Workshop on "Flavour changing and conserving processes" 2025 (FCCP2025)

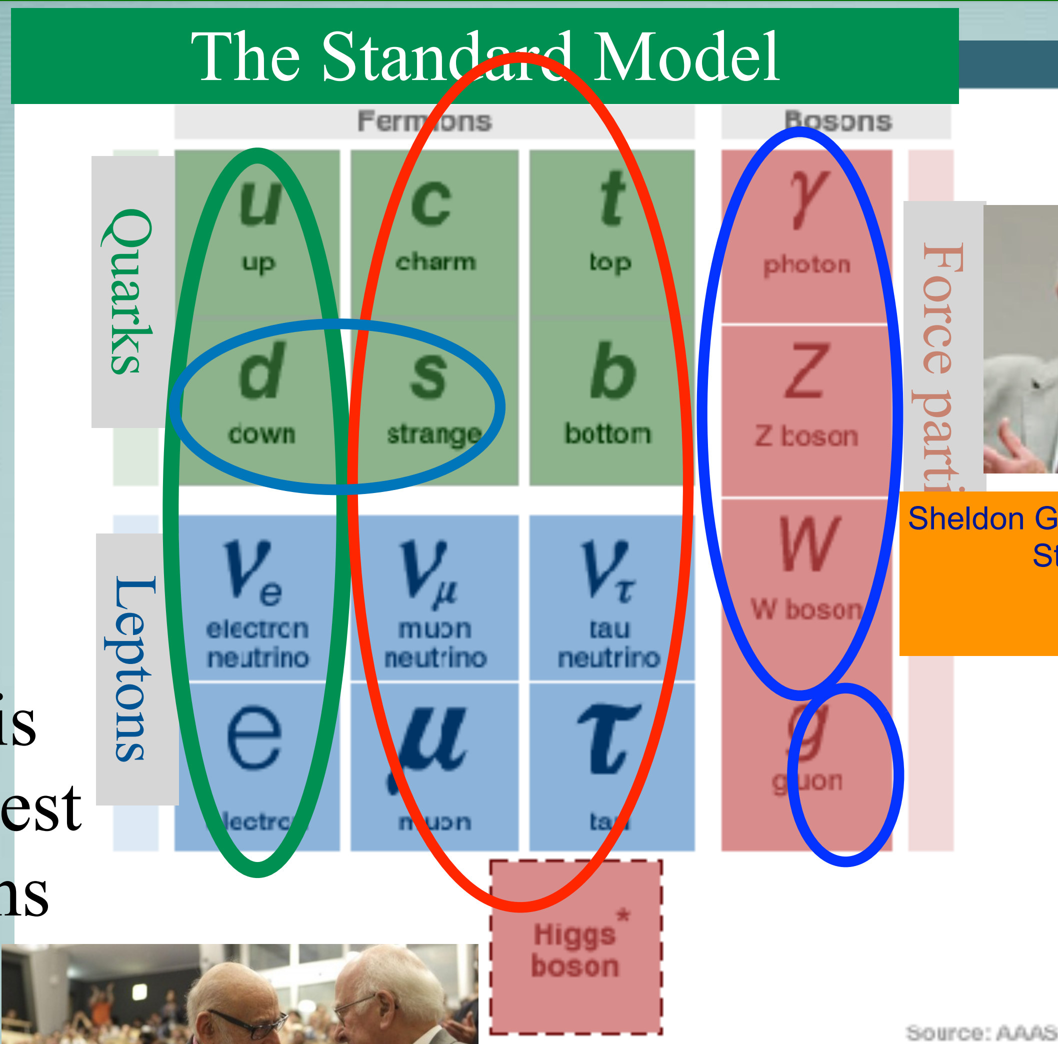
29 September 2025 to 1 October 2025
Villa Orlandi, Anacapri, Capri Island, Italy

Concluding Remarks:

Perspectives in Particle Physics

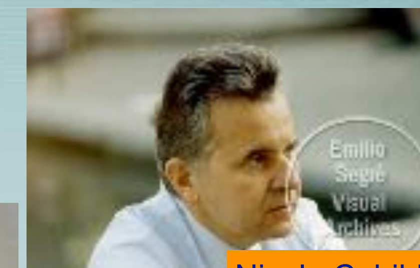
Luciano Maiani
Università di Roma La Sapienza
INFN, Sezione di Roma

1. Standard Theory in a Nutshell (circa 1984)



Murray Gell-Mann

Ordinary matter is made of the lightest quarks and leptons



Nicola Cabibbo

Sheldon Glashow
Steven Weinberg
Abdus Salam
@ ICTP Trieste

Carlo Rubbia

Sheldon Glashow, John Iliopoulos, Luciano Maiani

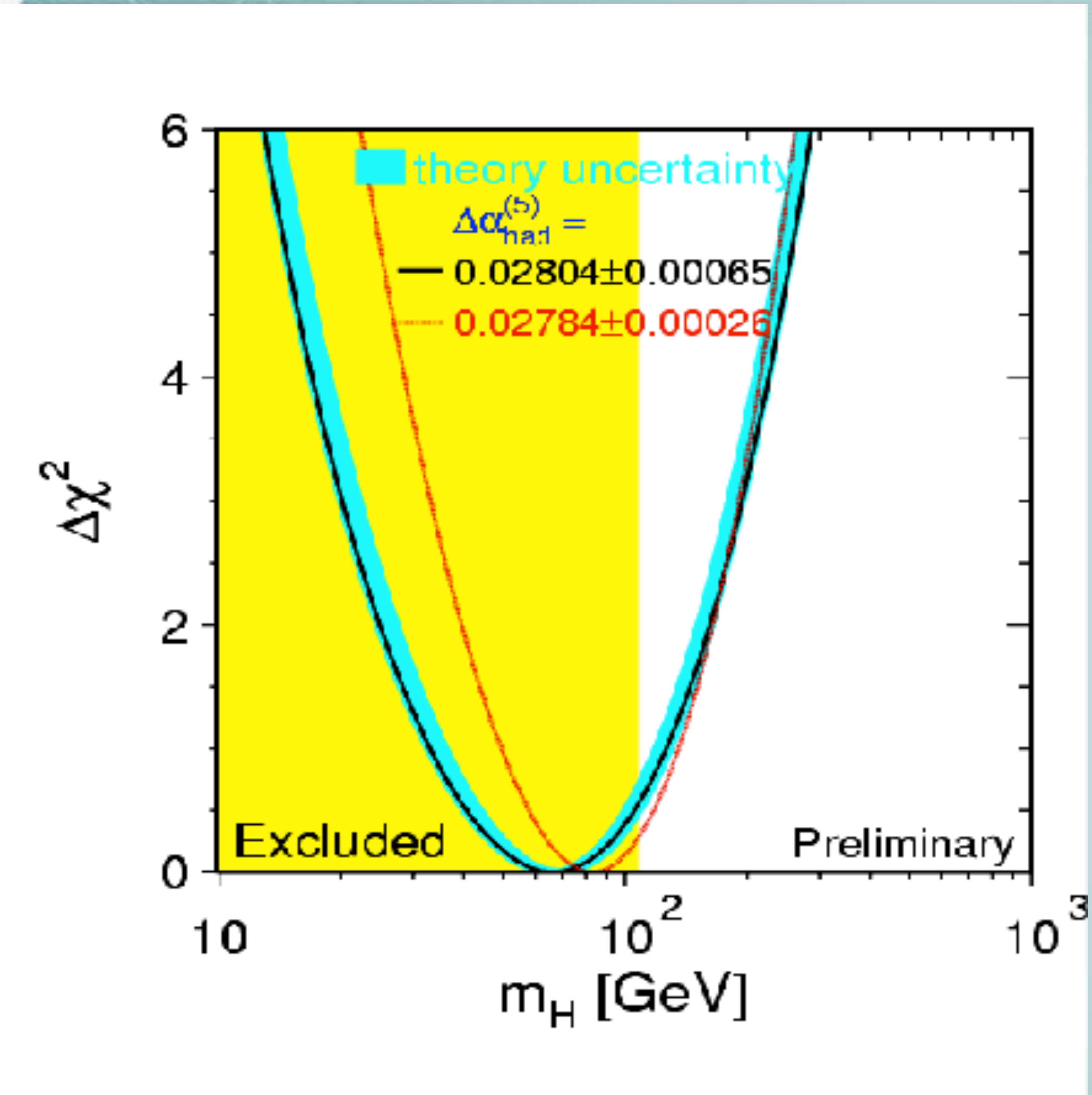
Makoto Kobayashi , Toshihide Maskawa

Robert Englert e Peter Higgs

Heavier quarks are unstable: what is their role in the Universe?

Strong interactions between quarks are mediated by neutral vector mesons (gluons) coupled to color, and are asymptotically free Gross&Wilczeck, Politzer (1973)

M_H prediction from precision Electroweak Measurements: The "blue band plot" circa 2006



- Includes all electroweak precision measurements (LEP, SLAC, FermiLab) ;
- Constrained by direct m_W and m_{top} determinations;

$$m_H = (77^{+69}_{-39})\ \mathrm{GeV/c^2}$$

QUANTUM STABILITY

$135 - 170\ GeV;\ \ \Lambda = 10^{19}$ GeV

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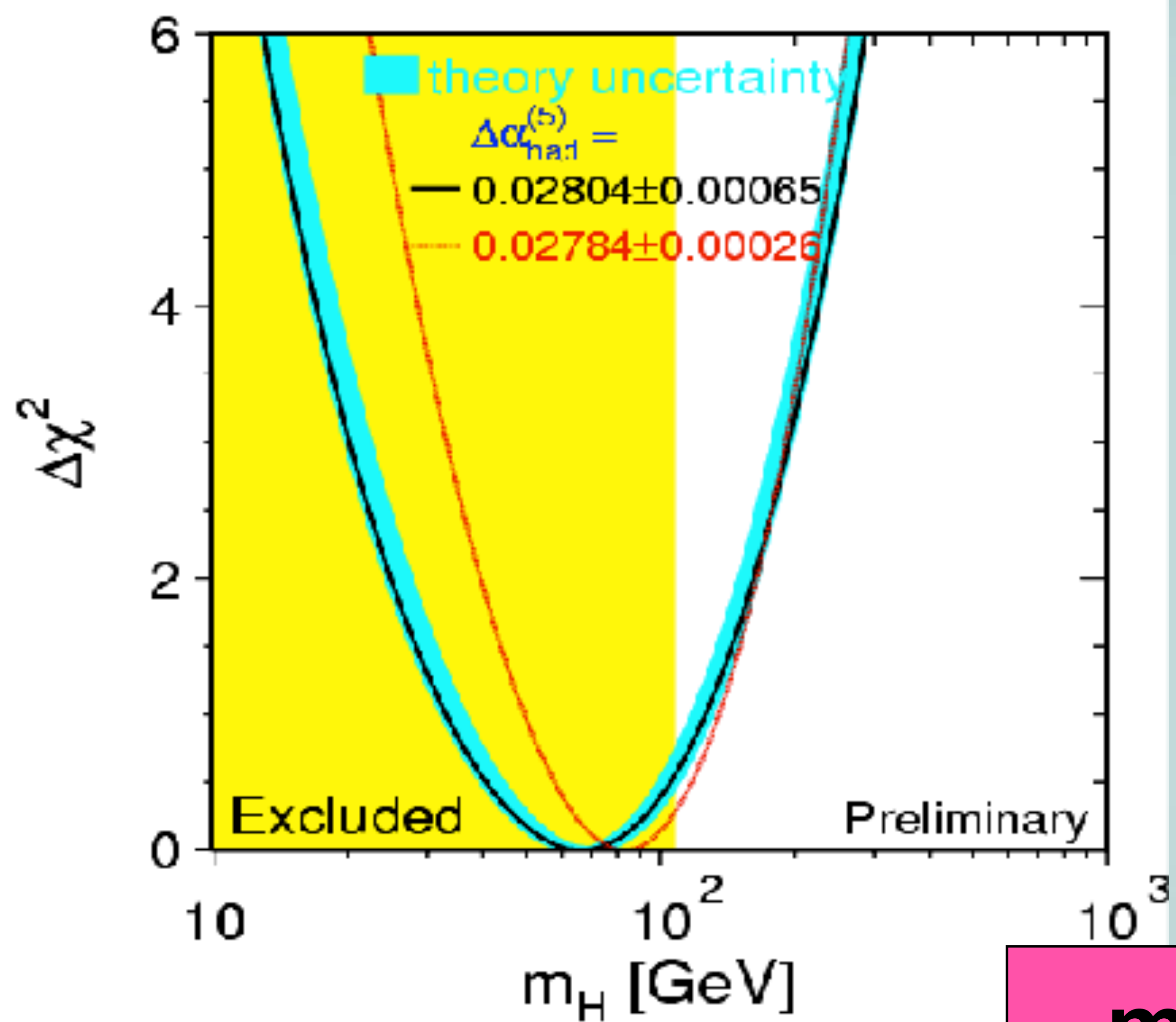

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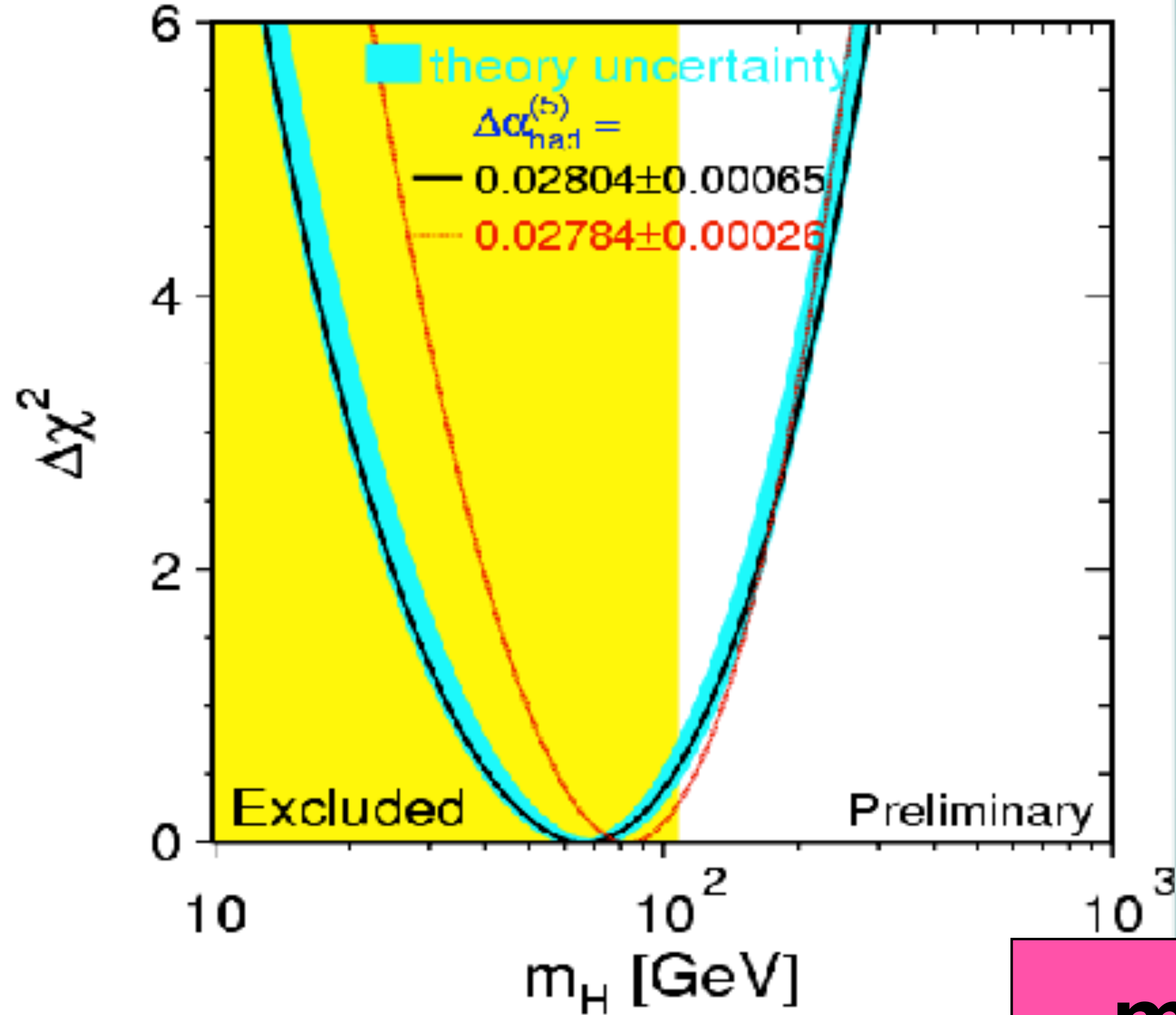

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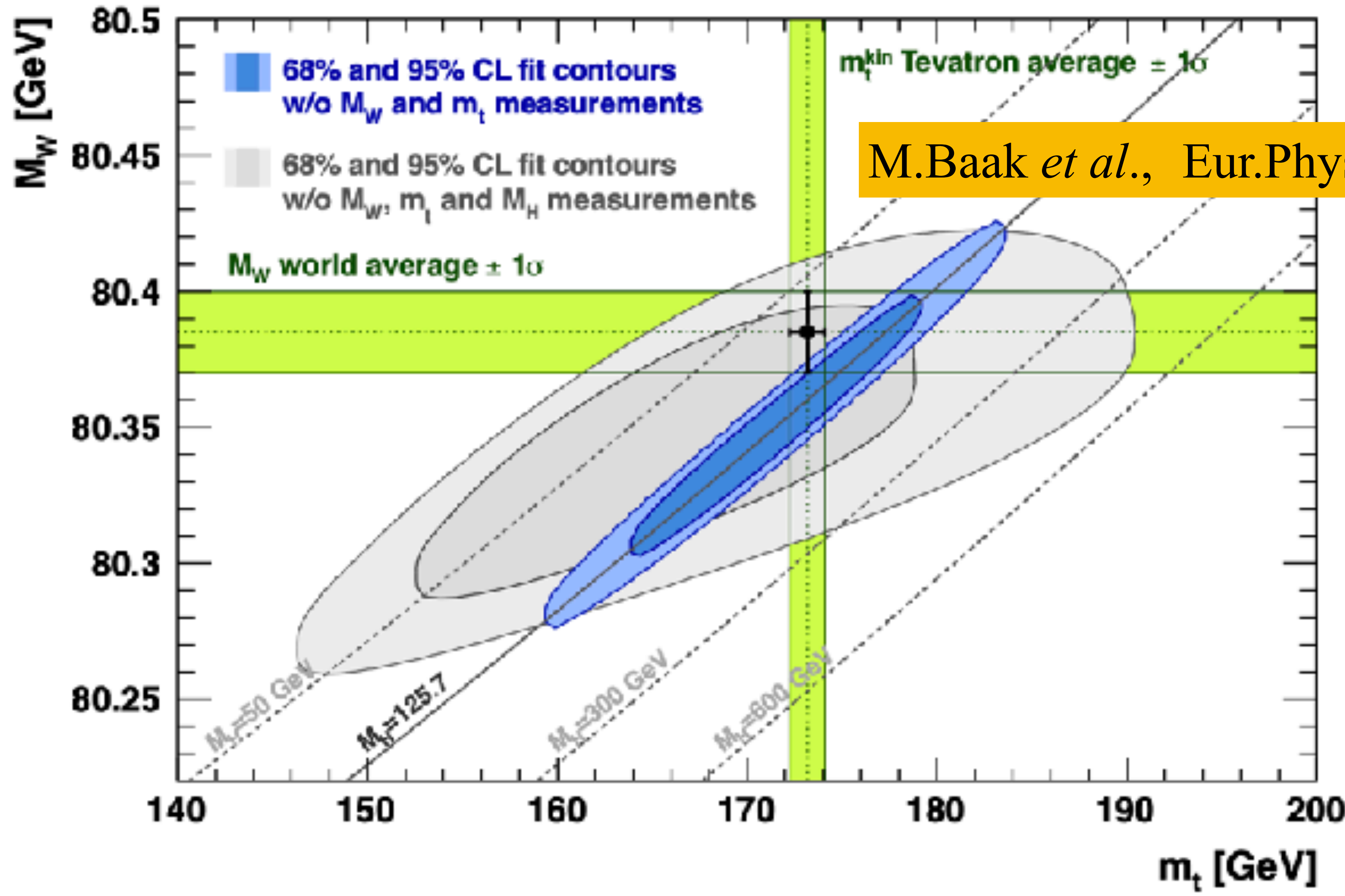
The search for the Higgs Boson, in the 1980 opened the era of large energy proton-proton Colliders. The first proposed was the SSC (Superconducting Super Collider) in the USA, followed by LHC at CERN.

MISSION ACCOMPLISHED ??

Electroweak observables measured until now are redundant to describe the EW coupling.
We can ***predict*** M_W and M_t, using M_H (blue area) or not using it (gray area).
Green bands correspond to the measured M_W and M_t.
The figure is consistent with the 125 GeV particle being the true "Higgs Boson" of EW Interactions.

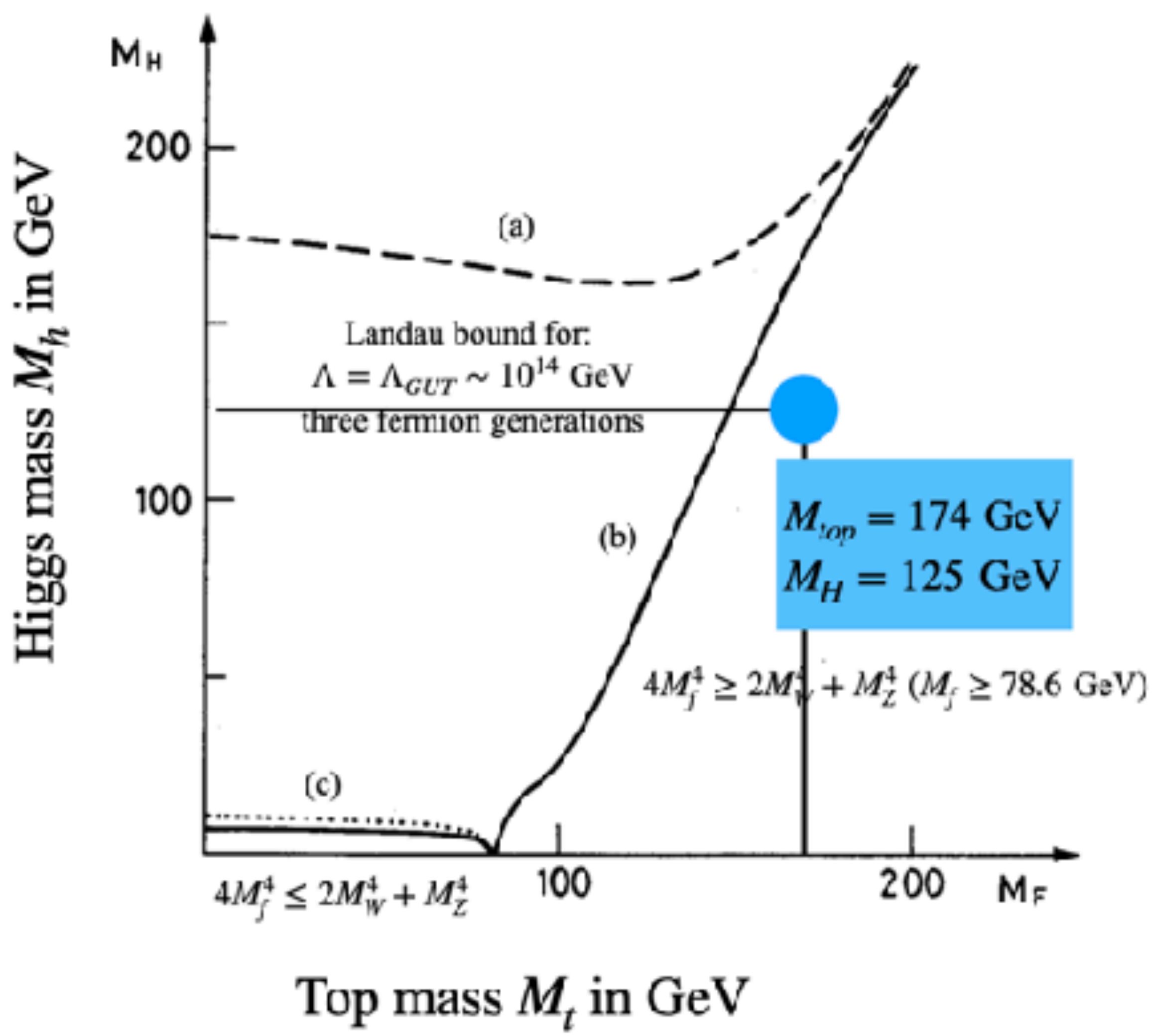


M.Baak *et al.*, Eur.Phys.J.C 72 (2012) 2205

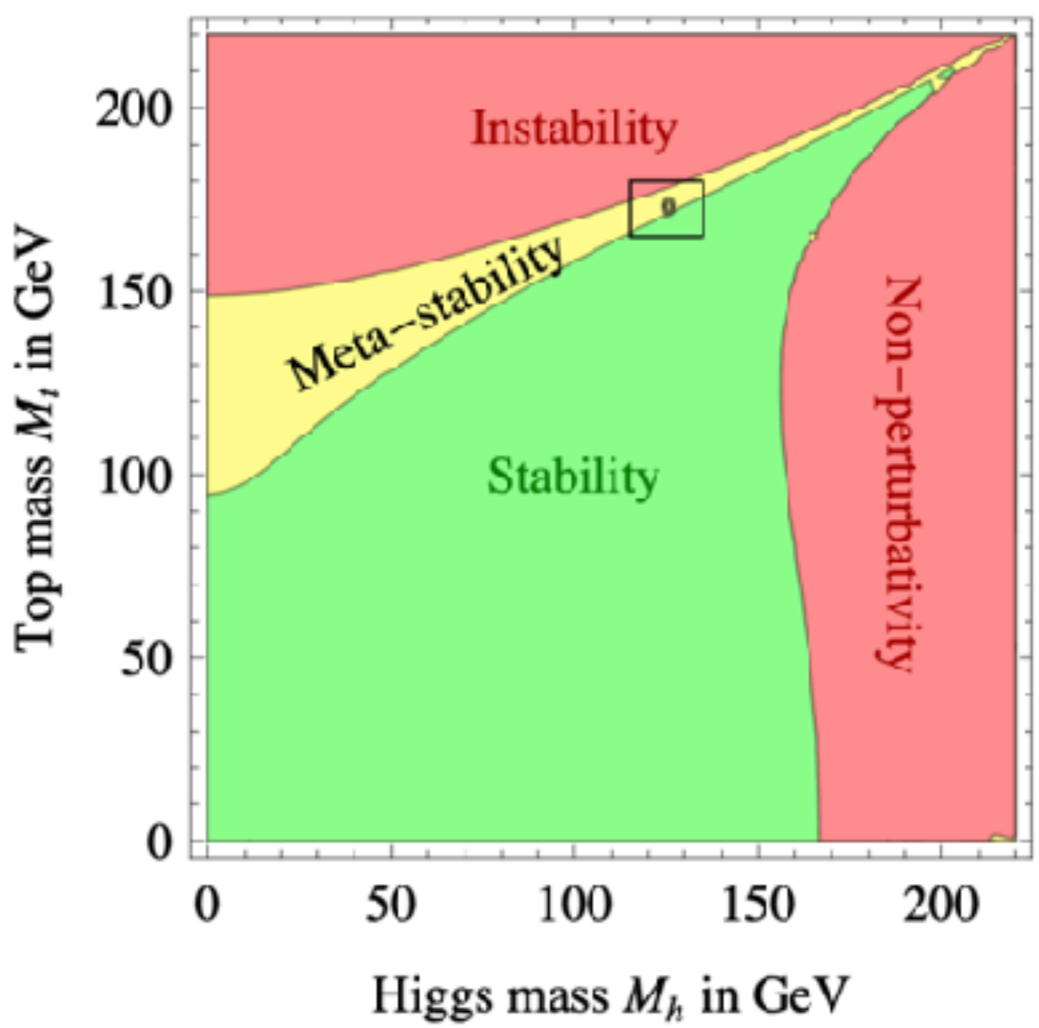
Figure 4: Contours of 68% and 95% CL obtained from scans of fixed M_W and m_t. The blue (grey) areas illustrate the fit results when including (excluding) the new M_H measurements. The direct measurements of M_W and m_t are always excluded in the fit. The vertical and horizontal bands (green) indicate the 1σ regions of the direct measurements.

If there are no other quark generations and no Supersymmetry, the Higgs mass is within the ultraviolet stability region, which extends up to $\Lambda \leq 10^8$ GeV (depending from the the top quark mass)!

one-loop β -functions
N.Cabibbo et al. Nucl. Phys. B 158 (1982), 295



three-loop β -functions
G. Degrassi *et al.* JHEP **1208** (2012) 098

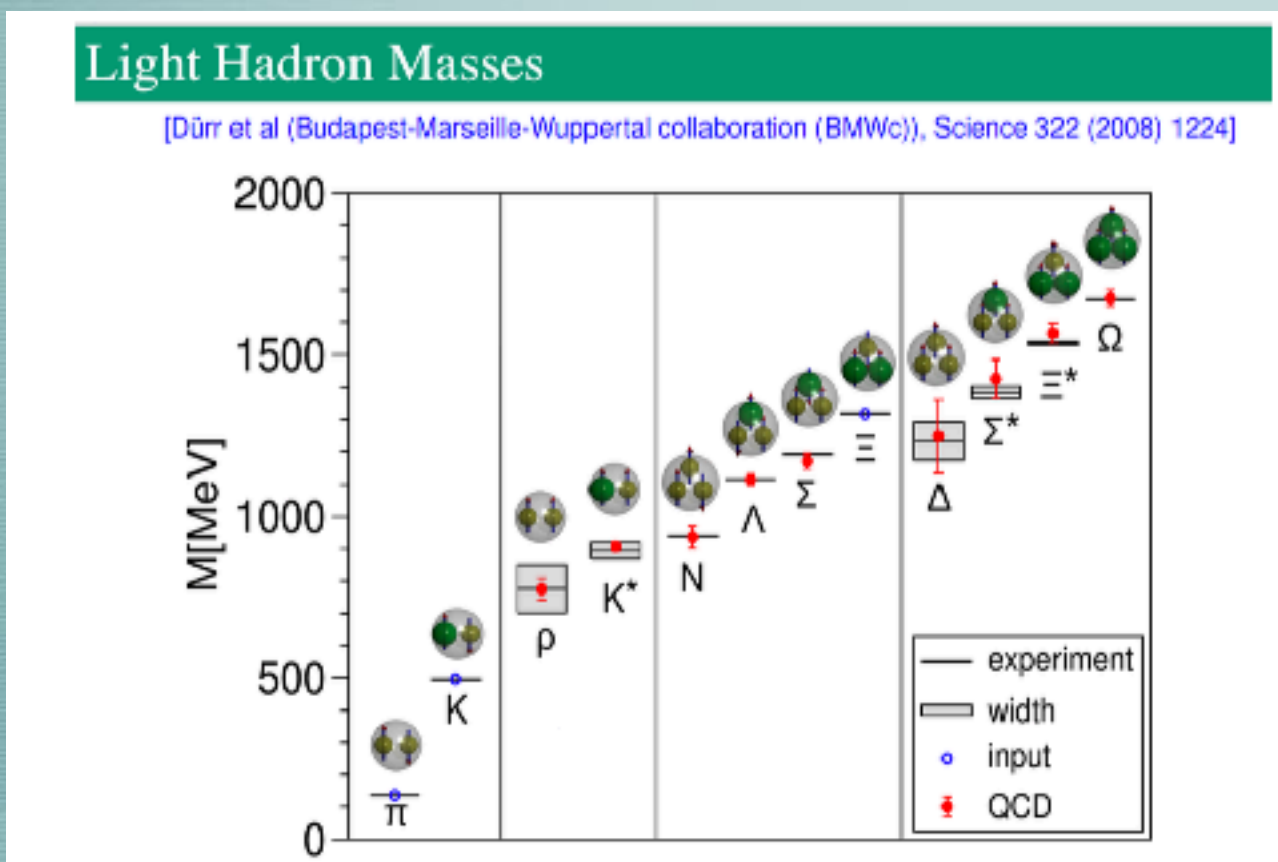


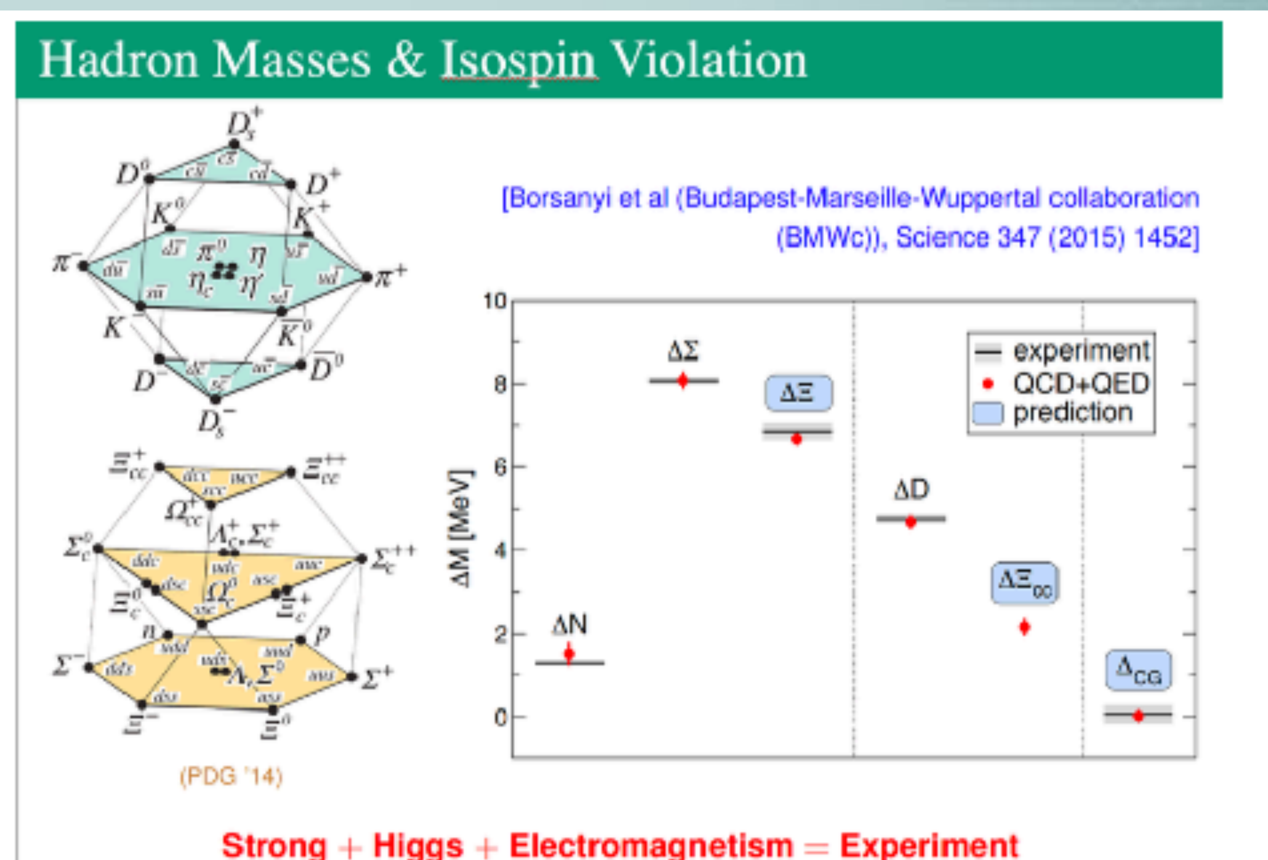
Note coordinate axis interchange

2. What do we do now in particle physics ? 4 lines

1. Solve QCD, going ***beyond the limit of large energy and feeble interactions*** by computer simulations of ***QCD on a discrete space-time lattice***:
Baryon (qqq) and meson ($\bar{q}q$) masses

- Ab-initio calculation of the Hadron spectrum





3 Input masses: m_π, m_K, m_Ξ

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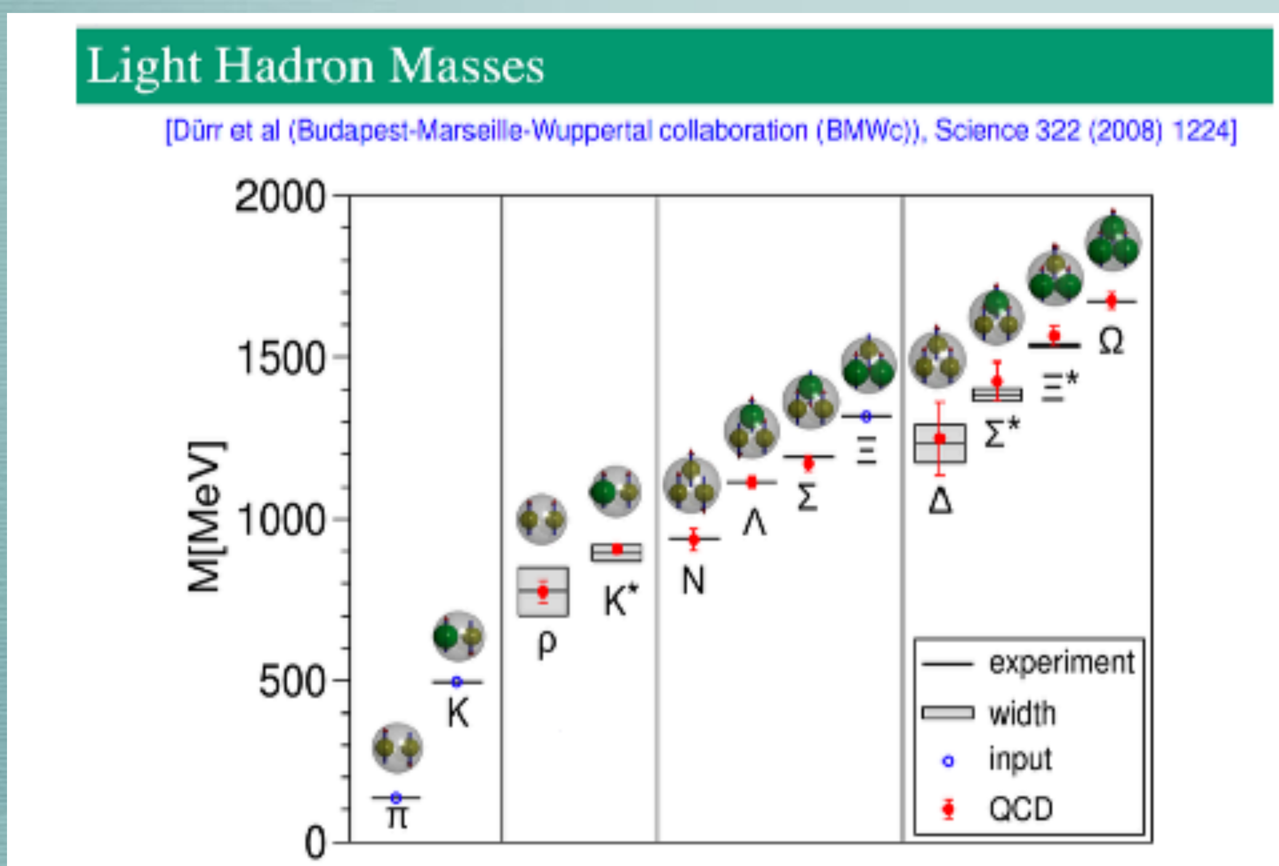
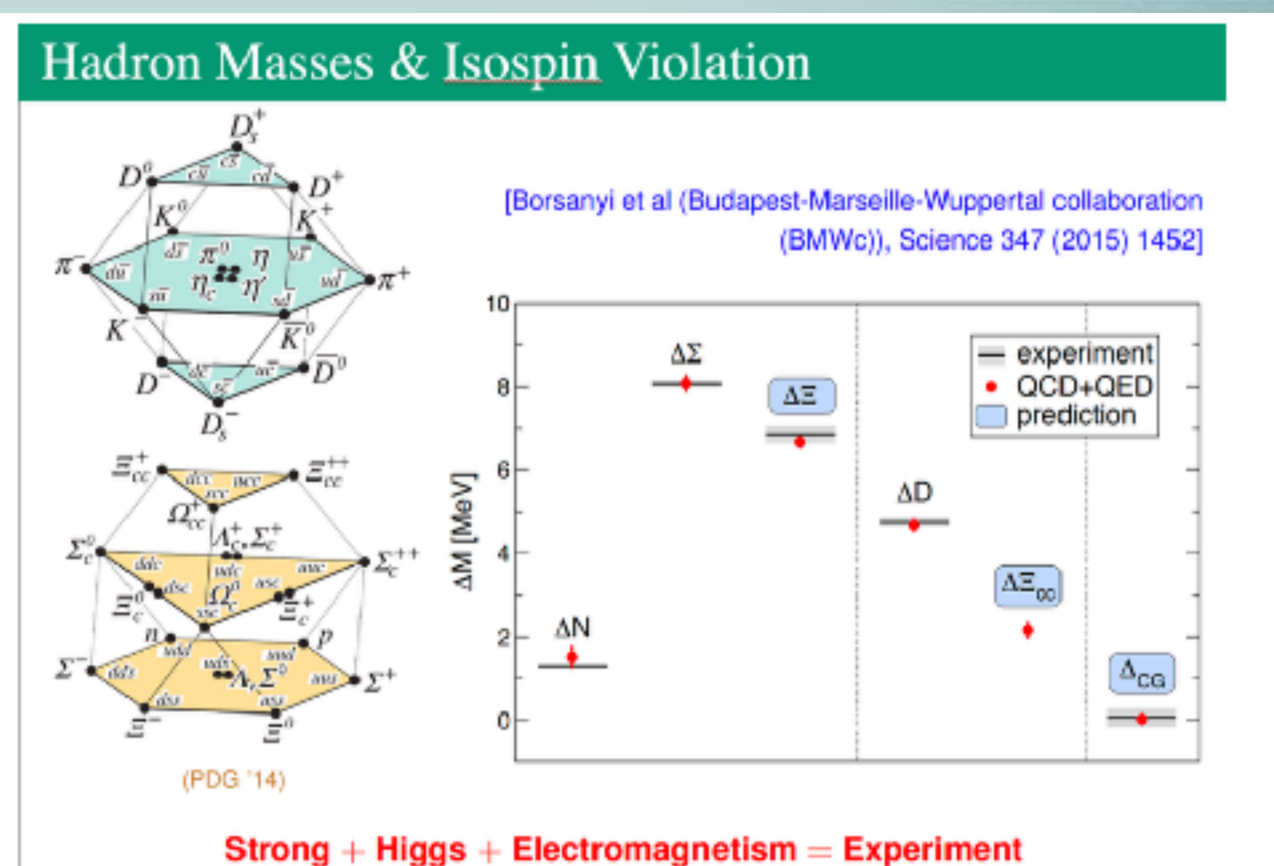
Baryon (qqq) and meson ($\bar{q}q$) masses

•Computing power increase: from 1 Gigaflop = 10^9 operations/sec (1980's) to 0.1 – 1 Exaflop = 10^9 Gigaflops (2020's), ***made all that (and more) possibile!***

- Ab-initio calculation of the Hadron spectrum





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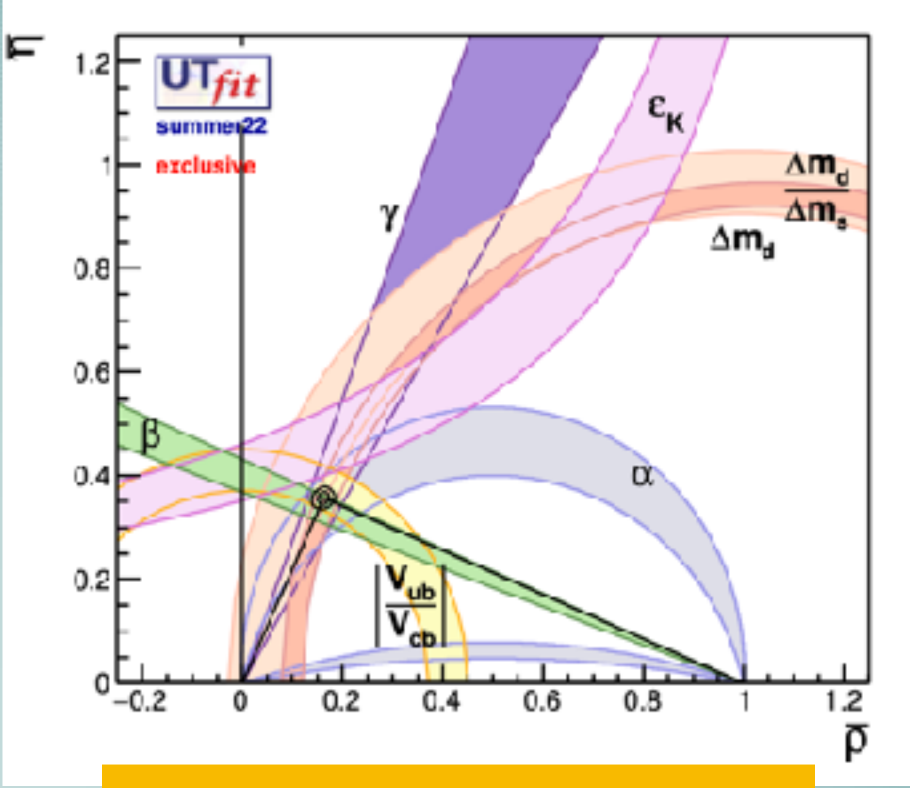
- QCD calculations of Weak Interaction processes:



- e.g. determination of the Cabibbo Kobayashi-Maskawa coefficients from the amplitude of : $B \to \ \ light \ \ vector \ \ meson$ which is affected by non-perturbative QCD corrections

$\bar{\rho} - \bar{\eta}$ plane with ***exclusive*** inputs for V_{ub}, V_{cb}.

M. Bona *et al.* [UTfit Collaboration], Rend.Lincei Sci.Fis.Nat. 34 (2023) 37

- $\Delta I = 1/2$ Rule in non-leptonic decays:

$$R = \sqrt{\frac{\Gamma(K_S^0 \to \pi^+\pi^-)}{\Gamma(K^+ \to \pi^+\pi^0)}} \sim 20$$

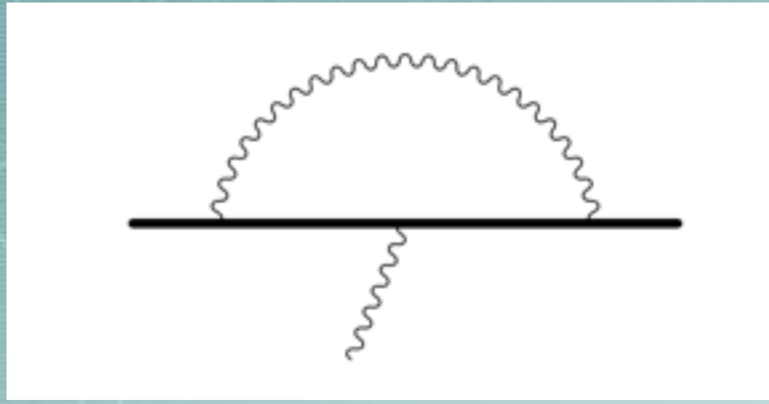
- 1974. The enhancement of the $\Delta I = 1/2$ is supported in QCD by Renormalization Group equations

M. K. Gaillard and B. W. Lee, G. Altarelli and L. Maiani, 1974

- 2020. $\Delta I = 1/2$ ***proved*** in recent Lattice QCD calculation !!

R.~Abbott *et al.* [RBC and UKQCD], PR D 102 (2020) 054509

2. Precision Frontier: the muon g-2



2^{nd} order
(J. Schwinger, 1947)

Histories: photons and electrons … (or muons..or hadrons)

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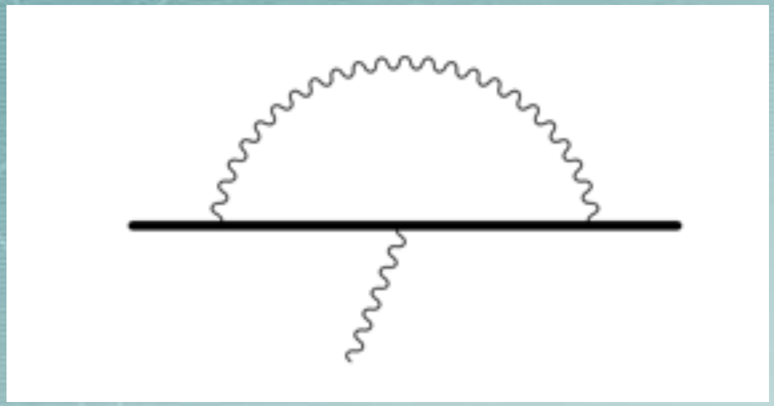

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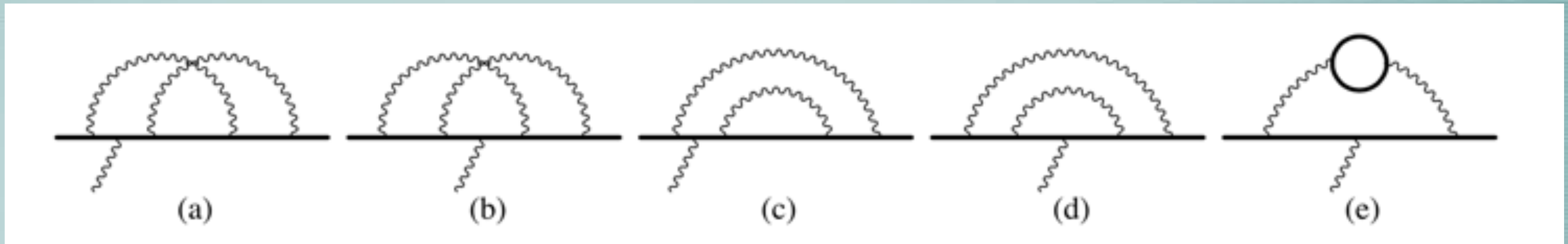
Histories: photons and electrons … (or muons..or hadrons)

… 4^{nd} order



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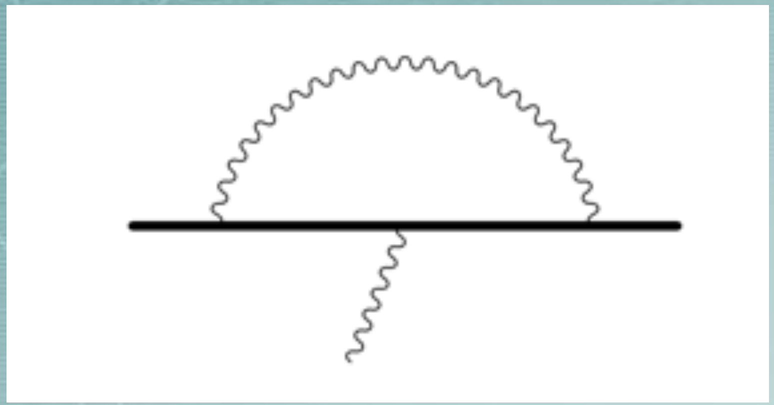

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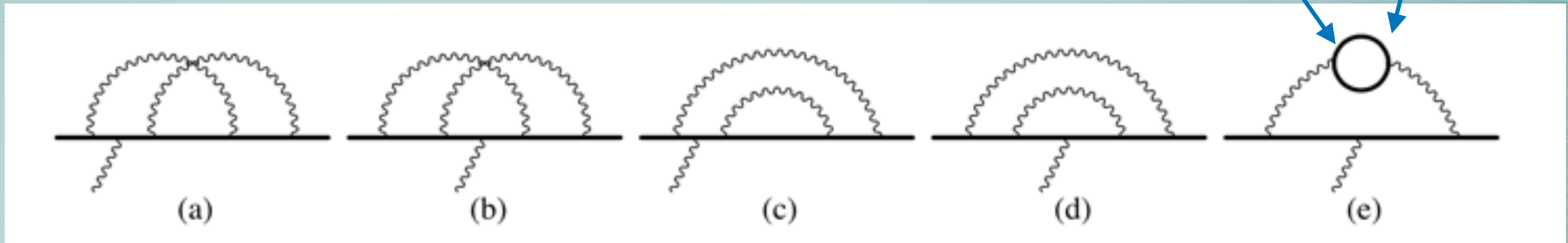

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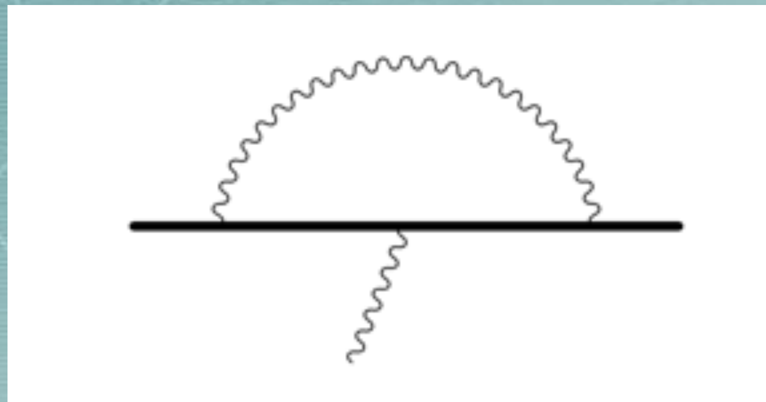

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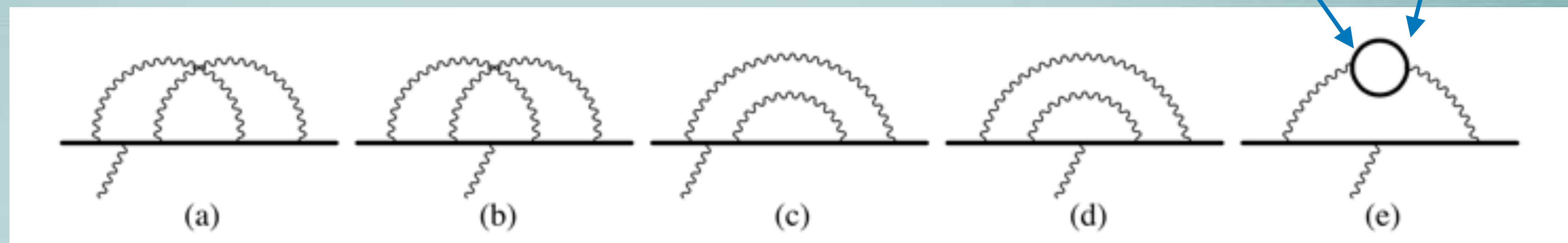
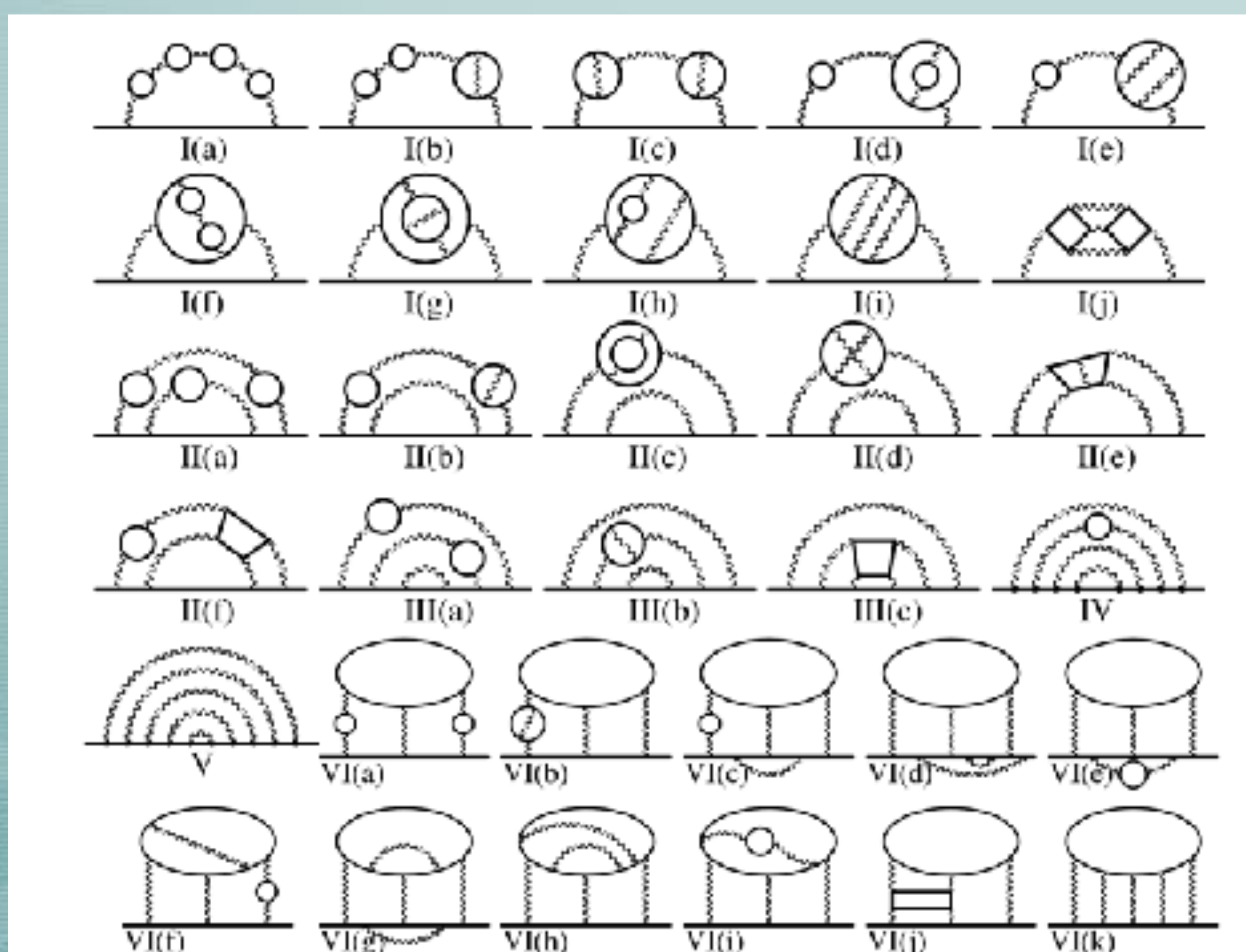




… up to 10^{th} order

Precision Frontier: the muon g-2 anomaly (cont'd)

$a_\mu = \frac{\alpha}{2\pi} = 0.00116$, J. Schwinger, 1947

- Fermilab and BNL most recent experimental result (2020):
- $g_\mu^{expt} - 2 = a_\mu^{expt} = 11659208.9\ 10^{-10}$
- define: $\Delta a_\mu^{expt} = (11659208.9 - 11659000.0) = 208.9 \pm 2.2$
- in the same convention, QED corrections are: $\Delta a_\mu^{QED} = -528.2$
- ElectroWeak corrections: $\Delta a_\mu^{EW} = 15.4$
- Hadronic corrections (HVP, HLbL):

  Hadron Vacuum Polarization- estimated from data on $e^+e^- \to hadrons$

  Subleading: Hadron Light-by Light scattering- resonance insertion in loop

ST predictions:
T. Aoyama *et al*. Phys. Rept. 887 (2020)

- $\Delta a_\mu^{HVP} = 684.5, \quad \Delta a_\mu^{HLbL} = 9.2$
- In total: $\Delta a_\mu^{ST} = 181 \pm 4.3$: 5σ discrepancy

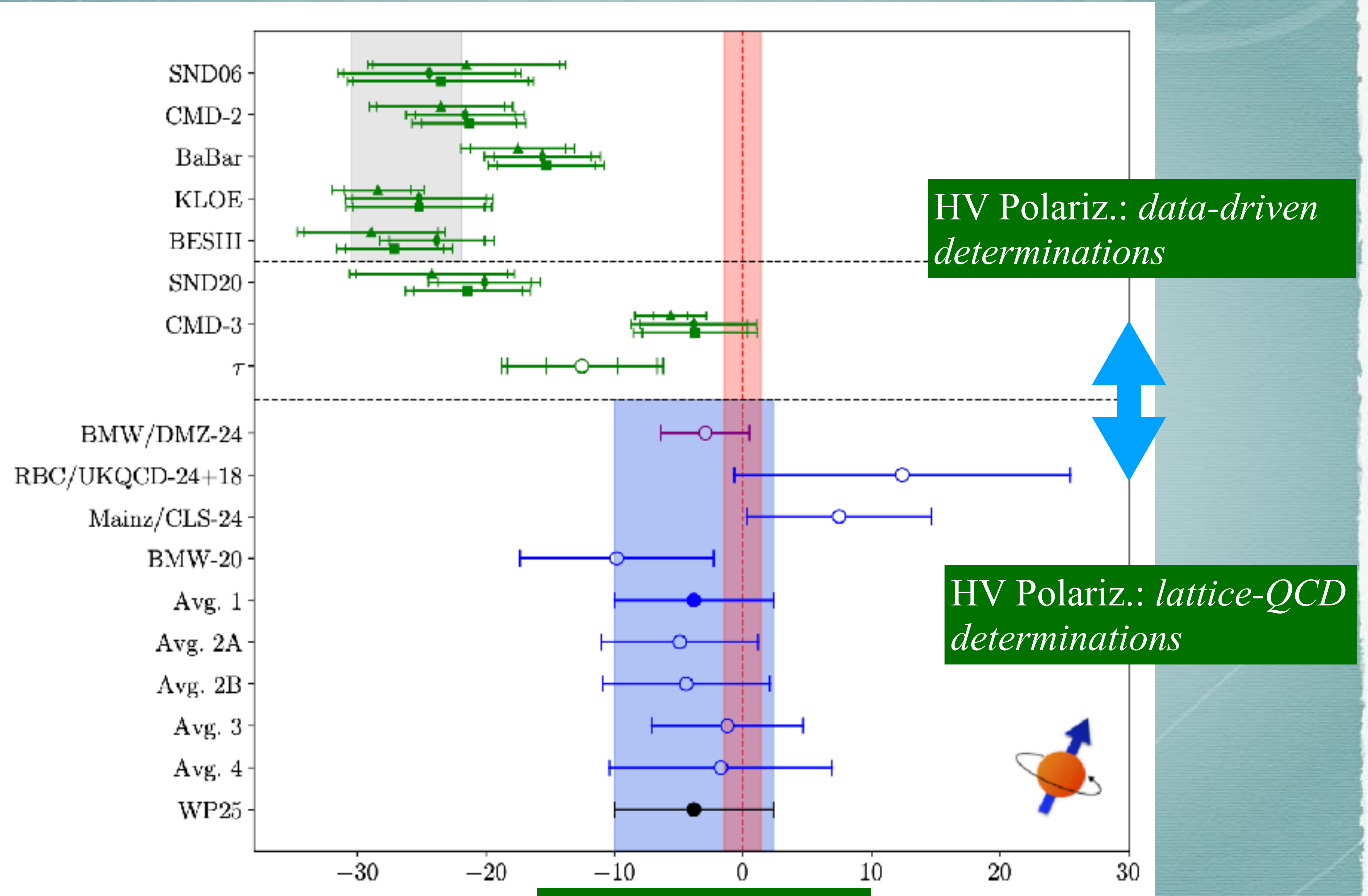
HVP, from experim. data. T. Aoyama *et al.*

- N***ew evaluation of HVP*** in a recent Lattice QCD contribution, by the ***BMW-DMZ Collaboration***:

  $\Delta a_\mu^{\text{BMW-DMZ}} = 201.9 \pm 3.8$ (QED + EW + HVP lattice +subleading hadronic)

A. Boccaletti *et al.*, arXiv:2407.10913

Last Update:
T. Aliberti *et al.*, arXiv:2505.21476v3 [hep-ph] 11 Sept. 2025



$10^{10} \cdot (a_\mu^{SM} - a_\mu^{expt})$

3. Unexpected Exotic Hadrons

The first unexpected hadron , the $X(3872)$, was discovered by BELLE in 2003, confirmed by BABAR and seen in many other High Energy experiments.

Since then, a wealth of Exotic Hadrons have been observed, mesons and baryons that cannot be described by the classical Gell-Mann configurations $(q\bar{q})$ and (qqq).

First observed:

$X(3872)$, $Z(3990)$, $Z(4020)$

CERN COURIER

November-December 2024

Main sources of Exotic Hadrons

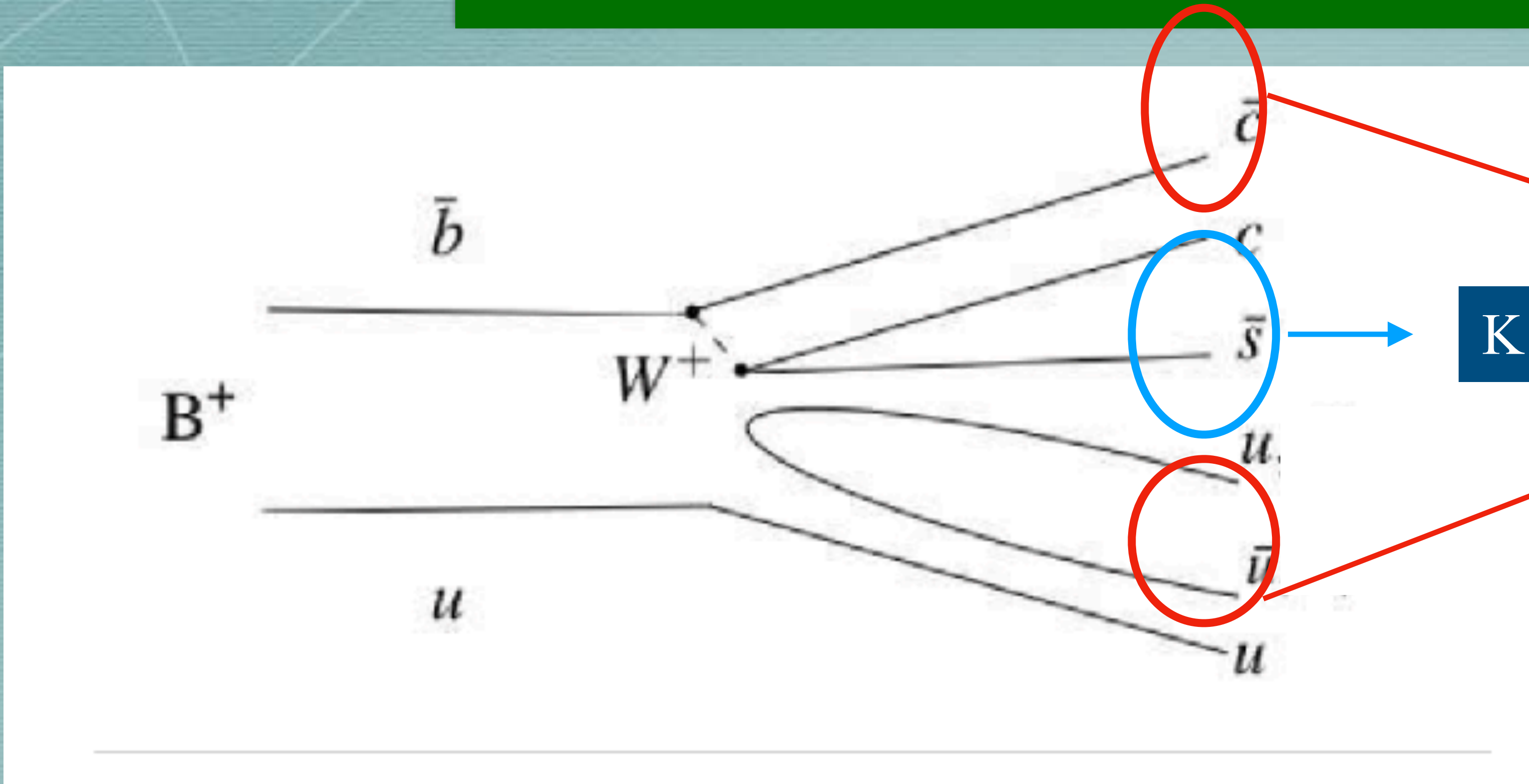


FIG. 1: Quark diagram for $B^+ \to K + X$, with $X = (c\bar{c}q\bar{q}')$.

K meson

tetraquark $\to J/\Psi + \rho$

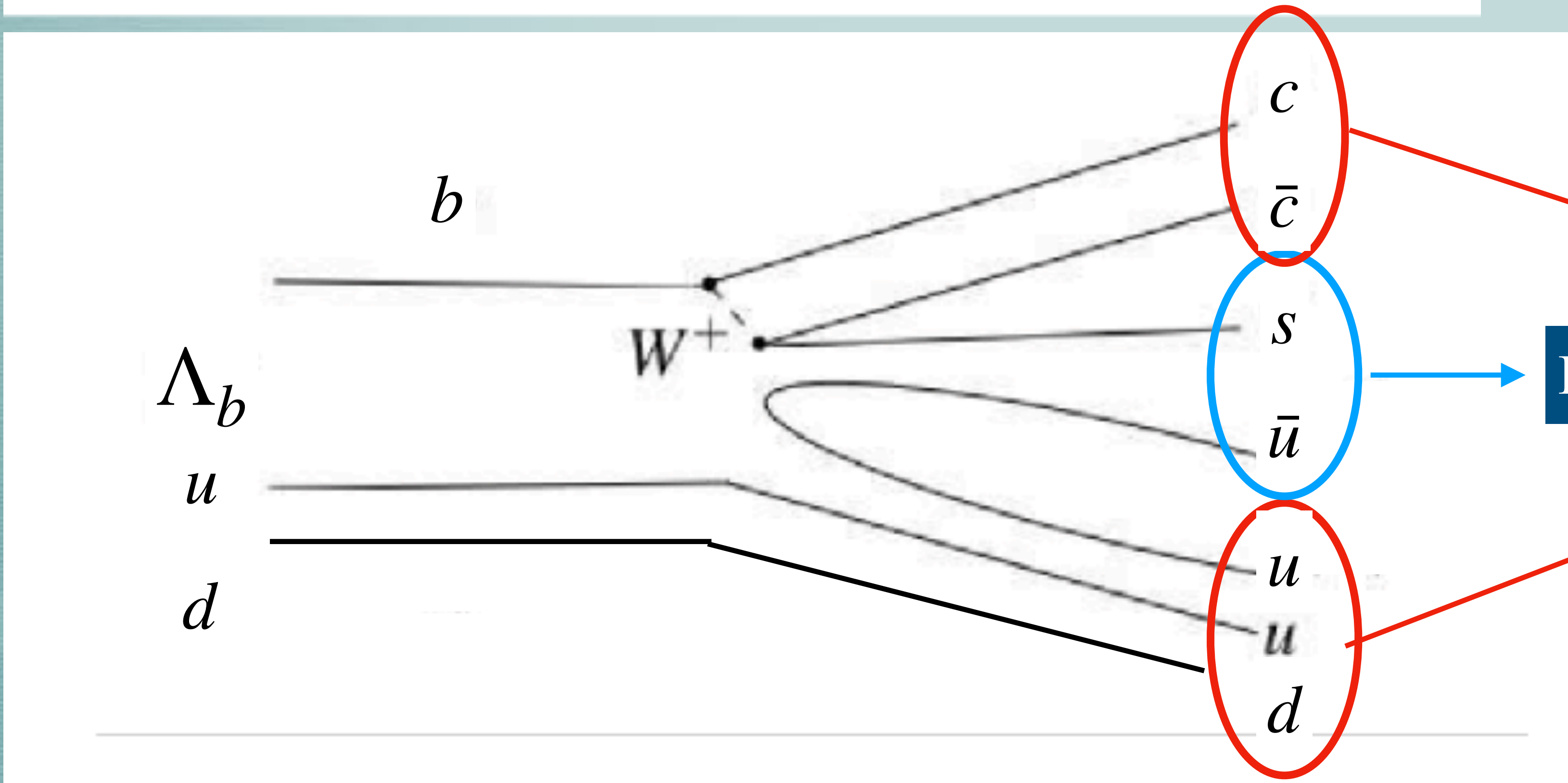


FIG. 2: Quark diagram for $\Lambda_b \to K + X$, with $X = (\bar{c}cuud)$

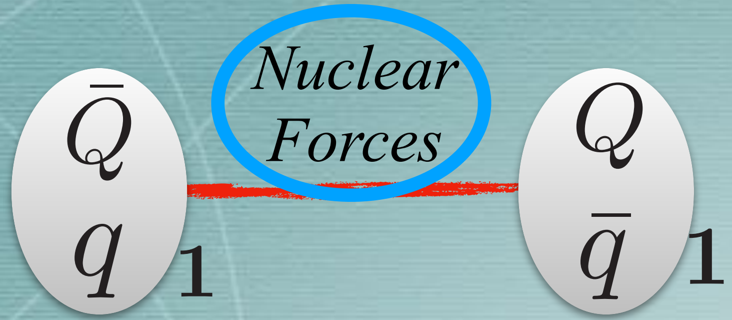
K meson

pentaquark $\to J/\Psi + p$

- Bigi et al. were the first to suggest that non-leptonic B meson decays could provide an efficient source of exotic hadrons, *a process much used in later experiments to discover tetra- and pentaquarks*.

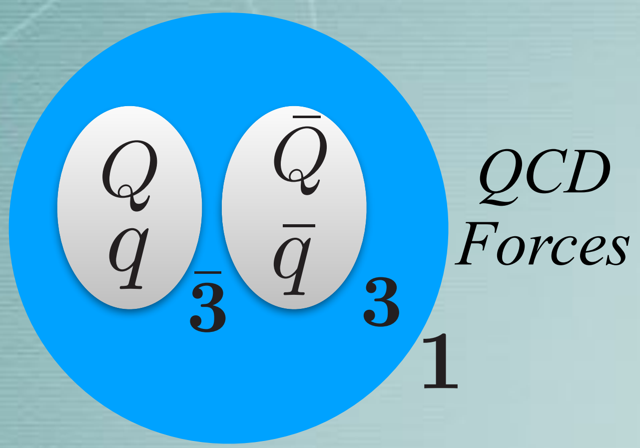
I. Bigi, L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, *Four-quark mesons in non-leptonic B decays*" Phys. Rev. D **72** (2005), 114016

No consensus, yet



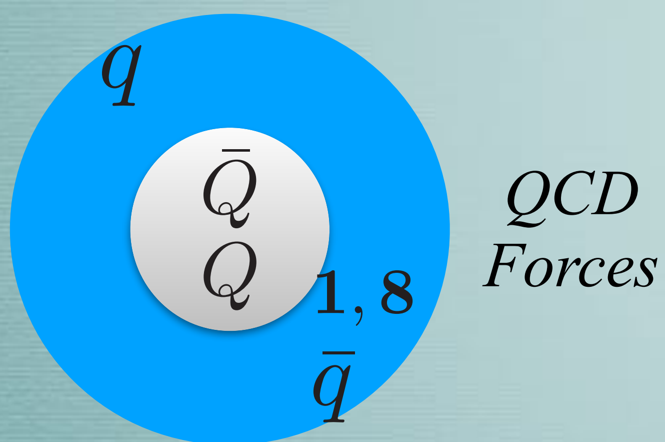
Hadron Molecule

F-K. Guo, C. Hanhart, U-G Meißner, Q. Wang, Q. Zhao, and B-S Zou, arXiv 1705.00141 (2017)



Compact Diquark-Antidiquark

L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, Phys. Rev. D 71 (2005) 014028; **D 89** (2014) 114010.

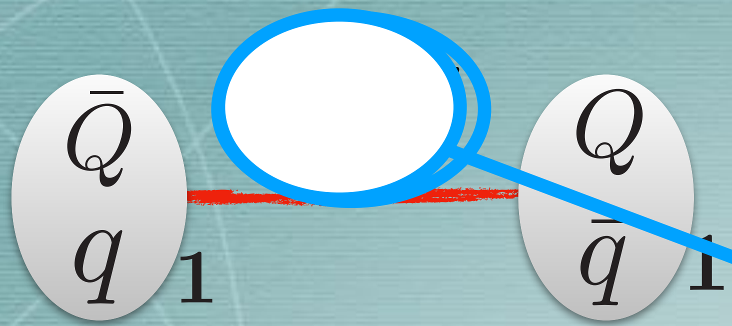


HadroCharmonium (1)
Quarkonium Adjoint Meson (8)

S. Dubynskiy, S. and M. B.Voloshin, Phys. Lett. **B 666**,(2008) 344.

E. Braaten, C. Langmack and D. H. Smith, Phys. Rev. **D 90** (2014) 01404

No consensus, yet



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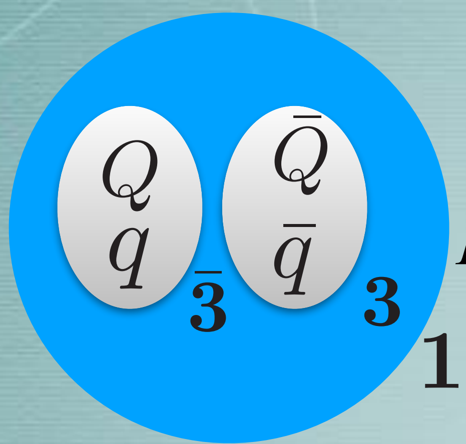
Contact interactions in Chiral Perturbation Theory

Z. H. Zhang *et al*., arXiv:2404.11215 [hep-ph] ***see later***



QCD Forces

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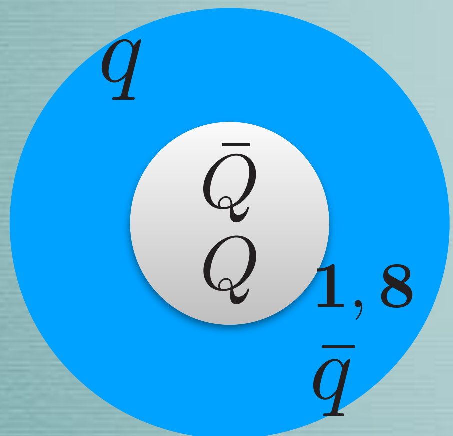

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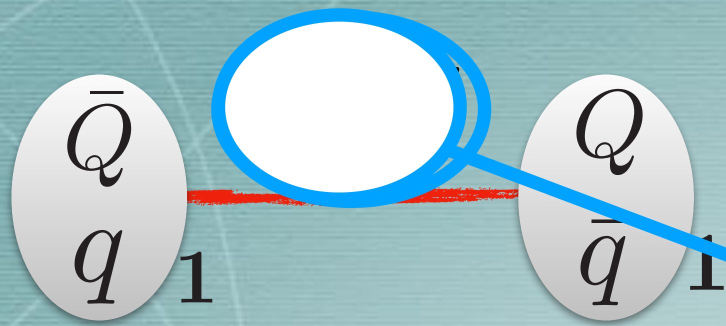

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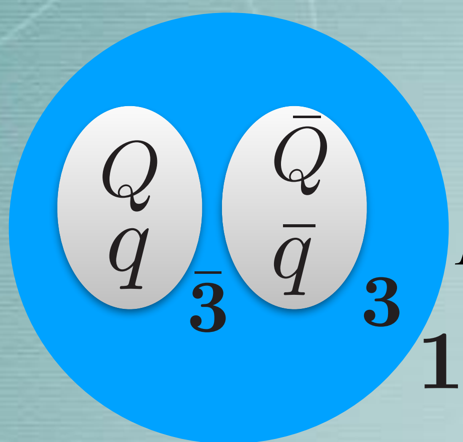

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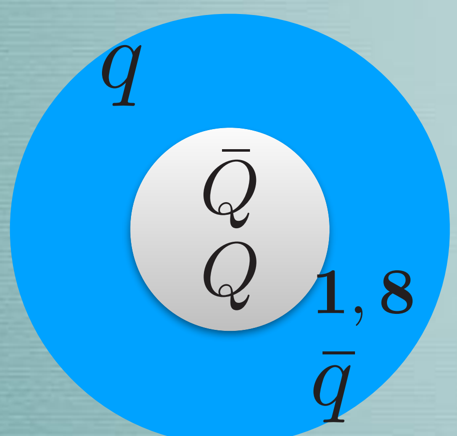

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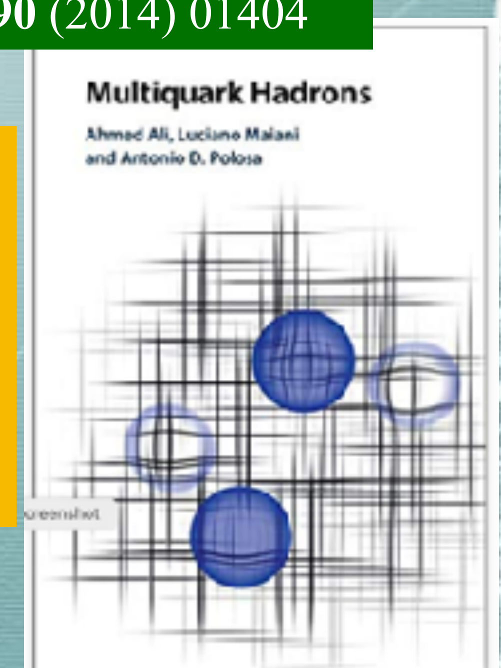
For a review, see:
A. Ali, L. Maiani and A.D. Polosa, *Multiquark Hadrons*, Cambridge University Press (2019)



Flavour Symmetry of Compact Tetraquarks

- QCD interactions are approximately symmetric under flavour SU(3) so diquark-antidiquark states must fall in complete SU(3) flavour multiplets, with mass differences determined by the quark mass difference

$$m_s - m_{u,d}$$

We have identified particles that can be assigned to 3 different multiplets:

- Hidden Charm $(\bar{c}cq_1\bar{q}_2)$, $SU(3)_f$: $\mathbf{8} \oplus \mathbf{1}$
- Single Charm $[(\bar{c}\bar{q}_1)_{S=0}(q_2q_3)_{S=0}]$, $J^P = 0^+$, $SU(3)_f$: $\mathbf{3} \oplus \bar{\mathbf{6}}$
- Double Charm (Beauty) $[(cc)_{S=1}(\bar{q}_2\bar{q}_3)_{S=0}]$, $J^P = 1^+$, $SU(3)_f$: $\mathbf{3}$

With $Z_{cs}(3082)$, $Z_{cs}(4003)$, $Z_{cs}(4220)$ we can almost fill three tetraquark nonets with the expected scale of mass differences

The same happens with the three states of Scalar , Single Charm Tetraquarks recently discovered by LHCb

We may produce estimates of mass and decay modes of the missing partners

4. Hidden Charm Tetraquarks

Hidden Charm Tetraquarks form ***nonets of flavor SU(3)*** with mass differences determined by the quark mass difference $m_s - m_{u,d}$

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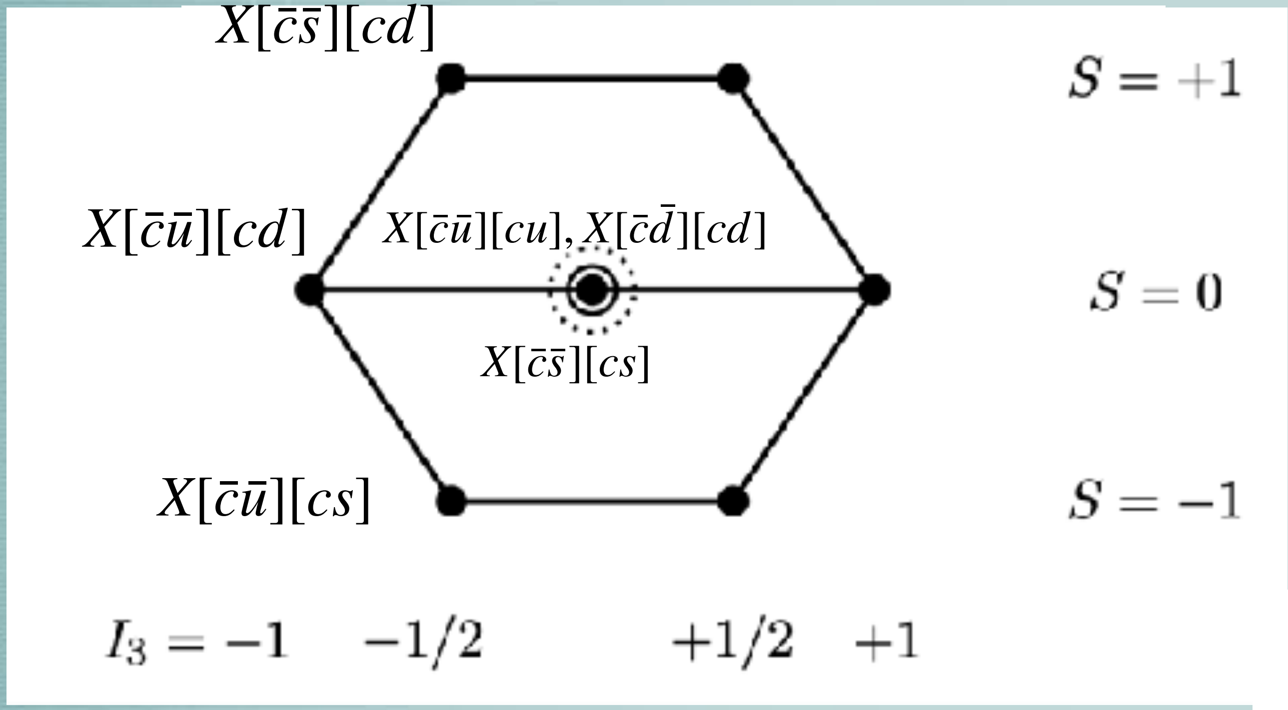
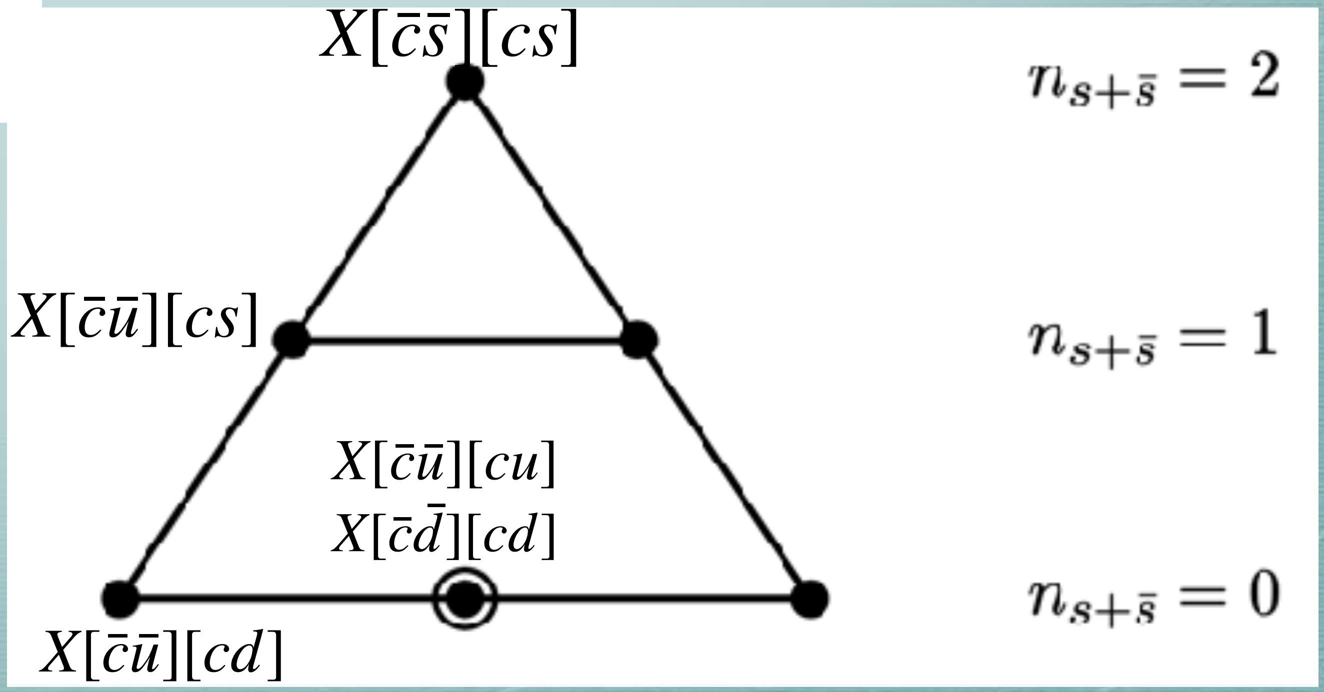
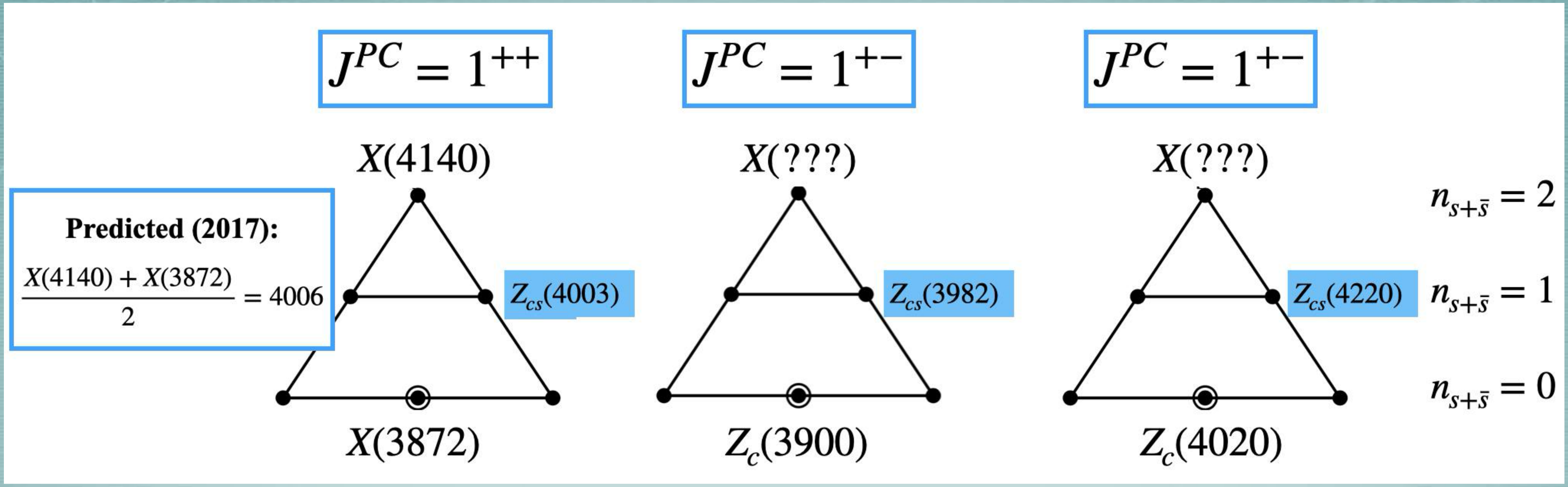


- Nonet multiplets can be also represented in function of the total number of $s + \bar{s}$ quarks;
- octet breaking implies ***the equal-spacing rule*** of masses in the ladder.

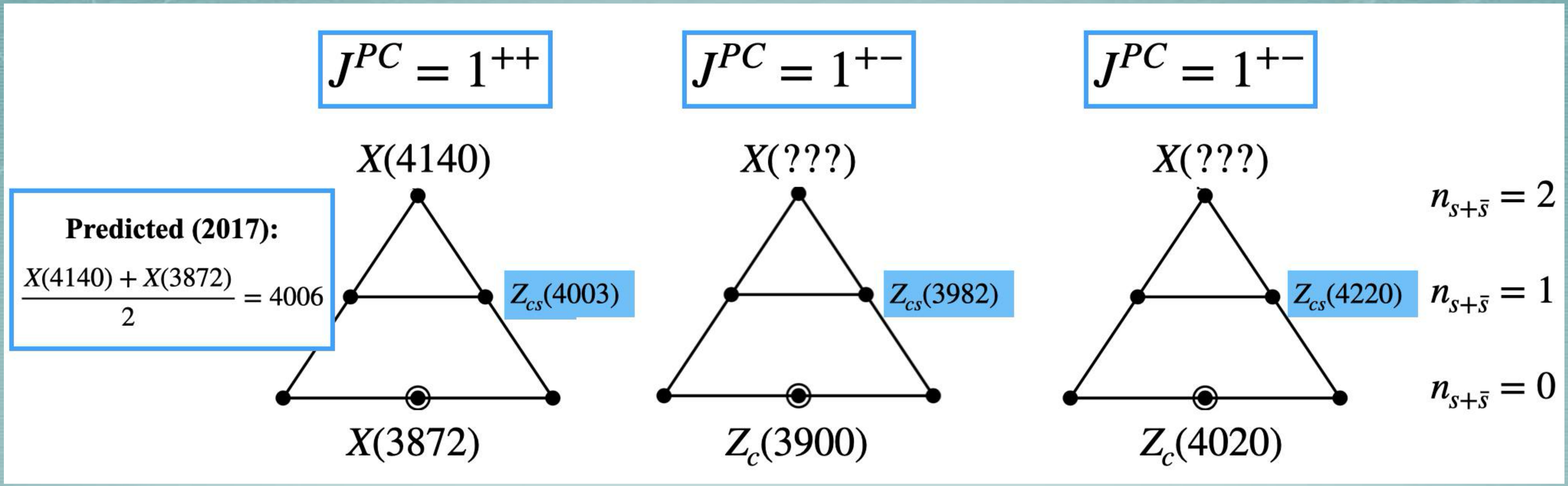


L. Maiani, A. D. Polosa and V. Riquer, Sci. Bull. **66** (2021), 1616, arXiv:2103.08331



- $Z_{cs}(3982)$, to be associated to the $Z_{cs}(3982)$, $J^{PC} = 1^{+-}$nonet, is lighter than expected and $Z_c(4220)$, to be associated to the nonet of $Z_c(4020)$ is heavier than expected.
- The discrepancy can be explained by a mixing of the two nonets with the same quantum numbers, since mixing implies the widening of the mixed levels w.r.t. the unmixed ones.
- Indeed, a mixing angle of $\sim 30^0$ would bring the unmixed masses in line with the mass difference observed for the 1^{+-} nonets.

L. Maiani, A. D. Polosa and V. Riquer, Sci. Bull. **66** (2021), 1616, arXiv:2103.08331



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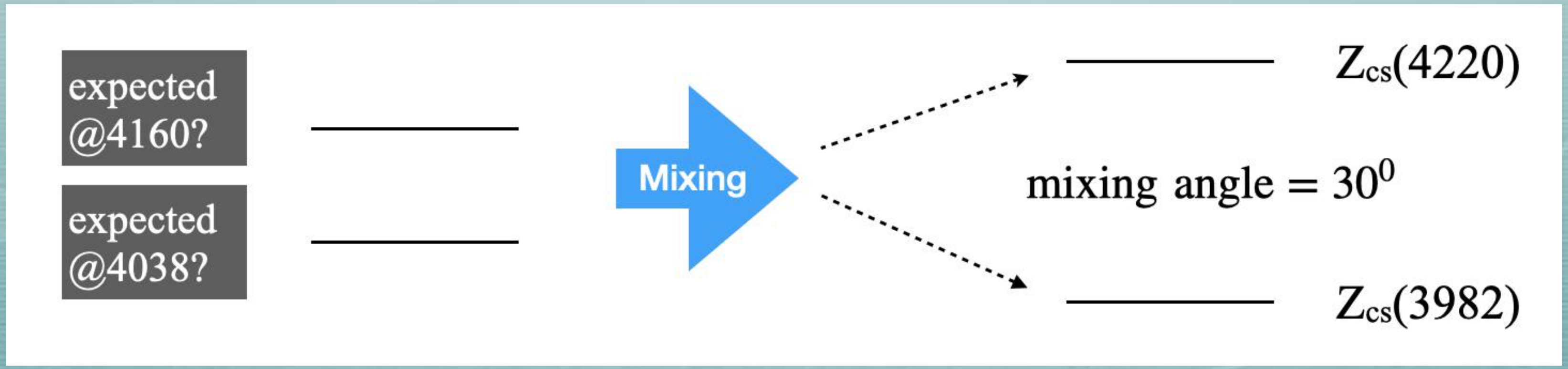
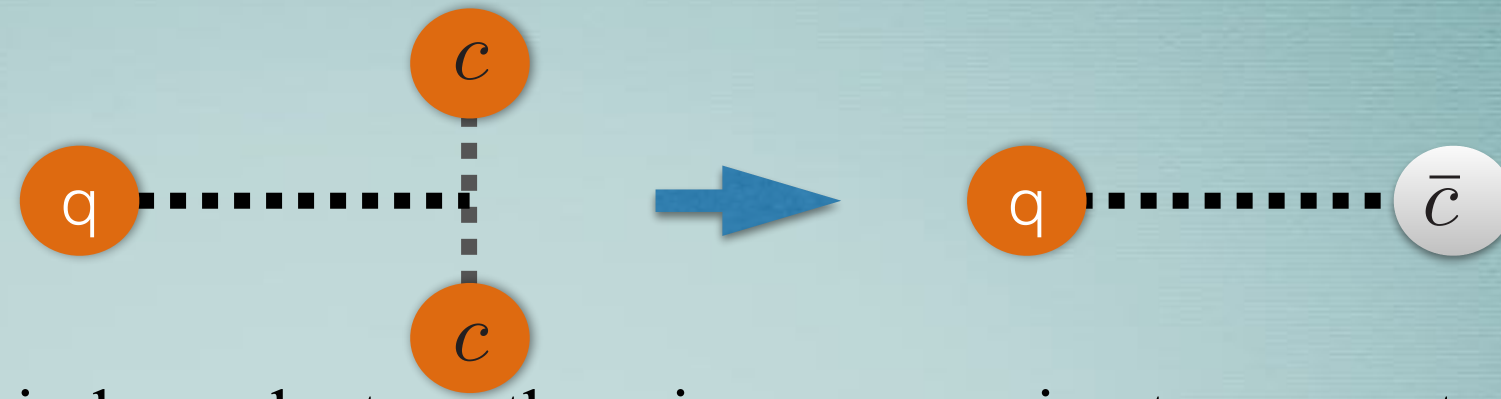
- Indeed, a mixing angle of $\sim 30^0$ would bring the unmixed masses in line with the mass difference observed for the 1^{+-} nonets.



5. Doubly heavy baryons and doubly heavy tetraquarks

Single heavy-doubly heavy quark symmetry: M. Savage, M. B. Wise, PLB 248,1990; N. Brambilla, A. Vairo and T. Rosch, PRD 72, 2005; T. Mehen, arXiv:1708.05020v3

- Doubly heavy baryons are related to single quark heavy mesons:



- QCD forces are mainly spin independent, so there is an approximate symmetry relating masses of DH baryons to SH mesons: e.g.

$$M(\Xi^*_{cc}) - M(\Xi) = \frac{3}{4}(M(D^*) - M(D))$$

- Doubly heavy tetraquarks have been anticipated long ago.

Esposito, M. Papinutto, A. Pilloni, A. D. Polosa, and N. Tantalo, Phys. Rev. D88, 054029 (2013)

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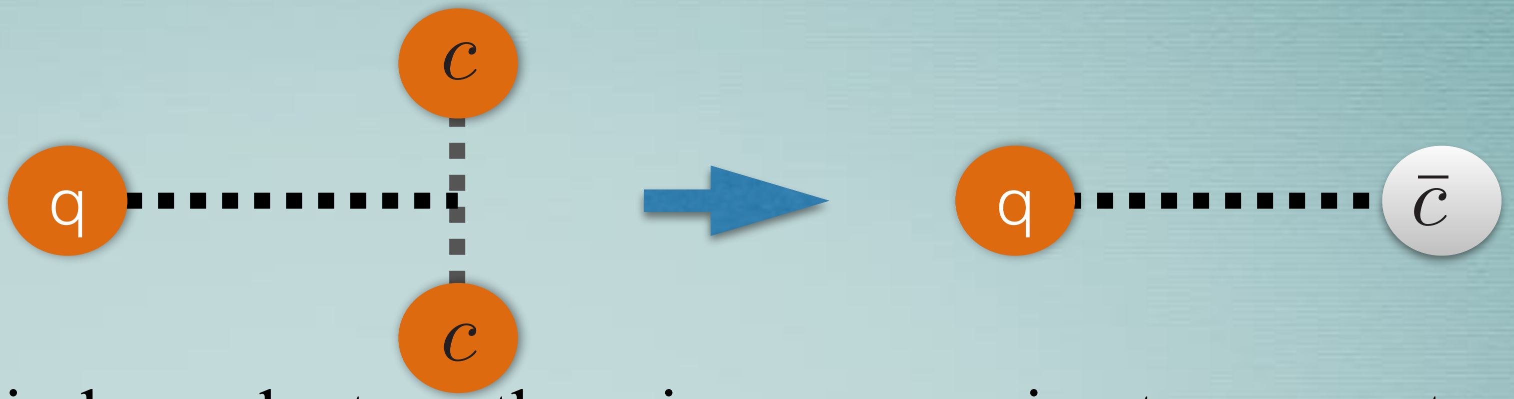

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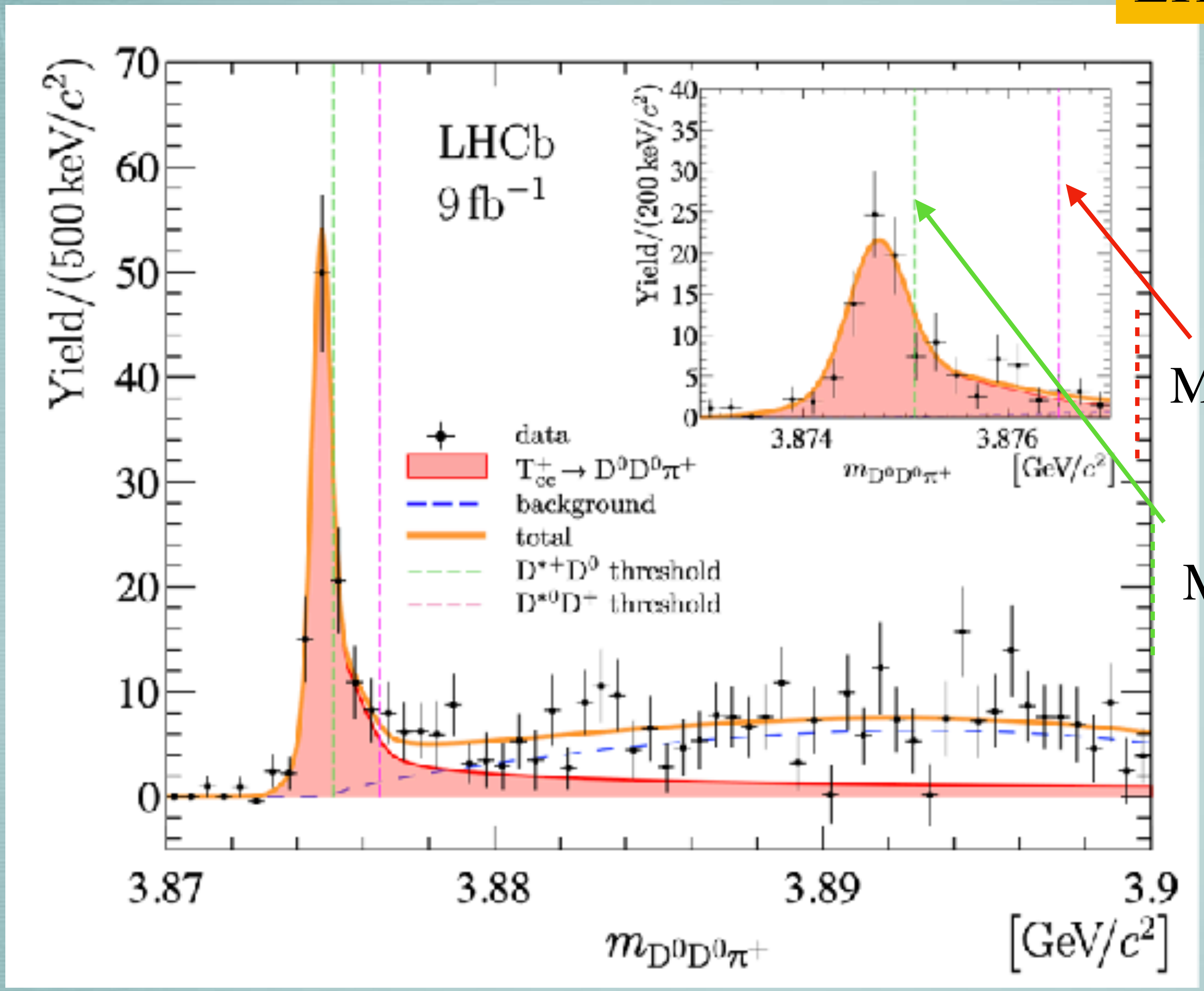
- extended calculations of $\mathcal{T}_{cc}$, $\mathcal{T}_{cb}$ and $\mathcal{T}_{bb}$ mass in the Born-Oppenheimer approximation have been presented: analytica and in Lattice QCD

Double charm tetraquark $\mathcal{T}^{+}_{cc}(1^{+})$

LHCb arXiv:2109.01056v2



Mass : $D^{*0}D^{+} = 3876.5$ MeV

Mass : $D^{*+}D^{0} =$ 3875.1 MeV

The limit of large heavy quark mass

•***Most clearly stated by Eichten and Quigg***:

-in the large mass limit, the heavy quarks go to short distance, where the coulomb-like QCD potential dominates

-the QQ binding energy is then given by the QCD Rydberg, so that:

$$Q_{\text{value}} = M(T) - 2M(P) = -\frac{1}{2}(\frac{2}{3}\alpha_s)^2\bar{M}_Q + \mathcal{O}(m, M^{-1})$$

-$\bar{M}_Q$ the reduced mass of the QQ pair

-P is the pseudoscalar $(Q\bar{q})$ meson

•for $\bar{M}_Q$ large enough $T = (QQ\bar{q}\bar{q})$ is stable against strong as well as electromagnetic decays into $PP + \gamma$.

Is b quark mass heavy enough for stability?

The mass of the lightest double heavy tetraquarks can be computed!

- Recent estimates of the mass of the lightest, double heavy tetraquarks indicate that the I=0, $bb\bar{u}\bar{d}$ tetraquark ***could be stable***. The table below gives a comparison of different theoretical results. $M(D^*) - M(D) = 140$ MeV
- ***Q-value is taken with respect to PS-PS threshold (not V-PS!)***

$QQ'\bar{u}\bar{d}$	BO(2023)[1]	K&R(2017)[2]	E&Q(2017)[3]	Luo(2017)[4]	Lattice QCD
$cc\bar{u}\bar{d}$	+136 (+111)	+140	+102	+39	-23 ± 11 Junn. et al.[5]
$cb\bar{u}\bar{d}$	+72 (+48)	~ 0	+83	−108	$+8 \pm 23$ Francis et al [6]
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Q values in MeV for decays into meson+meson+γ obtained with string tension 1/4 k (in parentheses string tension k). Models used in K&R (2017), E&Q (2017), Luo (2017) are different elaborations of the constituent quark model, more details are found in the original references. In the last column the lattice QCD results.

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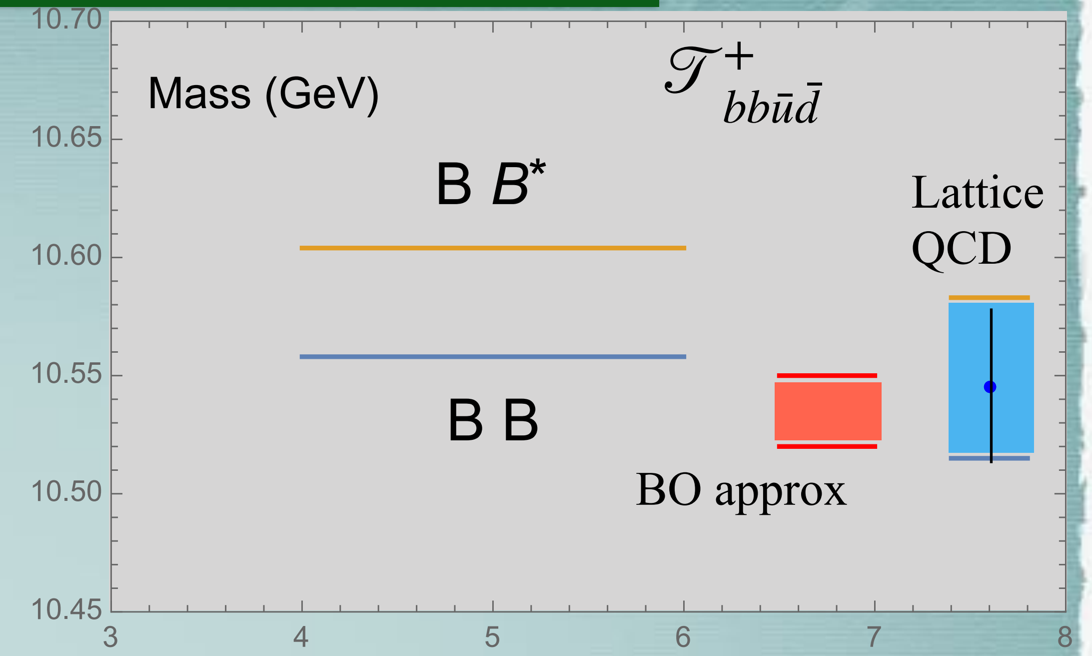

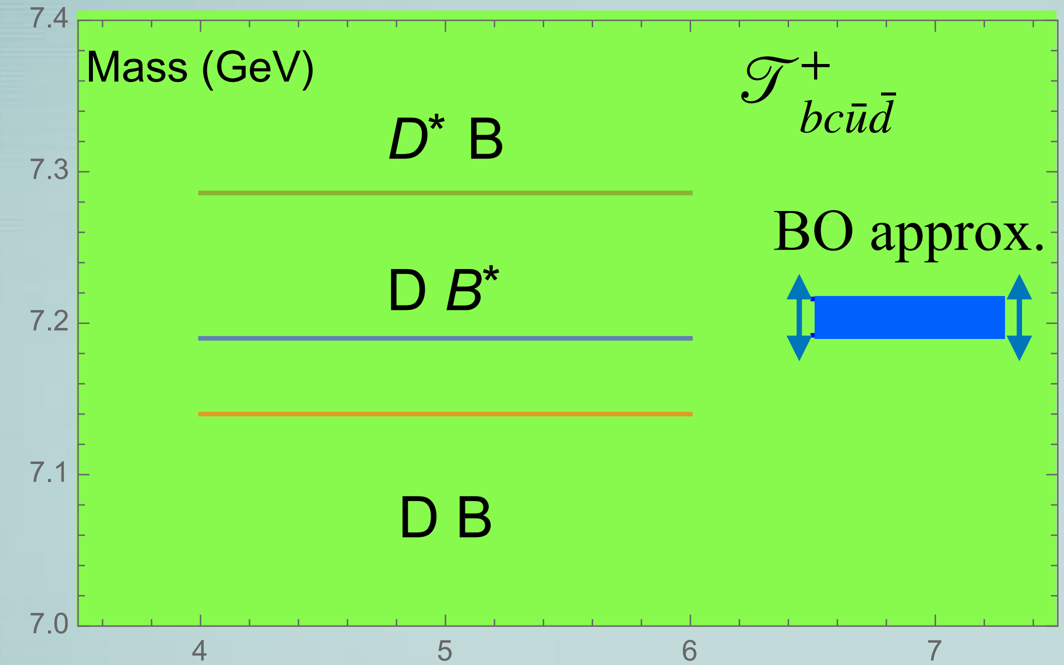

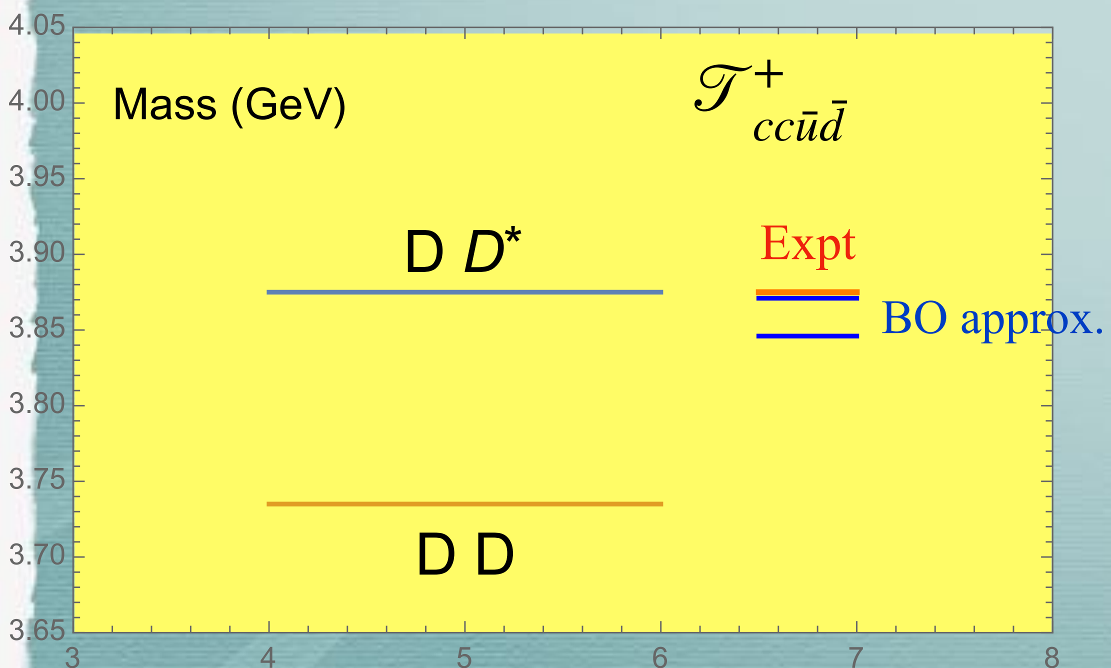

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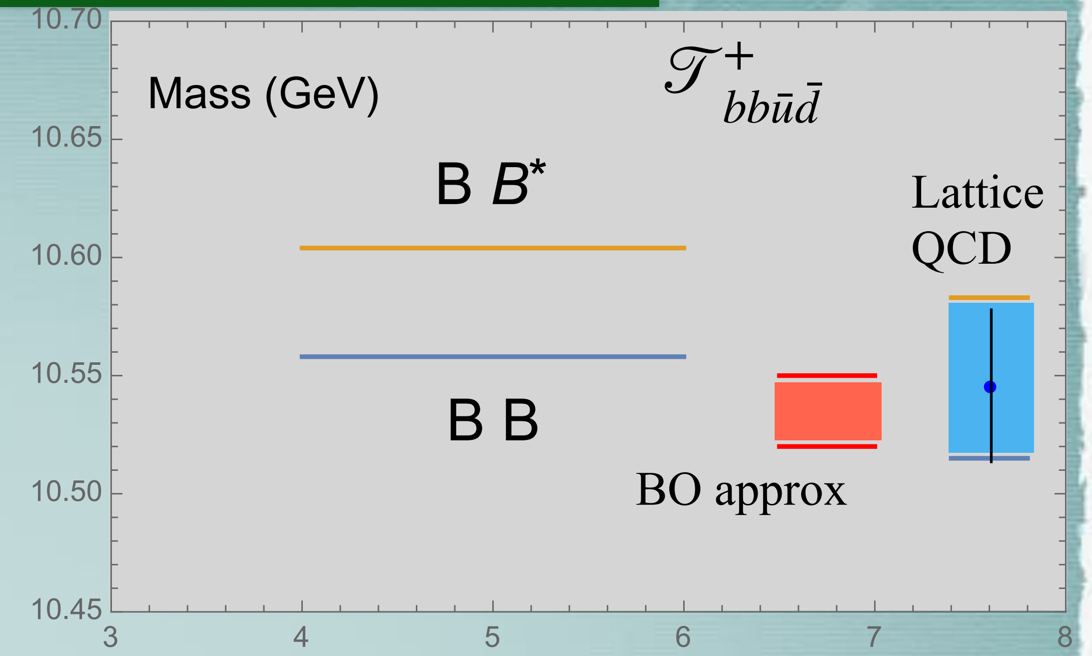
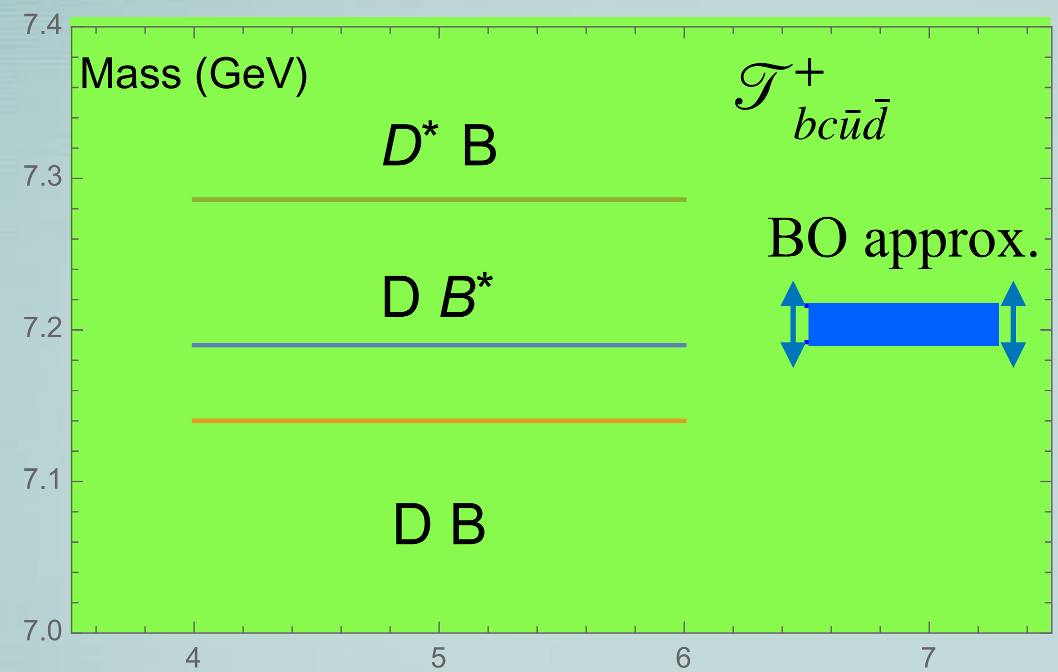
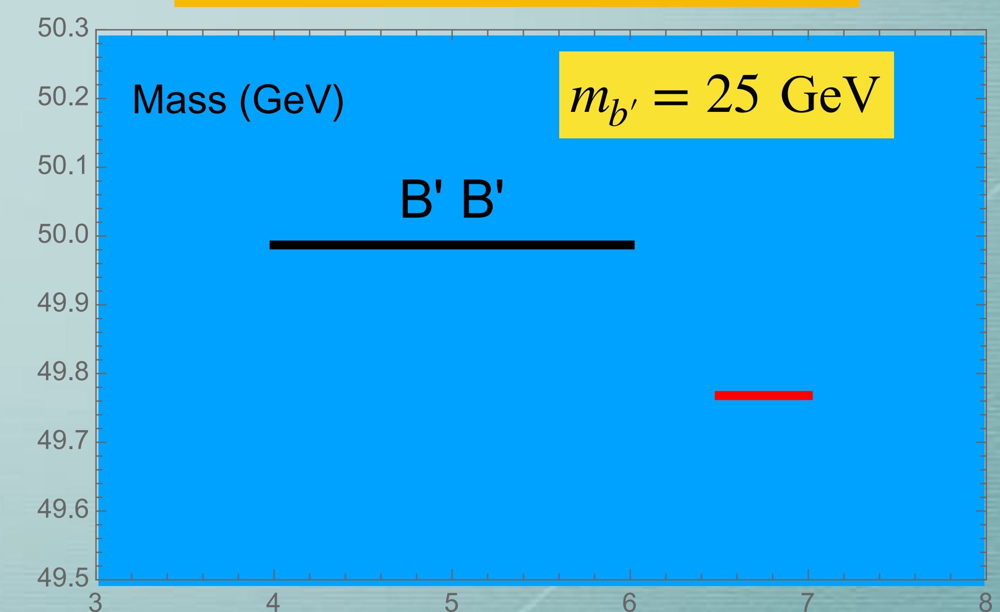
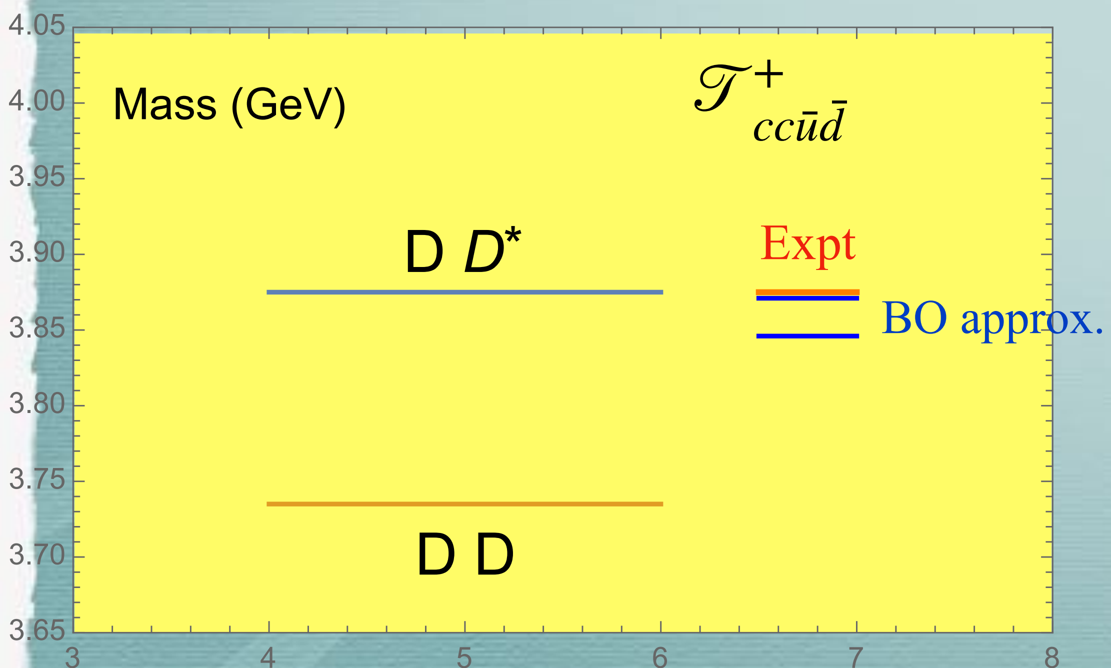




for very large b mass…
Eichten-Quigg's theorem
shows up more clearly





Is b quark mass large enough for a stable tetraquark?

Searching for a weakly decaying $\mathcal{T}_{\bar{b}\bar{b}}^{-}(1^+)$

- $\mathcal{T}_{\bar{b}\bar{b}}^{-}$ should be produced at LHCb, together with a $\bar{B}\bar{B}$ pair;
- if stable, $\mathcal{T}_{\bar{b}\bar{b}}^{-}$ should decay weakly with the b lifetime, at a ***detectable distance from the p-p interaction point***
- the expected weak decay $b \to c + \bar{c} + s$ (or $c + \bar{u} + d$) gives rise to the chain of Cabibbo allowed decays

$$\mathcal{T}_{\bar{b}\bar{b}}^{-} \to \bar{D}_s + \mathcal{T}_{bc}^{0} \to \bar{D}_s + D^{+/0} + B^{*-/0} + B \to \bar{D}_s + D + B + \gamma$$

or

$$\mathcal{T}_{\bar{b}\bar{b}}^{-} \to \ \pi^- + \mathcal{T}_{bc}^{0} \to \pi^- + D^{+/0} + B^{*-/0} \to \pi^- + D + B + \gamma$$

in total

$$p + p \to \bar{B}\bar{B} + \ldots + (\bar{D}_s + D + B + \gamma)_{(at\ a\ distance)}$$

or

$$p + p \to \bar{B}\bar{B} + \ldots + (\pi^- + D + B + \gamma)_{(at\ a\ distance)}$$

- the weak decay could produce also the tetraquark $\mathcal{T}_{bc}^{0}$ ($J^P = 0^+$), which would decay into $D + B$ without the gamma ray

6. Molecules vs Diquark-Antidiquarks

- For ***molecular tetraquarks***, in the limit of very massive charm quark, the light quark total spin is a separatly conserved quantity (this is the *light quark spin symmetry in the static heavy quark approximation* introduced by Isgur and Wise)
- For hidden charm molecules $(\bar{c}q)(\bar{q}'c)$, flavour symmetry, e.g. Isospin, is also an independent (commuting) conserved quantity. The possible combinations of light and heavy spin generate six states with definite Isospin, total angular momentum and charge conjugation:

Z. H. Zhang *et al*., arXiv:2404.11215 [hep-ph]

$$J_I^{PC} = 0_I^{++},\ 1_I^{+-},\ 1_I^{\prime +-},\ 1_I^{++},\ 0_I^{\prime ++},\ 2_I^{++}$$

- These are the same J_I^{PC} states predicted for diquark-antidiquark multiplets of the form $[cq]_S^{\bar{\mathbf{3}}}[\bar{c}\bar{q}']_{\bar{S}}^{\mathbf{3}}$, with spin S and $\bar{S}$, $J = S + \bar{S}$. Noticeably, they include the I=1 partner of $X(3872)$, i.e. X^+.

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The new molecular paradigm is not so far from a tetraquark QCD description !!??!!

A tale from the years 1970's:
Leonard Susskind in *Quark Confinement*
Cambridge University Press: 03 February 2010

By the end of the 1960s our empirical knowledge of hadrons consisted of a vast mountain of data about their spectrum, their low- and high-energy interactions, and their electromagnetic and weak properties.

To some extent the story of the eventual interpretation in terms of QCD was like digging a tunnel through the mountain with crews of diggers starting independently at the two ends.

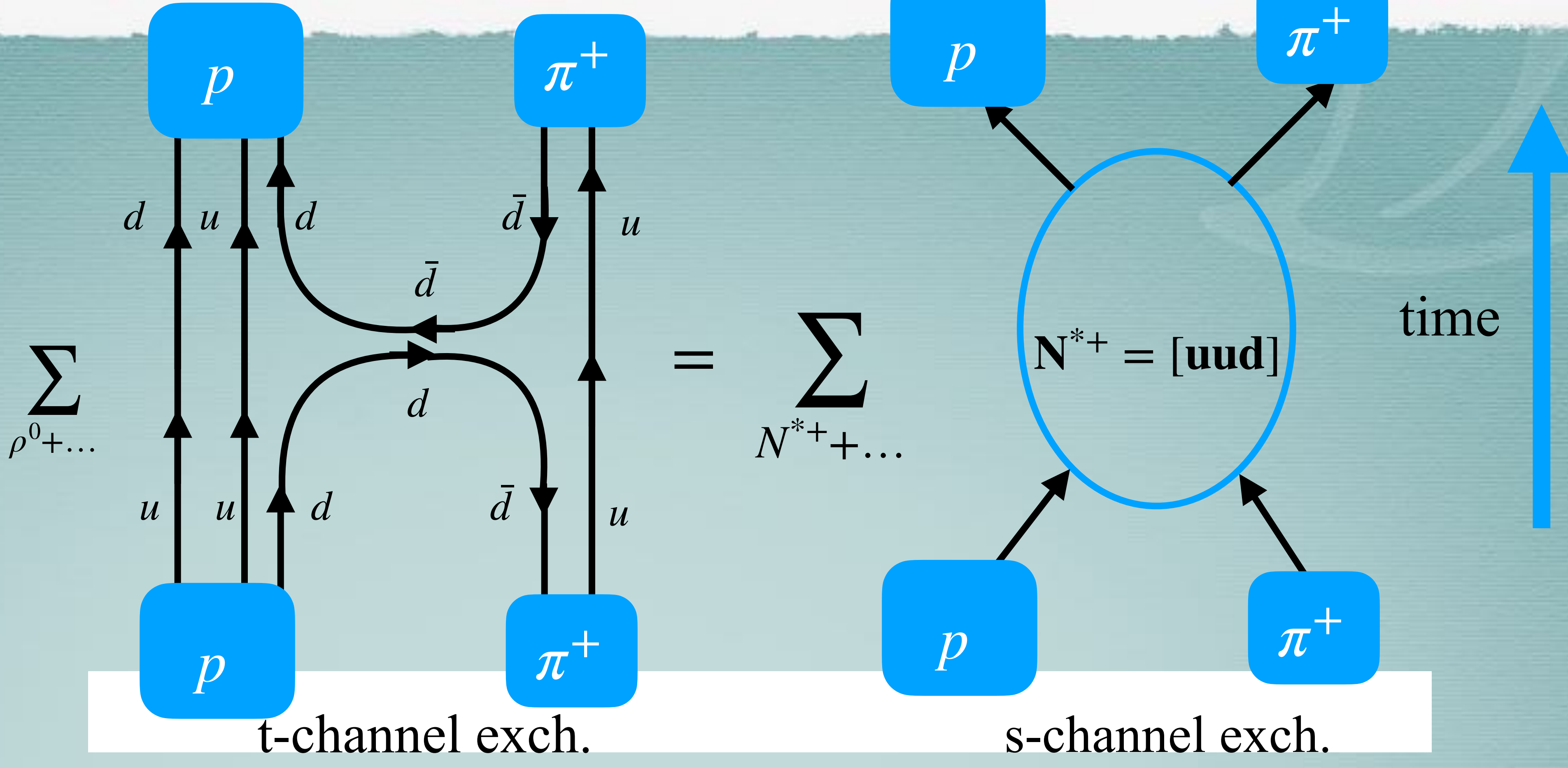
At one end was the short-distance behavior of local currents and its interpretation in terms of freely moving quark-parton constituents.

At the other end was the low-momentum-transfer Regge structure including a spectrum of highly excited rotational states…. but no free quarks.

Sometime in 1973 the two tunnel crews discovered that they had met and a complete picture of the strong interactions existed. Of course the two crews were not entirely unaware of each other.

The Regge workers were beginning to organize the trajectories by quantum numbers suggested by the quark model. Eventually, the Regge picture culminated in 1968 with a set of scattering amplitudes based on the duality principle of R. Dolen, D. Horn, and C. Schmidt.

Dolen-Horn-Schmidt duality



$$\sum_{\rho^0+\ldots} = \sum_{N^{*+}+\ldots}$$

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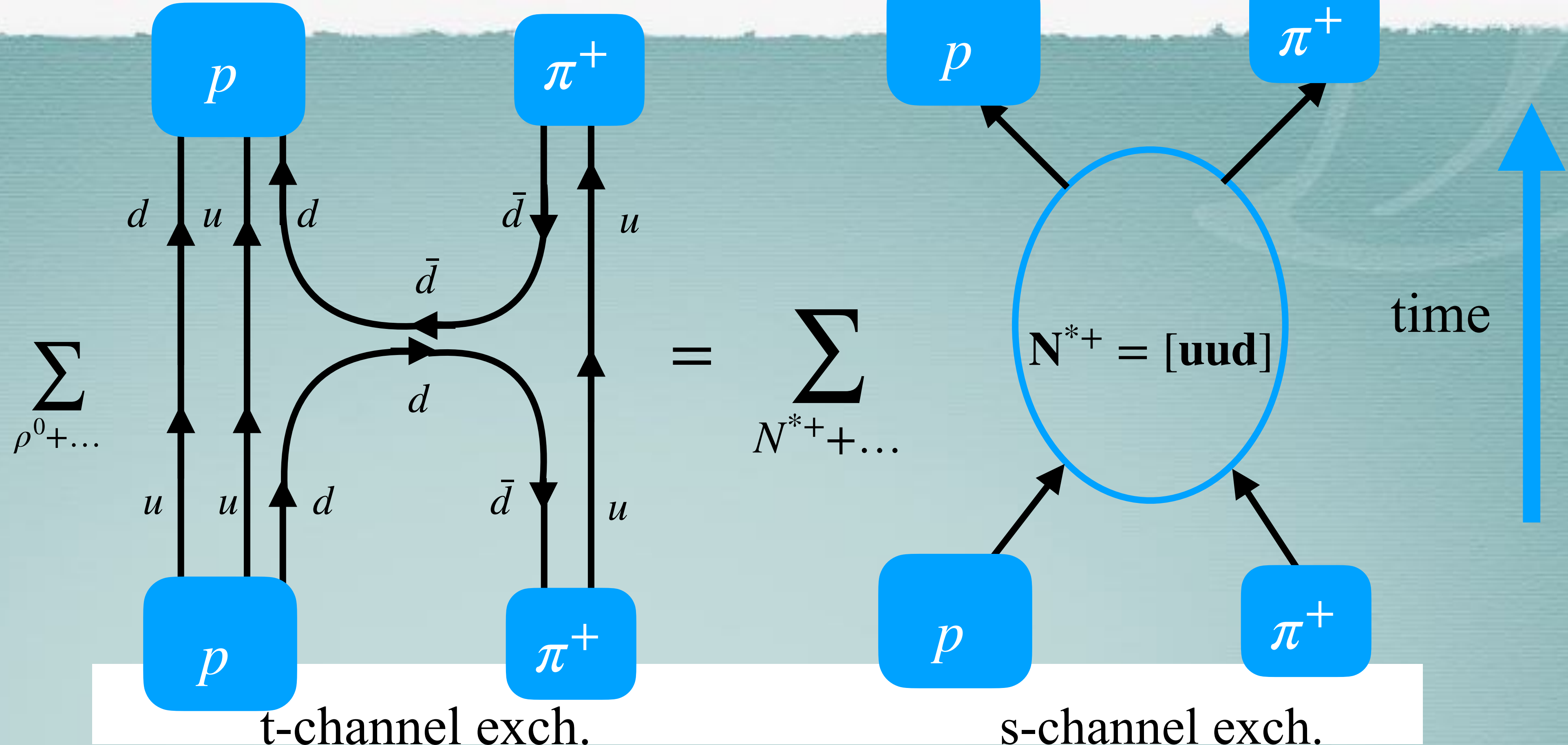

An infinite number of t-channel poles (forces) may produce s-channel poles (resonances)!
Duality is a property shared by the Veneziano Model and Large N QCD (G. 't Hooft, 1973)

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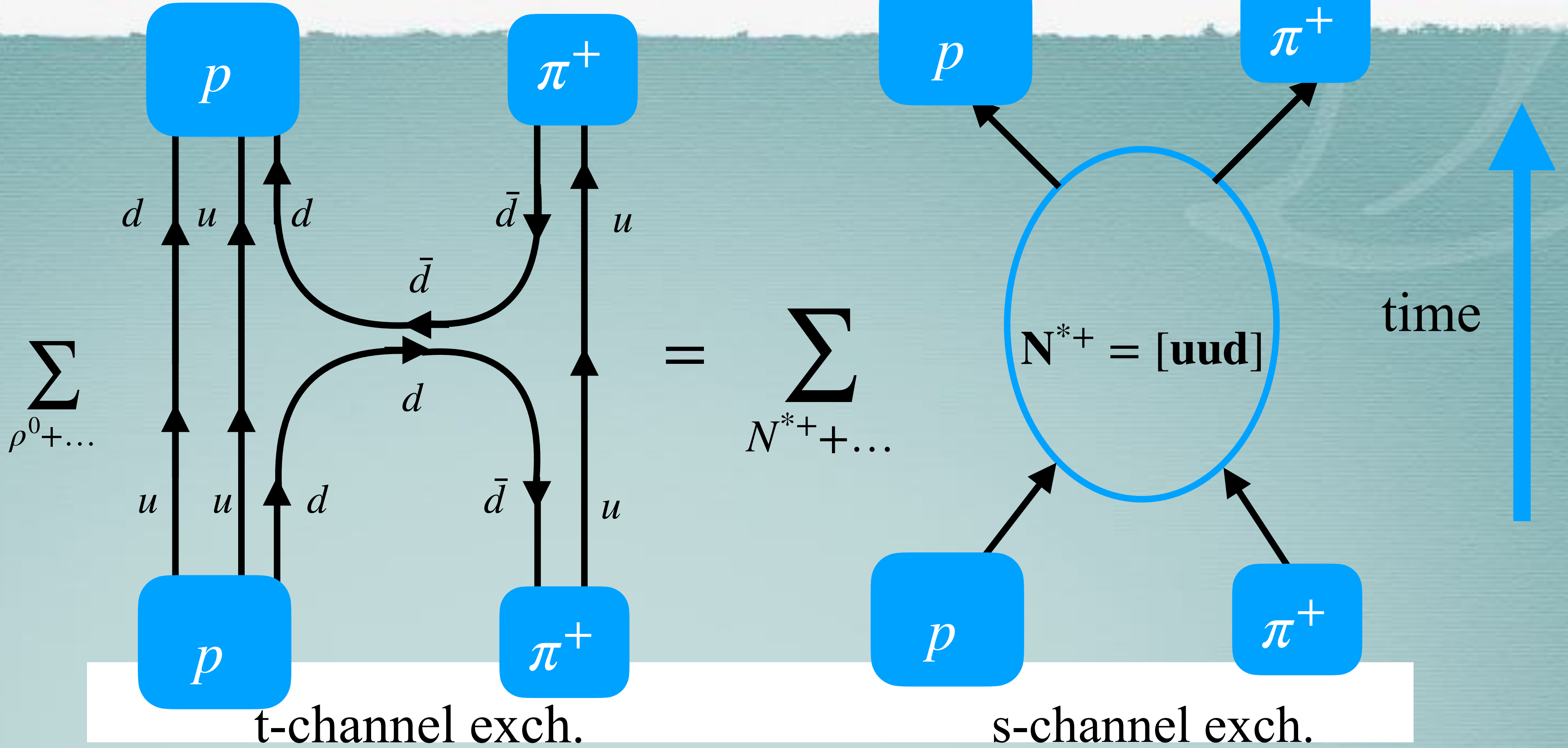

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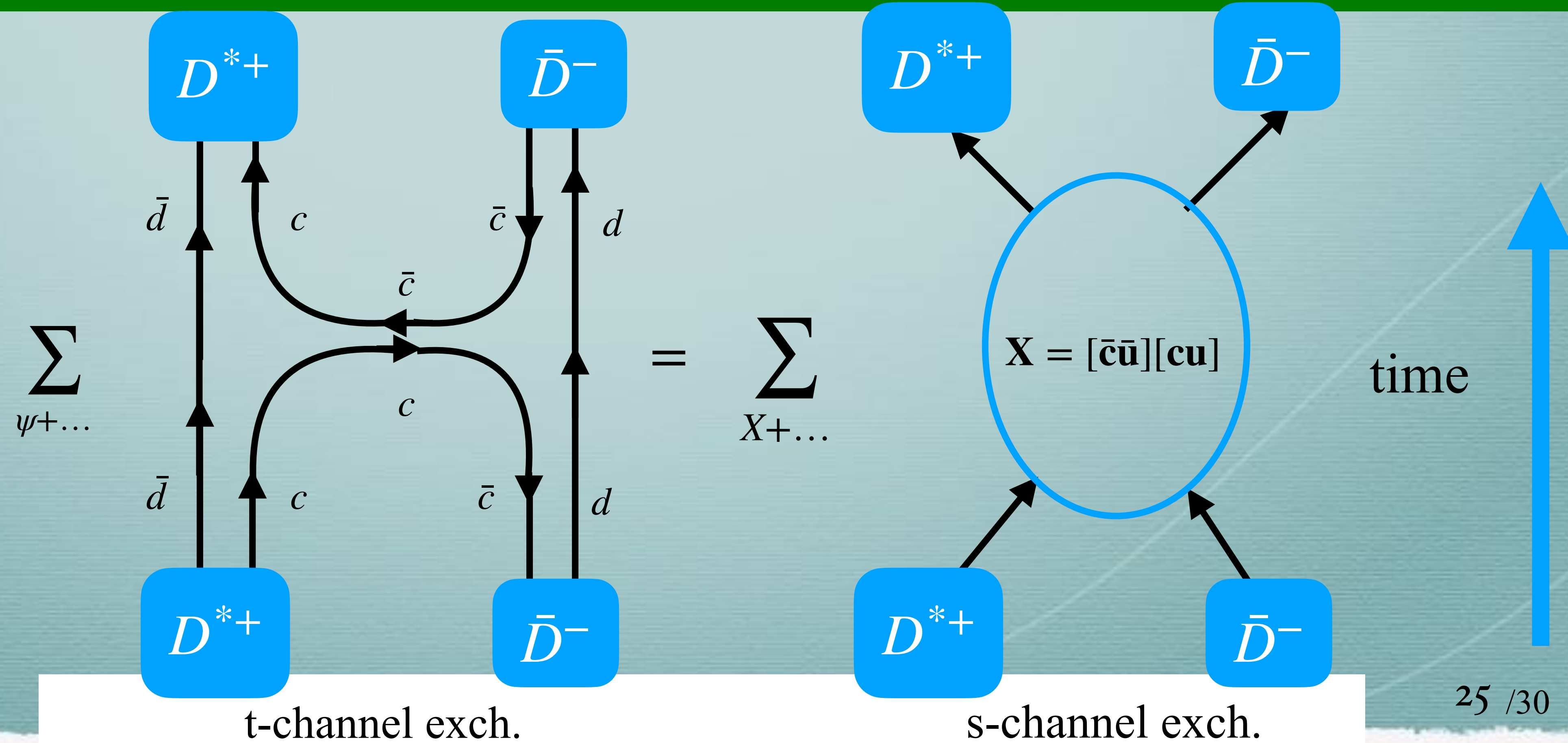
Extended to Exotics ? (Tetraquarks)



$$\sum_{\psi+\ldots} = \sum_{X+\ldots}$$

7. A few open questions for LHCb and BESIII

- Are $Z_{cs}(3986)$ and $Z(4003)$ two different states? is there a third $Z_{cs}(4220)$?

Hidden charm: complete nonets ?

- Can X^+ near $X(3872)$ be found in B decays?
- LHCb has used efficiently the channel $B \to (J/\Psi)\phi K + \ldots$to study $X_{ss}(4140)$ etc.., and Z_{cs} etc. of SU(3) nonet tetraquarks…
- Can the study of $B \to \bar{D}_s D\phi$ channel be similarly used to study single charm $[\bar{c}\bar{s}]_{S=1}[ss]_{S=0}$, $J^P = 1^+$ tetraquarks of the interesting $\mathbf{15} \oplus \mathbf{3}$, $J^P = 1^+$ multiplet ?
- Reconsider K-like states which decay into $K\phi$ (e.g. $K_1(2650)$), therefore unlikely to be $(s\bar{q})$ excited Kaons: could they be zero-charm $[\bar{u}\bar{s}][ss]$ tetraquarks?
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- ***Tough orders***: more luminosity, better energy definition, detectors with exceptional qualities… a lot of work…
- ***Close exchange between theory and experiments*** is essential and it has to continue.

Normal Science vs Revolutions
(Thomas Kuhn, 1962)

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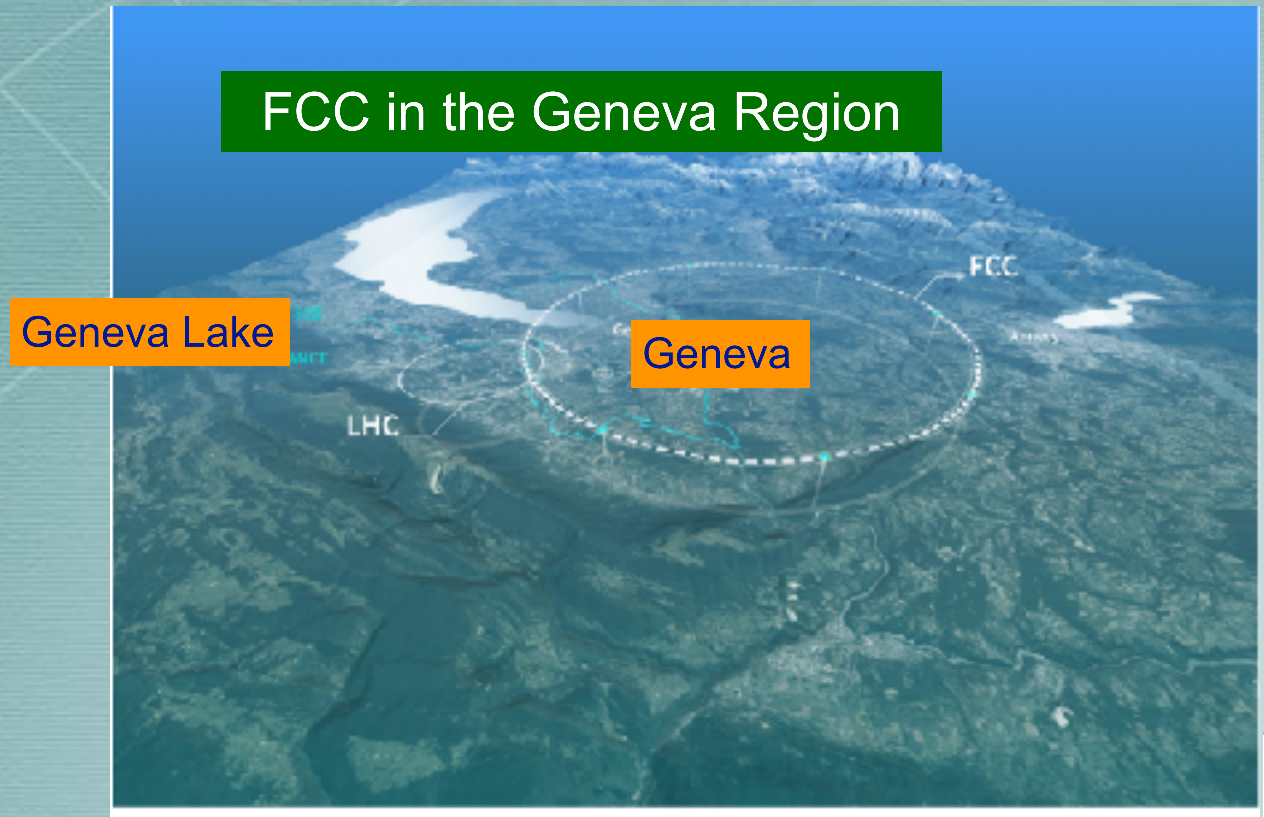
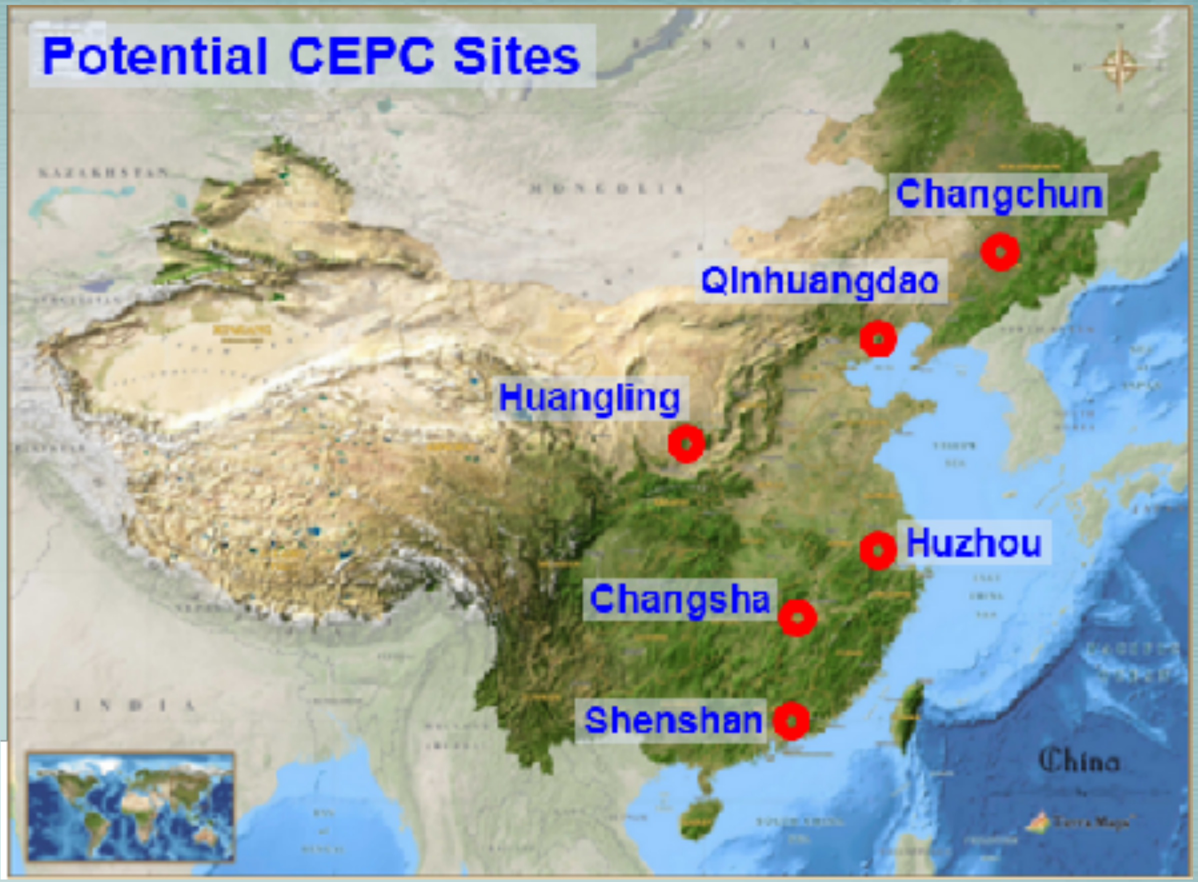
- Can MUonE data (see Piccinini *et al*) resolve the matter?
- Hints of new physics from Flavour Changing processes, $\Lambda \simeq 4$ TeV has been mentioned
- High energy search of new physics (dark Matter, Supersymmetry…) deferred to the next generation of Colliders

Dreams about the future??



A schematic map showing a possible location for the Future Circular Collider (Image: CERN)



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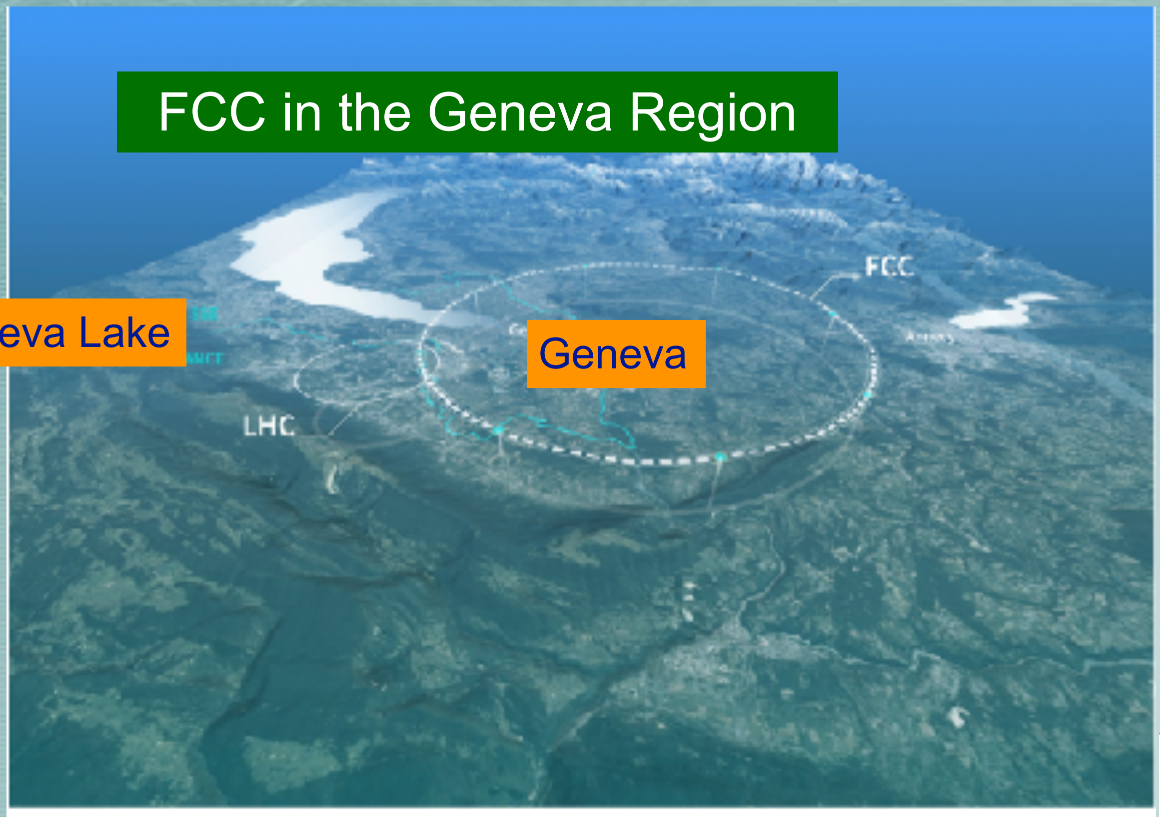

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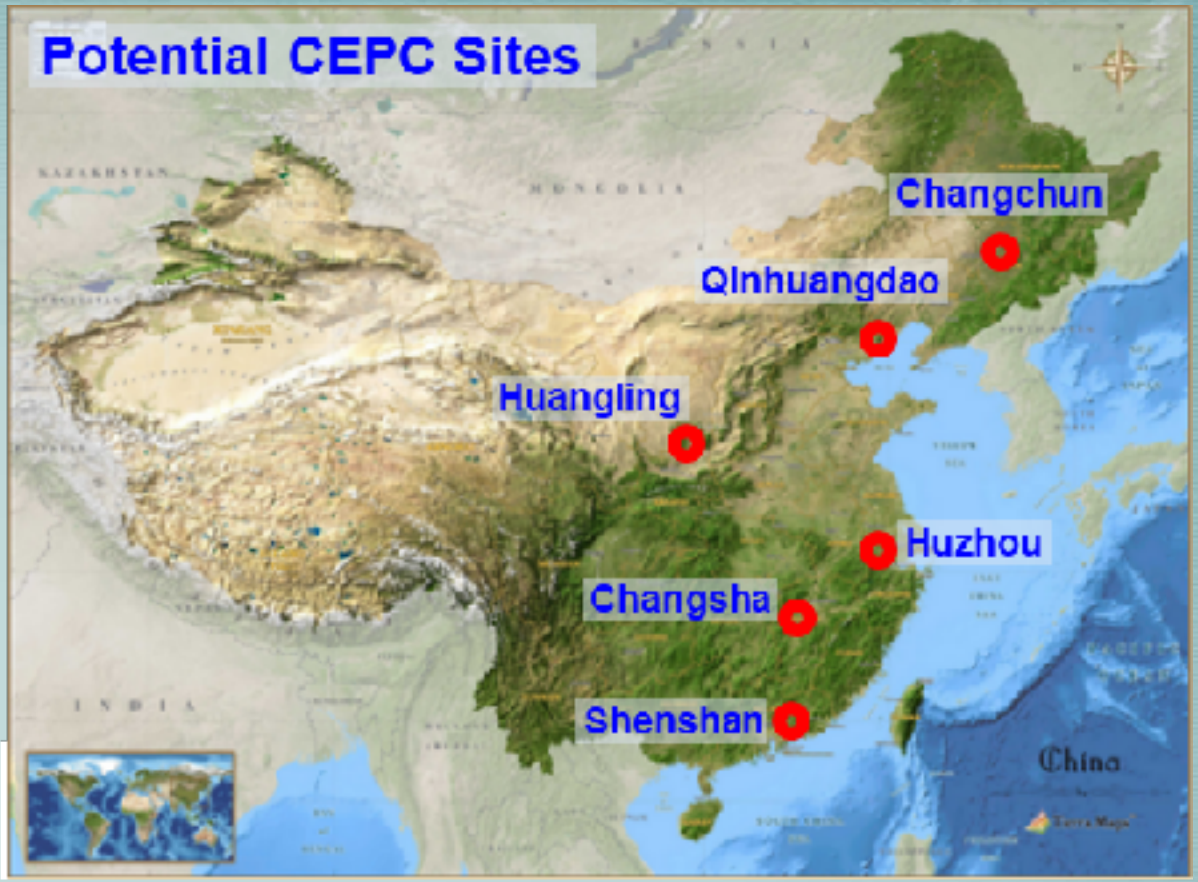

Breaking News!!!
Presented at the CERN SPC September 22
USA High Energy Choice: a Muon Collider

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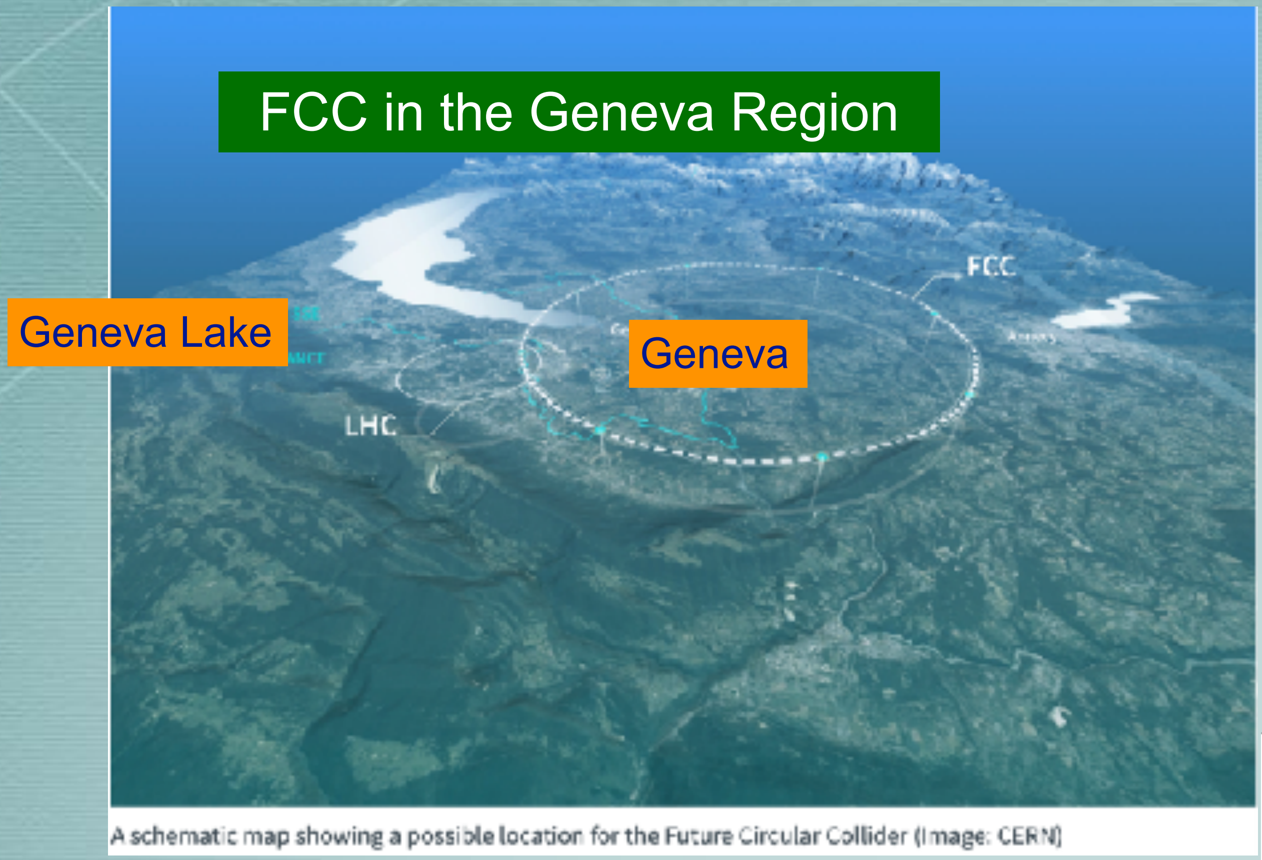

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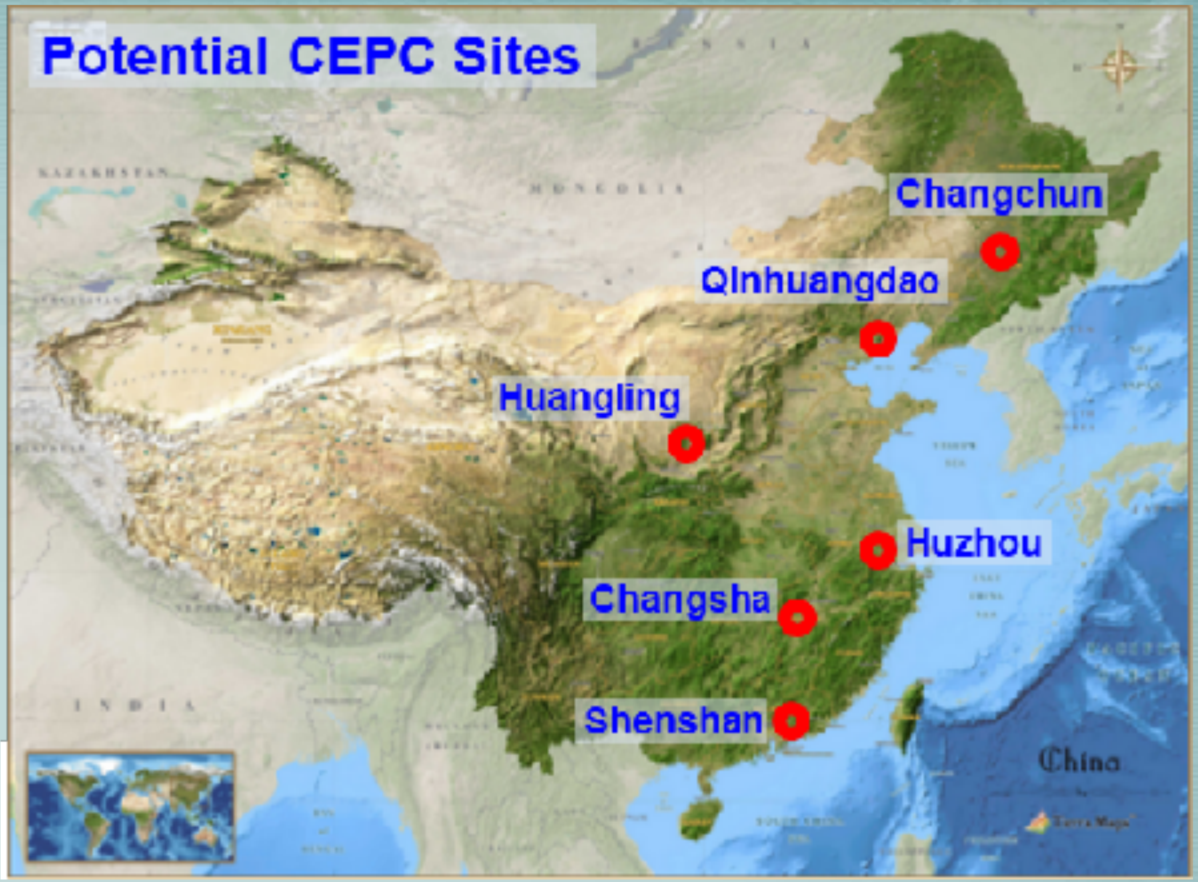

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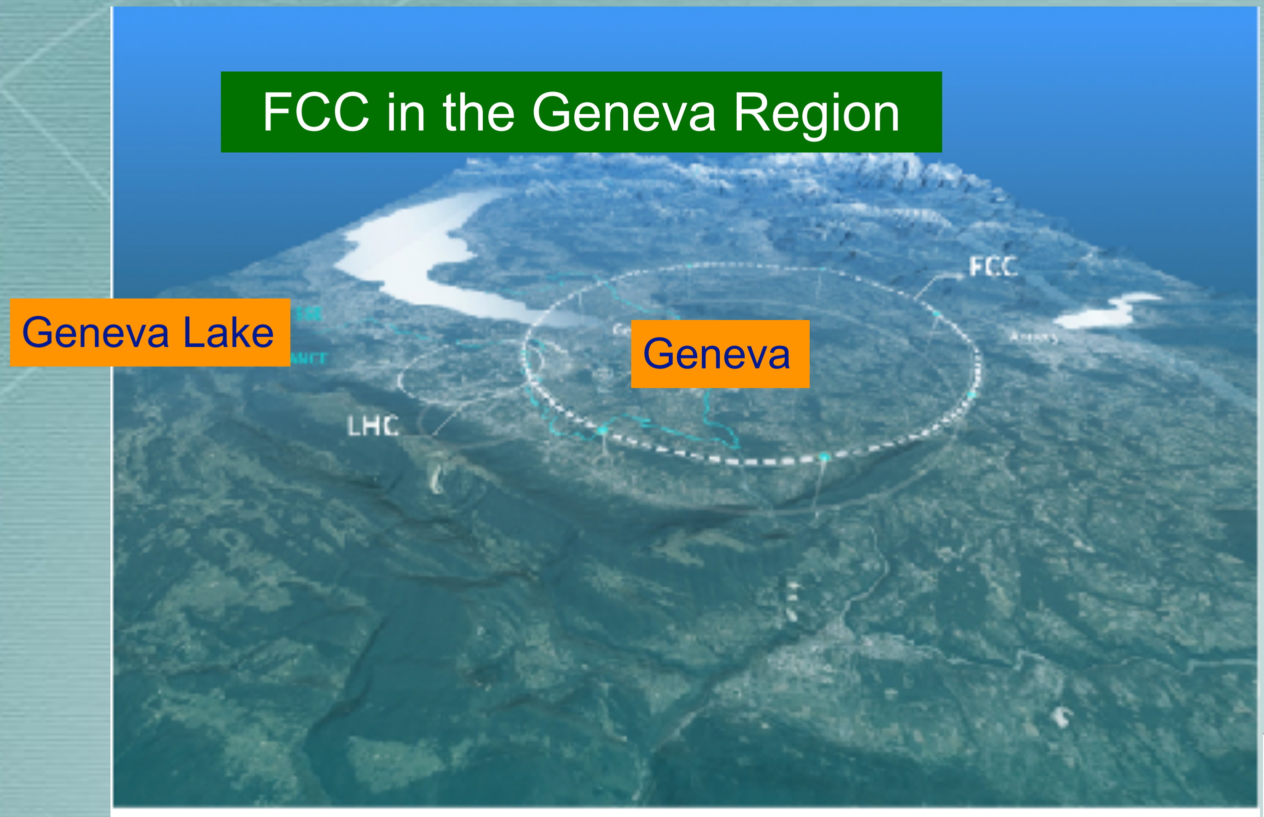
Dreams about the future??



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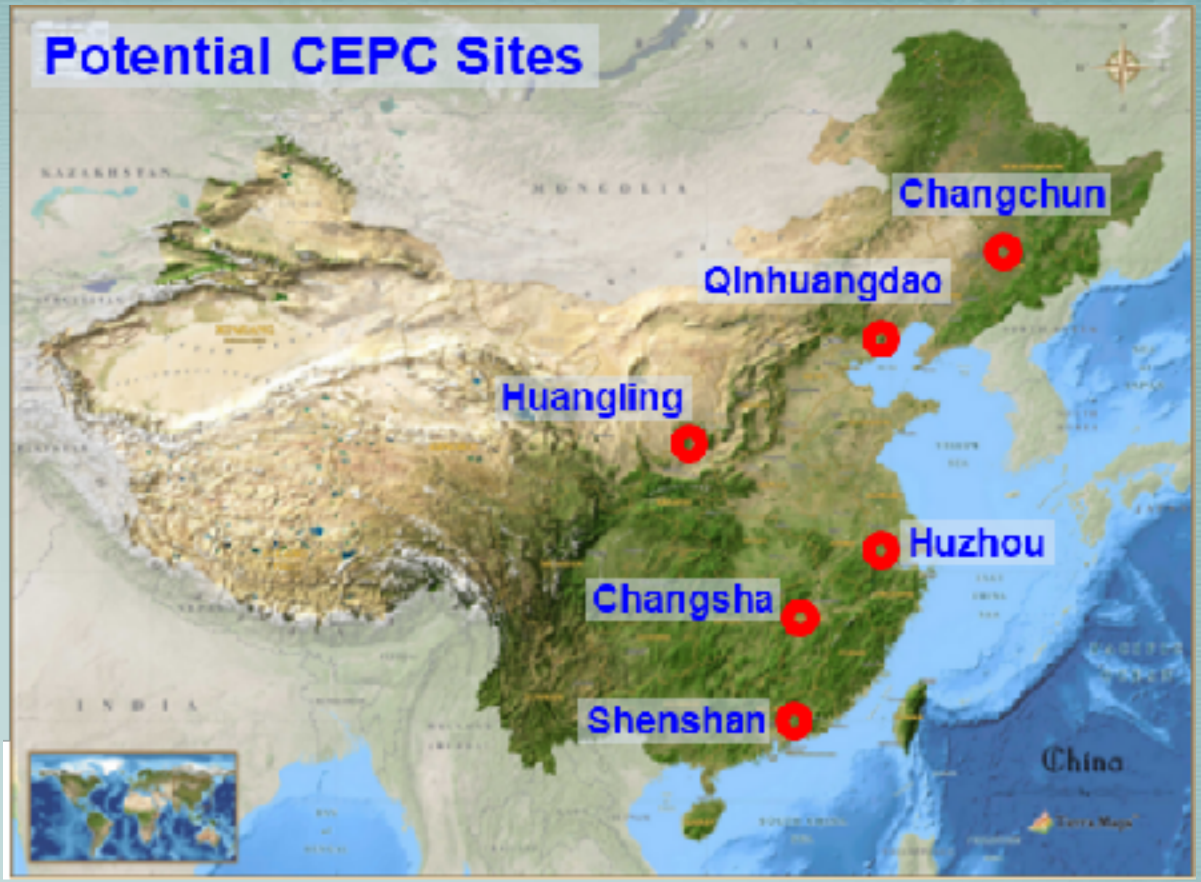

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Hopes of Globalization of Particle Physics: gone ?

Thanks !!!!