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SFB 676 – Projekt B2

Introduction to Particle Physics

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DESY Summer Student Lectures – Hamburg – 20th July '11

PHYSICS AT THE TERA SCALE Helmholtz Alliance

Outline

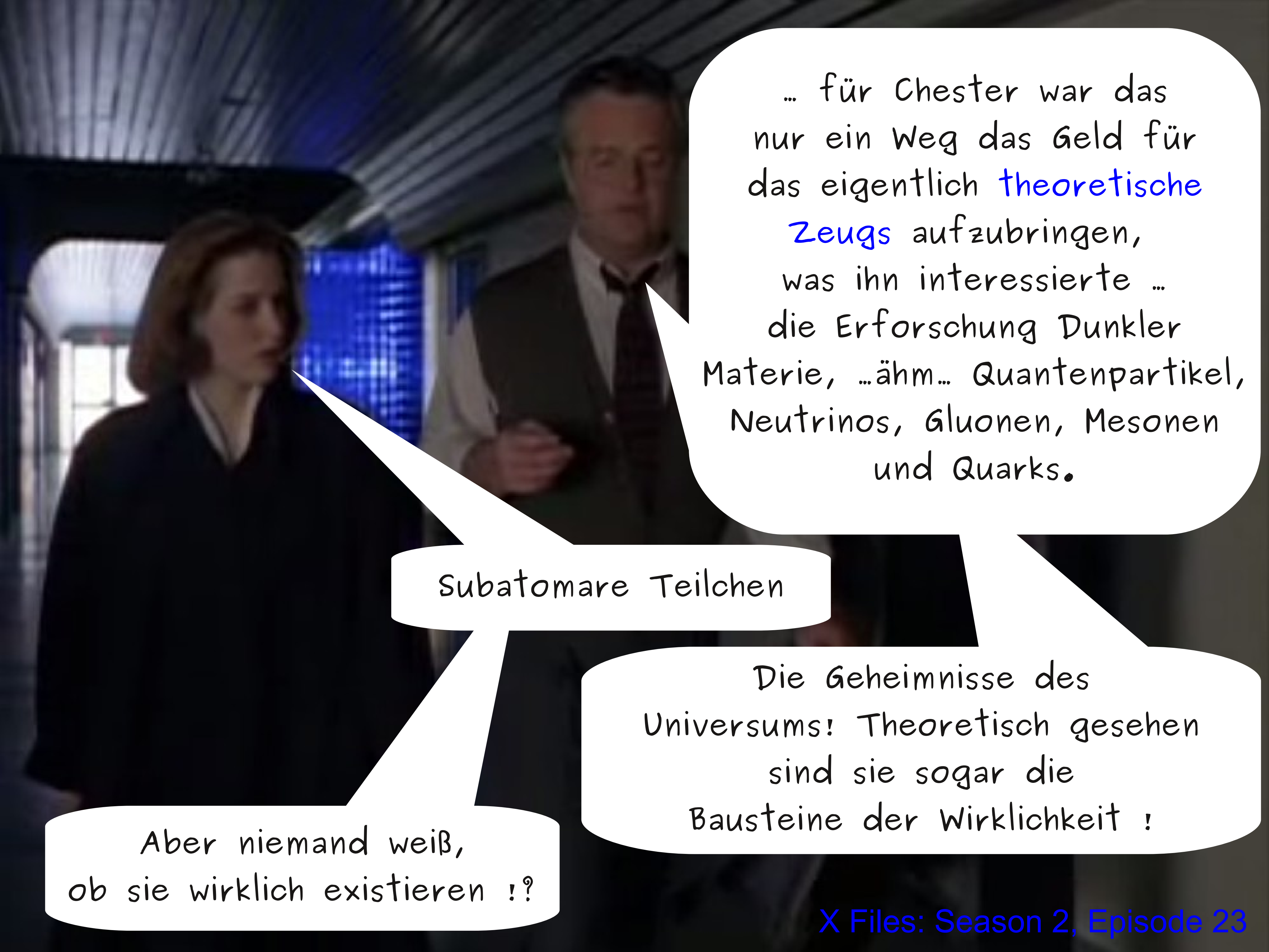
- **Introduction**
  - History: From Democrit to Thomson
- **The Standard Model**
  - Gauge Invariance
  - The Higgs Mechanism
  - Symmetries …

Break

- **Shortcomings of the Standard Model**
- **Physics Beyond the Standard Model**
- **Recent Results from the LHC**
- **Outlook**

Disclaimer: Very personal selection of topics and for sure many important things are left out!

X Files: Season 2, Episode 23

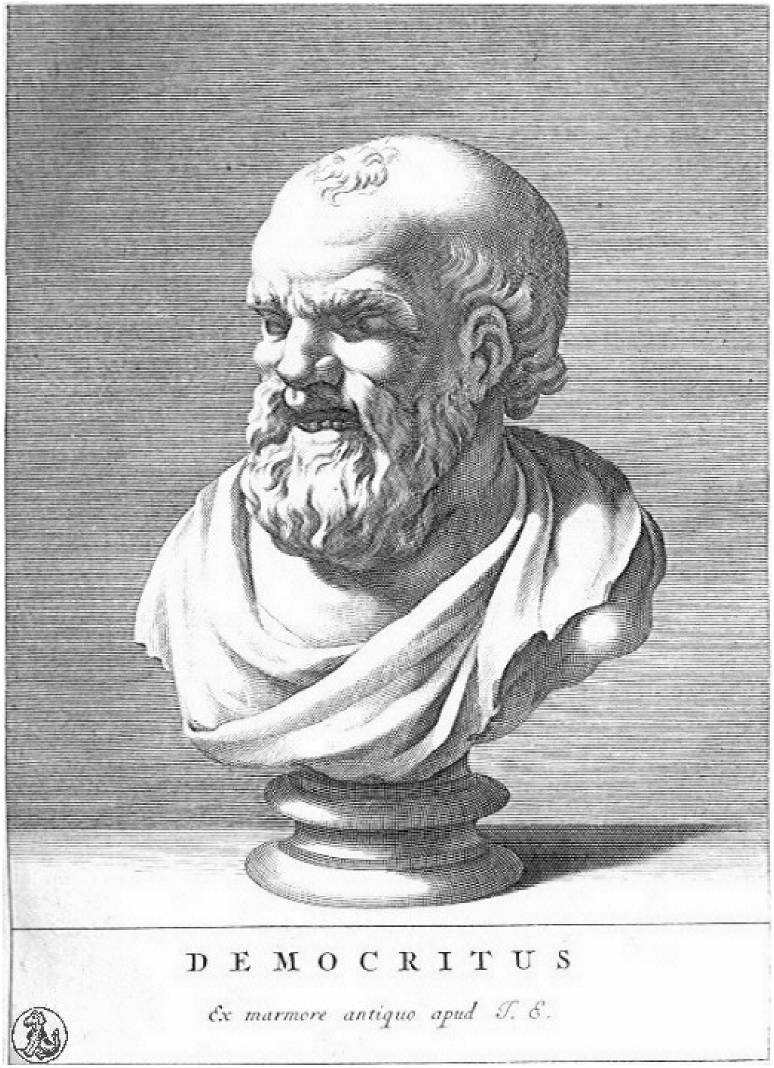


X Files: Season 2, Episode 23

The First Particle Physicist?

By convention ['nomos'] sweet is sweet, bitter is bitter, hot is hot, cold is cold, color is color; but in truth there are only atoms and the void.

Democrit, * ~460 BC, †~360 BC in Abdera



Hypothesis:

- Atoms have same constituents
- Atoms different in shape (assumption: geometrical shapes)
  - Iron atoms are solid and strong with hooks that lock them into a solid
  - Water atoms are smooth and slippery
  - Salt atoms, because of their taste, are sharp and pointed
  - Air atoms are light and whirling, pervading all other materials

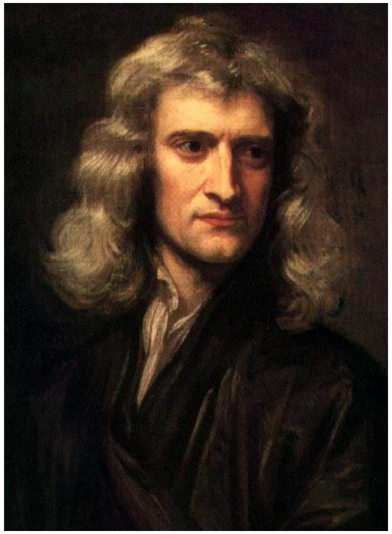
Corpuscular Theory of Light

Light consist out of particles (Newton et al.)

↕

Light is a wave (Huygens et al.)

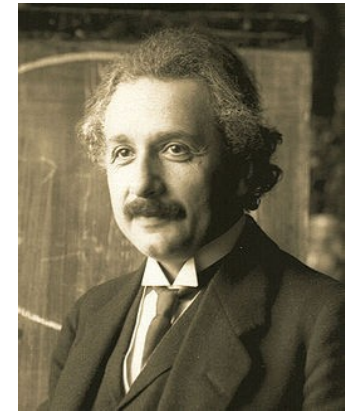
- Mainly because of Newtons prestige, the corpuscle theory was widely accepted (more than 100 years)
- Failing to describe interference, diffraction, and polarization (e.g. Fresnel) corpuscle theory was abandoned for Huygens wave theory
- Wave therory strongly supported by Maxwell equations and by H. Hertz experiments
- Until in the early 20th century ...



Sir Isaac Newton
*1643, †1727

Christiaan Huygens
*1629, †1695

Photoelectric Effect

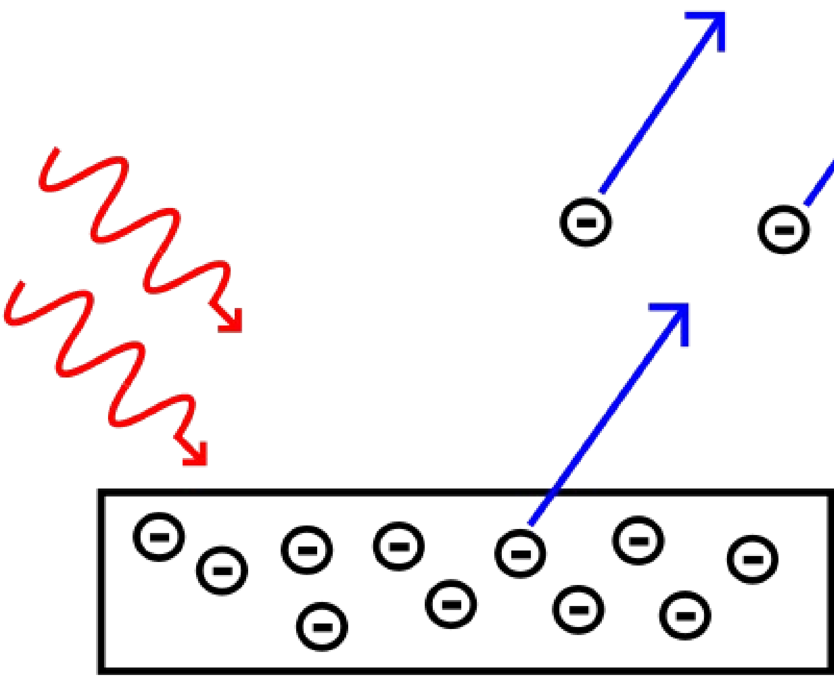


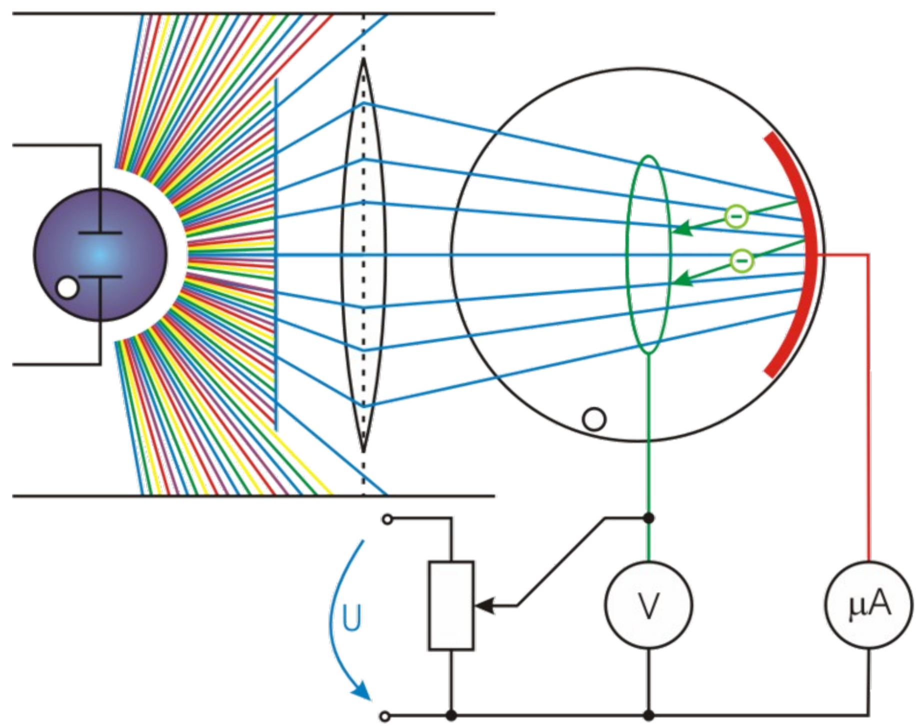
- **Observation:** 1836 Becquerel

  Metal absorbes light and emits electrons →

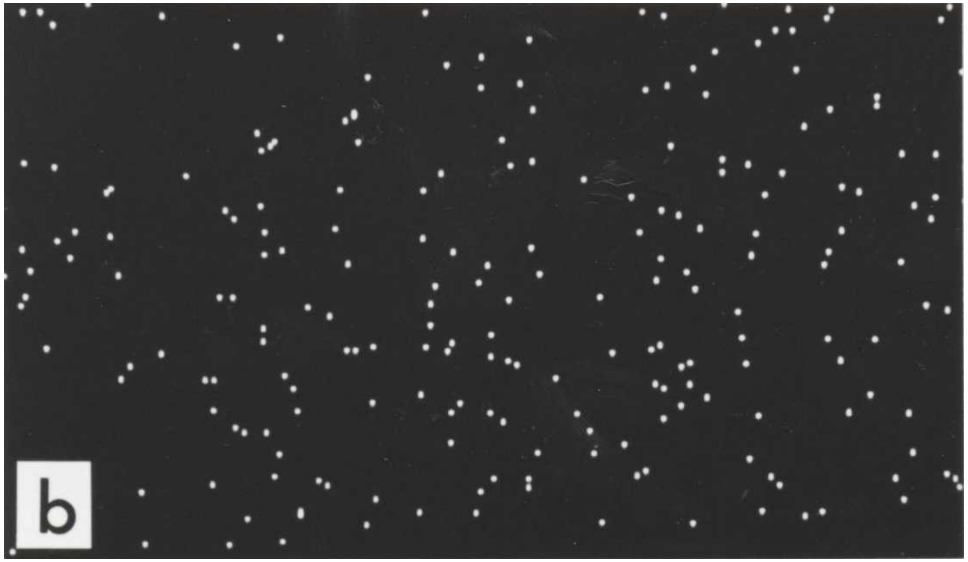
  Maximum energy of electrons independent on intensity (# of photons)
- **Interpretation:** 1905 Einstein (→ NP 1921)

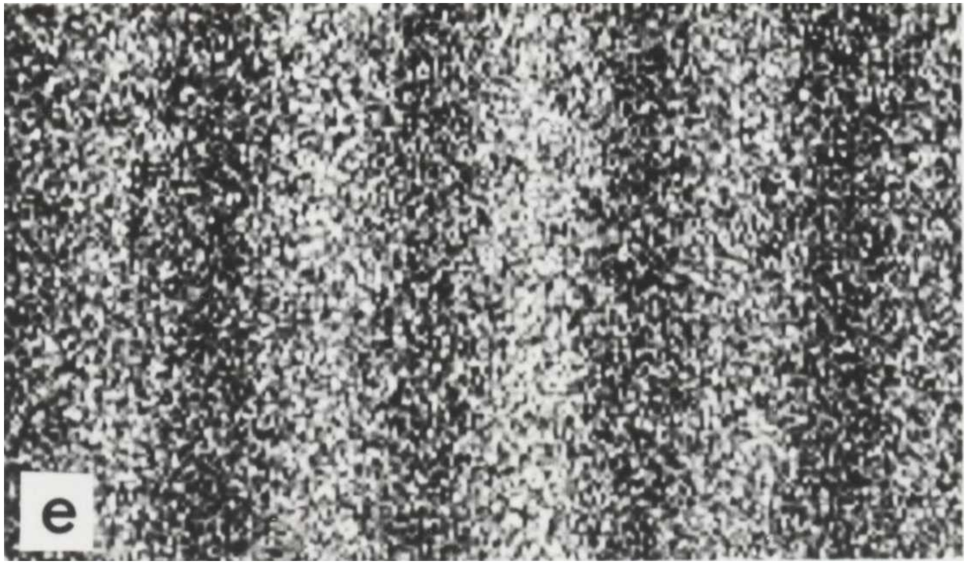
  Light consists of particles (photons) with quantized energy

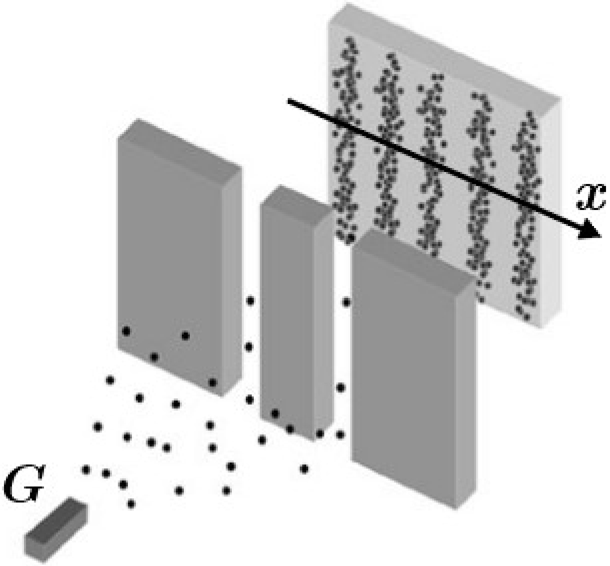




Double Slit with Electrons







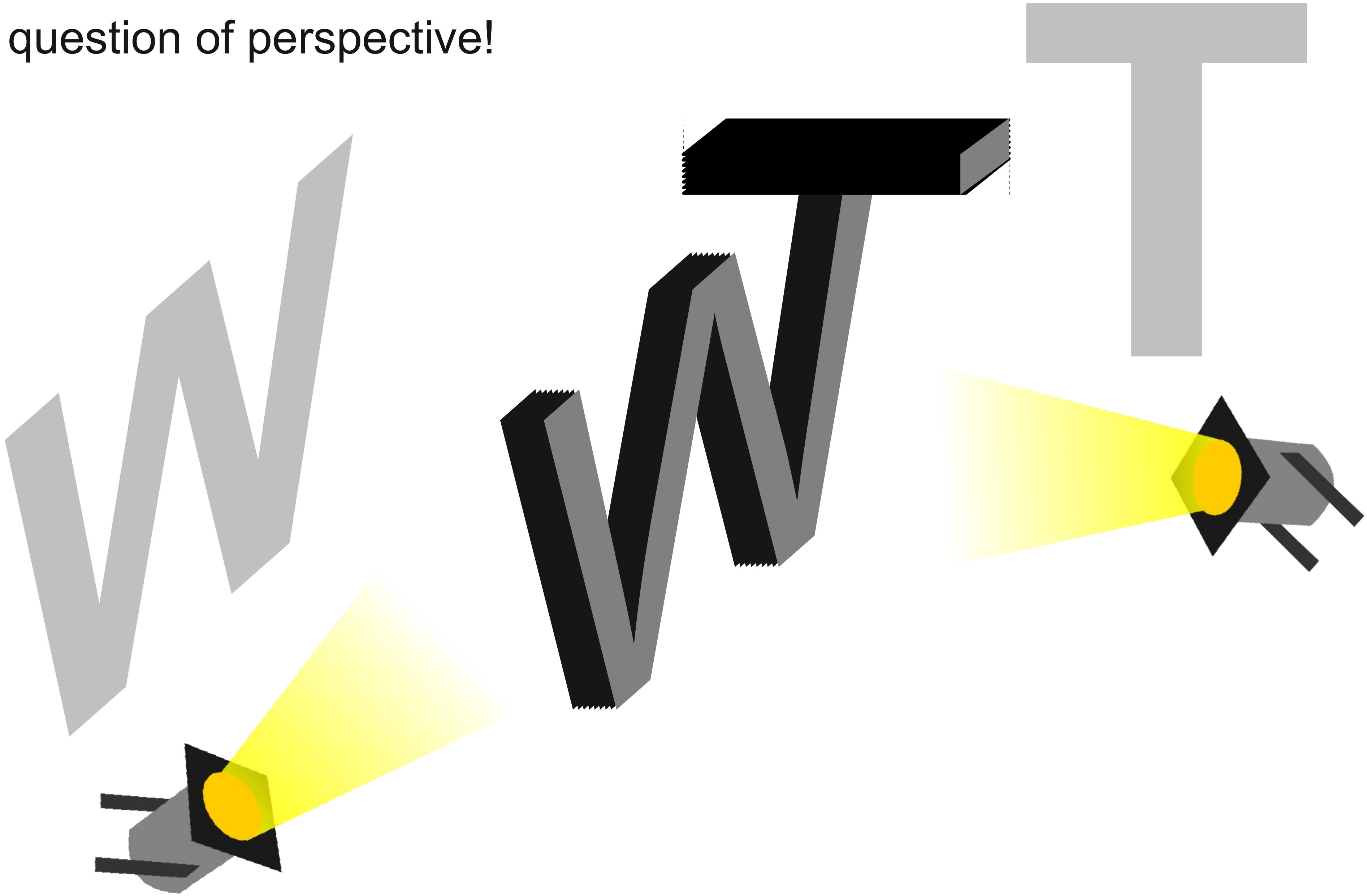
Electrons (particles) have wavelength

De Broglie wavelength:

$$\lambda = \frac{h}{p} = \frac{\text{Planck constant}}{\text{momentum} = \text{mass} \cdot \text{velocity}}$$

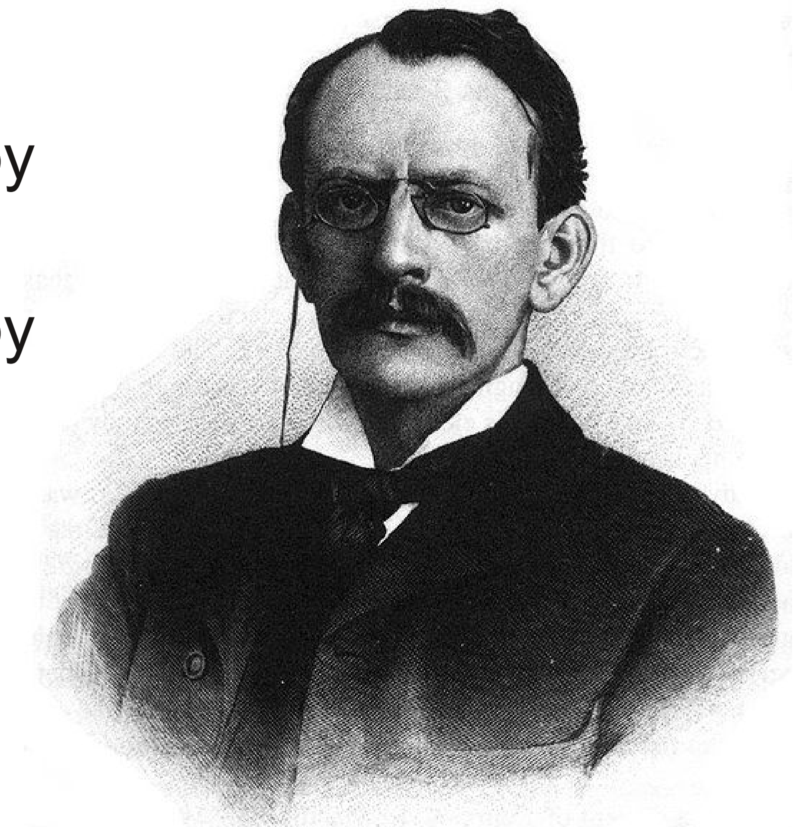
Wave-Particle Duality

All a question of perspective!

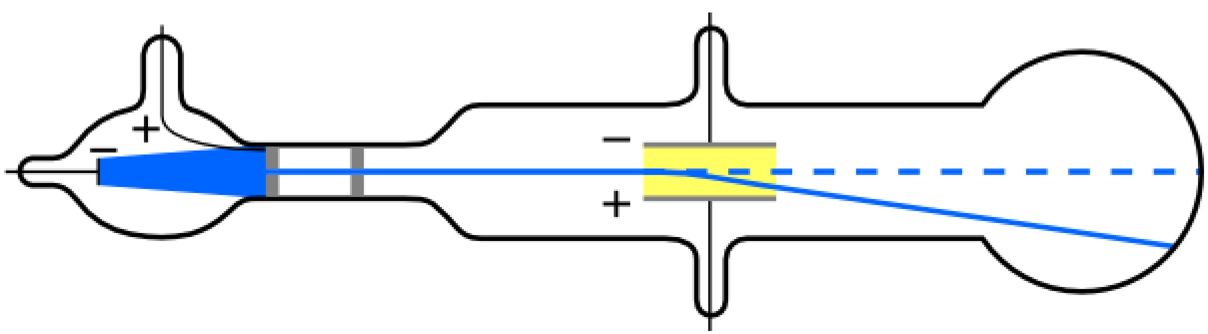


The Electron

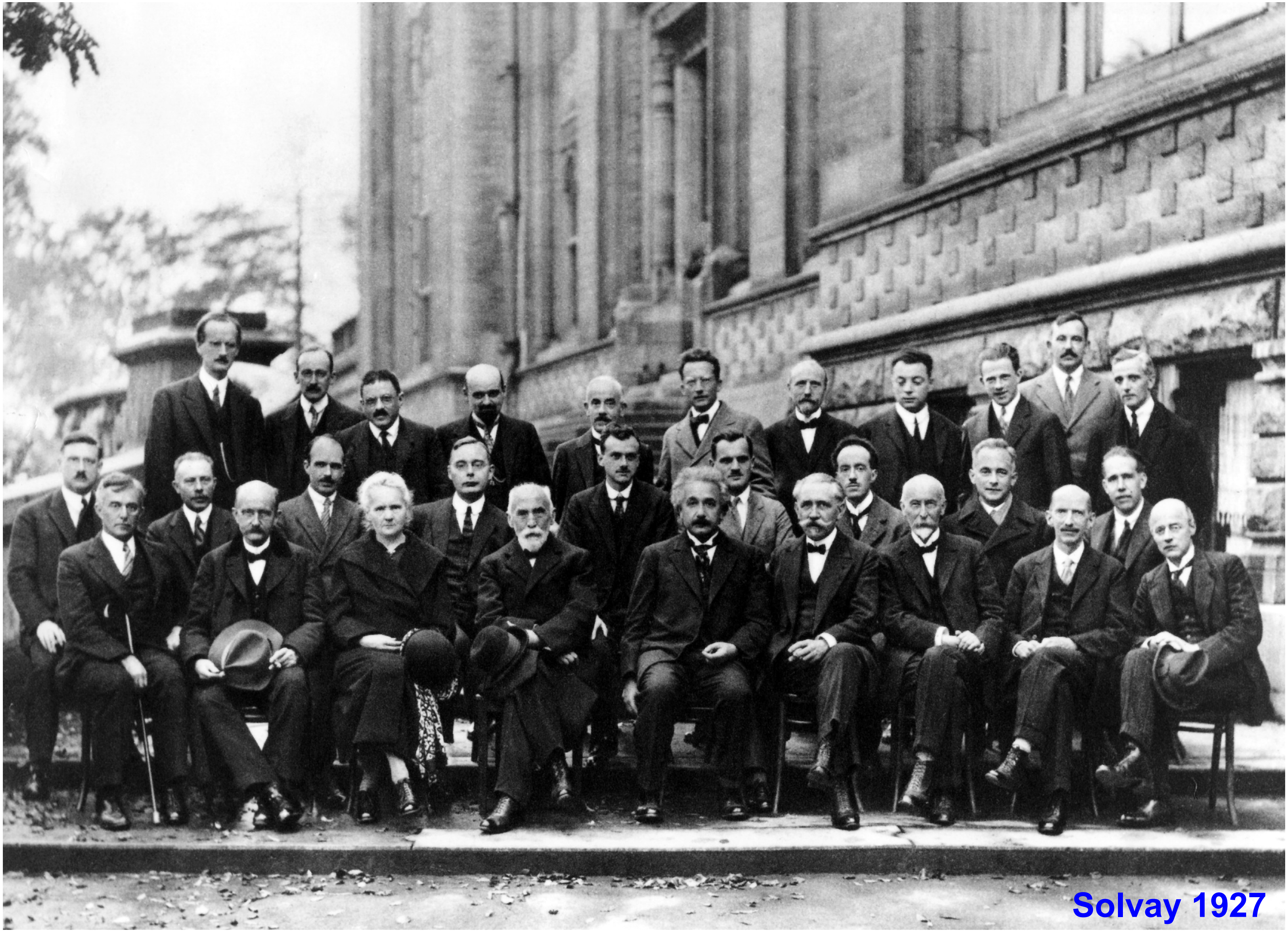
- **Observation: 1897**
  - Consitutents of cathode rays deflected by electric fields
  - Consitutents of cathode rays deflected by magnetic fields + heating of thermal junction → first mass/charge ratio
  - Higher precision of mass/charge from comparing deflection by electric and magnetic fields



Joseph J. Thomson, *1856, †1940 (NP 1906)



Quantum Mechanics

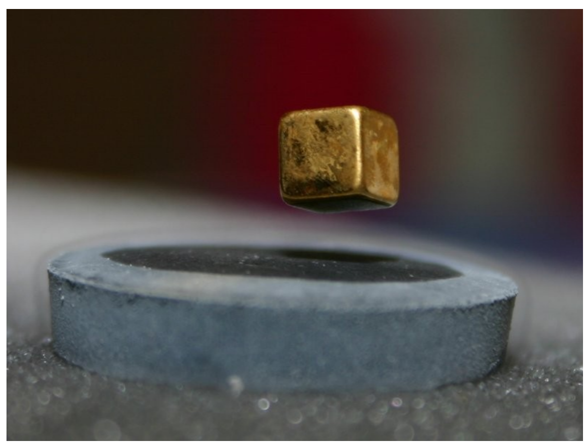


Fermions and Bosons

Fundamental characteristics of particles : Spin ("self angular momentum")

- Integer values (0, ±1, ...) → **Bosons**
- Half integer values (±1/2, ±3/2, ...) → **Fermions**

Bosons (Cooper pairs ...) can be described by **common wavefunction** → Funny effects (super conductivity, super fluidity, ...)



Fermions (electrons or protons ...) must be in different states

→ **Pauli's exclusion principle** (basis of all chemistry ... and much more)

Satyendranath Bose

Enrico Fermi (NP 1938)

Wolfgang Pauli (NP 1945)

Quantum Field Theory

Small $\rightarrow$

$\downarrow$ **Fast**

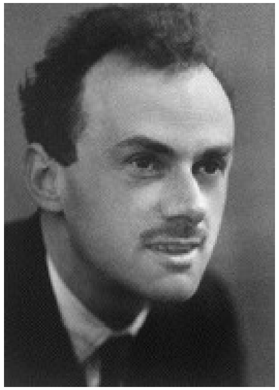
	Classical mechanics	Quantum mechanics
	Relativistic mechanics	**Quantum field theory**

First major achievement: Dirac's equation for free electrons (and positrons)

$$E^2 - \mathbf{p}^2 c^2 = m^2 c^4$$

$$E = \pm\sqrt{\mathbf{p}^2 c^2 + m^2 c^4}$$

Interpretation of negative energies: sea of electrons $\rightarrow$ holes in sea act as positively charged electrons $\rightarrow$ confirmed by Anderson 1932



Paul Dirac (NP 1933)

Carl Anderson (NP 1936)

QFT – Gauge Interactions

Example:

Requirement: Lagrangian $\mathcal{L} = \frac{1}{2}(\partial_\mu \Phi)^T \partial^\mu \Phi - \frac{1}{2} m^2 \Phi^T \Phi$

invariant under special local transformations $G(x)$ $\Phi \mapsto \Phi' = G\Phi$

Invariance is in general not guaranteed, since $\partial_\mu (G\Phi) \neq G(\partial_\mu \Phi)$

Introduce covariant derivatives (with gauge fields A_μ) $D_\mu = \partial_\mu + gA_\mu$

→ **Locally gauge invariant Lagrangian** $\mathcal{L}_{\text{loc}} = \frac{1}{2}(D_\mu \Phi)^T D^\mu \Phi - \frac{1}{2} m^2 \Phi^T \Phi$

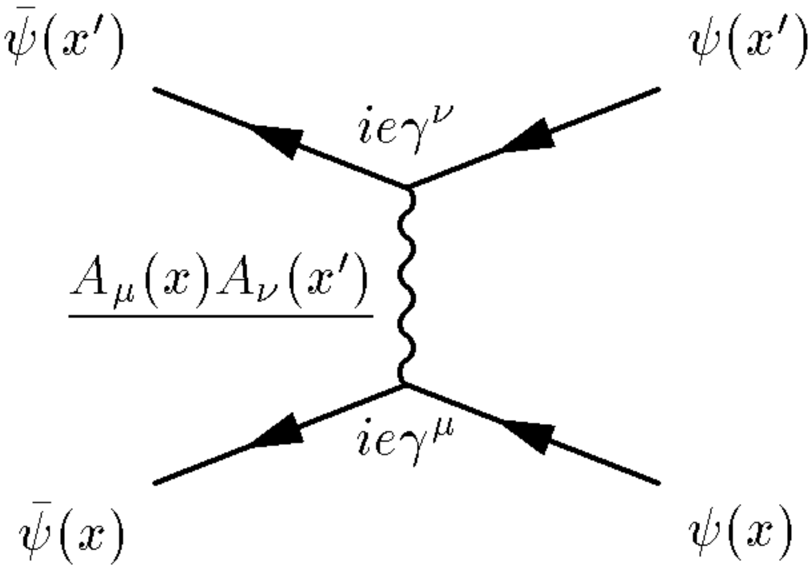
→ **Interaction terms:** $\mathcal{L}_{\text{int}} = \frac{g}{2} \Phi^T A_\mu^T \partial^\mu \Phi + \frac{g}{2} (\partial_\mu \Phi)^T A^\mu \Phi + \frac{g^2}{2} (A_\mu \Phi)^T A^\mu \Phi$

→ **Gauge fields (gauge bosons) are interaction ”particles”**

General recipe for a QFT:

- Write down Lagrangian of mass, kinetic, and interaction terms
- Quantize fields
- Decribe scattering theory with quantized fields

Feynman Diagrams / Renormalization



Feynman diagrams:

Powerful tool to write down scattering amplitudes (also for higher order perturbations)

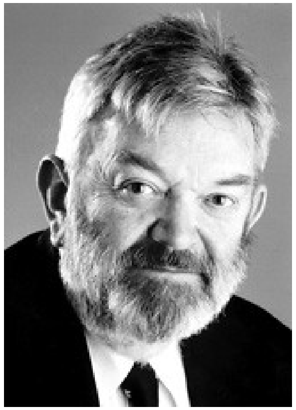
Feynman rules:

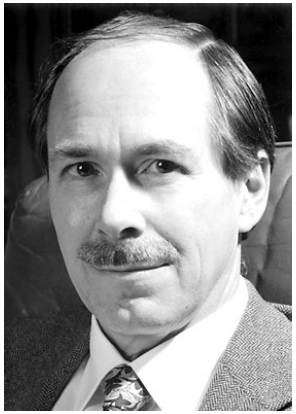
Set of rules to get from a Feynman diagram to the mathematical expression

R. Feynman
(NP 1965)

In QFTs perturbation theory is only **valid for finite energy range** → **divergences in calculation of scattering amplitudes**

Renormalization is a technique to remove these divergences





M. Veltman and G. 't Hooft
(NP 1999)

Quantum Electro Dynamics

Lagrangian invariant under local ($\theta=\theta(x)$) phase transition: symmetry group U(1)

$$\psi \mapsto e^{i\theta}\psi$$

Appropriate covariant derivative, with gauge field A_μ

$$D_\mu = \partial_\mu - i\frac{e}{\hbar}A_\mu$$

→ QED Lagrangian

$$\mathcal{L}_{\text{QED}} = \bar{\psi}(i\hbar c\,\gamma^\mu D_\mu - mc^2)\psi - \frac{1}{4\mu_0}F_{\mu\nu}F^{\mu\nu}$$

A_μ is the photon field!

Side remark: Generators of U(1) group commute (abelian group) → Gauge bosons have no charge (photons are electrically neutral)→ no self interaction

As in classical mechanics (Noether's Theorem):

Symmetry ↔ conserved quantity (which?)

Electroweak Theory

A. Salam, S. Glashow, and S. Weinberg (NP 1979)

Local symmetry:

$SU(2)_L \otimes U(1)$

Charges:

- Weak isospin I_3
- Weak hypercharge $Y = 2Q - 2I_3$

Gauge fields: W, B mix to $W^{\pm}$, Z^0, and γ

Generators of $SU(2)_L$ do not commute (non-abelian group)

$\rightarrow$ Self interaction

By construction all gauge bosons are massless (to keep local invariance)

However, short range of interaction implies heavy particles???

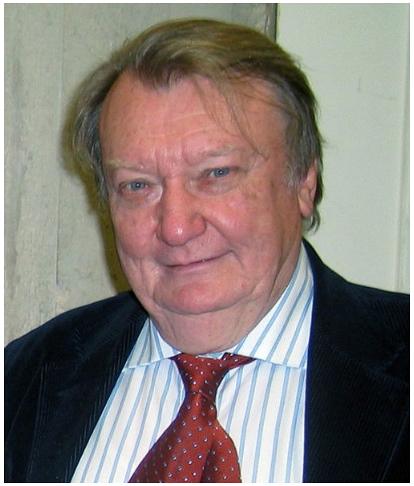
Electroweak Gauge Bosons

- Observation of neutral current in 1973
- Observation of W in May 1983 (and a few month later also the Z) at UA1 and UA2

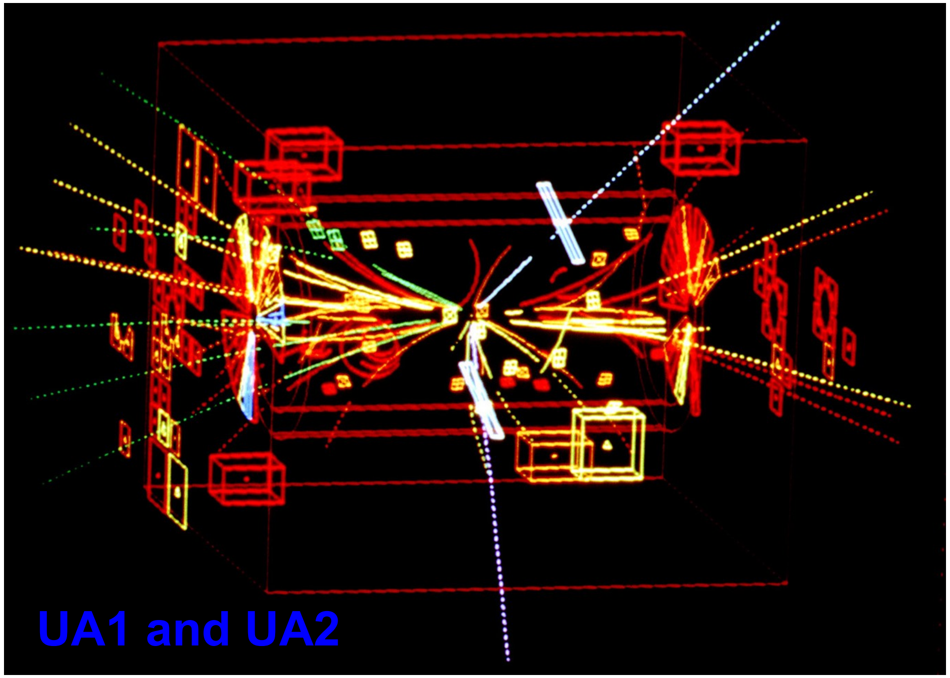
$$M_W \sim 80.4 \text{ GeV}$$

$$M_Z \sim 91.2 \text{ GeV}$$

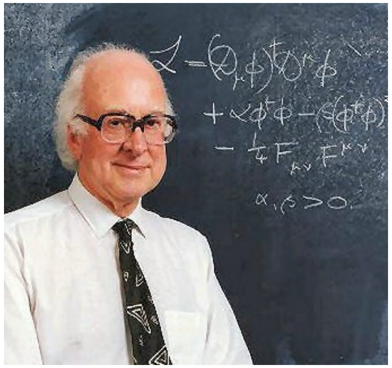
→ **Heavy particles!**




C. Rubbia and S. van der Meer (NP 1984)



The Higgs Mechanism



Peter Higgs

Formalism to obtain massive gauge bosons while keeping invariance of *L* intact by spontaneous symmetry breaking

Independently derived by Englert, Brout, Kibble, Hagen, Guralnik

Lagrangian of complex scalar Higgs field ϕ

$$\mathcal{L}_{\mathrm{Higgs}}(\phi,\ A) = (\hat{D}_\mu \phi)^\dagger (\hat{D}^\mu \phi) + \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2$$

If $\mu^2 > 0 \rightarrow$ trivial minimum at $\phi=0$
If $\mu^2 < 0 \rightarrow$ non trivial, degenerated minimum

Vaccum expectation value $|\langle 0|\phi|0\rangle| = v = \sqrt{\frac{-\mu^2}{2\lambda}}$

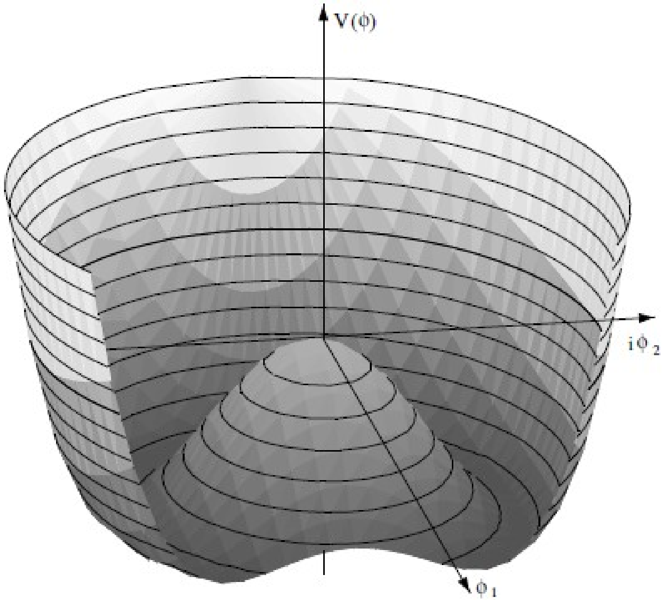
A. Choose arbitrary ground state in minimum

B. Expand Higgs field

C. Covariant derivatives → massive gauge bosons

$$M^2_{W^\pm} = \frac{g^2 v^2}{4} \qquad M^2_{Z^0} = \frac{(g^2 + g'^2) v^2}{4}$$

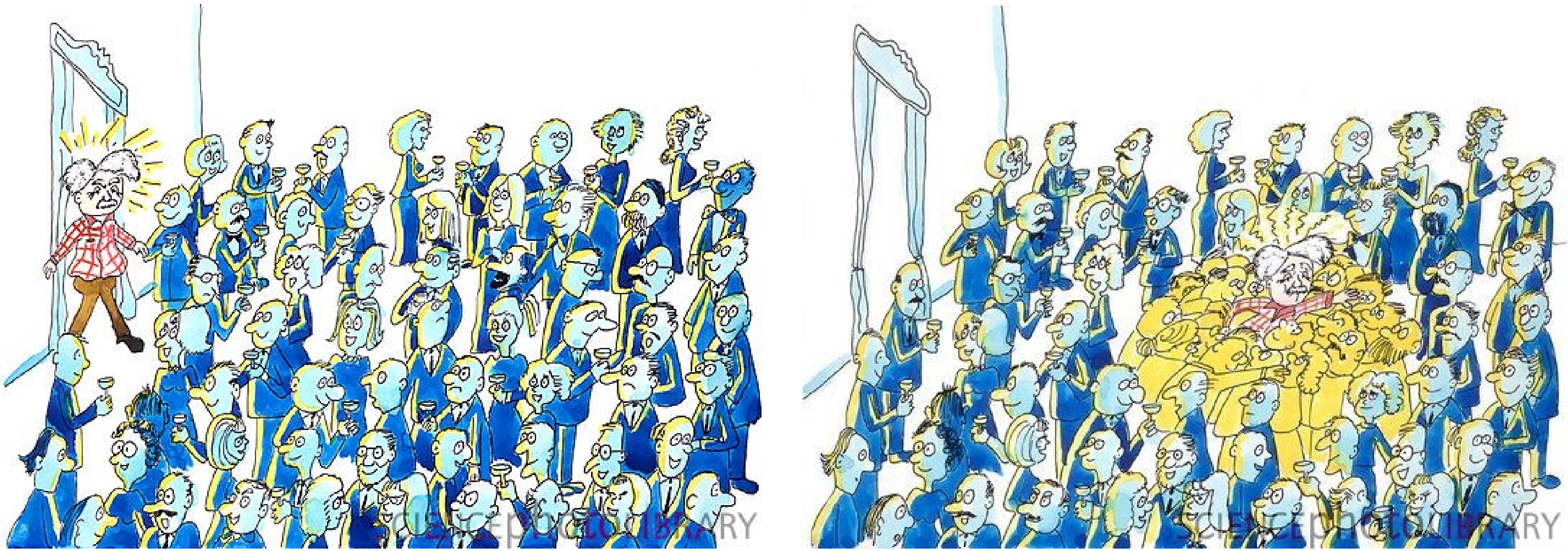
With g and g' as coupling constants of $SU(2)_L$ and U(1)



Mexican hat potential

The Higgs Mechanism

Fermions acquire mass by Yukawa couplings to the Higgs field



Open questions:

- What is the mass of the Higgs particle?
- What triggers the spontaneous breaking of the symmetry?
- Is the Higgs fundamental or composite?
- Is there more than one Higgs doublet?

The Neutrino

- Continous spectrum of electrons from β-decay

  → new undetectable particle predicted by Pauli in 1930
- First observation by Poltergeist experiment in inverse β-decays in 1957

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- Observation of the myon neutrino in 1962

F. Reimes (NP 1995)

L. Ledermann, M. Schwartz, J. Steinberger (NP 1988)

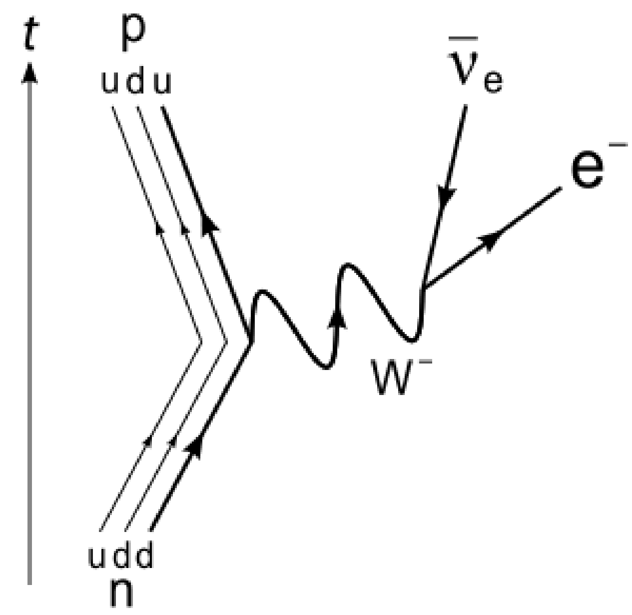
And much more spectacular physics:

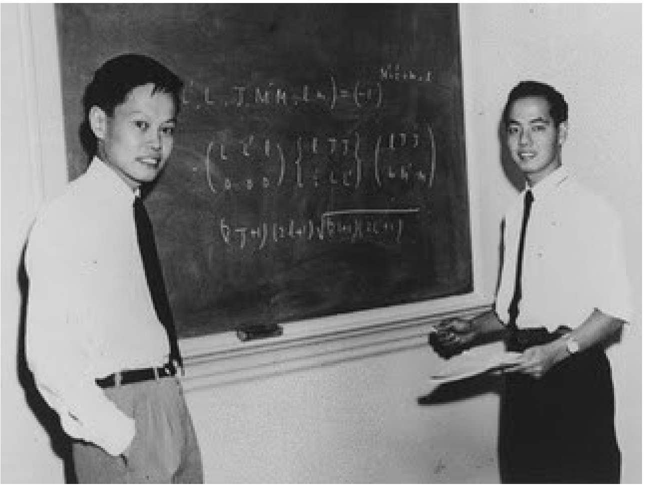
- Solar neutrino problem …
- Neutrino oscillations …
- Neutrino masses …
- Cosmological neutrinos …
- Neutrinos from super novae …

→ see C. Hagners lecture

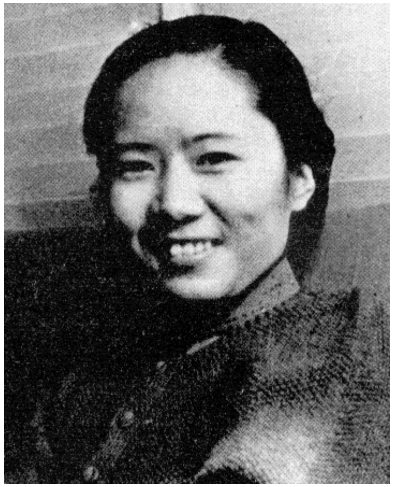
EW Decay – *C* and *P* Violation

- Classical gravitation, electromagnetism, and the strong interaction are invariant under charge *C* and parity *P* (”Mirror symmetry”) transformations
- Yang and Lee: *P* could be violated in EW interactions
- **Observation by Wu:** cryogenic Co^{60} in strong magnetic field → strong asymetry of direction of emitted electrons → maximal *P* violation
- *C* and *P* both violated by EW interactions, but *CP* (mostly) concerved

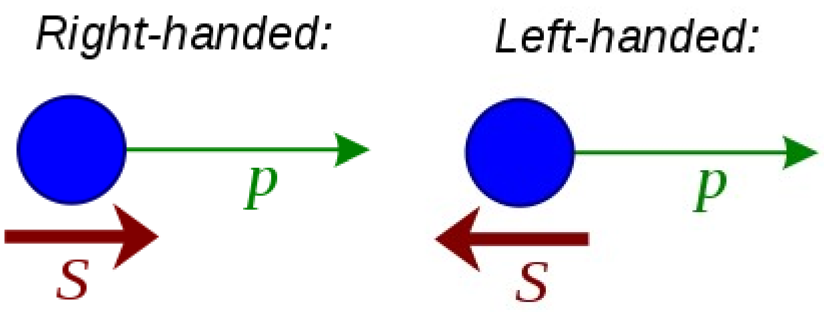




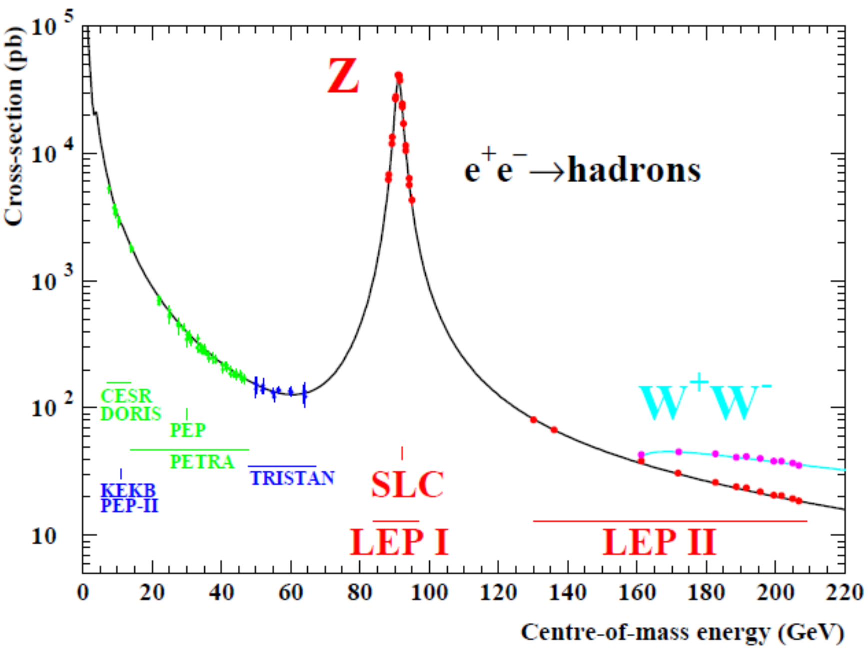
C. N. Yang and T.-D. Lee (NP 1956)



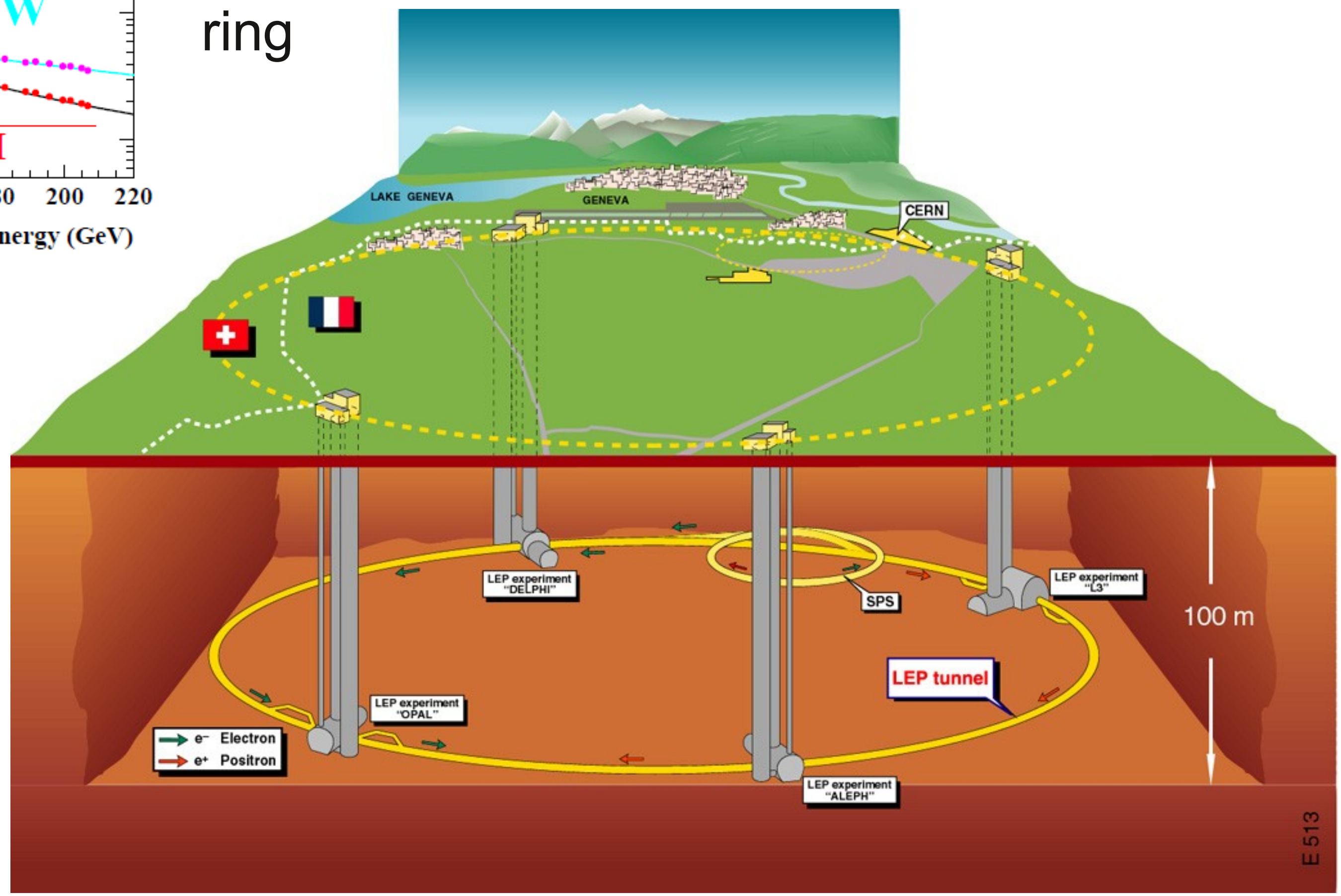
C. S. Wu



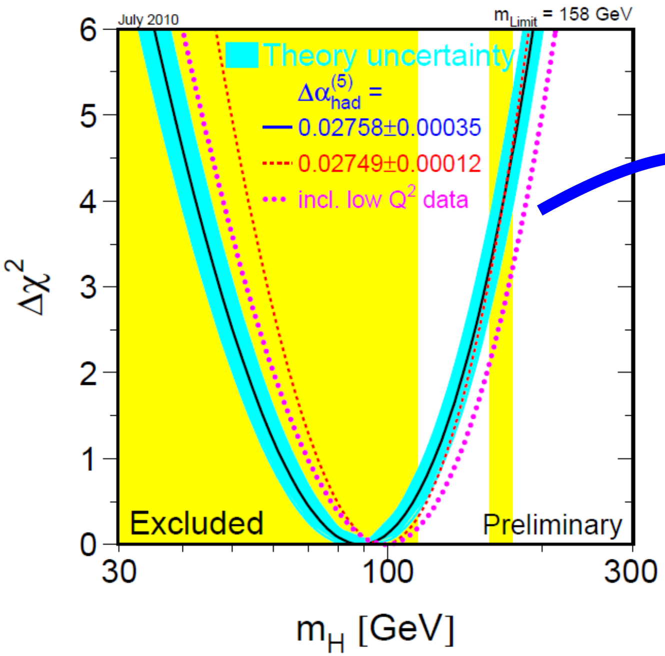
Large Electron Positron Collider



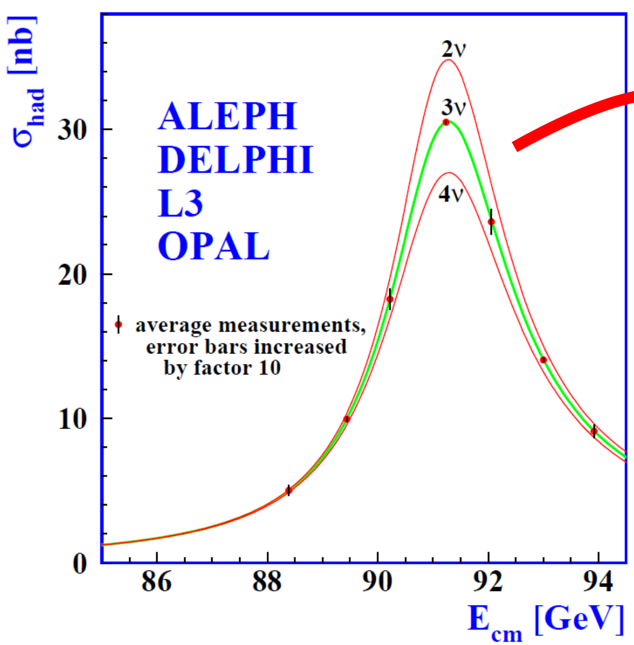
- 1989 … 2000: electron-positron collisions with $\sqrt{s}$ up to 209 GeV
- Very clean events → high precision measurements possible
- Former LEP tunnel now hosting LHC storage ring



Electroweak Precision Data

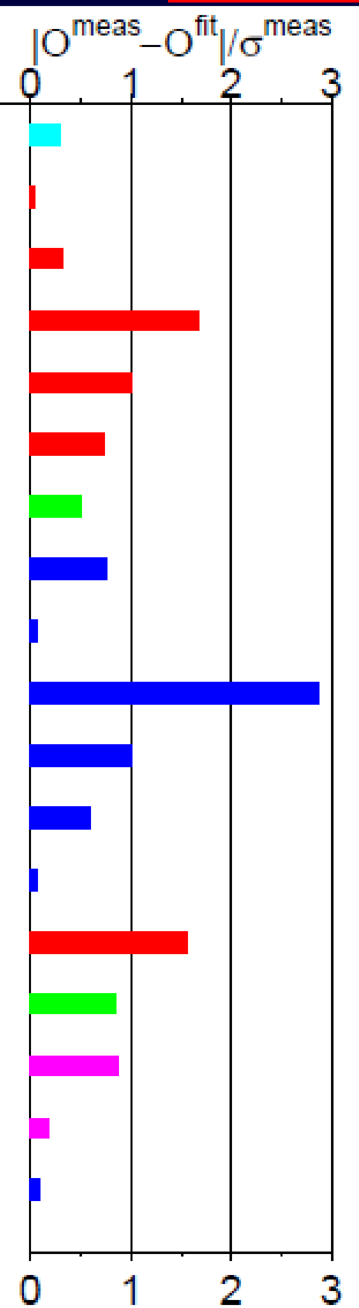


Indirect Higgs limit



Three light neutrino families!

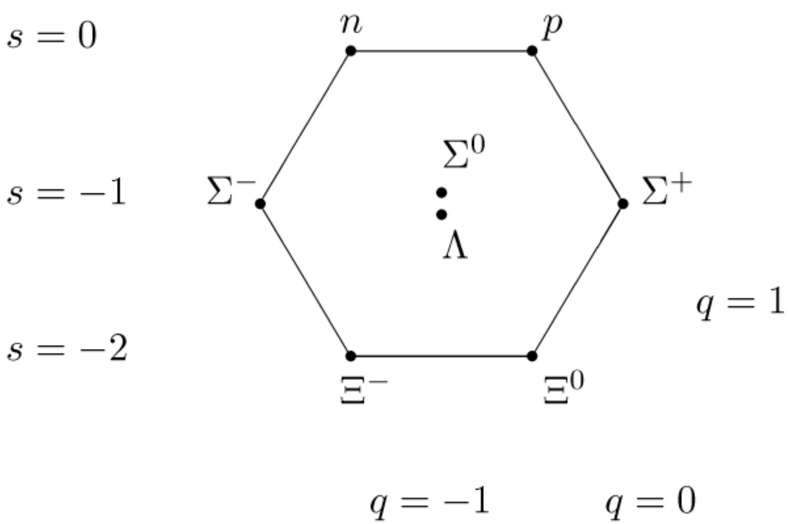
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4



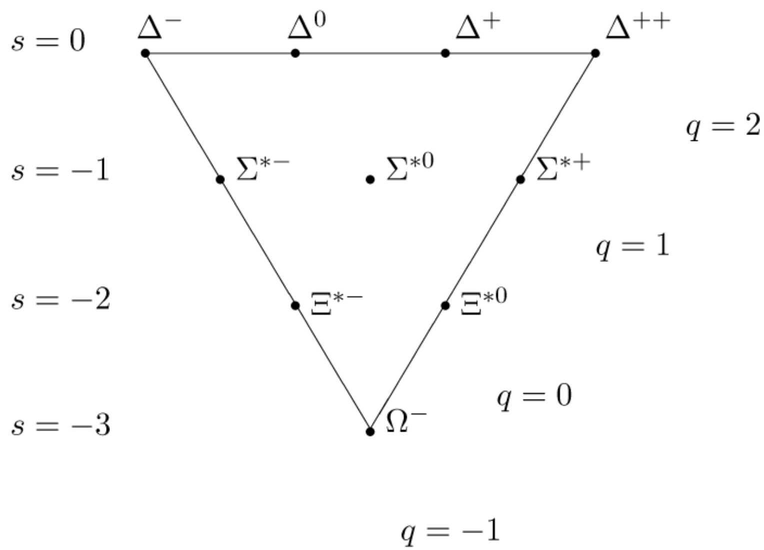
July 2010

The "Eightfold Way"

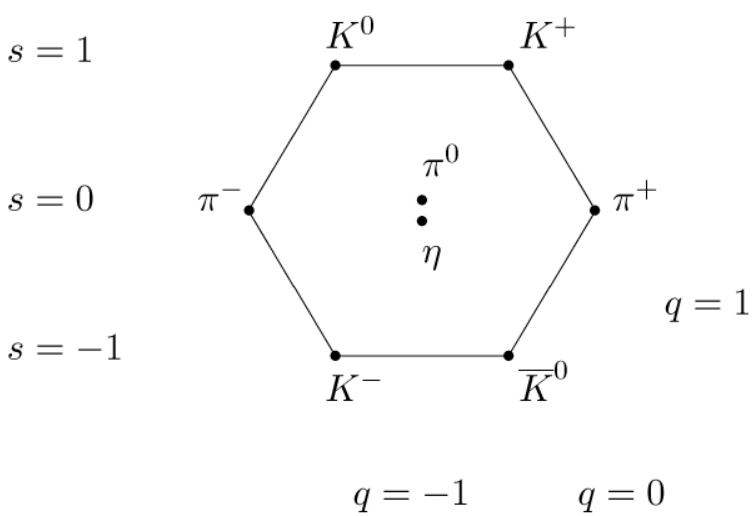
Baryon octet



Baryon decuplet



M. Gell-Mann
(NP 1969)



Meson octet

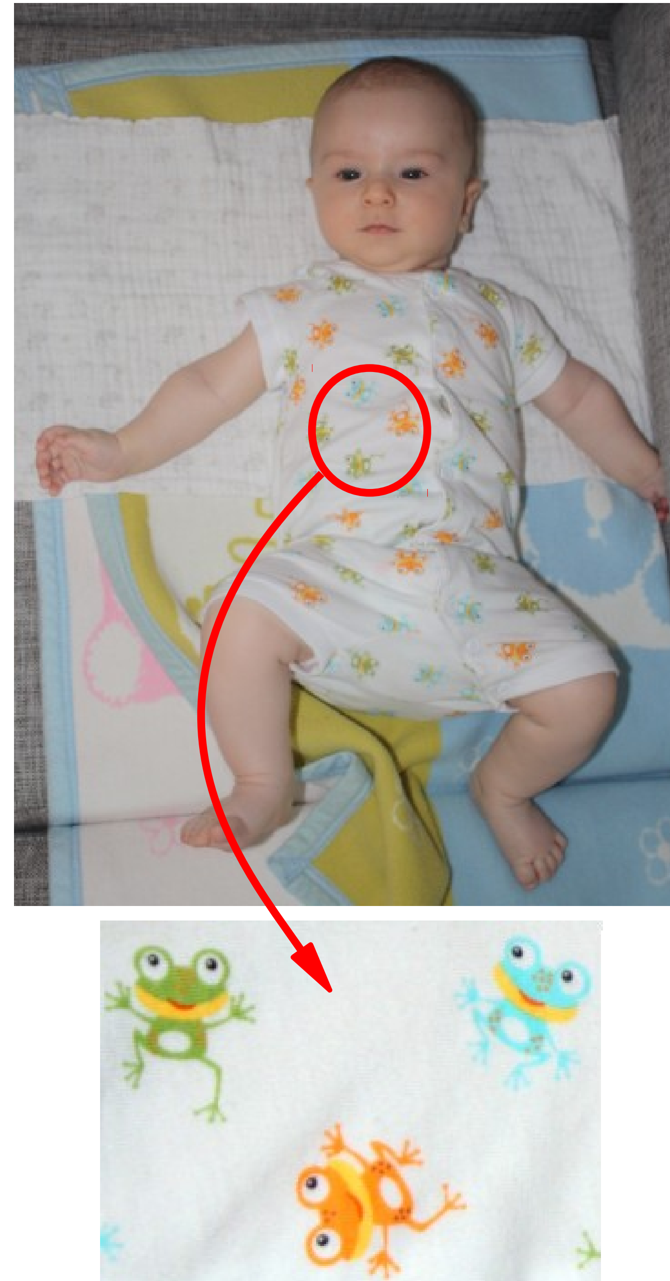
- Ordering Mesons and Baryons in octets (spin 1/2) and decuplets (spin 3/2), according to quantum numbers (i.e. quark composition)
- Prediction of baryons Ω^- with three *s* quarks (observed in 1964)
  $\rightarrow$ Pauli's exclusion principle
  $\rightarrow$ new quantum number (color)
- Number of colors from hadronic to leptonic branching ratio of e^+e^- collisions

Quantum Chromo Dynamics

- All ordinary matter consists of fermions and the largest fraction is carried by nucleons made of quarks and gluons
- **Strong interaction:** SU(3) → 8 massless gluons as gauge bosons
  - Quarks (and gluons) carry ”color” charge
  - Gluon self interaction

    → Coupling constant decreasing with energy: ”assymptotic freedom” at high energies

    → Quarks and gluons don't exist as free particles but as color neutral bound states: Mesons (quark-antiquark) or Baryons (three quarks)



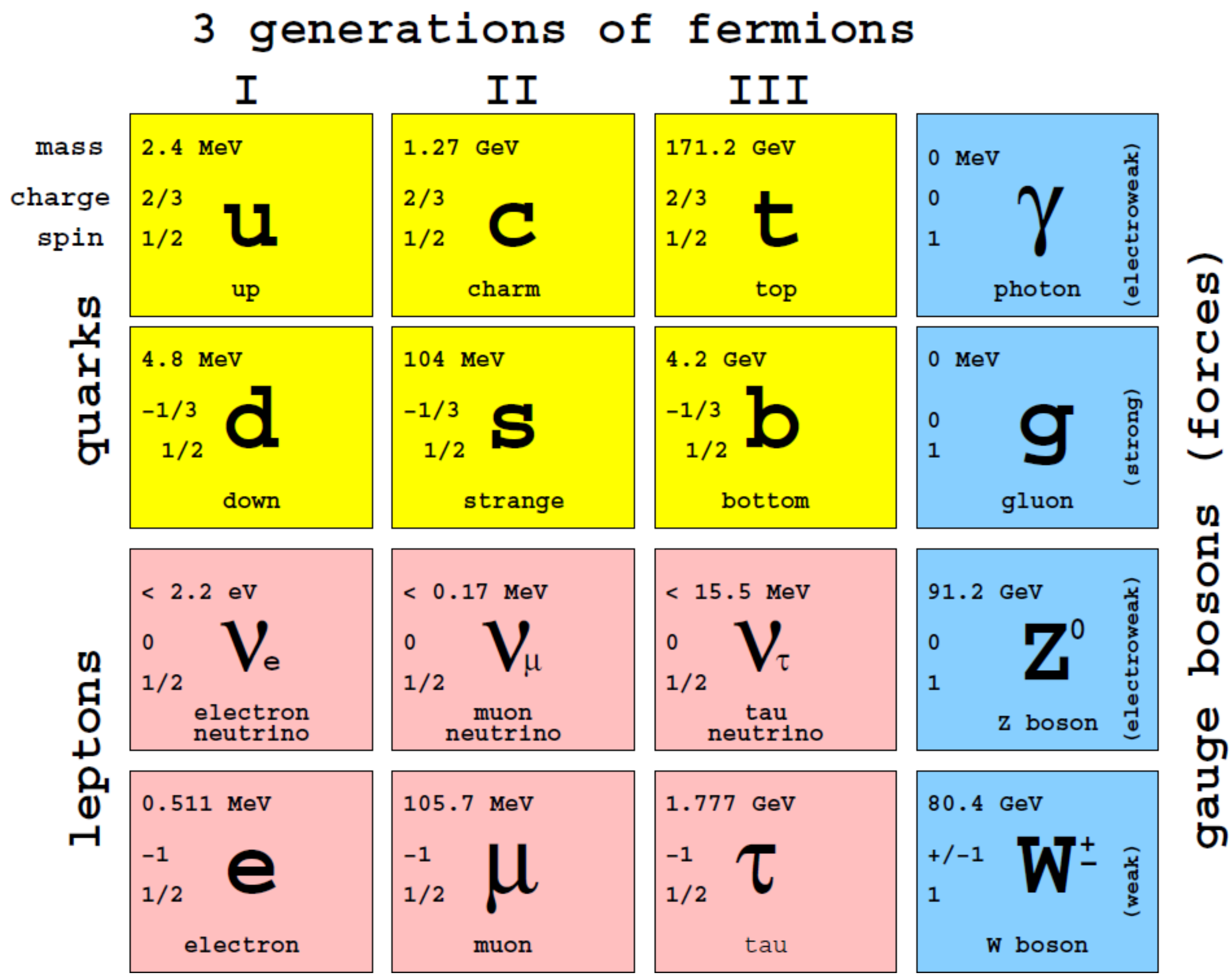
D. Politzer,
D. Gross,
F. Wilczek
(NP 2004)

The Standardmodell

- Interactions described by gauge groups:

  $$U(1) \otimes SU(2)_L \otimes SU(3)_C$$

- Higgs boson last missing particle
- **All measurements from colliders in excellent agreement with the SM**



+Higgs

BUT ...

Standard Model

Shortcomings of the SM

- **Why are there three generations, and not 42?**
- **Can the large number of free parameters in the SM (19 or even larger for massive νs) be reduced?**
- **Why is the electric charge of electron and proton equal?**
- **Should the gauge couplings unify at high energies? In the SM they do not!**
- **Why are ~17 orders of magnitude between EW and Planck scale? How can the fine tuning problem be solved ?**
- **What is the nature of dark matter and dark energy?**
- **Why is the gravitational force so weak? How can gravity be included in one formal description of all forces ?**
- **...**

There are many models which address one or more of these question!

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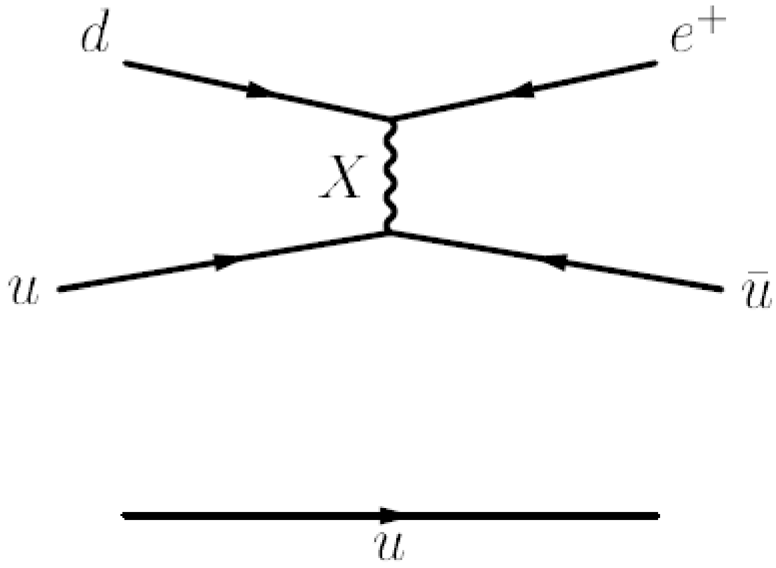
Grand Unified Theories

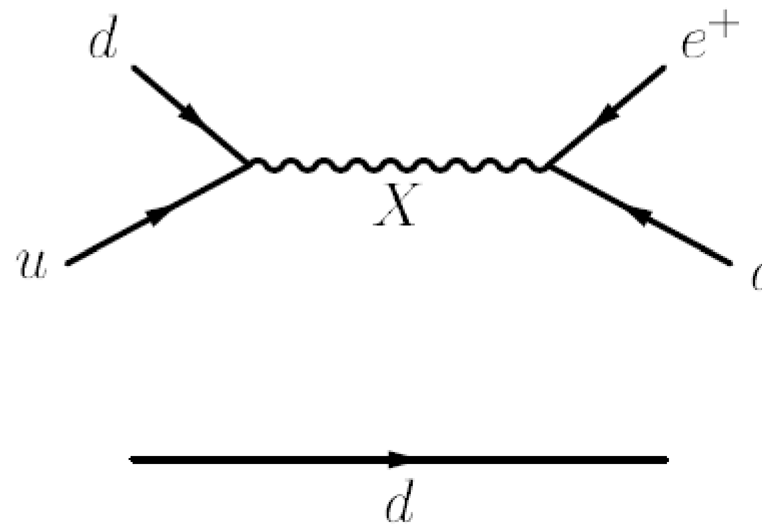
- Symmetry group of SM: $\mathbf{U(1)\otimes SU(2)_L \otimes SU(3)_C}$
- Can be embedded in larger group, e.g. **SU(5)** or SO(10)
  - N^2-1 generators to keep gauge invariance
  - Possible representations have quarks and leptons in the same multiplet

$$\{\bar{5}\} = \begin{pmatrix} d_g^C \\ d_r^C \\ d_b^C \\ e^- \\ -\nu_e \end{pmatrix}_L , \qquad \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u_b^C & -u_r^C & u_g & d_g \\ -u_b^C & 0 & u_g^C & u_r & d_r \\ u_r^C & -u_g^C & 0 & u_b & d_b \\ -u_g & -u_r & -u_b & 0 & e^+ \\ -d_g & -d_r & -d_b & -e^+ & 0 \end{pmatrix}_L$$

  - U(1)⊂SU(5) → electric charge Q is generator → trace of Q for a multiplet vanishes: e.g. for {5} $3 \times Q_d^C - Q_e = 0$ → $3 \times (1/3) - 1 = 0$ … $\mathbf{Q_{proton} = +1}$
  - Some generators carry fractional charge and color (→ lepton and baryon number violation) → **proton decay**

Proton Decay





- New gauge bosons *X* and *Y* (sometimes called leptoquarks) allow proton decay

$$\tau_{\text{proton}} = \frac{1}{\alpha^2_{SU(5)}} \frac{M_X^4}{M^5_{\text{Planck}}}$$

- Large scale experiments with many kilotons of water and good shilding against cosmic background (deep underground), e.g. Super-Kamikande (50 kt)

$$\tau_{\text{proton}} > 1 \cdot 10^{34}\text{a}$$

→ **Lower mass limit on M_X (and M_{GUT})** $M_{\text{GUT}} > 2.4 \cdot 10^{16}\text{GeV}$

Shortcomings of the SM

- Why are there three generations, and not 42?
- Can the large number of free parameters in the SM (19 or even larger for massive νs) be reduced?
- Why is the electric charge of electron and proton equal?
- Should the gauge couplings unify at high energies? In the SM they do not!
- **Why are ~17 orders of magnitude between EW and Planck scale? How can the fine tuning problem be solved ?**
- **What is the nature of dark matter and dark energy?**
- **Why is the gravitational force so weak? How can gravity be included in one formal description of all forces ?**
- **...**

There are many models which address one or more of these question!

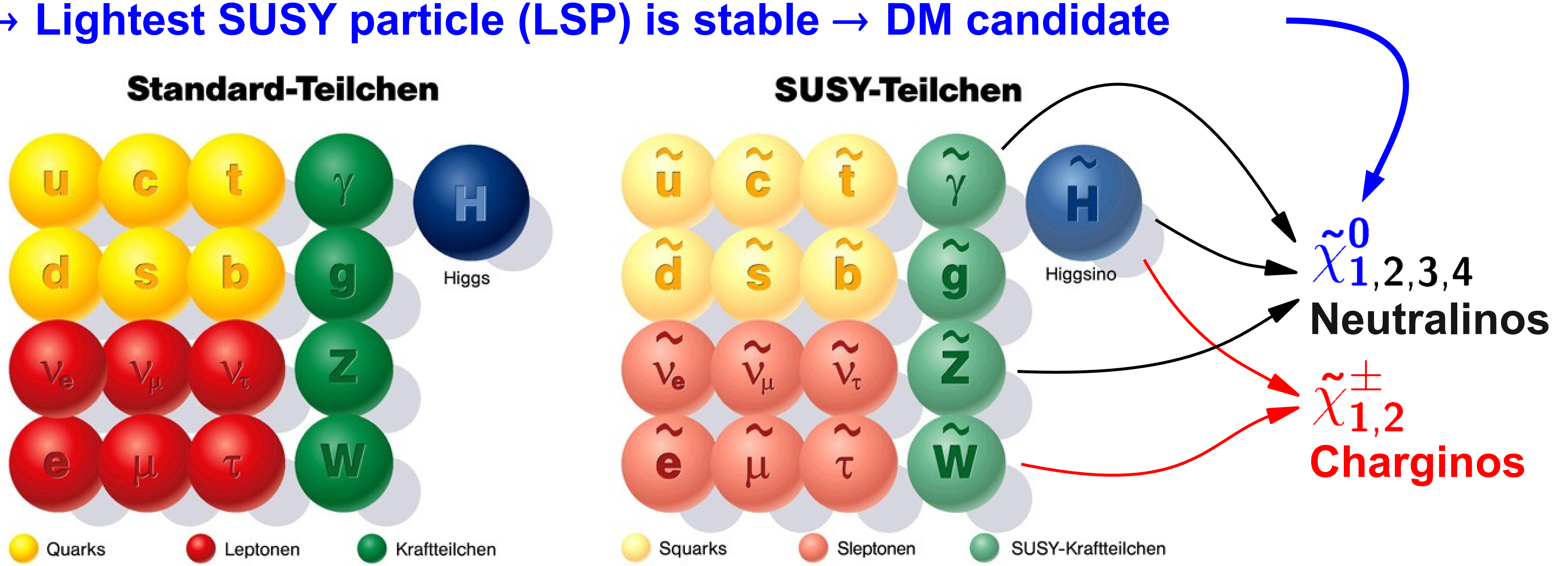
Supersymmetrie

- New (last possible) symmetry between fermions and bosons
- Each SM particle gets identical SUSY partner (except for spin: $\pm\frac{1}{2}$)
- Many attractive properties! **But: No SUSY particle discovered so far!**

  → **SUSY is broken** (typical masses $\leq$ ~1 TeV to keep attractive features)
- New conserved quantum number *R* parity: $\mathbf{R} = (-1)^{3(B-L)+2S}$

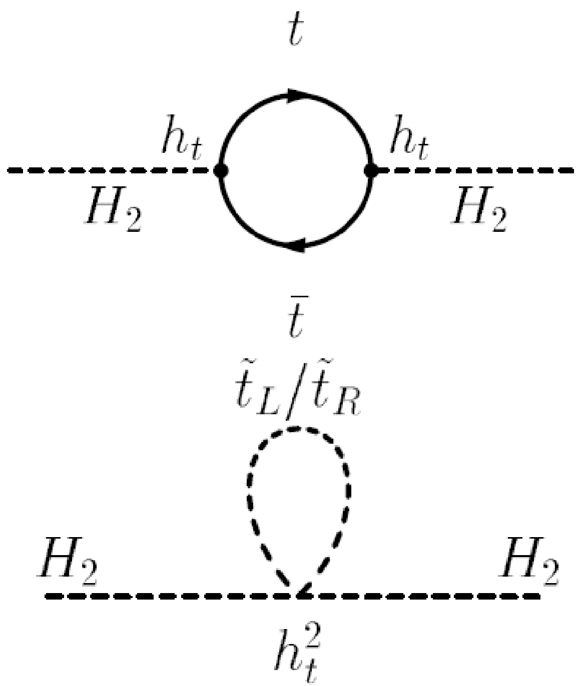
  → SUSY particles are only produced in pairs or associated

  → **Lightest SUSY particle (LSP) is stable → DM candidate**

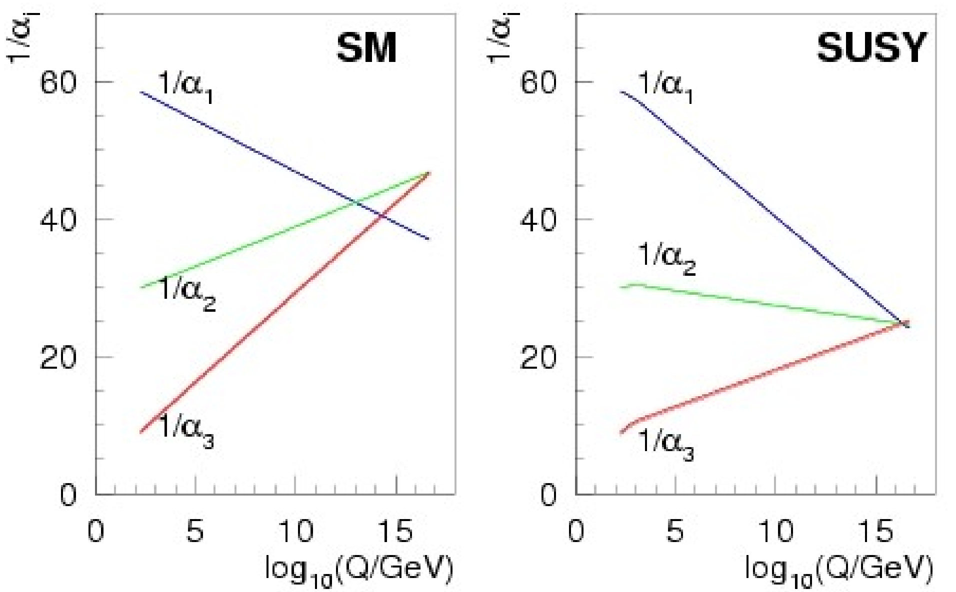


Supersymmetry

- **Fine tuning problem**
  - Radiative corrections to Higgs mass of order Λ (energy scale up to which SM is valid)
  - M_H at ~100 GeV requires accidental cancellations
  - **SUSY contributions = - SM contributions**
  - Similar arguments to explain hierarchy problem



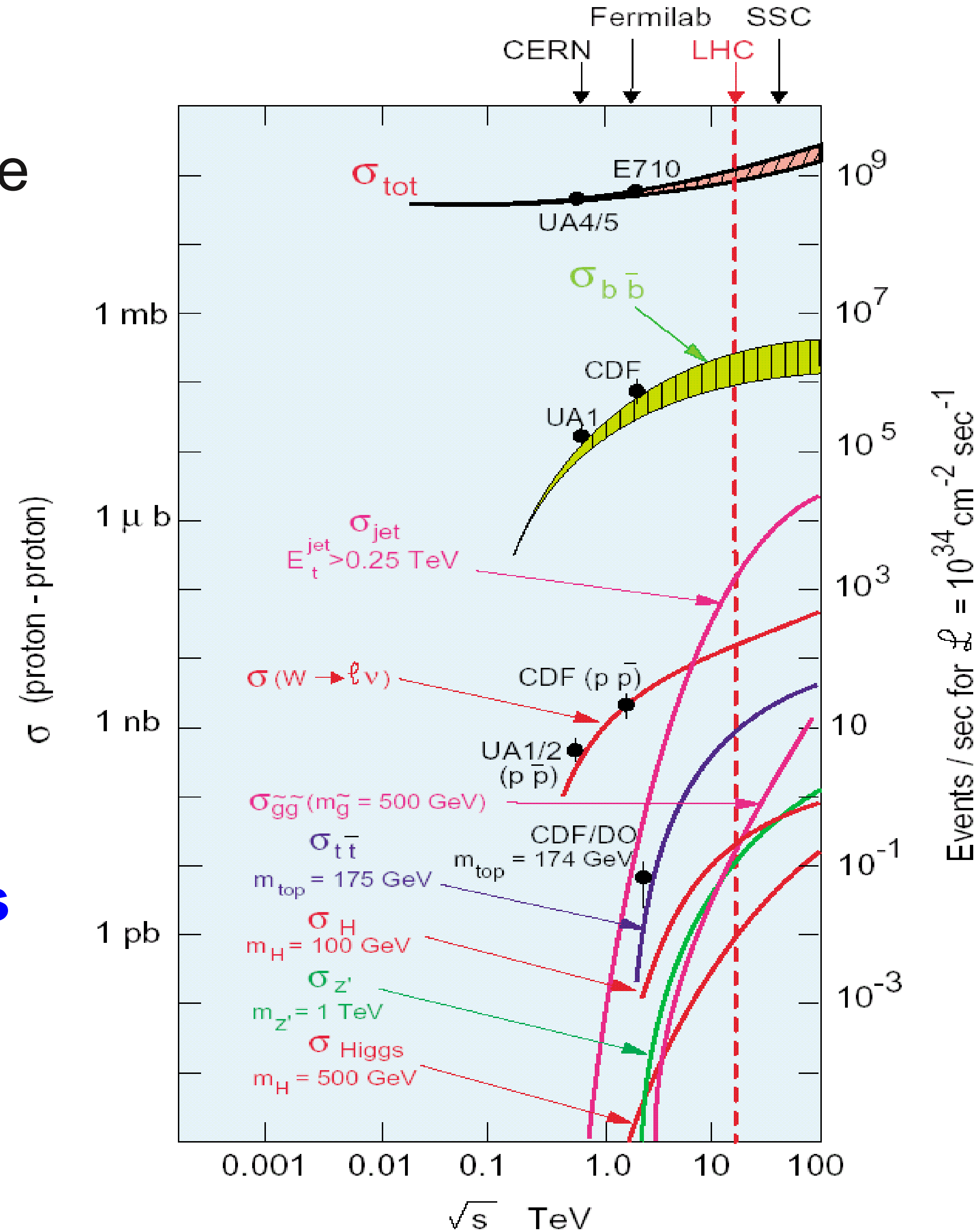
- **Gauge unification**
  - New particle content changes running of couplings
- Graviton (s = 2) ↔ $g/W/Z/\gamma$ (s = 1)
- **DM candidate**
  - In many scenarios the neutralino or the gravitino is a perfect candidate
- **“Natural” radiative EW symmery breaking**



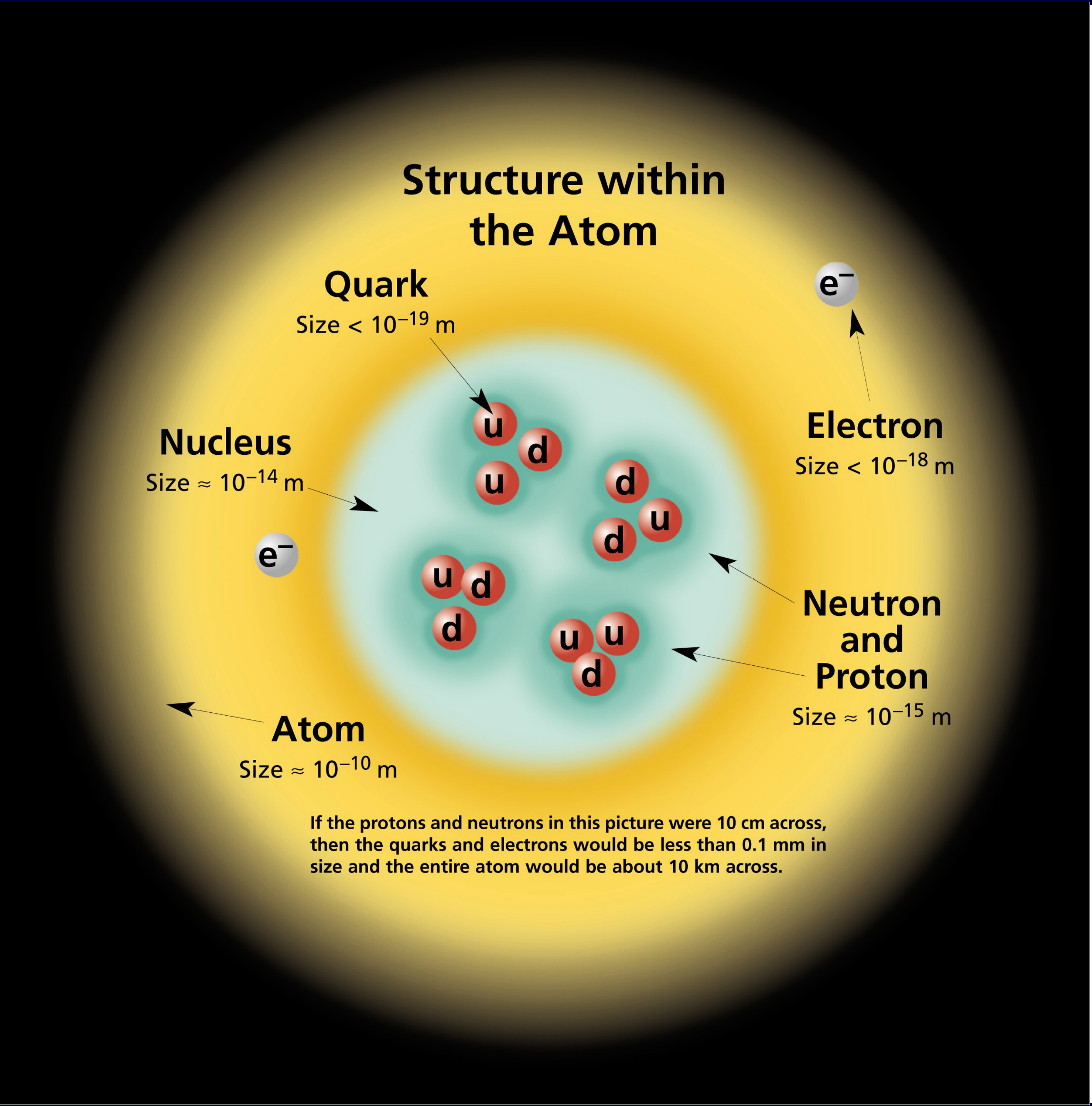
Physics at the LHC

- SM well established
- New physics expected at TeV scale (stabilizing *VV* cross section → Higgs, unification of gauge couplings → Supersymmetry)
- **SM processes:** many orders of magnitude larger cross sections than typical Higgs/BSM cross sections

→ Searches for Higgs/BSM signatures require a precise understanding of SM processes



Structure of the Proton



LHC is *pp* collider

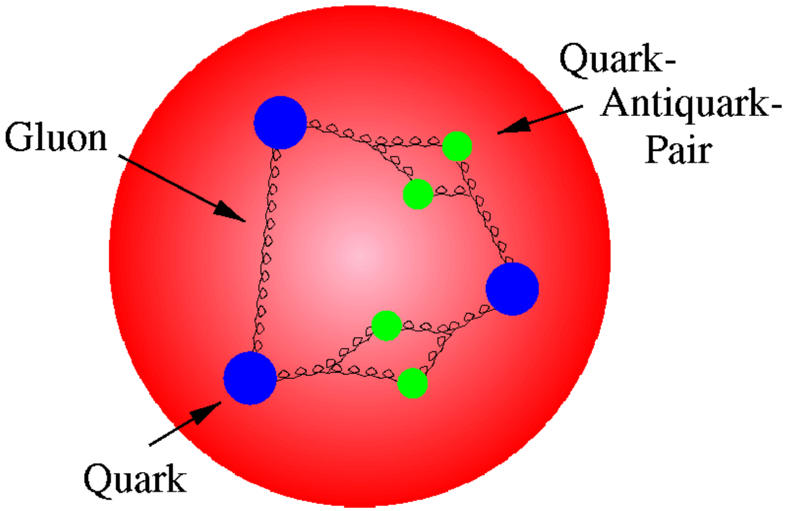
→ High $\sqrt{s}$ of *pp* collision

→ Large cross sections (strong interaction)

→ "Discovery machine"

→ No precise knowledge of $\sqrt{s}$ of hard process

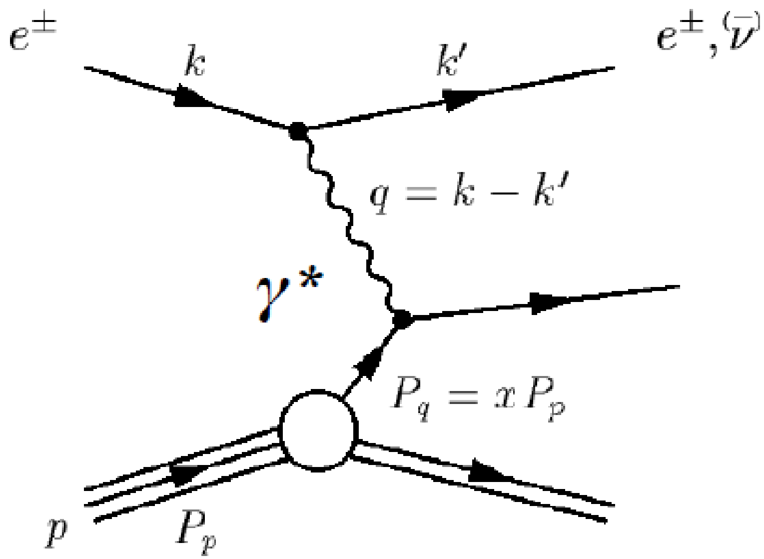
→ Input for all calculations: **Structure of proton**



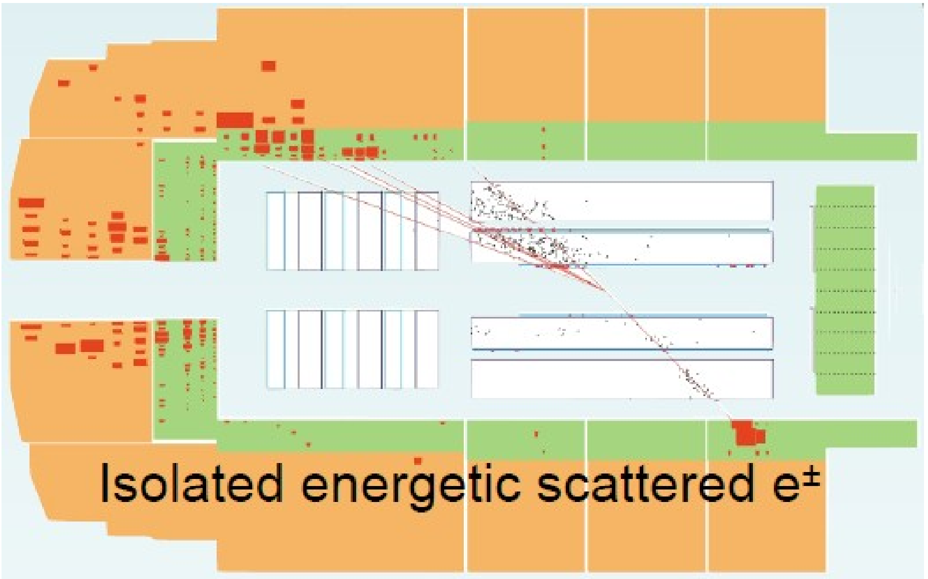
ep Collisions

- Most energetic and precise measurements done at HERA
- Kinematics:
  - Photon virtuality: $\mathbf{Q^2 = -q^2}$
  - Bjorken scaling: $\mathbf{x = -q^2/2P_p q}$
  - Photon energy fraction: $\mathbf{y = qP_p/kP_p}$

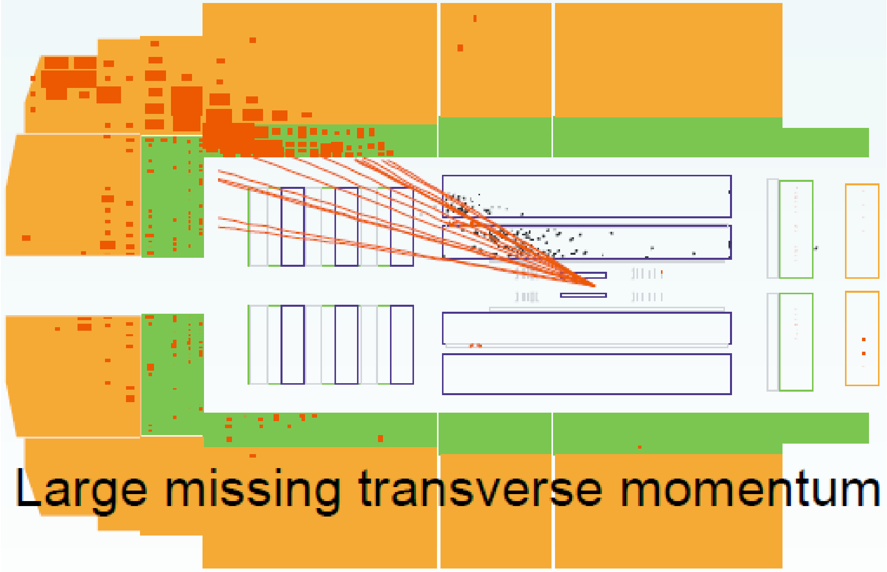
Diff. cross section measurements
→ structure function of proton



γ,*Z* (neutral current) *e* + *p* → *e* + *X*

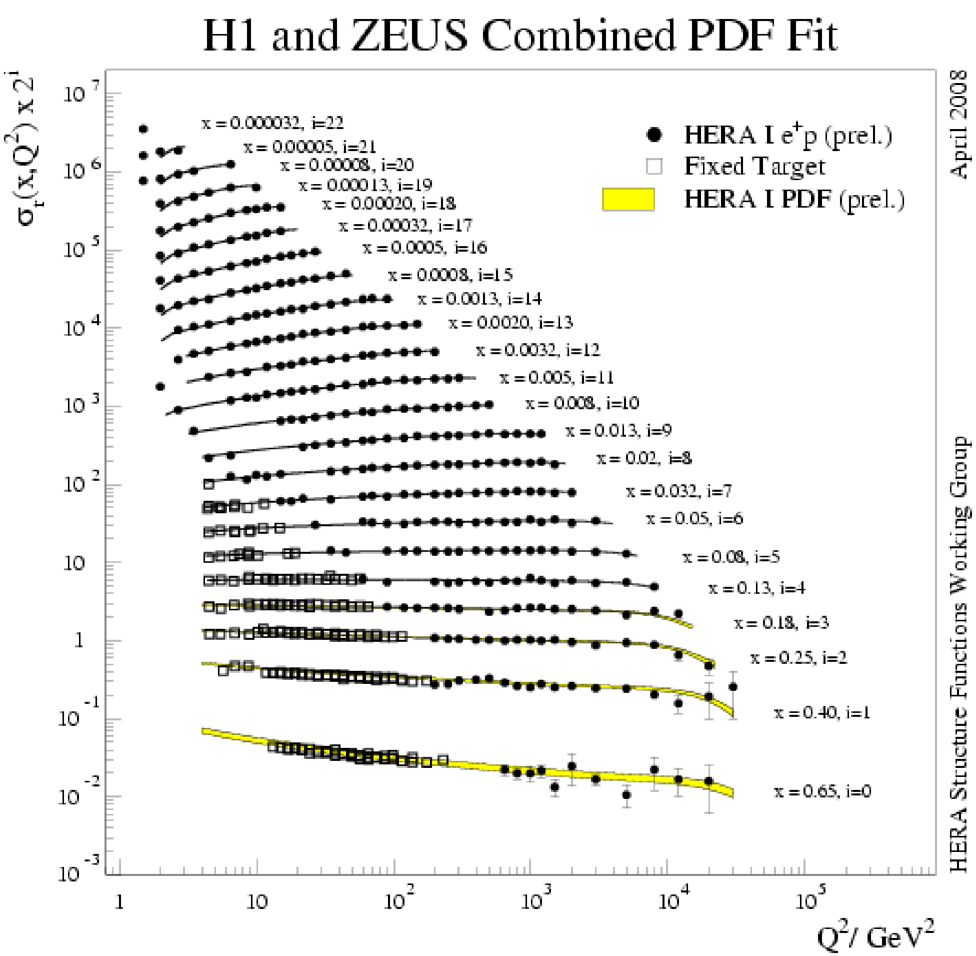


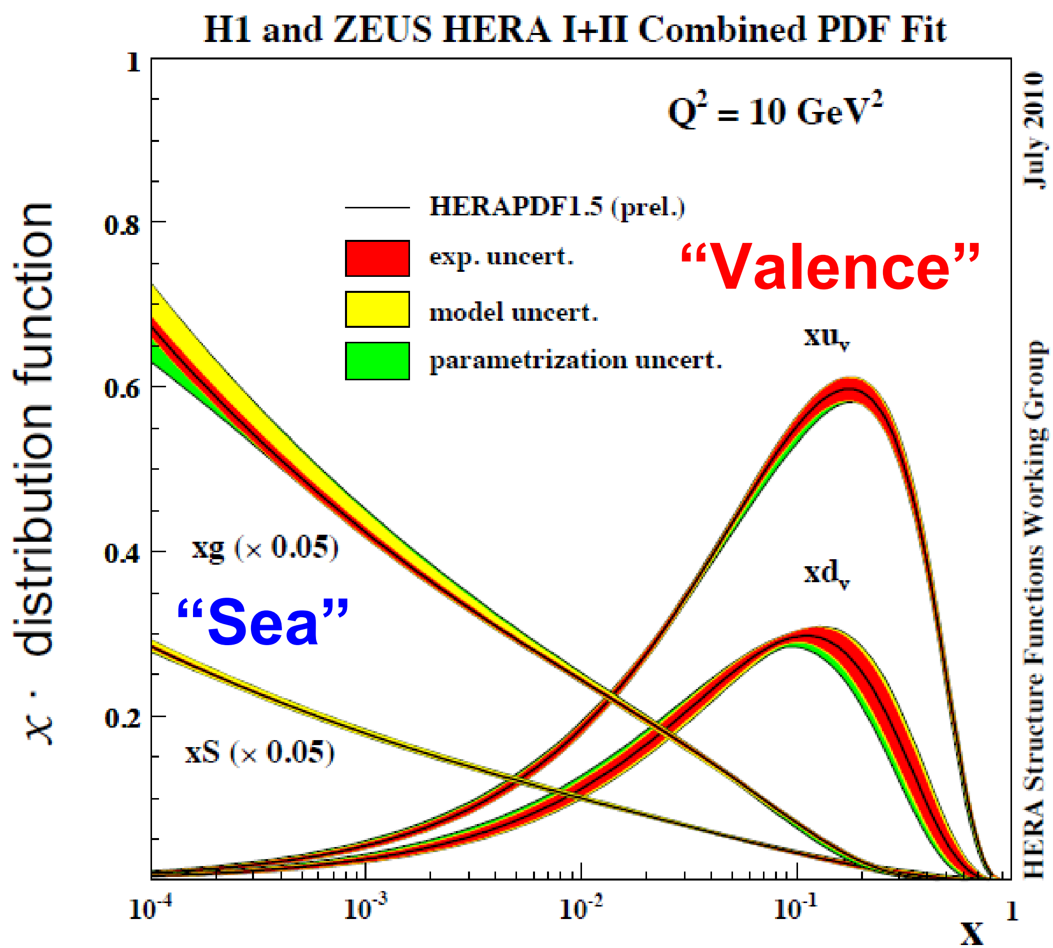
W*± (charged current) *e* + *p* → ν + *X



Combined Measurements

- **Combination from H1 and ZEUS data provide most precise PDFs**
- **At low x:** dominating gluon density (→ LHC)
- Dependence on $\mathbf{Q^2}$ → **Scaling violation**





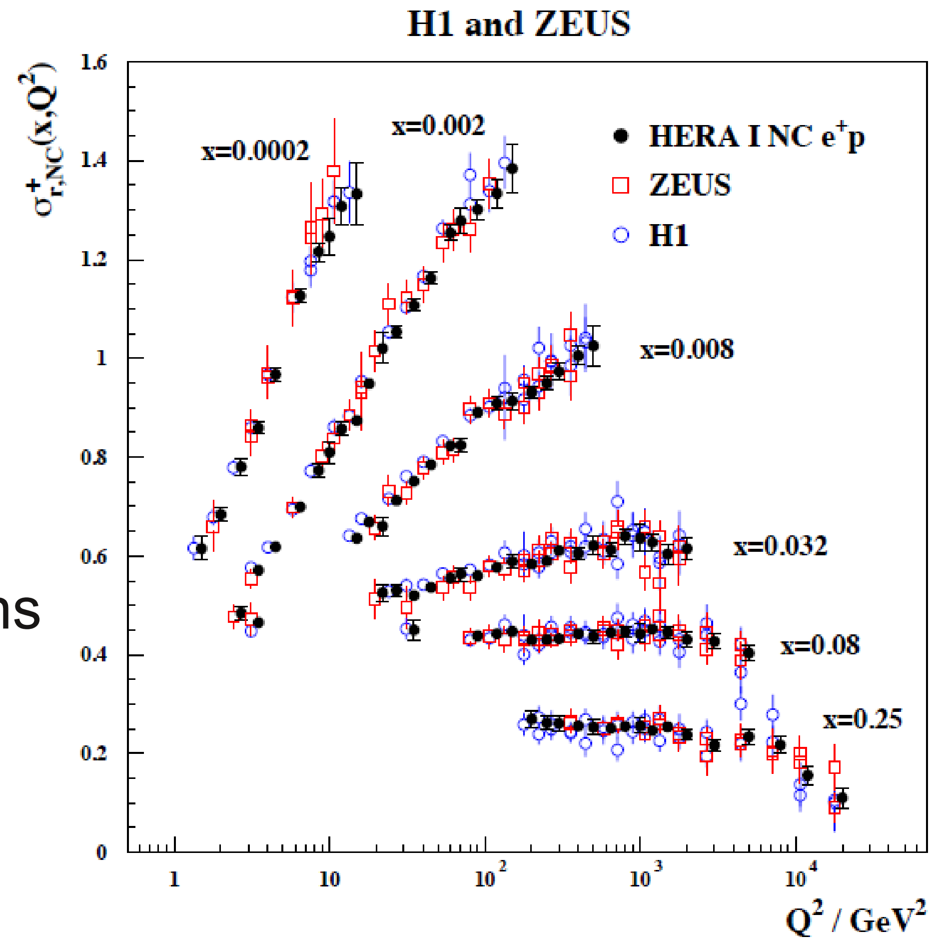
Scaling Violation / DGLAP

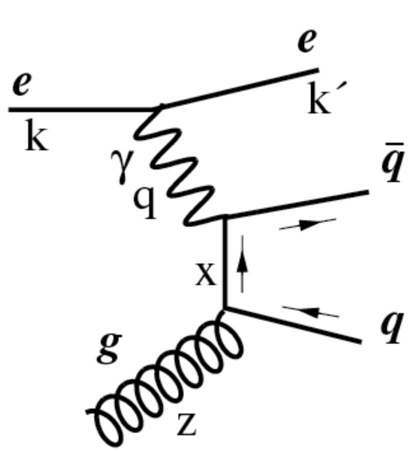
- Quarks do interact via gluon exchange
- **Interpretation of PDFs:** probability density of partons with momentum fraction **x**, as resolved at **Q²**:

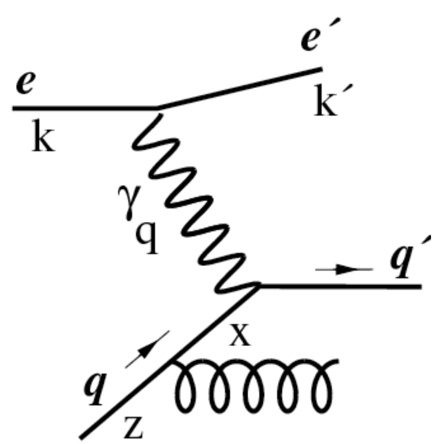
$$F_2(x) \rightarrow F_2(x,Q^2),\ q(x) \rightarrow q(x,Q^2)$$

- Dependence on **Q²** described in perturbative QCD via **D**okshitzer-**G**ribov-**L**ipatov-**A**ltarelli-**P**arisi (DGLAP) equations

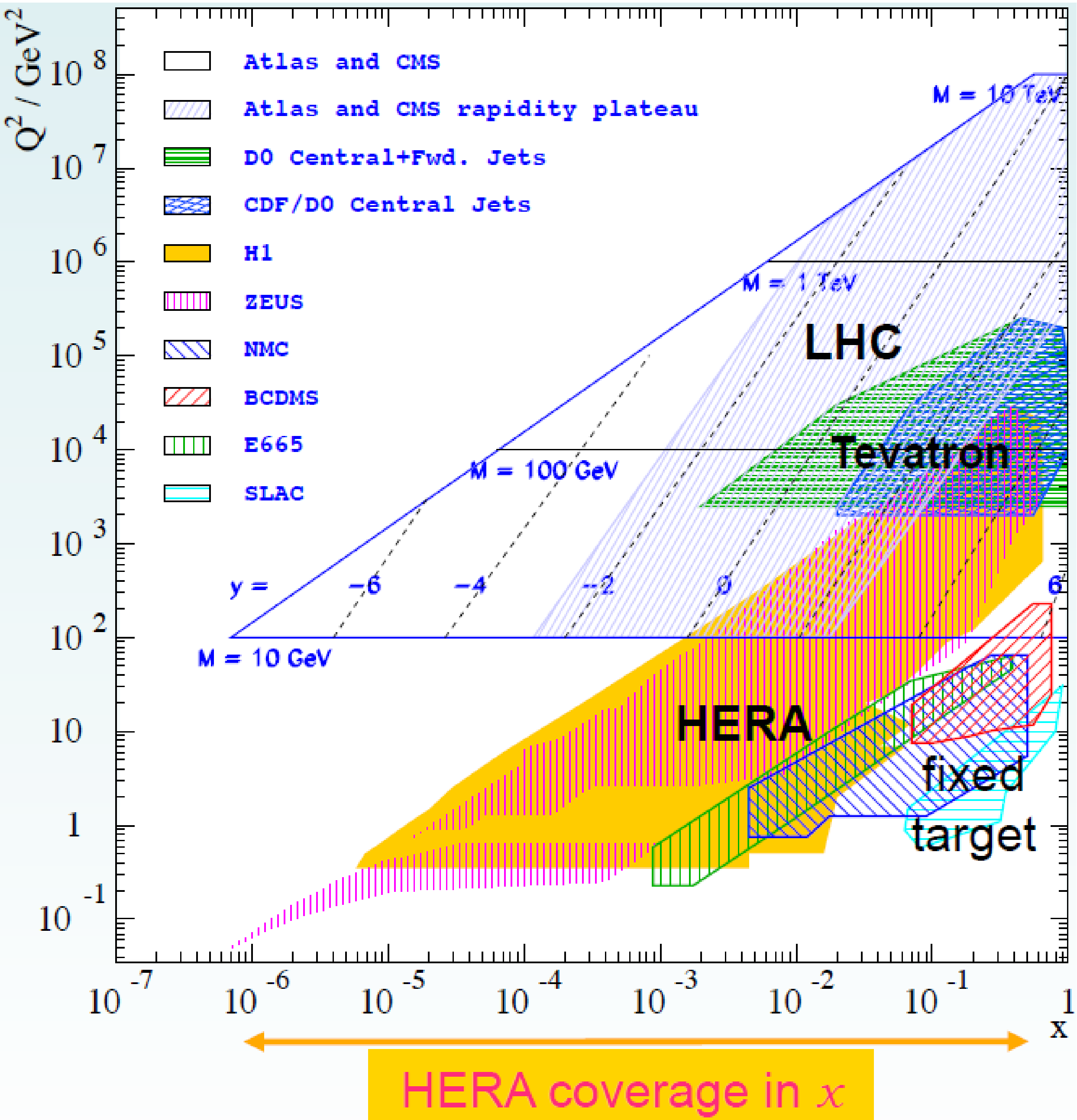
→ **Quark and gluon densities coupled**



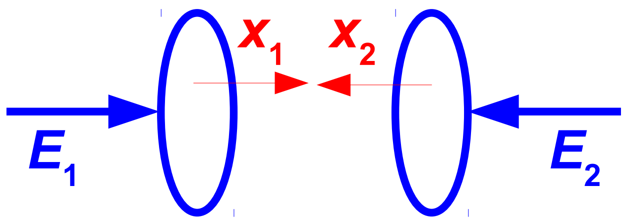




From Hera to the LHC



Kinematics in *pp* collisions



Center-of-mass energy:

$$\mathbf{s} = \mathbf{4} \cdot \mathbf{E_1} \cdot \mathbf{E_2}$$

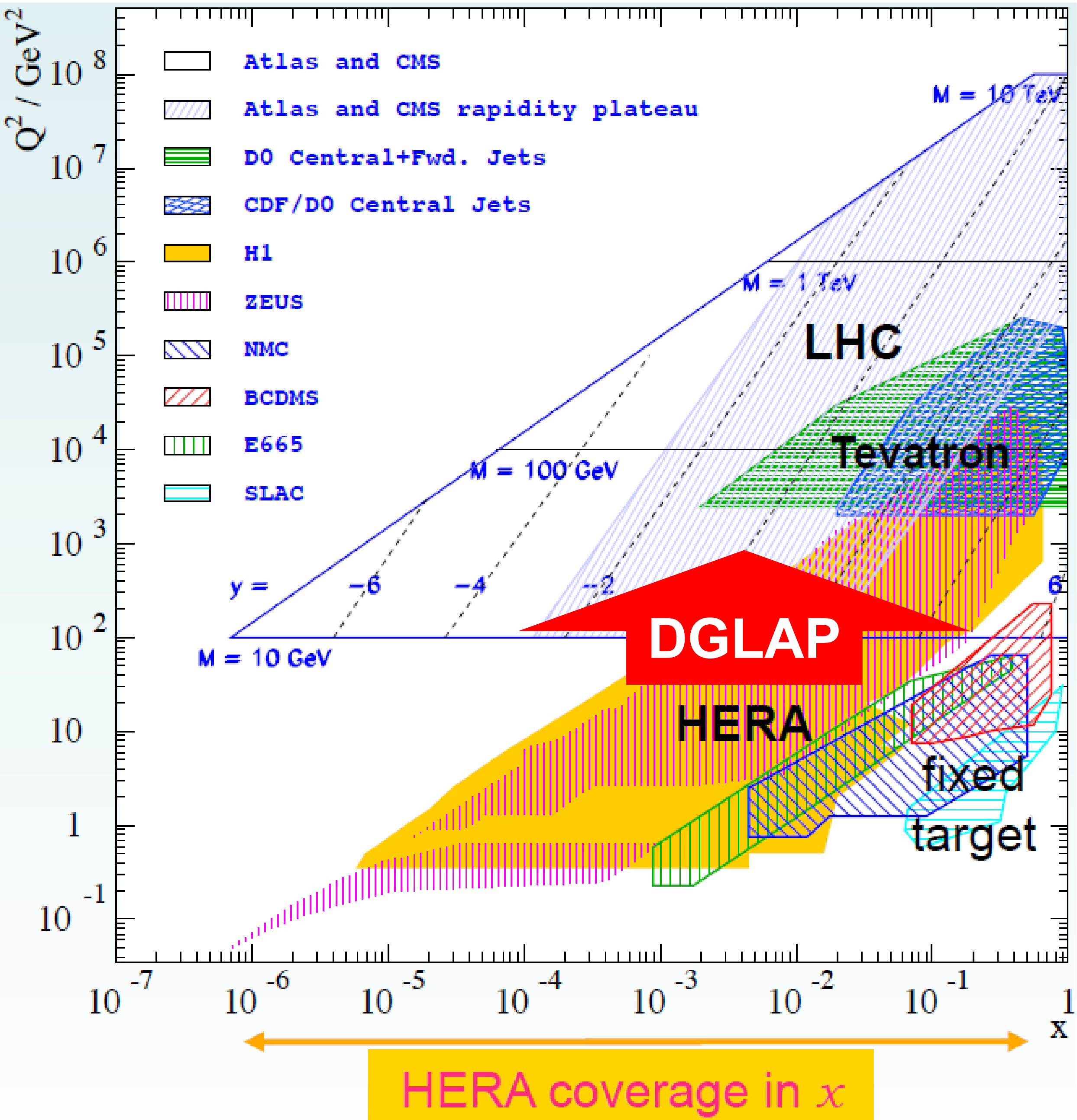
2-parton interaction:

$$\hat{\mathbf{s}} = \mathbf{x_1} \cdot \mathbf{x_2} \cdot \mathbf{s} \geq \mathbf{M}$$

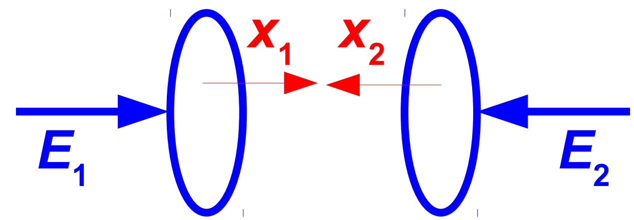
Energy scale $M = Q$

$$\mathbf{x_{1,2}} = \frac{\mathbf{M}}{\sqrt{\mathbf{s}}} \cdot \exp(\pm \mathbf{y})$$

From Hera to the LHC



Kinematics in *pp* collisions



Center-of-mass energy:

$$s = 4 \cdot E_1 \cdot E_2$$

2-parton interaction:

$$\hat{s} = x_1 \cdot x_2 \cdot s \geq M$$

Energy scale $M = Q$

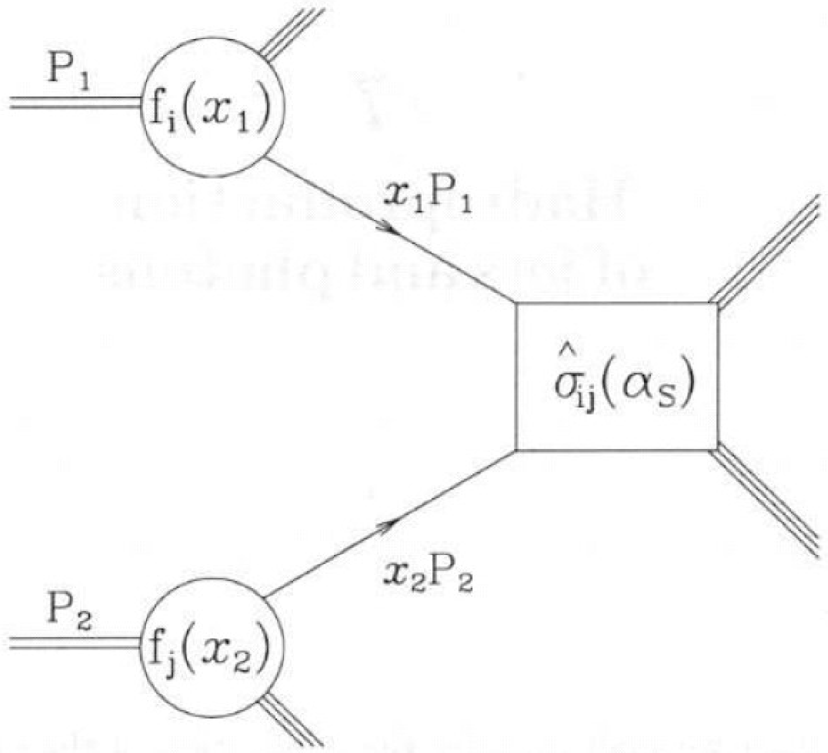
$$x_{1,2} = \frac{M}{\sqrt{s}} \cdot \exp(\pm y)$$

Factorization

Main statement:

Cross sections can be calculated by a product of

- Parton distribution functions (PDFs)
- Perturbative XS of the hard process
- **If needed:** Description of final state via parton shower …



At the LHC:

$$\sigma(\mathbf{pp} \to \mathbf{Y} + \mathbf{X}) = \sum_{\mathbf{q_i},\mathbf{q_j}} \int \mathbf{dx_1} \int \mathbf{dx_2}\ \mathbf{q_i}(\mathbf{x_1}, \mathbf{Q^2}) \otimes \mathbf{q_j}(\mathbf{x_2}, \mathbf{Q^2}) \otimes \hat{\sigma}_{\mathbf{q_i q_j} \to \mathbf{Y}}(\mathbf{x_1}, \mathbf{x_2}, \mathbf{Q^2})$$

Also important for PDF measurements itself

Factorization is often only an approximation: soft gluon interaction between hadrons, interactions of initial and final states …

Factorization

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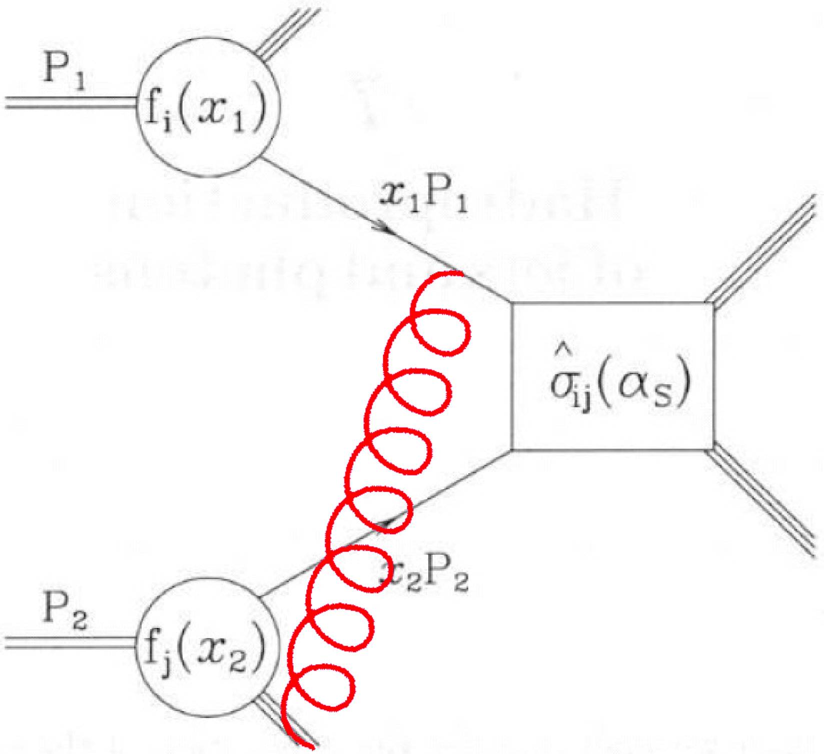

At the LHC:

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Also important for PDF measurements itself

Factorization is often only an approximation: soft gluon interaction between hadrons, interactions of initial and final states …

14 TeV → 7 TeV

At fixed $\sqrt{\hat{s}}$ a smaller $\sqrt{s}$ requires larger $\mathbf{x_1}$ and $\mathbf{x_2}$

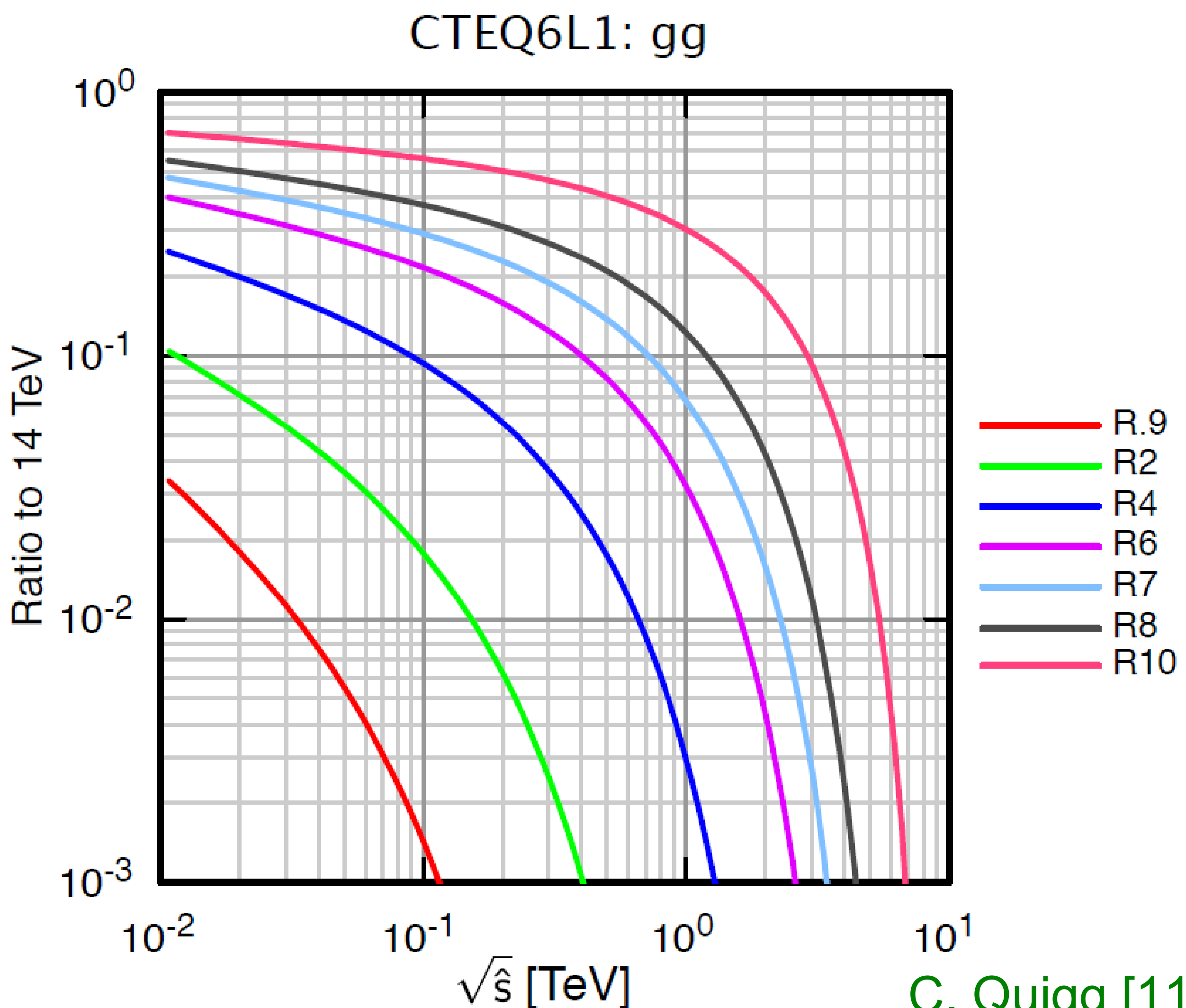
Steeply falling PDFs of "sea" quarks and gluons →
Decreasing cross section

Example: 14 TeV → 7 TeV (gluon-gluon processes)

$\sqrt{\hat{s}}$ = 300 GeV

→ Cross section drops by factor ~5

Ratio of parton luminosities (here: gluon-gluon) w.r.t. 14 TeV



C. Quigg [11]

Data Taking

2009: Data taking at √s=900 GeV and 2.36 TeV

Since 30th March 10: √s=7 TeV

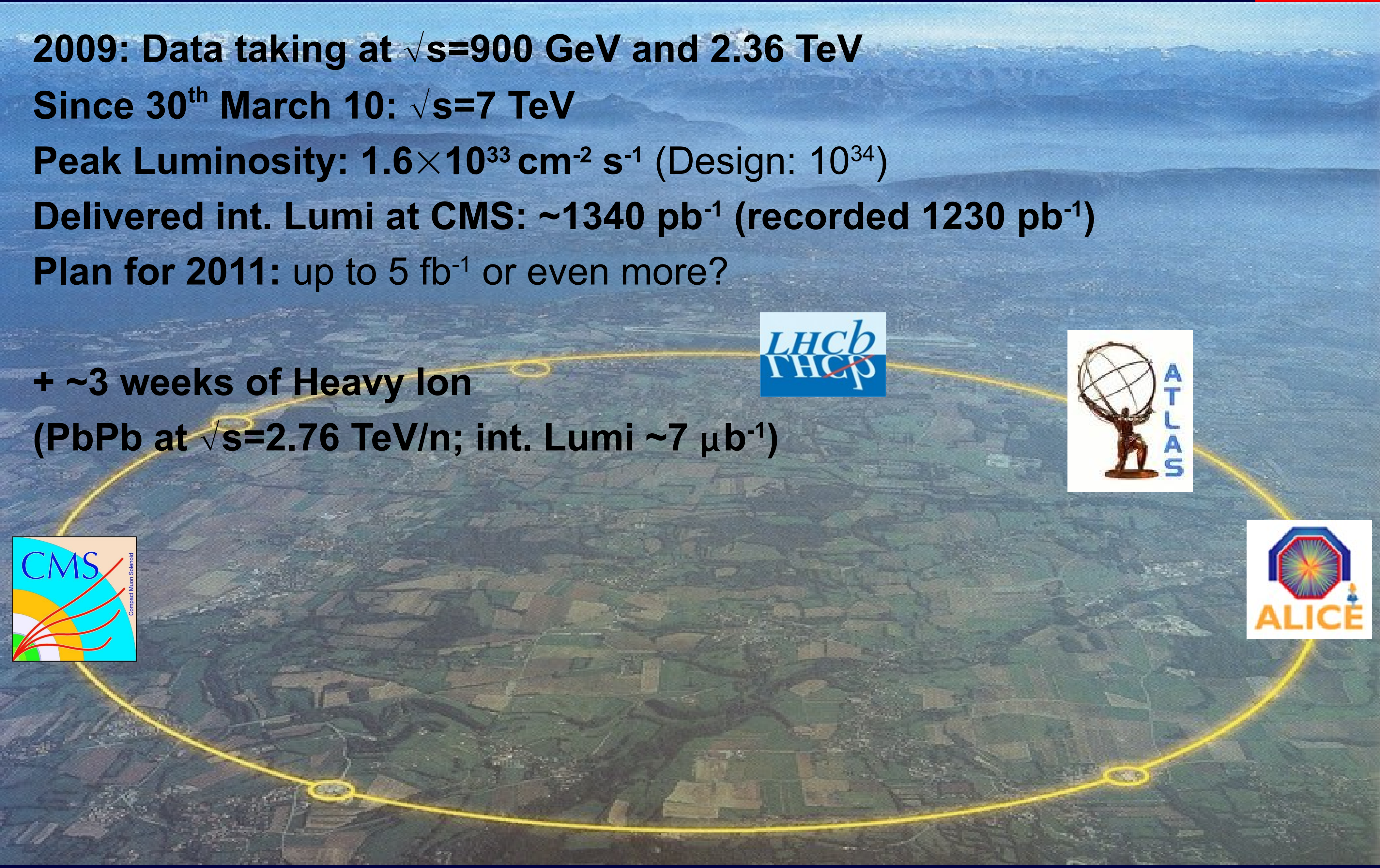
Peak Luminosity: 1.6×10^{33} cm^{-2} s^{-1} (Design: 10^{34})

Delivered int. Lumi at CMS: ~1340 pb^{-1} (recorded 1230 pb^{-1})

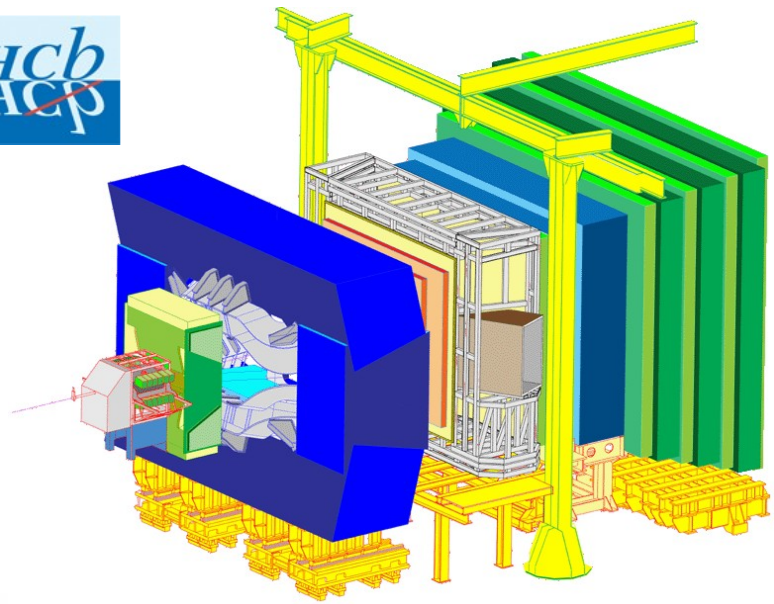
Plan for 2011: up to 5 fb^{-1} or even more?

+ ~3 weeks of Heavy Ion

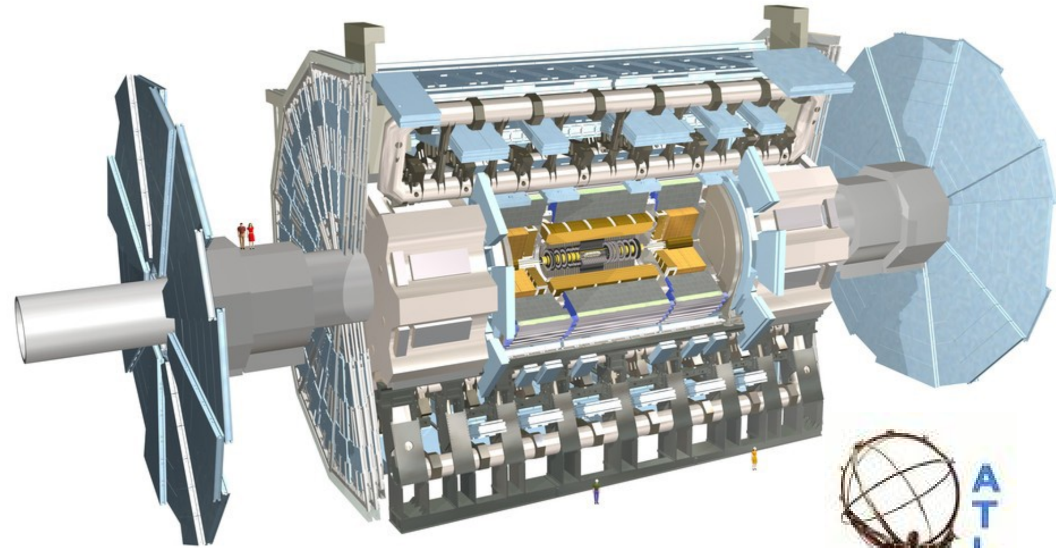
(PbPb at √s=2.76 TeV/n; int. Lumi ~7 μb^{-1})



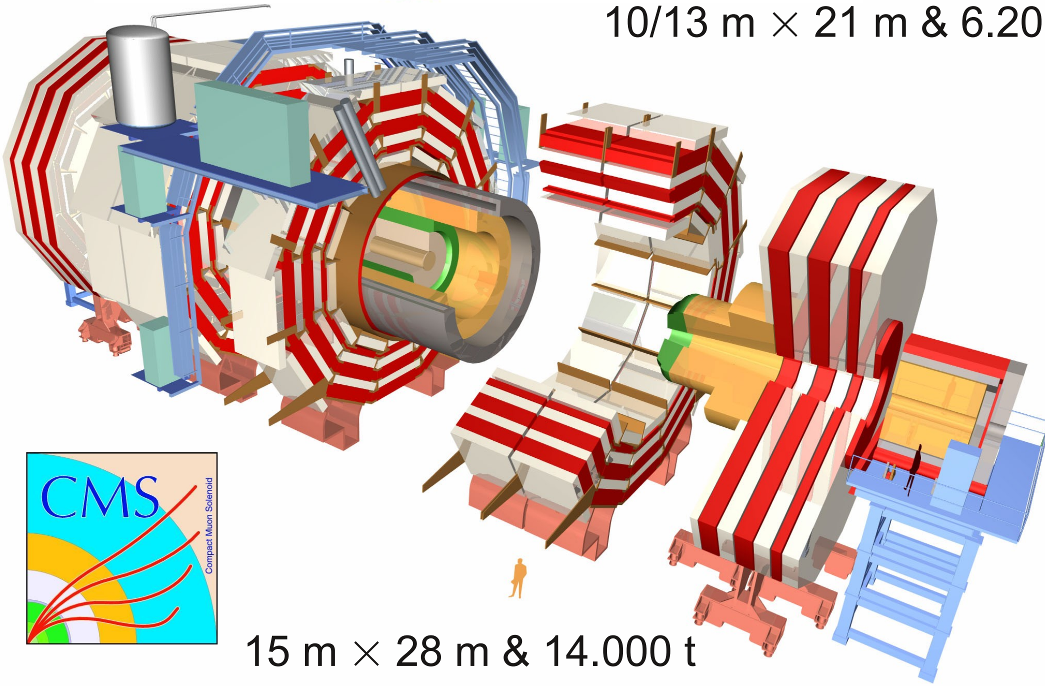
The Experiments



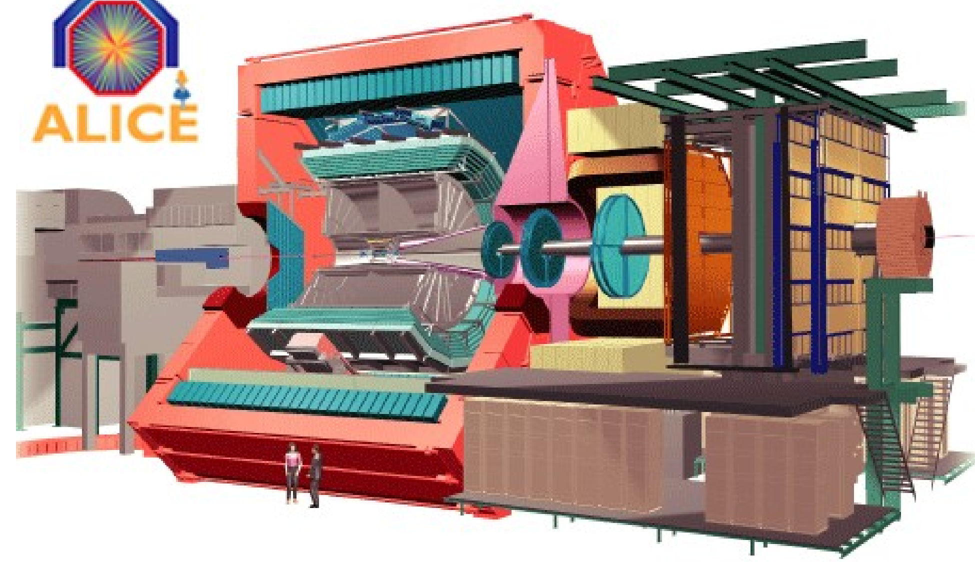
10/13 m × 21 m & 6.200 t



22 m × 44 m & 7.000 t



15 m × 28 m & 14.000 t



16 m × 25 m & 10.000 t

Particle Identification at ATLAS

Toroidal magnet

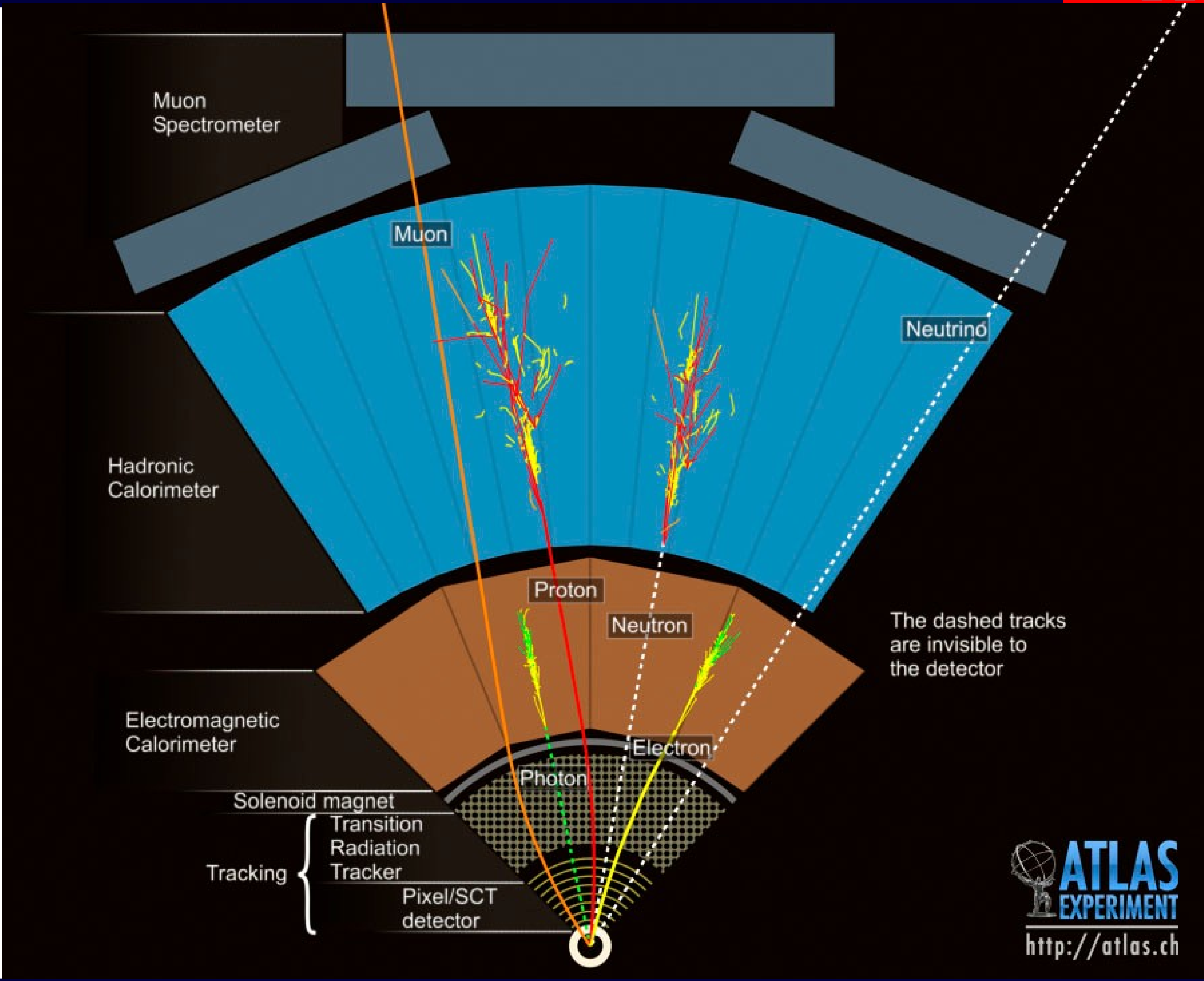
Muon chambers

HCAL
Outer: scintillator
Inner: liquid Argon

ECAL
liquid Argon

Solenoid ~2T

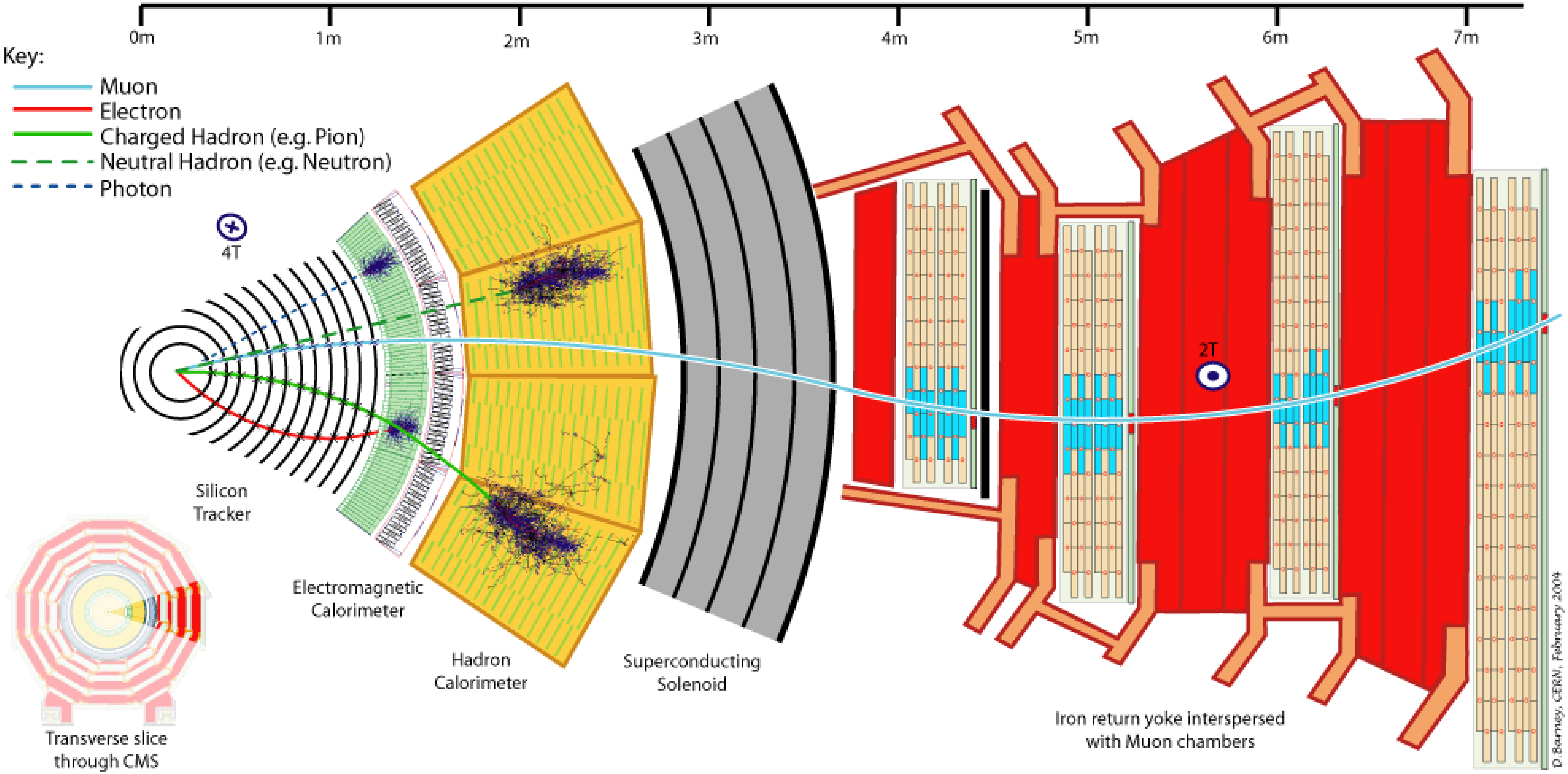
Tracking
Transion radiation
Si-Strip
Si-Pixel



Particle Identification at CMS

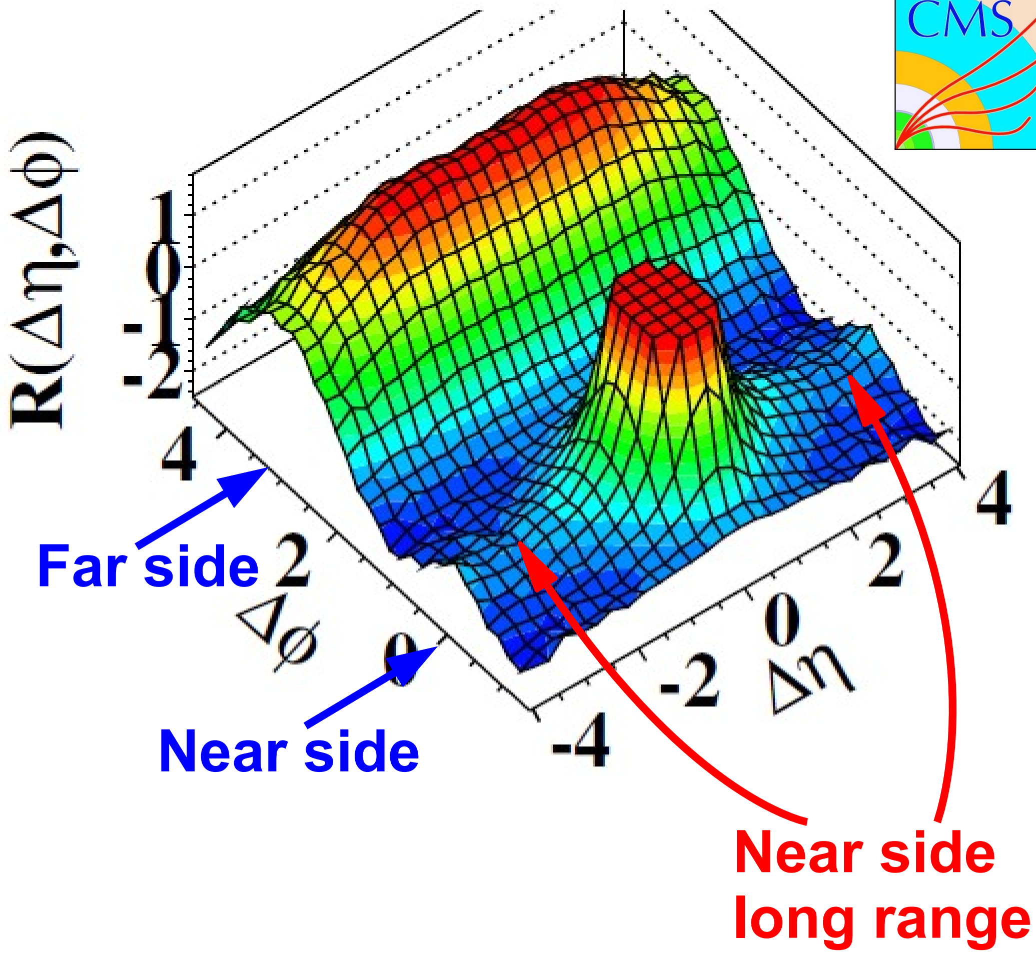
Main difference to ATLAS:

- All silicon tracker
- ECAL and HCAL mostly inside solenoid magnet (~4T)
- No toroidal magnet for muon bending



The Ridge

- Angular correlation in pp events at 7 TeV with high track multiplicity
  - 1 GeV < track p_T < 3 GeV
  - N_{tracks} > 110
- Ratio ***R*** of signal (same event pairs) and bg (different event pairs)
- Jet peak and back-to-back structure visible

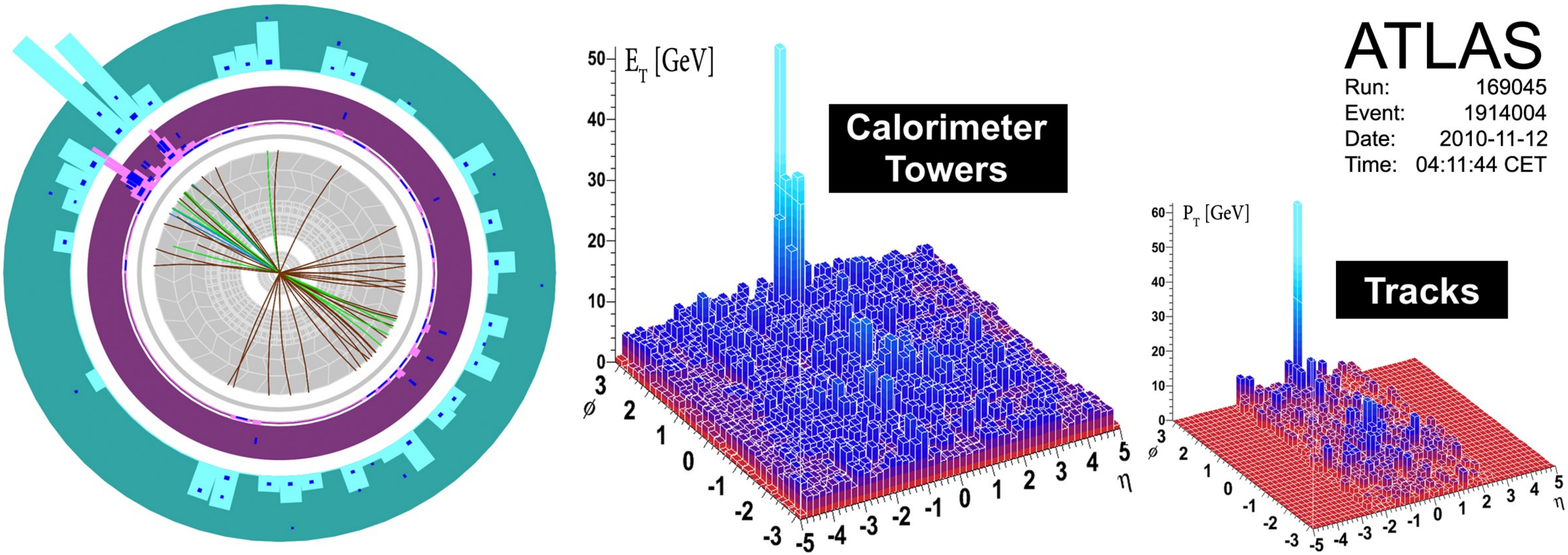


→ Structure at near side long range reassembles Bose-Einstein correlation observed in AuAu collisions at RHIC

JHEP 1009:091 (2010)

Heavy Ions – "Jet Quenching"

- New diJet asymmetry observed (increasing with centrality)
- Not observed in pp collisions

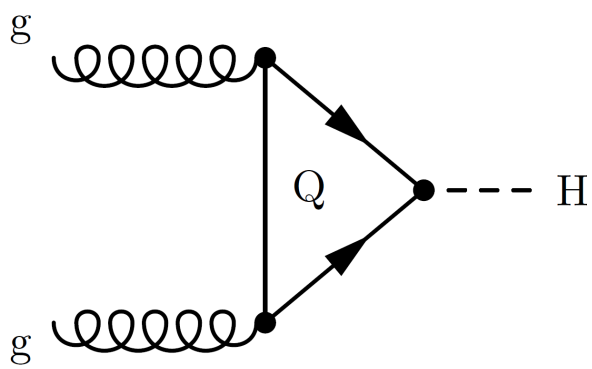


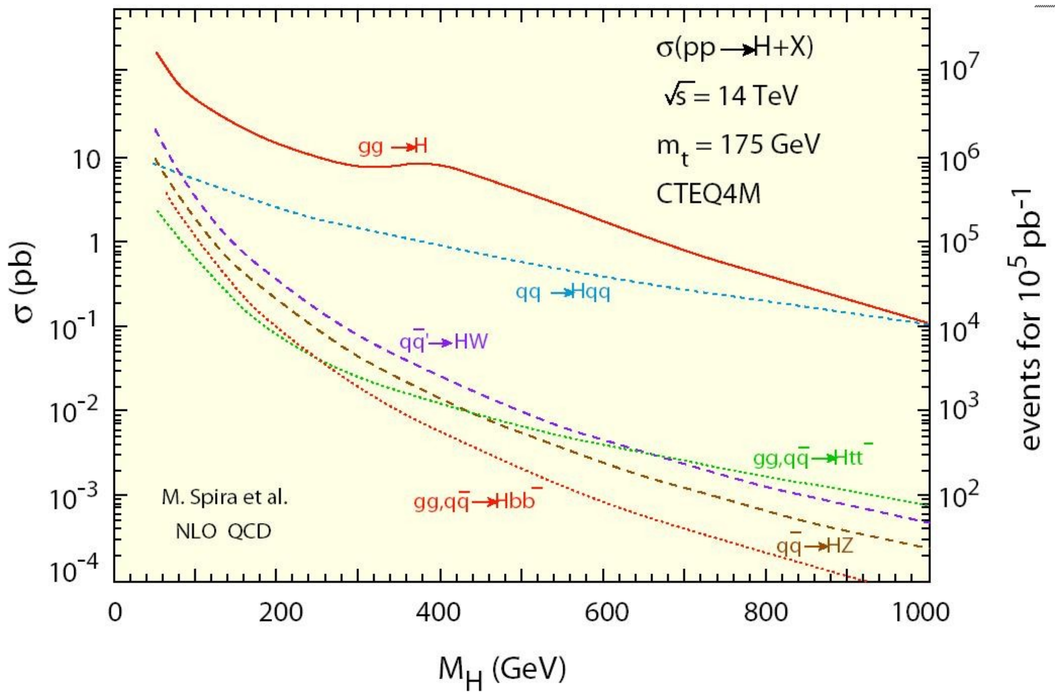
- **Possible interpretation:**

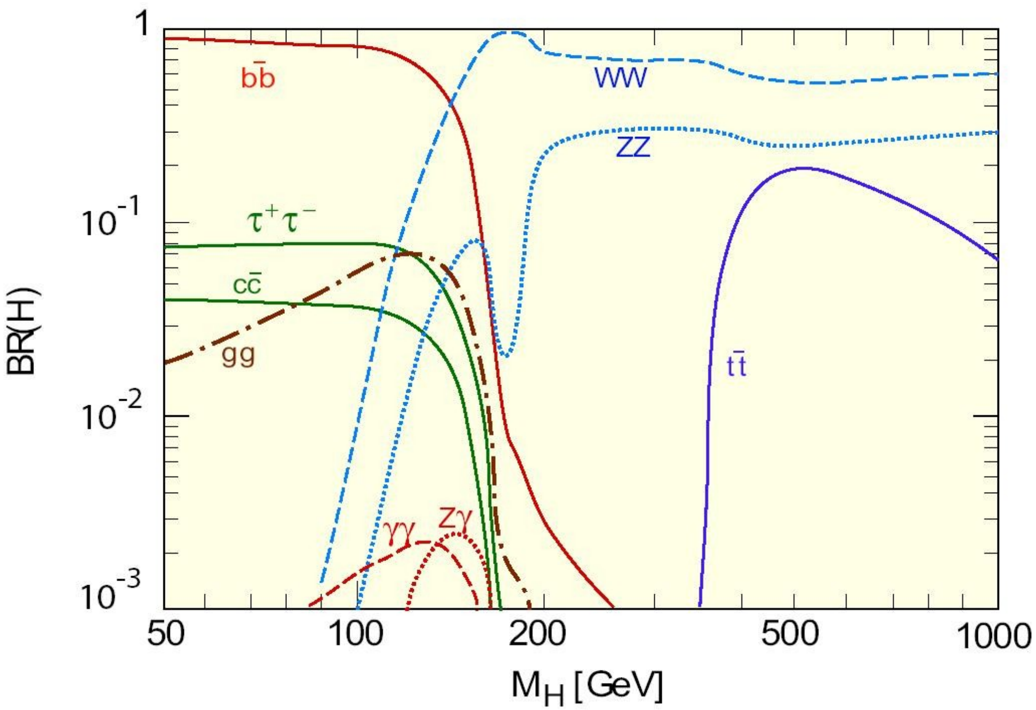
Strong jet energy loss in hot dense medium

CERN-PH-EP-2010-062

Dominant production cross section at LHC: gluon-gluon fusion







Branching ratio is fuction of M_H

→ **Many different search channels**

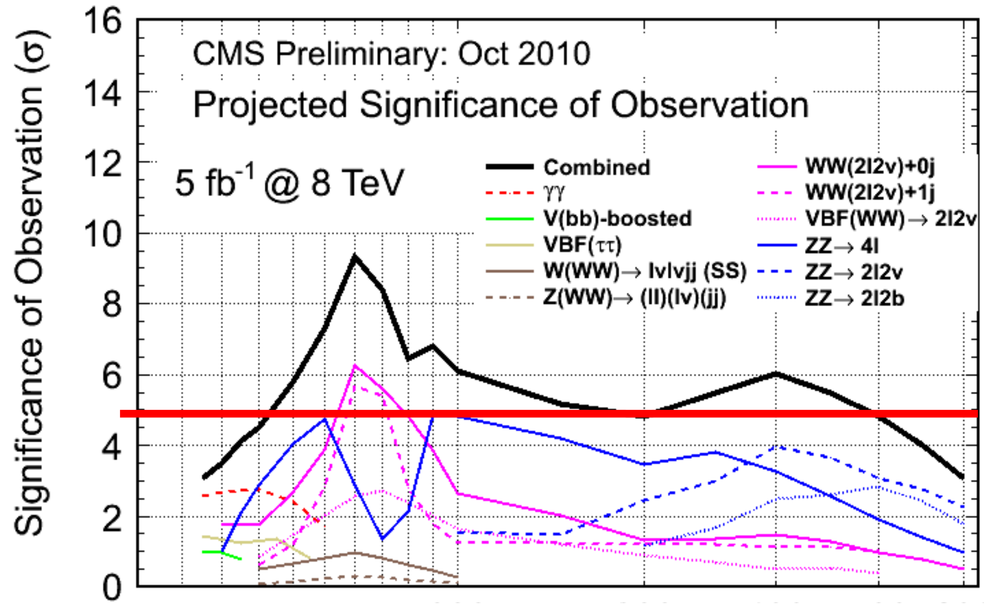
Higgs in 2011/12

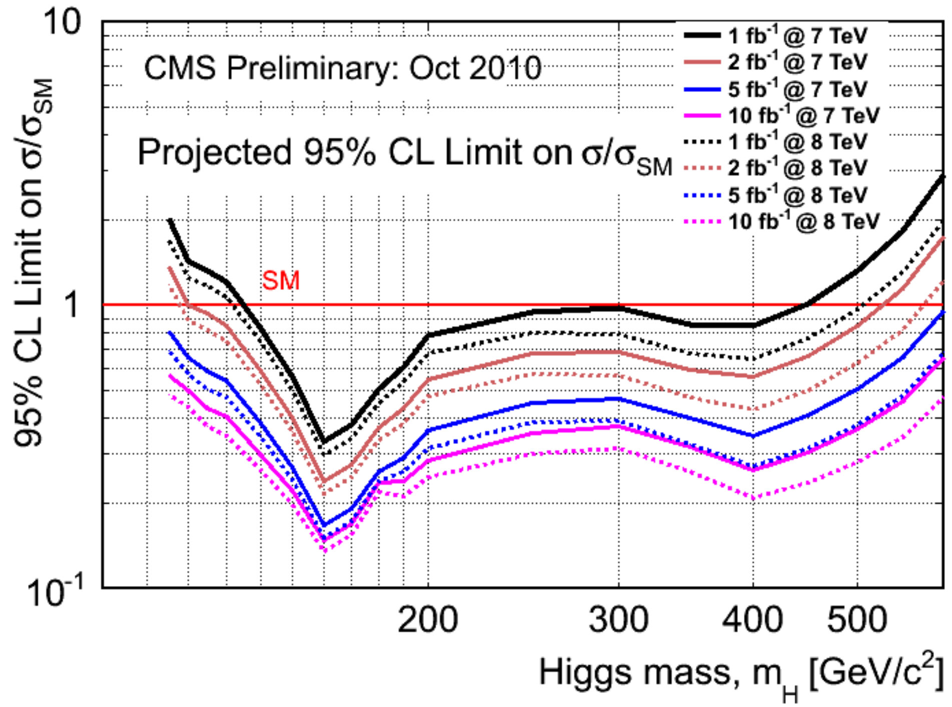
Low m_H region most challenging:

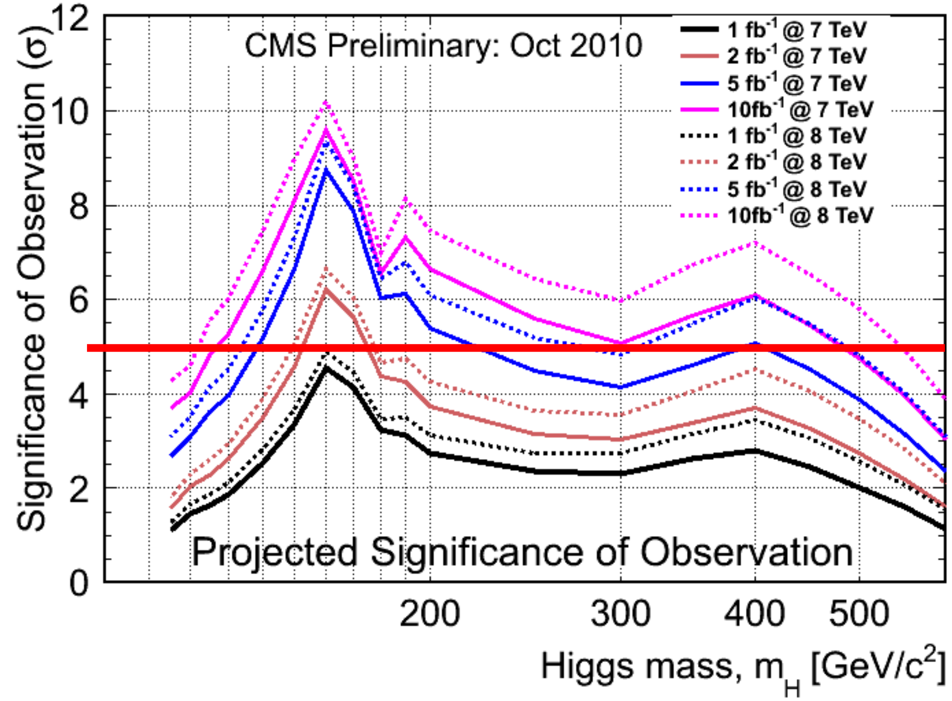
$H \rightarrow \gamma\gamma$: small cross section, but clear signature at CMS

5 fb^{-1}@7 TeV: exclusion at 95% CL over total mass range

10 fb^{-1}@7 TeV: discovery potential down to m_H ~ 130 GeV



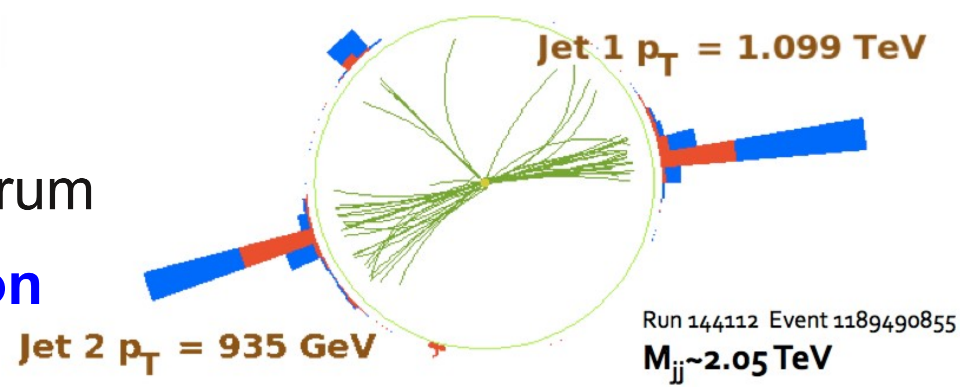


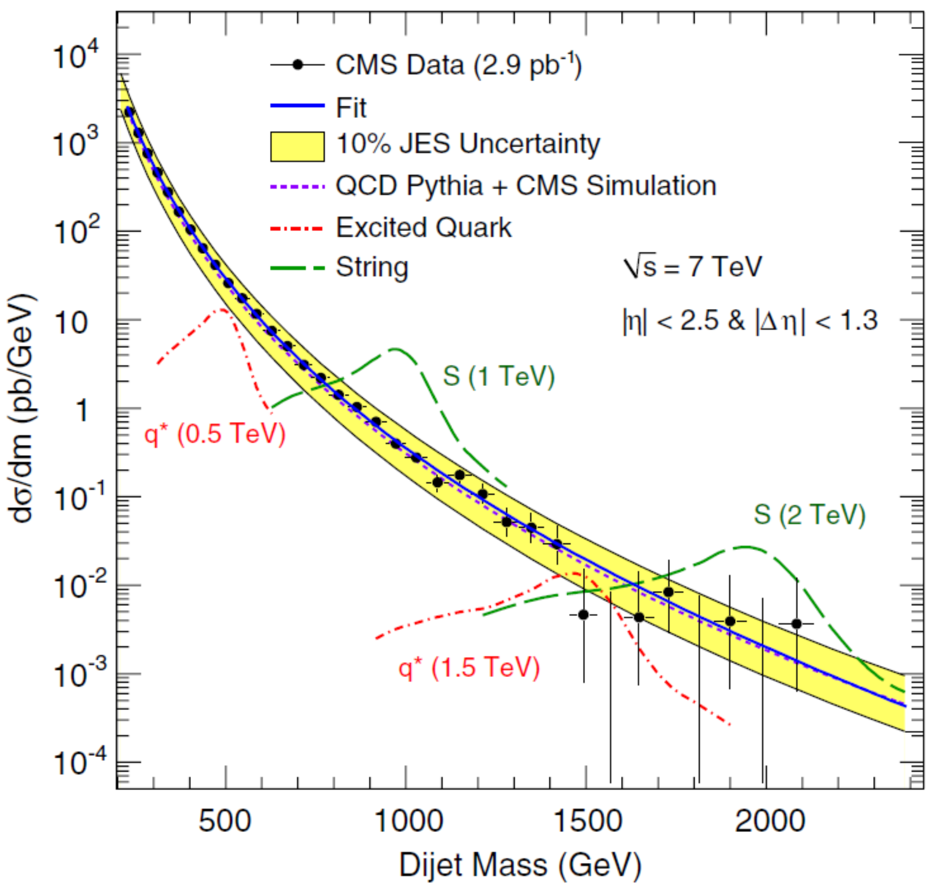


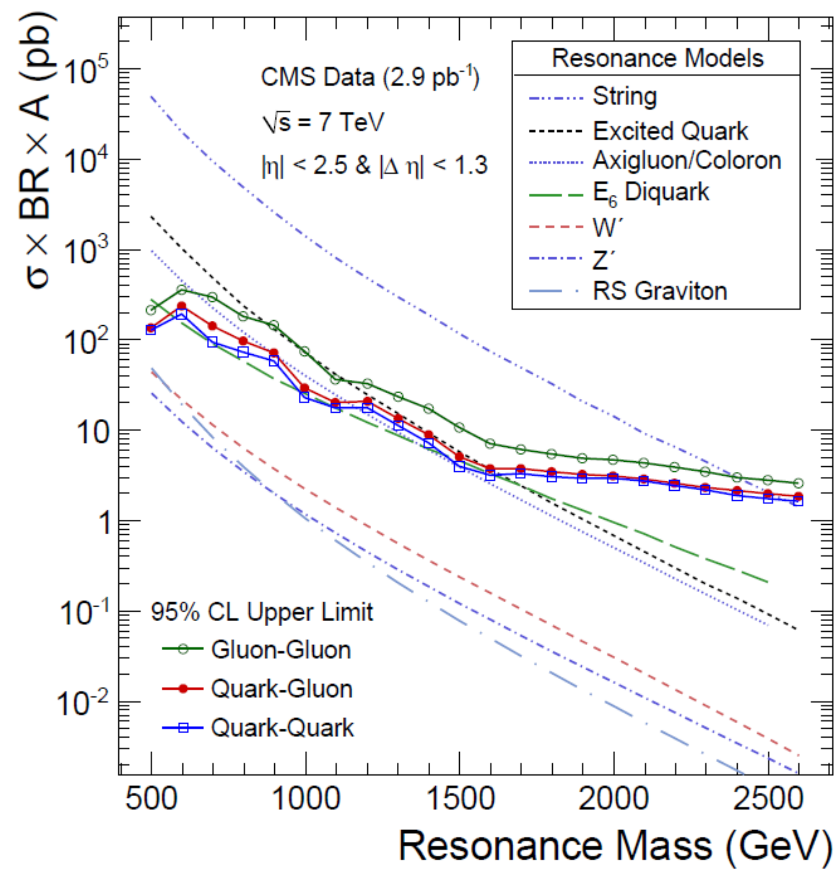
DiJet Resonances

Many extensions of the SM predict heavy particles coupling to quarks or gluons → Resonances in diJet invariant mass spectrum

LHC provides better limits than Tevatron with a few pb^{-1}

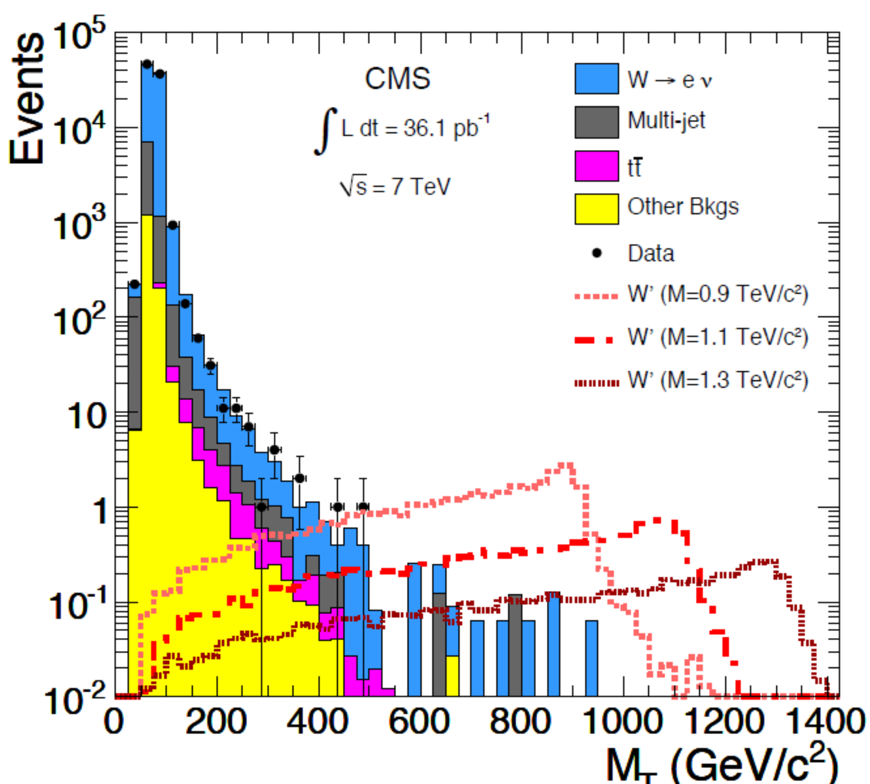


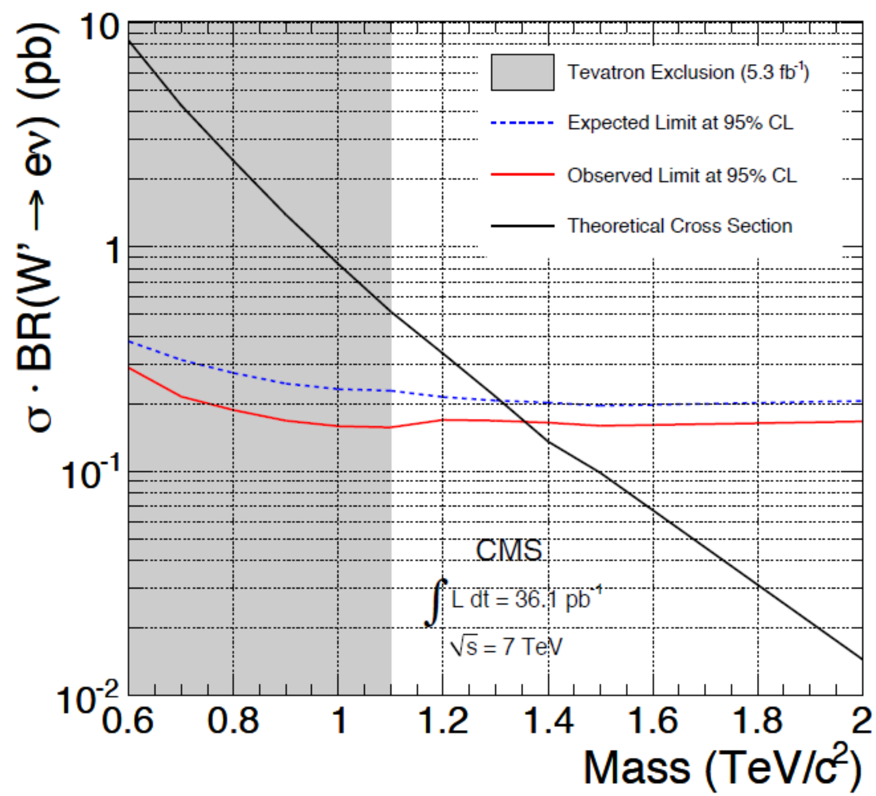




- Extra heavy gauge bosons predicted by left-right symmetric models or supersymmetric Grand Unified Theories
- **Signature:** lepton (here: *e*) and similar MET $0.4 < \mathbf{E_T^{electron}}/\mathbf{MET} < 1.5$ in opposite direction ($\Delta\phi > 2.5$)

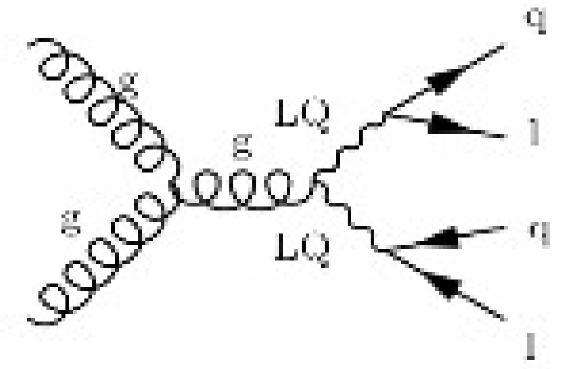
→ Better limits on $M_{W'}$ than Tevatron experiments



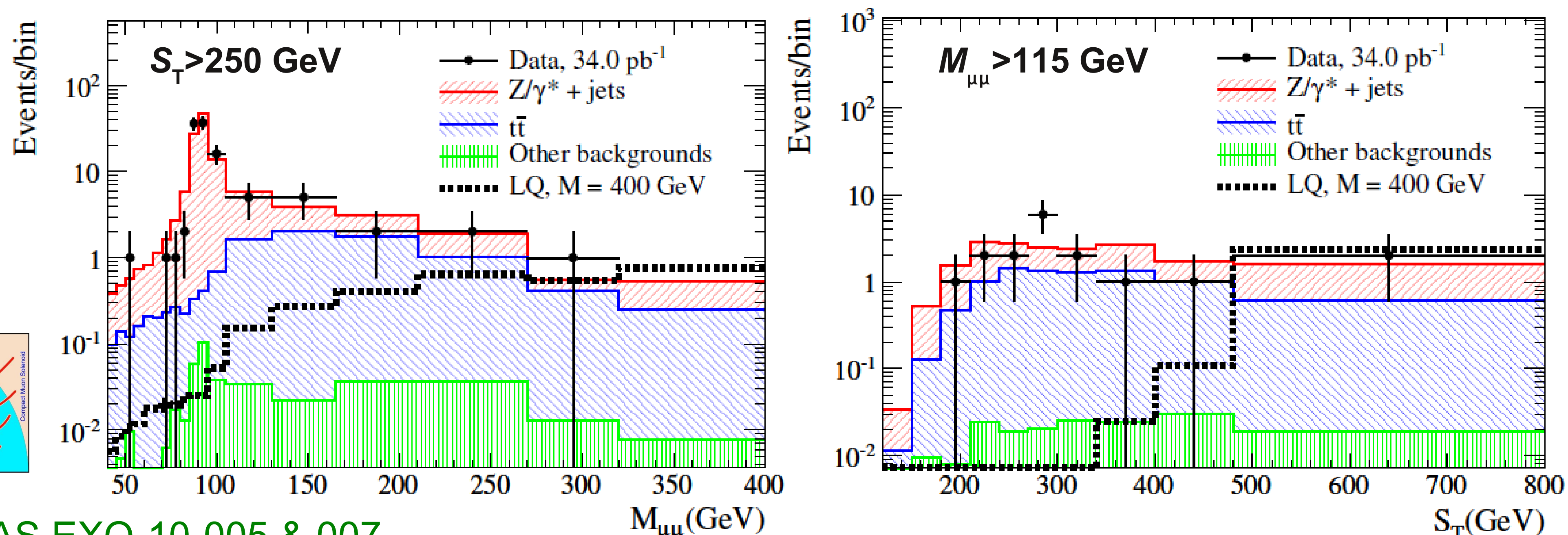


CMS PAS EXO-10-014

- LQ carry lepton and baryon numbers
- Fractionally charged
- Typically constrained to one lepton/quark generation
- LHC: dominant pair production via *gg* fusion or $q\bar{q}$ annihilation



- **Signature:** 2 OSSF leptons + 2 jets with high $M_{\mu\mu}$ and S_T (p_T sum of two leading jets and muons)



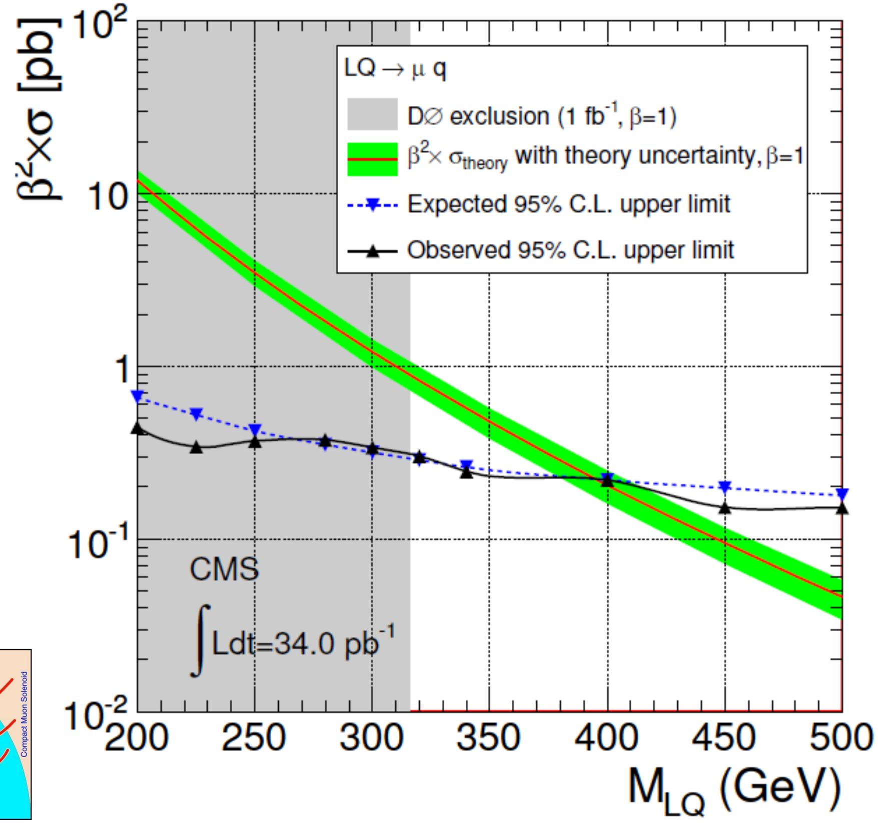
CMS PAS EXO-10-005 & 007

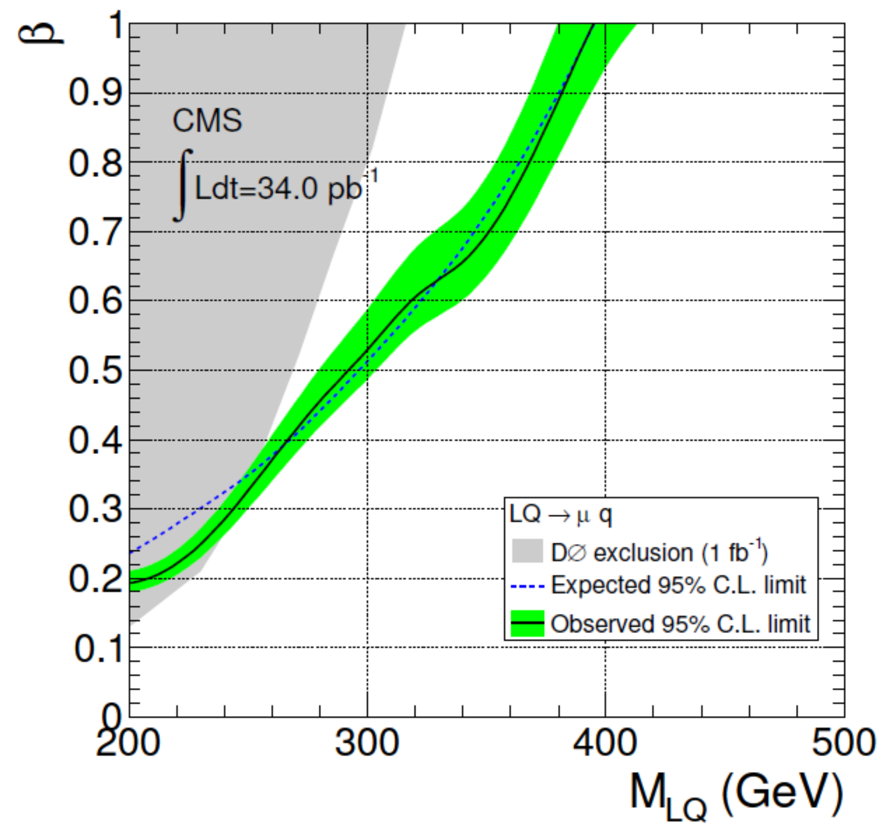
Leptoquarks

No excess of events observed

→ **Exclusion limits on $\beta^2 \times \sigma$** (β: Branching ratio of LQ in corresponding lepton, e.g. second generation LQ → $q\mu$)

(similar limits for first generation LQ)





CMS PAS EXO-10-005 & 007

Heavy Charged Stable Particles

- (Meta-) stable gluinos or squarks can form neutral bound states (*R*-hadrons) → not visible in muon detectors
- Search based on high d*E*/dx tracker hits: most probable value of d*E*/dx estimated by harmonic mean

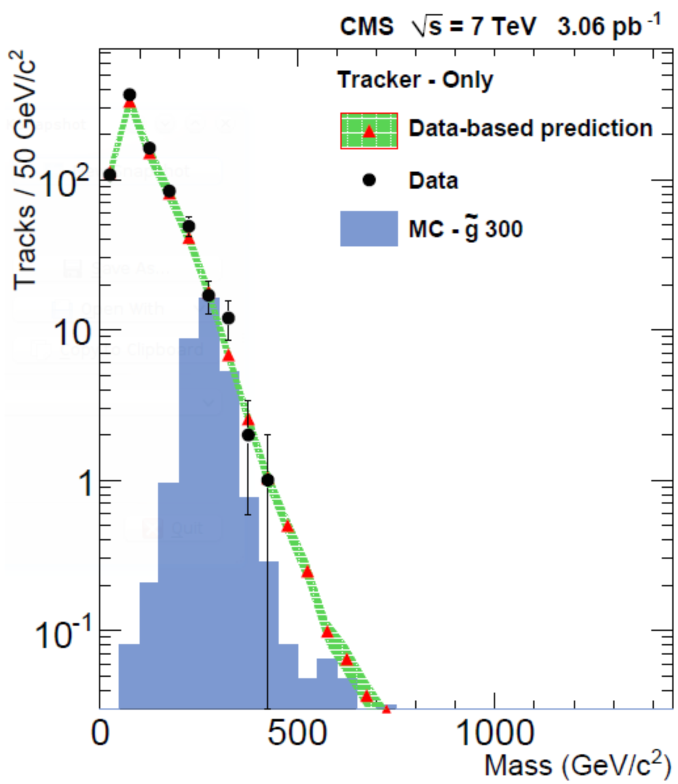
$$I_h = \left(\frac{1}{N} \sum_i (dE/dx)_i^k \right)^{1/k} \quad \text{with} \quad k = -2$$

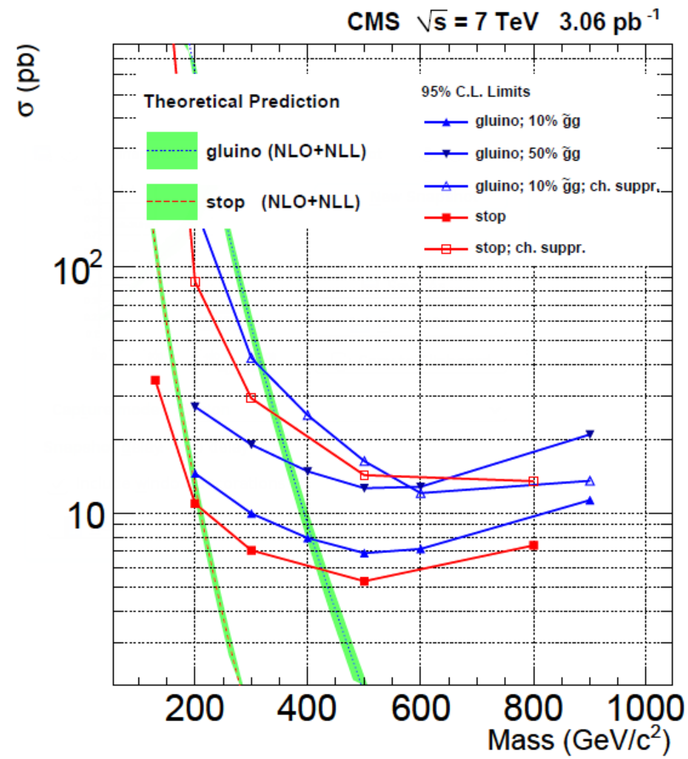
- Relation between I_h, mass *m* and momentum *p*

$$I_h = K \cdot \frac{m^2}{p^2} + C$$

with empircal constants *K* and *C* from low energy proton data

No excess → limits



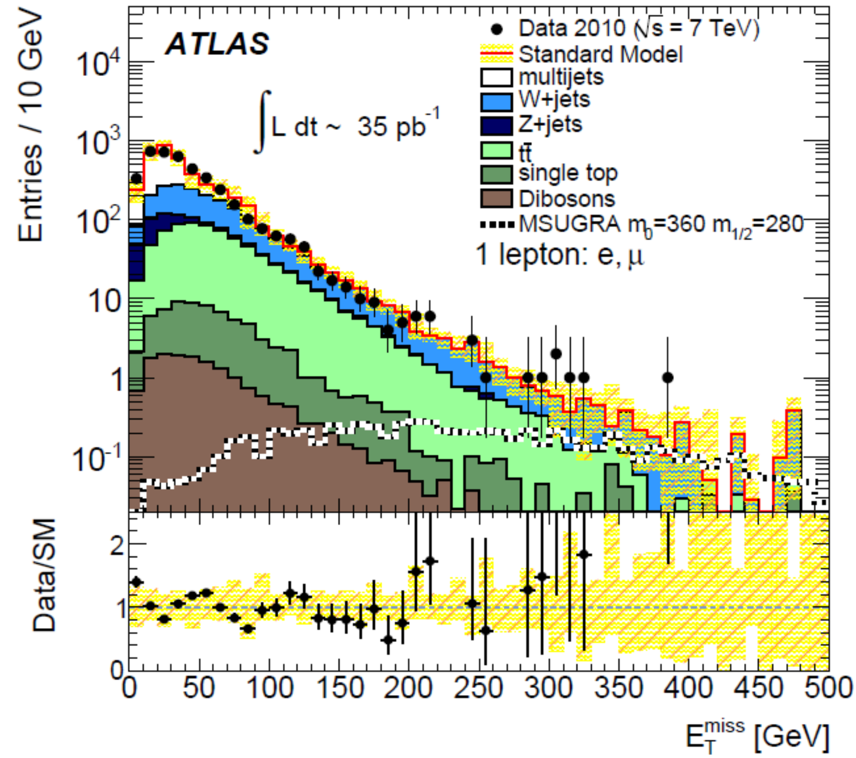


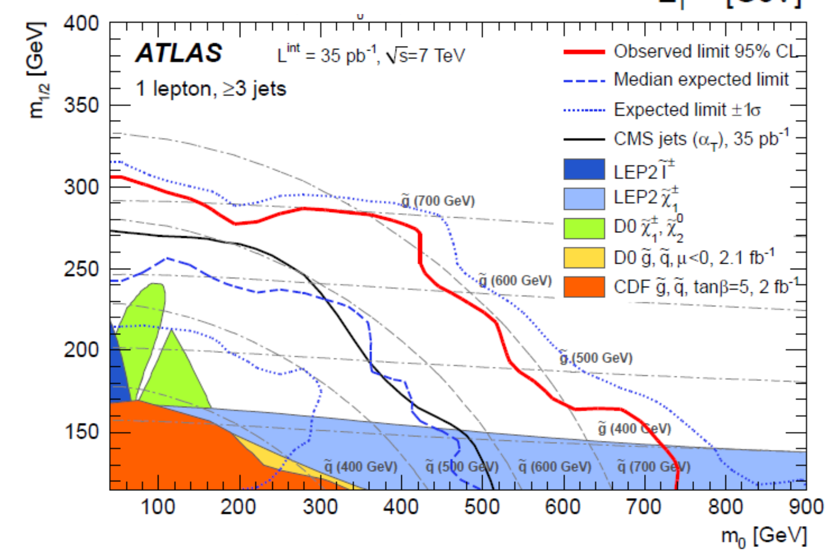
CMS PAS EXO-10-011

Leptonic SUSY Search

- Cascades with sleptons → more than one lepton, e.g. $\tilde{\mathbf{q}} \rightarrow \mathbf{q}\tilde{\chi}_2^0 \rightarrow \mathbf{q}\mathbf{l}\tilde{\mathbf{l}} \rightarrow \mathbf{q}\mathbf{l}\bar{\mathbf{l}}\tilde{\chi}_1^0$
- SUSY cascades with charginos → single leptons, e.g. $\tilde{\mathbf{q}} \rightarrow \mathbf{q}\tilde{\chi}_1^\pm \rightarrow \mathbf{q}\mathbf{l}\nu\tilde{\chi}_1^0$
- **Signature:**
  - exactly one isolated lepton
  - $\geq$3 jets
  - MET > 125 GeV
  - M_T(lepton+MET) >115 GeV
  - M_{eff}(lepton + 3 jets + MET) > 500 GeV
- QCD background from data; other bgs scaled MC simulation (control regions)
- **Observed:** 2 events
- **Expected:** ~4 events

→ **Limits**





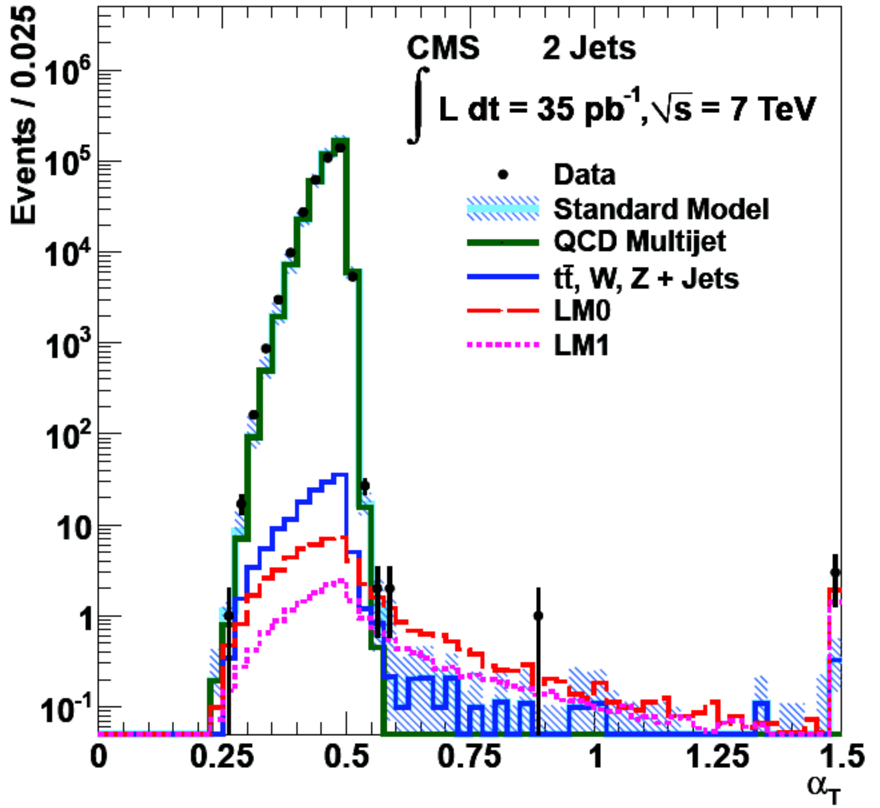
arXiv:1102.2357v2 [hep-ex]

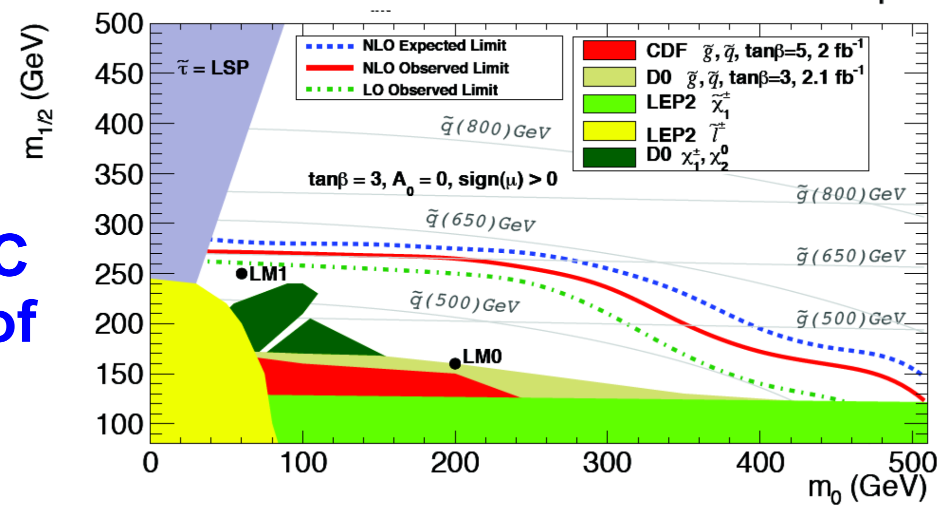
Hadronic SUSY Search with α_T

$$\alpha_T = \frac{E_T^{2nd}}{M_T} = \frac{E_T^{2nd}}{\sqrt{2 p_T^{1st} p_T^{2nd} (1 - \cos\phi_{12})}}$$

- Perfectly measured diJet events **α_T = 0.5**
- Mismeasurements of p_T: **α_T < 0.5**
- **Selection:** 3[rd] jet p_T < 50 GeV & α_T > 0.55
- **α_T > 0.5**
  - QCD: jets below threshold
  - Events with genuine MET (Top, *W*, *Z*)
- Possible extension on N_{jet} > 2 by forming two pseudo jets

→ Already with small statistics the LHC experiments are probing new regions of the SUSY parameter space

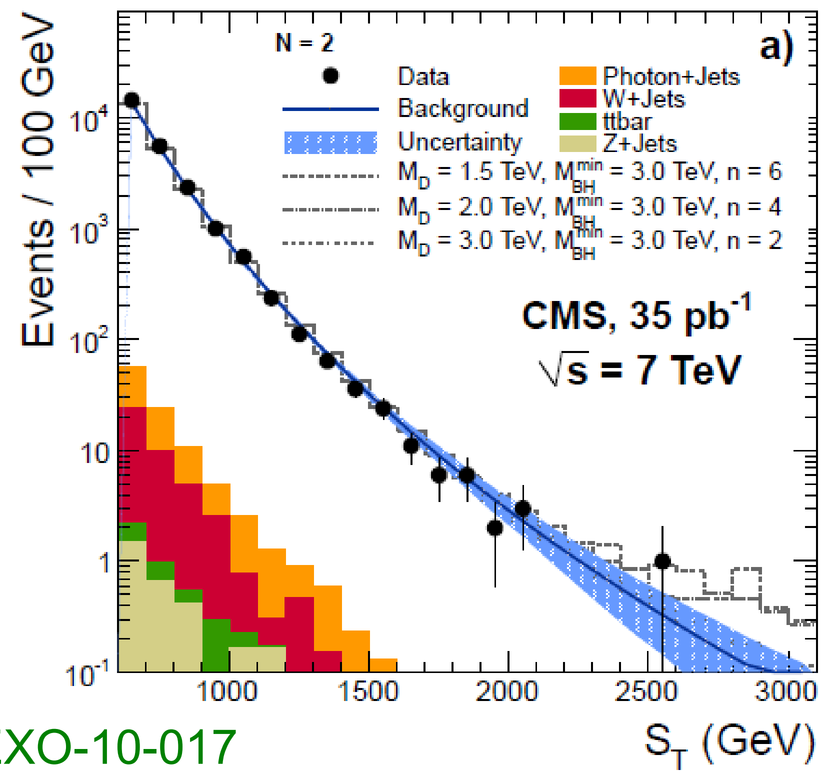


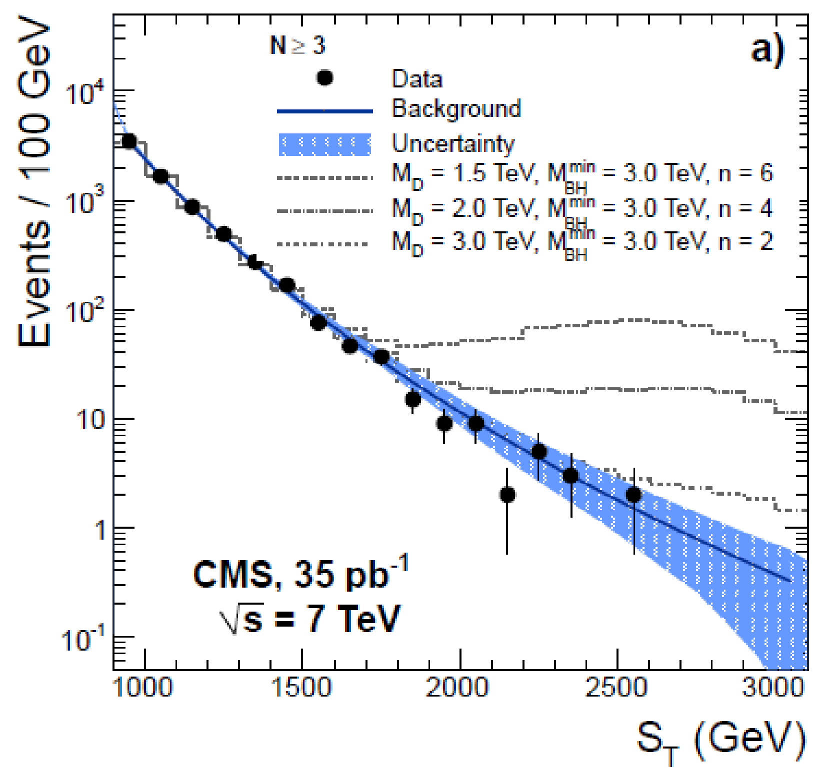


CMS PAS SUS-10/003

Black Holes

- Models with large flat extra spatial dimensions (e.g. ADD models): Black hole production at the LHC (~geometrical cross section: $\sigma = \pi \cdot R_S^2$)
- Hawking radiation: democratic evaporation (dominantly: quarks and gluons)
- **Signature:** High multiplicity of objects (p_T > 50 GeV), high $S_T = \Sigma_i \, p_{T,i}$
- **Dominant Bg:** QCD; **S_T shape independent on object multiplicity**





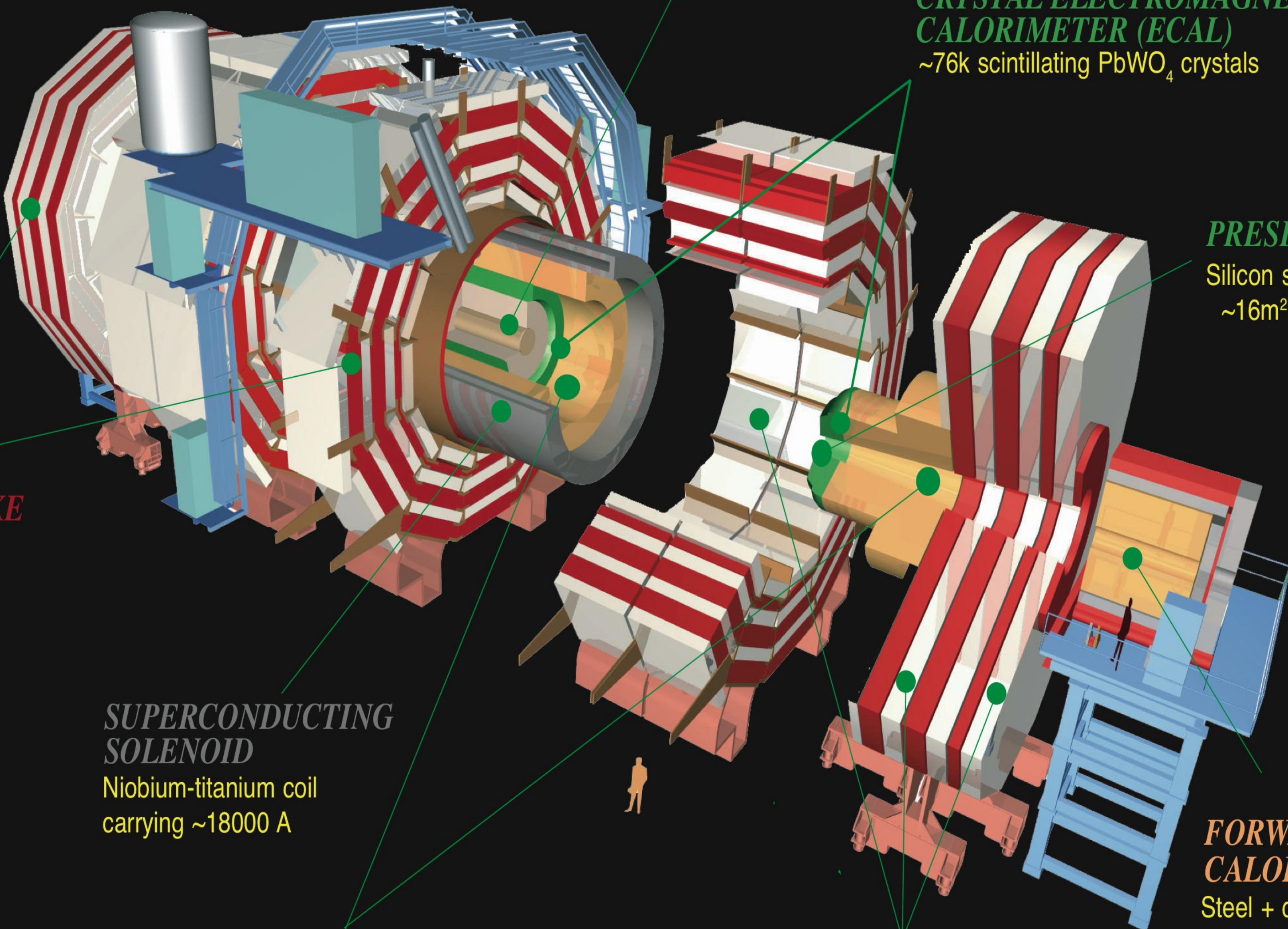
CMS PAS EXO-10-017

Summary

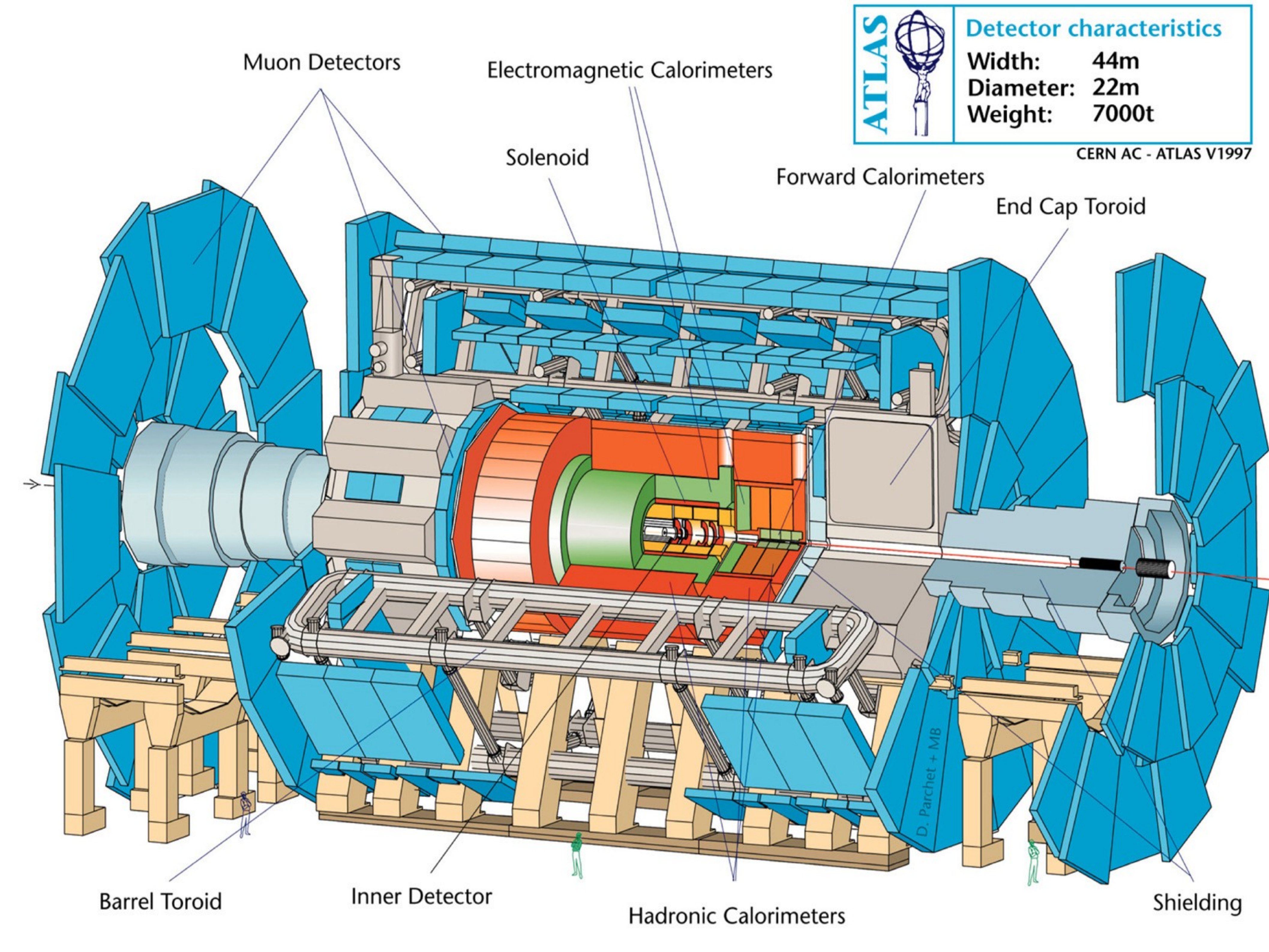
Very exciting times ahead of us!

Backup

CMS Detector



Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T


ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
D. Parchet + MB

PDF Measurements

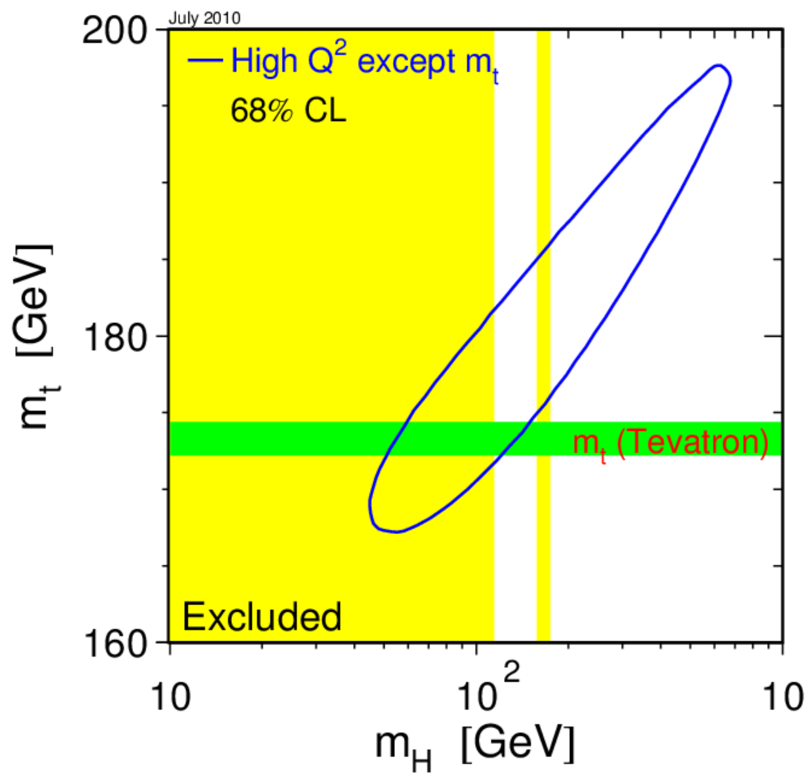
- E.g. neutral current:

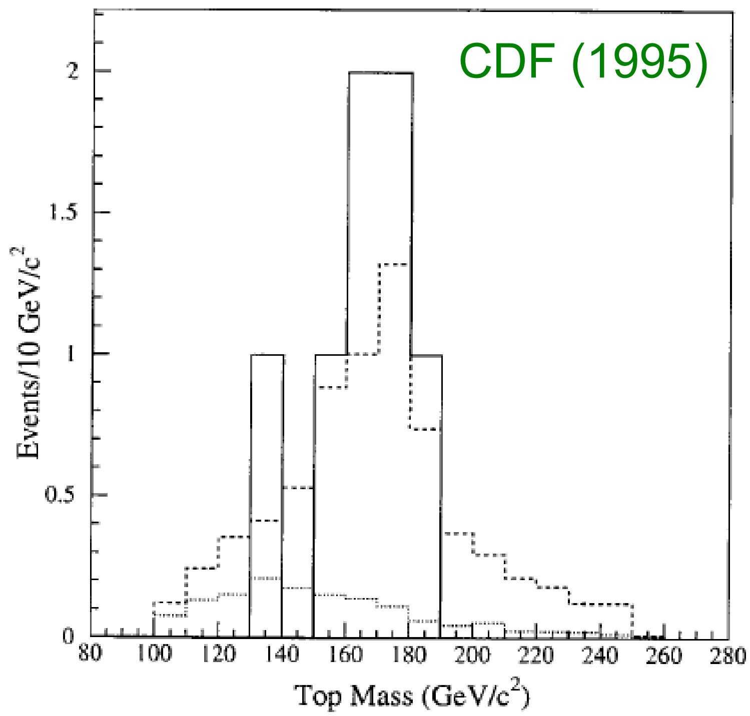
$$\frac{d^2\sigma^{ep}}{dx\,dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4}\left[\underbrace{(1+(1-y)^2)F_2}_{\text{Dominant contribution}} - y^2F_L \mp xF_3\right]$$

- **Quark-parton model:** $F_2 \propto \sum_f \left(q_f(x,Q^2) + \bar{q}_f(x,Q^2)\right)$

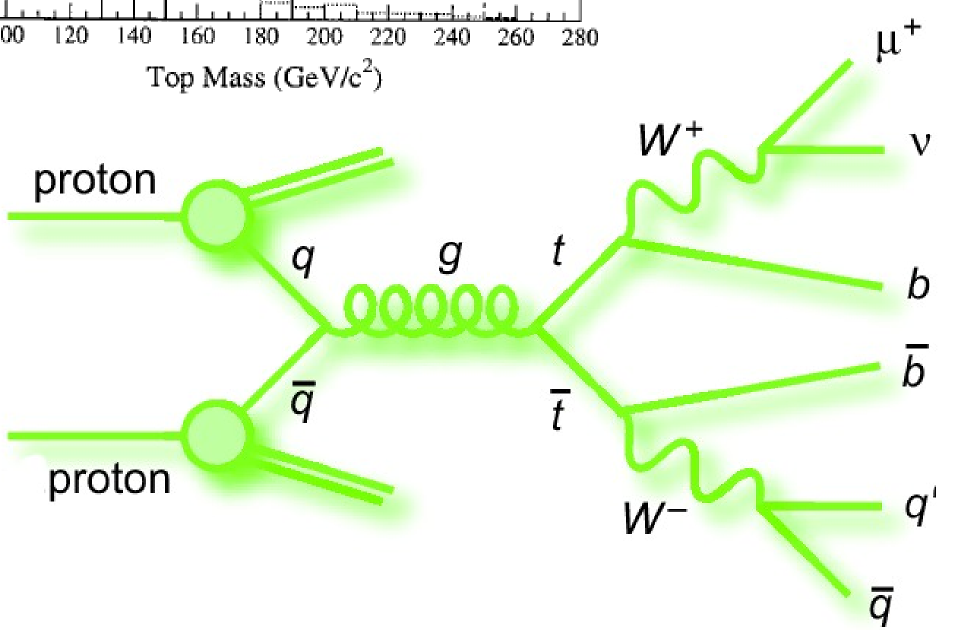
- **Parton distribution functions (PDFs):** $q_f/\bar{q}_f(x,Q^2)$
  - Probability density to find quark of flavor **f** with a momentum fraction **x**
  - **Bjorken scaling:** If partons do not interact: $q_f(x)$ and $F_2(x)$
  - PDF dependence on **x** not calculable in perturbative QCD

Top Quark



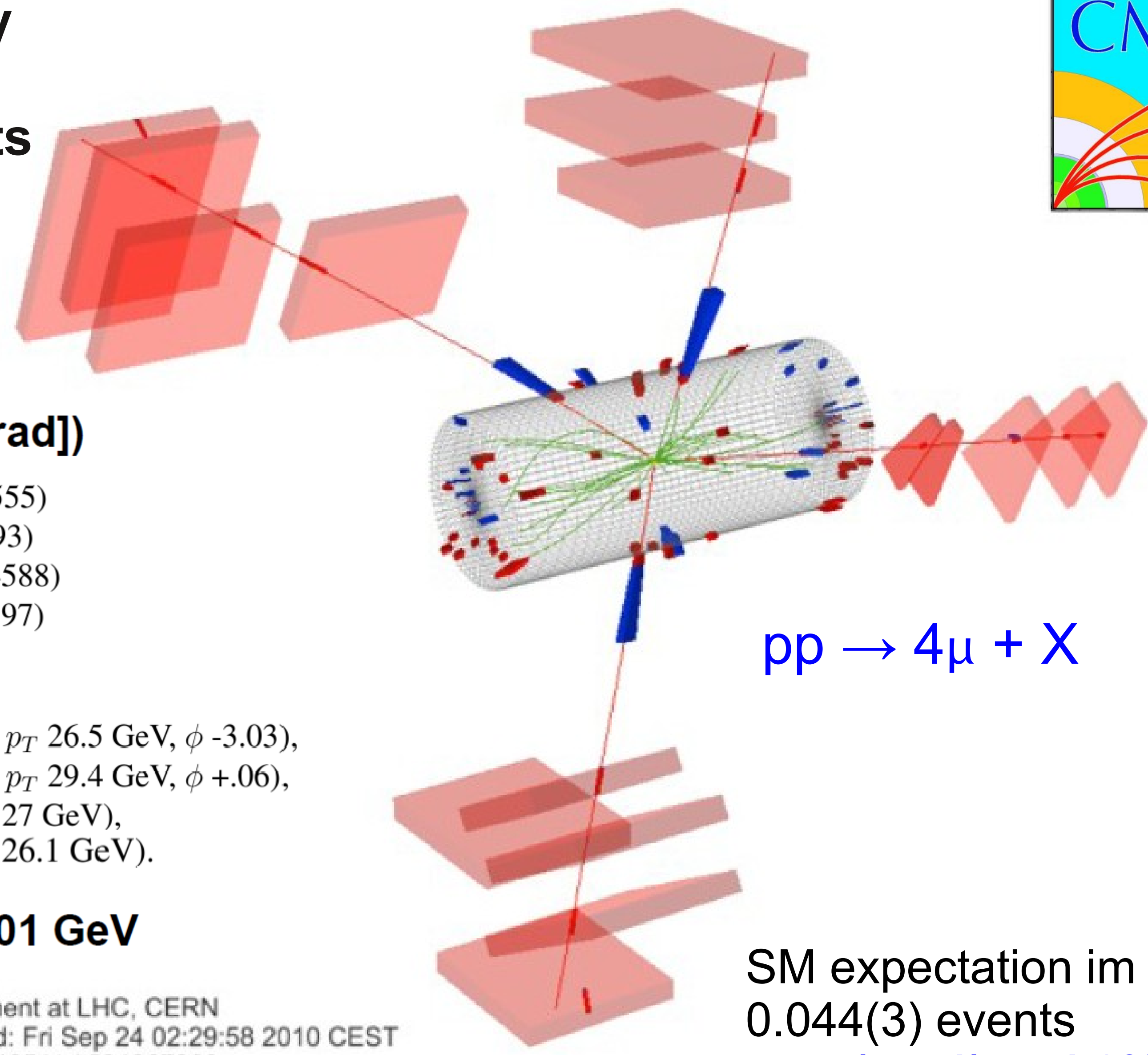


- Predicted in 70s after discovery of *b* quark
- EW precision data: radiative corrections to *W* and *H* mass → accurate prediction
- Discovered in 1995 by CDF atTevatron
- M_{top} ~ 178 GeV and very short lifetime (decay before hadronization)



Integrated Luminosity still small for cross section measurements

However, some exciting candidates!



Muons (p_T [GeV], η, φ [rad])

$\mu_0^-(48.1422, -0.412532, -1.92555)$
$\mu_1^+(43.4421, 0.204654, 1.79493)$
$\mu_2^+(25.8769, -0.782084, 0.774588)$
$\mu_3^-(19.5646, 2.01112, -0.980597)$

Invariant Masses

$\mu_0 + \mu_1$: 92.15 GeV (total(Z) p_T 26.5 GeV, ϕ -3.03),
$\mu_2 + \mu_3$: 92.24 GeV (total(Z) p_T 29.4 GeV, ϕ +.06),
$\mu_0 + \mu_2$: 70.12 GeV (total p_T 27 GeV),
$\mu_3 + \mu_1$: 83.1 GeV (total p_T 26.1 GeV).

Invariant Mass of 4μ: 201 GeV

CMS Experiment at LHC, CERN
Data recorded: Fri Sep 24 02:29:58 2010 CEST
Run/Event: 146511 / 504867308

pp → 4μ + X

SM expectation im 7/pb:
0.044(3) events
prob(N≥1) ≈ 4.2%