18 November 2024
LNF - INFN

The November J/Ψ Revolution Fifty Years Later with a Look to the Future

The J/Psi and the Standard Model

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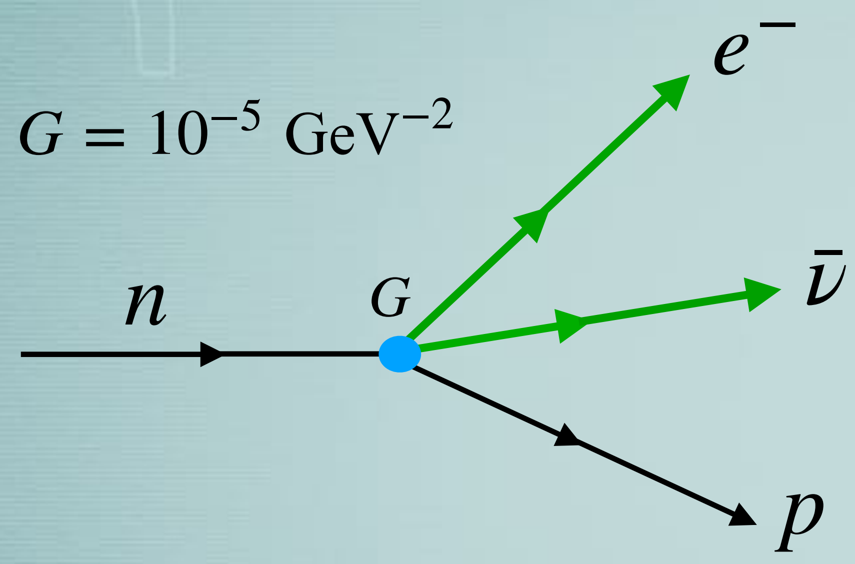
1. The Neutrino Puzzle

• In 1933, after the discovery of the neutron as a component of the atomic nuclei and following the neutrino hypothesis by W. Pauli, E. Fermi proposed a theory of

β-radioactivity as due to the decay:



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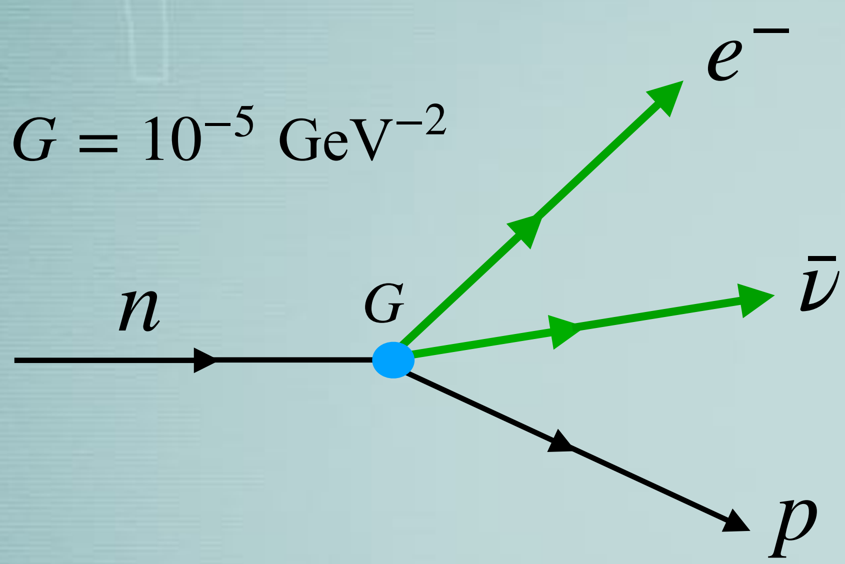

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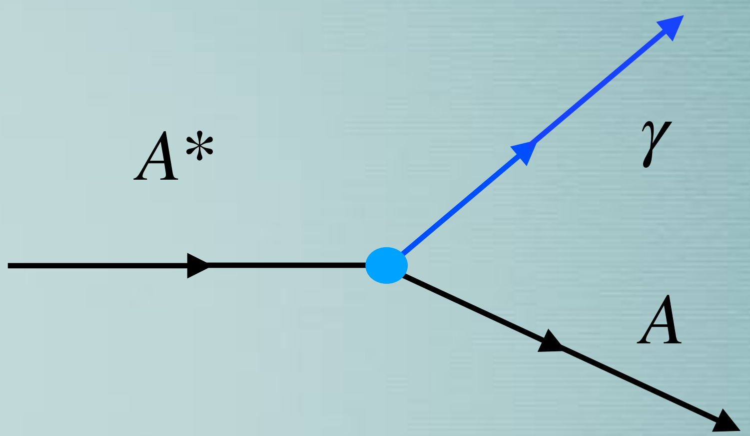

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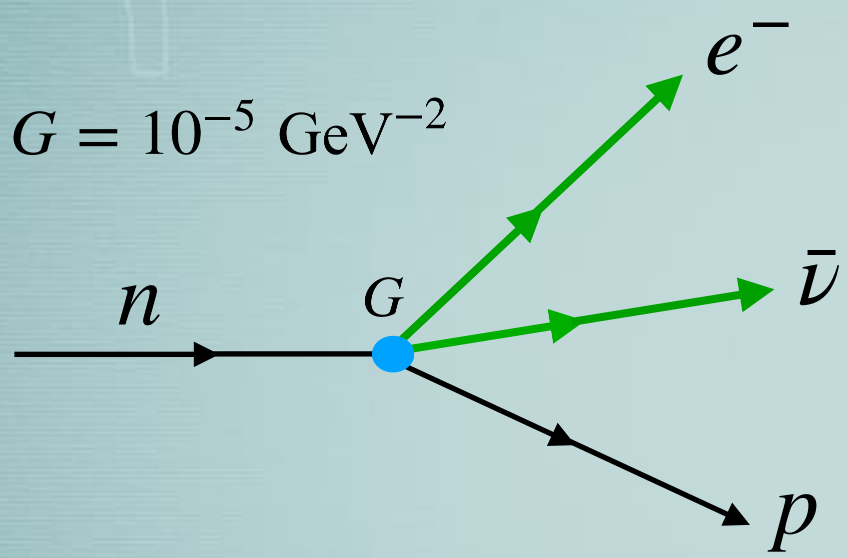

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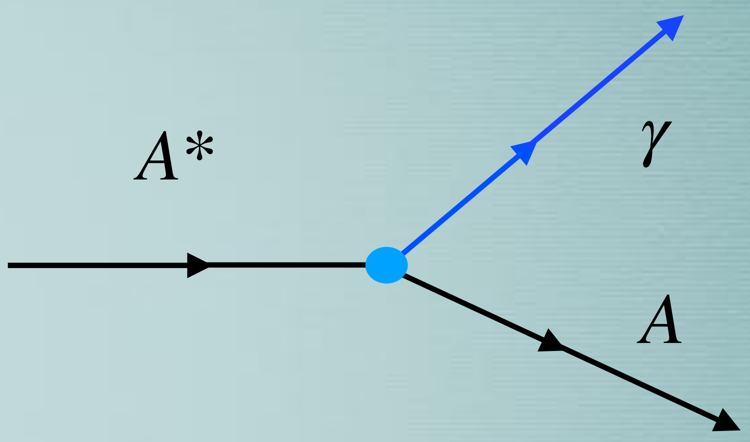

- The process is regulated by a very small coupling, the Fermi constant G
- Accordingly, neutrino has a very ***weak interaction*** with matter

However, if you have a very intense flux of neutrinos, as in a nuclear reactor, you may observe events of the inverse beta decay process: $\bar{\nu} + p \to e^+ + n$ (Reines and Cowan,1953).

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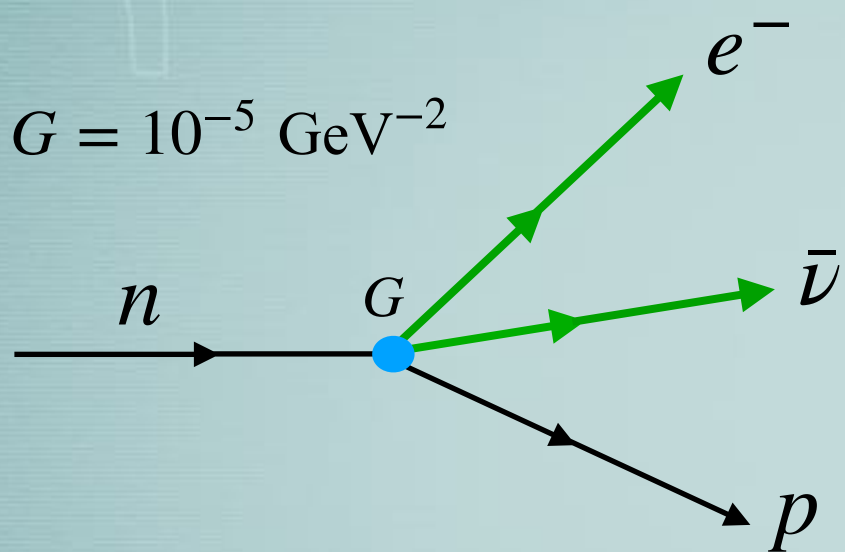

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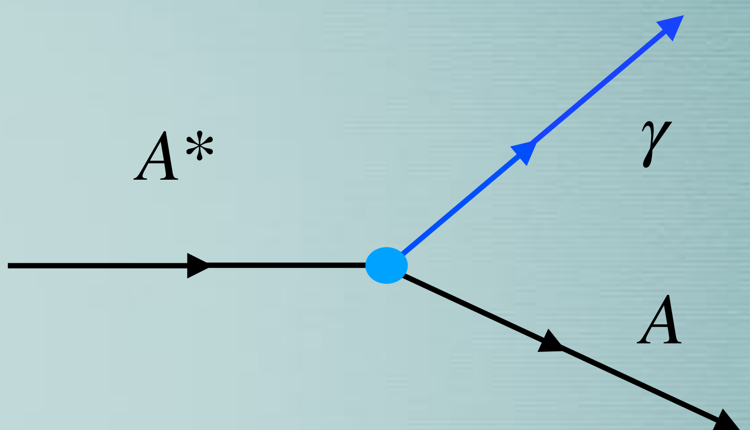

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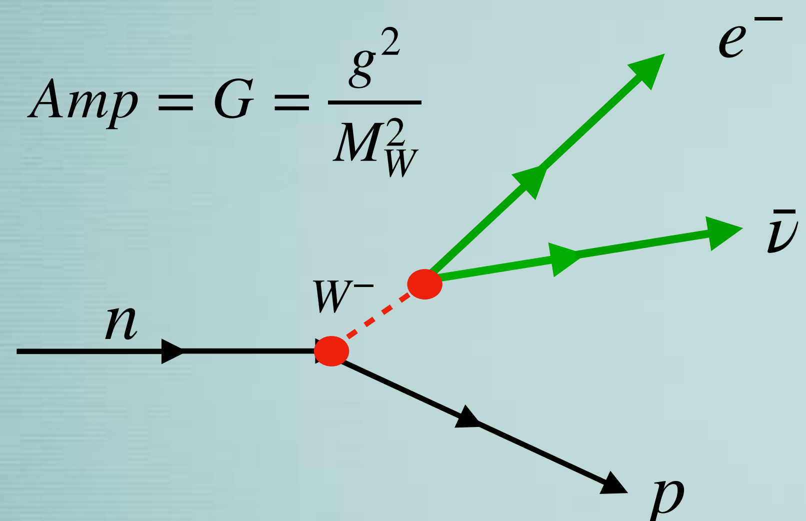
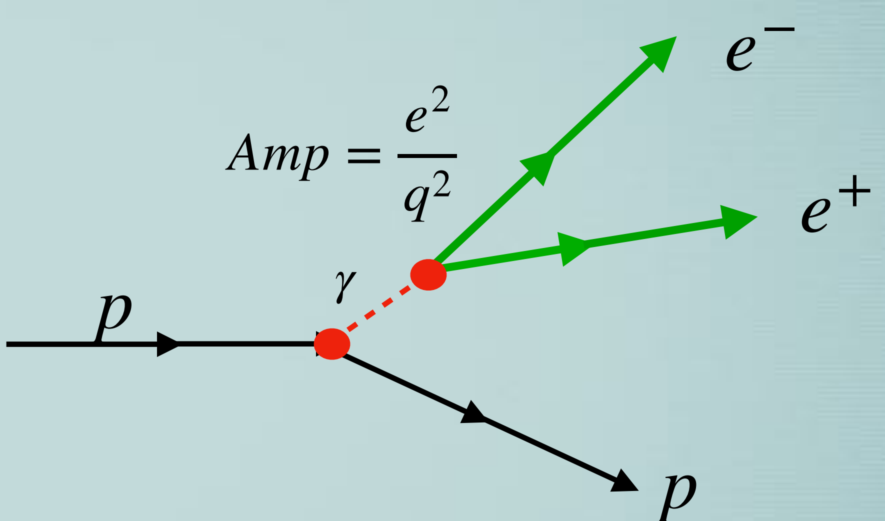
Neutrino is a real particle, not a ghost!!

2. Towards a Unified Theory of Electromagnetic and Weak Interaction

- Fermi made his theory *in analogy* to electromagnetism.
- The first step toward *real* unification was the hypothesis that Weak Interactions are transmitted by a new particle called *the Intermediate Vector Boson.*
- To reproduce Fermi theory IVB has to have a very large mass





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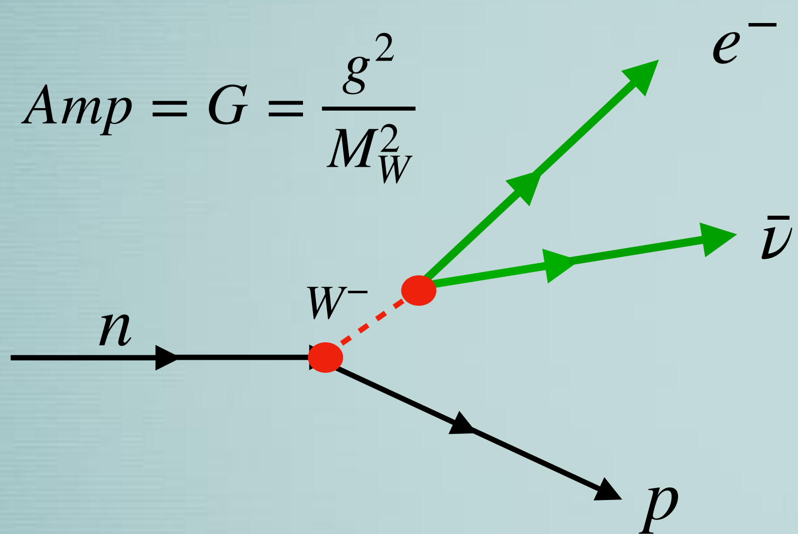
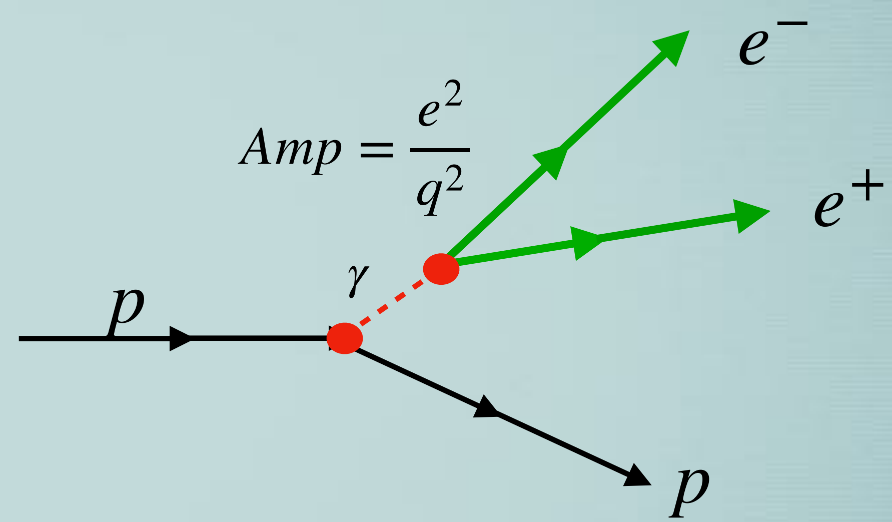




- After first suggestions by Julian Schwinger, in 1961 Sheldon Glashow proposed a Unified Theory ***with 4 intermediaries***: W^+, W^-, Z^0, γ. The theory was able to describe W&E.m. interactions of electrons and muons;
- the theory predicted new fenomena, like the existence of neutrino reactions in which a neutrino appears in the final state (***neutral current processes***), instead of transforming into a charged lepton as in the inverse beta decay (***charged current processes***).

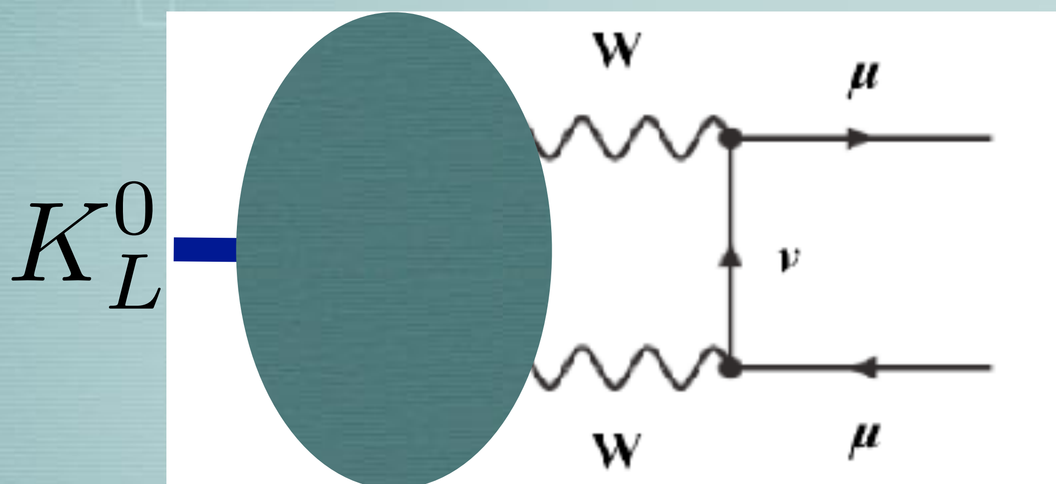
Unified Theory of Electromagnetic and Weak Interaction (cont'd)

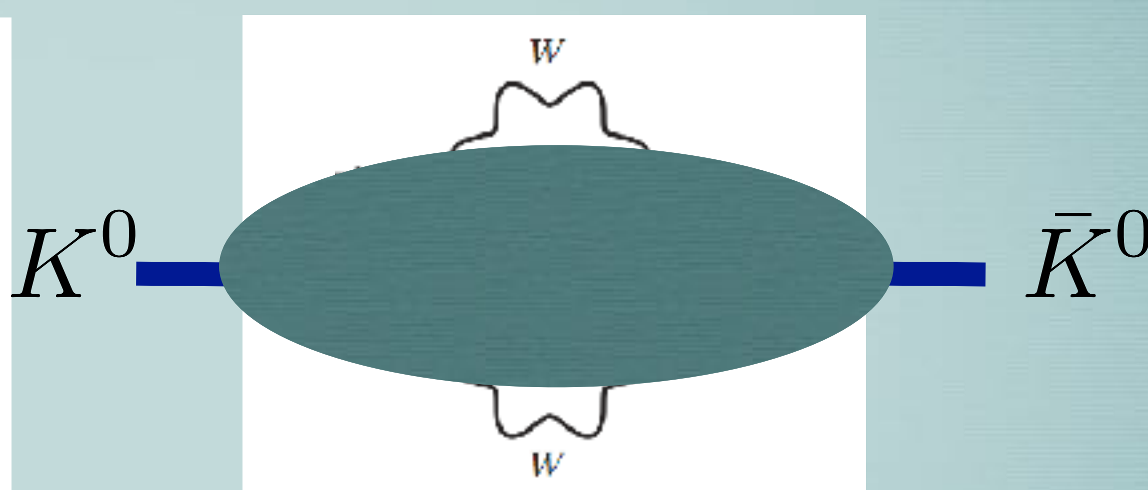
The 1961 Glashow theory left 4 questions open. ***The answers led to the present Unified Standard Theory of Electro-Weak Interactions:***

1. Can we give a mass to the IVB leaving the photon massless?
   Weinberg & Salam, 1967: mass generated by the Higgs -Brout-Englert mechanism, leaving a new, scalar, boson called by Weinberg"the Higgs Boson";
2. Can we extend the interaction to the hadrons, i.e with a coupling of the neutral Z^0 in agreement with the observed strong suppression of $K \to \mu^+\mu^-$?
   Glashow, Iliopoulos & Maiani: the GIM mechanism, 1970, introducing a new quark and the corresponding charmed particles, does just that;
3. Can we obtain a mathematically consistent (renormalizable) quantum theory like QED?
   Proved by G. 't-Hooft & M. Veltman, 1972
4. Can we describe the Matter-Antimatter asymmetry observed in K decays?
   Kobayashi and Maskawa, 1973: yes, introducing a third quark and lepton generation

3. A personal recollection, 1969-1970

- The discussion on higher order weak interactions was opened in 1968 by a calculation by Boris Ioffe and Evgeny Shabalin, indicating that $\Delta S = \pm 1$ neutral currents and $\Delta S=2$ amplitudes would result from higher order weak interactions, ***even in a theory with only T charged W coupled in Cabibbo's way***





Amplitudes were found to be divergent, of order $G(G\Lambda^2)$, and in disagreement with experiments, unless limited by an ultraviolet cut-off

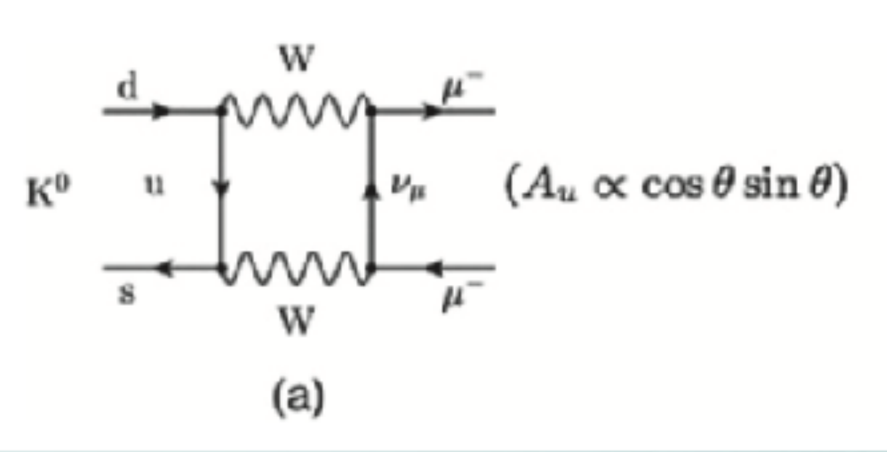
$\Lambda \approx$ 3-4 GeV (from Δm_K);

- Similar results were found by R. Marshak and coll. and by F. Low.
- The exceedingly small value of the cut-off raised a wide discussion.

Discussions at Harvard (1969-70)

L.Bonolis, L. Maiani, Eur. Phys. J. H **42** (2017) 611

- The Ioffe-Shabalin problem was still on the table in November 1969, when I moved to Harvard and met with John Iliopoulos, at work with Shelly Glashow on the $G\Lambda^2$ corrections
- So, we discussed for long, usually two of us arguing against the one at the blackboard, apparently getting nowhere.
- But during our discussions *a change in paradigm occurred*. Previous works had been done in the framework of the “algebra of currents”, but slowly we began to phrase more and more our discussion in terms of quarks.
- In quark language, the Ioffe-Shabalin problem for $K_L \to \mu^+\mu^-$ is represented by the box diagram in the Figure. The divergent amplitude is proportional to the product of the couplings of quarks d and s to the u quark, equal to $\cos\theta \sin\theta$, as required by the Cabibbo theory



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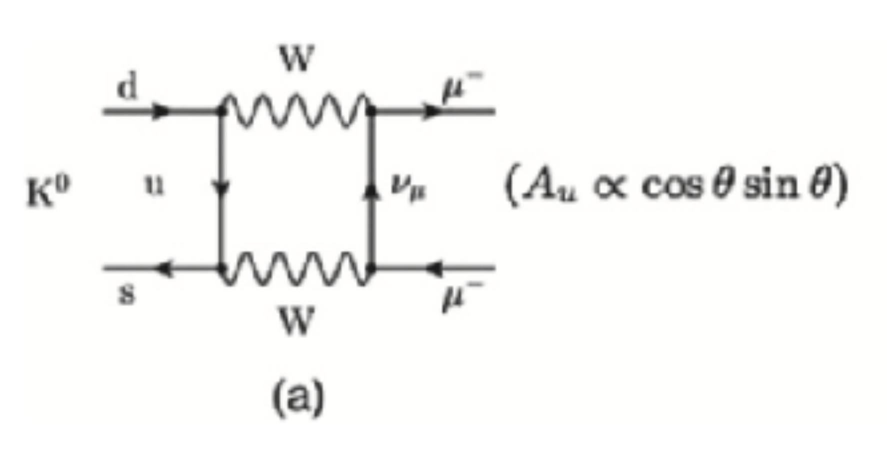


- By January 1970 we got convinced that we had to modify the weak interaction theory. ***Once we realised that, the solution was just under our eyes.***
- A fourth quark of charge +2/3, called the *charm* quark, had been introduced by Bjorken and Glashow (and others), for entirely different reasons.
- In the weak interaction, the charm quark is coupled to the s_C quark left out in the Cabibbo theory. c-quark exchange ($A_c \propto -\sin\theta\cos\theta$) cancels the singularity and produces an amplitude of order $G[G(m_c^2 - m_u^2)]$ (GIM mechanism):

Ioffe's cutoff becomes the prediction: $m_c \sim 1.5$ GeV

CERN Courier, March/April 2020

CULTURE AND HISTORY | **MEETING REPORT**

50 years of the GIM mechanism

24 January 2020

Hong-Jian He, John Ellis, John Iliopoulos, Sheldon Lee Glashow, Verónica Riquer and Luciano Maiani at a celebration of 50 years of the GIM mechanism in Shanghai. Credit: J Liu

4. Experimental Discoveries

- **1973.** The Gargamelle Collaboration led by the French physicist Andrè Lagarrigue, operating the heavy liquid, large bubble chamber exposed to the high energy CERN ν_μ beam, observes *muonless neutrino events:* events in which a hadronic jet is produced without an energetic muon track, interpreted as the neutral current process:

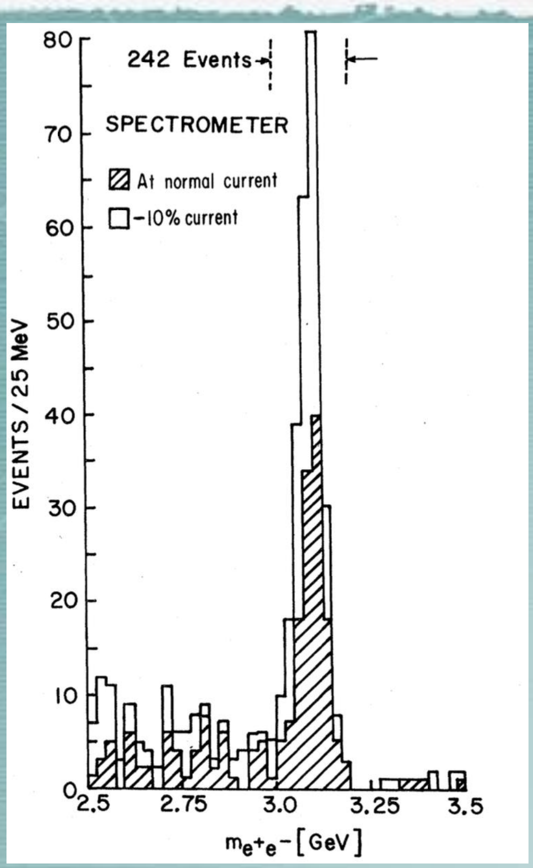
$$\nu_\mu + N \to \nu_\mu + \text{hadrons}$$

- The Collaboration observed also events with an isolated electron track, interpreted as:

$$\nu_\mu + e \to \nu_\mu + e$$

- **1974.** The Fermilab Neutrino Experiment led by Carlo Rubbia announced the observation of "*two-muon neutrino events*". It was the first positive indication of the existence of a new quark flavour produced off the nucleons in the transition (the first muon in the final state) and enough stable to decay semileptonically (the second muon):

$$\nu + d \to c + \mu^- \to s + \nu_\mu + \mu^+ + \mu^-$$



1974. The November Revolution

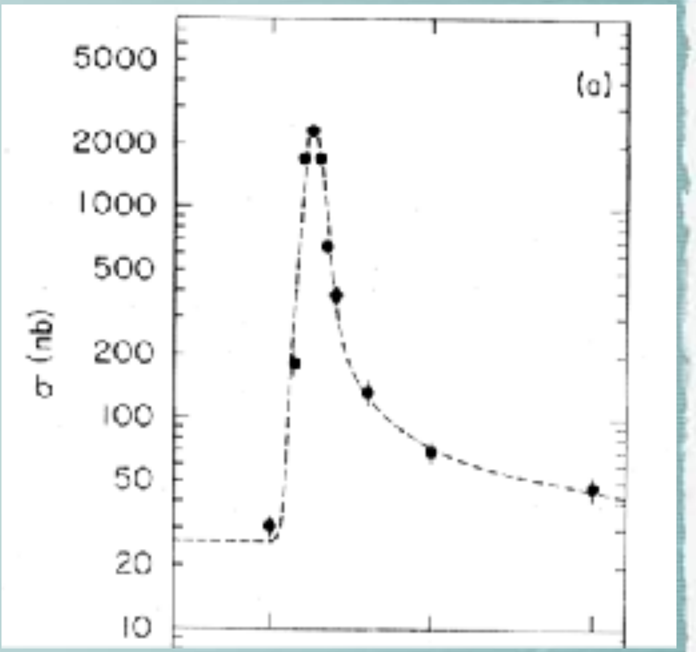
J.J. Aubert *et al.* PRL **33**, 12 Nov.1974

$p + p \to e^+ + e^- + \ldots .$ $\quad M = 3.1\ \text{GeV},\ \Gamma \sim 100\ \text{KeV}!!$

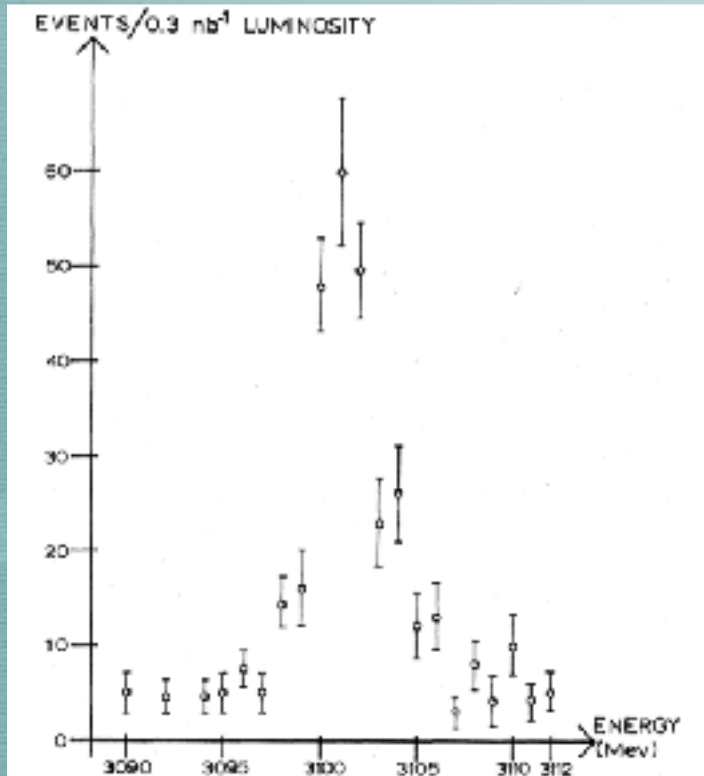
The most striking feature of J is the possibility that it may be one of the theoretically suggested charmed particles[2] or a's[3] or Z_0's,[4] etc.

J.E. Augustin *et al.* PRL **33**, 13 Nov.1974

$e^+ + e^- + \to$ hadrons



It is difficult to understand how, without involving new quantum numbers or selection rules, a resonance in this state which decays to hadrons could be so narrow.

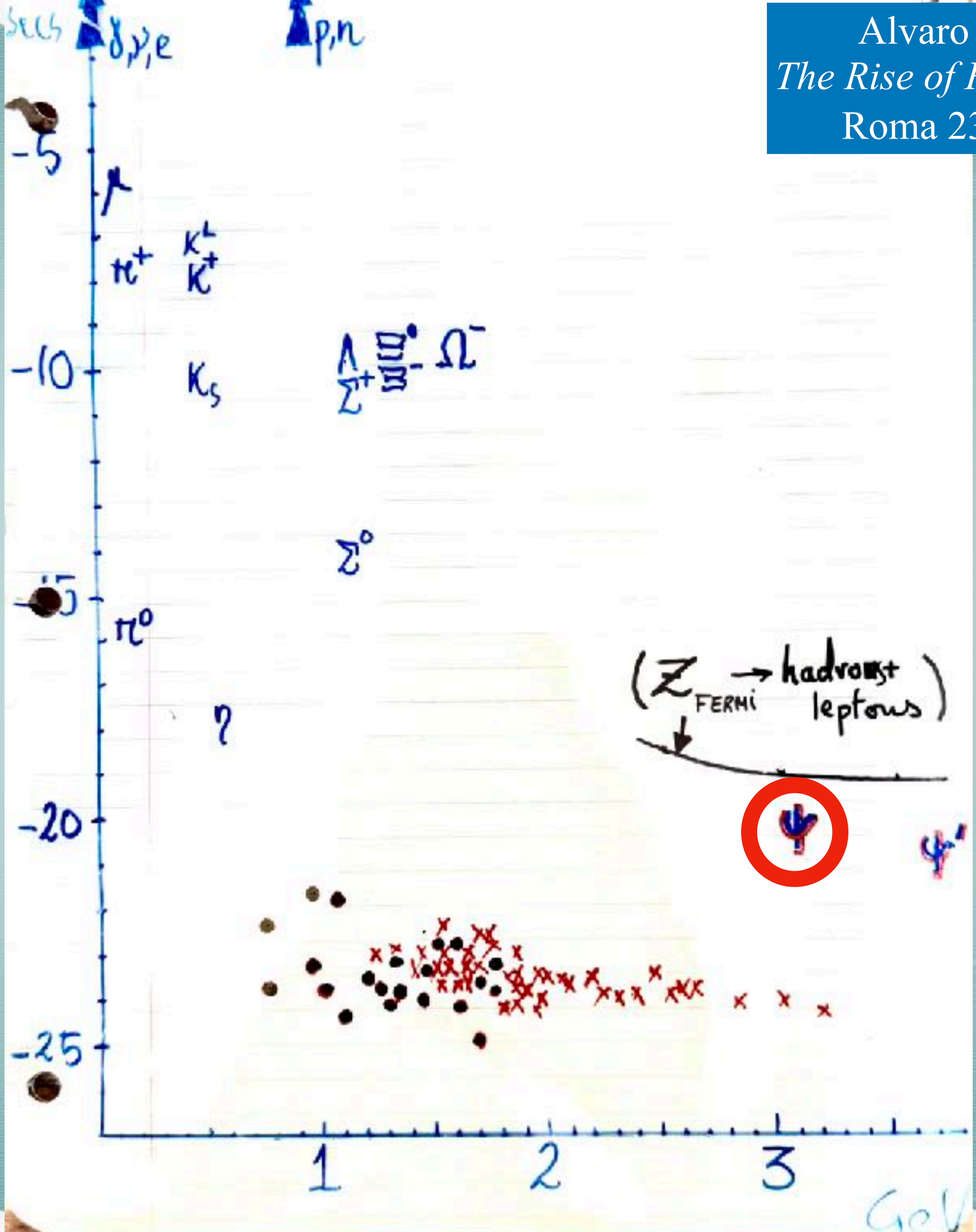


Confirmed by Adone (Frascati)

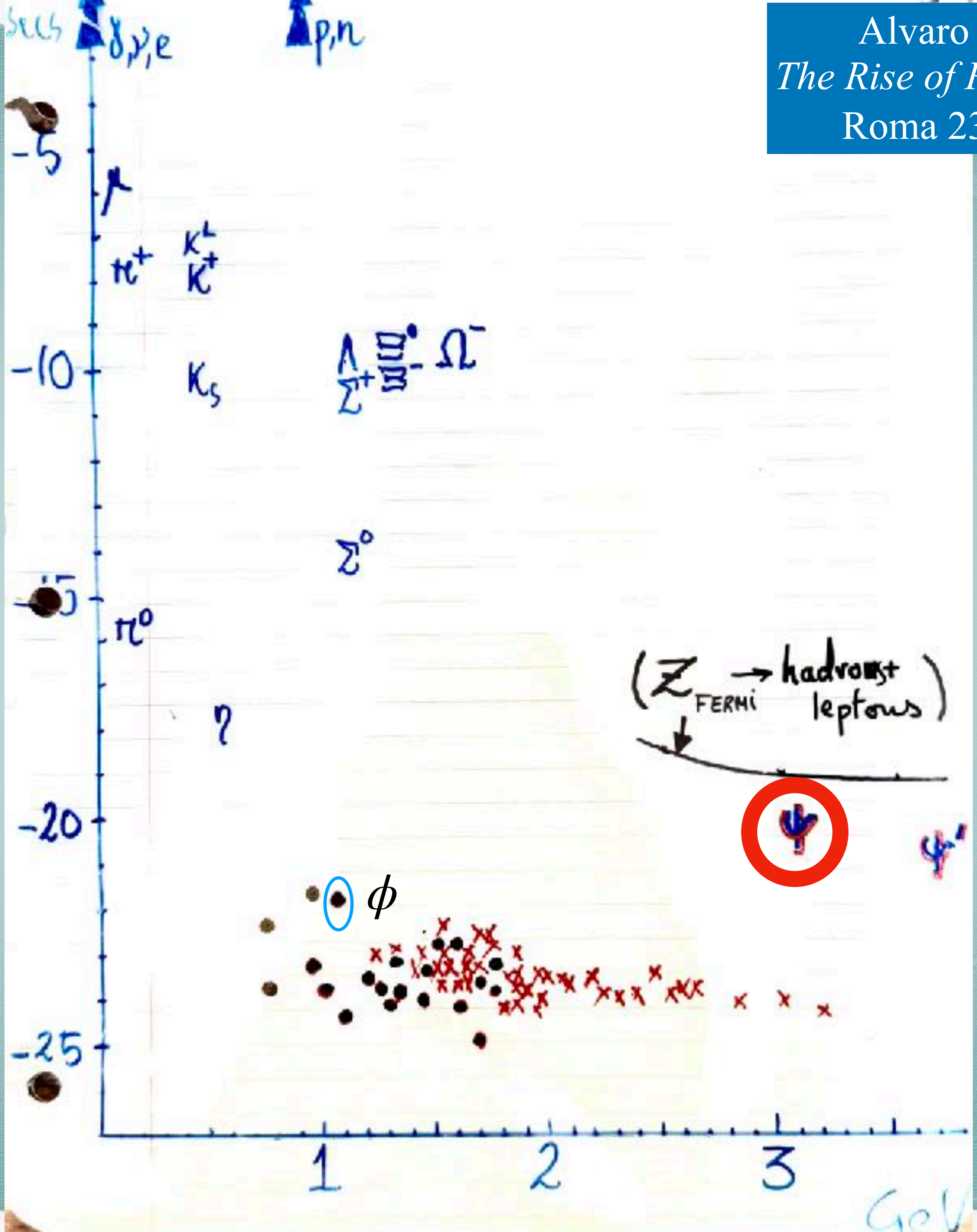
C.Bacci *et al.* PRL **33**, 18 Nov.1974

$e^+ + e^- + \to$ hadrons

Soon after the news that a particle of 3.1 GeV with a width consistent with zero had been observed at Brookhaven National Laboratory by the Massachusetts Institute of Technology group,[1] it was immediately decided to push ADONE beyond its nominal limit of energy (2×1.5 GeV) to look for this particle.


γ, ν, e
p, n
-5
-10
-15
-20
-25
π⁺
K^L
K⁺
K_S
Λ
Σ⁺
Ξ⁰
Ξ⁻
Ω⁻
Σ⁰
π⁰
η
(Z_FERMI → hadrons + leptons)
ψ
ψ'
1
2
3
GeV

Alvaro De Rujula
The Rise of Particle Physics
Roma 23 Sept 2024

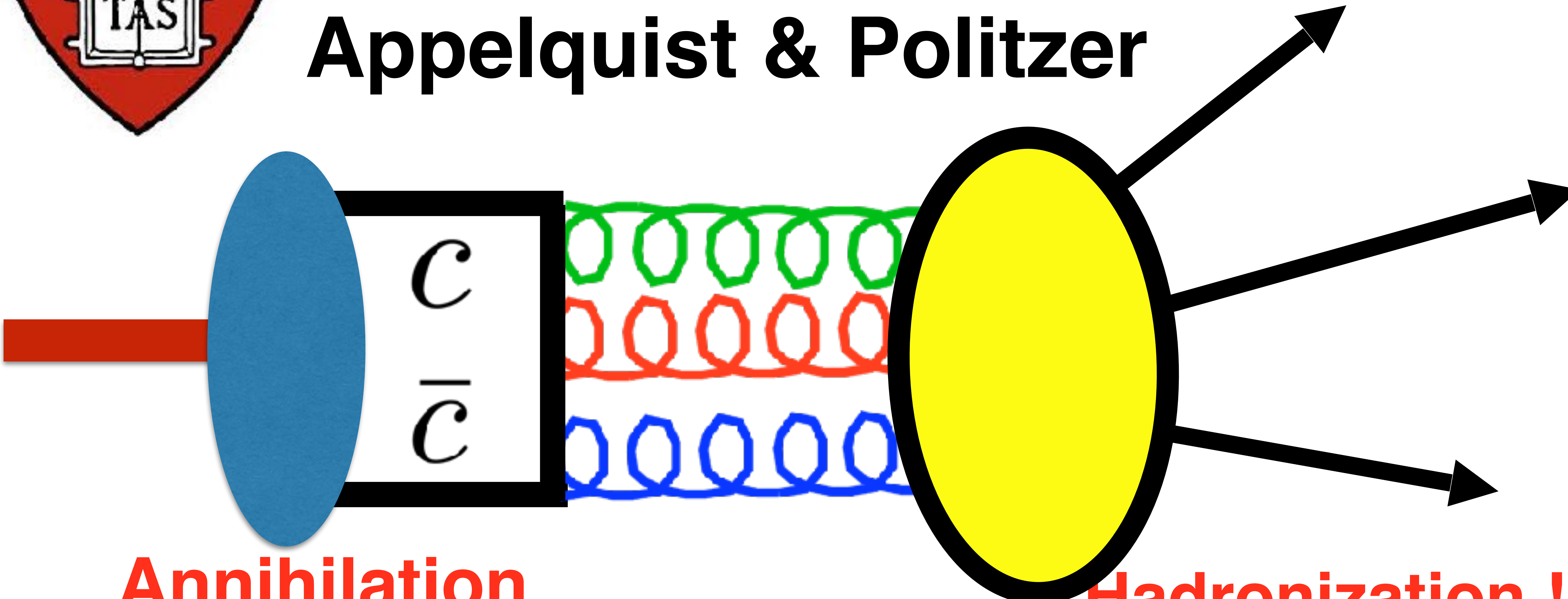


$\tau(\phi) = 0.15 \ 10^{-21}$ s

$\tau(\Psi) = 6.6 \ 10^{-21}$ s $\sim 43 \ \tau(\phi)$

J/Ψ as CHARMONIUM

Appelquist & Politzer



Annihilation

$$d \sim 1/m_c$$

Hadronization !?
Unitary !!

Why so narrow?

ADR & Glashow

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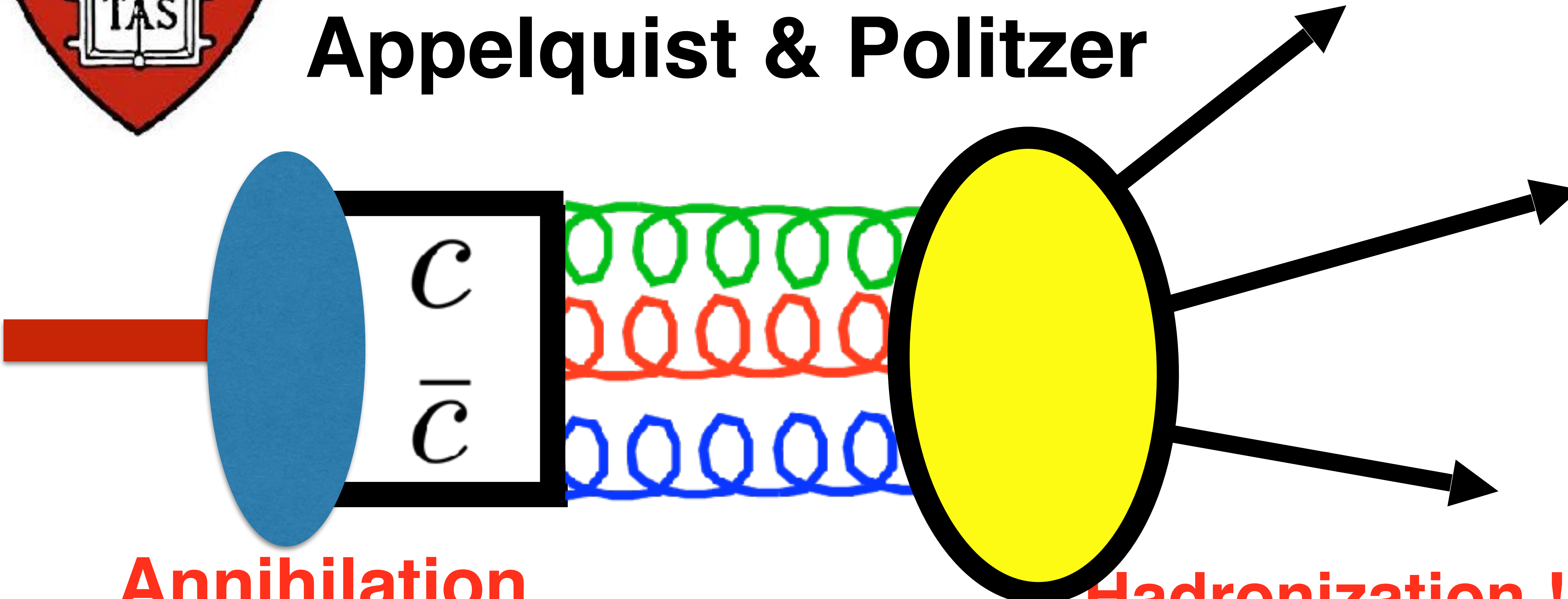

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$d \sim 1/m_c$ $\quad d \sim 1/\Lambda_{\mathrm{QCD}}$

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$\varphi(s\bar{s}) \rightarrow 3\,\pi$ **ETC**

The 1974 Events Chronology

(Dates of article reception by Journals)

Experiment

Nov. 12: J discovery, BNL
Nov. 13: ψ discovery, SLAC

Nov. 25: ψ' discovery, SLAC

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Theory

20 Nov. Altarelli et al.: *is it a* W_0 ?

27 Nov. DeRujula & Glashow: *bound charm*?

….few days later, I was in Trieste, giving a seminar.. a phone call by Nicola Cabibbo:

.. Shelly is right, at SLAC they discovered a new resonance, the ψ'….

30 Dec. Dominguez & Greco: $c\bar{c}$ *and the rise of R? V-meson dominated* e^+e^- *cross section…?*

C. A. Dominguez and M. Greco, Lett. Nuovo Cim. **12** (1975) 439

- $c\bar{c}$ interpretation of the rise of $e^+e^- \to$ hadrons in the J/Psi was not so obvious, due to the presence of problematic $e-\mu$ events.
- 1975-1977. M. Perl and coll. at SLAC: a new sequential lepton, ***the τ lepton***, is the origin of the $e-\mu$ events

M. L. Perl *The Discovery of the Tau Lepton,* 3rd International Symposium on the History of Particle Physics: *The Rise of the Standard Model*, SLAC-PUB-5937

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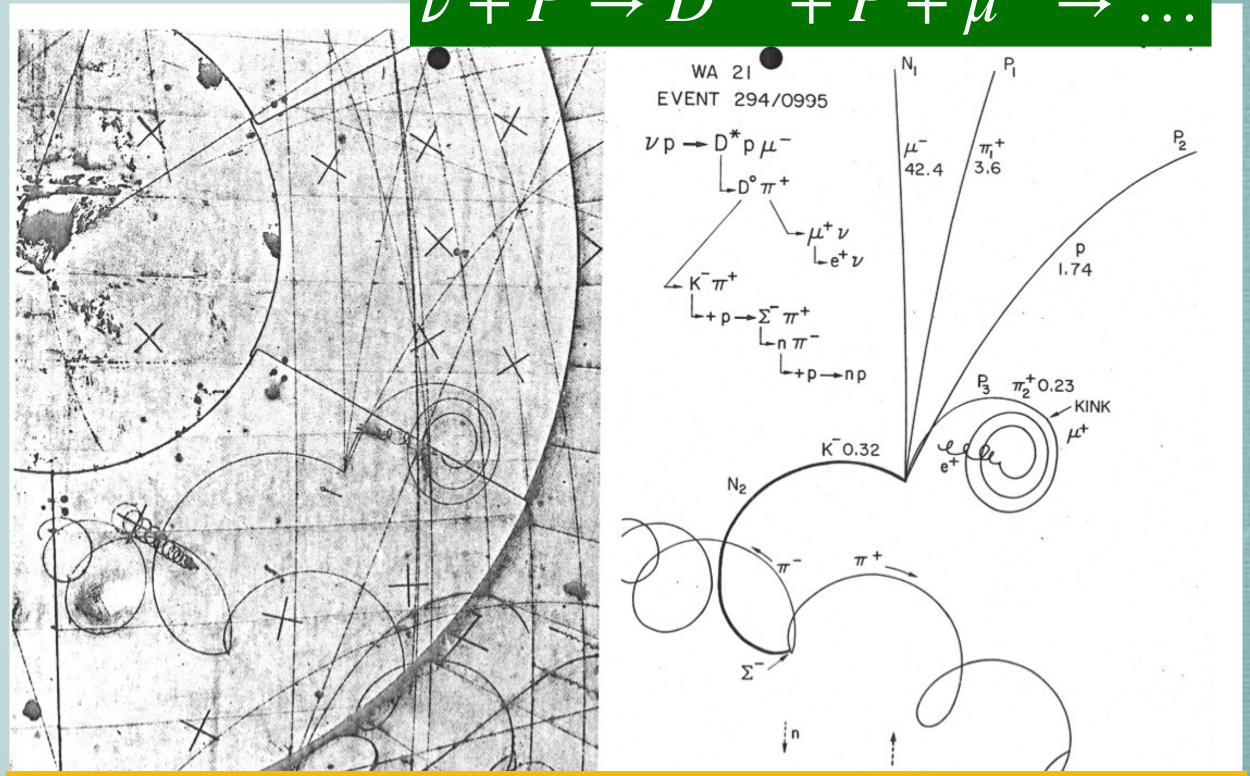
Charmed particle production and decay shows very complicated decay pattern….

$\nu + P \to D^{*+} + P + \mu^- \to \ldots$



Blietschau, J., et al. Physics Letters B 86 (1979)108

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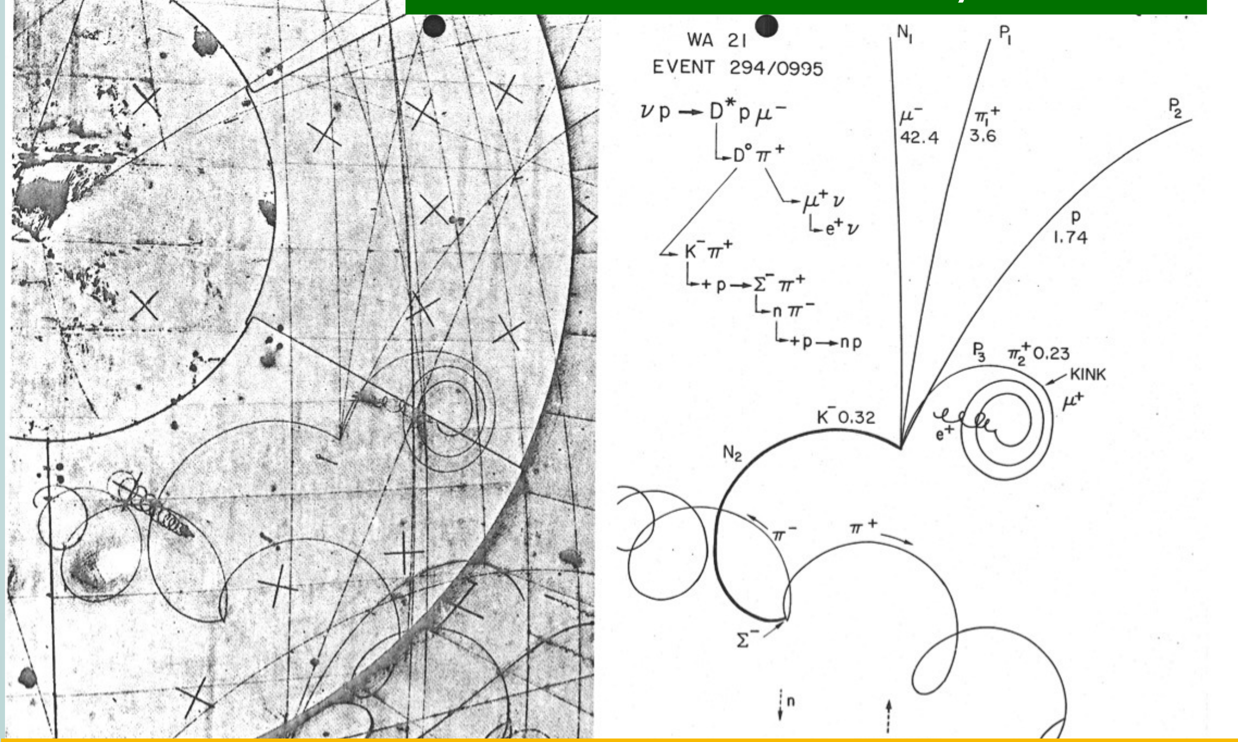

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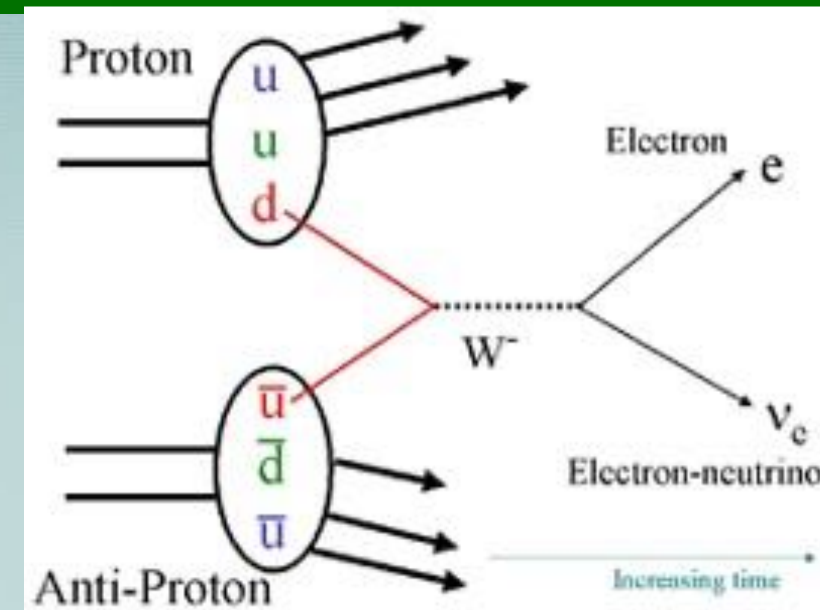
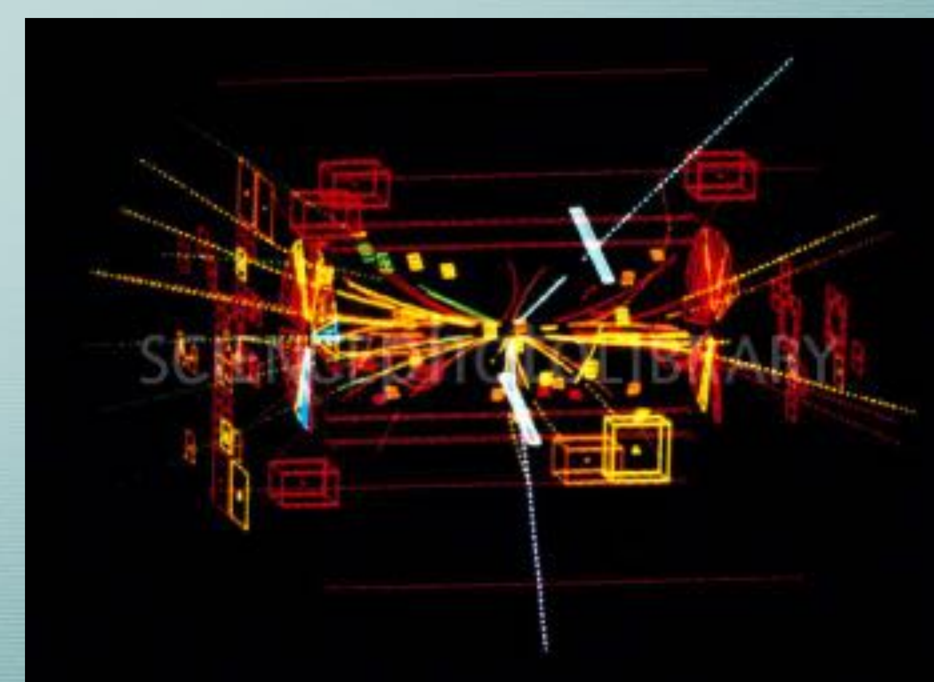
1976. L. Lederman and coll. discover the $\Upsilon = b\bar{b}$, evidence of the 3rd generation

- the 3$^{\rm rd}$ quark-lepton generation was completed in 1994 with the discovery of the top quark at FermiLab.

1983: UA1 and UA2 observe $W^{\pm}$ and Z^0 production at the $p-\bar{p}$ collider



Press Conference at CERN to annouce W and Z discovery.
From left:C. Rubbia, S. Van der Meer, E. Schopper



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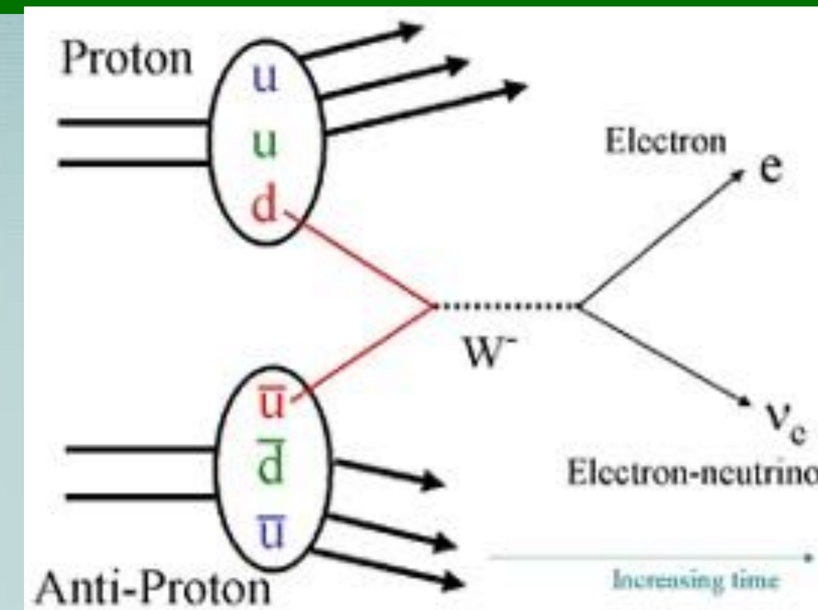

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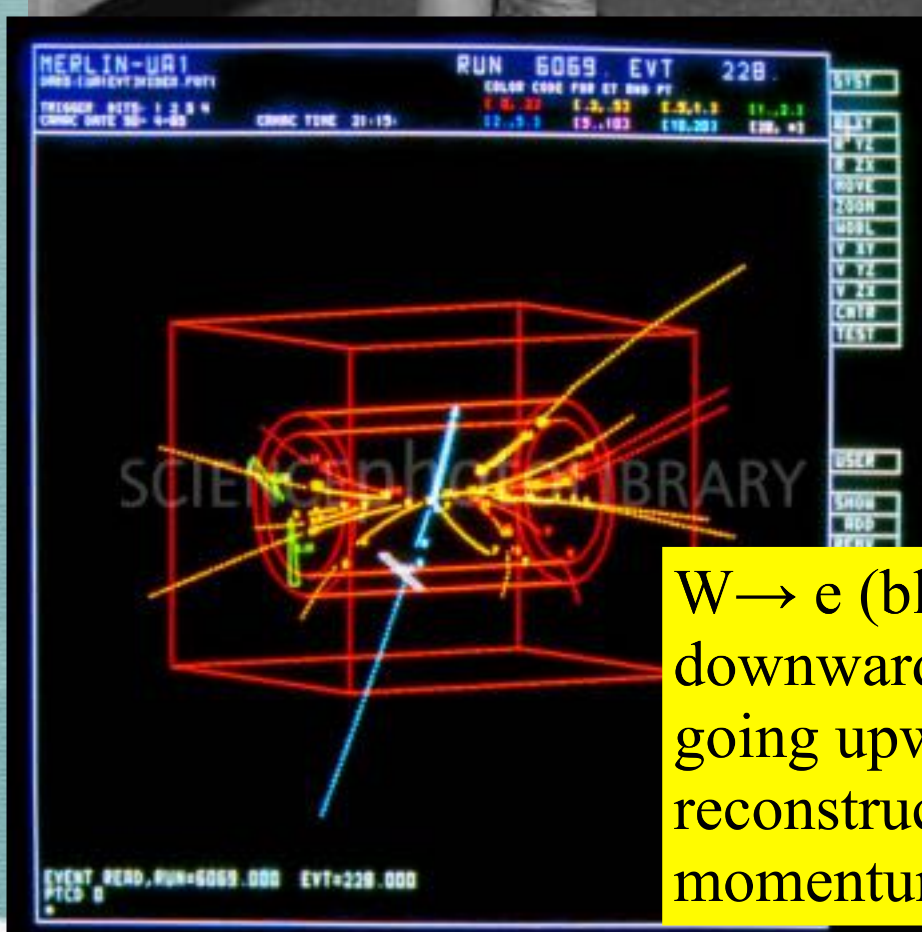
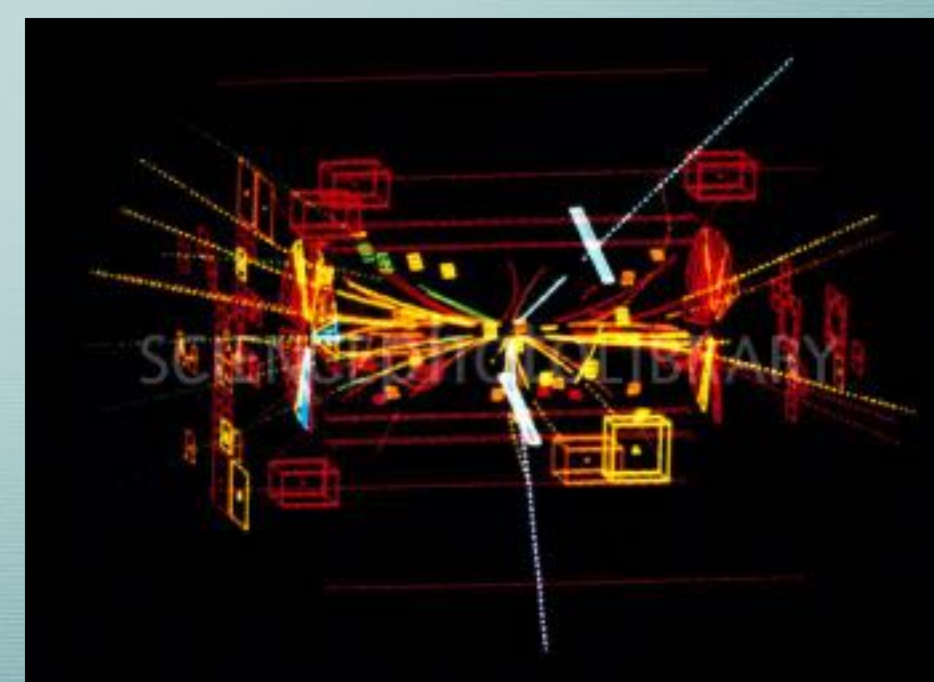


W⟶ e (blue going downward) + ν (blue going upward, reconstructed from momentum conservation)



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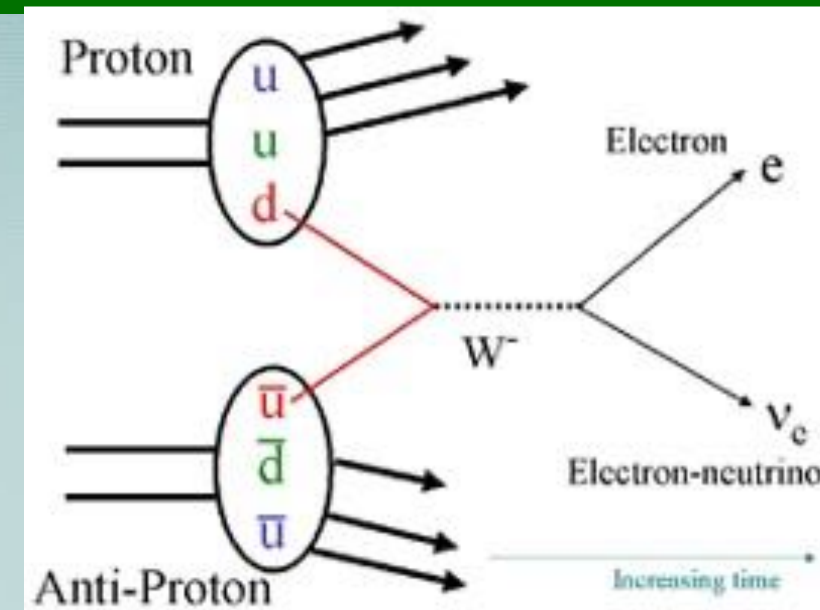

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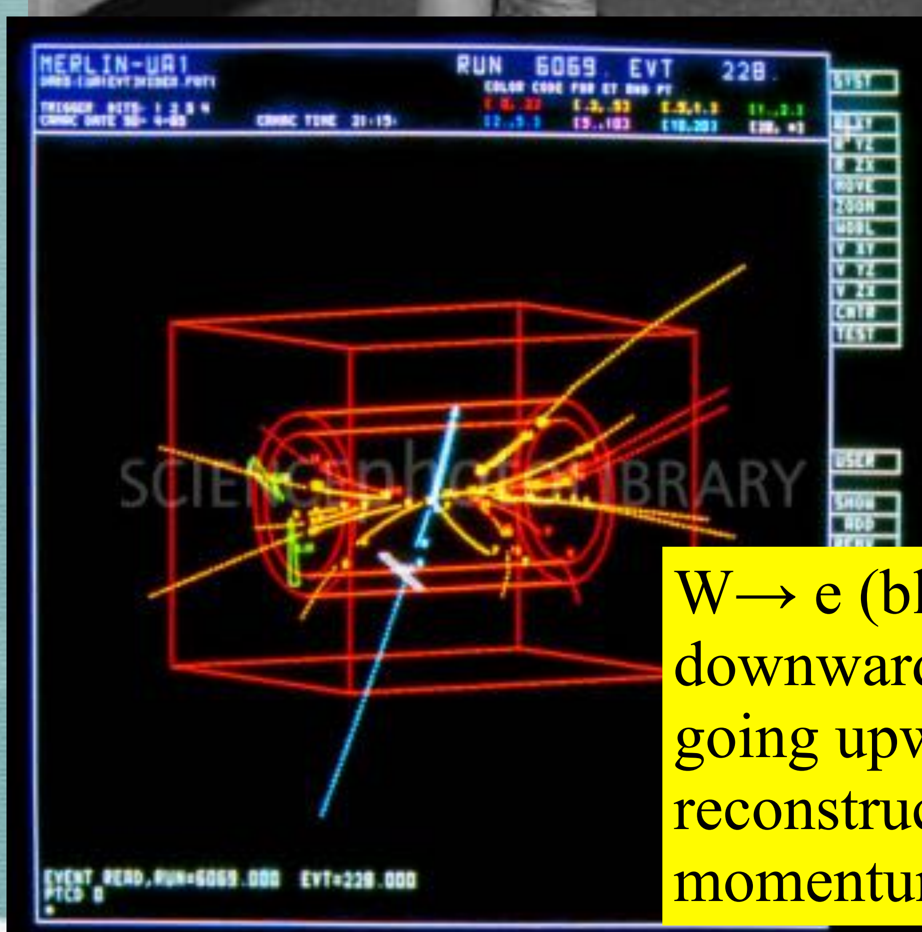

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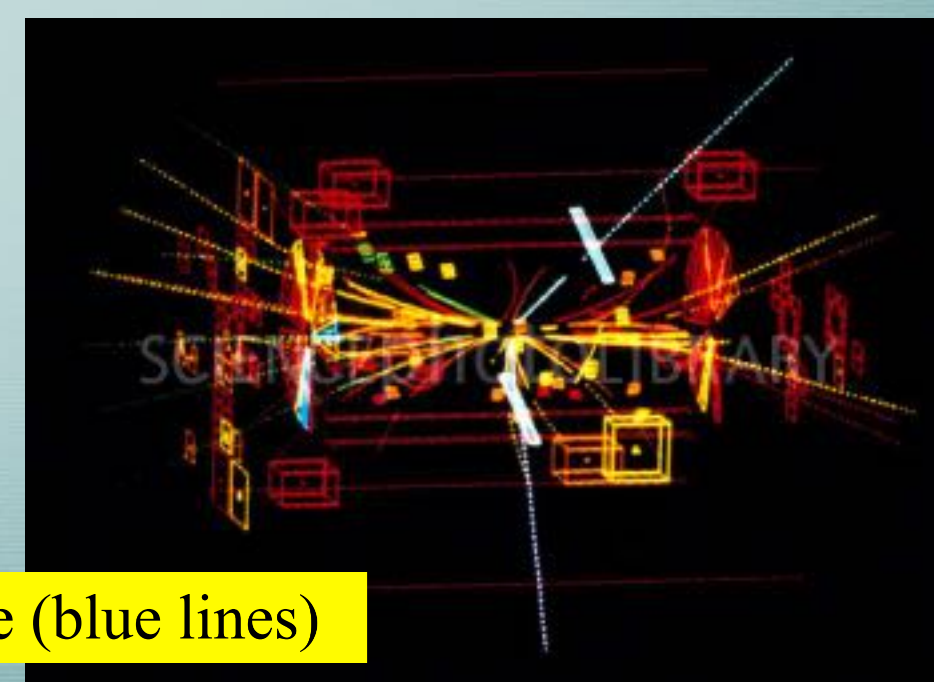
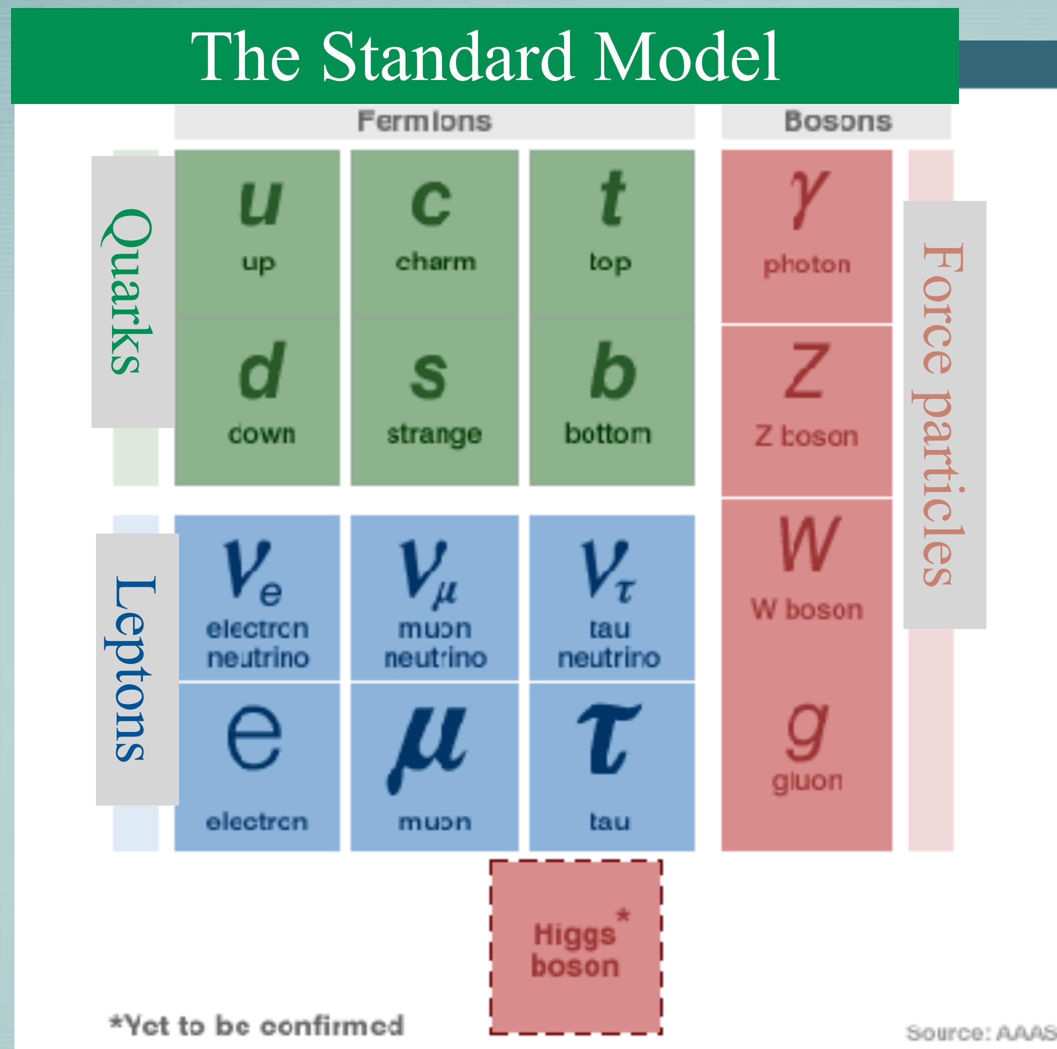


Z⟶ e e (blue lines)

Constituentsof matter and fundamental forces (circa 1984)


Murray Gell-Mann



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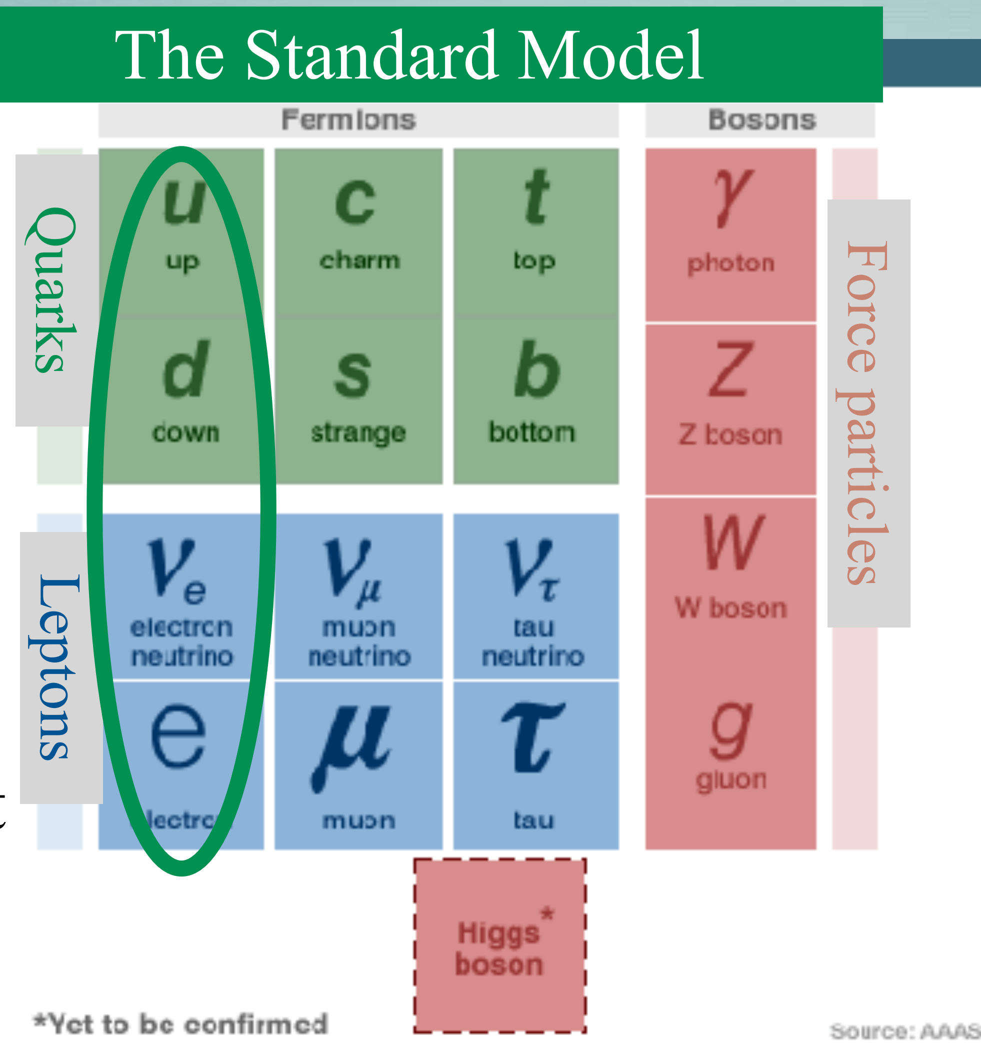

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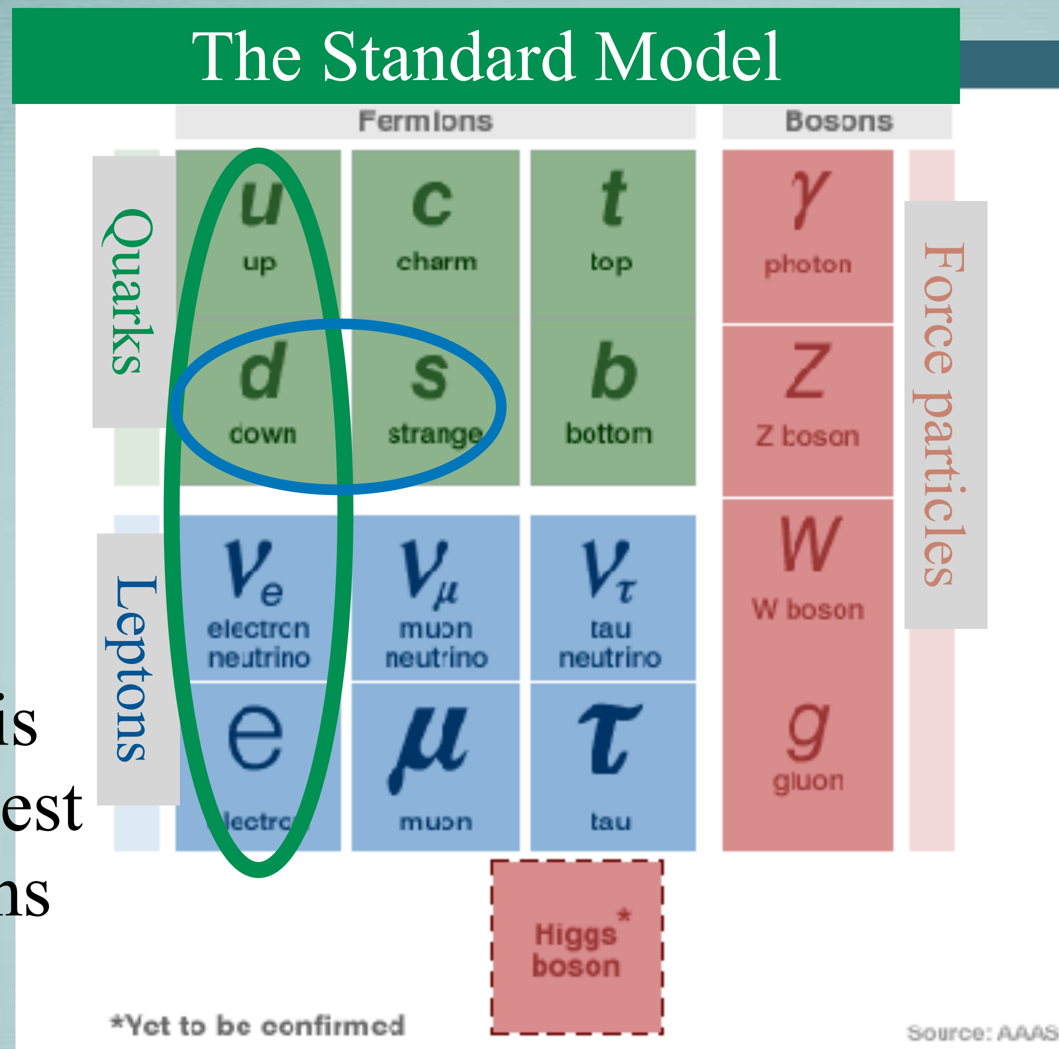

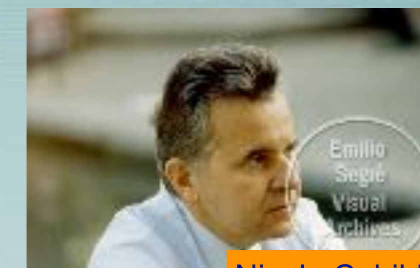

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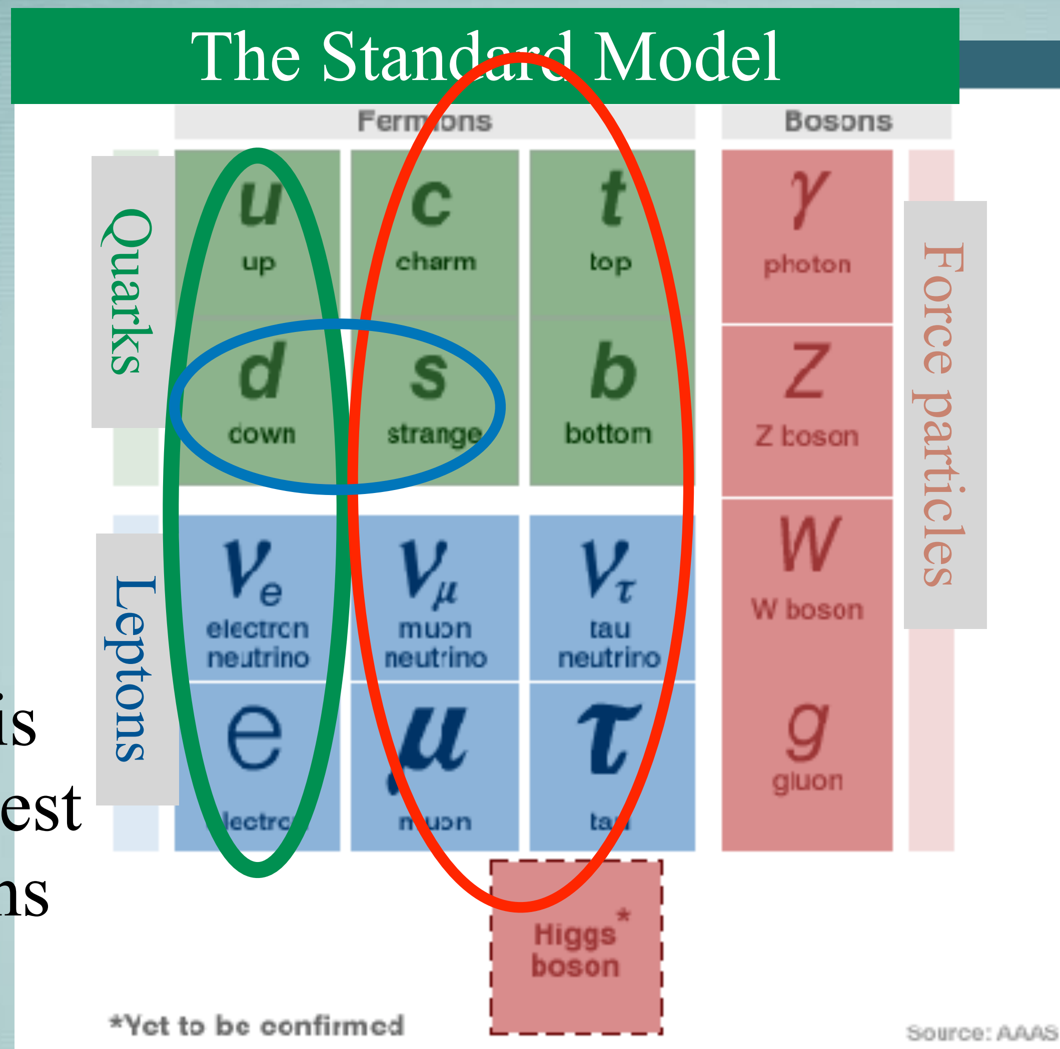

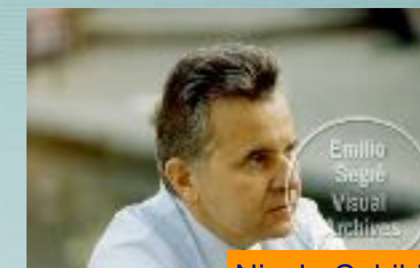
Nicola Cabibbo

Ordinary matter is made of the lightest quarks and leptons


Sheldon Glashow, John Iliopoulos, Luciano Maiani


Makoto Kobayashi , Toshihide Maskawa

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

Constituentsof matter and fundamental forces (circa 1984)


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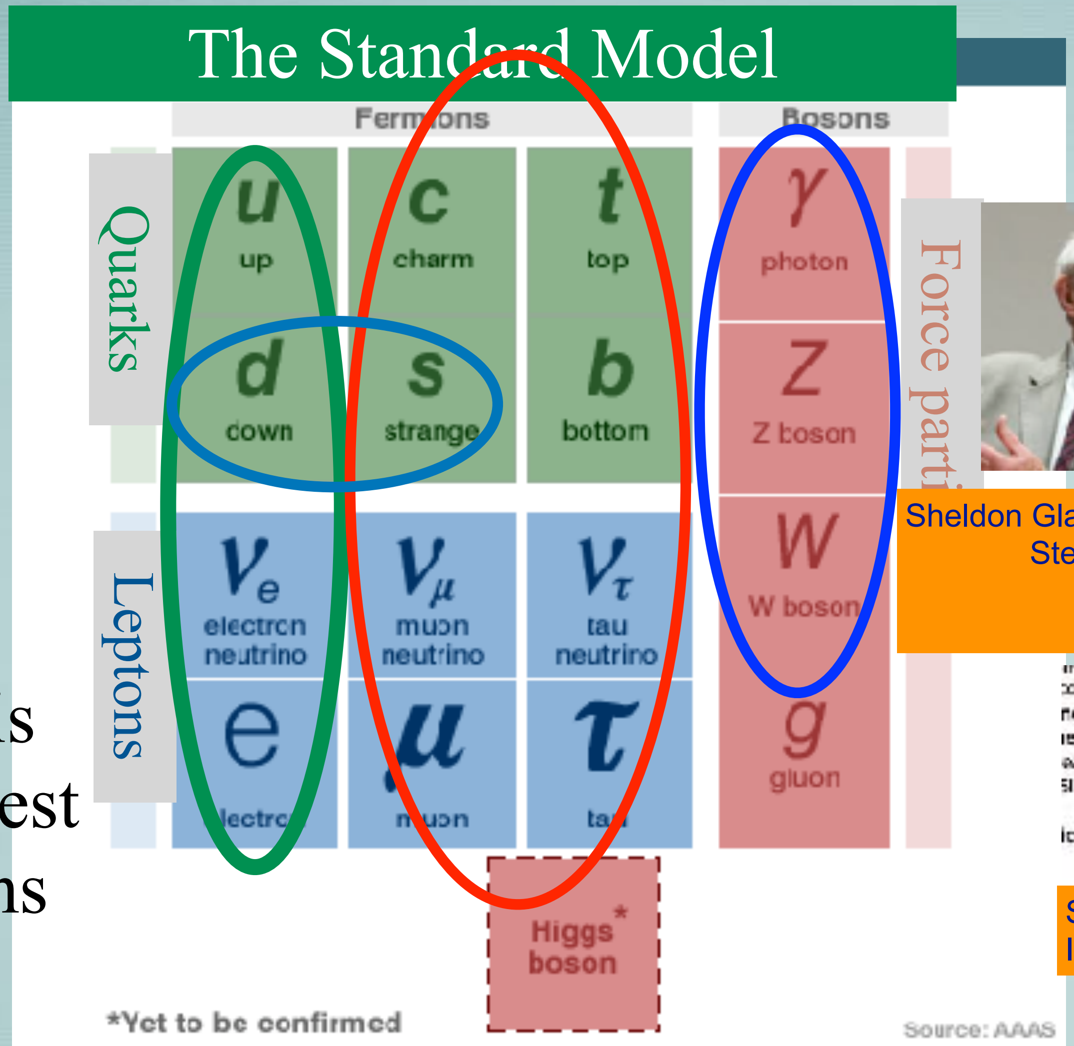

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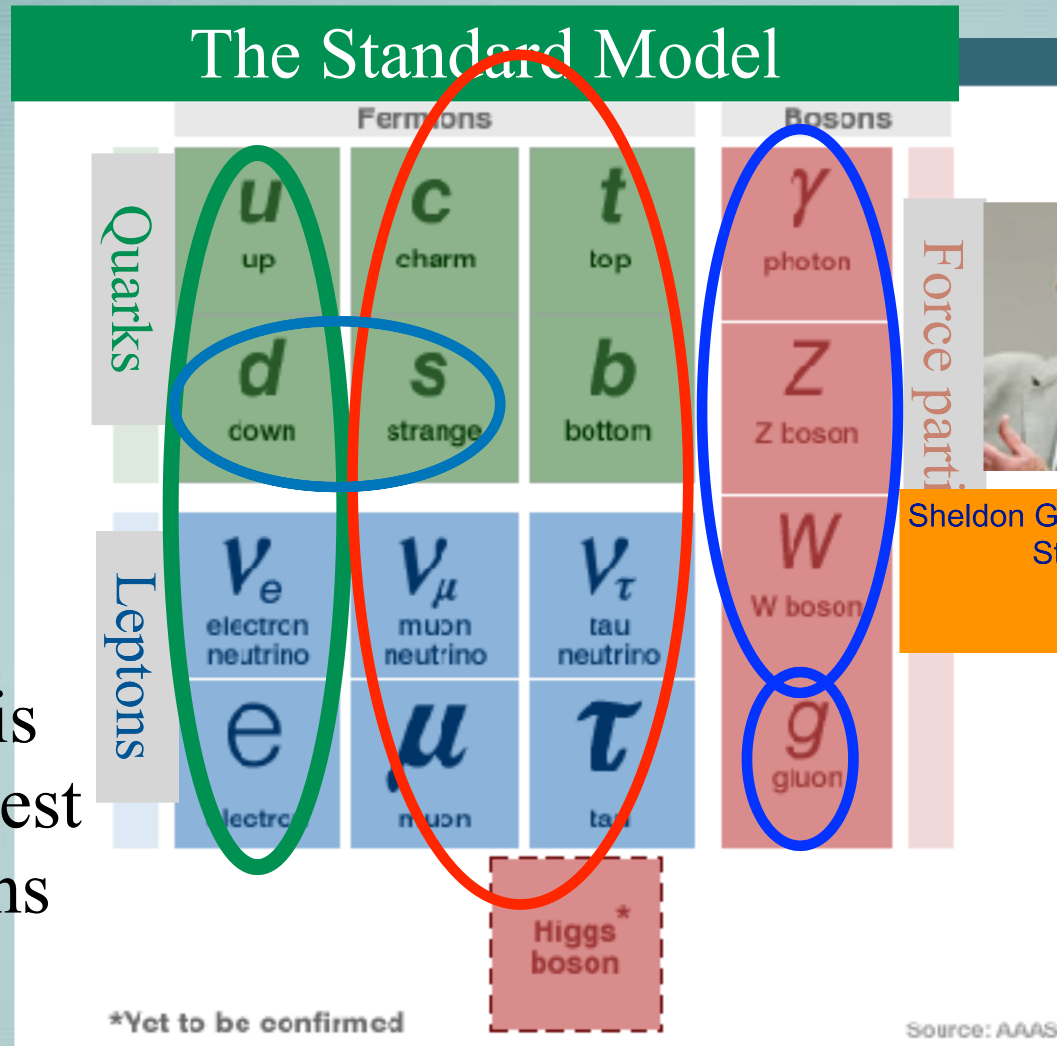

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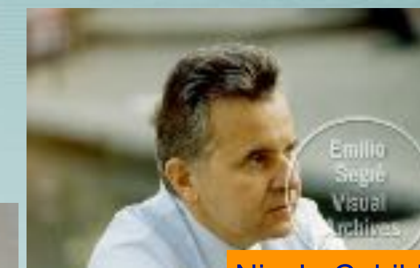

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Strong interactions between quarks are mediated by neutral vector mesons (gluons) coupled to color, and are asymptotically free Gross&Wilczeck, Politzer (1973)

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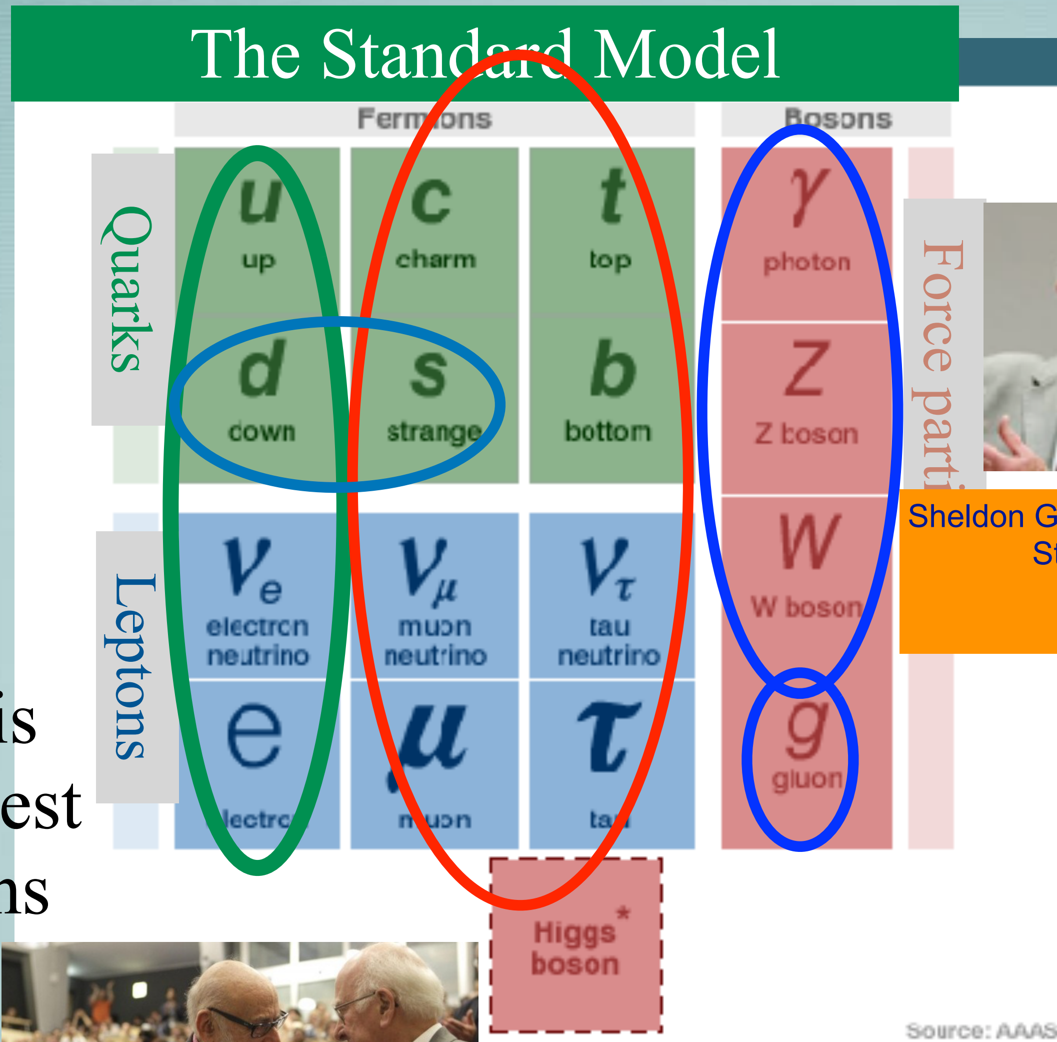

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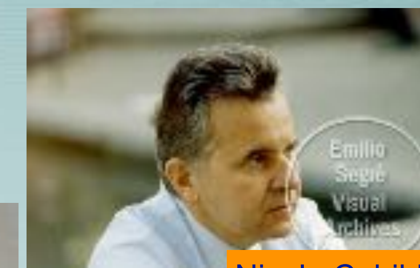
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Robert Englert e Peter Higgs

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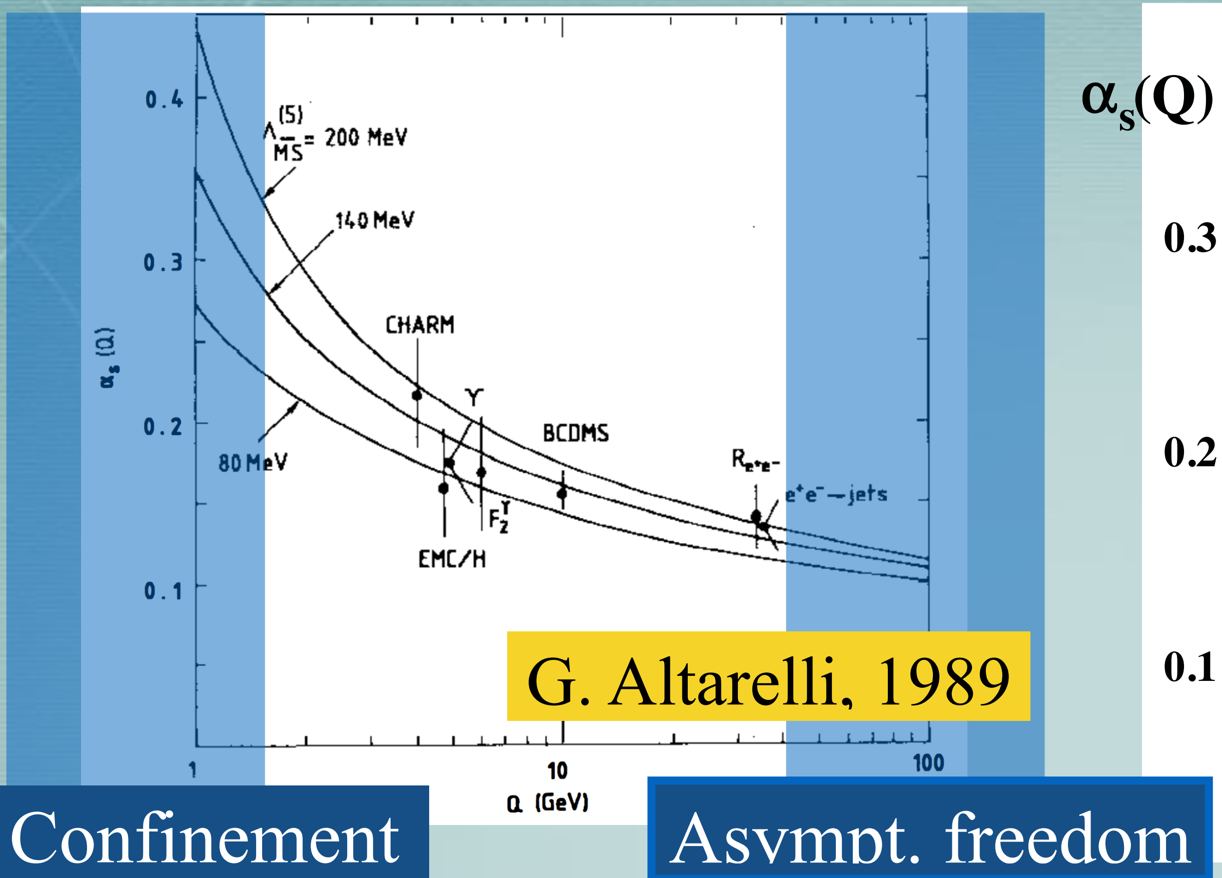
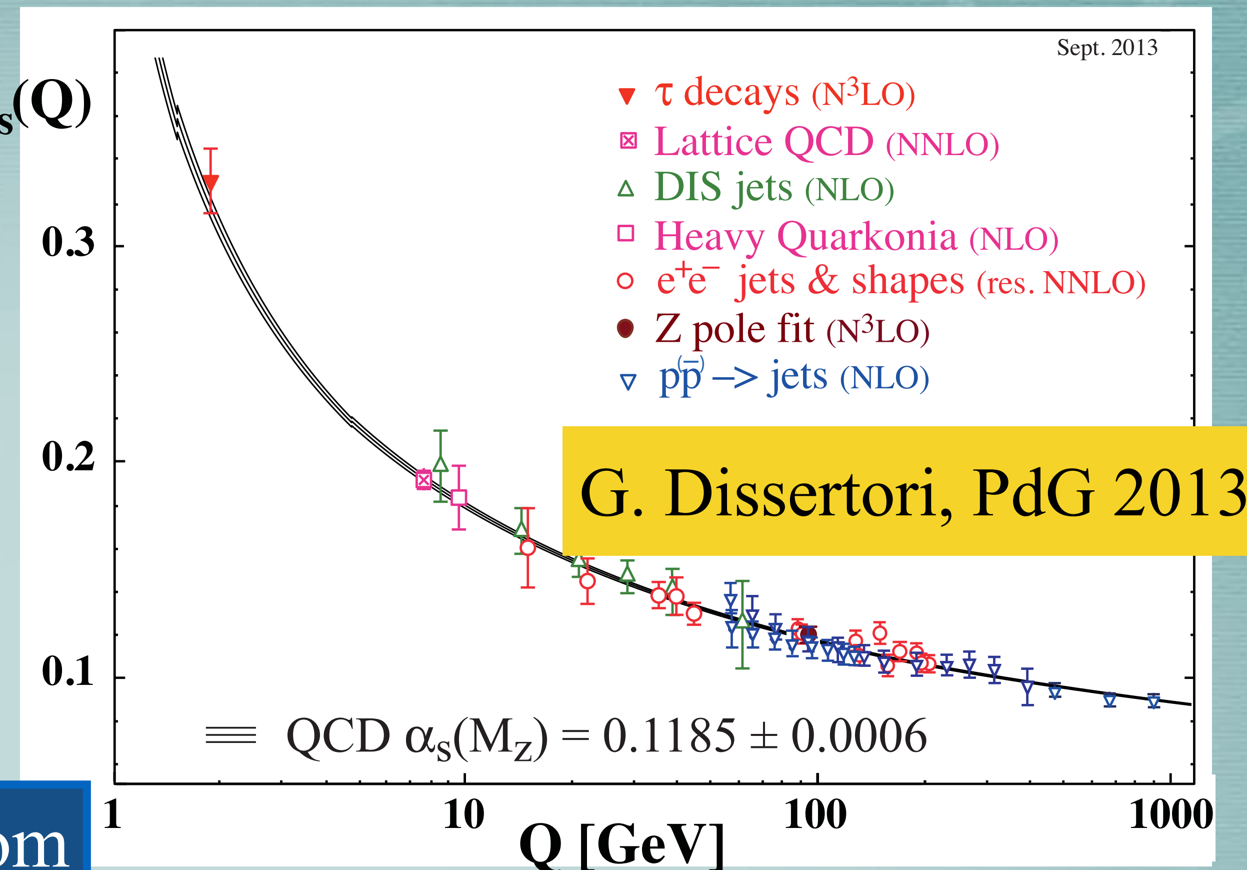
QCD is the answer to (almost) any Strong Interaction question





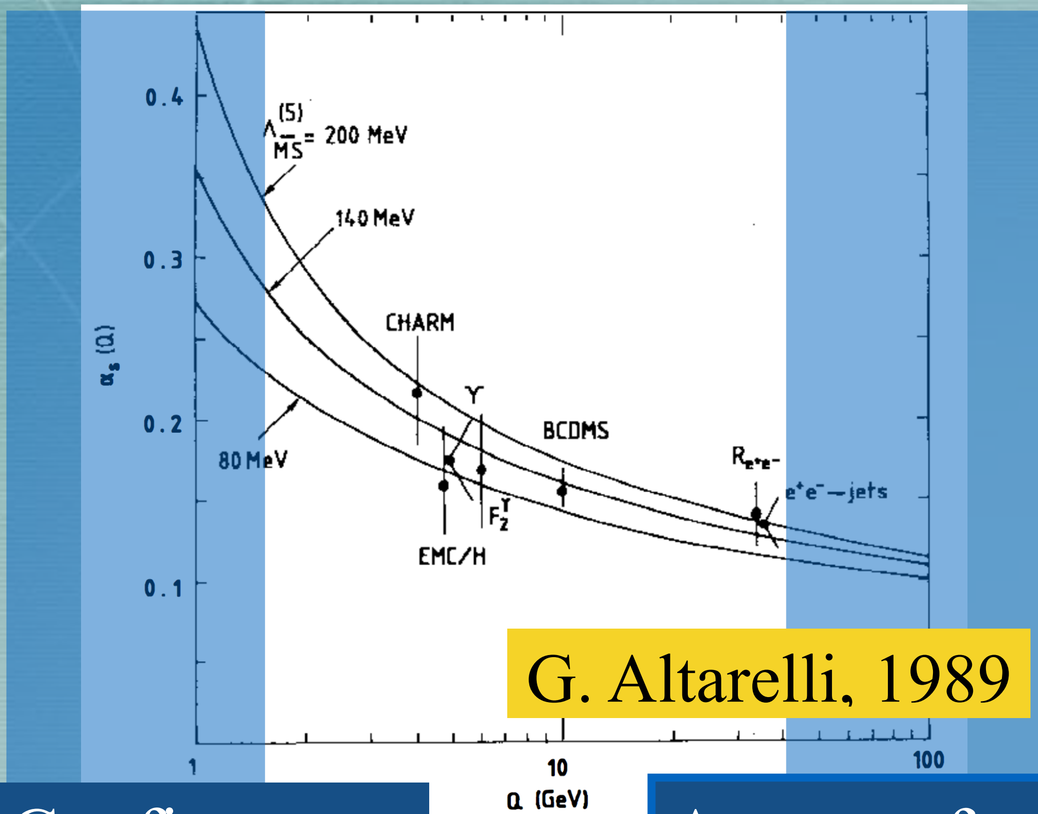
- QCD is asymptotically free
- quarks carry **color symmetry**, **SU(3)$_{\mathbf{col}}$**, and are confined inside **color singlet hadrons**,
- $\Delta^{(++)} = \epsilon^{\alpha\beta\gamma} u^{\uparrow}_{\alpha} u^{\uparrow}_{\beta} u^{\uparrow}_{\gamma}$: Fermi statistics is obeyed

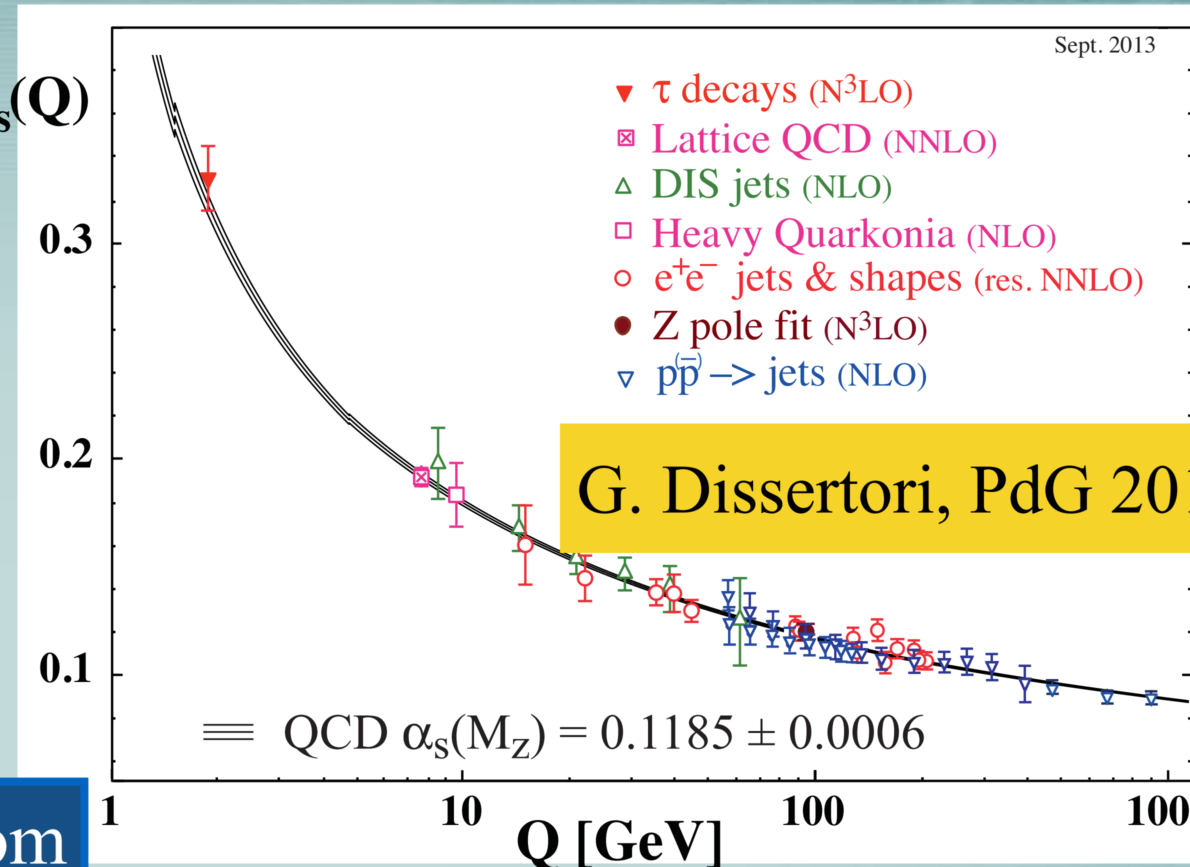
Constituent Quarks

- increasing q², quarks radiate gluons (the Altarelli-Parisi picture of scaling violations)
- at large q², we see quarks and neutral gluons as almost free partons.

QCD Partons

QCD is the answer to (almost) any Strong Interaction question





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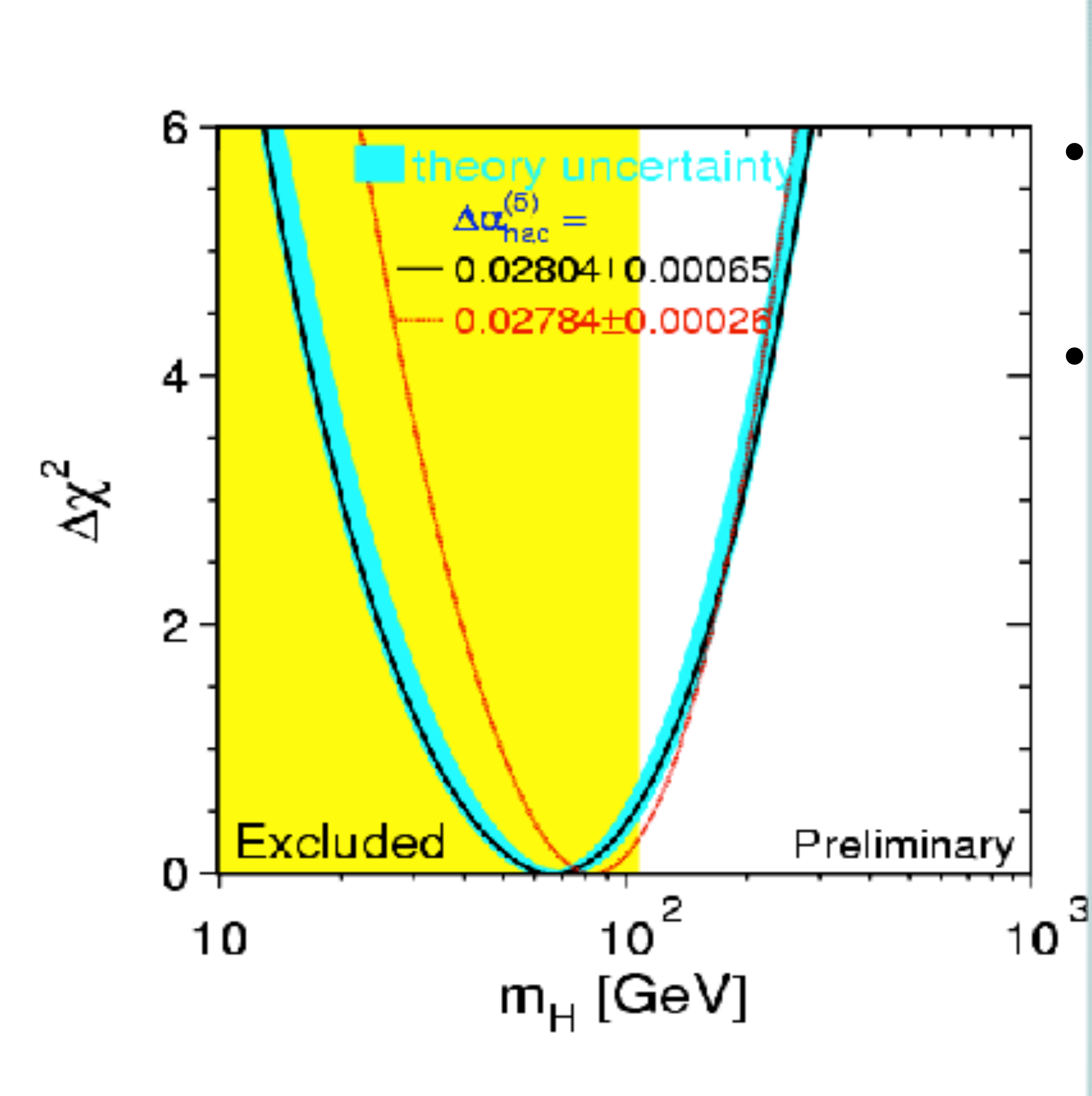
QCD Partons

***Heavy quarks (** $m_Q >> \Lambda_{QCD}$ **)**:*

- inclusive decays are calculable like deep inelastic processes;
- $c\bar{c}$ or $b\bar{b}$ bound states involve short distance forces: a calculable spectrum of charmonia/bottomonia;
- inside hadrons, $c\bar{c}$ or $b\bar{b}$ pairs are not easily created or destroyed:
- a hadron decaying into J/Ψ or $\Upsilon + \ldots$ indicates a valence $c\bar{c}$ or $b\bar{b}$ pair
- ***heavy-quark counting is possible.***

6. M_H prediction from precision Electroweak Measurements



- 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

M_H=135-170 GeV

$\Lambda = 10^{19}$ GeV

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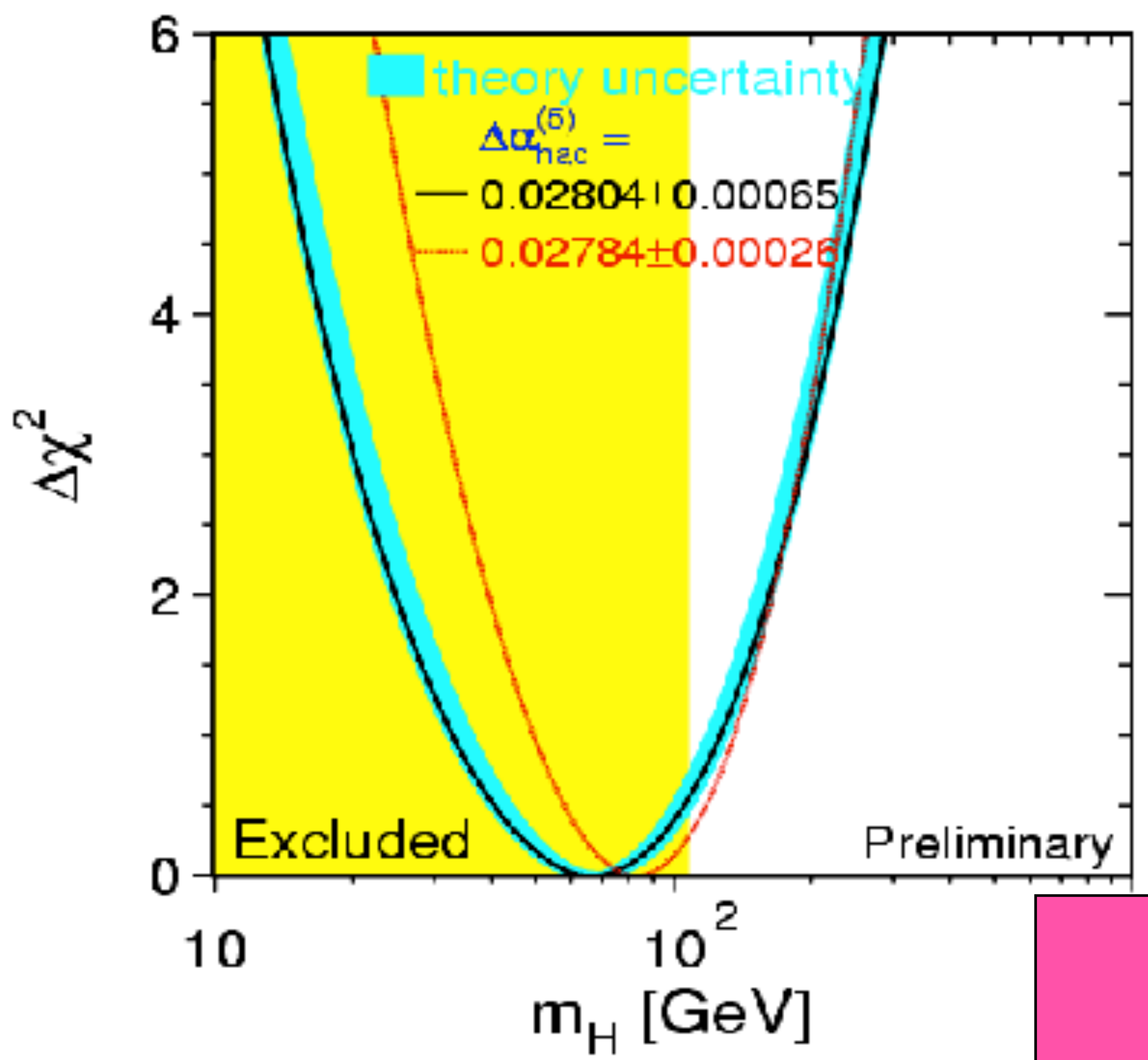

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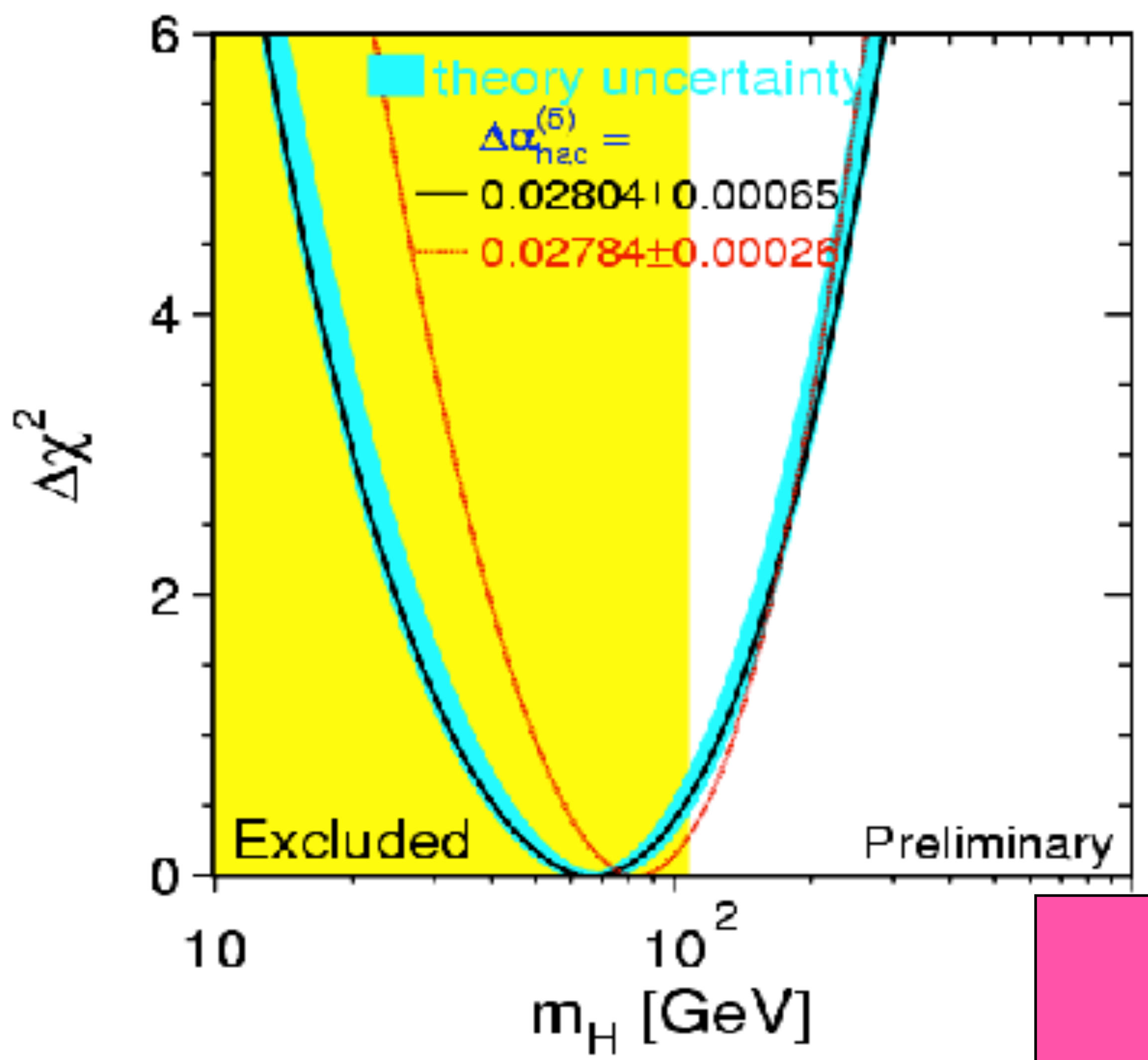

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In the 1980s, the search for the Higgs Boson opened the era of ***large energy proton-proton Colliders***.
The first proposed was the SSC (Superconducting Super Collider) in the USA.

The SSC drama

- The SSC (Superconducting Super Collider) was proposed in the US in the first 1980s: proton-proton, very high energy, 20 TeV/beam;
- **1988 SSC approved,** proton-proton, 20 TeV/beam, 87 km tunnel, cost 4-5 B US$;

  1989 SSC construction starts.
- **1993** SSC discontinued by the US Congress after a bitter discussion which invested all the scientific community (projected cost >10 B US $)

The Supercollider That Never Was (Scientific American, 2013)

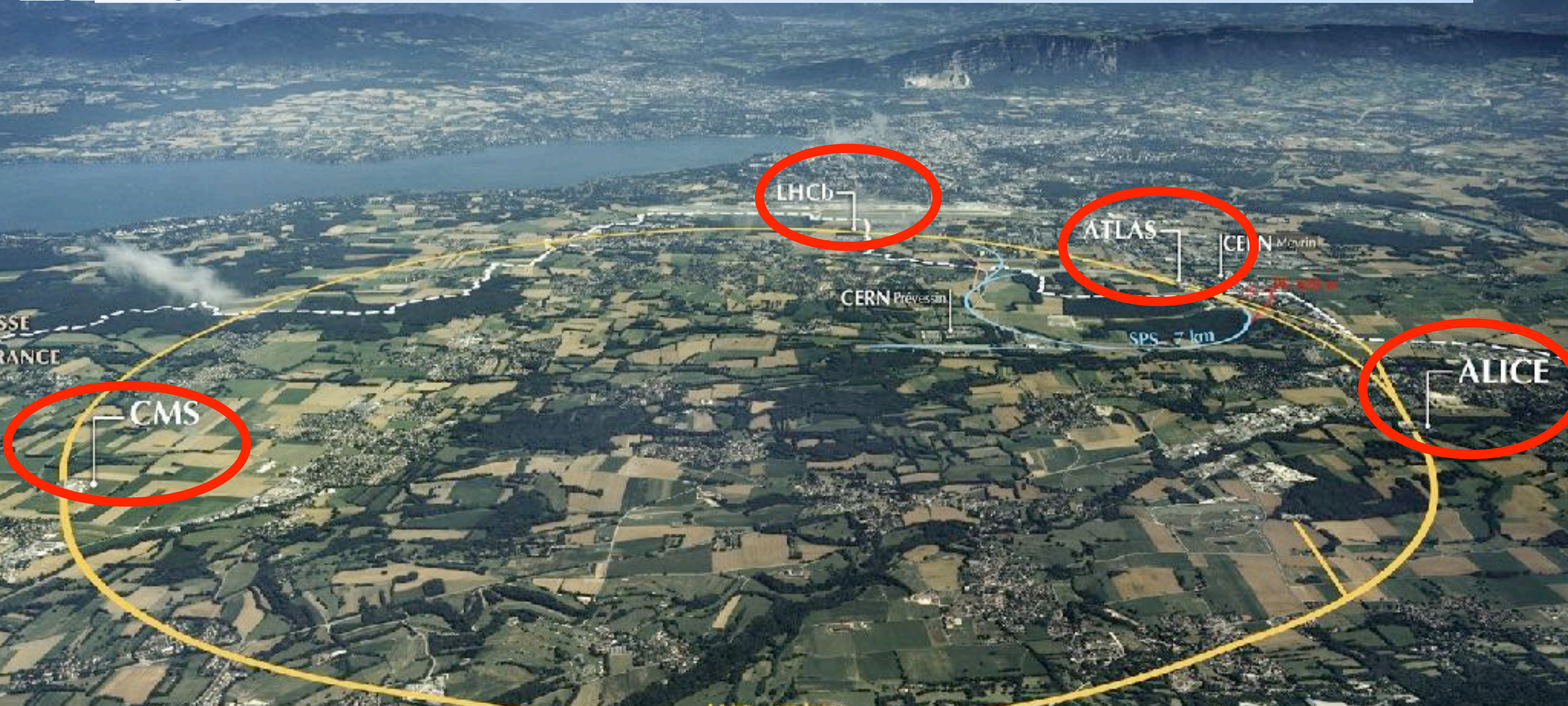
....The SSC was an epic project that ended in failure. The U.S. has yet to stride again its own once prominent footsteps; but perhaps worse, it no longer dares to dream in color.

1994: LHC is approved

- The cancellation of the SSC programme made a terrible shock-wave in Europe, firing back on particle physics and CERN.
- The top quark discovery had a very good balancing effect (as seen from Italy)
- the first prototype of 10 m superconducting LHC magnets was presented at CERN Council in Dec. 1993 with a positive effect
- Luckily, on the basis of the $Sp\bar{p}S$ and LEP successes, CERN project was approved in December 1994.

The first prototype of 15 m superconducting LHC dipole by CERN-INFN-Ansaldo Energia Collaboration,1998.

The Large Hadron Collider in the LEP Tunnel

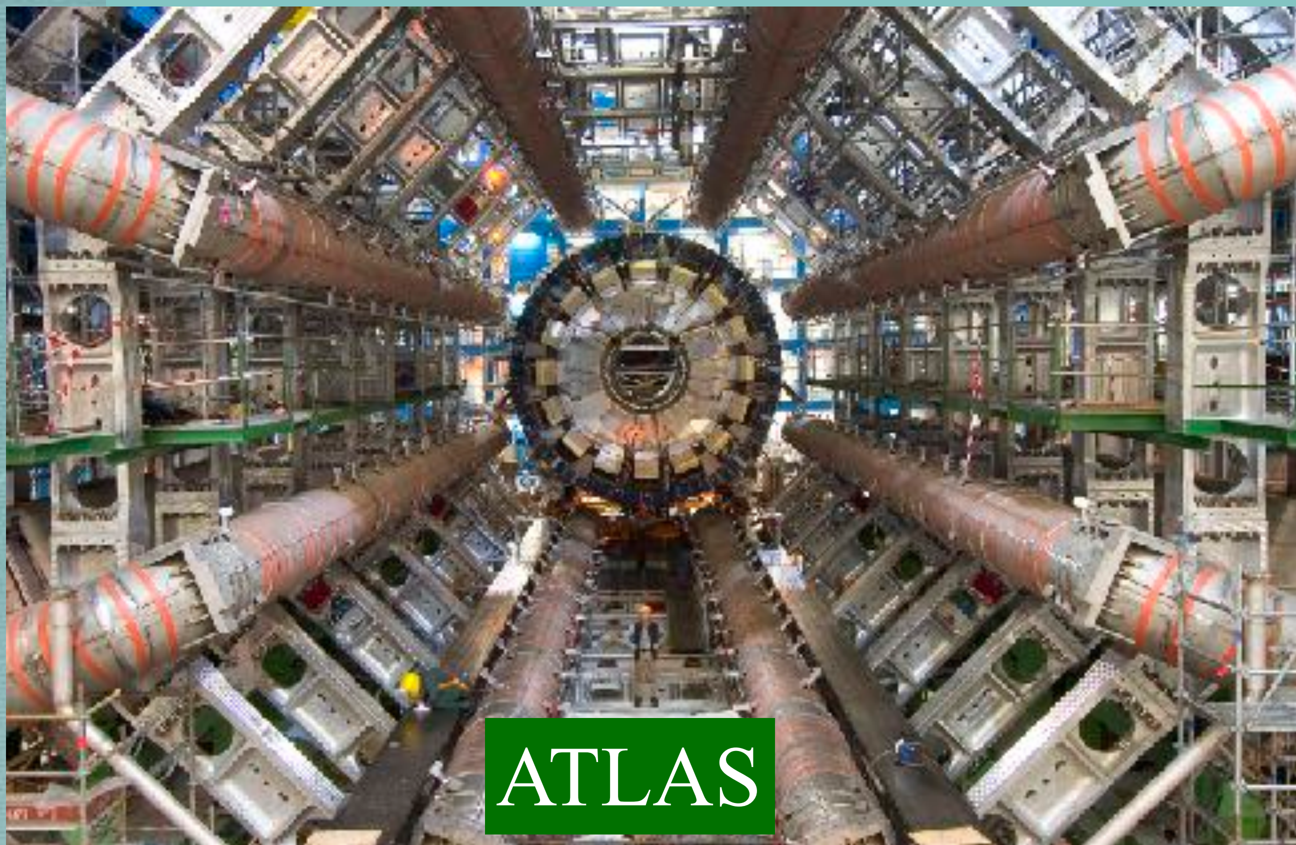


Tunnel: 27 km circumpherence, 100 m depth

Four big experiments by International Collaborations:
ATLAS, CMS, LHCb, ALICE

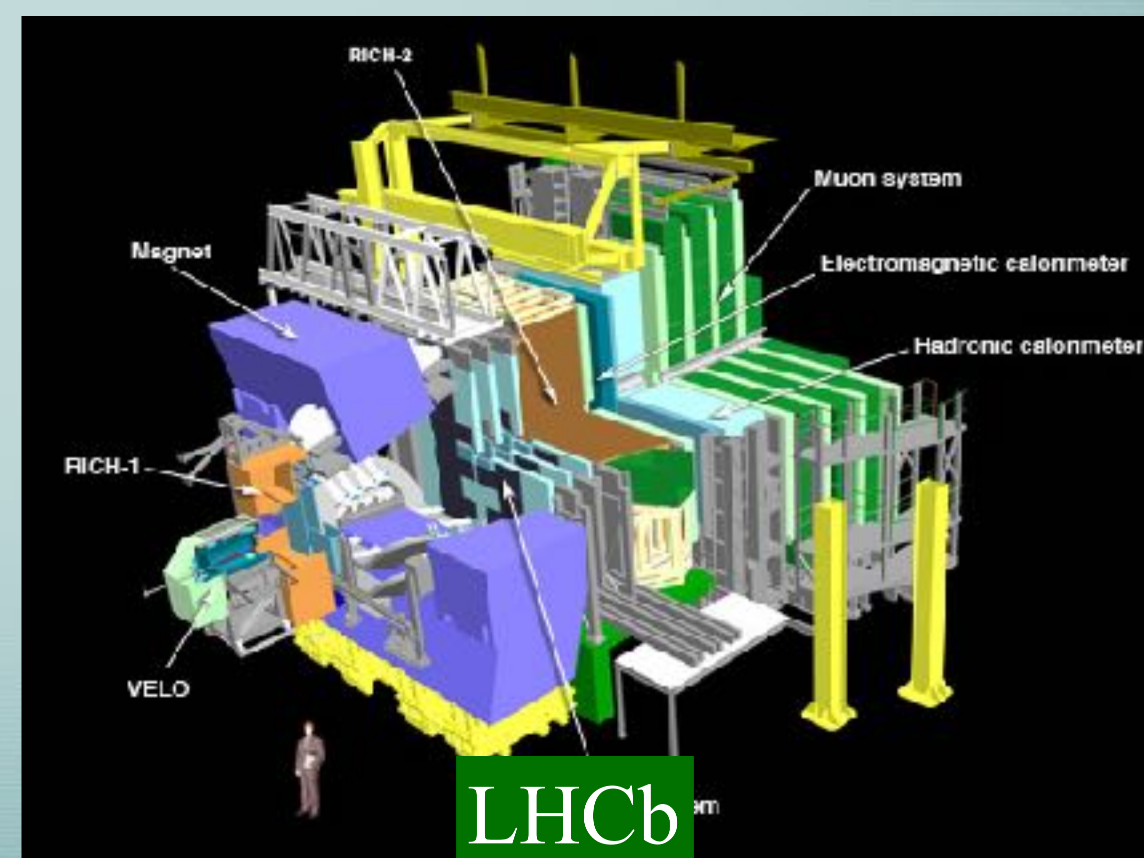
June 2001
Magnets from Novosibirsk

with Lynn Evans, A. Skrinsky, Kurt Hubner


ATLAS


CMS


ALICE


RICH-2
Muon system
Magnet
Electromagnetic calorimeter
Hadronic calorimeter
RICH-1
VELO
LHCb

TIME LINE OF THE LHC CONSTRUCTION

1.1. LHC Schedule

- Contracts for dipole cold mass assembly are being signed; CERN has a double role: supplier of SC cables, end-customer of the dipoles. We must be prudent in defining the dipole delivery schedule, hence the LHC schedule.
- SC cable production to end mid 2005;
- last dipole delivered July 1st, 2006;
- Machine closed and cold: Oct. 2006;
- First beam: April 2007;
- First physics: mid 2007;
- Very solid foundation of the LHC confirmed by SC cable panel and Machine Advisory Committee.

L. Maiani March 21, 2002 Committee of Council 8

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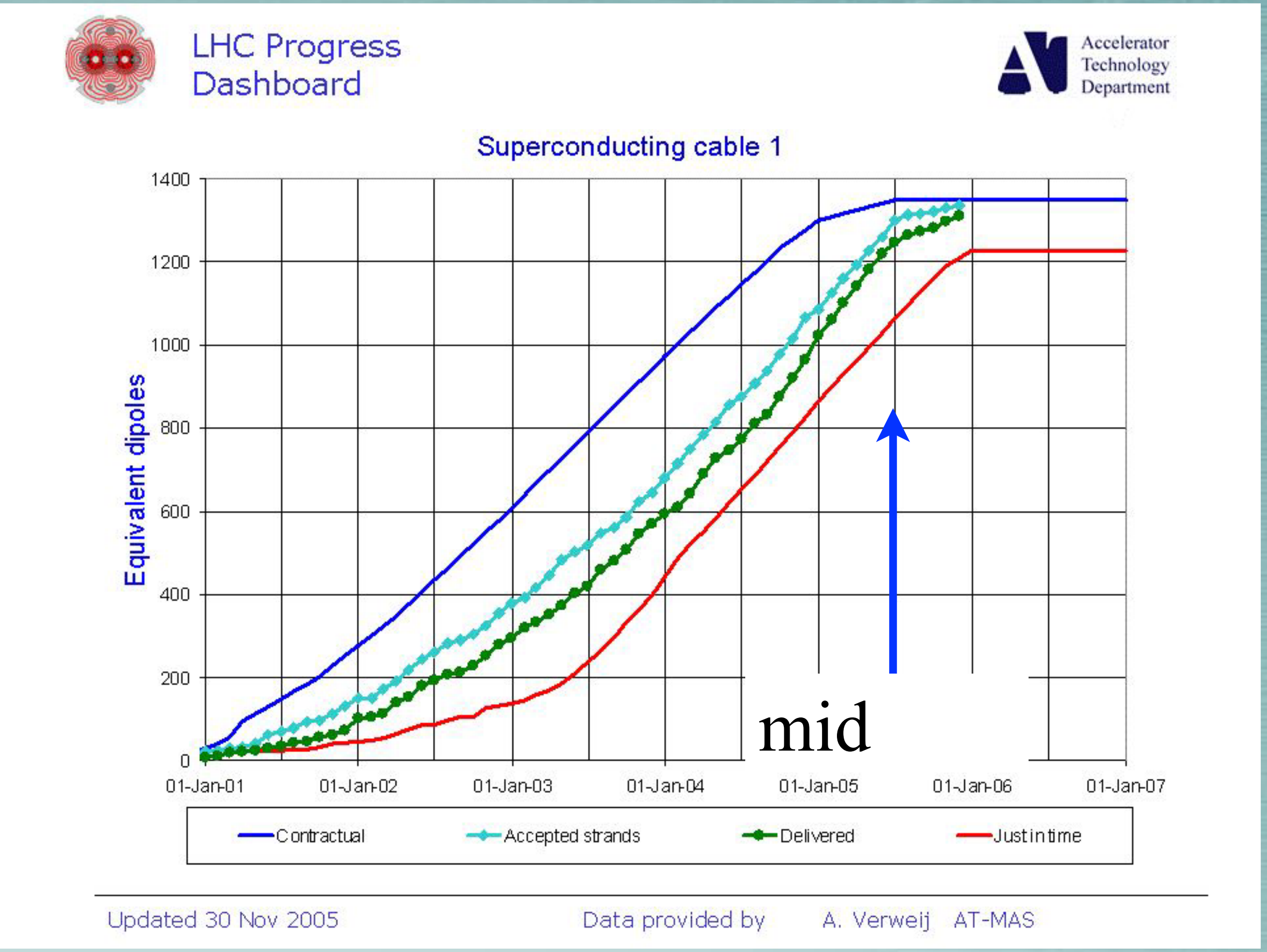

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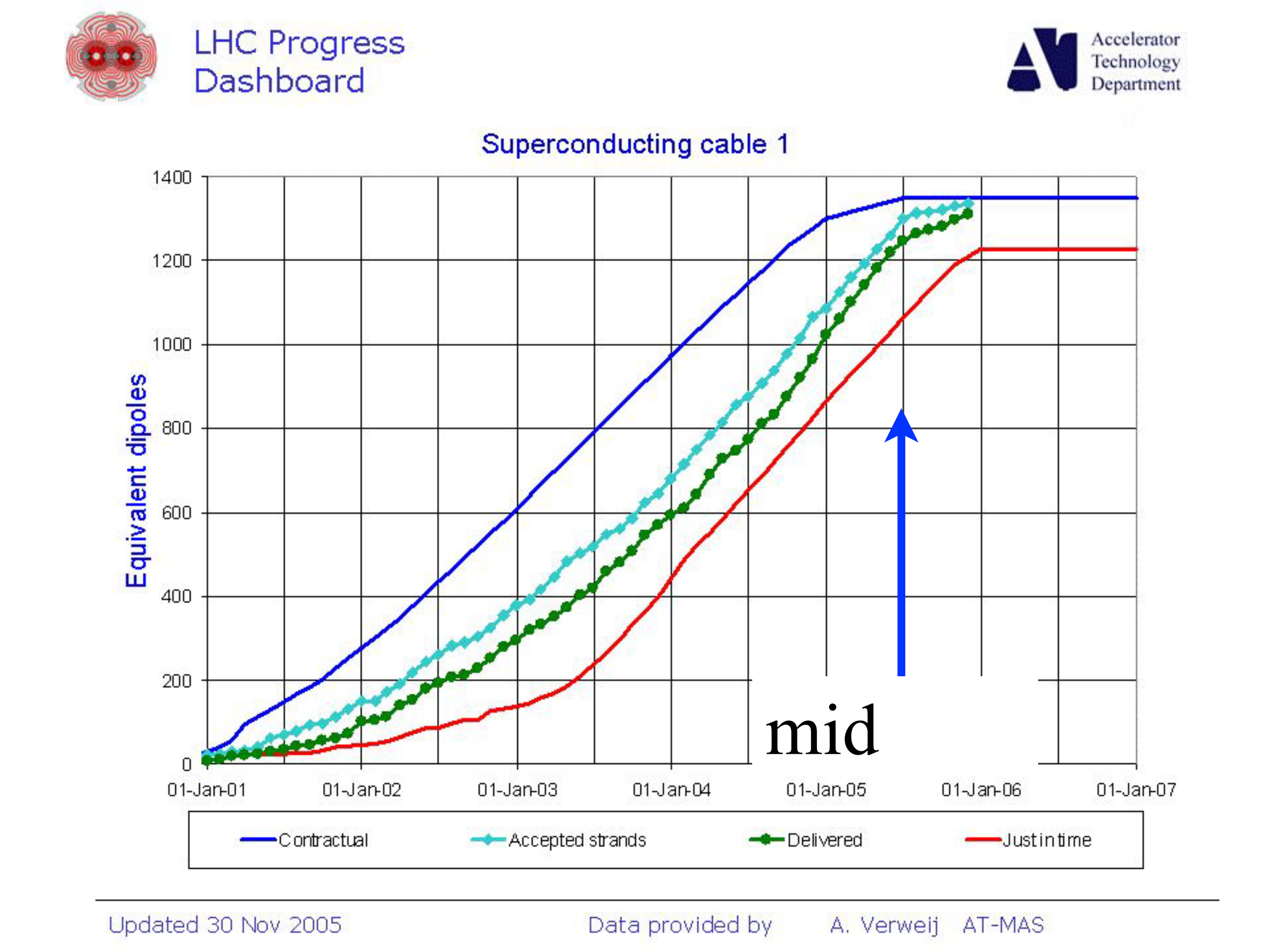

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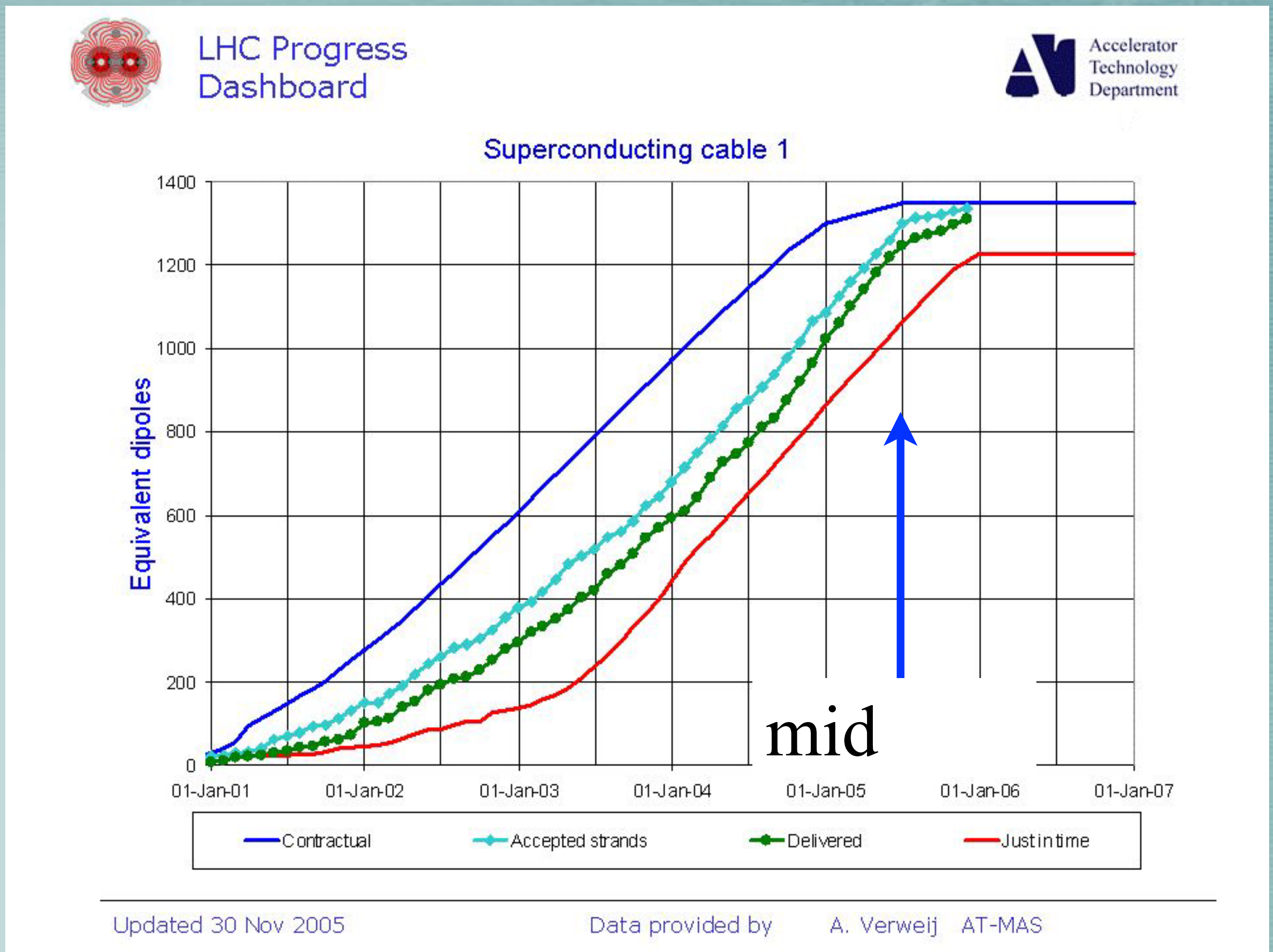

Sept. 10th 08: first beams

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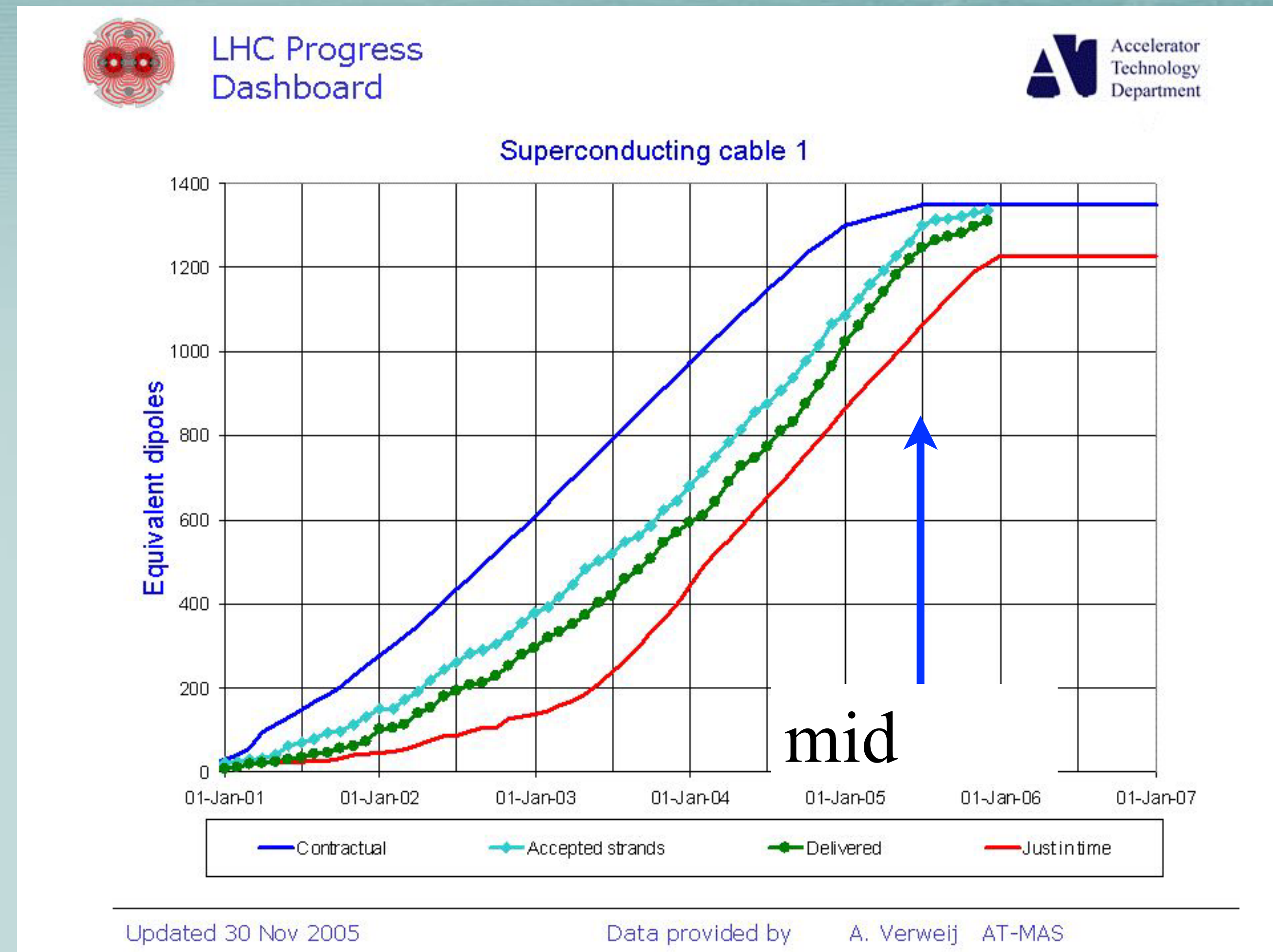

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- another 1.5 year for the magnets accident
- later resolved by Steve Myers

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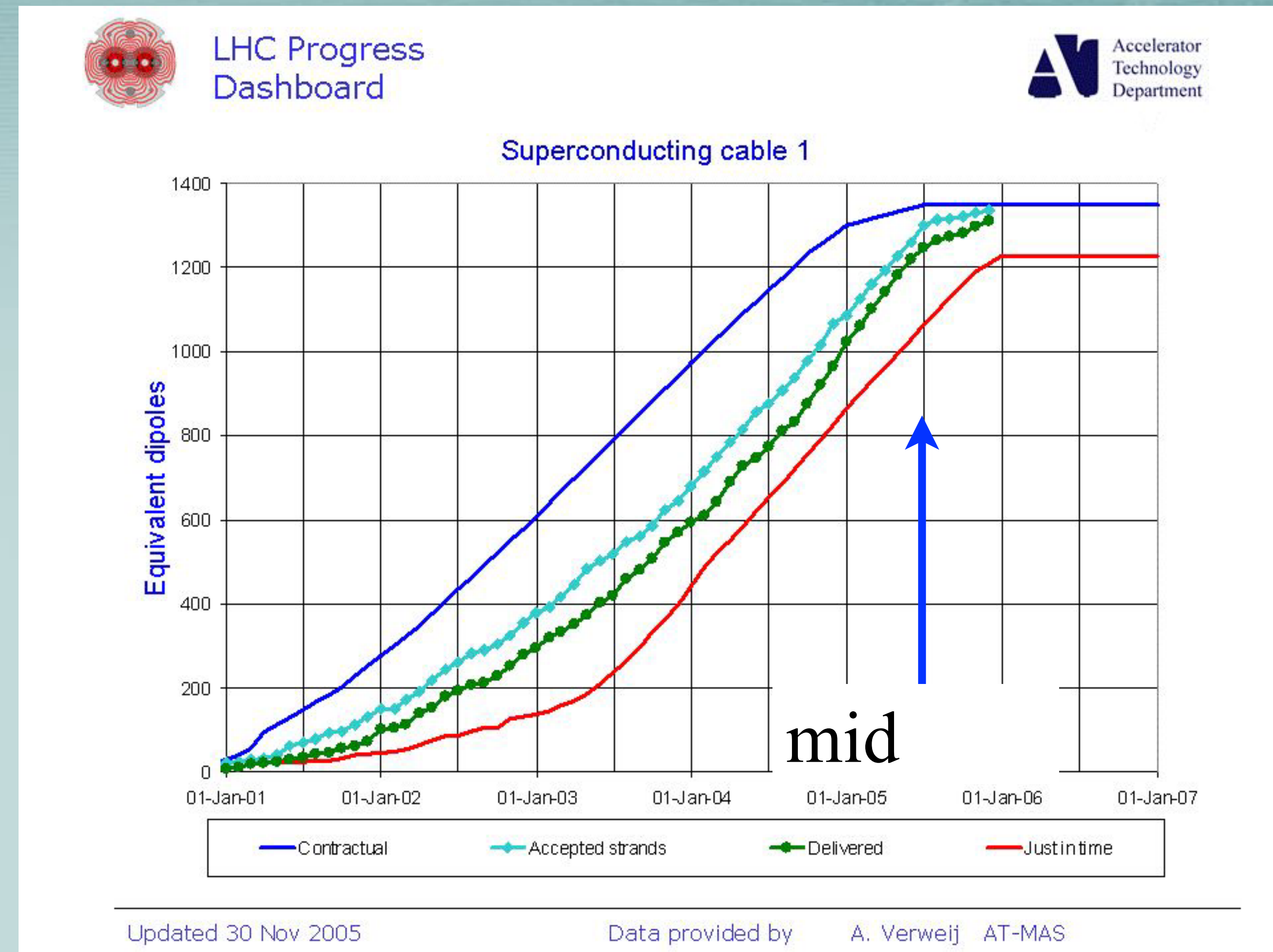

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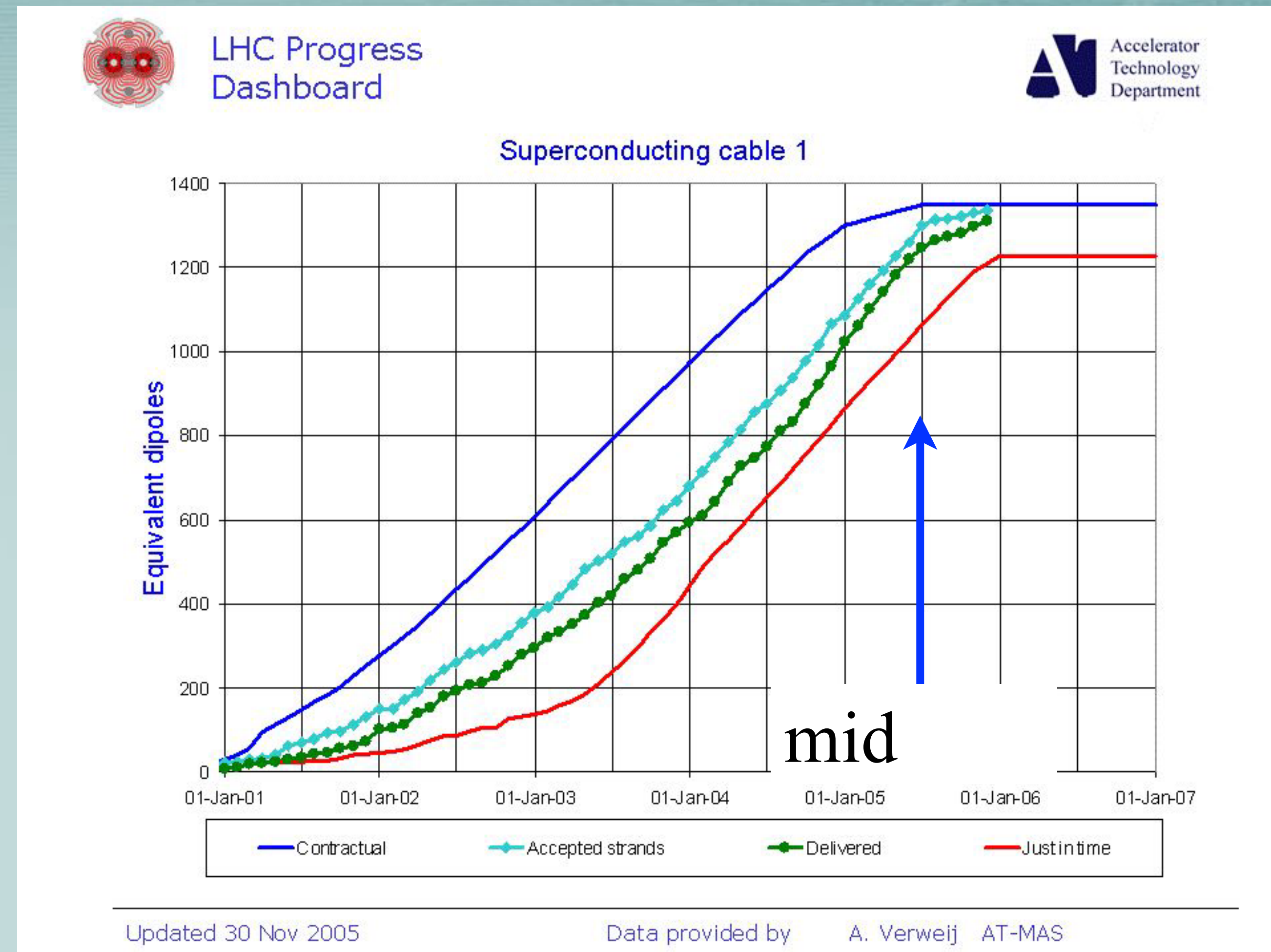

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. 10th 08: first beams

Lyn Evans and Lucio Rossi receive the last dipole at CERN

- useful beams: 2010
- Higgs physics: 2011

6. Announcing the boson:
ATLAS and CMS, CERN Seminar, July 4th, 2012

- People arrived 4 o'clock in the morning to find a seat
- a completely full conference room
- talks by Joe Incandelas, CMS, and Fabiola Gianotti, ATLAS

- François Englert (left) and Peter Higgs (right) at the CERN seminar …
- and Fabiola Gianotti, John Ellis..and many others

In the coming years, we will recognize a clear discontinuity in physics: BEFORE and AFTER the 4th of July talks by CMS and ATLAS.

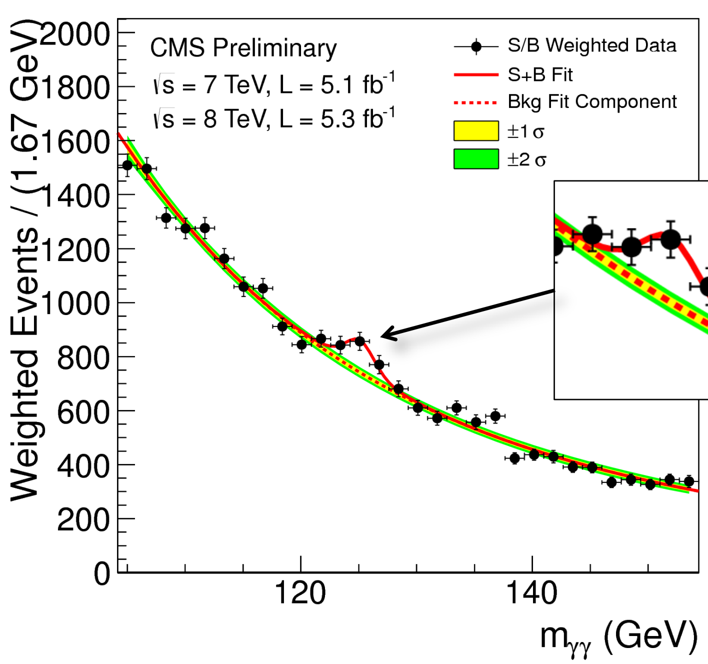
H must appear as a peak in the mass distribution of: 2 gammas: H-> γγ

CMS data

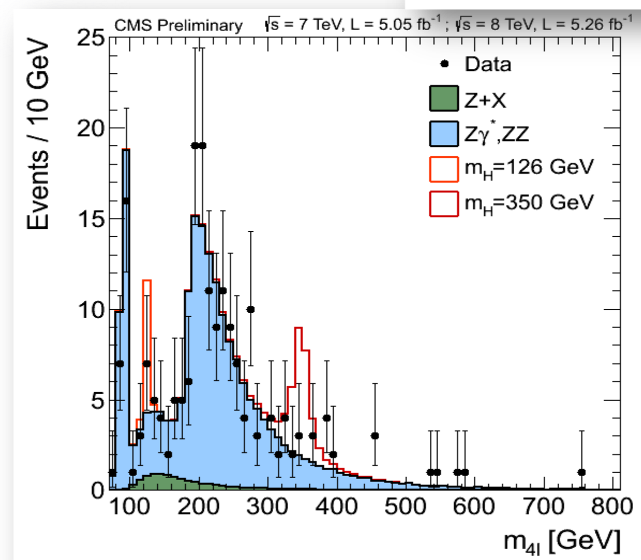
J. Incandelas

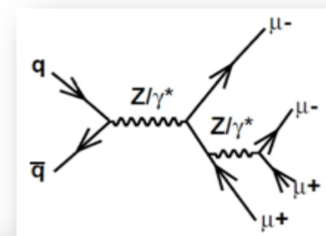
S/B Weighted Mass Distribution

- Sum of mass distributions for each event class, weighted by S/B
  - B is integral of background model over a constant signal f

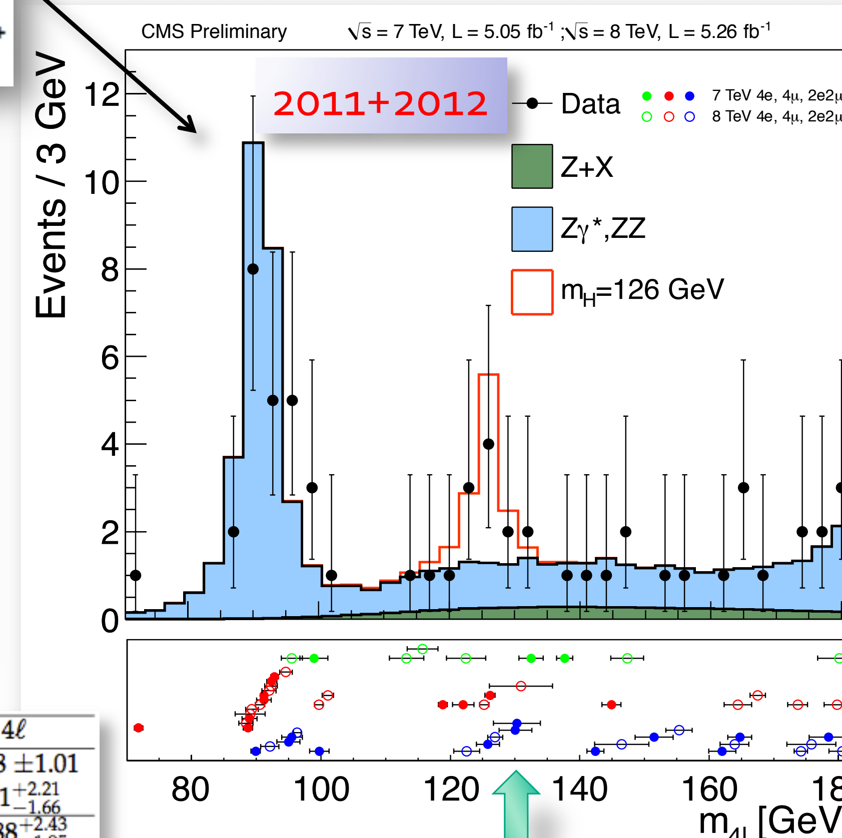


July 4th 2012 The Status of the Higgs Search J. Incandelas for the CMS COLLABORATION





Results: m(4l) spectrum



Event-by-event errors

Yields for m(4l)=110..160 GeV

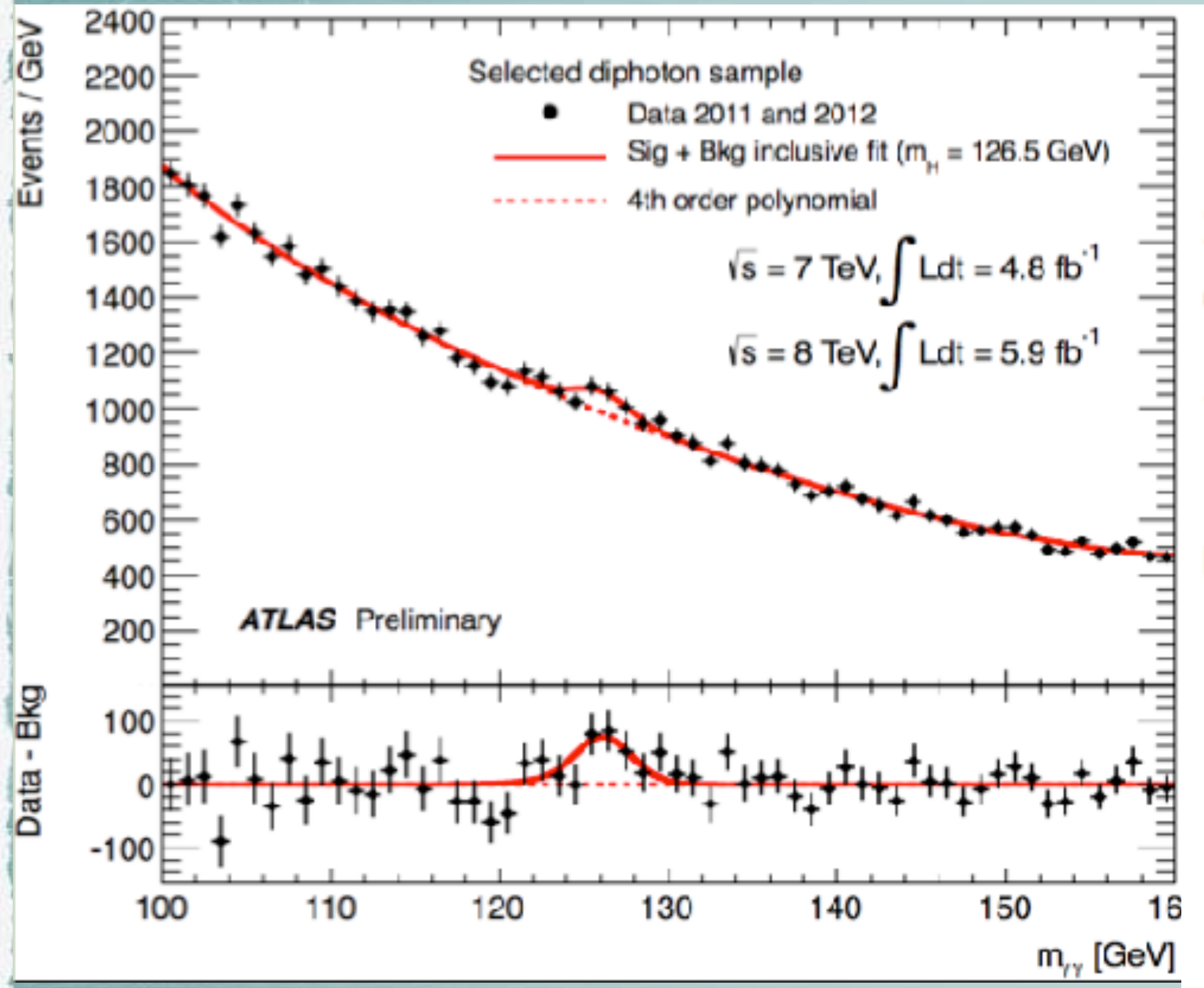
Channel	4e	4μ	2e2μ	4ℓ
ZZ background	2.65 ±0.31	5.65 ±0.59	7.17 ±0.76	15.48 ±1.01
Z+X	$1.20^{+1.08}_{-0.78}$	$0.92^{+0.65}_{-0.55}$	$2.29^{+1.81}_{-1.36}$	$4.41^{+2.21}_{-1.66}$
All backgrounds	$3.85^{+1.12}_{-0.84}$	$6.58^{+0.88}_{-0.81}$	$9.46^{+1.96}_{-1.56}$	$19.88^{+2.43}_{-1.95}$
$m_H = 126$ GeV	1.51 ±0.48	2.99 ±0.60	3.81 ±0.89	8.31 ±1.18

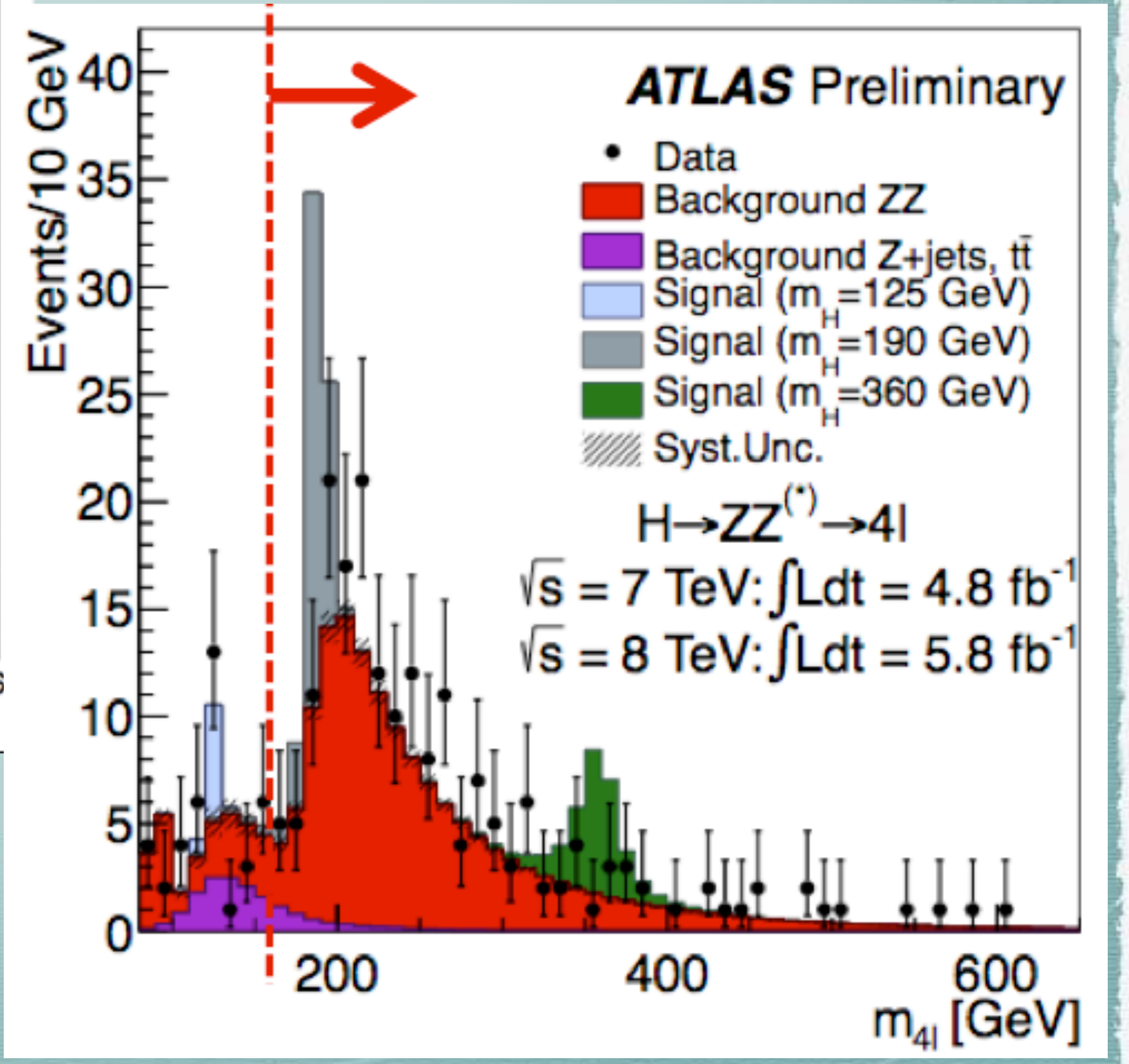
164 events expected in [100, 800 GeV]
172 events observed in [100, 800 GeV]

ATLAS

2 gammas: H-> γγ

F. Gianotti

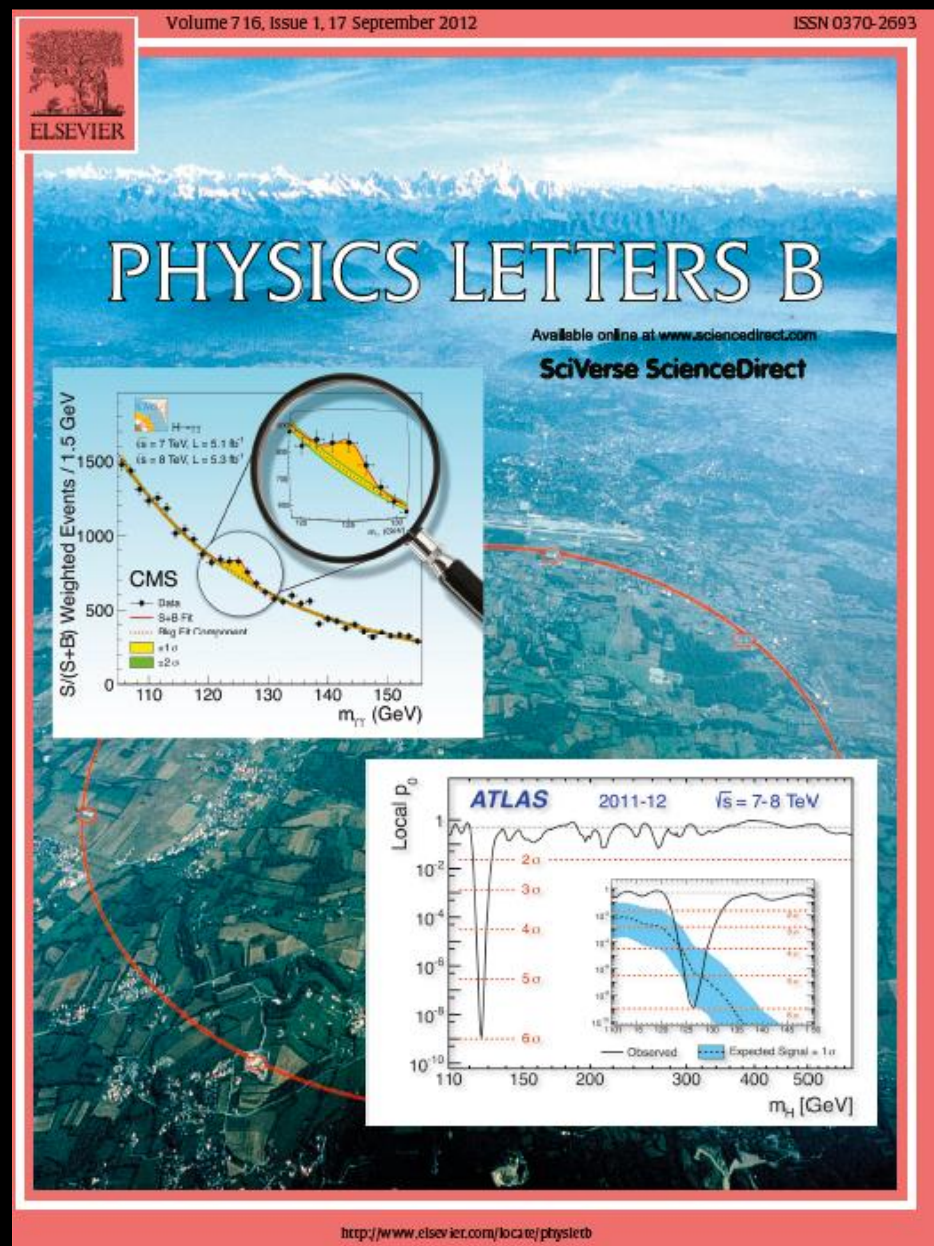




In scientific press

The Discovery

July 2012



~ 3800 citations / experiment so far

October 2013

"For the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

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

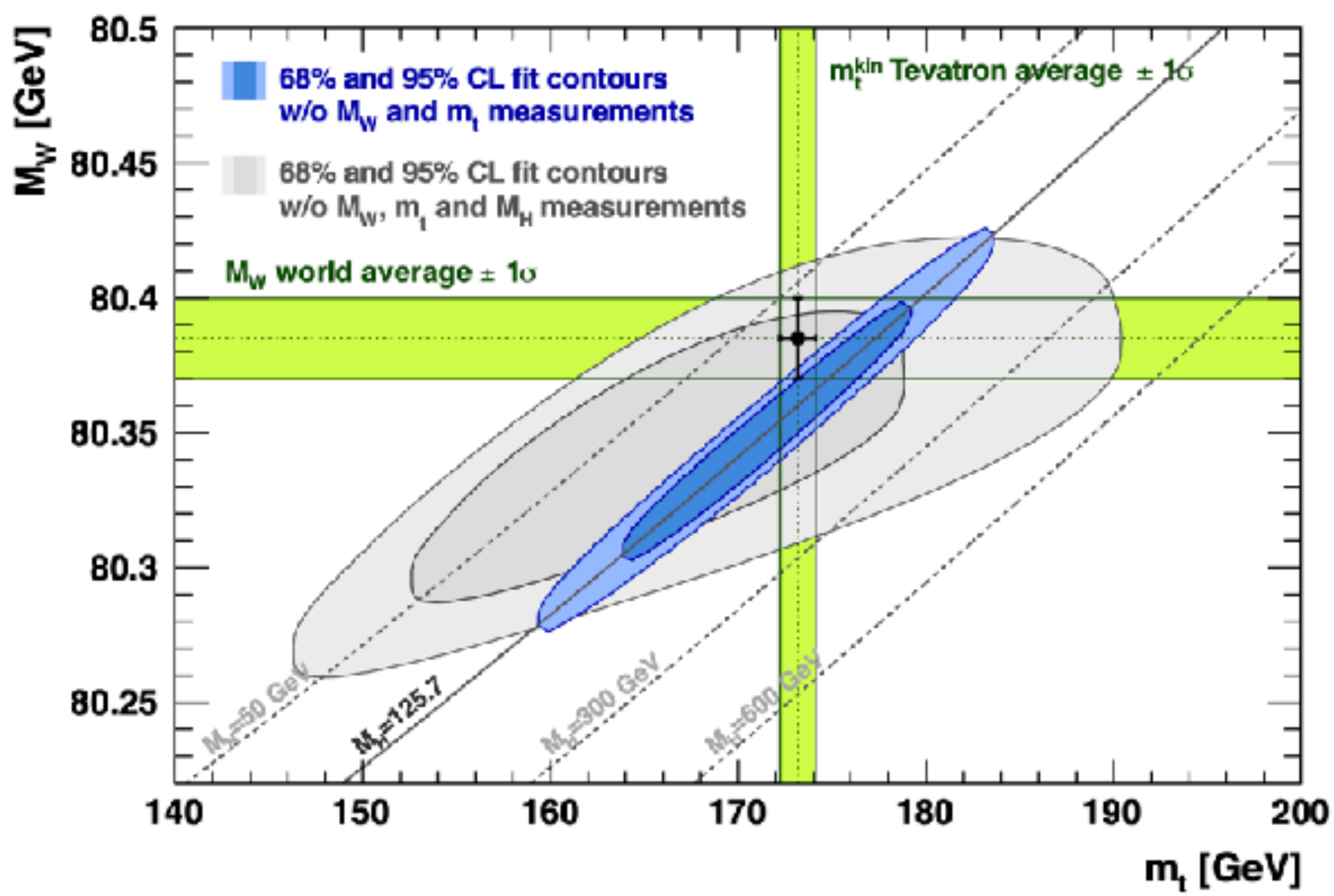
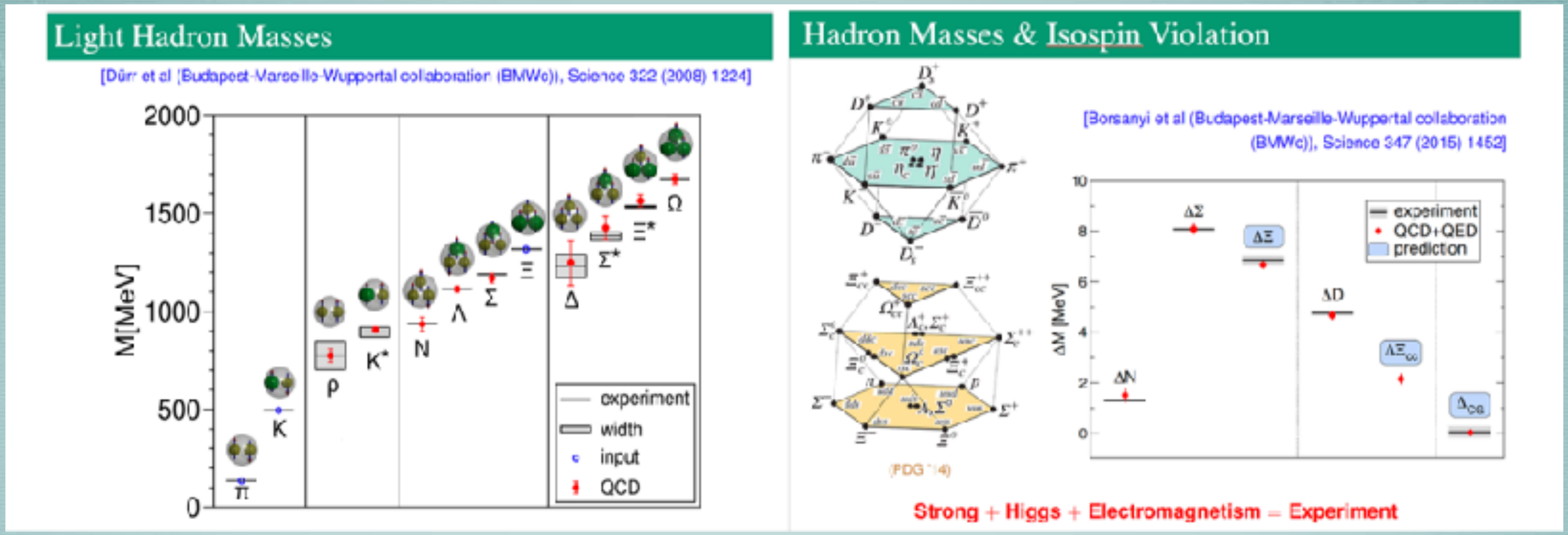


Figure 4: Contours of 68% and 95% CL obtained from scans of fixed M_W and m_t. The blue (grey) areas illustrate the fit results when including (excluding) the new M_H measurements. The direct measurements of M_W and m_t are always excluded in the fit. The vertical and horizontal bands (green) indicate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

7. What do we do now in particle physics ?

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



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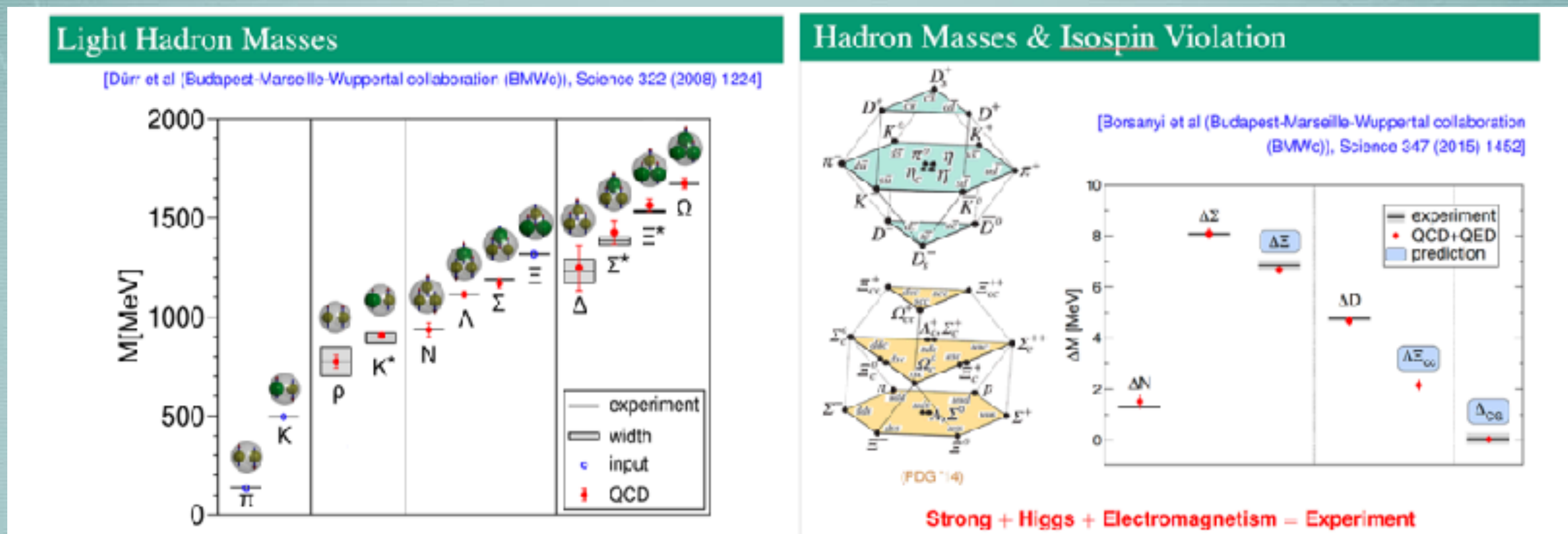
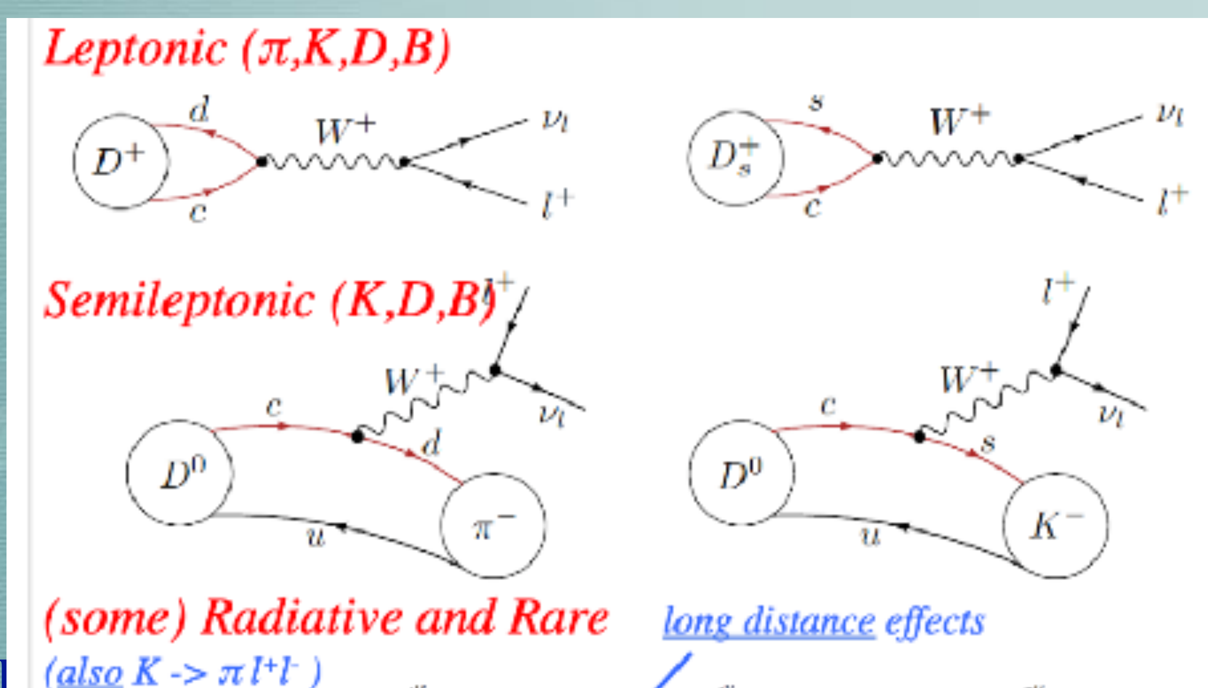
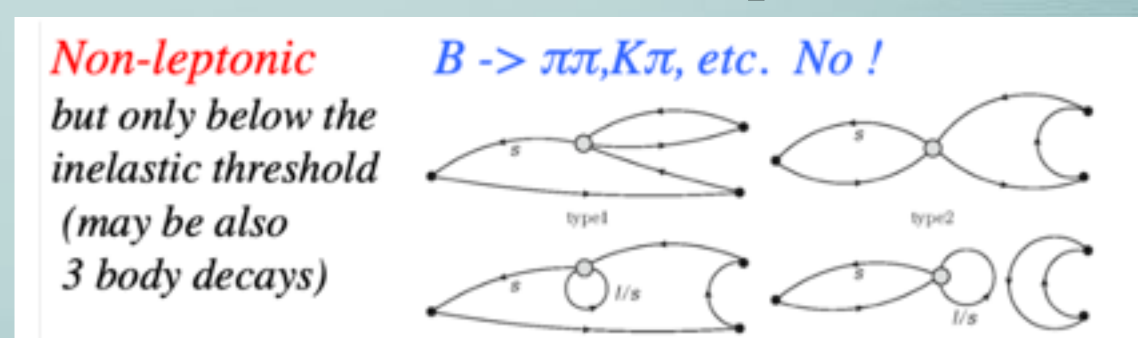


QCD corrections to weak interaction processes with or without leptons





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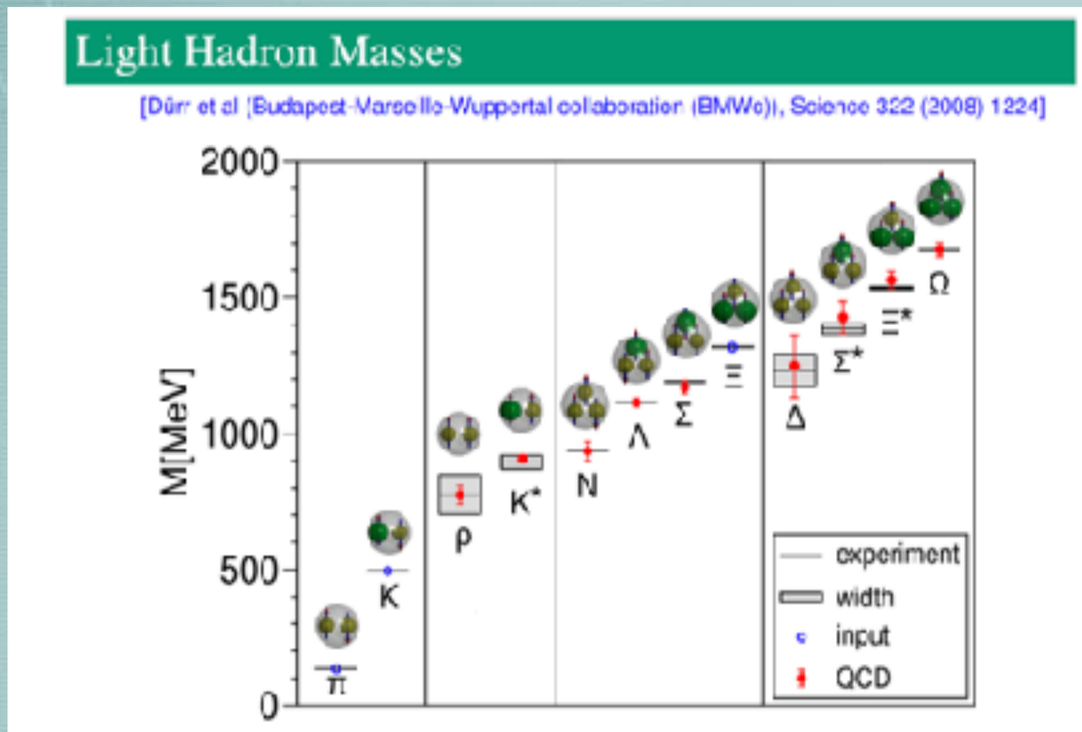

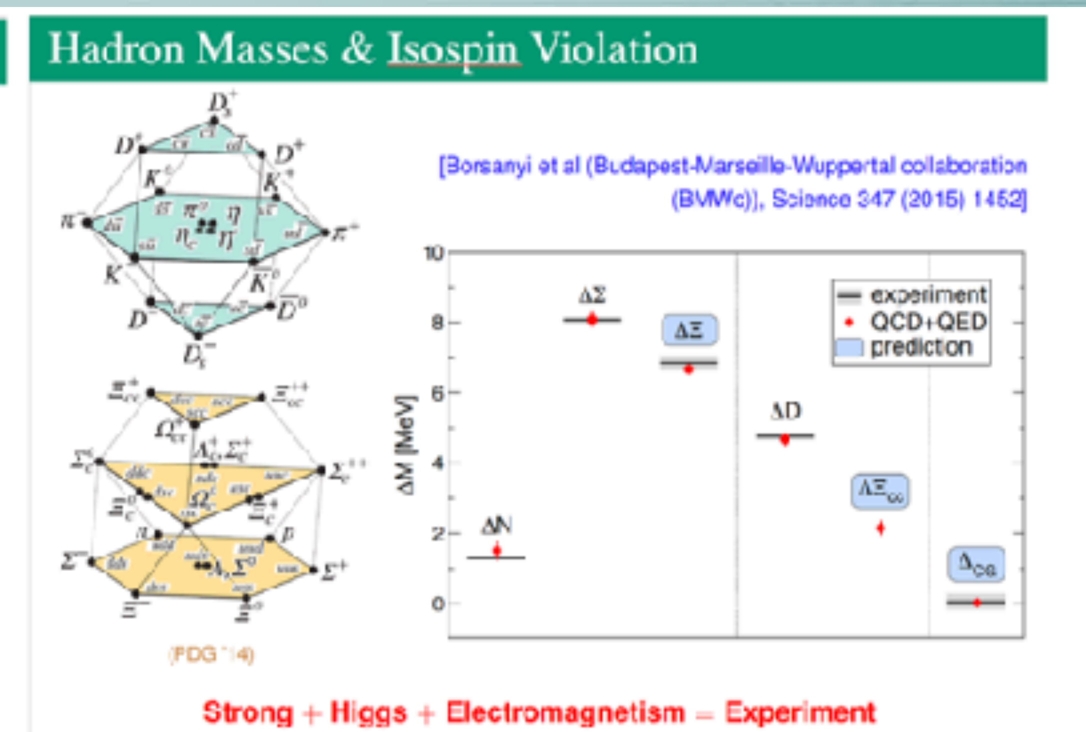

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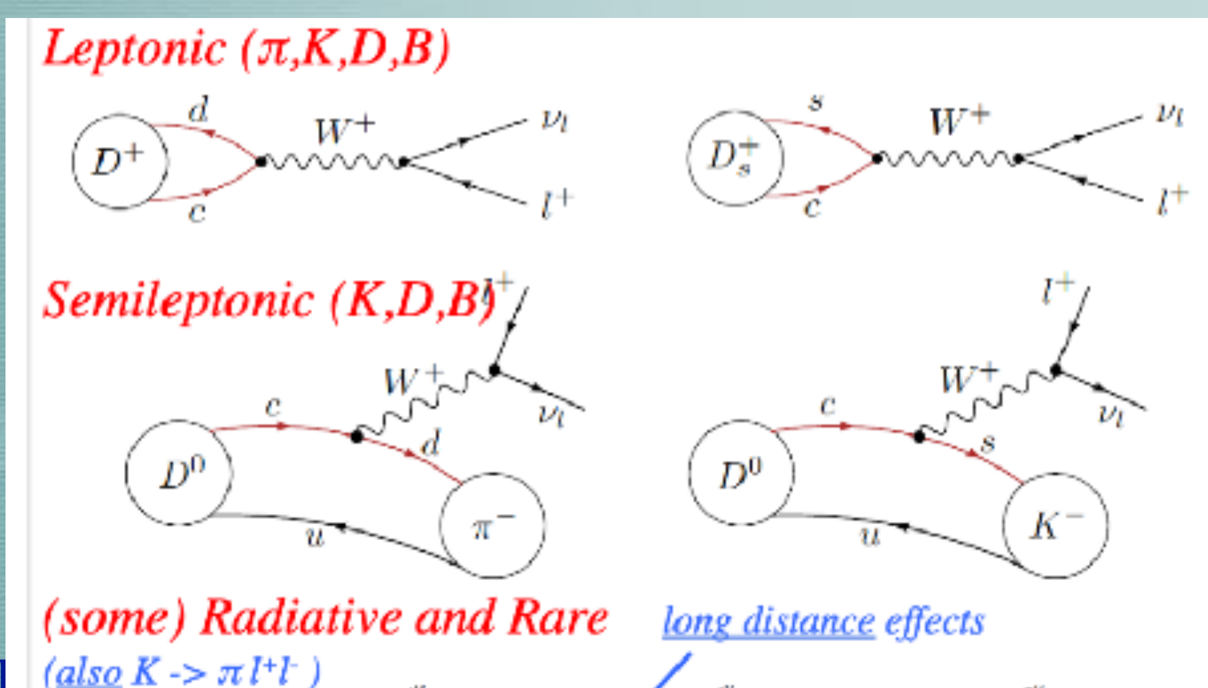
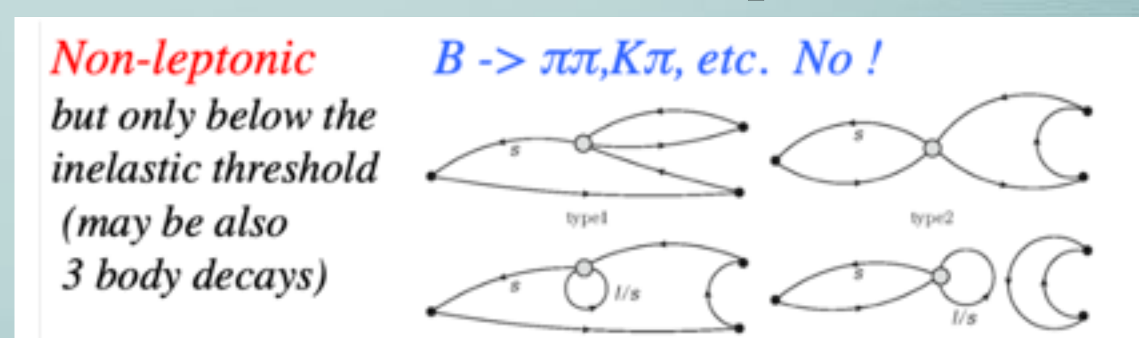


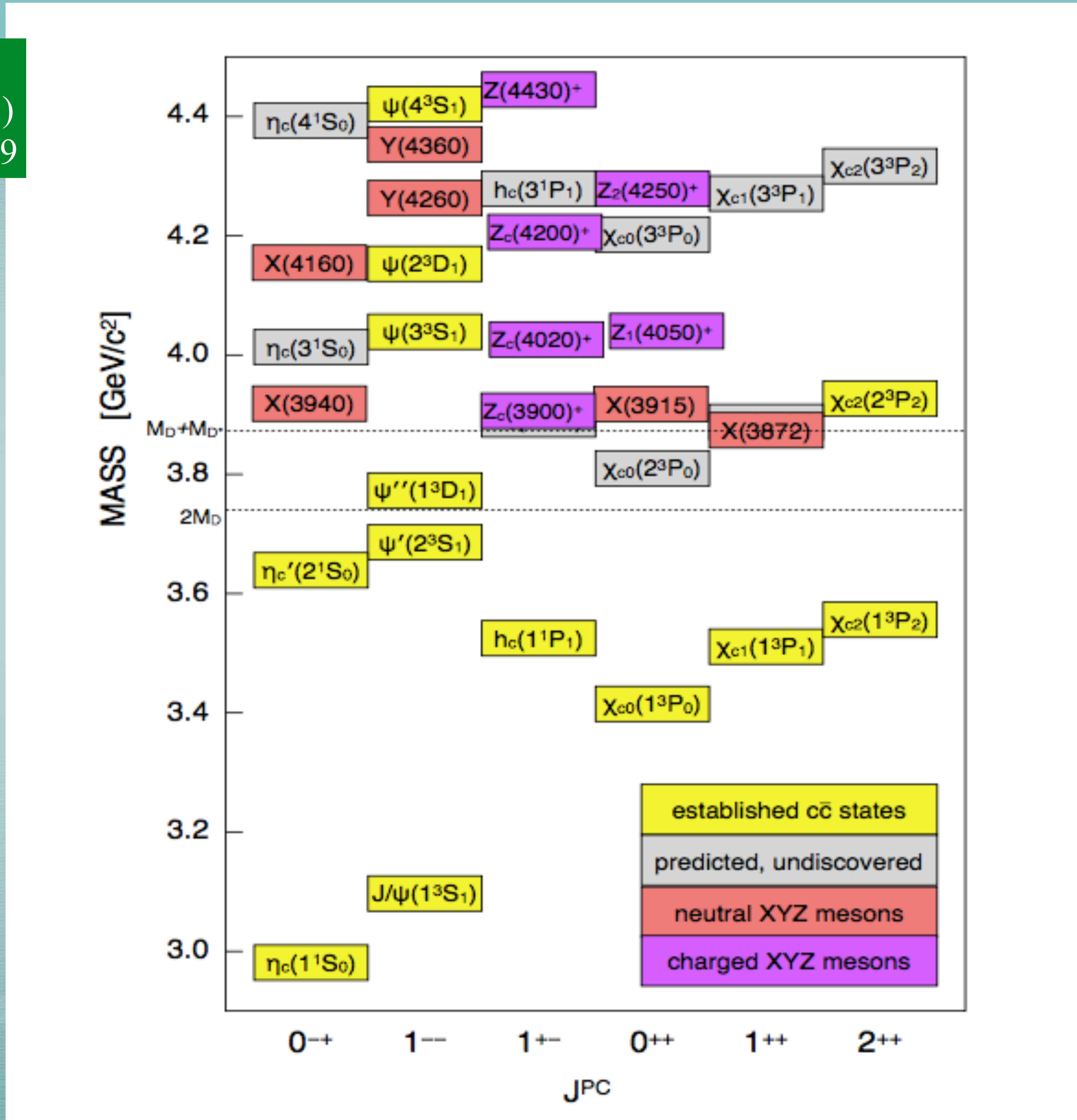


- Computing power increase, from
- 10^9 Gigaflops (1980's) to

$0.1 - 1 \cdot 10^{18}$ Gigaflops (2020's), ***made all that (and more) possibile!***

2. Find the correct Theory of Unexpected Charmonia (Exotic Hadrons)

figure by:
S. L. Olsen (2015)
arXiv:1511.01589



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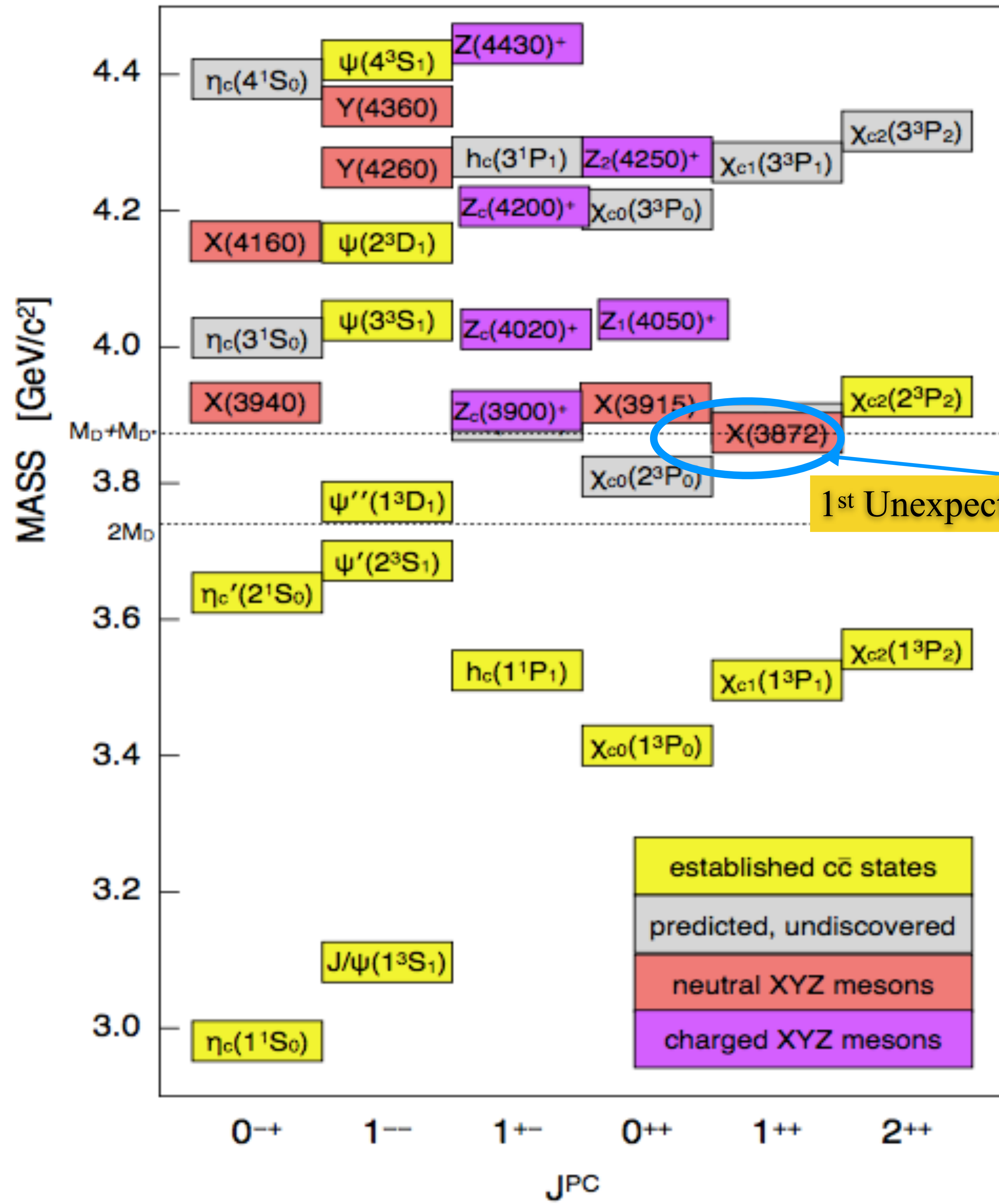

1st Unexpected (BELLE, BaBar, 2003)

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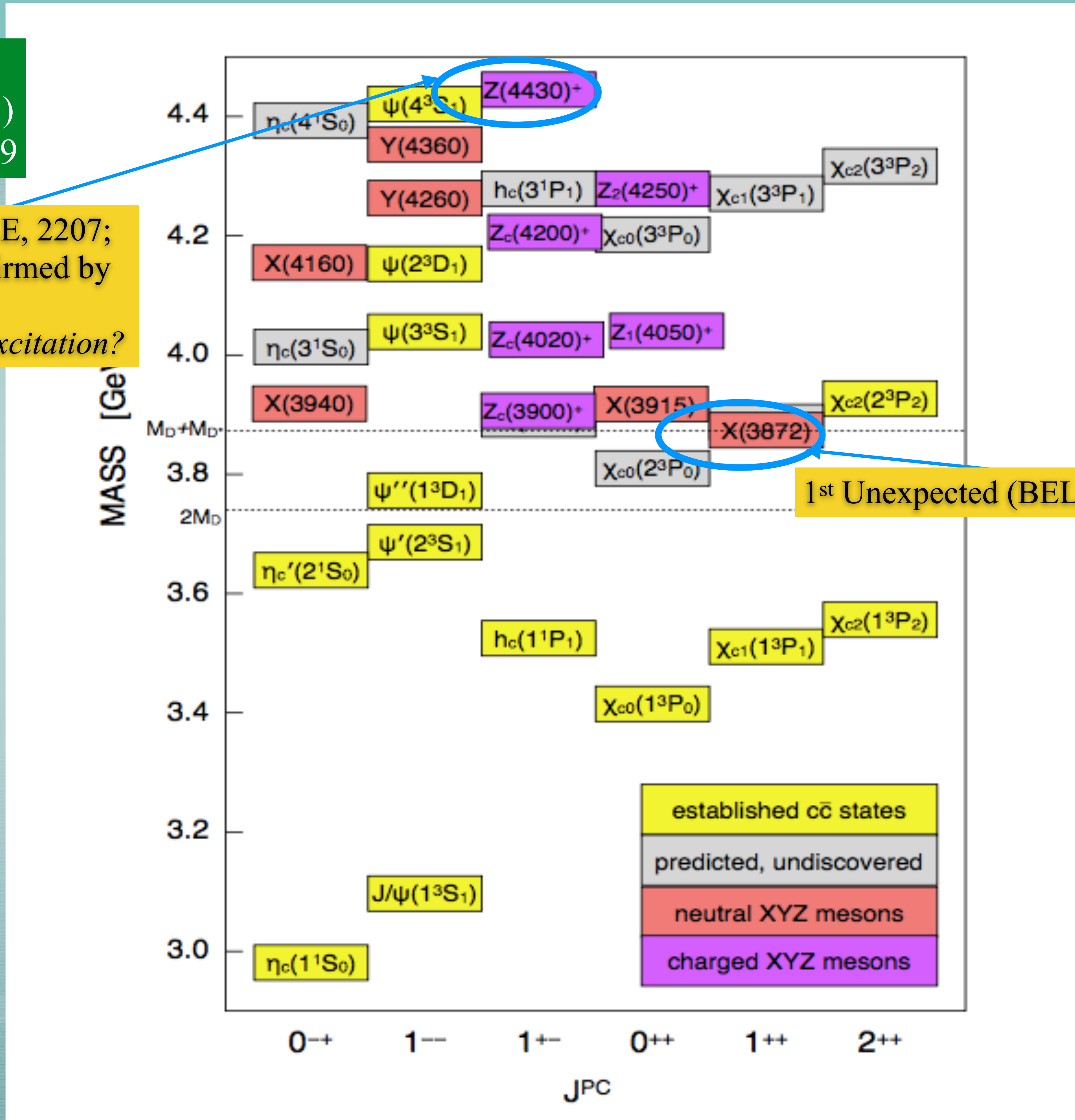
2nd Unexpected (BELLE, 2207; doubts by BaBar; confirmed by LHCb, 2014)
first charged, a radial excitation?



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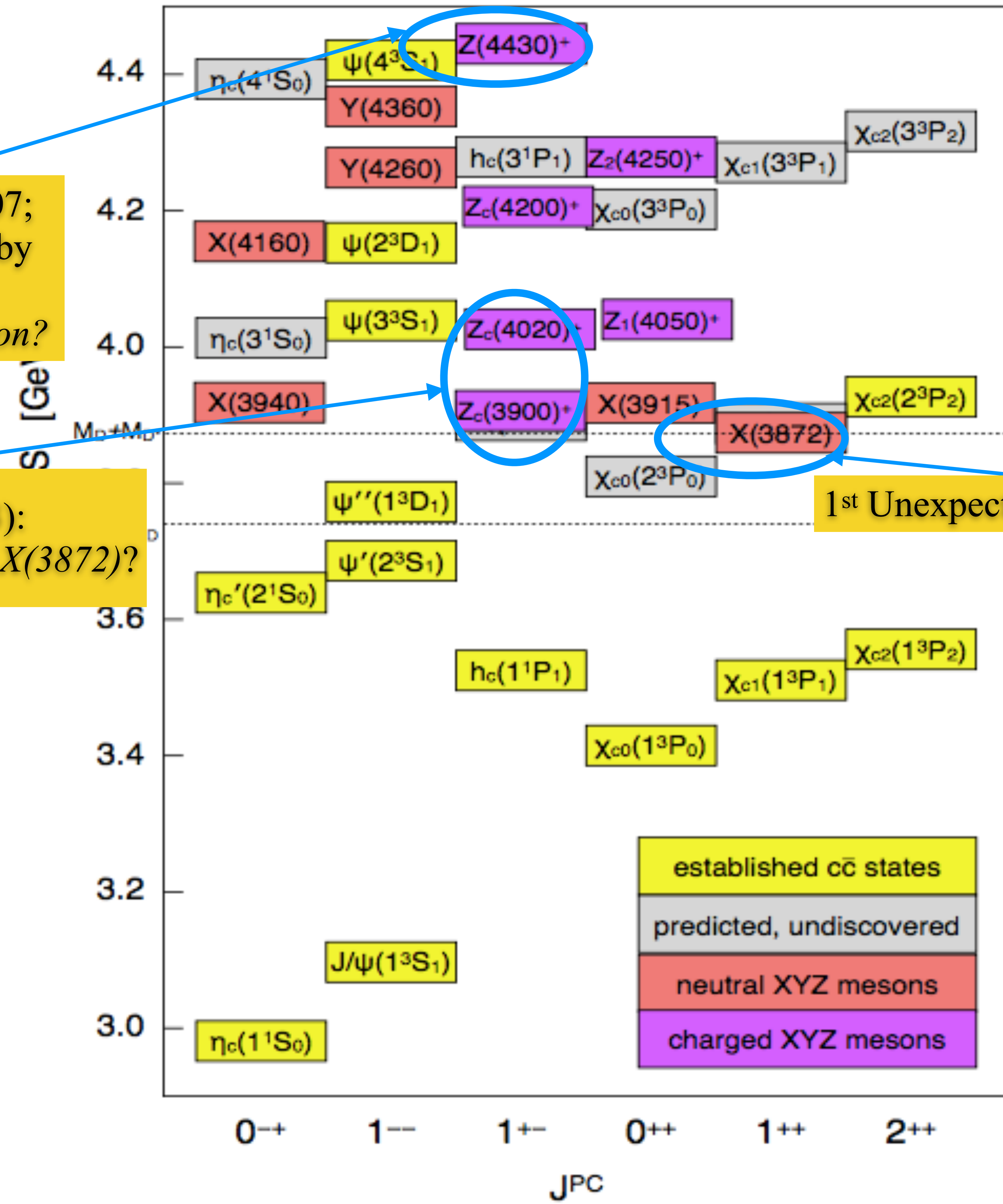

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3rd Unexpected (BES III, 2013):
ground state Tetraquarks with X(3872)?

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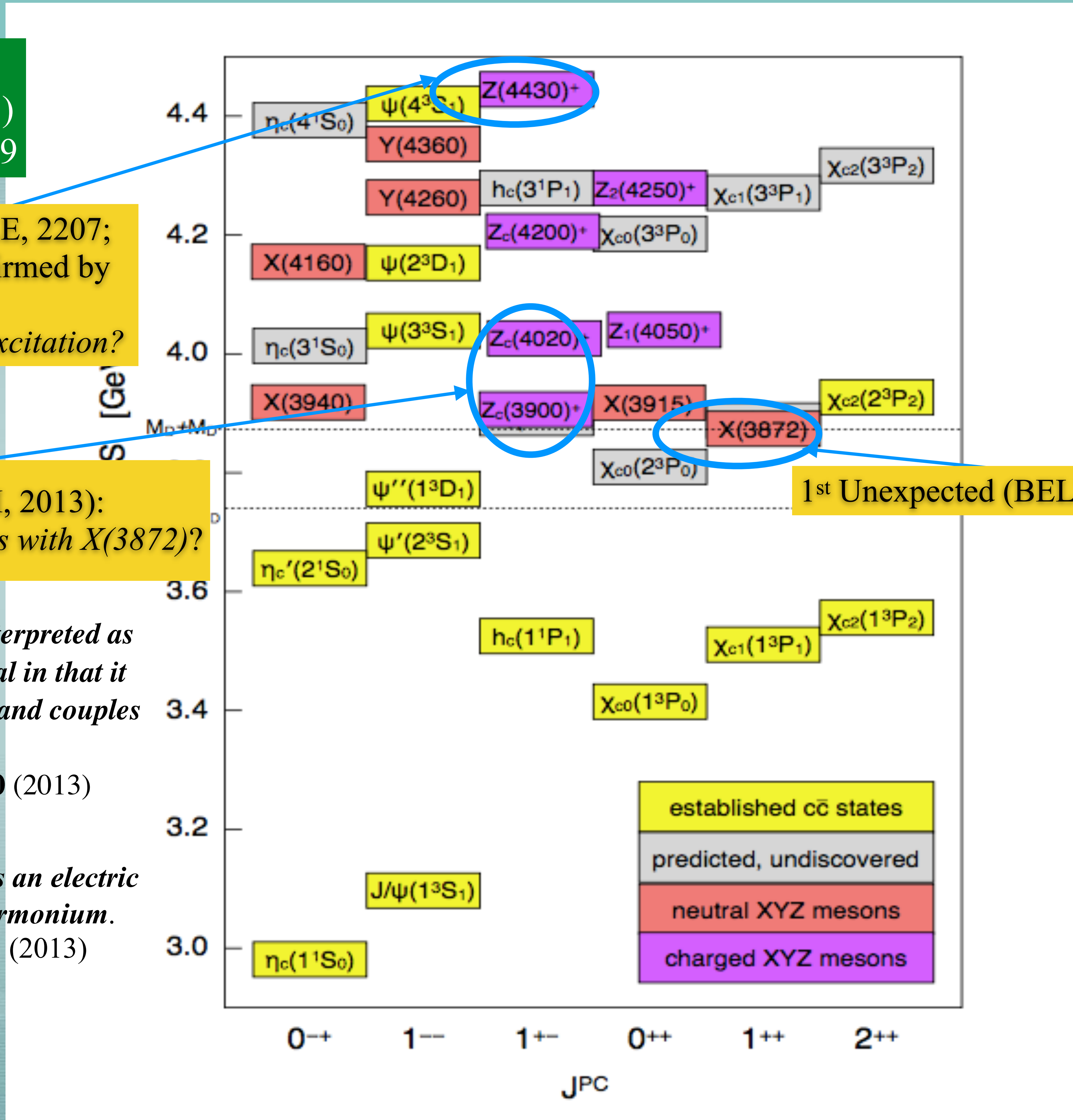

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$Z_c(3990)$ $\rightarrow \pi^{\pm} J/\Psi$. ***If interpreted as a new particle, it is unusual in that it carries an electric charge and couples to charmonium.***
BESII, Phys. Rev. Lett. **110** (2013) 252001

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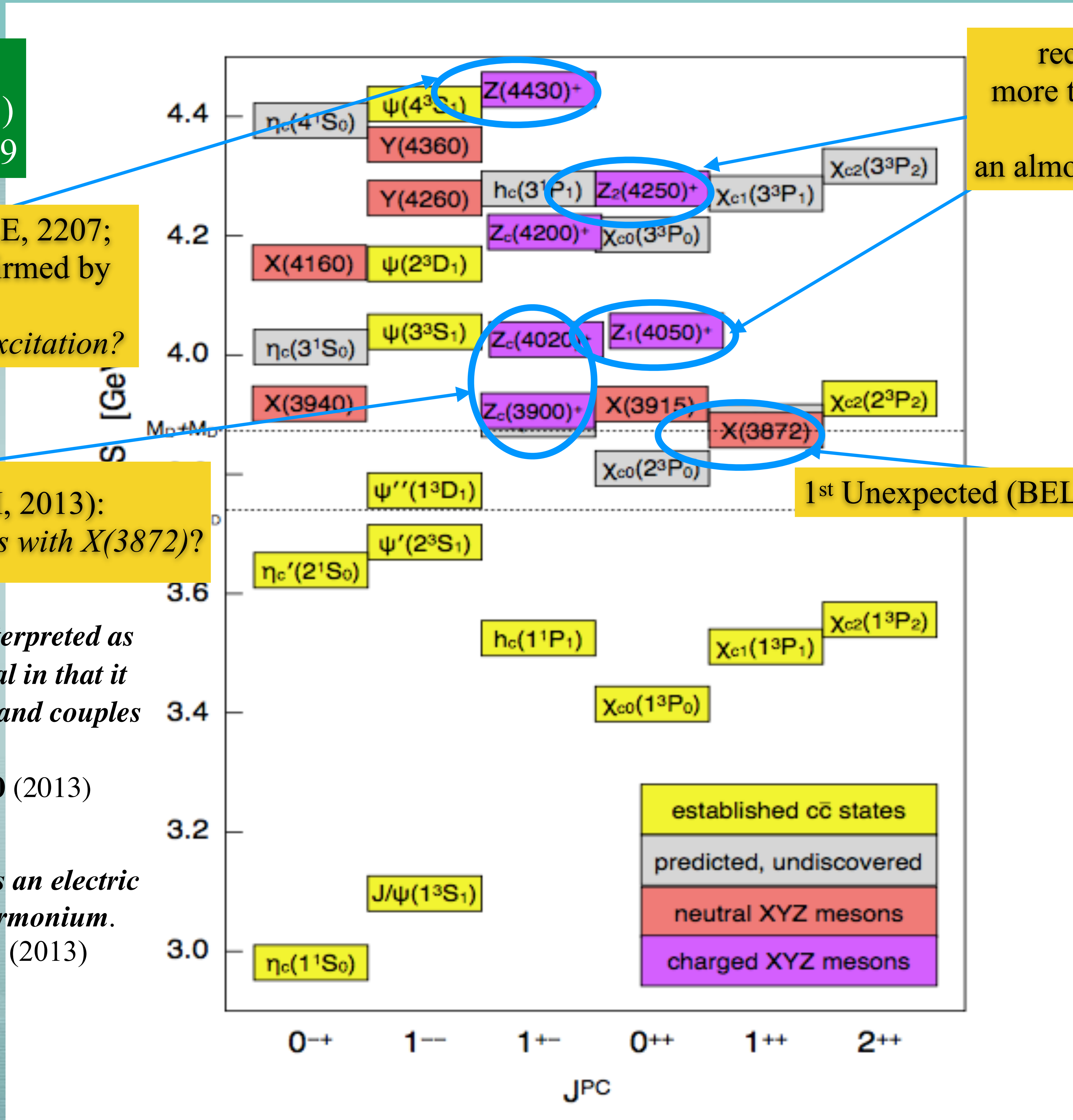

recent additions: more than coincidence? or an almost filled multiplet?

2nd Unexpected (BELLE, 2207; doubts by BaBar; confirmed by LHCb, 2014)
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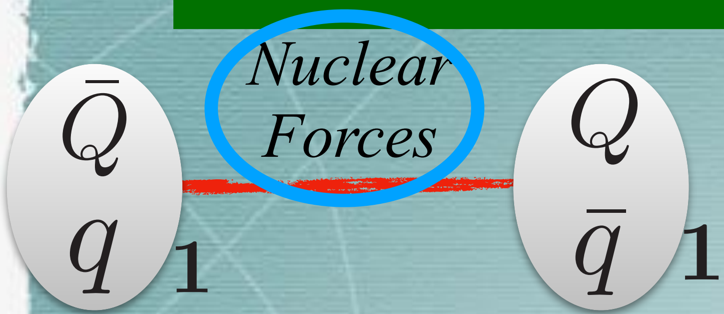
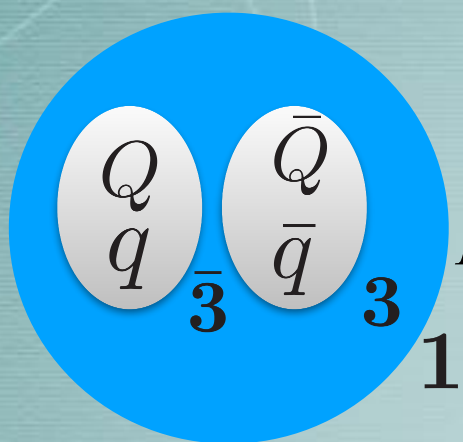
No consensus, yet



Hadron Molecule

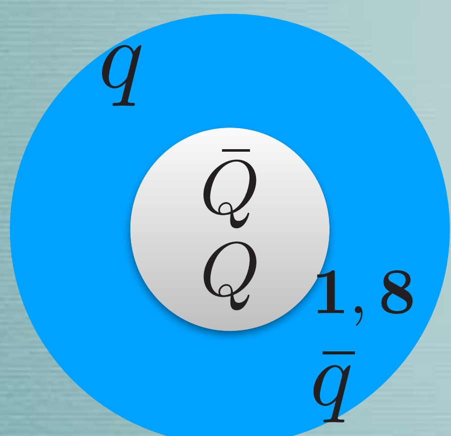
F-K. Guo, C. Hanhart, U-G Meißner, Q. Wang, Q. Zhao, and B-S Zou, arXiv 1705.00141 (2017)



QCD Forces

Compact Diquark-Antidiquark

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



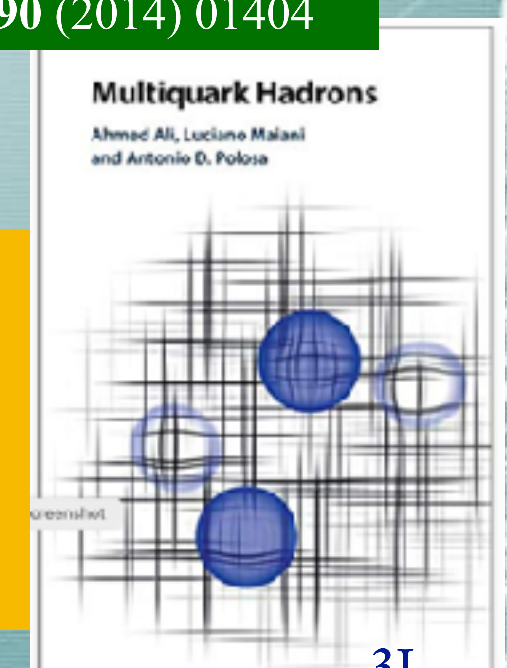
QCD Forces

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

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



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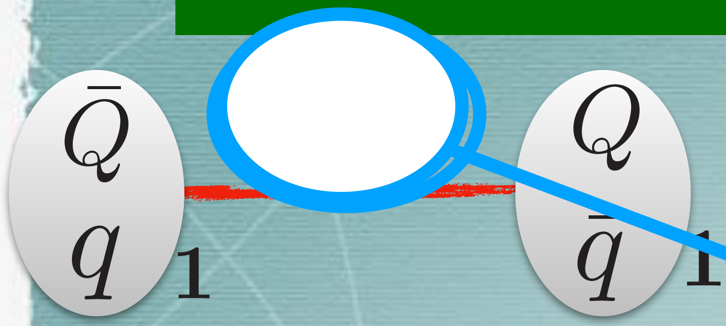

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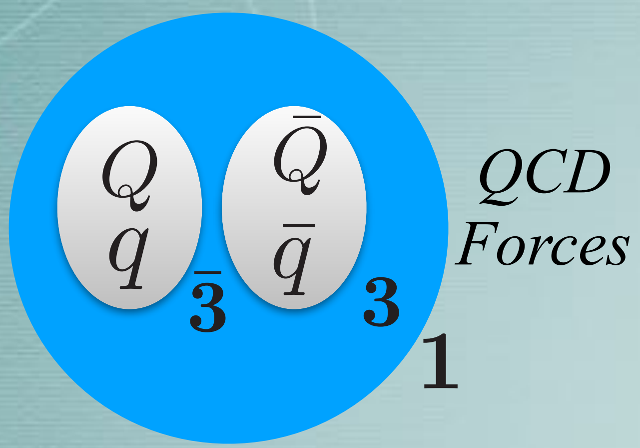
Contact interactions in Chiral Perturbation Theory

Z. H. Zhang *et al.*, JHEP **08** (2024) 130



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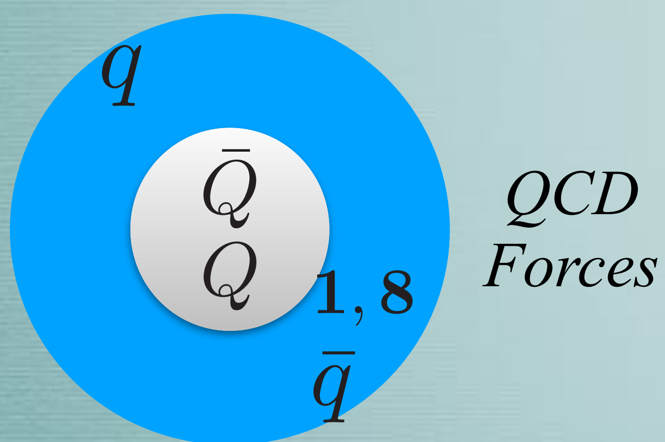

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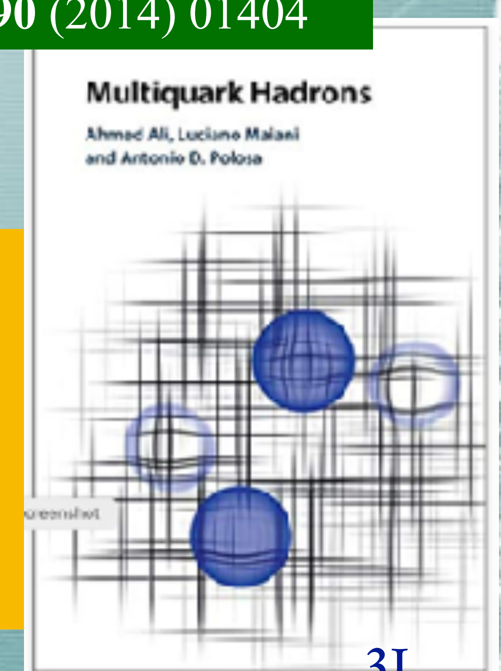
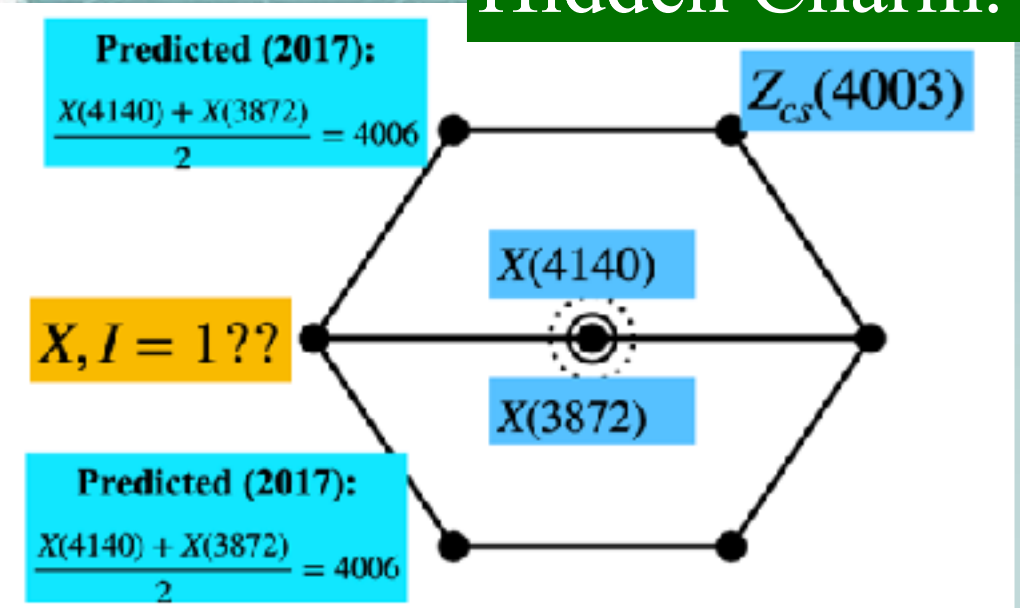
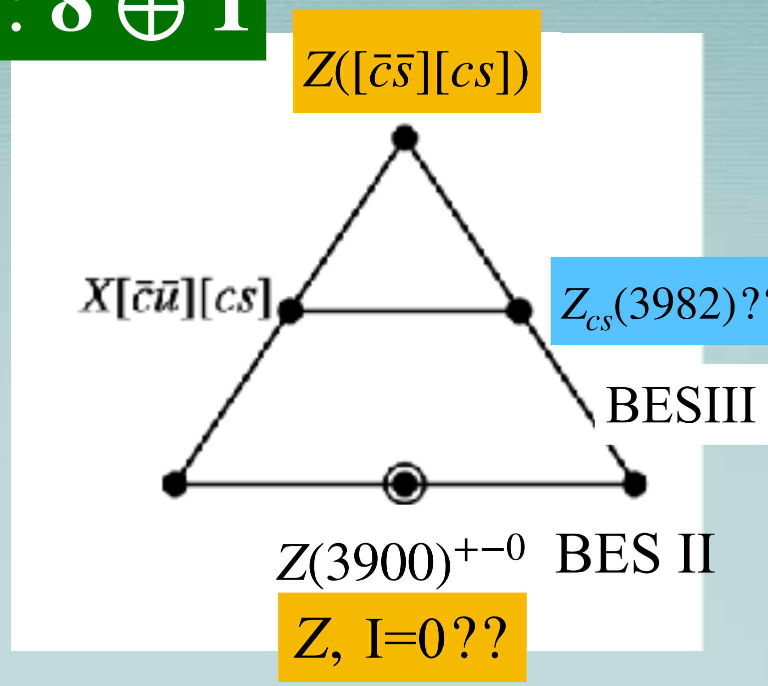
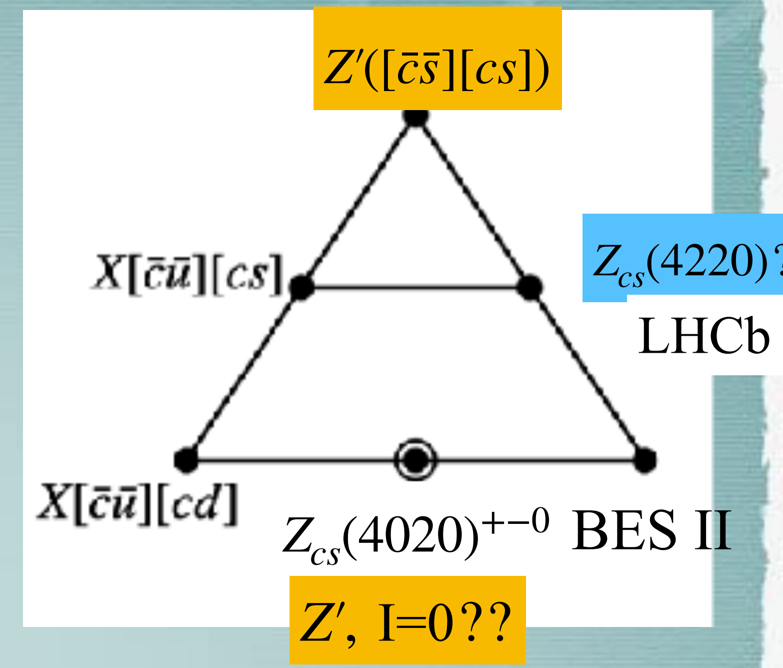


9. Summing up

Hidden Charm. : $\mathbf{8} \oplus \mathbf{1}$



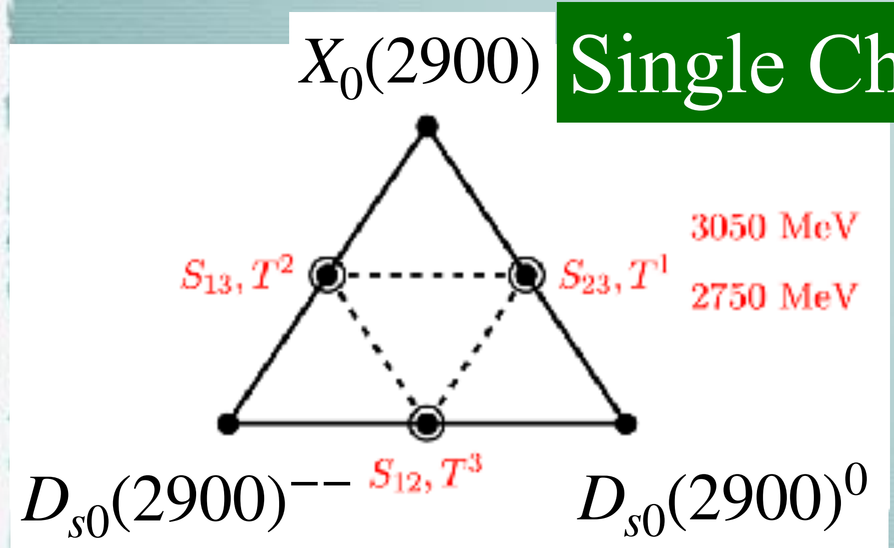




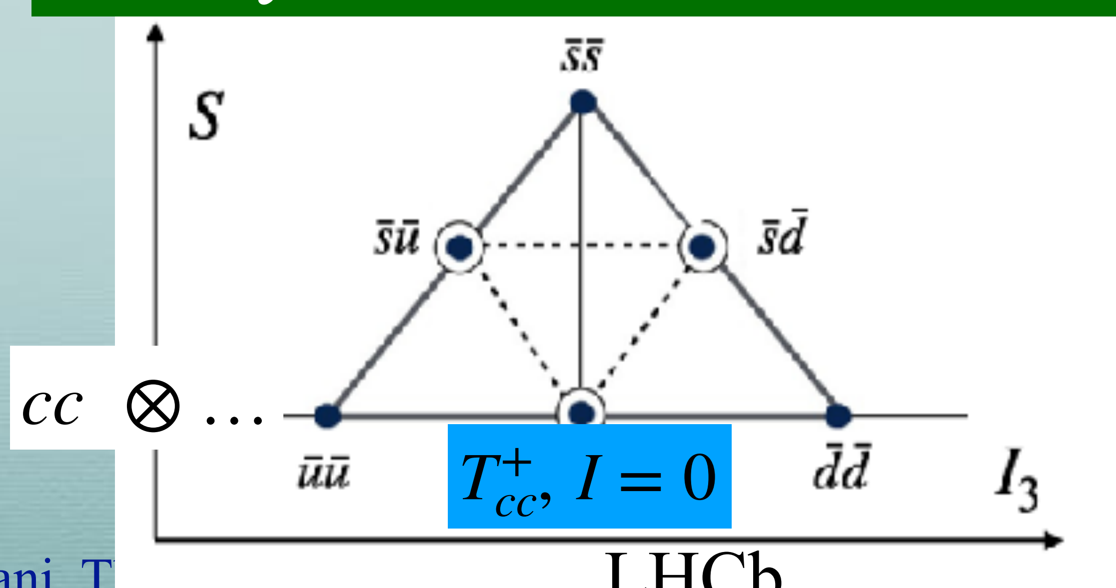
$X^+ \to J/\psi\, \rho^\pm \to J/\psi\, \pi^+\pi^0$

$$0.057 < R_{2\pi}^{(0+,00)} = \frac{\Gamma(B^0 \to K^+X^- \to K^+\psi\, \pi^0\pi^-)}{\Gamma(B^0 \to K^0X(3872) \to K^0\psi\, \pi^+\pi^-)} < 0.50$$

Single Charmed, $J^P = 0^+ : \mathbf{3} \oplus \bar{\mathbf{6}}$



Doubly Charmed: $J = 1^+ : \mathbf{3}$, $J = 0^+ : \bar{\mathbf{6}}$

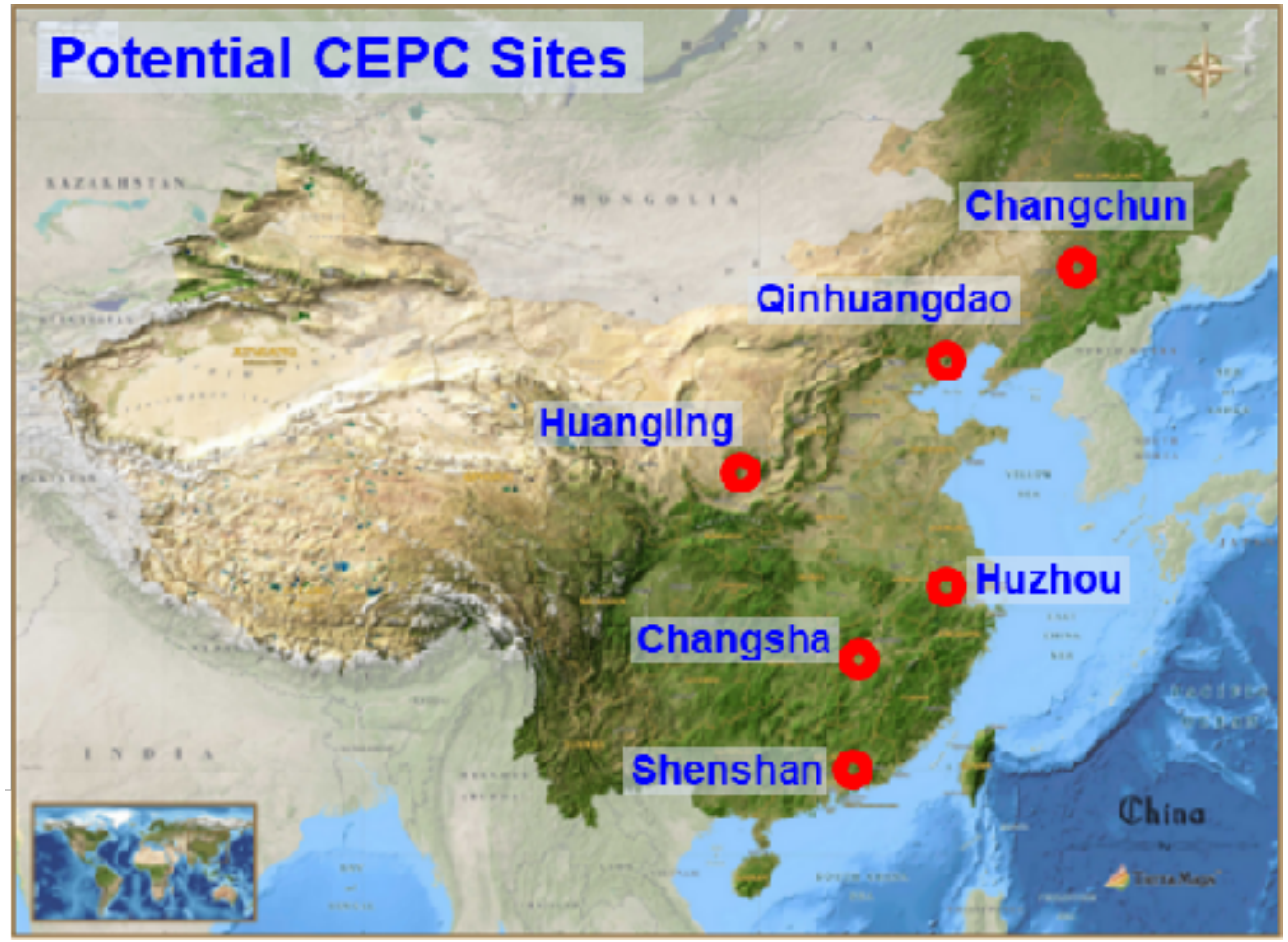


3. Physics Beyond the Standard Model: the High Energy Way

The large European Project:
Future Circular Collider
at CERN

Kick-off Meeting of the
Future Circular Collider Design Study
University of Geneva, 2014

CEPC site investigation and facility study



- Site selection based on geology, electricity supply, transportation, environment for foreigners, local support & economy,…
- North are better for running cost savings
- CDR study is based on Qing-Huang-Dao, 300 km towards the east of Beijing

- More invitations from local governments: Changsha, Changchun, …
- Recent visit to Shangsha: best for geology & transportation(20 km from a large city & an international airport)

Dreams about the future??

- 100 TeV proton Collider is a fantastic challenge
- new innovative technologies: material science, low temperatures, electronics, computing, big data
- an attraction for new physics ideas and young talents to solve the hardest scientific problem which we have been confronted over the last 100 years.

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1950's: National Laboratories in IT, FR, UK, DE... united forces to make CERN-Europa
2030's: Regional Laboratories in Europe, America, Asia … will they unite in a Global Accelerator Network - The World ??

THANK YOU !!