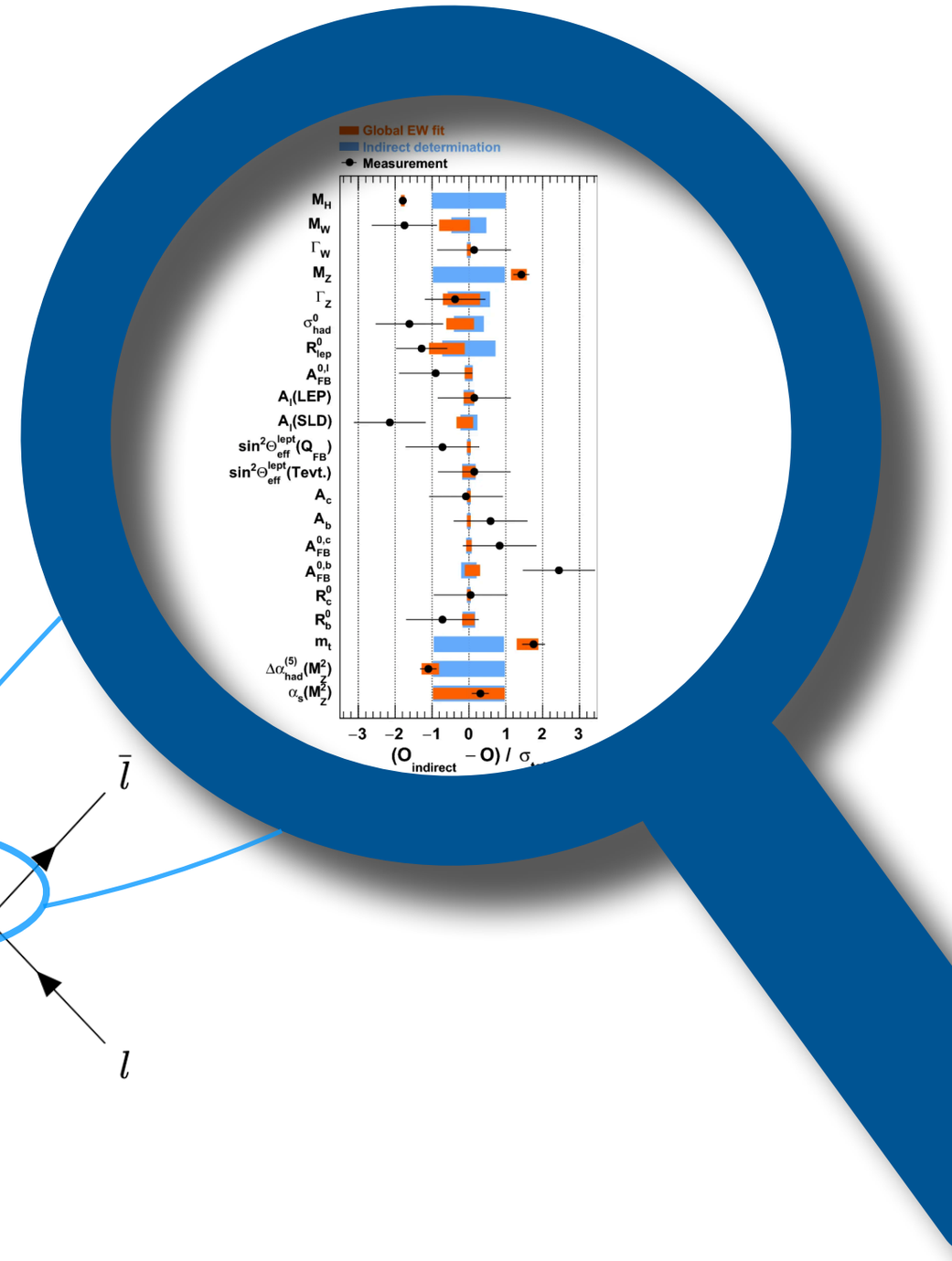
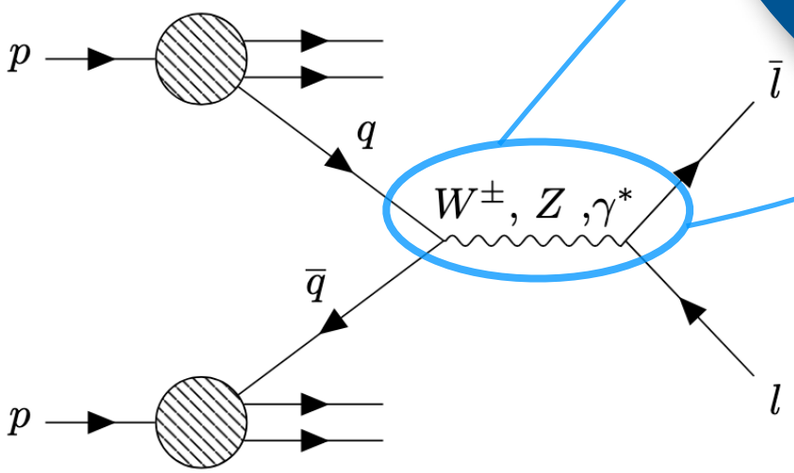
# Precision measurement @LHC with the ATLAS detector

DESY DAY 2024



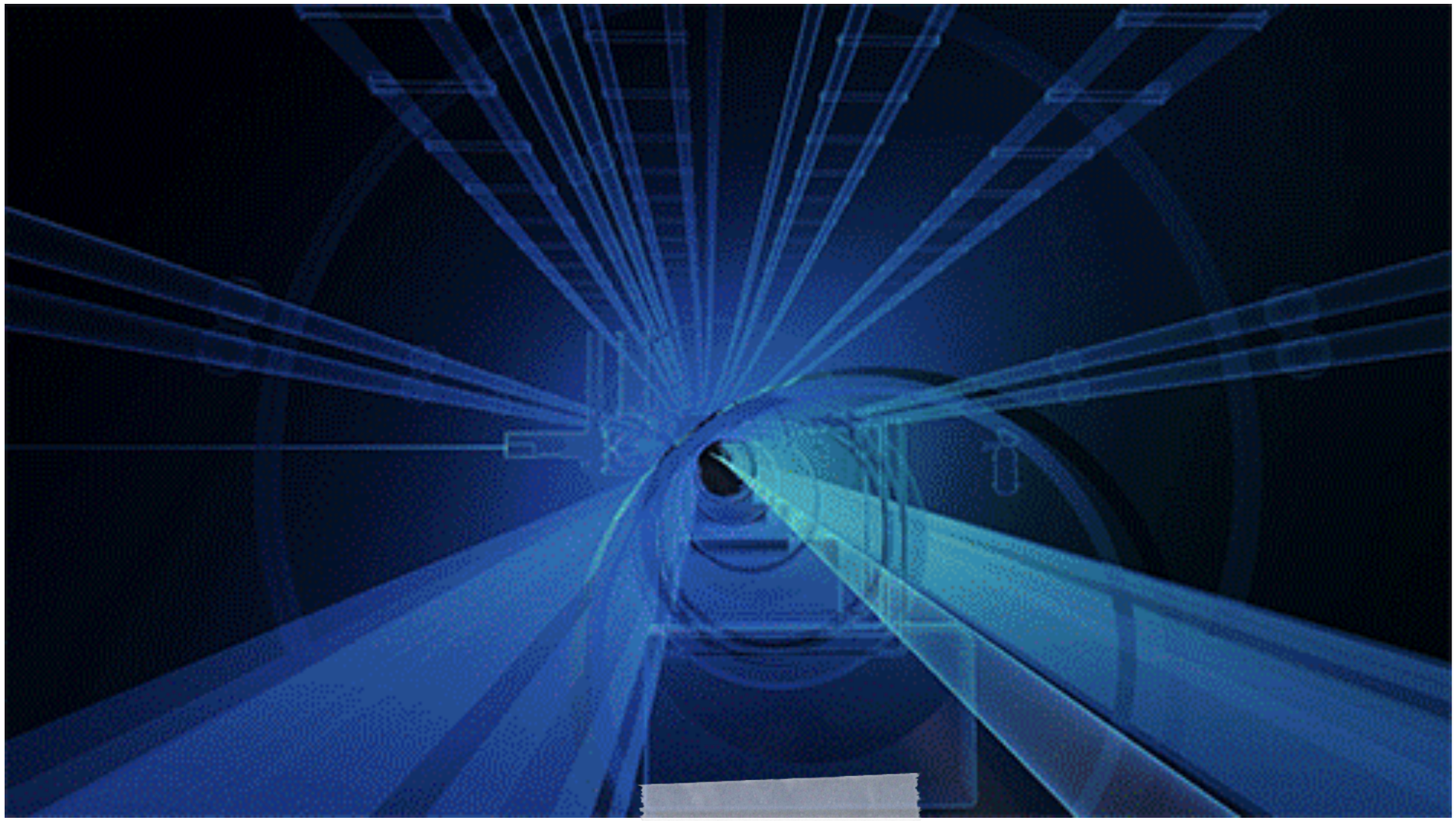


Ludovica Aperio Bella

DESY


14 November 2024

# LHC a discovery machine at energy frontier

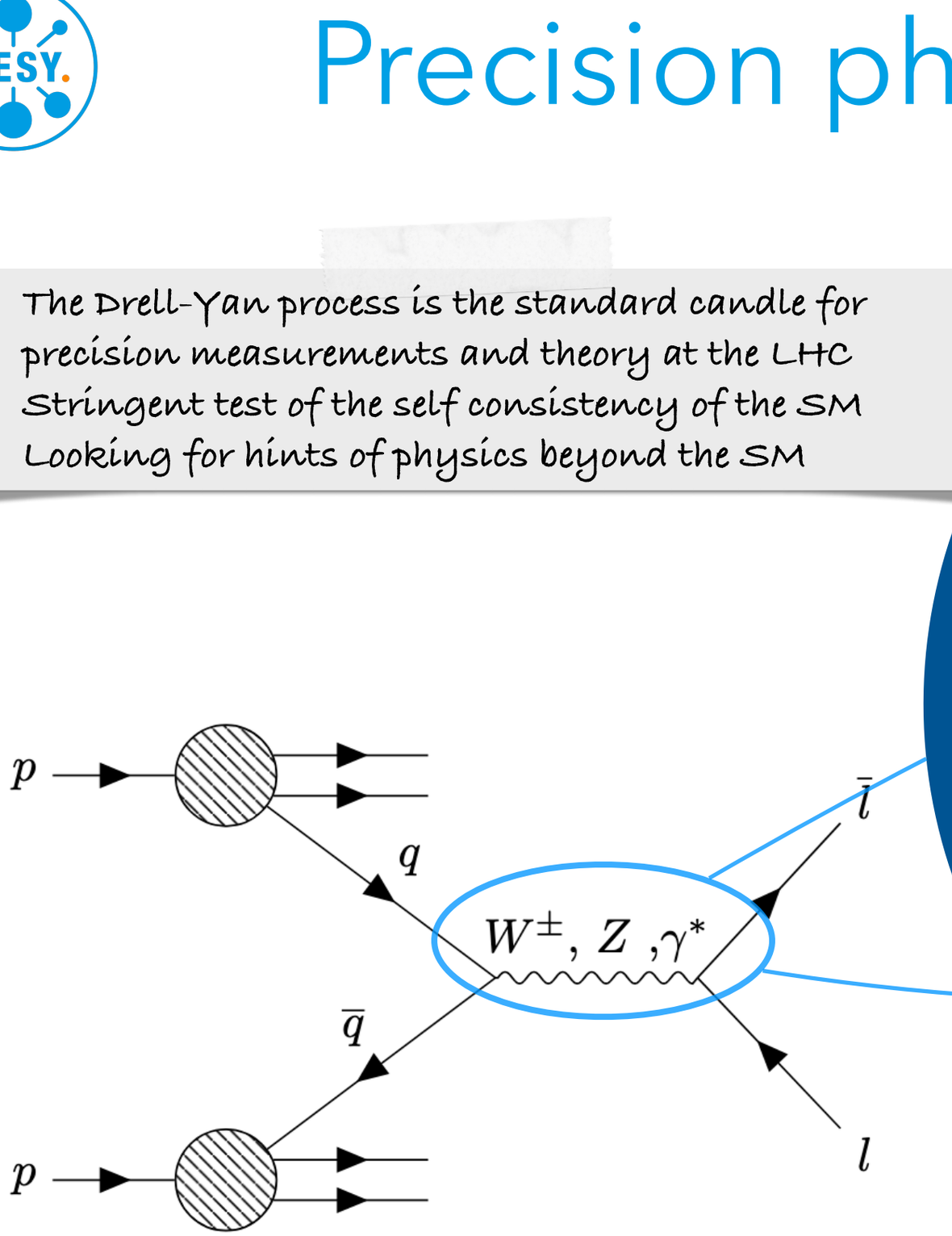


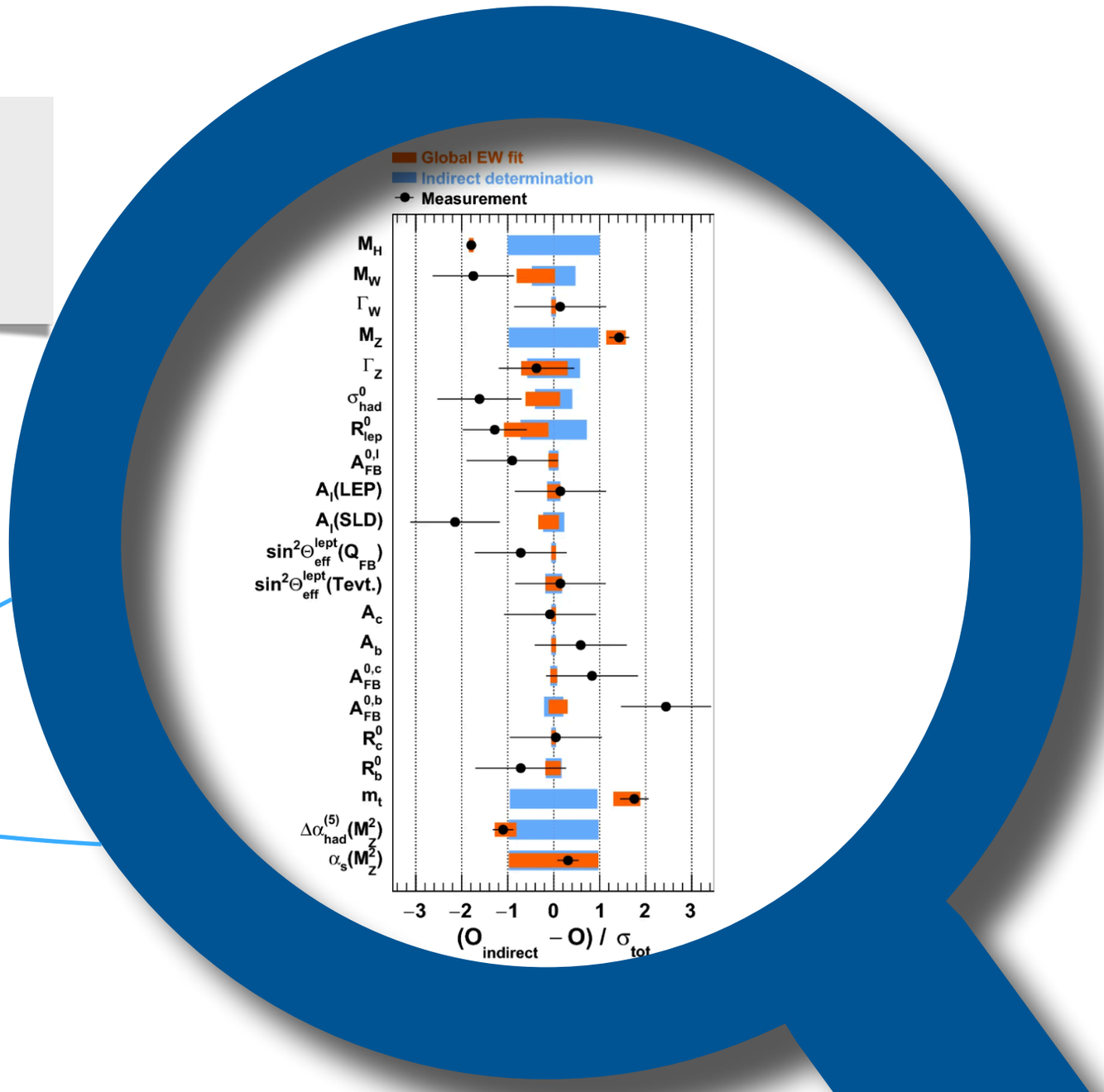
LHC was designed as *'discovery machine'* – explore a new energy regime

In the absence of direct signals for new physics, **precision** measurements of fundamental SM parameter could be the groundbreaking path for the next discovery.

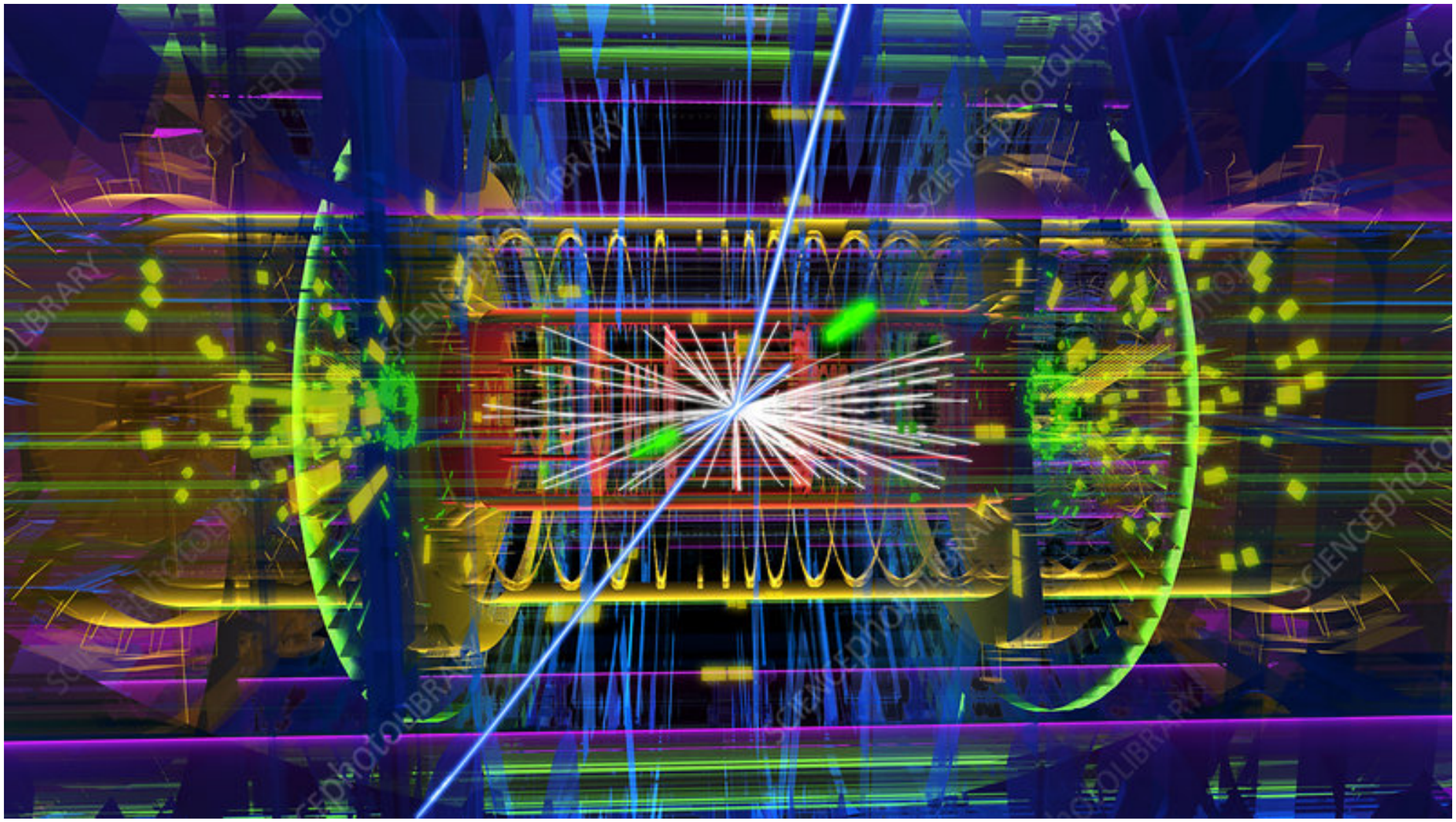
# Precision physics @ LHC

- The Drell-Yan process is the standard candle for precision measurements and theory at the LHC
- Stringent test of the self consistency of the SM
- Looking for hints of physics beyond the SM

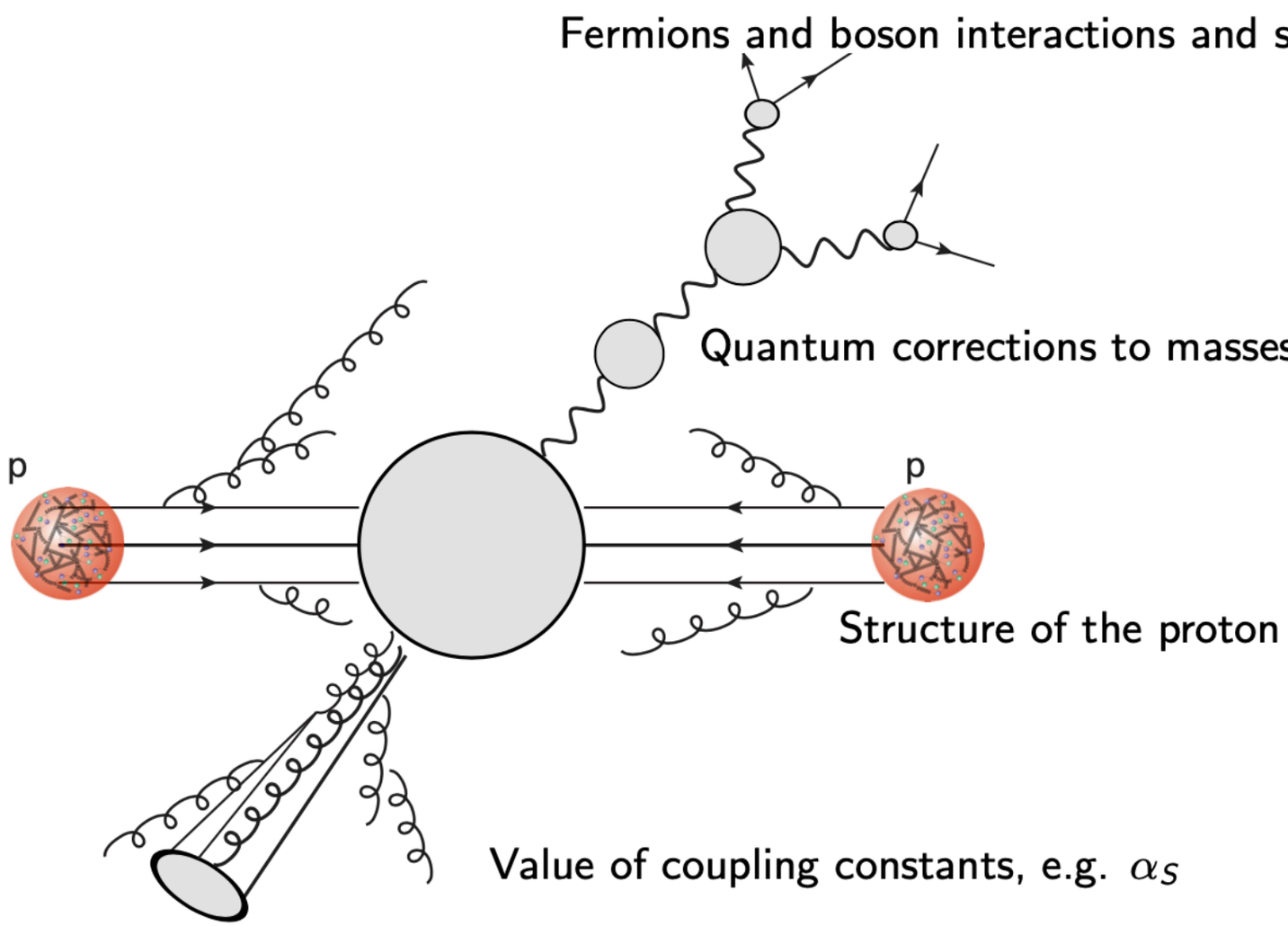


# Not obvious

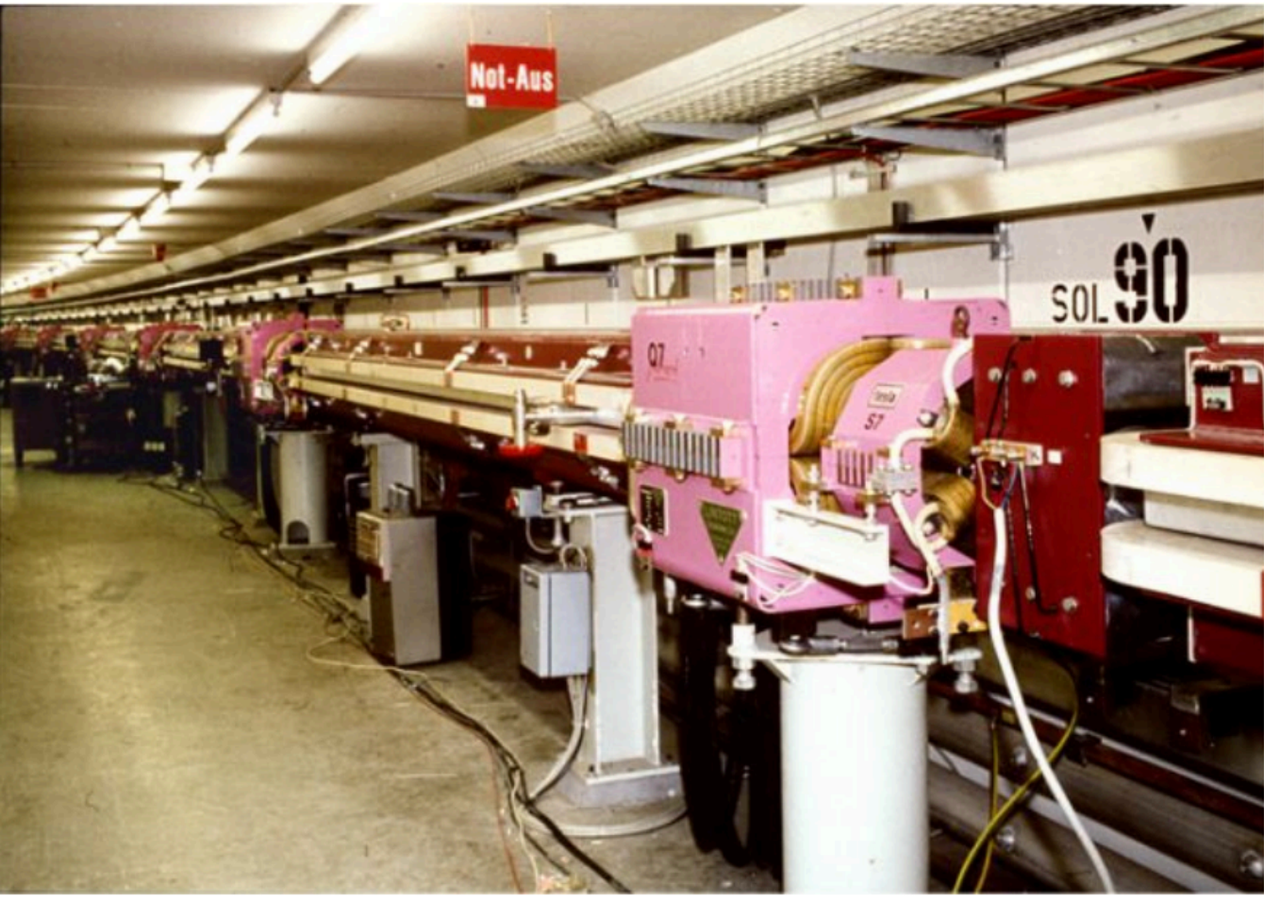


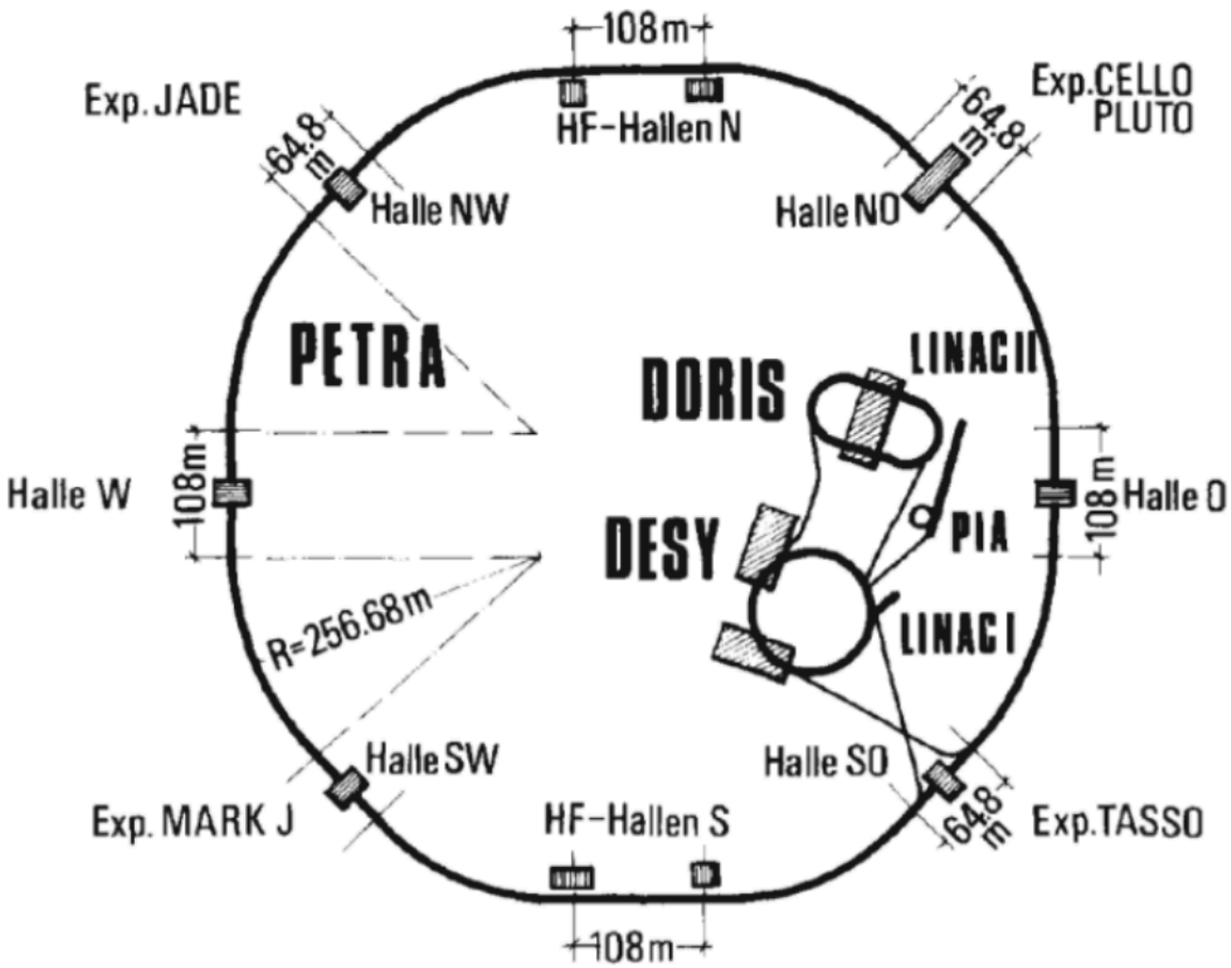
# LHC interaction are embedded in QCD




PETRA III

# back in time 1979




PETRA – an electron–positron collider with an initial centre-of-mass energy of 30 GeV [ Completed in 1978, far ahead of schedule and below budget. ]
PETRA was later upgraded to 46 GeV and, for the eight years of its lifetime, was the highest-energy electron–positron collider in the world.

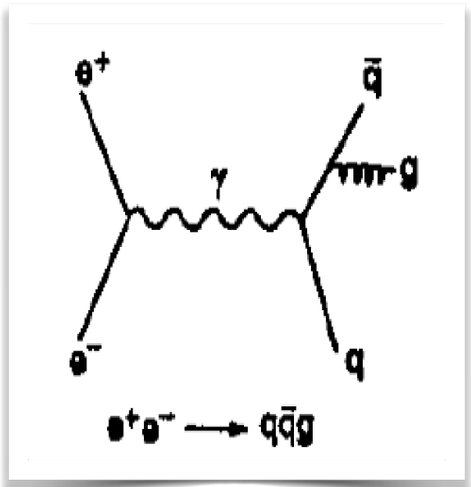
**EVIDENCE FOR PLANAR EVENTS IN $e^+e^-$ ANNIHILATION AT HIGH ENERGIES**

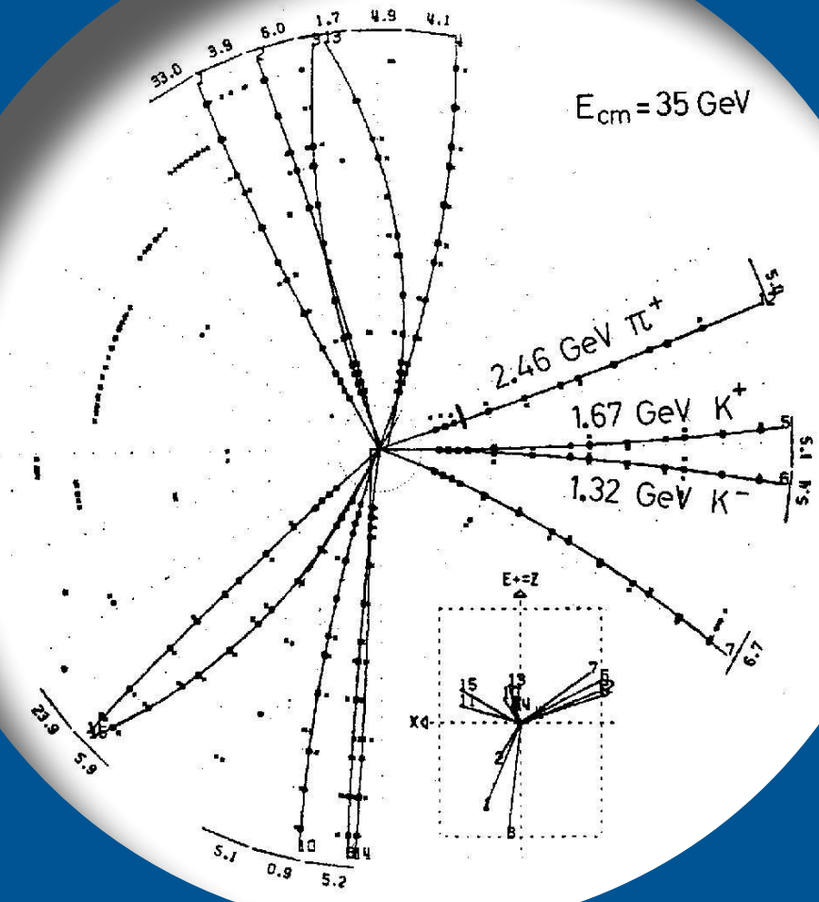
TASSO Collaboration

R. BÜHRING, R. FOHRMANN, D. HEYLAND, H. HULTSCHIG, P. JOOS, W. KOCH, U. KÖTZ, H. KOWALSKI, A. LADAGE, D. LÜKE, H.L. LYNCH, G. MIKENBERG[2], D. NOTZ, J. PYRLIK, R. RIETHMÜLLER, M. SCHLIWA, P. SÖDING, B.H. WIIK and G. WOLF

*Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany*

Received 29 August 1979




Typical 3 jet event in the TASSO detector: Two quarks produced in an e+e- collision emit a gluon; each of the particles turn into a jet of particles.

The year 1979 TASSO experiment saw the first observation of three-jet events at PETRA, leading to the discovery of the gluon and a measurement of its spin.

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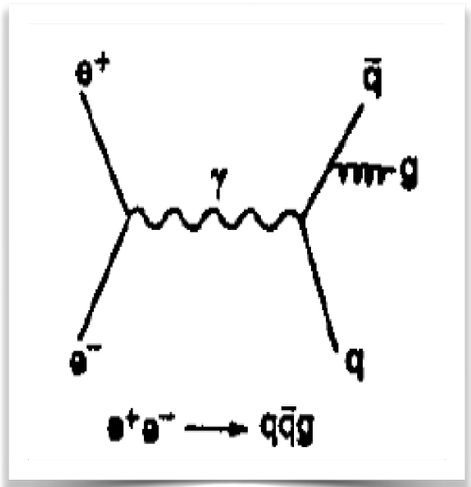



## 1995 EPS High Energy & Particle Physics Prize

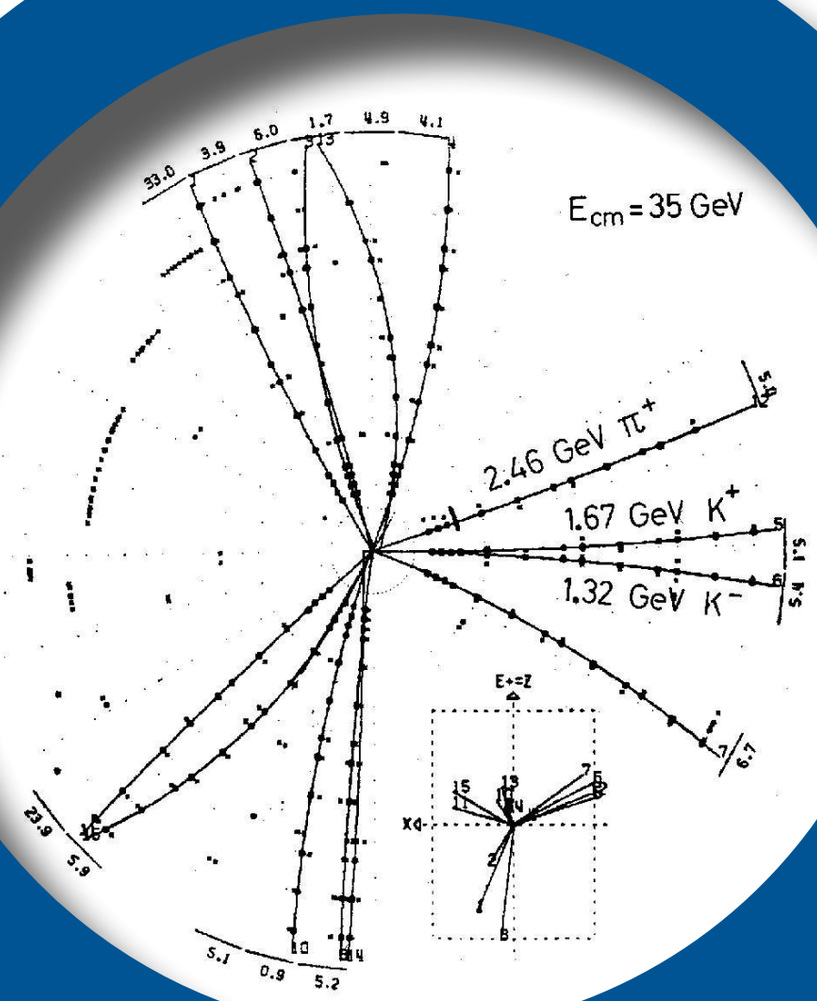
The EPS High Energy and Particle Physics Division (HEPP) has awarded the 1995 High-Energy and Particle Physics Prize to:

**Paul Söding**, DESY-Institute of High-Energy Physics, Zeuthen
**Björn Wiik**, Deutsches Elektronen-Synchrotron (DESY), Hamburg
**Günther Wolf**, DESY, Hamburg
**Sau Lan Wu**, University of Wisconsin, Madison, Wisconsin, USA.

for the first evidence for three-jet events in $e^+e^-$ collisions at PETRA, the 2.3 km in circumference storage ring at DESY which started operating in November 1978.

This important experimental contribution, first reported in June 1979, was the result of a large joint effort by accelerator and experimental particle physicists based both at DESY and collaborating institutes. It was obtained while the prizewinners were working with the TASSO detector, one of the four experiments initially installed at PETRA. It generated considerable interest and stimulated an enormous analytical effort because a possible interpretation invoked the creation of gluons by quark bremsstrahlung (in three-jet events, two jets — small bundles of several high-energy particles — originate from a quark and an anti-quark and a third jet from a radiated gluon).

The Prize was presented by the Chairman of the HEPP Division to the four prizewinners at the *1995 International Europhysics Conference on High Energy Physics* (Brussels; 27 July - 2 August 1995).

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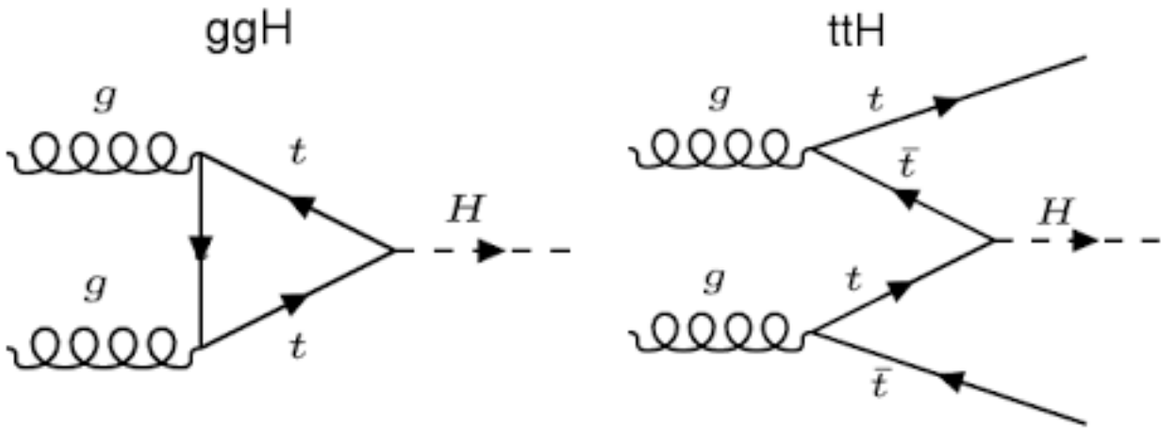
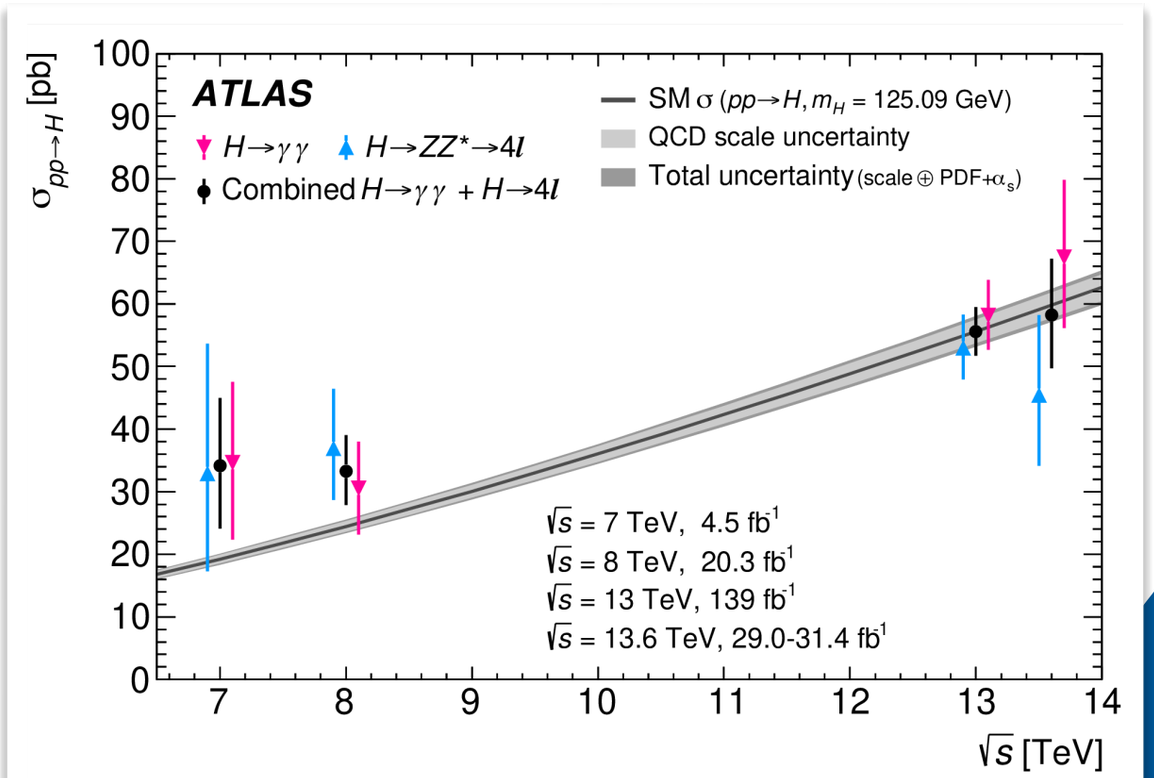
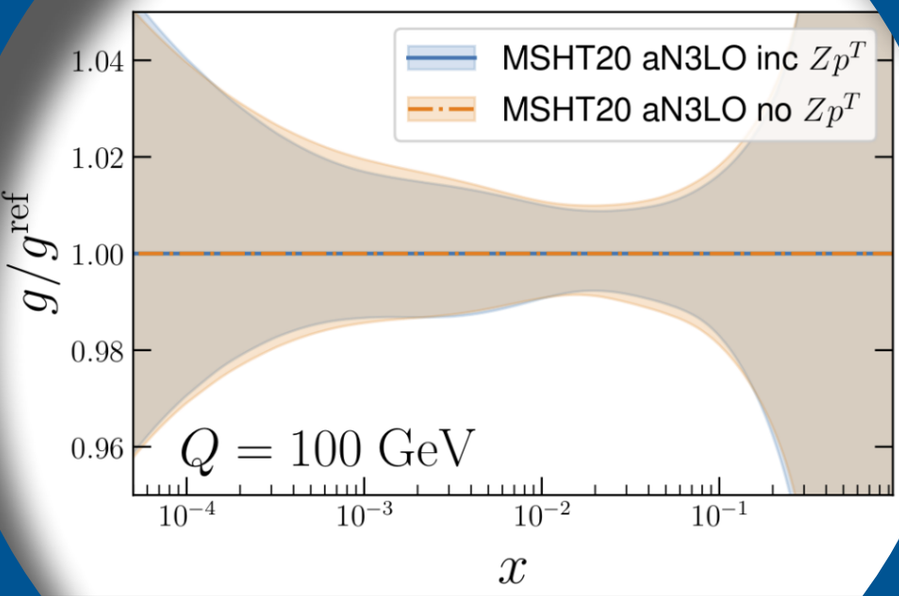
From 1988 to 2007 PETRA II was used as a pre-accelerator for the HERA lepton hadron collider ring.



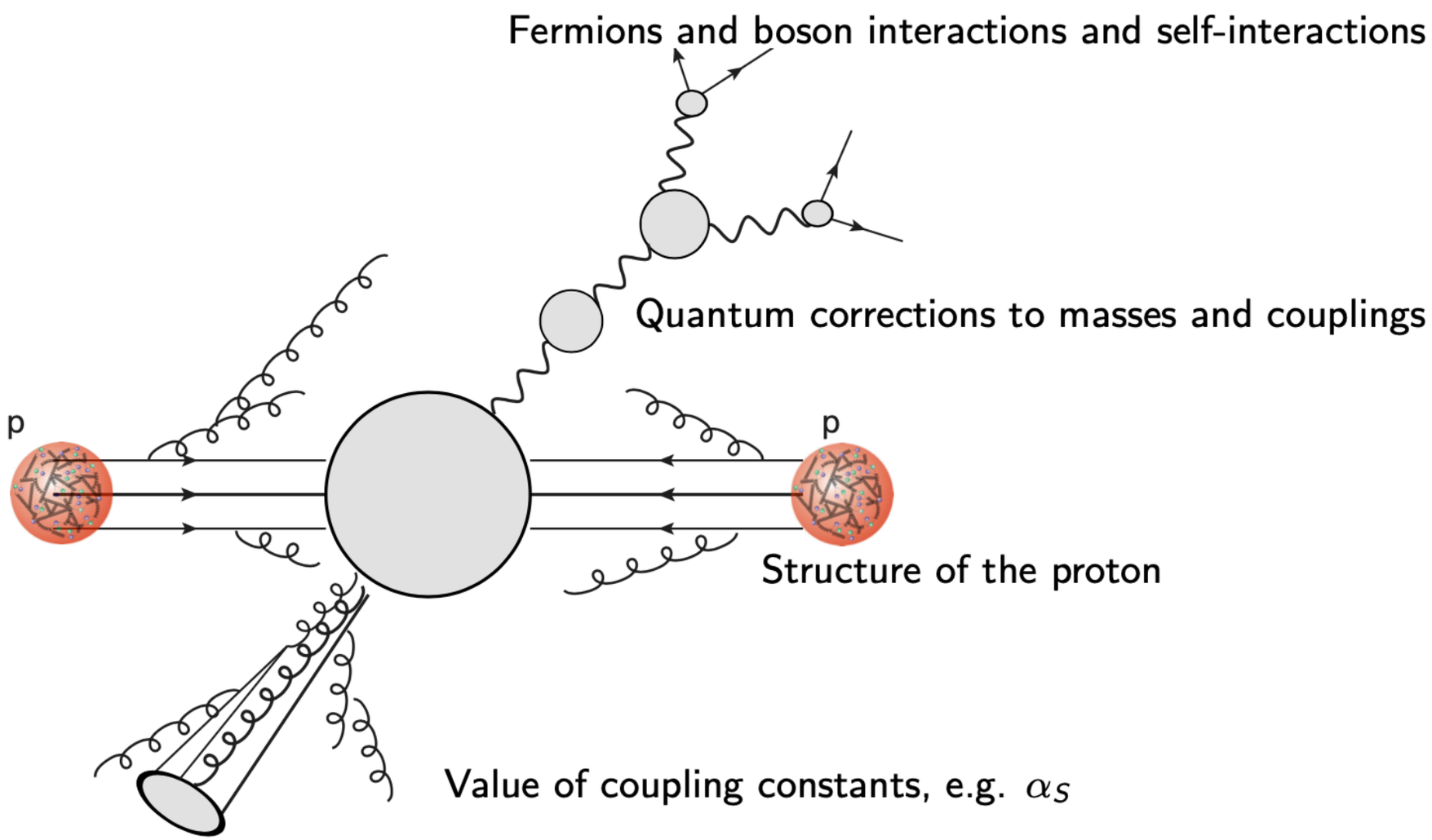




T. Cridge, L. A. Harland-Lang, R. S. Thorne, arXiv:2312.12505

(..) HERA physics exploitation resulting in the measurement of the proton´s structure in new kinematic regions of vital importance in confronting new aspects of quantum chromodynamics, and enabling discoveries at the Large Hadron Collider.

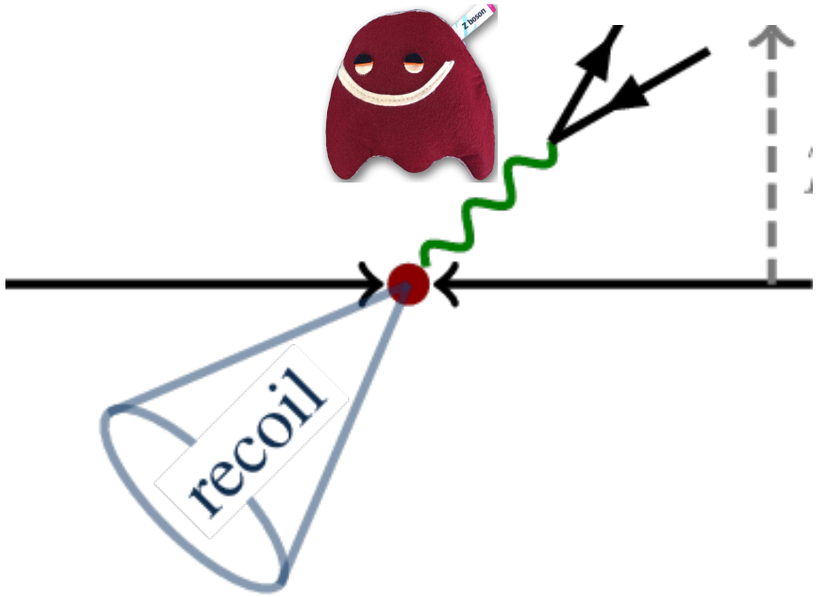
# How precise we can measure SM at LHC is strongly connected with the knowledge of QCD



# Transverse momentum of boson spectra

- very precise $p_T^V$ **modelling is a challenge for QCD theory** ( resummation, heavy flavour, multiple scale, no pQCD )
  - correct and precise modelling of the $p_T^W$ crucial input for $m_W$ **precision**
  - **Experimentally** very precise $p_T^Z$ measurement but $p_T^W$ precision limited by experimental resolution
  -

fundamental concept : in pp collision the Z boson is boosted in the transverse plane if some hard radiation are emitted by the incoming quarks.



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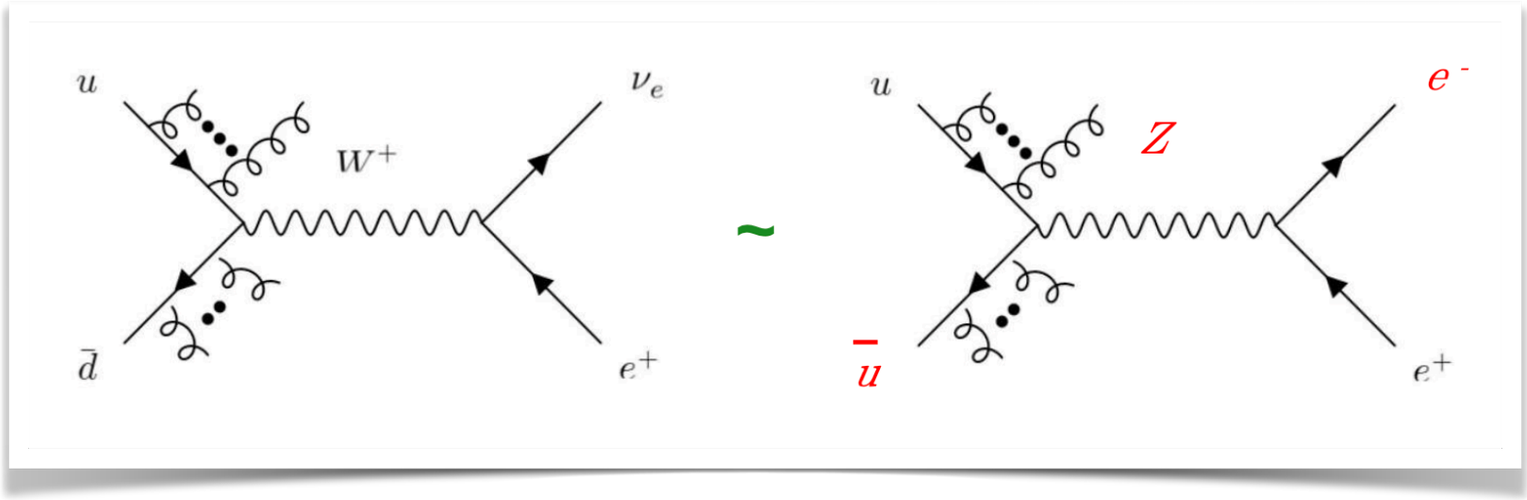

# bonus: Transverse momentum of boson spectra

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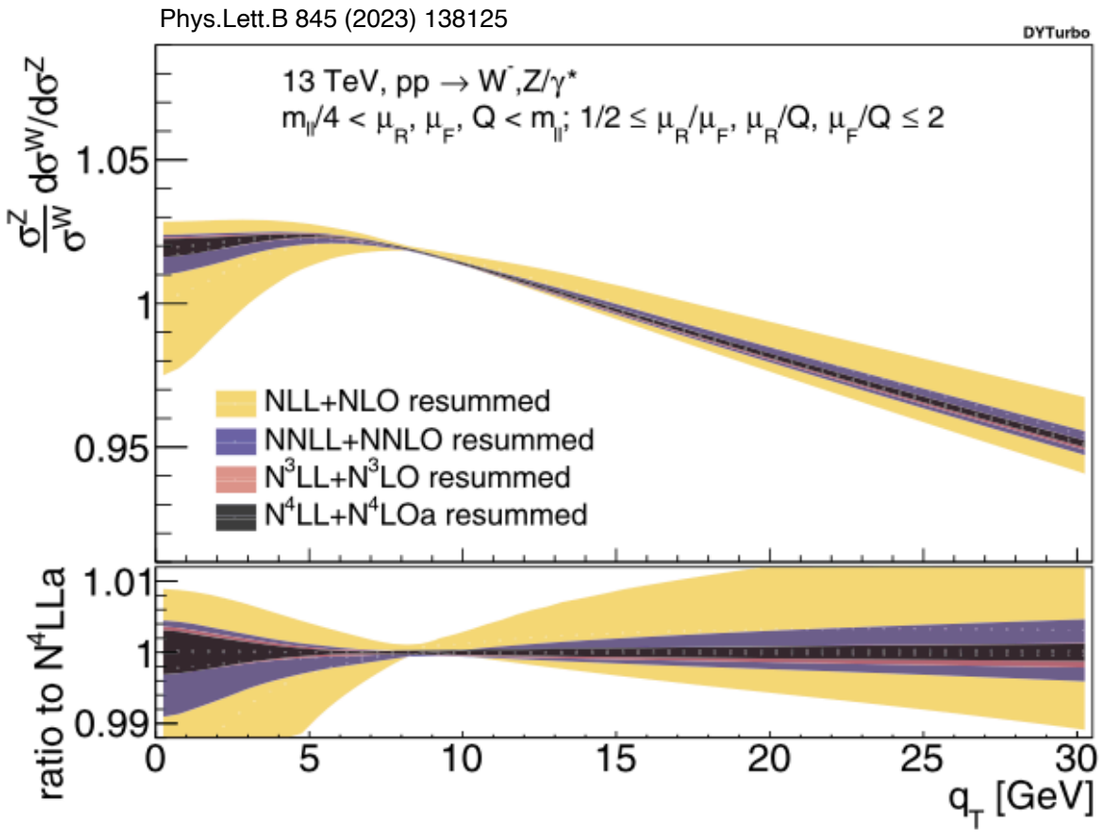
*current days several improvements done on analytic resummation programs ( improved treatment of HFI production, higher orders etc )*



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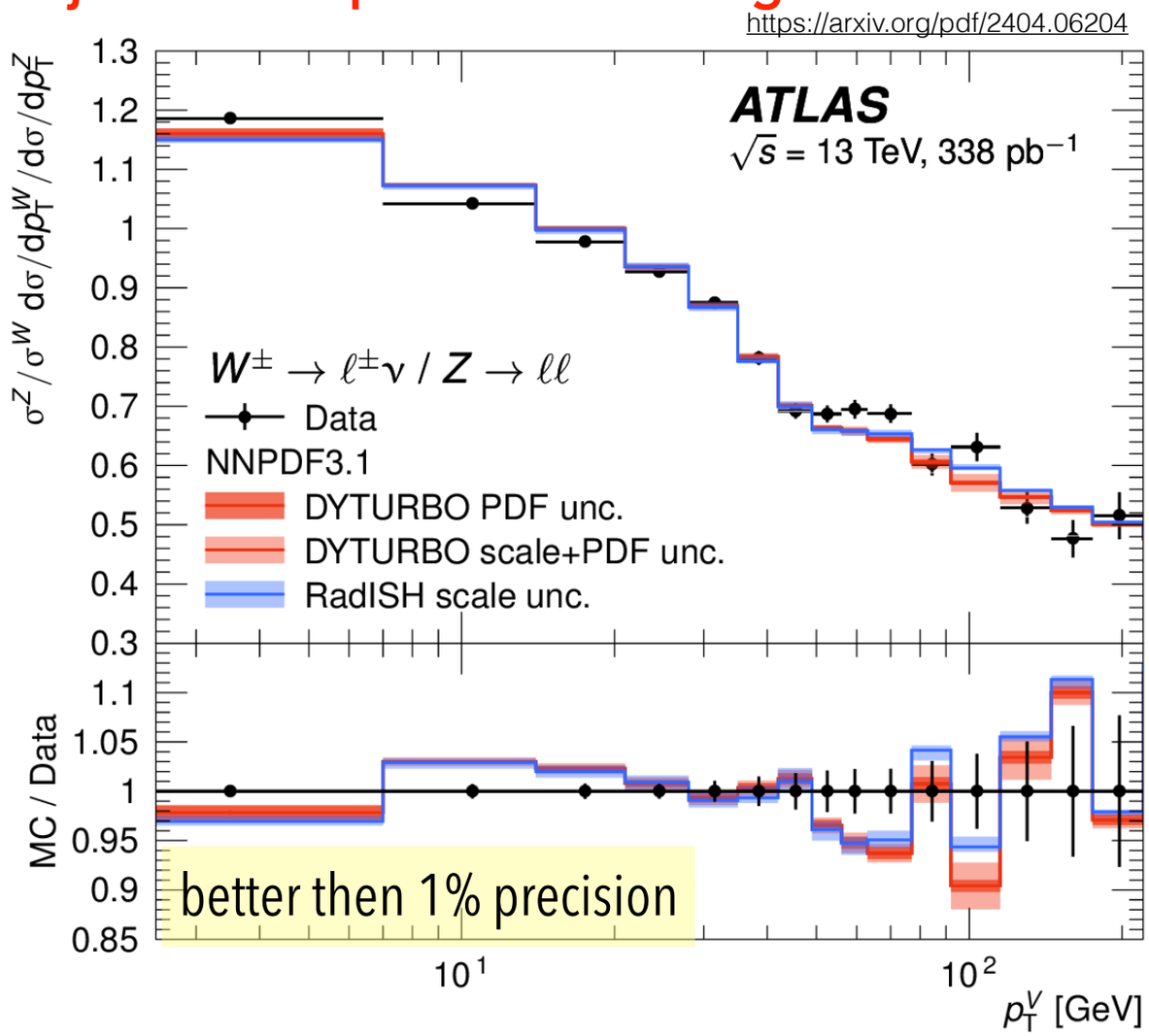
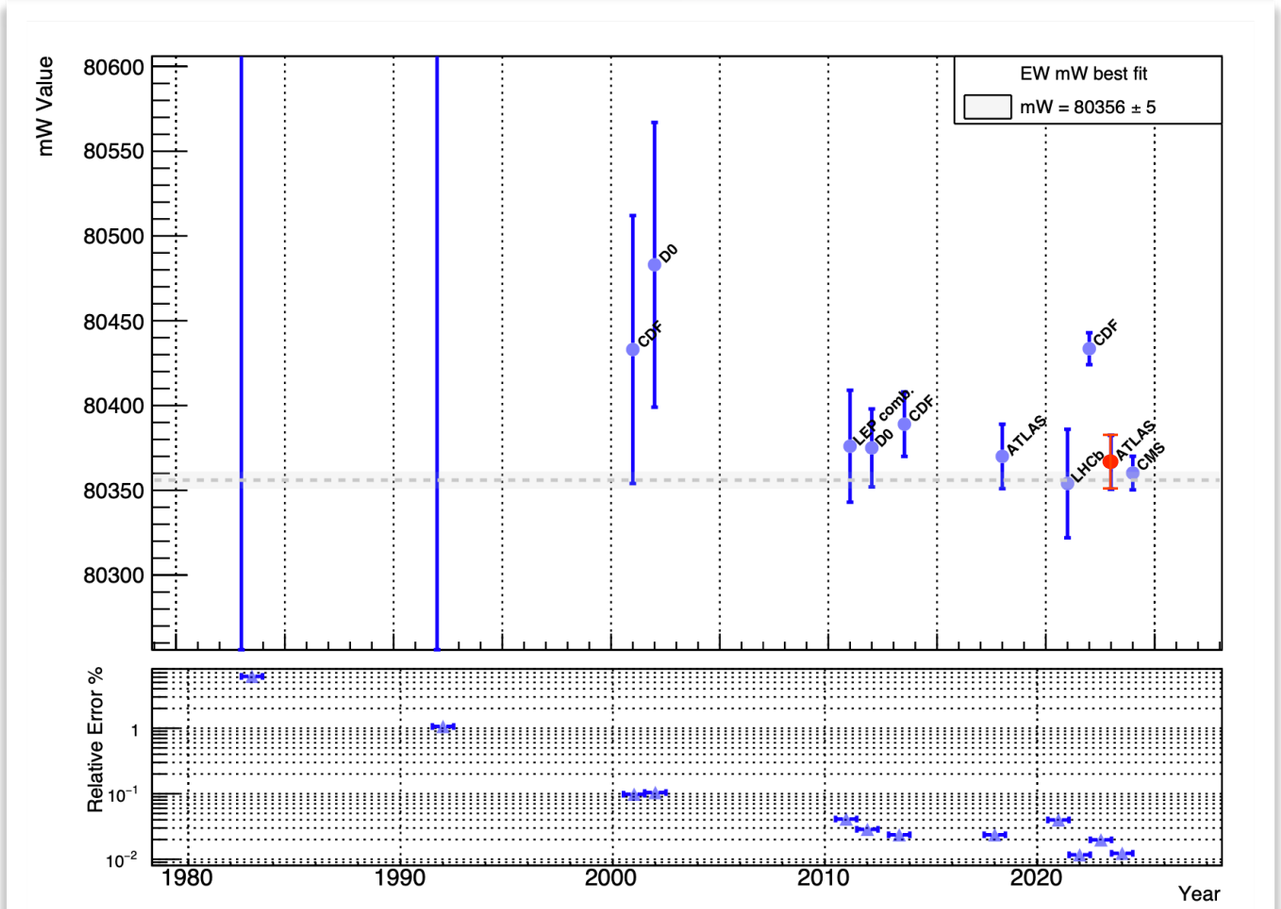
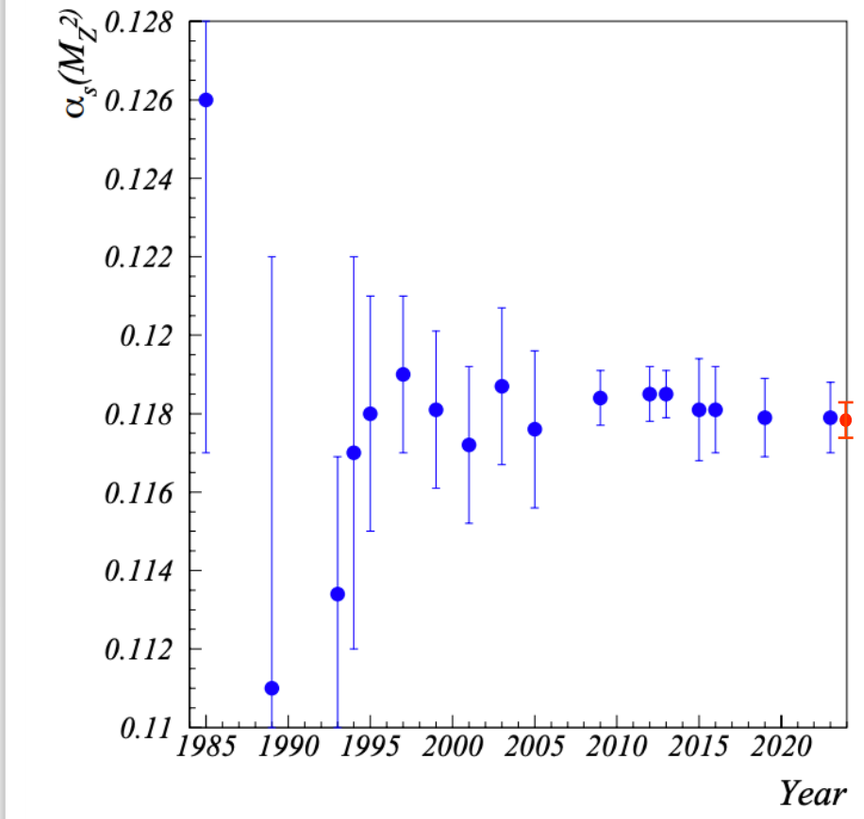
Extensive set of W,Z X-section measurements using ATLAS low-mu data (5 TeV and 13 TeV)
First measurement of $Wp_T$ in very fine bins in the soft part of the spectra
Goal measurement of the Z/W $p_T$ ratio to validate the $p_T$ W modelling uncertainty in future ATLAS $m_W$ measurement.

https://arxiv.org/pdf/2404.06204



# How precise we can measure SM at LHC ?

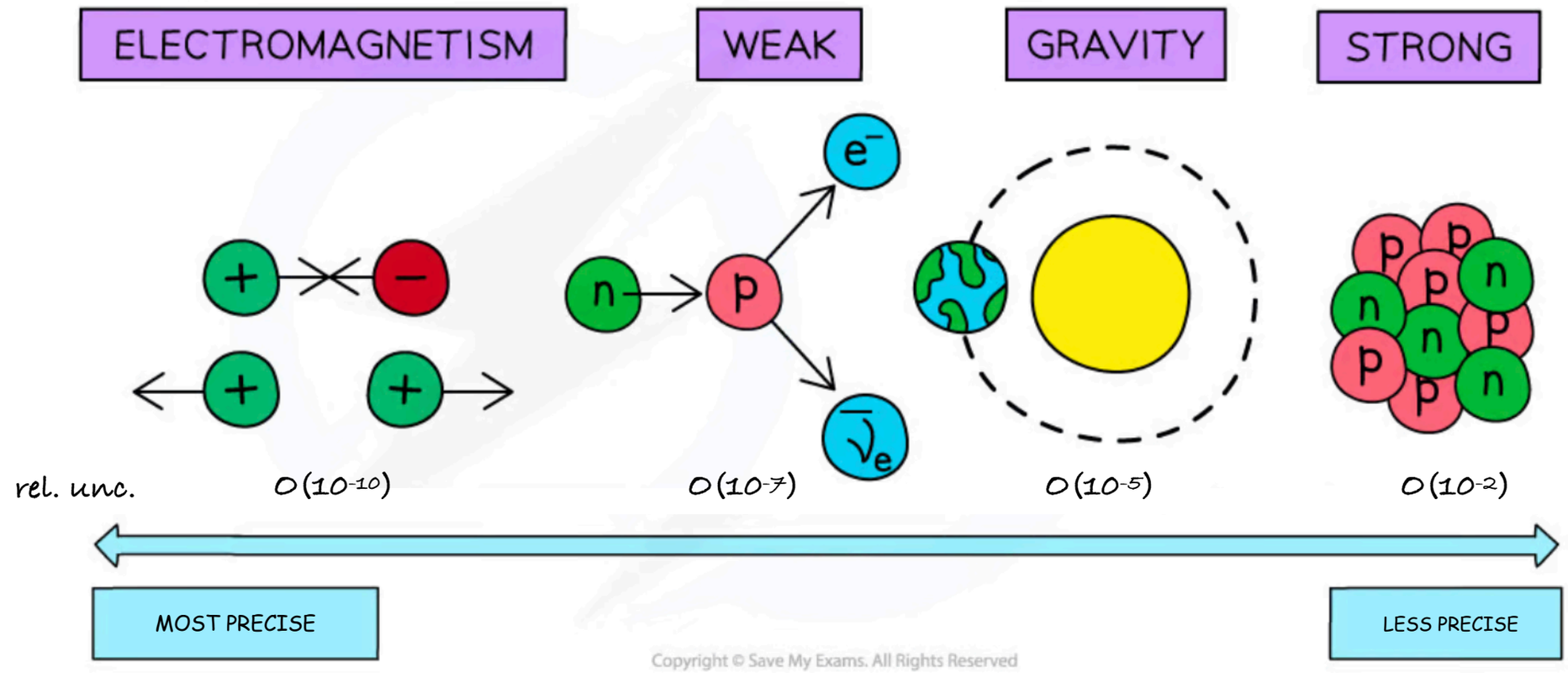



mW
alphaS
sin2TW

# why measuring $\alpha_s$ ? The strong coupling

The strong coupling, αs, is one of the **fundamental parameters** of the Standard Model… however is the ***least known fundamental force of nature*** …

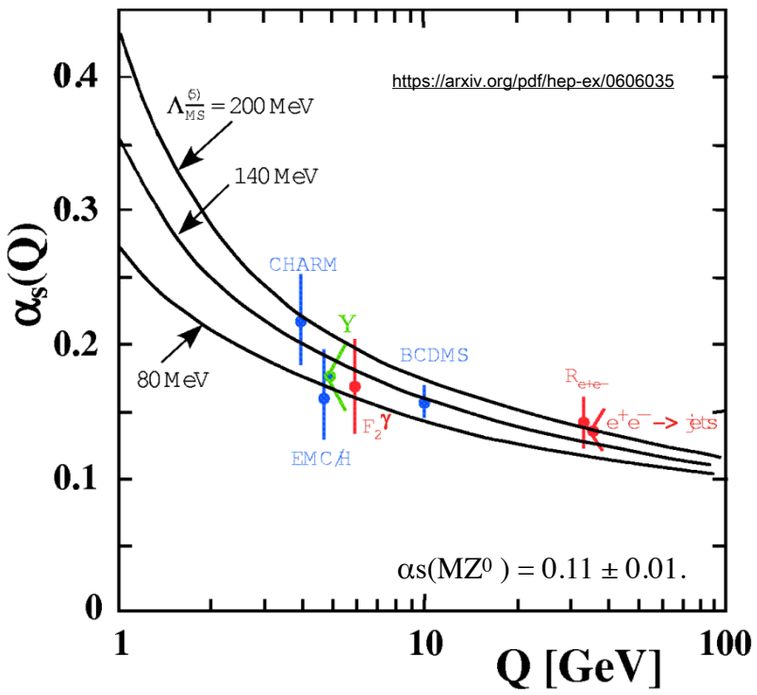




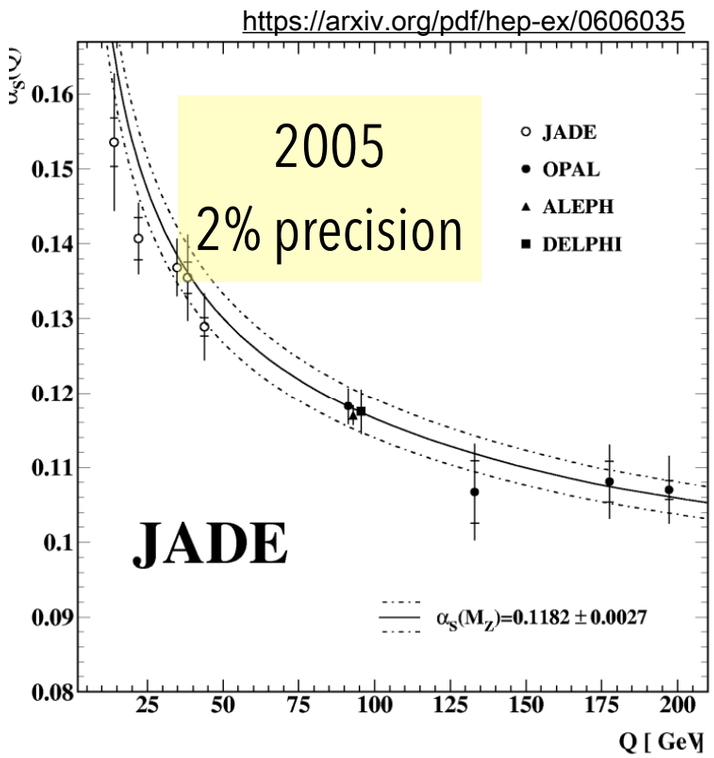
… as the LHC experiments' work evolves towards precision physics, accurate knowledge of the strong coupling is becoming increasingly important ( G. Salam )

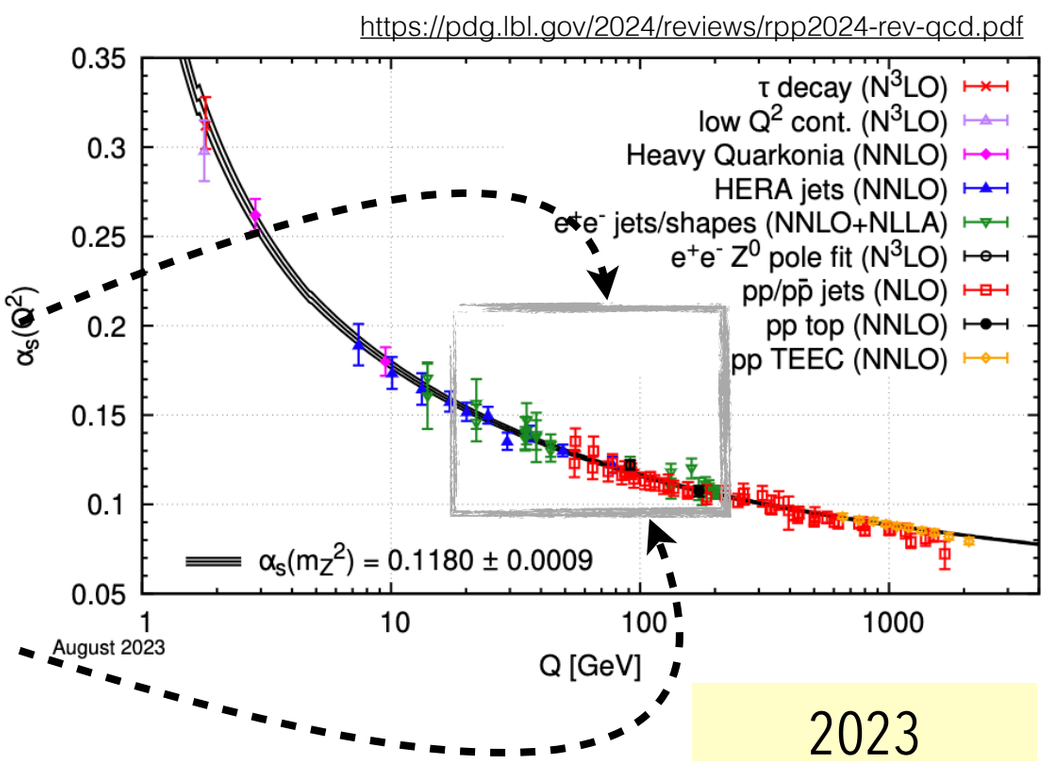
# The history of $\alpha_s$ measurements

**αs is determined at a ref. scale (Q=mZ ), decreases ("runs") as $\alpha_s \approx \ln(Q^2/\Lambda^2)^{-1}$**




1989
10% precision



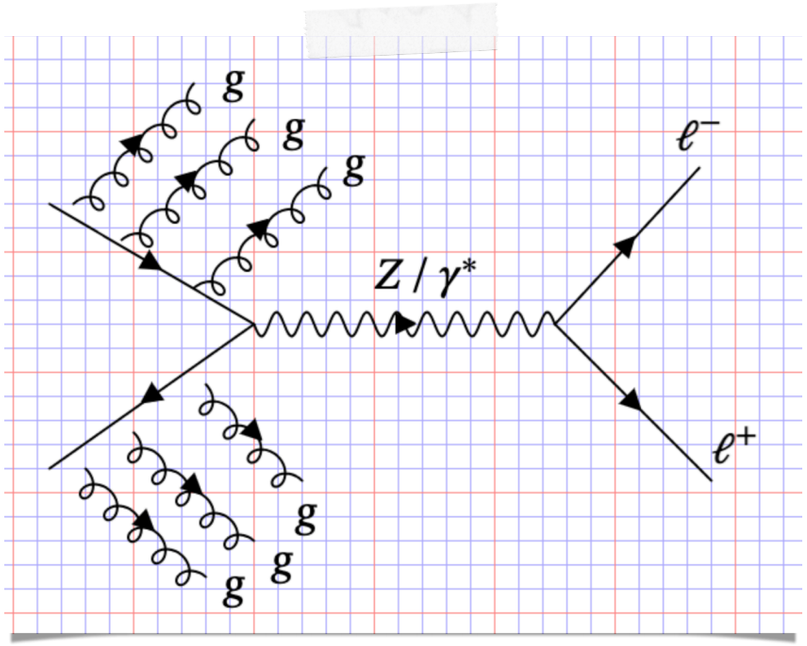



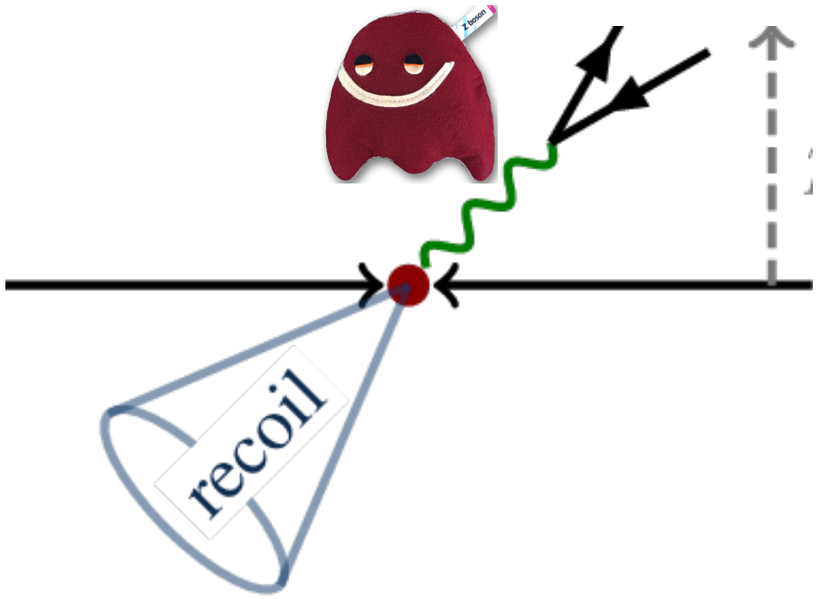

2023
0.8% precision

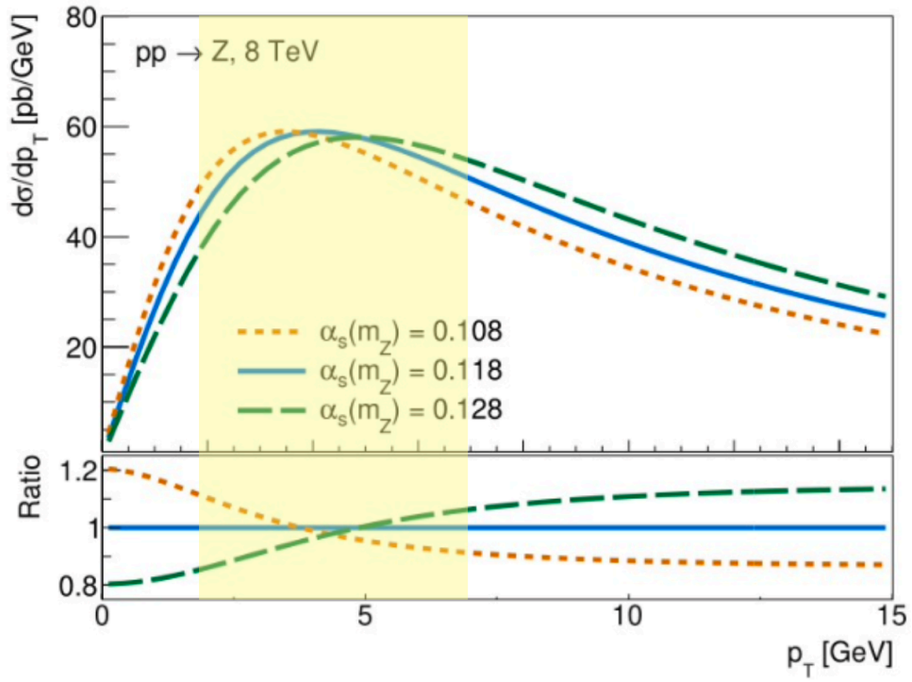
- The effort of measuring the strong coupling constant has a **long history of more than 35 years.**
- World $\alpha_s(m_Z)$ determination (August 2023) is done by comparing 7 experimental observables to pQCD NNLO,$N^3$LO predictions, plus global average at the Z pole scale.

# NEW $\alpha_s$ measurement

fundamental concept : in pp collision the Z boson is boosted in the transverse plane if some hard radiation are emitted by the incoming quarks.



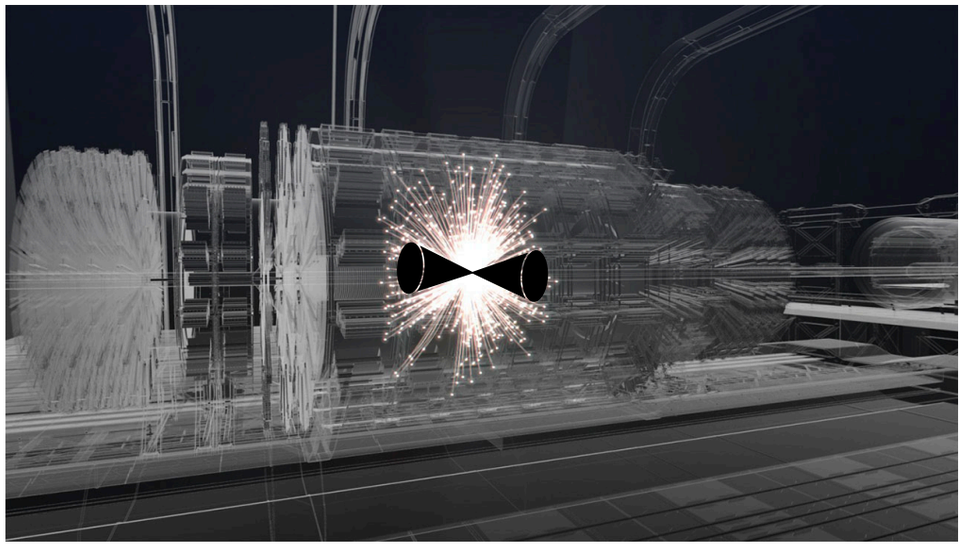

The peak region of the transverse momenta spectra has linear sensitivity to $\alpha_s$

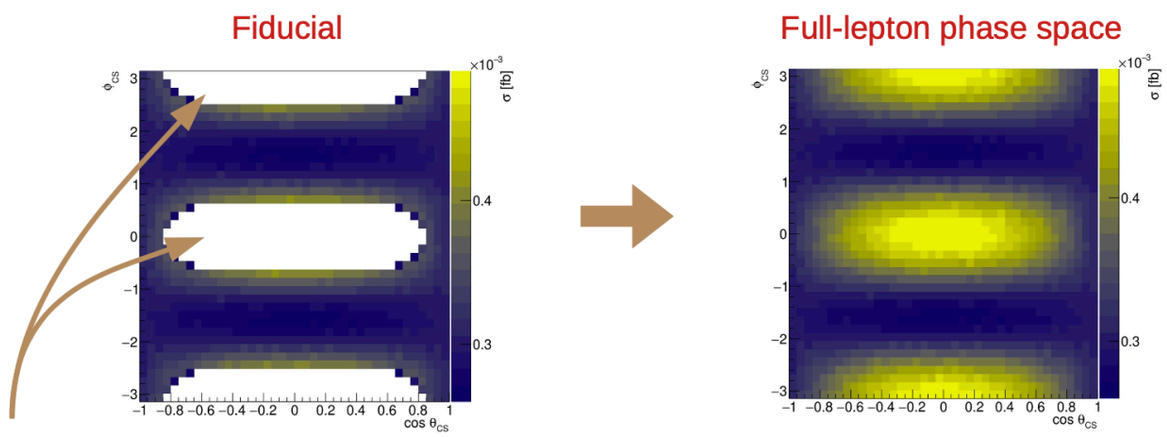
# Innovative experimental methods

**SMART IDEA: Exploit some powerful properties of the SM for DY production**

- **provides analytic extrapolation of experimental selection to measure the cross-section in the full face space**

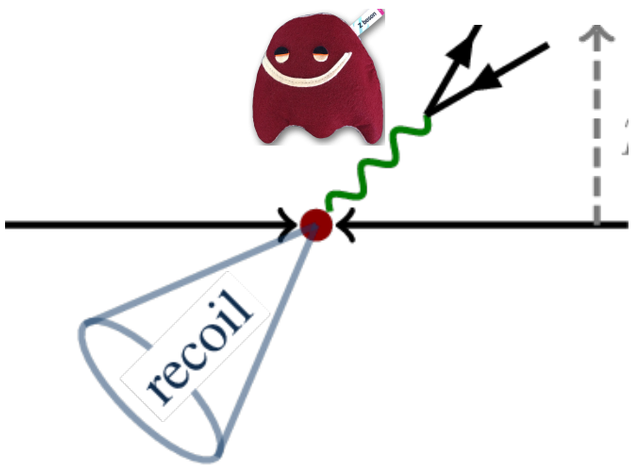
$$\frac{d^3\sigma^{U+L}}{dp_T dy dm}\left(1+\cos^2\theta+\sum_{i=0}^{7}A_i(y,p_T,m)P_i(\cos\theta,\phi)\right)$$



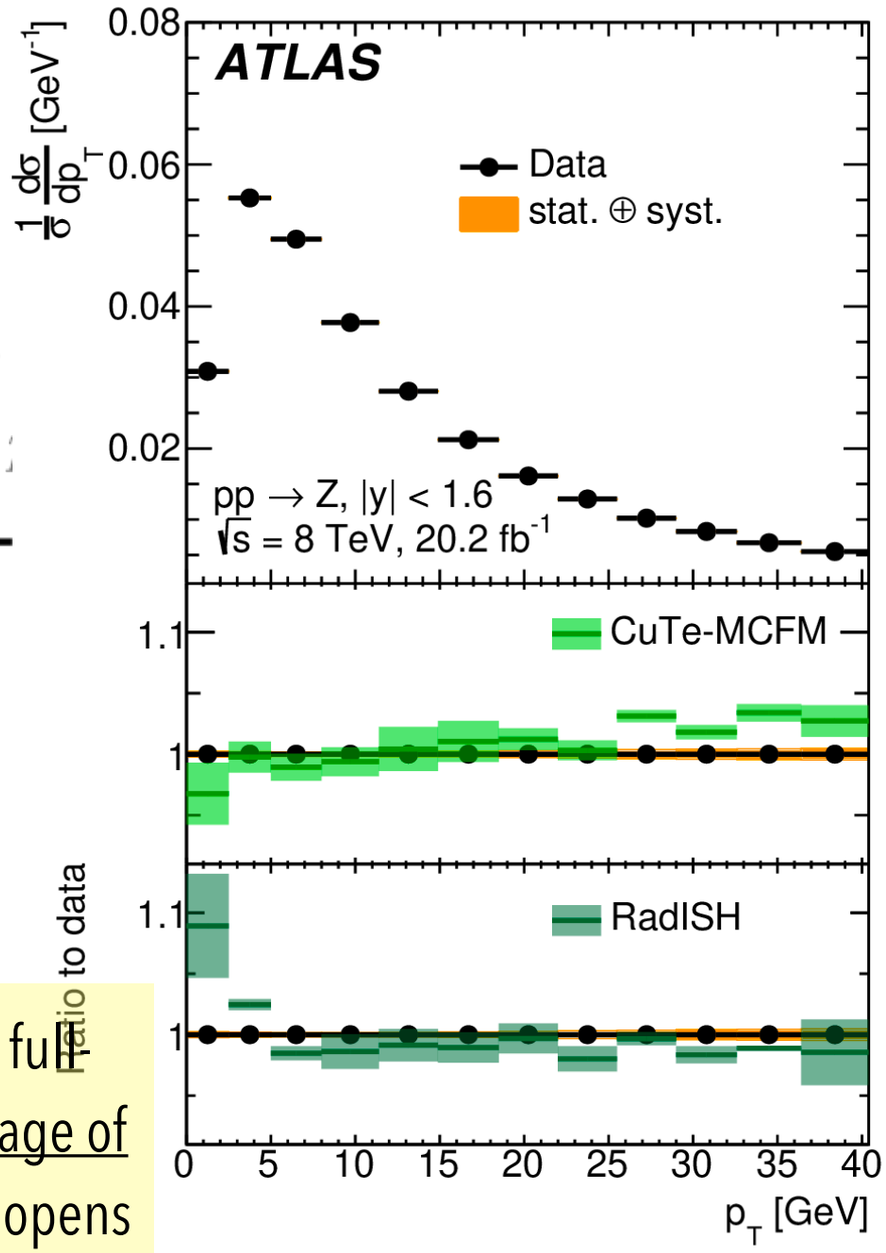



Effect of $p_T(\ell)$ and $\eta(\ell)$ cuts at fixed boson $p_T$,y,m

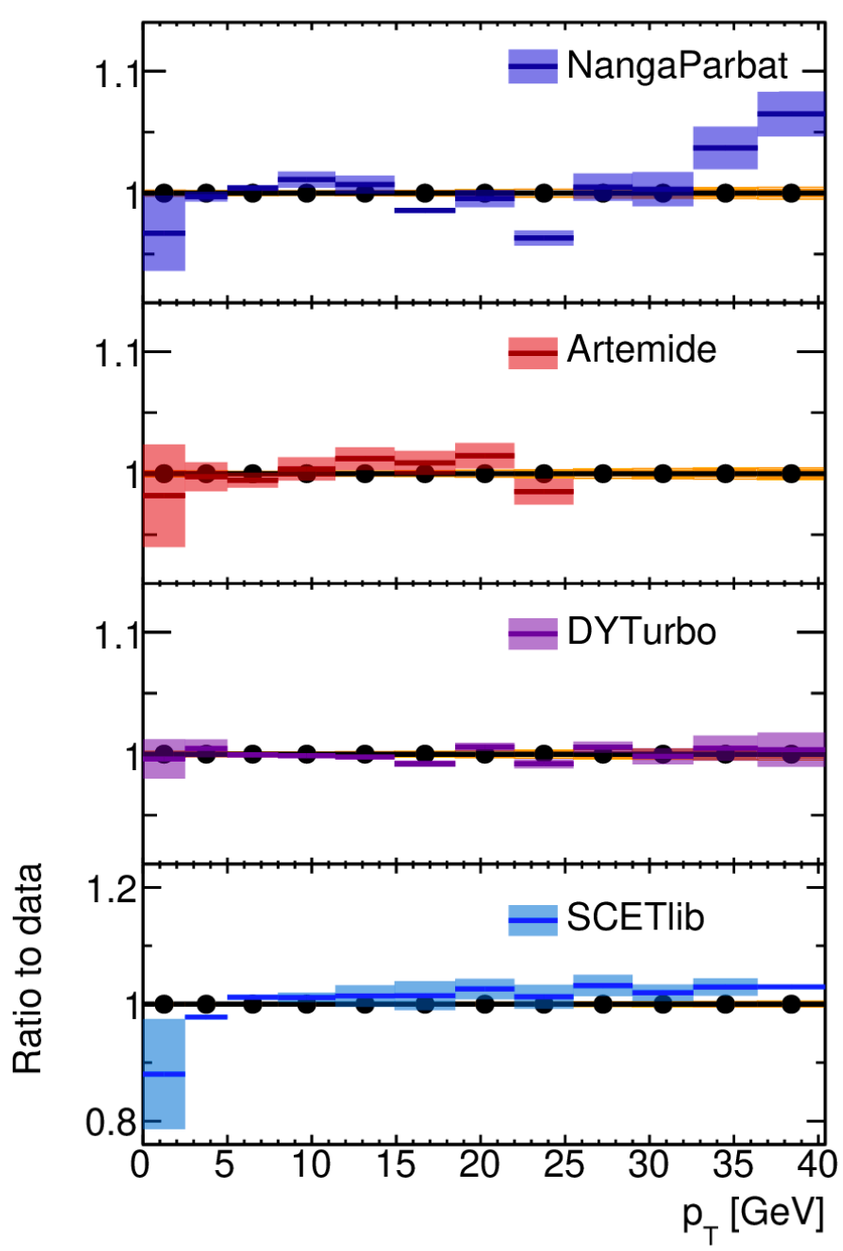
# very new experimental methods




$p_T^Z$ cross section measured in full-lepton phase space enables usage of state of the art predictions and opens new avenues for precise phenomenological interpretations




https://arxiv.org/pdf/2309.12986



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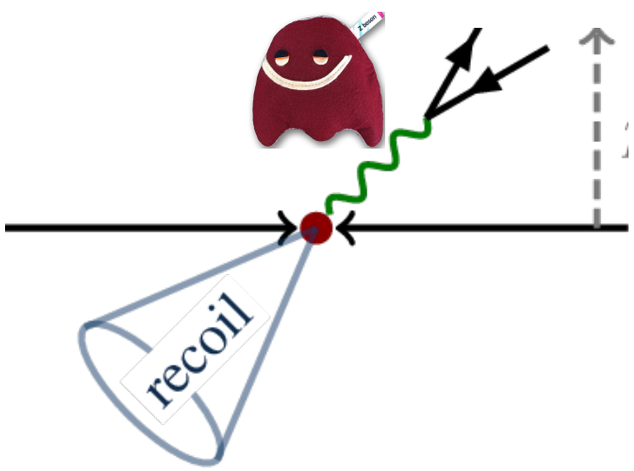


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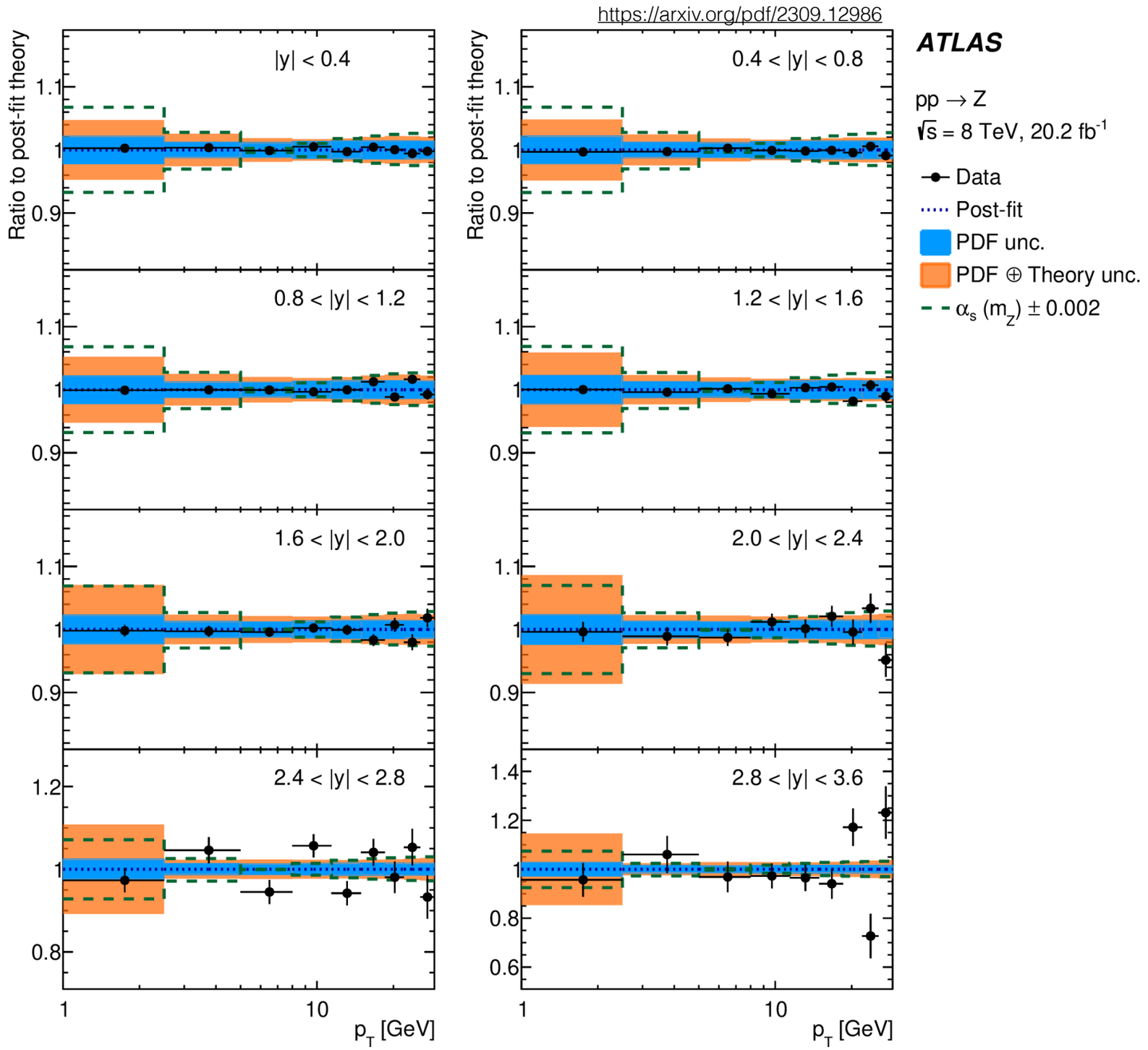
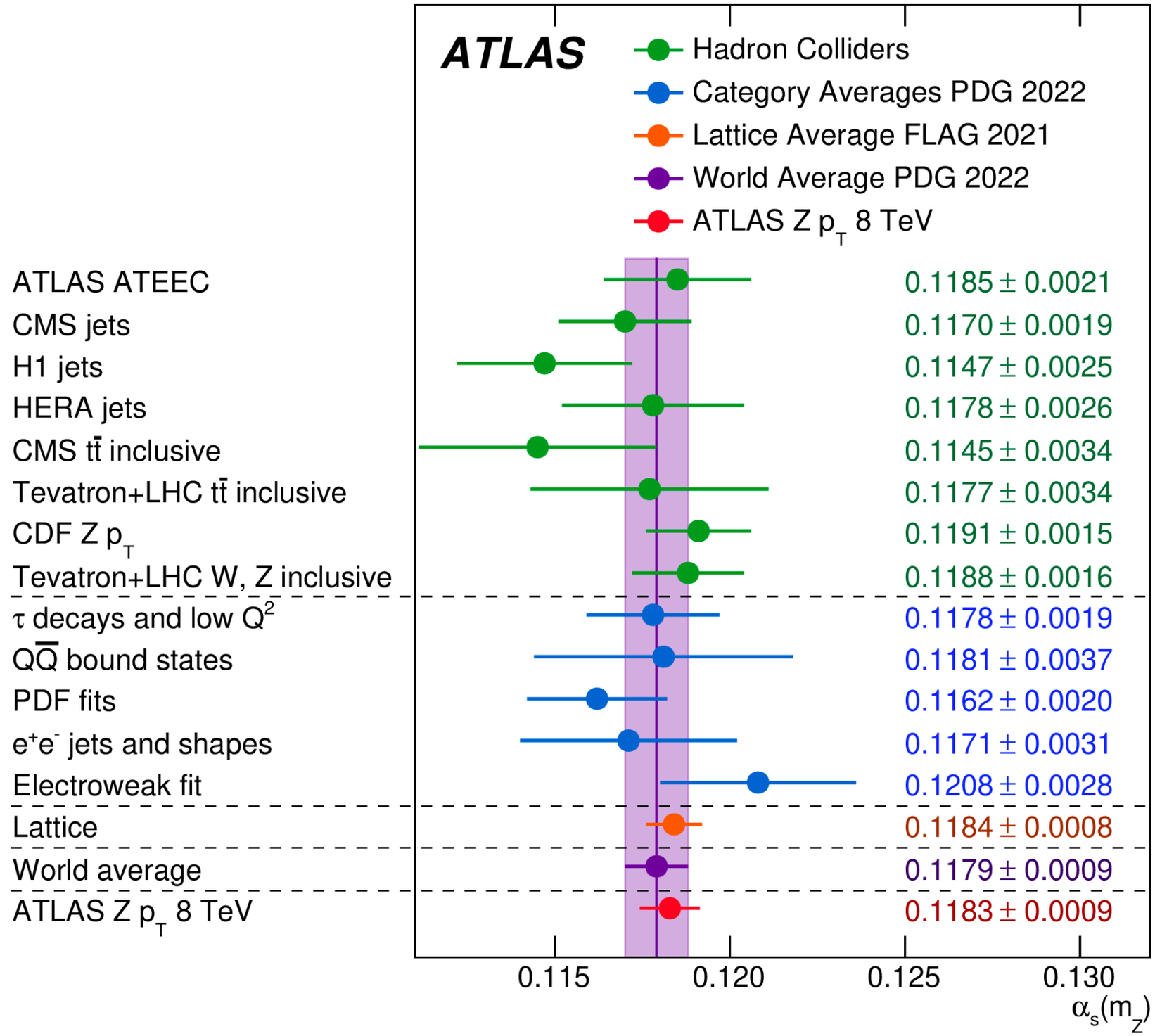


# the most precise determination of $\alpha_s$

Most precise experimental determination of as(mZ), as precise as the PDG and Lattice world averages
First as(mZ) determination at N3LO+N4LLa
Clean experimental signature with highest exp sensitivity

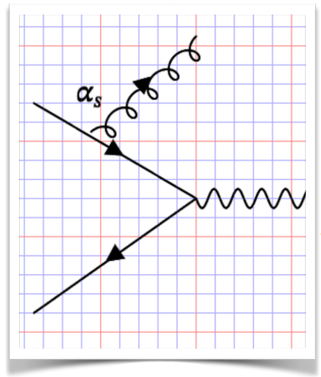
https://arxiv.org/pdf/2309.12986



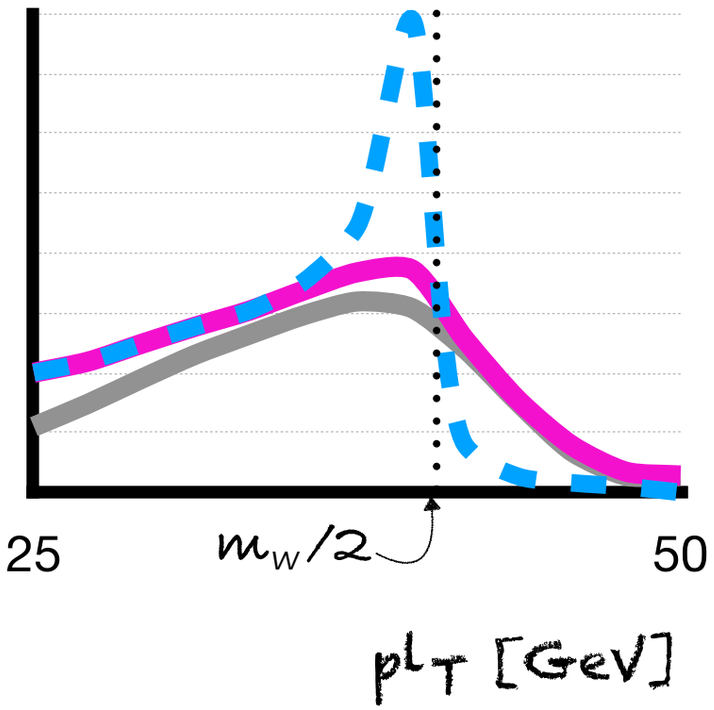
# THANK YOU

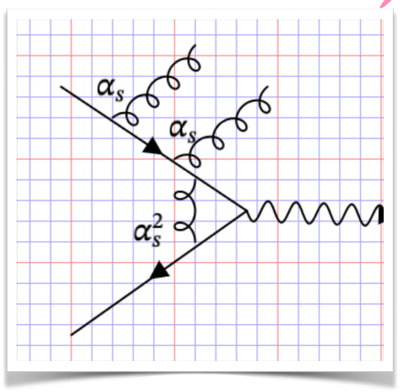
# Example of the $p_T$ boson spectra

**Quite challenging business ... higher order correction needed to describe the data**

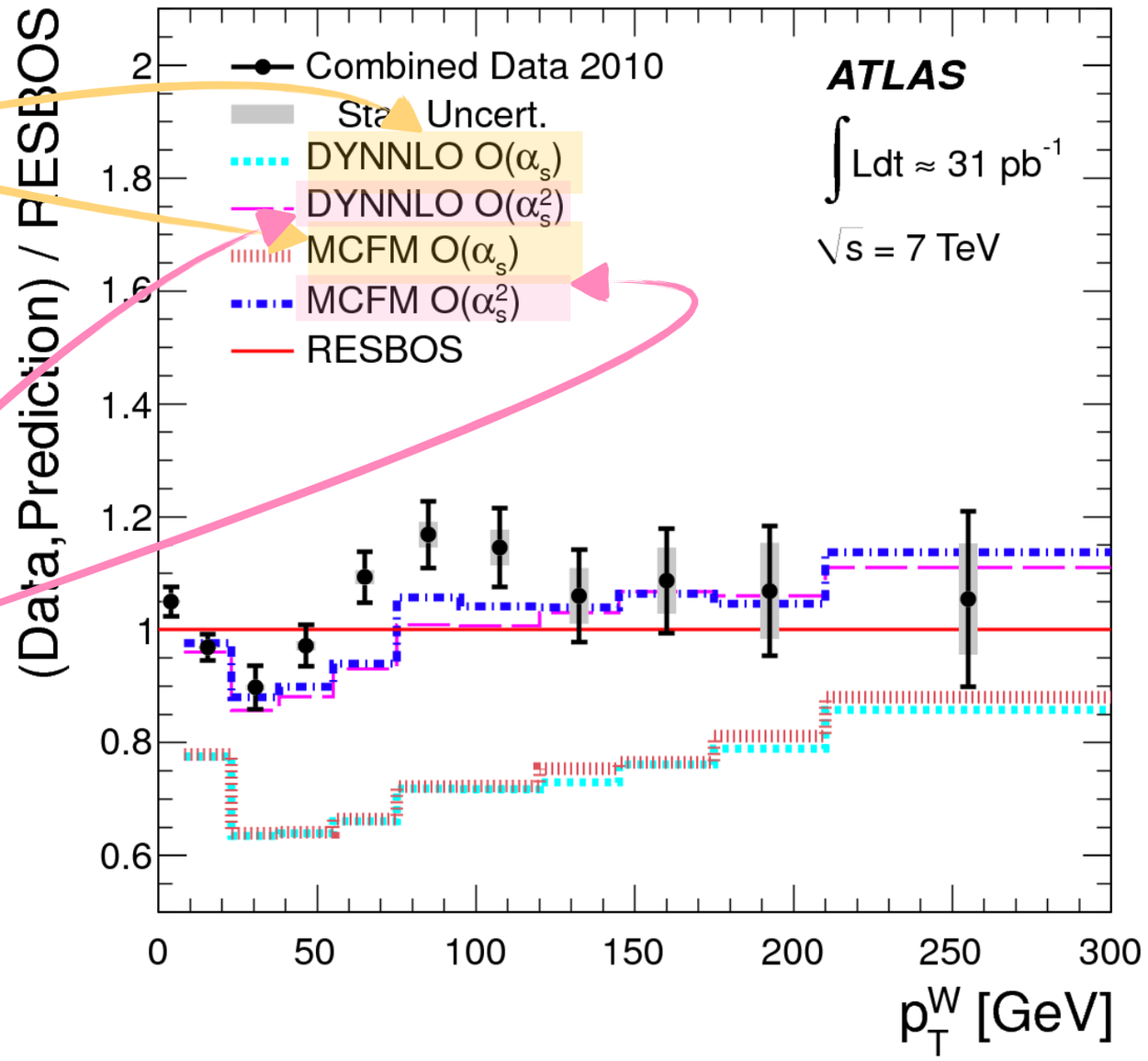



- Generator [2.1GeV pT(W) = 0
- pT(W) != 0
- Det. Resolution + selection

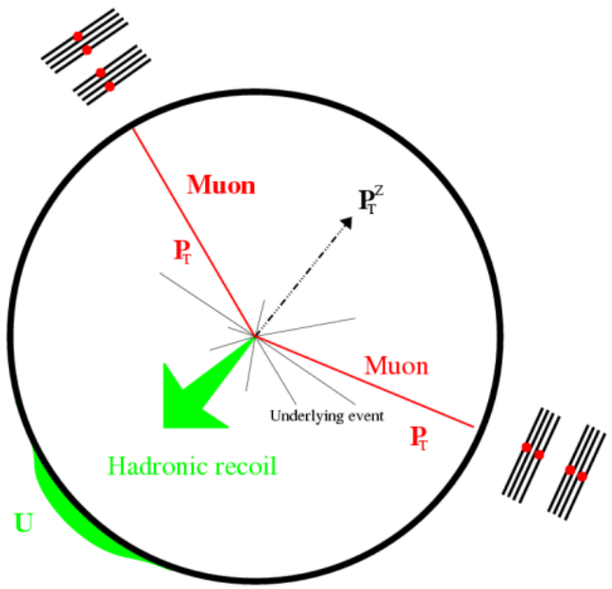


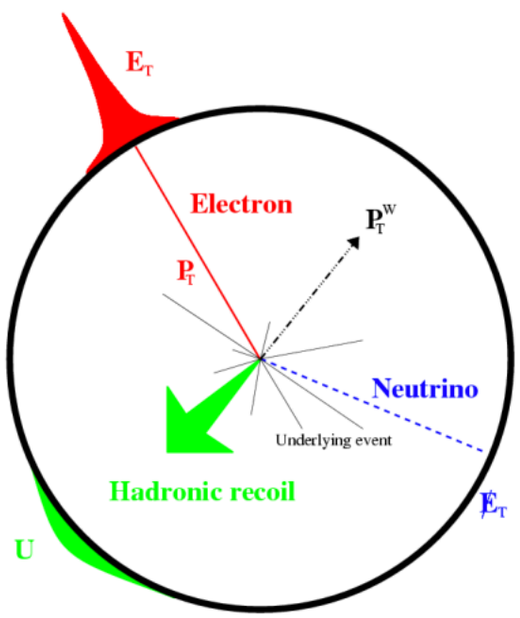

**SITUATION 12 YEARS AGO**



# Signatures of W and Z Production




- $Z \rightarrow \ell^+\ell^-$: pair of charged leptons:
  - high $p_T$
  - isolated
  - opposite-charge
- peak in $\ell^+\ell^-$ invariant mass




- $W \rightarrow \ell \upsilon$: single charged lepton:
  - high $p_T$
  - isolated
- from $\upsilon$: $p^T_\upsilon = \not{E}_T$
  - cannot measure longitudinal $\upsilon$
- peak in "transverse mass"

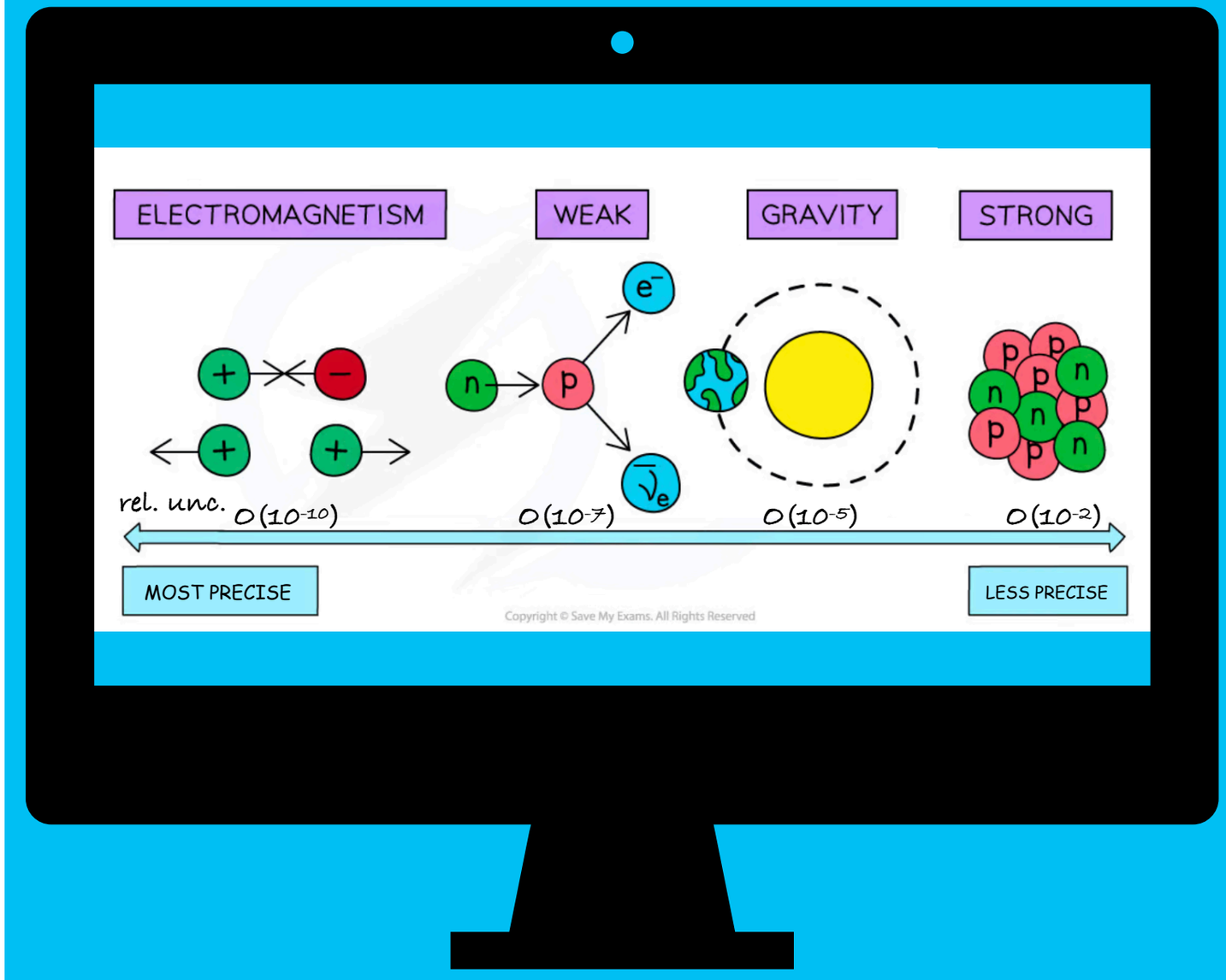
transverse mass: $m_T = \sqrt{2p_T^{\,l}\,p_T^{\,\nu}(1-\cos\phi_{l\nu})}$

# $\alpha_s$ THE STRONG COUPLING

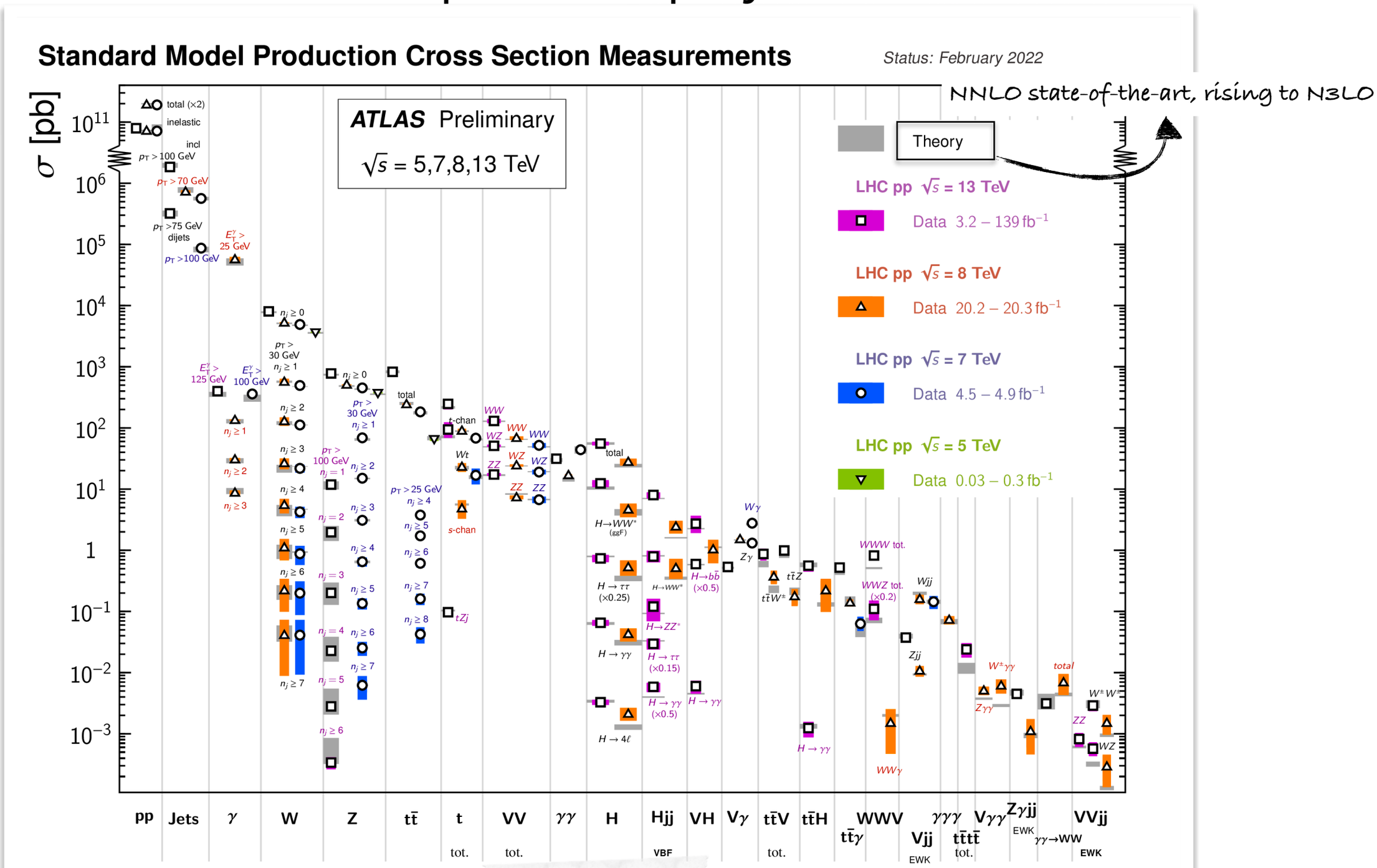
- The strong coupling, $\alpha_s$, is one of the <u>fundamental parameters</u> of the Standard Model.
  - It enters into all cross section calculations for processes at the LHC

... however is the *least known fundamental force of nature* ...

... as the LHC experiments' work evolves towards precision physics, accurate knowledge of the strong coupling is becoming increasingly important ( G. Salam )



# The SM of particle physics @LHC

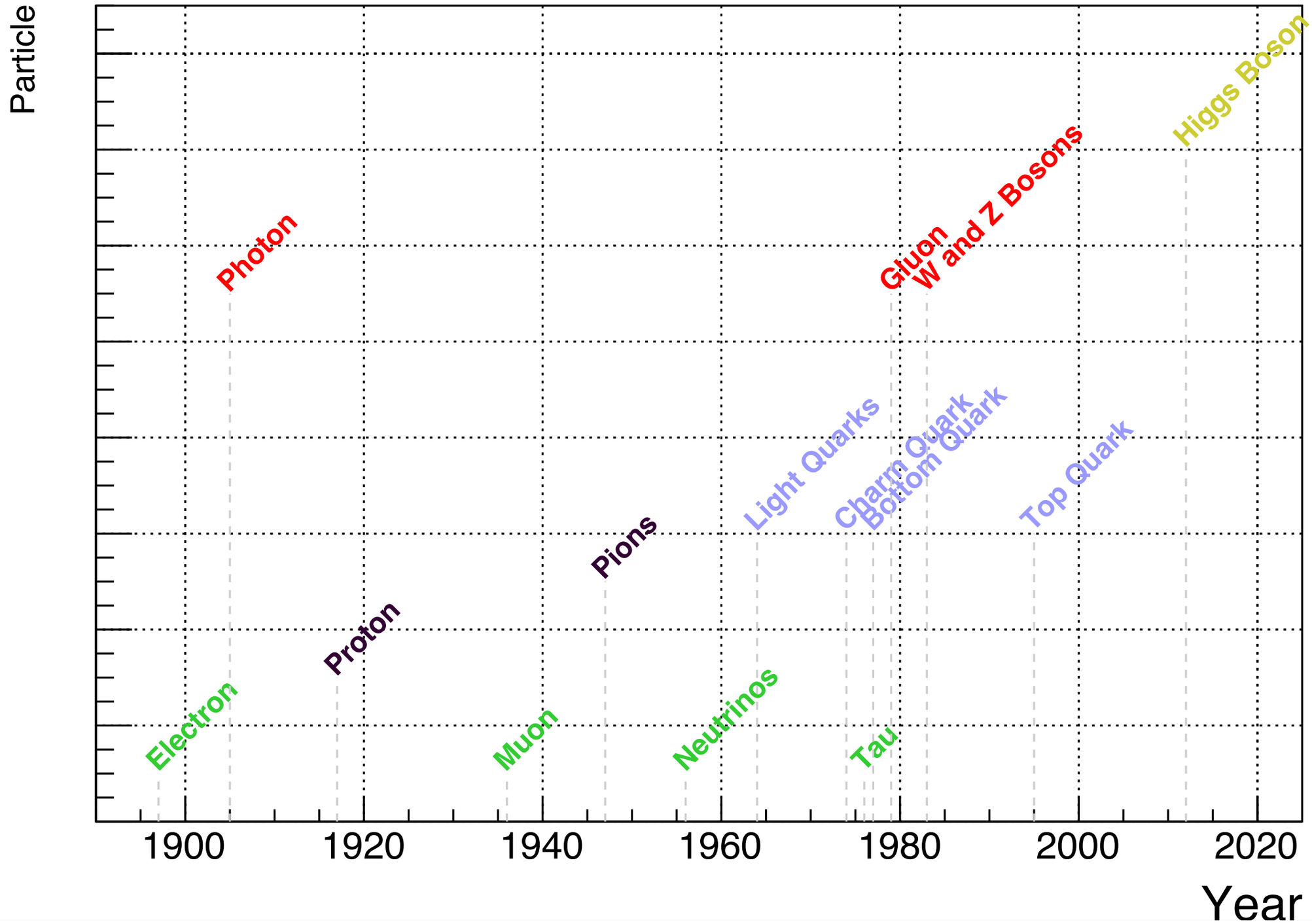


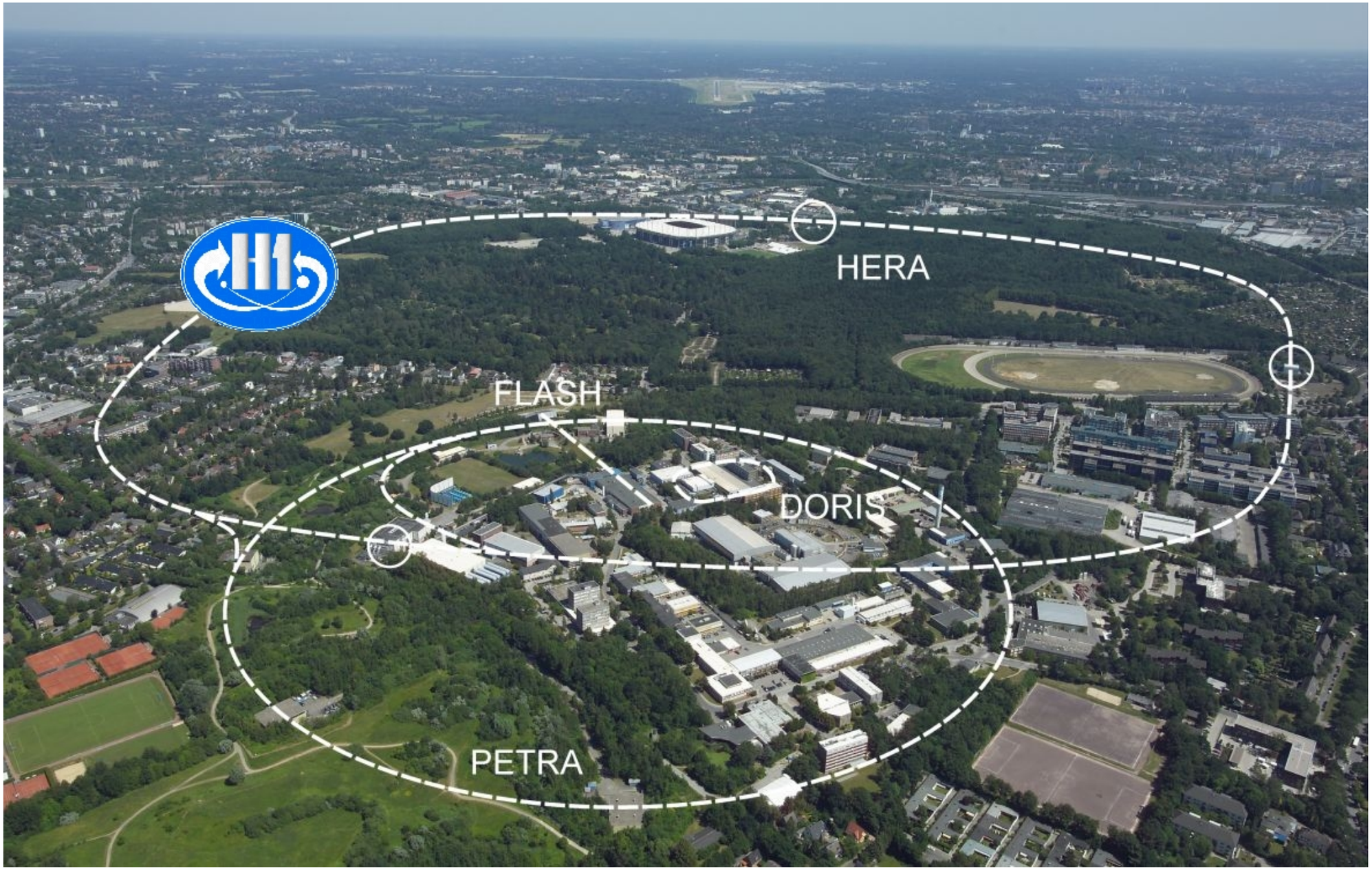

Some ( not so-obvious ) observations:

A. Theory agrees with measurements across wide range of processes and cross sections ...

B. Often data precision challenges the theory predictions...

# Particle Discovery Timeline



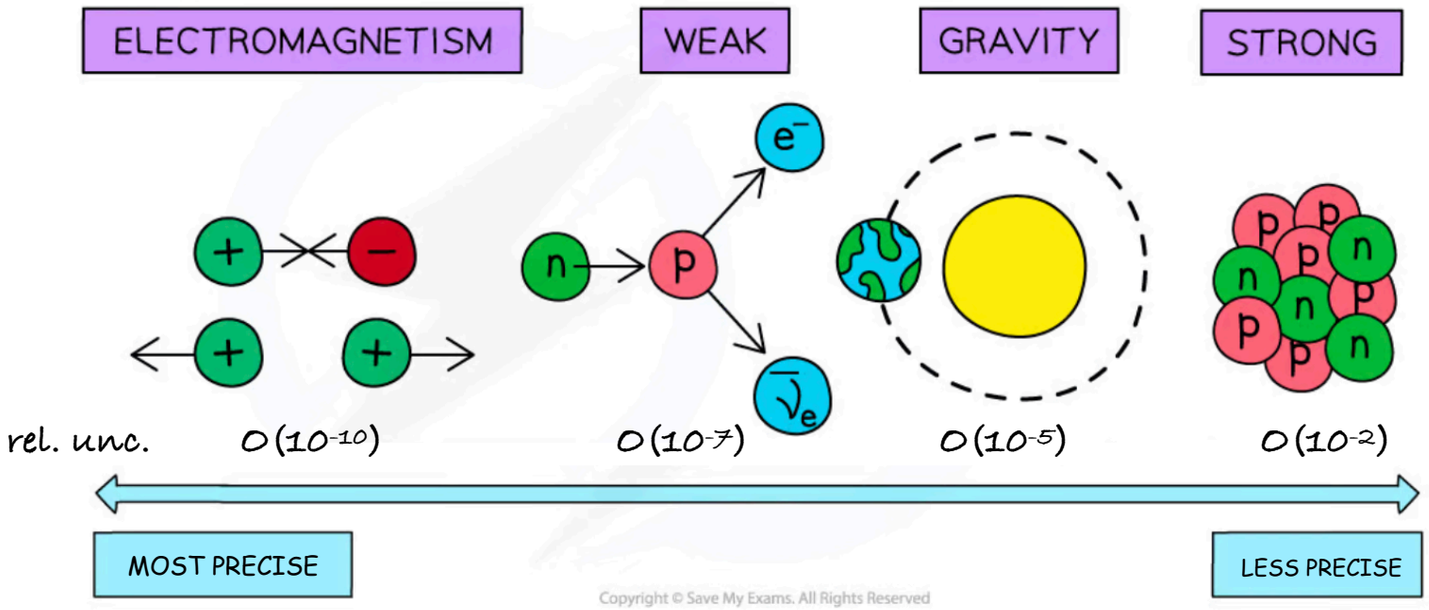

H1
HERA
FLASH
DORIS
PETRA

# discovery of the gluon

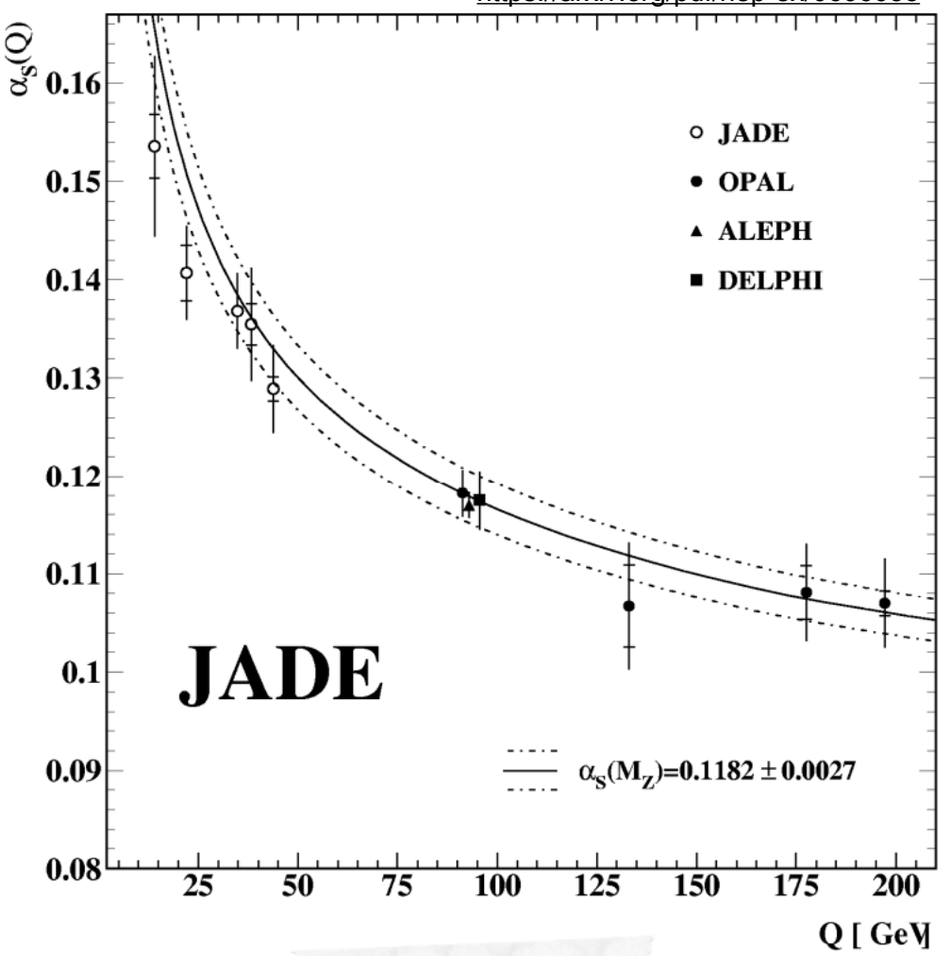
The strong coupling, αs, is one of the **fundamental parameters** of the Standard Model.

- Determines strength of the interaction between ***q*** and ***g***.
  - It enters into all cross section calculations for processes at the LHC, whether directly at leading order, or through higher-order QCD calculations.
  - It also enters indirectly through the evolution of PDFs and their correlation with the strong coupling.

… however is the ***least known fundamental force of nature*** …




https://arxiv.org/pdf/hep-ex/0606035




QCD is a most exceptional theory in that it generates an enormous complexity out of a very simple Lagrangian – describing for instance all atomic nuclei out of essentially one parameter.

# A convenient decomposition

A convenient way of expressing the radiation-inclusive DY cross section is through the factorisation of the production dynamic and the decay kinematic properties of the dilepton system.

$$\frac{d^3\sigma^{U+L}}{dp_T dy dm}\left(1+\cos^2\theta+\sum_{i=0}^{7}A_i(y,p_T,m)P_i(\cos\theta,\phi)\right)$$

The **unpolarised cross sections** do not depend on lepton variables, they are defined in "full-lepton phase space", only by cuts (or bins) in pT,y,m of the boson

Measuring the **angular coefficients** correspond to building a synthetic "quantized" representation of the (cosθ,ϕ) kinematic space decompose in helicity cross sections

**Smart idea**: Exploit the angular variables decomposition to perform a simultaneous 2D pT-y measurement of unpolarised full-lepton phase space cross sections + extraction of angular coefficients

- Very powerful: trade systematics for statistics
- Very useful: provides analytic extrapolation of lepton cuts and enables a rich interpretation programme