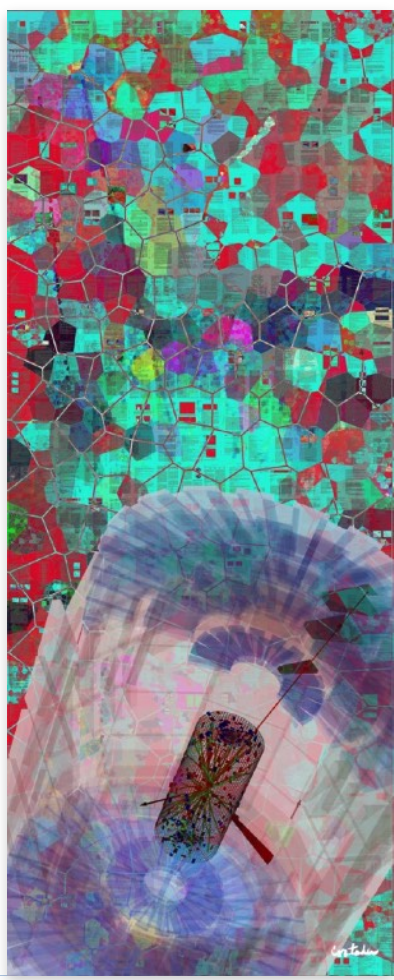
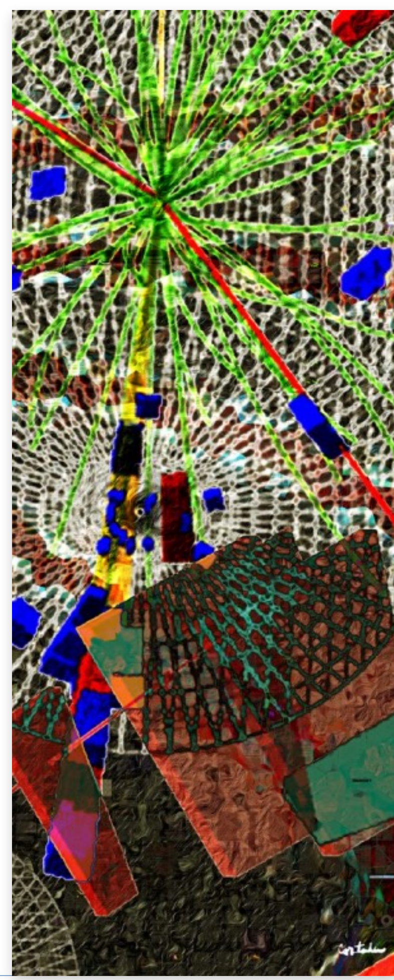
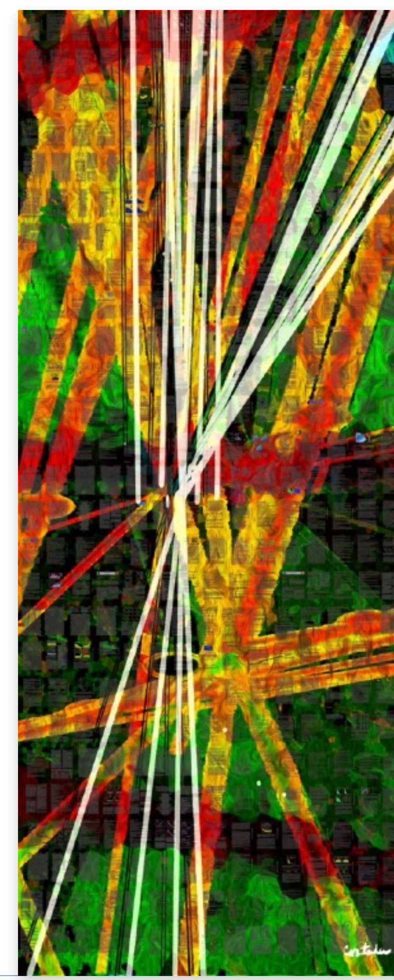
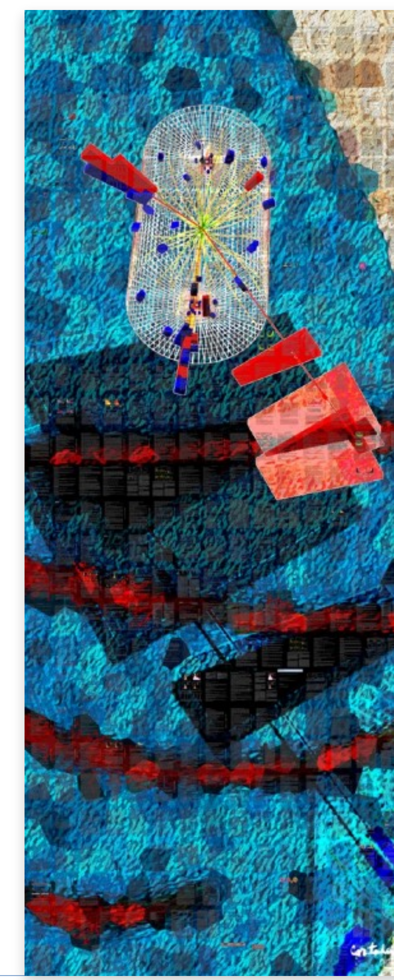
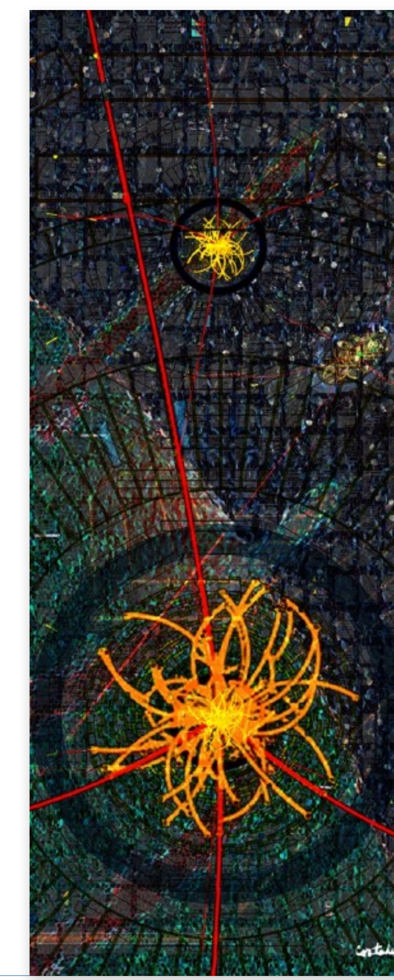
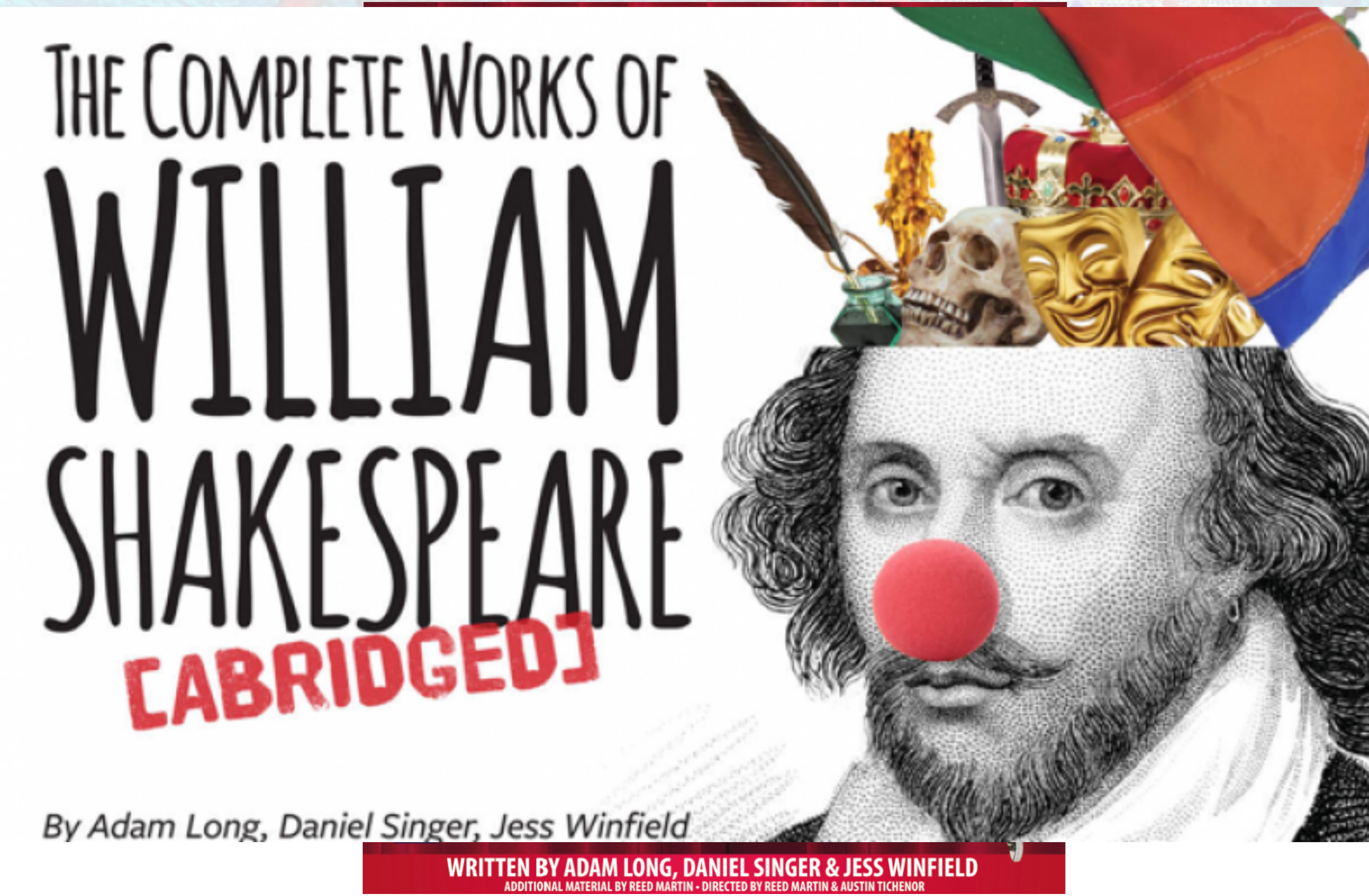
Physics Highlights from ZEUS and CMS

Observations as a fellow traveller

LATBauerdick at Wesley Fest, August 30, 2019

...not ALL physics highlights...

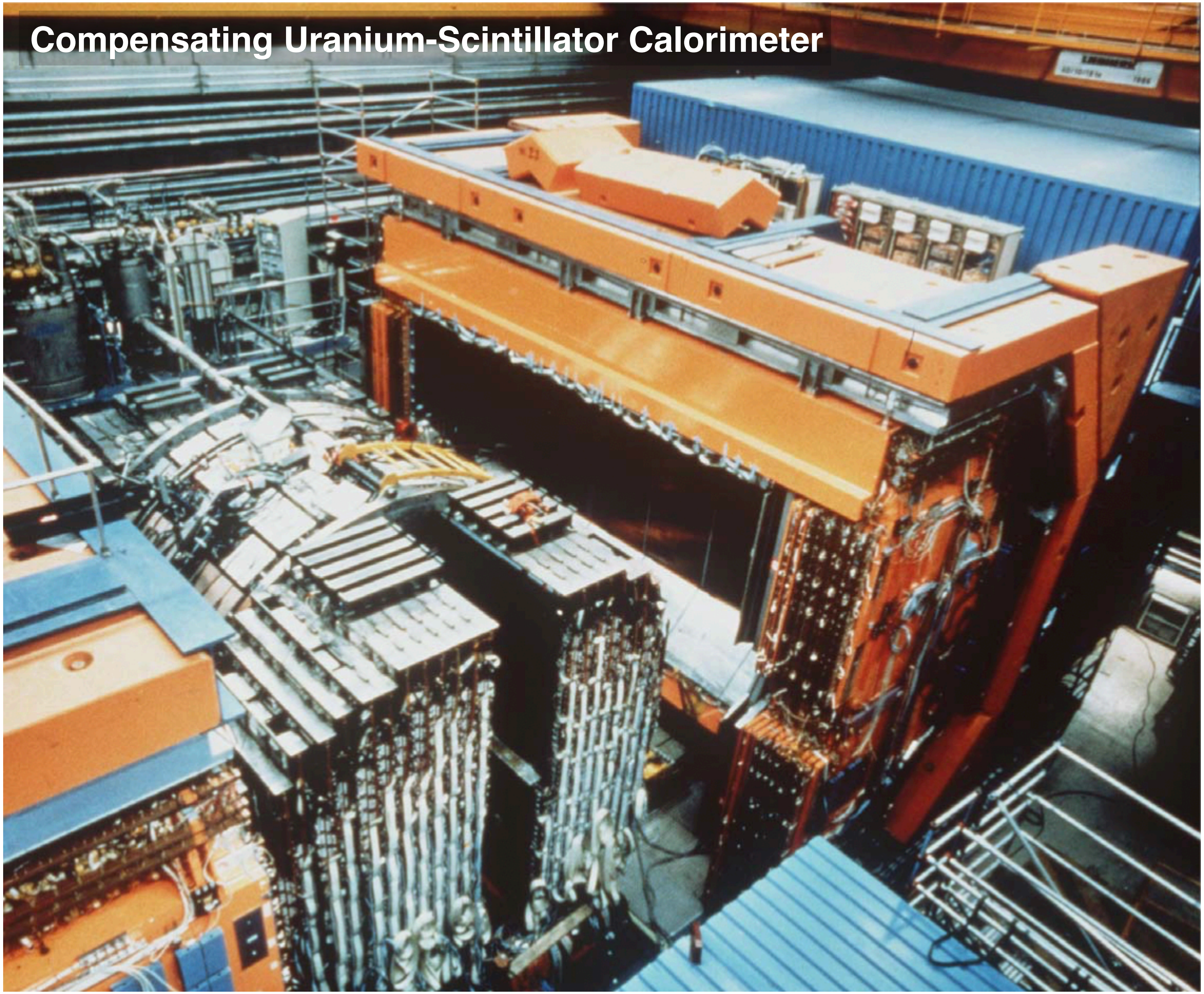


A (brief) Celebration of ZEUS and CMS Physics!

HERA at DESY in Hamburg, Germany

6.3km tunnel with storage rings for electron and proton beams
Superconducting magnets 4.7 Tesla for E_p of up to 920 GeV
Electrons at E_e = 27.5 GeV, polarization and spin rotators
$\sqrt{s}$ = 320 GeV allows for $Q^2_{max} \sim 10^5$ GeV^2, $\Lambda_{max} \sim 1/1000\ r_{proton}$
Operated from 1992 to 2007

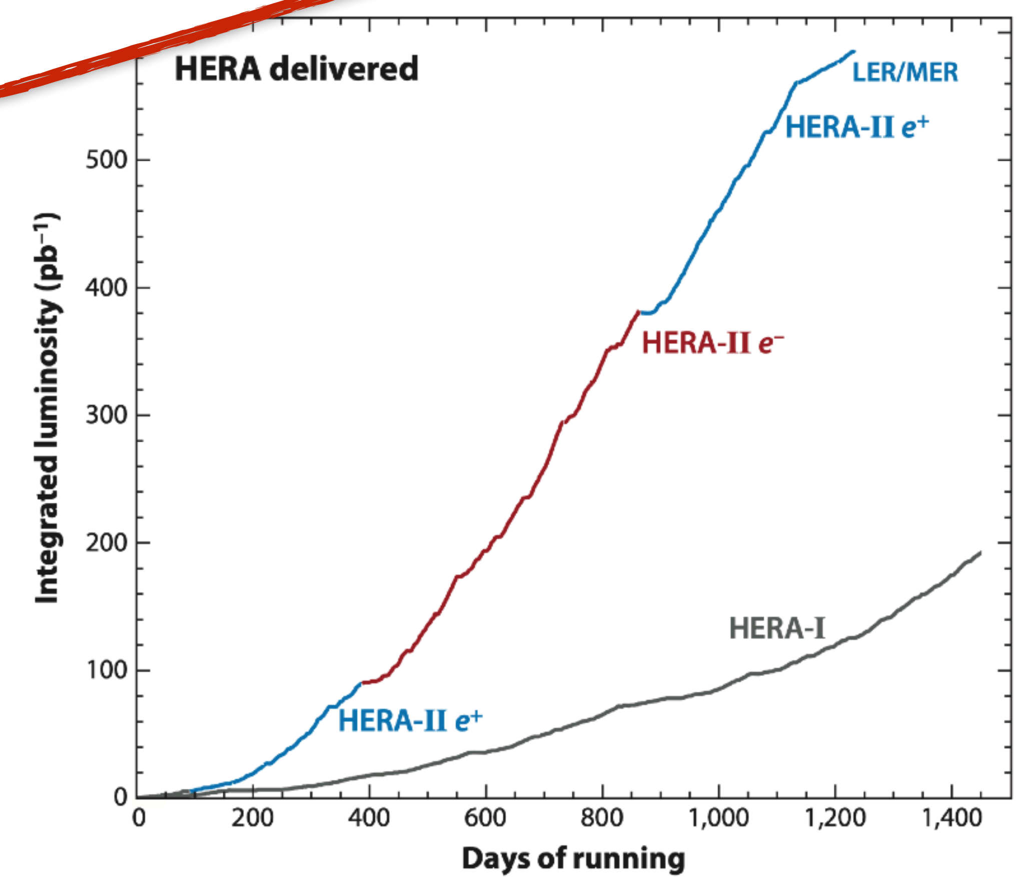
The ZEUS Detector



A Very Successful Program of DIS Physics

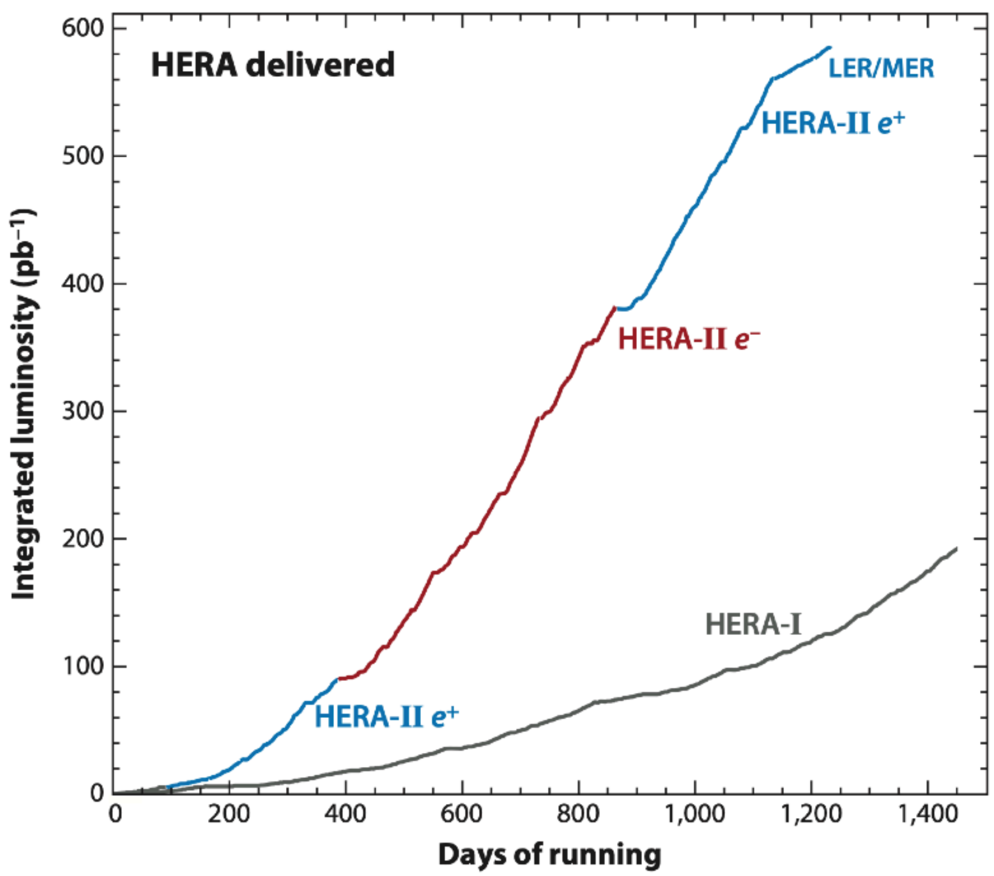
- The combined ZEUS + H1 precision data on deep-inelastic scattering reach a precision of almost 1% in the double-differential cross-section measurements
  - It's the largest coherent data set on proton str … ix orders of magnitude in the kinematic variables …
  - A QCD analysis of the HER … density functions, HERAP … riments.
  - Also, u … the stro … together …
- QCD and … ts are probed at … cision in the same data set, providing beautiful demonstrations of the validity of the Standard Model

LEGACY!



A Very Successful Program of DIS Physics

- The combined ZEUS + H1 precision data on deep-inelastic scattering reach a precision of almost 1% in the double-differential cross-section measurements
  - It's the largest coherent data set on proton structure, spanning six orders of magnitude in the kinematic variables x_{Bj} and Q^2
  - A QCD analysis of the HERA data alone results in a set of parton-density functions, HERAPDF2.0, without the need for data from other experiments.
  - Also, using HERA jet and charm data, the strong-coupling constant is measured together with the proton PDFs.
- QCD and electroweak effects are probed at high precision in the same data set, providing beautiful demonstrations of the validity of the Standard Model



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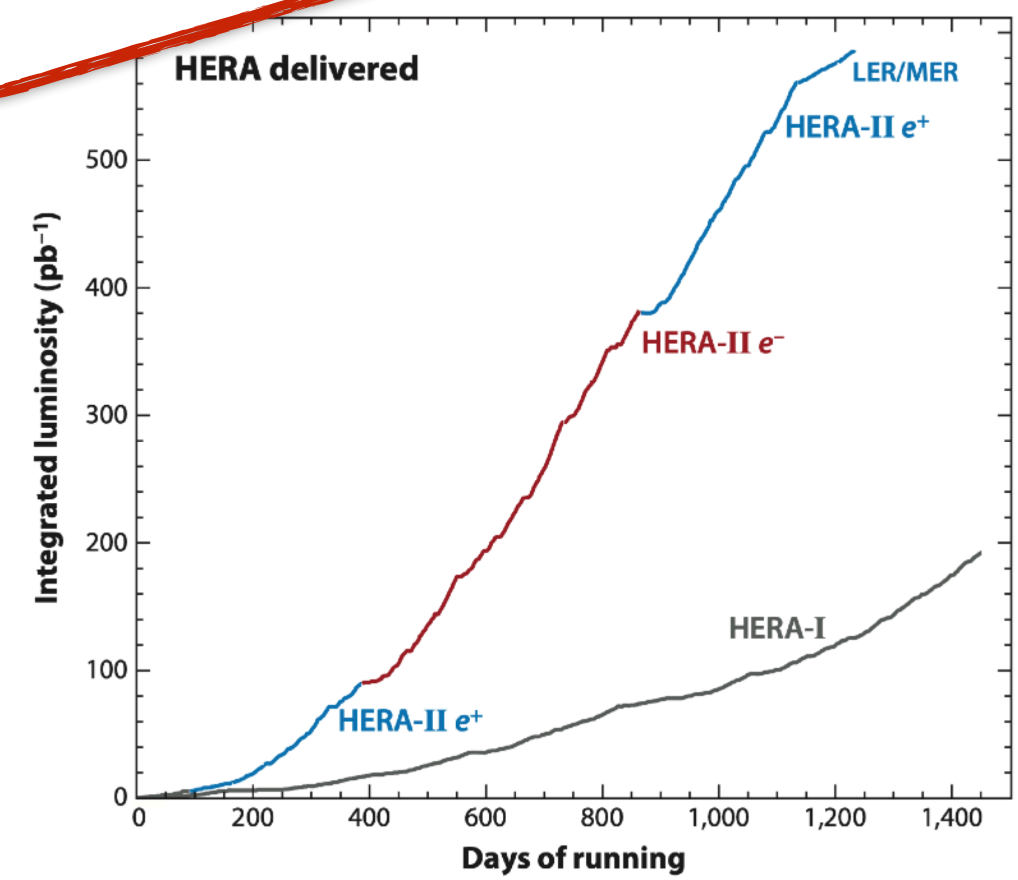

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OK, ANY SURPRISES??

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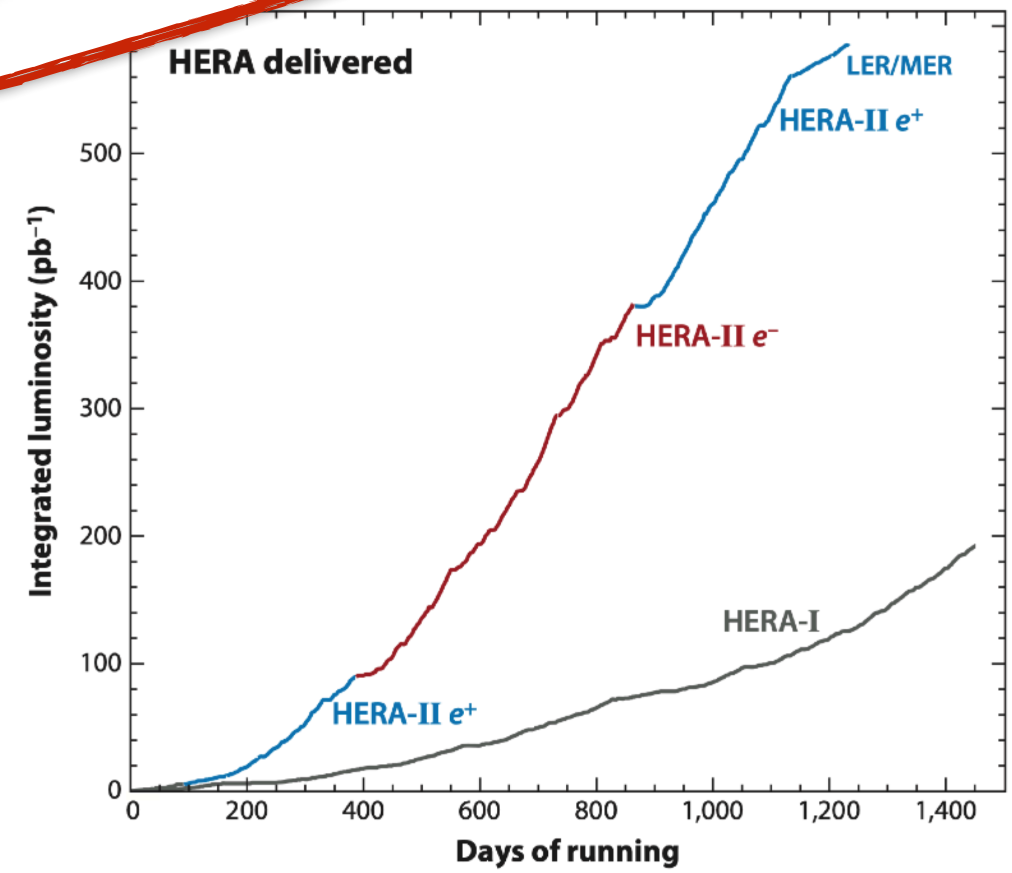
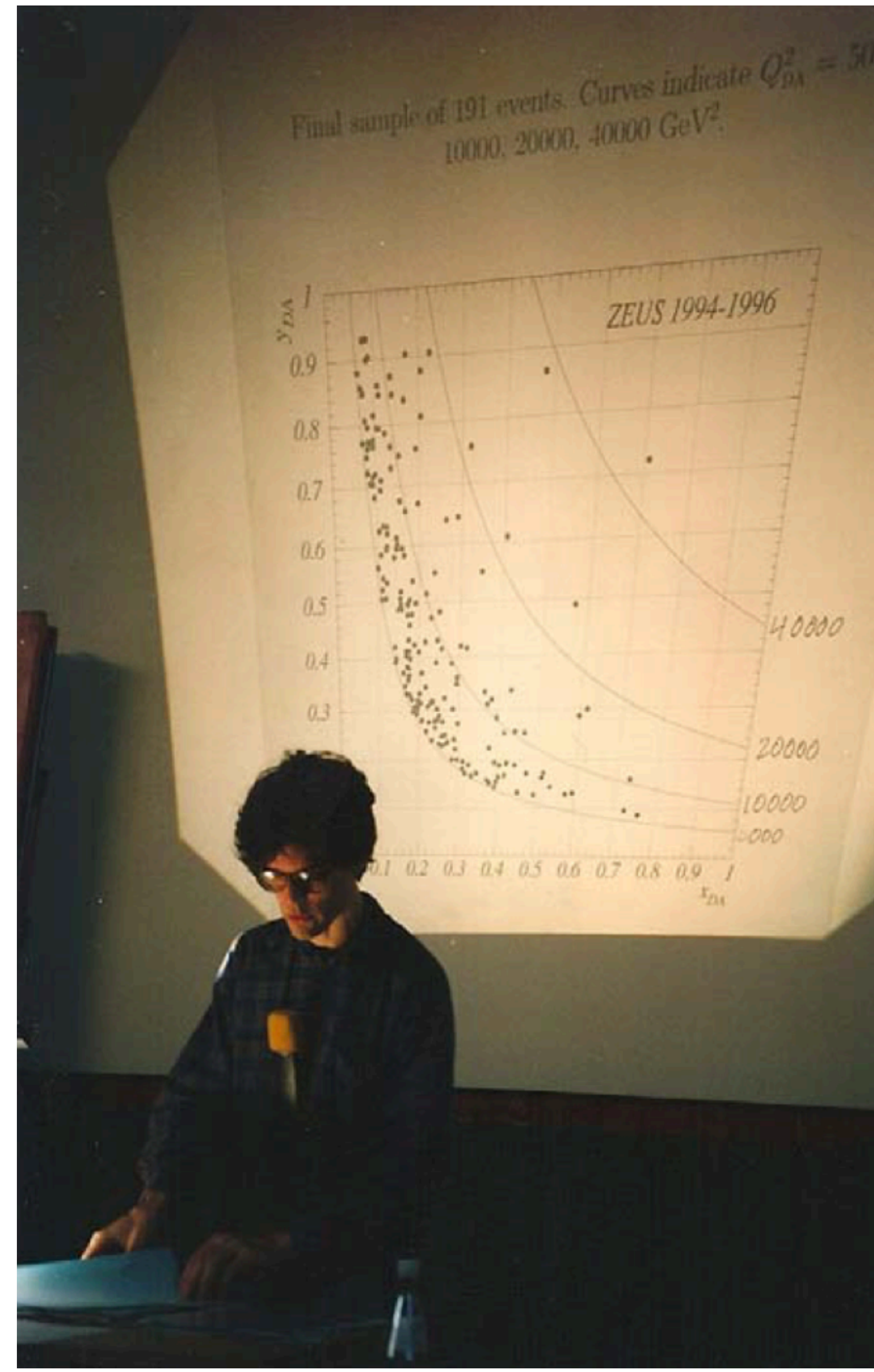


…that time when we "almost" discovered the Lepto Quark at HERA…

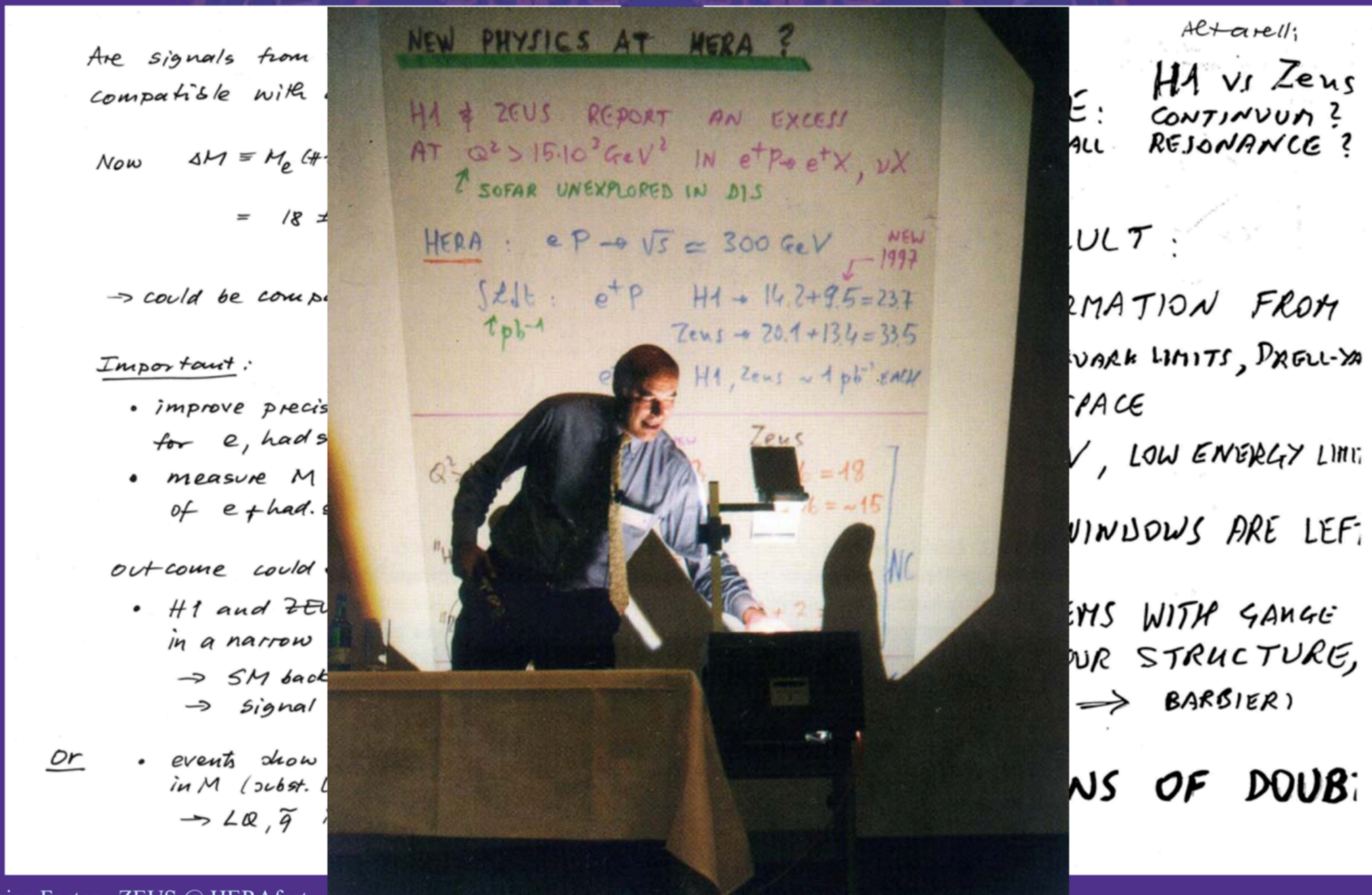
- Increasing excitement in 1996 about an excess of events at high-x, high-Q2.
- Eventually a press release and a seminar in a very crowded Hörsaal…



The Story Unfolds… as told by Brian Foster @ HERAfest 2007:

http://bit.ly/HeraFestFoster

- Literally 100's of papers appeared interpreting the data, though many were cautious.



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Brian Foster - ZEUS @ HERAfest

The Story Unfolds… as told by Brian Foster @ HERAfest 2007:

- So we waited and took data for another year - and of course the effect slowly went away as more data filled up the plot. Conclusion?
- On the one occasion that H1 & ZEUS agreed, both were wrong!
- On the ILC we often argue that we need two detectors to provide independent checks……

Brian Foster - ZEUS @ HERAfest

…or that time when we almost found a 750GeV di-γ resonance at LHC…

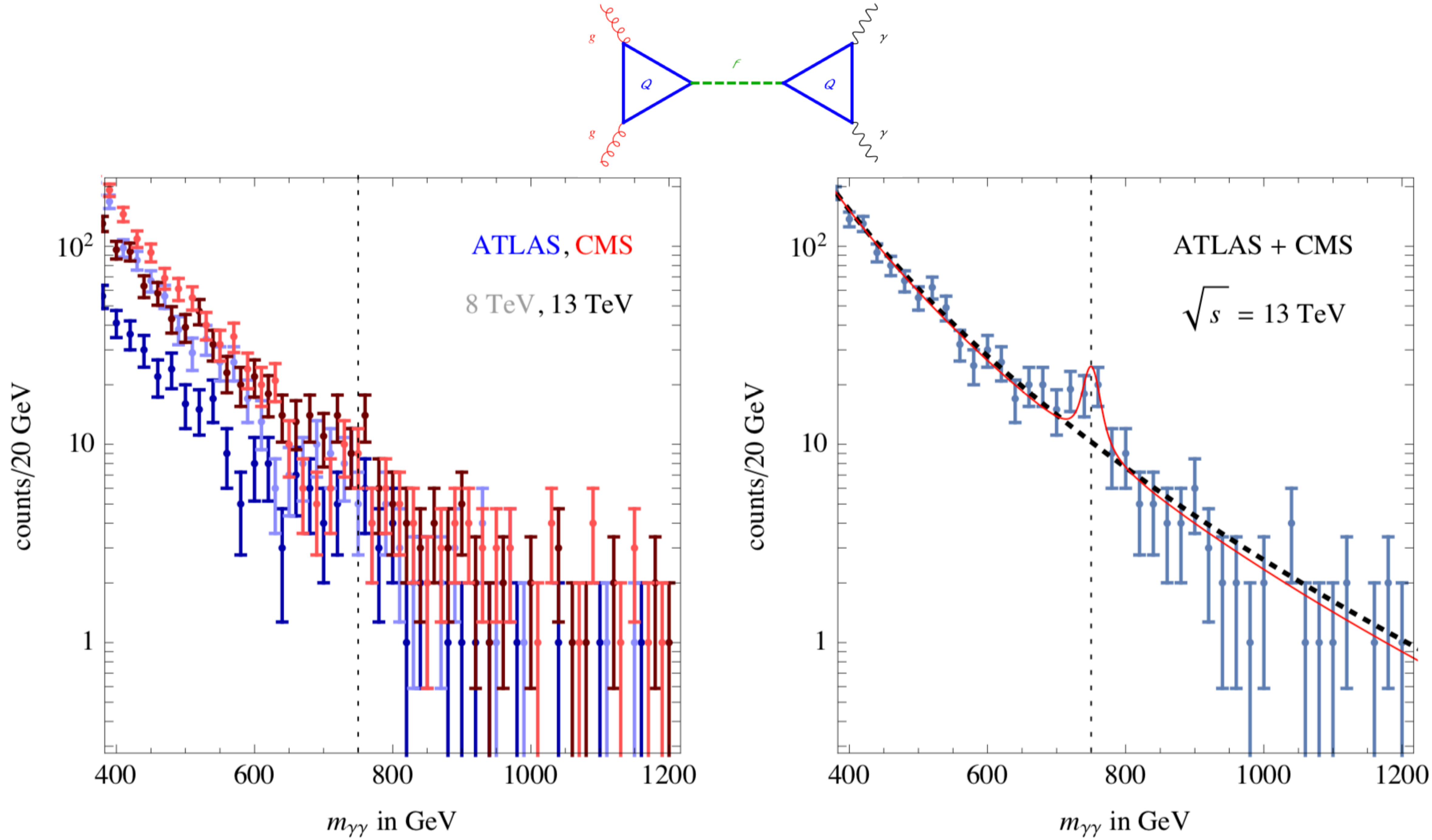


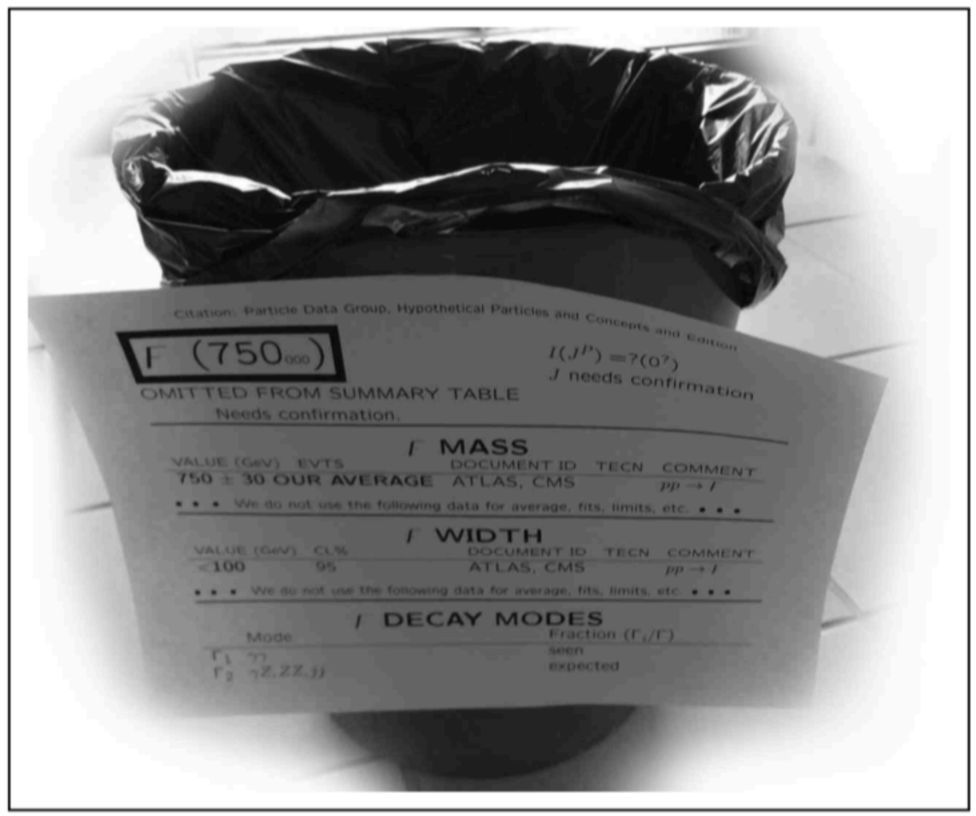
Figure 1 – *Left:* $\gamma\gamma$ *spectra measured by ATLAS (blue) and CMS (red) at* $\sqrt{s} = 8\,\mathrm{TeV}$ *(lighter colors) and* $13\,\mathrm{TeV}$ *(darker). Right: (warning: adult content) spectrum obtained summing ATLAS and CMS counts at* $\sqrt{s} = 13\,\mathrm{TeV}$.

arXiv:1605.09401v2 [hep-ph] 5 Aug 2016

Interpreting the 750 GeV digamma excess: a review

ALESSANDRO STRUMIA

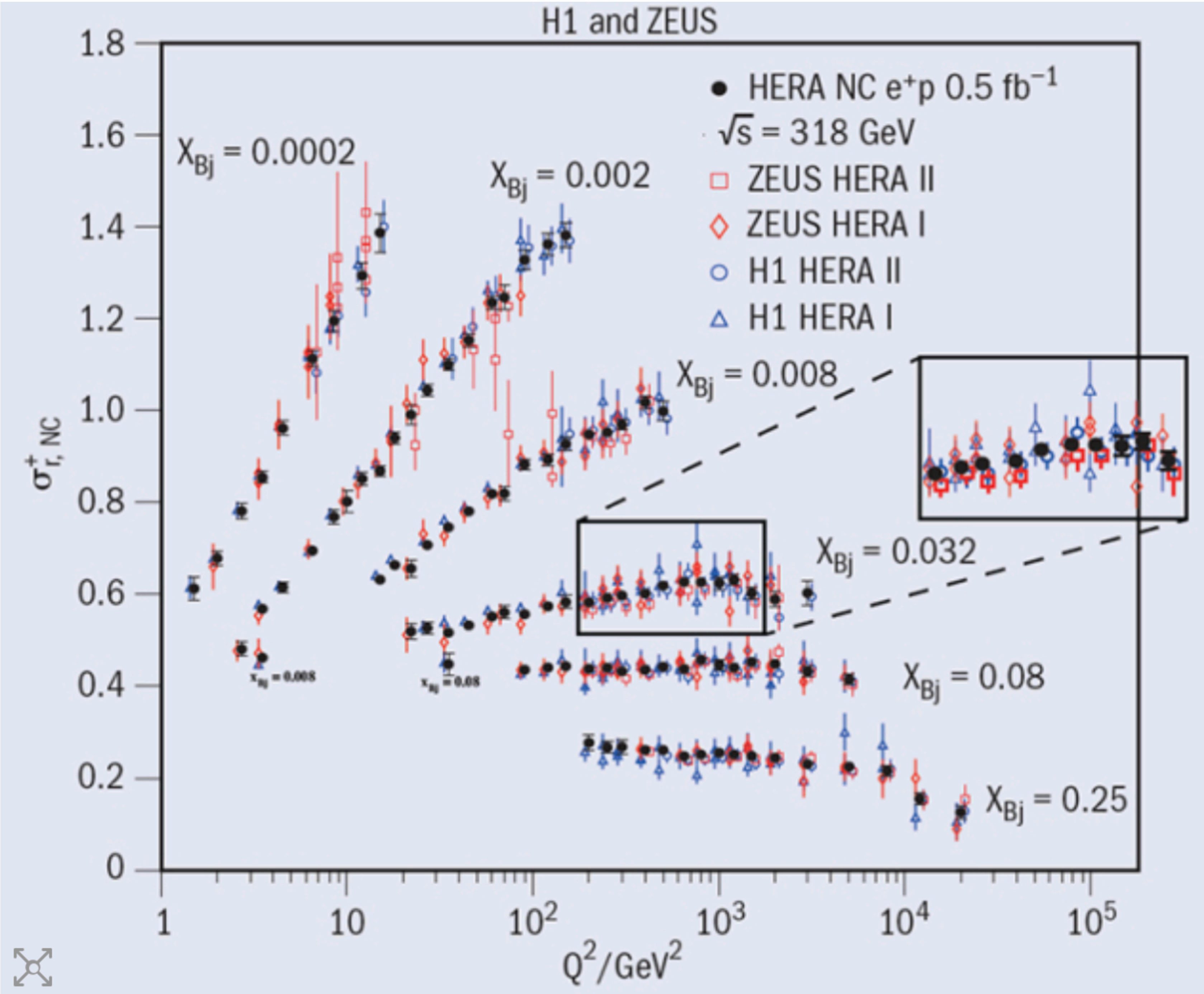
CERN, INFN and Dipartimento di Fisica, Università di Pisa



We summarise the main experimental, phenomenological and theoretical issues related to the 750 GeV digamma excess.

A Precise Picture of the Proton Structure

- Exploring the range of small x_{Bj}
  - the fraction of proton momentum
  - Measurements at larger x existed: scaling violation
- At lower values of x, the cross-section rises increasingly and dramatically more steeply with increasing Q2 and decreasing x
- This scaling violation is indicative of the density of gluons in the proton, which is increasing towards lower x



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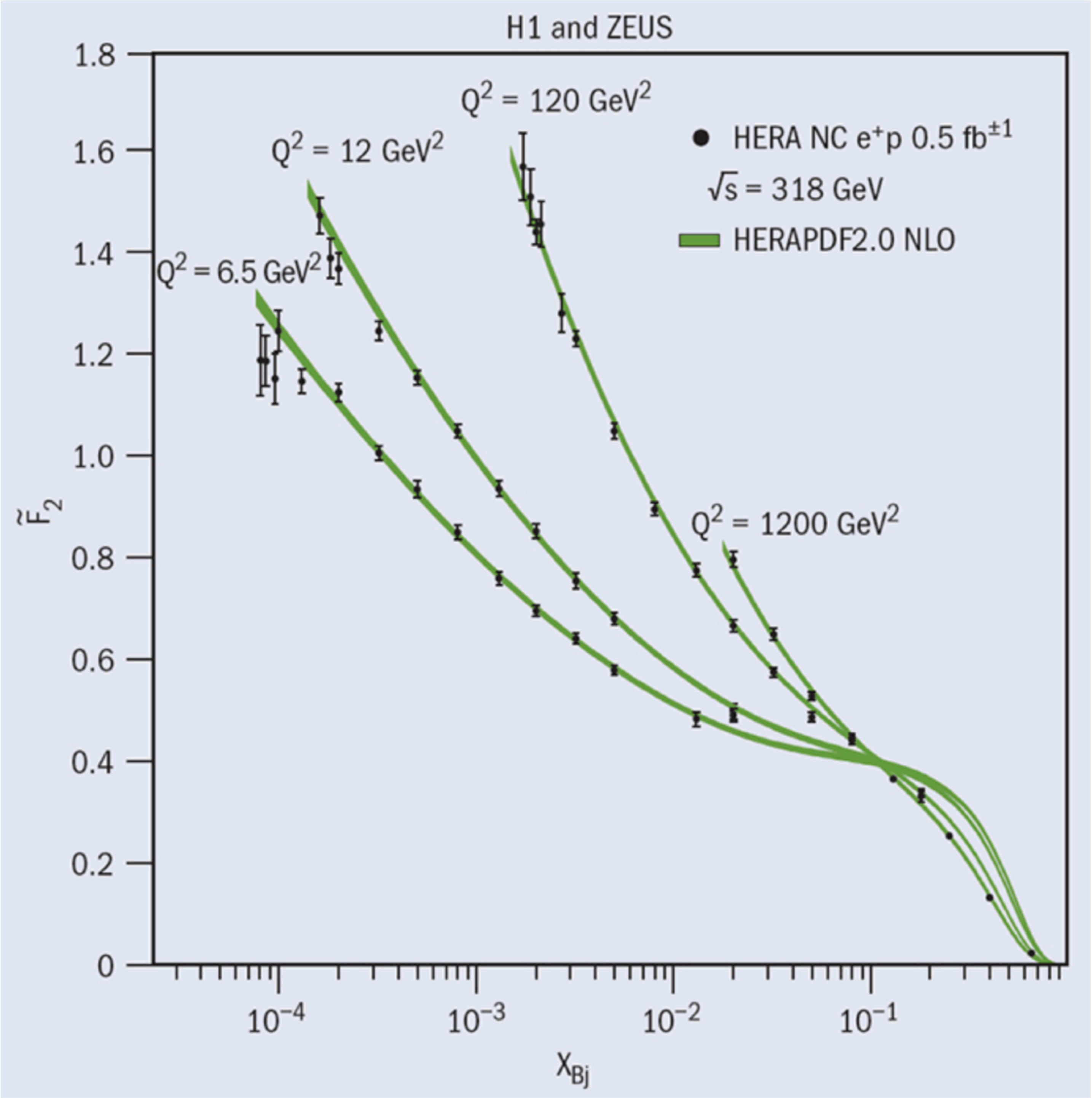
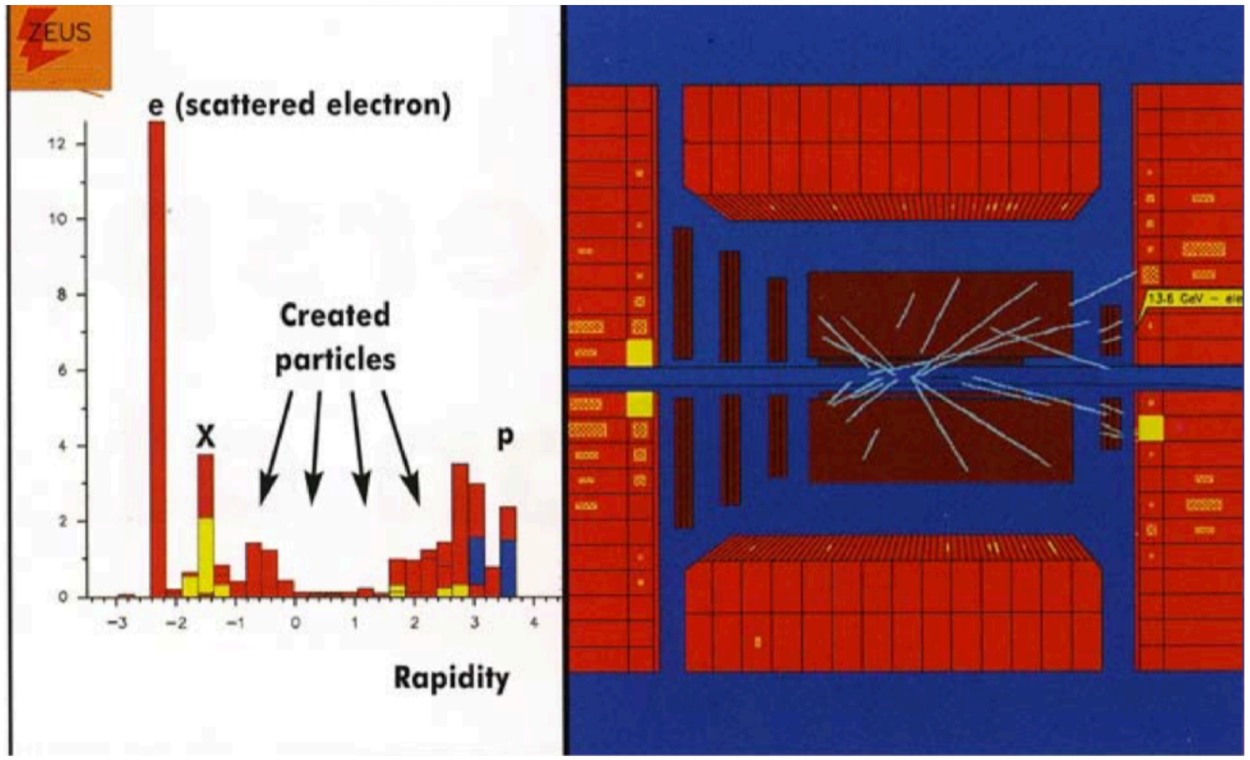
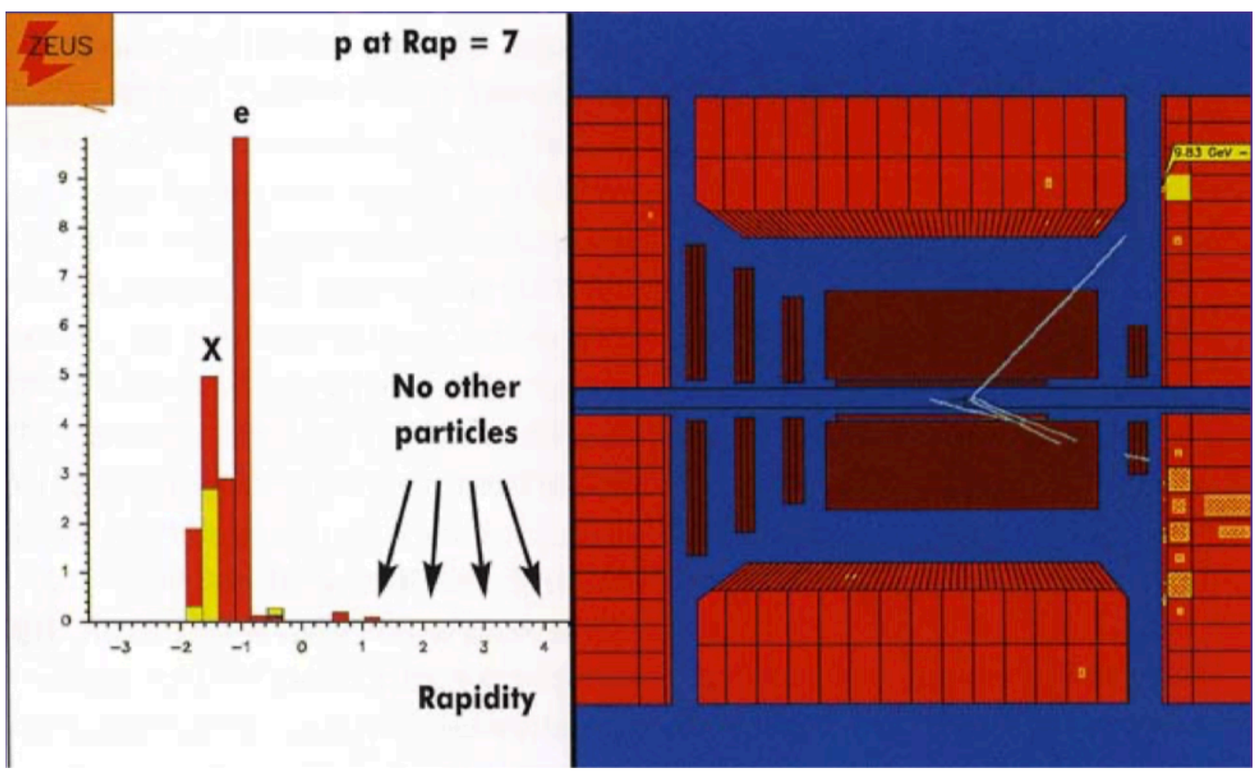


… and you'll find a LOT of gluons in the proton if you look "closely" at large Q^2 and small x!

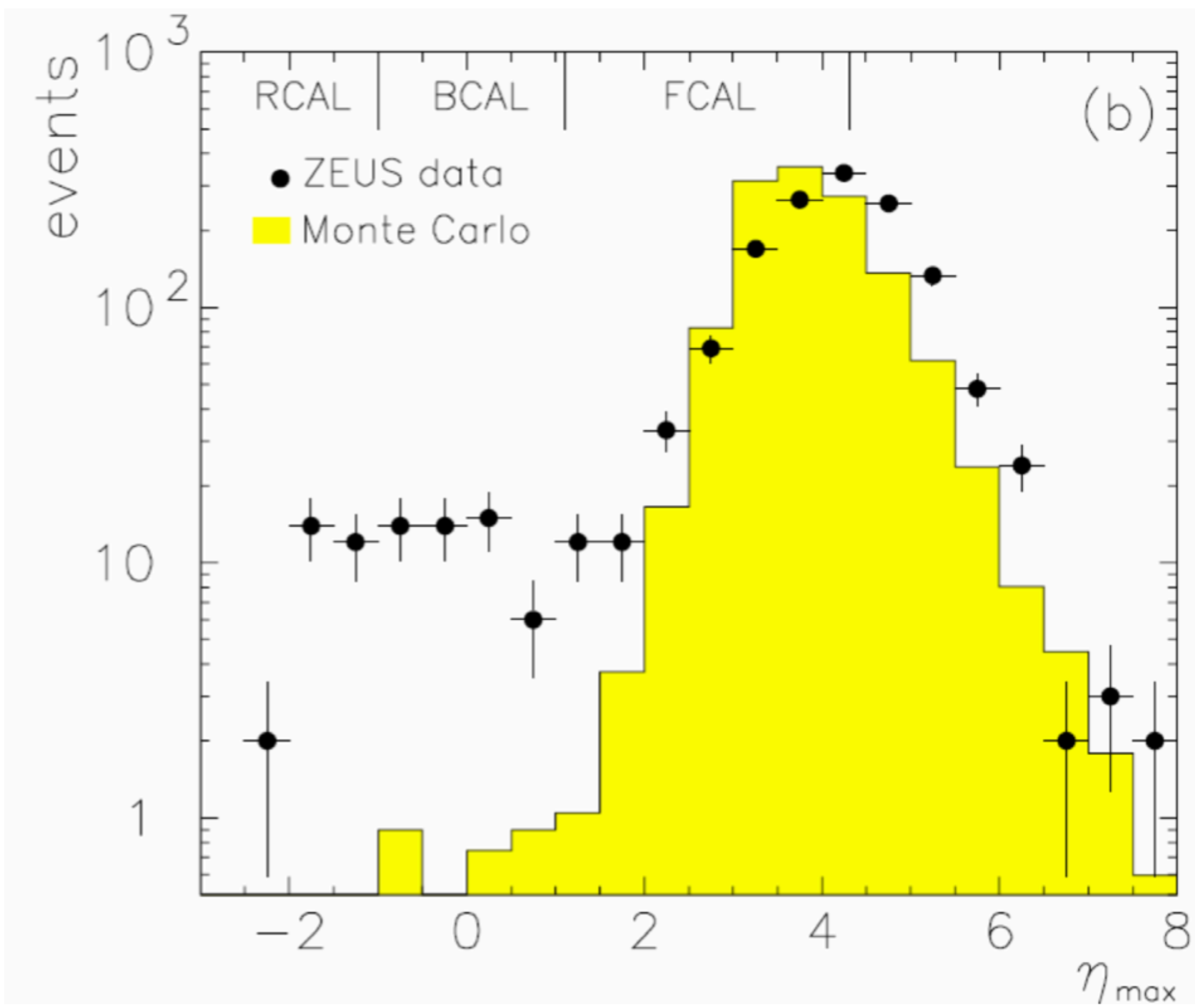
Rapidity Gaps!

- Right in the first weeks of HERA we found a class of events that looked like DIS events, but with no energy around the forward beam pipe





- Discovered diffractive component in DIS
  - proton escapes intact despite the hard hadronic interactions during the electron-proton collisions
  - distribution of η_{max}, the largest rapidity of energy deposition in the event, shows a component that was not simulated in the DIS MCs when HERA started!



Started a whole industry in ZEUS and H1!

- Detailed investigations of diffraction at high energies
  - Confirmed the “picture” of γ^*-p hadronic scattering, with a “soft” component that we can try to connect back to the perturbative QCD of “normal” DIS
- Q^2 behavior of the inclusive diffractive cross section is described by QCD
  - “In the naïve picture of deep-inelastic interactions, such processes do not occur with a sizable rate because the proton is described as a gas of uncorrelated quarks and gluons. The photon knocks out one of the partons, leaving behind a colored state, and hadronization occurs between the struck parton and the proton remnant.
  - The existence of a large diffractive component at high Q^2 shows that the structure of the proton is indeed not gas-like. Strong correlations between partons make the proton “grainy,” so that the interactions take place between the photon fluctuating into a quark-antiquark pair and a colorless correlated state made of more than one parton inside the proton. In QCD this state comprises at least two gluons and is sometimes termed the Pomeron.”

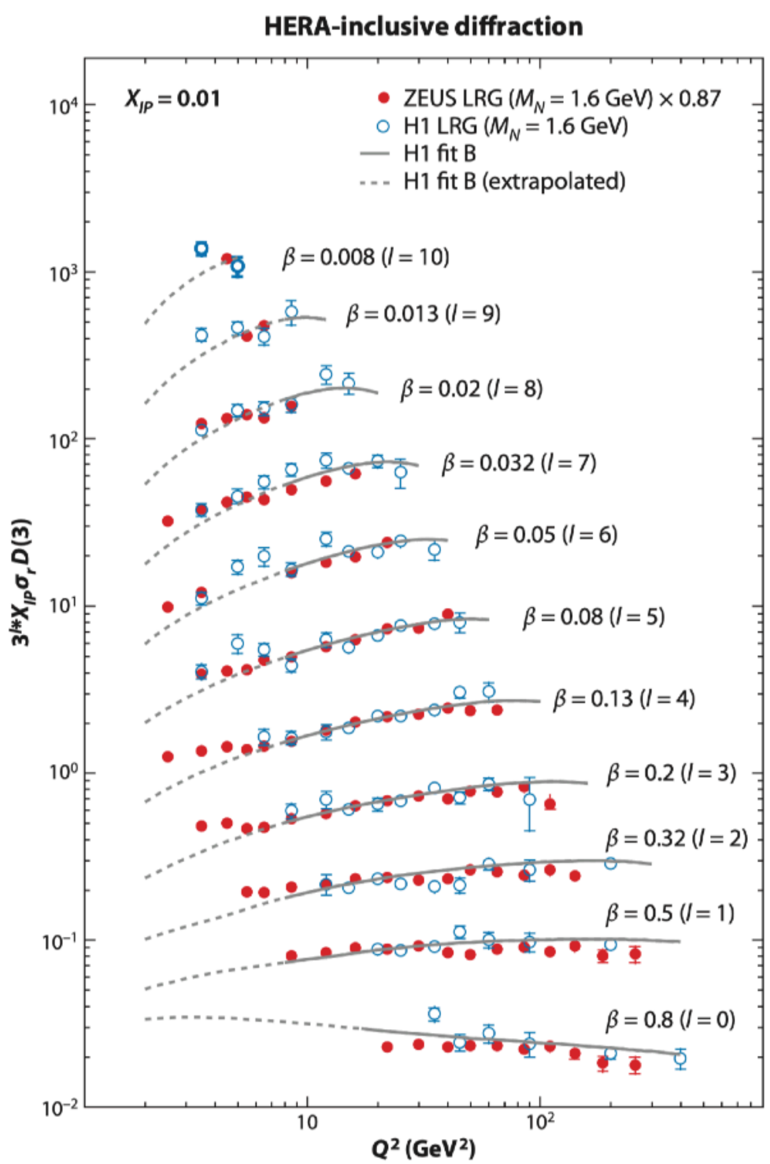


Figure 8

The diffractive structure function $F_2^{D(3)}$ as a function of Q^2 in different bins β at a value of $x_{IP} = 0.01$

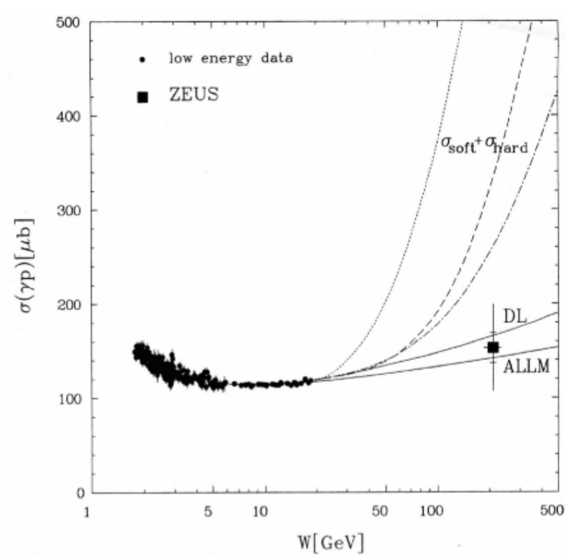
Annual Review of Nucl &Part Science, Diaconu, Haas, Medinnis, Rith, Wagner
https://doi.org/10.1146/annurev.nucl.012809.104458

The virtual γ^* really can interact "as a hadron"

- Aharon Levy: Acta Phys.Polon.B40:1775-1790,2009, arXiv:0905.2034v2 [hep-ex]

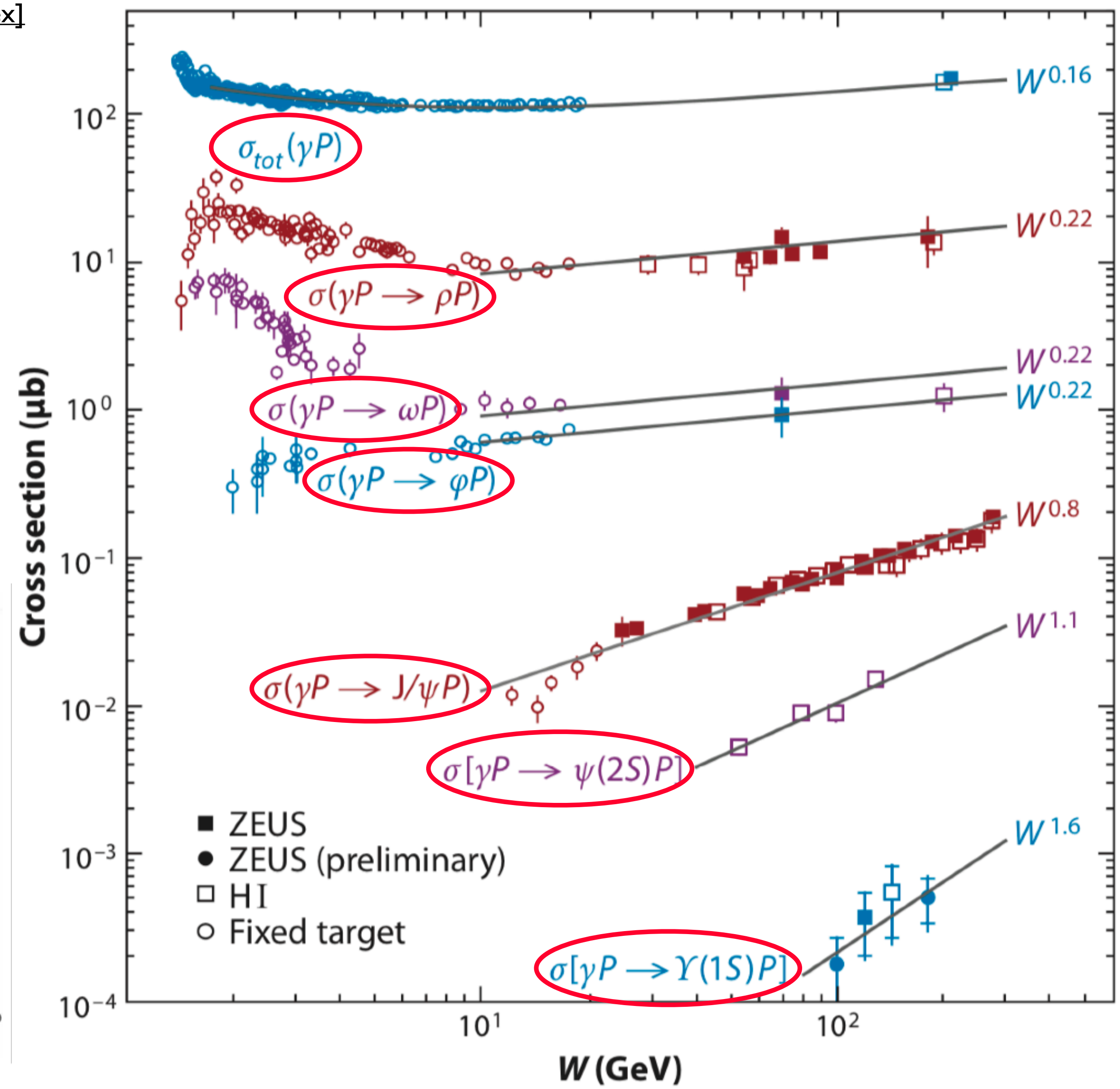
★ "When HERA started running there were quite extreme predictions for the value of the total photoproduction cross sections

★ "They ranged from 150 μb, compatible with the predictions of Donnachie and Landshoff, expected from a soft process, to values as high as 1 mb, coming from hard components which dominate the process.



★ "7 seconds of running and a handful of events were enough to establish that the photon behaves like a hadron at HERA energies.

★ "The mild increase with energy indicates that



The dominant configuration of the photon is its fluctuation in a large size quark-antiquark pair

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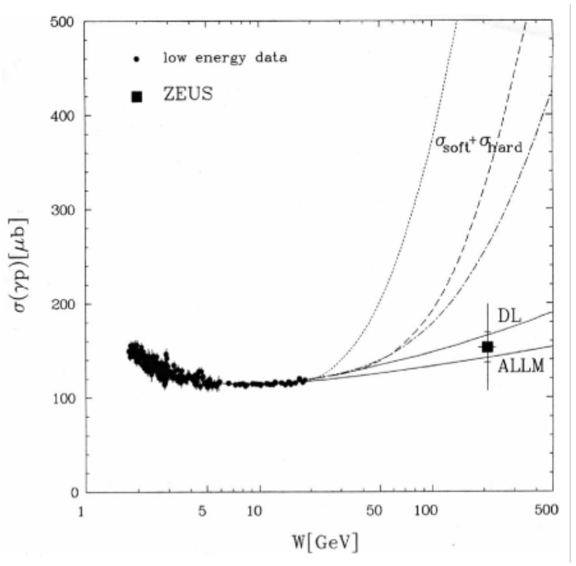

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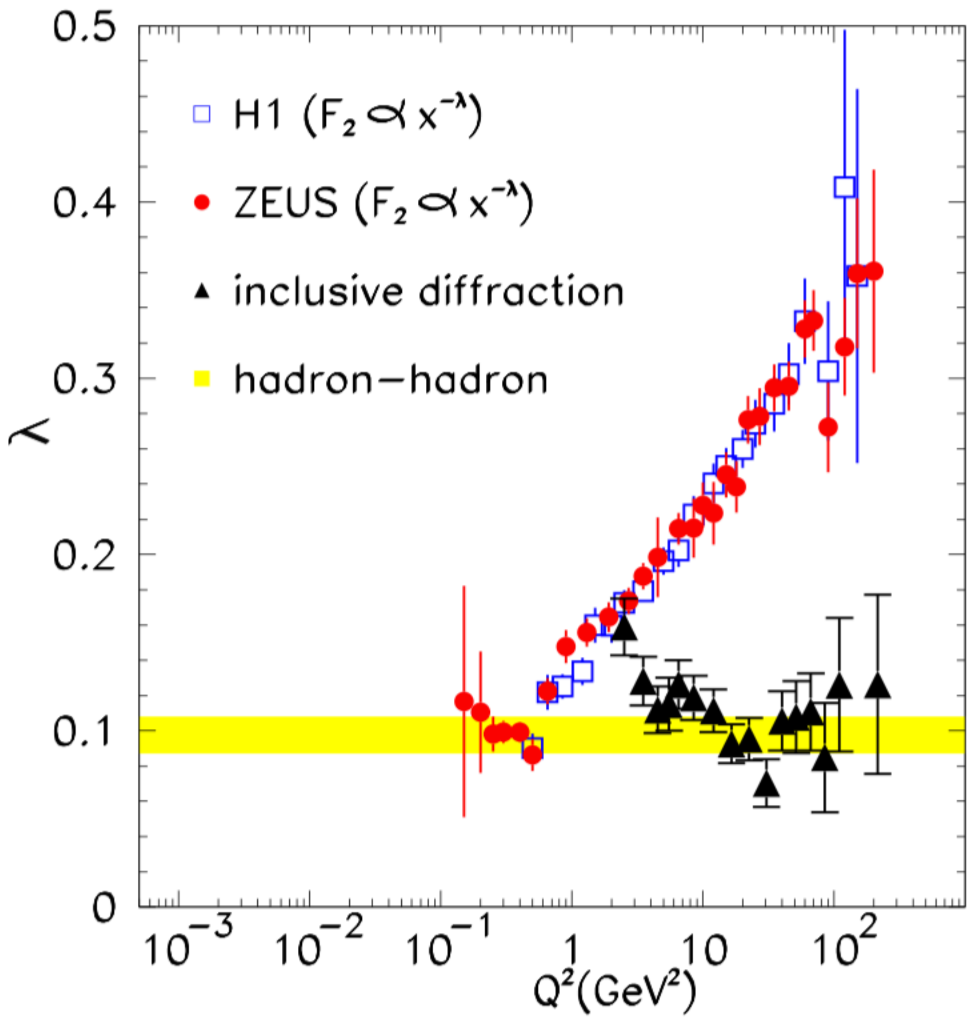
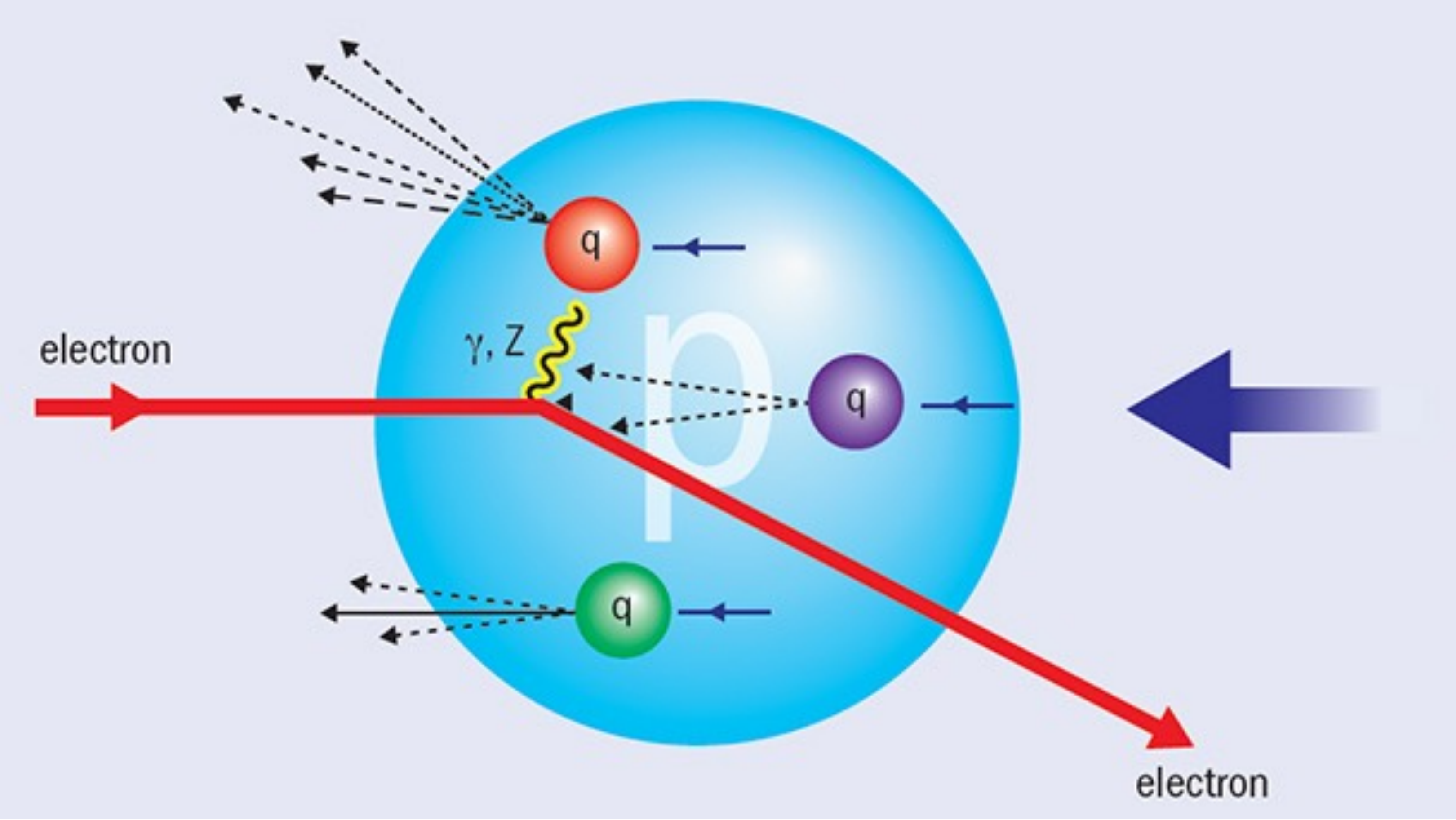
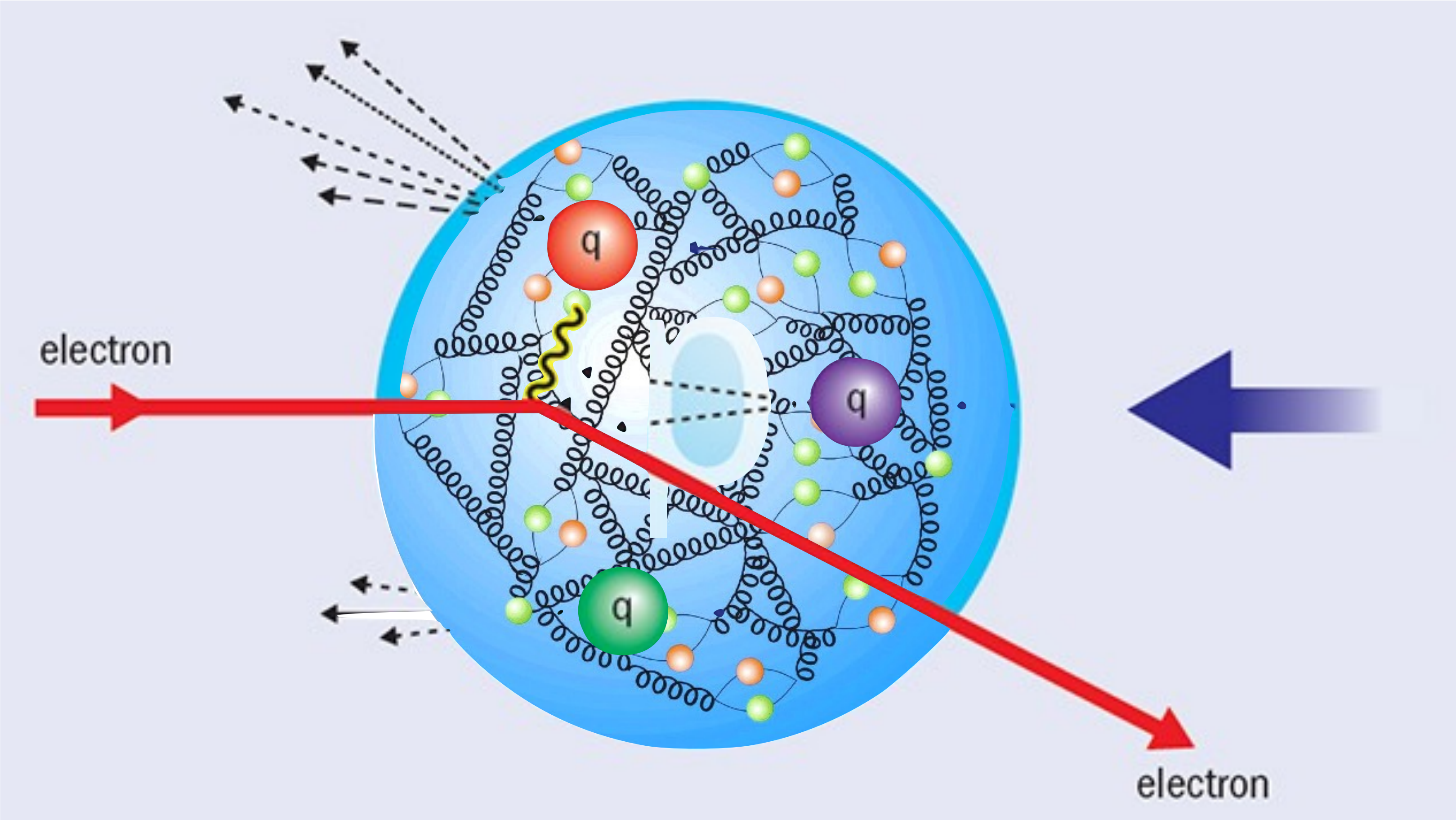


The dominant configuration of the photon is its fluctuation in a large size quark-antiquark pair

The “naïve” Bjorken DIS Picture…

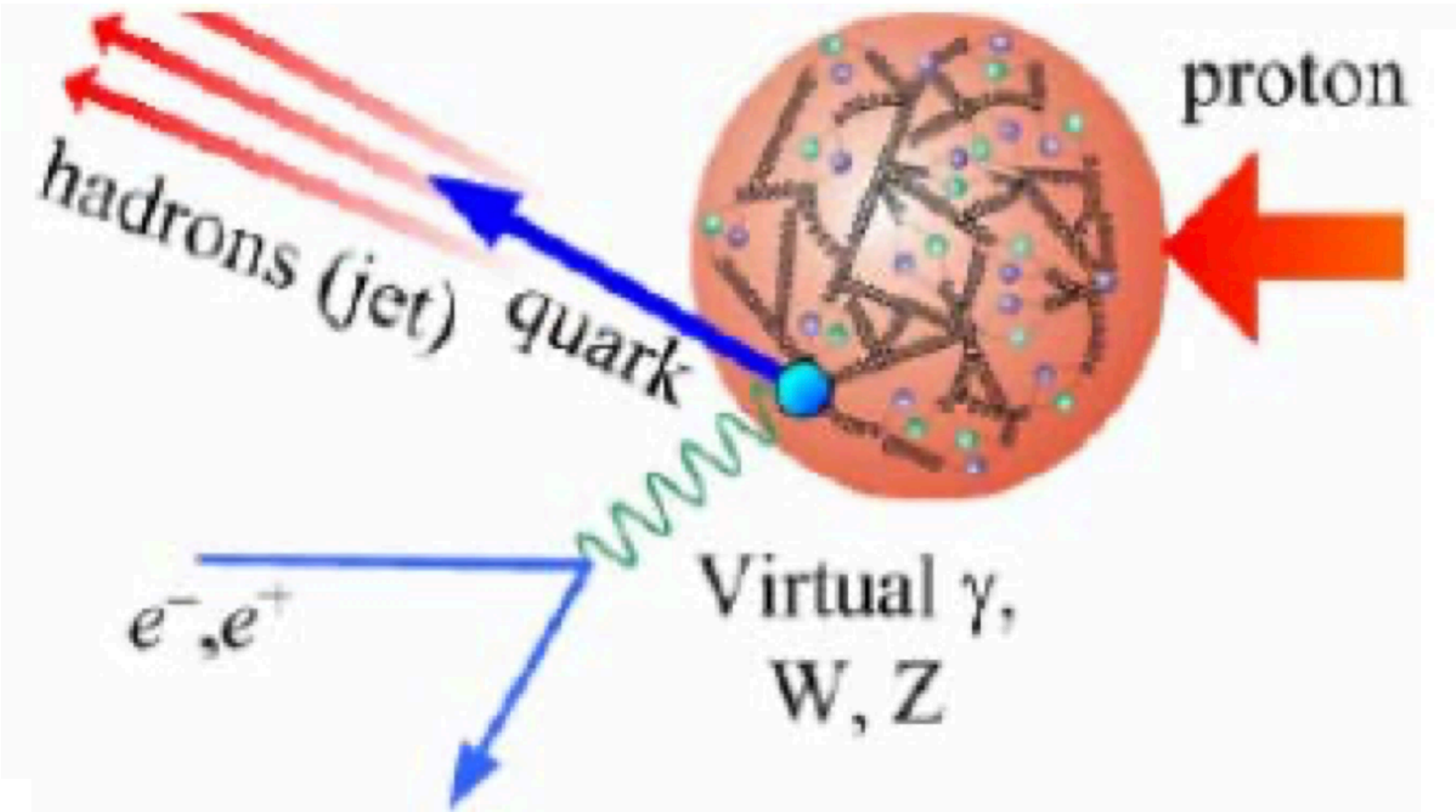


… plus there's lots of gluons!



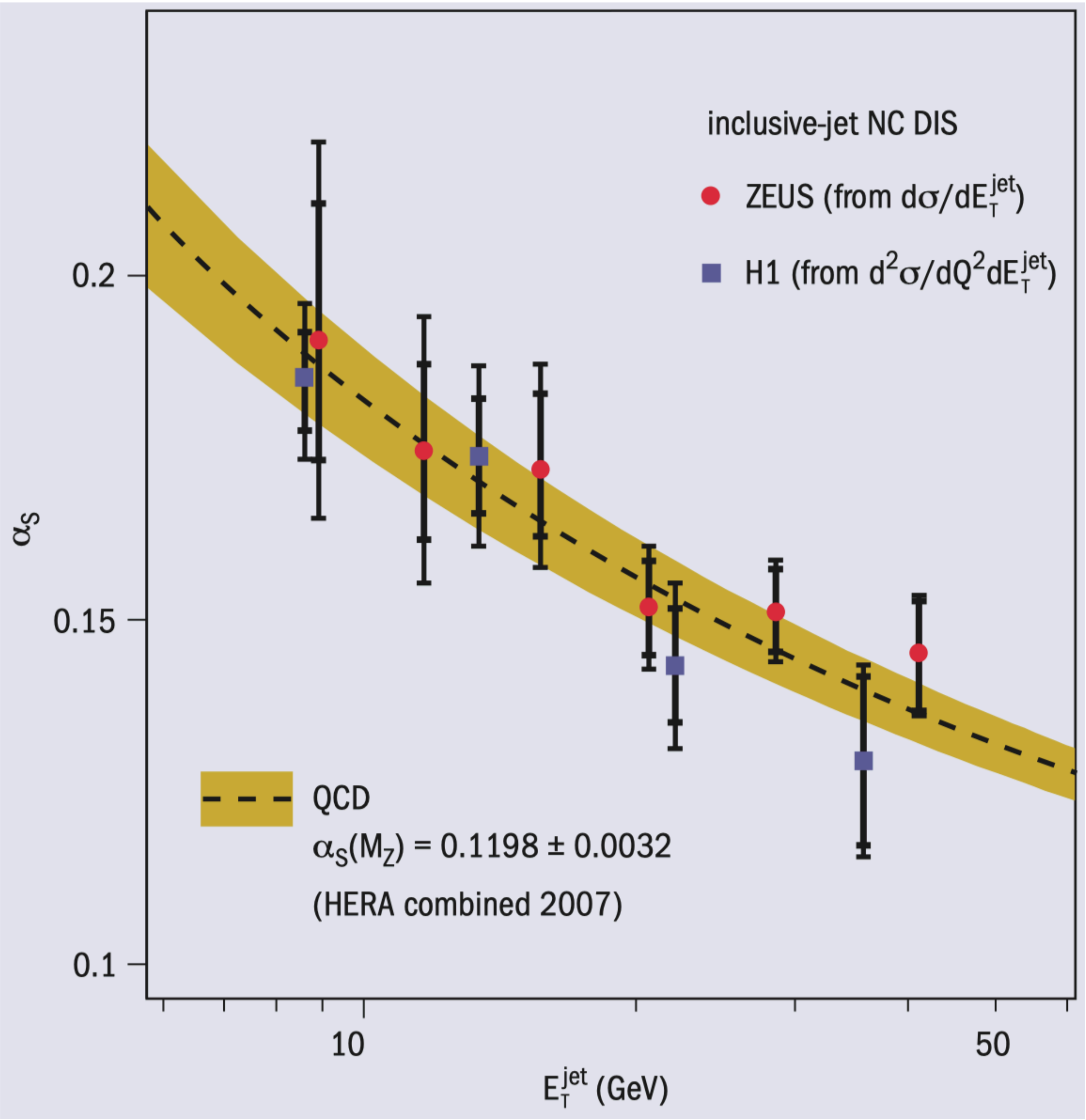
… a more “fuzzy” picture of low-x DIS

virtual γ^* interacting with proton QCD cloud



(as a matter of opinion/taste, one might consider the Photon as interesting a particle as the Higgs!! :-)

Precise Tests of Quantum Chromodynamics



- HERA demonstrated the characteristic running of α_S over a broad range of energies in a single experiment, impressively confirming *asymptotic freedom* in QCD

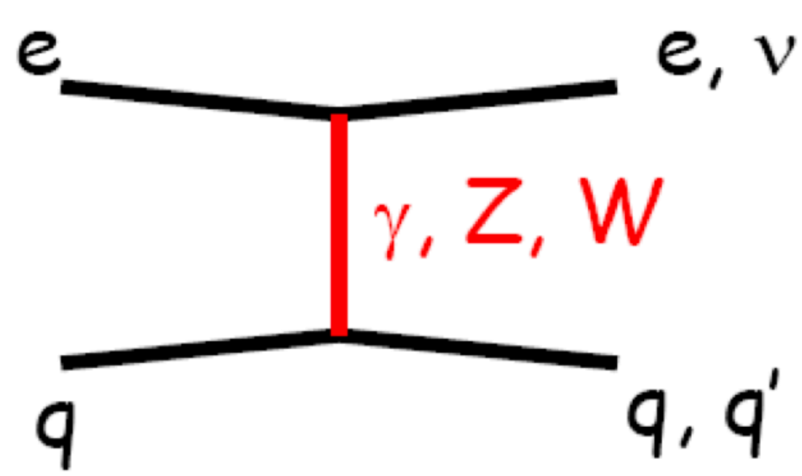
- Even better sensitivity by including inclusive data, charm data and jet data at NLO, results in an experimentally very precise measurement of the strong-coupling constant:

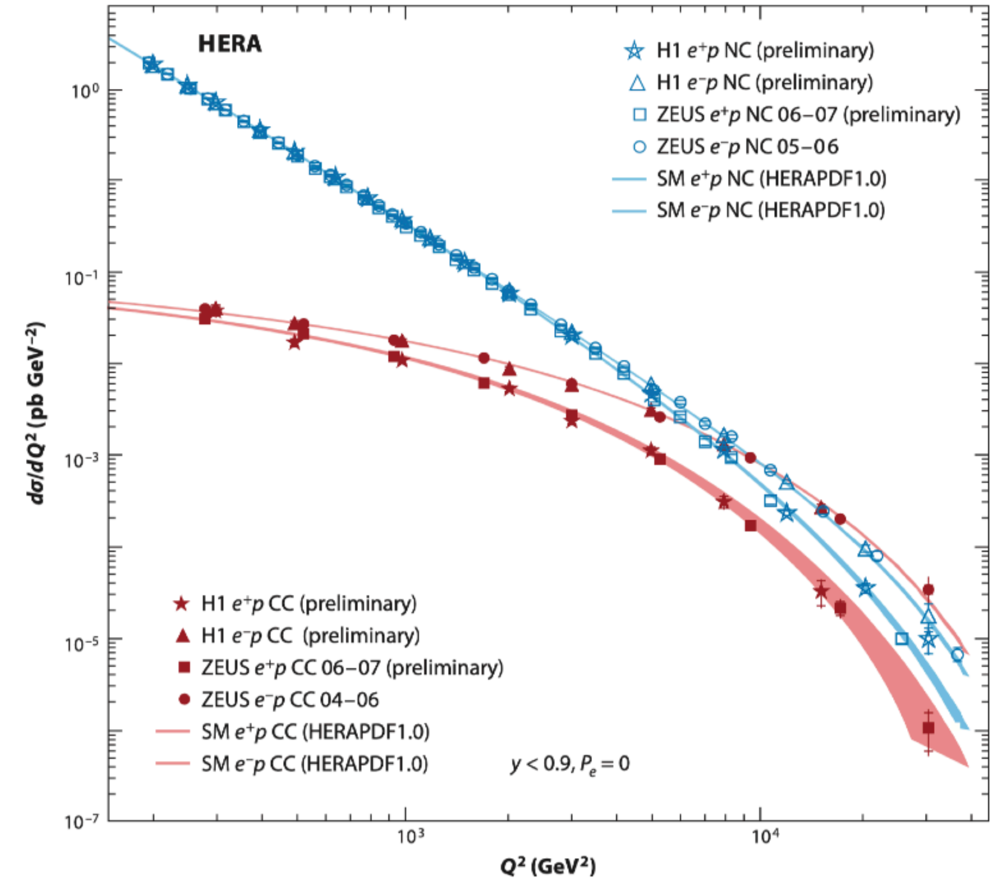
  $\alpha_S(M_Z) = 0.1183 \pm 0.0009$ (exp.)

  with significantly larger uncertainties of +0.0039 –0.0033 related to the model and theory

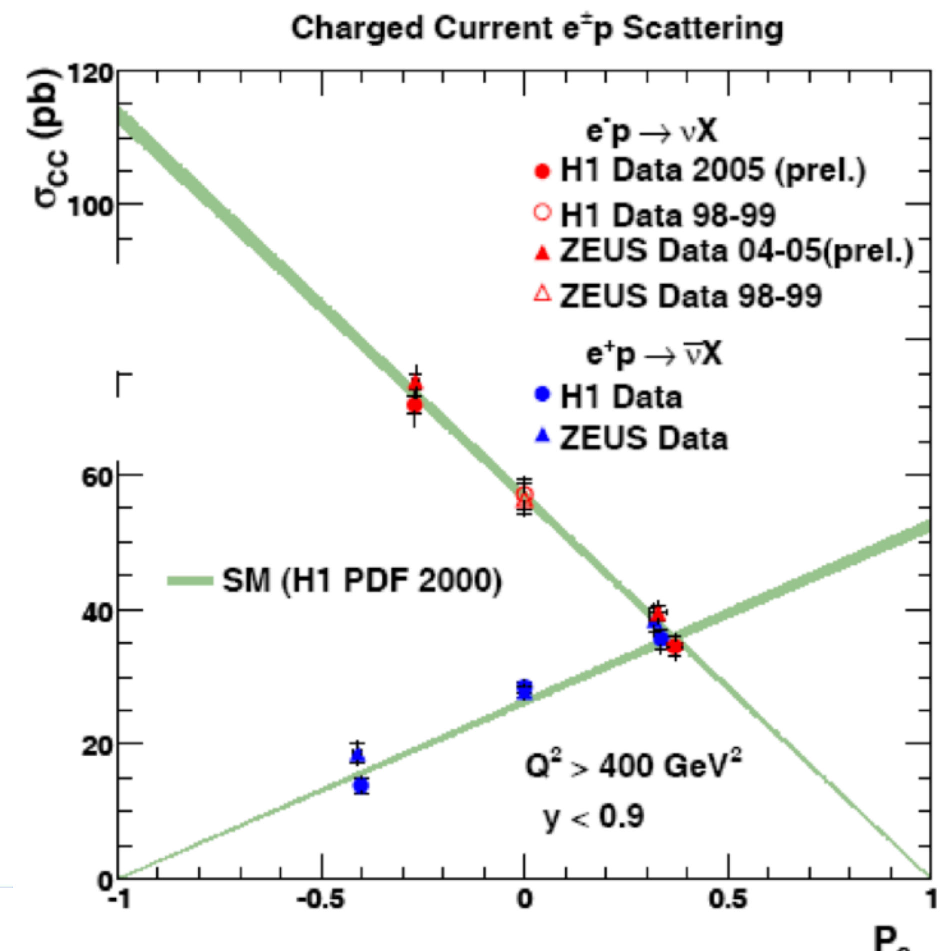
Exploring the Electro-weak Energy Frontier

- Electroweak Unification!





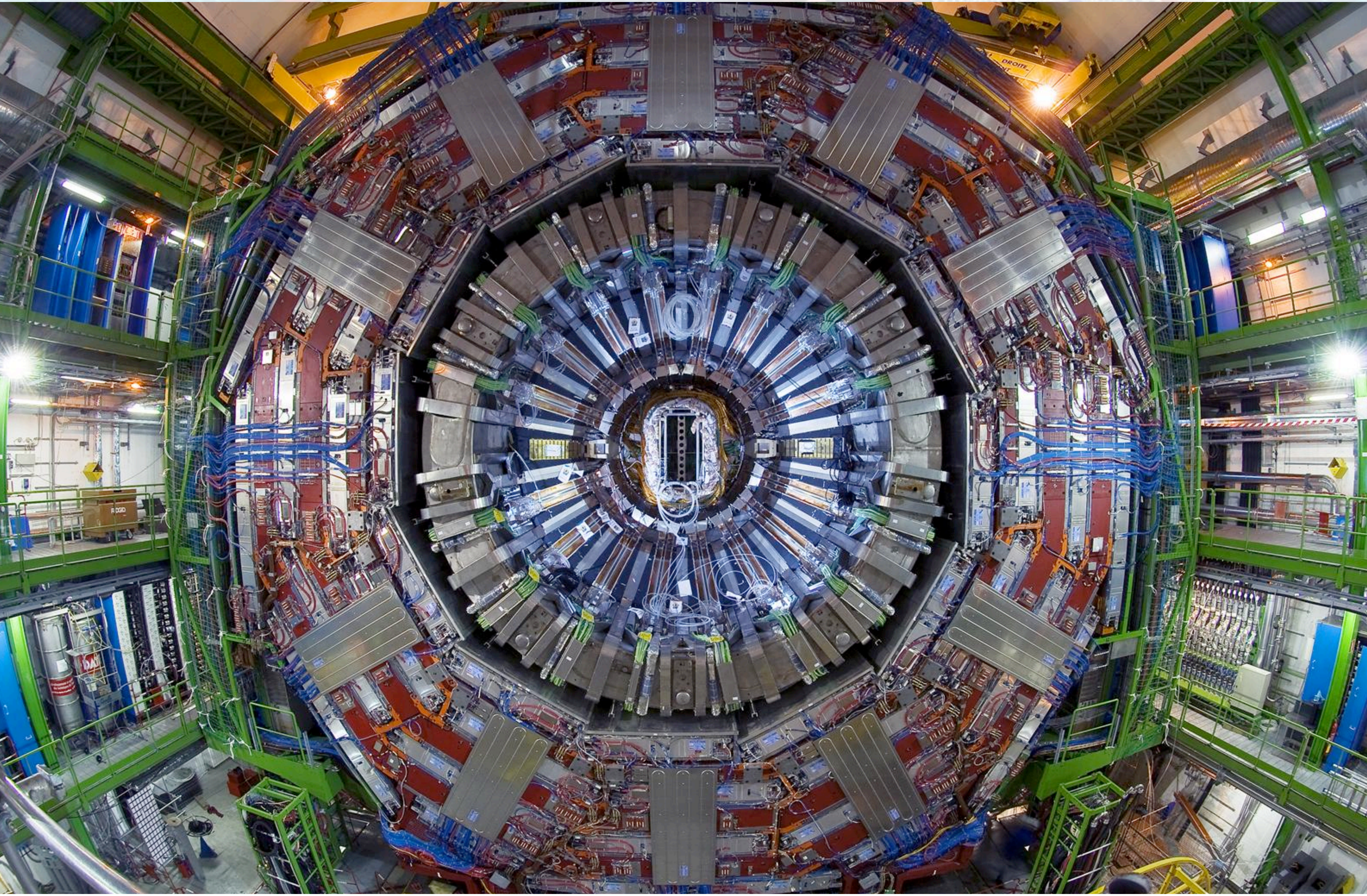
- Charged current W-Bosons indeed are left-handed!



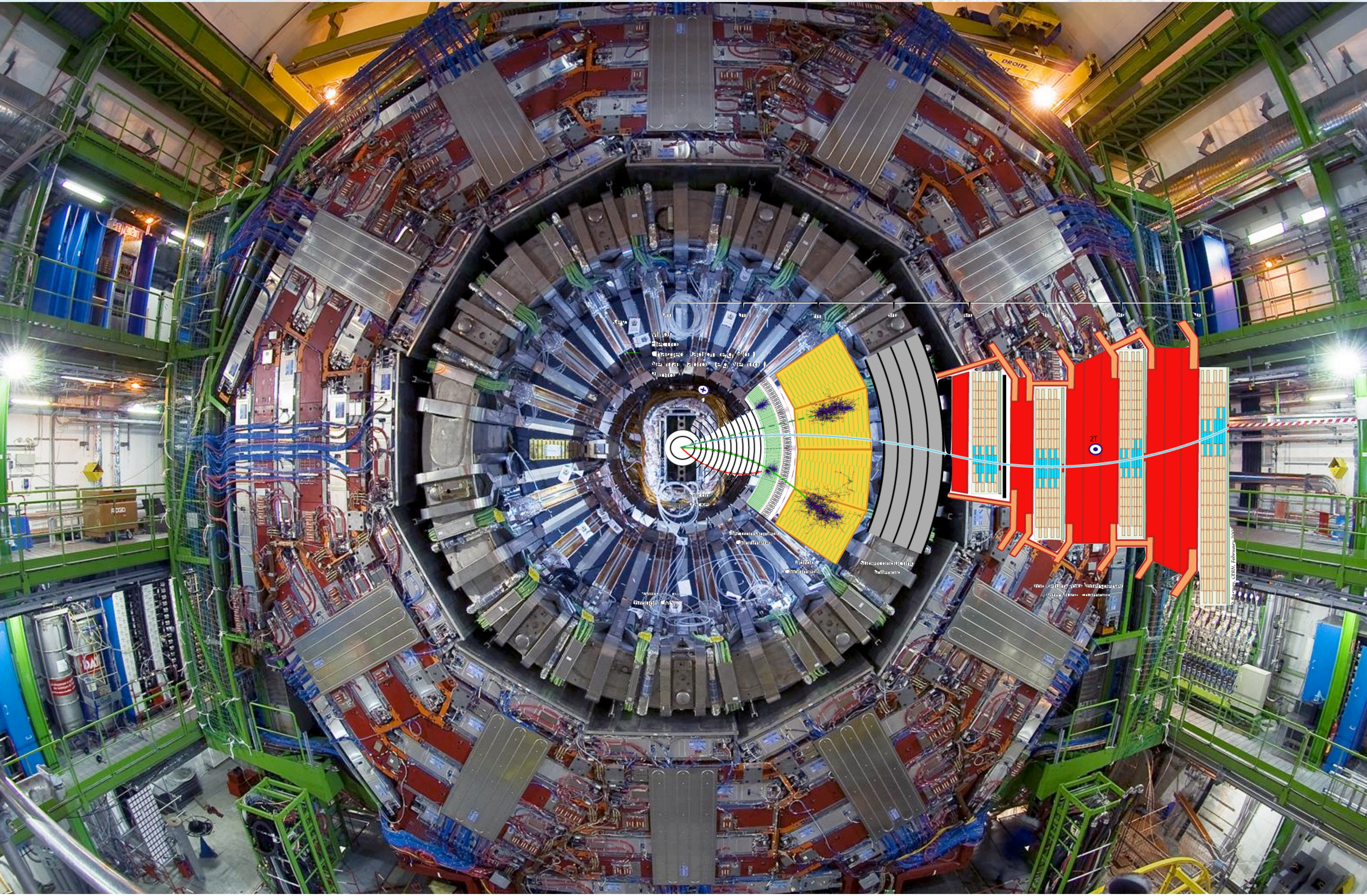
LHC at CERN in Geneva, Switzerland

Colliding proton beams at E_beam = 6.5 TeV,
Creating *pp* collision every 25ns
Very high luminosity, a peak of 2×10^{34} Hz/cm^2.
Given the pp X-section, almost 60 overlapping events every 25 ns
Level 1 Trigger every 10 μs; High Level Trigger every 1 ms
eg. $\sigma(pp \rightarrow W+X)$ ~ 150 nb ~ $2 \cdot 10^{-6}\, \sigma_{tot}(pp)$

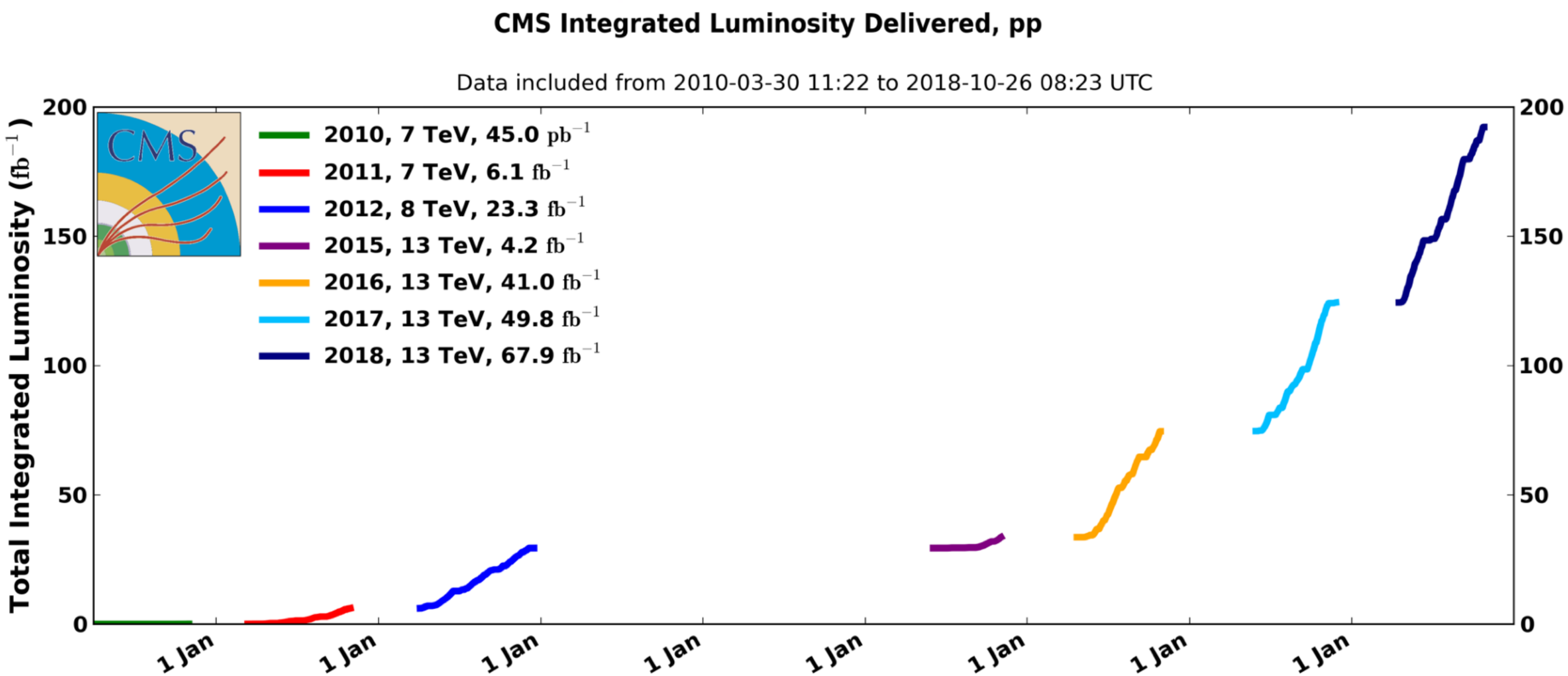
CMS Detector



CMS Detector



Two very successful LHC Runs



The CMS Physics Program

(T.Bose @ Fermilab Wine&Cheese)

- Precision measurements of SM processes
  - Understand SM backgrounds, look for deviations or anomalies
- Searches/measurements of rare SM processes
  - Take advantage of the large LHC datasets and look for (significant) enhancement from beyond-the-SM (BSM) particles

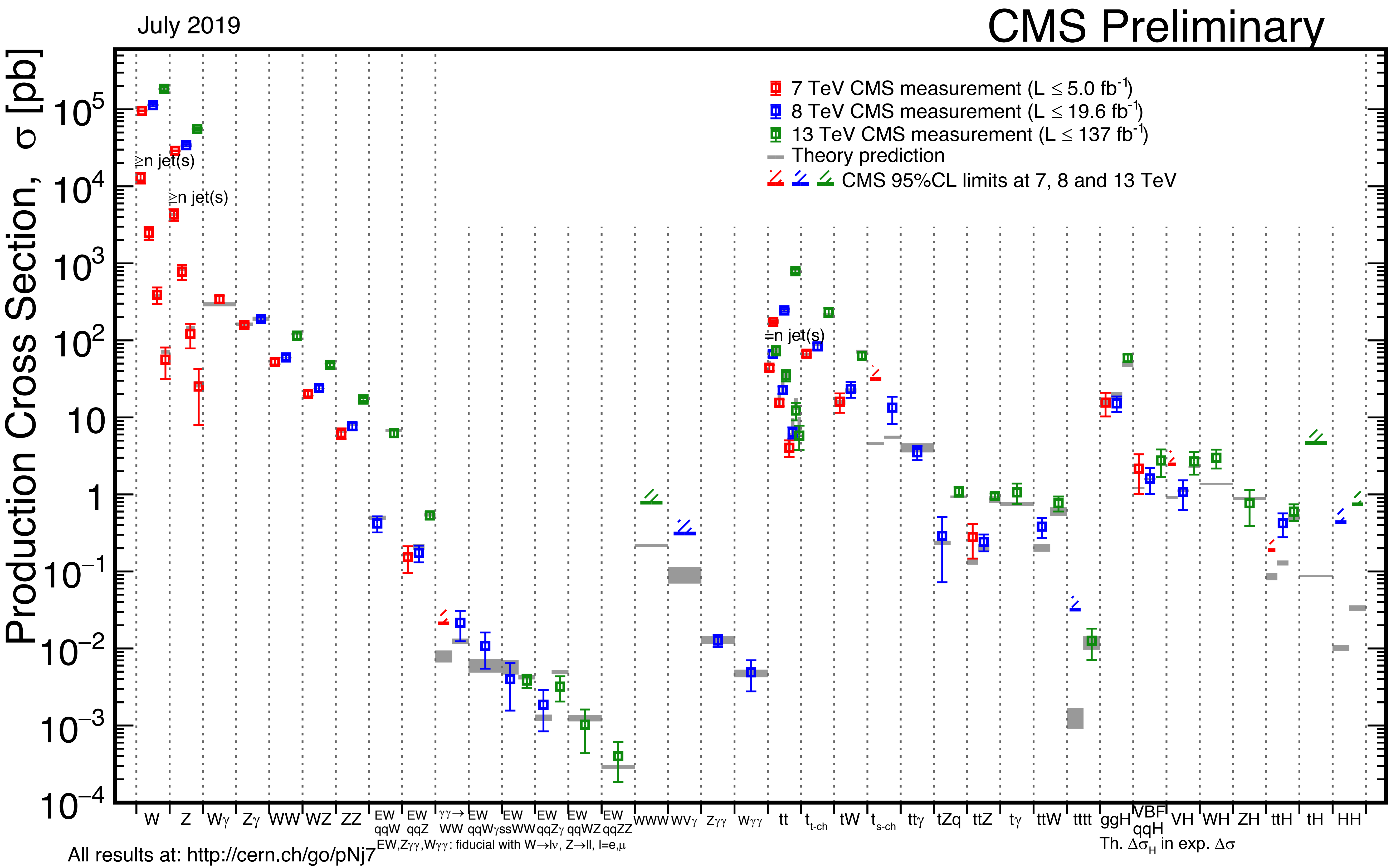
SM as a tool for discovery

- Direct searches for BSM particles
  - Go in new directions with new models, challenging topologies, enlarged parameter space → innovate!

Exploring the unknown

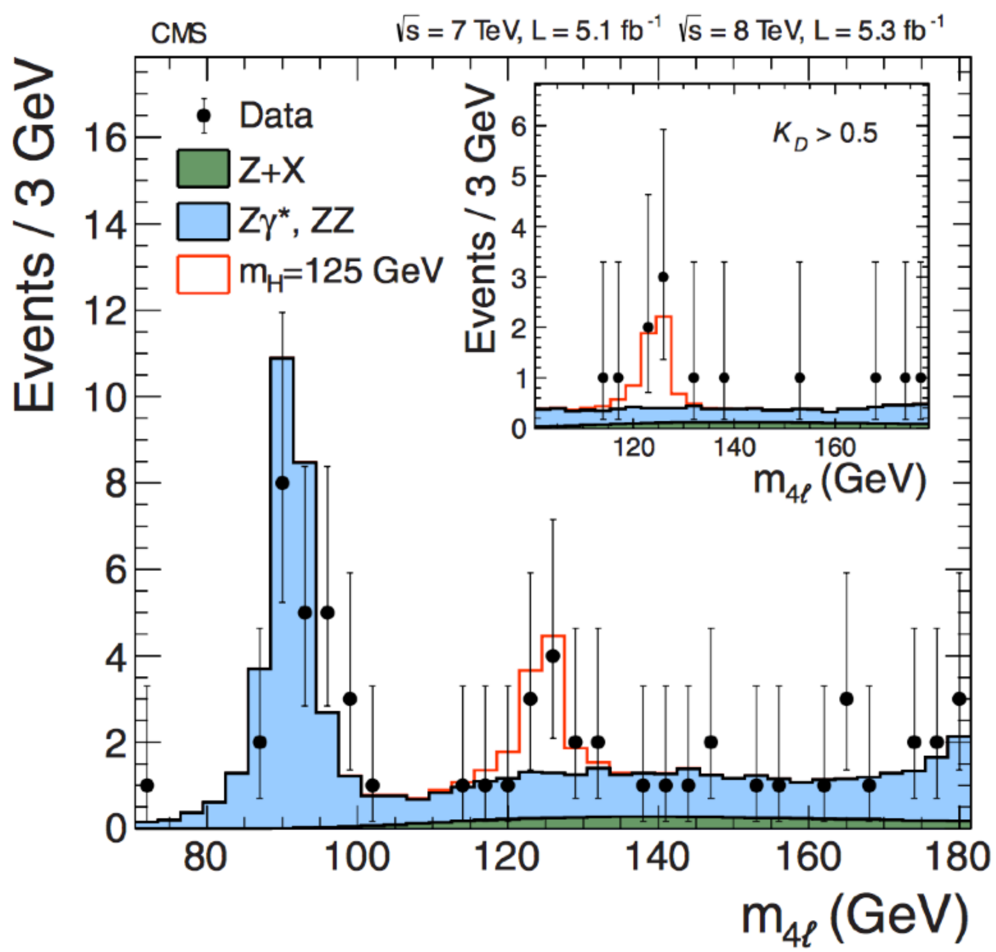
Take advantage of state-of-the-art analysis methods, data mining, machine learning, new technologies, upgraded detectors…

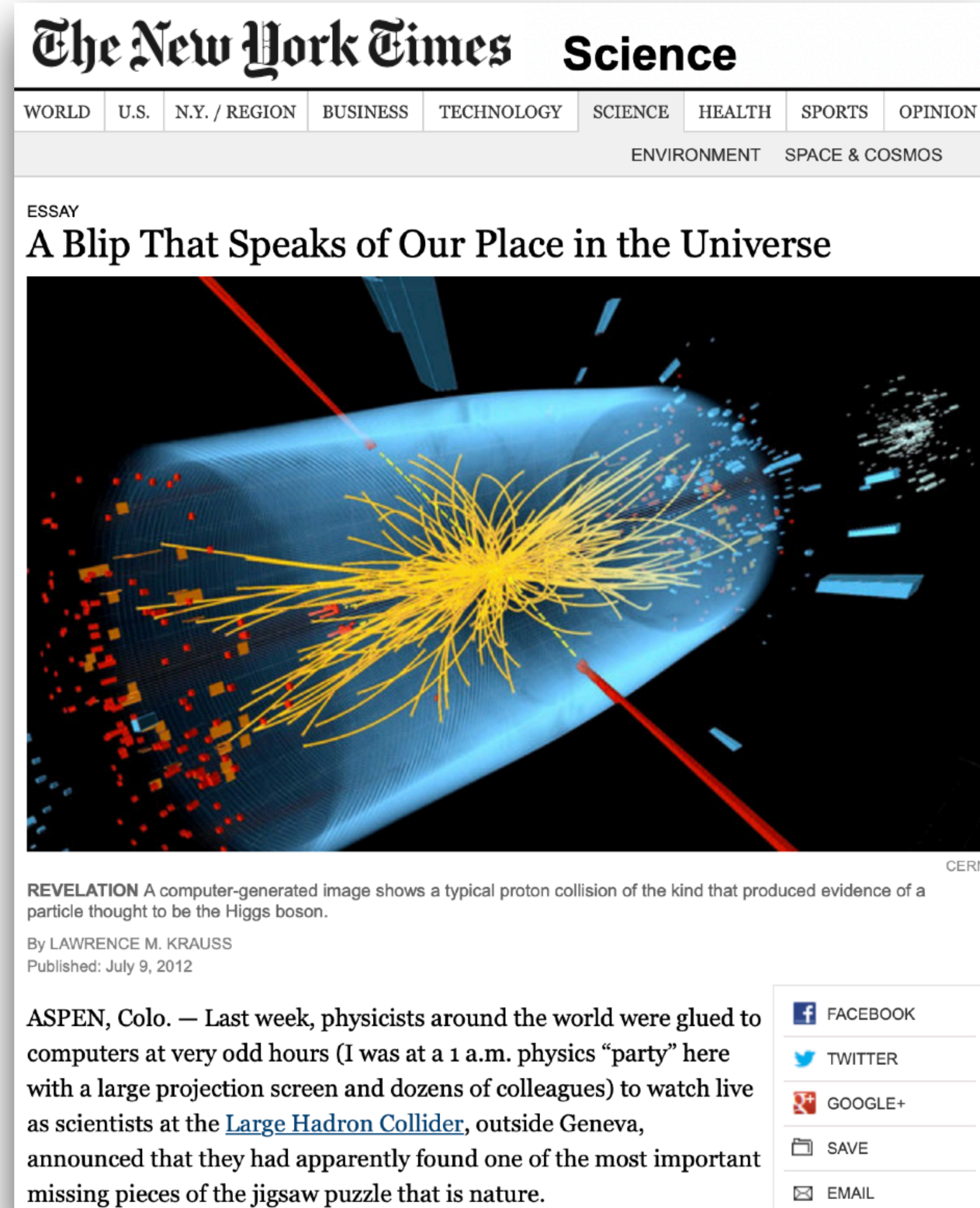
The Standard Model is Doing Amazingly Well!



Milestone in “Standard Model” Physics: Discovery of the SM Higgs Boson!

2012




The New York Times **Science**

WORLD | U.S. | N.Y. / REGION | BUSINESS | TECHNOLOGY | SCIENCE | HEALTH | SPORTS | OPINION

ENVIRONMENT SPACE & COSMOS

ESSAY

A Blip That Speaks of Our Place in the Universe

CERN

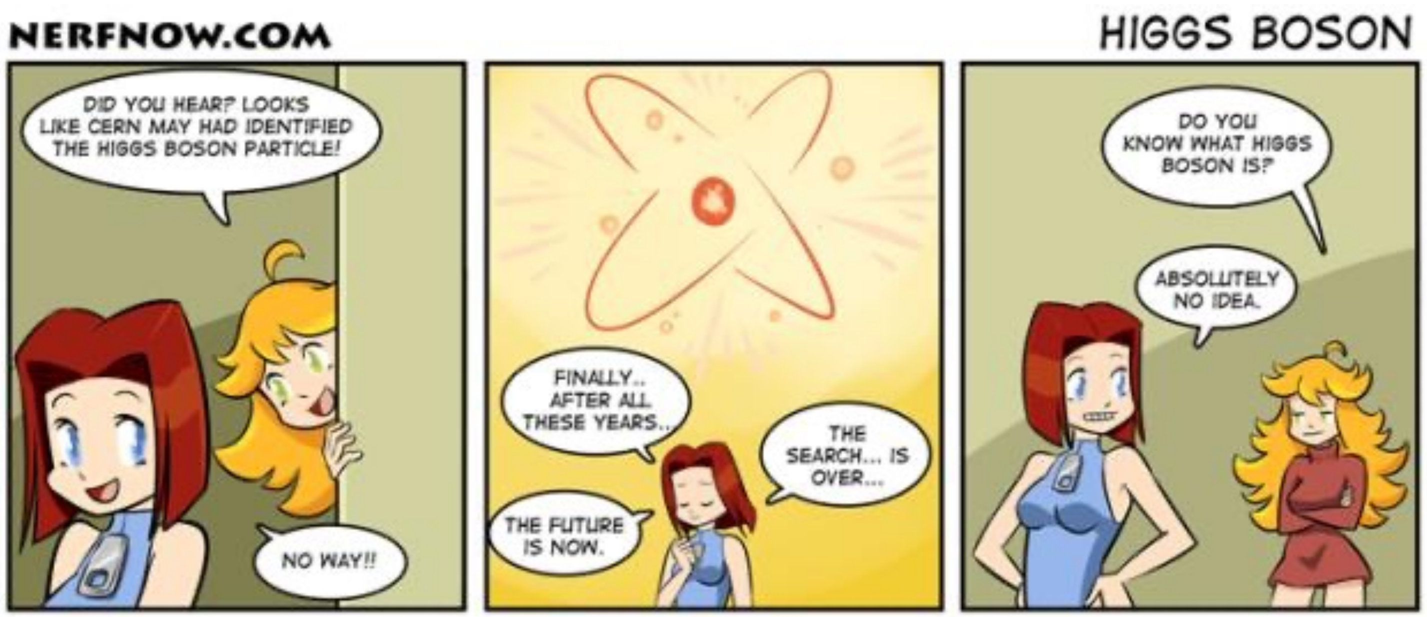
REVELATION A computer-generated image shows a typical proton collision of the kind that produced evidence of a particle thought to be the Higgs boson.

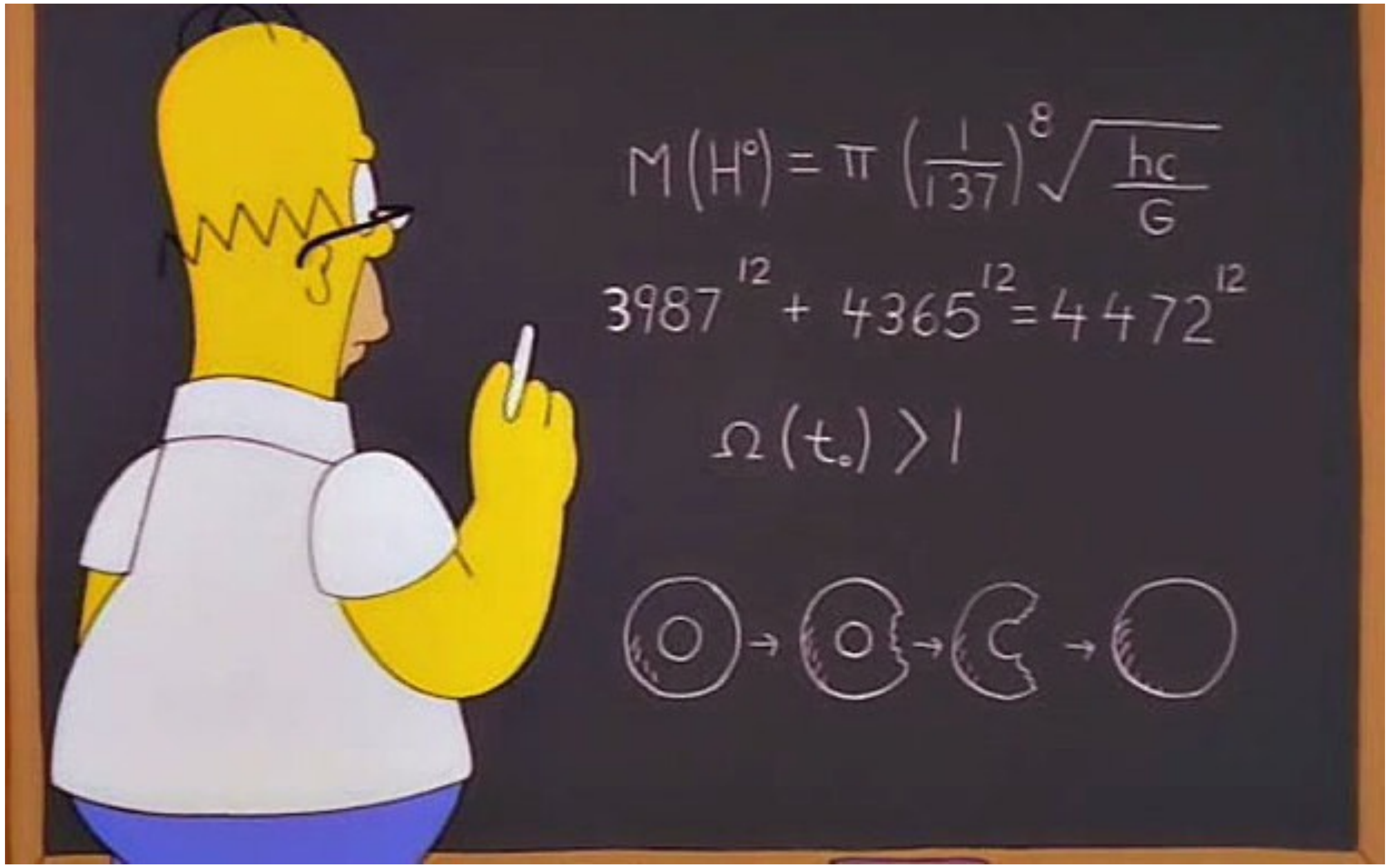
By LAWRENCE M. KRAUSS
Published: July 9, 2012

ASPEN, Colo. — Last week, physicists around the world were glued to computers at very odd hours (I was at a 1 a.m. physics “party” here with a large projection screen and dozens of colleagues) to watch live as scientists at the Large Hadron Collider, outside Geneva, announced that they had apparently found one of the most important missing pieces of the jigsaw puzzle that is nature.

FACEBOOK
TWITTER
GOOGLE+
SAVE
EMAIL

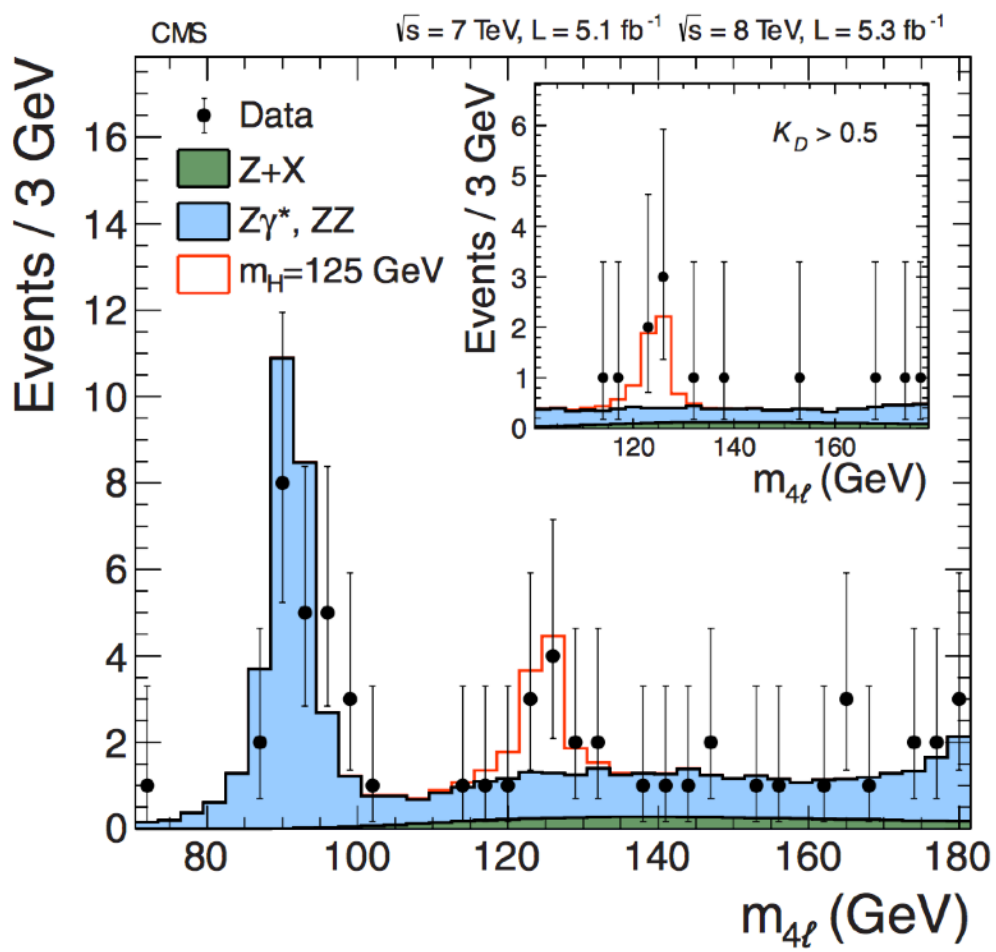
The Higgs has Entered Pop Culture





The Higgs has Turned 7!

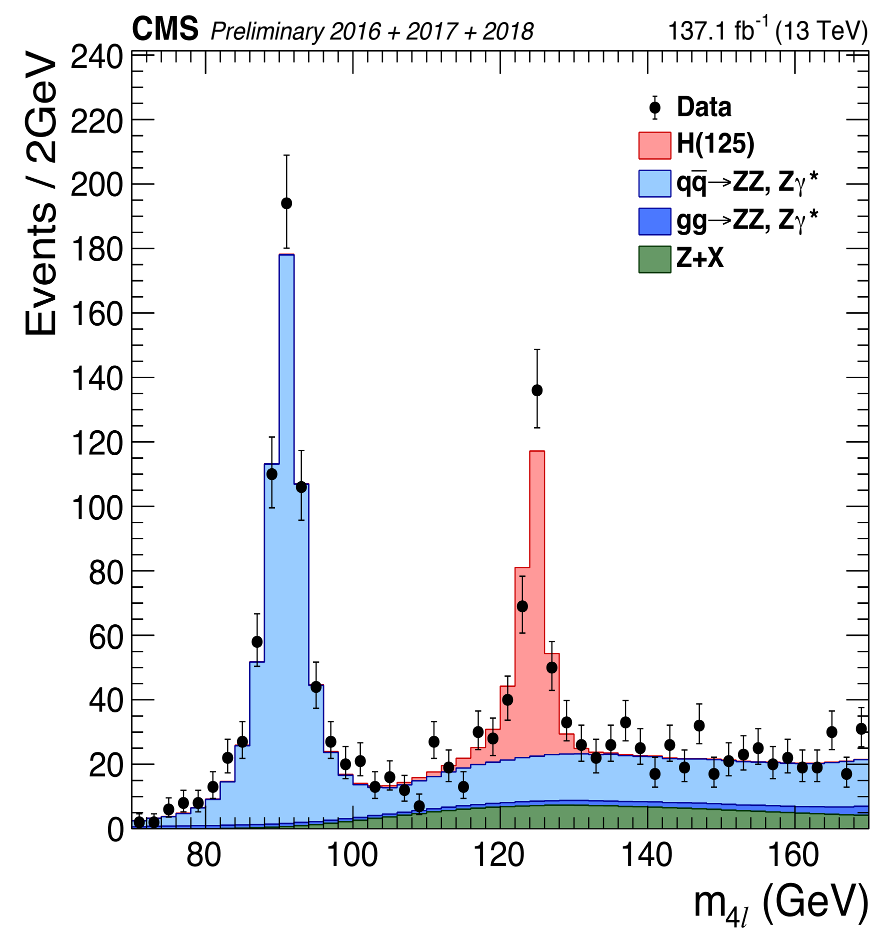
2012



Phys. Lett. B 716 (2012) 30

Discovery

2019

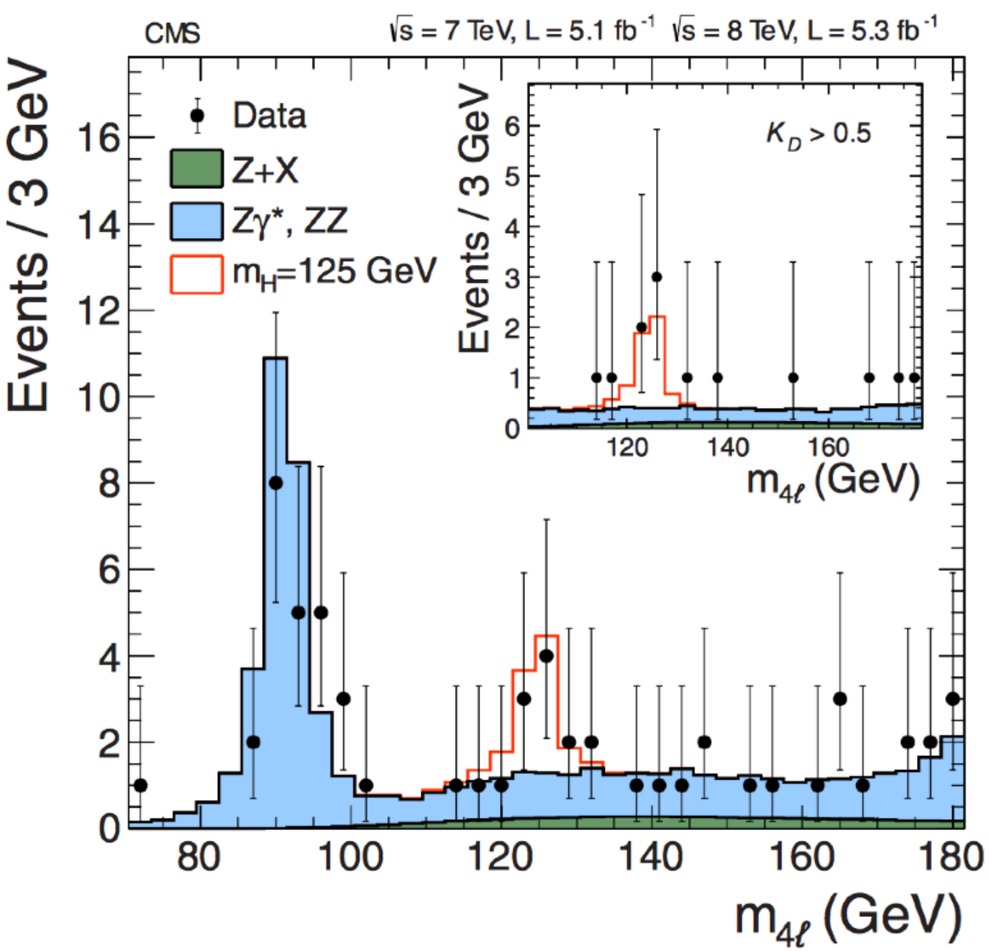


CMS-PAS-HIG-19-001

Precision

The Higgs has Turned 7!

2012



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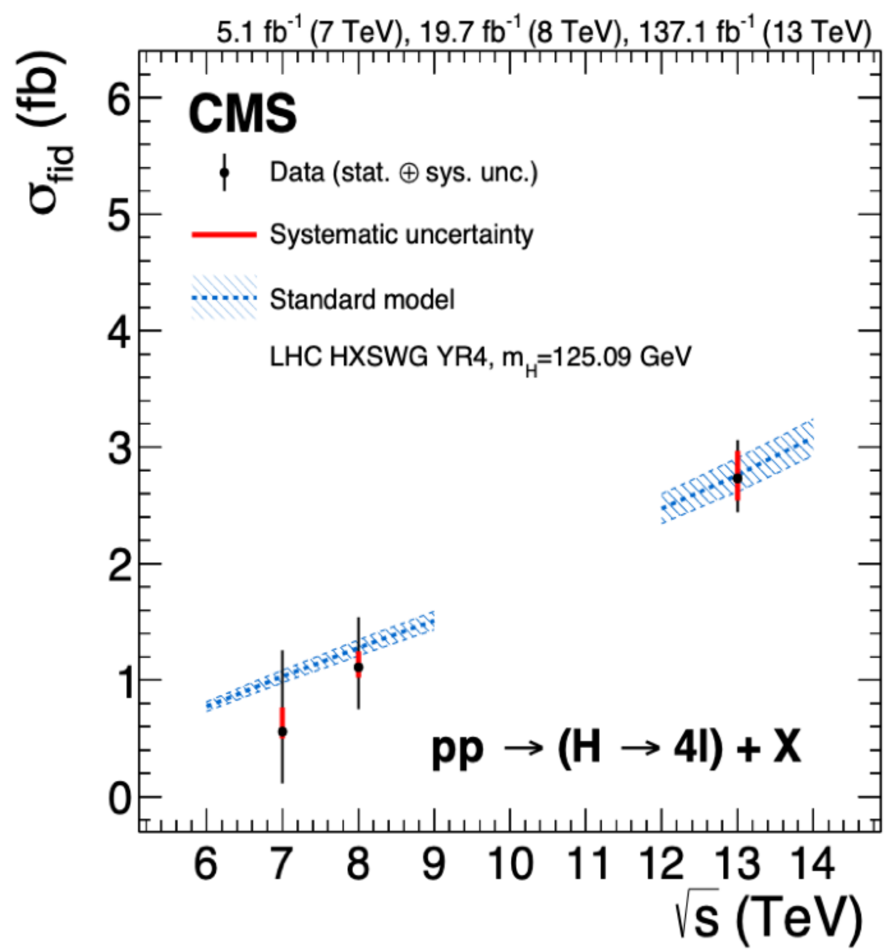

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Precision

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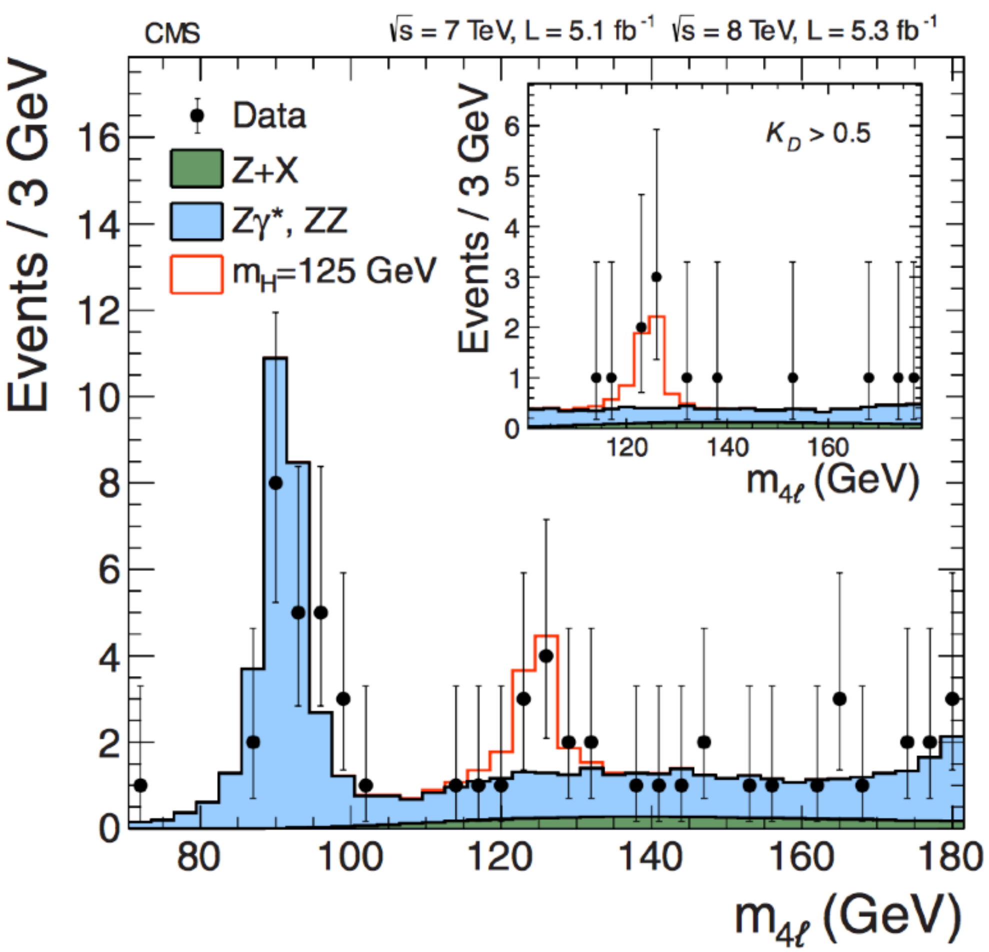
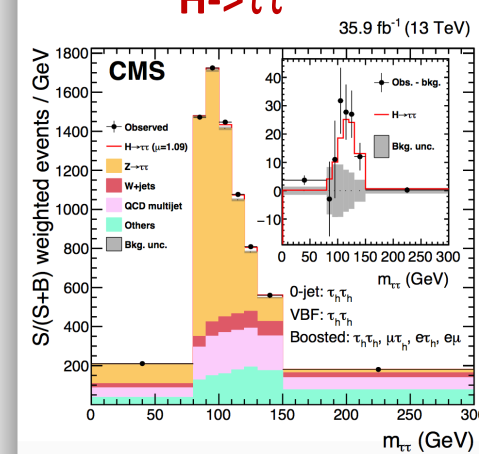


Tulika Bose:

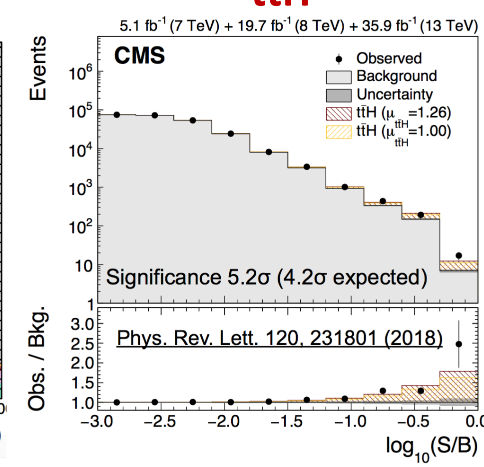
Establishing Higgs...

- Significant progress in the Higgs sector:
  - Firmly established $\gamma\gamma$, ZZ, WW decays
  - excellent mass measurement $\boxed{m_{\mathrm{H}} = 125.26 \pm 0.21\ (\pm 0.20\ \text{stat.} \pm 0.08\ \text{sys.})\ \text{GeV}}$
- Couplings to 3rd generation fermions established in the last two years by the > 5σ observation of:

H->ττ



ttH



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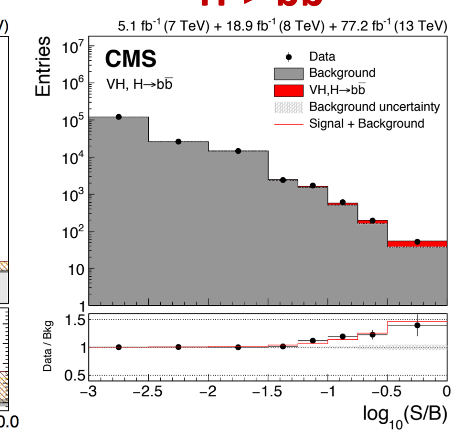
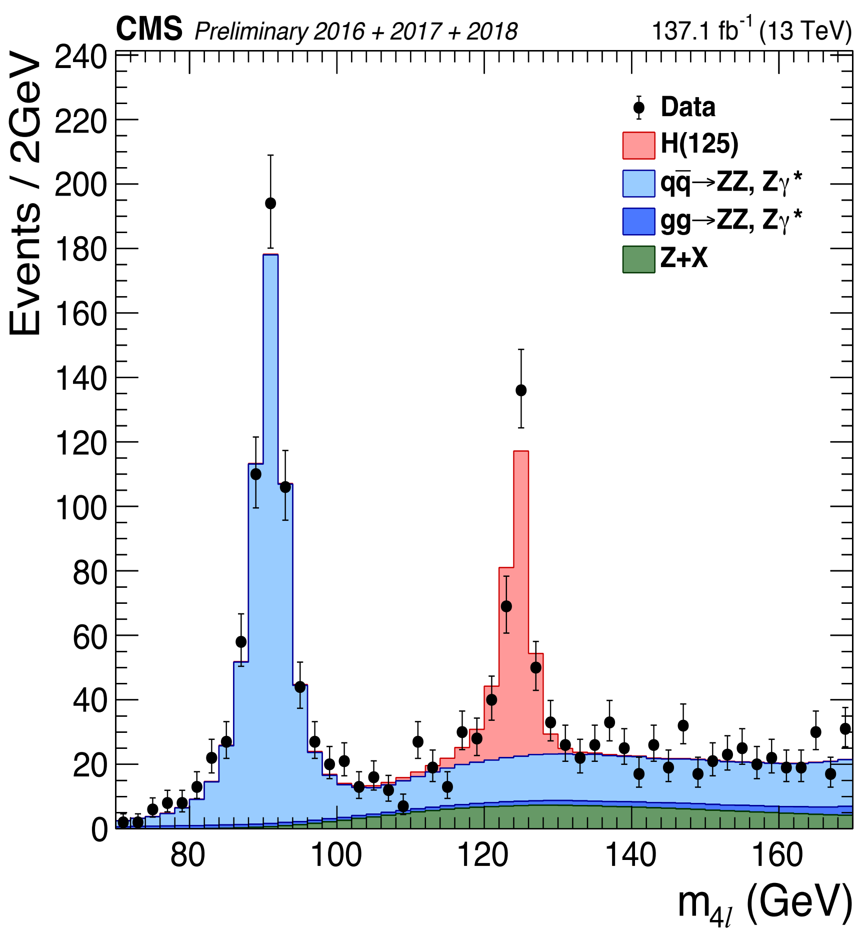


The Higgs: What’s next?

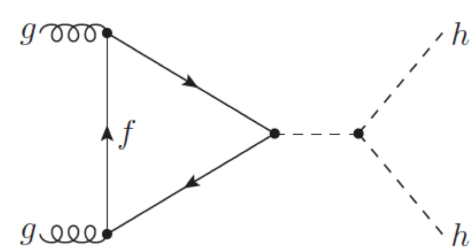
2019



Tulika Bose:

Key questions: post-discovery era

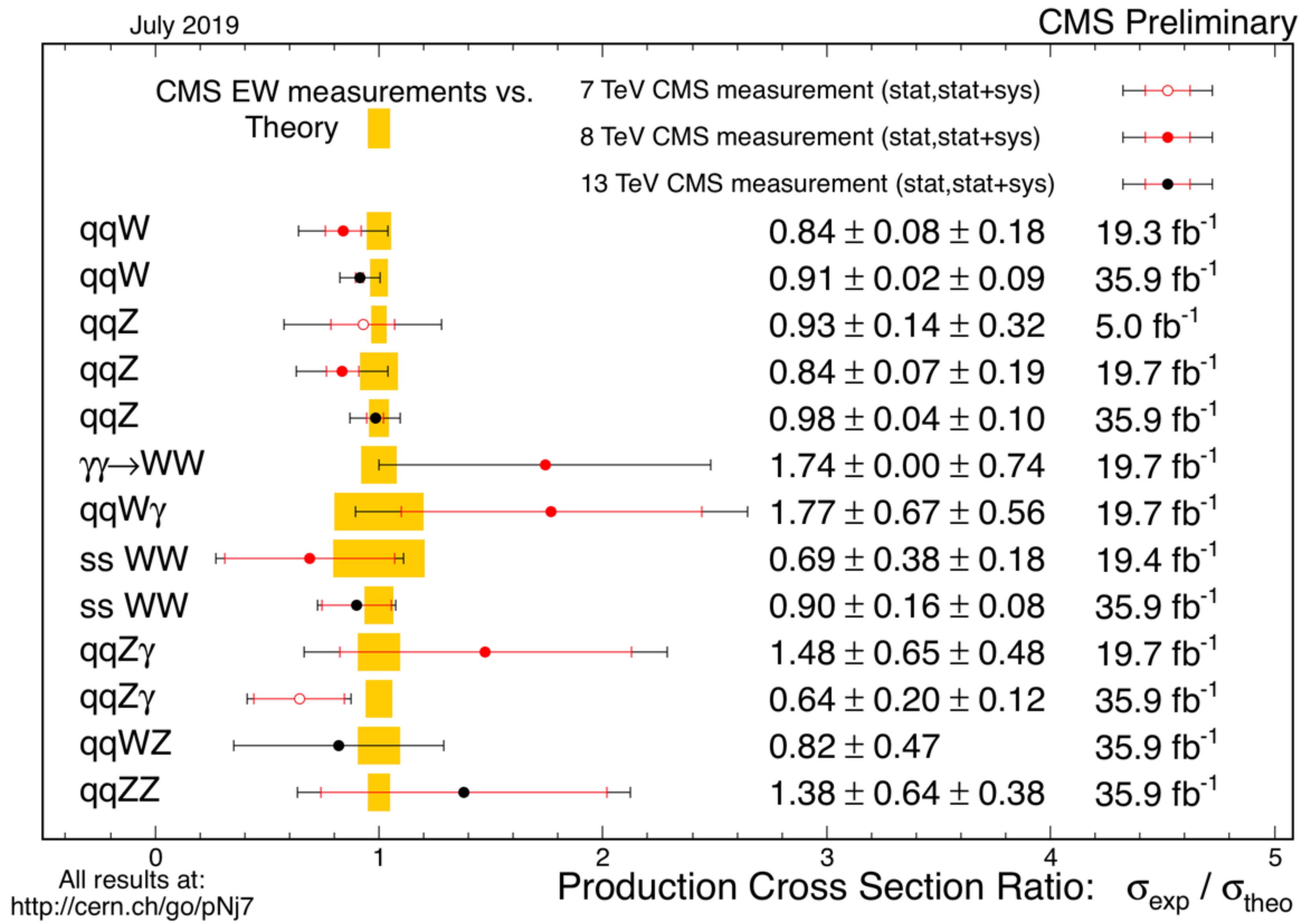
- Is it a Higgs boson or the Higgs boson ?
  - Is it elementary or composite ?
  - Does it interact with itself ?
  - Does it mediate a Yukawa force ?
- How does the Higgs couple to light particles (e.g. h → J/Ψ+γ)
- And how does it couple to muons ?
- Why is the Higgs so light ? Is m_H stabilized by ~TeV scale new physics or is it fine-tuned ?
- Are there additional Higgs bosons ?
- Are there exotic Higgs decays ?



✦ Understanding Higgs sector eventually requires measurement of its self-interaction

Measurements of Rare Processes

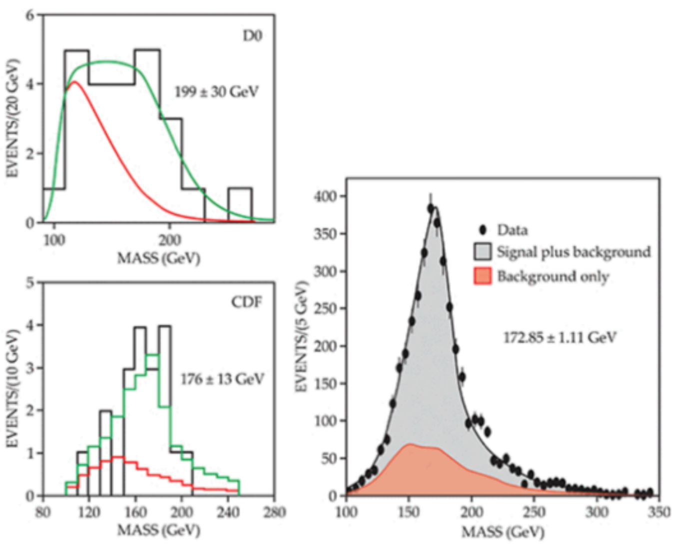
- Large datasets allow us to test SM in complementary ways
  - multi-differential X-section measurements
  - We have now sensitivity to rare multi-boson final states and production mechanisms

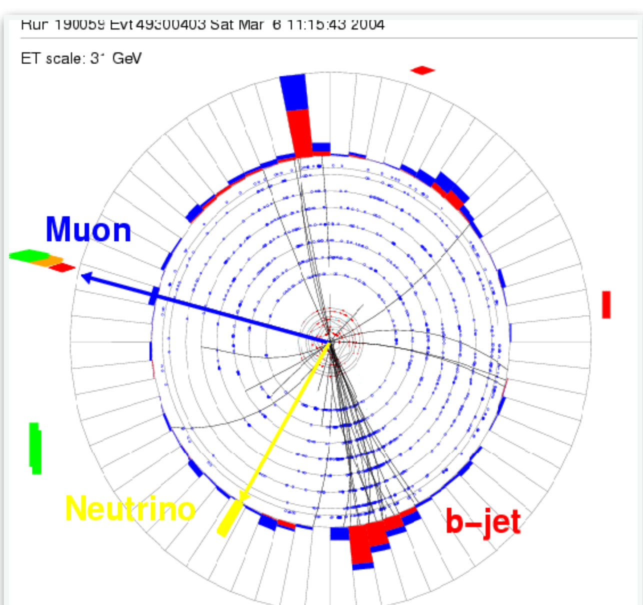


- There's room for surprises!
  - Quartic gauge couplings are known exactly in the SM and are sensitive to new physics
- The Higgs-Higgs self coupling is at 4-sigma reach for HL-LHC

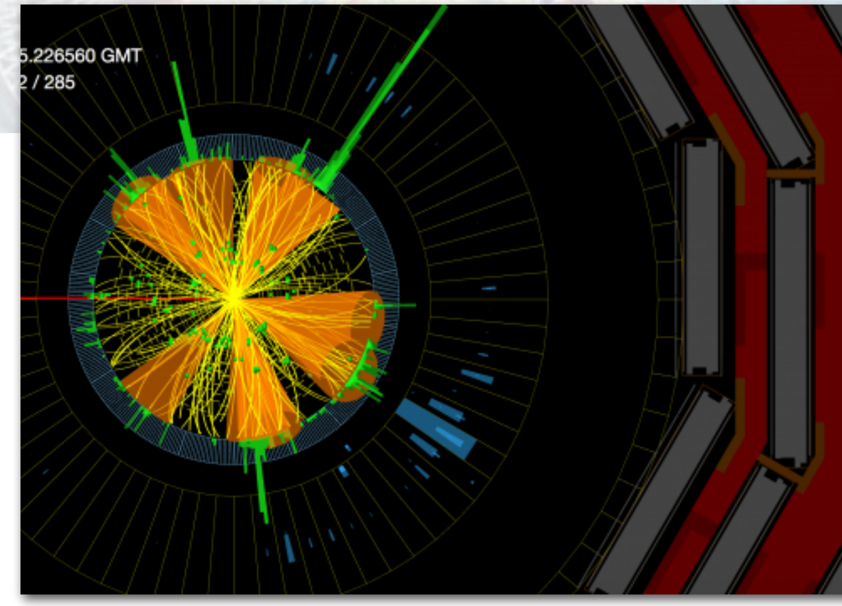
The LHC is a Top Factory

1995 @ Tevatron

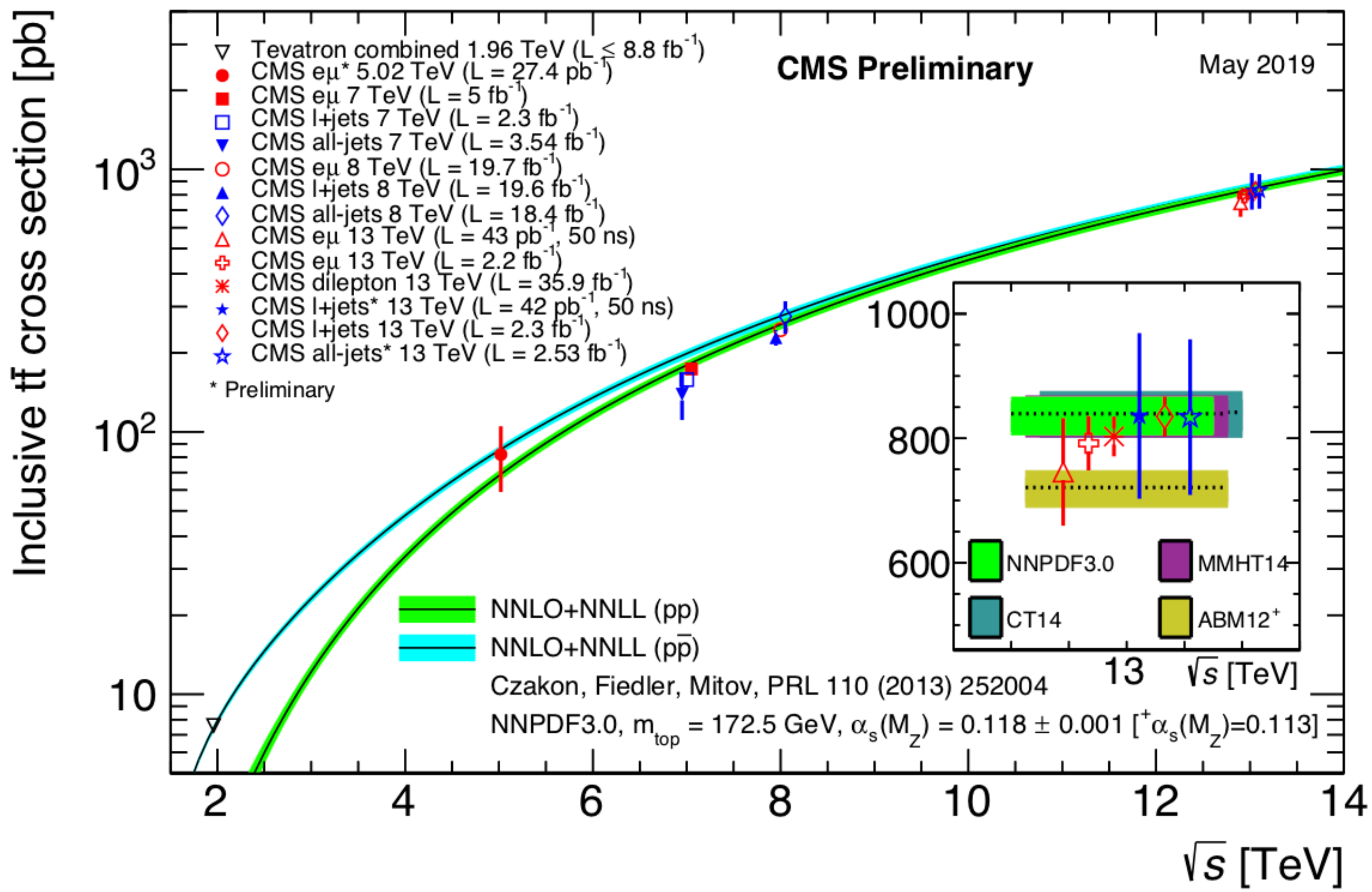




- ✦ We are having a very detailed look at the top properties

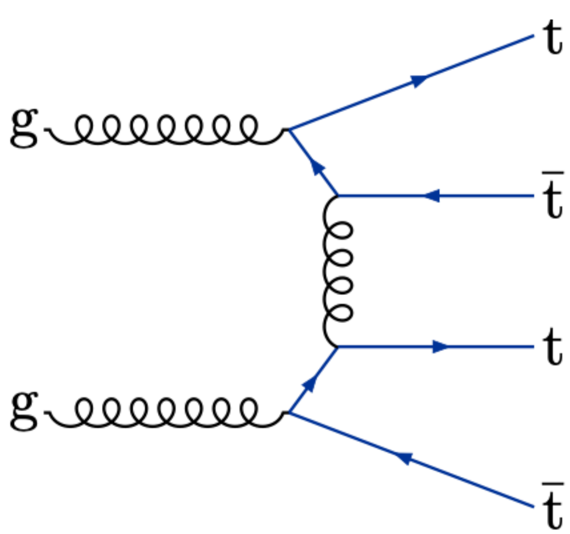


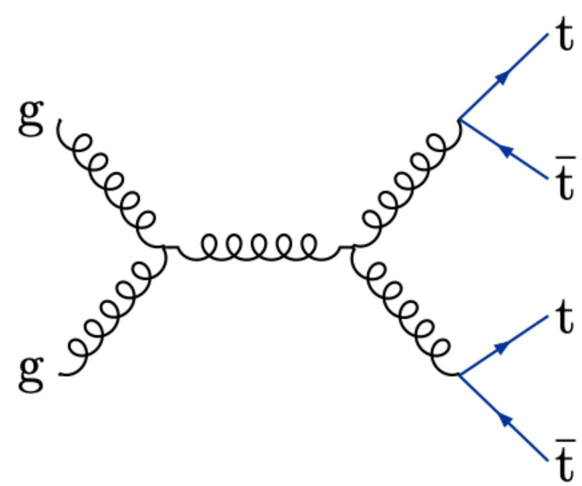
2019 @ LHC

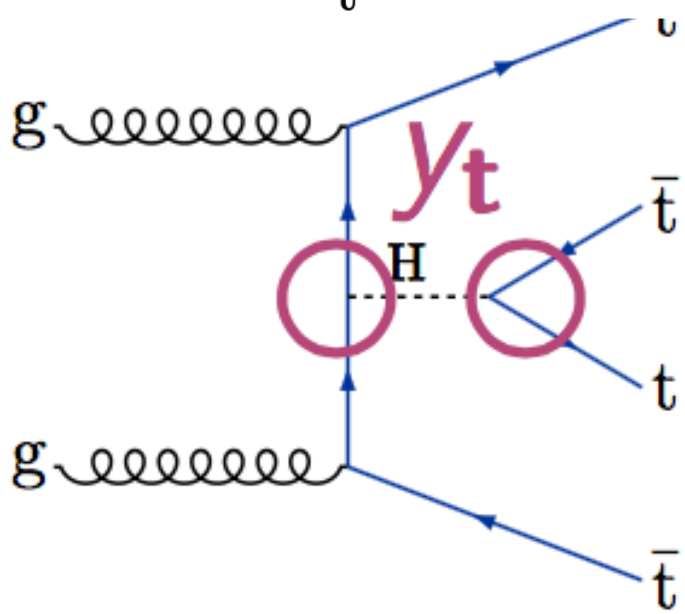


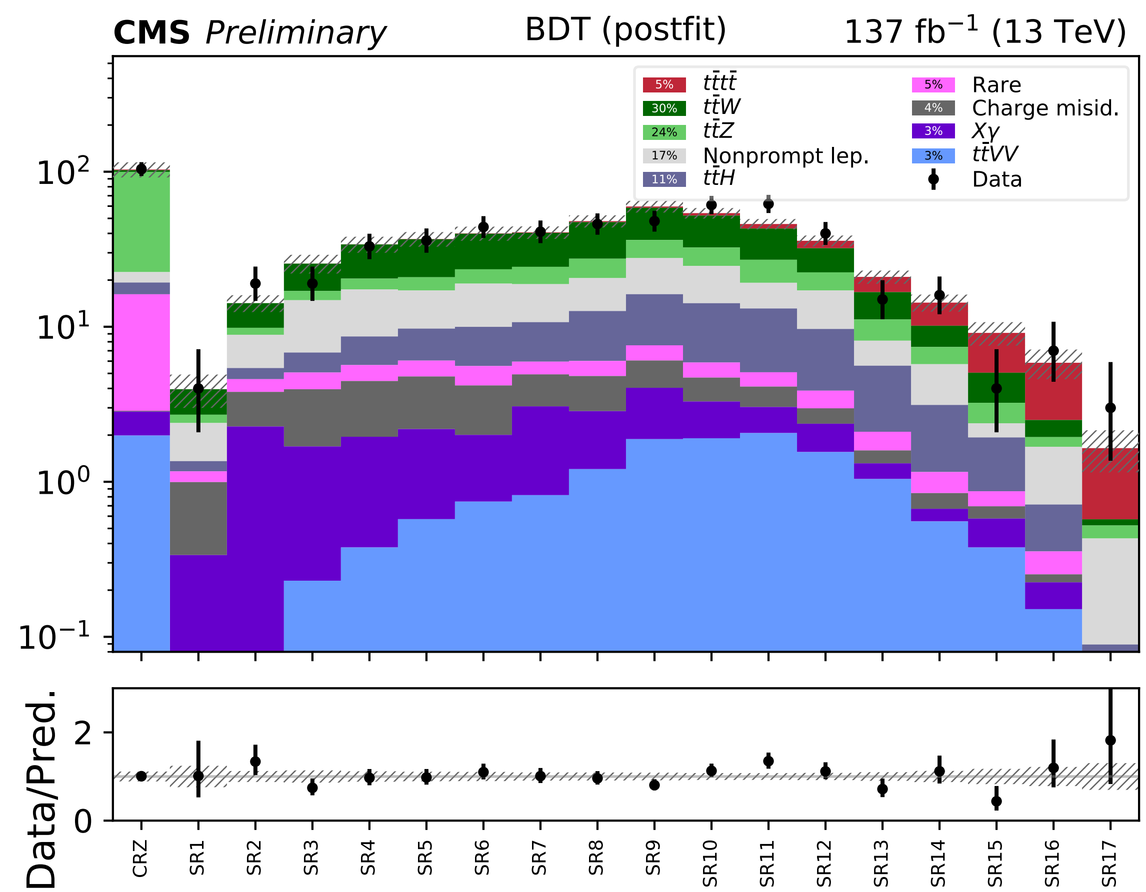
Sensitivity to extremely rare processes…

- e.g. tttt: unobserved, very rare process ($\sigma_{tttt} \approx 0.01$ pb)









Approaching sensitivity to 4-top: obs. (exp.): 2.6 (2.7) σ

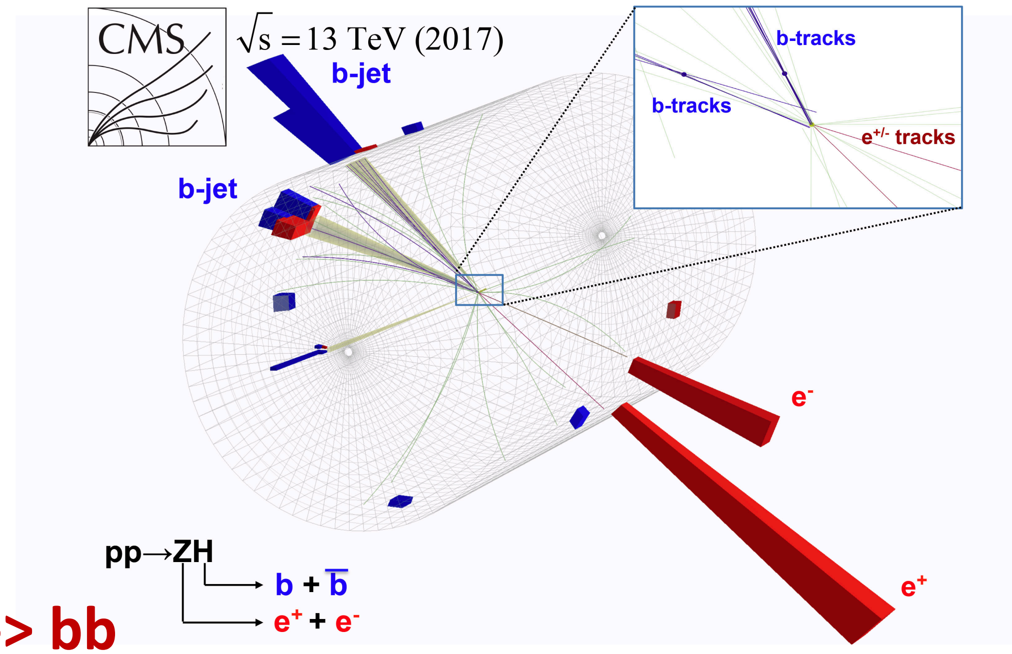
Sensitive to the top Yukawa coupling

$$|y_t/y_t^{SM}| < 1.7,$$

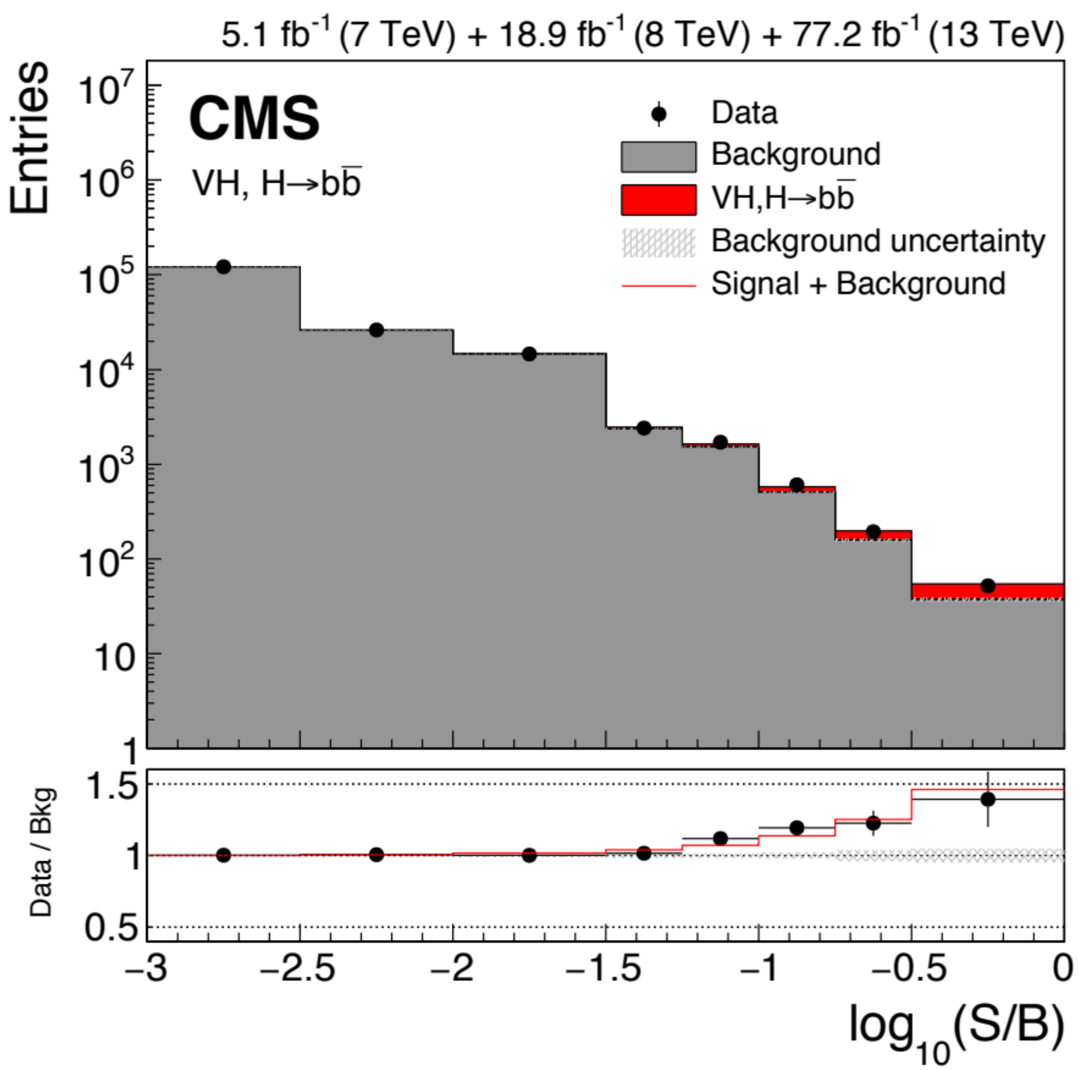
@ 95% CL

SM Fermions acquire mass through Higgs Yukawa couplings

- CMS presented the observation of the Higgs boson coupling to b quarks. With the observation of the couplings to τ lepton and top quark, we completed the observation of the coupling to 3rd generation fermions
  - Largest Higgs decay rate (58%) with significant (x1,000) background
  - advanced Deep Neural Network techniques for background rejection!
- A great success of LHC and the experiments, much earlier than expected thanks to the outstanding performance of LHC but also to very refined analysis techniques
- Next frontier: Higgs coupling to 2nd generation: charm, muons
  - Very advanced techniques required!
- Great summary in Tulika's Wine&Cheese at http://bit.ly/2NGNF4f

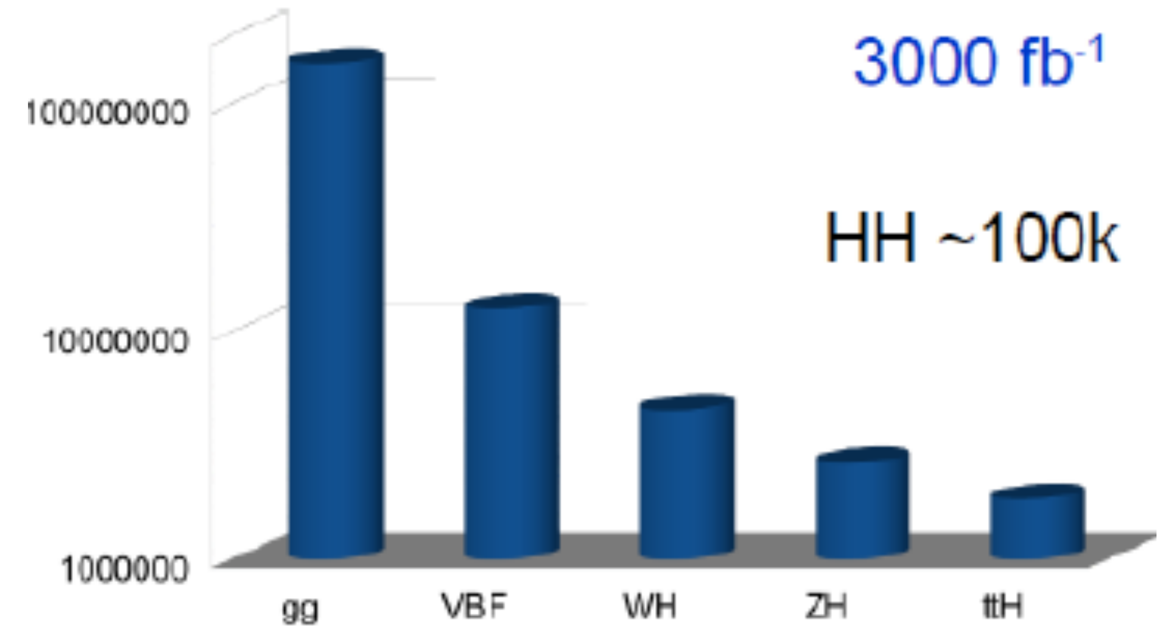


H-> bb



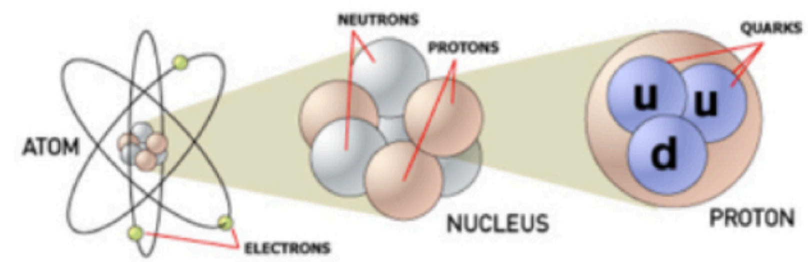
The Future is Bright: LHC as a Higgs Factory

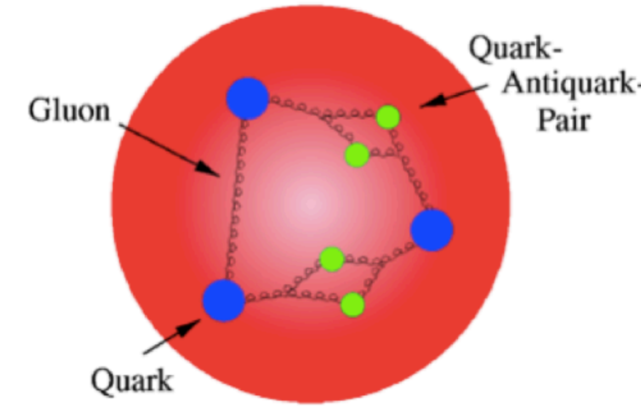
- HL-LHC is a Higgs factory
  - will produce > 150M Higgs bosons
  - Including ~120k of pair produced events
- Enables a broad program:
  - Precision O(1-10%) measurements of coupling across broad kinematics
  - can reveal new particles in loops or non-fundamental nature of Higgs
  - Exploration of Higgs potential (HH production)
  - BSM Higgs searches (extra scalars, BSM Higgs resonances, exotic decays…)



So, is the Higgs the key to understanding Mass?

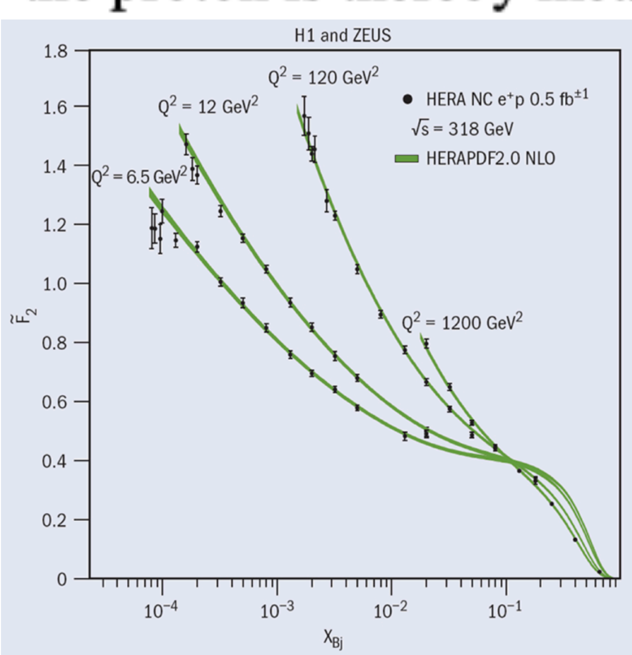
- Perhaps… Probably,
  But…

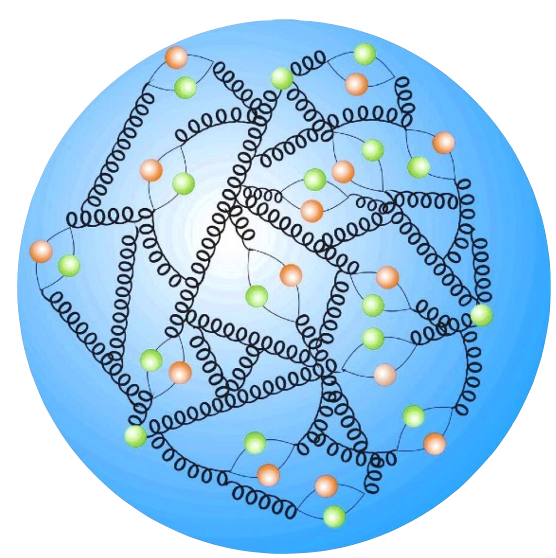




John Dainton:

HERA has discovered that hadron mass, us – humanity and the presently visible Universe, is chromodynamic field energy. Less than 1% of visible mass in the proton is attributable to constituent mass, that is to mass due to the spontaneous breaking of $SU(2) \times U(1)_{\text{broken}}$, the Higgs mechanism. We are gluons! HERA has measured with precision this discovery such that we now have a quantitative prescription for how a proton interacts in the SM in the form of chromodynamic phenomenology. HERA achieved this as an ever-improving instrument which probed the structure of the proton with the unified electroweak sector, that is, with each, and with all together, of lepton and quark flavour, of chirality, and of the differences between lepton–matter and anti-lepton–matter interactions. The anti-matter–matter asymmetry of the proton is thereby measured directly for the first time.



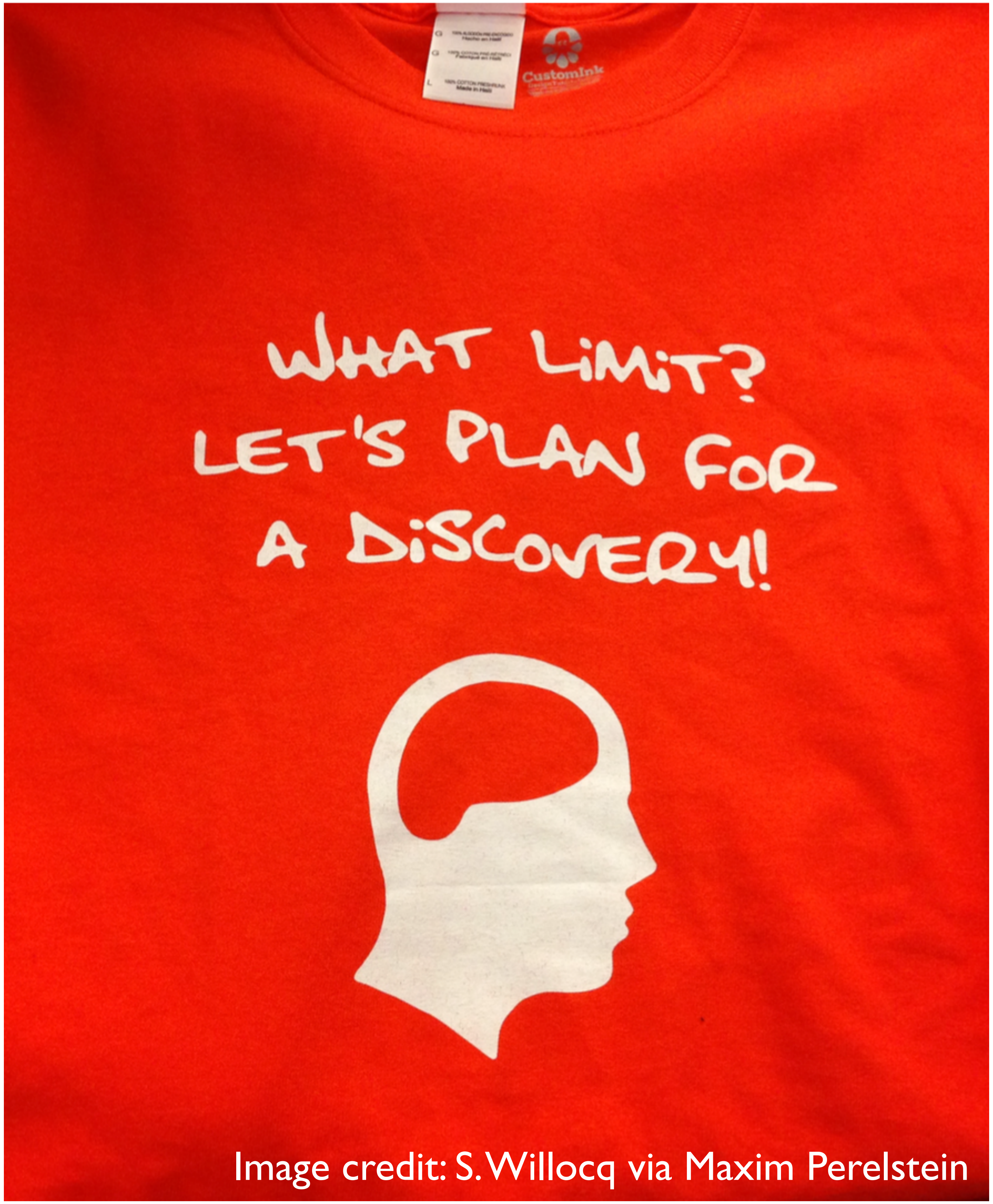


Proton mass
m_P = 938 MeV

Quark masses
m_u = 1.5-4.5 MeV
m_d = 5.0-8.5 MeV

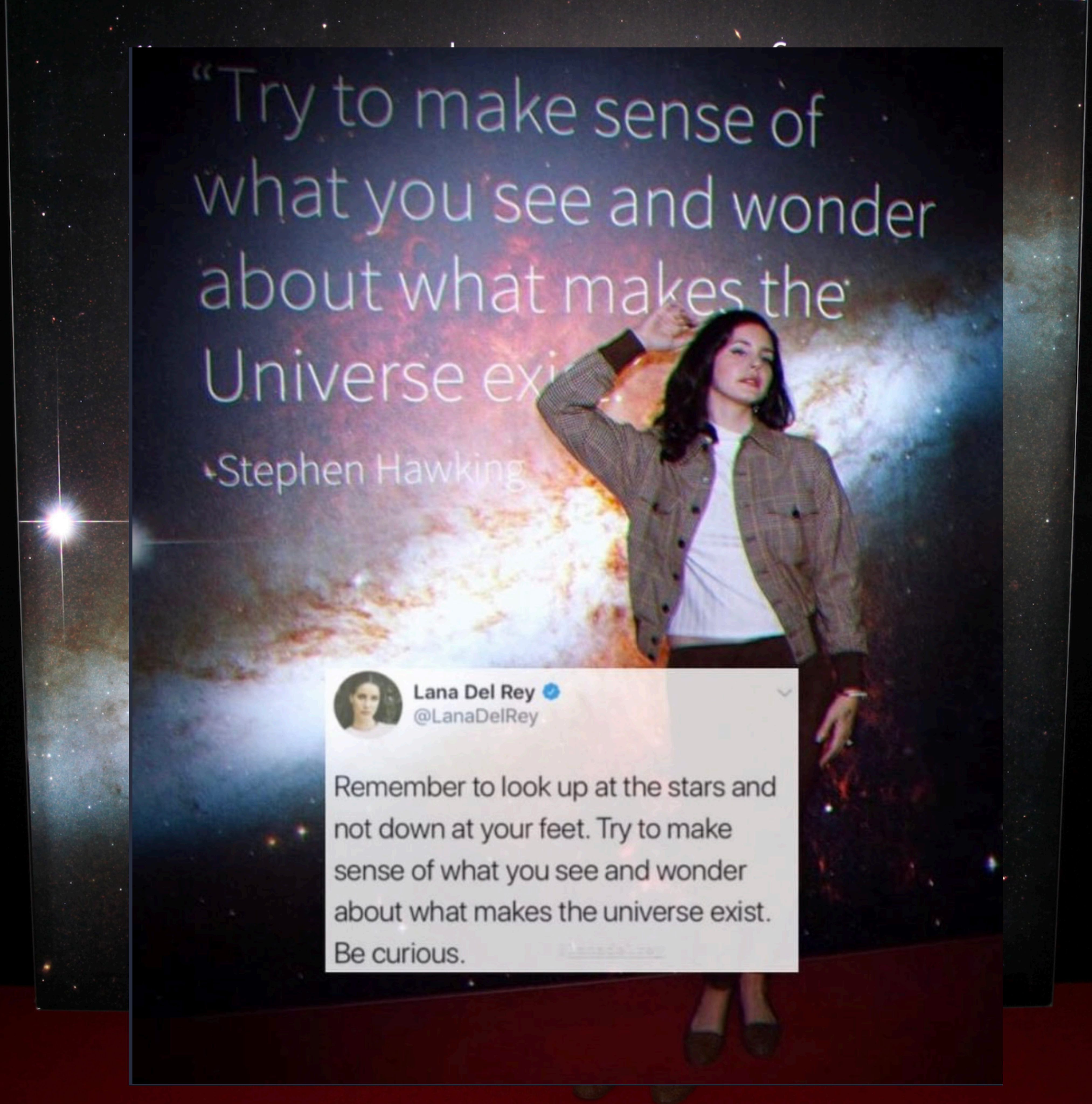
Inertial mass
mostly QCD effects

Let's Keep Up the Discovery Mindset



Today and tomorrow, we'll hear much more about past and present cutting edge physics highlights,

in recognition and in honor of Wesley's many contribution to the field


"Try to make sense of what you see and wonder about what makes the Universe exi
-Stephen Hawking
Lana Del Rey
@LanaDelRey
Remember to look up at the stars and not down at your feet. Try to make sense of what you see and wonder about what makes the universe exist. Be curious.

The End