PH4442 Advanced Particle Physics 2025/26
Lecture Week 11

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- Finish QCD
- Partons
- Hadron collider physics

Plan for this week

Finish Quantum Chromodynamics:

quark-quark scattering

Partons:

Parton Distribution functions

Deep Inelastic Scattering $\longrightarrow$ measuring PDFs

Hadron collider physics:

Variables for collider physics

Drell-Yan process

Defining jets

Dijet cross section

More hadron collider processes

Calculation of colour factor for ud $\longrightarrow$ ud

$$\sum_{i,j,k,l} \left| \sum_a T^a_{ji} T^a_{lk} \right|^2 = \sum_{i,j,k,l} \left(\sum_a T^a_{ji} T^a_{lk} \right) \left(\sum_b T^b_{ji} T^b_{lk} \right)^*$$

$$= \sum_{i,j,k,l} \sum_{a,b} T^a_{ji} (T^b_{ji})^* T^a_{lk} (T^b_{lk})^*$$

$$= \sum_{a,b} \left(\sum_{i,j} T^a_{ji} T^b_{ij} \right) \left(\sum_{k,l} T^a_{lk} T^b_{kl} \right)$$

$$= \sum_{a,b} \left[\mathrm{Tr}(T^a T^b) \right]^2 .$$

Use $\mathrm{Tr}(T^a T^b) = T_F \delta^{ab}$, $T_F = 1/2$ to find

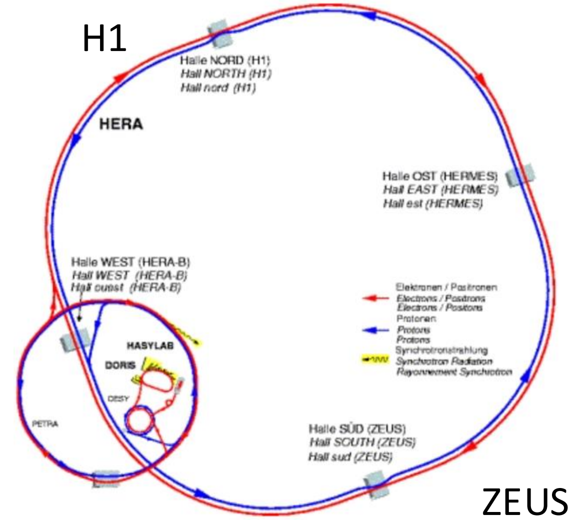
$$C = \frac{1}{N_c^2} \sum_{a,b} \left[\mathrm{Tr}(T^a T^b) \right]^2 = \frac{T_F^2}{N_c^2} \sum_{a,b=1}^{8} (\delta^{ab})^2 = \frac{8 T_F^2}{N_c^2} = \frac{2}{9}$$

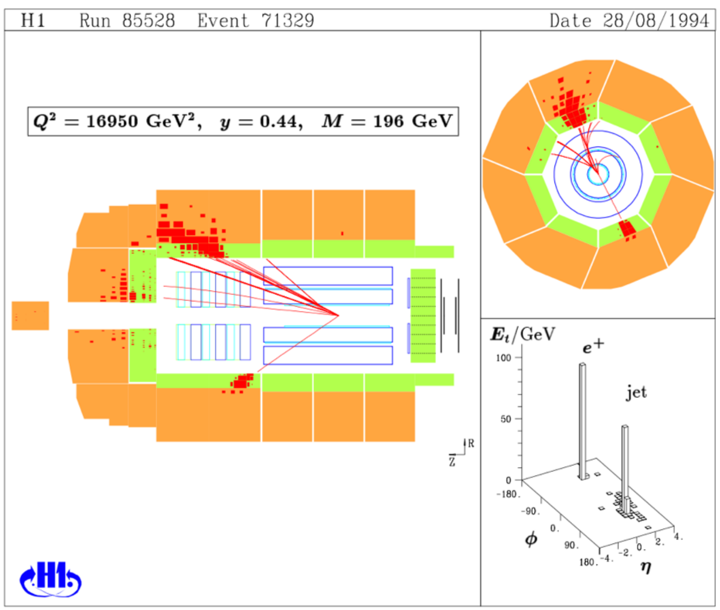
$|\mathcal{M}|^2$ at LO for parton-parton scattering processes

Process	$\langle\lvert\mathcal{M}\rvert^2\rangle/g_s^4$	$\theta^* = \pi/2$
$qq' \to qq'$	$\frac{4}{9}\frac{s^2+u^2}{t^2}$	2.22
$q\bar{q}' \to q\bar{q}'$	$\frac{4}{9}\frac{s^2+u^2}{t^2}$	2.22
$qq \to qq$	$\frac{4}{9}\left(\frac{s^2+u^2}{t^2}+\frac{s^2+t^2}{u^2}\right)-\frac{8}{27}\frac{s^2}{ut}$	3.26
$q\bar{q} \to q'\bar{q}'$	$\frac{4}{9}\frac{t^2+u^2}{s^2}$	0.22
$q\bar{q} \to q\bar{q}$	$\frac{4}{9}\left(\frac{s^2+u^2}{t^2}+\frac{t^2+u^2}{s^2}\right)-\frac{8}{27}\frac{u^2}{st}$	2.59
$q\bar{q} \to gg$	$\frac{32}{27}\frac{t^2+u^2}{tu}-\frac{8}{3}\frac{t^2+u^2}{s^2}$	1.04
$gg \to q\bar{q}$	$\frac{1}{6}\frac{t^2+u^2}{tu}-\frac{3}{8}\frac{t^2+u^2}{s^2}$	0.15
$gq \to gq$	$-\frac{4}{9}\frac{s^2+u^2}{su}+\frac{u^2+s^2}{t^2}$	6.11
$gg \to gg$	$\frac{9}{2}\left(3-\frac{tu}{s^2}-\frac{su}{t^2}-\frac{st}{u^2}\right)$	30.4

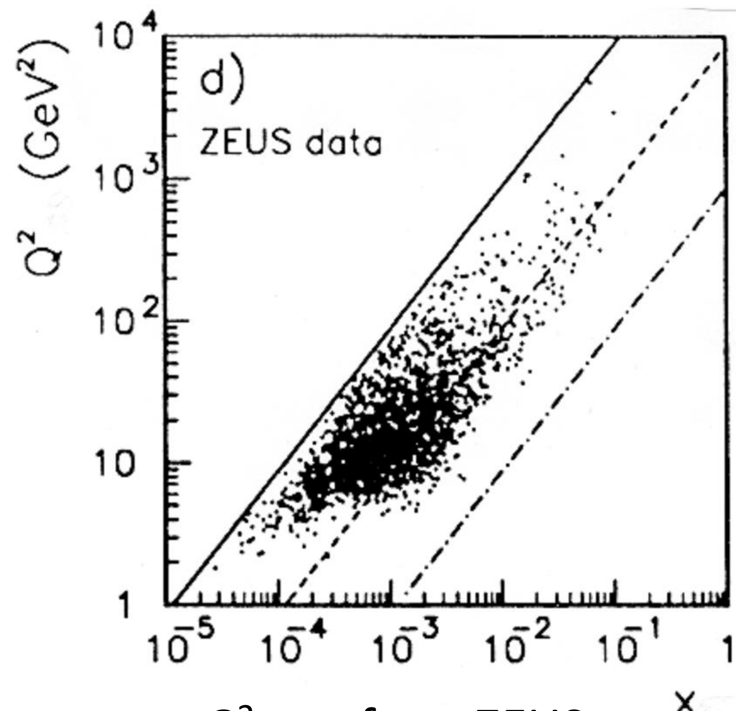
Deep Inelastic Scattering at HERA

820 GeV protons on 27.5 GeV e^- (or e^+) at DESY (Hamburg)



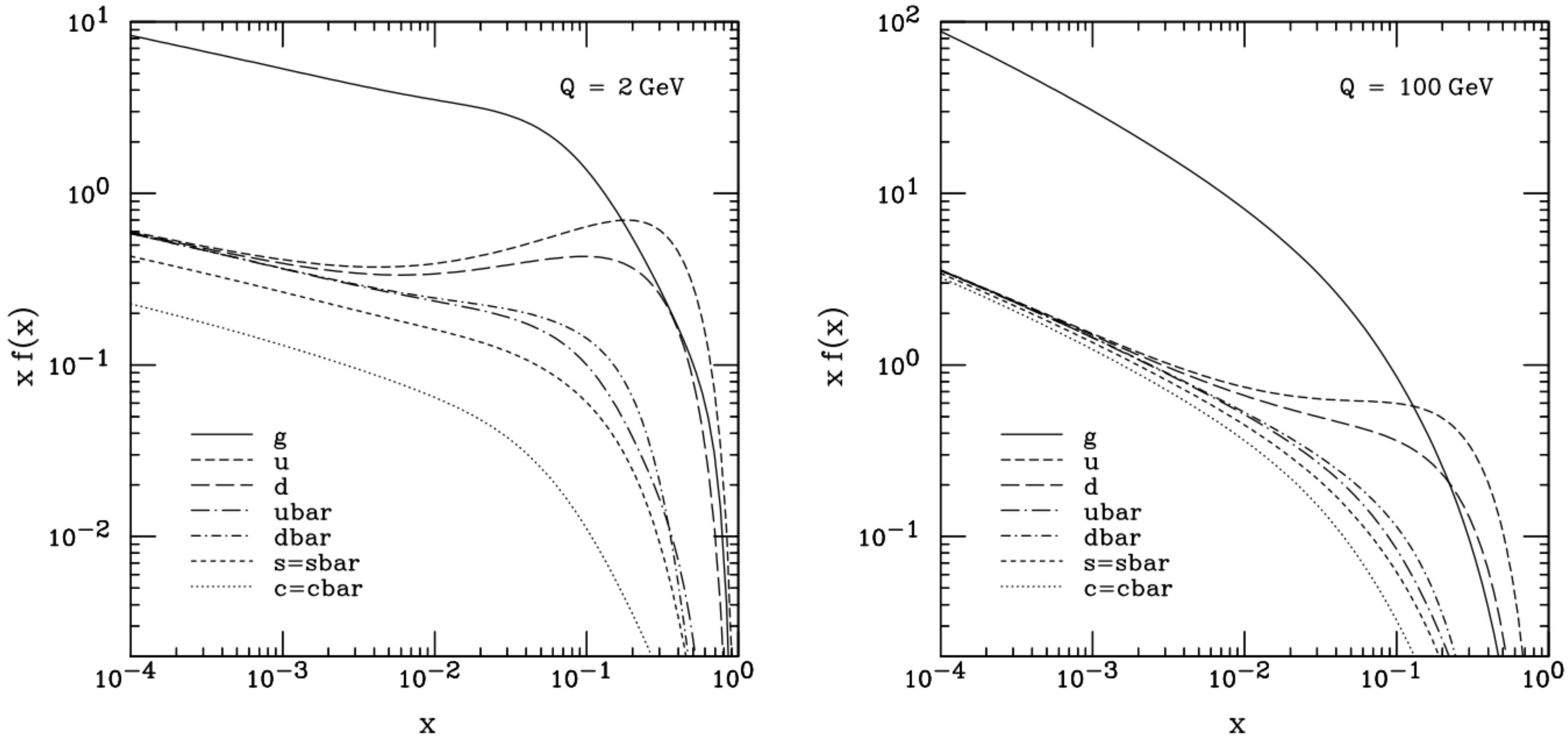


High Q^2 event at H1



Q^2 vs x from ZEUS

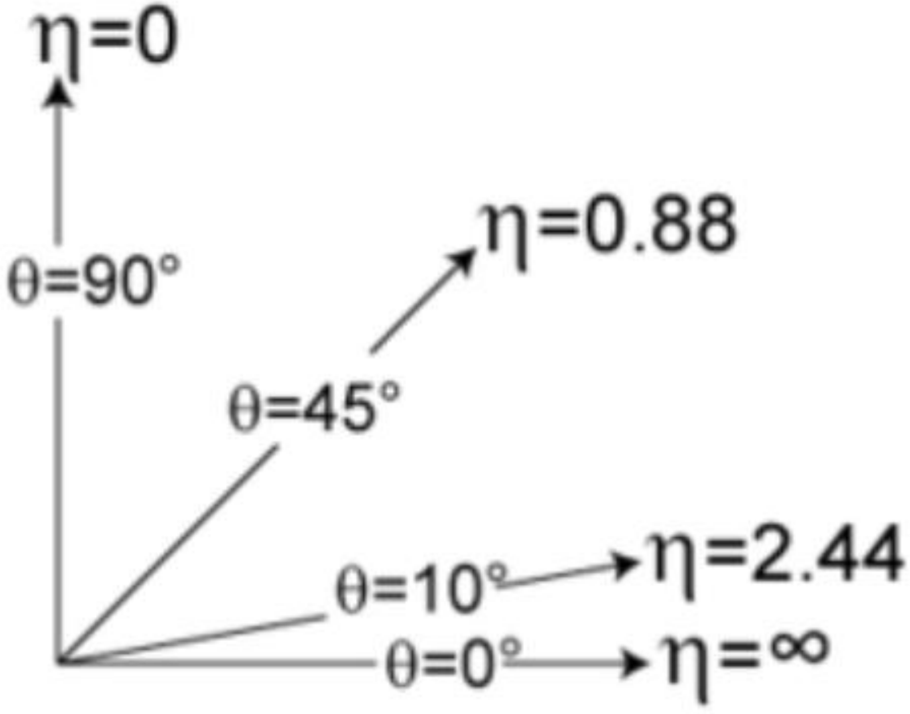
Parton Distribution Functions



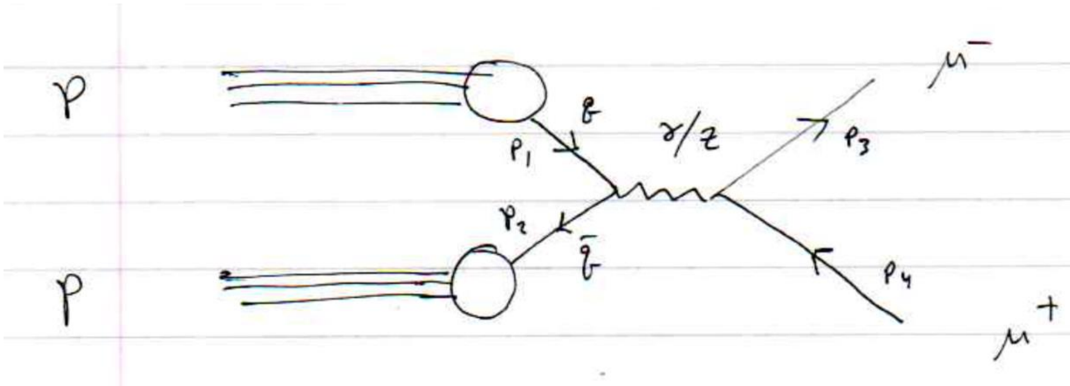
J. Pumplin et al. (CTEQ Collaboration), New Generation of Parton Distributions with Uncertainties from Global QCD Analysis, JHEP 0207:012,2002.

Pseudorapidity

$$\eta = -\ln \tan \frac{\theta}{2}$$



The Drell-Yan Process $pp \to \ell^+\ell^- + X, \; \ell = e, \mu, \tau$



For $\hat{s} << M_Z^2$, only g diagram important:

$$\sigma(q\overline{q} \to \mu^+\mu^-) = \frac{4\pi\alpha^2 Q_q^2}{3N_c\hat{s}} \quad , \qquad \hat{s} = x_1 x_2 s$$

For pp collisions, need to get $\overline{q}$ from "sea", giving

$$\frac{d^2\sigma}{dx_1 dx_2}(pp \to \mu^+\mu^- X) = \frac{4\pi\alpha^2}{9sx_1x_2}\sum_q Q_q^2\left[f_q(x_1)f_{\overline{q}}(x_2) + f_{\overline{q}}(x_1)f_q(x_2)\right]$$

Similar for $p\overline{p} \to \mu^+\mu^- + X$, e.g., at Tevatron using

$$f_{p,q}(x) = f_{\overline{p},\overline{q}}(x)$$

$$f_{p,\overline{q}}(x) = f_{\overline{p},q}(x)$$

Transforming the Drell-Yan cross section

For, e.g., the different cross section with respect to invariant mass and rapidity of the $\mu^+\mu^-$ system:

$$m_{\mu\mu} = \sqrt{x_1 x_2 s} \qquad\qquad y = \tfrac{1}{2}\ln(x_1/x_2)$$

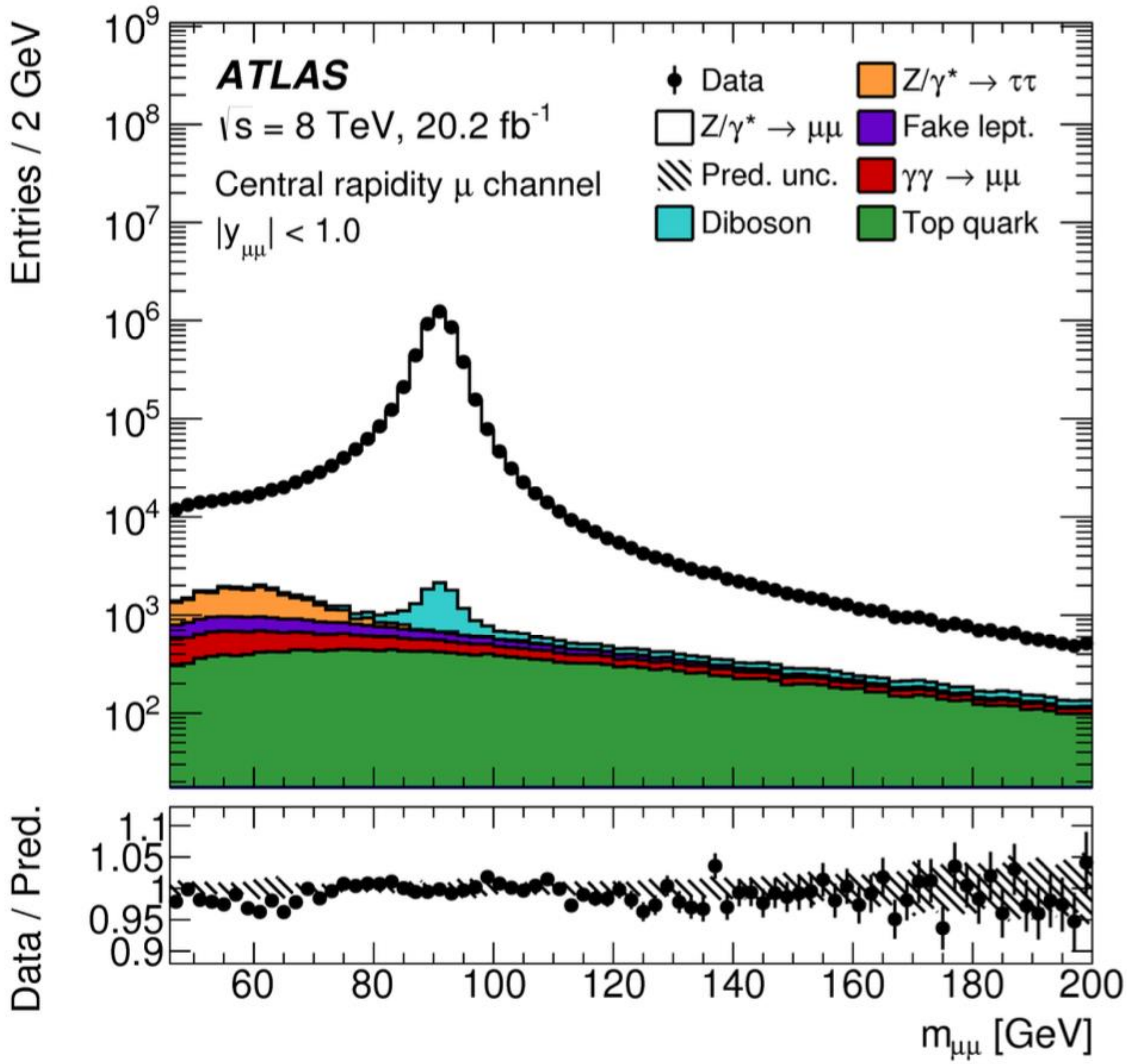
The Jacobian is:

$$J = \begin{vmatrix} \frac{\partial x_1}{\partial m_{\mu\mu}} & \frac{\partial x_1}{\partial y} \\ \frac{\partial x_2}{\partial m_{\mu\mu}} & \frac{\partial x_2}{\partial y} \end{vmatrix} = -\frac{2m_{\mu\mu}}{s}$$

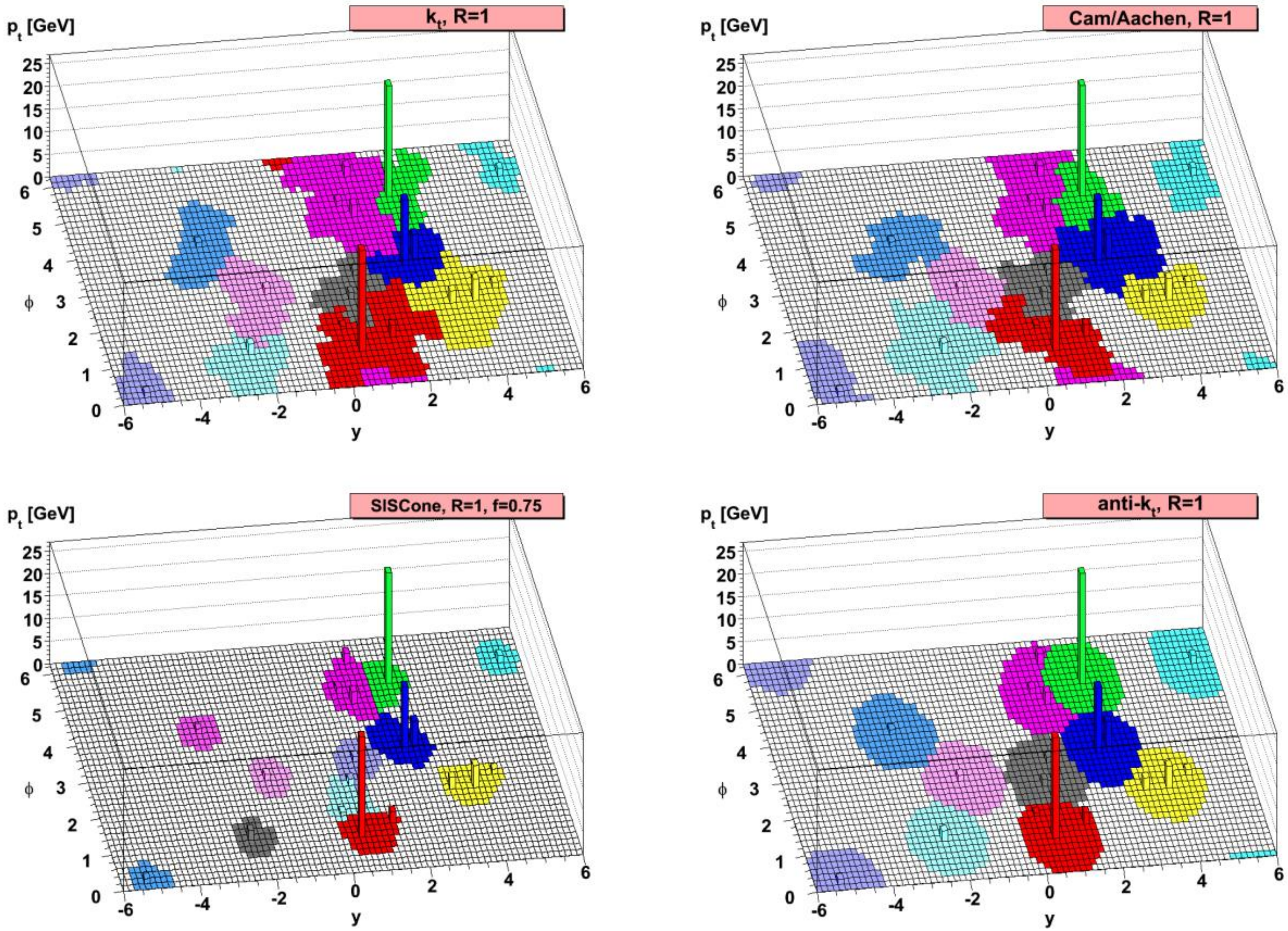
For the pp case this gives

$$\begin{aligned} \frac{d^2\sigma}{dm_{\mu\mu}dy}(pp \to \mu^+\mu^- X) &= \frac{8\pi\alpha^2}{9sm_{\mu\mu}} \sum_q Q_q^2 \left[f_q\left(\frac{m_{\mu\mu}}{\sqrt{s}}e^y\right) f_{\bar{q}}\left(\frac{m_{\mu\mu}}{\sqrt{s}}e^{-y}\right) \right. \\ &+ \left. f_{\bar{q}}\left(\frac{m_{\mu\mu}}{\sqrt{s}}e^y\right) f_q\left(\frac{m_{\mu\mu}}{\sqrt{s}}e^{-y}\right) \right] . \end{aligned}$$

Drell-Yan data



Jet finding algorithms



Dijet cross section

Earlier we found the cross section for ud scattering:

$$\frac{d\hat{\sigma}}{dQ^2} = \frac{4\pi}{9}\frac{\alpha_s^2}{Q^4}\left[1 + \left(1 - \frac{Q^2}{\hat{s}}\right)^2\right]$$

For pp → ud → ud + X:

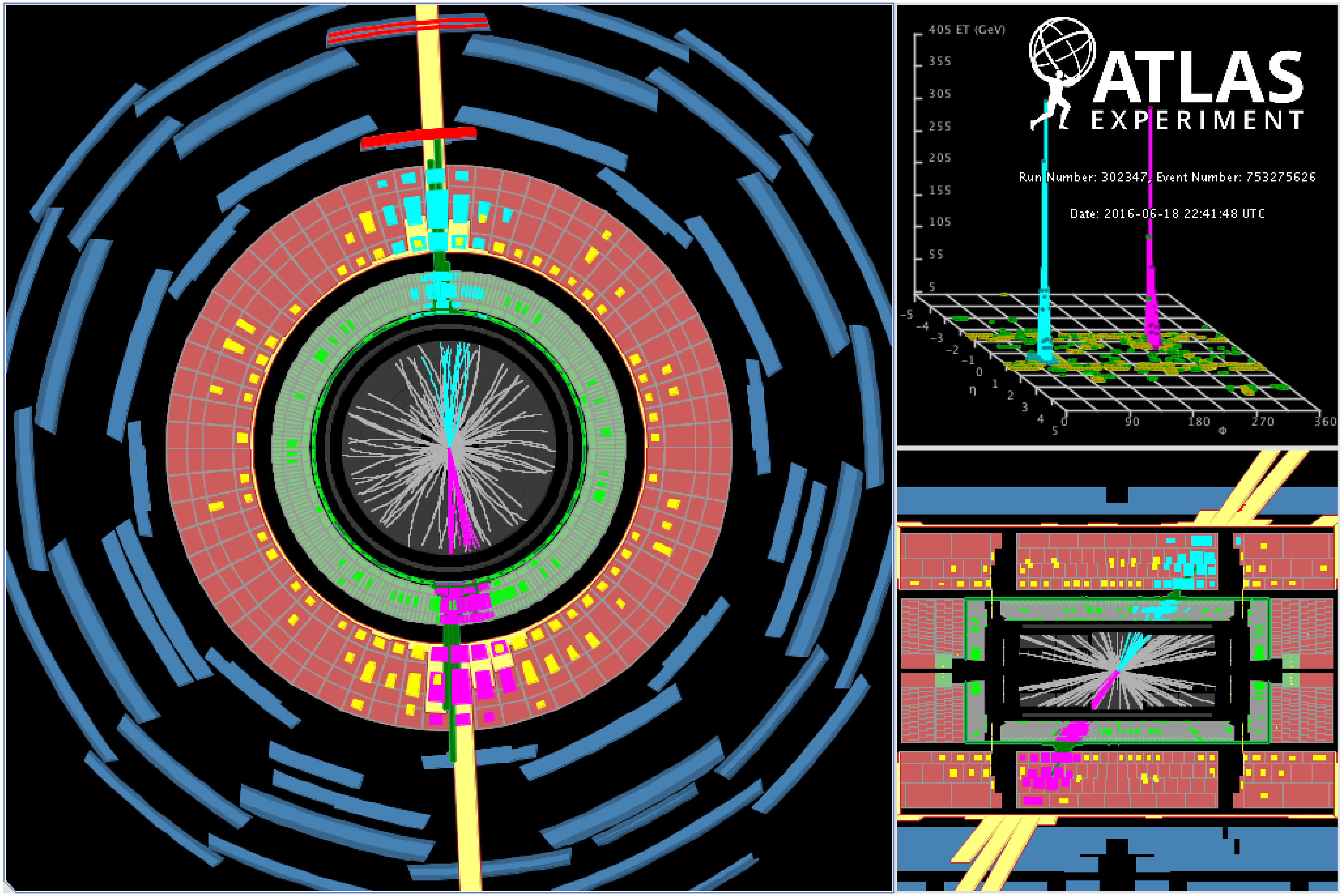
$$\frac{d^3\sigma}{dQ^2 dx_1 dx_2} = \left.\frac{d\hat{\sigma}}{dQ^2}\right|_{\hat{s}=x_1 x_2 s} 2 f_u(x_1) f_d(x_2)$$

Transform variables to jet-jet invariant mass m_{jj}, rapidity of parton c.m. y and rapidity η* of outgoing u quark in parton c.m.:

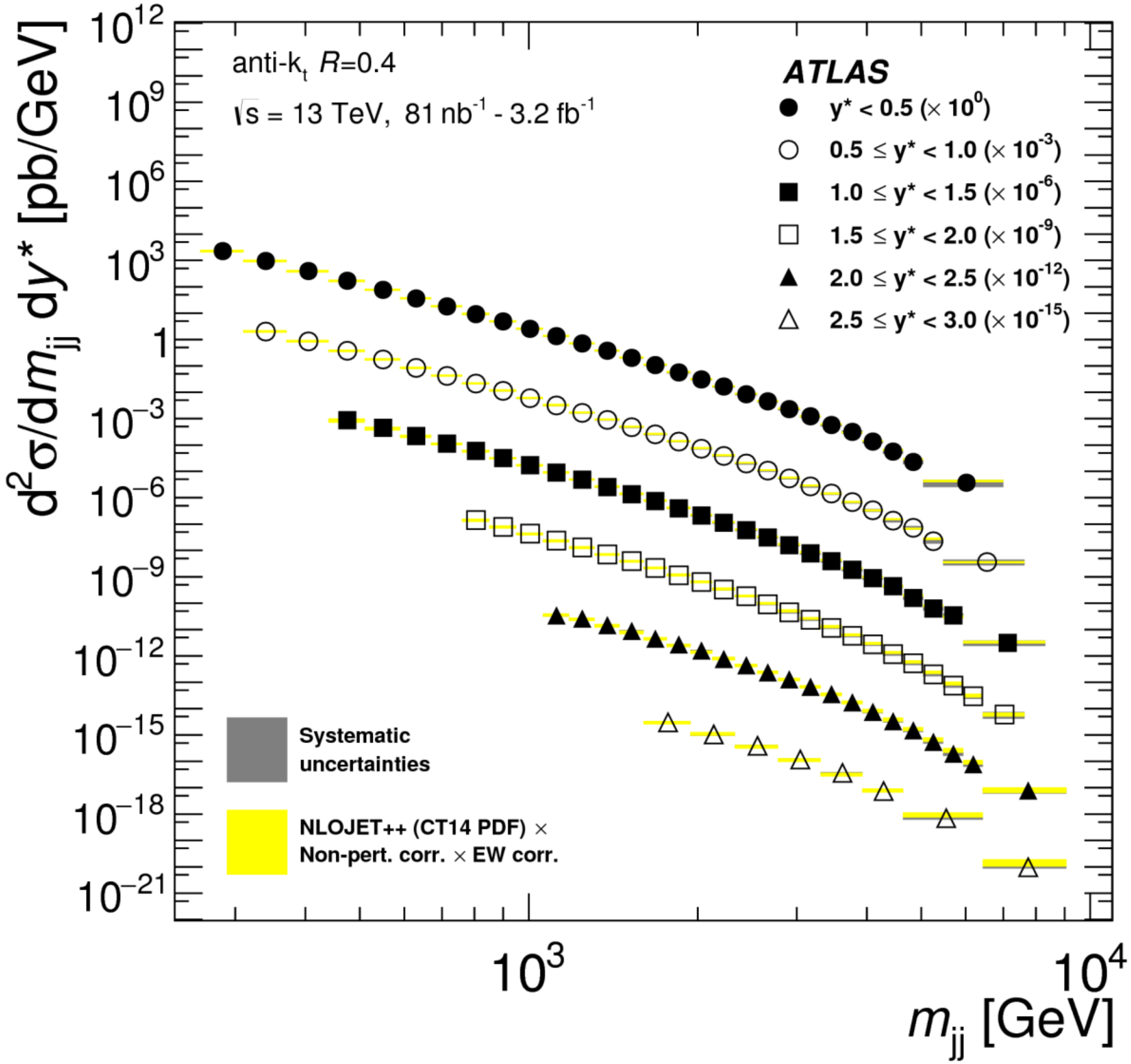
$$\frac{d^3\sigma}{dm_{jj} d\eta^* dy} = \frac{4\pi}{9}\frac{\alpha_s^2}{Q^4}\left[1 + \left(1 - \frac{Q^2}{m_{jj}^2}\right)^2\right]\frac{m_{jj}^3}{s}(1 - \tanh^2\eta^*) f_u\left(\frac{m_{jj}}{\sqrt{s}}e^y\right) f_d\left(\frac{m_{jj}}{\sqrt{s}}e^{-y}\right)$$

Include all parton-parton combinations that give two outgoing jets (at LHC dominant contribution from gg → gg).

Dijet event at the LHC in ATLAS

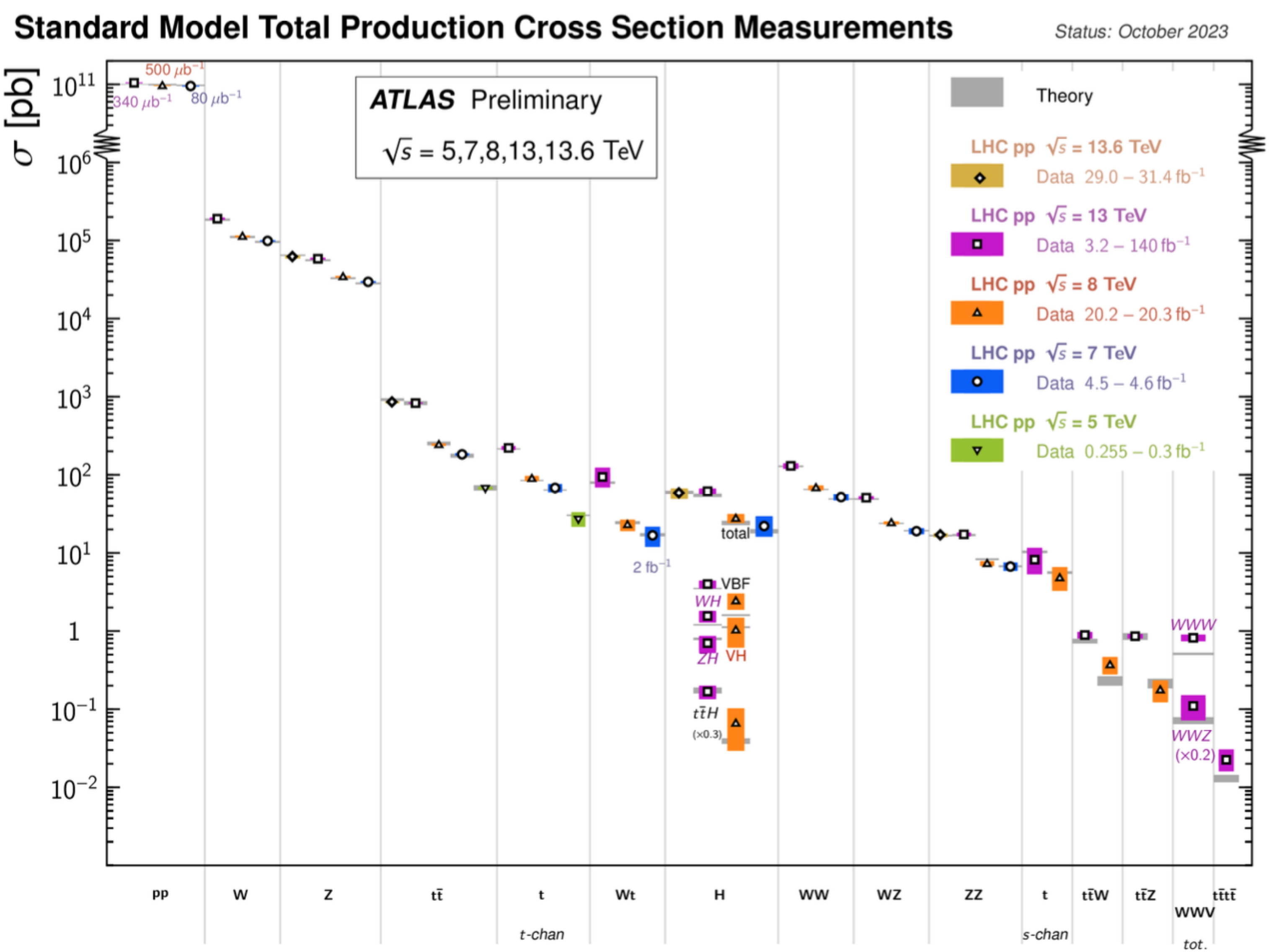


Dijet production in pp collisions

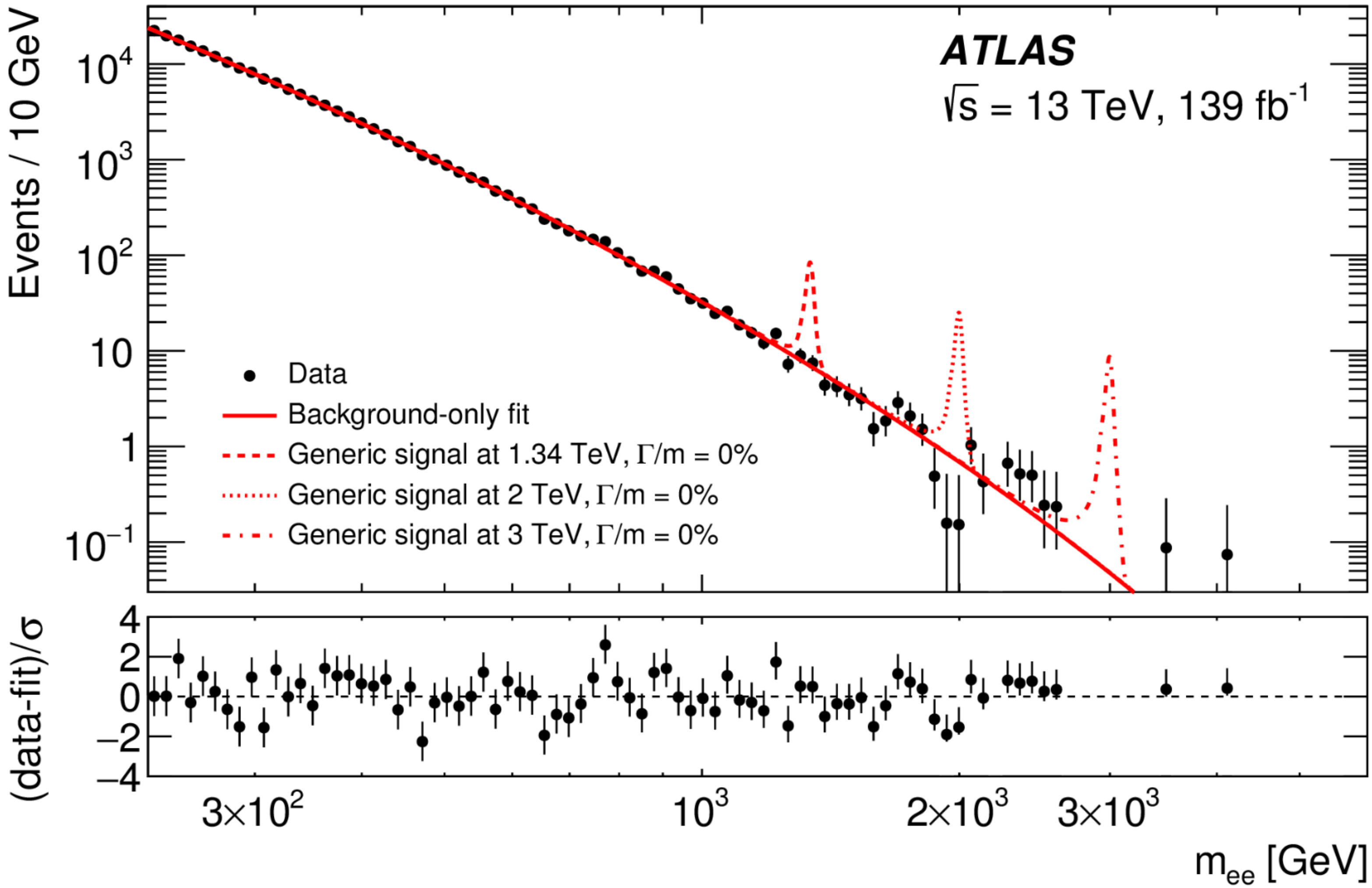


Véronique Boisvert

Production cross sections at LHC



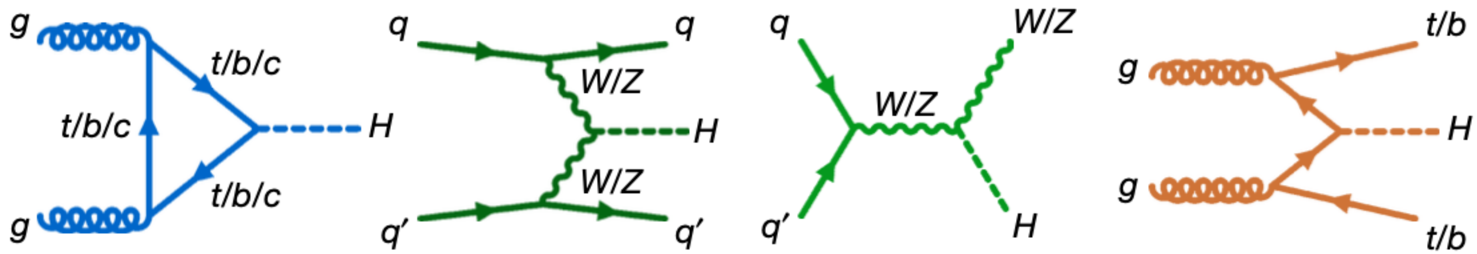
Search for Z’



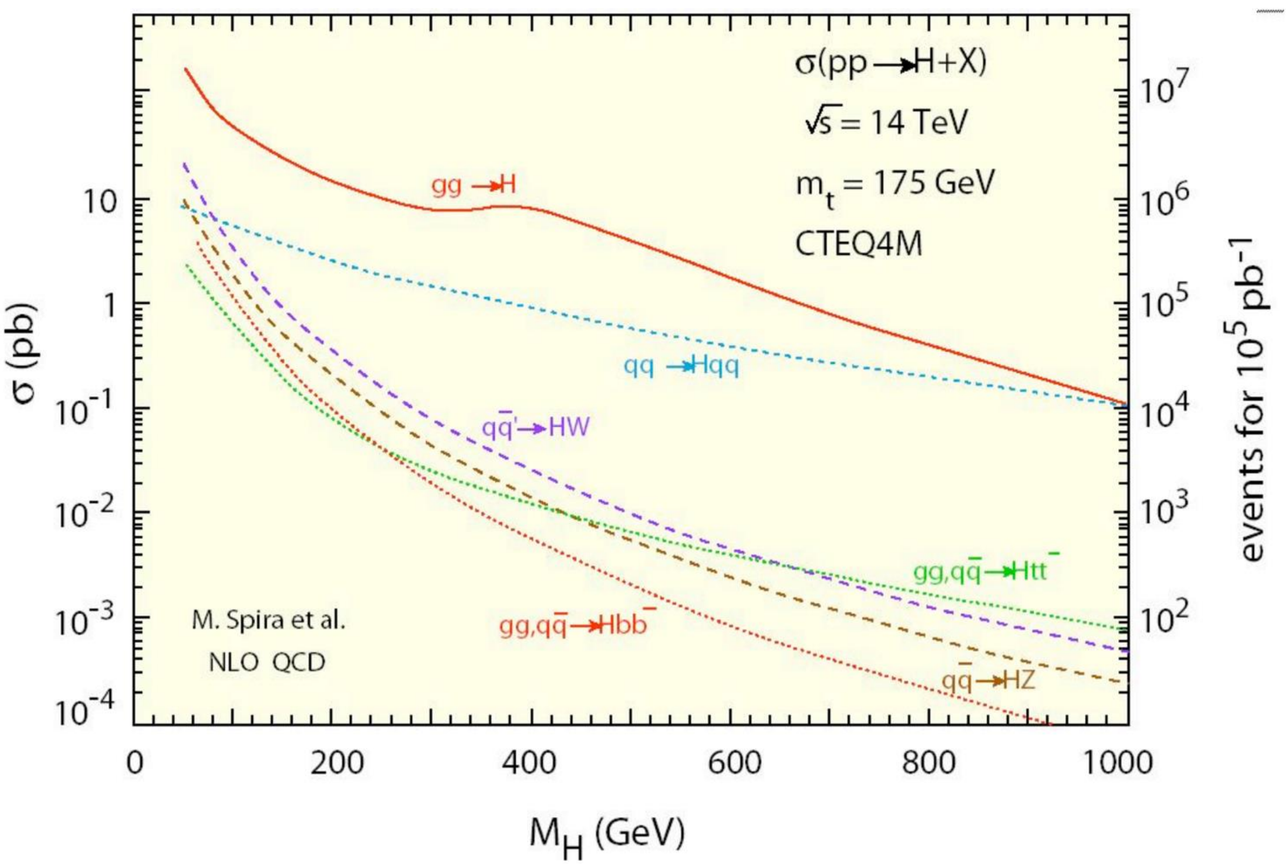
ATLAS
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
Data
Background-only fit
Generic signal at 1.34 TeV, Γ/m = 0%
Generic signal at 2 TeV, Γ/m = 0%
Generic signal at 3 TeV, Γ/m = 0%
Events / 10 GeV
(data-fit)/σ
m_{ee} [GeV]

Higgs production in pp collisions

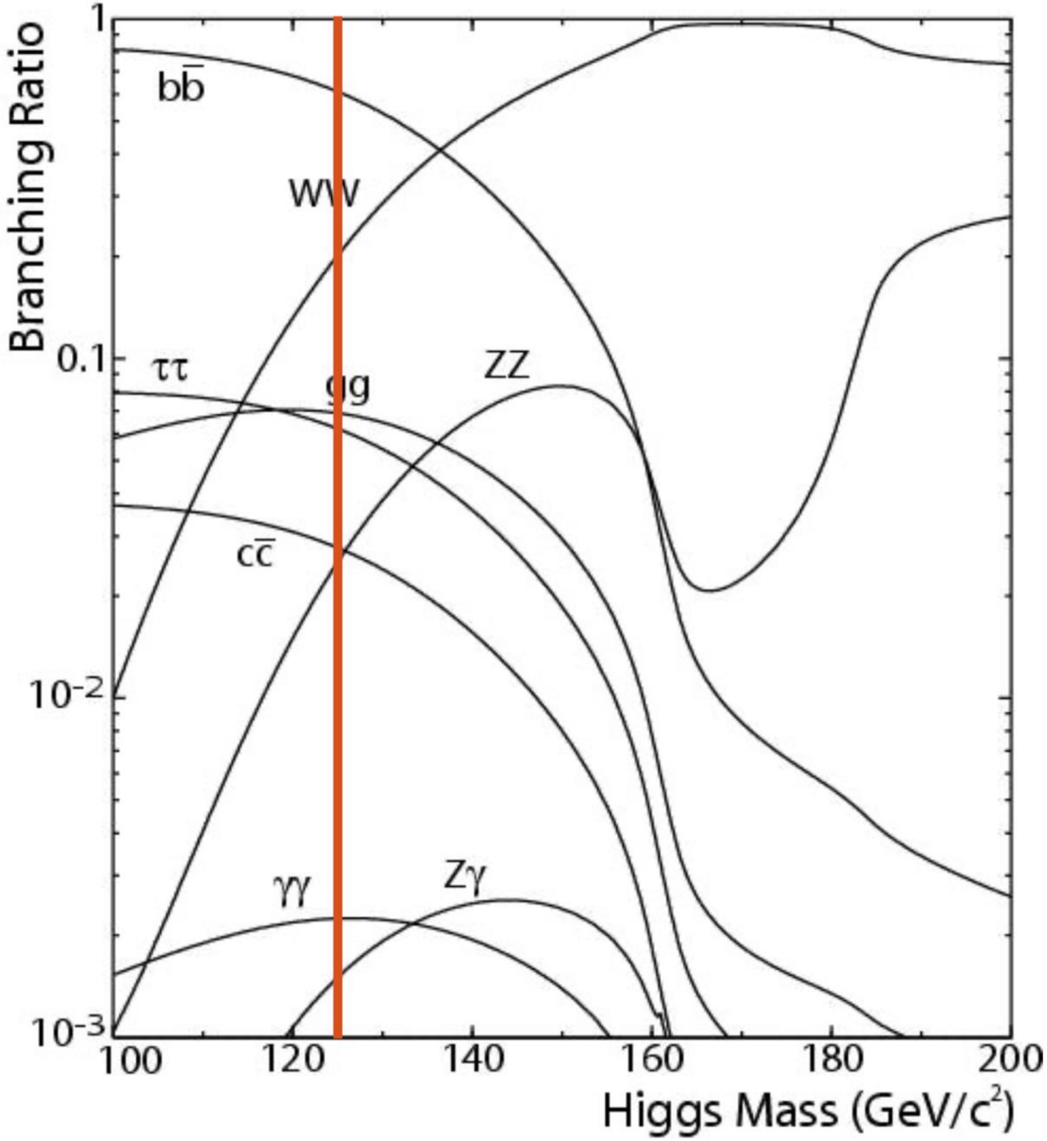
The ATLAS Collaboration, Nature 607 (2022) 52–59



gluon-gluon fusion   vector-boson fusion (VBF)   associated production (VH)   ttH



Higgs boson decays



ATLAS Collaboration, Phys.Lett. B716 (2012) 1-29

Higgs discovery: H $\longrightarrow$ γγ

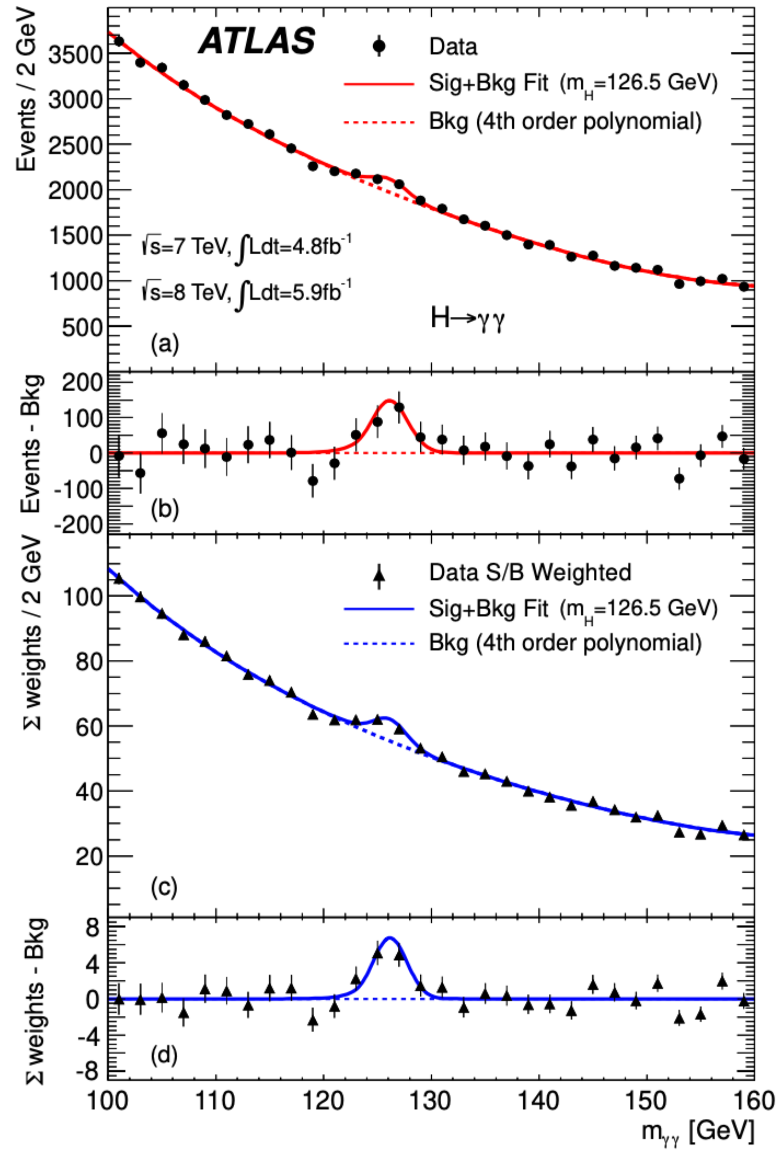


Figure 4: The distributions of the invariant mass of diphoton candidates after all selections for the combined 7 TeV and 8 TeV data sample. The inclusive sample is shown in (a) and a weighted version of the same sample in (c); the weights are explained in the text. The result of a fit to the data of the sum of a signal component fixed to m_H = 126.5 GeV and a background component described by a fourth-order Bernstein polynomial is superimposed. The residuals of the data and weighted data with respect to the respective fitted background component are displayed in (b) and (d).

$H \rightarrow ZZ^* \rightarrow llll$ $\quad$ $H \rightarrow WW^* \rightarrow l\nu l\nu$

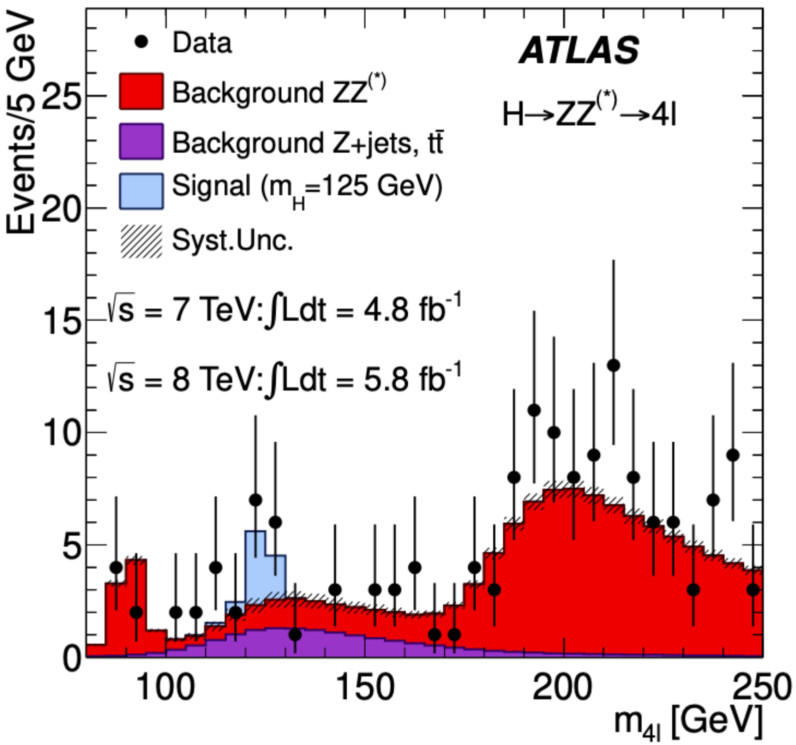


Figure 2: The distribution of the four-lepton invariant mass, $m_{4\ell}$, for the selected candidates, compared to the background expectation in the 80–250 GeV mass range, for the combination of the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data. The signal expectation for a SM Higgs with $m_H = 125$ GeV is also shown.

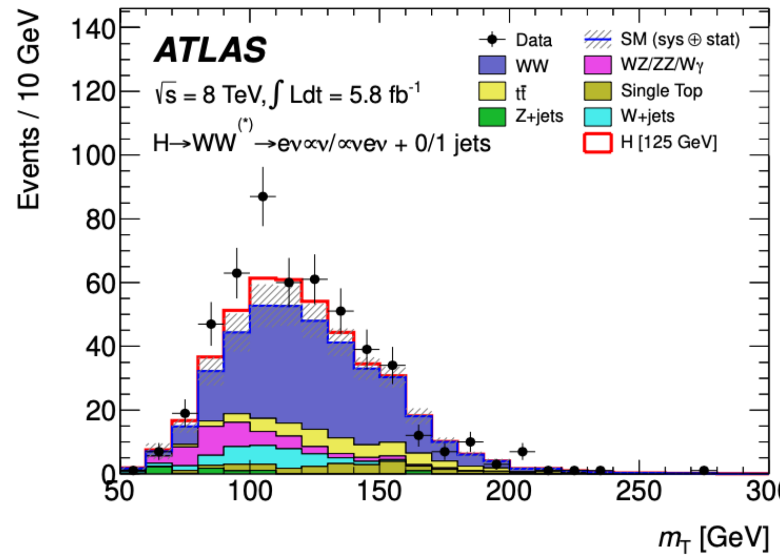
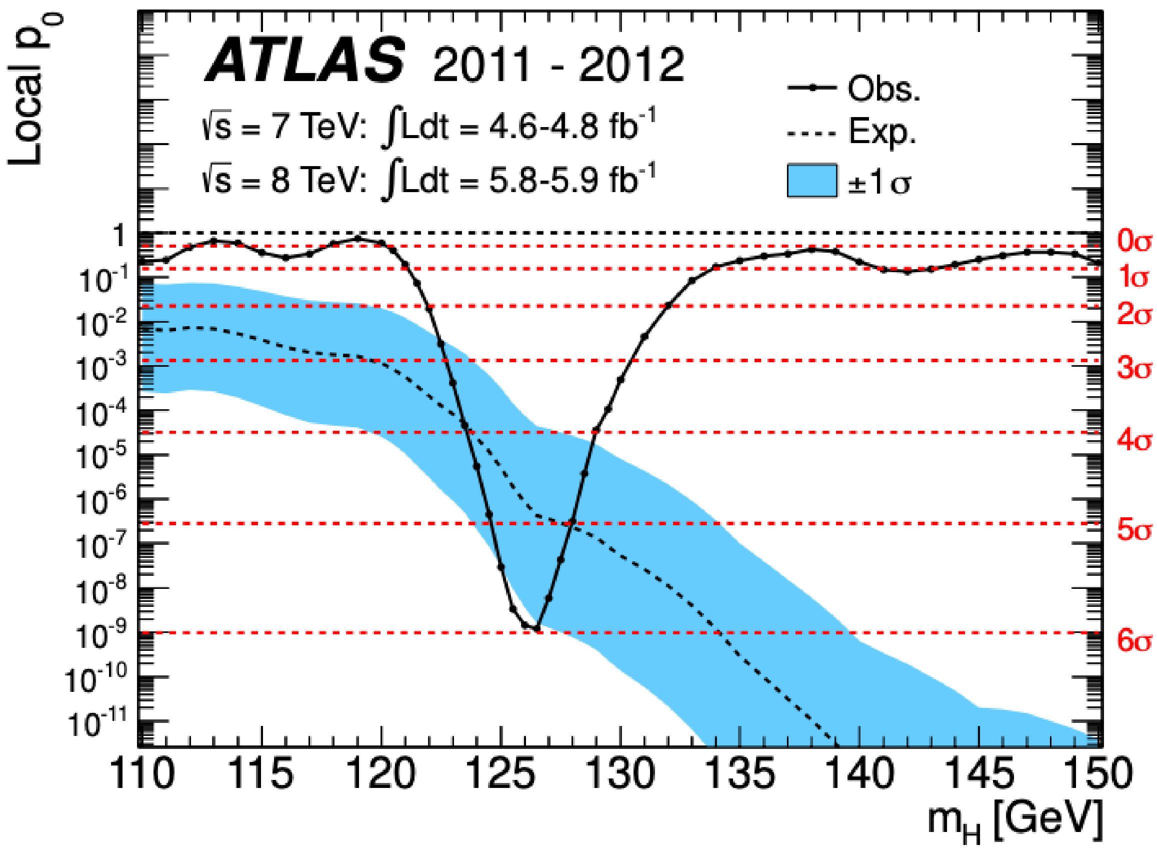


Figure 6: Distribution of the transverse mass, m_T, in the 0-jet and 1-jet analyses with both $e\mu$ and μe channels combined, for events satisfying all selection criteria. The expected signal for $m_H = 125$ GeV is shown stacked on top of the background prediction. The W+jets background is estimated from data, and WW and top background MC predictions are normalised to the data using control regions. The hashed area indicates the total uncertainty on the background prediction.

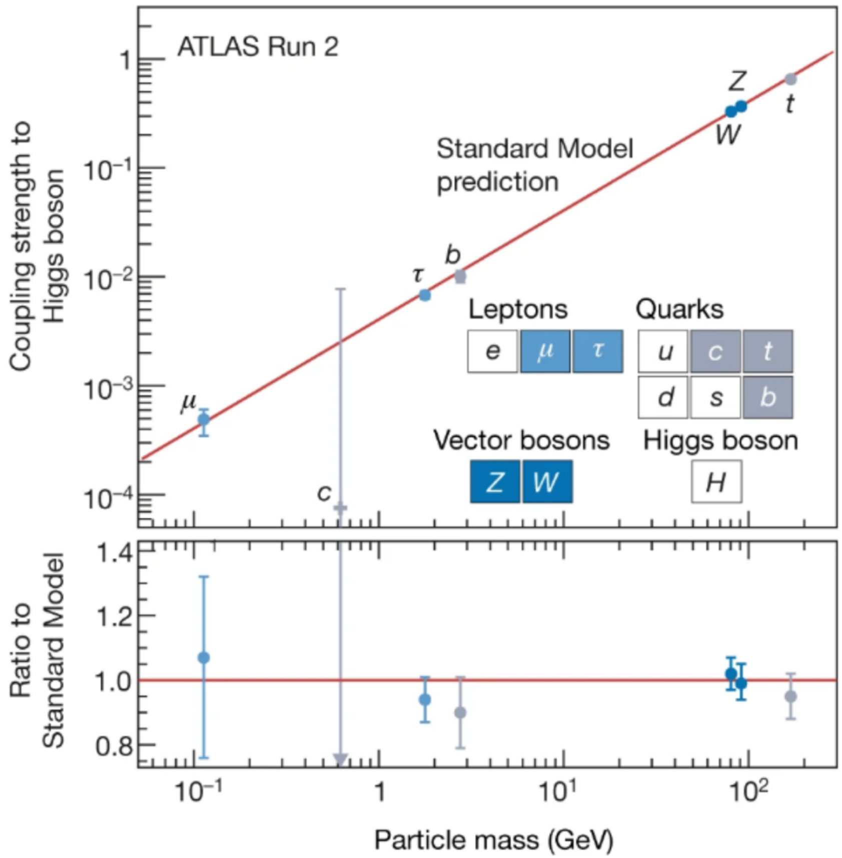
Higgs discovery

At every hypothesized m_H, find p_0 = p-value of hypothesis that the data are composed of background only.

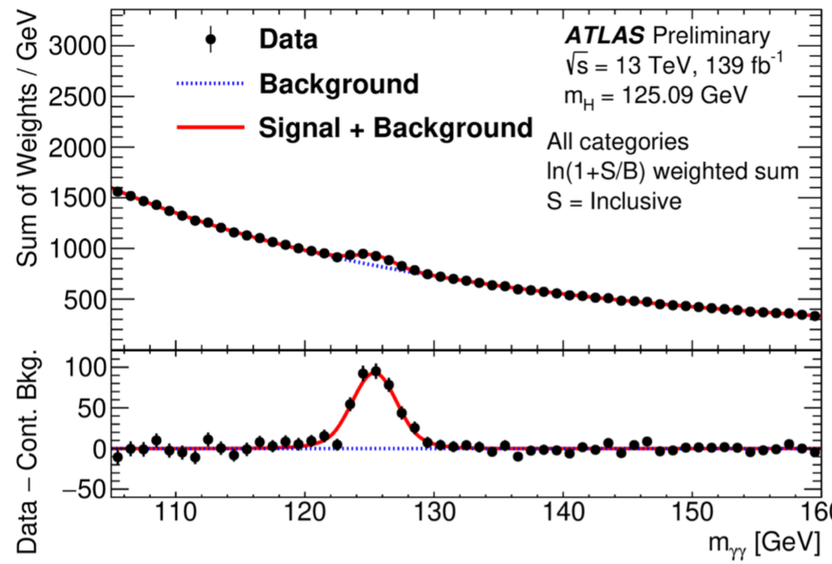


Higgs 2022 update

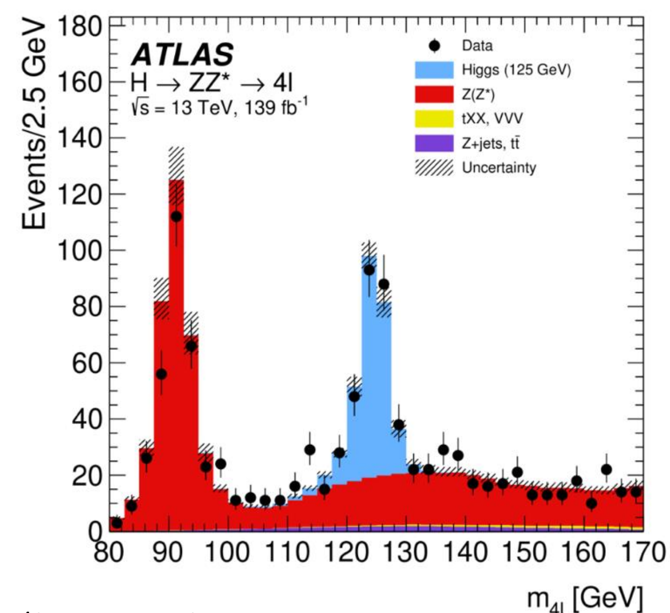
m_H = 125.0 GeV (+/- 0.2 GeV)



$H \to \gamma\gamma$

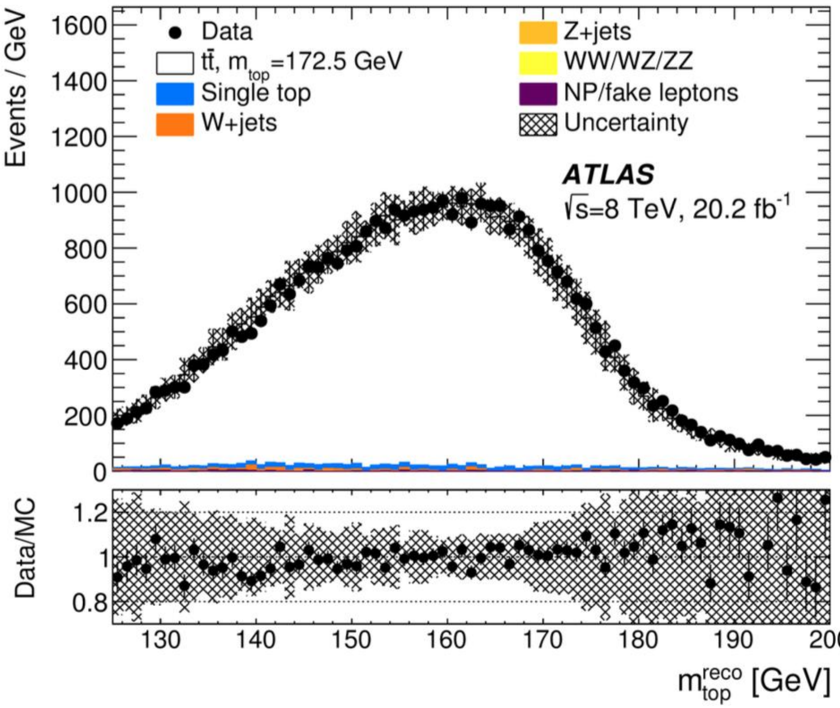


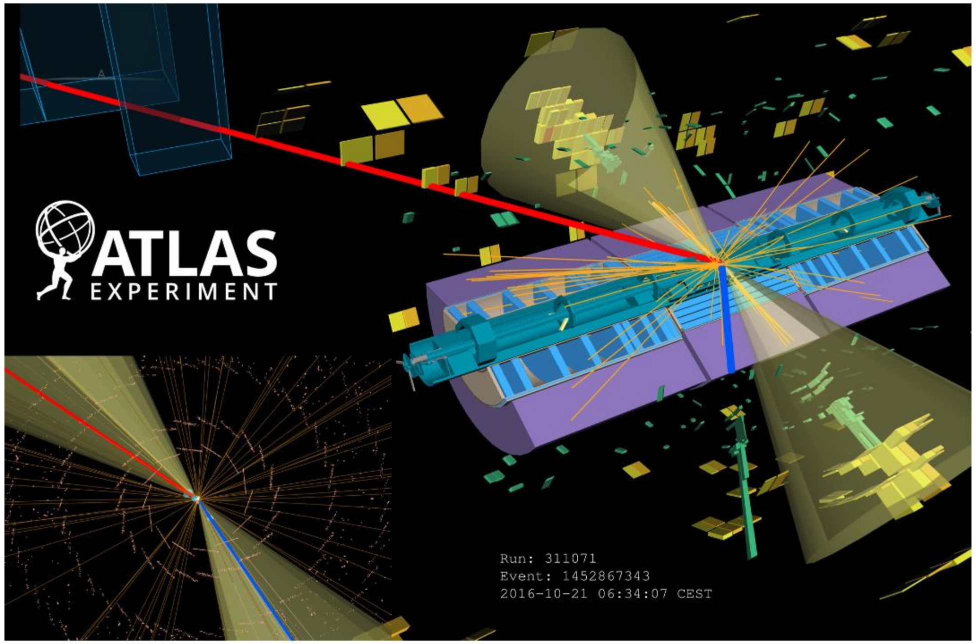
$H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$



Top Quark Physics

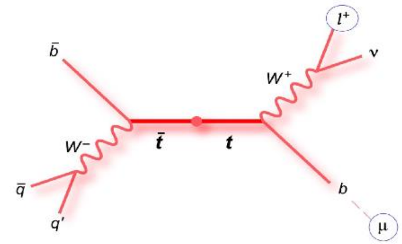
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2017-03/

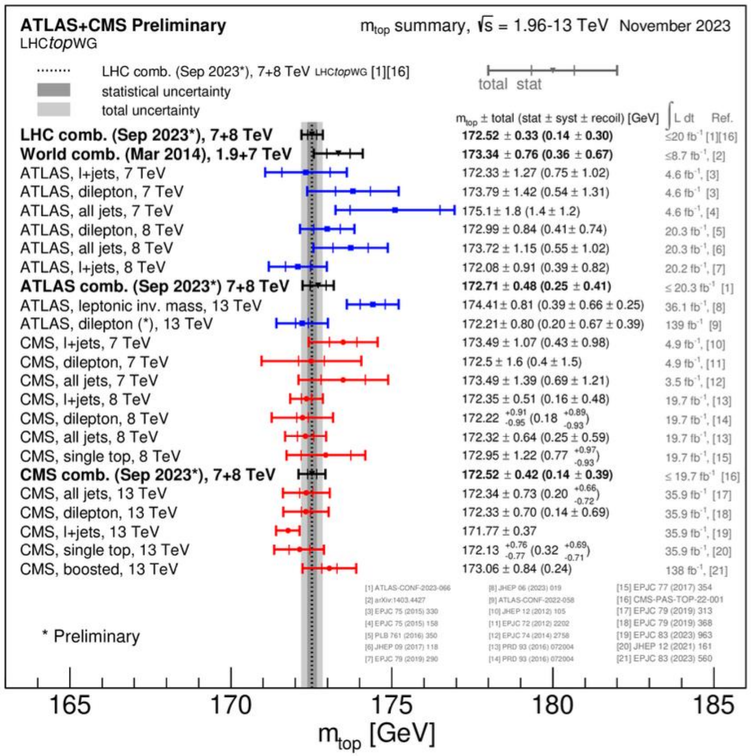


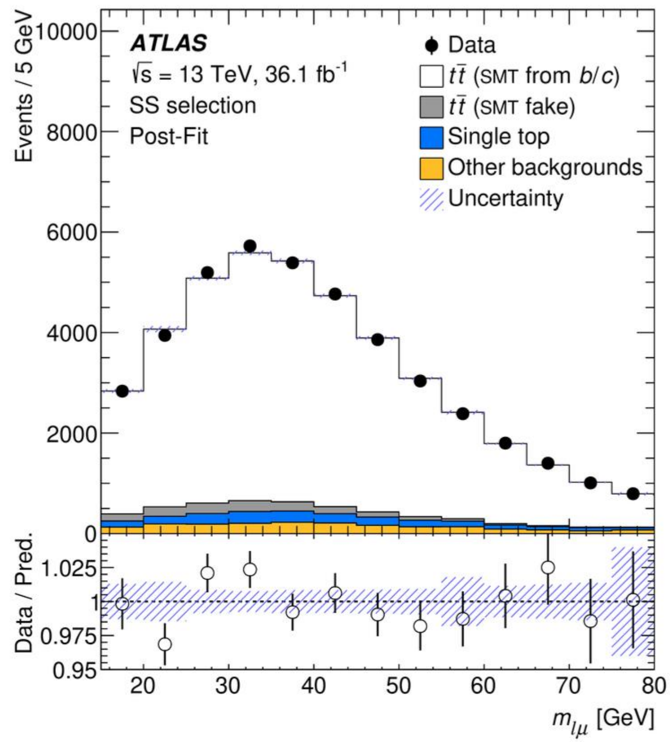


Dilepton channel: electron, muon, 2 b-tag jets

Top Quark Physics







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