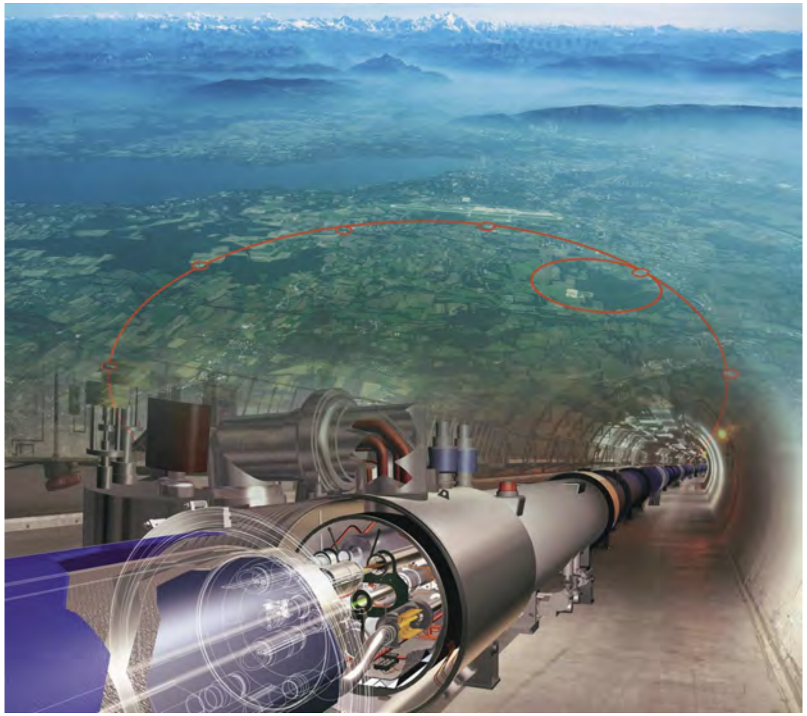
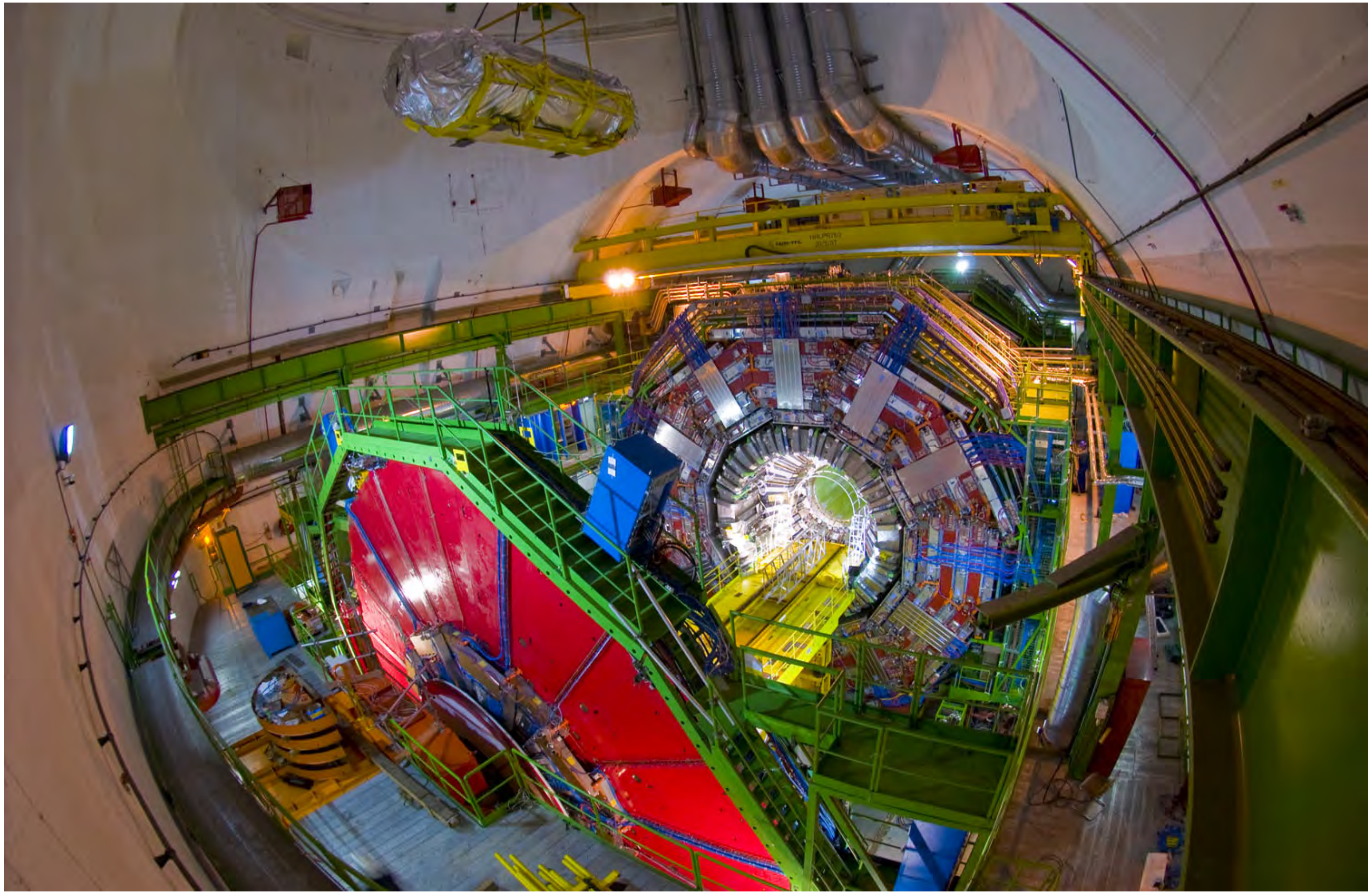
Two examples of high light results of HIP projects at the CERN LHC

- Discovery of a Higgs boson by CMS and ATLAS in 2012

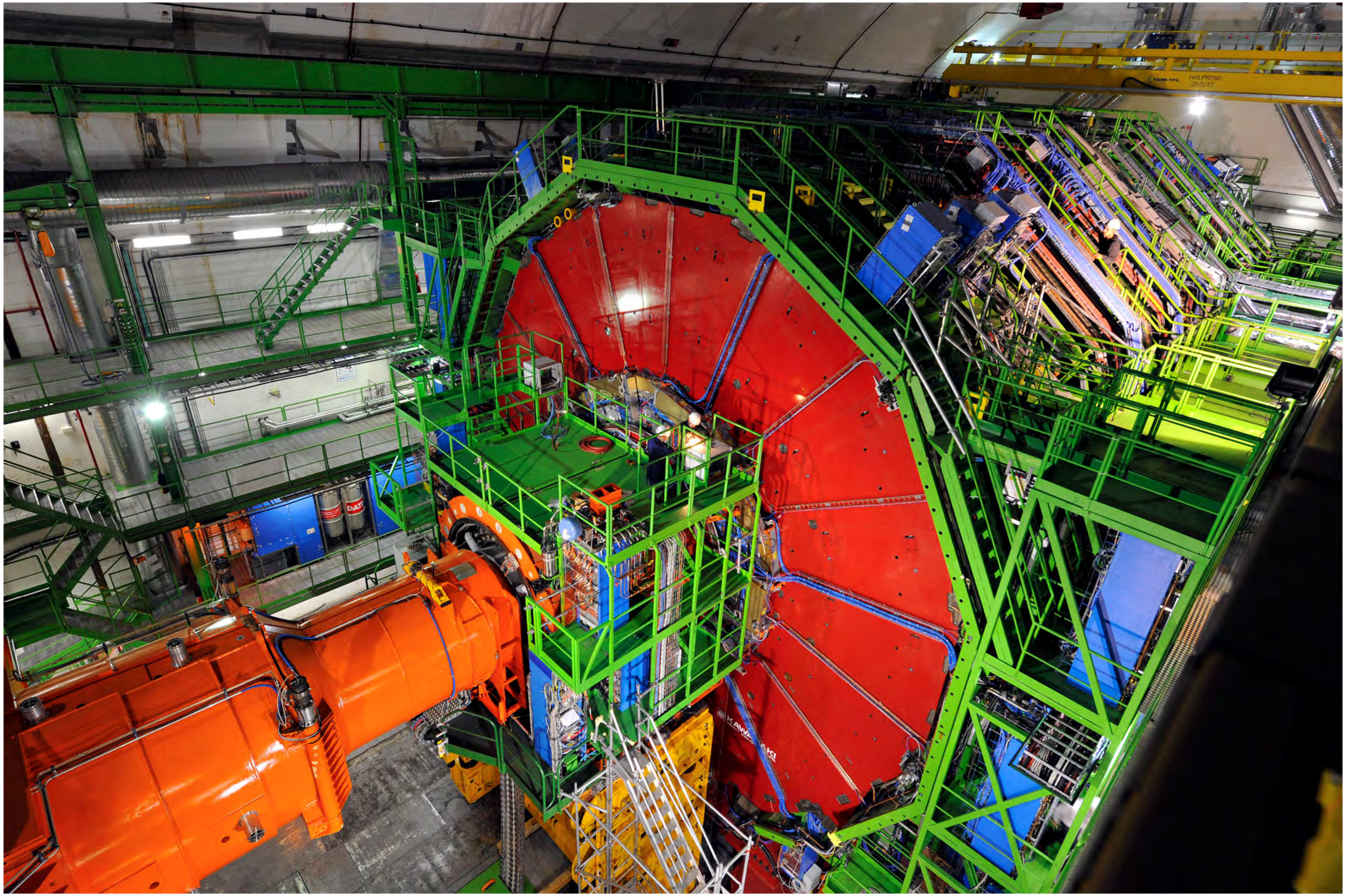
- Observation of odderon scattering by TOTEM/D0 in 2021



Installation of the CMS Central Tracker in 2007



CMS detector 2008



LHC Run 1

2010-2011

Collision energy: *3.5+3.5 TeV,*

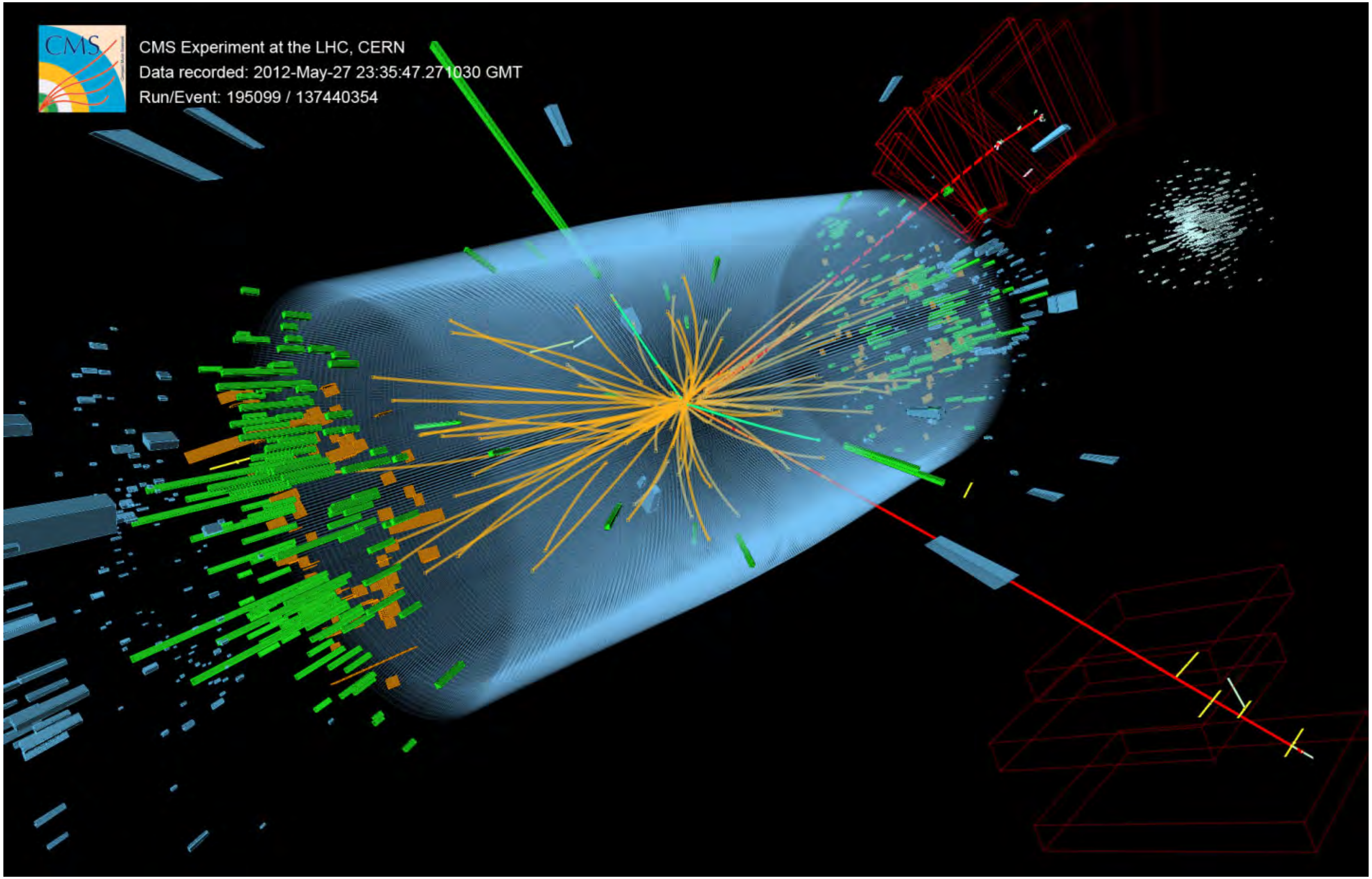
Integrated luminosity: $L = 5.1.\ fb^{-1}$

2012

Collision energy: *4+4 TeV,*

Integrated luminosity: $L = 19.6\ fb^{-1}$

H -> ZZ -> $\mu^+\mu^-e^+e^-$

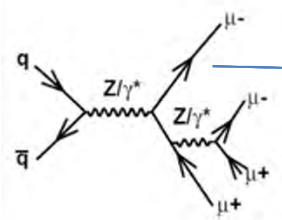

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354

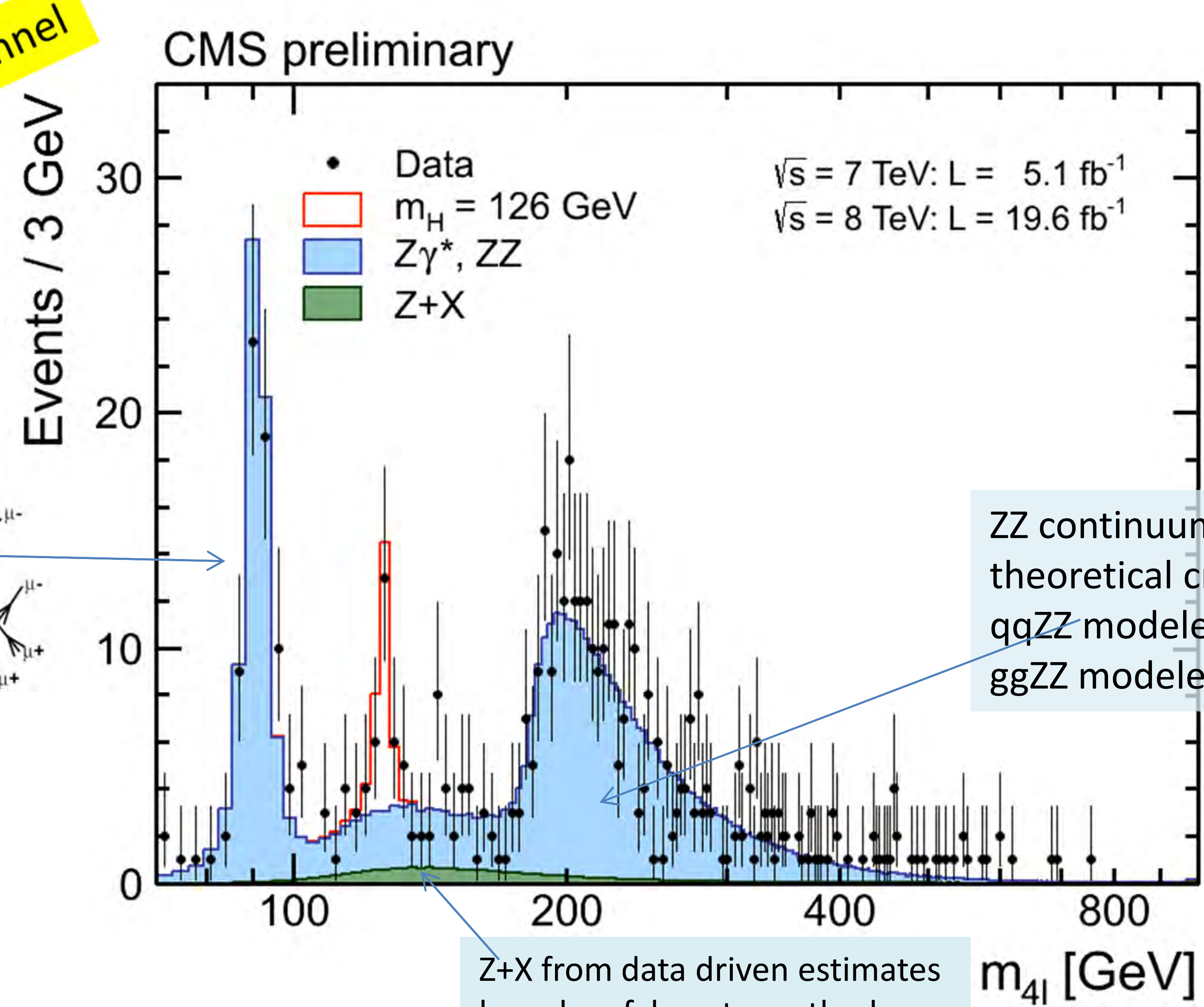
H -> ZZ -> 4 leptons

Run1
L = 24.7 fb^{-1}

Most sensitive, high-resolution channel for low mass Higgs

Golden channel





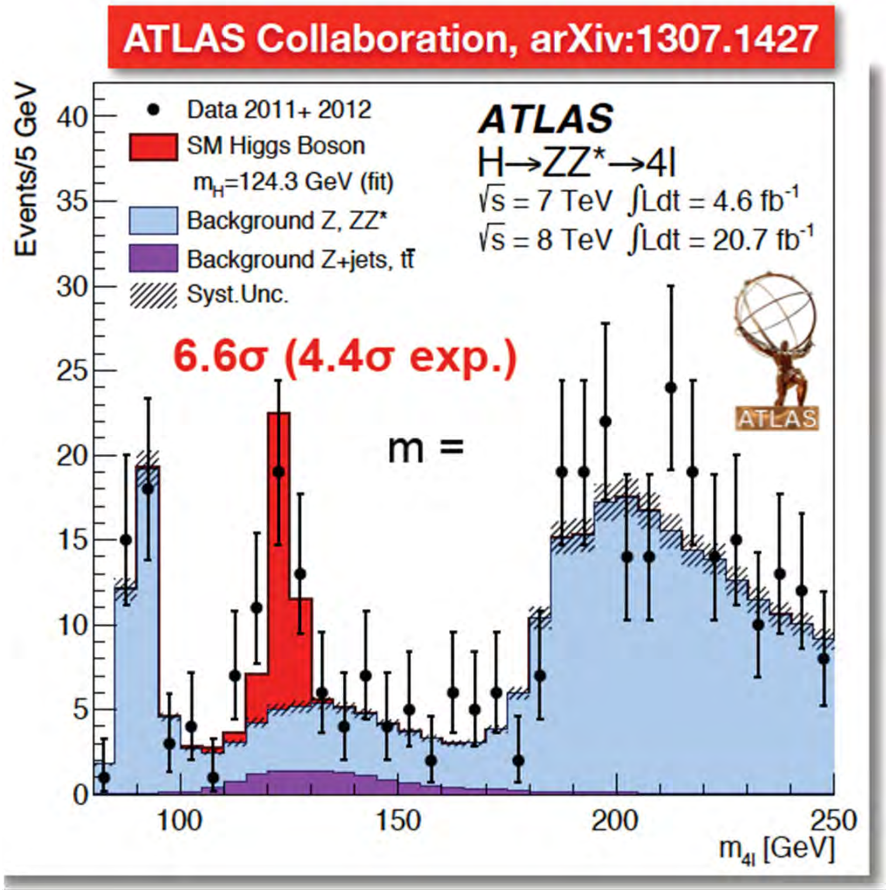
ZZ continuum from theoretical cross sections
qqZZ modeled by POWHEG
ggZZ modeled by GG2ZZ

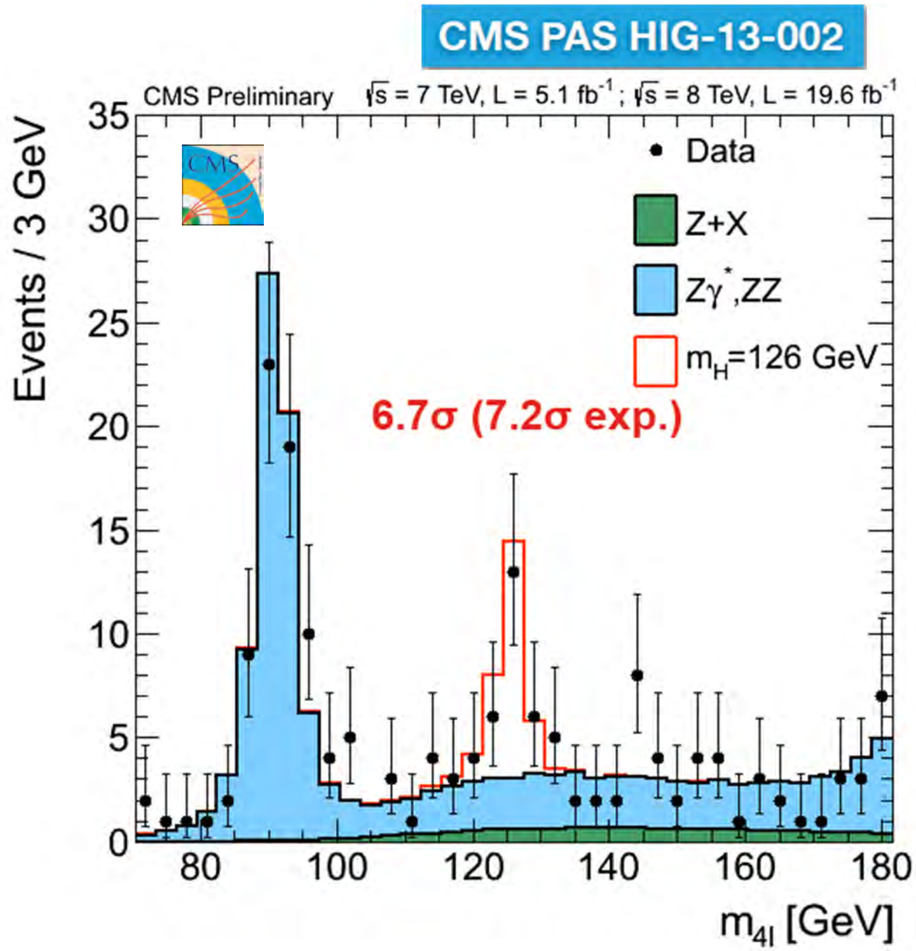
Z+X from data driven estimates based on fake rate method

H -> 4leptons

Run1 2011-2012
L = 24.7 fb1

- ATLAS: Cut-in-Categories, FSR accounting, untagged + VBF + VH
- CMS: MELA (angular analysis), FSR recovery, untagged + VBF

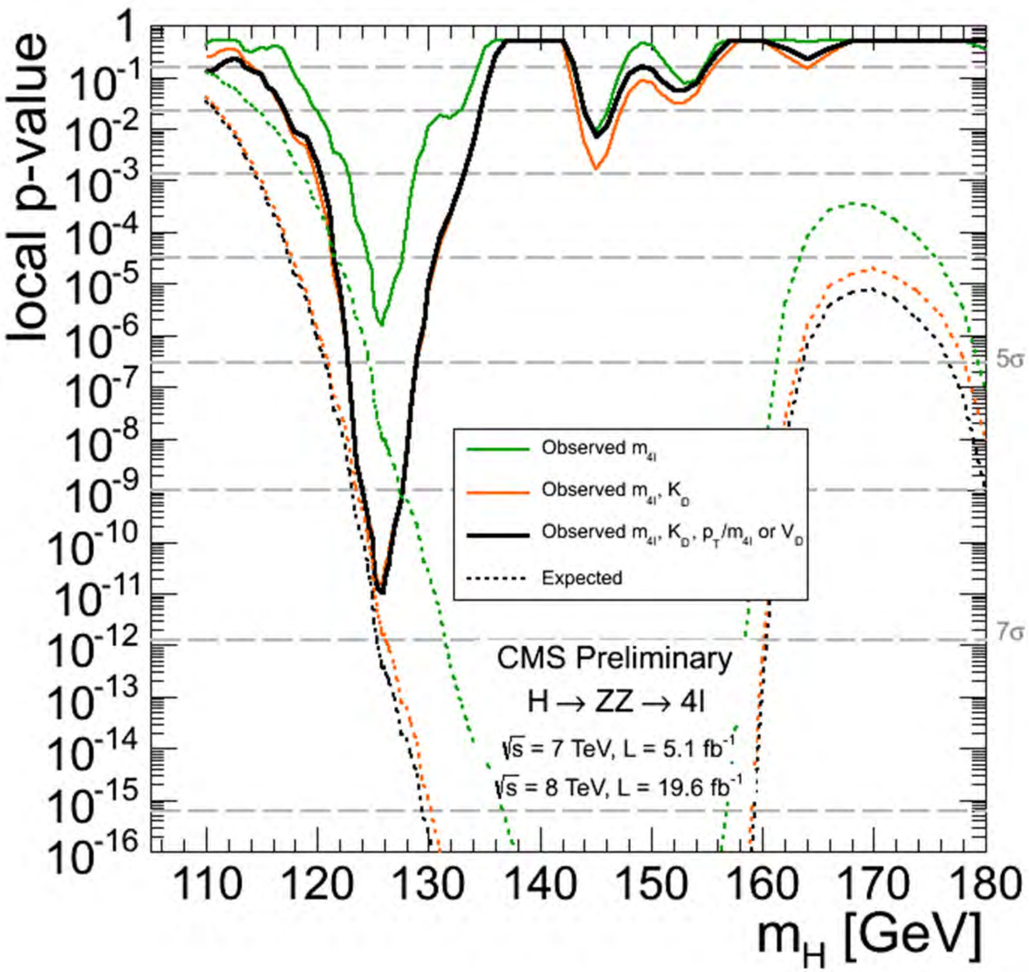




H -> 4l significance

Run1
L = 24.7 fb^{-1}

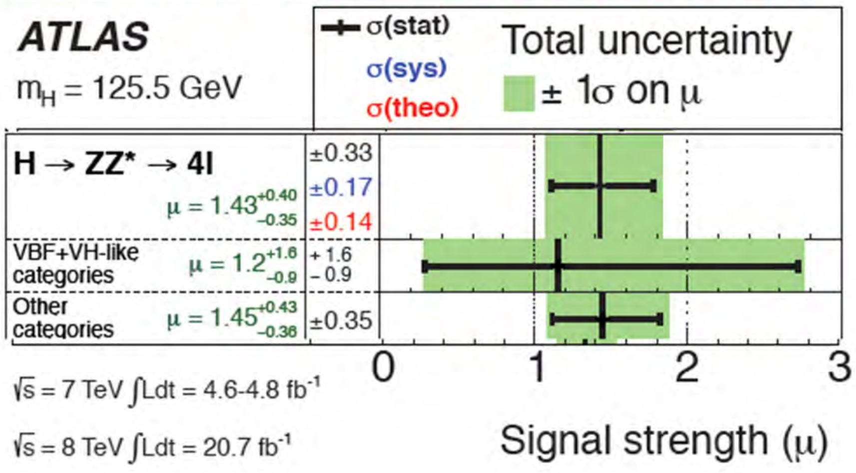
Significance improved with the kinematical discriminant



H-> 4l signal strength and mass

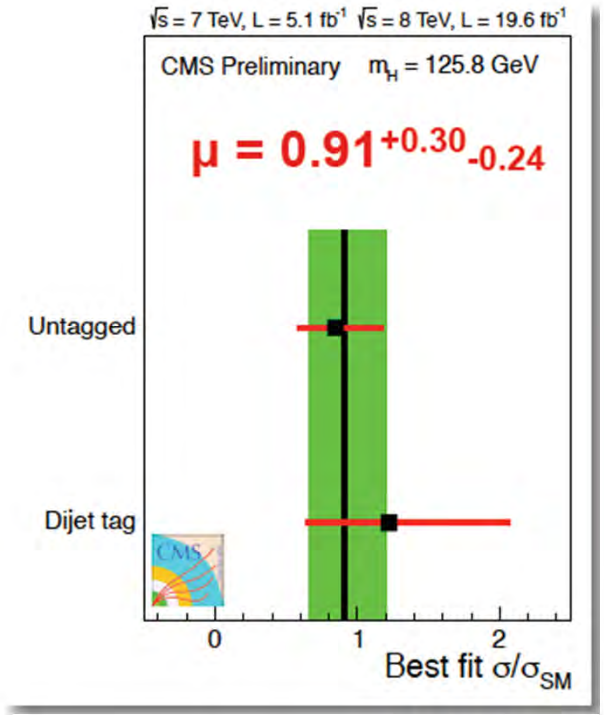
Run1

ATLAS Collaboration, arXiv:1307.1427



$m_H = 124.3^{+0.6}_{-0.5}{}^{+0.5}_{-0.3}$ GeV

$m_H = 125.8 \pm 0.5 \pm 0.2$ GeV



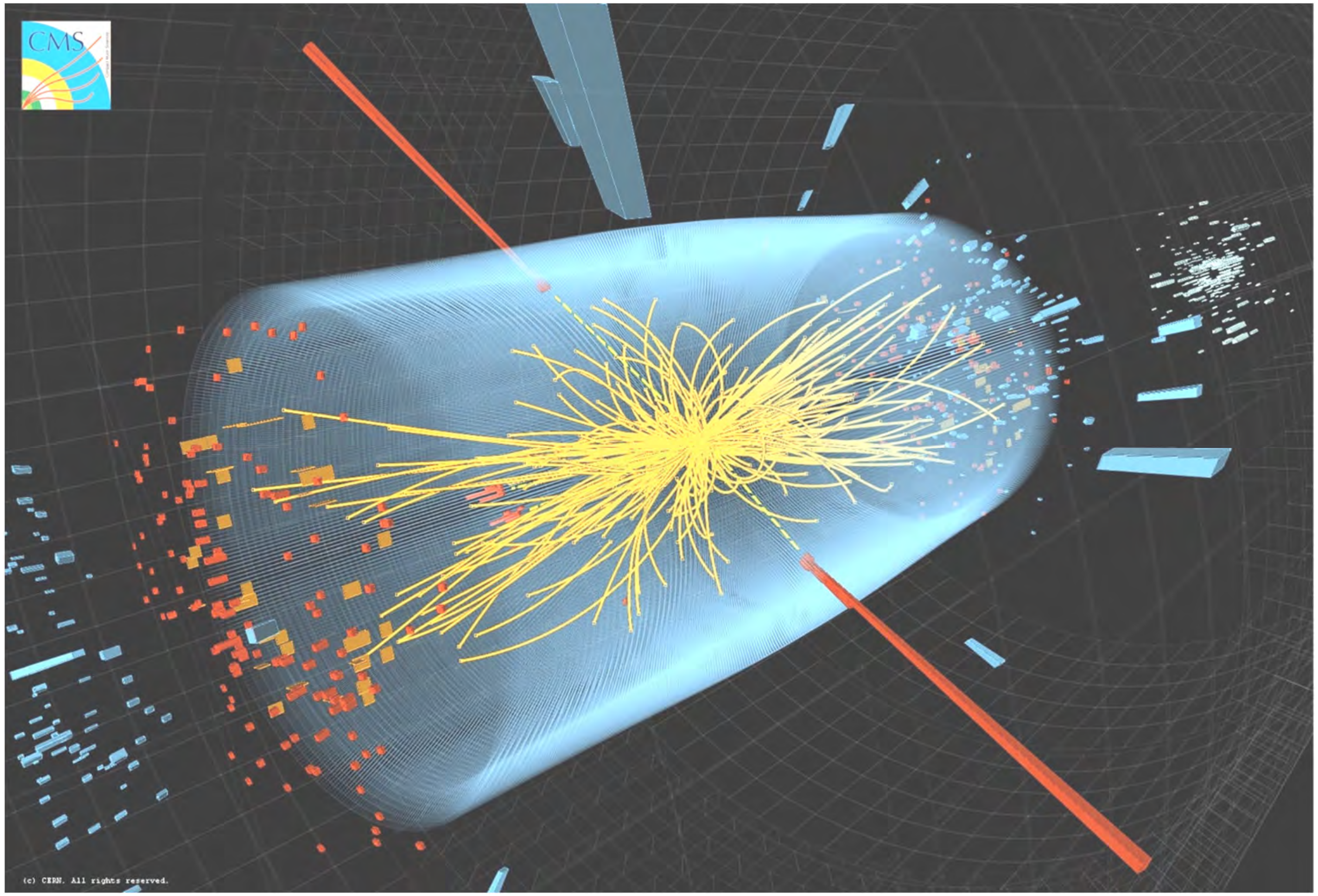
H -> $\gamma\gamma$

- Small branching fraction (0.23%), but experimentally favourable.

- *Challenge*: large irreducible QCD background from direct diphotons + photons from neutral pion decays in jets.
  - Background estimated from mass sidebands

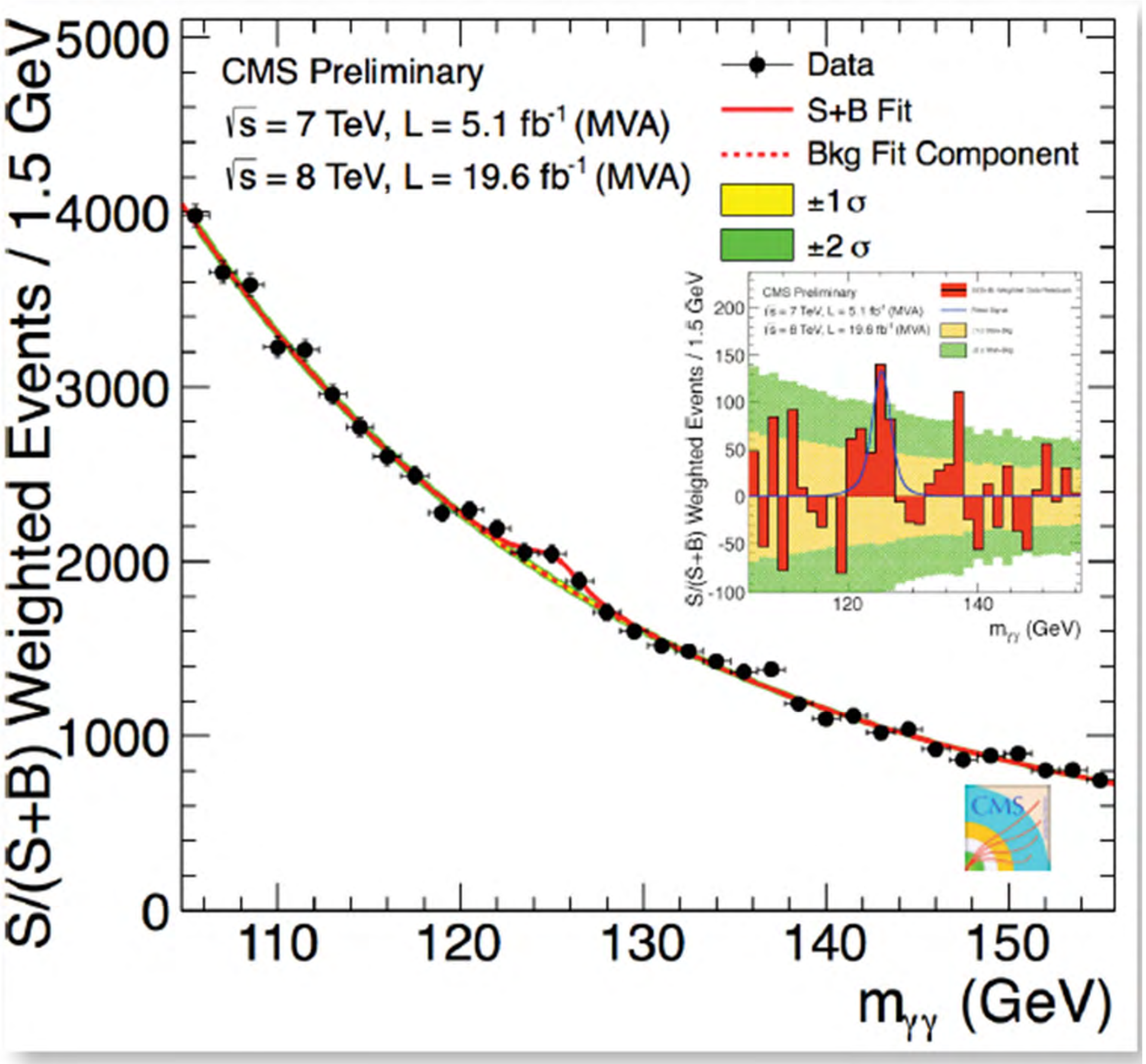
- *Second challenge*: selection of the correct vertex (pile-up).
  - ATLAS: photon pointing
  - CMS: dedicated Multivariate Analysis (MVA)

H -> $\gamma\gamma$



CMS γγ mass distribution

Run 1
2012



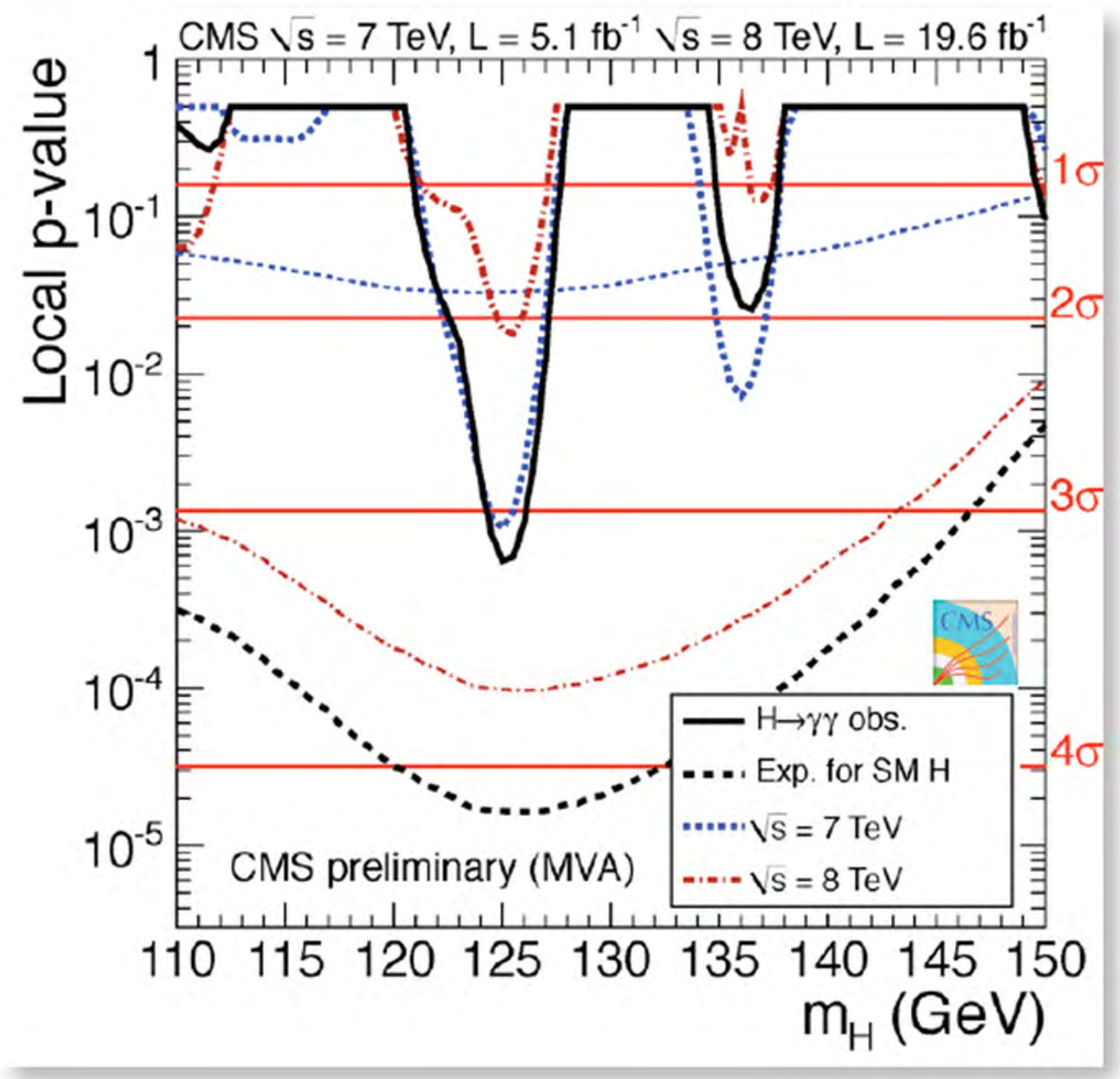
Mass: 125 ± 0.8 GeV

Analysis done
with MVA method
and cross-checked with
Cut-in-Categories method.

Significancies:

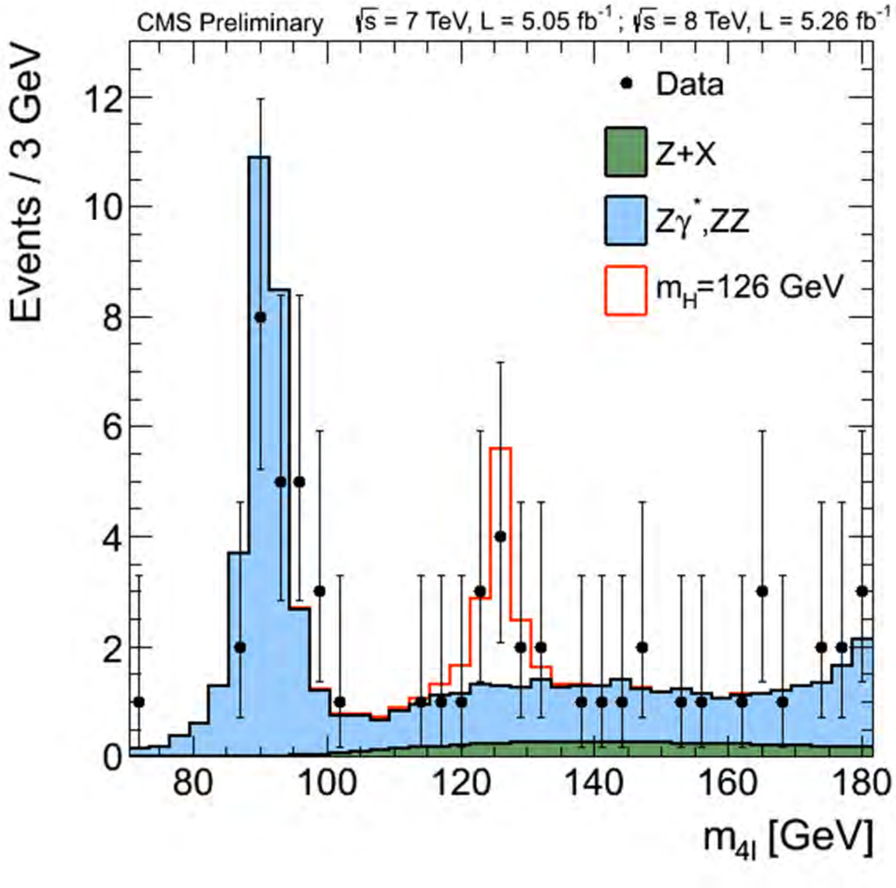
MVA: 3.2σ (4.2σ expected)
CiC: 3.9σ (3.5σ exp.)

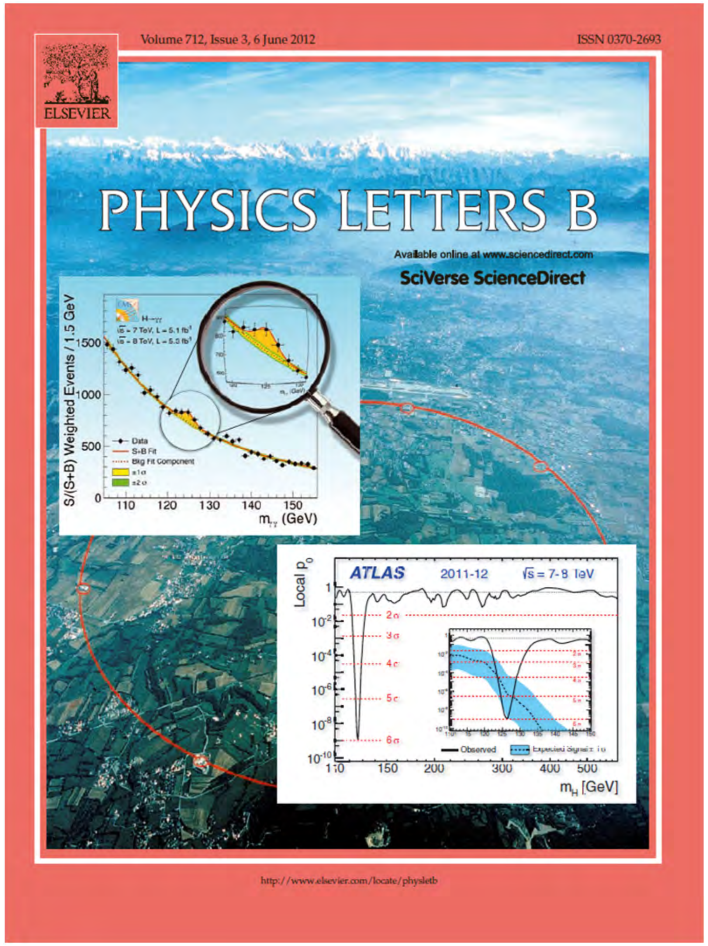
H -> γγ significance (CMS)



2012: start of Higgs physics at LHC

4.7.2012

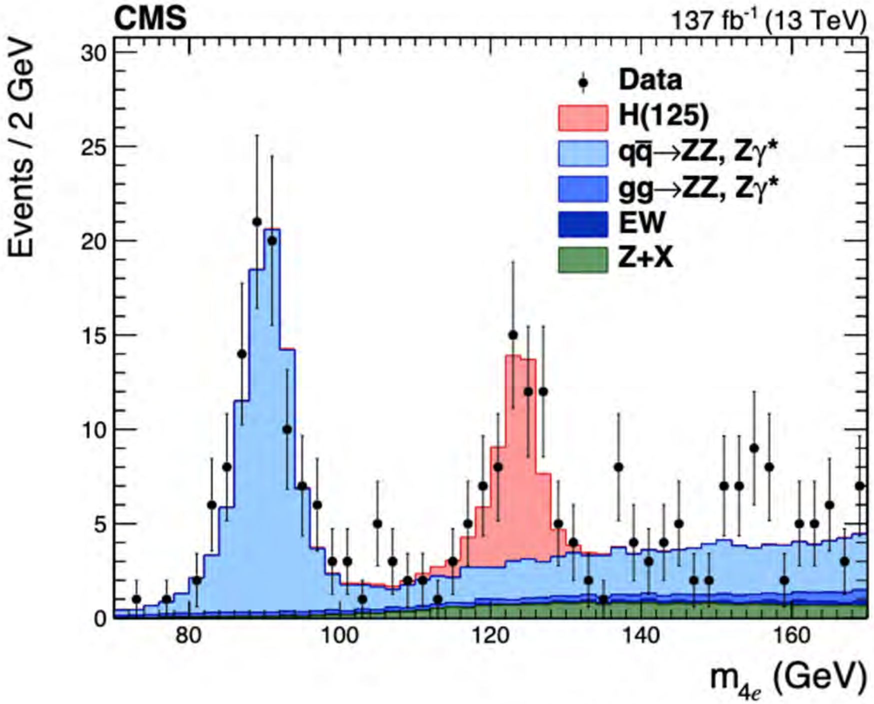


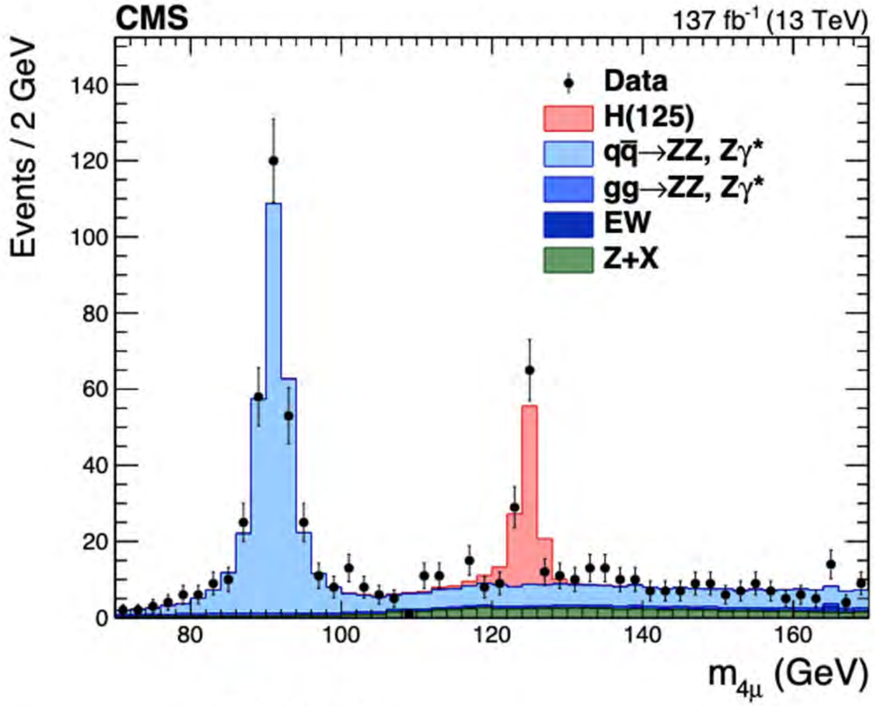


LHC Run 2 : 2015-2018

- Collision energy: *13 TeV*

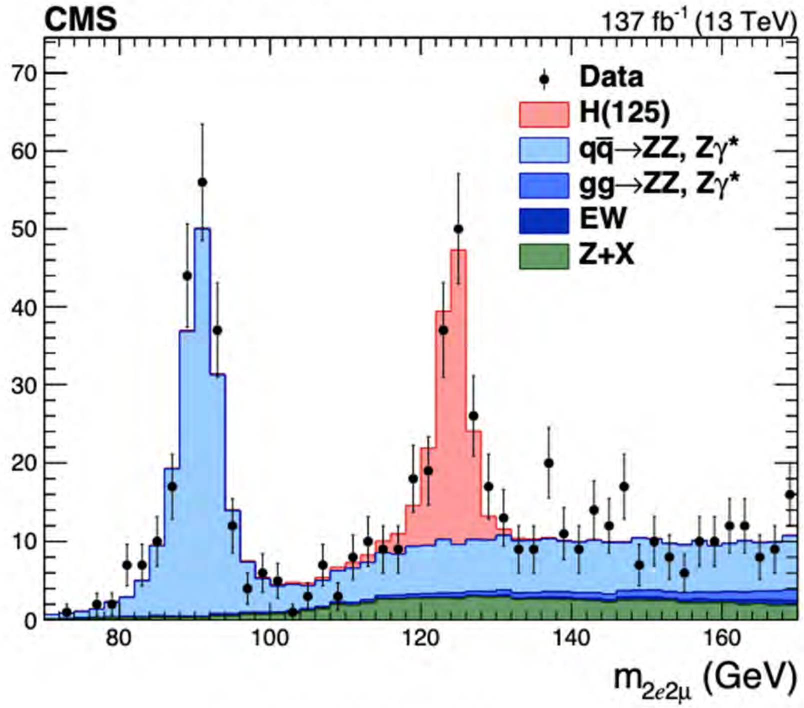
- Integrated luminosity 2016-2018: *138 fb^{-1}*



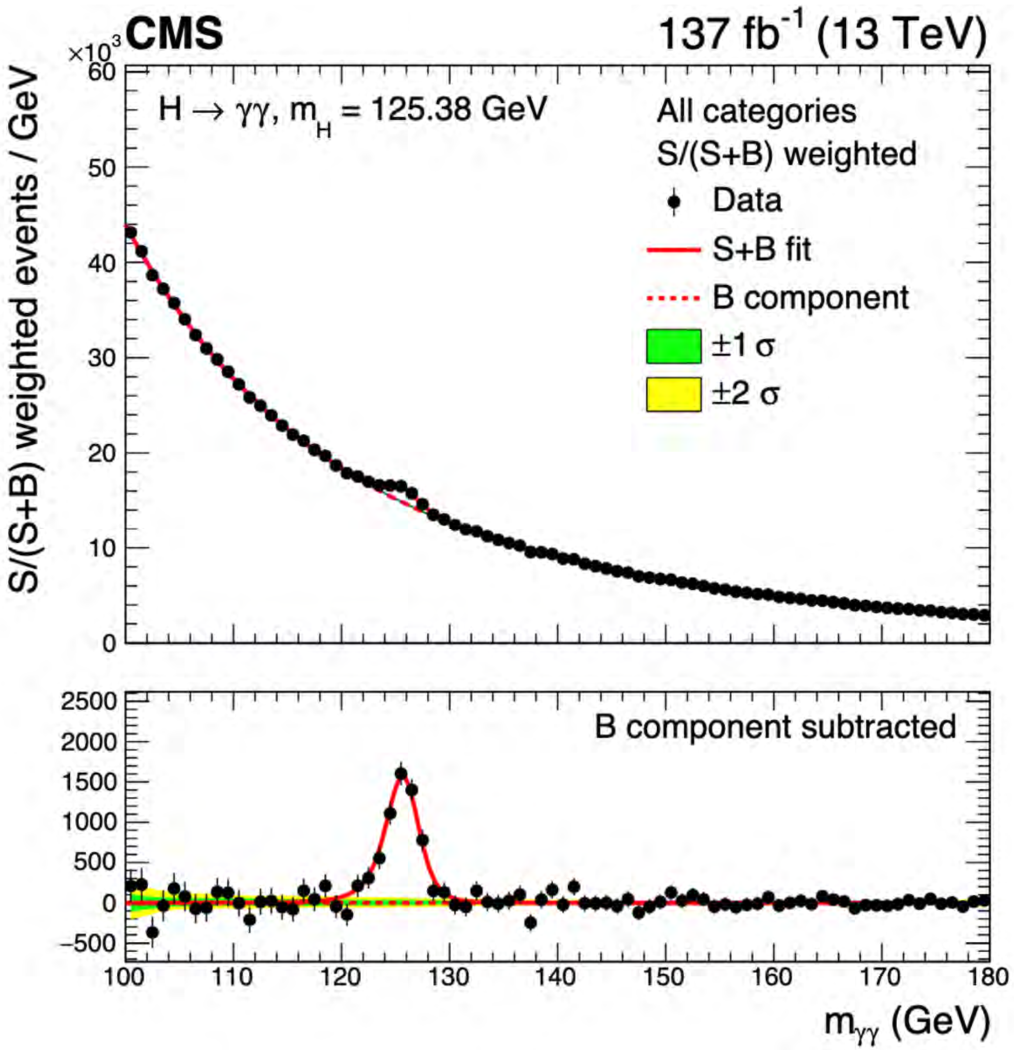


CMS results
*2022 (*Run2)

m_H=125.46 + 0.16 GeV



H-> γγ (Run 2, 2016-2018)



Run2:

m_H = 125.78 ± 0.26 GeV

Higgs boson mass 2022

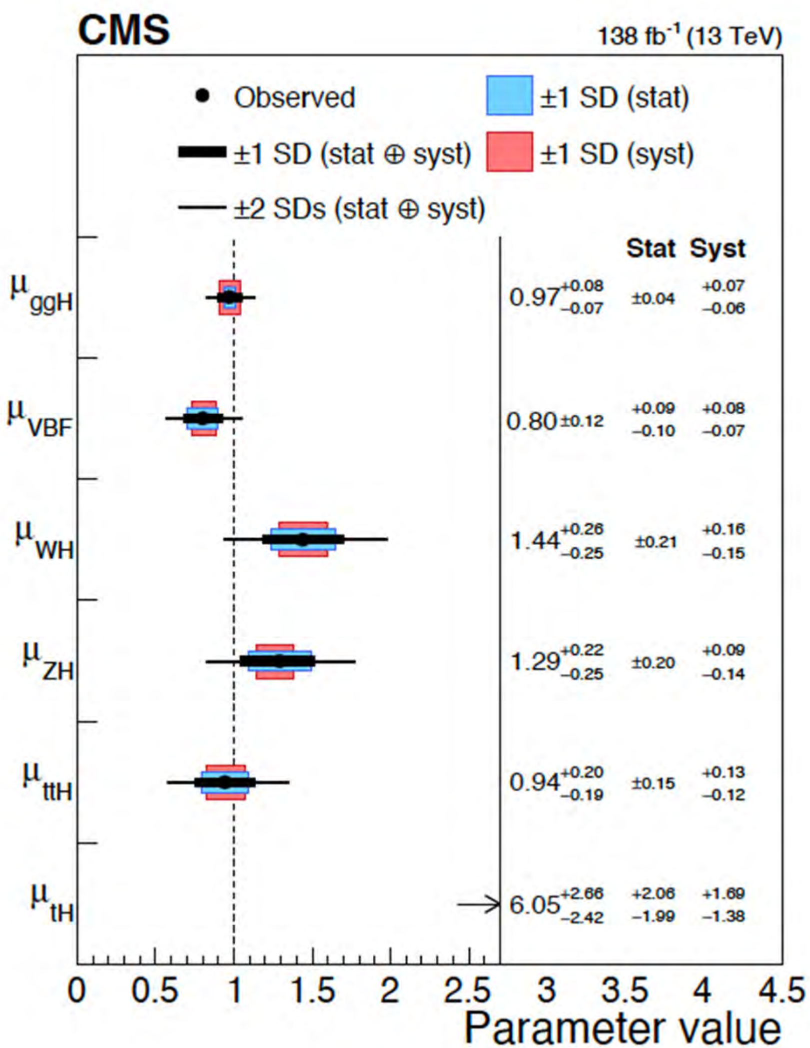
- *H-> γγ* and *H-> 4leptons* combined

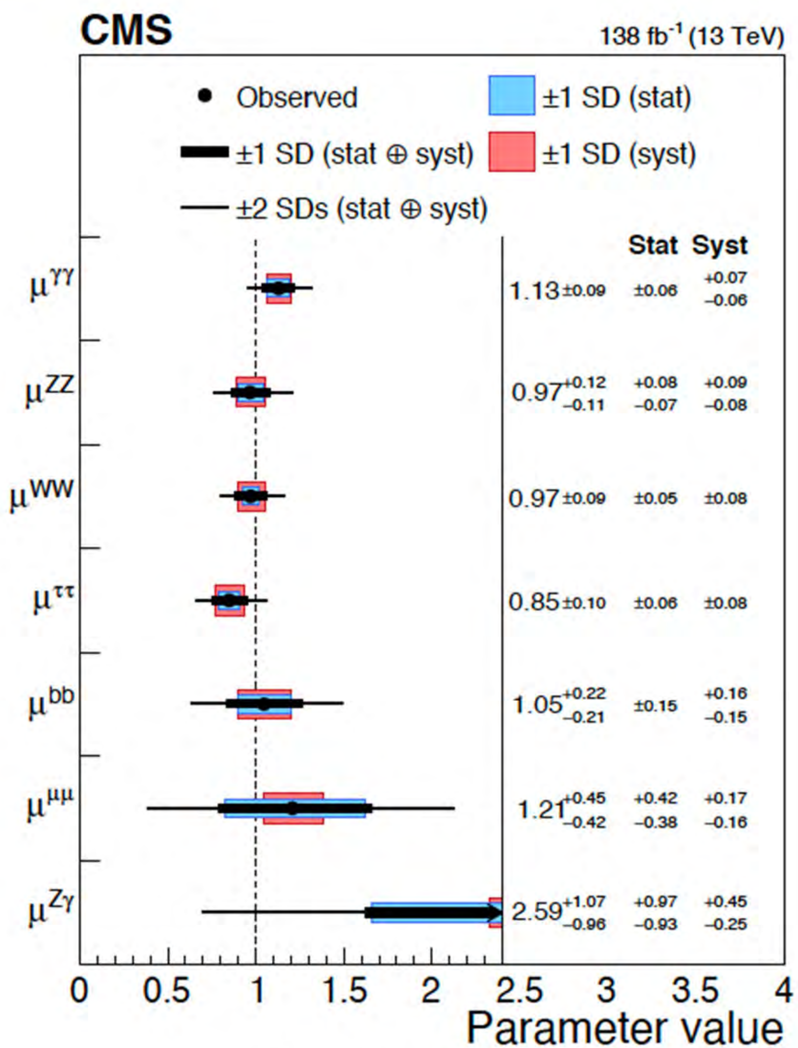
  m_H = 125.46 ± 0.16 GeV

- Run1 and Run2 combined

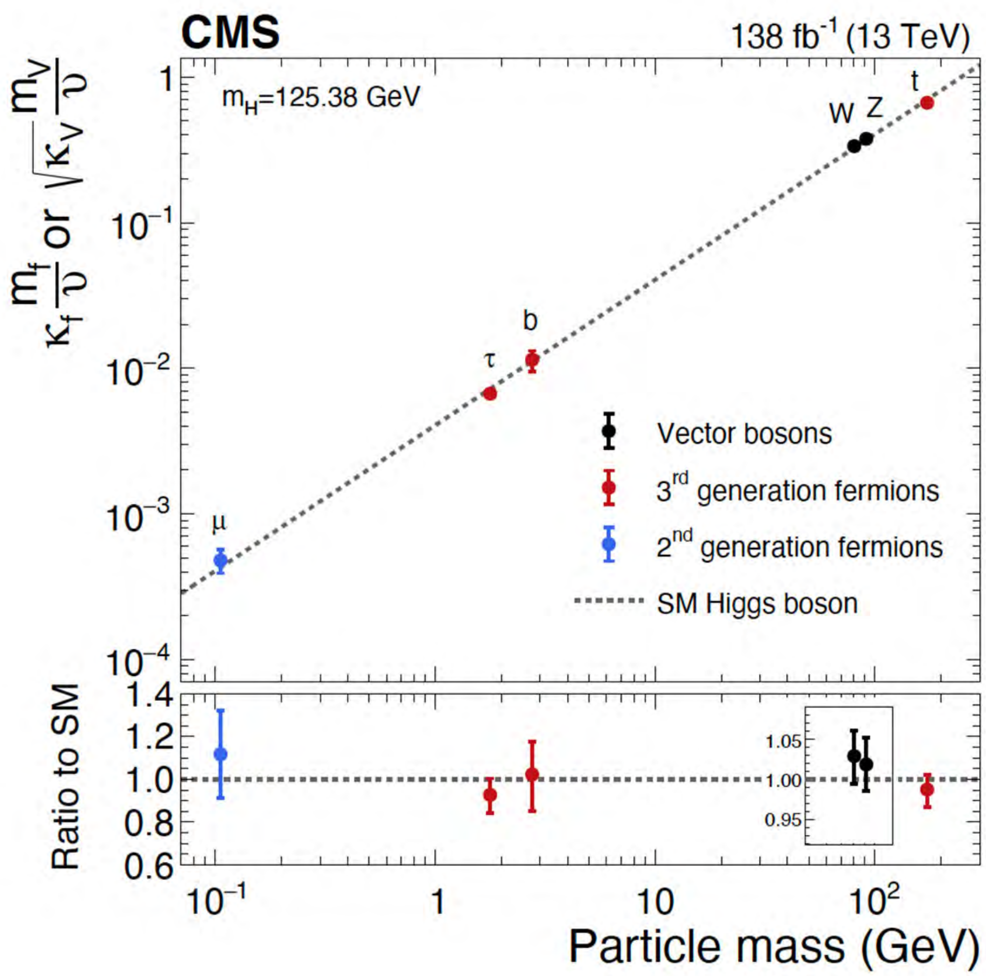
  m_H = 125.38 ± 0.14 GeV

Summary of measured decay channels





Measured couplings versus particle mass



First measurements of the Higgs boson Breit-Wigner width

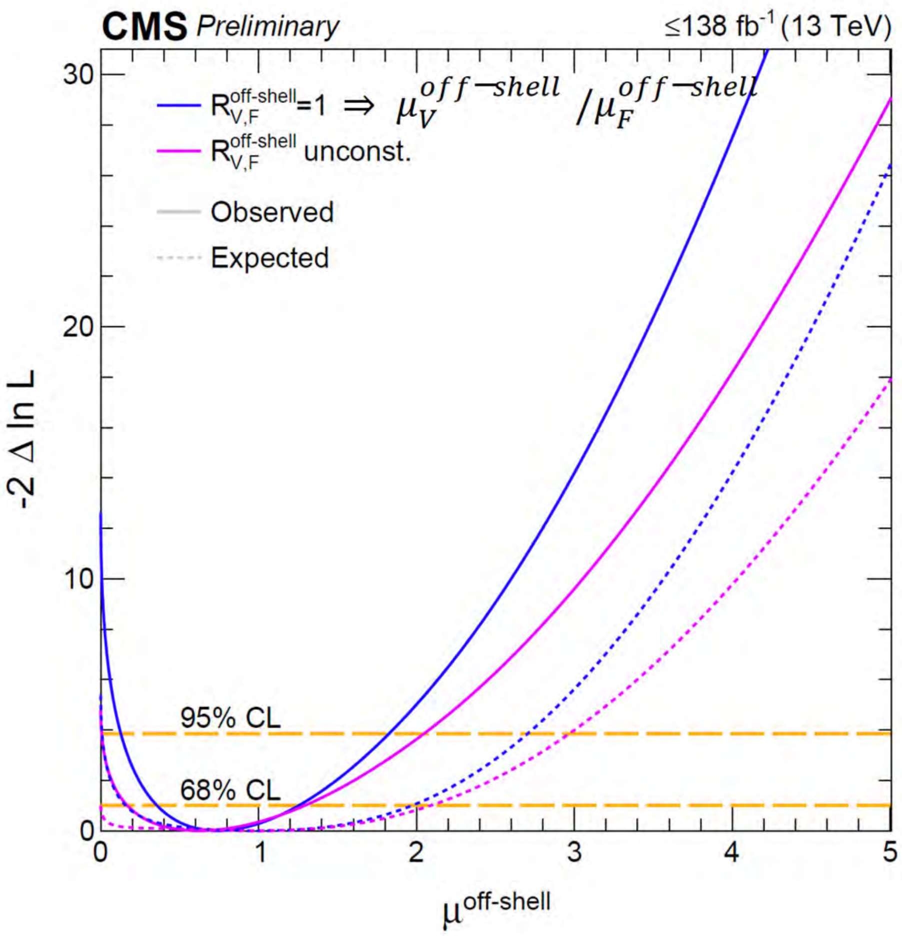
$$\sigma = \int \frac{g_{prod}^2 g_{dec}^2}{(m^2 - m_{\mathrm{H}}^2)^2 + m_{\mathrm{H}}^2 \Gamma_{\mathrm{H}}^2} \dots dm^2$$

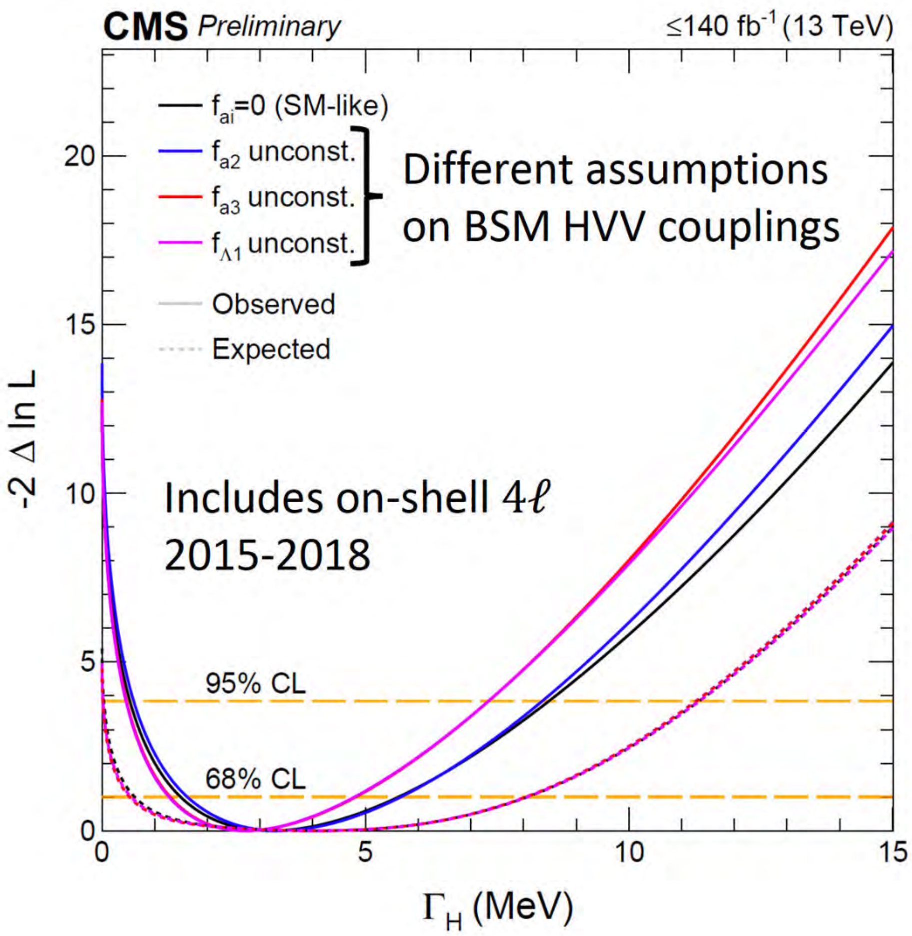
On-shell: $$\sigma \propto \frac{g_{prod}^2 g_{dec}^2}{\Gamma_{\mathrm{H}}} \propto \mu_{prod}$$

Off-shell $$\sigma \sim \int \frac{g_{prod}^2 g_{dec}^2}{(m^2 - m_{\mathrm{H}}^2)^2} \dots dm^2 \propto \underbrace{\mu_{prod} \cdot \Gamma_{\mathrm{H}}}_{\mu_{prod}^{off-shell}}$$

SM: m >2m_Z 10% of on-shell value

H->llνν + 4l mass distribution fits



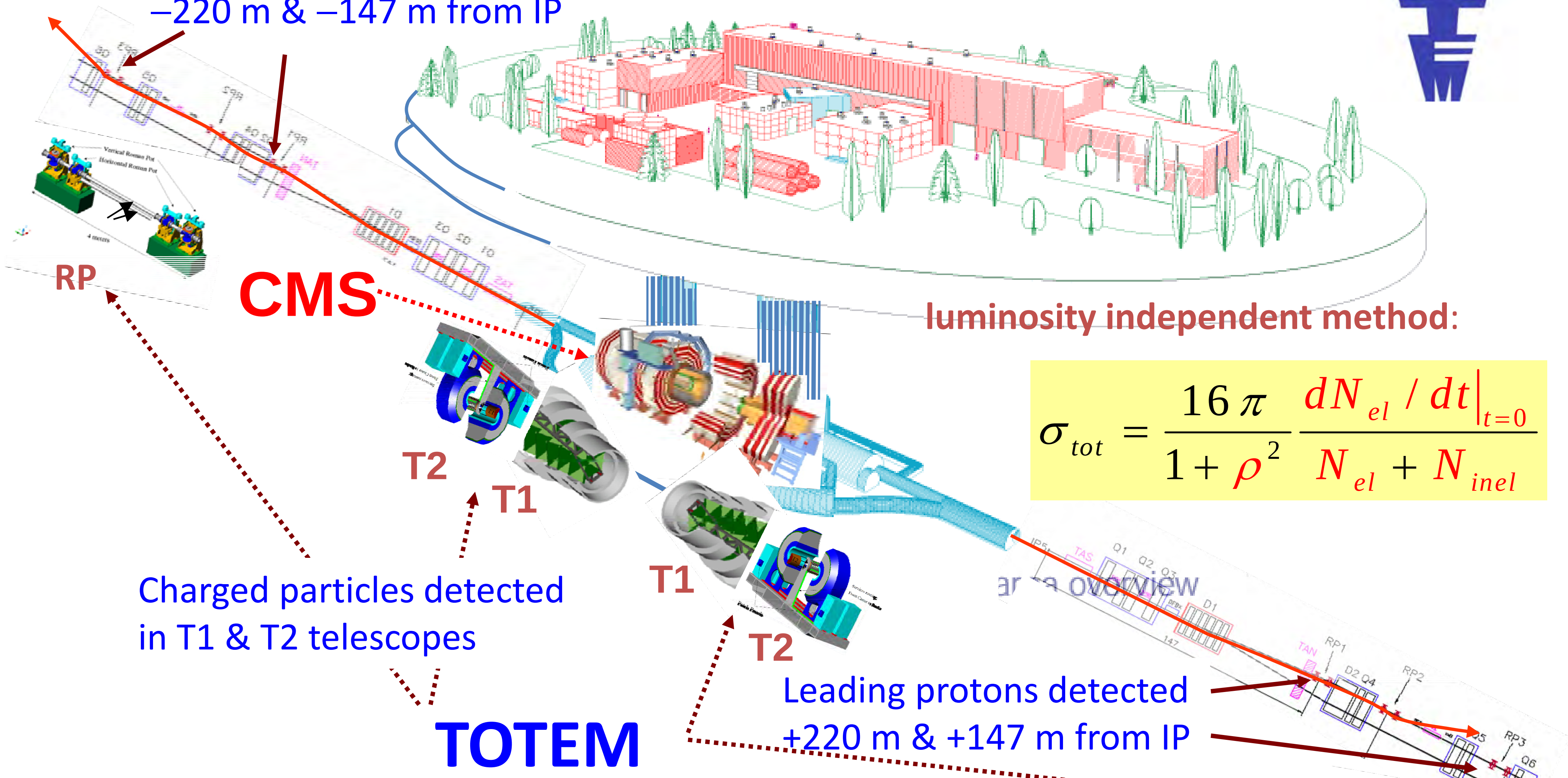


No off-shell ($\mu_{off\text{-}shell}$ = 0) is excluded by more than 99.9% confidence level

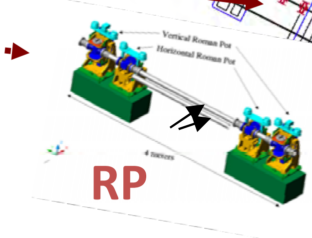
Observed Γ_H = 3.2 +2.4 -1.7 MeV at 95% CL
SM: $\Gamma_H = 4.1$ MeV

TOTEM experiment

Courtesy of Kenneth Österberg



$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \frac{dN_{el}/dt|_{t=0}}{N_{el}+N_{inel}}$$



- Elastic & diffractive protons in RP detectors close to beam
- Charged particles at large |η| using T1 & T2 telescopes

pp elastic scattering

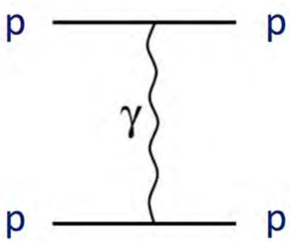
Elastic scattering: t-channel exchange

Elastic proton (anti)proton scattering at TeV scale: gluonic exchange

Experimental variable: $t \approx -P^2\theta^2$, four-momentum transfer squared

Strong interaction (non-pertutative QCD)

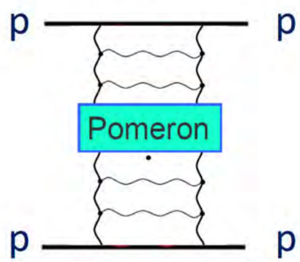
Electromagnetism (QED): $J^{PC} = 1^{--}$



Photon exchange

dominates at very low |t| ($< \approx 10^{-3}$)

Crossing even C = +

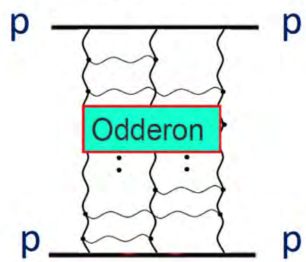


"Pomeron" exchange: system of 2 (or more number of) gluons

dominates at low |t|, $\approx$ imaginary part of A_{el}^{nucl}

same for pp & $p\bar{p}$

Crossing odd C = –



"Odderon" exchange: system of 3 (or more number of) gluons

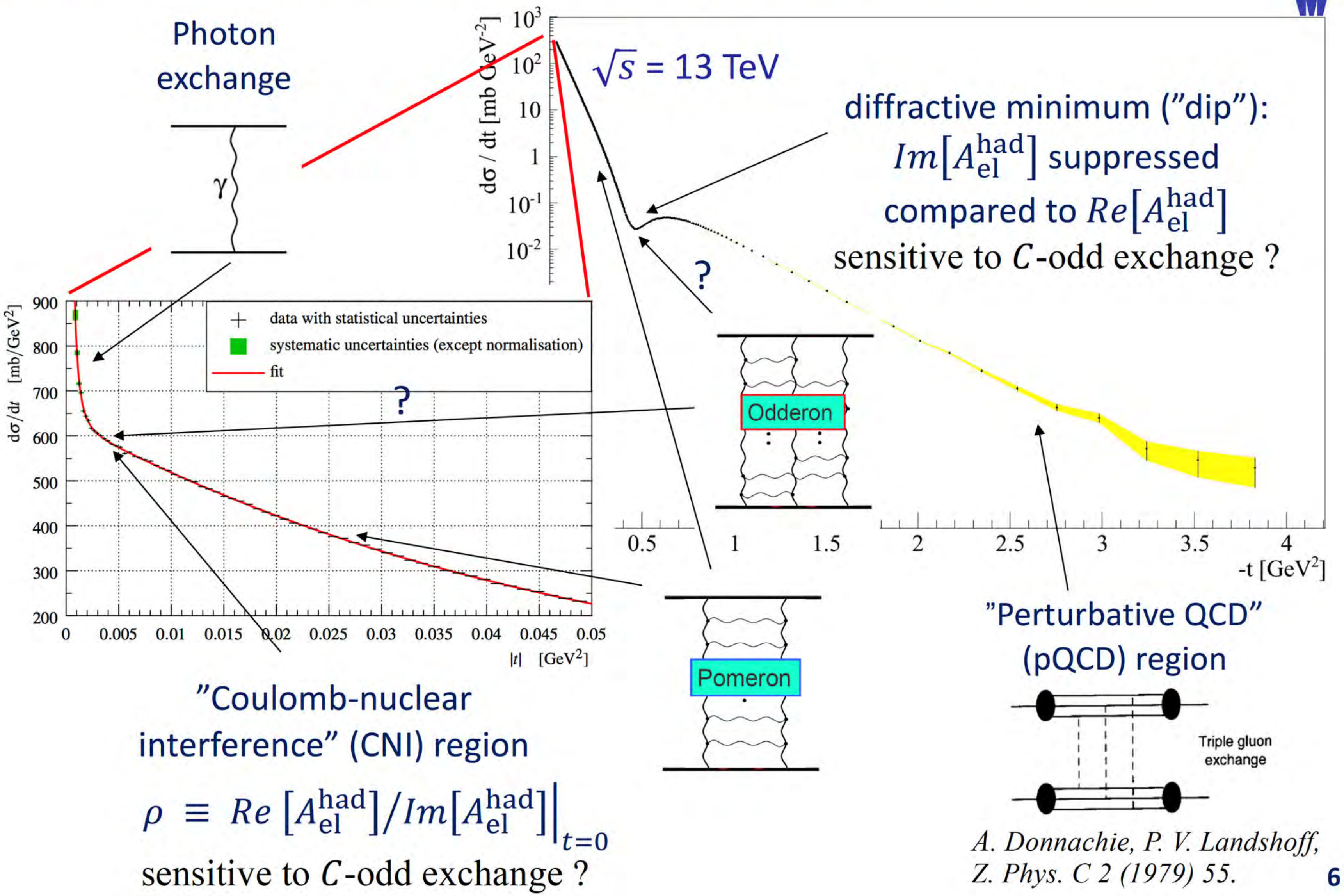
mostly suppressed, mainly real part of A_{el}^{nucl}

different sign for pp & $p\bar{p}$

3

Courtesy of Kenneth Österberg

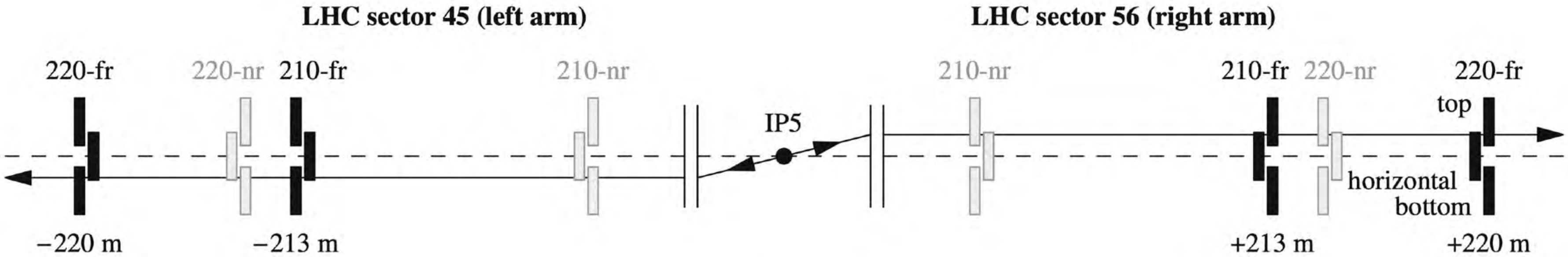
Elastic pp differential cross-section

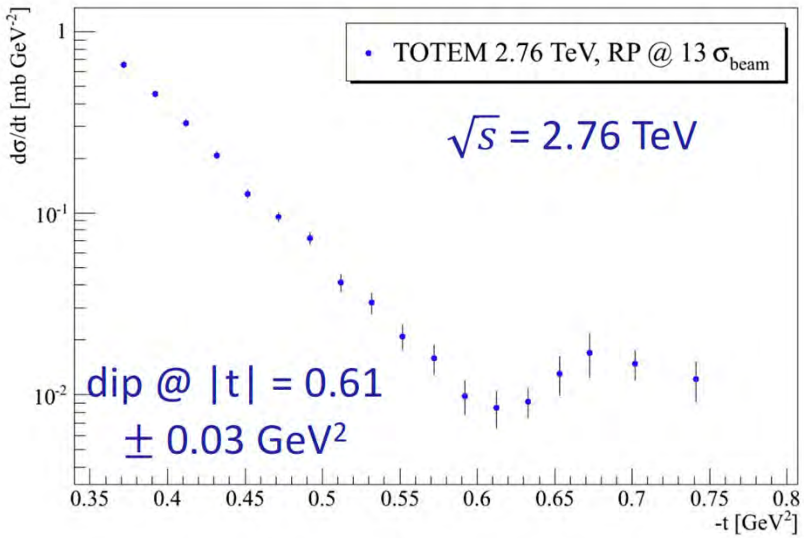


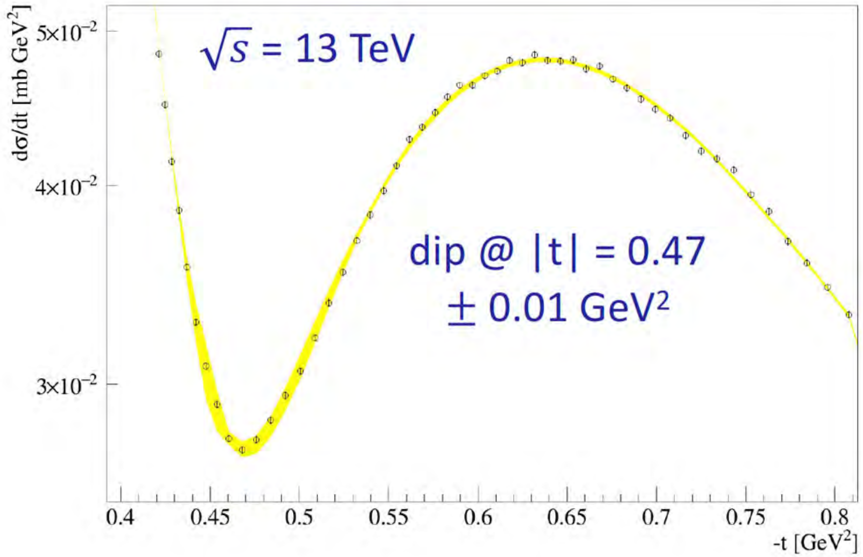
Courtesy of Kenneth Österberg

Elastic pp cross-section measurements

- ✓ Elastic pp $d\sigma/dt$ measurements: measure both intact p's in TOTEM Roman Pots at 210-220 m from IP with silicon detectors.
- ✓ Precise measurements at $\sqrt{s}$ = 2.76, 7, 8 and 13 TeV: EPJC 80 (2020) 91; EPL 95 (2011) 41004; NPB 899 (2015) 527; EPJC79 (2019) 861.



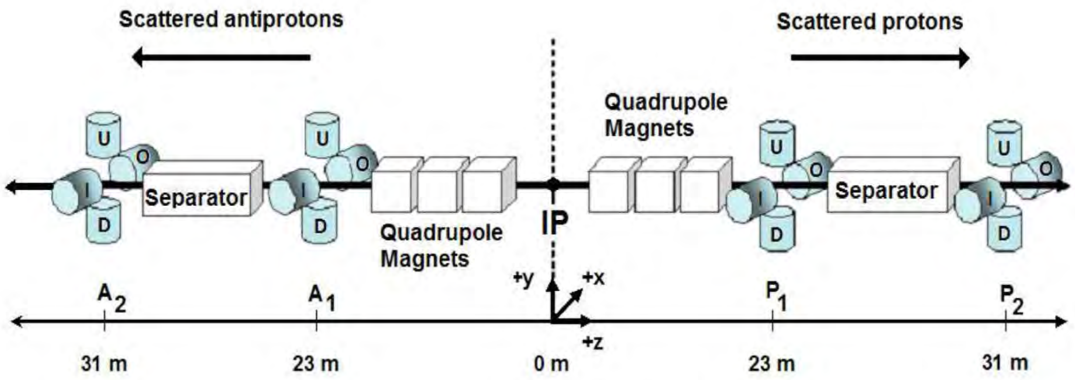


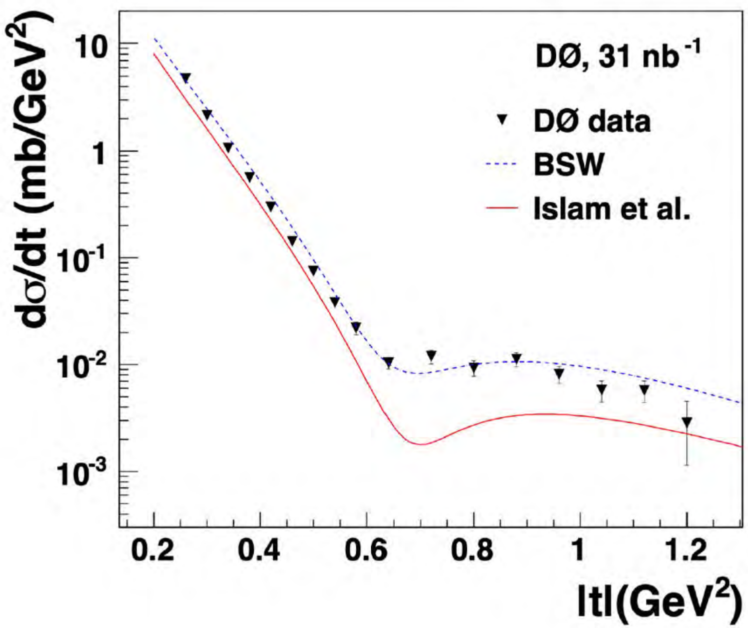


Courtesy of Kenneth Österberg

Elastic $p\bar{p}$ cross-section measurements

- Elastic $p\bar{p}$ $d\sigma/dt$ measurements: measure both the intact p & $\bar{p}$ in D0 Roman Pots at 23-31 m from IP with scintillating fibre detectors.
- Measurement at $\sqrt{s}$ = 1.96 TeV: PRD 86 (2012) 012009.





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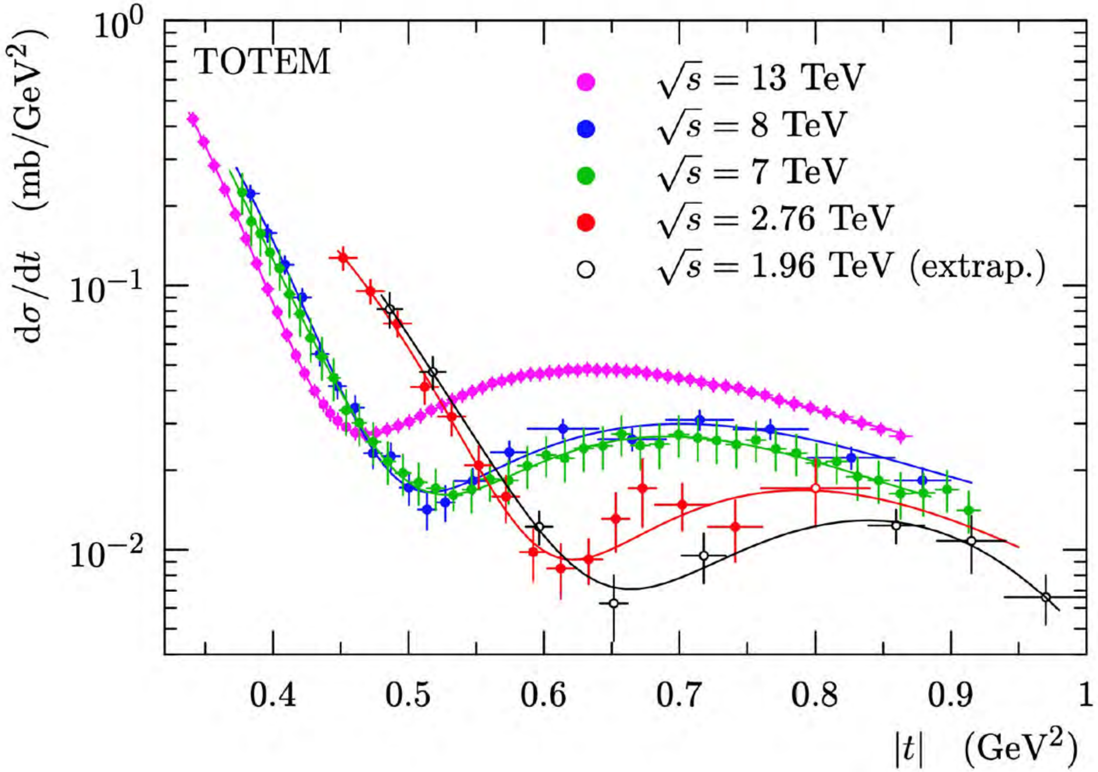
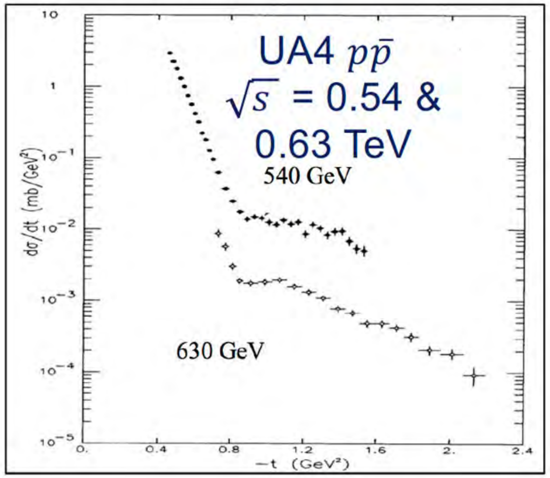
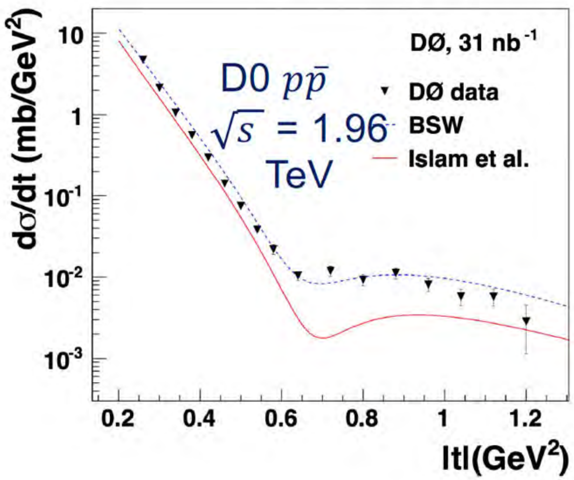
Courtesy of Kenneth Österberg

Elastic $pp/p\bar{p}$ cross-section characteristics

At TeV-scale, pp elastic $d\sigma/dt$ characterized by a diffractive minimum ("dip") & a secondary maximum ("bump"), wheras $p\bar{p}$ $d\sigma/dt$ characterized only by a "kink".





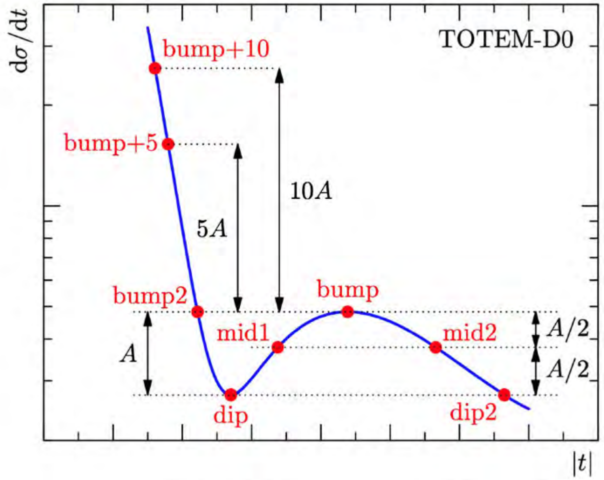


@TeV scale: persistancy of dip & bump for pp, absence of dip & bump for $p\bar{p}$

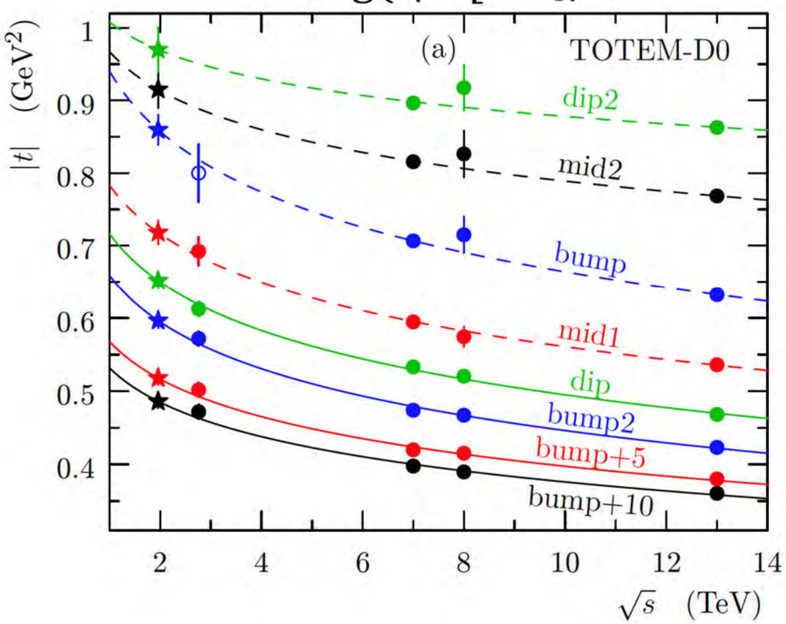
Courtesy of Kenneth Österberg

Extrapolation of pp cross section

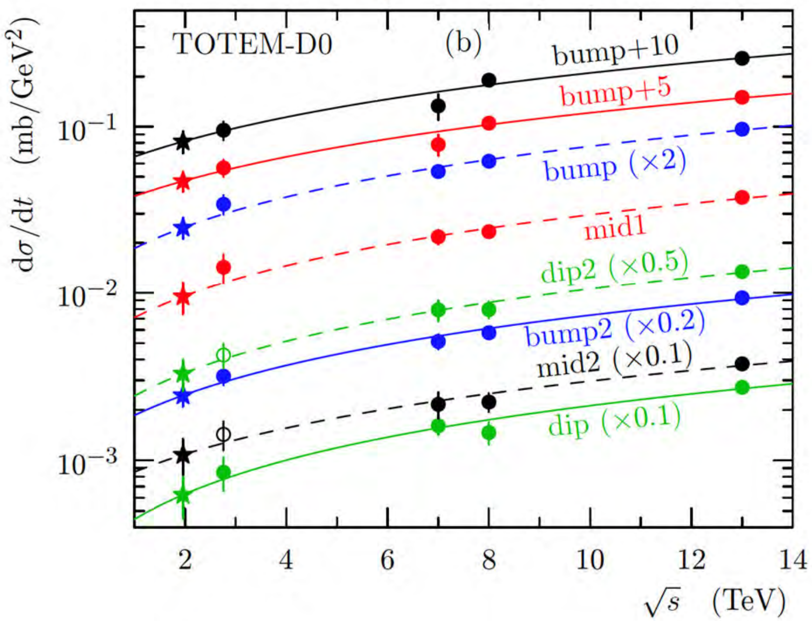
- Extrapolate 8 characteristic points (both their $d\sigma/dt$ & t) in dip-bump region of the pp elastic $d\sigma/dt$ @ 2.76, 7, 8 & 13 TeV to 1.96 TeV $\Longrightarrow$ pp elastic $d\sigma/dt$ points @ 1.96 TeV
- Alternative forms lead to compatible results within quoted uncertainties



$t = a\log(\sqrt{s}\ [\text{TeV}]) + b$



$(d\sigma/dt) = c\sqrt{s}\ [\text{TeV}] + d$



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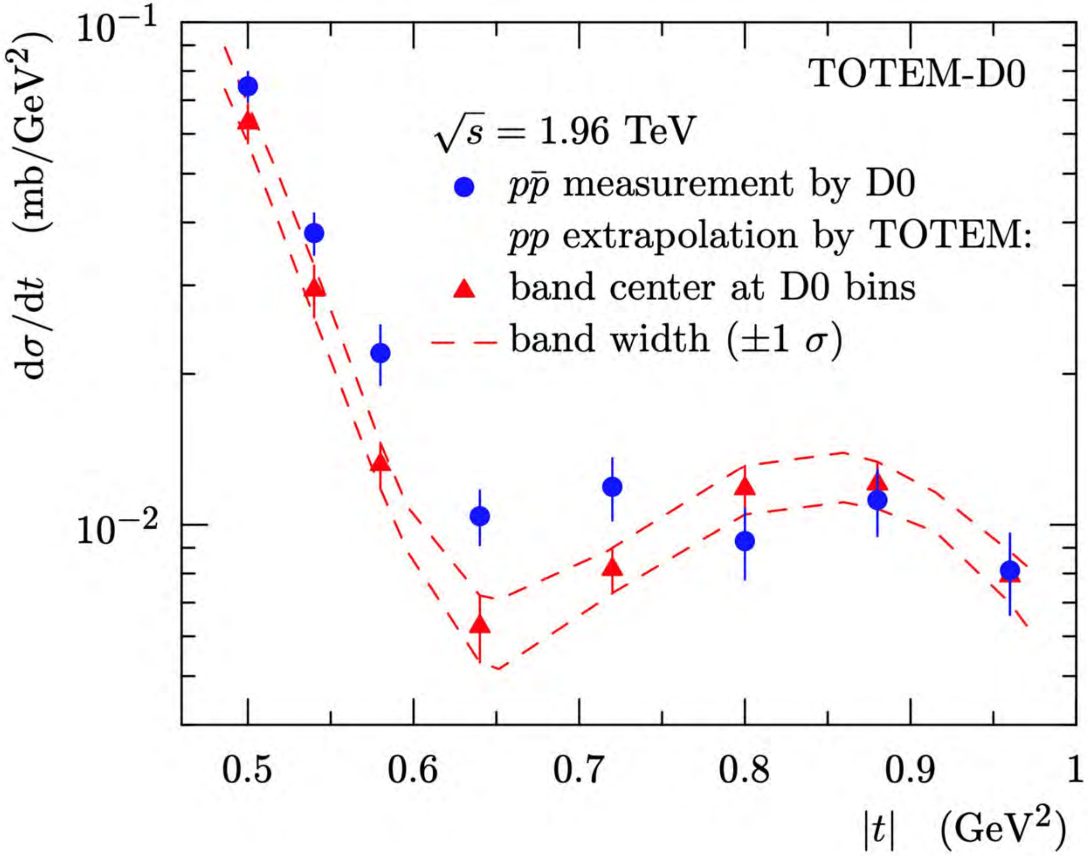
Courtesy of Kenneth Österberg

Comparison of pp & $p\bar{p}$ cross section

Uncertainties of pp data points @ D0 measured |t|-values strongly correlated; full covariance matrix used



χ^2 test of pp & $p\bar{p}$ difference:
3.4σ significance for t-channel exchange of a colourless C-odd gluonic compound ("odderon")

Significance confirmed by a combined Kolmogorov-Smirnov & normalization test

Courtesy of Kenneth Österberg