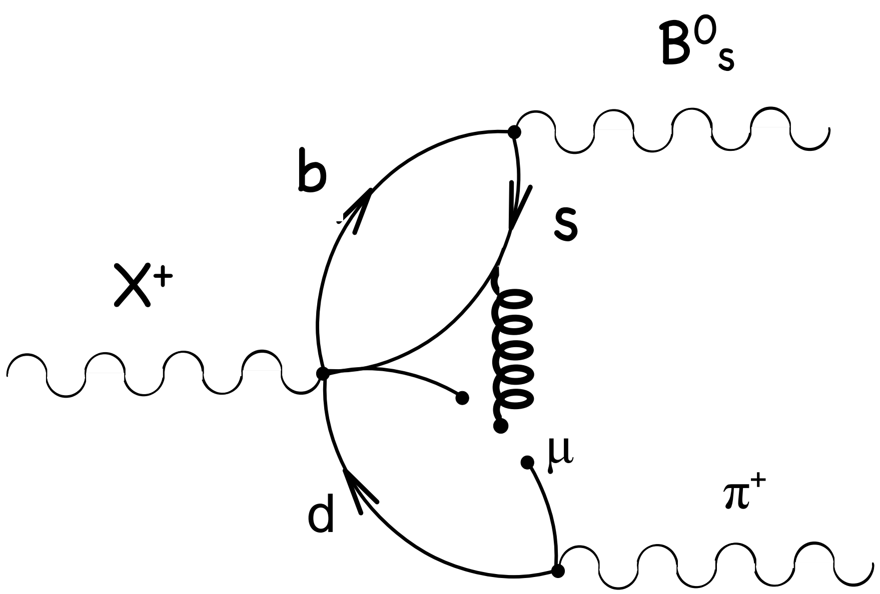
How to solve this problem?



require color exchange during the decay

If X+(5568) is a genuine tetraquark state, only color-conected diagrams will contribute

OPE side



Phen. side

$$\Gamma^{phen}(p^2,p'^2) = \frac{\lambda_X m^2_{B_{s0}} f_{B_{s0}} F_\pi \, g_{X B_{s0}\pi}}{(m_b+m_s)(p^2-m_X^2)(p'^2-m^2_{B^0_s})} + \int_{m_b^2}^{\infty} \frac{\rho_{cont}(p^2,u)}{u-p'^2}\, du.$$

from the 2-point QCDSR

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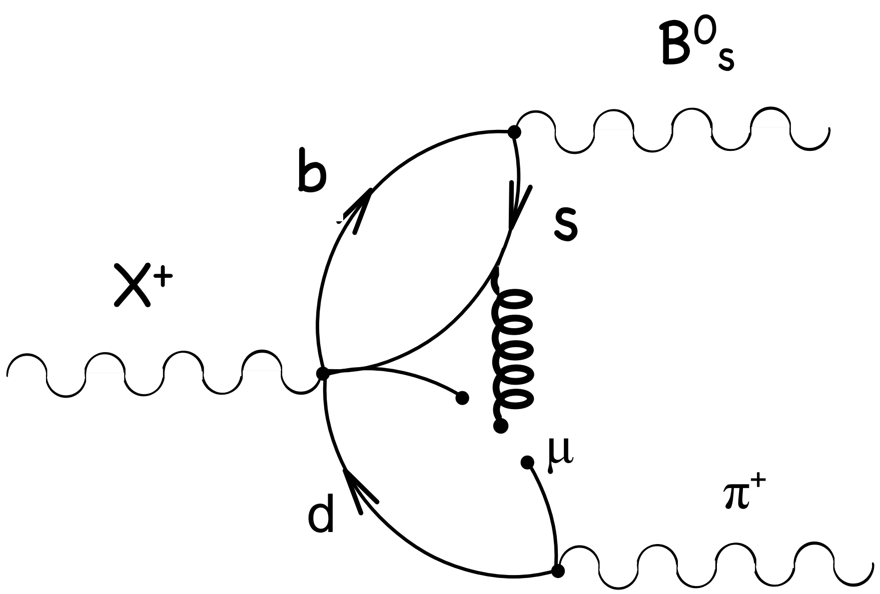
OPE side

Phen. side



$$\Gamma^{phen}(p^2,p'^2)=\frac{\lambda_X m^2_{B_{s0}} f_{B_{s0}} F_\pi g_{XB_{s0}\pi}}{(m_b+m_s)(p^2-m_X^2)(p'^2-m^2_{B_s^0})}+\int_{m_b^2}^{\infty}\frac{\rho_{cont}(p^2,u)}{u-p'^2}du.$$

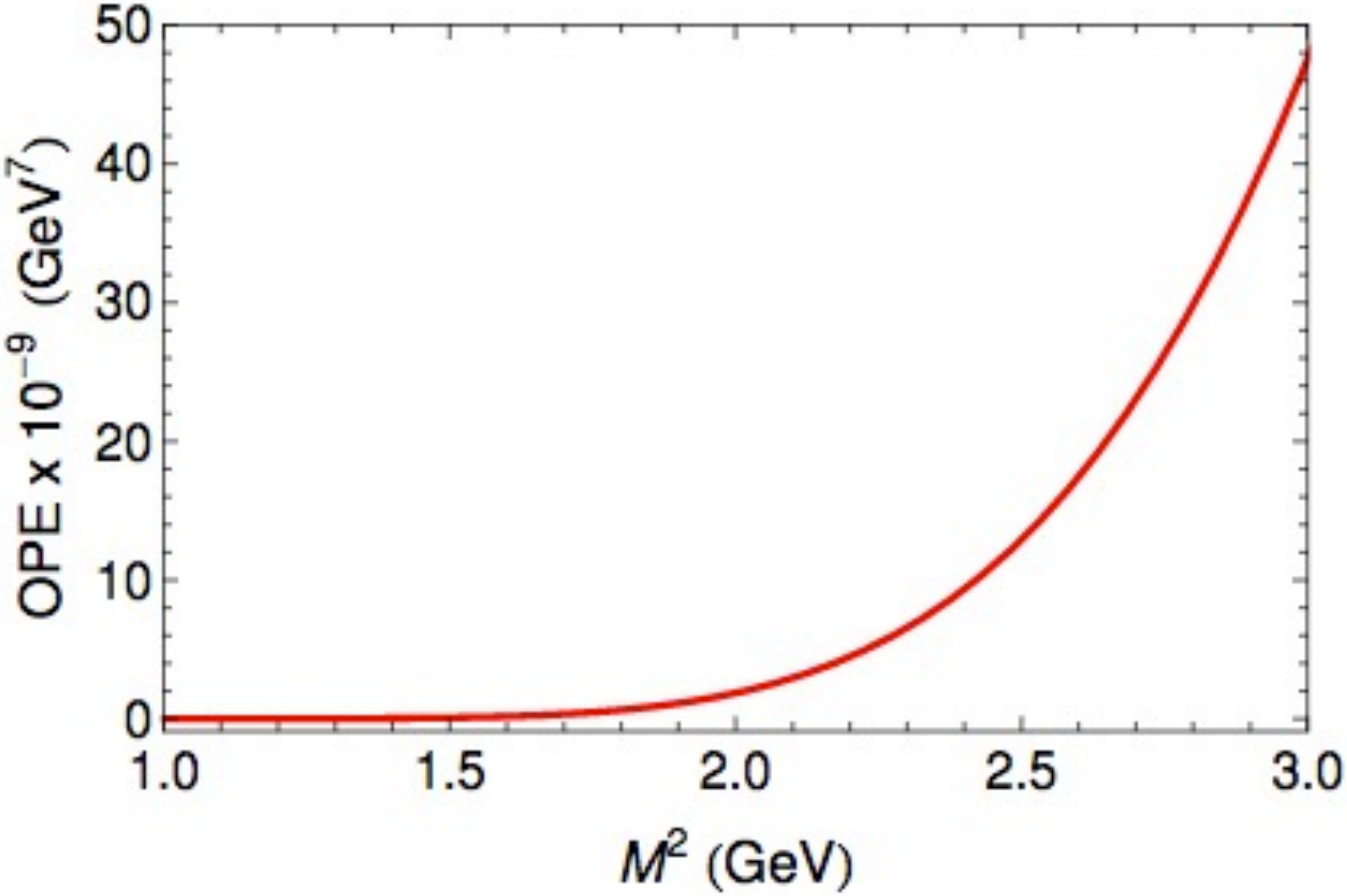
from the 2-point QCDSR

$$\Gamma(X(5568)\to B_s^0\pi^+)=\frac{g^2_{XB_s^0\pi}}{16\pi m_X^3}\sqrt{\lambda(m_X^2,m^2_{B_s^0},m_\pi^2)}.$$

coupling constant

OPE side: $$\frac{\langle\bar{q}g\sigma.Gq\rangle}{2^5\pi^2}\int_{m_b^2}^{u_0}\left(\frac{2}{3}-\frac{m_b^2}{u}\right)e^{-u/M^2}$$

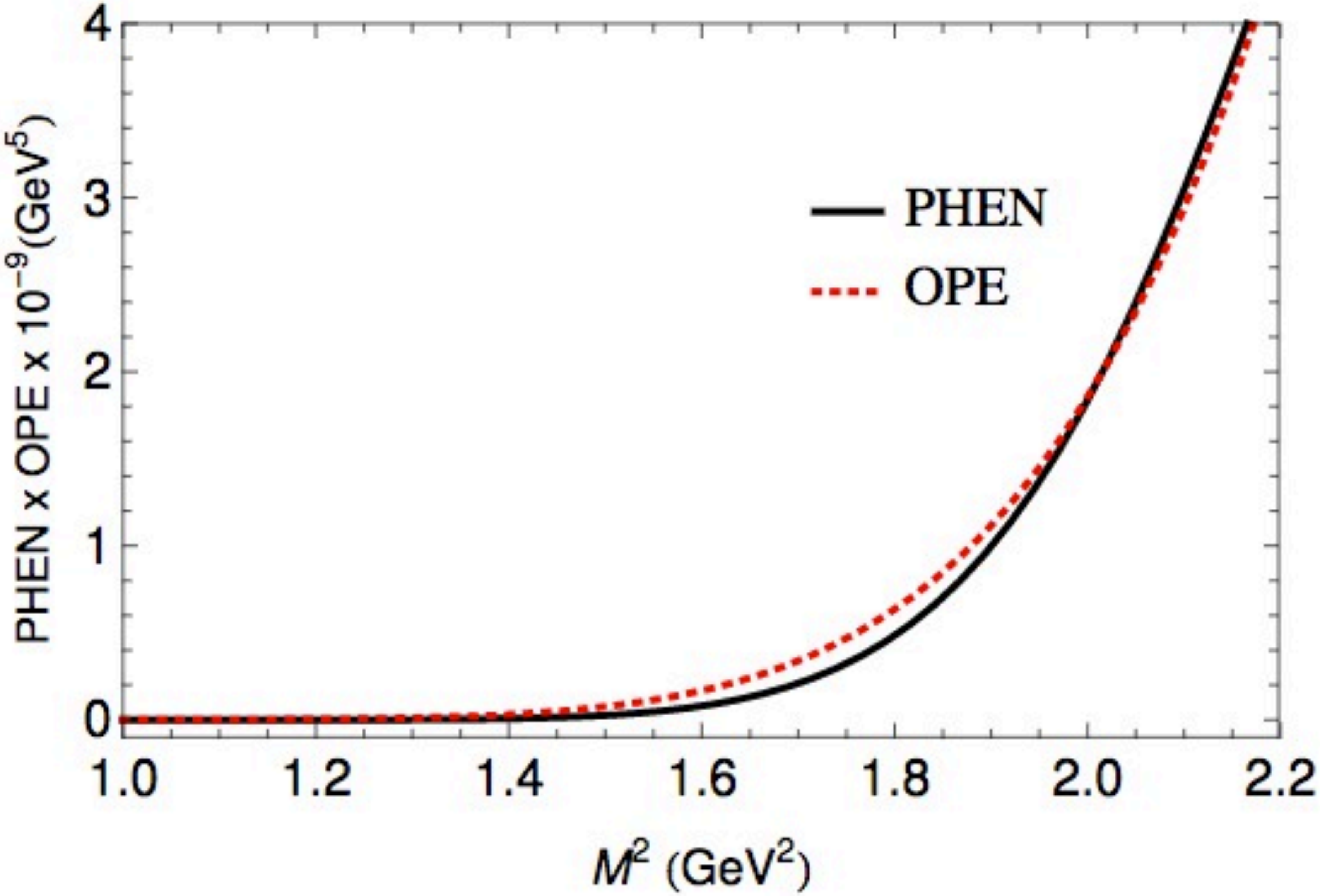
$u_0 = M_X^2$



very stable in the range: $1.0 \leq M^2 \leq \ 2.2\ \mathrm{GeV}^2$

Phen. side   OPE side

$$C\left(e^{-m^2_{B^0_s}/M^2} - e^{-m^2_X/M^2}\right) + A\, e^{-s_0/M^2} = \frac{\langle \bar{q} g \sigma.G q\rangle}{2^5\pi^2}\int_{m_b^2}^{u_0}\left(\frac{2}{3} - \frac{m_b^2}{u}\right) e^{-u/M^2}$$

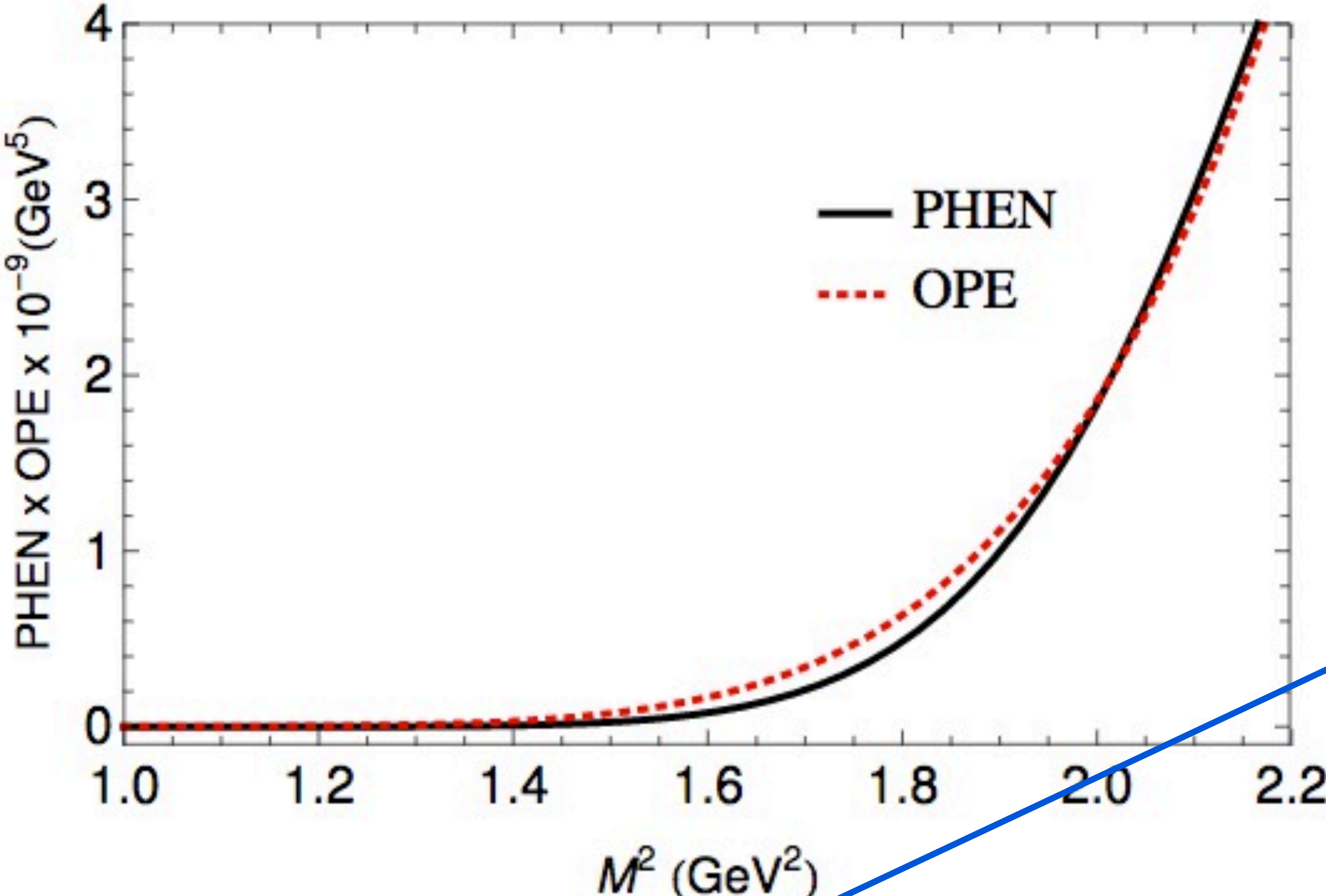


$$C = \frac{\lambda_X m^2_{B^0_s} f_{B^0_s} F_\pi\, g_{X B^0_s \pi}}{(m_b + m_s)(m_X^2 - m^2_{B^0_s})}$$

Dias, Khemchandani, Martínez Torres, MN, Zanetti: arXiv:1603.02249

Phen. side | OPE side

$$C\left(e^{-m_{B_s^0}^2/M^2} - e^{-m_X^2/M^2}\right) + A\, e^{-s_0/M^2} = \frac{\langle \bar{q} g\sigma.G q\rangle}{2^5\pi^2}\int_{m_b^2}^{u_0}\left(\frac{2}{3} - \frac{m_b^2}{u}\right) e^{-u/M^2}$$



$$C = \frac{\lambda_X m_{B_s^0}^2 f_{B_s^0} F_\pi\, g_{XB_s^0\pi}}{(m_b+m_s)(m_X^2 - m_{B_s^0}^2)}$$

using m_X=5568 MeV we get: $g_{XB_S^0\pi} = (10.3 \pm 2.3)\,\text{GeV}$

using the results from a trustable QCDSR:
m_X=(6.39±0.10) GeV and s_0=(48±2) GeV^2 we get:

$$g_{XB_s^0\pi} = (5.7 \pm 0.8)\ \text{GeV},$$

$$\Gamma(X^{\pm}(5568) \to B_s^0\pi^{\pm}) = (20.4 \pm 8.7)\ \text{MeV}$$
$$\Gamma(X^{\pm}(6390) \to B_s^0\pi^{\pm}) = (30.1 \pm 8.6)\ \text{MeV}$$

but this is not the total width since there are more open channels now (BK, B*K*, $B_s\rho^+$)!

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$$\Gamma^{exp} = 21.9 \pm 6.4(\text{sta})^{+5.0}_{-2.5}(\text{syst})\ \text{MeV}$$

compatible with exp. width, but...

Conclusions

- Lots of exotic states in the last years: a new spectroscopy?
- Discovery of $X^{+}(5568)$ represents a challenge
- We need better bounds in the experimental reports