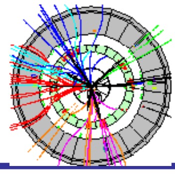


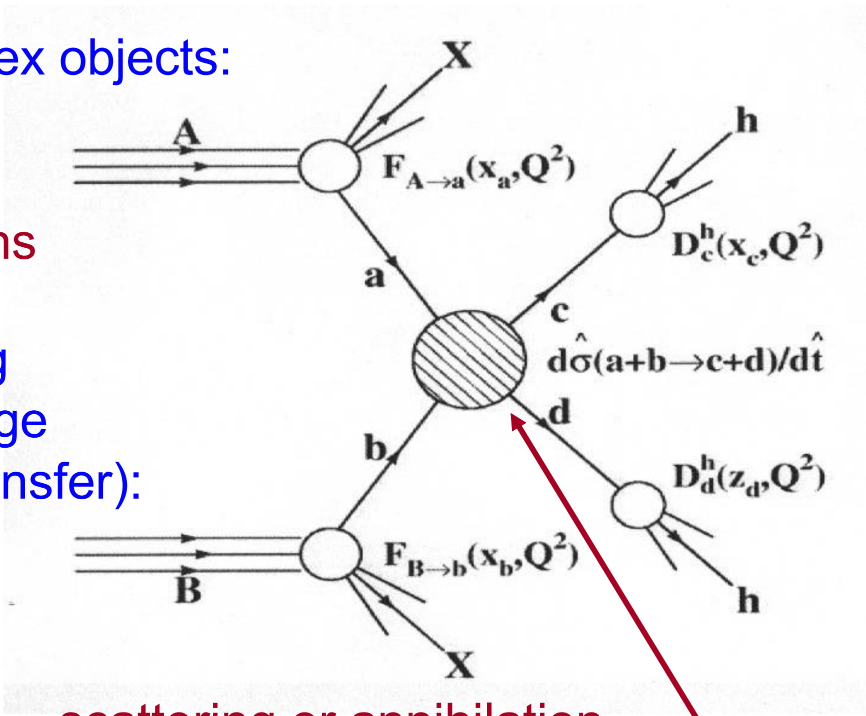
Physics at hadron colliders

- Hadron-hadron interactions
- Top physics
- Higgs
- HL-LHC
- Next collider after LHC: FCC

Hadron-hadron interactions

protons complex objects:
partonic substructure: quarks & gluons

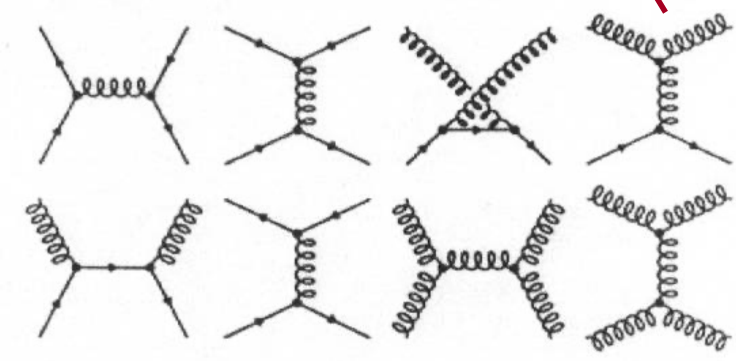
hard scattering processes (large momentum transfer):



quark-quark
quark-gluon
gluon-gluon

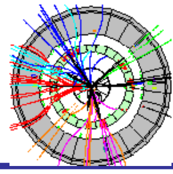
scattering or annihilation

at parton level



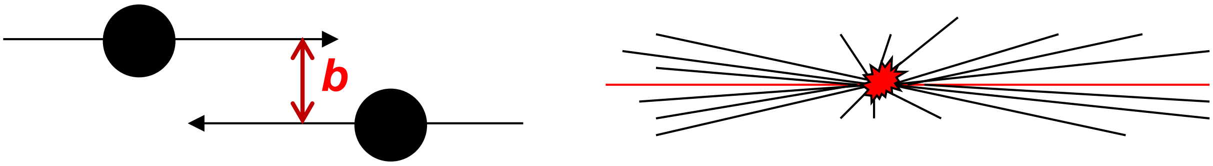
however: hard scattering (high p_T processes) represent only a tiny fraction of the total inelastic pp cross section. e.g. total inelastic cross section ~80 mb at $\sqrt{s}$ = 13 TeV.

Dominated by events with small momentum transfer, in particular by two event types: diffractive (colourless exchange with the quantum numbers of vacuum between the two protons) & minimum-bias (exchange of colour).



Inelastic low p_T hadron-hadron collisions

Most interactions due to interactions at large distance between incoming protons where protons interact as "a whole" $\rightarrow$ small momentum transfer ($\Delta p \approx \hbar / \Delta x$) / large impact parameter b $\rightarrow$ particles in final state have large (small) longitudinal (transverse) momentum.



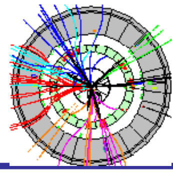
$< p_T > \approx 500$ MeV (of charged particles in final state)

$\frac{dN}{d\eta} \approx 6$ ~6 charged particles per pseudorapidity unit in central region of experiment (uniform distribution in azimuthal angle)

(LHC numbers)

most energy escapes down the beam pipe.

Called minimum-bias events ("soft" events) & constitute a large fraction of the total cross section e.g. ~ 60 mb of ~ 110 mb at $\sqrt{s}$ = 13 TeV. Perhaps not very interesting in themselves but needs to be understood. Cross section large that they occur multiple times per bunch crossing (e.g. 2024-26: ~ 60 times) $\Rightarrow$ overlap interesting collisions ("pile-up") & change measured event quantities.

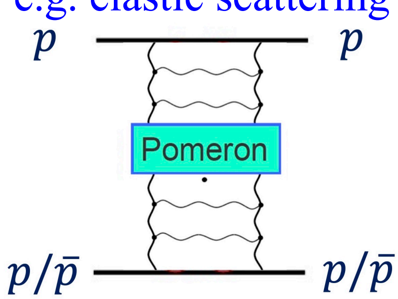


Diffractive processes

another large part of the total cross section are diffractive processes, where non-colored object(s) are exchanged refered to as ”Pomeron(s)”. Pomeron is described by a system of two (or even number) of gluons or gluon ladder

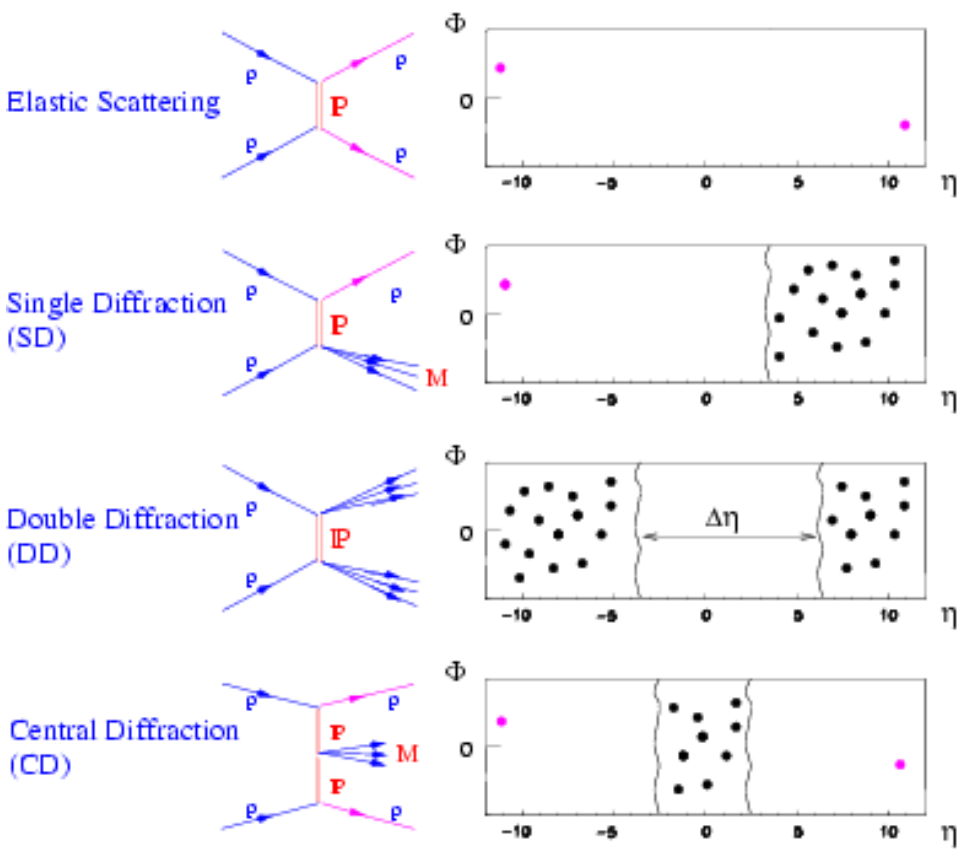
diffractive events characterized by ”rapidity gaps”
(= regions of pseudorapidity without primary particle production)

e.g. elastic scattering

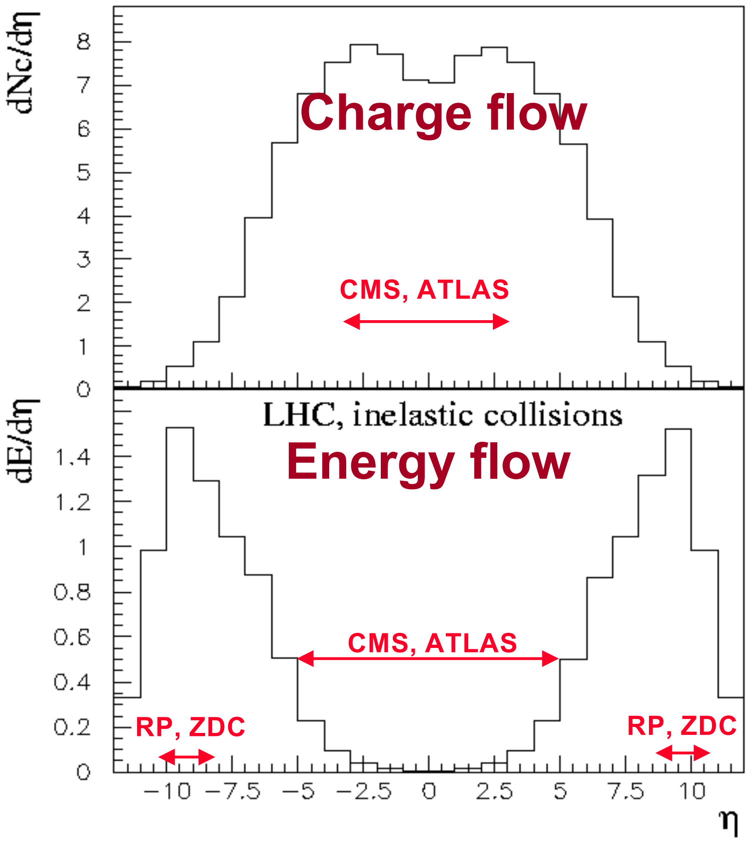


elastic scattering	~ 30 mb
single diffraction	10 – 16 mb
double diffraction	5 – 10 mb
central diffraction	~ 1 mb

in total ~ 50 mb @ $\sqrt{s}$ = 13 TeV.



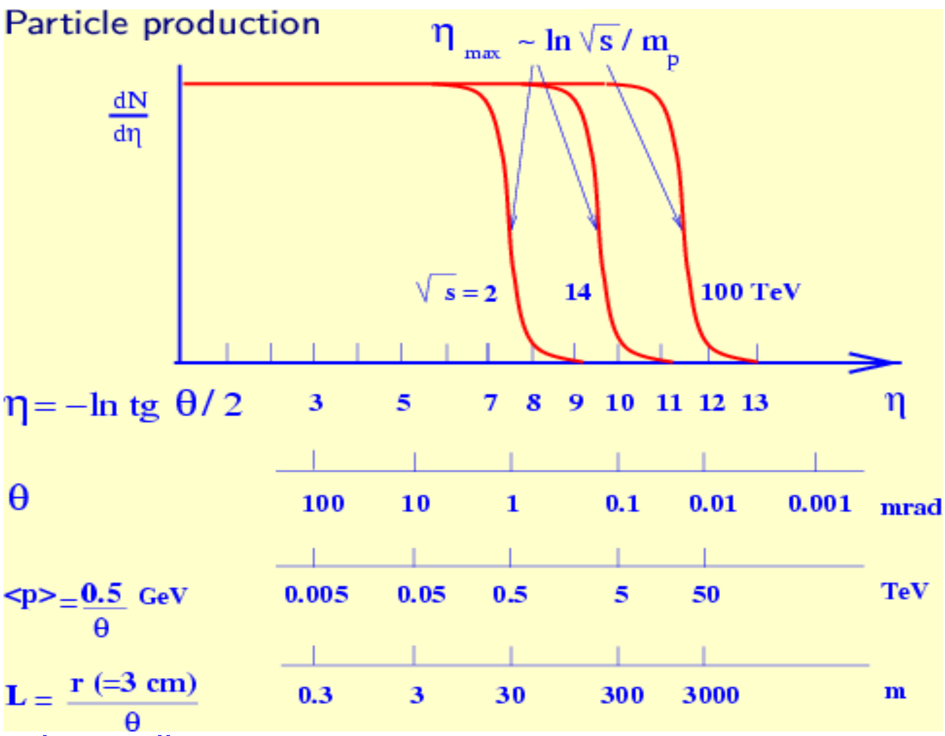
	σ (1.8 TeV)	(13 TeV)
Elastic Scattering	17.8+–0.6 mb	~ 30 mb
Single Diffraction (SD)	9.46+–0.44 mb	10 -16 mb
Double Diffraction (DD)	6.3+–1.7 mb (for Δη > 3)	5 -10 mb
Central Diffraction (CD)		~ 1 mb



charged particle & energy flow in an average proton-proton collision at LHC.

The acceptancies of baseline ATLAS & CMS experiments are also indicated

RP = Roman Pots (detect intact protons)
ZDC = Zero Degree Calorimeters (detect neutral particles)



pseudorapidity

polar angle

average particle momentum

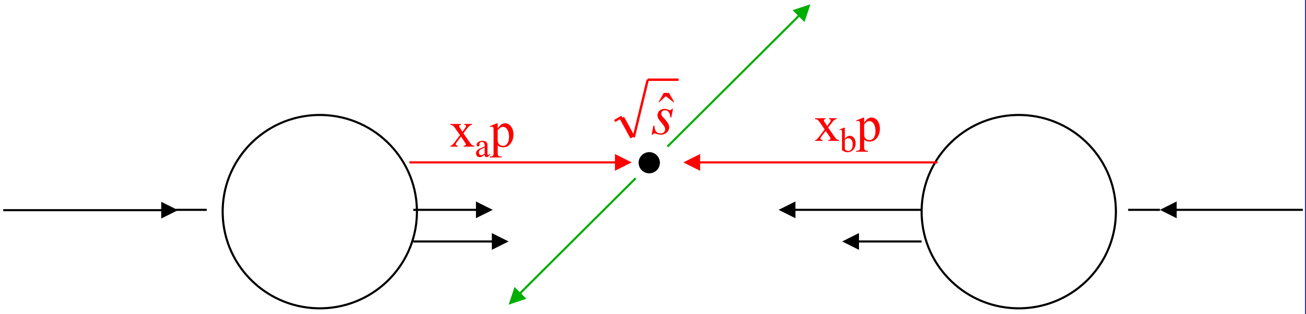
distance to IP @ LHC vacuum chamber radius

IP = interaction point

Inelastic high p_T hadron-hadron collisions

proton beam can be seen as a beam of quarks & gluons with a wide band of energies, occasionally occurs hard scattering between constituents of incoming hadrons.

constituents carry only a fraction 0 < x < 1 of proton momentum.



p ≡ momentum of incoming hadron

- effective centre-of-mass energy $\sqrt{\hat{s}}$ smaller than $\sqrt{s}$ of colliding beams:

if $x_a \approx x_b$

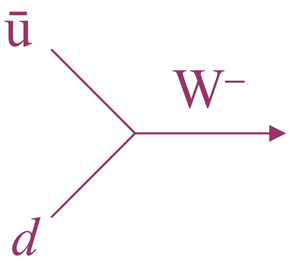
$$\sqrt{\hat{s}} = \sqrt{x_a x_b s} \approx x\sqrt{s}$$

<u>to produce at LHC a mass of:</u>

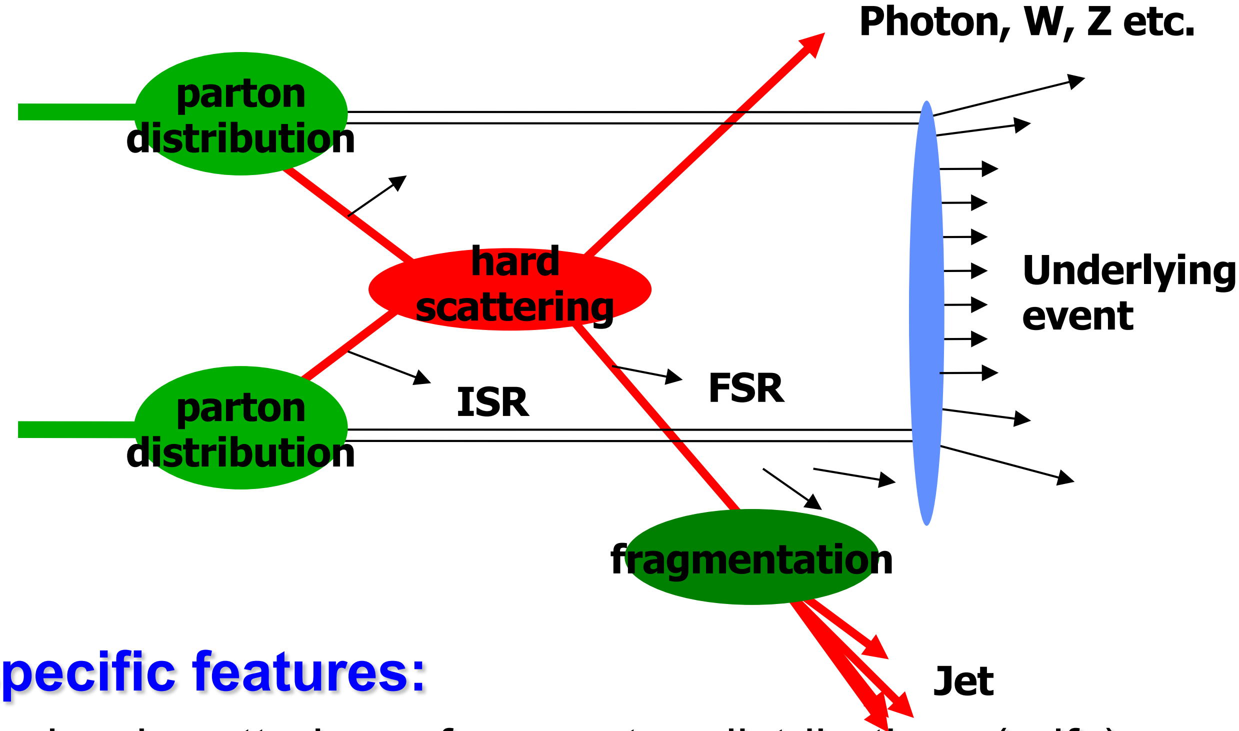
100 GeV: x ~ 0.007
1 TeV: x ~ 0.07
5 TeV: x ~ 0.4

these are interesting physics events but they are rare.

e.g. ū + d → W^-



$\sigma\,(pp \to W) \approx 150\ \text{nb} \approx \mathbf{10^{-6}}\,\sigma_{tot}\,(pp)$



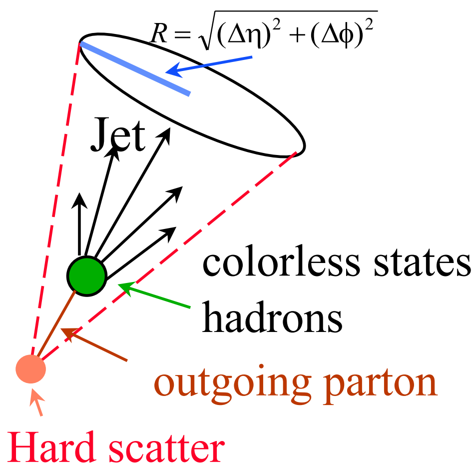
specific features:

- hard scattering σ from parton distributions (pdfs)
- initial and final states can "radiate" gluons (ISR & FSR)
- colored final states fragment to form "jets"
- underlying event from proton remnants

fragmentation (hadronization):

- quarks/gluons produced give raise to lots of radiation (α_S is large!) & recombine to form colorless spray of almost collinear hadrons: a jet
- jets = experimental signature of quarks/gluons & observed as locali-zed energy deposits in calorimeters.
- jet energy $\neq$ parton energy due to calorimeter response, missing (ν's, low p_T & out of cone) particles & overlapping particles (from min. bias events). average corrections applied.

at hadron colliders jets usually formed using simple cone algorithms ($R \approx 0.7$)



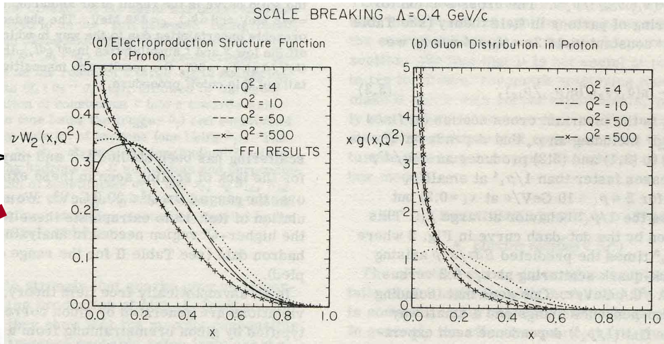
- cross-section :

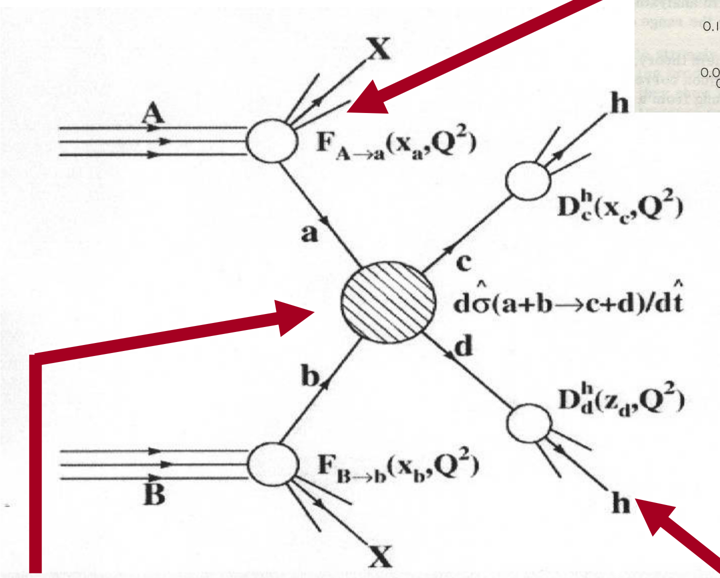
$$\sigma = \sum_{a,b} \int dx_a \, dx_b \, f_a(x_a, Q^2) \, f_b(x_b, Q^2) \, \hat{\sigma}_{ab}(x_a, x_b)$$

$\hat{\sigma}_{ab}$ $\equiv$ hard scattering cross-section

$f_i(x, Q^2) \equiv$ parton distribution function

parton distribution functions measured in DIS & hadron-hadron collisions



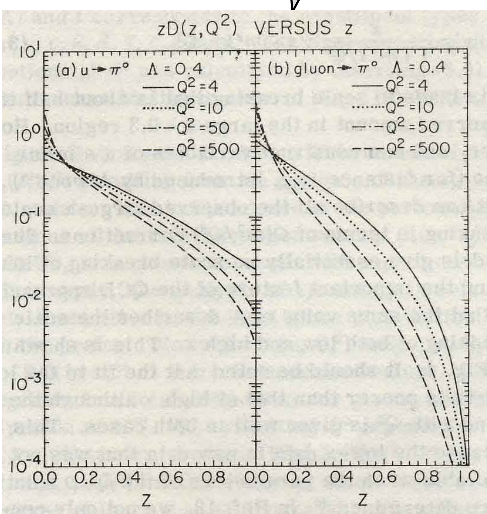


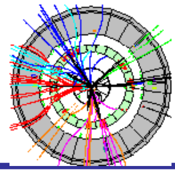
quark & gluon fragmentation functions measured mostly in e⁺e⁻ collisions; modeled by fragmentation MC

TABLE I. Cross sections for the various constituent quark-quark, quark-gluon, and gluon-gluon subprocesses.[a] The differential cross section is given by $d\hat{\sigma}/d\hat{t} = \pi \alpha_s^2(Q^2)|A|^2/\hat{s}^2$, where $\alpha_s(Q^2)$ is the effective coupling given by Eq. (3.1).

	Subprocess	$\|A\|^2$
1.	$q_i q_j \to q_i q_j$, $q_i \bar{q}_j \to q_i \bar{q}_j$ $(i \neq j)$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$
2.	$q_i q_i \to q_i q_i$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\frac{\hat{s}^2}{\hat{u}\hat{t}}$
3.	$q_i \bar{q}_i \to q_i \bar{q}_i$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}}$
4.	$q_i \bar{q}_i \to gg$	$\frac{32}{27}\left(\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}\right)-\frac{8}{3}\left(\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}\right)$
5.	$gg \to q_i \bar{q}_i$	$\frac{1}{6}\left(\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}\right)-\frac{3}{8}\left(\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}\right)$
6.	$q_i g \to q_i g$	$-\frac{4}{9}\left(\frac{\hat{u}^2+\hat{s}^2}{\hat{u}\hat{s}}\right)+\left(\frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}\right)$
7.	$gg \to gg$	$\frac{9}{2}\left(3-\frac{\hat{u}\hat{t}}{\hat{s}^2}-\frac{\hat{u}\hat{s}}{\hat{t}^2}-\frac{\hat{s}\hat{t}}{\hat{u}^2}\right)$

quark & gluon cross-sections calculable in QCD





Parton fragmentation functions

Parton fragmentation function $D_i^h(x, Q^2)$ describes the probability to produce certain hadron h from parton i (= $q, \bar{q}, g$ ...). Analogous to pdf's obtain from DIS.

In fragmentation function, x represents fraction of partons momentum carried by produced hadron h ↔ In pdf, x represents fraction of momentum of original hadron carried by interacting parton. Q^2 describes here the energy (scale) of the original parton when produced instead of the momentum transfer as for pdf's in DIS.

Fragmentation functions $D_i^h(x, Q^2)$ exhibit similar scaling violations as pdf's $f_i(x, Q^2)$ from DIS. The Q^2 evolution described by similar "DGLAP"–equations:

$$\frac{\partial D_i(x,Q^2)}{\partial \ln Q^2} = \sum_j \int_x^1 \frac{dz}{z} \frac{\alpha_s}{2\pi} P_{ji}(z,\alpha_s) D_j\left(\frac{x}{z}, Q^2\right),$$

where $$P_{ji}(z,\alpha_s) = P_{ji}^{(0)}(z,\alpha_s) + \frac{\alpha_s}{2\pi} P_{ji}^{(1)}(z,\alpha_s) + \ldots$$

Lowest–order functions $P_{ji}^{(0)}(z)$ same as those for pdf's in DIS but higher–order terms different. NB! Splitting function P_{ji} (& not P_{ij}) since D_j describes fragmentation of final parton. P_{ji} = probability for parton i to transfer into parton j.

Effect of Q^2 evolution same as for DIS pdf's: x–distribution shifted towards lower values for larger Q^2's. P_{ji}'s contain singularities at $z = 0$ & $z = 1$, which have important effects on fragmentation at small & large x, for details see O. Biebel, P. Nason & B.R. Webber, hep-ph/0109282.

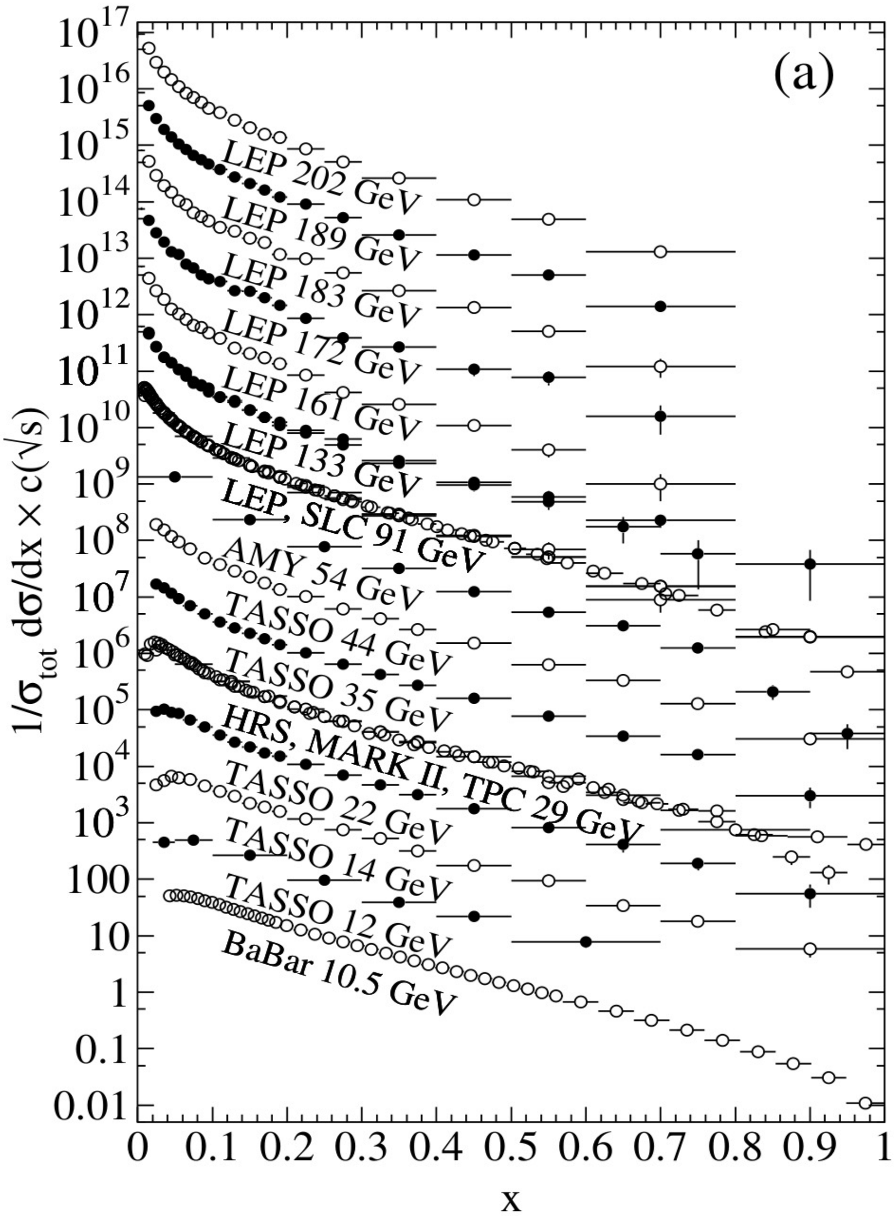
Parton fragmentation function $D_i^h(x,s)$ usually determined from e^+e^- fragmentation functions $F^h(x,s)$.

$$F^h(x,s) = \frac{1}{\sigma_{\text{tot}}}\frac{d\sigma}{dx}(e^+e^- \to hX) = \sum_i \int_x^1 \frac{dz}{z} C_i(s;z,\alpha_s) D_i^h\left(\frac{x}{z},s\right),$$

$$C_q(s;z,\alpha_s) = g_q(s)\delta(1-z) + O(\alpha_s) \;\; \& \;\; C_g(s;z,\alpha_s) = O(\alpha_s)$$

& $g_i(s)$ appropriate (e.g. q) electroweak coupling.

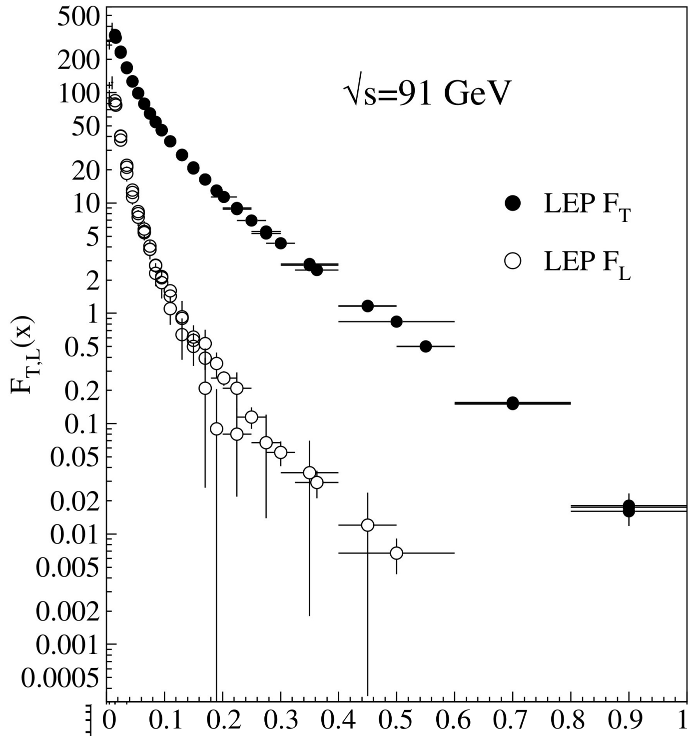
The e^+e^- fragmentation functions for all charged particles for different $\sqrt{s}$. The influence of scaling violations can be seen. Larger $\sqrt{s}$ shifts the x–distribution towards smaller x's & exponential becomes steeper.

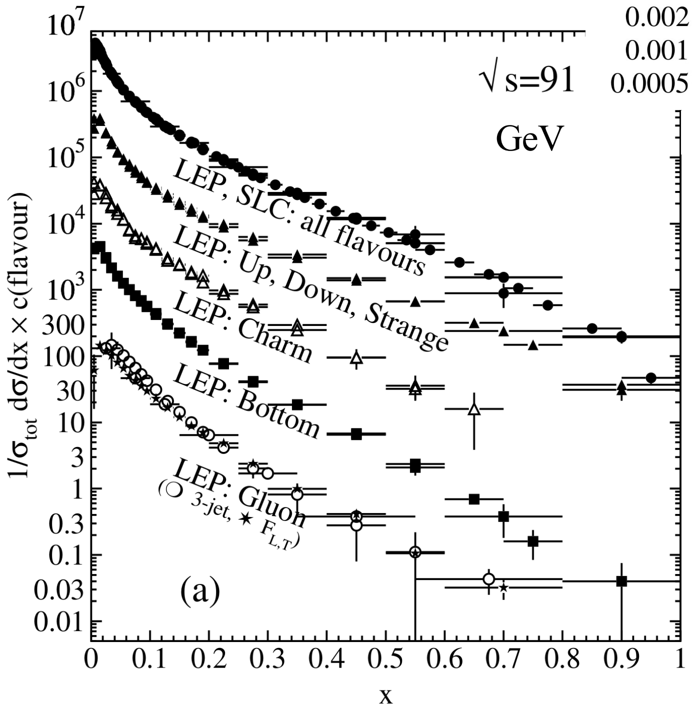


In $e^+e^- \to \gamma/Z^0 \to hX$, differential x & $\cos\theta$ distribution (ignoring parity-violating F_A-term, θ = angle between h & e^+):

$$\frac{1}{\sigma_{\rm tot}}\frac{d^2\sigma}{dx\,d\cos\theta}(e^+e^- \to hX) = \frac{3}{8}(1+\cos^2\theta)\,F_T(x,s) + \frac{3}{4}\sin^2\theta\,F_L(x,s),$$

where $F_L(x,s)$ & $F_T(x,s)$ longitudinal & transverse fragmentation functions representing contributions from virtual bosons having longitudinal or transversal polarization (w.r.t. direction of motion of hadron).

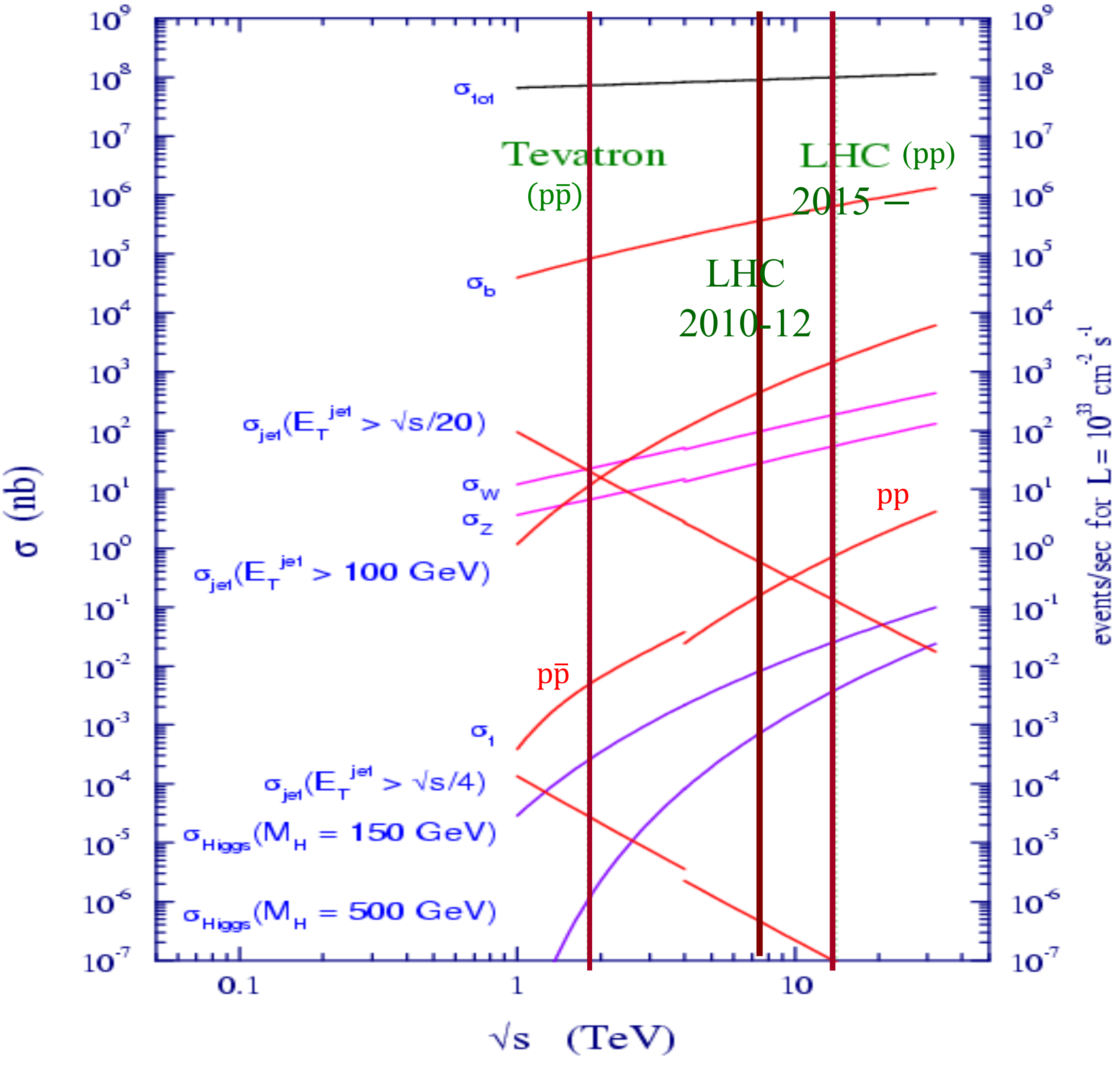




Gluon fragmentation function $D_g(x)$ can be extracted from measured $F_T(x)$ & $F_L(x)$. Coefficient functions C_i's of q & g comparable at $O(\alpha_s)$.

$$F_L(x,s) = C_F\frac{\alpha_s}{2\pi}\int_x^1\frac{dz}{z}\left[F_T(z,s)+4\left(\frac{z}{x}-1\right)D_g(z,s)\right]+O(\alpha_s^2) \quad \& \; C_F = \frac{4}{3}$$

Most interesting processes are **rare processes**:
- involve **heavy particles**
- have **small cross-sections** (e.g. W production)



main background: QCD jets → lepton & photon signatures
important trigger signatures: a) μ (charged particle beyond cal.), b) γ/e (em. shower) & c) neutrinos (missing transverse energy).
note: pay a prize for branching ratio i.e. BR(W $\rightarrow l\nu$) ≈ 30%

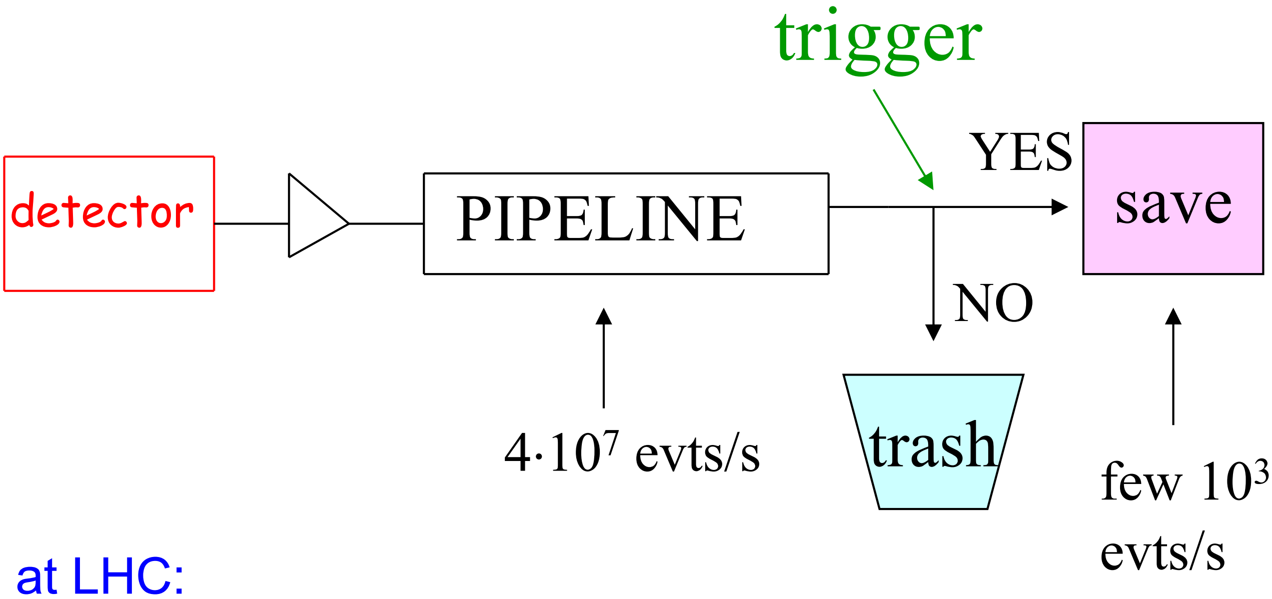
- trigger: much more difficult than in e^+e^- collisions (LHC numbers given)

bunch crossing rate: ~ $4 \cdot 10^7$ events/second
can record ~ few kHz (event size: few MB)

⇒ **trigger rejection ~ 10^4**

trigger decision ≈ μs ⟶ > interaction rate (of 25 ns)

→ store massive amount of data in pipelines while special trigger processors performs calculations



at LHC:

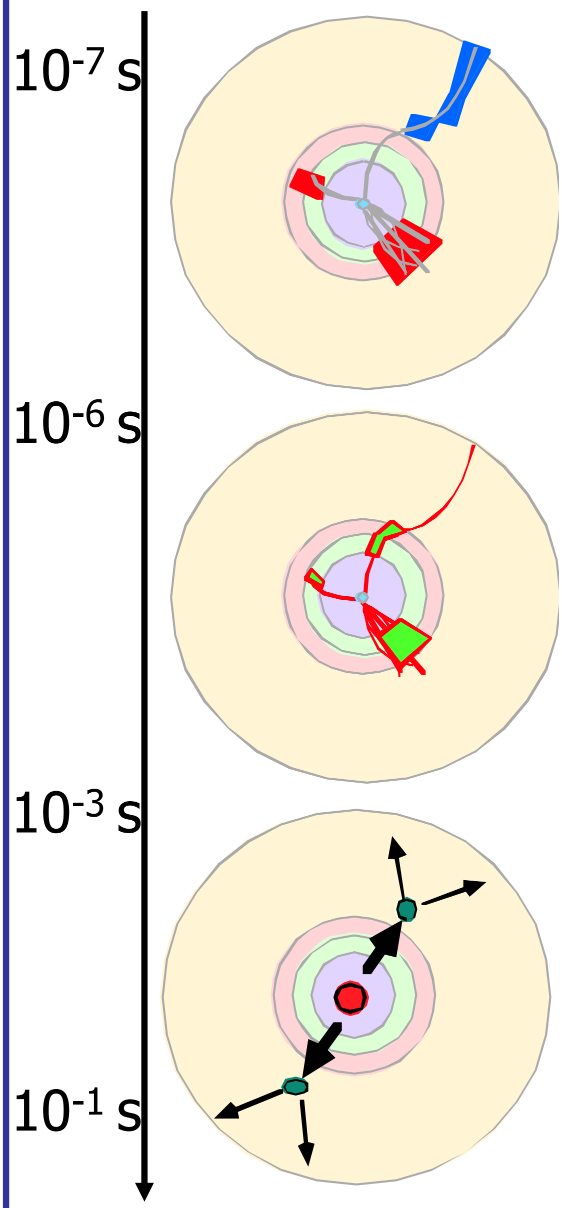
- low level (1^{st}) trigger based (mostly) on calorimetry & muons chamber info ⇒ change for high lumi LHC
- high level trigger (HLT) software based using a (crude) full event reconstruction.
- exceptions: LHCb triggerless (online analysis)

Trigger

Trigger decision taken on several levels with increasing complexity & selectivity ('divide et impera'). Start with coarse information & refine as you go along. Employ parallelism as much as possible in search of relevant info.

All data of previous level must be stored until subsequent trigger decision has been taken.

Level "0": Event rate: $4 \cdot 10^7$ Hz. Detector channels: 10^7 - 10^8 DAQ running constantly at 40 MHz. Data flow ≈ 10^{14} B/s

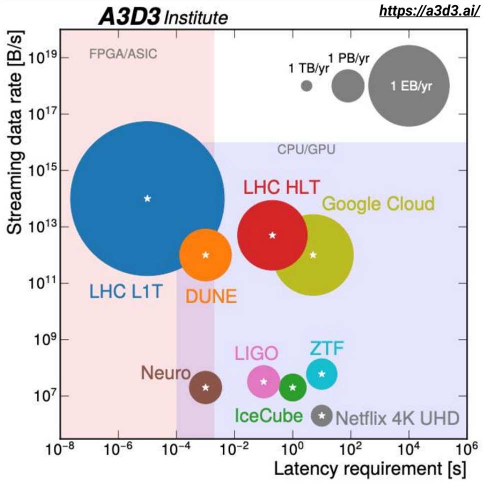


Level-1 trigger: coarse selection of interesting candidate events within a few μs. L1-trigger output rate ≈ 100 kHz. Implementation: specific hardware (ASICS, FPGA, DSP)

High Level Trigger (HLT): full event reconstruction based on cruder information. Writing data to storage medium. Output rate: a few kHz. Total event size: few MB. Implementation: fast processor farms.

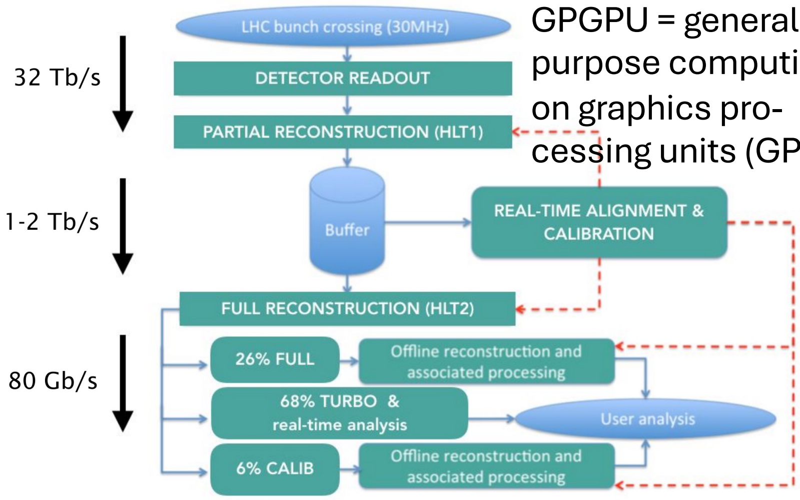
New paradigm: Triggerless readout implemented by LHCb. Possible due to zero suppression on detectors & comparatively small total event size (~100 kB).

- Limiting factor is bandwidth = maximimal output data rate.
- Employ machine learning techniques to make trigger selection more ”efficient”



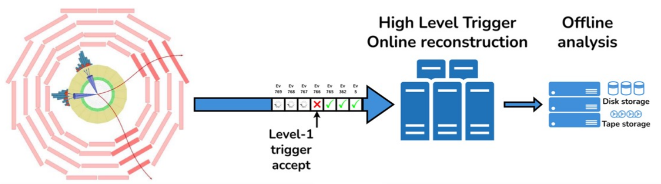
LHCb triggerless readout

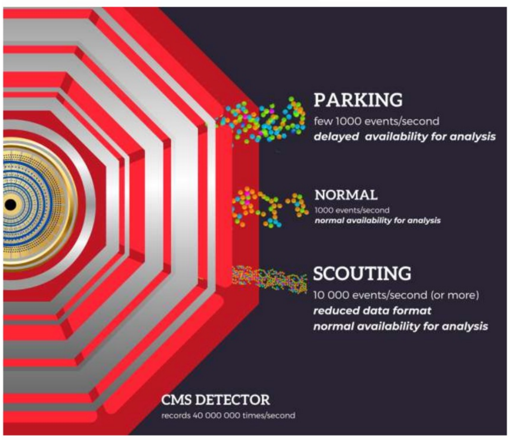
- Two stages of software filtering:
  1) "HLT1" on GPGPUs
  2) "HLT2" on CPUs
- Large storage buffer to decouple the two
- Calibration and alignment are performed "semi-live", while the data are buffered



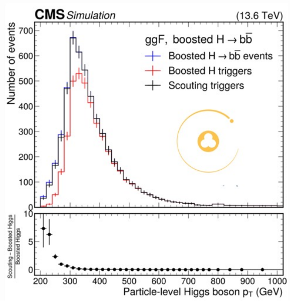
GPGPU = general-purpose computing on graphics pro-cessing units (GPUs)

CMS HLT data streams





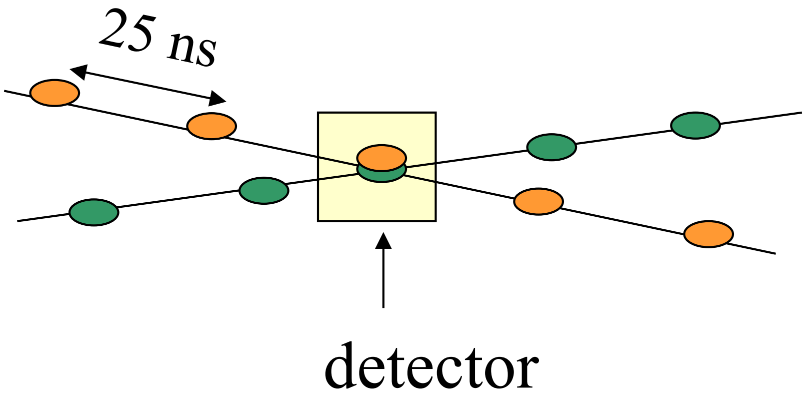
- In the second step, CMS software trigger, **High Level Trigger** (HLT), reconstructs the events selected by L1T
  - Capacity increased by 20% in 2024
  - GPU-accelerated reconstruction in O(100 ms) per event
  - Increasingly ML-based object identification
- **Record-high rates of events stored in 2024:**



  - **~2 kHz** for prompt reconstruction (twice the design value)
  - **~5 kHz** for opportunistic reconstruction ("**parking**")
  - **~27 kHz** for **HLT Scouting** i.e. analysis with HLT-reconstructed events and objects

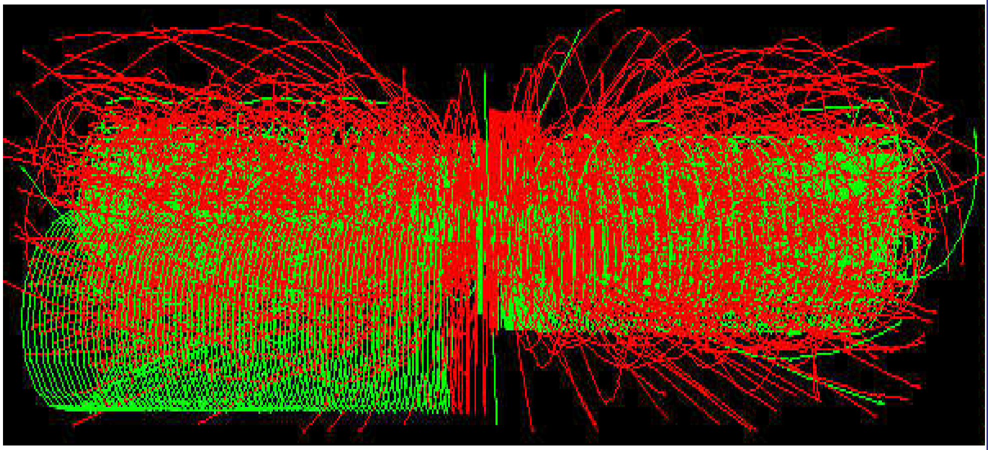
2025:
~3 kHz
~6 kHz
~30 kHz

Typical of LHC:
protons grouped in bunches (of ~ few 10^{11} protons) crossing each other at the interaction points every 25 ns

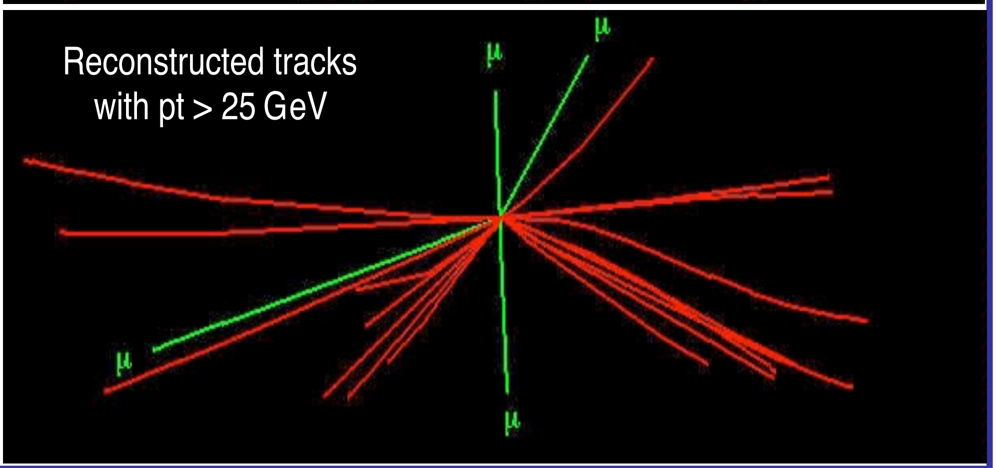


⇒ at each beam crossing ~ 50-60 minimum-bias events are produced at $L \approx$ few 10^{34} $cm^{-2}s^{-1}$. these overlap with high p_T physics events, giving rise to so-called pile-up

~ 3000 charged particles in the detectors however most particles have low p_T



example: a $H \to ZZ$; $Z \to \mu^+\mu^-$ at $L = 10^{+34}$ $cm^{-2}s^{-1}$



trick: focus on high p_T particles

Pile-up, a very serious experimental difficulty at LHC

Large impact on detector design:

- LHC detectors must have fast response, otherwise integrate over many bunch crossings → too large pile-up

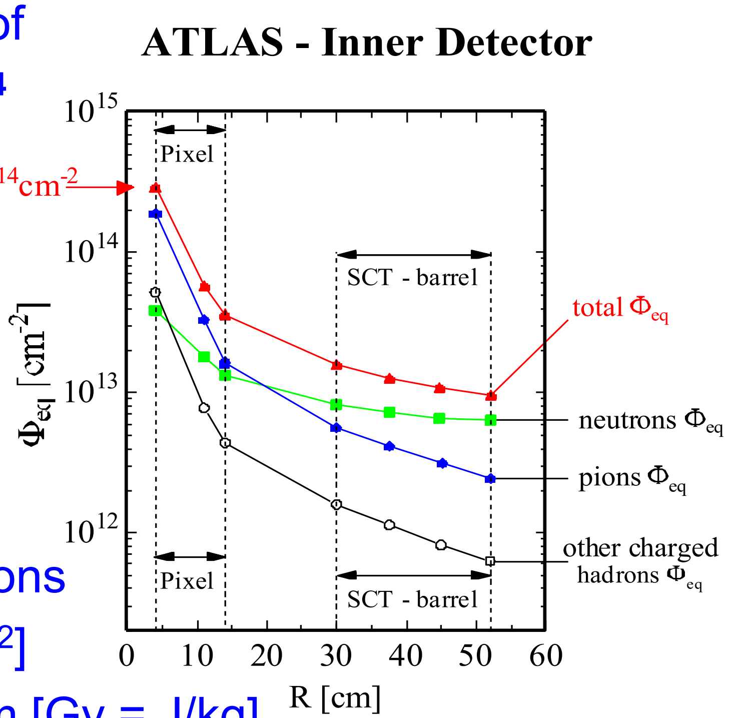
Typical response time : 15-50 ns → integrate over 1-2 bunch crossings → pile-up of ~ 50-120 minimum bias ⇒ very challenging for readout electronics

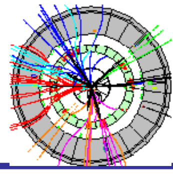
- LHC detectors must be highly granular to minimize probability that pile-up particles are in the same sensitive detector element as interesting object (e.g. γ from H → γγ) → large number of electronic channels ⇒ high cost

- LHC detectors must be radiation resistant: high flux of particles from pp collisions → high radiation environment

Fluence of different type of particles in 1 year at 10^{+34} cm^{-2} s^{-1} in ATLAS silicon tracker as function of distance to collsion vertex. Innermost pixel layer (at 4 cm) survives ~3 years with current technology. Some definitions

- fluence: $\Phi = N_{part}/A$ [cm^{-2}]
- dose: D = deposited E/m [Gy = J/kg]





Keyword: large event statistics

Expected event rates in ATLAS & CMS for representative (both known & new) physics processes at current high luminosity running ($\mathcal{L} \approx 2 \cdot 10^{34}$ cm^{-2} s^{-1})

Process	Events/s	Events/year	Other machines (total statistics)
$W \to e\nu$	300	10^9	10^4 LEP / 10^7 Tev.
$Z \to ee$	30	10^8	10^7 LEP
$t\bar{t}$	16	$5 \cdot 10^7$	10^4 Tevatron
$b\bar{b}$	10^6	few 10^{12}	10^8 B-factories
$\tilde{g}\tilde{g}$ ($m_{gluino} = 1$ TeV)	0.02	$5 \cdot 10^4$	—
H ($m_H = 125$ GeV)	~ 1	few 10^6	10^4 Tevatron
QCD jets $p_T > 200$ GeV	10^3	few 10^9	10^7 Tevatron

High lumi LHC ($\sim 5 \cdot 10^{35}$ cm^{-2}s^{-1}): statistics 2.5 times larger

→ LHC is a B-factory, top factory, W/Z factory, Higgs factory, etc…. (the difficult challenge is to extract the signal) top quark (t) discovered by the CDF and D∅ experiments at the Tevatron in 1995 ($SU(2)_L$ partner of the b quark)

a most intriguing fermion : $m_{top} \approx$ 172.6 GeV (heaviest known fundamental particle, $\times$ 40 heavier than b quark) $\rightarrow$ clues about origin of particle masses ($h_{top} = m_{top}/v_{EW} \sim 1$)

top decays instanteneously and almost exclusively to Wb

$\Gamma\,(t \rightarrow Wb) \sim$ 1.5 GeV » Λ_{QCD}

- top decay a (almost?) pure electroweak process
- no hadronization (no T mesons, “toponium”?)

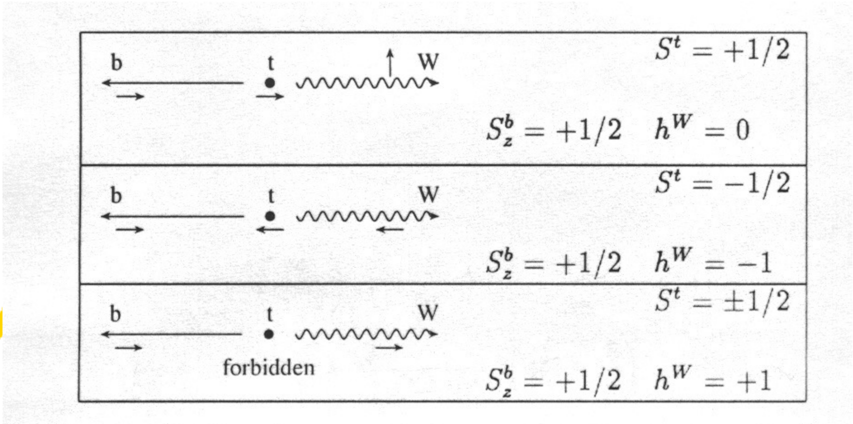
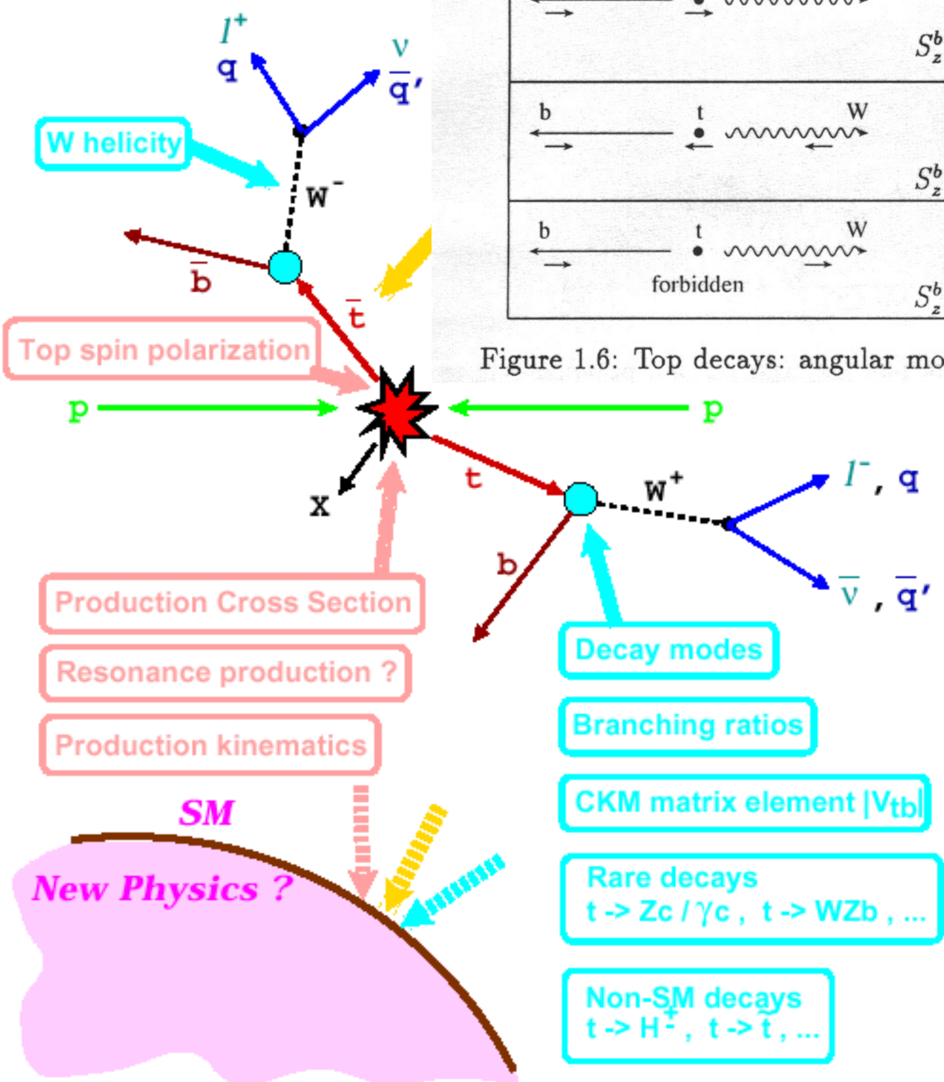


Figure 1.6: Top decays: angular momentum conservation

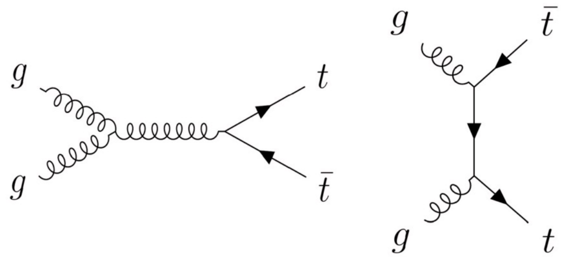


polarisation of the top quark transmitted to the W-boson

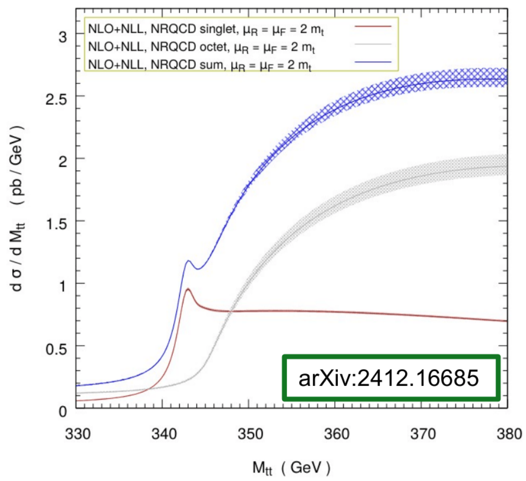
”toponium” = a bound state of a top and antitop quark

Top Quark QCD Production

Top quark production @ LHC dominated by pair production via QCD diagrams: 830-880 pb @ $\sqrt{s}$ = 13-13.6 TeV



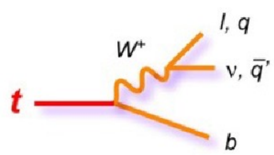
- color octet ($^1S_0[8]$ or $^3S_1[8]$) - repulsive
  → contributions small below threshold
- color singlet ($^1S_0[1]$) - attractive
  → peak below the $t\bar{t}$ threshold



Top Pair Decay Channels

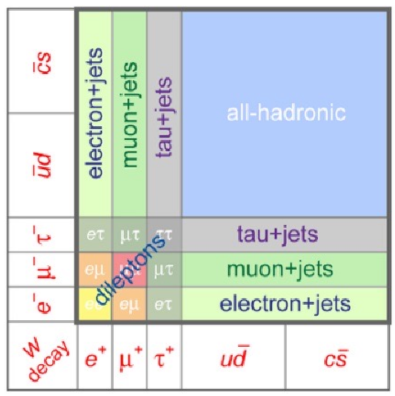
In the SM the top quark decays exclusively into a W boson and a b quark

$\mathcal{B}(t \to Wb) \simeq 100\%$

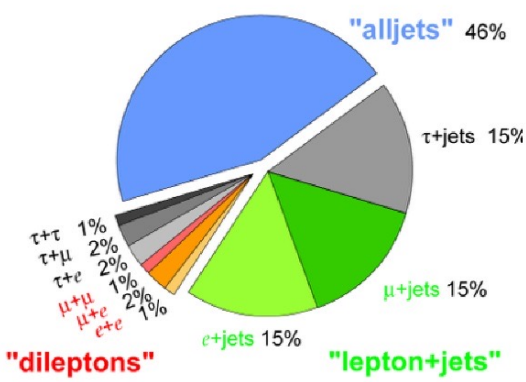


the branching fractions of the t-tbar final states depend on the W boson branching fractions

Top Pair Decay Channels



Top Pair Branching Fractions



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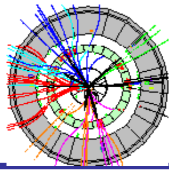
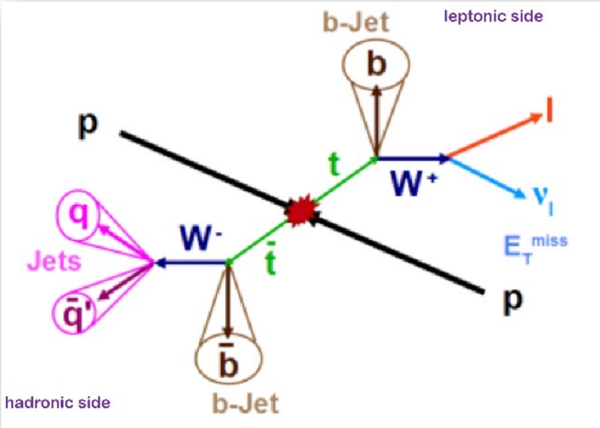


Lepton+Jets

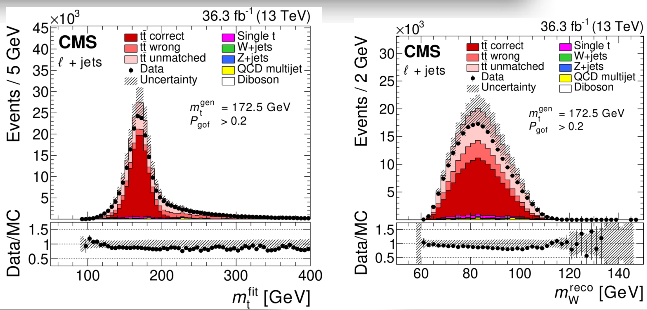


Golden mode at the LHC

- High rate: 30% of top pairs
- Low backgrounds: S/B>1
- W reconstructed in hadronic channel
  in situ constraint of jet energy scale
- full reconstruction of the top quark on the hadronic side
  direct mass measurement

But

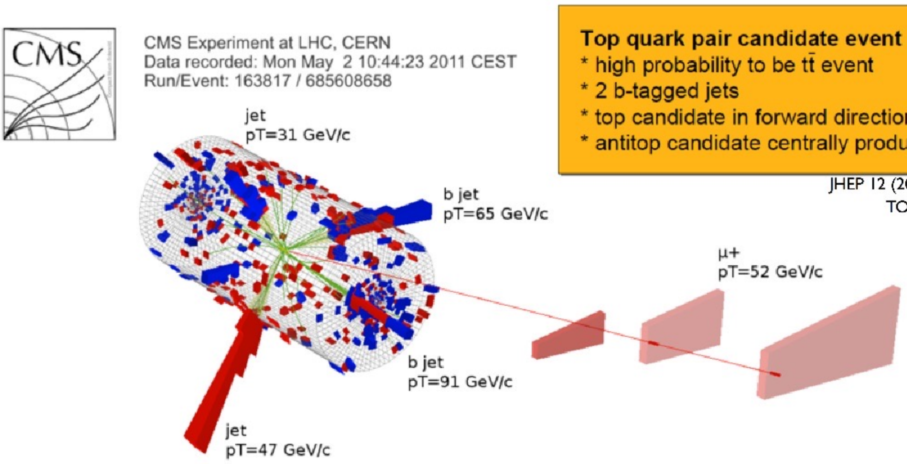
- large combinatorics
  reduced by efficient b-tagging
  and good di-jet mass resolution



Reconstructed top mass improved significantly by profile likelihood fit

7

Lepton+Jets Event Selection



Top quark pair candidate event
* high probability to be $t\bar{t}$ event
* 2 b-tagged jets
* top candidate in forward direction
* antitop candidate centrally produced

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TOP-14-001

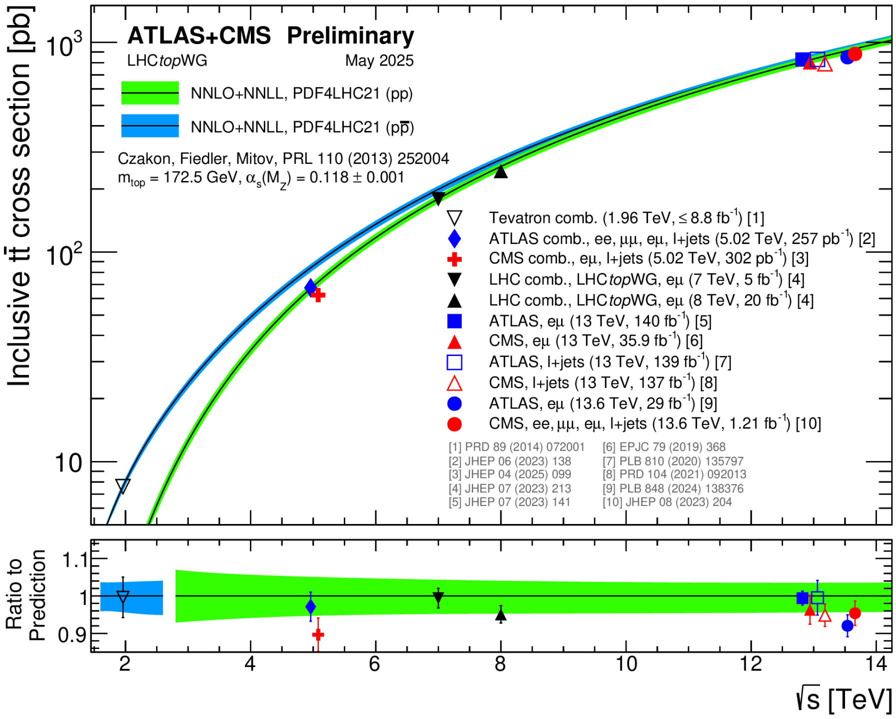
Typical event selection

- trigger lepton + jets
- exactly one lepton p_T > 30 GeV and and $|\eta|$ < 2.1
- ≥ 4 jets with p_T > 30 GeV and $|\eta|$ < 2.4
- 2 b-tagged jets among the 4 leading jets

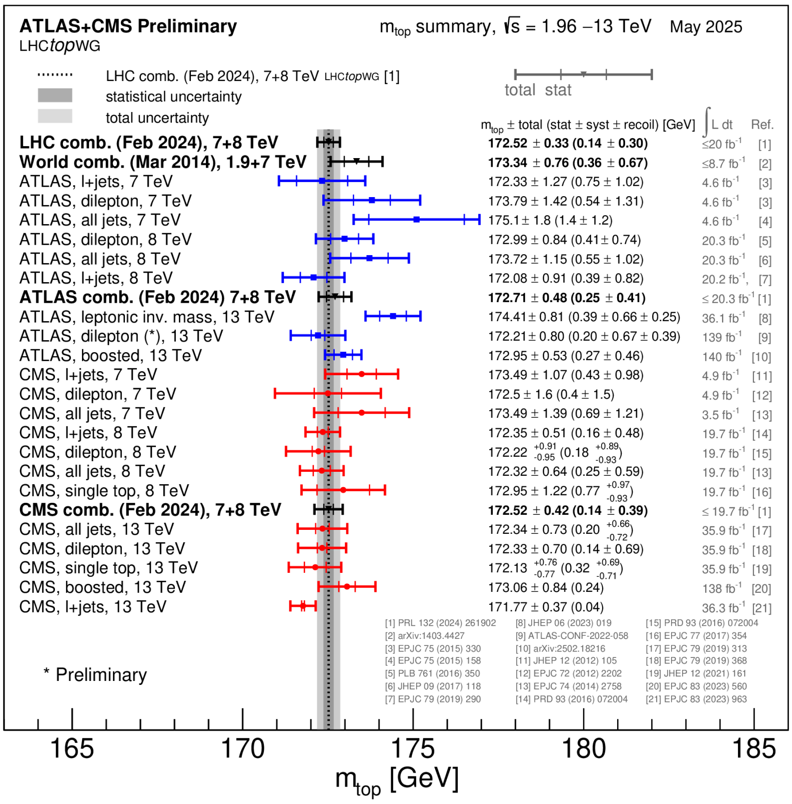
8

Top quark mass

Production cross section



Summary of Mass Measurements



PDG:
$m_t = 172.56 \pm 0.31$ GeV

ATLAS:
$m_t = 172.71 \pm 0.48$ GeV

CMS:
$m_t = 172.52 \pm 0.42$ GeV

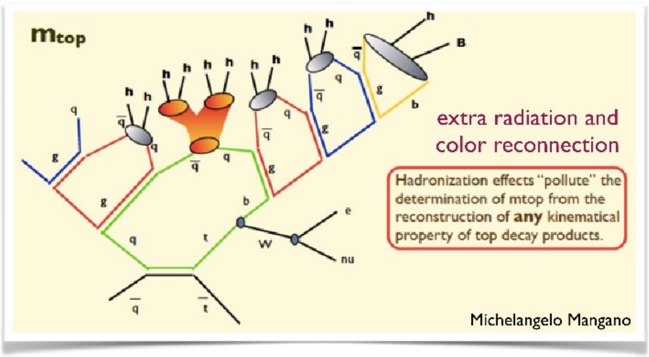
- excellent agreement between ATLAS and CMS

What Mass for the EW fit?

The definition of the mass of the top quark is ill-defined

- the mass measured from bW decay products is assumed to be close from pole m_{pole}
- problem: m_{pole} for a coloured particle cannot be determined with accuracy better than Λ_{QCD} ($\approx$ 0.2 GeV)
- the top quark decays before hadronising but still the b quark has to hadronise

Which final state particles to assign to the original top quark?

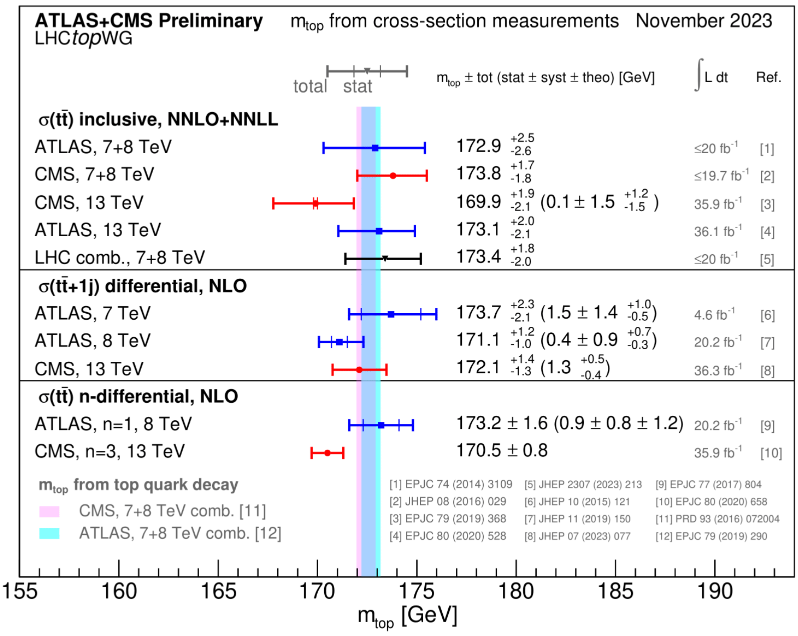


- Importance of measuring the mass using alternate techniques
  - mass and end point of bℓ spectrum
  - decay length (boost) of B hadrons

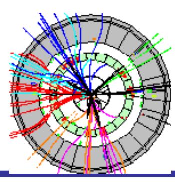
theoretically a good approach is to extract the mass from measurements of the cross section

Mass from Cross Section

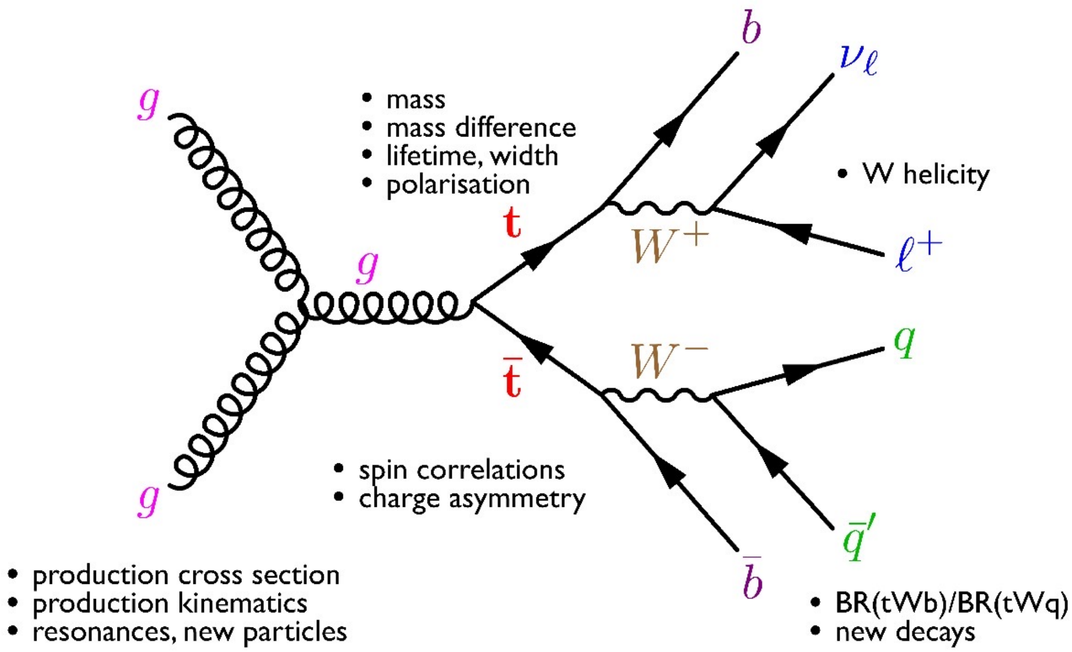
- use the best x-section measurement (dilepton)
- use most recent NNLO calculations of top pair x-section to extract m_t
- also provide a measurement of the strong coupling constant at m_t



PDG:
m_t = 172.4 $\pm$ 0.7 GeV

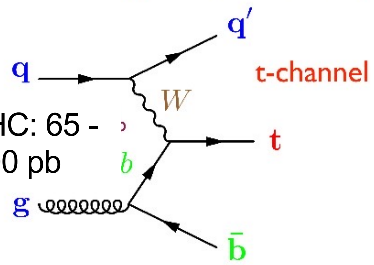


Top Quark Properties

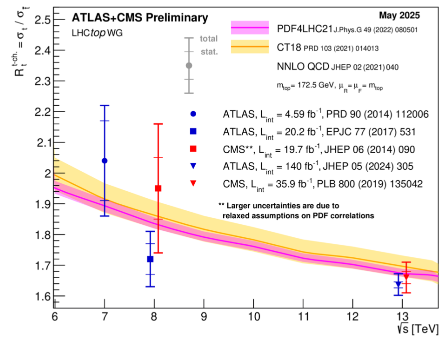


Electroweak Production: Single Top

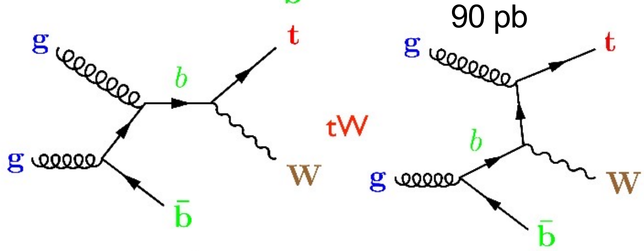
EW production of a top quark

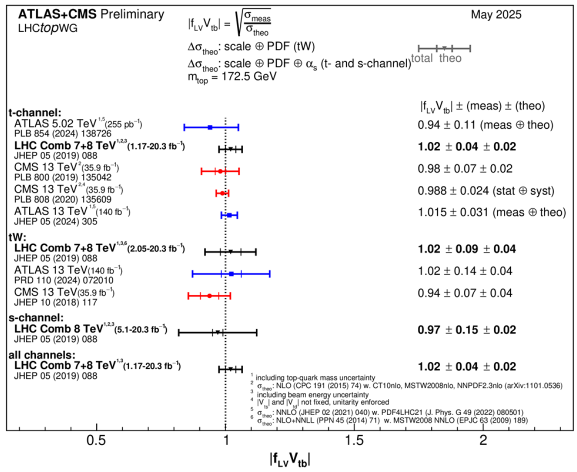


LHC: 65 - 200 pb

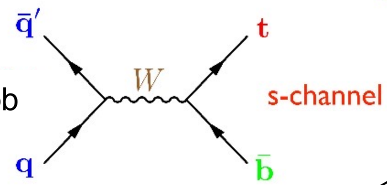


LHC: 15 - 90 pb





LHC: 5 -10 pb



allows direct measurement of V_{tb}

Electroweak precision measurements:

$$m_W = \left(\frac{\pi \alpha_{EM}}{\sqrt{2}\, G_F} \right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}} \longleftarrow \propto m_{top}^2 \,\&\, \ln(m_H^2)$$

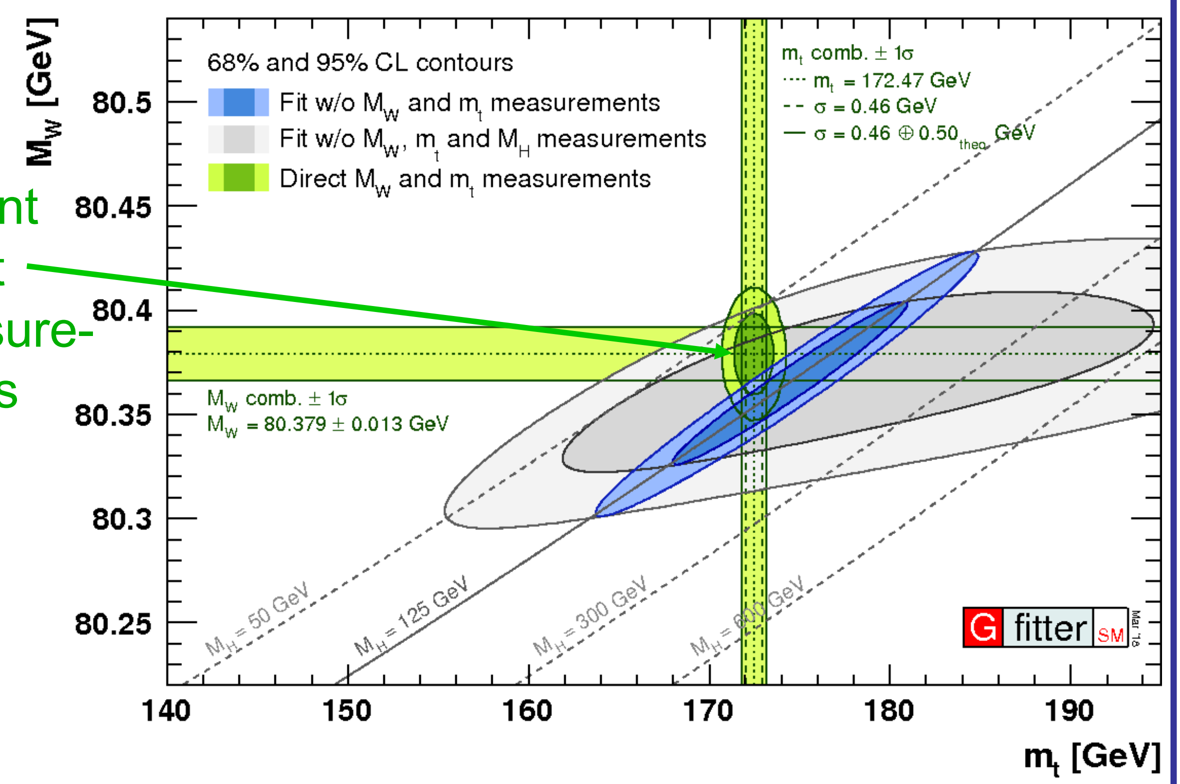
since G_F, α_{em}, $\sin\theta_W$ are known with high precision, precise measurements of m_{top} & m_W constrain radiative corrections & Higgs mass (weakly due logarithmic dependence)

m_W (LEP2/Tevatron/LHC) = 80.369 ± 0.013 GeV — $2\cdot10^{-4}$

m_{top} (Tevatron/LHC) = 172.52 ± 0.33 GeV — $3\cdot10^{-3}$

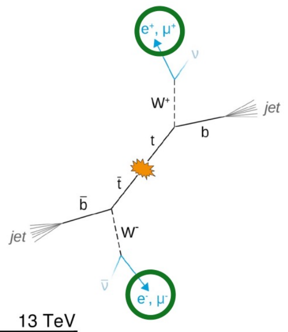
ultimate Standard Model test: compare direct Higgs mass with radiative correction prediction.

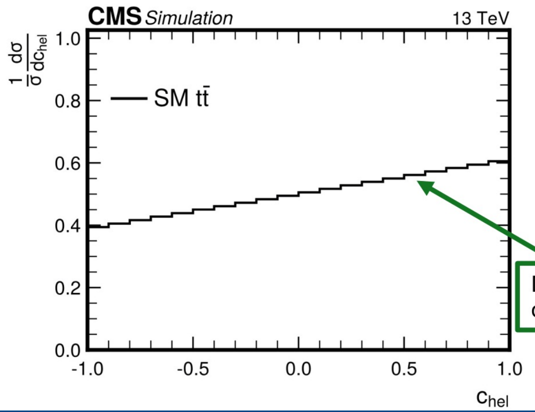
current direct measure-ments



Quantum entanglement at tt̄ threshold

- idea:
  - lepton directions perfectly correlated with top spin
  - measure spin correlation strength (D) from cosine of opening angle (c_{hel}) of charged leptons in parent top rest frames

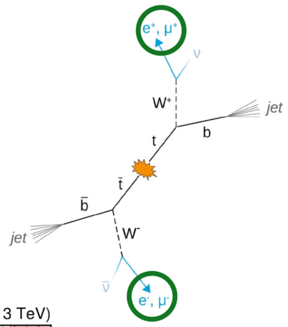




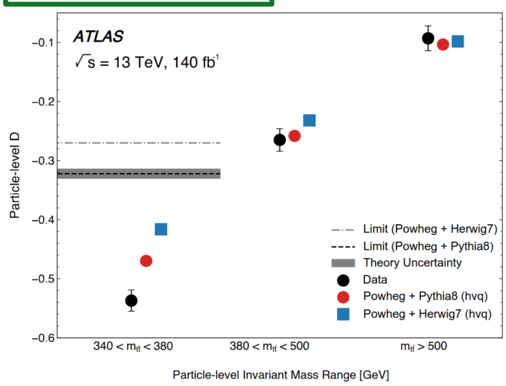
Quantum entanglement at tt̄ threshold

- idea:
  - lepton directions perfectly correlated with top spin
  - measure spin correlation strength (D) from cosine of opening angle (c_{hel}) of charged leptons in parent top rest frames

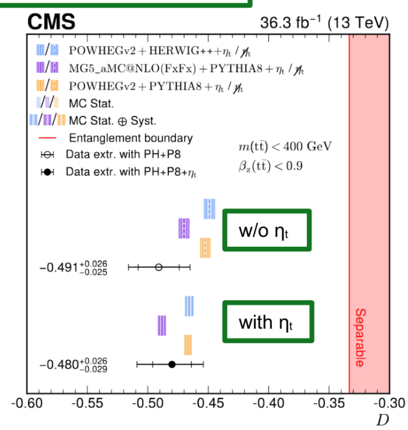
  - Peres-Horodecki-Criterion:
    D < -1/3 proofs entangled tops (assuming QM)



Nature 633 (2024) 542



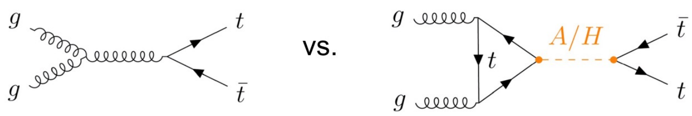
RPP 87 (2024) 117801

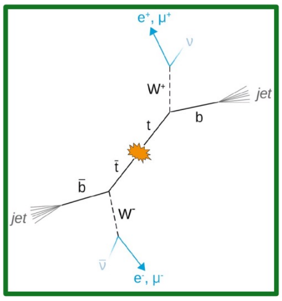


Improved description of data considering tt̄ quasi-bound states

A closer look at the $t\bar{t}$ threshold

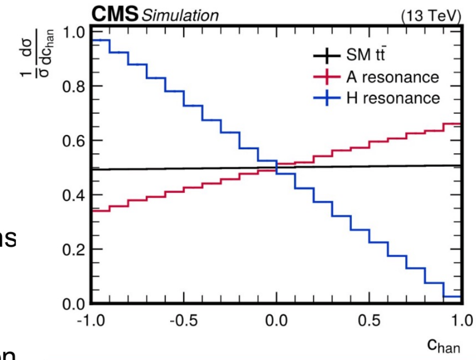
- explore differences in production mode
  - distinguish $t\bar{t}$ continuum from pure (pseudo)scalar states





  - distinguish $^1S_0$ (A/η_t) from $^3P_0$ (H) $t\bar{t}$ states

→ spin correlation observables!
  - direction of down-type fermion fully correlated with parent top quark spin
  - easiest in the dilepton channel



- c_{hel}: cosine of opening angle between charged leptons in parent top quark rest frames
- c_{han}: as c_{hel} but inverted component along top direction

3 search variables: $m_{t\bar{t}}$ x c_{hel} x c_{han}

Extracting η_t cross section

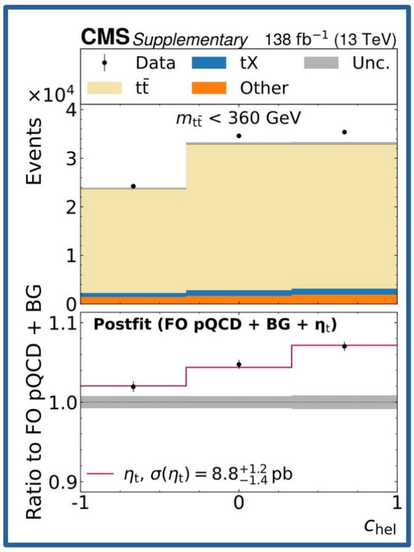
RPP 88 (2025) 087801

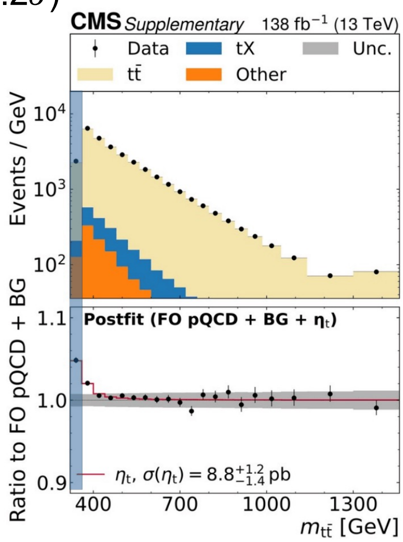
- profile-likelihood fit to 20 bins of $m_{t\bar{t}}$ x 3 bins of c_{hel} x 3 bins of c_{han}

Confirmed by ATLAS

$\sigma(\eta_t)$ = 8.8 ± 0.5 (stat) $^{+1.1}_{-1.3}$ (syst) pb = 8.8 $^{+1.2}_{-1.4}$ pb

(> 6.2σ)



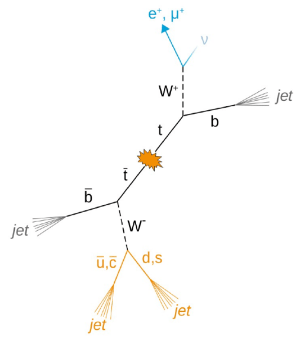


Toponium or new pseudo-scalar? Indistin-guable but SM expla-nation (toponium) seems more pausible.

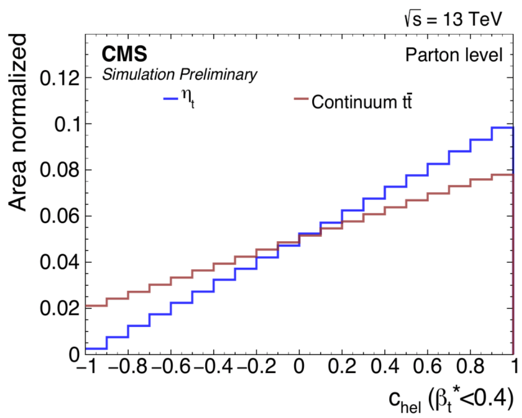
Excess from $t\bar{t}$ in $^1S_0$ state

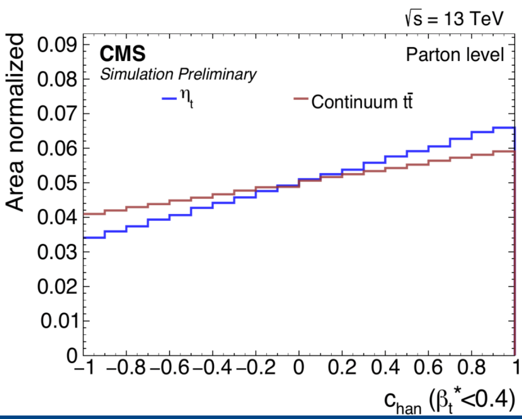
First studies of the $t\bar{t}$ threshold in lepton+jets final states

- results based on 138 fb^{-1} of e/μ + jets events recorded at 13 TeV



- probe relative velocity β_t^*:
  - |**p**|/E of leptonic top in ZMF of hadronic top
- combine with spin and parity sensitive observables c_{hel} and c_{han}



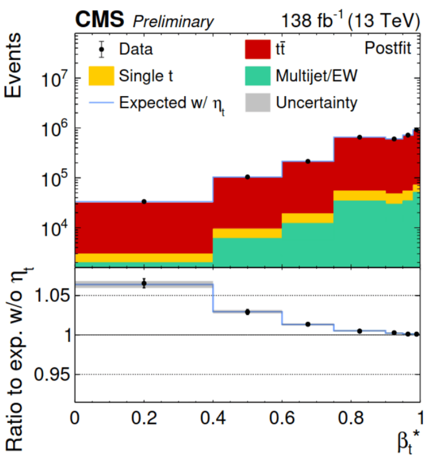


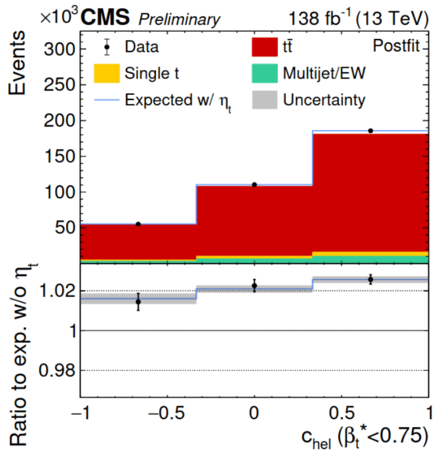
Signal extraction

CMS-PAS-TOP-25-002

- perform fit in 16 categories
  - one or two b-tagged jets
  - low or high value of S_{NN}
  - four data taking periods
- use 7 β_t^* x 3 c_{hel} x 3 c_{han} bins

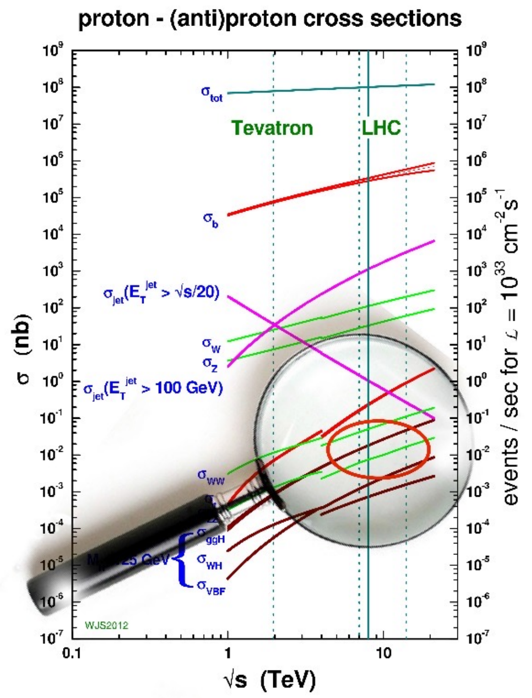
$\sigma(\eta_t)$ = 5.1 ± 0.9 pb (> 6 σ SD)

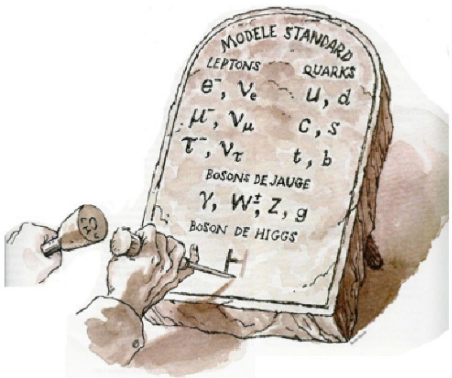




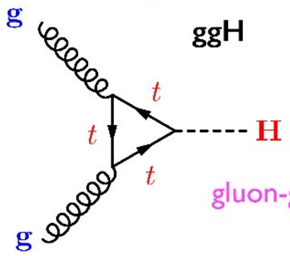
Spin correlation well described

Higgs Physics



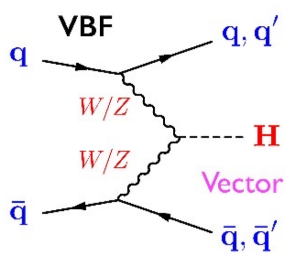


Production of the Higgs Boson



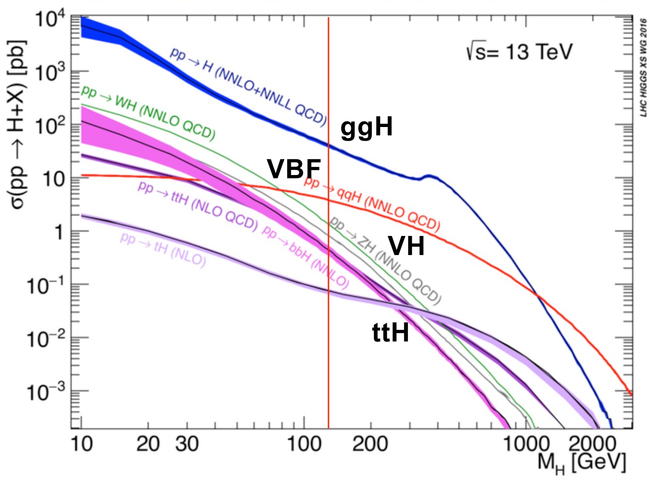
87%

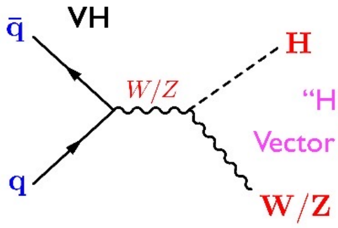
gluon-gluon Fusion



7%

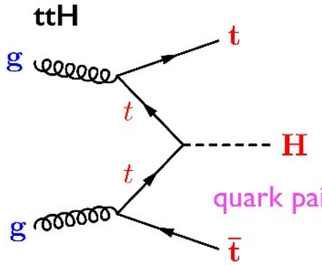
Vector Boson Fusion





4%

"Higgsstrahlung"
Vector Boson associated



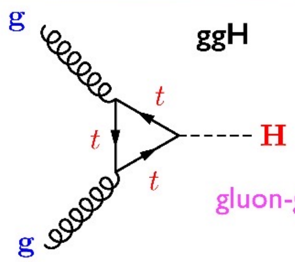
1%

quark pair associated

18

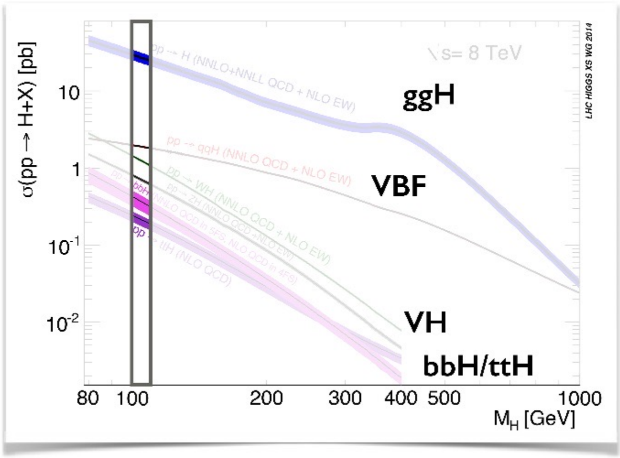
Higgs production & decay

Production of the Higgs Boson



87%

gluon-gluon Fusion



Cross sections (m_H = 125 GeV)

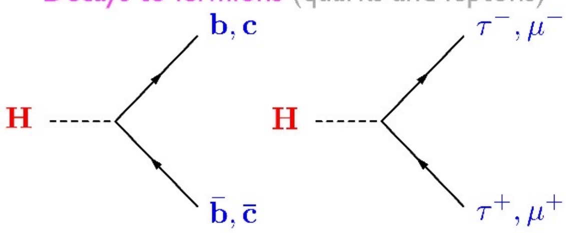
- Tevatron 1.96 TeV
  1.2 pb
  ggH=78% VH=17% VBF=5%
- LHC 8 TeV
  23 pb
  ggH=86% VBF=7% VH=5% ttH<1%
- LHC 13 TeV
  51 pb
  ggH=86% VBF=7% VH=4% ttH=1%

Typical theory uncertainties

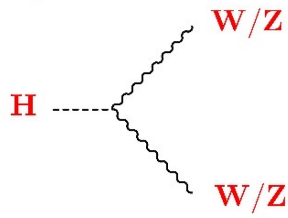
- ggH 15% NNnLO
- VBF 5% NLO
- VH 5% NNLO
- ttH 15% LO

Decays of the Higgs Boson

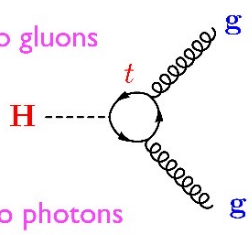
Decays to fermions (quarks and leptons)



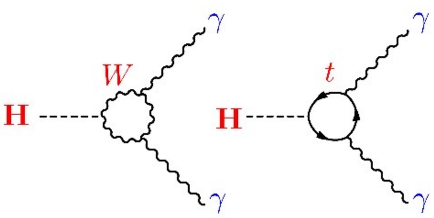
Decays to EW vector bosons

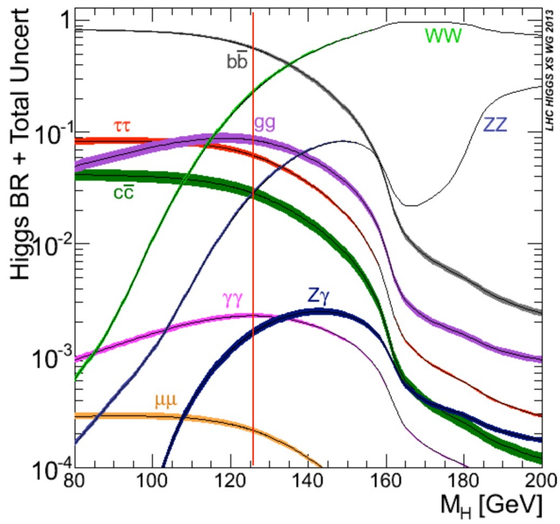


Decay to gluons



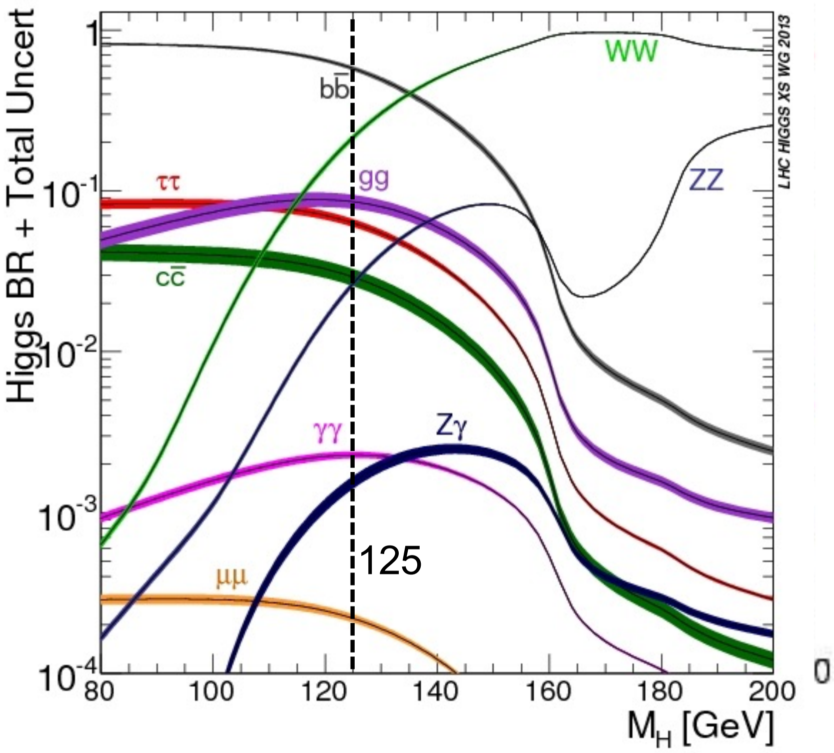
Decay to photons





Higgs decay branching ratios

"Higgs couples to mass"



BR(%)	Higgs 125 GeV	Z boson
$q\bar{q}$		70
$b\bar{b}$	58.2	15
$c\bar{c}$	2.9	12
gg	8.2	0
$\ell^+\ell^-$	0.022 (μ)	10
$\tau^+\tau^-$	6.3	3
γγ	0.23	
W*W*	21.4	
Z*Z*	2.6	

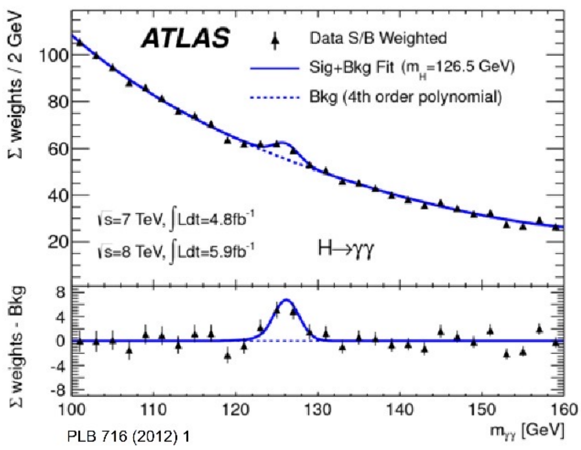
$$\beta_f \equiv \sqrt{1 - \frac{4m_f^2}{m_H^2}}$$

at 1st order: $\Gamma\left(H \to f\bar{f}\right) = \frac{N_c^f G_F m_f^2}{4\sqrt{2}\pi} m_H \beta_f^3$

where β_f is the fermion velocity in the decay.

CERN 4 July 2012

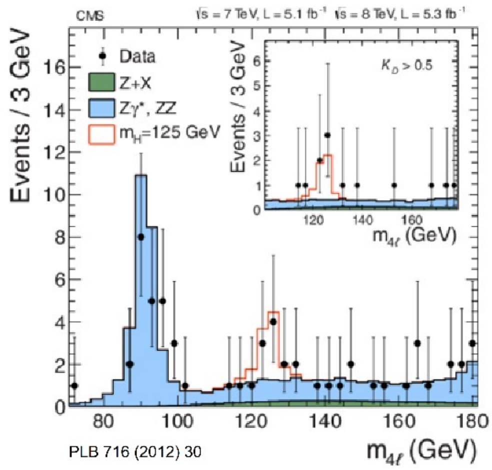
The Discovery



PLB 716 (2012) 1

m_H = 126.0 ± 0.4 (stat) ± 0.4 (syst) GeV

Combined significance: 5.9σ



PLB 716 (2012) 30

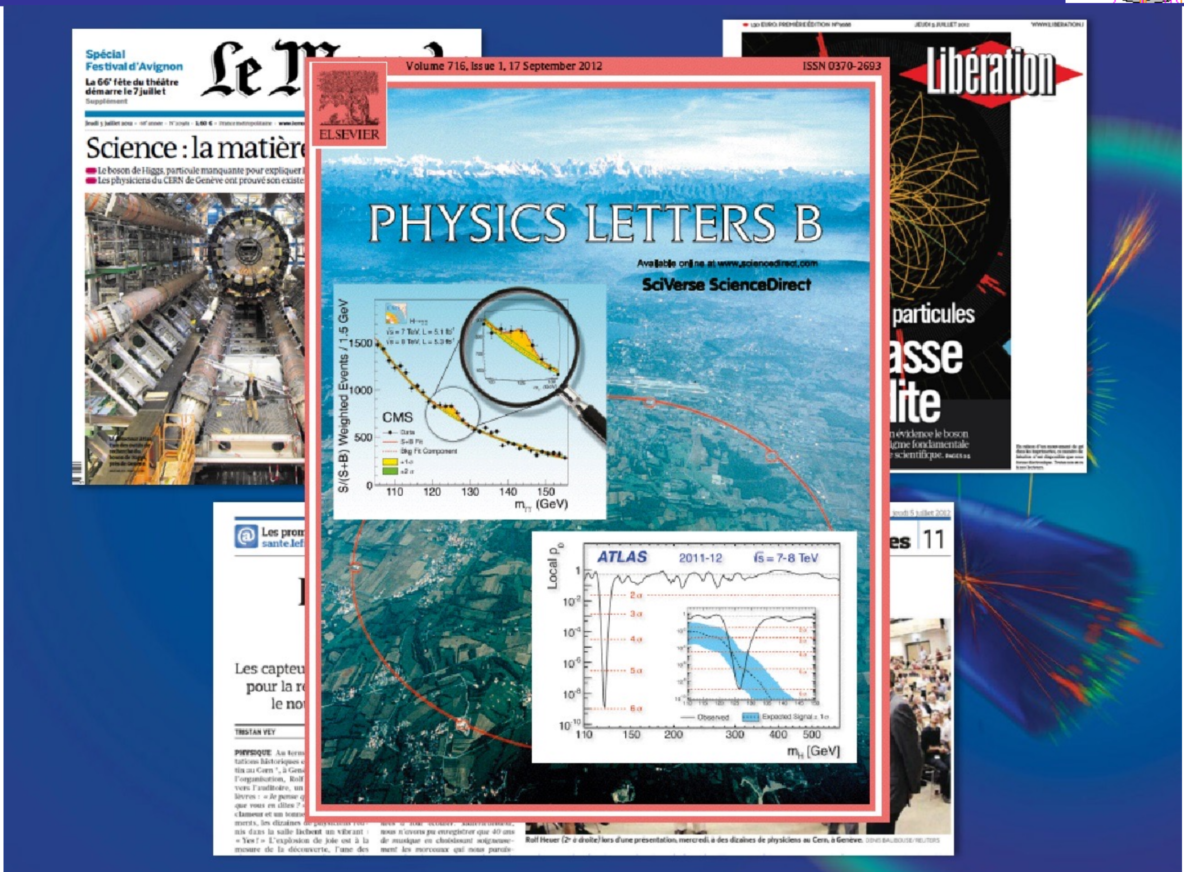
m_H = 125.3 ± 0.4 (stat) ± 0.5 (syst) GeV

Combined significance: 5.0σ

Three decay mode WW, ZZ and γγ

Five decay modes analysed but no significance signal in H → ττ and bb

Higgs discovery



LHC: Production and Decay

Not an exhaustive table!

★ "seen" ☆ "tried"	H→bb	H→ττ	H→WW	H→ZZ	H→γγ	H→inv.	H→μμ	Σ H→xx
ggH		★	★	★	★		☆	
VBF	☆	★	★	☆	★	☆	☆	
VH	★	☆	☆	☆	☆	☆		
ttH	☆	☆	☆		☆			★
	$\sigma(m_{bb})$ ~20%	$\sigma(m_{\tau\tau})$ 10-20%	$\sigma(m_{WW})$ ~16%	$\sigma(m_{ZZ})$ 1-2%	$\sigma(m_{\gamma\gamma})$ 1-2%			

courtesy André David

Run-I (25 fb^{-1} at 7 and 8 TeV):
Approximate number of Higgs boson decays before selection cuts (m_H = 125 GeV)

- 9,000 H → WW* → $\ell\nu\ell\nu$
- 900 H → γγ
- 60 H → ZZ* → 4ℓ

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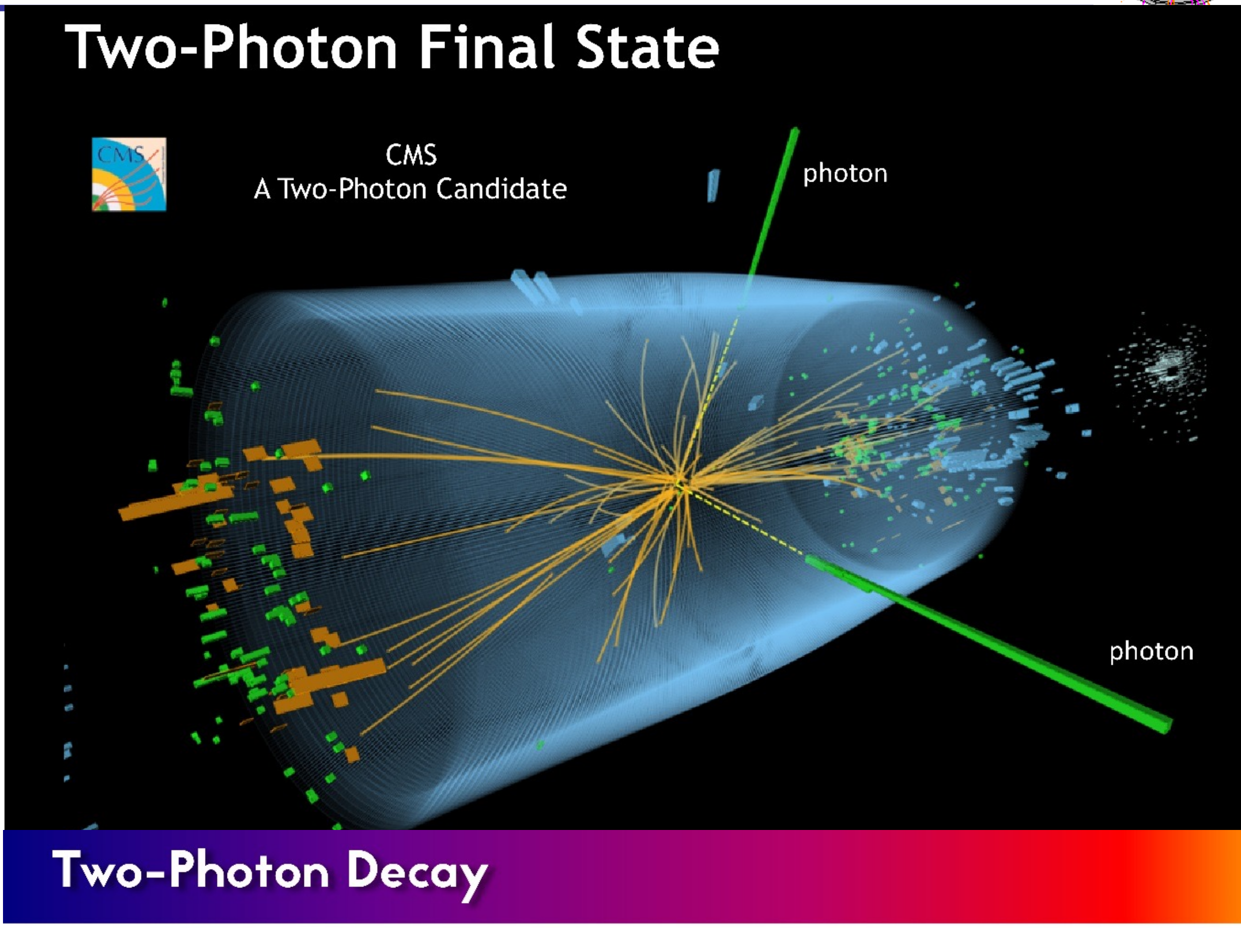
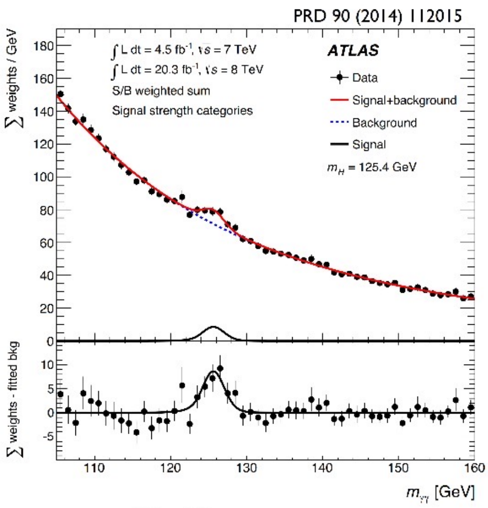


ATLAS

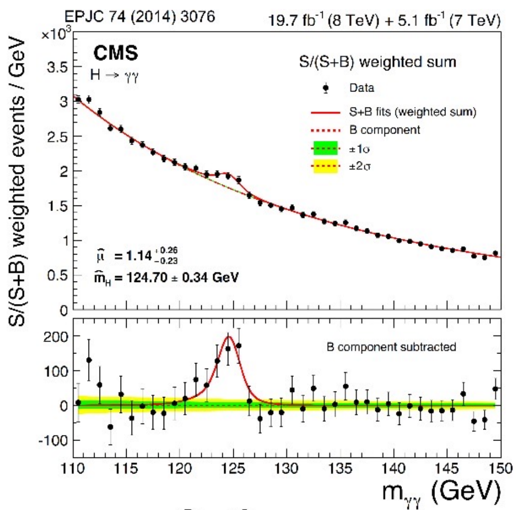


Significance

- observed : **5.2 σ**
- expected: 4.6σ

m_H = 126.02 ± 0.43 (stat) ± 0.27 (syst) GeV

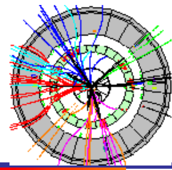
CMS



Significance

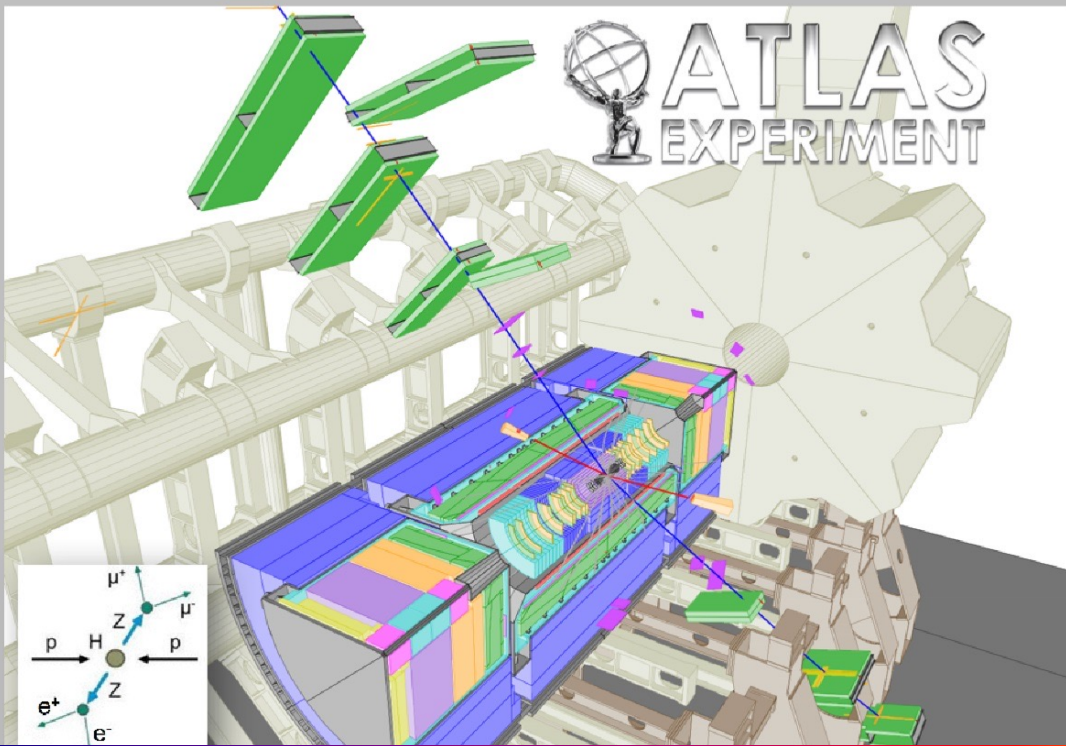
- observed : **5.7 σ**
- expected: 5.2σ

m_H = 124.70 ± 0.31 (stat) ± 0.15 (syst) GeV



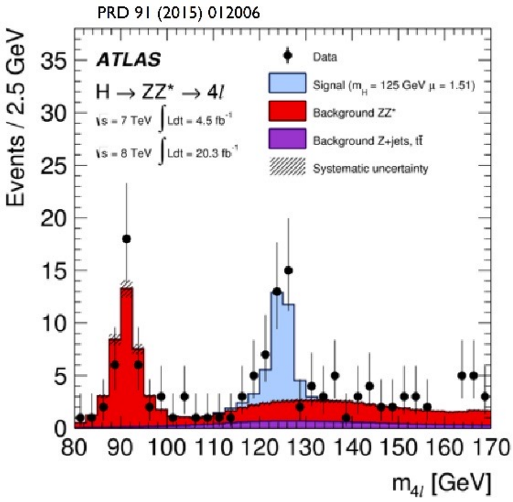
H → ZZ*

Four-Lepton Mode



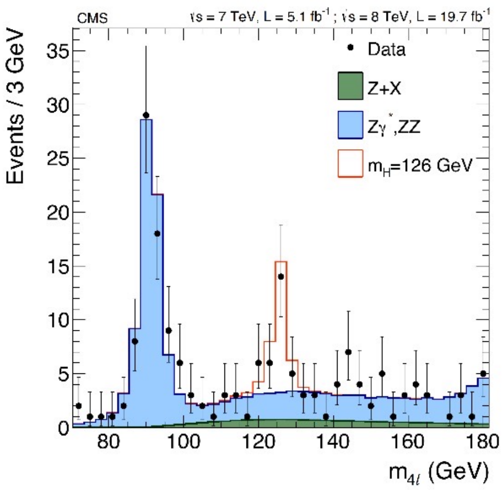
Four-Lepton Decay

ATLAS



m_H = 124.51 ± 0.52 (stat) ± 0.04 (syst) GeV

CMS



m_H = 125.59 ± 0.45 (stat) ± 0.17 (syst) GeV

Both experiments observe signals with > 6σ

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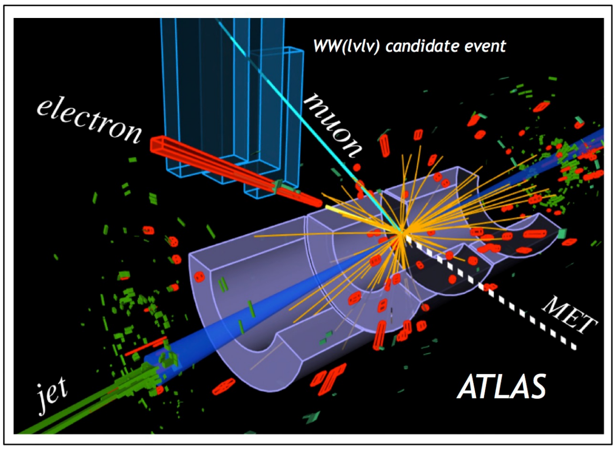
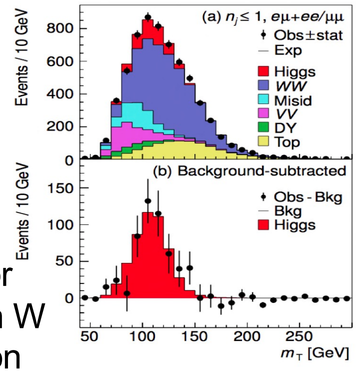
The Discovery Channels

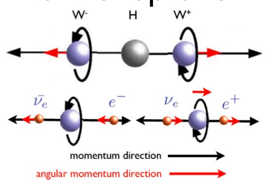
A discovery channel of a different kind: the WW

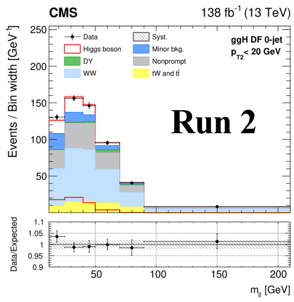


Requires good simulation of backgroinds and control regions in the data.

Uses V-A nature of W coupling that transfers the W spin correlation to the leptons.







For hadronic W decay channels very poor S/N ratio, a bit better S/N ratio when both W decays leptonically but mass recontruction spoiled by the unmeasured neutrinos.

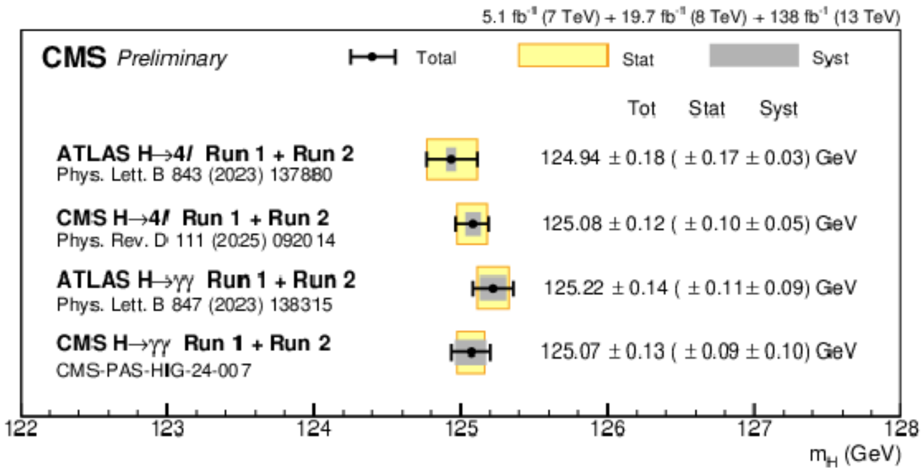
Larger event rates but significant backgrounds from WW and $t\bar{t}$.

⇒ tends to result in a low diilepton invariant mass..

First Precision Measurement at the LHC?

Higgs boson mass measurement

- Measurements done exclusively in categories with best mass resolution (diphoton & 4-lepton channels) to optimize precision.
- In Run 1 already a 0.2 % precision (combined with Run 2 < 0.1 %)



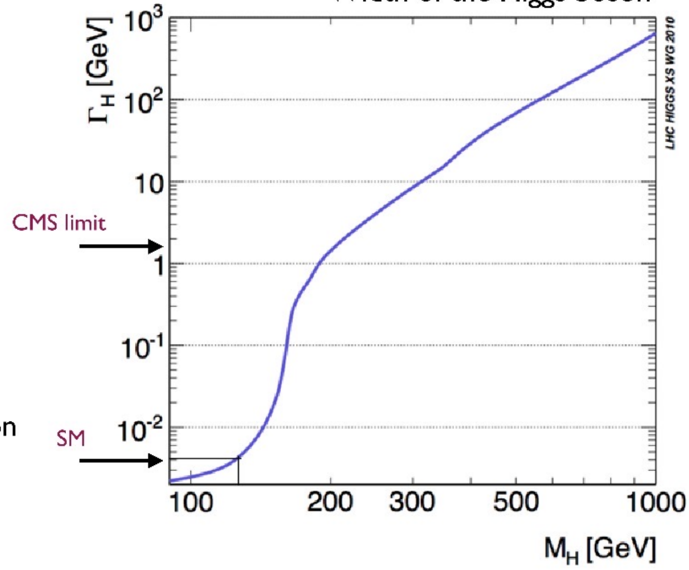
Width of the Higgs Boson

Upper limits on the width can be obtained from the mass peaks (at the level of the experimental resolution)

Width of the Higgs boson

Γ_H < 1.7 GeV (95%CL)

The width of the SM Higgs boson is of the order of 4MeV



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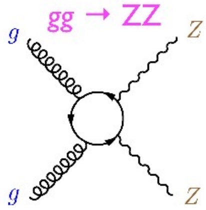
Off-Shell Higgs Boson

ZZ production = $qq \rightarrow ZZ$

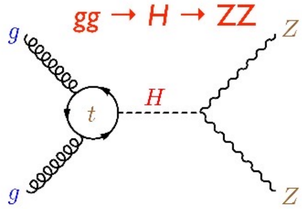
but also

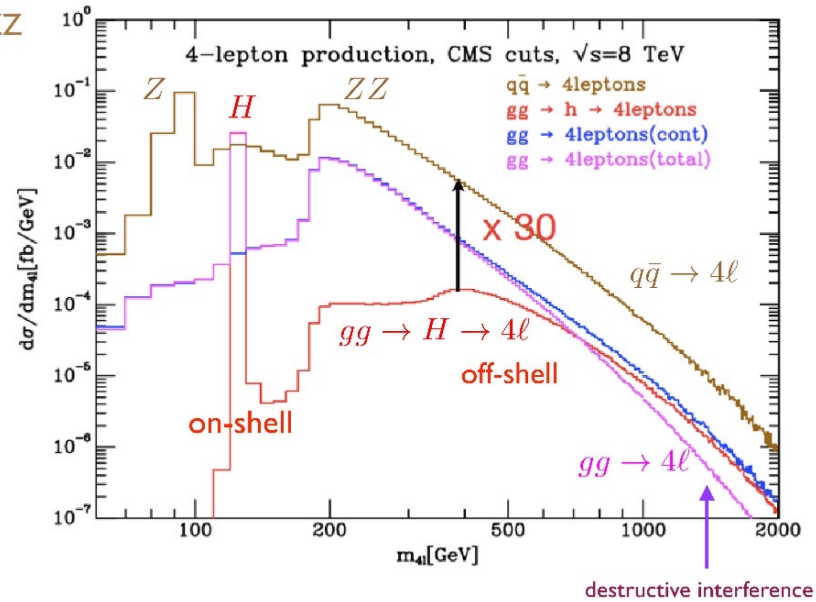
gg → ZZ



and

gg → H → ZZ





$$\frac{\sigma^{\text{off-shell}}_{gg\to H\to ZZ}}{\sigma^{\text{on-shell}}_{gg\to H\to ZZ}} \sim \Gamma_H$$

CMS: $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

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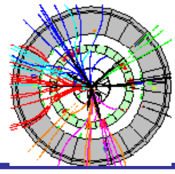


Run 2 Higgs Headlines

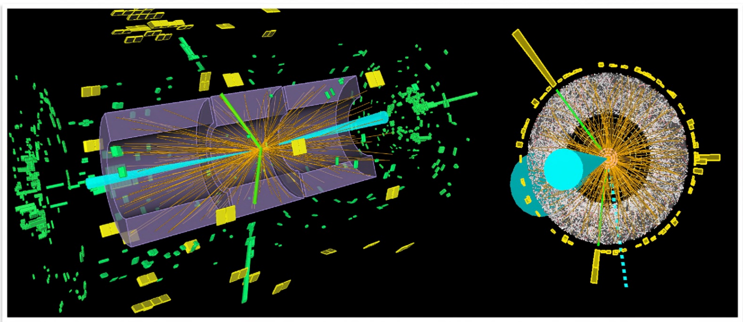
Run 2 Higgs Physics **major milestones** reached: **Third Generation (Charged) Observation Completed!**

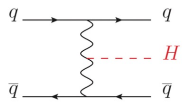
Yukawas at LHC		tau	b	top
ATLAS	Exp. Sig.	5.4 σ	5.5 σ	5.1 σ
	Obs. Sig.	6.4 σ	5.4 σ	6.3 σ
	mu	1.09 $\pm$ 0.35	1.01 $\pm$ 0.20	1.34 $\pm$ 0.21 *
CMS	Exp. Sig.	5.9 σ	5.6 σ	4.2 σ
	Obs. Sig.	5.9 σ	5.5 σ	5.2 σ
	mu	1.09 $\pm$ 0.27 *	1.04 $\pm$ 0.20	1.26 $\pm$ 0.26 **

* 13 TeV only derived from cross section measurements
** Lower uncertainty (upper uncertainty 31)

+ evidence for coupling to second generation: $H \rightarrow \mu^+\mu^-$

Higgs boson decays to Taus & Muons

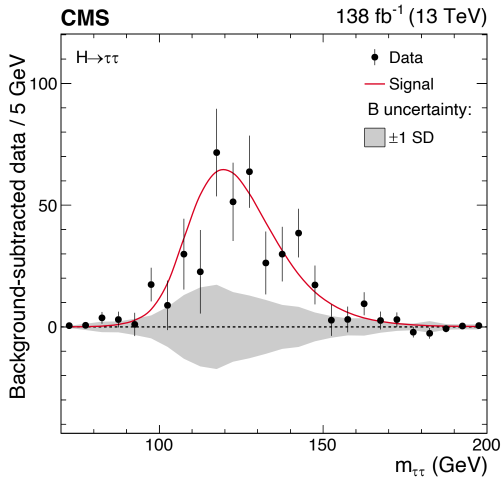


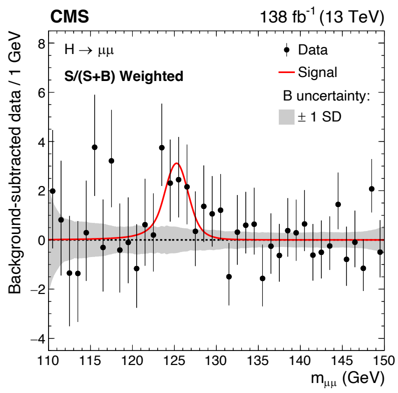


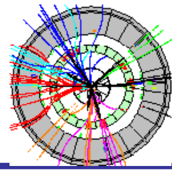
Special VBF process

With two forward jets and a large rapidity gap between the jets (due to the color singlet exchange in the t-channel

Background is Z production with two jets, in this region of phase space it is difficult to predict!



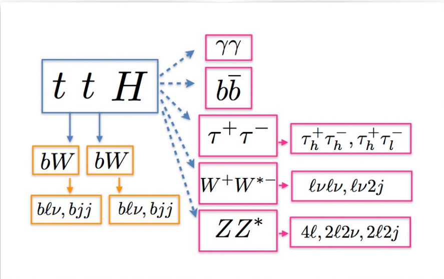




Higgs couplings

Direct probe of the top Yukawa coupling

ttH Analyses at LHC: Massively Complex!



- Large number of final states which are typically very complex (mixture of b-jets, leptons, taus and photons)
- But, many different channels, also means different backgrounds and different systematic uncertainties and therefore also a strength!
- With the new Run at close to double centre-of-mass energy and increased statistics, changes in leading channels.

ttH(bb)

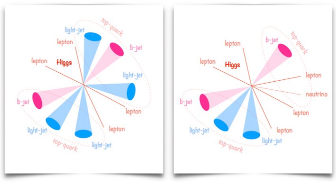
Very large backgrounds of top pair production associated with b jets

Dominated by background modelling uncertainties

ttH(WW, ZZ and tau tau)

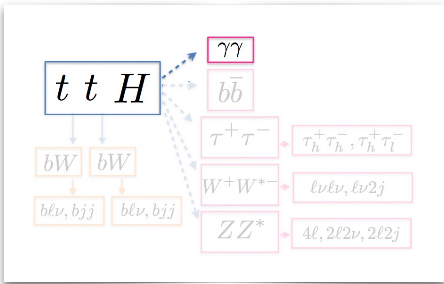
So-called multi-lepton channel

Large number of topologies intricate reducible backgrounds of jets faking leptons.

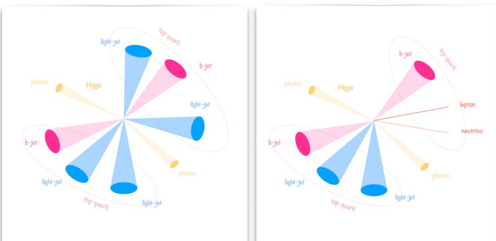


Direct probe of the top Yukawa coupling

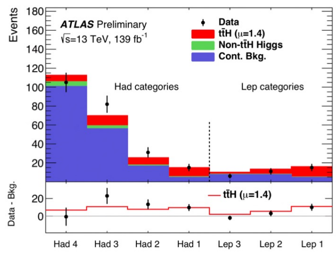
ttH Analyses at LHC: Massively Complex!

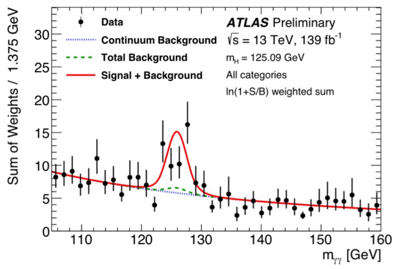


Currently most sensitive channel



Background and signal modelled using analytic functions.





Cross section dominated by statistical uncertainties:

$$1.59^{+0.38}_{-0.36}\,(\text{stat.})\,{}^{+0.15}_{-0.12}\,(\text{exp.})\,{}^{+0.15}_{-0.11}\,(\text{theo.})\ \text{fb}$$

Expected (4.2σ)

Observed 4.9σ

In combination with the other channels:

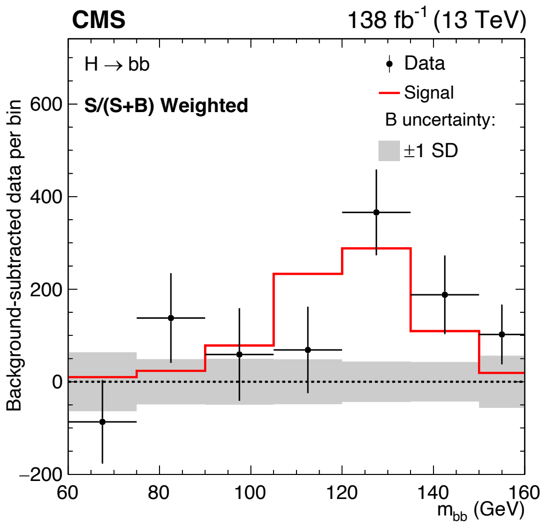
Expected 5.1σ

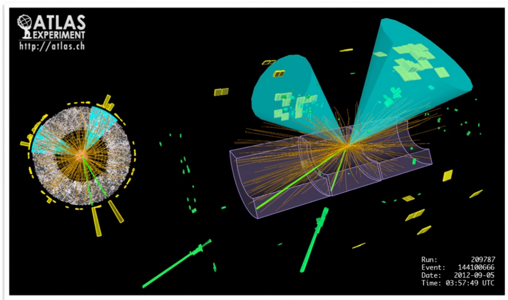
Observed 6.3σ

Observation!!

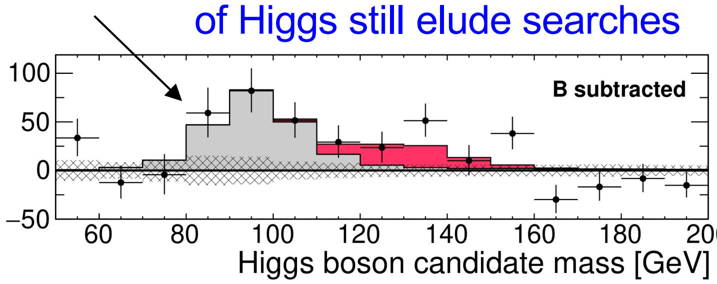
Higgs boson decays to b-quarks & c-quarks

b-quark decay channel of Higgs solidly confirmed





…but c-quark decay channel of Higgs still elude searches



Combination Procedure and Master Formula

What is done in Higgs boson couplings analyses is to count number of signal events in specific production and decay channels.

$$n_s^c = \mu \sum_{i \subset \{\mathrm{prod}\}} \sum_{f \subset \{\mathrm{decay}\}} \mu^i \sigma^i_{SM} \times \mu^f Br^f \times \mathcal{A}^{ifc} \times \varepsilon^{ifs} \times \mathcal{L}$$

Same formula as the total cross section measurement formula

These « mu » or signal strength factors cannot be fitted simultaneously, typical fit models include:

μ	$\mu_{if} = \mu_i \mu_f$	$\mu_i \ (\mu_f = 1)$	$\mu_f \ (\mu_i = 1)$
Extrapolated total cross section	Cross section times branching	Cross sections	Branching fractions

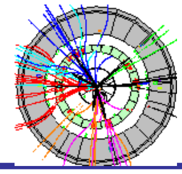
Manifest in this formula why absolute couplings cannot be measured with this procedure: μ_i, μ_f cannot be fitted simultaneously.

Introducing simple scale factors of the Standard Model couplings in a « naive » effective Lagrangian.

$$\mathcal{L} \supset \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu + \kappa_W \frac{m_W^2}{v} W_\mu W^\mu + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} + \sum_f \kappa_f \frac{m_f}{v} f\bar{f}$$

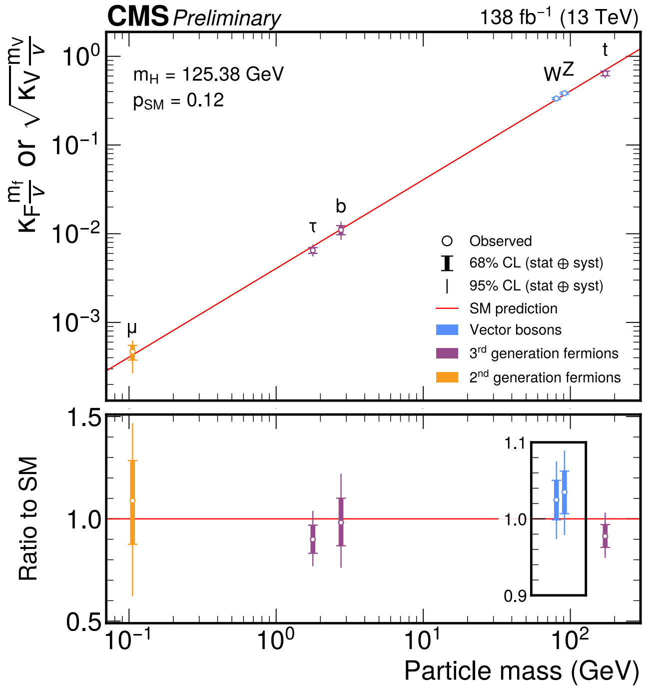
Simply reparametrise the mu values using the kappas!

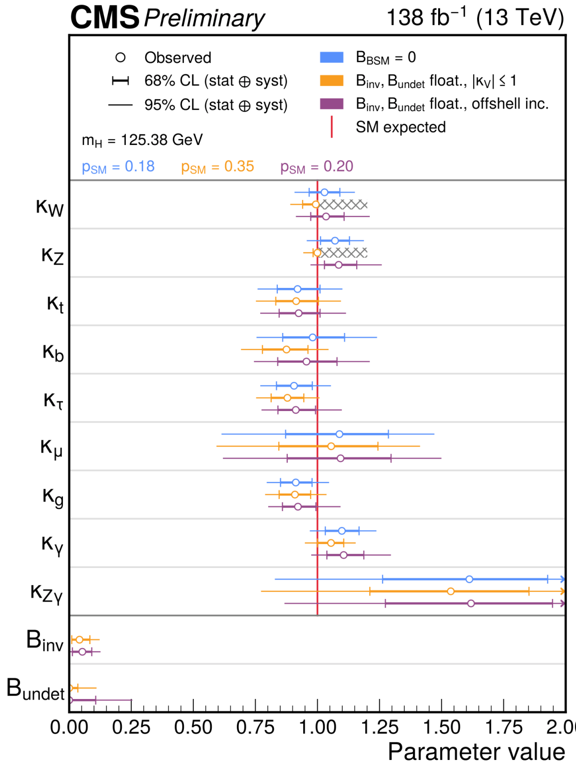
For a complete description see (link) - Chapter 10



Higgs couplings

Run 2 Couplings Measurements

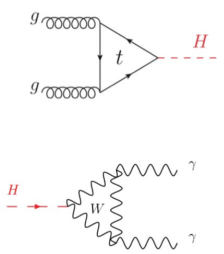




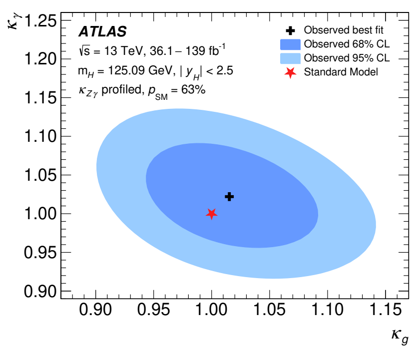
Higgs boson is Standard Model like

Run 2 Couplings Measurements

Choosing suitable assumptions to probe interesting new physics scenarios scenarios

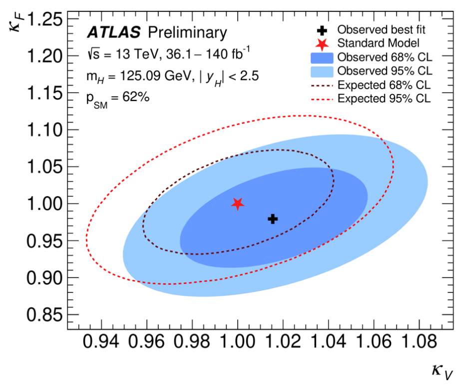


Probing new particles in the loops



All couplings are set to their Standard Model value except the effective couplings to the photon and the gluon (probing new physics in the loops).

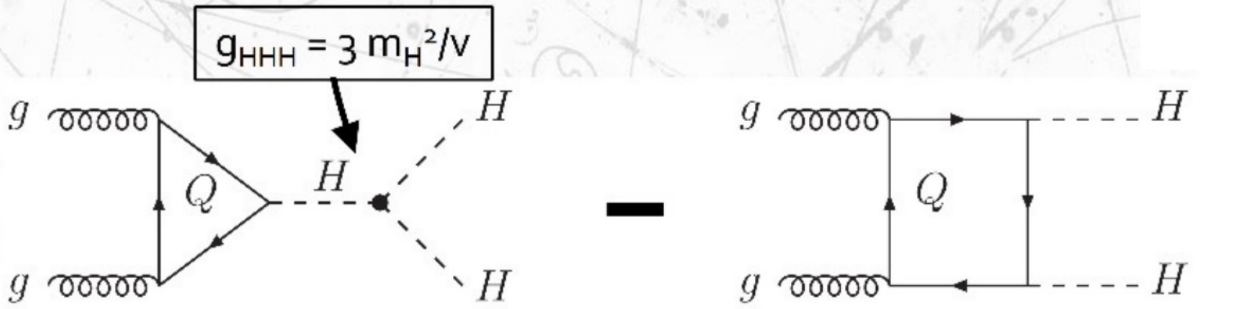
Probing the Gauge bosons vs fermions



All fermion couplings are fixed to one parameter and similarly for all boson, the couplings to the gluons and the photons are resolved.

Higgs self-couplings

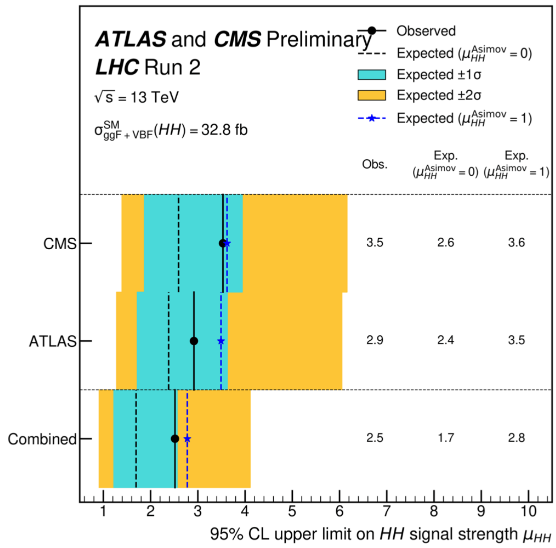
- **Higgs self coupling**
  - Measurable through double Higgs production



(accidental) negative interference between the two diagrams reduces cross section and hence sensitivity to g_{HHH} coupling

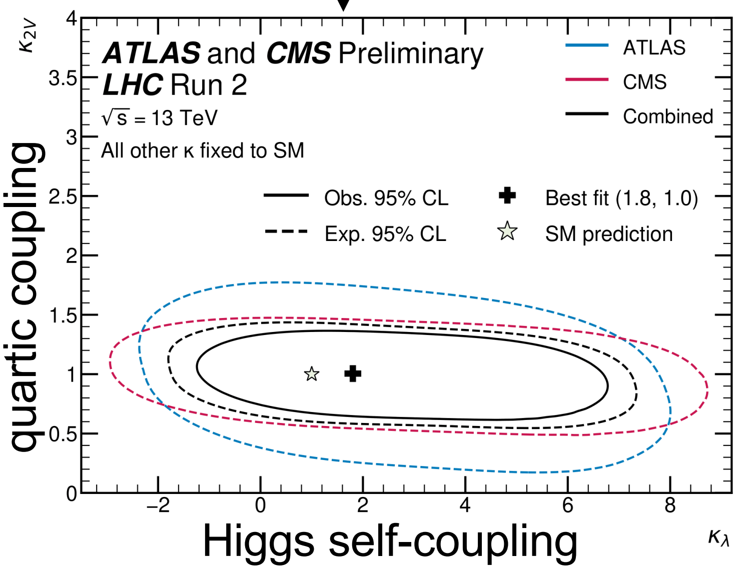
Rule of thumb: event yield ~ 1000 smaller than for single H

Most sensitive channels: $H\,(\rightarrow b\bar{b})$ + $H\,(\rightarrow \tau^+\tau^-|b\bar{b}|\gamma\gamma)$



Limits on di-Higgs cross section

Limits on couplings



Not yet enough sensitivity!

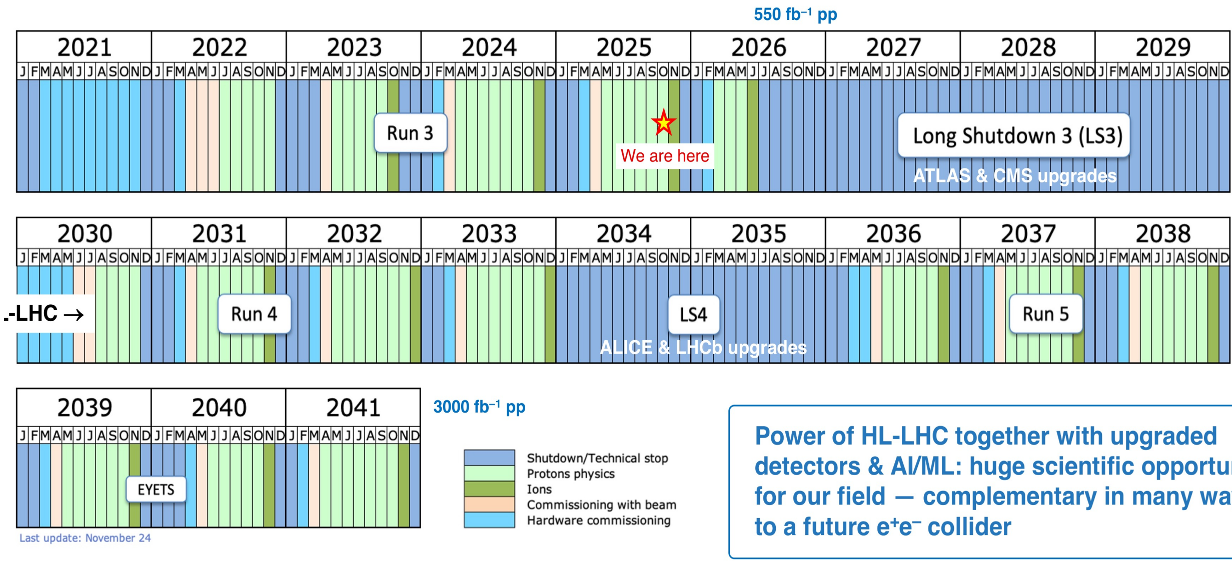
Maybe evidence of di-Higgs production with Run 3 data but certainly high luminosity LHC needed to measure it.

LHC and High-Luminosity-LHC (HL-LHC) project timeline

Huge effort ongoing to construct HL-LHC and experiment upgrades

World's flagship collider project during the next decade — 10 times currently analysed dataset (350M H, 240k HH, 13B top, 720M WW, …)

Large-scale ATLAS & CMS upgrades under construction, ALICE & LHCb plan significant upgrades for Run 5



Power of HL-LHC together with upgraded detectors & AI/ML: huge scientific opportunity for our field — complementary in many ways to a future e^+e^- collider

LHC machine upgrade to HL-LHC

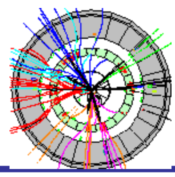
Ambitious goal: $L_{int} > 2500$ fb^{-1} in 9 years of operation (for a total delivered luminosity of 3 ab^{-1})

	Bunch intensity [protons / bunch]	β* [cm]	Peak lumi [cm^{-2}s^{-1}]	Pileup ⟨μ⟩	Int. lumi / year [fb^{-1}]
LHC design	$1.15 \cdot 10^{11}$	55	$1 \cdot 10^{34}$	23	30
LHC today	$1.6 \cdot 10^{11}$	60/18	$2.2 \cdot 10^{34}$	64	120
HL-LHC	**$2.2 \cdot 10^{11}$**	**15**	**$5\text{–}7 \cdot 10^{34}$**	**140–200**	**up to 300**

↑ Improved crygenic cooling and collimators, make all systems more radiation hard

↑ Stronger focussing: 12 new Nb_3Sn "inner triplet" quadrupoles at ATLAS & CMS (aperture: 70 → 150 mm, B-field: 8 → 11.5 T)

↑ RF crab cavities to restore effective head-on collisions, LIU high-brightness upgrade during LS2



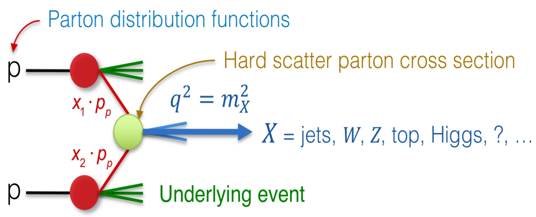
New opportunities at the HL-LHC

20 times more luminosity than Run 2 and better detectors offer significantly enhanced physics reach

- Sensitivity increase by up to 2 TeV for searches

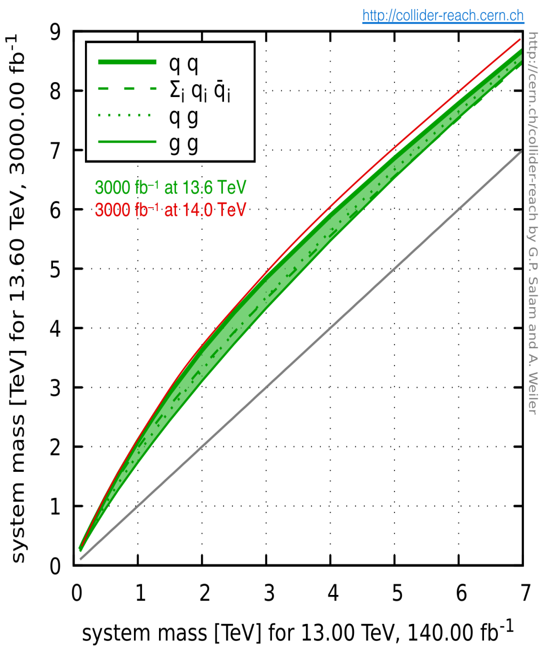
factor ~2 increase in probed mass range for searches

Proton–proton collisions correspond to a convolution of Parton Density Functions (PDF) with parton–parton scattering matrix element



CM energy-squared of parton collision: $\hat{s} = M_X^2 = x_1 \cdot x_2 \cdot s_{LHC}$

More luminosity allows to explore the high-x tails of the PDFs and thus reach higher parton collision energies



HL-LHC Physics prospects — Higgs

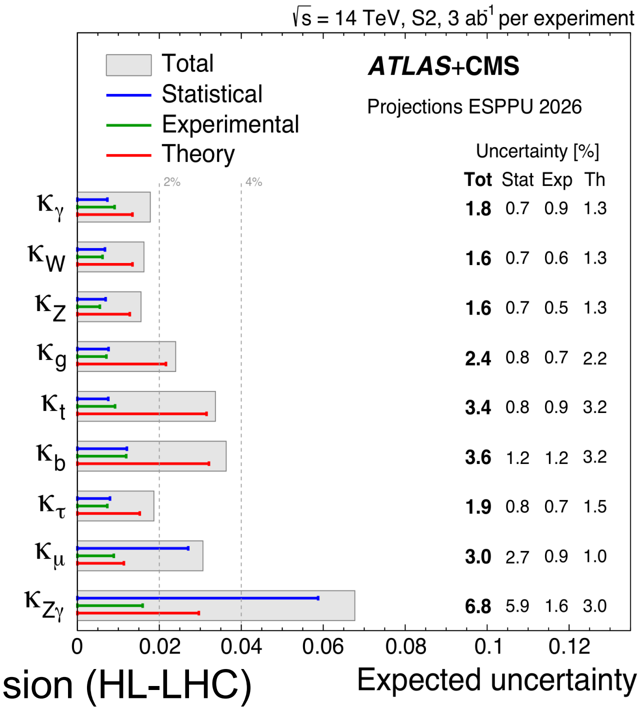
Higgs coupling prospects

The **best measured coupling probes compositness** of the Higgs boson

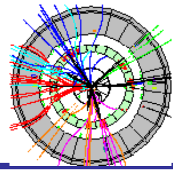
Coupling modifier	ATLAS ($\Gamma_{H\to inv/und} = 0$, $\kappa_c = \kappa_t$) [ATLAS-CONF-2025-006]	CMS ($\Gamma_{H\to inv/und} = 0$ $\kappa_c = \kappa_t$) [CMS-PAS-HIG-21-018]
κ_Z	0.96 ± 0.05	1.07 ± 0.06
κ_W	0.99 ± 0.04	1.05 ± 0.05
κ_γ (effective)	0.97 ± 0.06	1.10 ± 0.07
κ_τ	0.94 ± 0.06	0.94 ± 0.07
κ_t	0.99	0.92

5.0 (0.1)% precision on κ_i probes f_H ~ 1.1 (7.8) TeV

Coupling strength modifiers: $\kappa_i^2 \equiv \sigma_i/\sigma_i^{SM}$ or $\kappa_i^2 \equiv \Gamma_i/\Gamma_i^{SM}$



5 % precision (current) → < 2 % precision (HL-LHC)

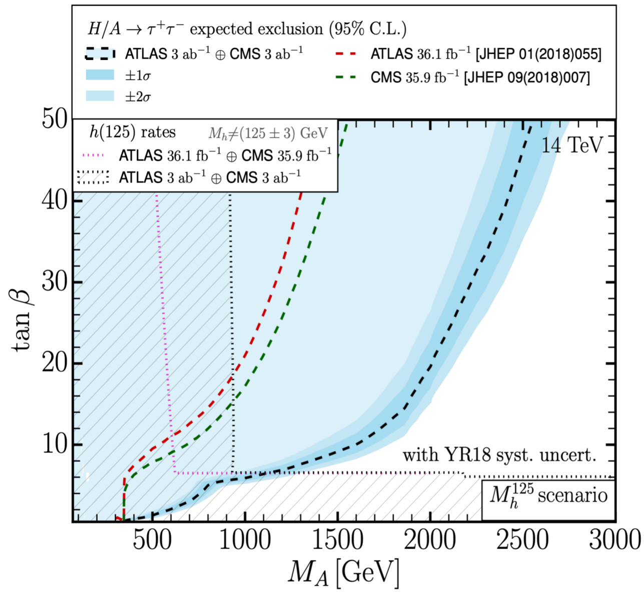


HL-LHC Physics prospects — Higgs

Higgs width from off-shell measurement and invisible decays, Higgs sector extensions (2HDM)

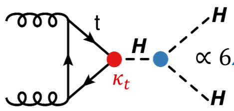
- Γ_H via $\mu_{\text{off-shell}} / \mu_{\text{on-shell}}$ in $H \to 4\ell$ & $2\ell 2\nu$ with < 20% uncertainty
- BR(H → invisible) < 2.5%
- Discover or exclude MSSM two Higgs doublets scenario deep into TeV scale for tanβ > 6

ATLAS & CMS Snowmass White Paper



HL-LHC Physics prospects — Higgs

Higgs self-coupling via Higgs pair production: complex final states, eldorado for ML enthusiasts, strongest channels: HH → bbγγ, bbττ, bbbb. Best sensitivity to λ at low m(HH)



$$\propto 6\lambda v = \frac{3m_H^2}{v}$$

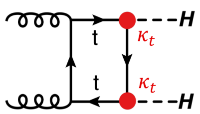
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

After expansion around potential minimum:

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4$$

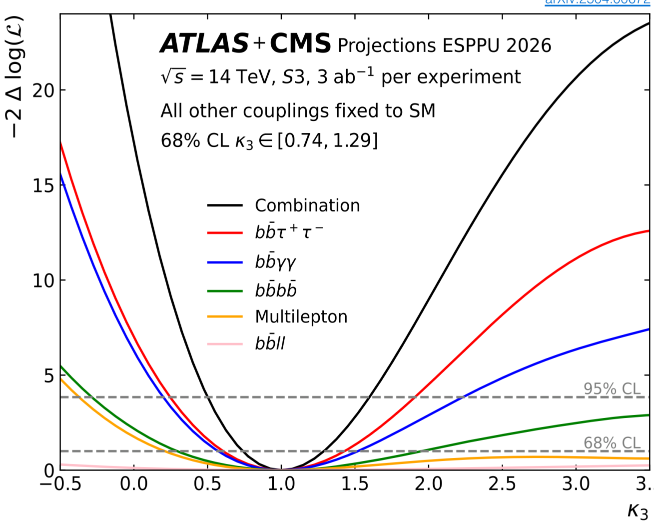
where: $\lambda_3^{\text{SM}} = \lambda_4^{\text{SM}} = \lambda^{\text{SM}}$ and: $\kappa_\lambda \equiv \lambda_3^{\text{obs}} / \lambda^{\text{SM}}$

Destructive interferes with box diagram:



leads to small HH SM cross section of 36 fb at 13.6 TeV, dominated by gluon fusion

arXiv:2504.00672



For SM: **expect HH observed > 7σ, and λ precision < 30%**

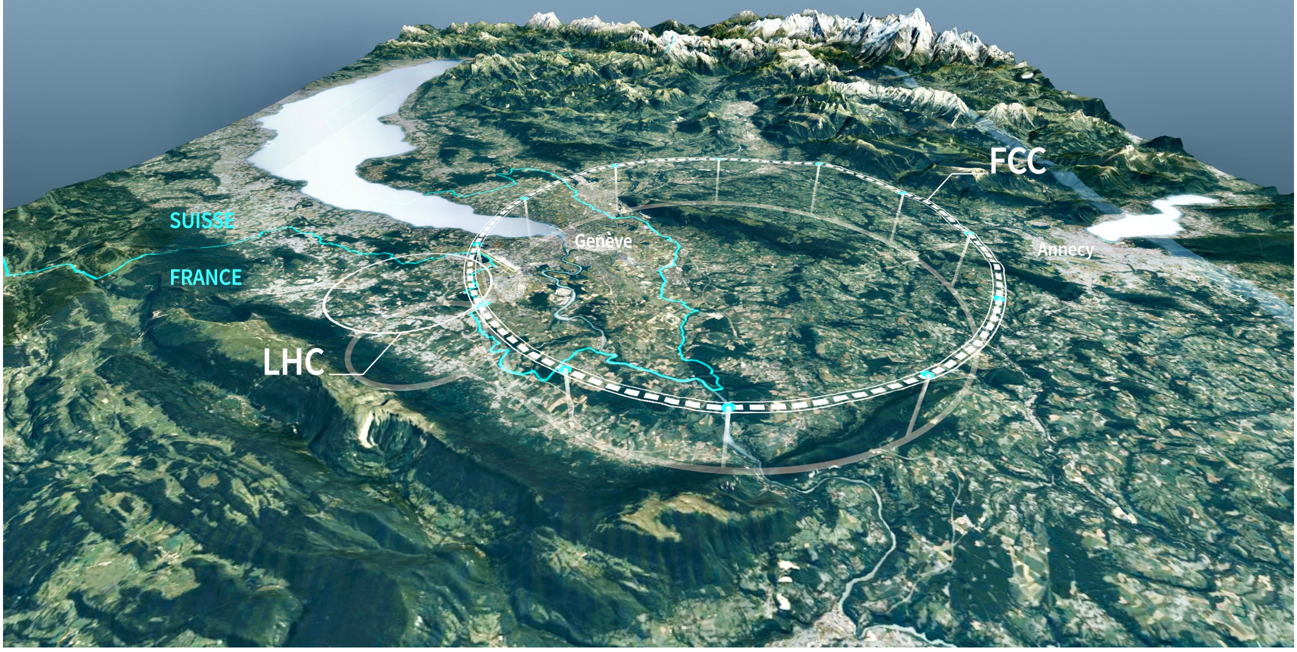
discovery of diHiggs boson production & first λ measurement expected at HL-LHC (especially if ATLAS & CMS data combined).

Future Circular Collider — integrated programme

90.7 km circumference tunnel facility to host an e^+e^- and a hadron collider

Feasibility study Vol 1, Vol 2 (March 2025)

Preferred option by national inputs to ESPPU

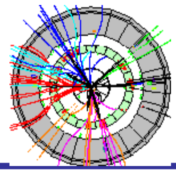


FCC-ee — parameters

FCC-ee main parameters (assuming 4 IPs / experiments)

Ref: arXiv:2505.00274

Parameter	Z	WW	H (ZH)	$t\bar{t}$	
Collision energy $\sqrt{s}$ [GeV]	88, 91, 94	157, 163	240	340–350	365
Synchrotron radiation/beam [MW]	50	50	50	50	50
Beam current [mA]	1294	135	26.8	6.0	5.1
Number bunches / beam	11200	1852	300	70	64
Total RF voltage 400 / 800 MHz [GV]	0.08 / 0	1.0 / 0	2.1 / 0	2.1 / 7.4	2.1 / 9.2
Luminosity / IP [10^{34} cm^{-2}s^{-1}]	144	20	7.5	1.8	1.4
Luminosity / year [ab^{-1}]	68	9.6	3.6	0.83	0.67
Run time (including lumi ramp-up) [years]	4	2	3	1	4
Total integrated luminosity [ab^{-1}]	205	19.2	10.8	0.4	2.7
Total number of events	$6 \cdot 10^{12}$ Z	$2.4 \cdot 10^{8}$ WW (incl. WW at higher $\sqrt{s}$)	$2.2 \cdot 10^{6}$ ZH 65k WW → H	$2 \cdot 10^{6}$ $t\bar{t}$ + 370k ZH + 92k WW → H	
	~350,000 × LEP-1 (~6 years) ~26 × HL-LHC (~9 years)	~5,000 × LEP-2 (~5 years)	0.5% of HL-LHC (~9 years)	0.01% of HL-LHC (tt) (~9 years)	



FCC-ee – the Higgs factory

Why "factory"? 2.2M Higgs (FCC-ee) vs 350M (HL-LHC), production through Higgsstrahlung rather than s-channel
→ e^+e^- collisions offer exceptionally clean Higgs reconstruction, unmatched precision on decays with large branching ratios

FCC-ee feasibility stydu (Vol 1): arXiv:2505.00272

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh	Uncertainty HL-LHC / FCC-ee
κ_Z (%)	1.6	0.10	0.10	16
κ_W (%)	1.6	0.29	0.25	5.5
κ_b (%)	3.6	0.38 / 0.49*	0.33 / 0.45	7.3
κ_g (%)	2.4	0.49 / 0.54	0.41 / 0.44	4.4
κ_τ (%)	1.9	0.46	0.40	4.1
κ_c (%)	~ 40	0.70 / 0.87	0.68 / 0.85	~ 44
κ_γ (%)	1.8	1.1	0.30	1.6
$\kappa_{Z\gamma}$ (%)	6.8	4.3	0.67	1.6
κ_t (%)	3.4	3.1	0.75	1.1
κ_μ (%)	3.0	3.3	0.42	0.9
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$	$^{+29}_{-67}$	–
Γ_H (%)	< 25	0.78	0.69	< 32
$\mathcal{B}_{inv}$ (<, 95% CL)	0.025	5×10^{-4}	2.3×10^{-4}	50
$\mathcal{B}_{unt}$ (<, 95% CL)	0.04	6.8×10^{-3}	6.7×10^{-3}	5.9

*Incl. SM parametric uncertainties

Note: current uncertainties on Higgs branching fraction predictions O(1.5%)

Most precise coupling, probes $f_H \sim 8$ TeV (κ_Z)

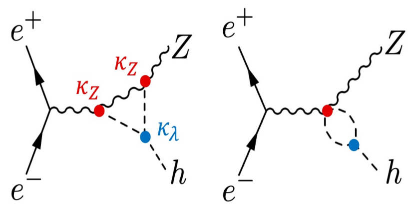
Particularly large improvement over HL-LHC (κ_b, κ_c, $\lvert\kappa_s\rvert$)

BR(H → 4ν) = $10.6 \cdot 10^{-4}$ ($\mathcal{B}_{inv}$)

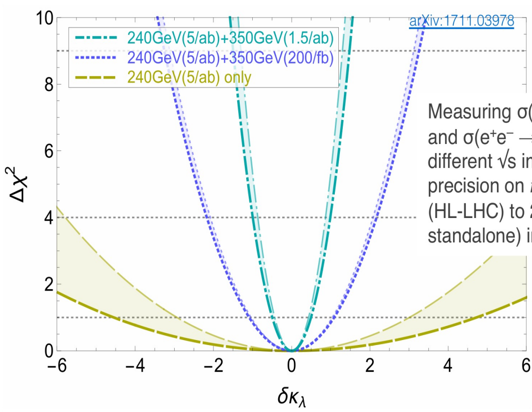
HL-LHC numbers updated from arXiv:2504.00672; they assume SM value for Γ_H, and incl. theoretical uncertainties (mostly dominant)

FCC-ee – the Higgs factory

Higgs self-coupling — no HH production at FCC-ee, sensitivity through H–H–H loops



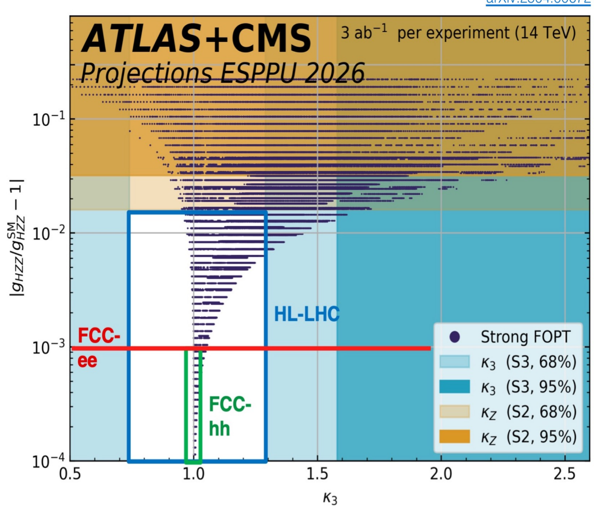
NLO vertex corrections to Higgsstrahlung (similar for W-boson fusion)



Measuring σ(e^+e^- → ZH) and σ(e^+e^- → ννH) at different √s improves precision on κ_λ from 30% (HL-LHC) to 20% (or 40% standalone) in EFT analysis

FCC-ee+hh tightly constrains BSM models with 1st order EW phase transition

arXiv:2504.00672

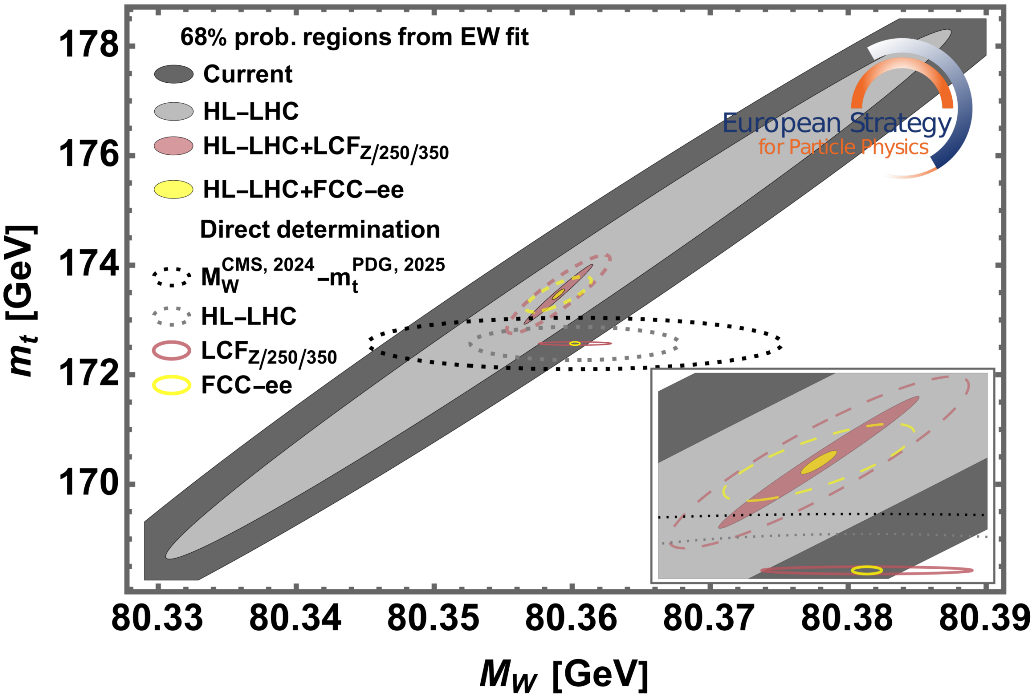


FCC-ee – also a Tera-Z, W and top factory

Global electroweak fit expressed on top versus W mass

ESPPU 2025 Briefing Book

FCC-ee: preferred option for next collider after LHC by the European Particle Physics community



The big picture: next-generation collider projects for CERN

Project	Construction start	First beams	Peak lumi at Z per IP [10^{34} cm^{-2}s^{-1}]	Peak lumi at HZ per IP [10^{34} cm^{-2}s^{-1}]	Years of operation	Construction cost* [BCHF]	Next stage collider	Start of operation	Total construction cost* [BCHF]
FCC-ee	2033	2046	144	7.5	14	15.3	FCC-hh	2079	34.7
LEP3	2037	2047	40	1.6	15	4.1	FCC-hh	2074	32.5
LCF 250 → 550 GeV	2035	2045	0.28	1.4 – 2.7	19	9.4 + 5.4 = 14.8	> 1 TeV collider?	–	–
CLIC 380 → 1500 GeV	2035	2045	–	$1.2_{380\ GeV}$	20	7.5 + 7.1 = 14.6	3 TeV collider?	–	–
LHeC	2037	2044	–	2.3	7	2.1	FCC-hh	2064	30.5

Similar start dates driven by HL-LHC running until 2041

*Construction costs include experiments