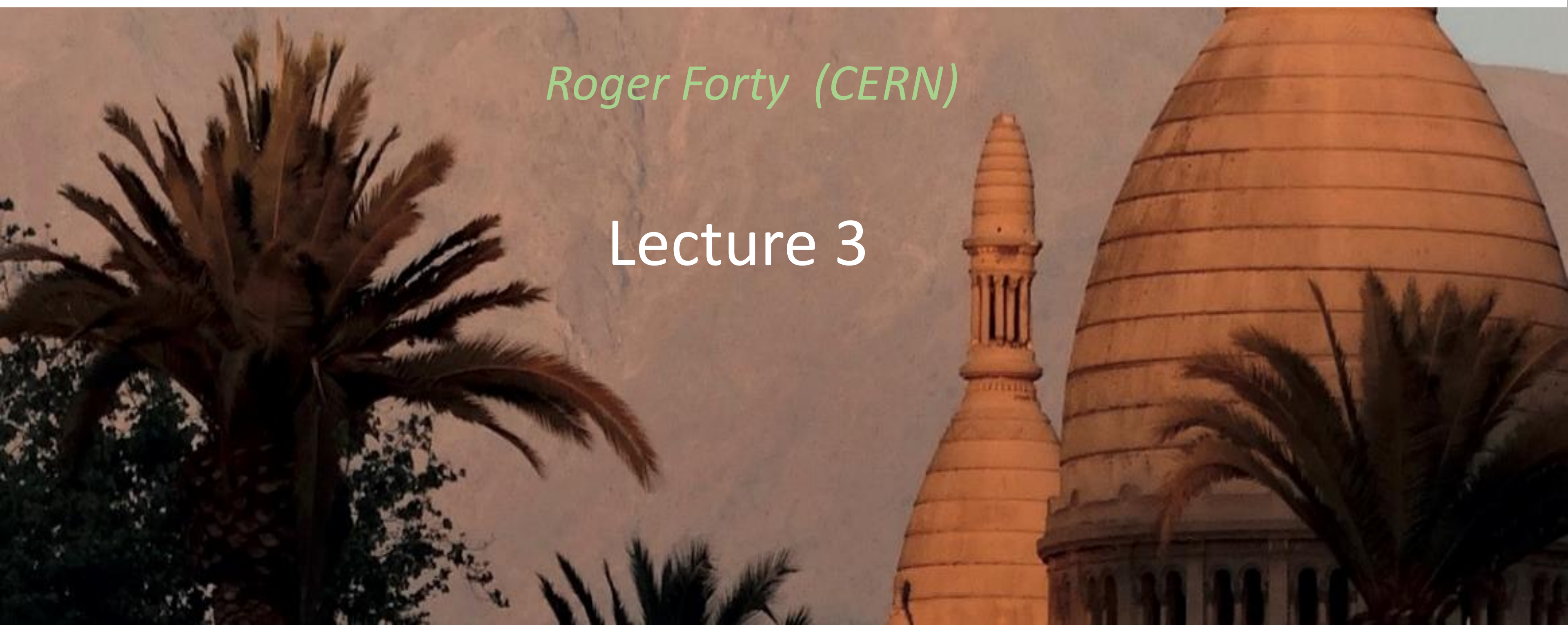
11th CERN LATIN-AMERICAN SCHOOL OF HIGH-ENERGY PHYSICS

San Esteban, Chile
15 – 28 March 2023

Collider Experiments

the LHC & beyond



Roger Forty (CERN)

Lecture 3

Outline

Lecture 1: Accelerators

Lecture 2: Experiments

Lecture 3: LHC physics highlights

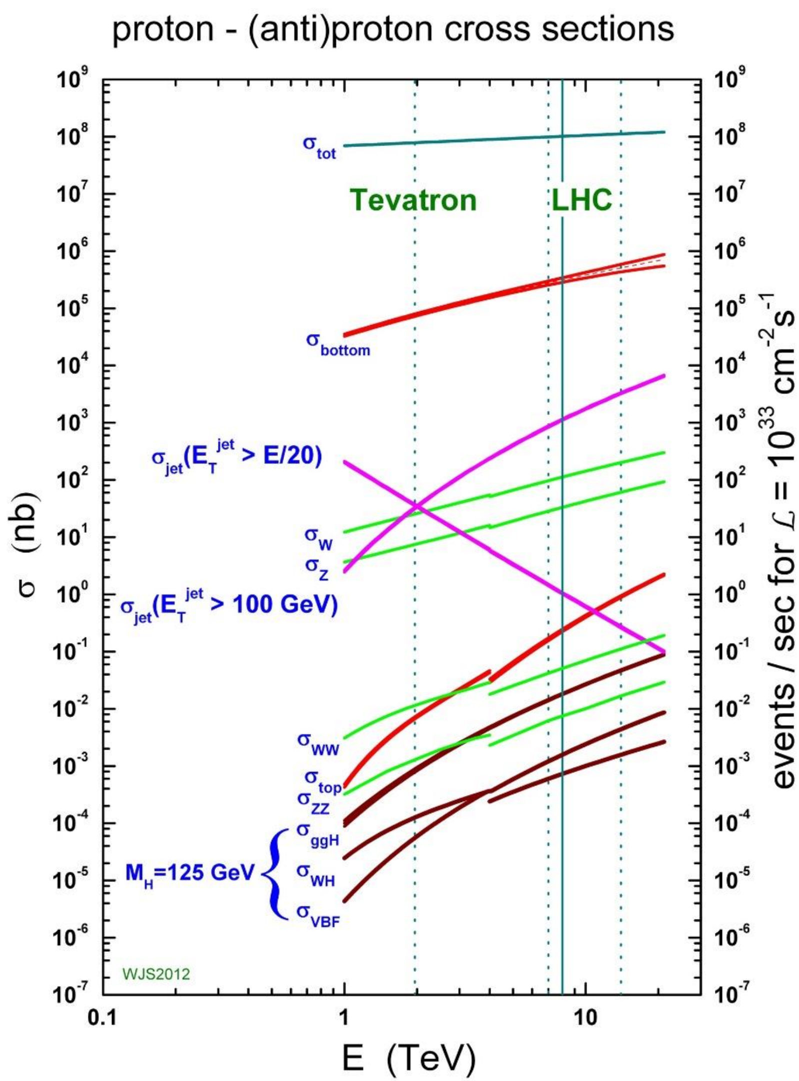
1. Strong interactions
   Cross-sections, jets, QGP, top quark
2. Flavour physics
   Mixing, CP violation, rare decays
3. Electroweak physics
   W, Z, multibosons
4. Higgs boson properties
   Mass, width, couplings, HH

It is only possible to include a limited selection of highlights, which I have selected according to my personal taste – *many* more results are available from the websites of the experiments: ATLAS CMS LHCb ALICE

Lecture 4: Looking beyond

Introduction

- Proton-proton collisions at high energy in the LHC enable a wide variety of physics processes to be studied
- **Cross-sections** (measuring probability of a given final state being produced) vary over 12 orders of magnitude!
- This enables a rich physics programme, and makes model-independent searches possible
- But the collision rate is overwhelmed by mundane processes, so background discrimination and modeling are crucial
- In this lecture will go “down the SM ladder” of the processes in order of roughly decreasing cross-section



Cross-section measurement

Number of observed candidates
(fitted or counted)

Number of background candidates
(measured from data
or calculated from theory)
(minimize)

Cross section in cm^2
(or μb, nb, pb)

$$\sigma = \frac{N_{\mathrm{obs}} - N_{\mathrm{backg}}}{\epsilon \cdot \int \mathcal{L} dt}$$

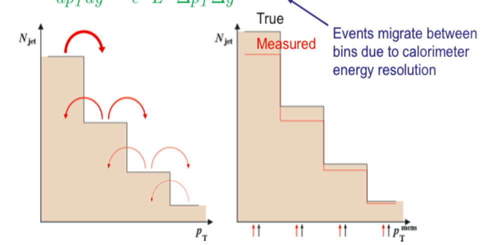
Efficiency/acceptance
(maximize)

Integrated Luminosity in cm^{-1}
(or μb^{-1}, nb^{-1}, pb^{-1})
(maximize,
unless systematically limited)

$$\frac{\delta\sigma}{\sigma} = \sqrt{\frac{\delta N_{\mathrm{obs}}^2 + \delta N_{\mathrm{backg}}^2}{(N_{\mathrm{obs}} - N_{\mathrm{backg}})^2} + \left(\frac{\delta\mathcal{L}}{\mathcal{L}}\right)^2 + \left(\frac{\delta\epsilon}{\epsilon}\right)^2}$$

Care needed when measuring differential cross-sections: resolution effects can bias distribution

$$\frac{d^2\sigma}{dp_T dy} = \frac{N}{\epsilon \cdot L \cdot \Delta p_T \Delta y} \cdot C_{\mathrm{smear}} \text{ vs. } p_T$$

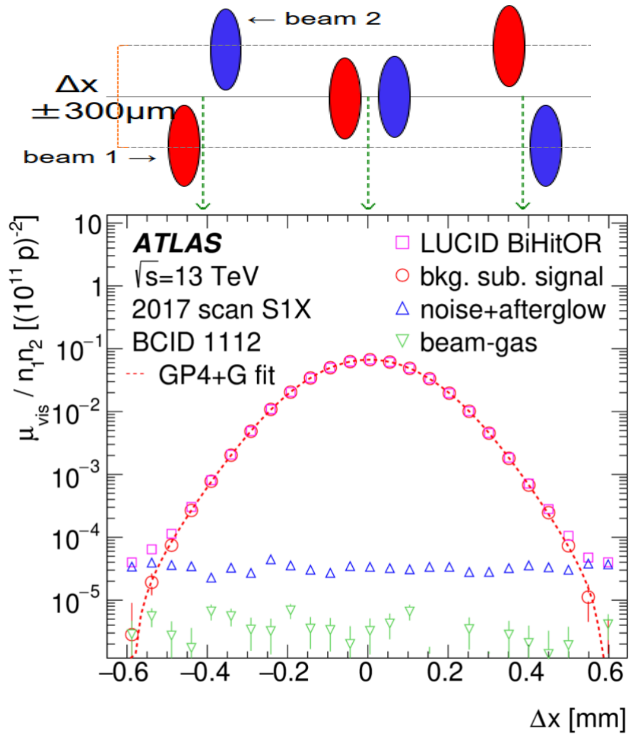


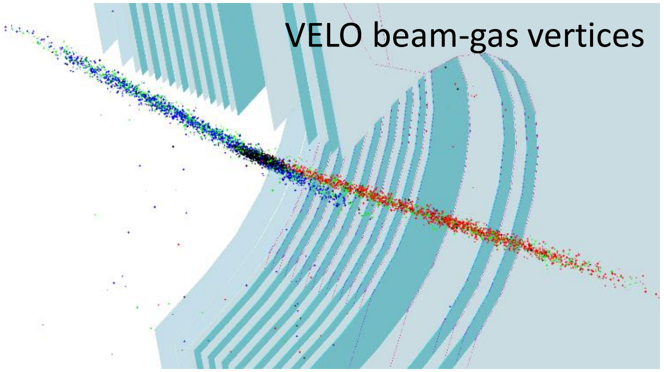
See lectures of Harrison Prosper

- "**Errors**" quoted for measurements = uncertainties on the central value
  - *statistical* from fit to the data: quoted as ±1σ (RMS), scale with 1/√N
  - *systematic* from uncertainties in the other parameters that affect the result, such as luminosity – estimating these is a difficult art

Luminosity measurement

- Measuring cross-sections requires knowledge of the *integrated* luminosity
- The *instantaneous* luminosity can be determined by manipulating the beams in a special run, known as a **Van de Meer scan**: the offset between the beam positions is adjusted in steps to determine the beam profile, and the bunch charges are measured
- Need to transfer that information via signals in other detectors, so that luminosity can be monitored throughout the run [arXiv:2212.09379]
  ~ 1% precision achieved on luminosity measurement
- The profiles of the beams can also be seen in **beam-gas** collisions, e.g. at the LHCb VELO:
- The luminosity delivered can be levelled by adjusting the beam offset, e.g. to limit pileup
  or to provide lower luminosity for LHCb



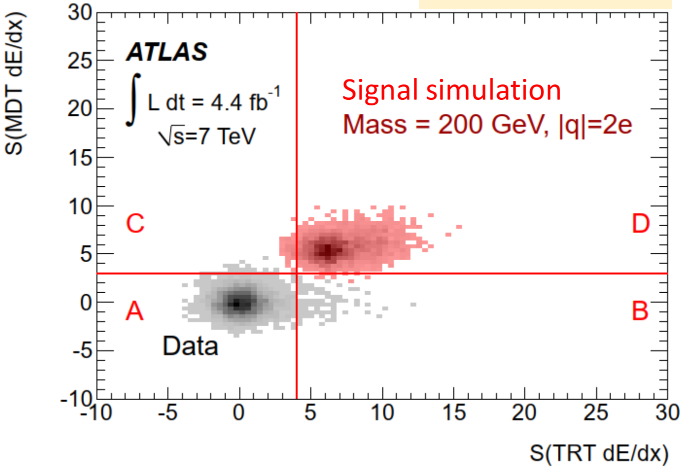


Background estimation

- The main challenge is **background**: events from other processes which look like signal events
  - *instrumental* (fake) background in the detector: a different type of object fakes the one present in the signal decay
  - *physics* (irreducible) background: a different physics process with same final state as the signal

arXiv:1301.5272

- Background contribution to signal region can be estimated using "ABCD" method: regions are defined by dividing the plane of two selection variables using final cuts; region D is defined as the signal region, A, B and C as control regions

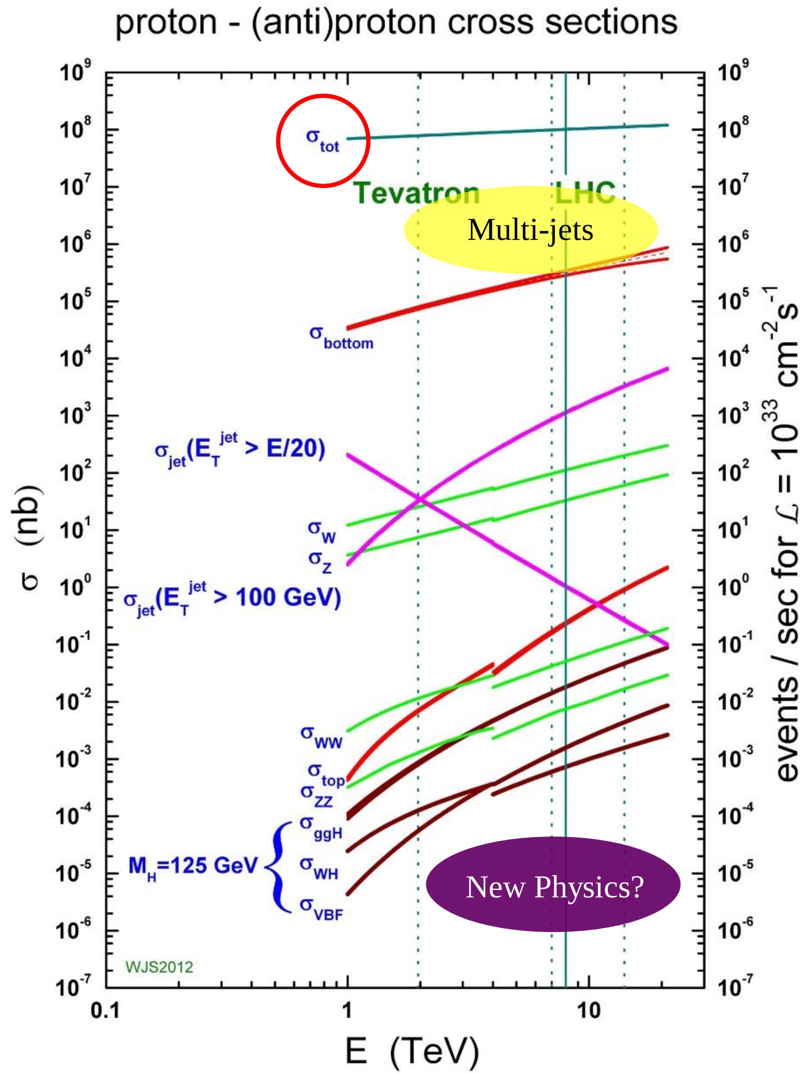


- The expected number of candidates from background in signal region D is estimated from the numbers of observed data candidates in the other regions

$$N^{\mathrm{D}}_{\mathrm{data}} = \frac{N^{\mathrm{B}}_{\mathrm{data}} \times N^{\mathrm{C}}_{\mathrm{data}}}{N^{\mathrm{A}}_{\mathrm{data}}}$$

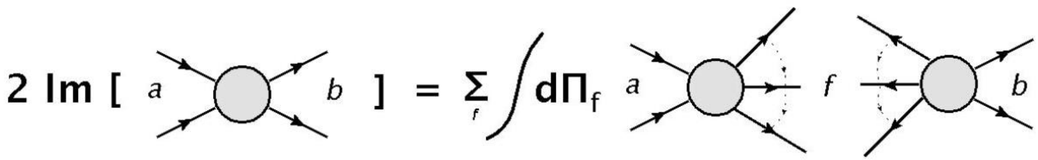
1. Strong interactions

- Hadron collisions are swamped by multi-jet processes
  - To discover new physics, we need a quantitative understanding of QCD processes in rate and shape
- In itself, the study of multi-jet final states is a test of perturbative QCD
  - It can also serve as a window to new physics such as compositeness or excited quarks
- Only small datasets are needed, statistics are not a problem
- First discuss the *total* cross-section



Total cross-section

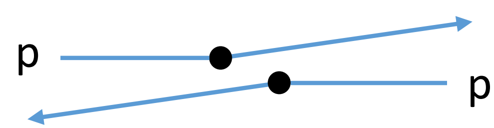
- The total cross-section is a very basic measurement: the total interaction probability when two protons hit each other
- Make use of the *Optical Theorem* from quantum mechanics:



The imaginary part of the amplitude between states *a* and *b* is given by the product of the amplitudes from *a* and *b* to all available intermediate states *f*, integrated over their phase space

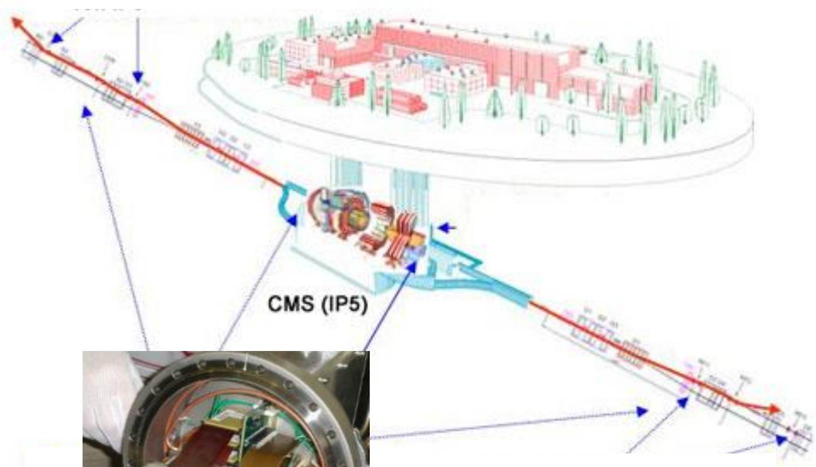
→ the total cross-section is equal to the imaginary part of the forward scattering amplitude $\sigma_{tot} \propto 4\pi \cdot \mathrm{Im}\left(f_{el}\right)_{t\to 0}$ $t = -\left(p\theta^*\right)^2$

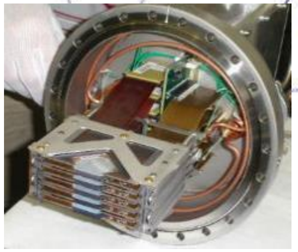
- Requires measurement of differential *elastic* cross-section in *t*: $\sigma_{tot}^2 = \frac{1}{L} \cdot \frac{16\pi}{1+\rho^2} \cdot \left.\frac{dN_{el}}{dt}\right|_{t\to 0}$ $\rho = \left.\frac{\mathrm{Re}\left(f_{el}(t)\right)}{\mathrm{Im}\left(f_{el}(t)\right)}\right|_{t\to 0}$
- Elastically scattered protons will escape from the general-purpose experiments inside the beam-pipe – need a dedicated "**forward physics**" detector



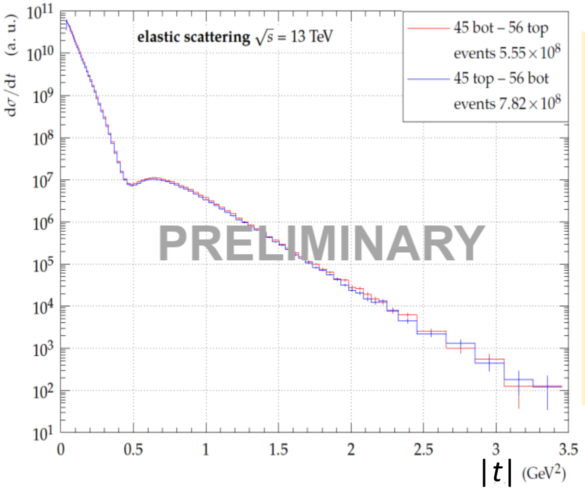
TOTEM

- Silicon tracking detectors mounted in "Roman Pots" very close to the beam to measure elastic scattered protons (similar principle to the LHCb VELO)

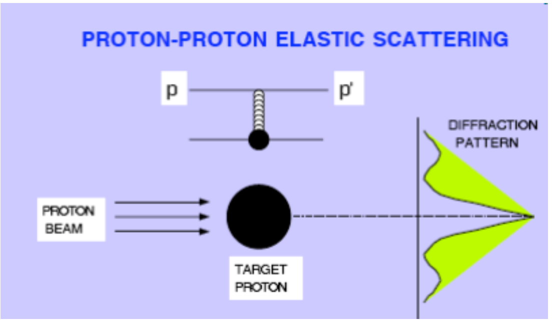


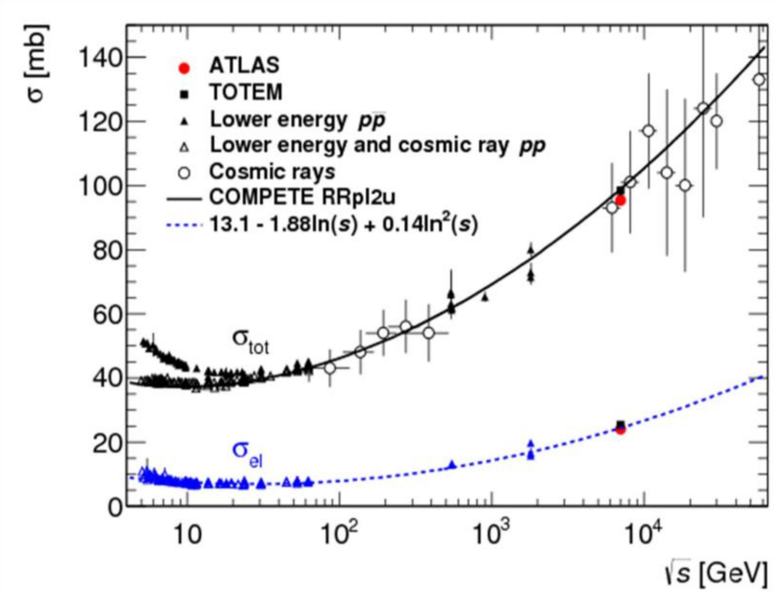


220 m from CMS IP



N. Turini, La Thuile (2018)



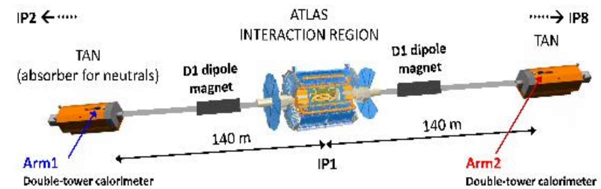


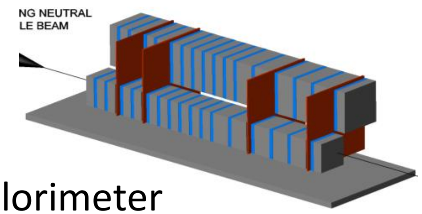
Nucl. Phys. B889 (2014) 486-548

LHCf

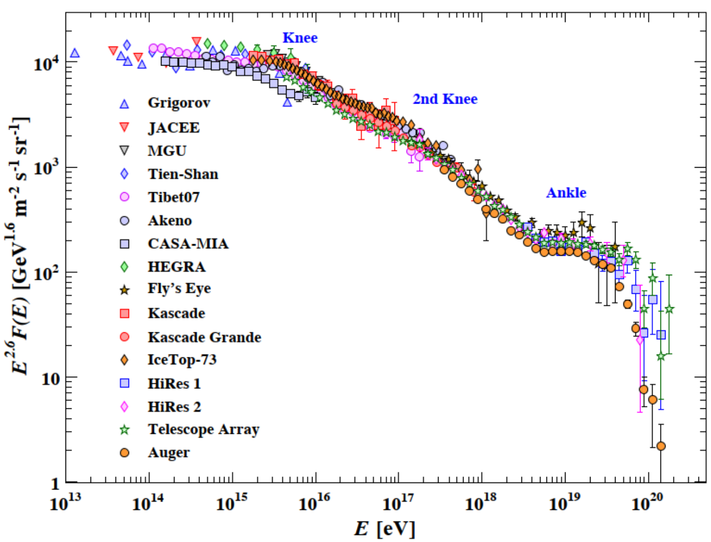
See lecture of Miguel Mostafa

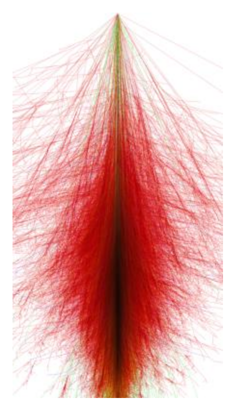
- Another forward-physics experiment **LHCf** (at ATLAS IP) uses a zero-degree calorimeter to study neutral production, relevant to cosmic rays
- 13 TeV pp collisions correspond to 10^{17} eV cosmic rays impinging on the atmosphere (fixed-target collisions), above the “knee” in the CR spectrum
- LHCf data helps tune simulation of CR air showers



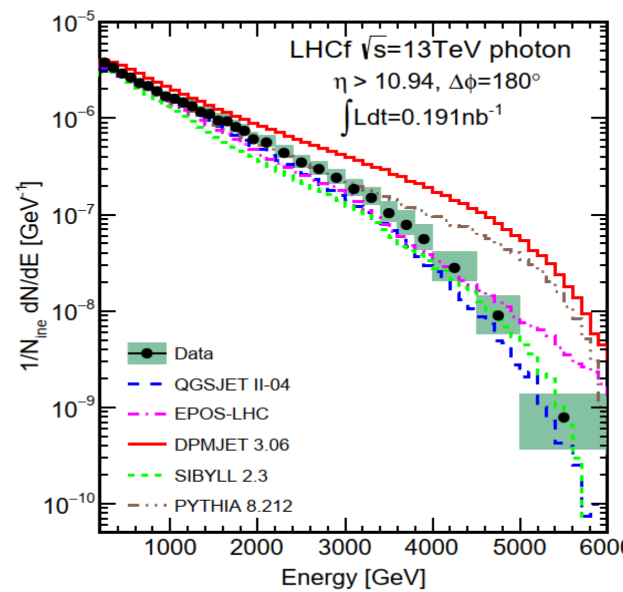


LHCf calorimeter





Air shower (simulation)



Jet clustering

- Jets are collimated sprays of stable charged and neutral particles
  They can be reconstructed using different algorithms:
- **Fixed Cone**
  - Variations in how to choose seed and cone size (R = 0.3 … 1)
- **Sequential Clustering**
  - Pairwise examination of input 4-vectors
  - Merging determined by proximity in space and transverse momentum between particles *i*, *j* and beam-axis *b*
  - If $d_{ij} < d_{ib}$, combine the particles otherwise *i* is taken as a jet

$$d_{ij} = \min(p_{T,i}^{2\beta}, p_{T,J}^{2\beta})\frac{\Delta R_{ij}^2}{R^2}$$

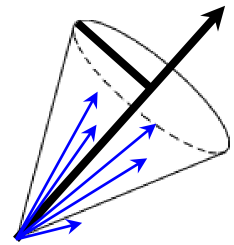
$$d_{ib} = p_{T,i}^{2\beta}$$

Different variants

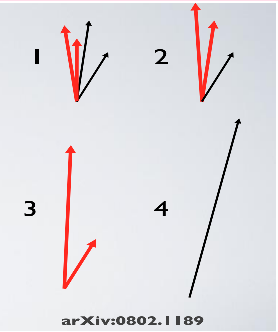
$$\beta = \begin{cases} -1, & \text{Anti-}k_T \\ 0, & \text{Cambridge-Aachen} \\ 1, & k_T \end{cases}$$

Fixed Cone

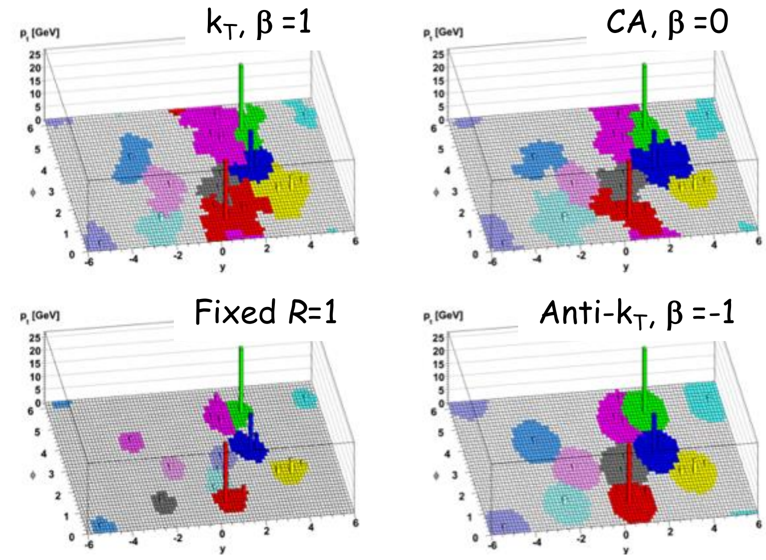
$$R^2 = \eta^2 + \phi^2$$



Sequential Clustering



Applied to same parton-level event:

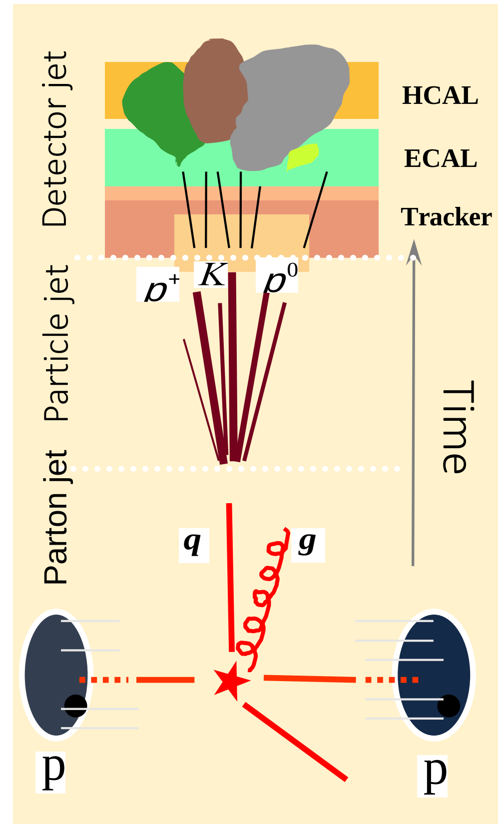


Kt	C/A	Anti-Kt
d_{ij} dominated by soft	d_{ij} independent of pt	d_{ij} dominated by hard
Area fluctuates considerably	Area fluctuates somewhat	Area fluctuates slightly
Susceptible to UE & PU	Somewhat susceptible to UE & PU	Only slightly susceptible to UE & PU
Good for jet sub structure	Best for jet sub structure	Worst for jet substructure

R. Atkin, HEPP2015

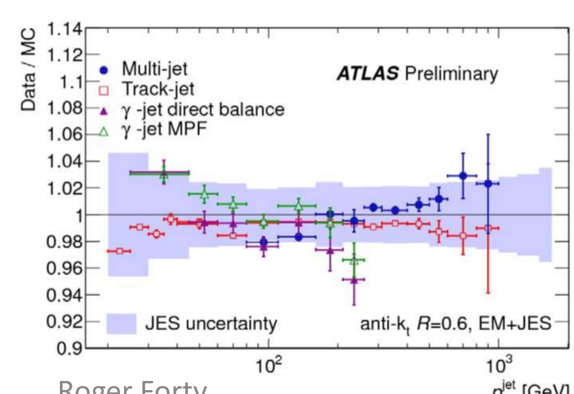
Jet calibration

- Jets can be defined at different levels in an event
  - **Parton jet** made of quarks and gluons (after hard scattering, before hadronization)
  - **Particle jet** composed of final-state colourless particles (after hadronization)
  - **Detector jet** reconstructed from measured energy depositions and tracks



- The *Jet Energy Scale* (JES) and *Resolution* (JER) are important ingredients for precision studies

Energy scale calibration restores the jet energy to that of jets reconstructed at the particle level correcting for detector imperfections, pileup, etc.



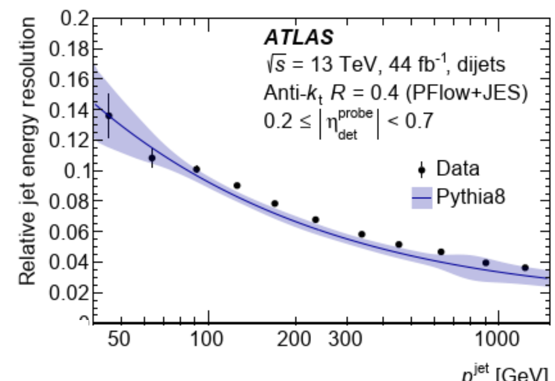
Jet energy scale

Eur. Phys. J. C75 (2015) 17

Few % precision achieved

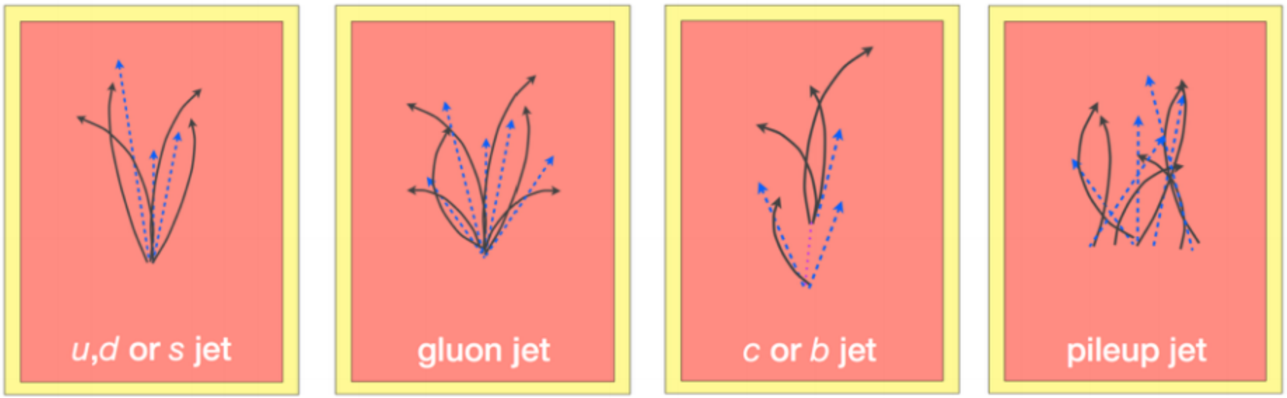
Jet energy resolution

arXiv:2007.02645



Jet topologies

- Qualitatively different quarks/gluons produce different jet topologies: different radiation patterns & lifetimes can be discriminated via topologies



- Jets can also form from hadronic decays of high-p_T heavy particles
  - By studying the patterns gain information about the process in the event
  - Can be used to identify new physics signatures

$W/Z \rightarrow q\bar{q}$ $\quad H \rightarrow b\bar{b}$ $\quad t \rightarrow Wb \rightarrow q\bar{q}b$

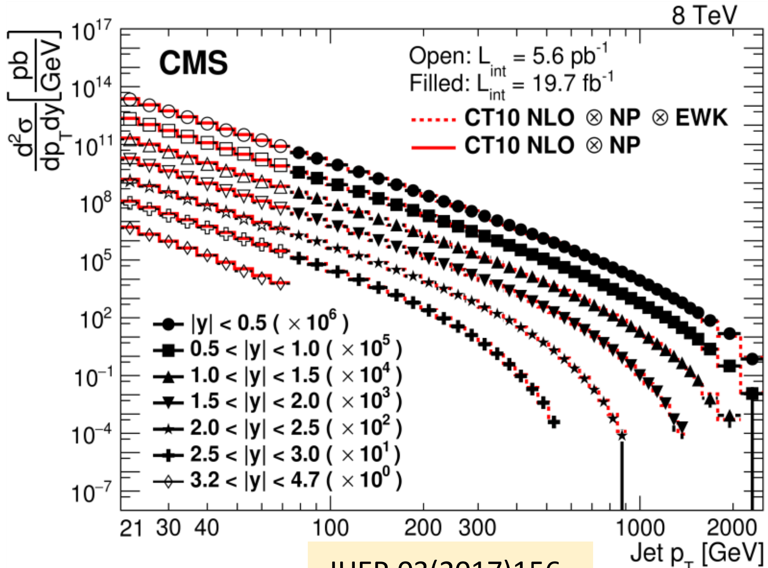
Inclusive jet cross-sections

- Double-differential in p_T and y:

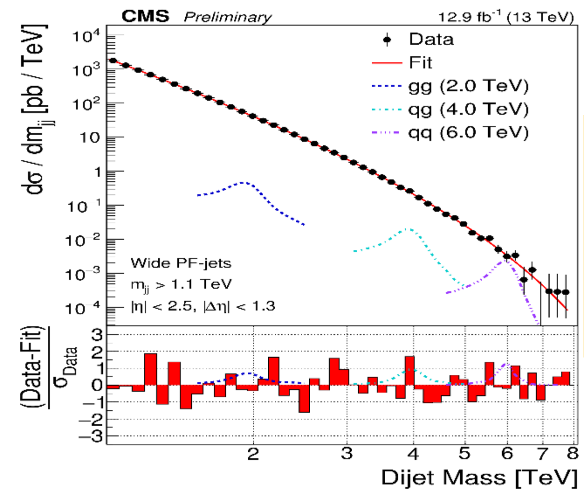
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}\mathrm{d}y} = \frac{1}{\epsilon\mathcal{L}_{\mathrm{int,eff}}} \frac{N_{\mathrm{jets}}}{\Delta p_\mathrm{T}\,(2\Delta|y|)}$$

- Dominant systematic uncertainties: JES and JER (range from 2-30%, largest at low p_T, high rapidity regions)
- NLO predictions agree well with data → improved constraints on parton distribution functions (PDFs)
- **Dijet mass**: good agreement too

  If deviations were seen from QCD at large p_T they could hint at substructure inside the quarks (as in Rutherford scattering) or other new physics



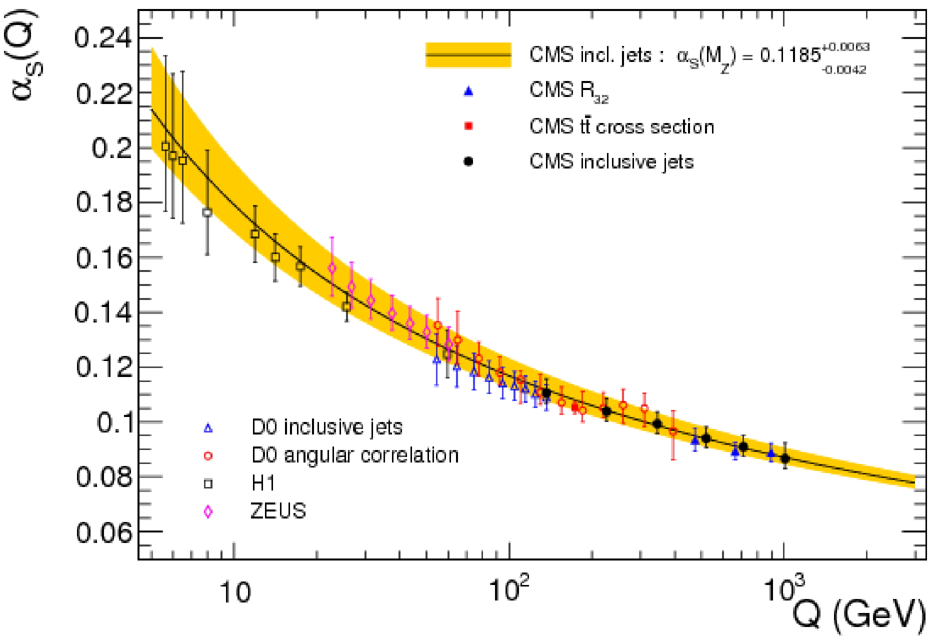
JHEP 03(2017)156



CMS-PAS-16-032

Strong coupling constant

- The strong coupling constant α_s can be extracted from the inclusive jet measurements by varying its value in the theoretical prediction (for a given PDF set) and comparing to the data to find the best fit



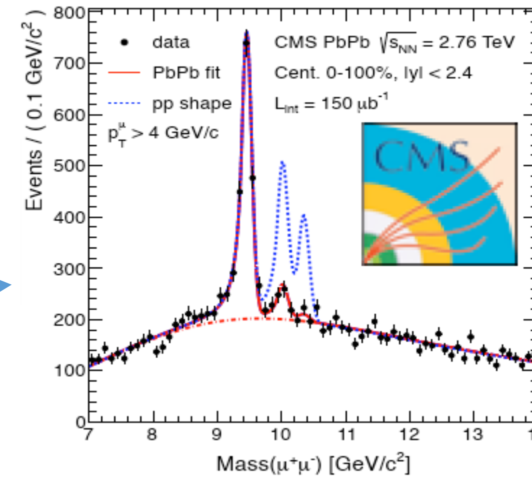
arXiv:1410.6765

- The "running" of α_S to lower values as the energy increases can be seen as expected in QCD – the energy scale Q is taken to be the jet p_T

Quark Gluon Plasma

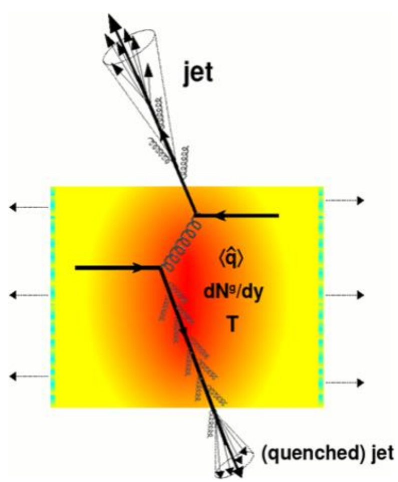
See lectures of Maelena Tejeda-Yeomans

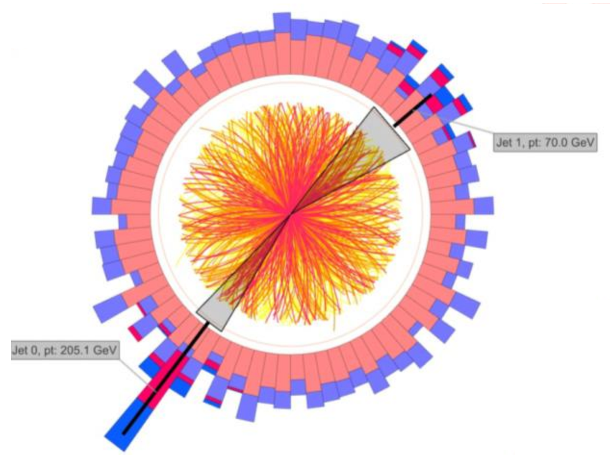
- A deconfined state of strongly interacting matter described by QCD is expected in *heavy-ion* collisions at high energy at the LHC
- Numerous observables including **jet quenching**, as well anisotropic flow, J/ψ and upsilon ($b\bar{b}$) suppression provide evidence that the hot QCD state produced is a *quark-gluon plasma*



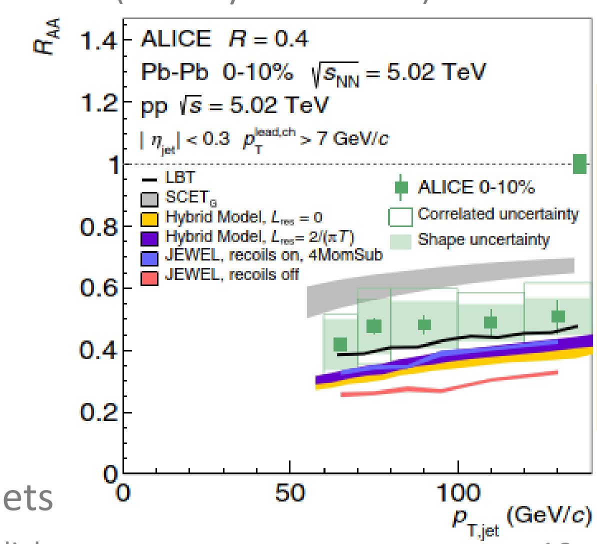
PRL 109 (2012) 222301

Jet quenching: suppression due to losing energy in medium





Ratio between jets in Pb-Pb and pp (suitably normalized)



PRC 101(2020) 034911

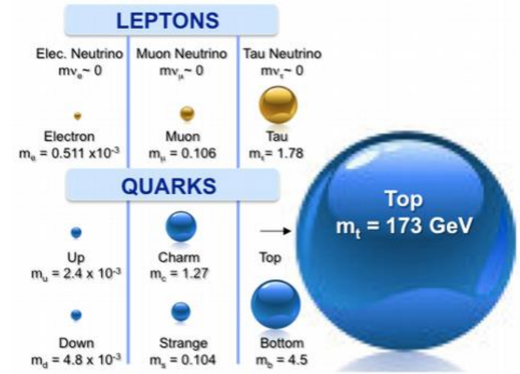
Larger jet quenching seen for gluon jets compared to quark jets

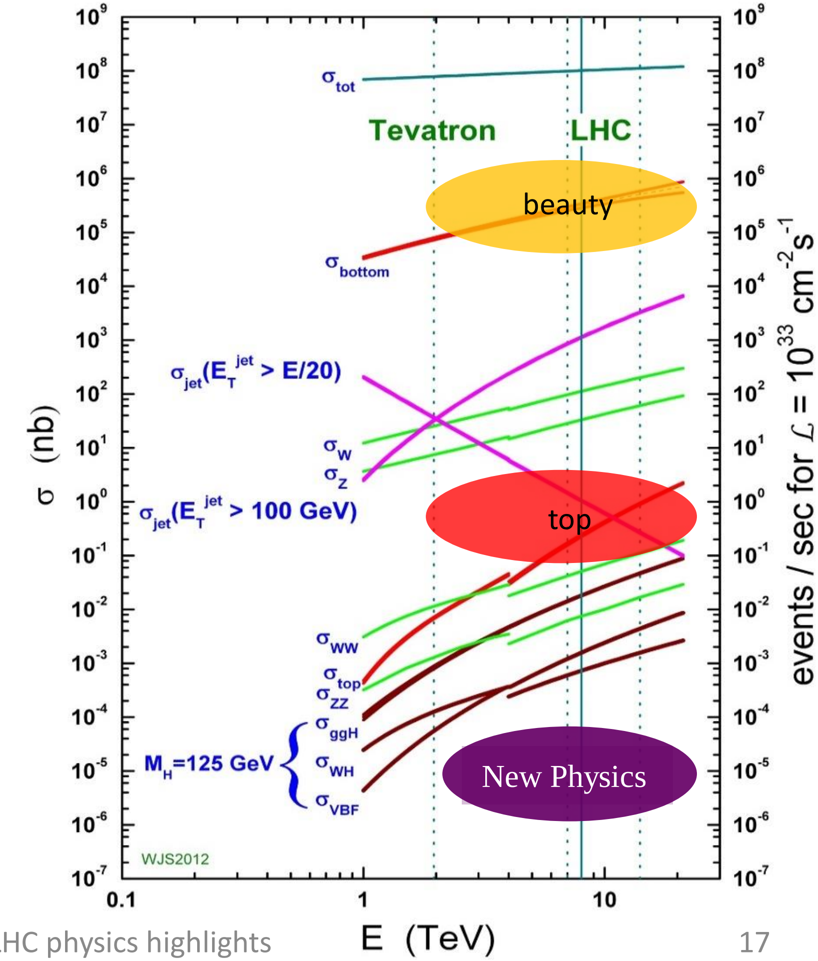
Top quark

- The most massive elementary particle
- Within the Standard Model it can be produced singly or in pairs, and has a very short lifetime: 5×10^{-25} s

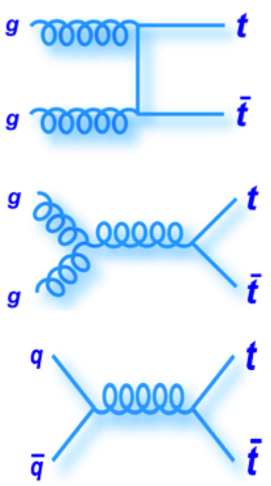
→ it decays before hadronisation
unique opportunity to study bare quark
At boundary between strong & EW physics

- Top-Higgs Yukawa coupling $\lambda_t \approx 1$
  - special role in EWSB
  - window to new physics that might couple preferentially to top
  - Precision measurements allow for stringent tests of the SM
- Next heaviest quark: **b** (bottom or beauty) produced more copiously but does hadronise – discussed later



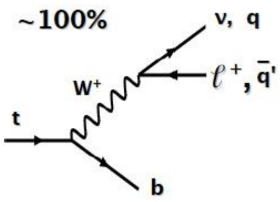


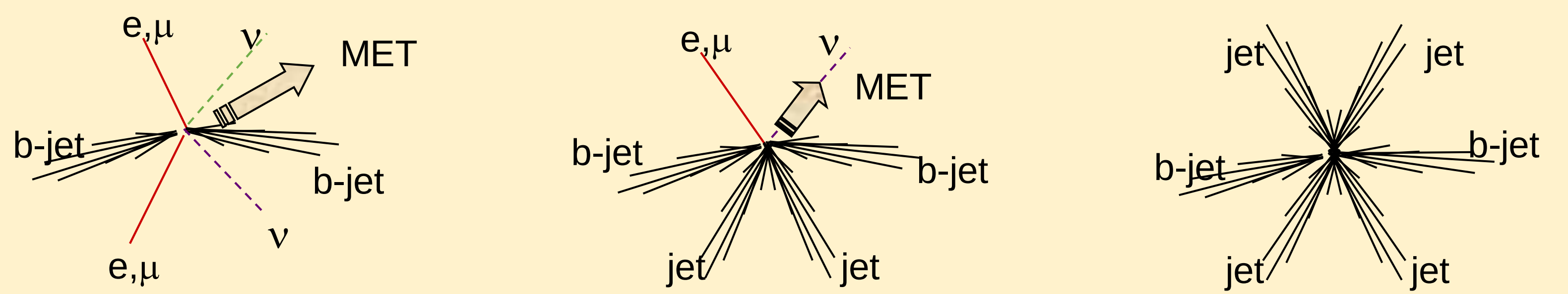
Top production



- Main top production mechanism at the LHC: pair production via the strong interaction
- Within SM the top quark decays into b+W ~ 100% of the time
- The W boson can decay into two quarks or into a charged lepton + neutrino; a $t\bar{t}$ event should therefore have either:
  - 6 quarks
  - 4 quarks, 1 charged lepton and 1 neutrino
  - 2 quarks, 2 charged leptons and 2 neutrinos

In all cases, 2 b-quark jets are present in the event



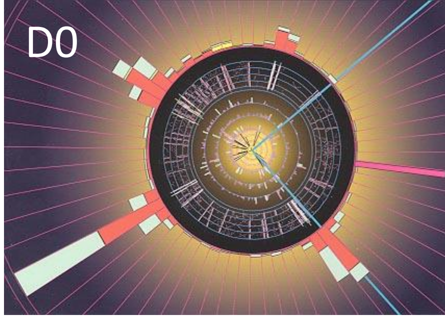


Dilepton (BR~5%, low bkg)

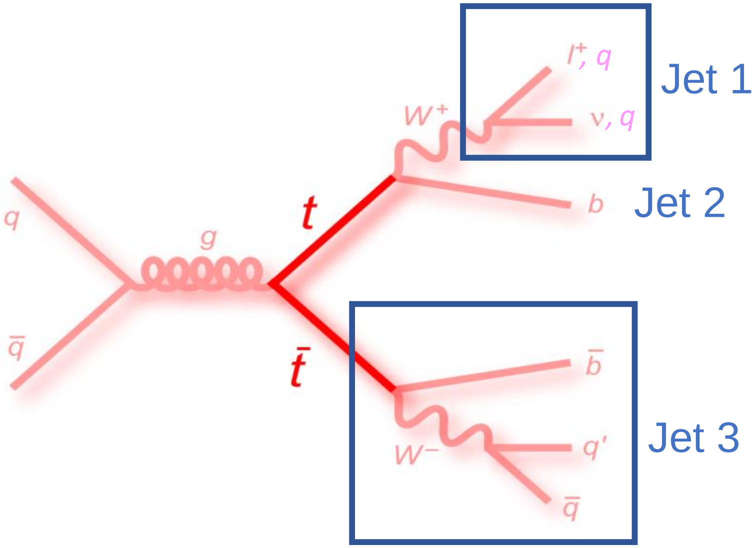
Lepton+jets (BR~30%, moderate bkg)

All-hadronic (BR~46%, huge bkg)

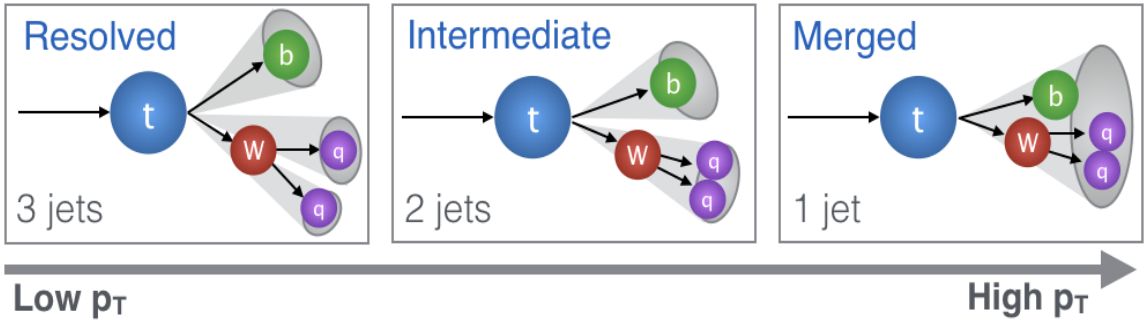
Jet substructure

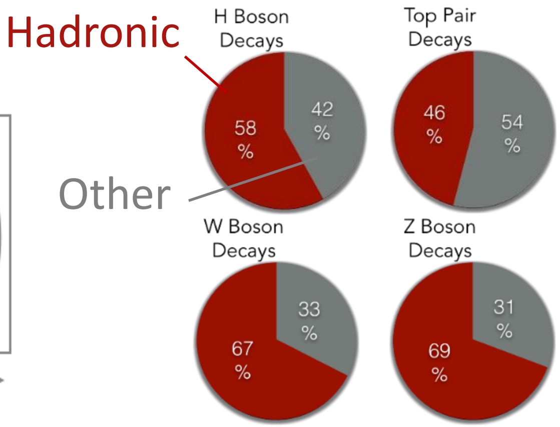


- Identifying $t\bar{t}$ events traditionally done by associating one object to each final state decay product
  - Combine objects to reconstruct each top
  - Combinatorics can become unwieldy
    6+ jets in the all-hadronic decay mode!



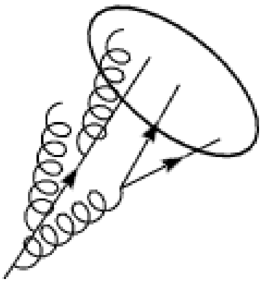
- If top quarks are boosted, decay products are collimated → reconstructed in same jet
  Large amount of acceptance can be gained for hadronic channels, using substructure
- These merged decays can be used in other cases as well: W, Z, Higgs bosons

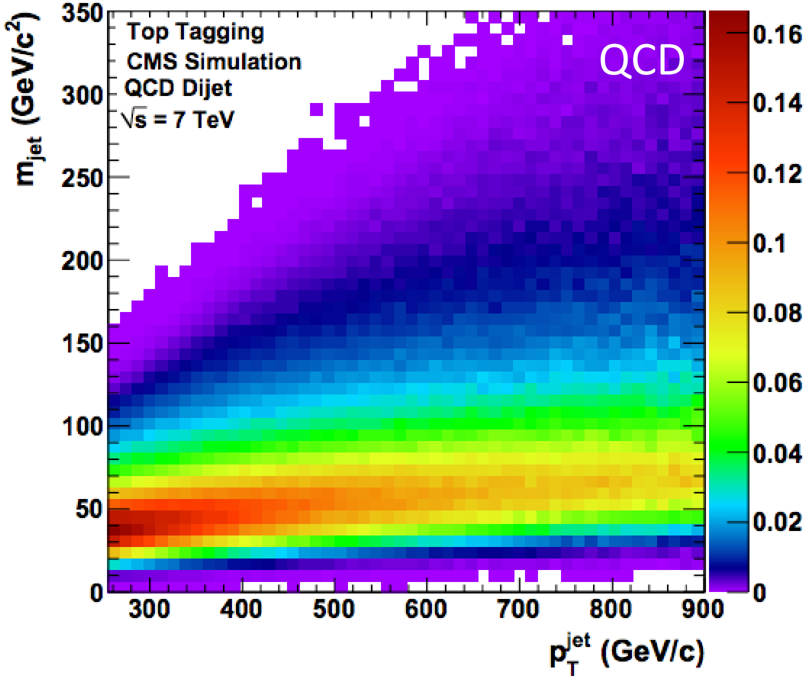


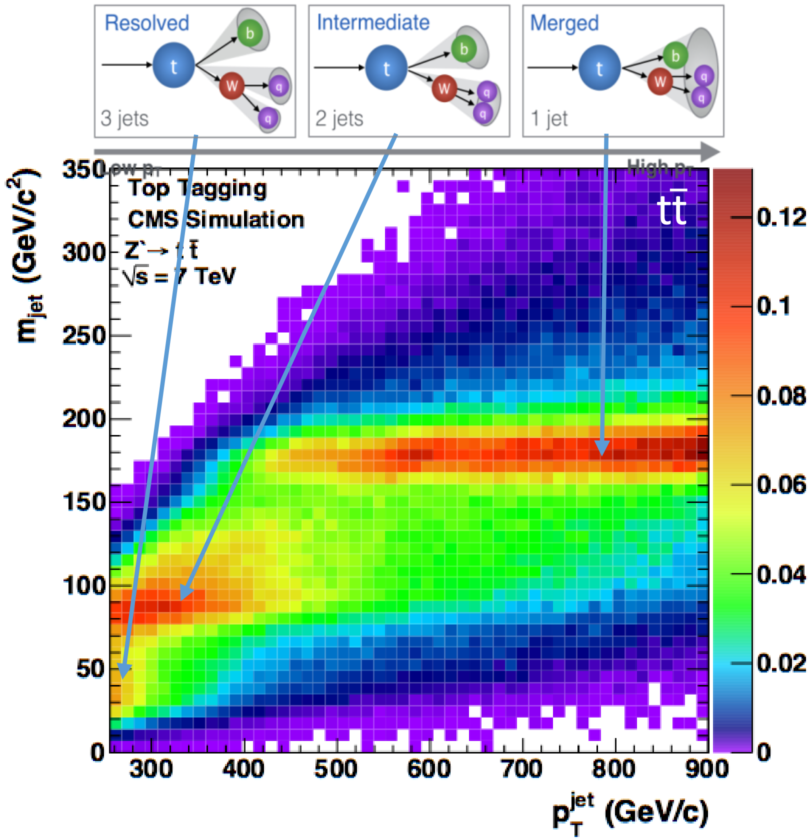


Jet mass

- Computed by adding up constituent particle 4-vectors and calculating the mass
- Choose *R* = 0.8 for heavy object reconstruction
  - Merged W/Z at p_T ~ 200 GeV
  - Merged top at p_T ~ 400 GeV

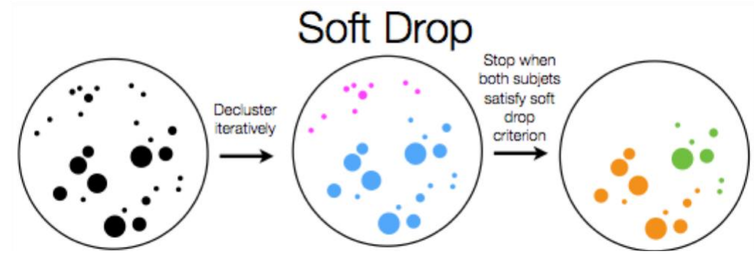




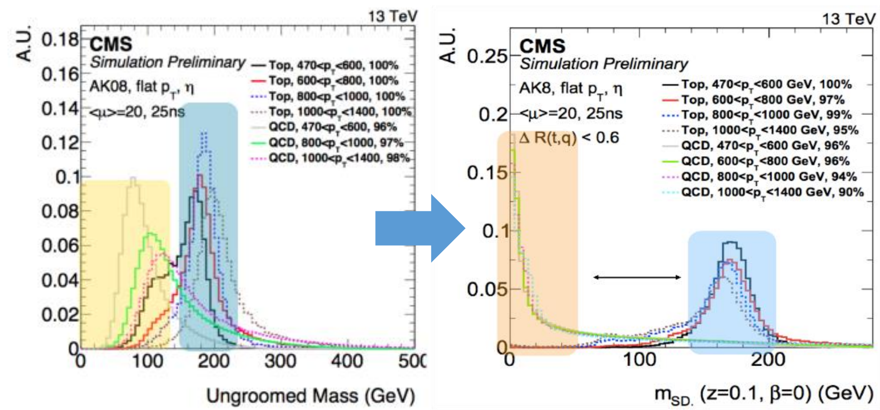


Advanced techniques

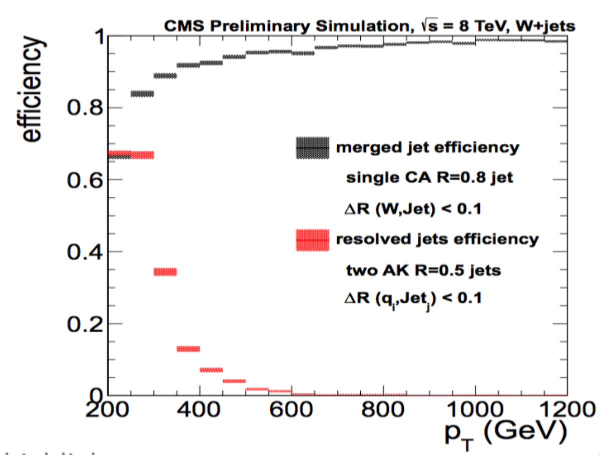
- Jet grooming algorithms can improve the discrimination between QCD and top quark jets: remove soft and wide-angle radiation from within jet

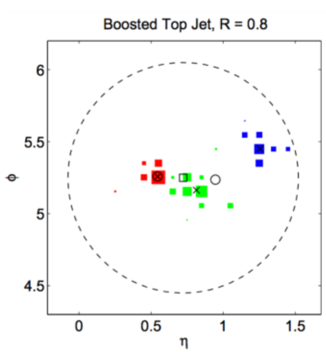


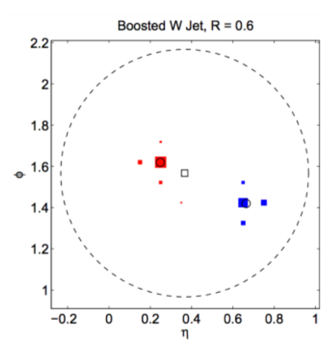
- Can also look inside the jet for the expected substructure
  - Top decays → 3 sub-jets
  - W/Z/H decays → 2 sub-jets



- A quantity called N-subjettiness is a measure of how consistent a jet is with hypothesized number of sub-jets



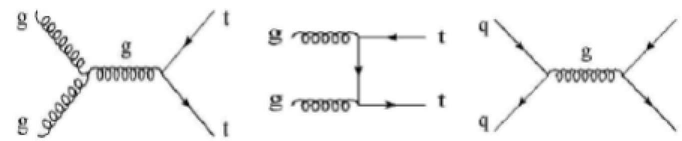




Top cross-section

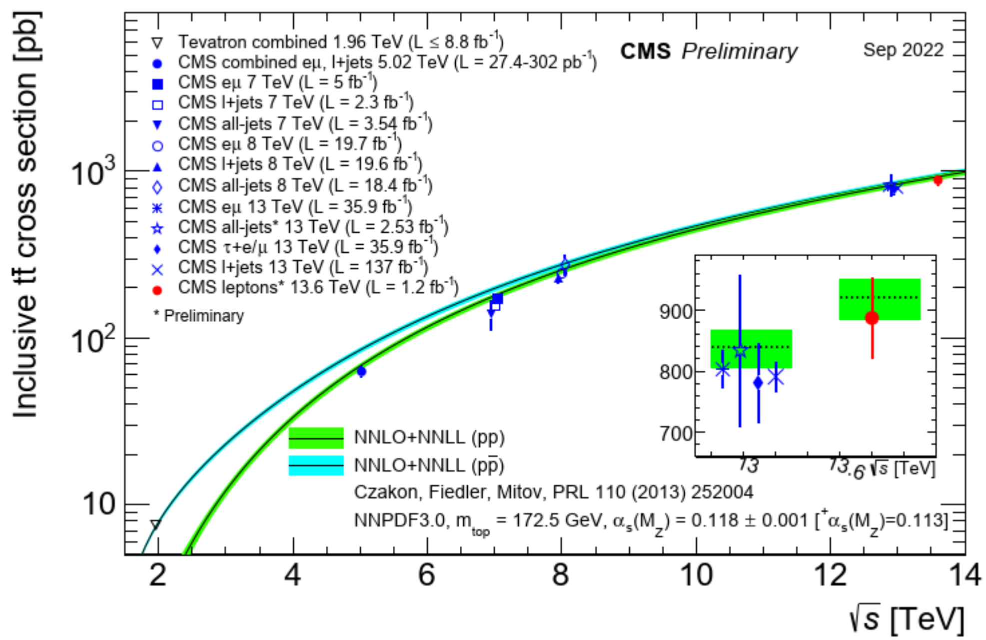
- First measurement of the top-pair cross-section at 13.6 TeV
  → first new result from Run 3
- Combination of five channels:
  eμ, ee, μμ, e+jets, μ+jets
- The measurement is in agreement with predictions at next-to-next-to-leading order (NNLO) in perturbative QCD, including resummation of the next-to-next-to-leading-logarithmic (NNLL) soft gluon terms using TOP++ v2.0 program

CMS PAS TOP-22-012



$$\sigma_{tt} = 887^{+43}_{-41}\ (\mathrm{stat+syst}) \pm 53\ (\mathrm{lumi})\ \mathrm{pb}$$

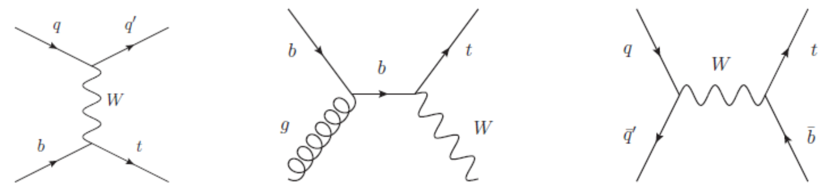
Theory prediction: 921^{+29}_{-37} pb



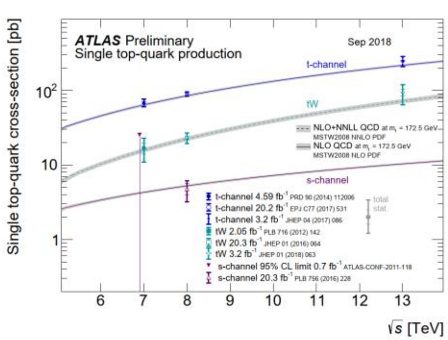
Single top production

- Probe of the Wtb interaction with no assumption on the number of quark families or unitarity of the CKM matrix
- Different production mechanisms: ***t*-channel** is dominant, then **Wt** (which both required a b quark from the sea) and finally ***s*-channel** (which requires an antiquark)
- All agree with predictions

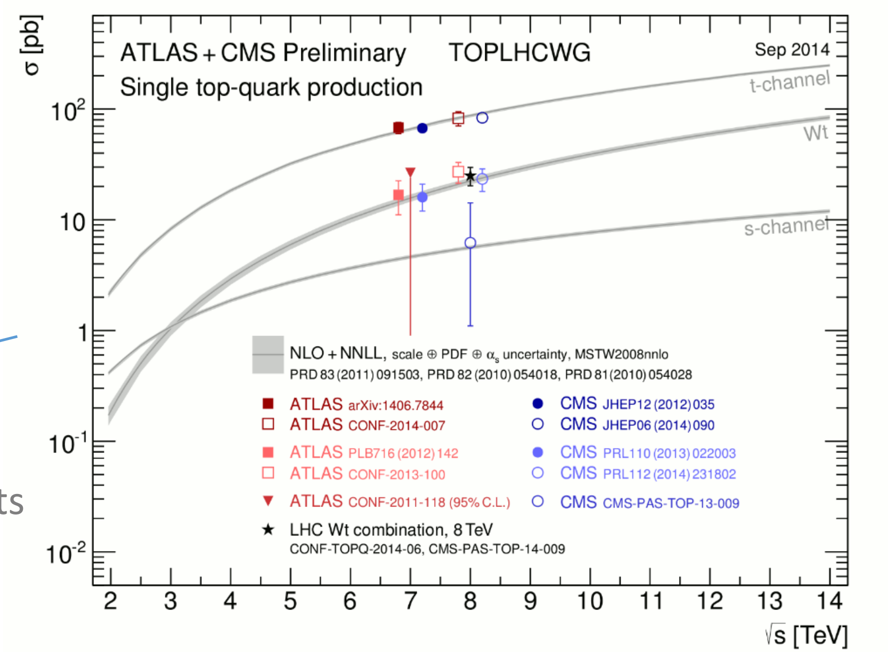
t-channel Wt *s*-channel



e.g. *t*-channel selection: lepton + MET from W, two jets – one jet b-tagged, the other forward



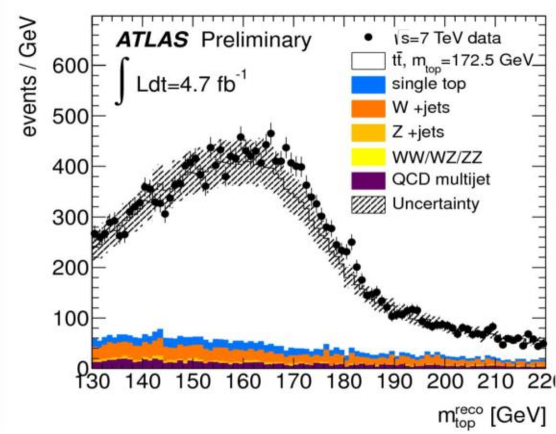
Update with 13 TeV results

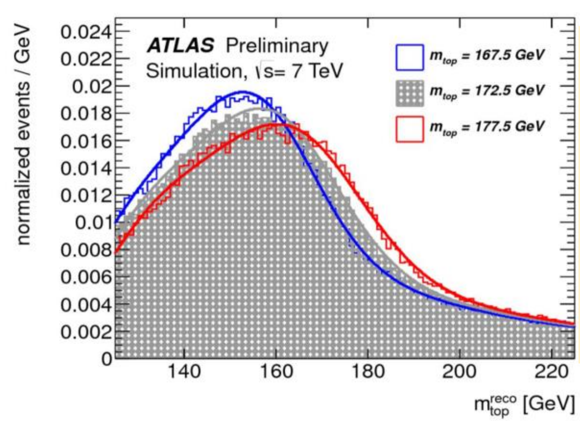


Top mass

- Fundamental parameter of the SM, affects theory predictions for exploring Higgs-boson properties and searching for new physics
- Top quark is colour charged and does not exist as an asymptotic state: the value of m_t extracted from the experiments depends on the theoretical definition of the mass, which varies according to the renormalisation scheme adopted: *pole mass* or *running mass*
- Relating the mass extracted based on Monte Carlo simulation and the (theoretically well-defined) pole mass is subject to an uncertainty of ~ 1 GeV, comparable to the present experimental precision

Example: templates in the lepton-jet final state channel





ATLAS-CONF-2013-046

Top mass (2)

- Alternative approaches investigated to measure the top mass: e.g. extracting it from the measured top cross-section
- All values consistent, world average: $m_t = 173.34 \pm 0.76$ GeV (0.4% precision)

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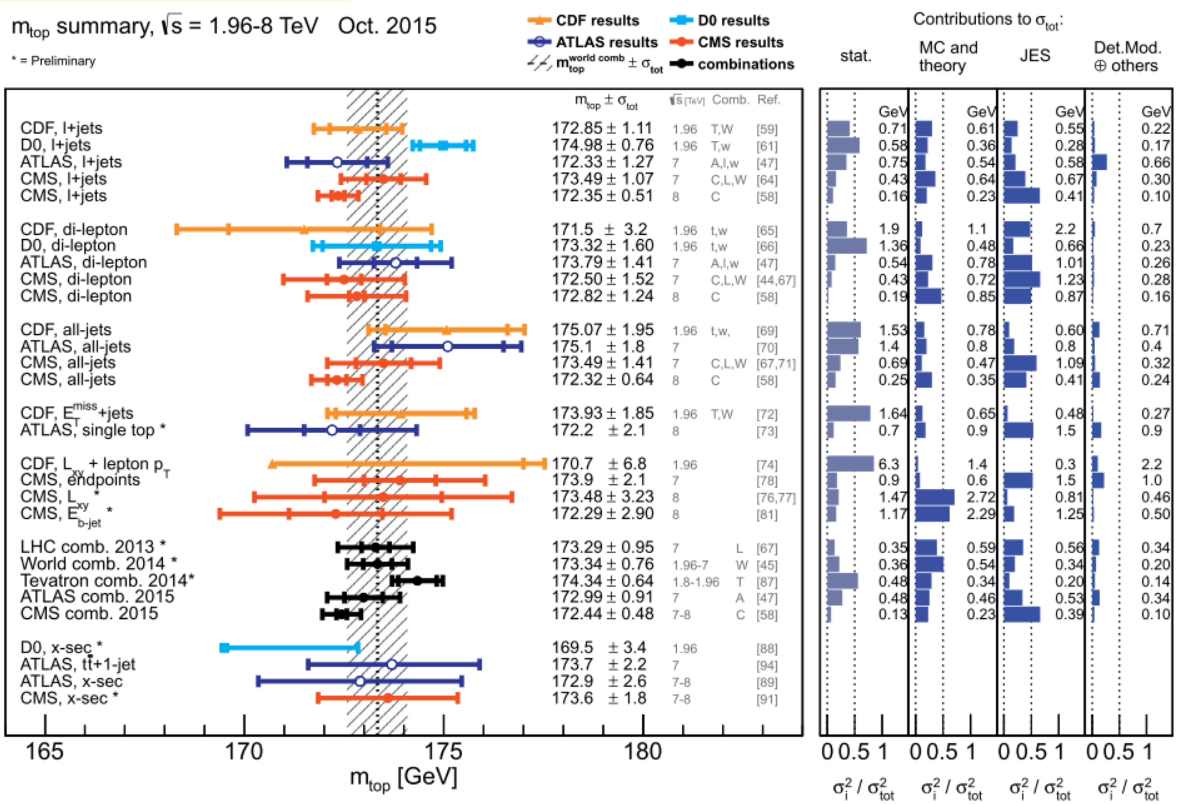
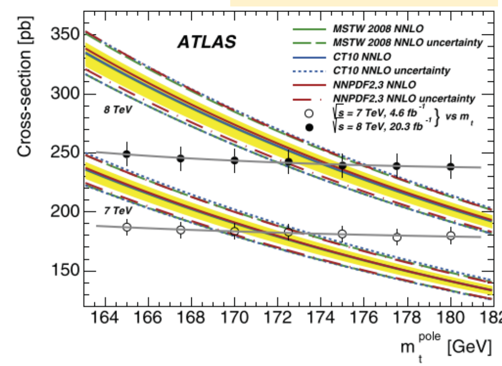


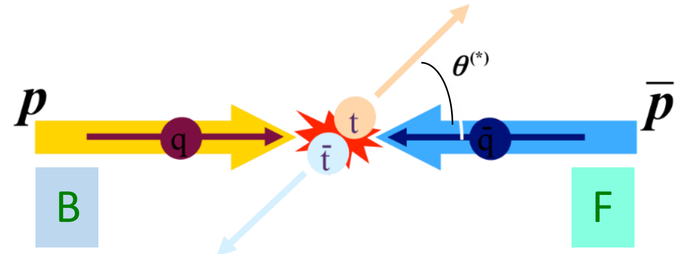
arXiv: 1406.5375

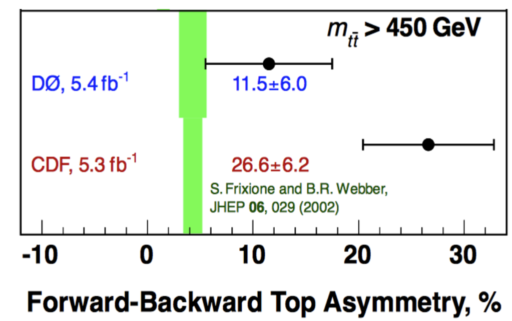


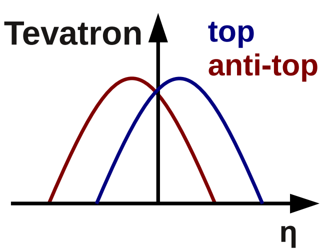
Predicted tt̄ production cross-sections at √s = 7 and 8 TeV for different PDF sets, as a function of m^{pole}
Measurements of $\sigma_{t\bar{t}}$ from the ATLAS di-lepton analysis are overlaid, with their dependence on the assumed value of m^{MC}

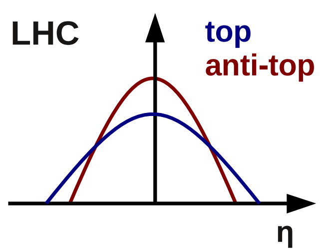
Top production asymmetry

- At the Tevatron (pp̄) top quarks are emitted preferentially in the direction of incoming quark, anti-top in the direction of incoming anti-quark → **forward-backward asymmetry**
- Inclusive asymmetries measured using ~ 5 fb^{-1} exceeded SM predictions by ~ 2σ
- At the LHC (pp) the initial state is symmetric but there is a related **charge asymmetry** due to the difference in rapidity distributions





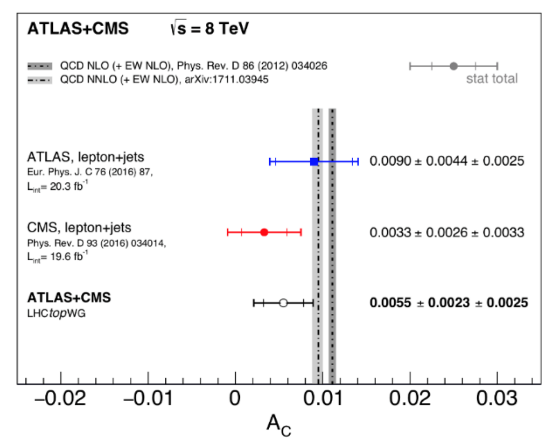




$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

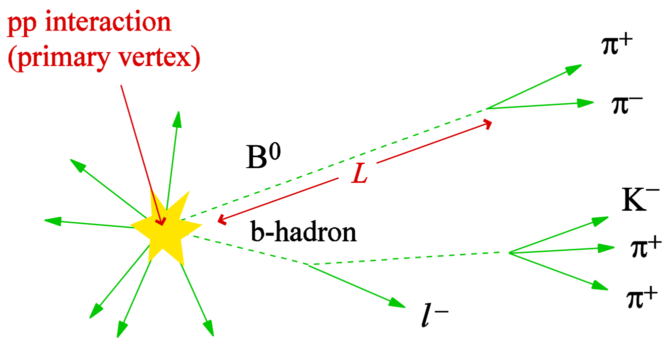
Prediction: ~ 6% ~ 1%



→ Discrepancy not confirmed

2. Flavour physics

- Top is the heaviest quark but it doesn't hadronize; the next heaviest are *beauty* and *charm*, with a rich hadron spectrum + interesting weak decays
- Cross-section for $b\bar{b}$ production at 14 TeV: $\sigma_{b\bar{b}} \sim 500\ \mu b$, charm even higher
  → Enormous production rate at LHC: ~ 10^{12} $b\bar{b}$ pairs per year
  (much higher statistics than the earlier B factories)
  $\sigma_{b\bar{b}} < 1\%$ of inelastic cross-section → background from non-b events
  In addition, *all* b-hadron species are produced: B^0, B^+, B_s, B_c, Λ_b ...
- LHCb is the main LHC flavour physics experiment – ATLAS and CMS also participate but mostly via lepton triggers, and poorer hadron identification
  LHCb runs at lower luminosity, to limit pileup for precision vertexing
- Need to measure proper time of B decay:
  $t = m_B L / pc$
  and hence decay length L (~ 1 cm in LHCb)
- Also need to tag *production* state of B, i.e. whether it was B or $\bar{B}$: use charge of lepton or kaon from decay of *other* b hadron in event



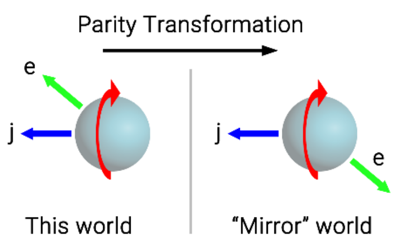
Parity violation

- The strong and electromagnetic interactions conserve **C**, **P** and **T**
- e.g. pion decay via the electromagnetic interaction: $\pi^0 \to \gamma\gamma$ but not $\gamma\gamma\gamma$

Initial state: $C(\pi^0) = +1$
Final state: $C(\gamma\gamma) = (-1)^2 = +1$
$C(\gamma\gamma\gamma) = (-1)^3 = -1$

$\pi^0 = (u\bar{u} - d\bar{d})_{L=0,\,S=0}$	$C(\pi^0) = +1$
$B, E \to -B, -E$	$C(\gamma) = -1$

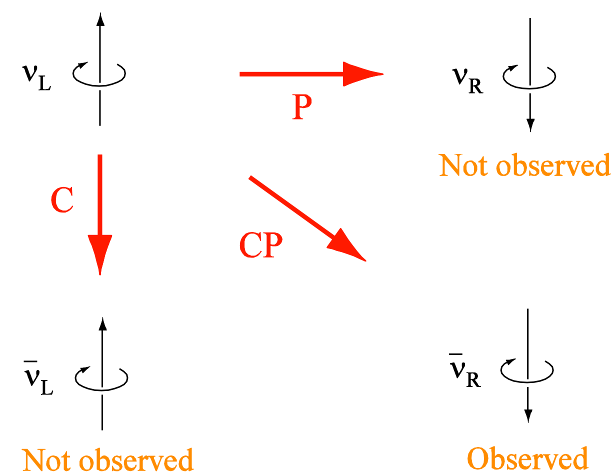
- The weak interaction violates Parity



Nobel prize 1957 (Yang, Lee)
Experiment of Wu (overlooked for prize)

Polarised Cobalt-60 atoms undergoing β decay

- Neutrinos are left-handed, while antineutrinos are right-handed
  → perhaps the weak interaction conserves the combined operation, CP?
  e.g. $\Gamma(\pi^+ \to \mu^+ \nu_L) = \Gamma(\pi^- \to \mu^- \bar{\nu}_R)$



CP violation

See lectures of Matthias Neubert

- Weak interaction appeared to conserve CP until the experiment of Christenson *et al* (1964):

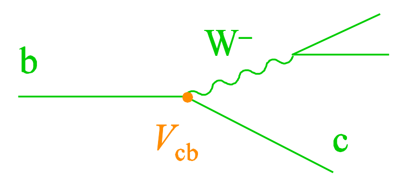
  $K^0_L \to \pi^+\pi^-\pi^0$ (CP = −1) BR = 34%

  $K^0_L \to \pi^+\pi^-$ (CP = +1) BR = 2×10^{-3} → CP violation observed

Nobel prize 1980 (Cronin, Fitch)

- BR ($K^0_L \to \pi^- e^+ \nu$) = 19.46% > BR ($K^0_L \to \pi^+ e^- \bar{\nu}$) = 19.33% unambiguously differentiates matter from antimatter: relevant to baryogenesis
- In Standard Model, CP violation arises from quark mixing Weak eigenstates are a "rotated" combination of flavour states

$$\text{Weak charged current} \sim (u, c, t)\,(1-\gamma_5)\,\gamma_\mu \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$



where

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

V = unitary CKM matrix (Cabibbo-Kobayashi-Maskawa) Its elements give the weak couplings between quark flavours

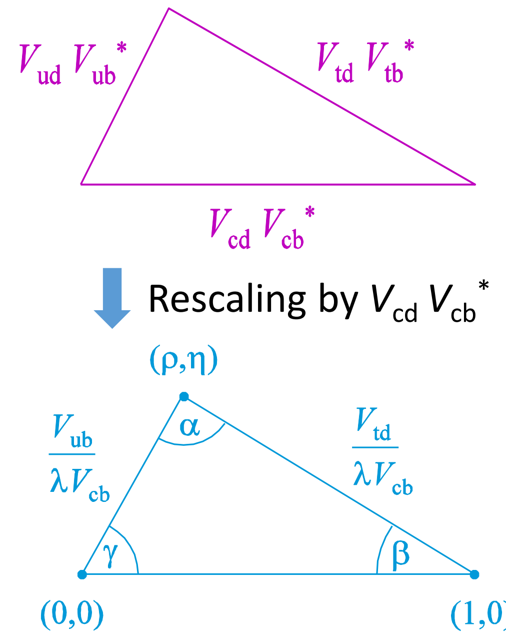
Nobel prize 2008 (Kobayashi, Maskawa, Nambu)

Unitarity Triangle

- Unitarity of the CKM matrix gives relationships between rows and columns: $\Sigma\, V_{ij}\, V_{ik}^* = 0 \;\; (j \neq k)$
- One of these relationships has terms of similar size:

  $$\boldsymbol{V_{ud}\, V_{ub}^* + V_{cd}\, V_{cb}^* + V_{td}\, V_{tb}^* = 0}$$

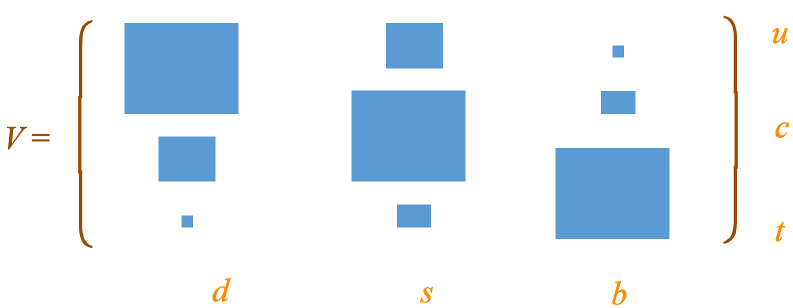
  → triangle relationship in the complex plane



- (3×3) CKM matrix has 4 independent parameters: 3 angles and one non-trivial phase → CP violation

  — only present with ≥ 3 generations, and at present is the *only* known source of CP violation in the Standard Model

- CKM matrix observed to have a hierarchy of elements
  Parameterized expanding in powers of Cabibbo angle: $\lambda = \sin\theta_C \approx 0.22$

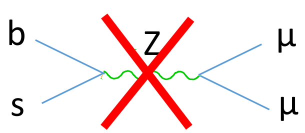


Parameters (λ, A, ρ, η)
$A \approx 0.8$, measured → leaves
ρ and η to be determined
$\eta \neq 0 \leftrightarrow$ CP violation

Matrix is quite diagonal for quarks (unlike the equivalent mixing matrix for neutrinos)

Indirect searches

- Flavour physics observables have sensitivity to new particles at high mass scales via their virtual effects in *loop* diagrams
- Loop diagrams include the "*penguin*" (first order) and "*box*" (second order) diagrams
Decays without loops (known as "*tree*" diagrams) expected to be less affected
- Penguin was named by John Ellis
(you can ask him why he chose that name…)
and contribute to Flavour Changing Neutral Current (FCNC) decays like $B_s \rightarrow \mu\mu$

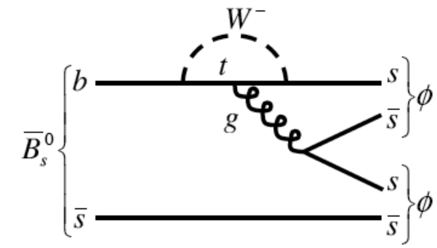


not possible at tree level in SM

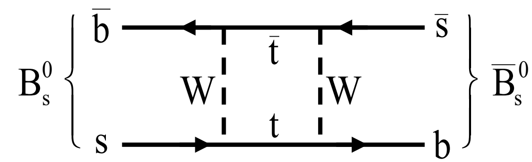
- Box diagram is interesting as it allows a particle to transform into its antiparticle → quantum mechanical effect of oscillation between states (also seen for neutrinos & neutrons)

Loop diagrams

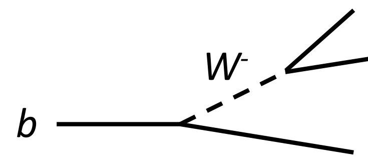
Penguin



Box



Tree diagram



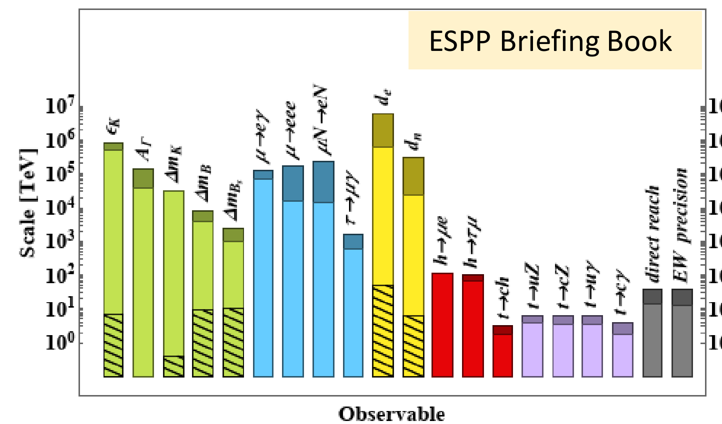
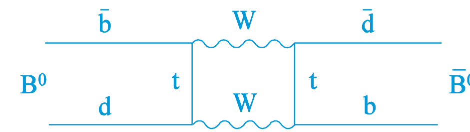
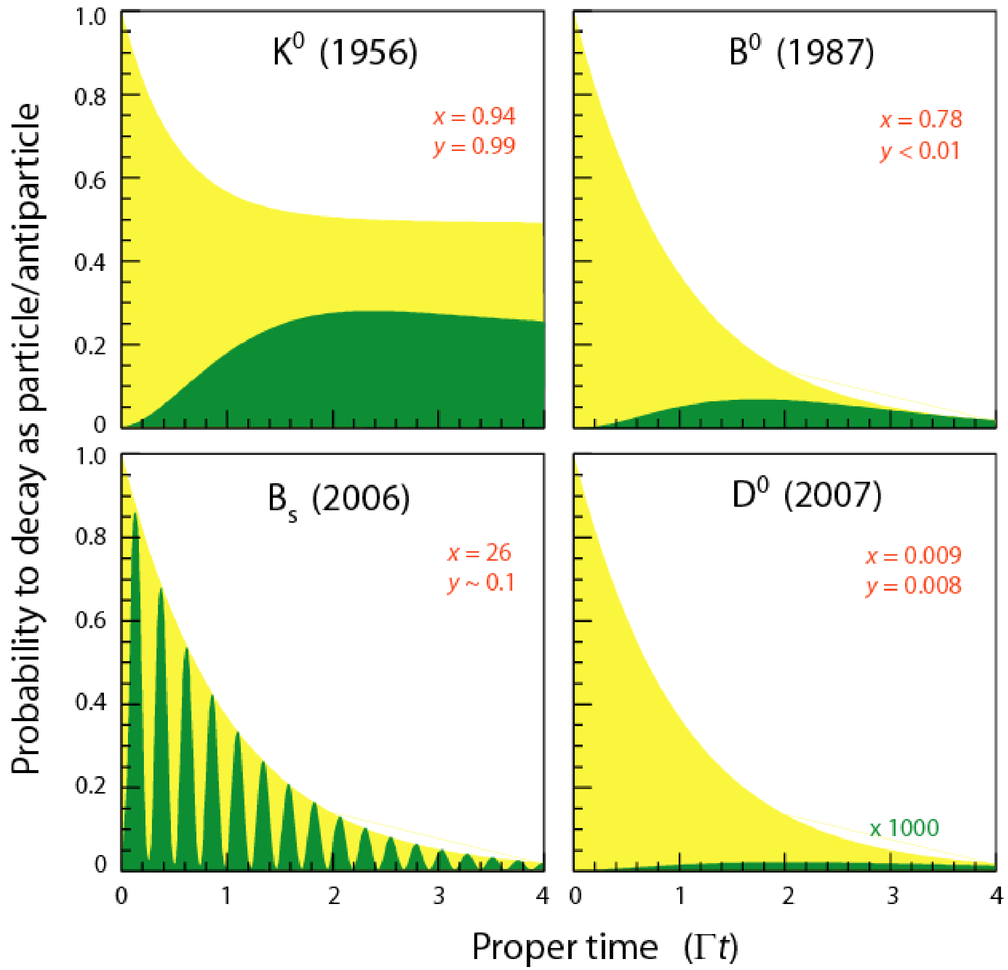


Fig. 5.1: Reach in new physics scale of present and future facilities, from generic dimension six operators. Colour coding of observables is: green for mesons, blue for leptons, yellow for EDMs, red for Higgs flavoured couplings and purple for the top quark. The grey columns illustrate the reach of direct flavour-blind searches and EW precision measurements. The operator coefficients are taken to be either ~ 1 (plain coloured columns) or suppressed by MFV factors (hatch filled surfaces). Light (dark) colours correspond to present data (mid-term prospects, including HL-LHC, Belle II, MEG II, Mu3e, Mu2e, COMET, ACME, PIK and SNS).

Flavour oscillation



- Neutral mesons oscillate between their particle and antiparticle states via the box second-order weak transition
- Frequency of the oscillations depends on mass difference Δm between the weak eigenstates e.g. $\propto |V_{td}|^2$ for B^0
- Expressed in terms of dimensionless parameters:
  frequency $x = \Delta m / \Gamma$
  width difference $y = \Delta\Gamma / 2\Gamma$
- Oscillations have now been observed for *all* of the species
  Pattern observed consistent with SM expectations



(scaled to average lifetime of particle = $\hbar/\Gamma$)

Oscillation results

- Measurement of B_s–$\overline{B}_s$ oscillations in LHCb with $B_s \rightarrow D_s^- \pi^+$ channel
- World's best precision: arXiv:2104.04421

$$\Delta m_s = (17.7683 \pm 0.0051 \pm 0.0032)\ \mathrm{ps}^{-1}$$

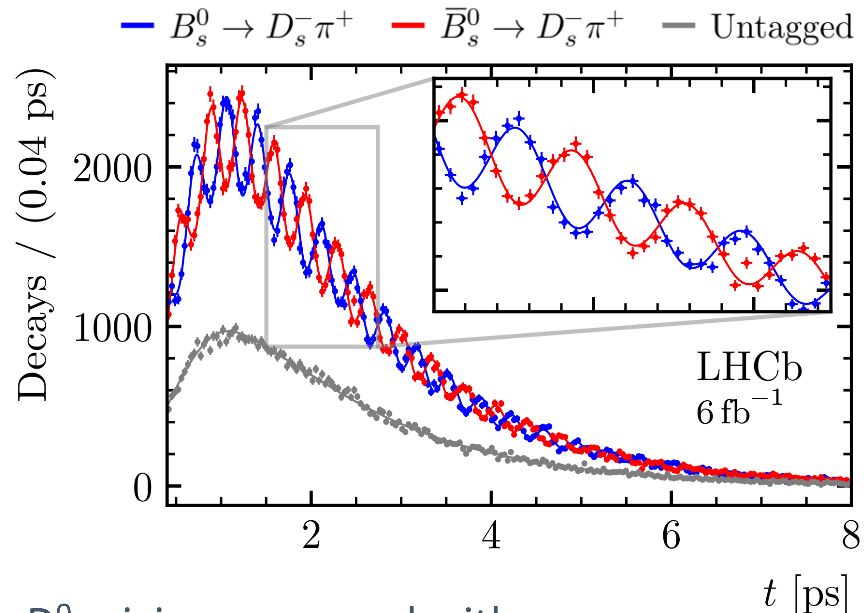
- Prediction:

$$\Delta M_q = \frac{G_F^2}{6\pi^2} \eta_B m_{B_q} (B_{B_q} F_{B_q}^2) M_W^2 S_0(x_t) |V_{tq}|^2$$

- Non-perturbative hadronic factors can be estimated by solving QCD on a discrete space-time lattice using **Lattice gauge theory**
- For B^0 mixing this gave first clear (indirect) evidence that the top quark mass was heavy

$$\Delta M_d = 0.50/\mathrm{ps} \cdot \left[\frac{\sqrt{B_{B_d}} F_{B_d}}{200\,\mathrm{MeV}}\right]^2 \left[\frac{\overline{m}_t(m_t)}{170\ GeV}\right]^{1.52} \left[\frac{|V_{td}|}{8.8 \cdot 10^{-3}}\right] \left[\frac{\eta_B}{0.55}\right]$$

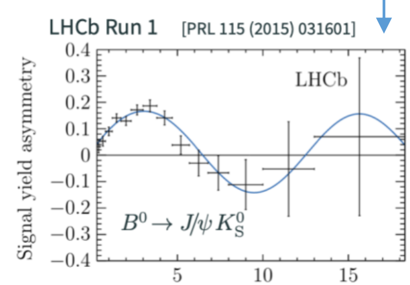
arXiv:hep-ph/9704376 PLB 192 (1987) 245

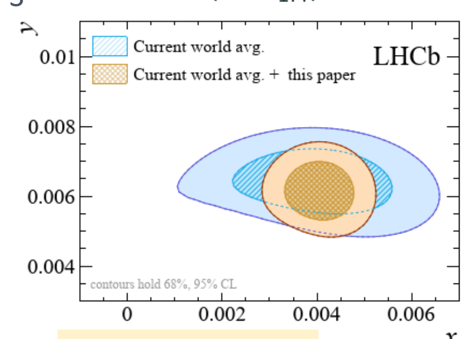


D^0 mixing measured with $K_S\pi^+\pi^+$ decays

$$x = (3.98^{+0.56}_{-0.54}) \times 10^{-3}$$
$$y = (4.6^{+1.5}_{-1.4}) \times 10^{-3}$$

B^0 mixing with $J/\psi\ K_S$

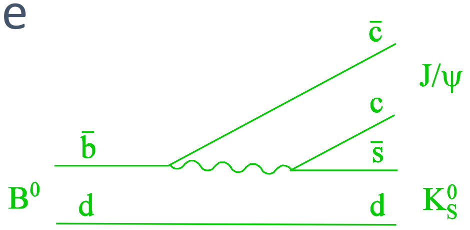




PRL 127, 111801

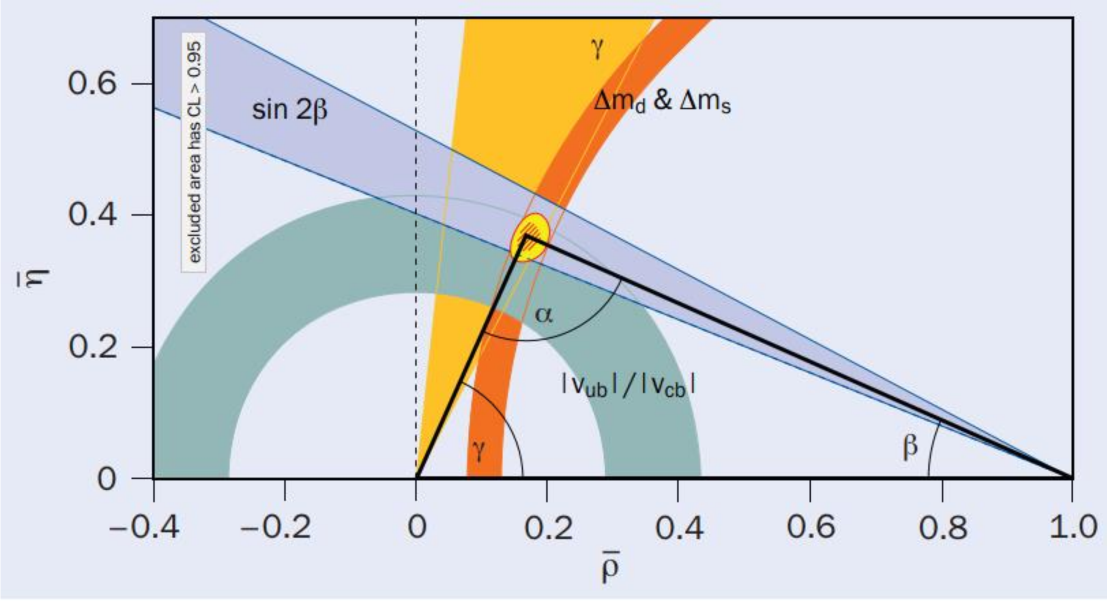
Unitarity Triangle status

- Many of the measurements made of hadrons containing the b-quark can be presented as constraints on the Unitarity Triangle
- In addition, CP violation measures the relative phases of the matrix elements → measure the *angles* (α, β, γ), depending on the decay



e.g. $B^0 \to J/\psi K^0_S$ ↘ $\bar{B}^0$ ↗ (= CP eigenstate) Decay "via mixing" with different phase

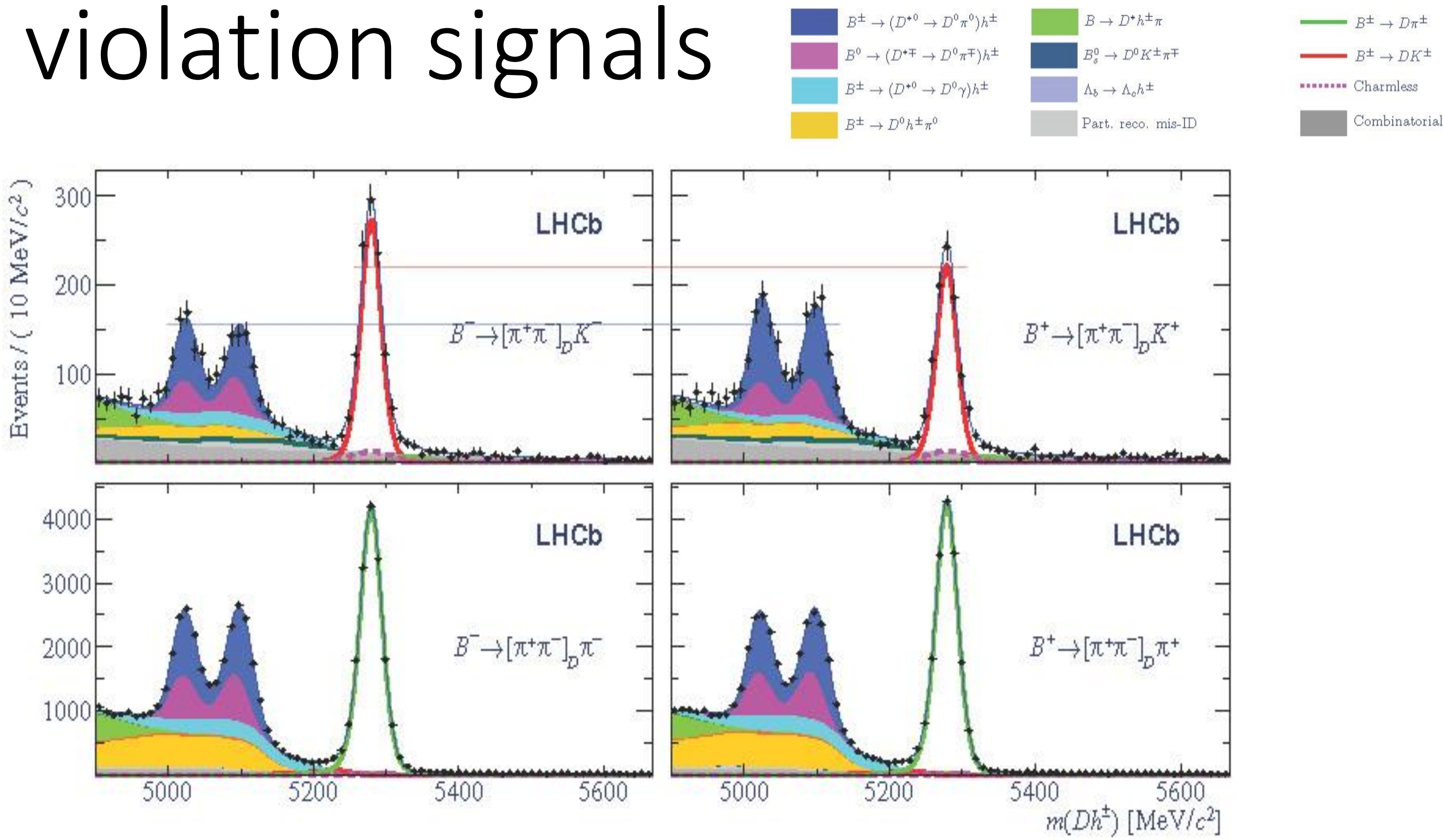
Depends on phase of B^0–$\bar{B}^0$ oscillation: $\arg(V_{td}) \to$ angle β



Triumphant agreement!
Constraints on the apex of the triangle from all flavour results are consistent

The Standard Model description of CP violation appears to be correct
(at least to the level tested)

CP violation signals



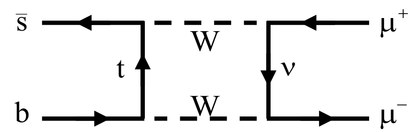
- Example of a measurement showing clear CP violation: **B → DK** (depends on γ)
  Many different channels studied, all consistent with the CKM picture
- CP violation also seen in *charm* decays for the first time:

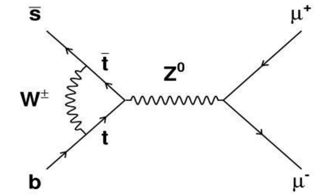
$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$$

PRL 122, 211803 (2019)

Expected to be small in Standard Model, observed value is within expectations

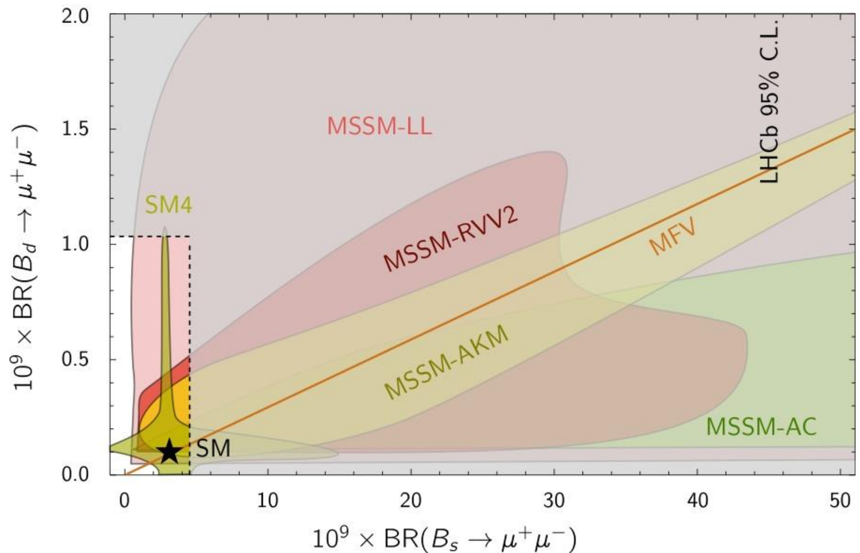
Rare decays



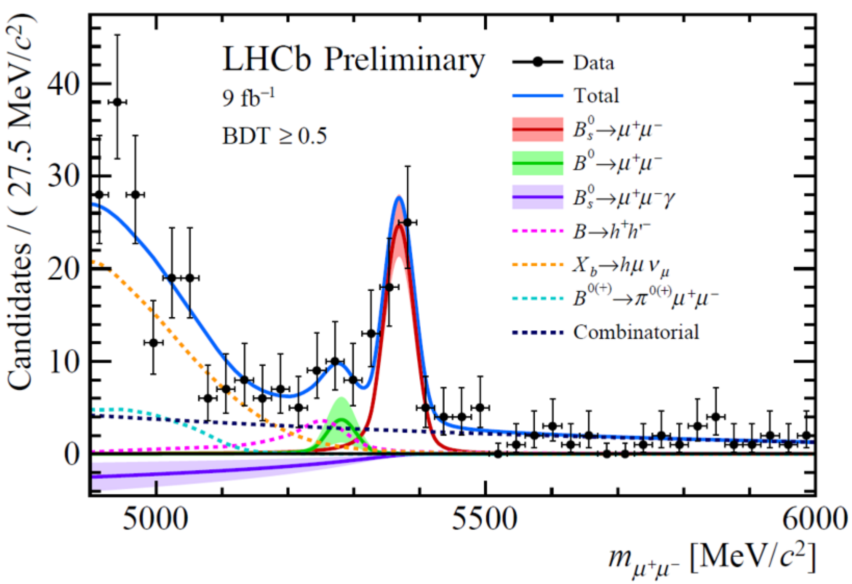


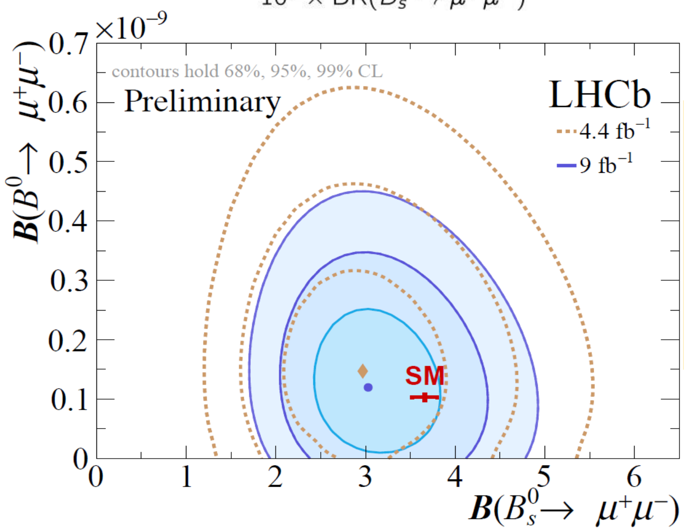
- $B_s \to \mu^+\mu^-$ decay very strongly suppressed, but precisely predicted in Standard Model
  $BR(B_s \to \mu^+\mu^-) = (3.7 \pm 0.2) \times 10^{-9}$

  → excellent place to search for new physics contributions, which could enhance branching ratio



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46}_{-0.43}{}^{+0.15}_{-0.11}) \times 10^{-9}$$



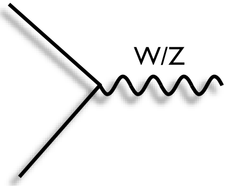


arXiv:2108.09284

3. Electroweak physics

- Vector boson production:
  - Precision measurement of Standard Model parameters
  - Test of perturbative QCD, input to PDF fits
- Irreducible background to many searches where signal events decay to W or Z's: top, Higgs, BSM…
- Leptonic decays provide clean samples with adequate statistics for performance measurements

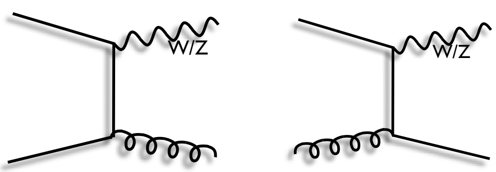
Leading Order

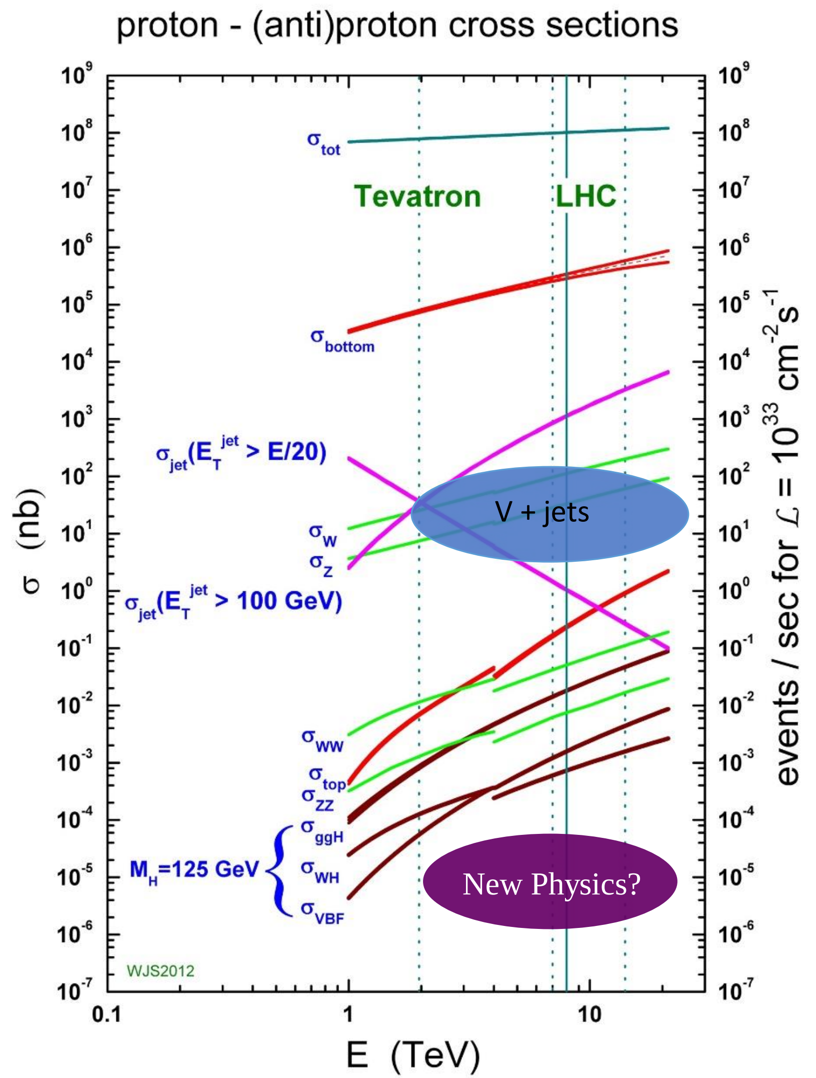


Next-to-Leading Order

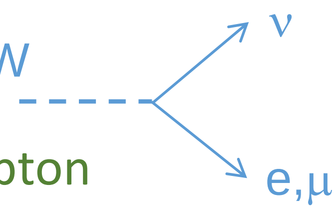
Tevatron

LHC

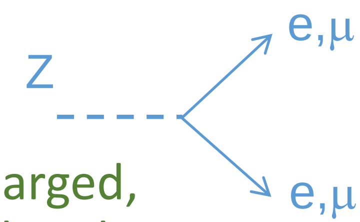




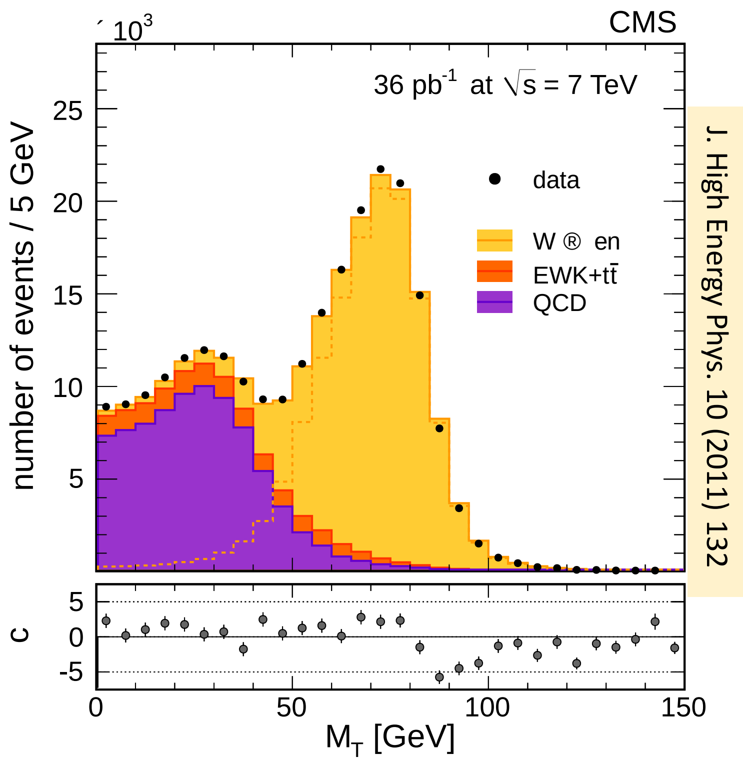
Vector boson leptonic decays

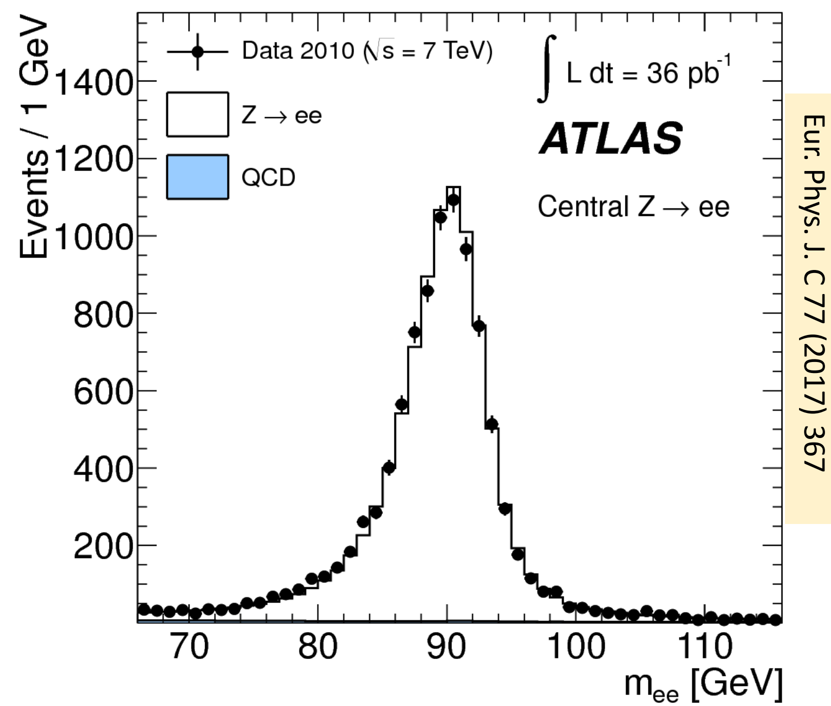


- W signature:
  - High p_T isolated lepton
  - Large missing E_T



- Z signature:
  - Two opposite-charged, same flavour high p_T leptons



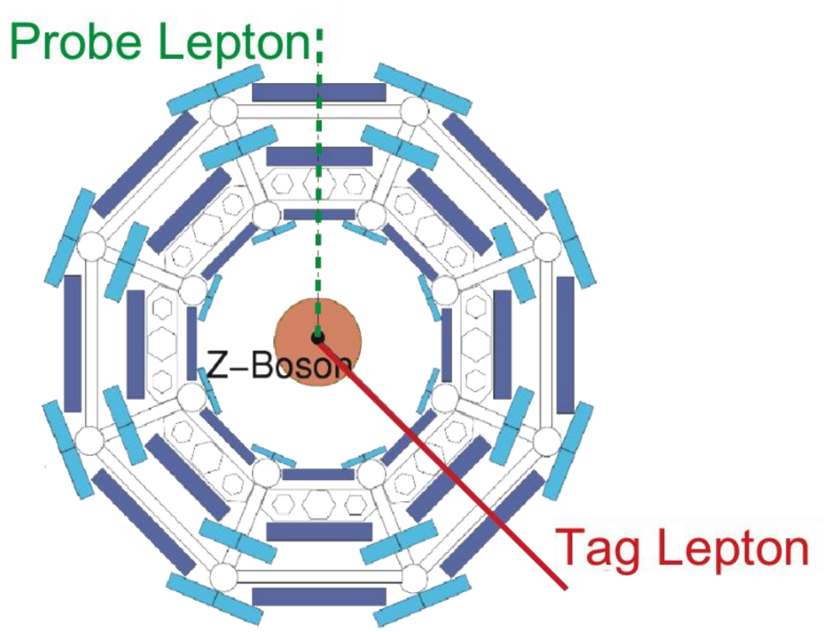


Transverse mass $M_T \equiv \sqrt{2\, p_T^{\ell}\, E_T^{\rm miss}\, (1 - \cos(\phi_\mu - \phi_{E_T^{\rm miss}}))}$

→ large, pure samples available

Tag and Probe method

- Can use the clean $Z \rightarrow e^+e^-$ or $\mu^+\mu^-$ sample to measure lepton selection efficiencies (trigger, ID, isolation)
  - **Tag** lepton passes tight selection requirements to ensure sample purity
  - **Probe** lepton is unbiased w.r.t. the selection that we want to study
  - Count how often the probe lepton passes the requirement under study
- If the statistics are high enough, this method can be applied in bins of the relevant variables

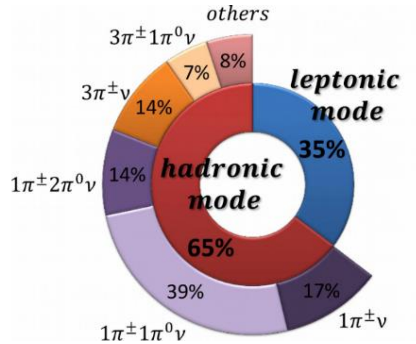


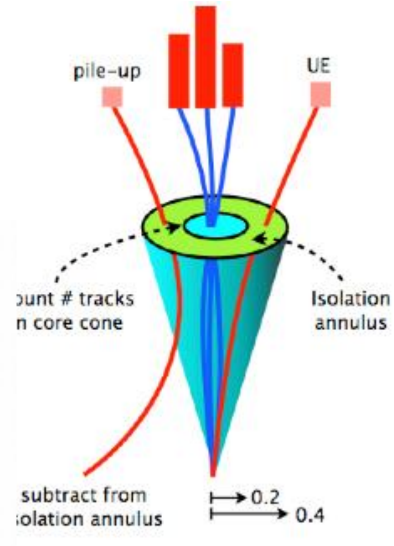
Apply same method to data and simulation to extract a data-to-MC correction factor for use in analysis

Other resonances like $J/\psi \rightarrow \mu^+\mu^-$ can also be used for this method

W → τν

- Tau leptons are an important probe for new physics processes at the LHC, such as searches for light Higgs bosons, Supersymmetry or extra dimensions

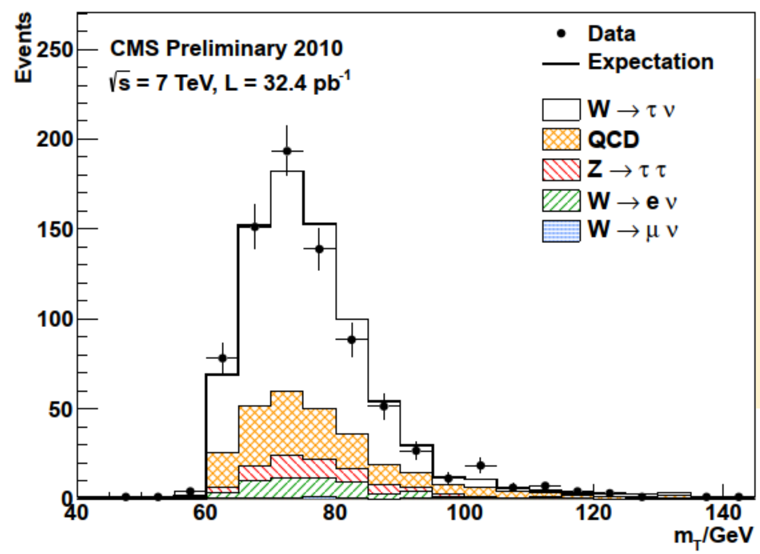




- Taus decay to either an electron or muon or into a system of hadrons: hadronic decay modes (τ_{had}) are characterized by a highly collimated jet of low particle multiplicity
- Dominant source of τ in SM is from W decays; selected using *isolation* criteria
- Charge asymmetry measured:

$$\frac{\mathcal{B}(W^{+} \to \tau^{+}\nu)}{\mathcal{B}(W^{-} \to \tau^{-}\nu)} = 1.55 \pm 0.19(\text{stat.})^{+0.11}_{-0.13}(\text{syst.}),$$

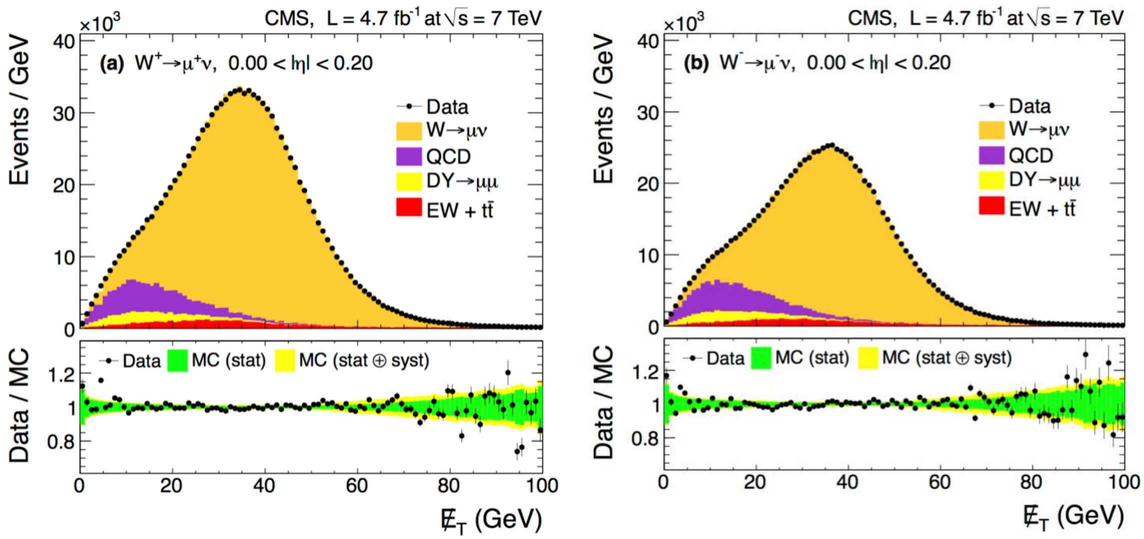
in agreement with prediction 1.43 ± 0.04 at NNLO based on the various parton distribution functions

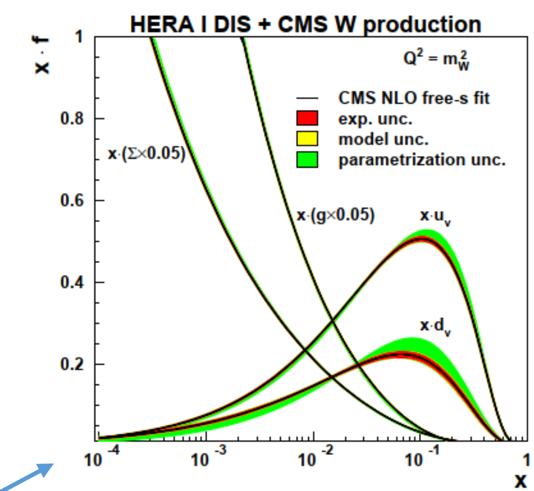


CMS-PAS-EWK-11-019

W production asymmetry

- The dominant processes for inclusive W-boson production in pp collisions are annihilation processes: $u\bar{d} \to W^+$ and $d\bar{u} \to W^-$ involving a valence quark from one proton and a sea antiquark from the other
- Since p = uud the cross-section is higher for $u\bar{d}$ than for $d\bar{u}$, leading to a clear charge asymmetry: $1.421 \pm 0.006\,(\mathrm{stat}) \pm 0.032\,(\mathrm{syst})$ arXiv:1312.6283





~ 20 million W candidates!

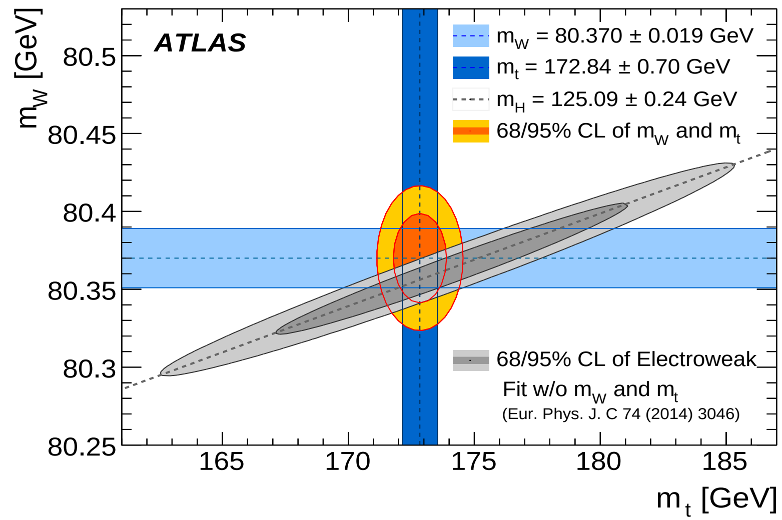
- Can be used to improve knowledge of parton distribution functions (PDFs)

Such W decay distributions are also sensitive to the W mass…

W mass

- Aiming for uncertainty of O(10 MeV) on a mass of ~ 80 GeV, i.e. 0.01% precision
- Statistics are not the issue, but systematics from modelling missing neutrino and PDFs
- ATLAS were the first to publish a W mass measurement at the LHC
- Used 8M $W \to \mu\nu$ + 6M $W \to e\nu$
  W mass obtained from template fits to p_T^ℓ and transverse mass m_T
- $Z \to \ell\ell$ used for lepton energy and W recoil calibration

m_W, m_t and m_H related via radiative corrections: precision test of the SM (update from 1st lecture)



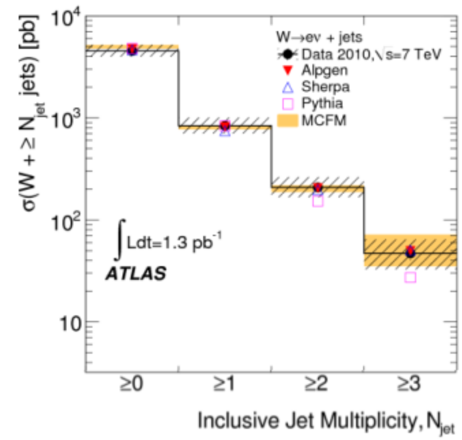
- Result: $m_W = 80370 \pm 7\ \text{(stat)} \pm 11\ \text{(exp. syst)} \pm 14\ \text{(model syst)}$ MeV

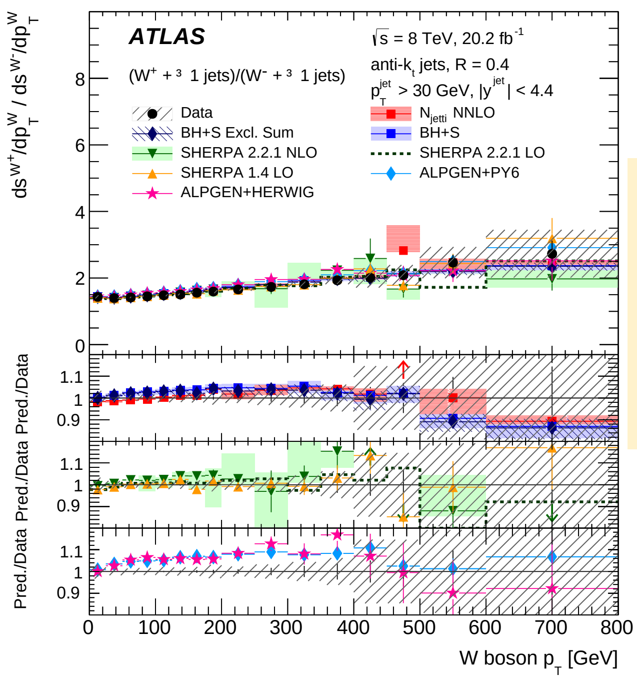
Combined	Value	Stat.	Muon (Experimental systematics)	Elec. (Experimental systematics)	Recoil (Experimental systematics)	Bckg. (Experimental systematics)	QCD (Modelling systematics)	EW (Modelling systematics)	PDF (Modelling systematics)	Total
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5

Eur. Phys. J. C 78 (2018) 110

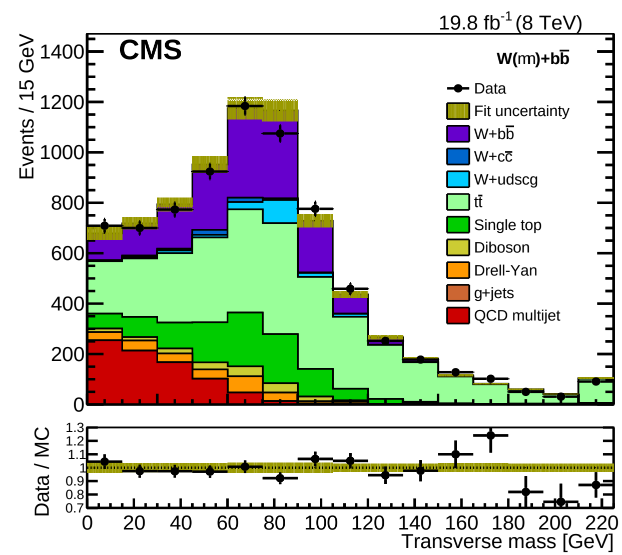
W + jets production

- Events selected with one high p_T isolated lepton and at least one jet
- Provide valuable input for the u, d and g PDFs of the proton





JHEP 05 (2018) 077

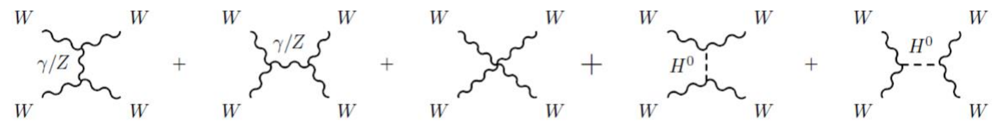


JHEP 03 (2014) 032

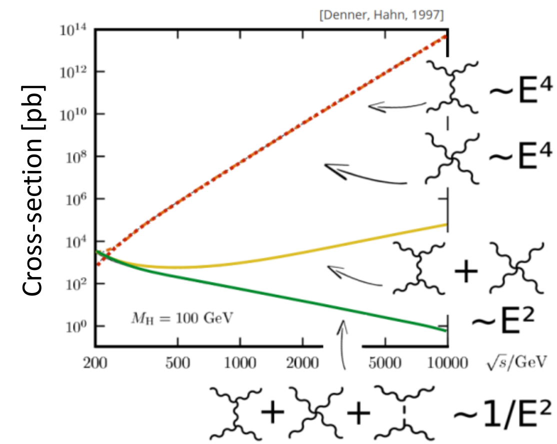
Data well described by ME generators matched to parton shower and normalized to NLO pQCD

W+b/c samples valuable for understanding background to Higgs searches

Multi-bosons



- Scattering of two vector bosons (VBS) VV → VV (with V = W or Z) is an important process to study the mechanism of electroweak symmetry breaking
- VBS was one motivation for introducing the Higgs boson: the forward scattering cross-section would violate unitarity at high energy without the Higgs



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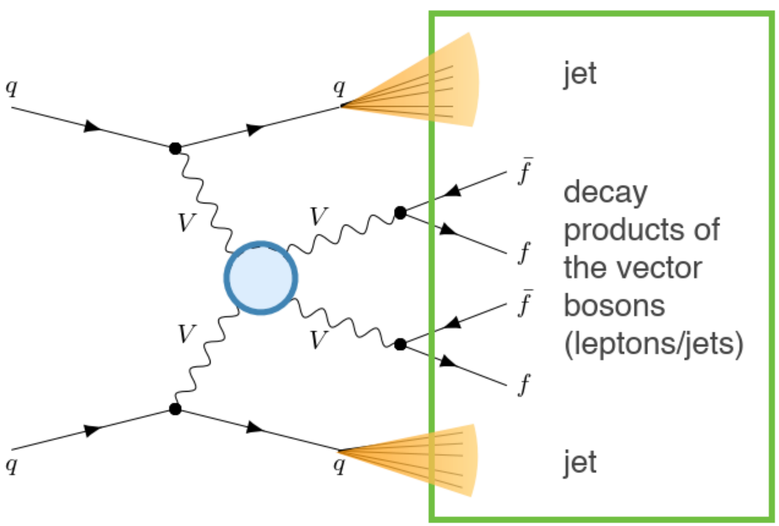
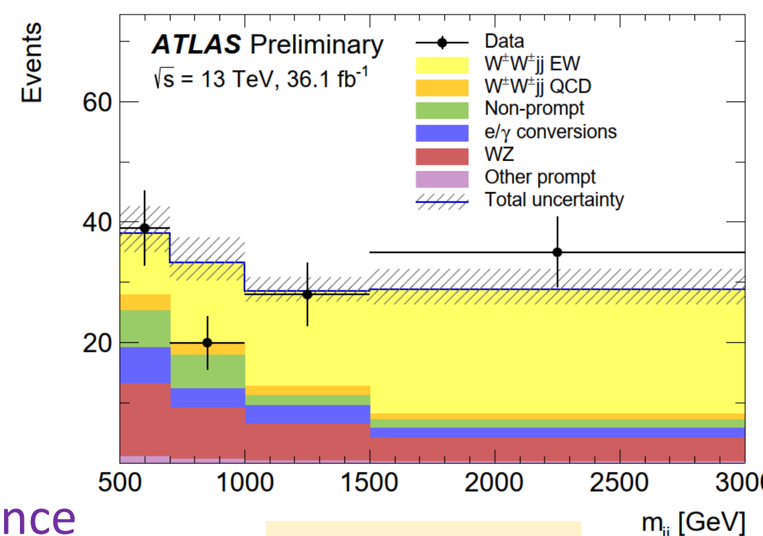


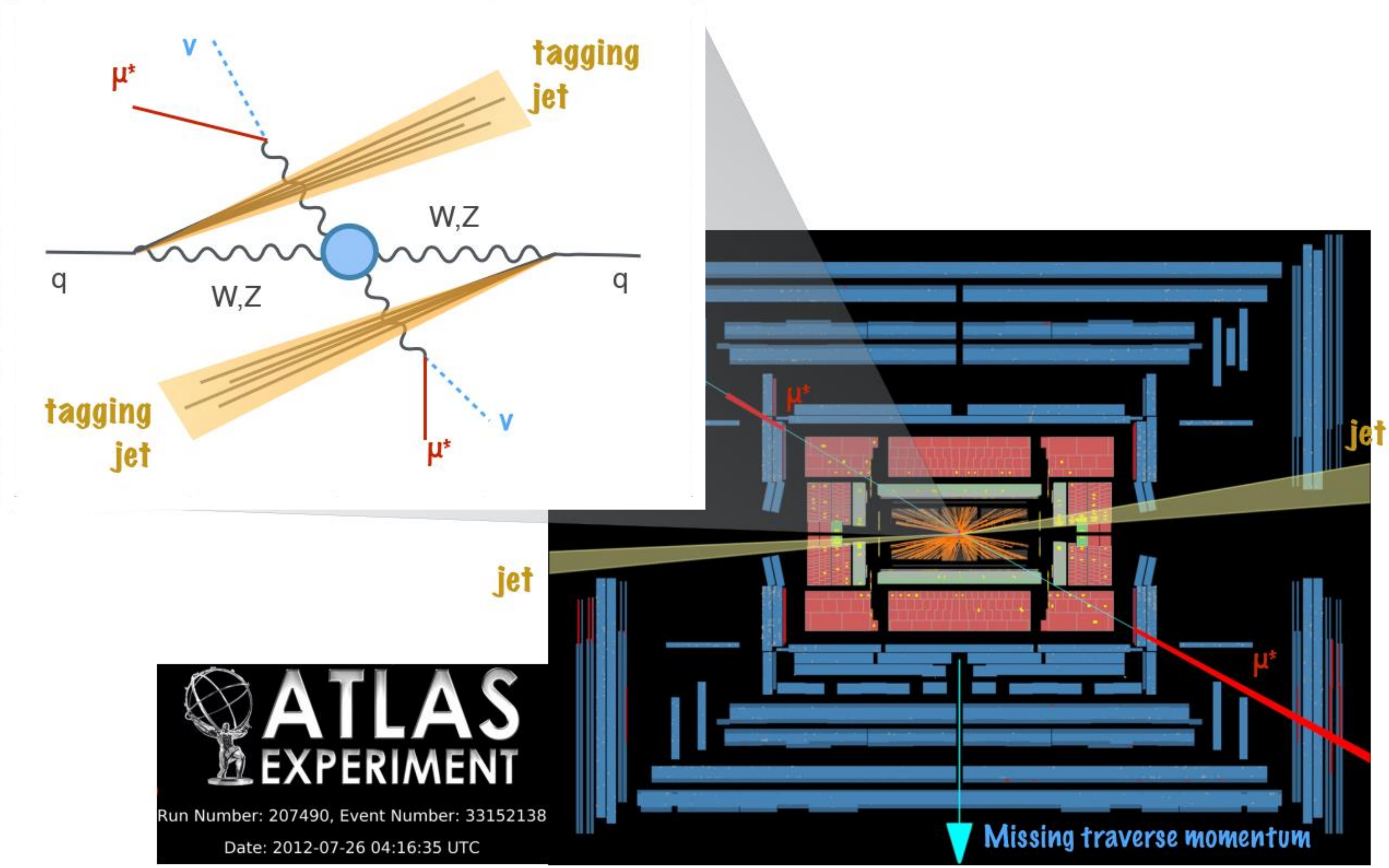


ATLAS-CONF-2018-030

W±W±jj production seen with 6.9 σ significance

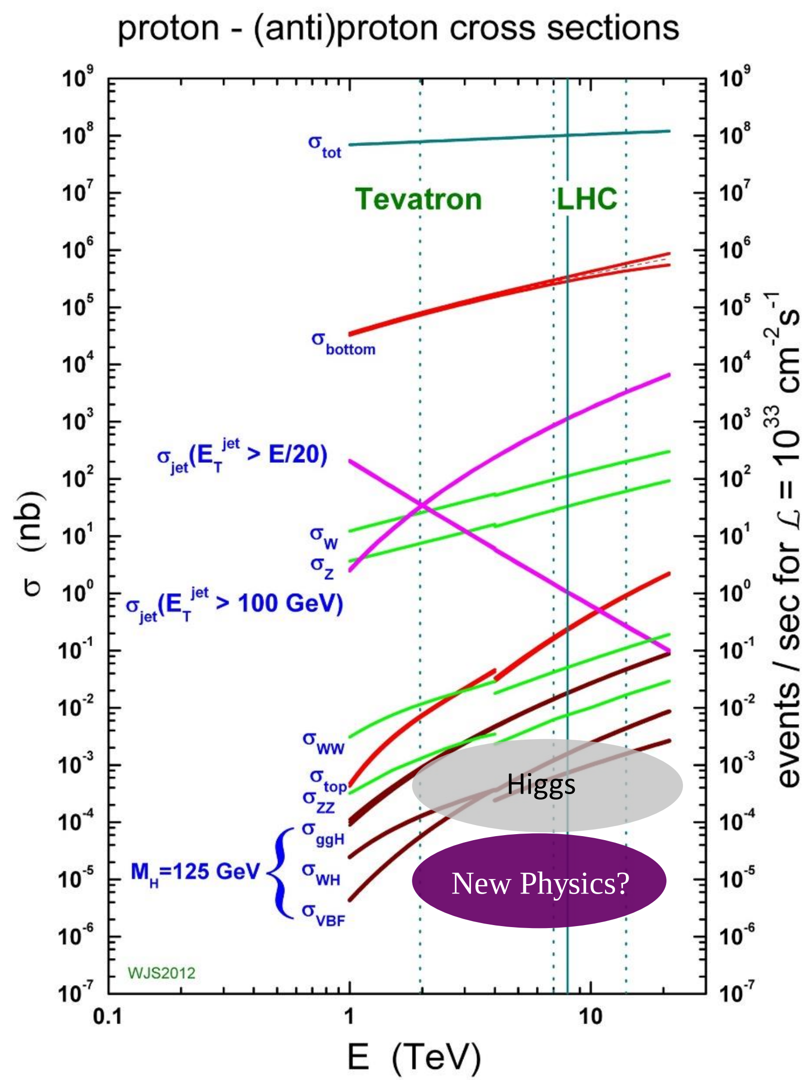
in agreement with the Standard Model expectation

VBS signal topology



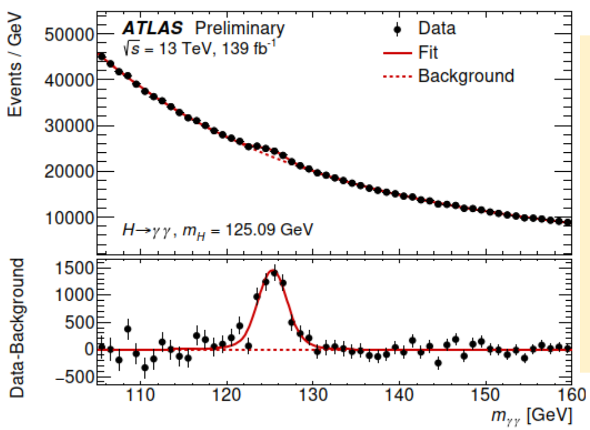
4. Higgs boson properties

- Finally discovered in 2012 after 50 years of searching: discovery channels $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$
- Precision measurements of the Higgs boson properties will provide a crucial test of the Standard Model
- It represents a potential window to physics beyond the Standard Model: it is the most recent discovery, and the mechanism feels a little ad hoc – the Higgs boson found may be the first sighting in a more complex sector
- However, so far it looks pretty much like a SM Higgs – but several aspects still remain to be explored

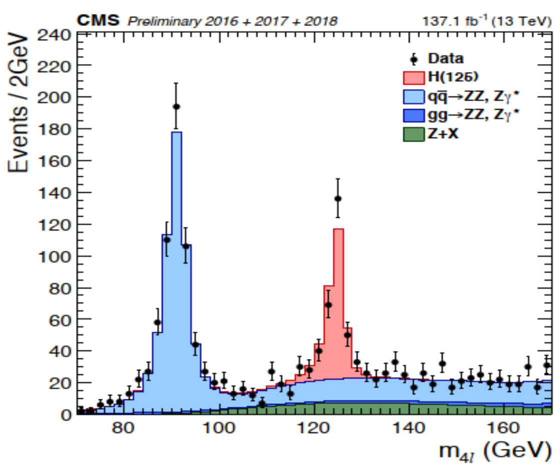


Higgs mass

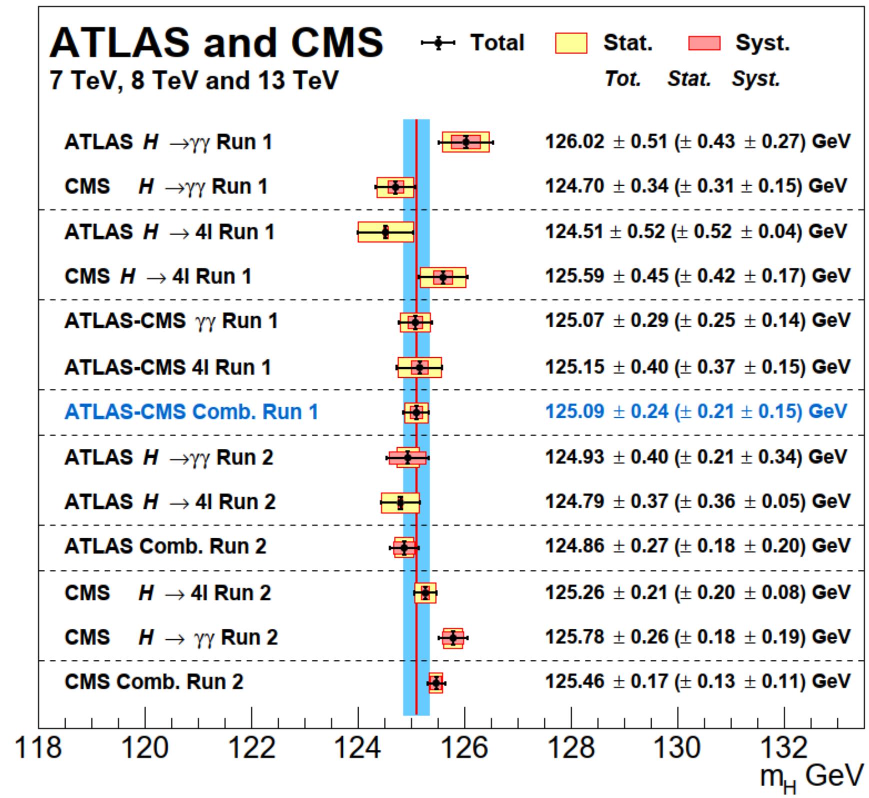
- Recall the mass is not predicted in Standard Model: it had to be *measured*
- The discovery modes are also the ones with the highest sensitivity to the Higgs boson mass: now updated with much higher statistics



ATLAS-CONF-2017-045



CMS-PAS-HIG-19-001

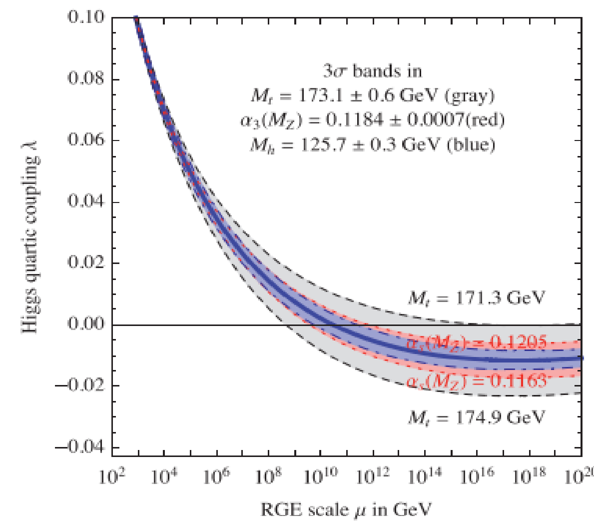


PRD 98 (2018) 030001

m_H = 125.09 ± 0.24 GeV (i.e. 0.2% precision)

Vacuum stability

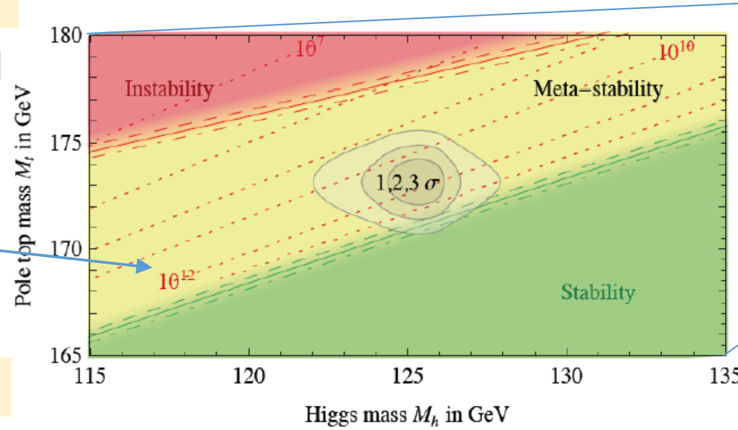
- Precision measurements of Higgs and top masses take a central role in the question of the stability of the electroweak vacuum: top quark radiative corrections can drive the Higgs-boson self-coupling (λ) towards negative values → **unstable vacuum**
- Energy scale (μ) at which this happens: requires new physics to appear by then
- Measured values: at the boundary of stability!
  Meta-stable, but lifetime >> that of universe

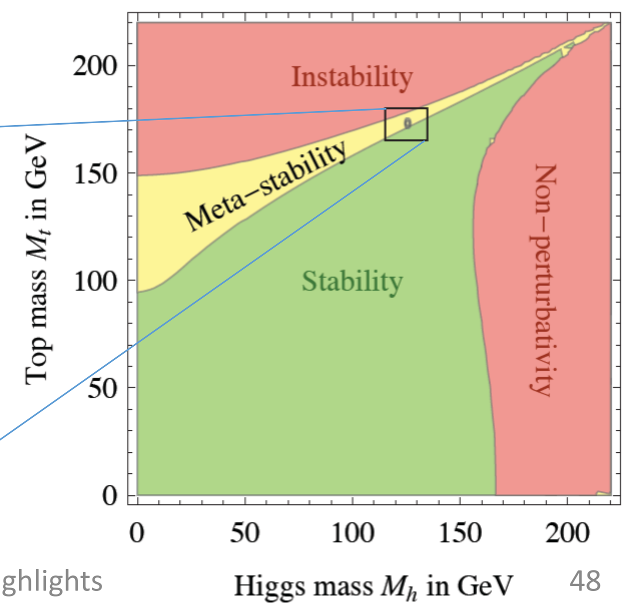


arXiv:1311.1970

Zoom around measured values

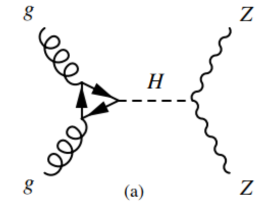
Contours of instability scale in GeV





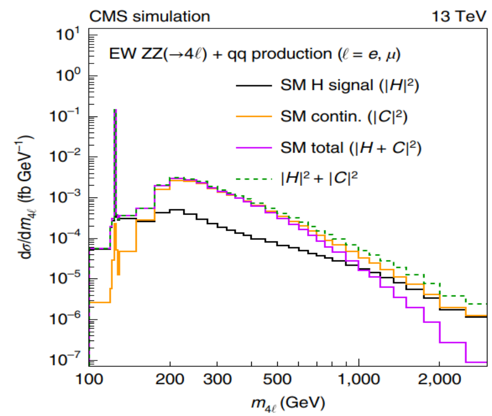
arXiv: 1205.6497

Higgs width



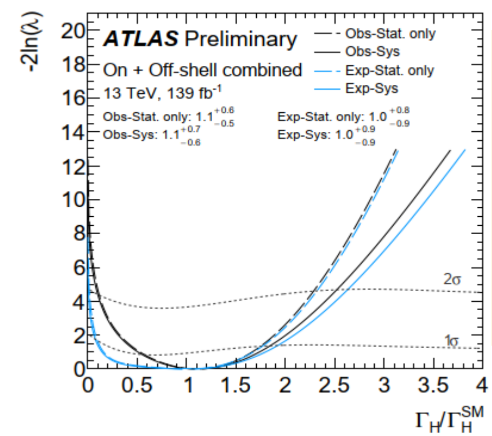
- Direct measurement of the width from the mass distribution is limited by the experimental resolution of ~ 1 GeV, observed mass distributions consistent with a natural width << resolution
- In addition to the peak at 125 GeV from *on-shell* Higgs production, non-resonant (*off-shell*) production is expected at higher masses
  Assuming no new particles enter the gluon-fusion diagram loop, Γ_H can be extracted from the ratio of Higgs boson events observed in the two regimes:

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}\,g^2_{HZZ}}{m_H \Gamma_H} \quad , \quad \sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}\,g^2_{HZZ}}{m^2_{ZZ}}$$



arXiv: 2202.06923

- Both ATLAS and CMS see ~ 3σ evidence for off-shell production, and extract values for width consistent with the SM expectation of 4.1 MeV (at m_H = 125 GeV)
- Remember: lifetime ∝ inverse of width, $\tau = \hbar / \Gamma$
  Although width is small, lifetime still short: ~ 10^{-22} s
  ($\hbar$ = 6.6 x 10^{-16} eV·s)

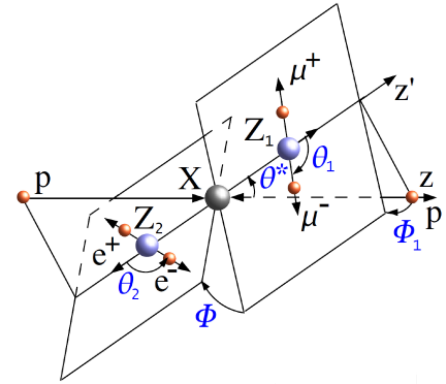


ATLAS-HIGG-2018-32

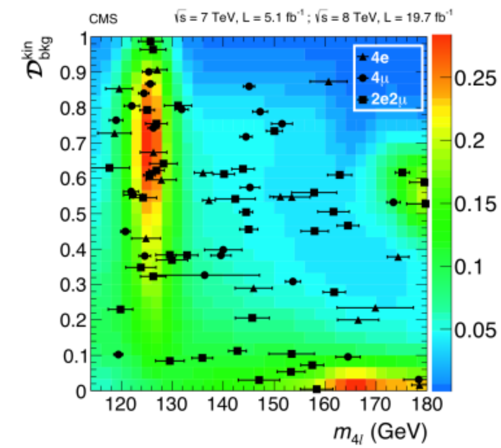
$\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV

Spin-parity

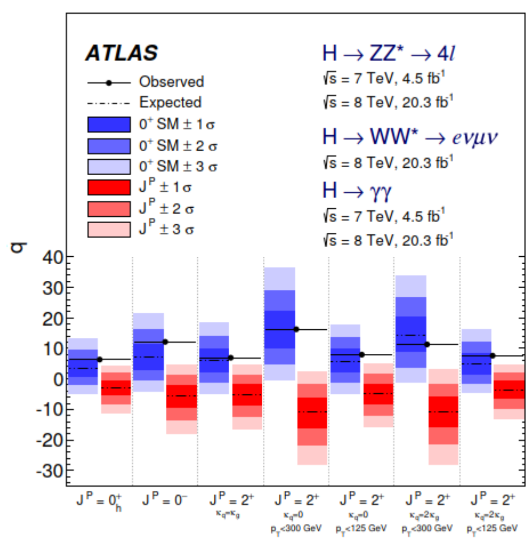
- Following its discovery, the key question was to determine the quantum numbers J^P of the new particle: its spin (J = 0 for a scalar) and parity P = +1 in the Standard Model
- Since it decays to two photons, it is not spin-1 (Landau-Yang theorem) → it is either spin-0 or spin-2 (it could also be higher spin, but that is strongly disfavored)
- Using the *angular* information in the $H \to ZZ^* \to 4\ell$ decays, the different spin-parity hypotheses can be tested
- Alternatives to 0^+ ruled out at > 99% CL

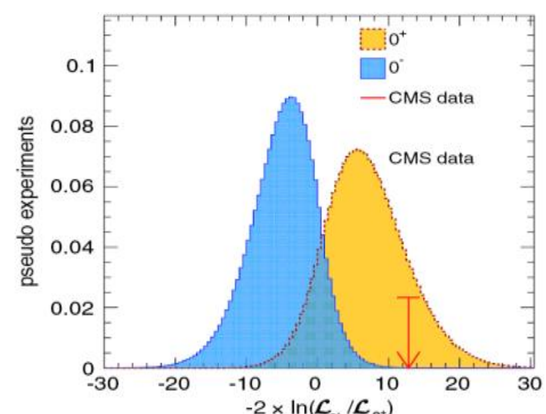


Compare data to discriminant distributions → calculate likelihood



Testing different hypotheses

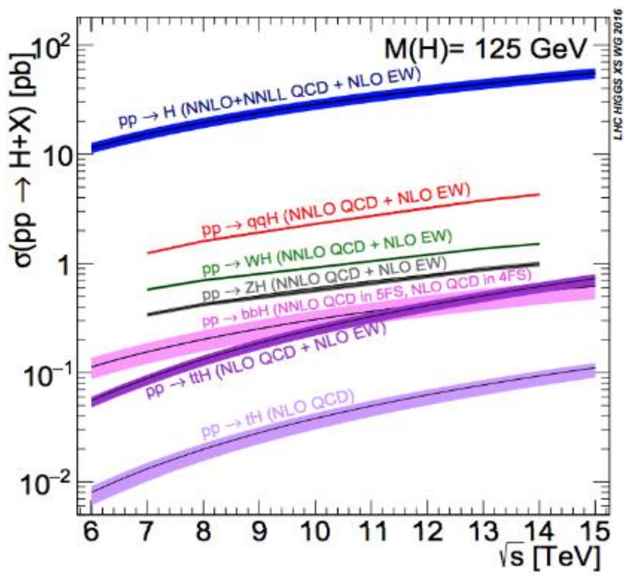


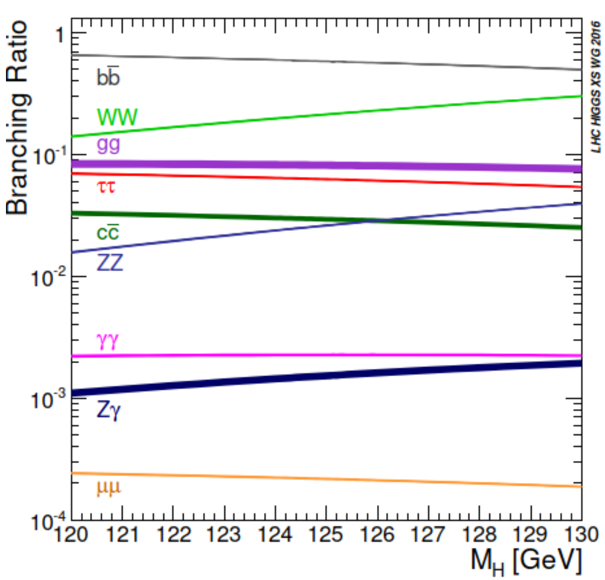


PRD 98 (2018) 030001

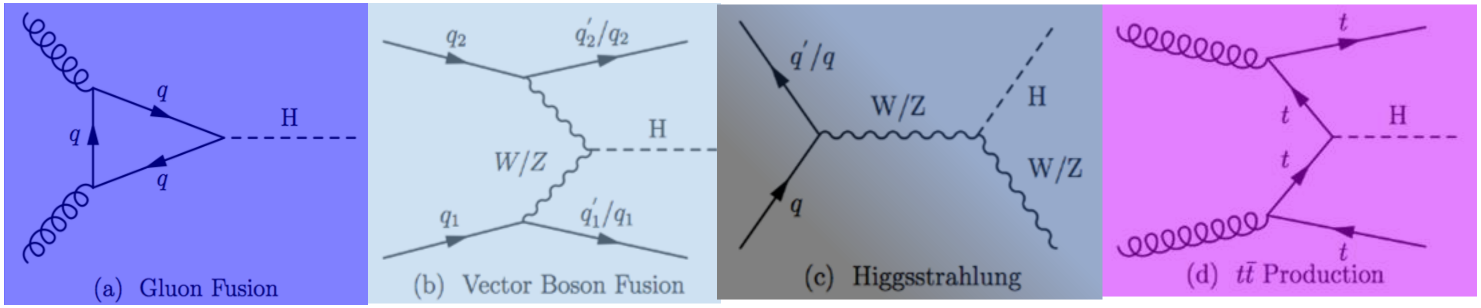
Higgs production

- Once m_H measured, the production and decay modes can all be calculated:



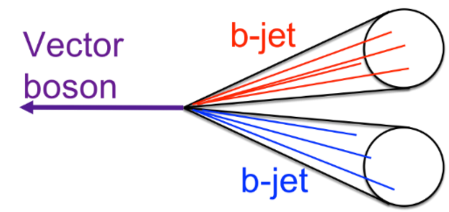


At LHC: ggF (83%) VBF (7%) VH (7%) ttH (3%)

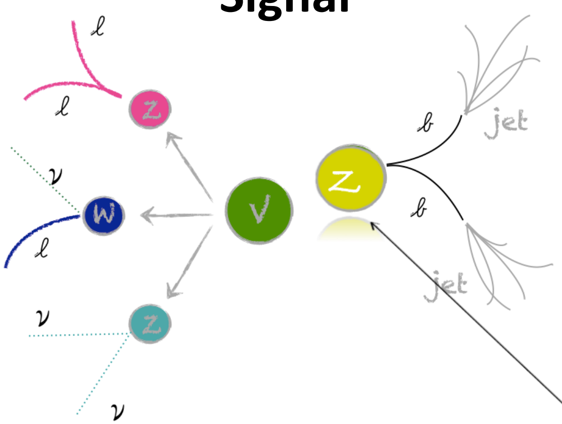


Example: search for VH(bb)

- H $\rightarrow b\bar{b}$ is the largest BR, but has severe multi-jet QCD backgrounds
  Search for associated production with a vector boson (W or Z)
- 3 channels with 0, 1, and 2 leptons and 2 b-tagged jets, targeting Z(νν)H, W(ℓν)H and Z(ℓℓ)H processes with H(bb)
- Require W/Z to have large boost (~ 150 GeV) → multi-jet QCD background is highly suppressed

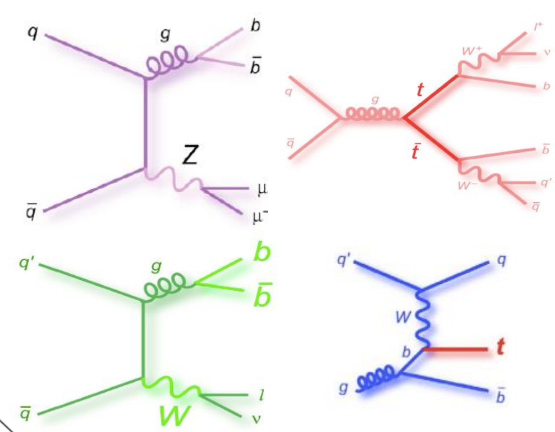


Signal

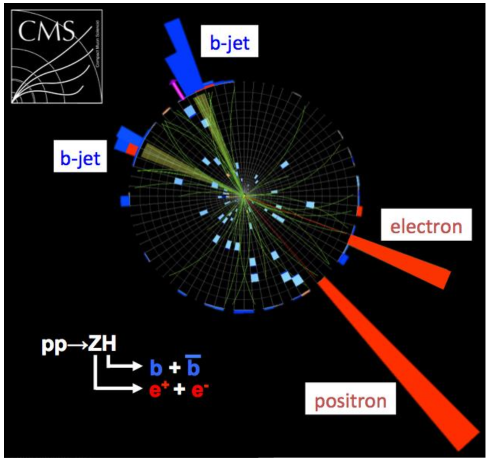


0-lepton (MET)
1-lepton (e, μ)
2-OS leptons (ee, μμ)

Irreducible backgrounds



and diboson, of course

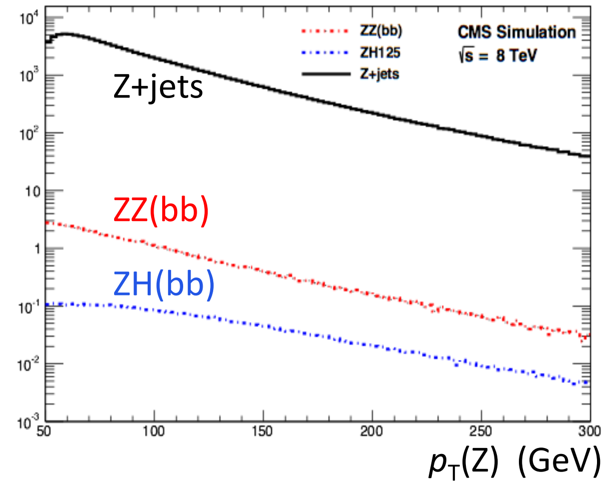


Signal discrimination

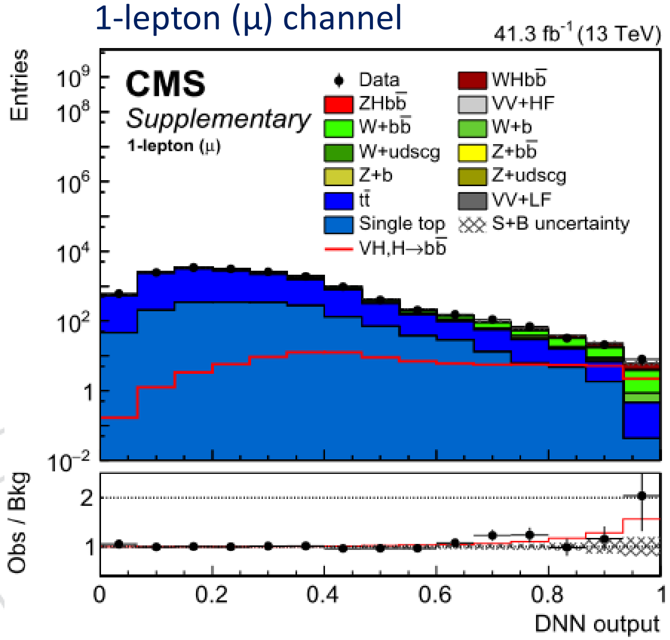
- Control regions used to validate analysis variables and constrain background normalizations
- Simultaneous fit made to signal and control regions
- **Machine Learning**: Neural Network discriminator used to separate signal from background, multivariate analysis exploiting the most discriminating variables: $m_{b\bar{b}}$, $p_T(V)$, b-tagging

See lectures of Harrison Prosper

- Validated with data/MC comparison, trained separately in each channel
- Performance optimized using *blind analysis* (i.e. masking the central value until the selection has been decided)



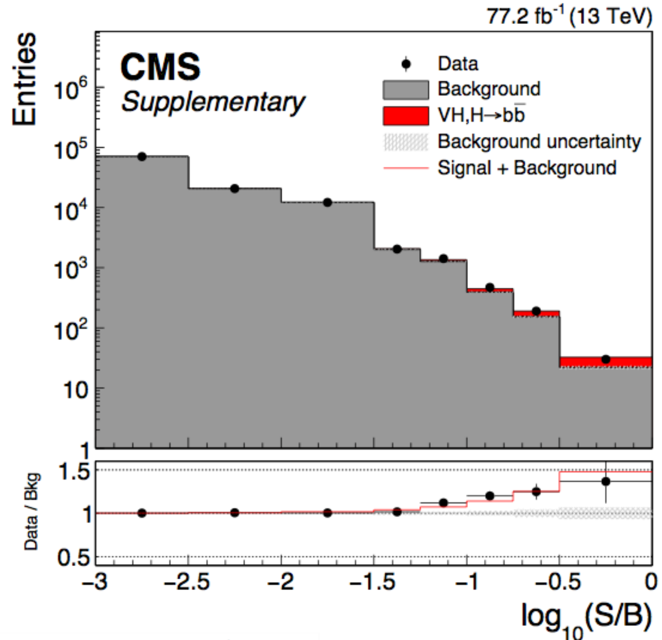
1-lepton (μ) channel

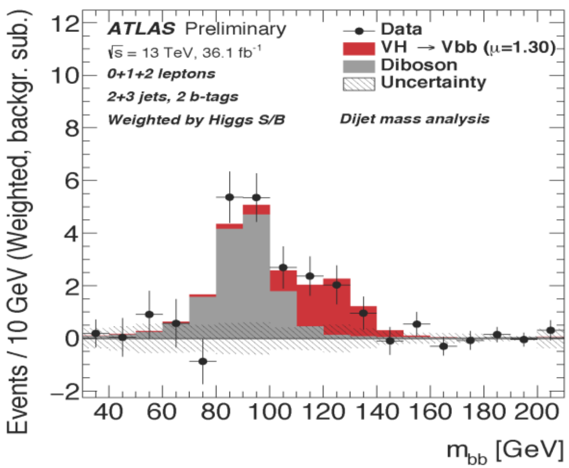


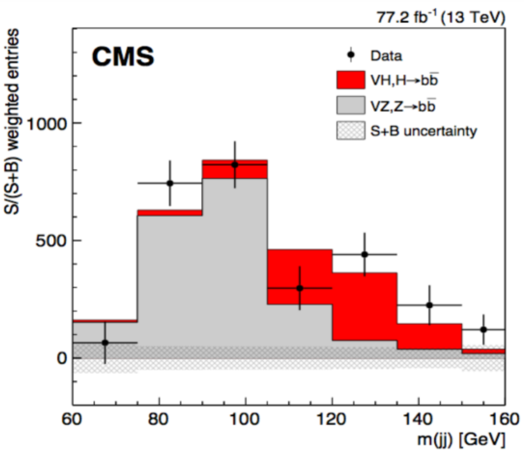
Combining all channels

- Combine all signal channels and plot as a function of Signal/Background per event
  Overall compatible with S+B hypothesis
- Signal significance = 4.8 σ, μ = 1.01 ± 0.23
- Combined with Run 1 data:
  5.6 σ (5.5 σ expected), μ = 1.04 ± 0.20
  > 5 σ → decay has been observed
- Very similar analysis made by ATLAS
  (including choice of colours for the final plot!)

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}}$$





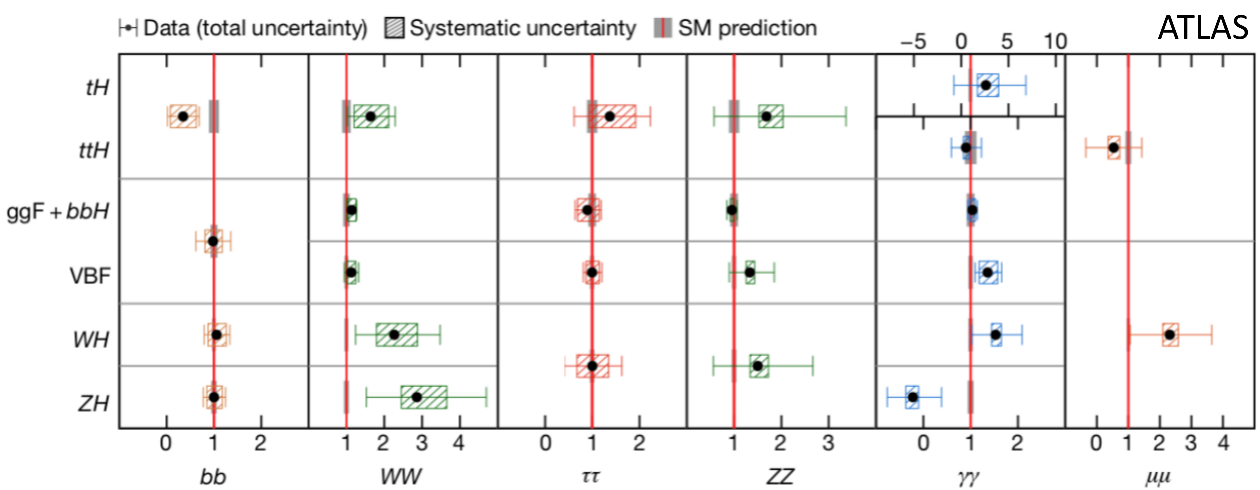


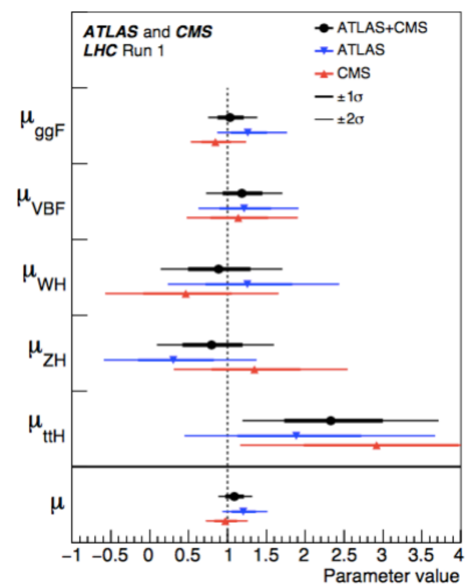
PRL 121 (2018) 121801

Experimental status

- Enormous effort has been invested to study all aspects of the Higgs boson: all the production mechanisms seen, as expected in the Standard Model
- Decay modes: **WW** seen early (Run 1) then **ττ** (2017) and **$b\bar{b}$** (2018) – important as measure couplings to fermions rather than gauge bosons
- So far only decays to third generation fermions seen clearly (since the Higgs boson couples to mass, they have highest branching ratios)
- For the second generation, some evidence has been seen for **μμ** (to be confirmed), **$c\bar{c}$** under study but still far from reaching SM sensitivity

$$\mu^{(\mathrm{LHC})} = 1.09 \pm^{0.11}_{0.10}$$

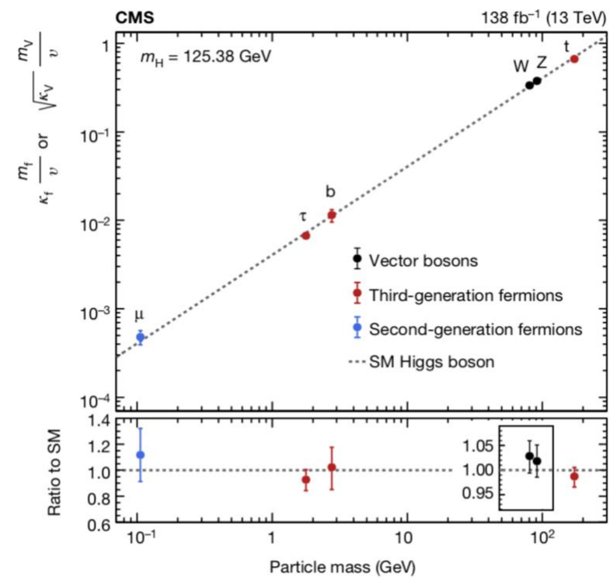


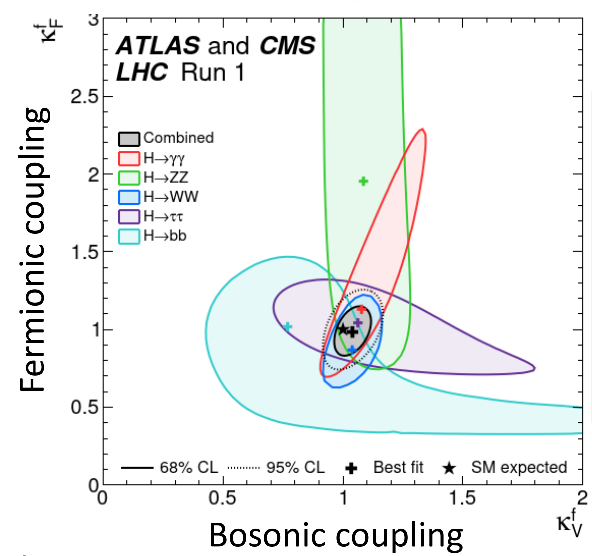


Higgs couplings

- The Higgs boson couplings are *non-universal*: it couples to particles with coupling strength proportional to their **mass**
- All results seen so far are consistent with this prediction, and the SM in general
- There could be invisible decays of the Higgs boson: in the Standard Model this is only via $H \to ZZ^* \to 4\nu$ with a tiny BR ~ 0.1%
- However, could be strongly enhanced if the Higgs couples to Dark Matter – after all, the evidence for DM is gravitational, and the Higgs couples to mass
- Searched for using associated production (VBF or VH) with large MET
Best limit so far: $BR(H \to inv) < 19\%$ at 95% CL

arXiv:1809.05937





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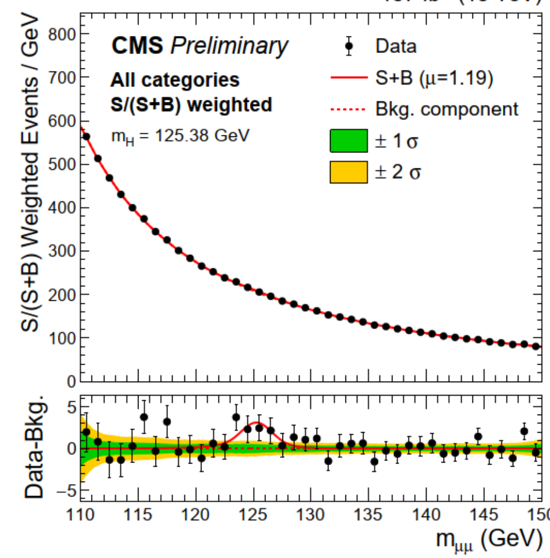
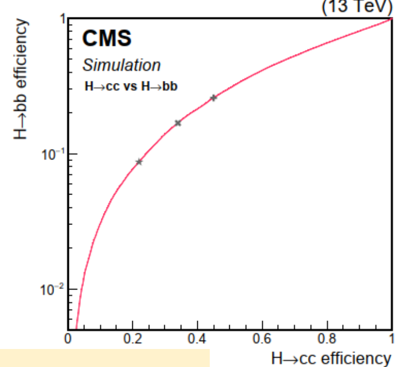
Rare decays

- Second-generation couplings searched for: **H → μμ** has BR (in SM) 2.2 x 10^{-4}, evidence now seen at 3σ significance
- **H → c$\bar{c}$**: very tough, have to suppress H → b$\bar{b}$ background Current upper limit 70x SM
- **Lepton Flavour Violating** decays such as H → eτ or μτ also searched for

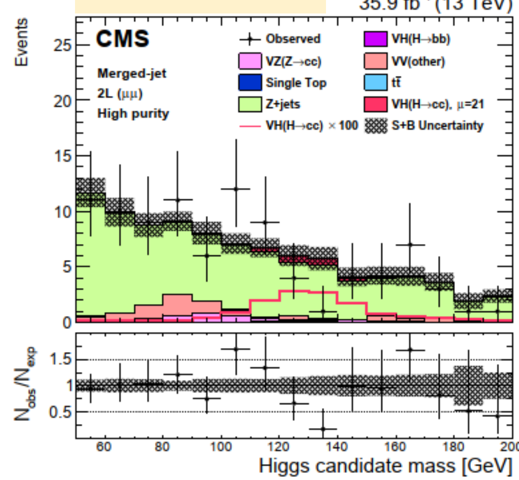
H → μ+μ-

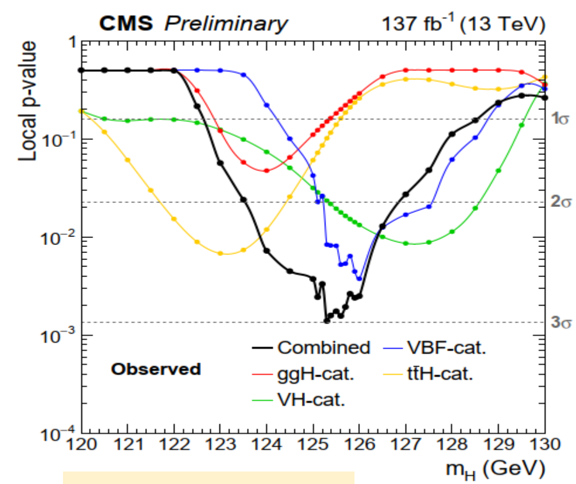


H → c$\bar{c}$



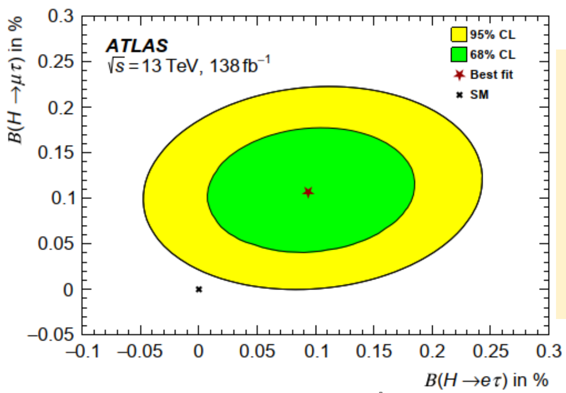
arXiv:1912.01662





CMS PAS HIG-19-006

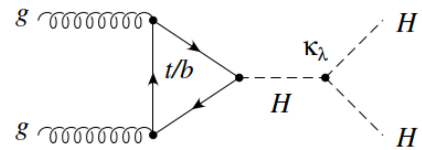
H → ℓτ

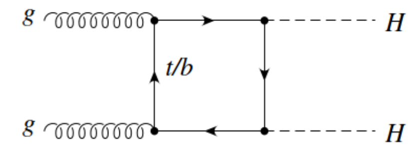


arXiv:2302.05225

Interesting 2.5 σ discrepancy to keep an eye on in future

HH



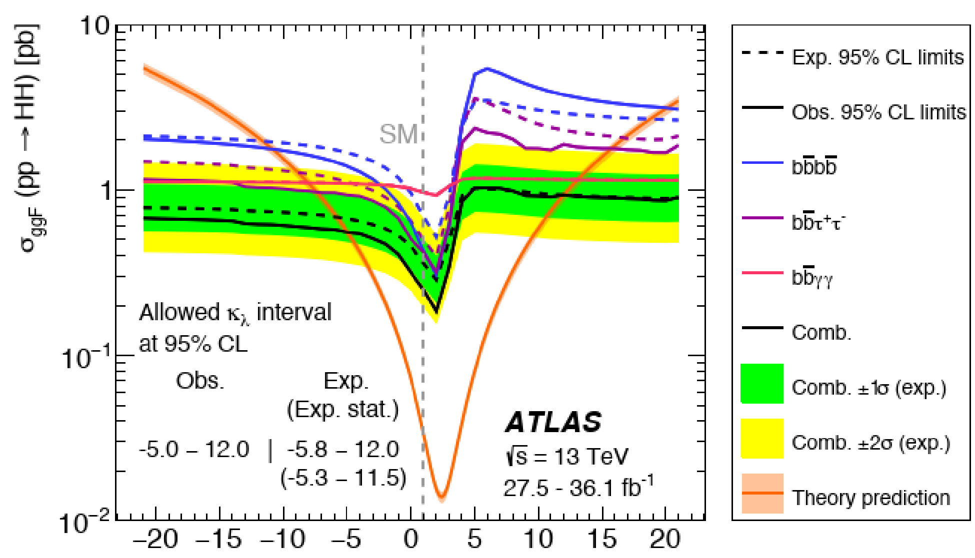


- There is a still a lot to be understood about the Higgs mechanism Searching for Higgs boson **pair-production** is vital step towards measuring the *self-coupling* of the Higgs boson, λ

- Measurements of the trilinear Higgs interaction would provide constraints on the shape of the Higgs potential close to the minimum, and would allow to verify the electroweak symmetry breaking mechanism of the SM

- HH production is also possible via box diagram, *without* self-coupling, and the two diagrams interfere → rare process

- Upper limits are currently about 7x higher than the expected signal strength in the Standard Model



$-5.0 < \kappa_\lambda < 12.0$

$\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$

arXiv:1906.02025

Summary (Lecture 3)

- There is a very wide range of physics results from the LHC, out of which I have only been able to present selected highlights
- **Strong interactions**: the total cross-section, jet production studied and the Quark Gluon Plasma (at ALICE and elsewhere), many results for top quarks
- **Flavour physics**: striking results shown (mostly from LHCb), for particle-antiparticle oscillations, CP violation in beauty and charm decays, and the study of rare decays
- **Electroweak physics**: this is mostly the province of the general-purpose experiments ATLAS & CMS, and illustrates the tendency towards precision measurements, e.g. for the W mass
- **The Higgs boson** can currently *only* be studied at the LHC: its properties have started to be measured in detail, but more remain to be revealed – in particular its self-coupling and potential
- Overall the Standard Model continues to be triumphant, with the measured cross-sections agreeing with predictions over 12 orders of magnitude

Next: Remarkable agreement seen with SM predictions over 12 orders of magnitude
Why are we not satisfied? Where will new physics be found?