Research-based Particle Physics

FYS5555 – FYS9555

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Collider Physics II

Hadron collisions at Tevatron and LHC, Parton distribution functions and parton-parton collisions, Physics results

High pT Physics at hadron colliders
Modern Particle Physics, M. Thomson

Drell-Yan process: $q\bar{q} \rightarrow \mu^+\mu^-$

- You calculated the process

$$e^+e^- \rightarrow \mu^+\mu^- \quad ; \quad e^+e^- \rightarrow q\bar{q}$$

- Corresponding cross section for $q\bar{q} \rightarrow \mu^+\mu^-$

$$\sigma(q\bar{q} \rightarrow \mu^+\mu^-) = \frac{1}{N_c} Q_q^2 \frac{4\pi\alpha^2}{3\hat{s}}$$

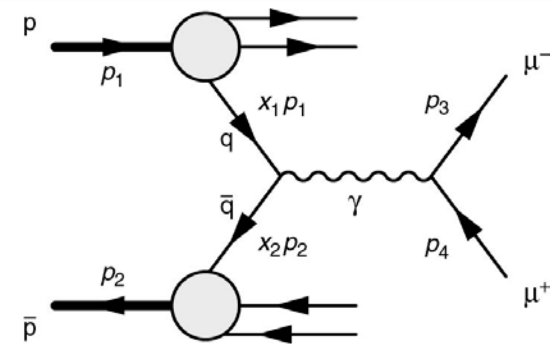
  - N_c=3 accounts for conservation of color charge
    - Implying that of the 9 possible color combinations of the qqbar system, annihilation process only occurs for 3: rrbar, ggbar, bbbar

- Parton Distribution Functions
  - u-quark within proton with momentum fraction $x_1 \rightarrow x_1+\delta x_1$
  - anti-u-quark within anti-proton with momentum fraction $x_2 \rightarrow x_2+\delta x_2$

- CoM energy of hard process

$$\hat{s} = (x_1 p_1 + x_2 p_2)^2 = x_1^2 p_1^2 + x_2^2 p_2^2 + 2 x_1 x_2 p_1 \cdot p_2$$

$$p_1^2 = p_2^2 = m_p^2 \approx 0 \Rightarrow \hat{s} \approx 2 x_1 x_2 p_1 \cdot p_2 = x_1 x_2 s$$



$$p\bar{p} \rightarrow \mu^+\mu^- + X$$

$$d^2\sigma_u = Q_u^2 \frac{4\pi\alpha^2}{9\hat{s}} u^p(x_1)dx_1 \bar{u}^{\bar{p}}(x_2)dx_2$$

$$\bar{u}^{\bar{p}}(x) = u^p(x) = u(x)$$

$$d^2\sigma_u = \frac{4}{9}\frac{4\pi\alpha^2}{9\hat{s}} u(x_1)u(x_2)dx_1dx_2$$

$$d^2\sigma_u = \frac{4}{9} \cdot \frac{4\pi\alpha^2}{9 x_1 x_2 s} u(x_1)u(x_2)dx_1dx_2$$

- Accounting for (smaller) contribution from ubar from proton and u from anti-proton and contribution from ddbar annihilation:

$$d^2\sigma = \frac{4\pi\alpha^2}{9x_1x_2s}\left\{\frac{4}{9}\left[u(x_1)u(x_2)+\bar{u}(x_1)\bar{u}(x_2)\right]+\left[d(x_1)d(x_2)+\bar{d}(x_1)\bar{d}(x_2)\right]\frac{1}{9}\right\}dx_1dx_2$$

$$d^2\sigma = \frac{4\pi\alpha^2}{9x_1x_2s} f(x_1, x_2)dx_1dx_2$$

- In terms of experimental observables:
  - Rapidity & invariant mass of di-muons

$$M^2 = \hat{s} = x_1x_2s$$

$$y = \frac{1}{2}\ln\left(\frac{E_3+E_4+p_{3z}+p_{4z}}{E_3+E_4-p_{3z}-p_{4z}}\right) = \frac{1}{2}\ln\left(\frac{E_q+E_{\bar{q}}+p_{qz}+p_{\bar{q}z}}{E_q+E_{\bar{q}}-p_{qz}-p_{\bar{q}z}}\right)$$

$$p_q = \frac{\sqrt{s}}{2}(x_1, 0, 0, x_1) \quad ; \quad p_{\bar{q}} = \frac{\sqrt{s}}{2}(x_2, 0, 0, -x_2)$$

$$\Rightarrow y = \frac{1}{2}\ln\left(\frac{(x_1+x_2)+(x_1-x_2)}{(x_1+x_2)-(x_1-x_2)}\right) = \frac{1}{2}\ln\left(\frac{x_1}{x_2}\right)$$

$$x_1 = \frac{M}{\sqrt{s}}e^{y} \quad ; \quad x_2 = \frac{M}{\sqrt{s}}e^{-y}$$

- Differential cross section: $dx_1\, dx_2 \rightarrow dy\, dM$
  - Determination of the Jacobian matrix

$$dy\, dM = \frac{\partial(y, M)}{\partial(x_1, x_2)} dx_1\ dx_2 = \begin{vmatrix} \frac{\partial y}{\partial x_1} & \frac{\partial y}{\partial x_2} \\ \frac{\partial M}{\partial x_1} & \frac{\partial M}{\partial x_2} \end{vmatrix} dx_1\ dx_2$$

$$dy\, dM = \frac{s}{2M} dx_1\ dx_2$$

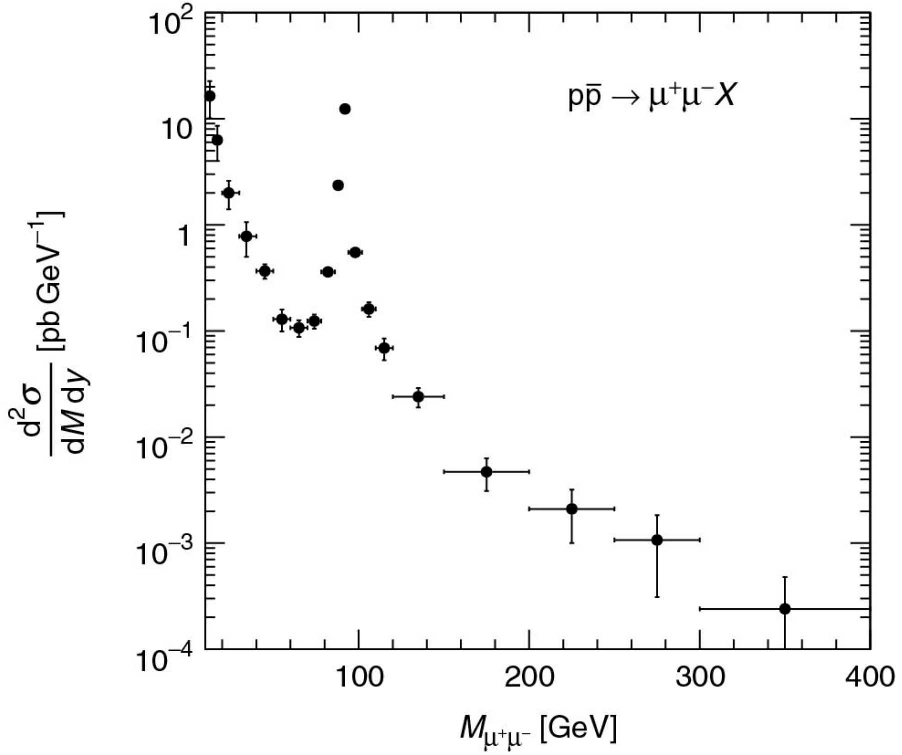
$$d^2\sigma = \frac{4\pi\alpha^2}{9 x_1 x_2 s} f(x_1, x_2) dx_1 dx_2$$

$$d^2\sigma = \frac{4\pi\alpha^2}{9 M^2 s} f(x_1, x_2) \frac{2M}{s} dy\, dM$$

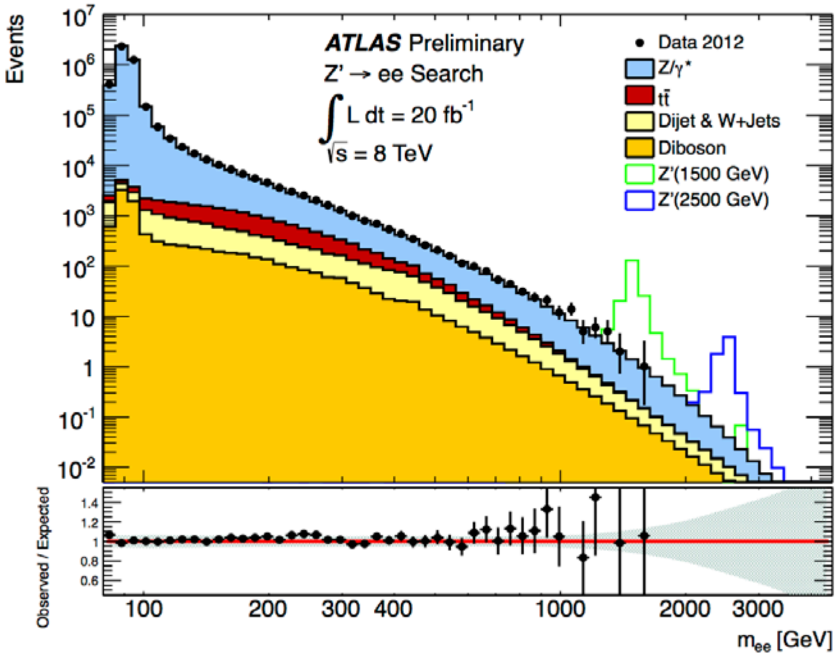
$$\frac{d^2\sigma}{dy\, dM} = \frac{8\pi\alpha^2}{9 M s^2} f(x_1, x_2)$$

- As in project 2
  - Z-exchange (and any other exchange, Z′, …) can be added
- Experimental distribution
  - CDF @ Tevatron (1989-2011), showing Z-resonance
  - ATLAS @ LHC (pp→$\mu^+\mu^-$+X)

Drell-Yan cross section in ppbar collisions at 1.8 TeV, CDF @ Tevatron



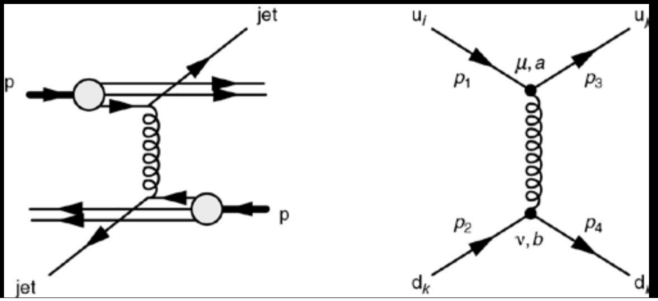
$pp \to e^+e^- + X$ at 8 TeV, ATLAS at LHC
And search for new gauge bosons



Gluons and QCD

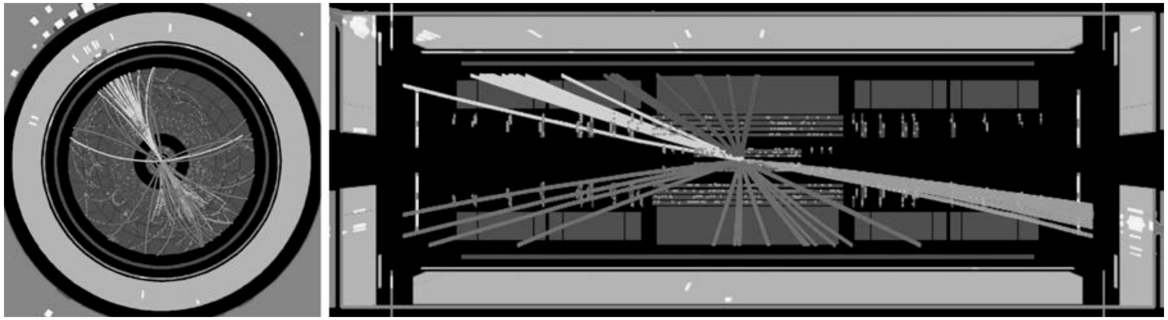
- See M. Thompson: chapter 10 on QCD
- Short summary on how to calculate QCD processes
- Fys5555-19-QcdProcesses

pp→jet-jet+X: qq→qq



- Example of hard QCD scattering
  - Contributing to 2-jet cross section
    - Back-to-back in transverse plane (no p_T)
    - Boost in the other view (net momentum of colliding partons along beam axis)
  - Many other contributions, gg, qg, qqbar, … (see later)

$$\left.\begin{array}{c} qq \xrightarrow[g]{} qq: \\ \hat{s} = x_1 x_2 s \ , \ Q^2 = -q^2 \end{array}\right\} \frac{d\sigma}{dQ^2} = \frac{4\pi\alpha_s^2}{9Q^4}\left[1+\left(1-\frac{Q^2}{\hat{s}}\right)^2\right]$$



$$pp \rightarrow qq\ldots: \ \frac{d\sigma}{dQ^2} = \frac{4\pi\alpha_s^2}{9Q^4}\left[1+\left(1-\frac{Q^2}{x_1 x_2 s}\right)^2\right] g(x_1, x_2)dx_1 dx_2$$

$$g(x_1, x_2) = [u(x_1)u(x_2) + u(x_1)d(x_2) + d(x_1)u(x_2) + d(x_1)d(x_2)]$$

$$\frac{d^3\sigma}{dQ^2 dx_1 dx_2} = \frac{4\pi\alpha_s^2}{9Q^4}\left[1+\left(1-\frac{Q^2}{x_1 x_2 s}\right)^2\right] g(x_1, x_2)$$

$$(Q^2, x_1, x_2) \rightarrow (p_T, y_3, y_4)$$

Exercise

10.6 The observed events in the process pp $\to$ two-jets at the LHC can be described in terms of the jet p_T and the jet rapidities y_3 and y_4.

(a) Assuming that the jets are massless, $E^2 = p_T^2 + p_z^2$, show that the four-momenta of the final-state jets can be written as

$$p_3 = (p_T \cosh y_3, +p_T \sin\phi, +p_T \cos\phi, p_T \sinh y_3),$$
$$p_4 = (p_T \cosh y_4, -p_T \sin\phi, -p_T \cos\phi, p_T \sinh y_4).$$

(b) By writing the four-momenta of the colliding partons in a pp collision as

$$p_1 = \frac{\sqrt{s}}{2}(x_1, 0, 0, x_1) \quad \text{and} \quad p_2 = \frac{\sqrt{s}}{2}(x_2, 0, 0, -x_1),$$

show that conservation of energy and momentum implies

$$x_1 = \frac{p_T}{\sqrt{s}}(e^{+y_3} + e^{+y_4}) \quad \text{and} \quad x_2 = \frac{p_T}{\sqrt{s}}(e^{-y_3} + e^{-y_4}).$$

(c) Hence show that

$$Q^2 = p_T^2(1 + e^{y_4 - y_3}).$$

10.7 Using the results of the previous question show that the Jacobian

$$\frac{\partial(y_3, y_4, p_T^2)}{\partial(x_1, x_2, q^2)} = \frac{1}{x_1 x_2}.$$

Exercise

$$(Q^2, x_1, x_2) \rightarrow (p_T, y_3, y_4)$$

$$p^\mu = \left(E, p_x, p_y, p_z\right) = \left(m_T \cosh y, p_T \cos\phi, p_T \sin\phi, m_T \sinh y\right)$$

- m=0 → $m_T = p_T$

$$\Rightarrow p_3 = \left(p_T \cosh y_3, p_T \cos\phi, p_T \sin\phi, p_T \sinh y_3\right)$$

$$p_4 = \left(p_T \cosh y_4, p_T \cos\phi, p_T \sin\phi, p_T \sinh y_4\right)$$

- Conservation of E/P

$$p_1 = \frac{\sqrt{s}}{2}(x_1, 0, 0, x_1) \quad ; \quad p_2 = \frac{\sqrt{s}}{2}(x_2, 0, 0, -x_2)$$

⇒

$$x_1 = \frac{p_T}{\sqrt{s}}(e^{+y_3} + e^{+y_4})$$

$$x_2 = \frac{p_T}{\sqrt{s}}(e^{-y_3} + e^{-y_4})$$

$$Q^2 = p_T^2(1 + e^{y_4 - y_3}),$$

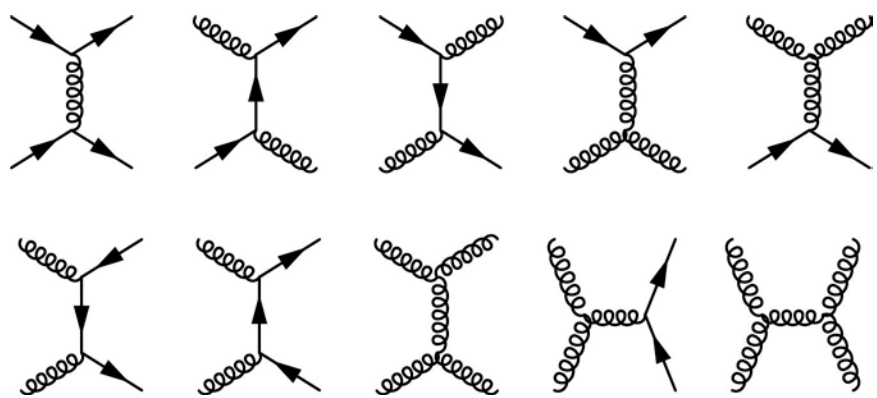
Exercise

$$(Q^2, x_1, x_2) \rightarrow (p_T, y_3, y_4)$$

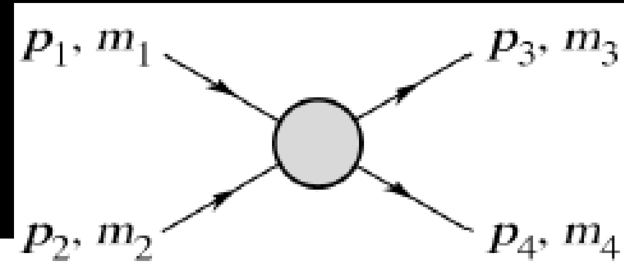
$$x_1 = \frac{p_T}{\sqrt{s}}(e^{+y_3} + e^{+y_4})$$
$$x_2 = \frac{p_T}{\sqrt{s}}(e^{-y_3} + e^{-y_4})$$
$$Q^2 = p_T^2(1 + e^{y_4 - y_3}),$$

$$dx_1 dx_2 dQ^2 = \frac{\partial(y_3, y_4, p_T^2)}{\partial(x_1, x_2, Q^2)} dp_T^2 dy_3 dy_4$$
$$= \frac{1}{x_1 x_2} dp_T^2 dy_3 dy_4$$

- Add all other contributions
  - 2-jet cross section!
  - Need higher orders QCD!

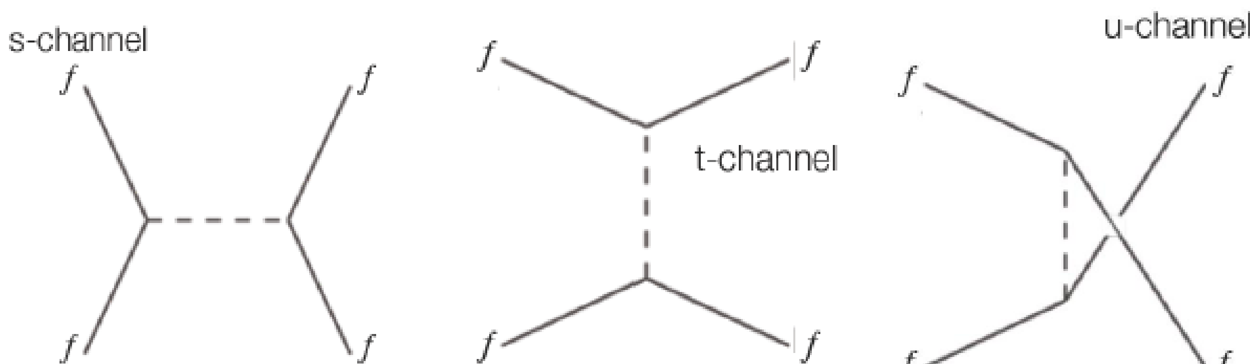


2→2 processes



- Mandelstam variables

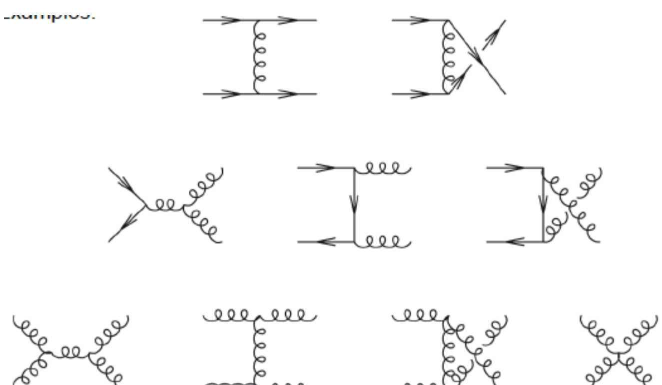
$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$
$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$
$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$

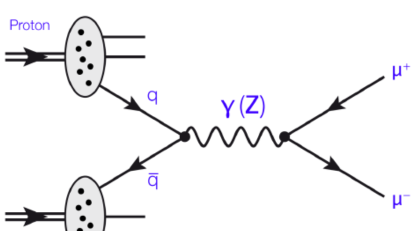


$$\sigma \propto \frac{t^2 + u^2}{s^2} \qquad \sigma \propto \frac{s^2 + u^2}{t^2} \qquad \sigma \propto \frac{s^2 + t^2}{u^2}$$

- Example:
  - Drell-Yan

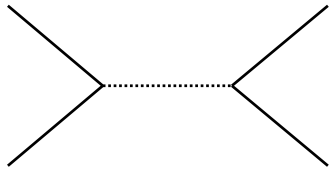
QCD processes





QCD matrix elements – point-like scattering of partons

- Point-like partons have Rutherford like behavior



$\sigma \sim \pi(\alpha_1\alpha_2)|A|^2/s$

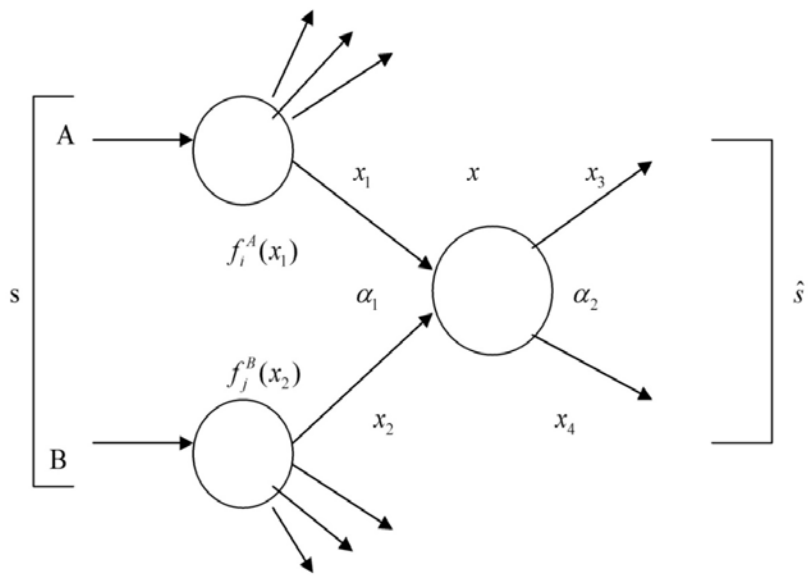
- $|A|^2 \sim 1$ at y=0 ($\theta=\pi/2$).

Process	$\lvert A\rvert^2$	**Value at $\theta = \pi/2$**
$q+q' \to q+q'$	$\frac{4}{9}[s^2+u^2]/t^2$	2.22
$q+q \to q+q$	$\frac{4}{9}[(s^2+u^2)/t^2+(s^2+t^2)/u^2]-\frac{8}{27}(s^2/ut)$	3.26
$q+\bar{q} \to q'+\bar{q}'$	$\frac{4}{9}[t^2+u^2]/s^2$	0.22
$q+\bar{q} \to q+\bar{q}$	$\frac{4}{9}[(s^2+u^2)/t^2+(t^2+u^2)/s^2]-\frac{8}{27}(u^2/st)$	2.59
$q+\bar{q} \to g+g$	$\frac{32}{27}[t^2+u^2]/tu-\frac{8}{3}[t^2+u^2]/s^2$	1.04
$g+g \to q+\bar{q}$	$\frac{1}{6}[t^2+u^2]/tu-\frac{3}{8}[t^2+u^2]/s^2$	0.15
$g+q \to g+q$	$-\frac{4}{9}[s^2+u^2]/su+[u^2+s^2]/t^2$	6.11
$g+g \to g+g$	$\frac{9}{2}[3-tu/s^2-su/t^2-st/u^2]$	30.4
$q+\bar{q} \to \gamma+g$	$\frac{8}{9}[t^2+u^2]/tu$	
$g+q \to \gamma+q$	$-\frac{1}{3}[s^2+u^2]/su$	

Proton structure functions (see D. Green, M. Thomson)

- Assume proton is incoherent sum of "valence" *u* and *d* quarks, radiated gluons, and a "sea" of quark and anti-quark pairs.
- Proton quantum numbers satisfied if proton is bound state of u + u + d "valence" quarks.
- The "sea" can arise from radiation by the valence quarks and the antiquarks and subsequent gluon "splitting" or virtual decay into quark-antiquark pairs.

- "Hard" p_T, scales well above the binding energy scale, $P_T >> \Lambda_{QCD}$



- For large E_T/P_T, or short distances, the proton can be treated as containing partons defined by distribution "structure" functions.
- f(x) is the probability distribution to find a parton with momentum fraction x

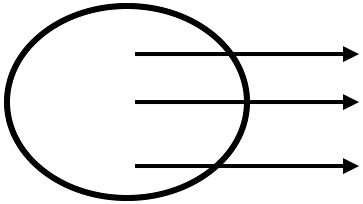
$$x = \frac{p_{parton}}{p_{proton}}$$

$$\sqrt{s} = \sqrt{(p_A + p_B)^2}$$

$$\sqrt{\hat{s}} = x_1 x_2 \sqrt{s}$$

Parton distribution functions

- Assume very weak binding of the u,u,d "valence" quarks in the proton → all 3 quarks same velocity
  - $x = p_{parton}/p_{proton} \sim 1/3$
  - $f(x)$ δ-function



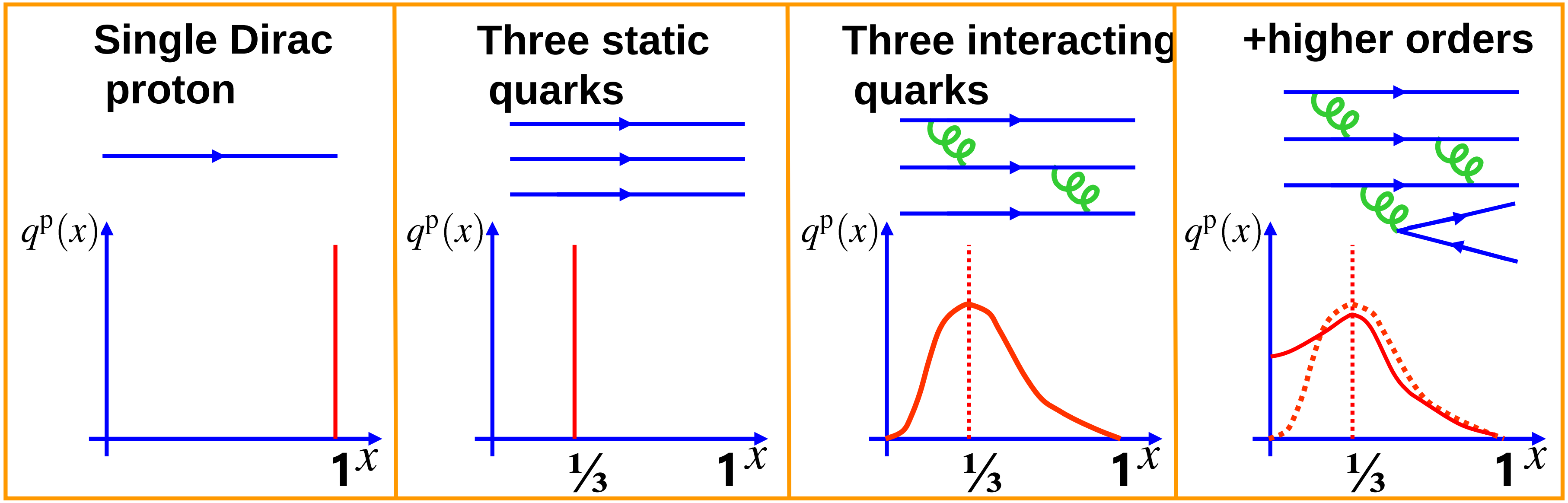
- But quarks are bound →

$$\Delta x \Delta p_x \approx \hbar$$

$$\Delta x = 1\,fm \rightarrow \Delta p_x = 0.2\,GeV \approx \Lambda_{QCD}$$

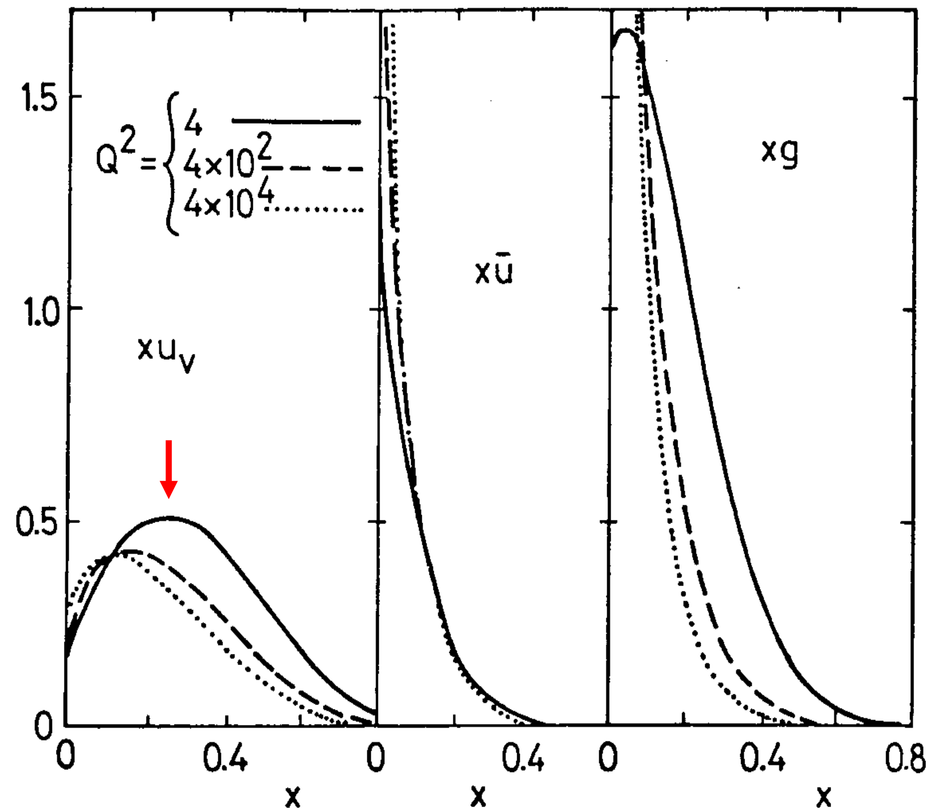
- $m_q \sim 5$MeV → relativistic system
  - valence quarks can radiate gluons ($xg(x) \sim$ constant for small x)
  - gluons can split into q-qbar pairs (including strangeness with $xs(x) \sim$ constant)
- The parton distribution is, in principle, calculable but not perturbatively
  - In practice measured in lepton-proton scattering

Proton structure functions - pictorial



Experimental determination of parton distribution functions

- In proton, u & d quarks have largest probability density at large x
  - residual memory of x~1/3 for valence quarks
  - reduction due to gluon emission
- Gluons and "sea" anti-quarks have large probability at low x.
  - gluons carry ~ 50% of proton momentum
- Simple parameterisations



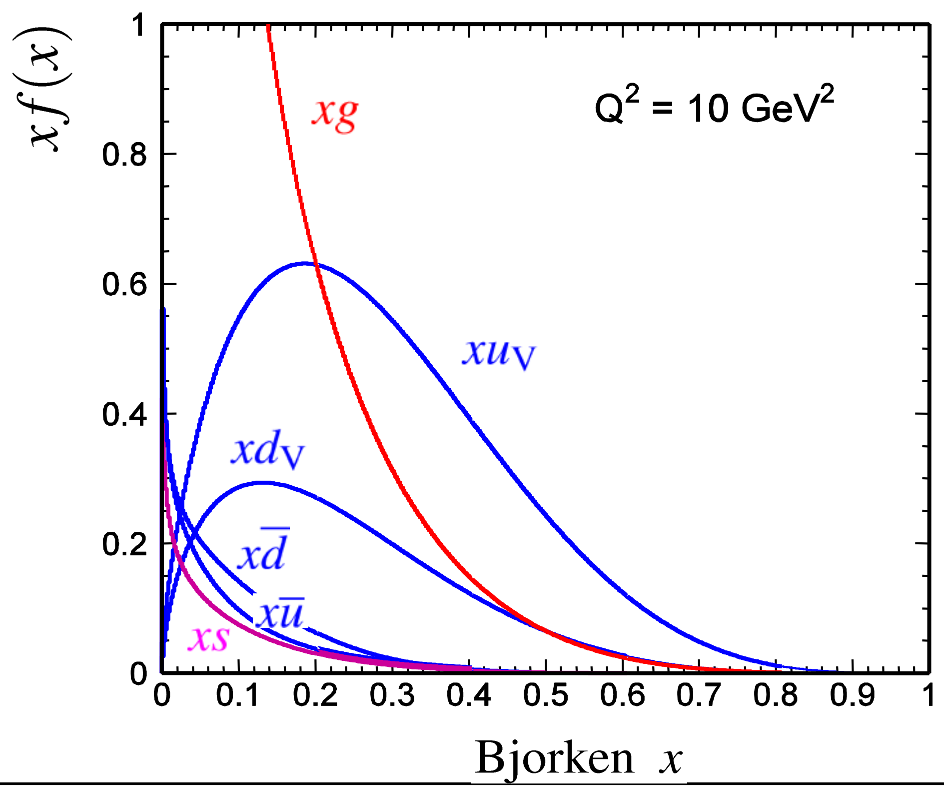
$$xg(x) = \tfrac{7}{2}(1-x)^6 \quad ; \quad \int xg(x)dx = \tfrac{1}{2}$$

$$x\bar{f}(x) \sim (1-x)^\alpha$$

Parton Distribution Functions

- Ultimately the parton distribution functions are obtained from a fit to all experimental data including e-p and e-n scattering, neutrino-nucleon scattering,
  - Hadron-hadron collisions also give information, especially on gluon pdf $g(x)$
  - different experimental measurements give access to different PDFs

Fit to all data: constraints imposed by theoretical QCD framework such as DGLAP evolution equations

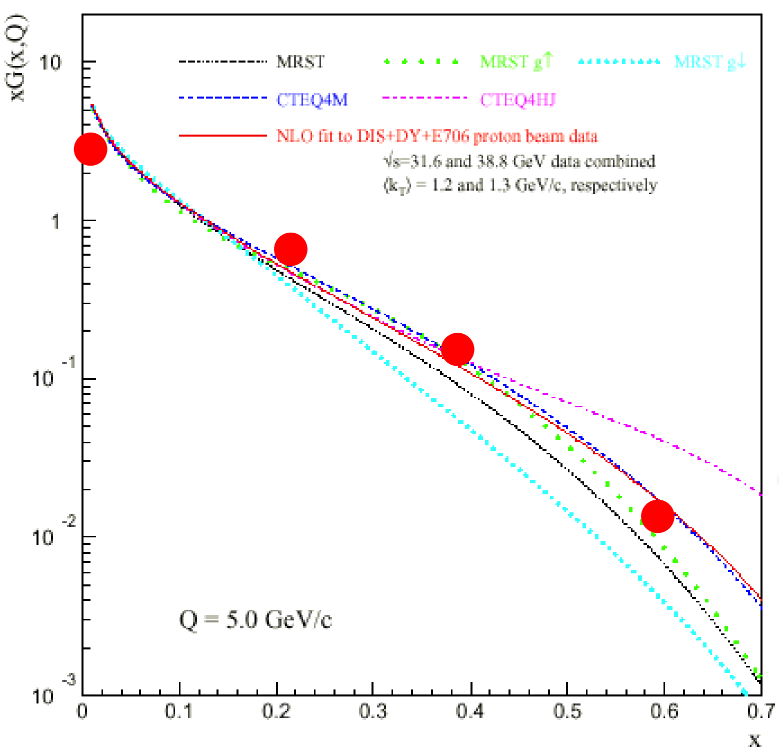


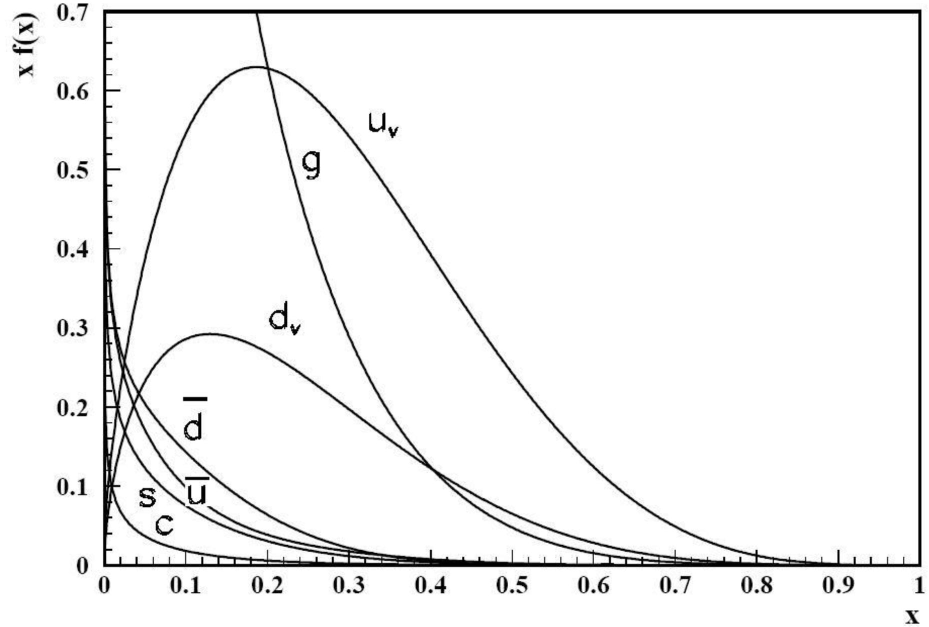
Note:

- Apart from at large x
  $$u_V(x) \approx 2d_V(x)$$
- For $x < 0.2$ gluons dominate
- In fits to data assume
  $$u_s(x) = \bar{u}(x)$$
- $\bar{d}(x) > \bar{u}(x)$ not understood – suppression $g \to u\bar{u}$ due to exclusion principle?
- Small strange quark component $s(x)$

Experimental determination of parton distribution functions

- g dominates for x < 0.2
- at large x, u dominates over d and g
- "sea" dominates for x < 0.03 over valence





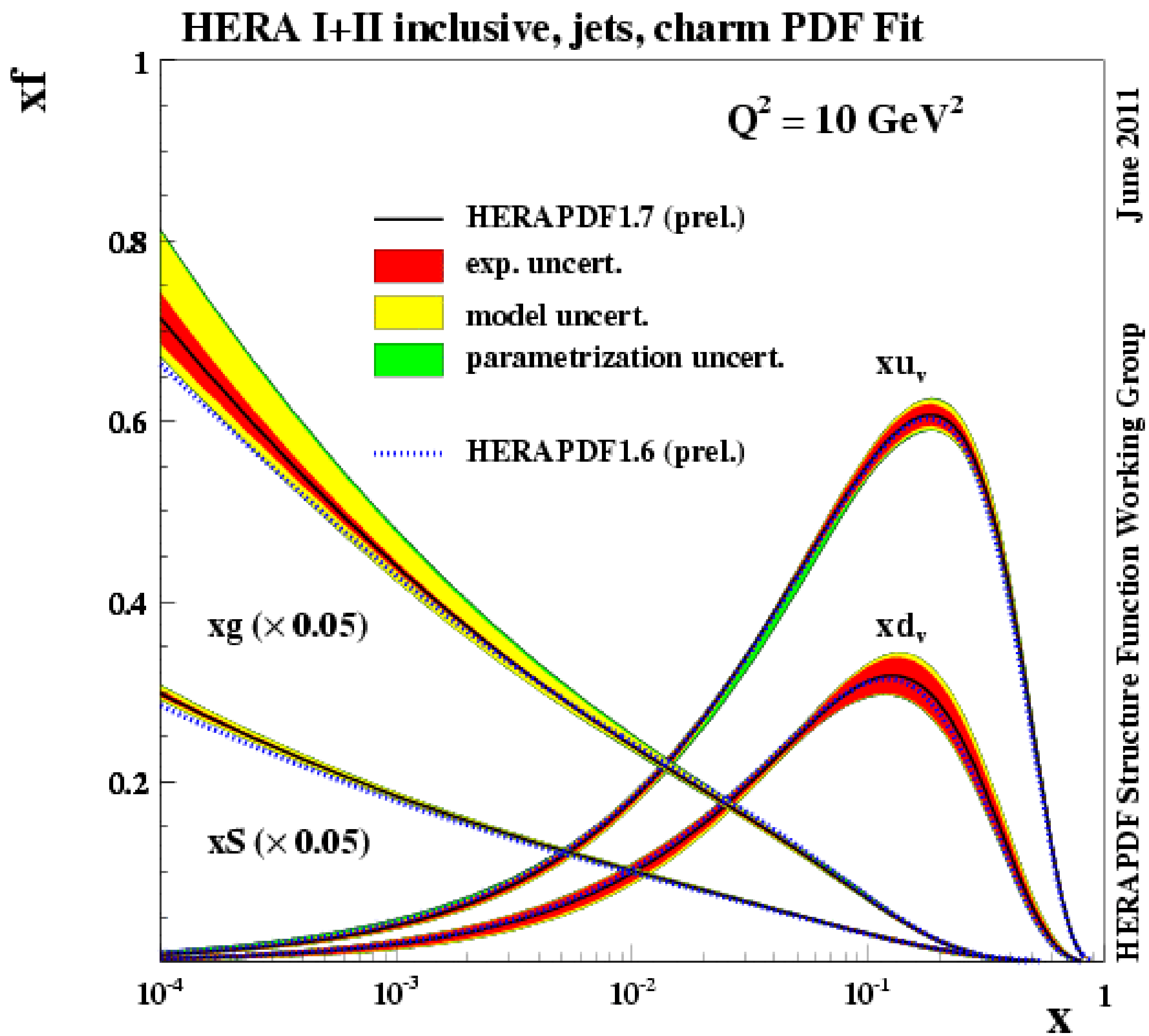
- Lines: different fits to experimental data
- Points: simple xg(x) parameterization

$$xg(x) = \frac{7}{2}(1-x)^6$$

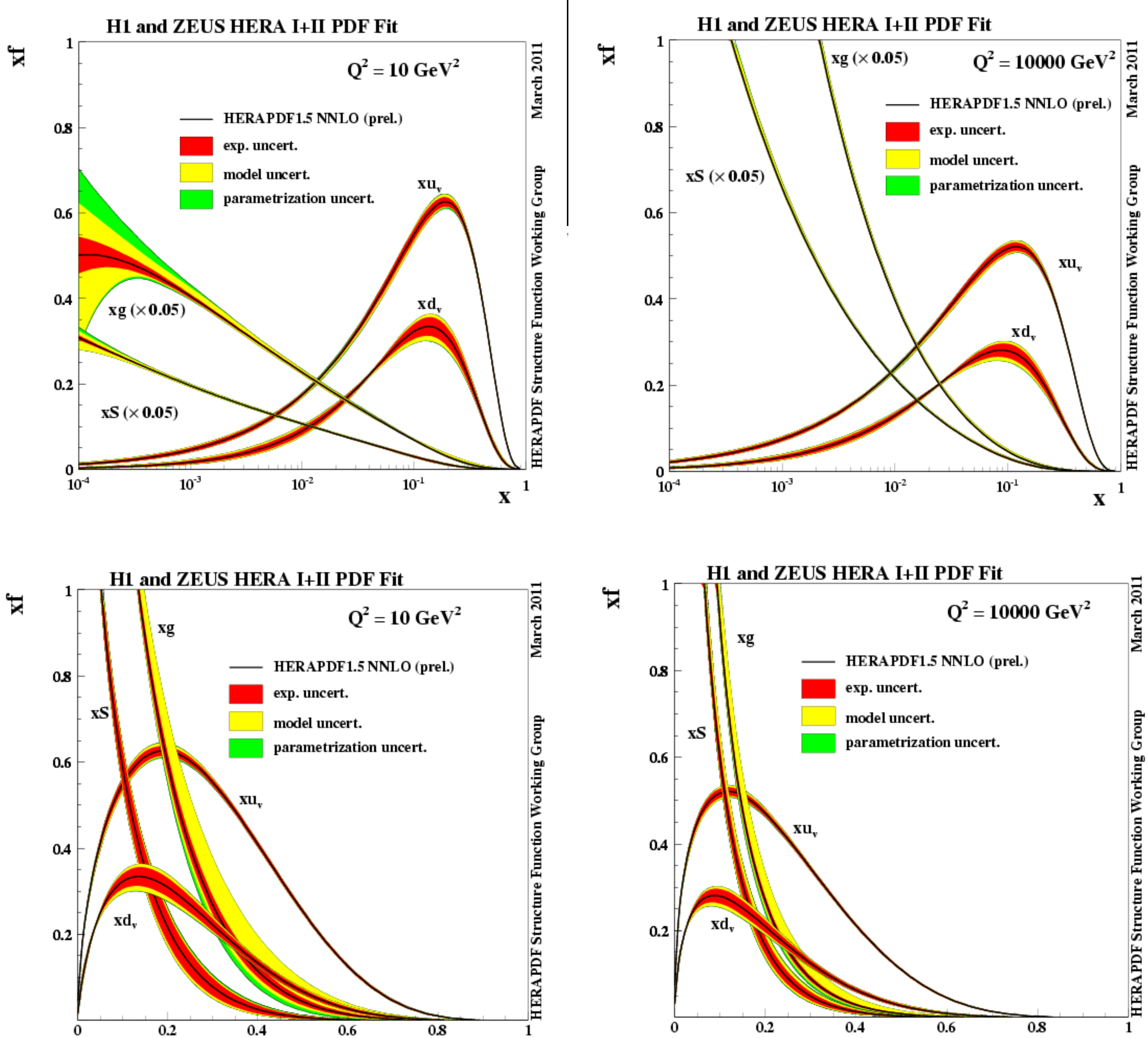
- In CompHEP:
  - can run different distribution functions (MRST, CTEQ, ...) for same process.

Structure functions and ep-collider HERA

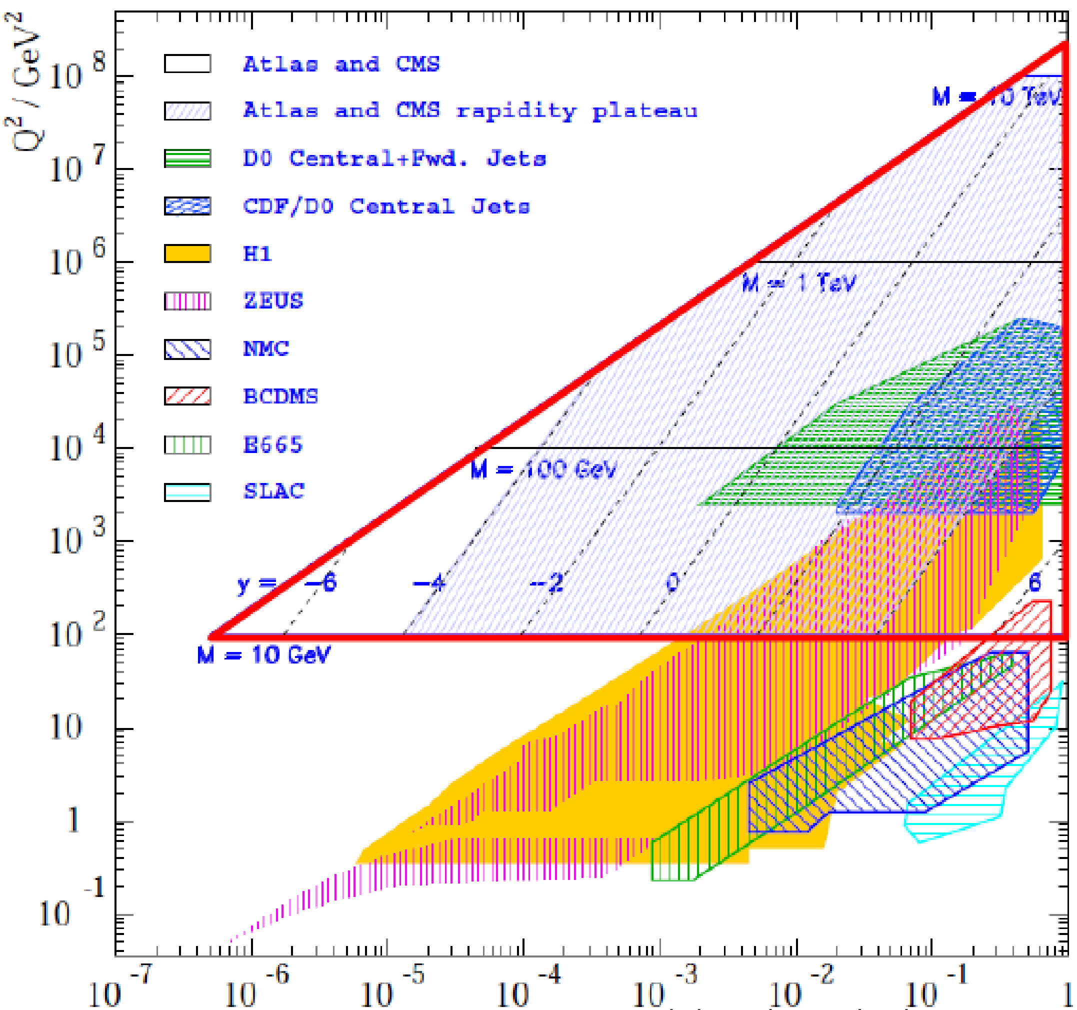
- Parton distributions ($xf(x,Q^2)$) are obtained from (QCD) fits to cross section of various measured processes (ep NC, CC, high PT jet production, charm production, ...)
  - And theoretical extrapolations, DGLAP evolution equations



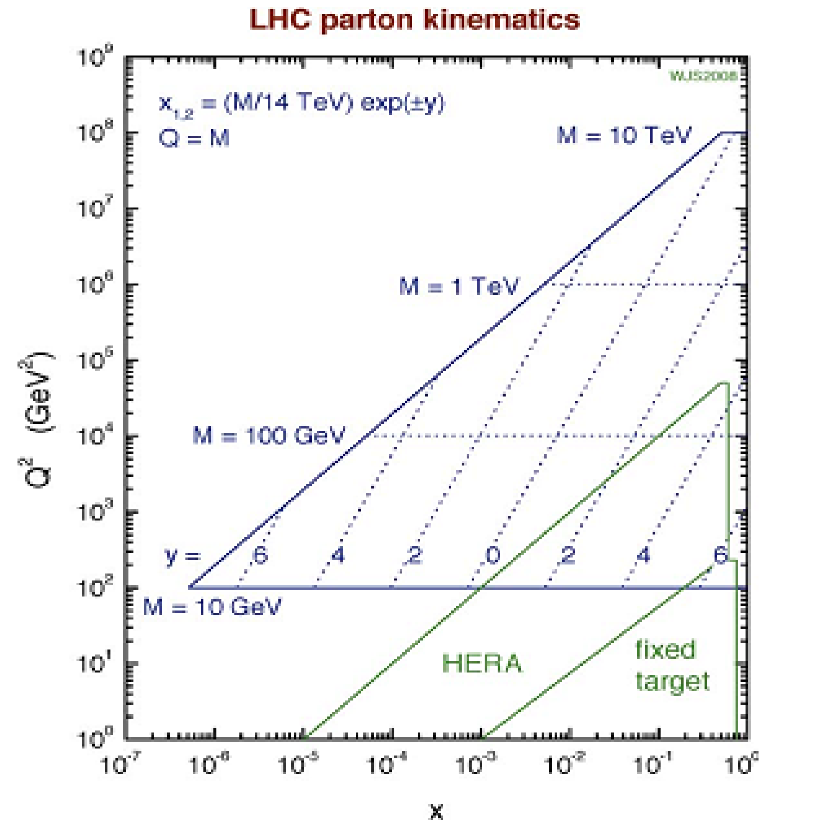
HERA Probability Density Functions



Parton kinematics – overview



S. Glazov, Braz.J.Ph. 37 (2007) 793.



- The LHC data probe regions of the distribution functions which were not explored by fixed target and HERA experiments
- It is important to have a reliable set of verified PDF in order to model new physics and SM backgrounds.

$F_2(x,Q^2)$ structure function Results

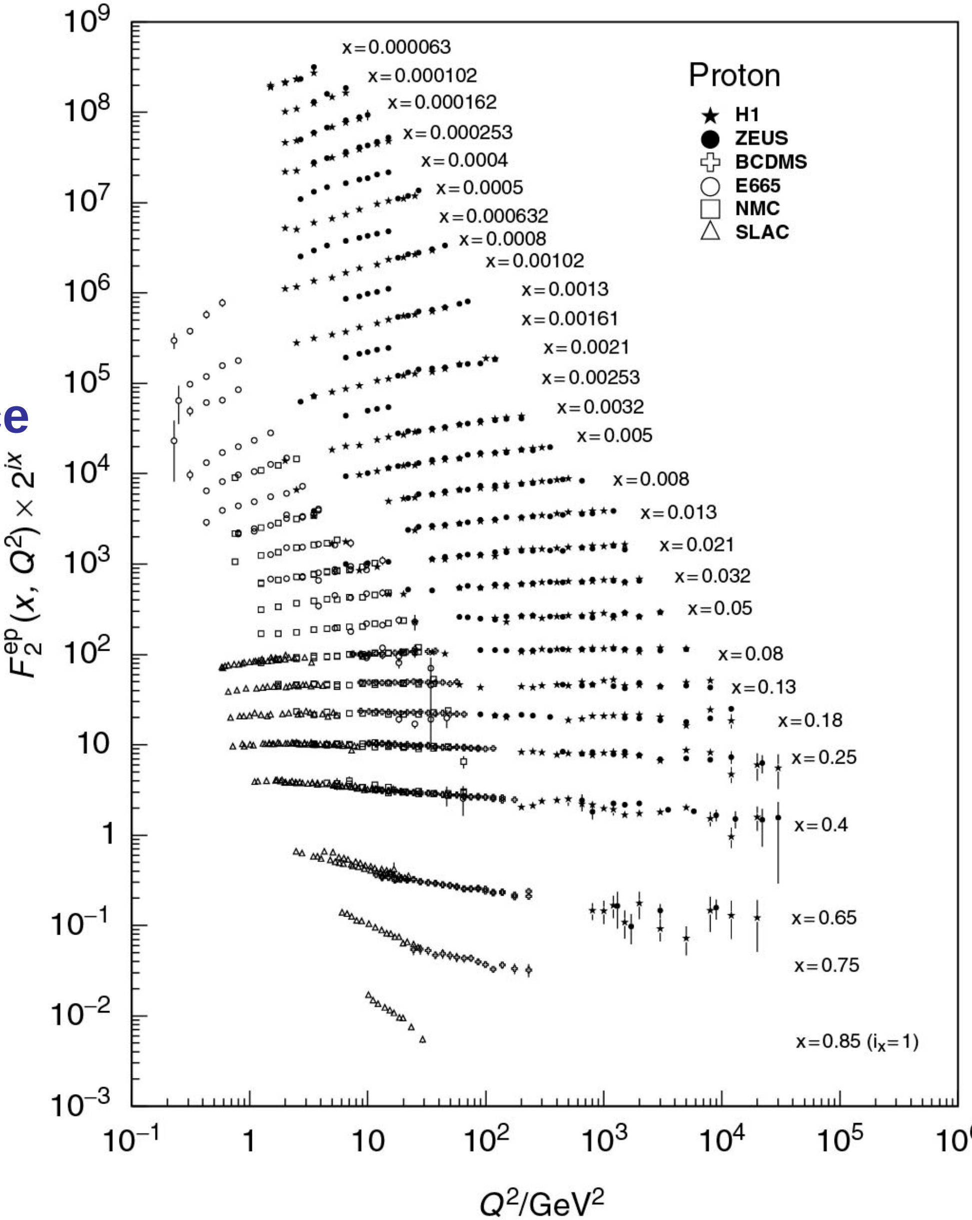
★ No evidence of rapid decrease of cross section at highest Q^2

$$\Rightarrow \quad R_{\text{quark}} < 10^{-18}\,\text{m}$$

★ For x > **0.05**, only weak dependence of F_2 on Q^2 : consistent with the expectation from the quark-parton model

★ But observe clear scaling violation at high and low values of x

$$F_2(x,Q^2) \neq F_2(x)$$

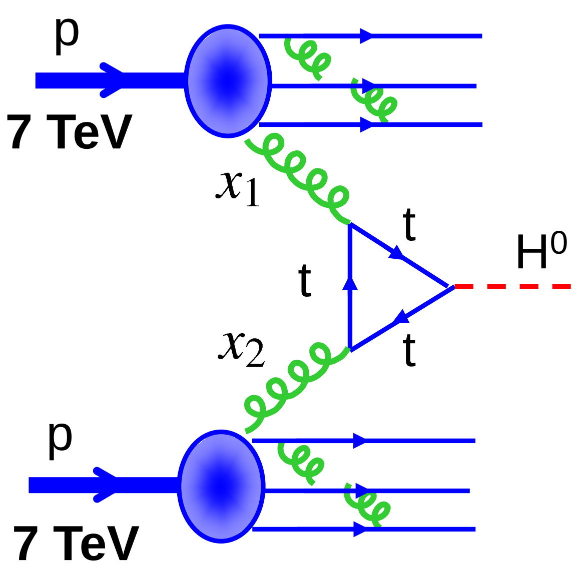


Proton-Proton Collisions at the LHC

★ Measurements of structure functions not only provide a powerful test of QCD, the **parton distribution functions** are essential for the calculation of cross sections at pp and $p\bar{p}$ colliders.

• **Example:** Higgs production at the Large Hadron Collider LHC

- The HE-LHC will collide 7 TeV protons on 7 TeV protons
- However underlying collisions are between partons
- Higgs production at the LHC dominated by "gluon-gluon fusion"



- Cross section depends on gluon PDFs

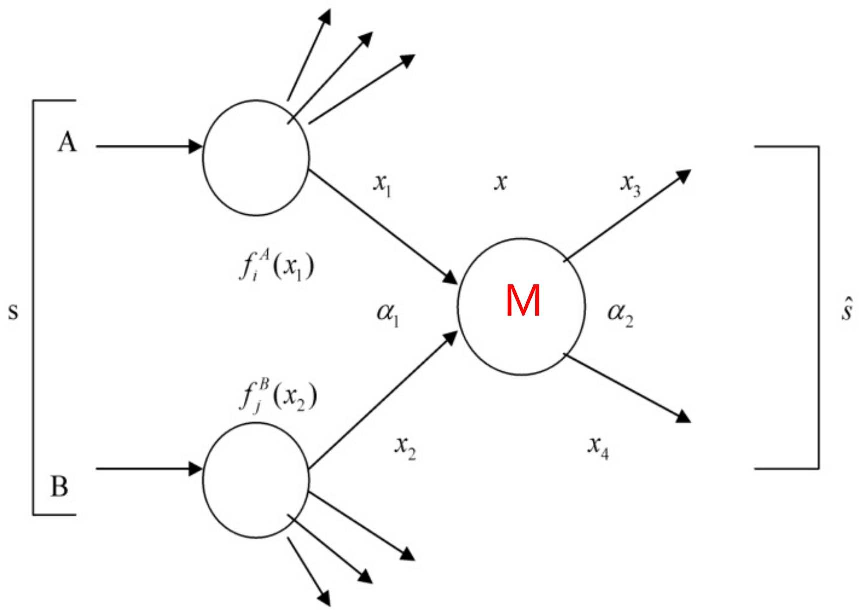
$$\sigma(pp \to HX) \sim \int_0^1 \int_0^1 g(x_1)g(x_2)\sigma(gg \to H)\mathrm{d}x_1\mathrm{d}x_2$$

- Uncertainty in gluon PDFs lead to a ±5 % uncertainty in Higgs production cross section
- Prior to HERA data uncertainty was ±25 %

Hadronic cross-sections (see D. Green)

- A+B→1+2+X→M+X→3+4+X
- Cross section is a convolution of matrix elements (ME) and parton distribution functions (PDF)

$$\sigma = \sum_{i,j} \int f_i^A(x_1) f_j^B(x_2) dx_1 dx_2 \hat{\sigma}_{ij}$$



$$d\sigma_{12} = f_1(x_1) f_2(x_2) dx_1 dx_2 d\hat{\sigma}(1+2 \to 3+4)$$

$p_1=x_1P$ $p_2=x_2P$

$$\sqrt{s} = \sqrt{(p_A + p_B)^2} = 2P$$

$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} = M$$

$$\left.\begin{array}{l} x = x_1 - x_2 \\ \tau \equiv \dfrac{M^2}{s} = x_1 x_2 \end{array}\right\} x = 0 \Rightarrow \langle x \rangle = \sqrt{\tau} = \frac{M}{\sqrt{s}}$$

More 2-body kinematics

- 1+2→M→3+4
  - <x> to produce $t\bar{t}$
    $M \sim 2m_t \sim 350$GeV

$$x = 0 \Rightarrow \langle x \rangle = \sqrt{\tau} = \frac{M}{\sqrt{s}}$$

$$Tevatron(1.8) \quad : M = 2m_t \Rightarrow \langle x \rangle \approx 0.194$$

$$LHC(8/14) \quad : M = 2m_t \Rightarrow \langle x \rangle \approx 0.044/0.025$$

- Higher x means higher M
  - To produce mass of 100 GeV with accelerator running at 14 TeV requires <x>=0.007
  - To produce mass of 5 TeV requires x = 0.36
- To produce M at zero rapidity
  - need partons with same x
- M at higher rapidities
  - one parton at higher x, the other one at smaller x

Hadronic cross-sections

- Values x_1 from A and x_2 from B picked out of probability distributions with the joint probability $f_1 f_2$ to form a system of mass M moving with momentum fraction x
  - C is a color factor.
- Change of variable in order to express σ in terms of variables in final state
  - M and y measured → determine x_1 and x_2

$$d\sigma_{12} = Cf_1(x_1)f_2(x_2)dx_1dx_2d\hat{\sigma}(1+2\to 3+4)$$

$$dx_1dx_2 = d\hat{s}/s dy = d\tau dy$$

$$\tau = \hat{s}/s = M^2/s$$

$$d\sigma = Cf_1(x_1)f_2(x_2)d\tau dy d\hat{\sigma}(1+2\to 3+4)$$

$$y = 0 \to x_1 = x_2 = \sqrt{\tau}$$

$$\left(d\sigma/d\tau dy\right)_{y=0} = Cf_1(\sqrt{\tau})f_2(\sqrt{\tau})d\hat{\sigma}(1+2\to 3+4)$$

- On the rapidity plateau, the cross section can be estimated as $d\sigma \sim (d\sigma/dy)_{y=0}\Delta y$
- At fixed energy, value of Δy varies only slowly with mass ~ ln(1/M)

2→2 cross sections

- Estimate cross section
  - Change of variable τ→M
  - Consider gg→gg

$$\left(d\sigma/d\tau dy\right)_{y=0} = Cf_1(x_1)f_2(x_2)d\hat{\sigma}(1+2\rightarrow 3+4)$$

$$\tau = \hat{s}/s = M^2/s \Rightarrow d\tau = 2MdM/s$$

$$gg\rightarrow gg\ :\ f(x) = g(x)$$

$$\left(sd\sigma/2MdMdy\right)_{y=0} = C\left[xg(x)\right]^2/x^2\left(d\hat{\sigma}\hat{s}/M^2\right)$$

$$x^2 = M^2/s$$

$$M^3\left(d\sigma/dMdy\right)_{y=0} = 2C\left[xg(x)\right]^2\left(d\hat{\sigma}\hat{s}\right)$$

$$2\rightarrow 2:$$

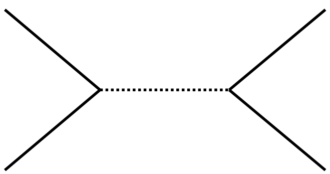
$$M^3\left(d\sigma/dydM\right)_{y=0} = 2C\left[xf_1(x)xf_2(x)\right]_{x=\sqrt{\tau}}\left(d\hat{\sigma}\hat{s}\right)$$

$$d\hat{\sigma}\approx \pi\alpha_1\alpha_2/\hat{s}$$

$$M^4(d\sigma/dydM^2)_{y=0}\sim C[xf_1(x)xf_2(x)]_{x=\sqrt{\tau}}(\pi\alpha_1\alpha_2)$$

QCD matrix elements
– point-like scattering of partons

- Point-like partons have Rutherford like behavior



$\sigma \sim \pi(\alpha_1\alpha_2)|A|^2/s$

- $|A|^2 \sim 1$ at y=0 ($\theta=\pi/2$).

Process	$\|A\|^2$	**Value at $\theta = \pi/2$**
$q+q' \to q+q'$	$\frac{4}{9}[s^2+u^2]/t^2$	2.22
$q+q \to q+q$	$\frac{4}{9}[(s^2+u^2)/t^2+(s^2+t^2)/u^2]-\frac{8}{27}(s^2/ut)$	3.26
$q+\bar{q} \to q'+\bar{q}'$	$\frac{4}{9}[t^2+u^2]/s^2$	0.22
$q+\bar{q} \to q+\bar{q}$	$\frac{4}{9}[(s^2+u^2)/t^2+(t^2+u^2)/s^2]-\frac{8}{27}(u^2/st)$	2.59
$q+\bar{q} \to g+g$	$\frac{32}{27}[t^2+u^2]/tu-\frac{8}{3}[t^2+u^2]/s^2$	1.04
$g+g \to q+\bar{q}$	$\frac{1}{6}[t^2+u^2]/tu-\frac{3}{8}[t^2+u^2]/s^2$	0.15
$g+q \to g+q$	$-\frac{4}{9}[s^2+u^2]/su+[u^2+s^2]/t^2$	6.11
$g+g \to g+g$	$\frac{9}{2}[3-tu/s^2-su/t^2-st/u^2]$	30.4
$q+\bar{q} \to \gamma+g$	$\frac{8}{9}[t^2+u^2]/tu$	
$g+q \to \gamma+q$	$-\frac{1}{3}[s^2+u^2]/su$	

Low mass LHC rates – design numbers

- Total reaction rate
  - For small x and strong production, the cross section is a large fraction of the inelastic cross section.
  - Therefore, the probability to find a "small Pt "minijet" in an LHC crossing is not small.
- "Minijet" rate (see D. Green)

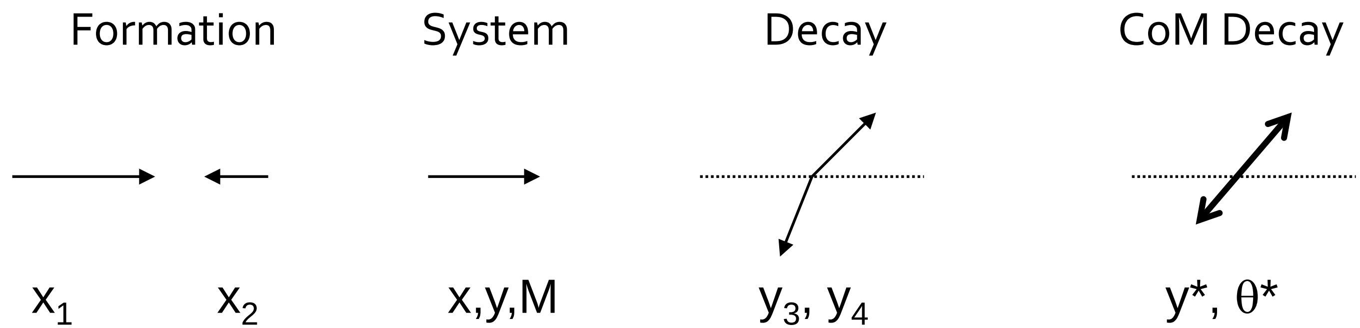
$$\sigma \sim 100\ mb$$
$$L \sim 10^{34}\ /(cm^2 \sec)$$
$$\Delta t \sim 25\ n\sec$$
$$\sigma L \sim 10^9\ Hz$$
$$< n_x > \sim 25 \text{ minbias events/ crossing}$$

$$M^3 (d\sigma / dMdy)_{y=0} = 2[xg(x)]^2 C (d\hat{\sigma}\hat{s})(\hbar c)^2$$
$$\Delta\sigma(M > M_o) \sim \Delta y [xg(x)]^2 [\pi\alpha^2 \,|A|^2 / M_o^2]$$
$$xg(x) \sim 7/2, \Delta y \sim 10, \alpha_s \sim 0.1, C = 3$$
$$for\ M_o = 10\ GeV, |A|^2 = 30\ (gg \rightarrow gg)$$
$$\Rightarrow \Delta\sigma \sim 1\ mb$$

$$[\sigma] = [L^2] = \left[\frac{1}{M^2}\right] = \left[\frac{1}{s}\right]$$

$$(\hbar c)^2 = 0.4\ (mb.GeV)^2, 1\ mb = 10^{-27} cm^2$$

2→2 decay kinematics



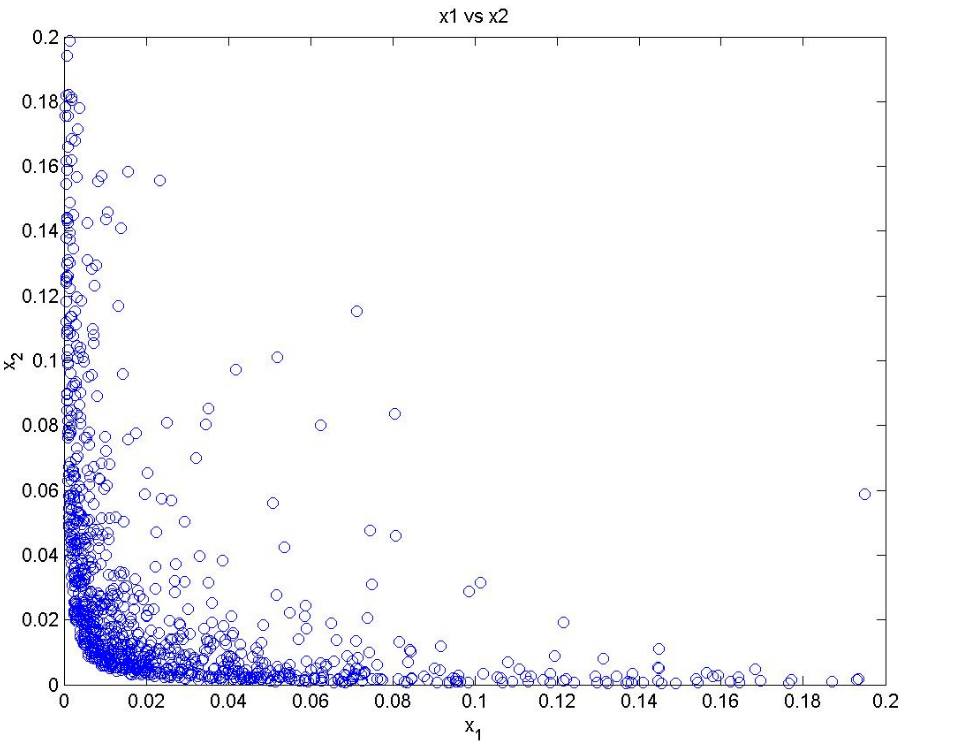
- The measured values of y_3, y_4 and p_T allow to solve for x, M and the com decay angle, hence the initial state x_1 and x_2

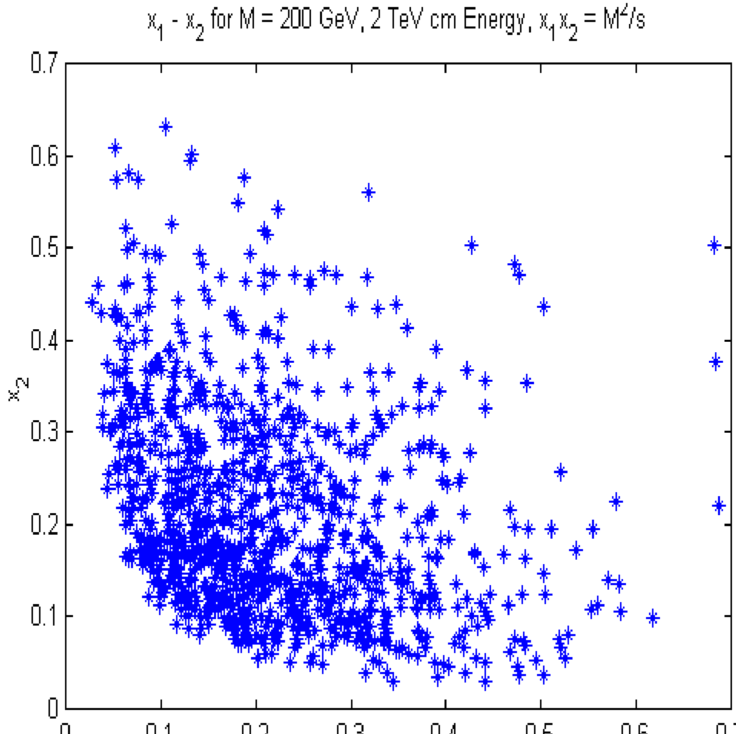
$$x_1 = [M/\sqrt{s}]e^{y} \;, y = (y_3 + y_4)/2$$
$$x_2 = [M/\sqrt{s}]e^{-y}$$

$$y^* = (y_3 - y_4)/2$$
$$\cos\theta^* = \tanh(y^*)$$

gg→gg CompHEP

- p_T>50 GeV
- σ=0.013 mb





- Fixed mass
  - kinematics: $x_1\ x_2=M^2/s=0.01$

2→1 Drell-Yan processes

- Resonance ($\Gamma \ll M$)
  - Partial wave unitarity (D. Green)
  - Integrate over narrow width

$$\int \sigma ds = \pi^2 (2J+1)(\Gamma_{12}/M)$$

$$M^2 (d\sigma/dy)_{y=0} = C[xf_1(x)xf_2(x)]_{x=\sqrt{\tau}}[\pi^2 \Gamma_{12}(2J+1)/M]$$

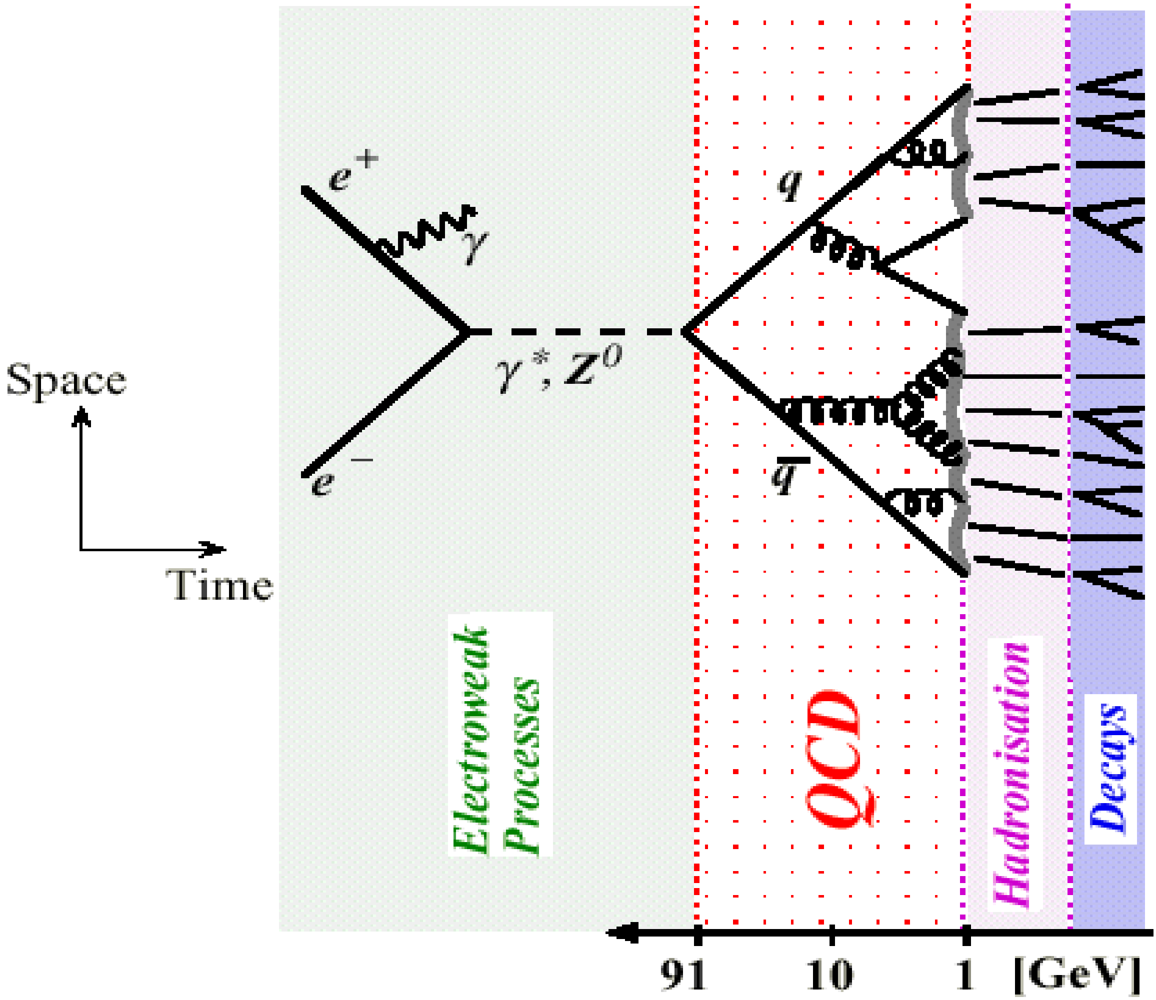
$$\Gamma_{12}/M \sim "\alpha_{12}"$$

$$M^2 (d\sigma/dy)_{y=0} = C[xf_1(x)xf_2(x)]_{x=\sqrt{\tau}}[\pi^2 \alpha_{12}(2J+1)]$$

- "scaling" behavior – cross section depends only on τ and not on M and s separately

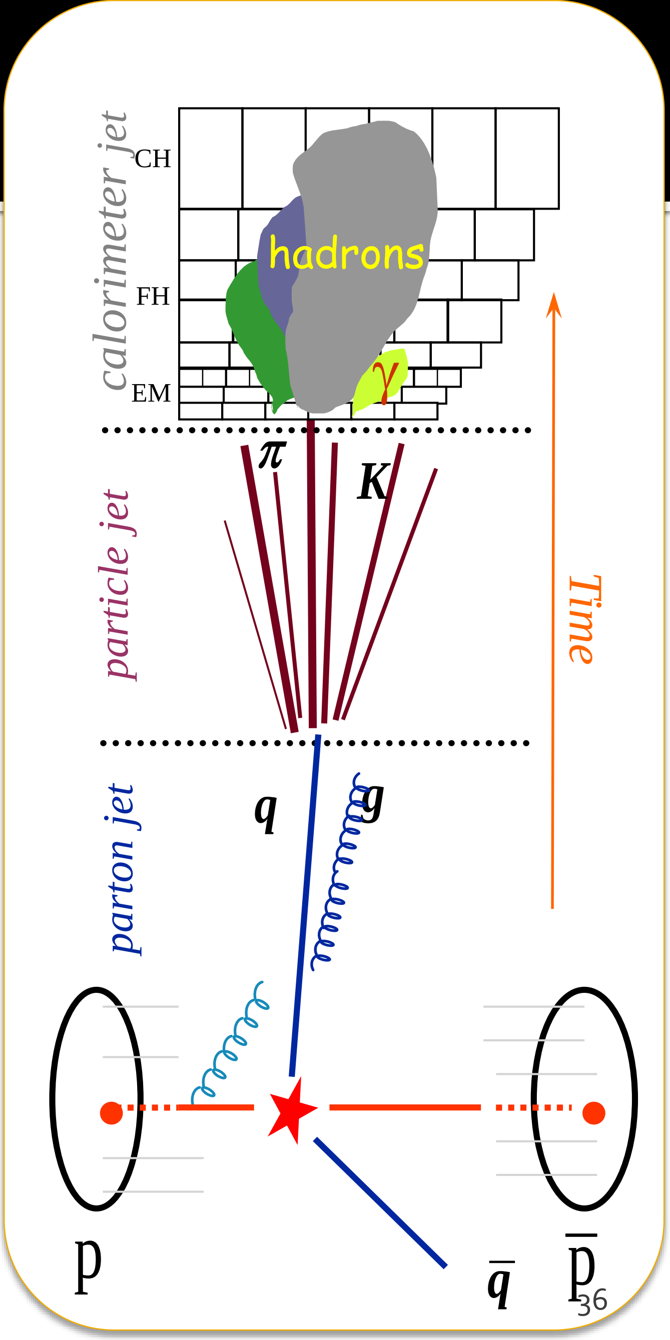
Hadronisation

- Quarks and gluons have color, while hadrons (the asymptotic states) are colorless.
- The process of "hadronization" occurs at energy scales where QCD is strong ~ Λ so that perturbation theory cannot be used.
- This makes direct experimental QCD predictions difficult.

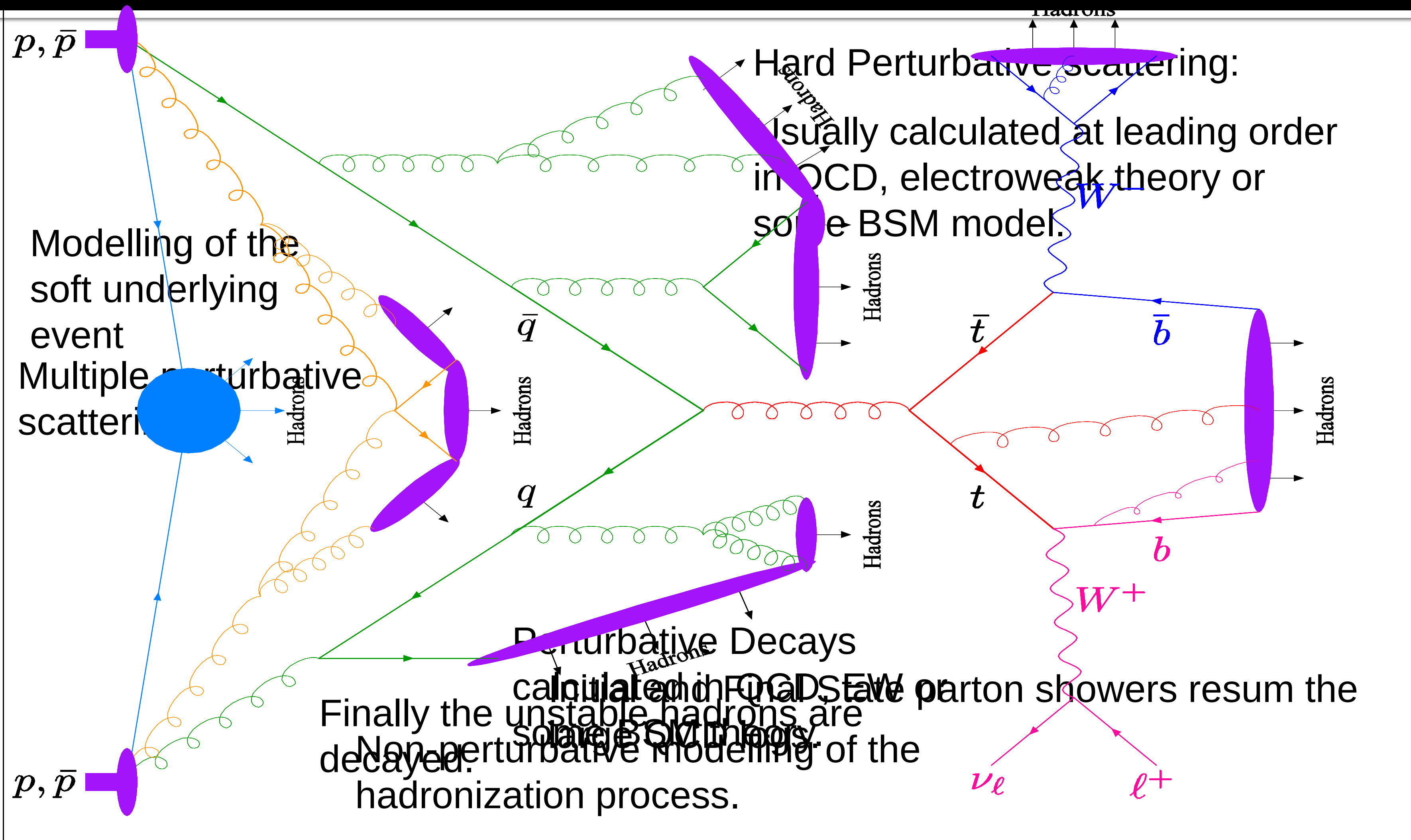


Simulation tools

- A "Monte Carlo" is (a usually) C++ program that generates events
- Events vary from one to the next (random numbers)
  - expect to reproduce both the average behavior and fluctuations of real data
- Event Generators may be
  - parton level:
    - Parton Distribution functions
    - Hard interaction matrix element
  - and may also handle:
    - Initial state radiation
    - Final state radiation
    - Underlying event
    - Hadronisation and decays
- Separate programs for Detector Simulation
  - GEANT – most commonly used



A Monte Carlo event



Hard Perturbative scattering:

Usually calculated at leading order in QCD, electroweak theory or some BSM model.

Modelling of the soft underlying event

Multiple perturbative scattering.

Perturbative Decays calculated in QCD, EW or some BSM theory.

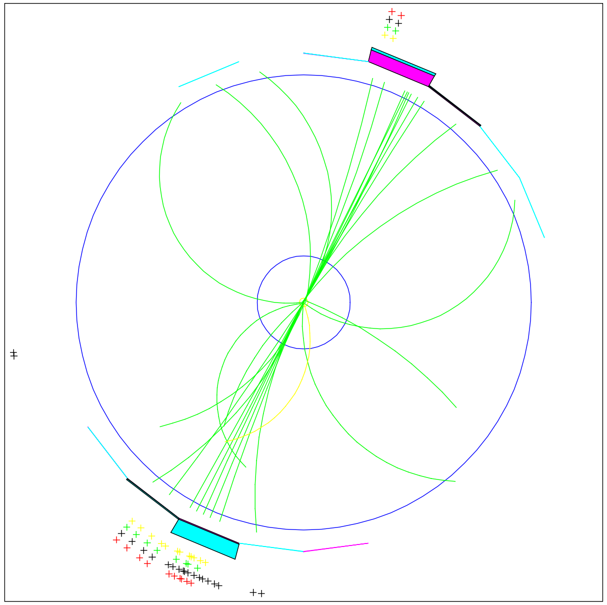
Initial and Final State parton showers resum the large QCD logs.

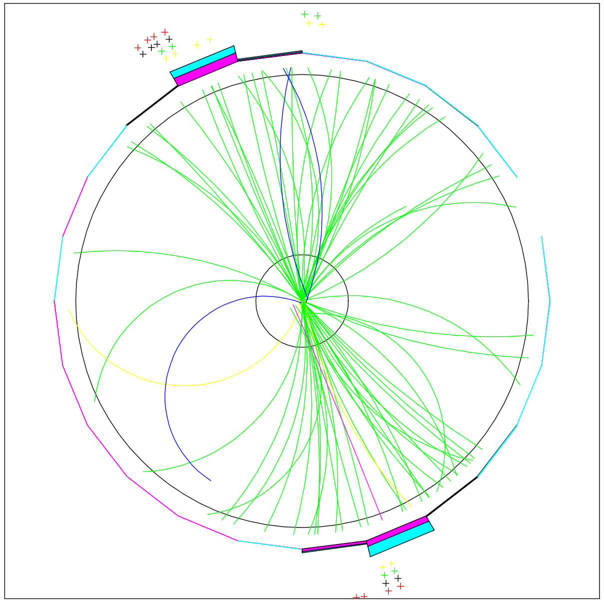
Finally the unstable hadrons are decayed.

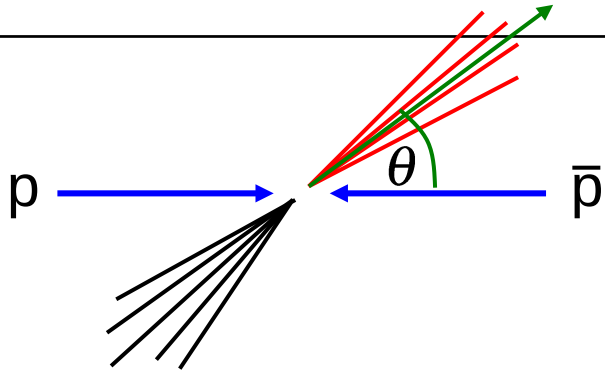
Non-perturbative modelling of the hadronization process.

★ **Test QCD predictions by looking at production of pairs of high energy jets**

$p\bar{p} \rightarrow$ jet jet + X

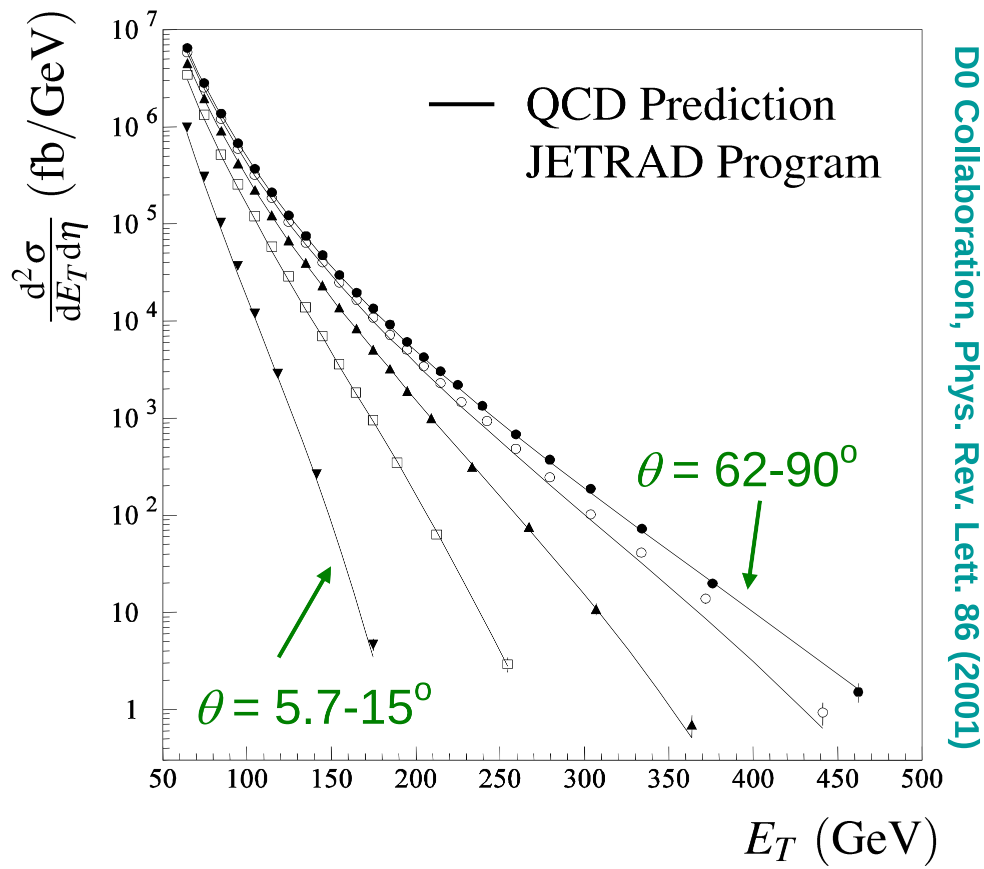






★ **Measure cross-section in terms of**

- **"transverse energy"** $E_T = E_{\text{jet}} \sin\theta$
- **"pseudorapidity"** $\eta = \ln\left[\cot\left(\frac{\theta}{2}\right)\right]$



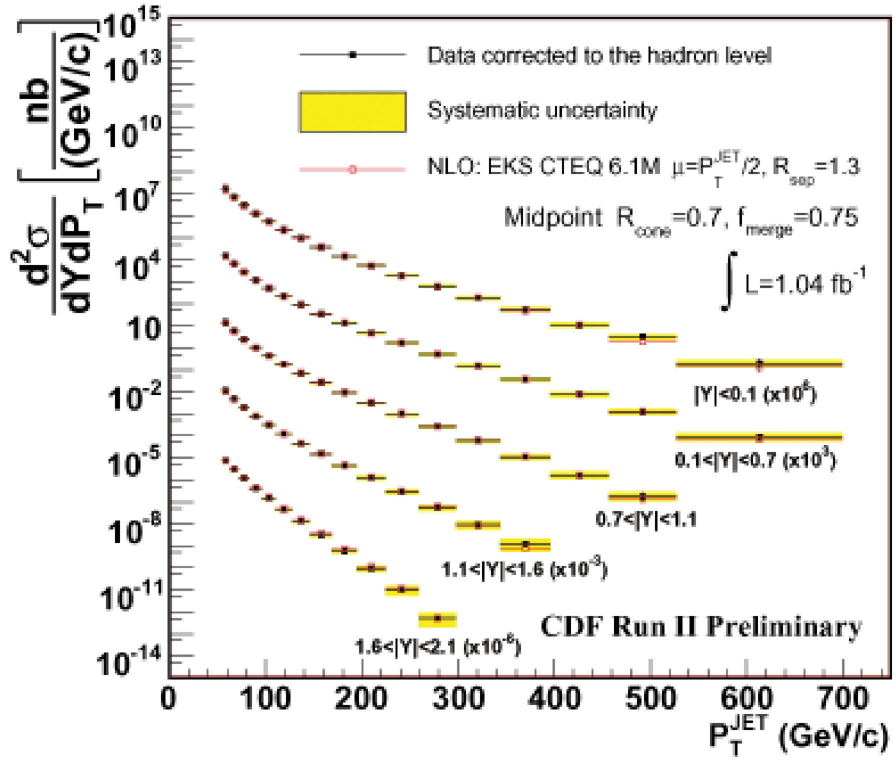
★ **QCD predictions provide an excellent description of the data over many orders of magnitude**

★ **NOTE:**

- **at low E_T cross-section is dominated by low x partons i.e. gluon-gluon scattering**
- **at high E_T cross-section is dominated by high x partons i.e. quark-antiquark scattering**

Inclusive jet cross section at Tevatron

- CDF and Do results



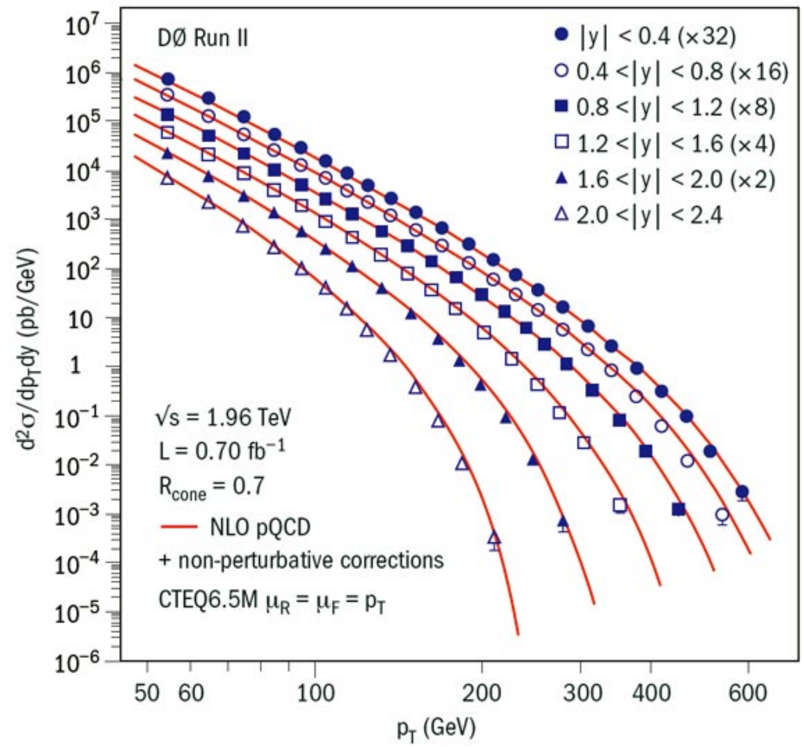
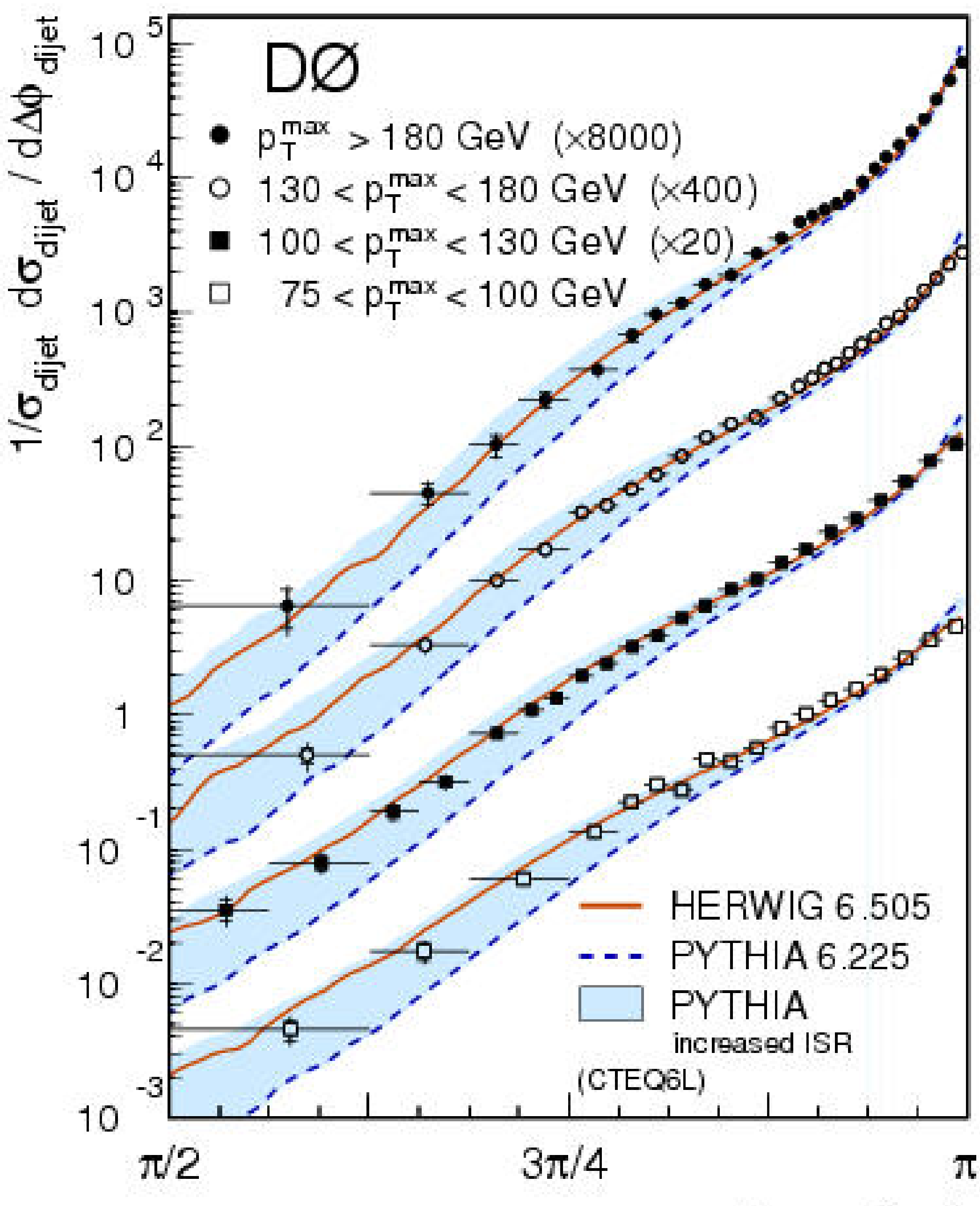
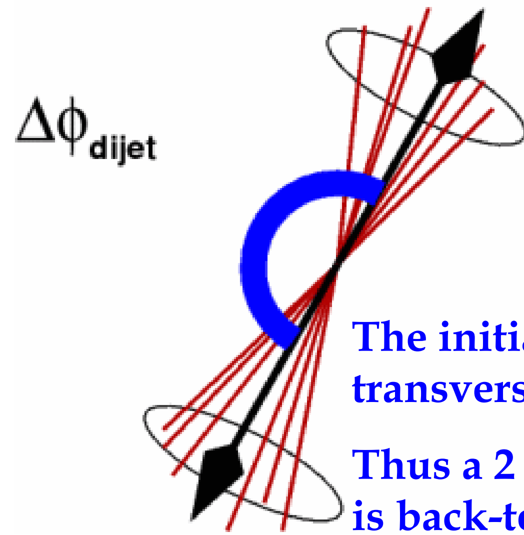


FIG. 2: The inclusive jet cross section with MidPoint algorithm in the different rapidity regions.The different rapidity region cross sections are scaled by a given factor for presentation purposes.





Initial, Final State Radiation

The initial state has ~ no transverse momentum.

Thus a 2 body final state is back-to-back in azimuth.

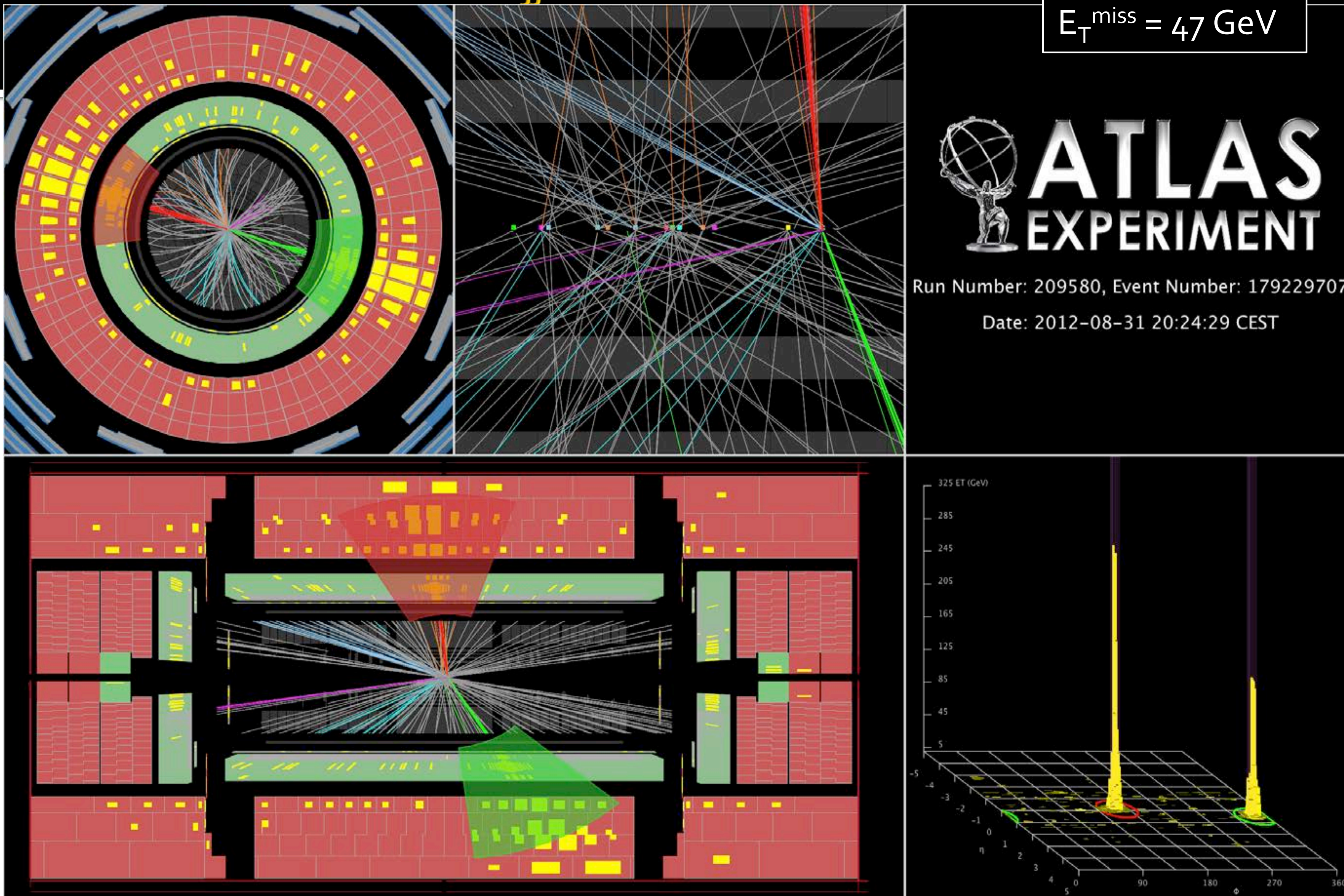
Take the 2 highest E_T jets.

- LO 3-jet calculation fails to describe very small or very large angle regions
- NLO 3-jet calculation (NLOJET++) does a pretty good job

HERWIG and PYTHIA (with some tuning) also describe the data

High-pT di-jet: M_{jj} = 4.7 TeV!

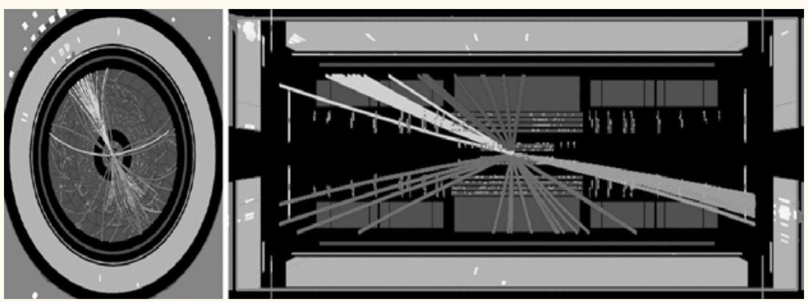
m_{jj} = 4.7 TeV
p_T^j = 2.3 TeV
E_T^{miss} = 47 GeV

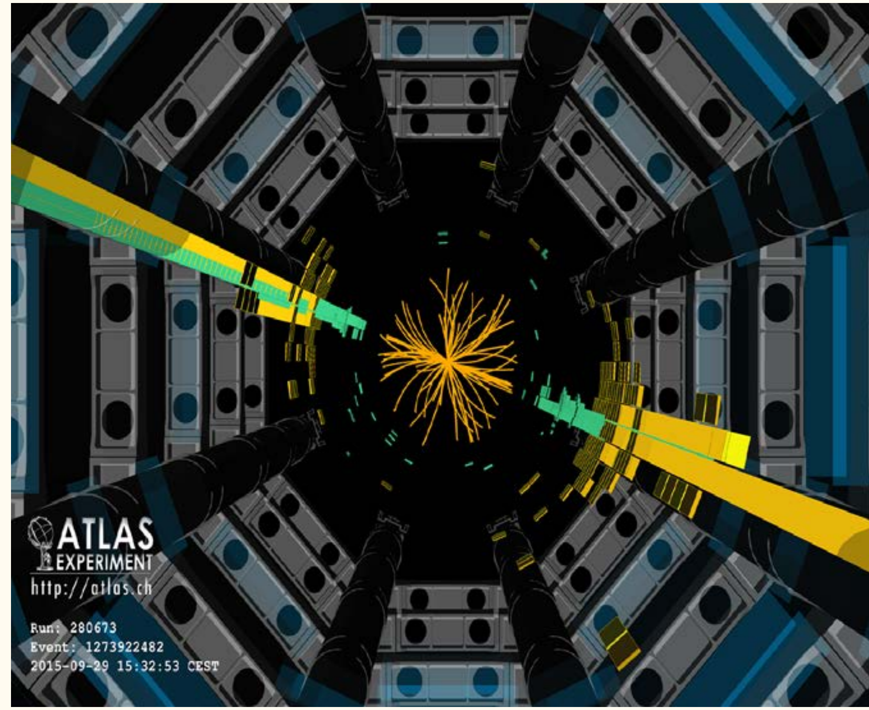


$$x = x_1 - x_2 = 0 \Rightarrow \langle x \rangle = \frac{M}{\sqrt{s}}$$

$$y = \frac{1}{2}\ln\left(\frac{x_1}{x_2}\right)$$

- ❖ To produce M at rapidity
  - ➢ y~0 - need partons with same x
  - ➢ High y - one parton at high x, the other at low x
- ❖ Di-jet event in 2 views
  - ➢ Back-to-back in transverse plane (no p_T)
  - ➢ Boost in the longitudinal view (net momentum of colliding partons along beam axis)

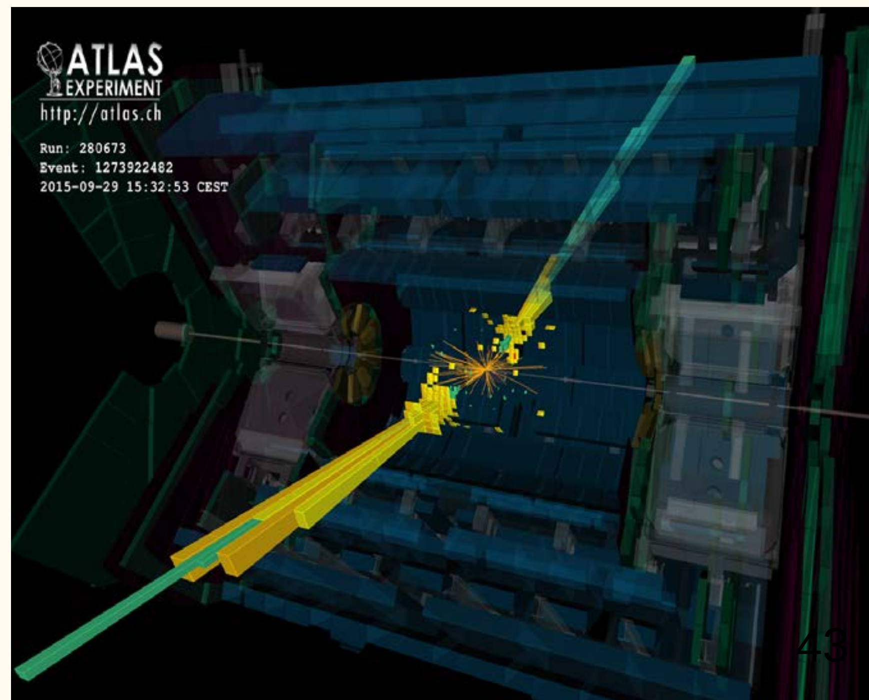




- ❖ High mass di-jet

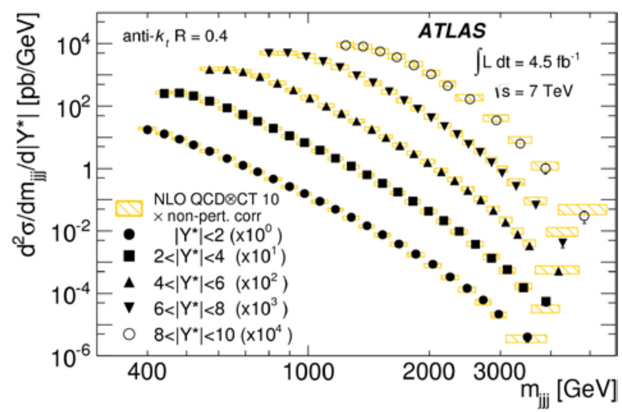
$\Rightarrow$

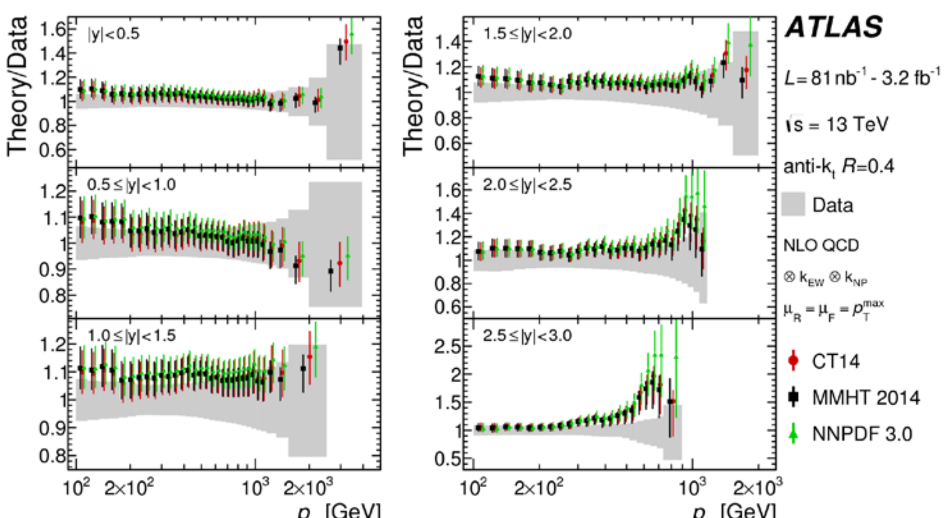
- ➢ m_{jj}: 6.9 TeV
- ➢ 2jets: p_T=3.2

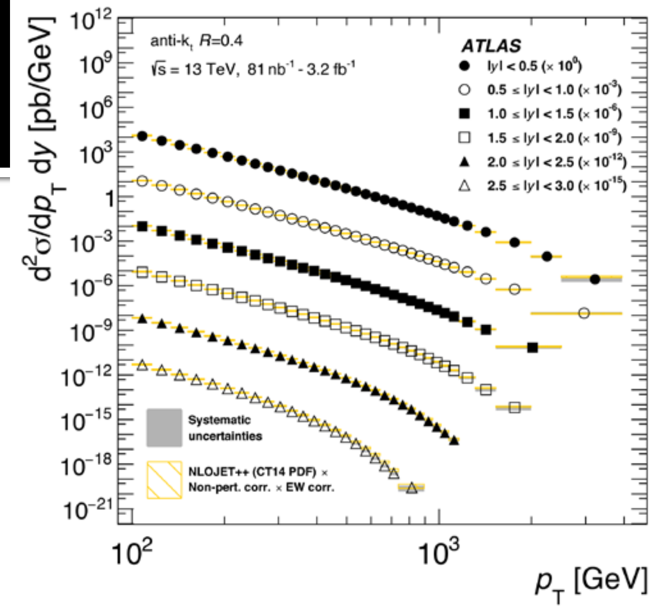


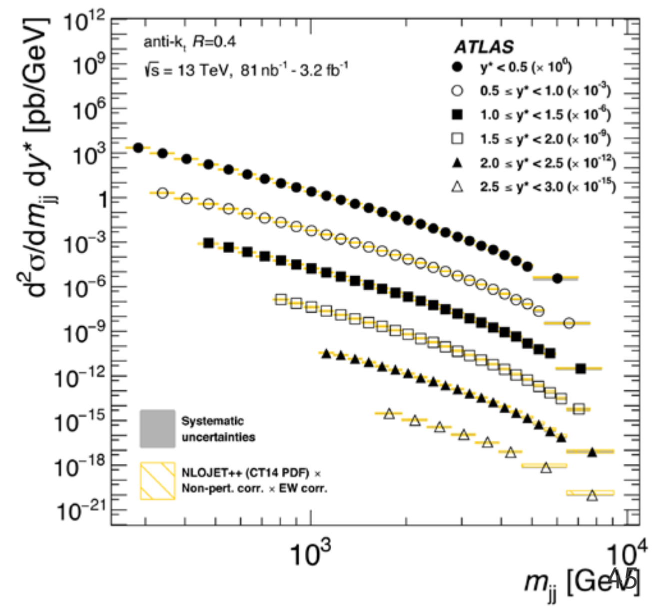
Measurement of inclusive jet and dijet cross-sections, … At LHC

- Inclusive Jet cross sections
  - QCD works well and fits data over orders of magnitude!





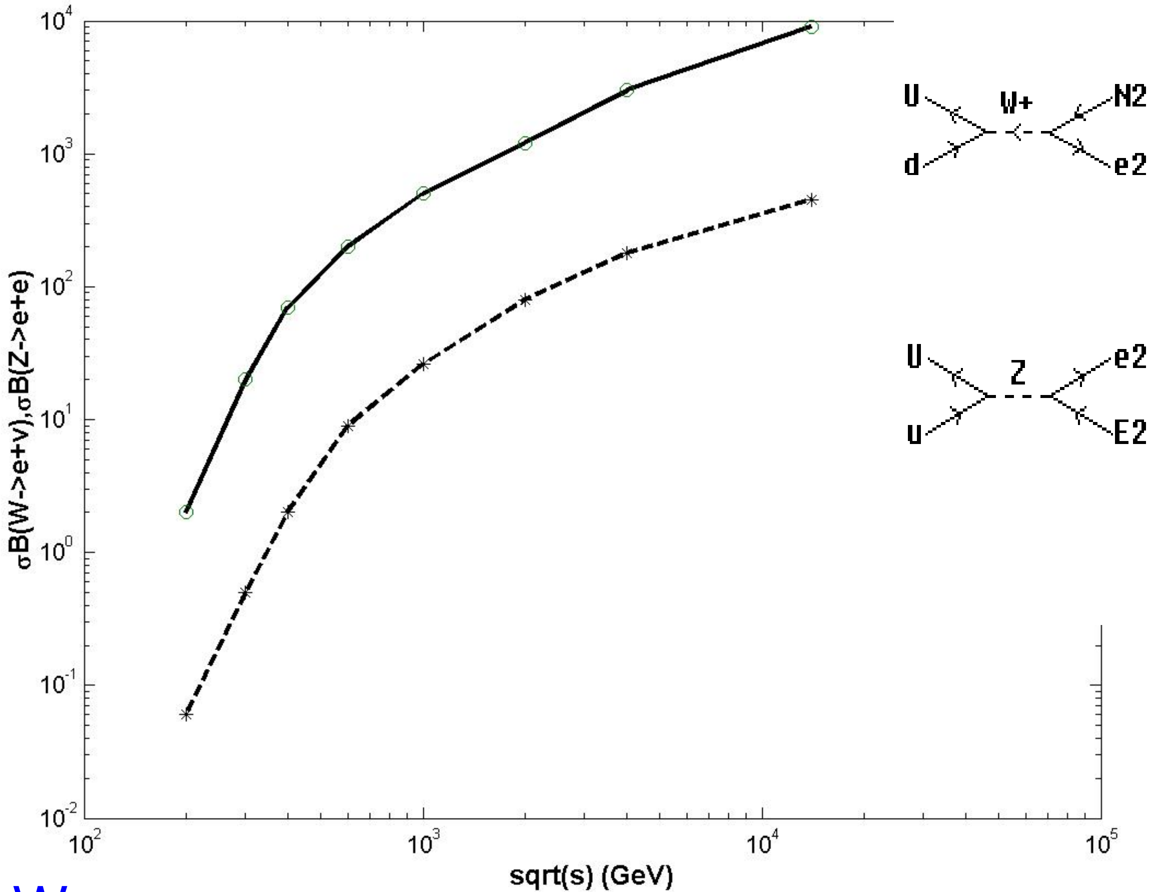




Drell-Yan production of W/Z bosons

$$\bar{u} + u \rightarrow Z \rightarrow e^{+} + e^{-}, \; \bar{u} + d \rightarrow W^{-} \rightarrow e^{-} + \bar{\nu}_e$$

- Single production of W and Z bosons
- σ_W at the LHC, 10 times more than Tevatron

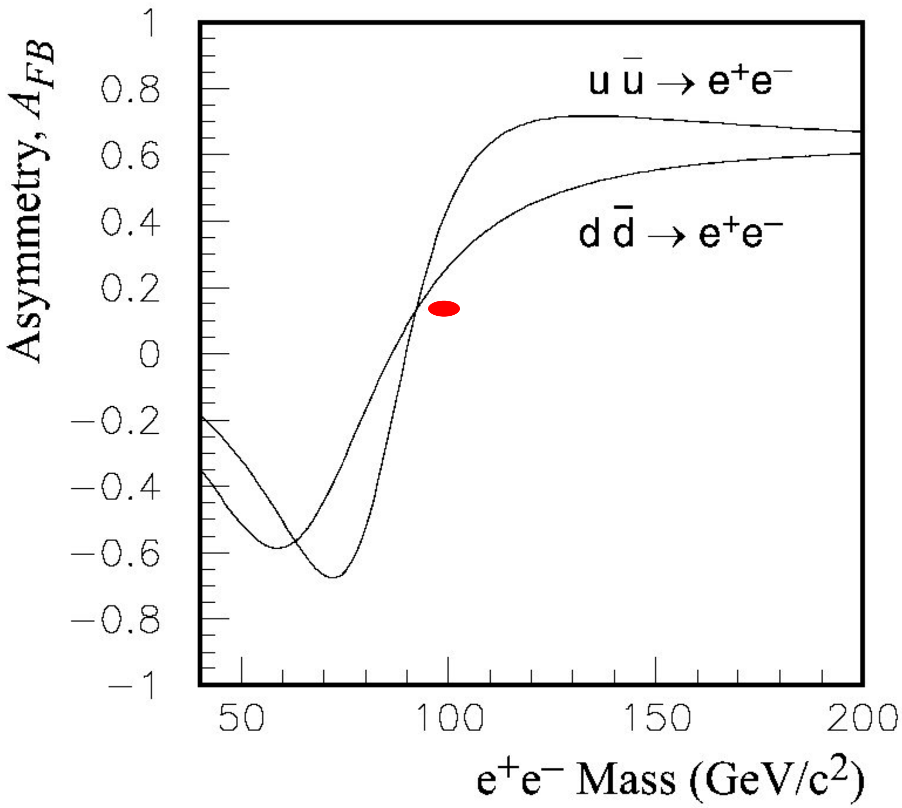


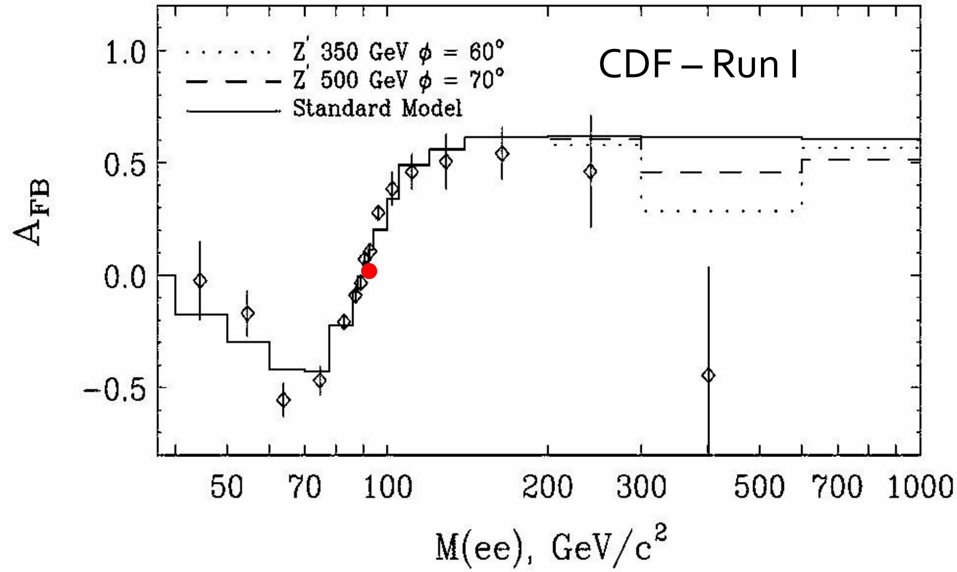
Cross section and width for W:

$\sigma \sim \pi^2\Gamma(2J+1)/M^3$, $\Gamma \sim 2$ GeV, $\sigma = 47$ nb.

$$\sigma_{12} \approx \Gamma_{12} / M^3 \approx \alpha_{12} / M^2$$

Z production
A_{FB}





- Z couples to LH and RH quarks differently
- Leading to parity violating asymmetry in γ-Z interference.
- A_{FB} asymmetry sensitive to Z′

W production at LHC

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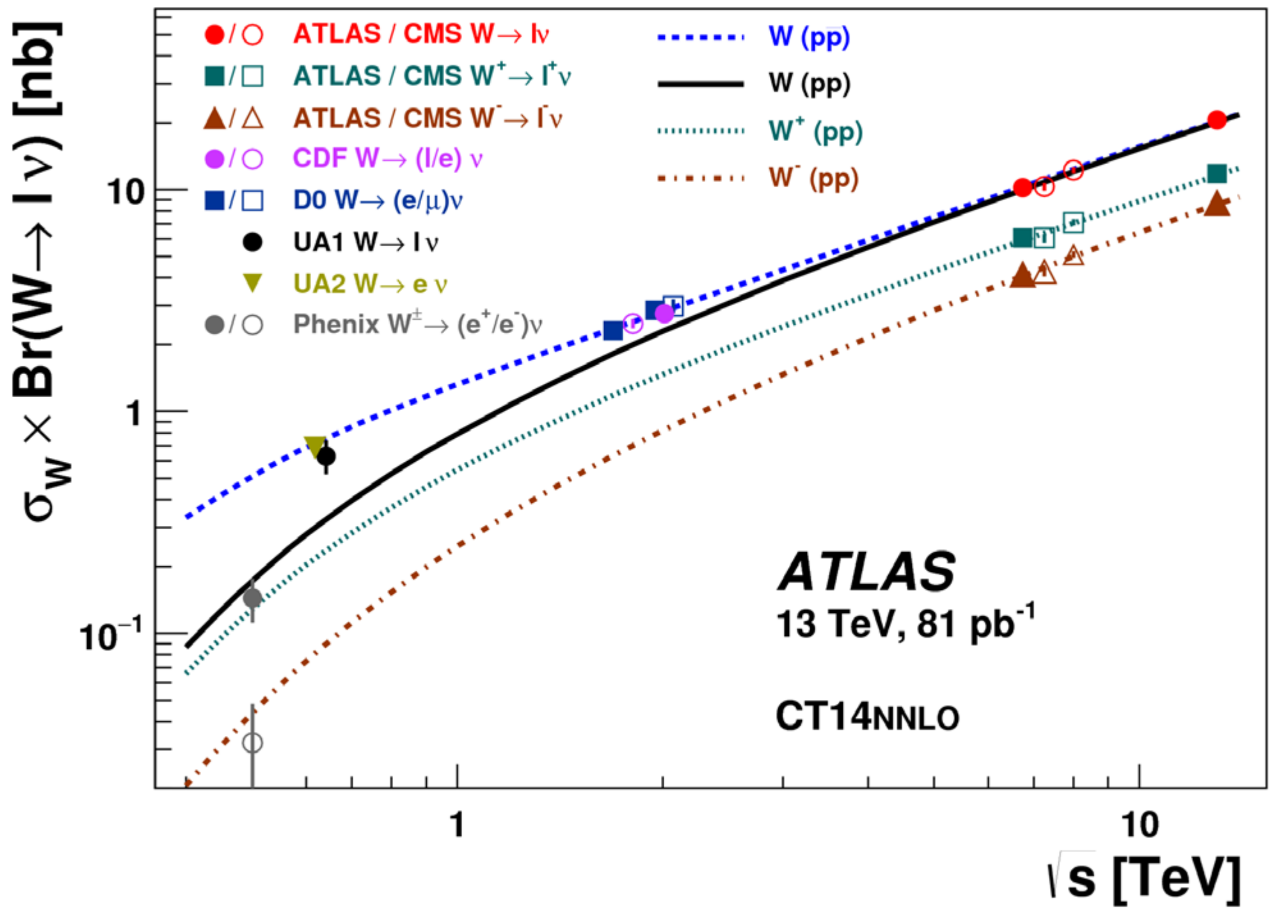
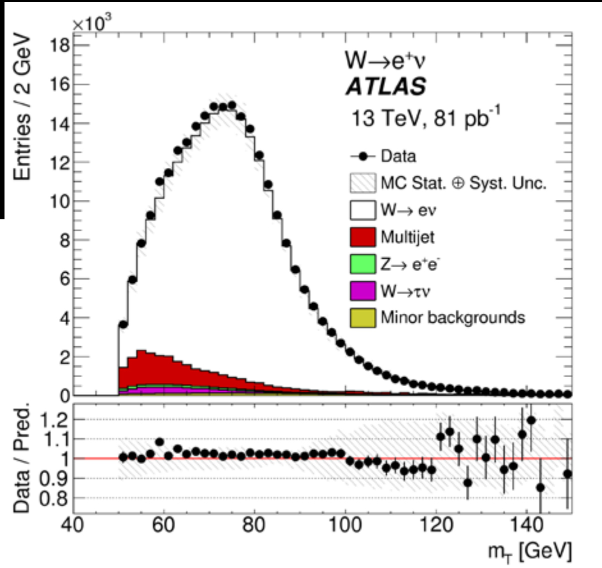
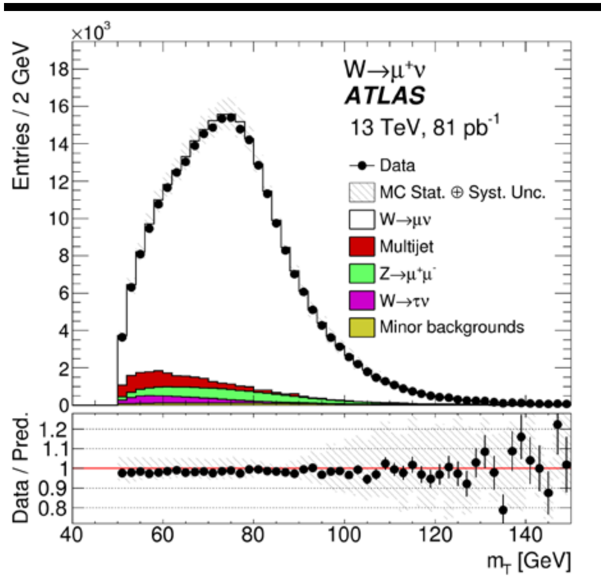
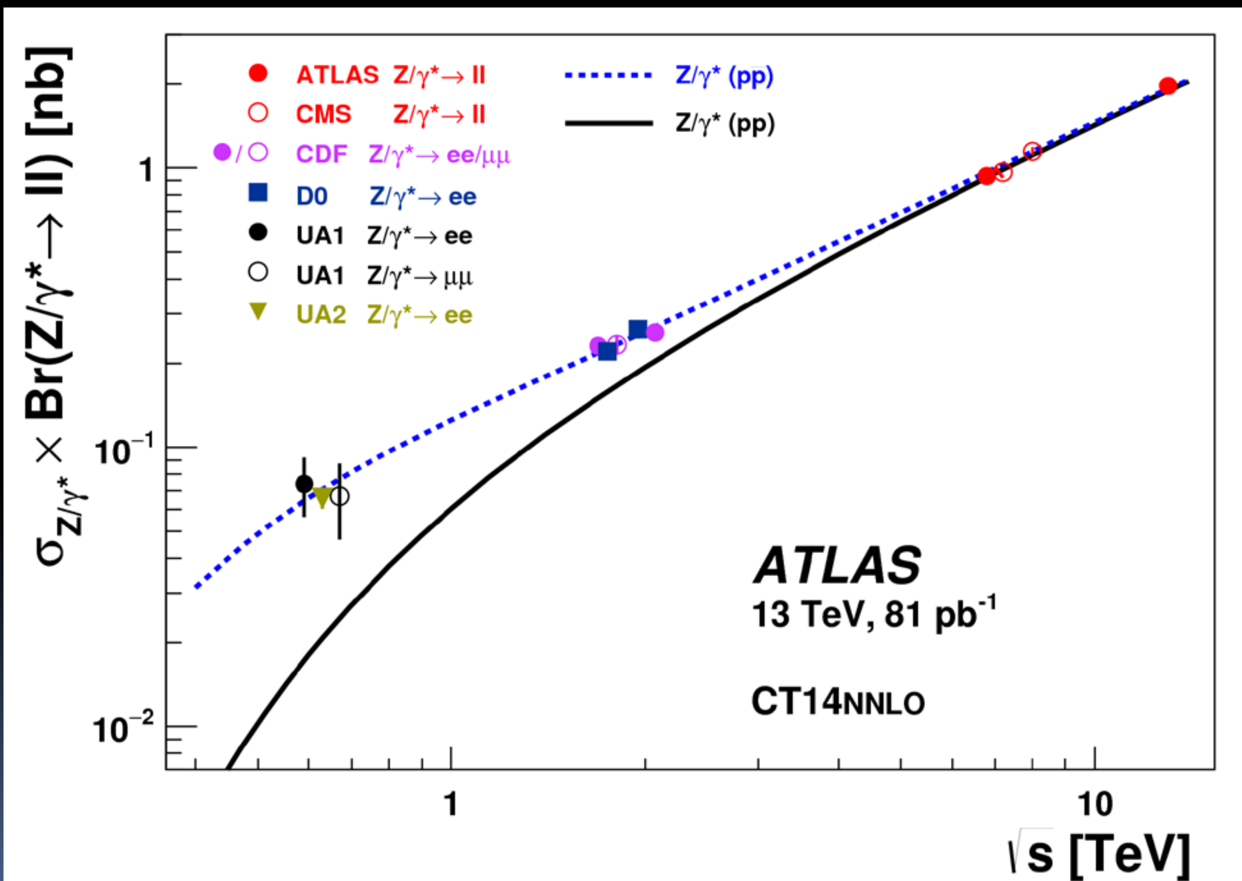
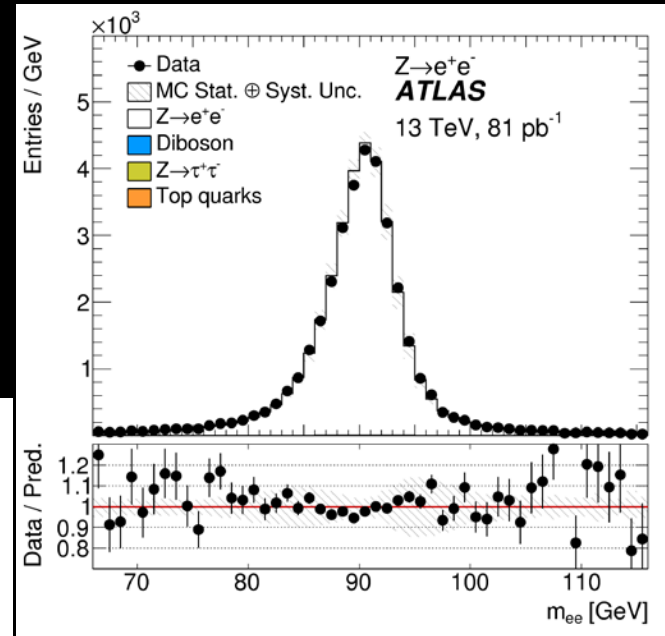


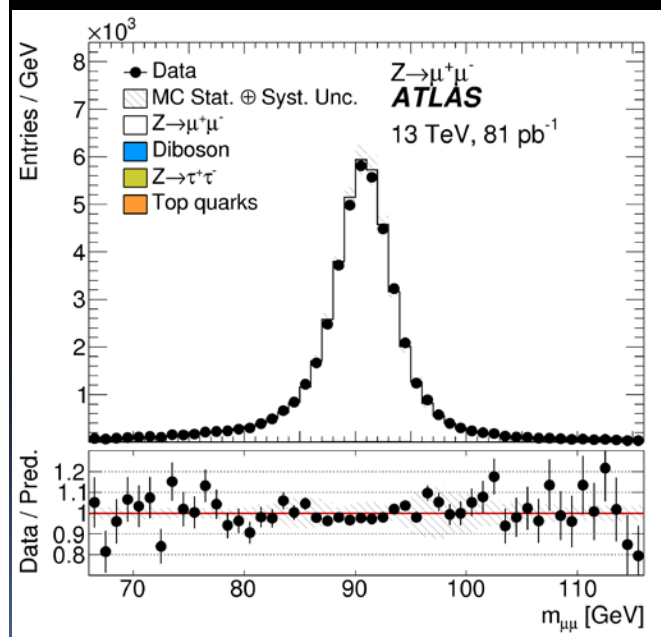




Z production at LHC

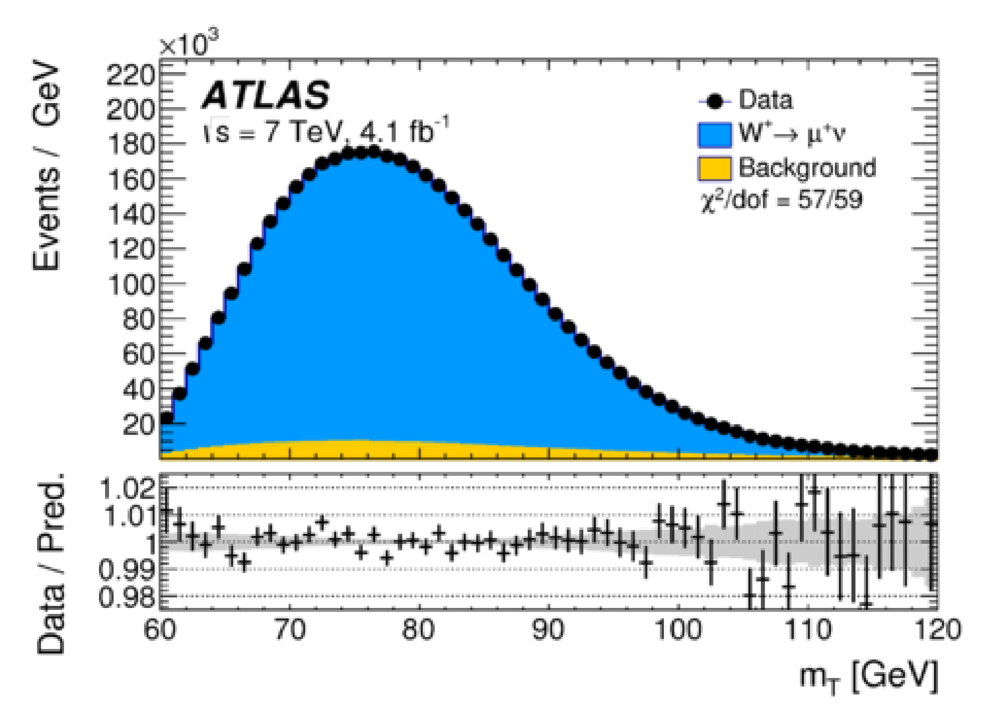


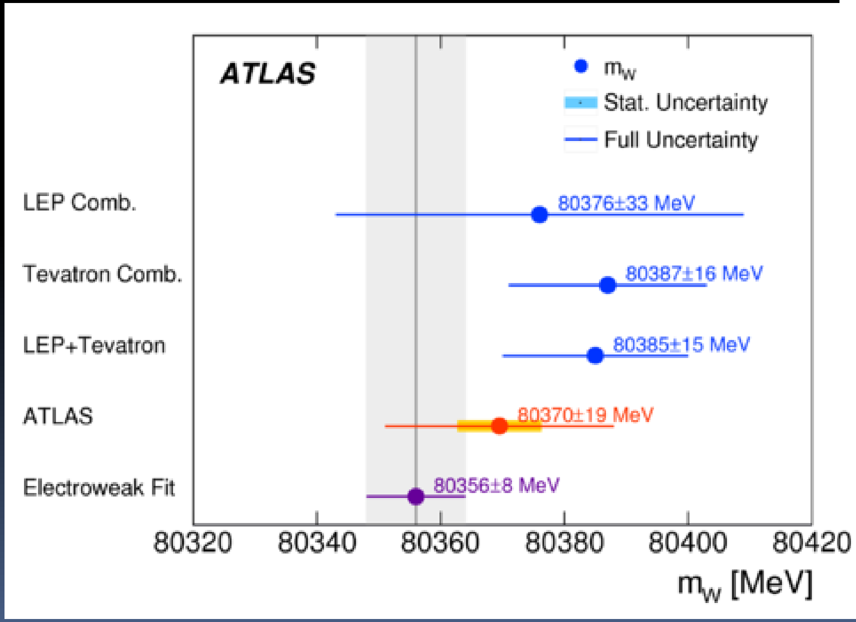




W-mass measurement by ATLAS

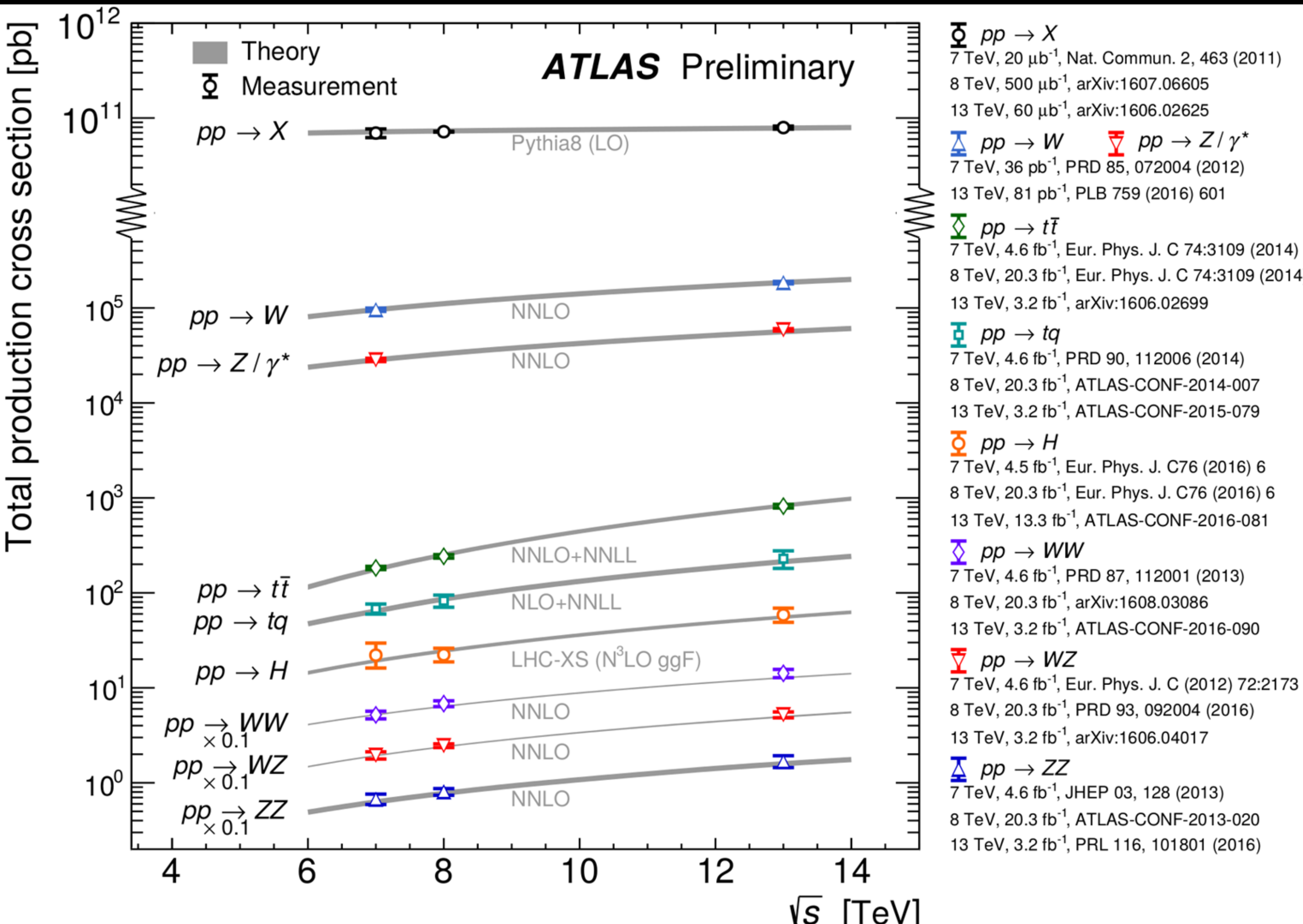
- Transverse mass: data vs simulation including signal and background contributions



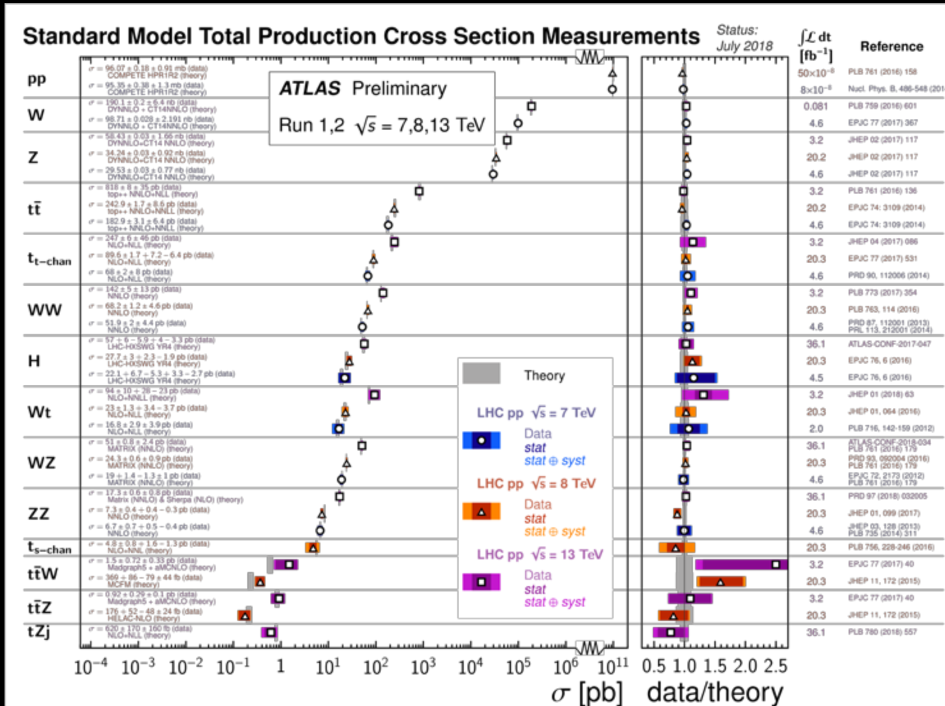


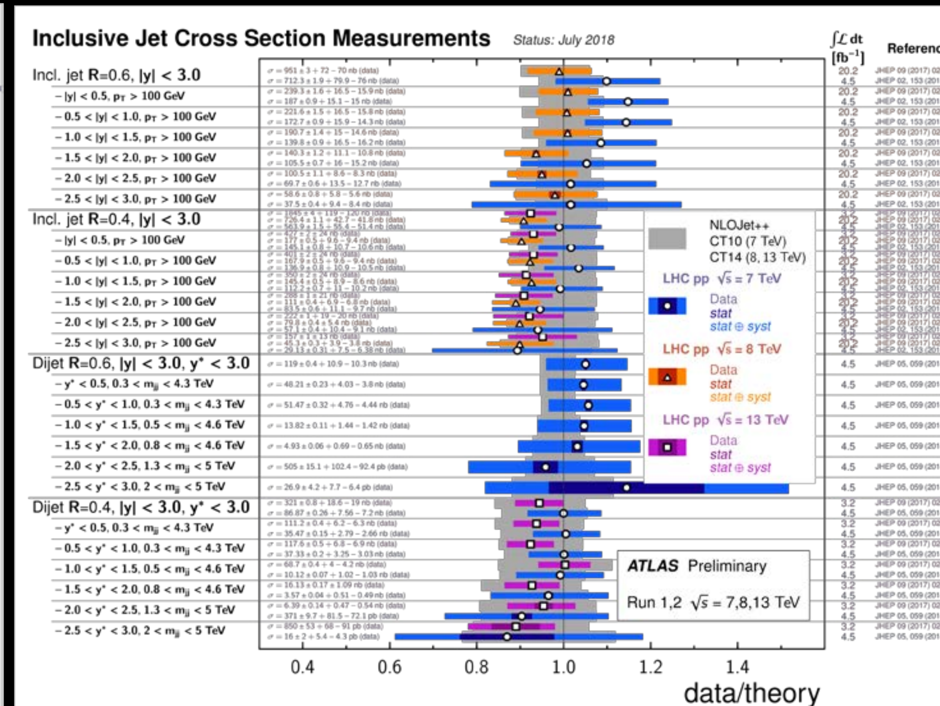
- ATLAS present measurement of m_W compared to SM prediction from global electroweak fit [16] updated using recent measurements of m_t=172.84±0.70GeV [122] and m_H=125.09±0.24GeV [123], and to combined values of m_W measured at LEP [124] and at Tevatron collider [24]

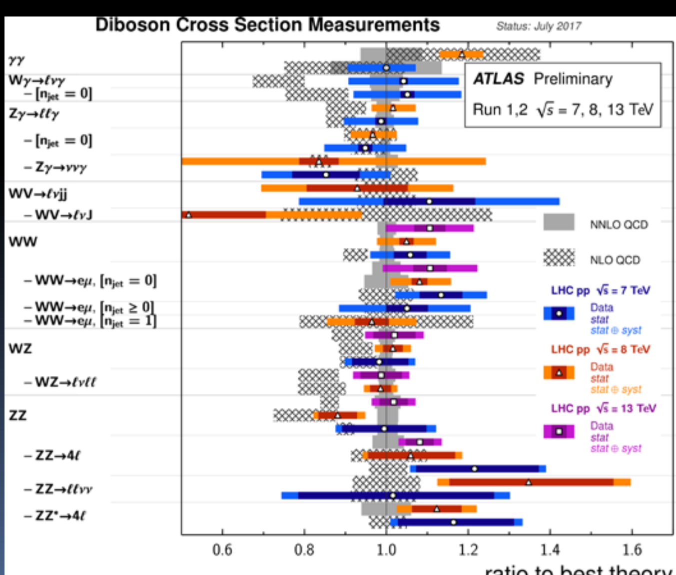
SM Cross section measurements: 7, 8, 13 TeV

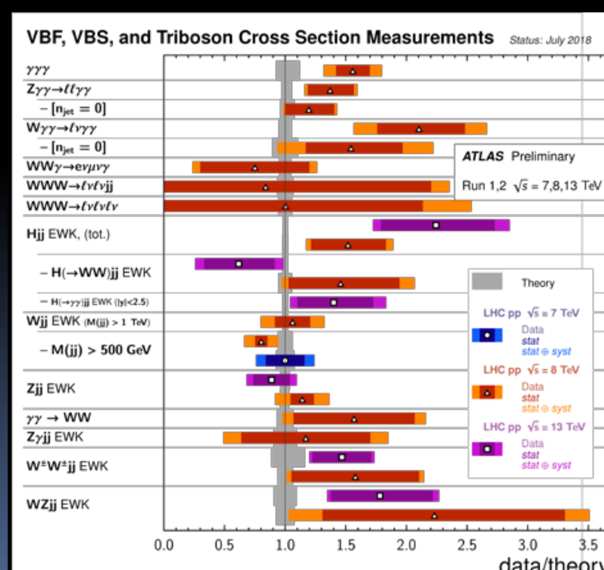


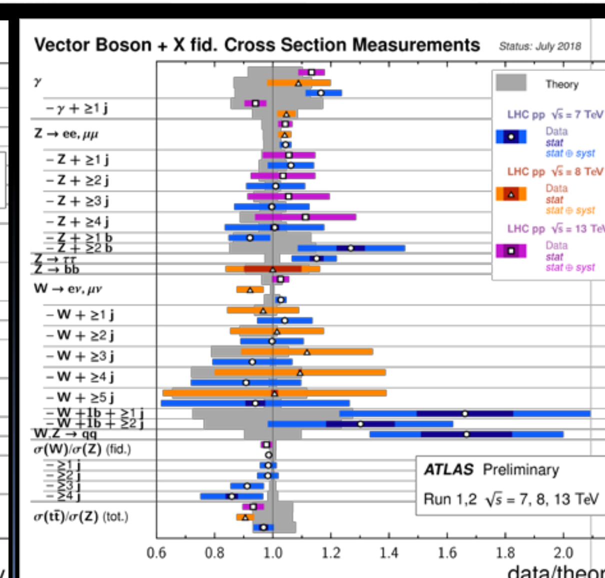
- Impressive agreement data - theory Next-Next -Leading-Log (NNLL)
- LHC surpassed (or does as well as) Tevatron and LEP in many precision measurements …
- Before New Physics shows up ?
  - Control Standard Model processes, especially (but not only) QCD!


Standard Model Total Production Cross Section Measurements
Status: July 2018
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
pp
W
Z
tt̄
t_t-chan
WW
H
Wt
WZ
ZZ
t_s-chan
tt̄W
tt̄Z
tZj
Theory
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
LHC pp √s = 13 TeV
∫ℒ dt [fb⁻¹]
Reference
σ [pb]
data/theory


Inclusive Jet Cross Section Measurements
Status: July 2018
Incl. jet R=0.6, |y| < 3.0
Incl. jet R=0.4, |y| < 3.0
Dijet R=0.6, |y| < 3.0, y* < 3.0
Dijet R=0.4, |y| < 3.0, y* < 3.0
NLOJet++
CT10 (7 TeV)
CT14 (8, 13 TeV)
LHC pp √s = 7 TeV
LHC pp √s = 8 TeV
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
∫ℒ dt [fb⁻¹]
Reference
data/theory

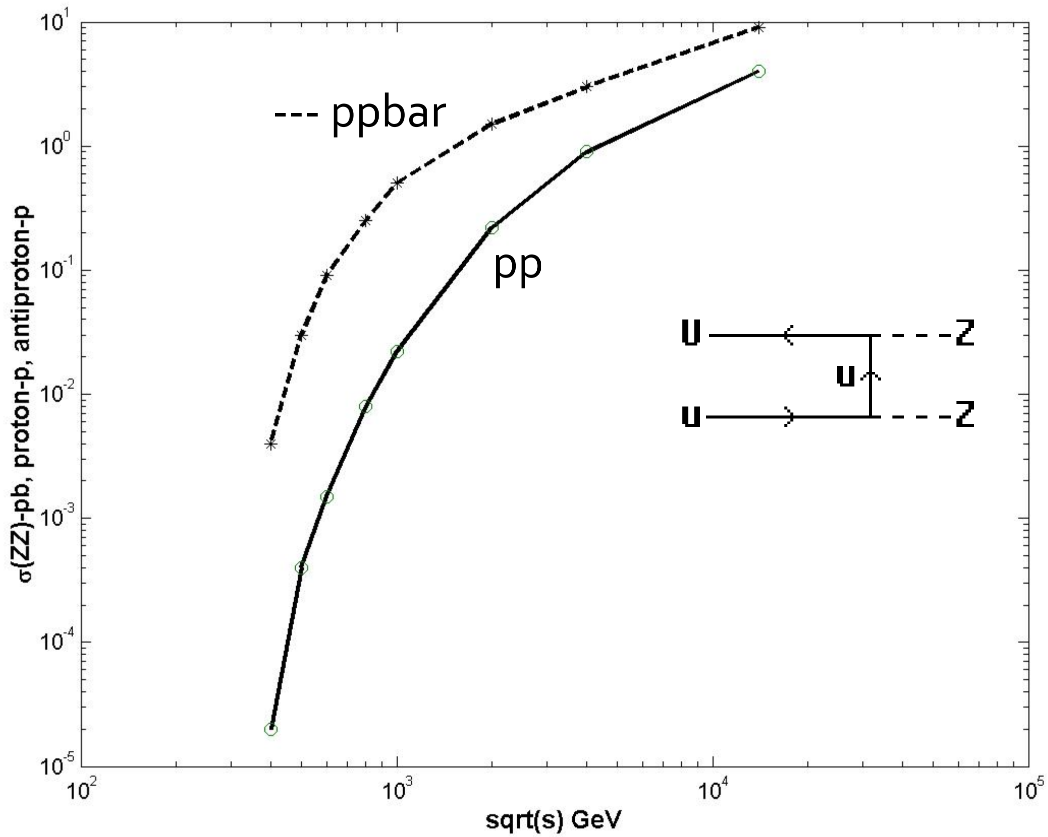

Diboson Cross Section Measurements
Status: July 2017
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
γγ
Wγ→ℓνγ
Zγ→ℓℓγ
WV→ℓνjj
WW
WZ
ZZ
NNLO QCD
NLO QCD
LHC pp √s = 7 TeV
LHC pp √s = 8 TeV
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
ratio to best theory


VBF, VBS, and Triboson Cross Section Measurements
Status: July 2018
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
Theory
LHC pp √s = 7 TeV
LHC pp √s = 8 TeV
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
data/theory


Vector Boson + X fid. Cross Section Measurements
Status: July 2018
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
LHC pp √s = 8 TeV
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
data/theory

ZZ-production

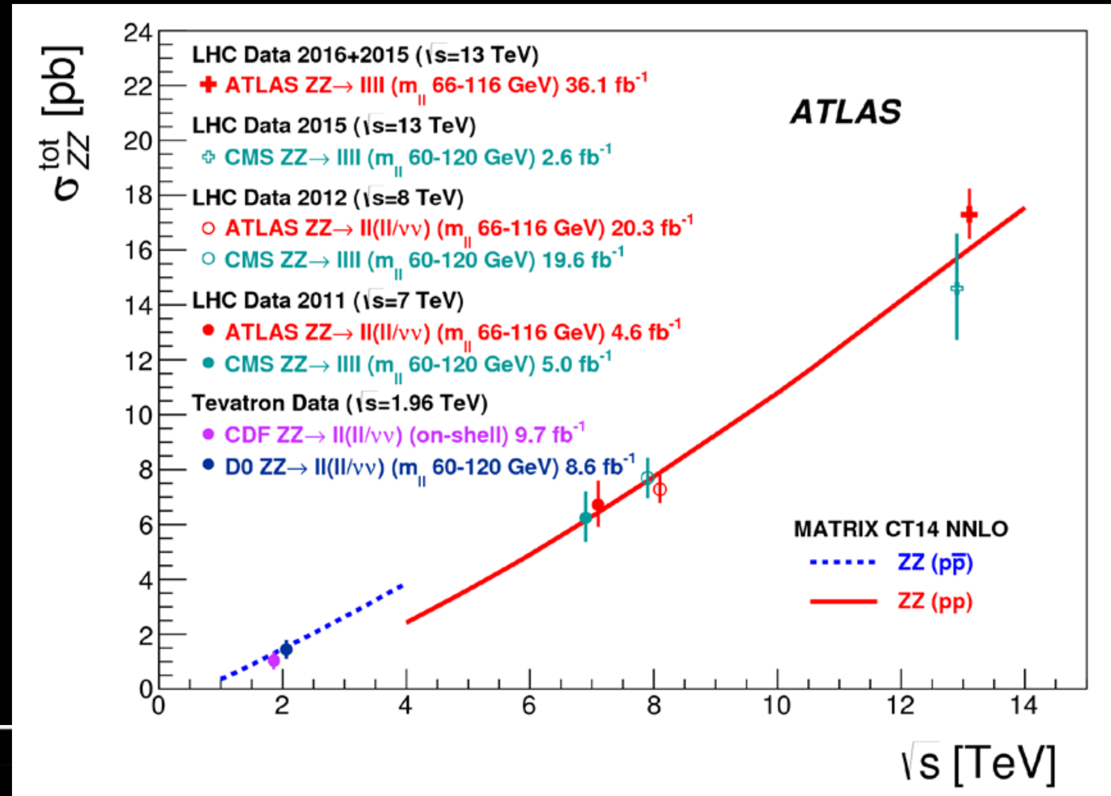
- Cross-section
  - Steep rise near threshold.
  - 20 fold rise from the Tevatron to the LHC
  - σ_{ZZ}~10pb at LHC
  - Possibility to investigate triple gauge boson coupling
- Not much gain in using anti-protons once the energy is high enough that the gluons or "sea" quarks dominate.

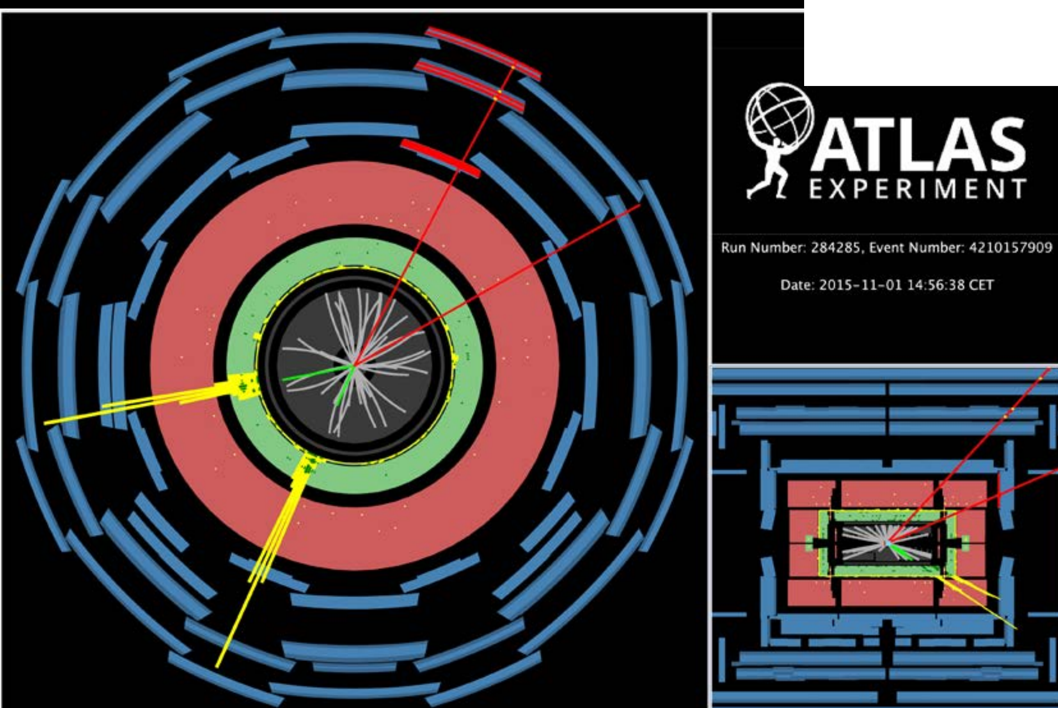


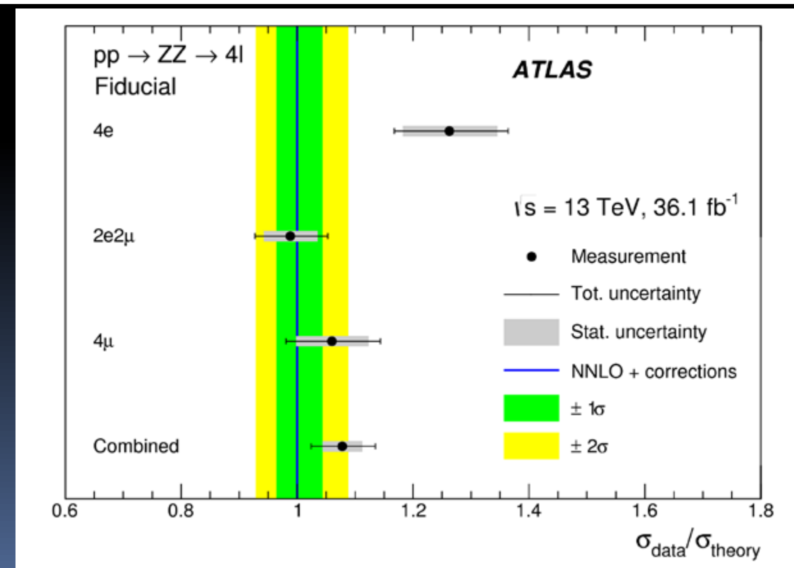
At 0.4TeV: <x>~2M_Z/sqrt(s)~0.46 dominated by valence quarks (ppbar > pp)

At LHC: less than 2 difference between pp and ppbar

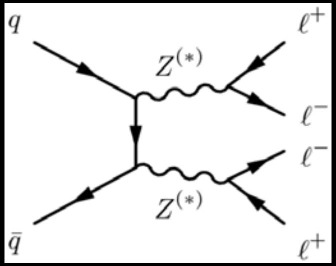
Di-Z-boson production at LHC

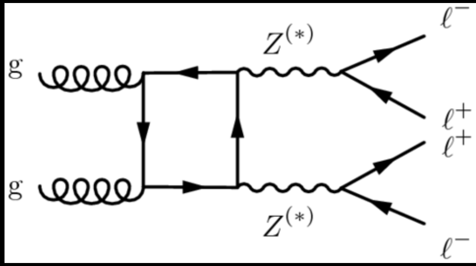


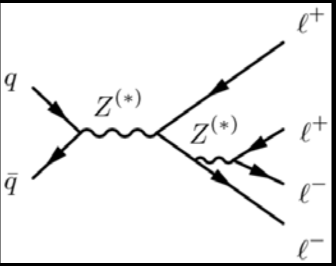


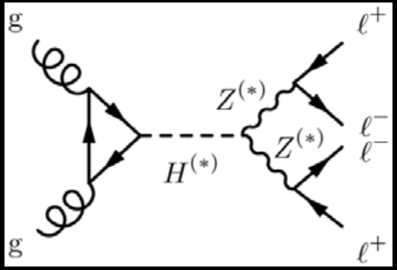


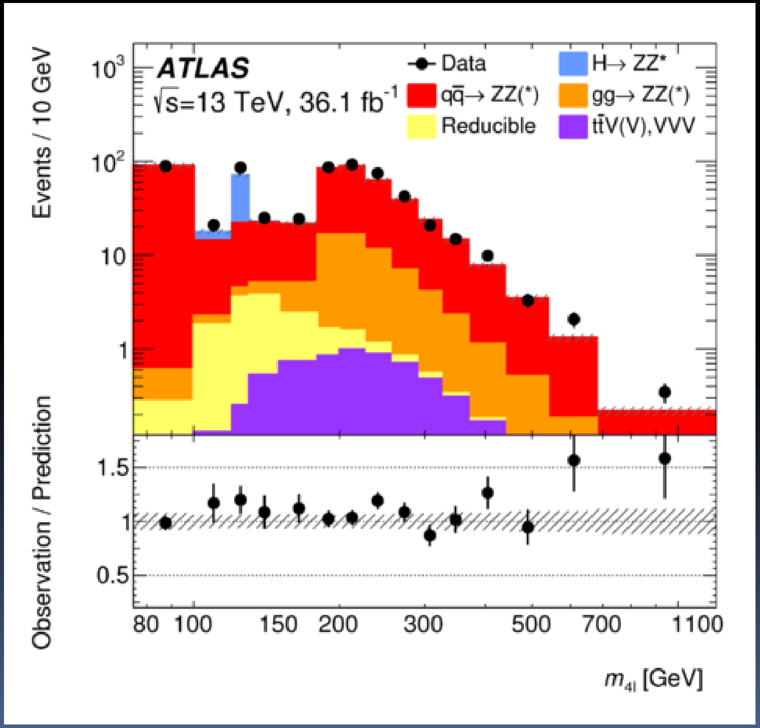
4-lepton invariant mass at 13 TeV

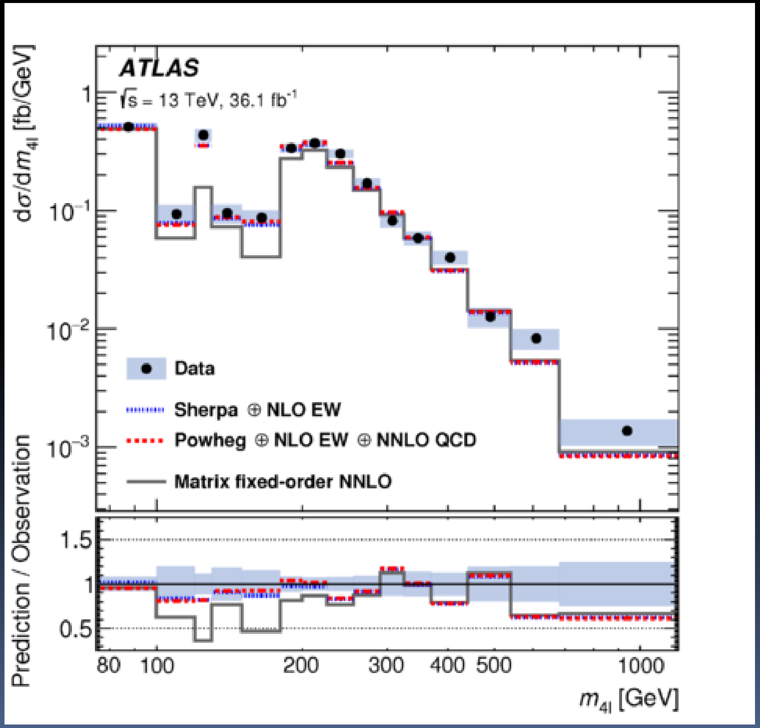




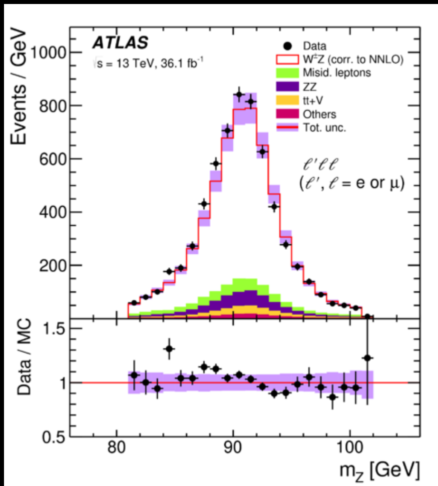


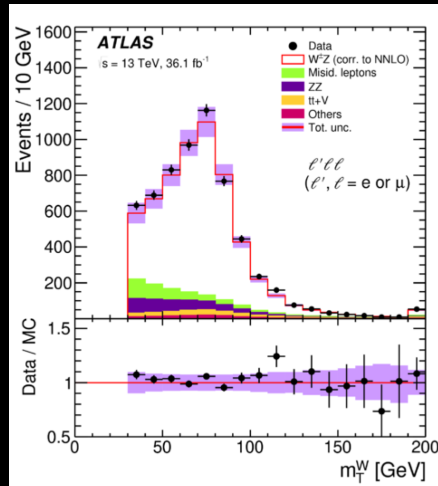


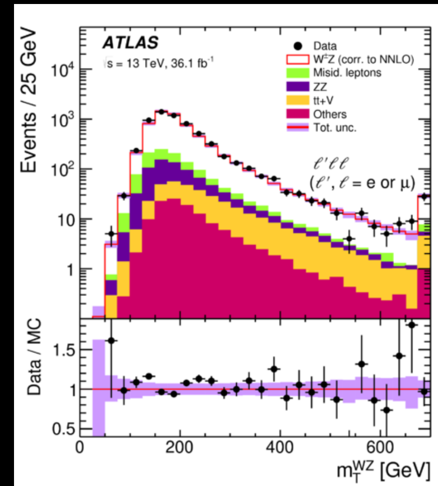


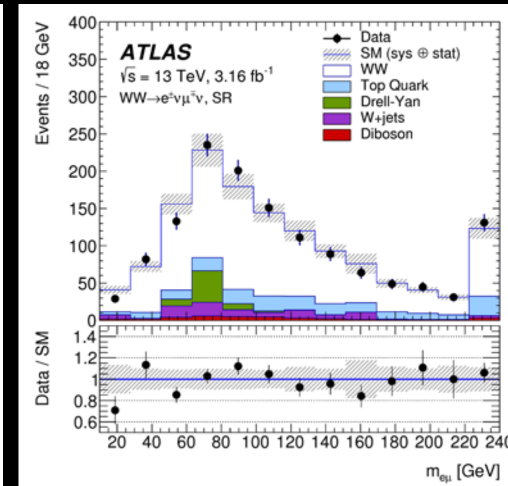


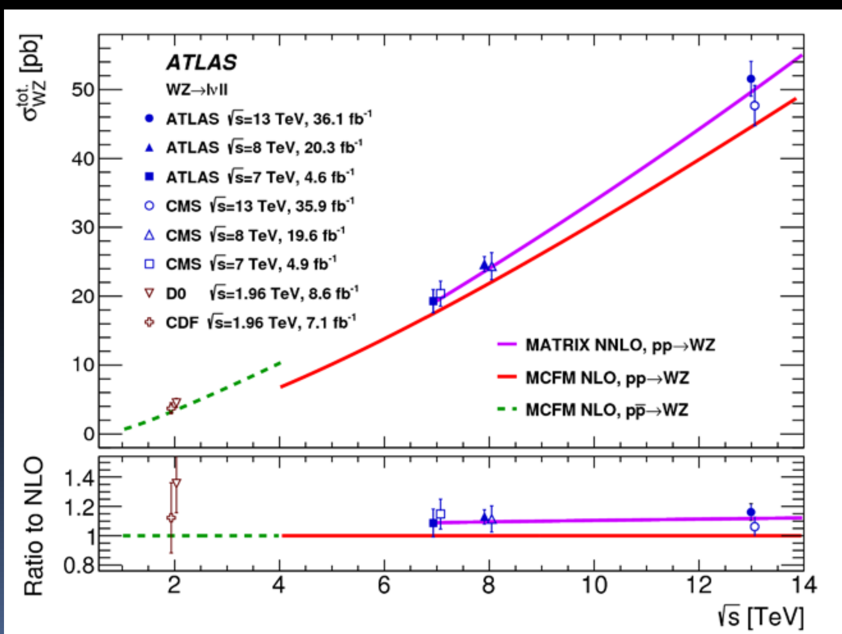
WW and WZ production

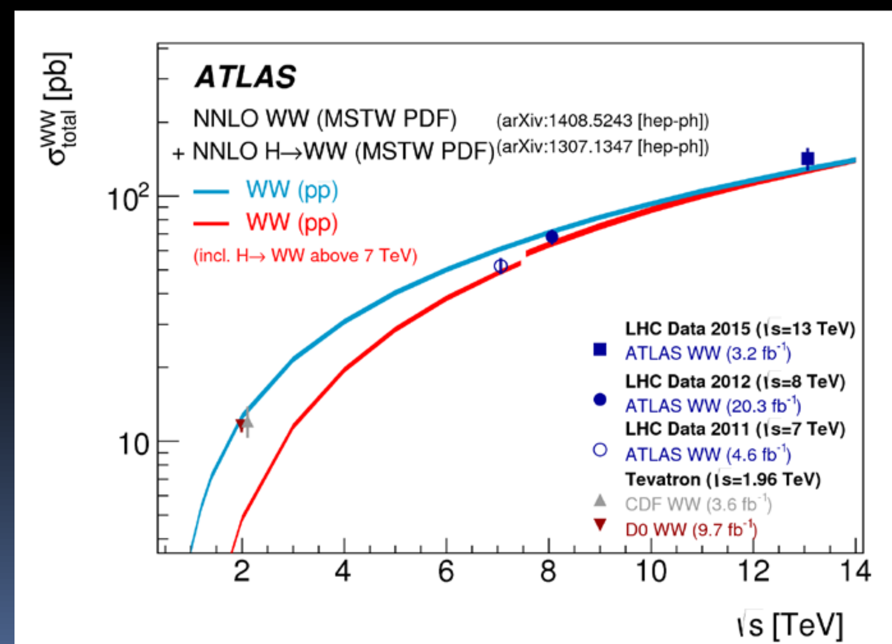






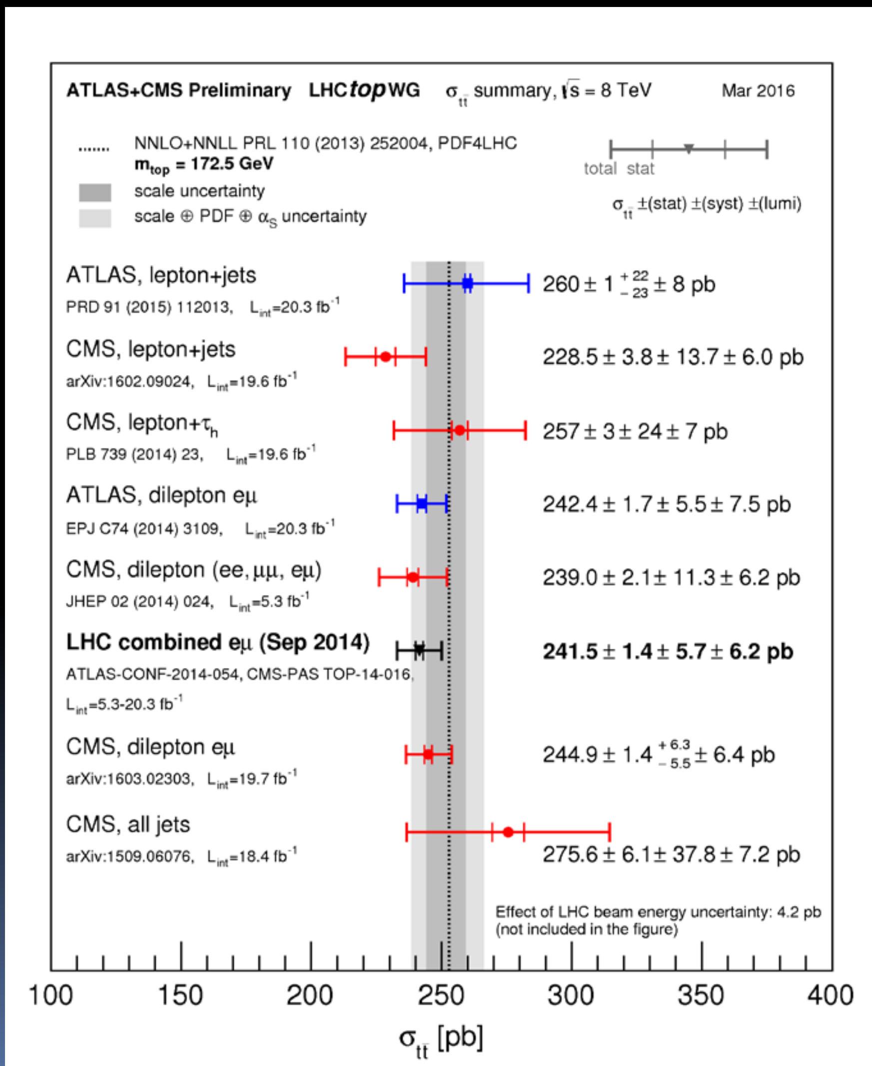


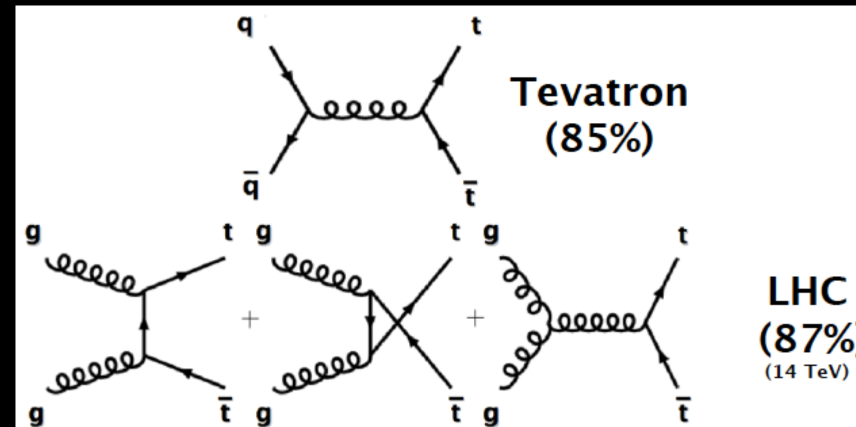


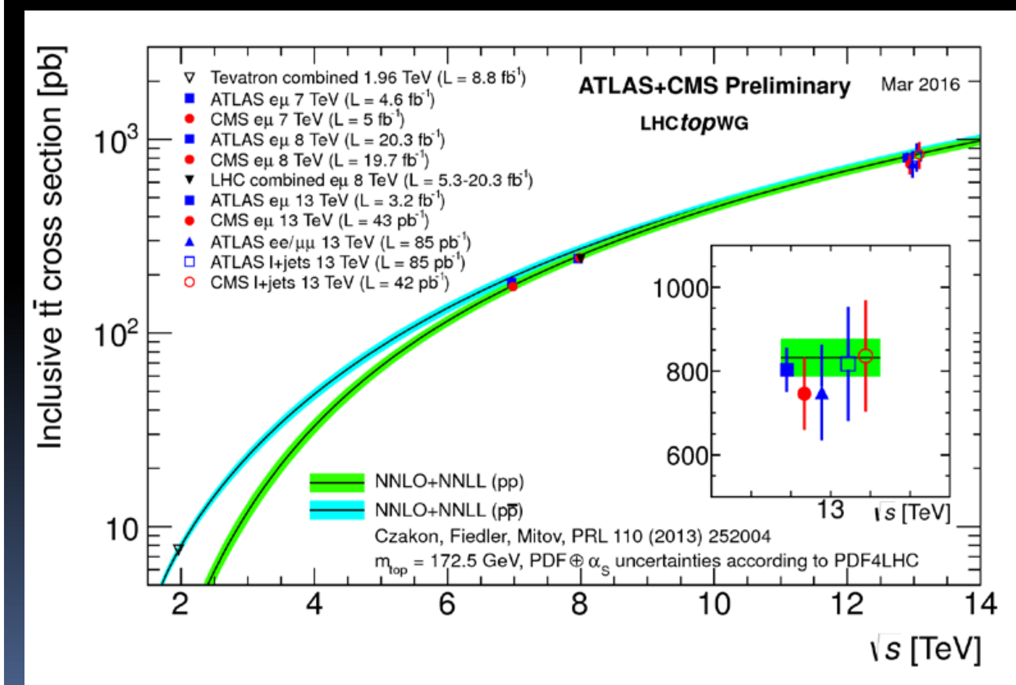


Top quark @ ATLAS ++

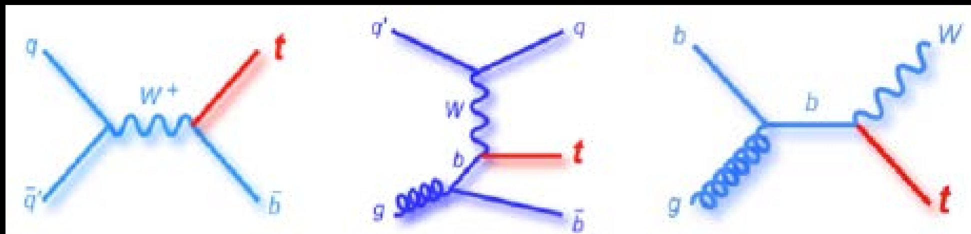
- Ttbar, cross sections

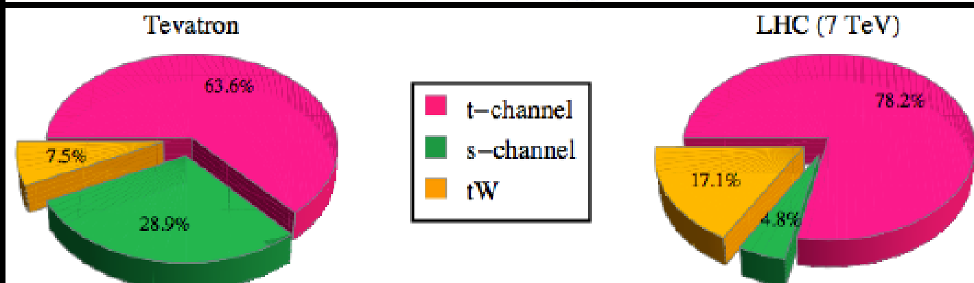


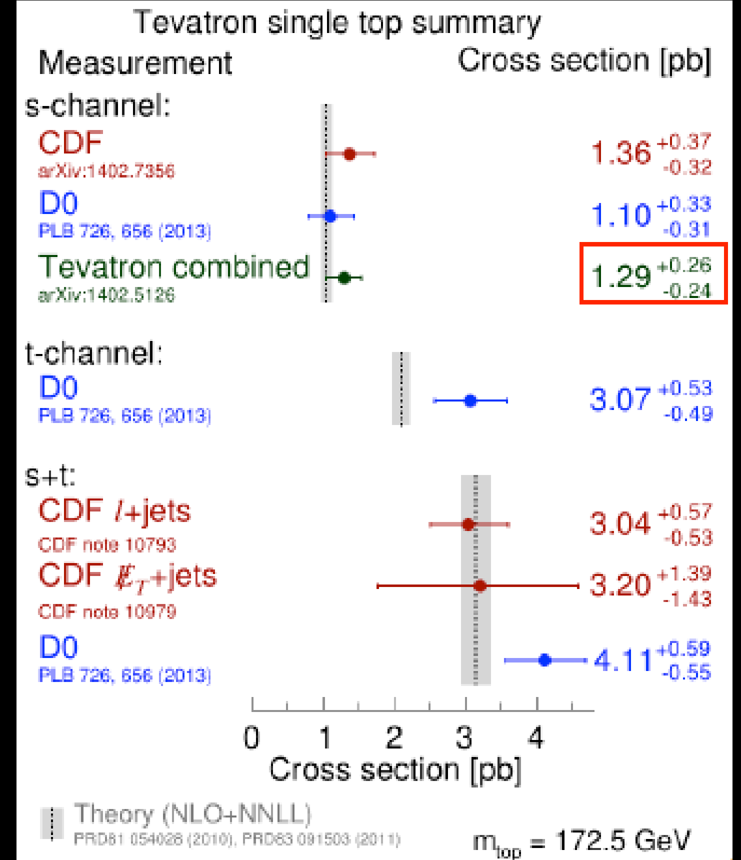


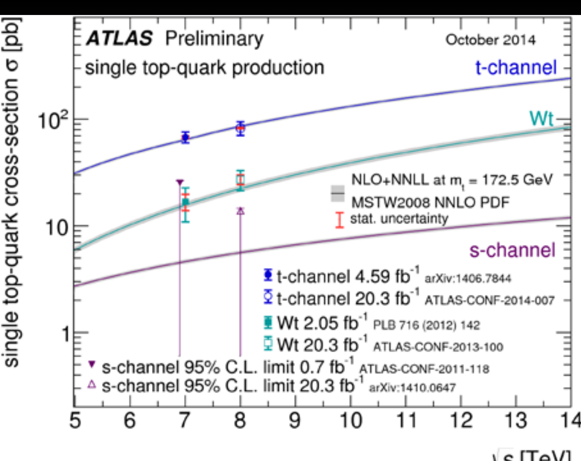


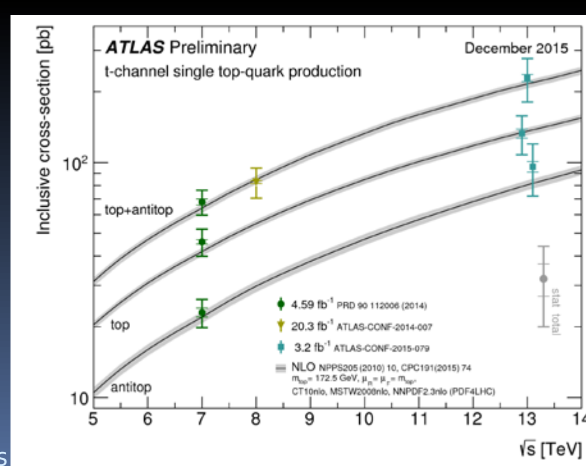
Single top @ ATLAS ++

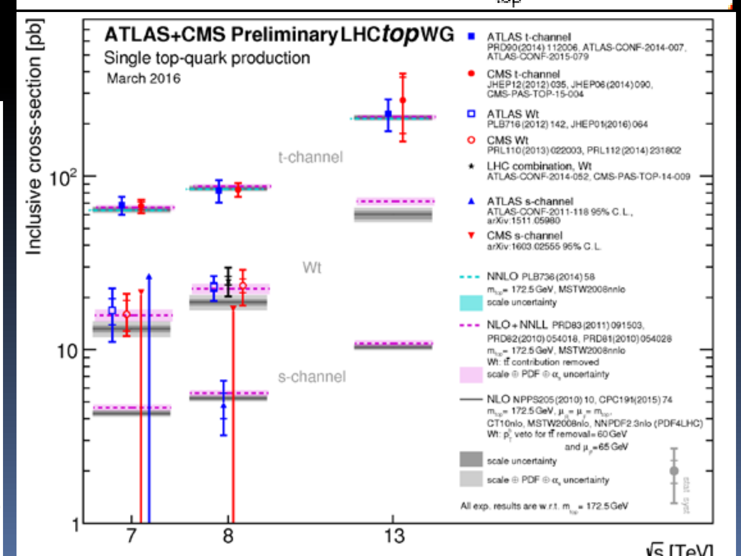




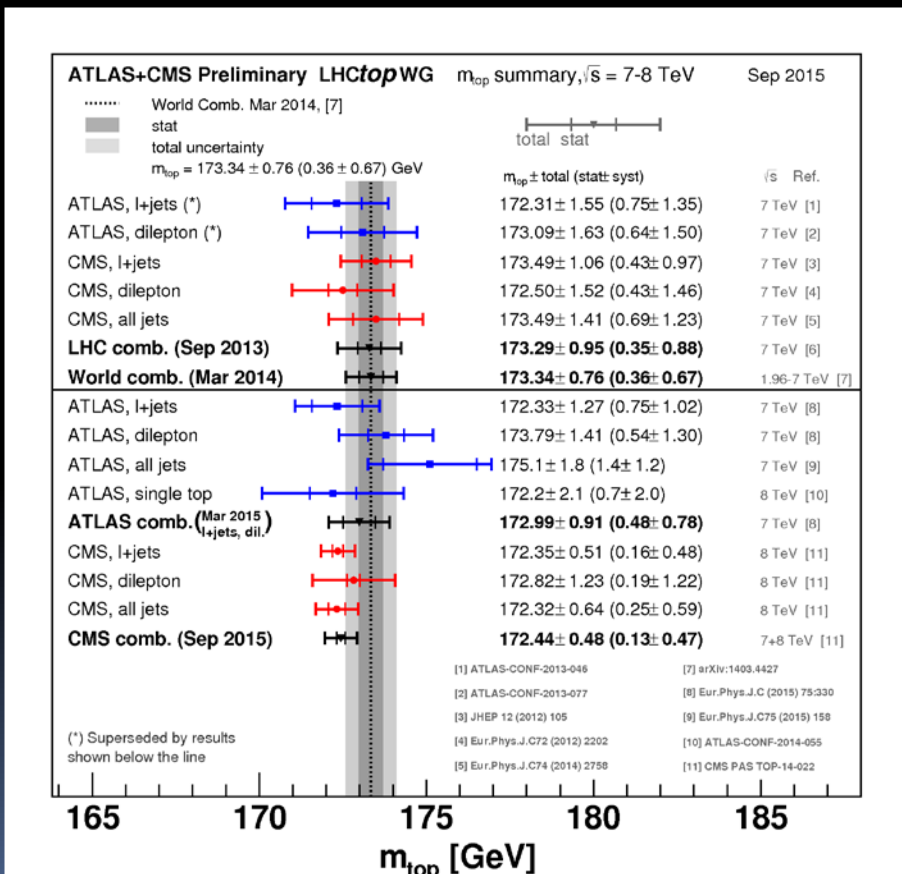


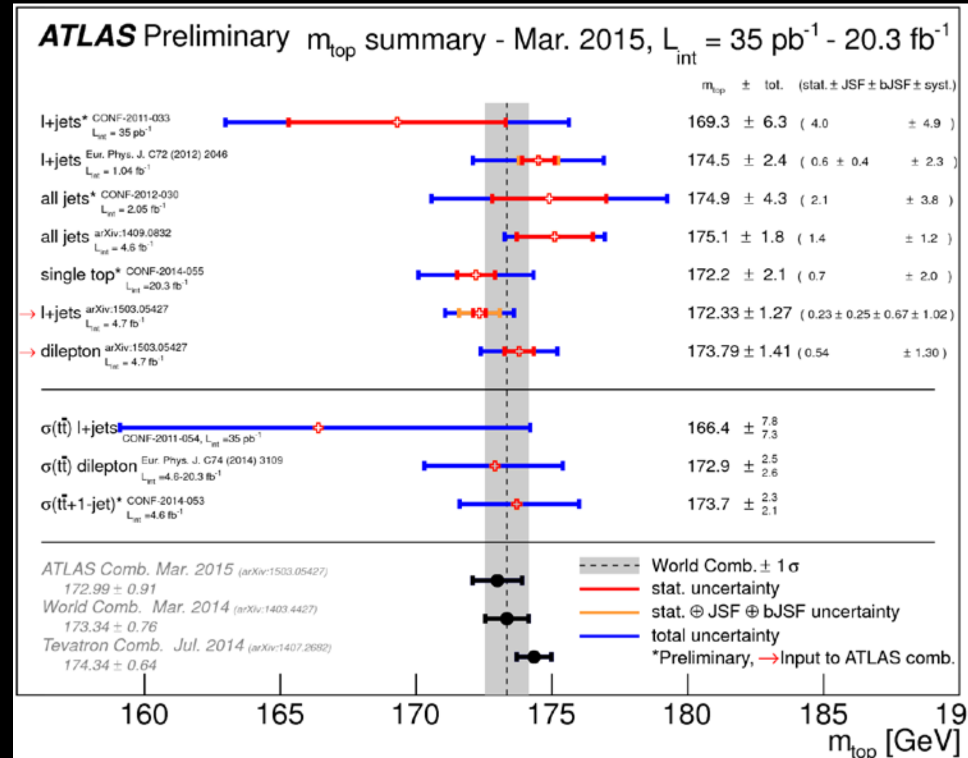


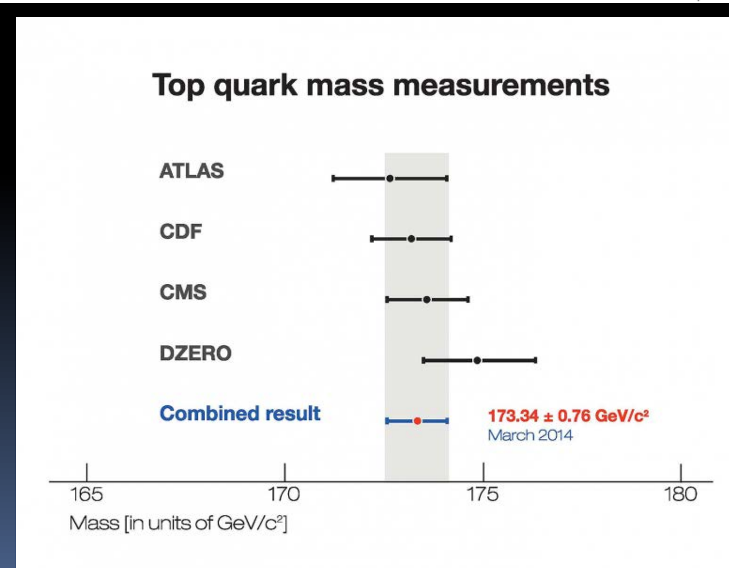




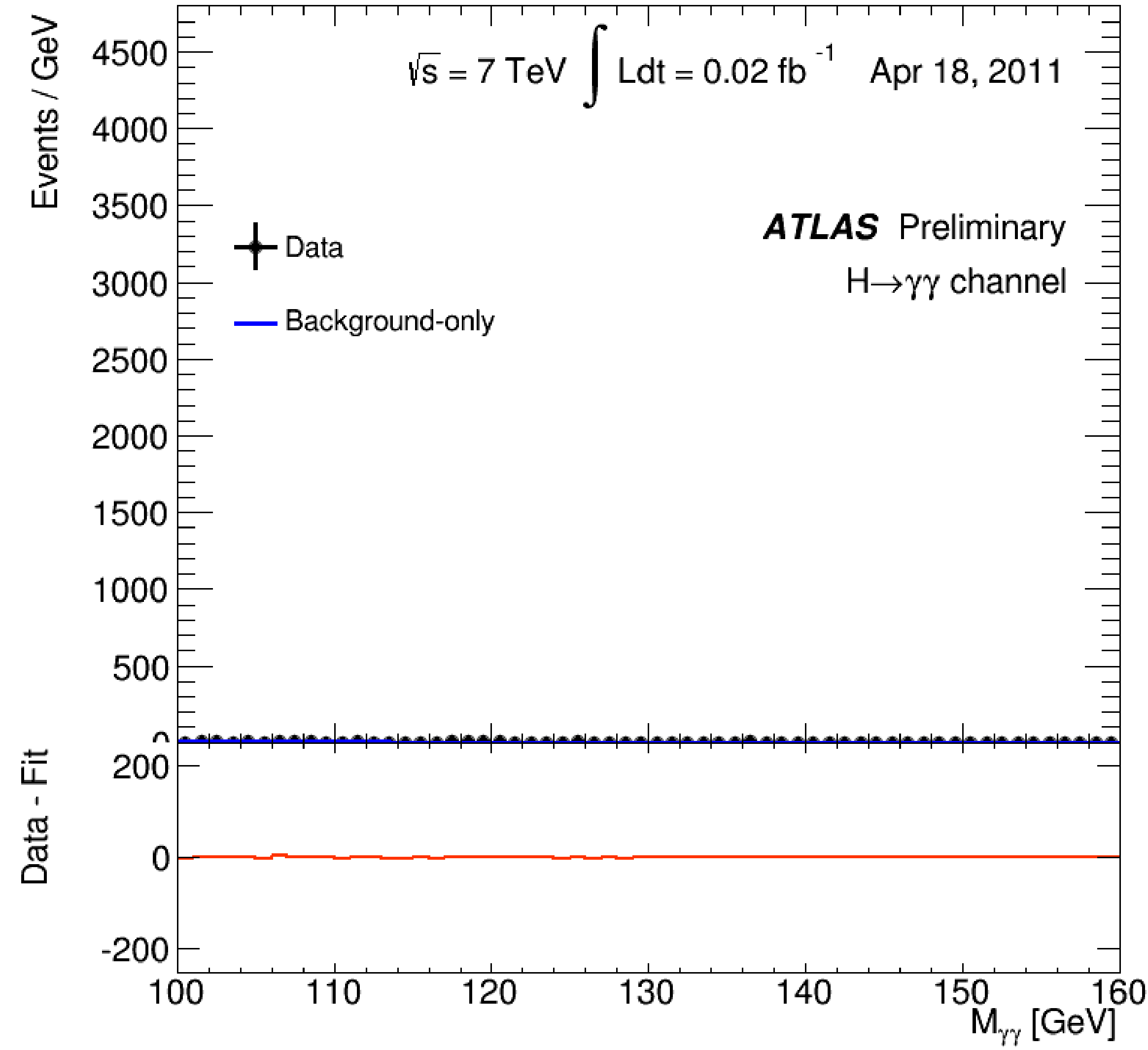
Top mass measurements



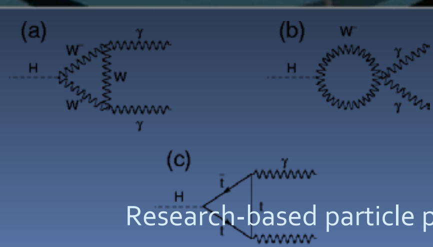




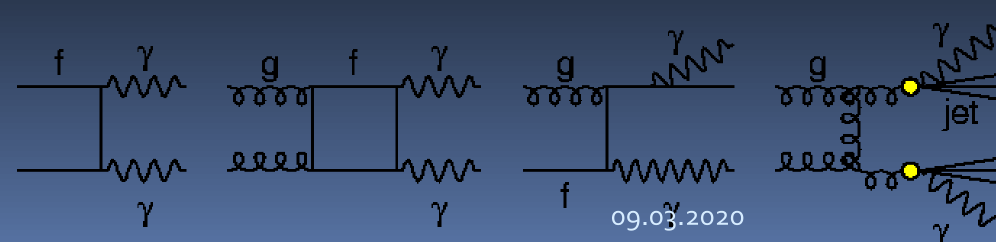
H→γγ
ATLAS
EXPERIMENT
Run Number: 204769, Event Number: 24947130
Date: 2012-06-10 08:17:12 UTC



$\sqrt{s}$ = 7 TeV $\int$ Ldt = 0.02 fb^{-1} Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
Data - Fit
$M_{\gamma\gamma}$ [GeV]



(a)
(b)
(c)



jet

(Statistical significance)

- Plot number of events or cross section as function of chosen variable
  - observed or measured (Data)
  - expected "background" (SM or some established theory)
  - ratio observed/SM
  - predicted by new physics theory

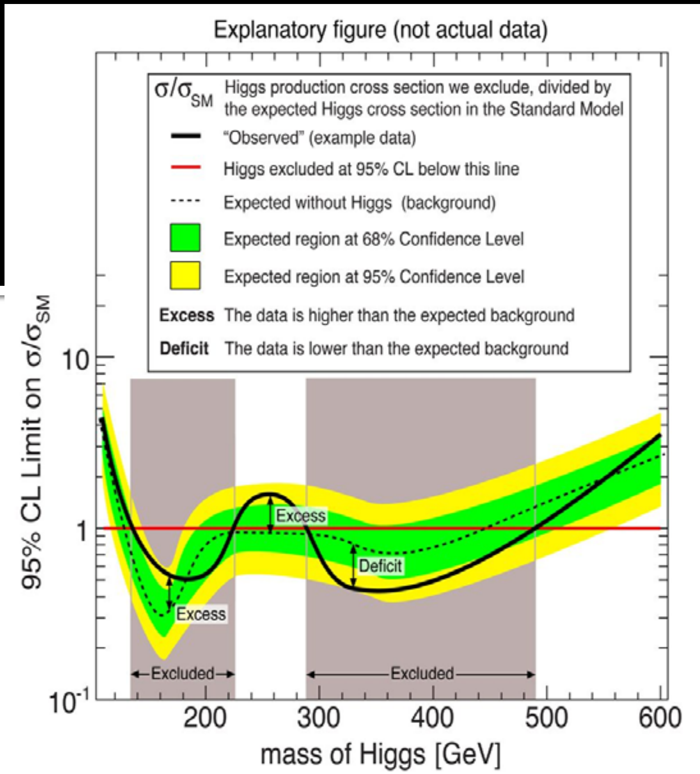


Figure A

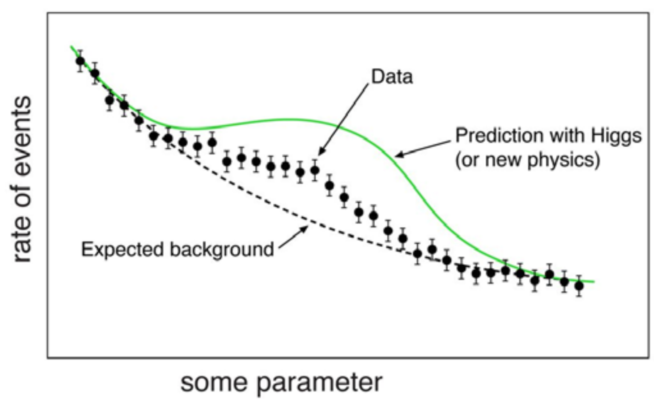
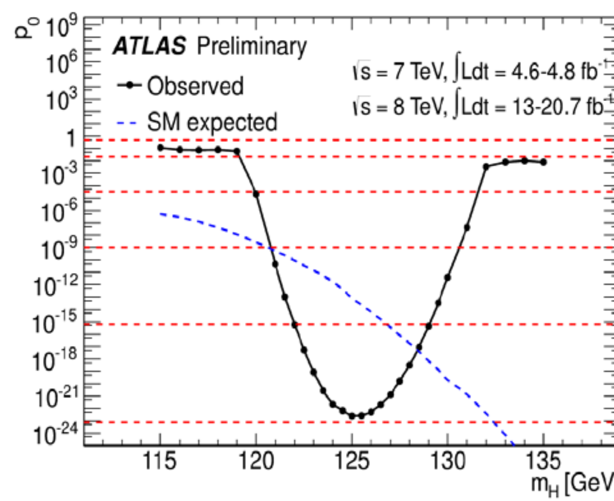


Figure B

- New Physics?
  - Local probability p_0 for a background-only experiment to be more signal-like than the observation as a function of new particle mass
  - The higher the Significance, the lower the probability of background fluctuation



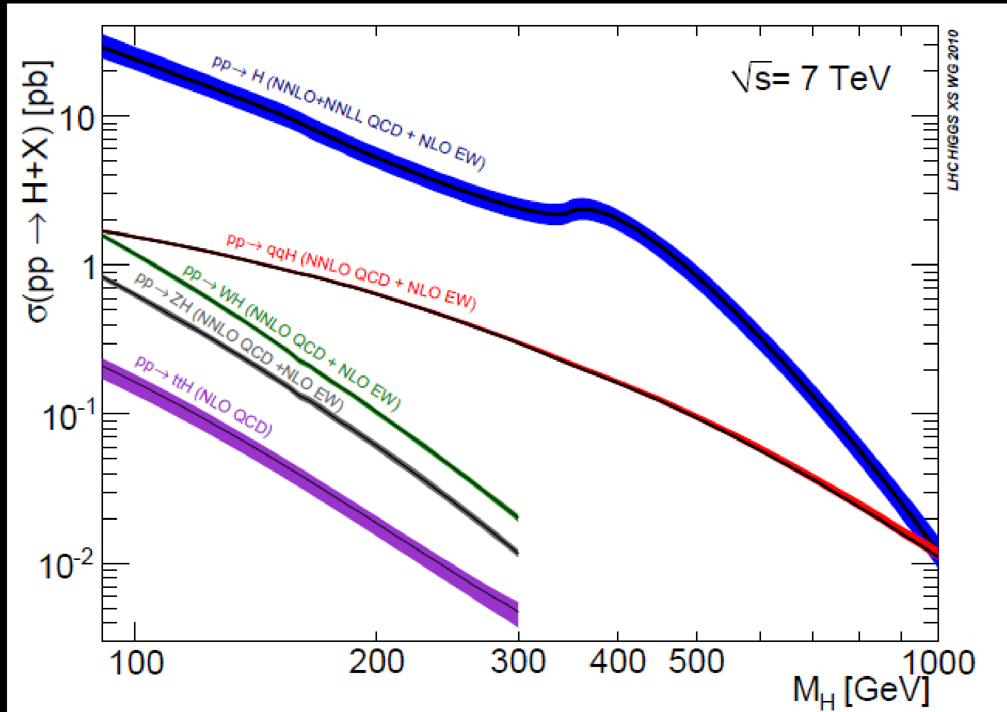
Mid-term evaluation

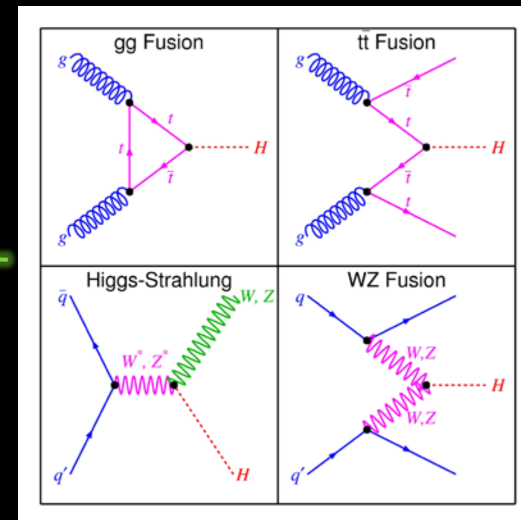
- Feedback most welcome
- Things to improve – short-term
- Method
- Projects
- All-hands sessions & tools
- Lectures
- …
-

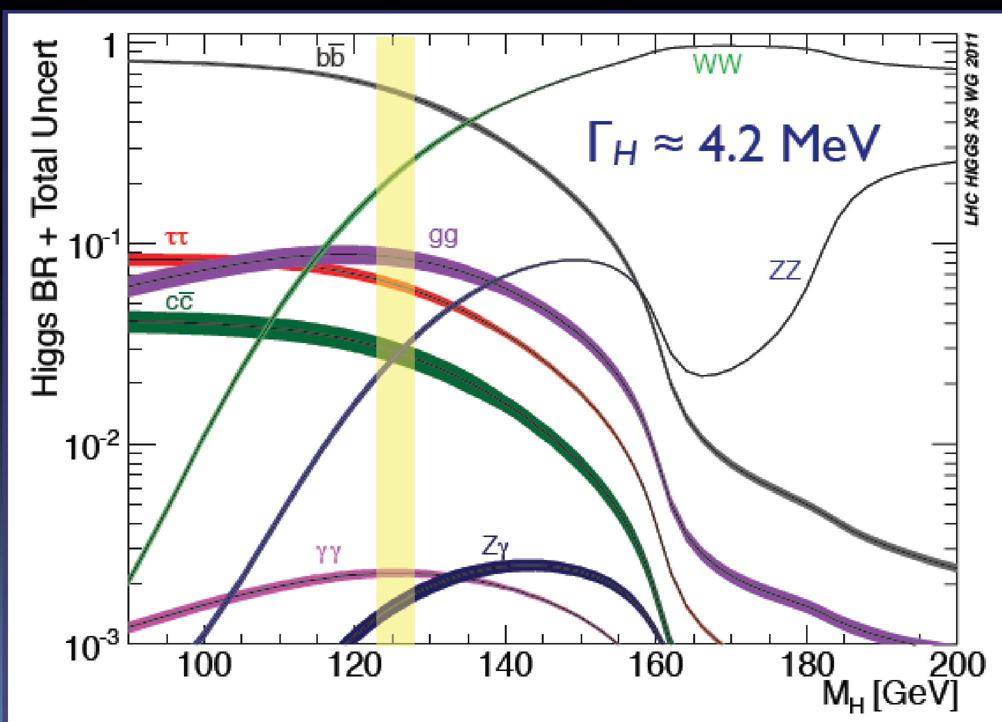
- CERN visit
  - See link to preparatory material
  - go through the stuff before

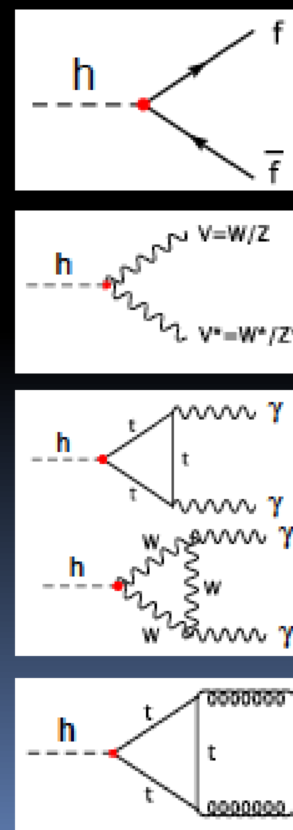
- Final Projects
  - See googledoc preparatory document

Higgs production and decay at LHC









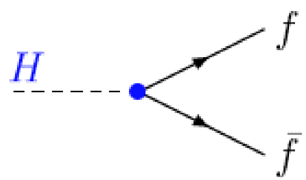
- 125 GeV … a rather good compromise
- 5/5 production processes
- ≥5 decay channels

Higgs mechanism in SM

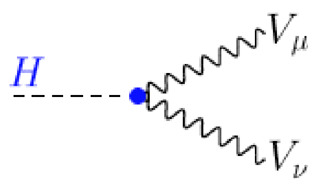
- For details about Higgs, see Djouadi's book: The Anatomy of Electro–Weak Symmetry Breaking:
  - The Higgs boson in the Standard Model
  - The Higgs bosons in the Minimal Supersymmetric Model

Higgs couplings SM

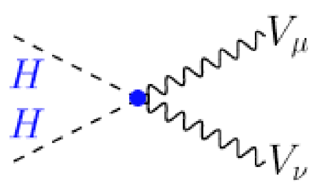
Feynman rules for the SM Higgs:



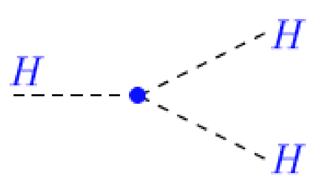
$$g_{Hff} = m_f/v = (\sqrt{2}G_\mu)^{1/2} m_f \quad \times (i)$$



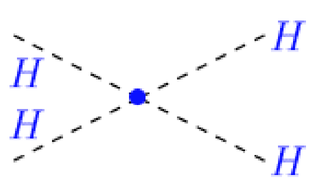
$$g_{HVV} = 2M_V^2/v = 2(\sqrt{2}G_\mu)^{1/2} M_V^2 \times (-ig_{\mu\nu})$$



$$g_{HHVV} = 2M_V^2/v^2 = 2\sqrt{2}G_\mu M_V^2 \times (-ig_{\mu\nu})$$



$$g_{HHH} = 3M_H^2/v = 3(\sqrt{2}G_\mu)^{1/2} M_H^2 \times (+i)$$



$$g_{HHHH} = 3M_H^2/v^2 = 3\sqrt{2}G_\mu M_H^2 \times (+i)$$

Higgs decays to fermions and gauge bosons

$$\Gamma_{\mathrm{Born}}(H \to f\bar{f}) = \frac{G_\mu N_c}{4\sqrt{2}\pi} M_H\, m_f^2\, \beta_f^3$$

$$\beta = (1 - 4m_f^2/M_H^2)^{1/2}$$

$$N_c = 3\,(1) \text{ for quarks (leptons)}$$

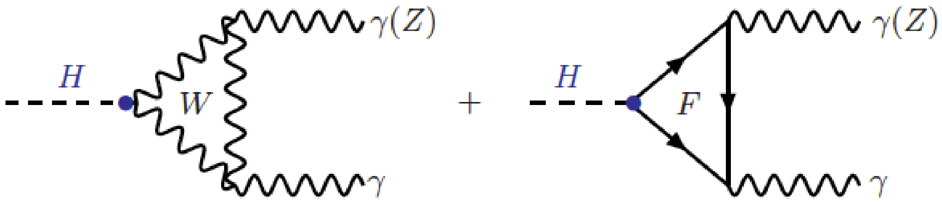
$$\Gamma(H \to VV) = \frac{G_\mu M_H^3}{16\sqrt{2}\pi}\, \delta_V\, \sqrt{1-4x}\,(1 - 4x + 12x^2)\ , \quad x = \frac{M_V^2}{M_H^2}$$

$$\delta_W = 2 \text{ and } \delta_Z = 1$$

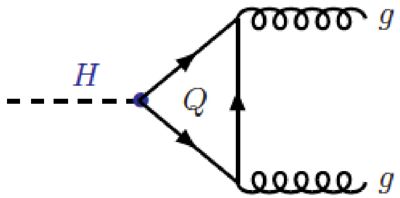
$$\Gamma(H \to WW + ZZ) \sim 0.5 \text{ TeV}\, [M_H/1 \text{ TeV}]^3$$

Loop induced Higgs decays

a)



b)



$$\Gamma(H \to gg) = \frac{G_\mu \alpha_s^2 M_H^3}{36\sqrt{2}\pi^3} \left| \frac{3}{4} \sum_Q A_{1/2}^H(\tau_Q) \right|^2$$

$$\Gamma(H \to \gamma\gamma) = \frac{G_\mu \alpha^2 M_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 A_{1/2}^H(\tau_f) + A_1^H(\tau_W) \right|^2$$

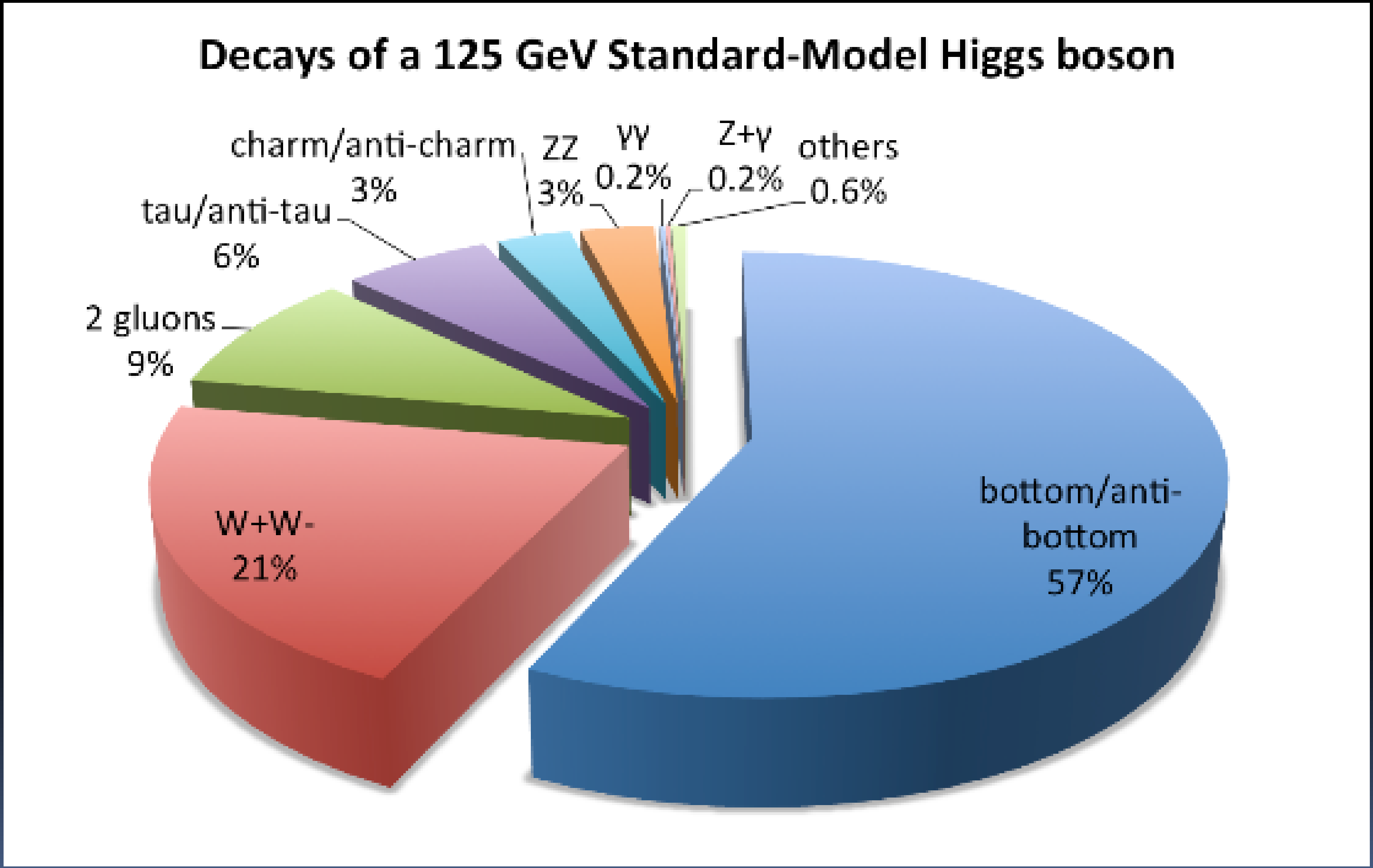
$$A_{1/2}^H(\tau) = 2[\tau + (\tau - 1) f(\tau)]\, \tau^{-2}$$

$$A_1^H(\tau) = -[2\tau^2 + 3\tau + 3(2\tau - 1) f(\tau)]\, \tau^{-2}$$

$$\tau_i = M_H^2 / 4M_i^2 \text{ with } i = f, W$$

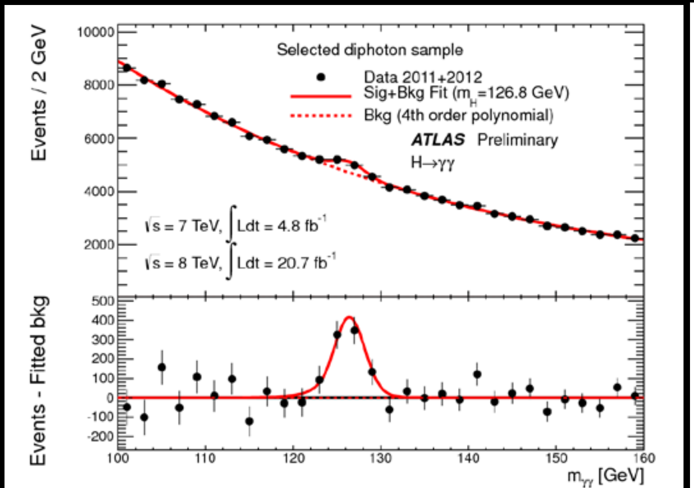
$$f(\tau) = \begin{cases} \arcsin^2 \sqrt{\tau} & \tau \le 1 \\ -\frac{1}{4}\left[\log \frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2 & \tau > 1 \end{cases}$$

The 125 GeV Higgs cake …

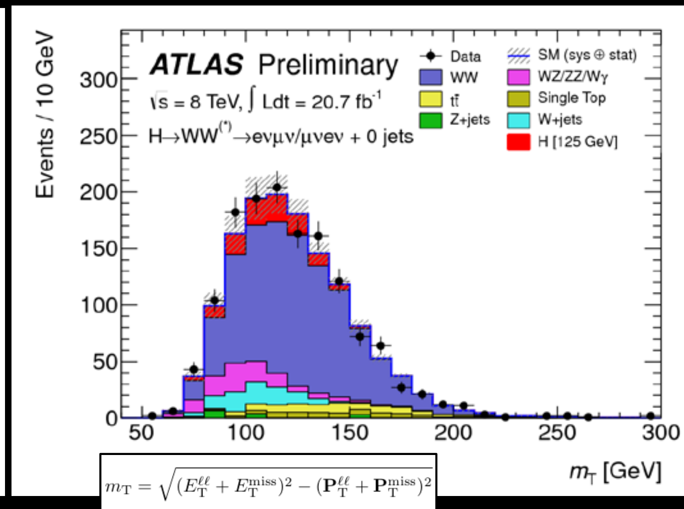


Higgs discovery?

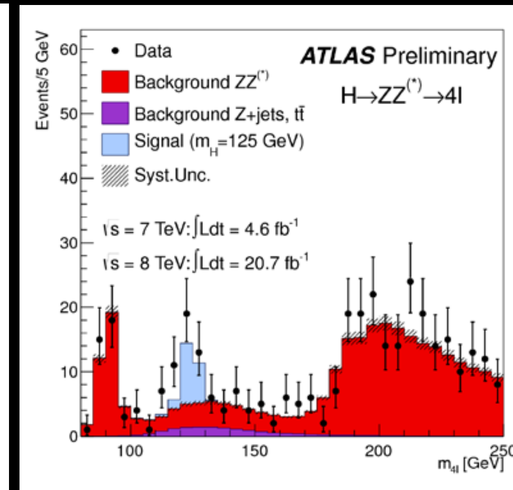
H→γγ



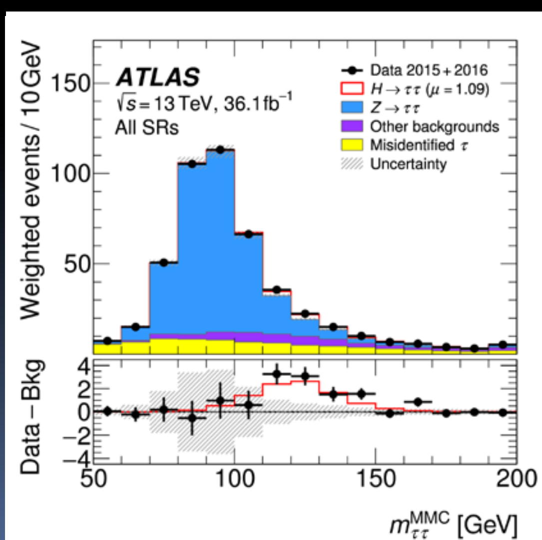
H→WW*→lνlν



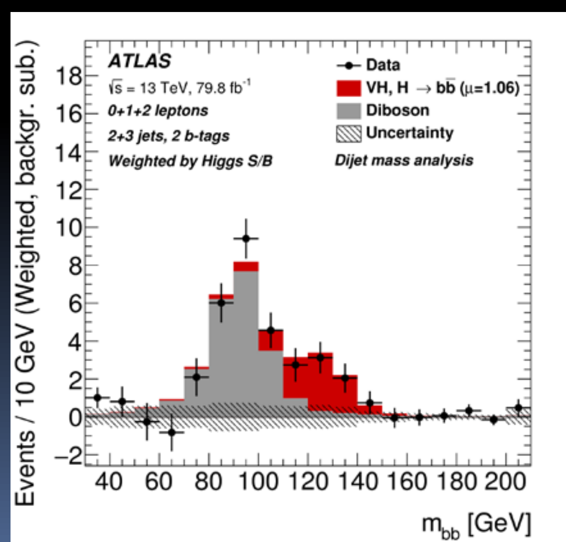
H→ZZ*→llll



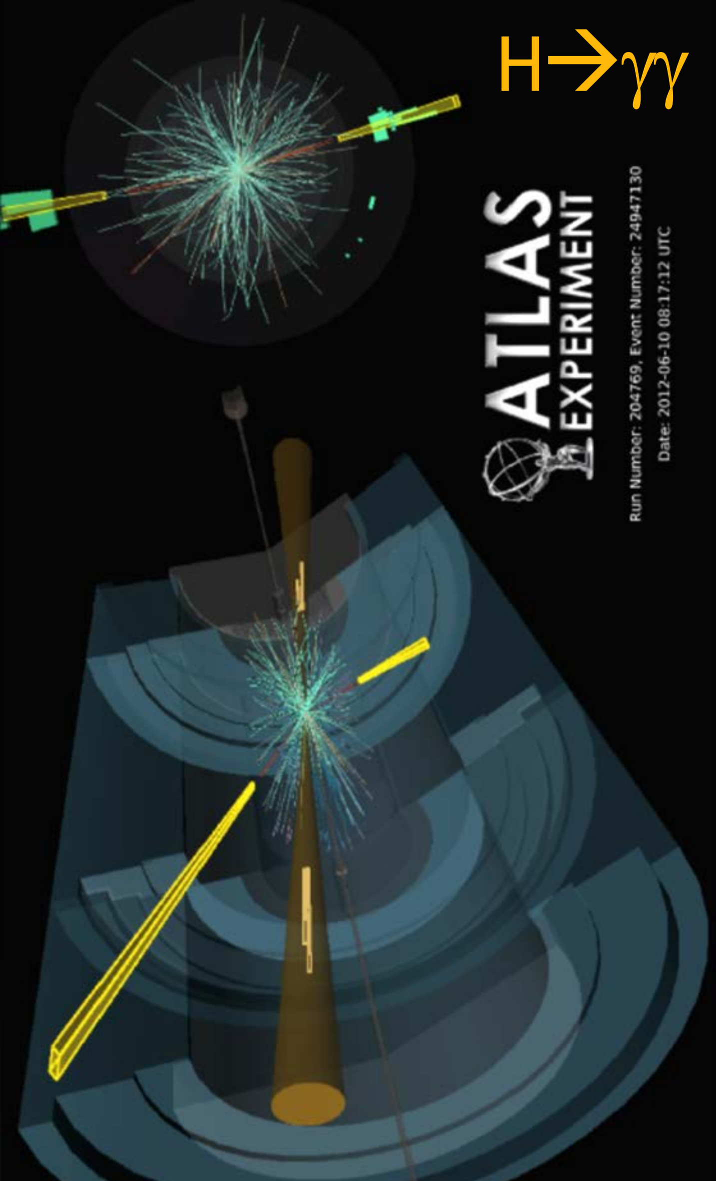
H→ττ

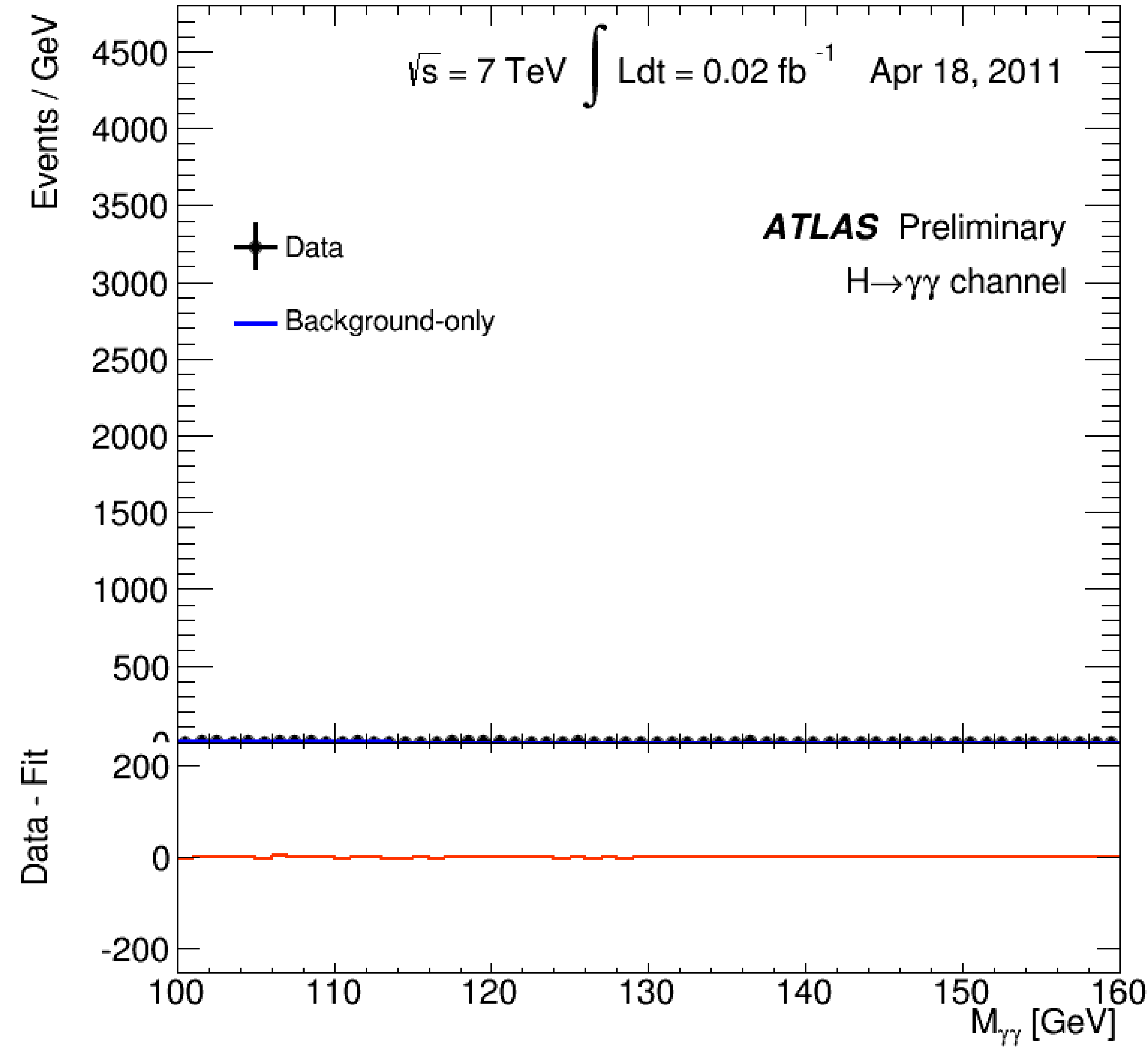


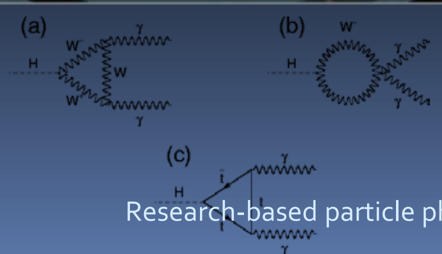
H→bb

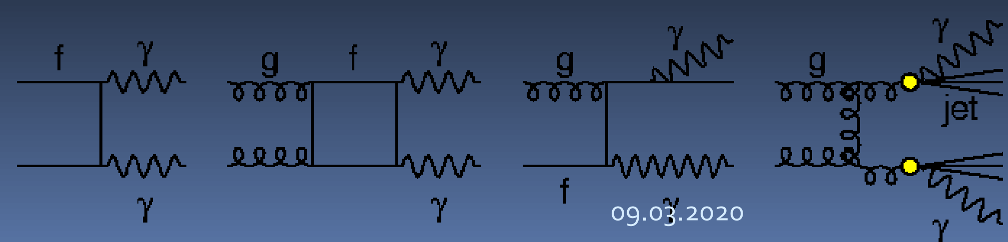


$H \rightarrow \gamma\gamma$

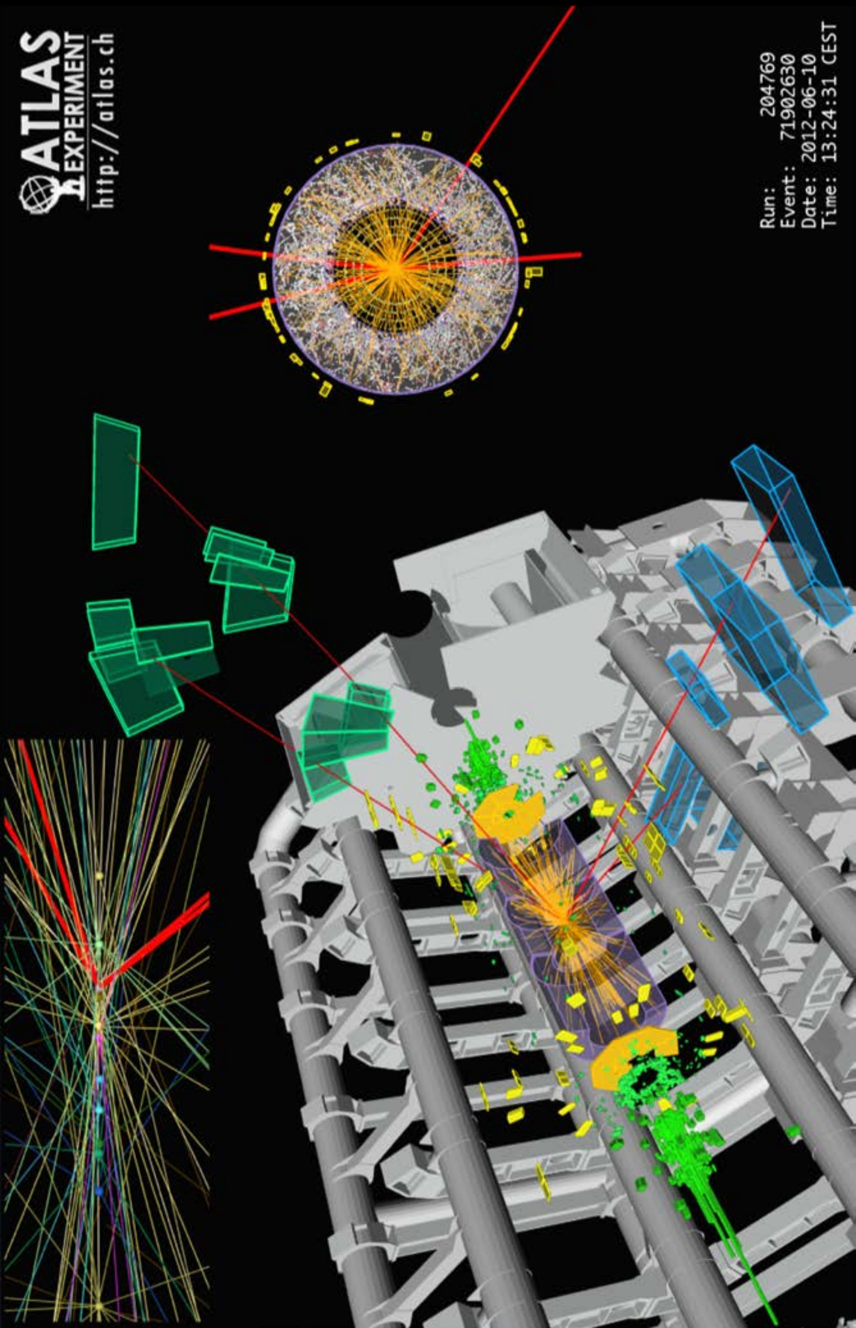


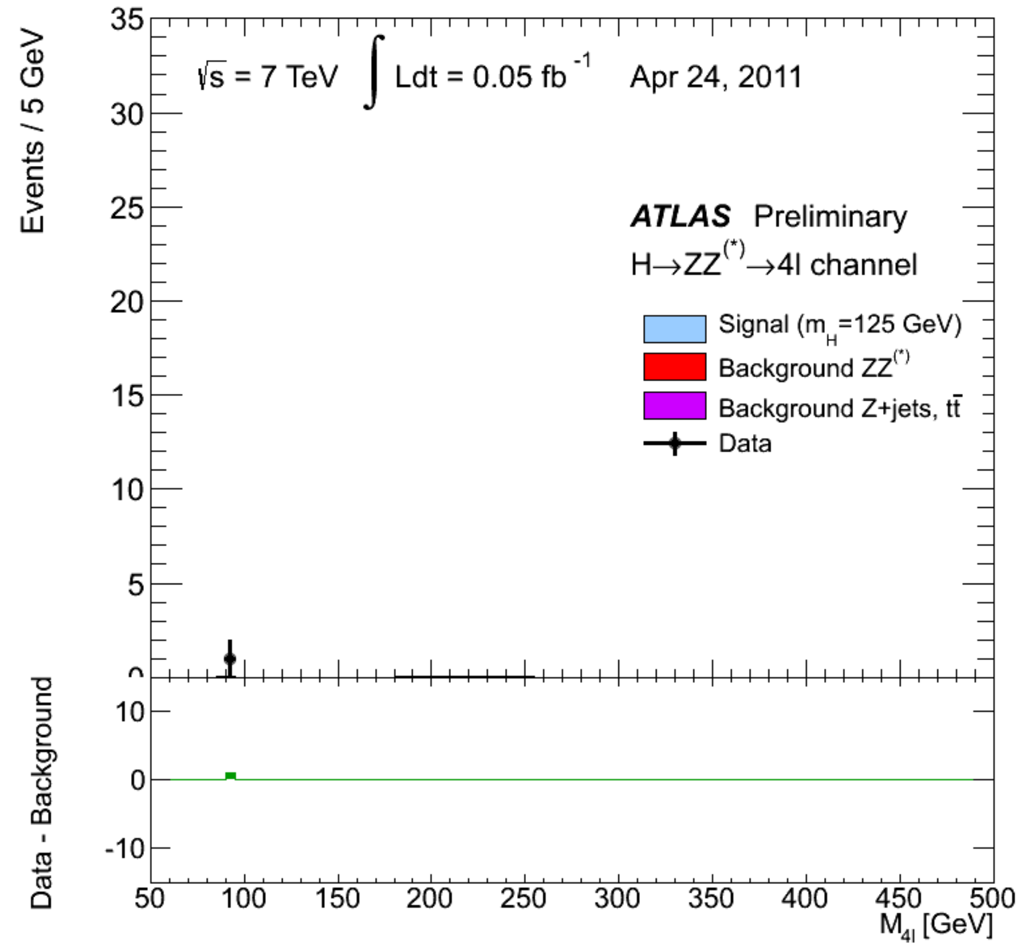






$H \rightarrow ZZ^* \rightarrow l^+l^-l^+l^-$

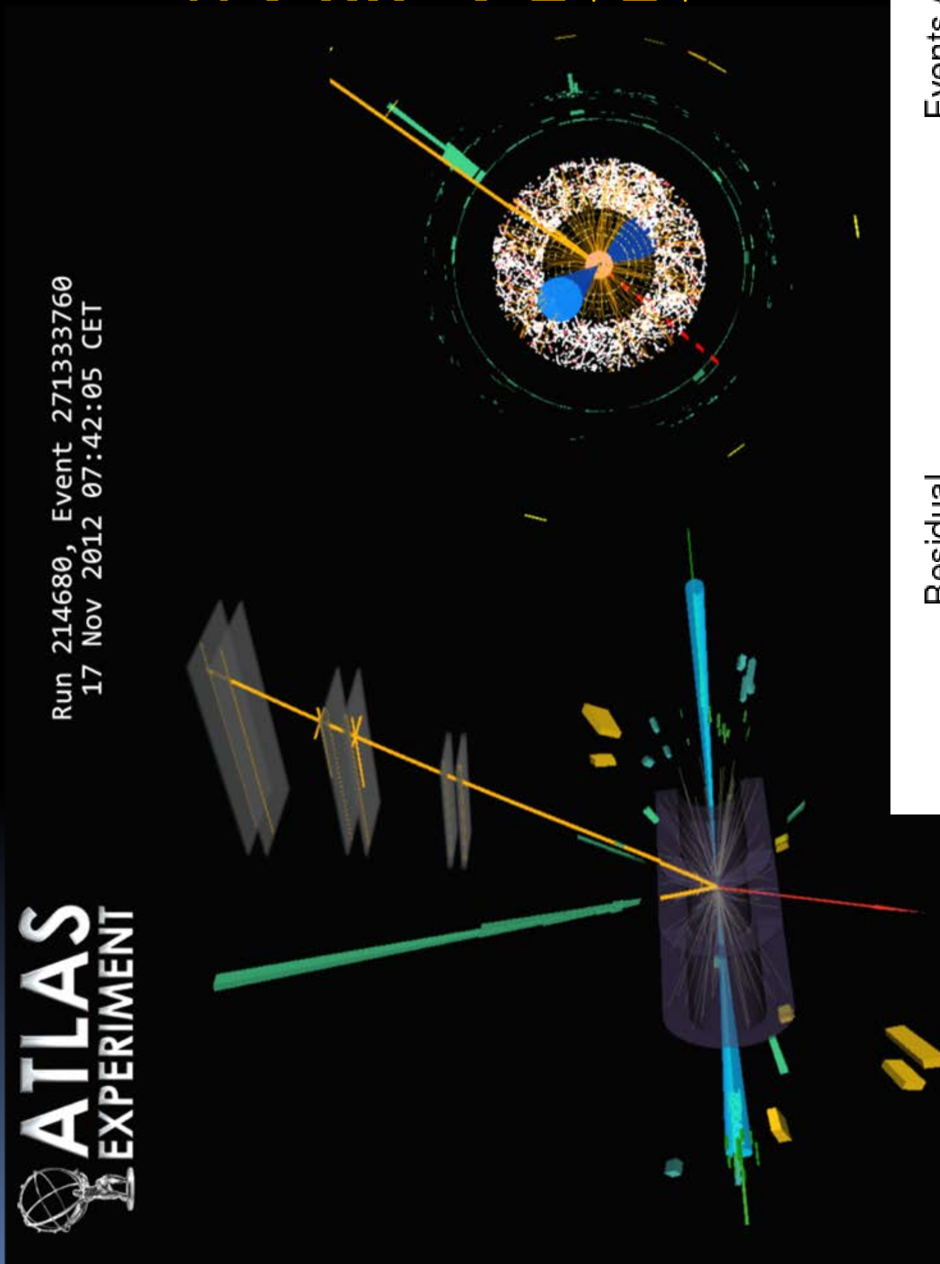


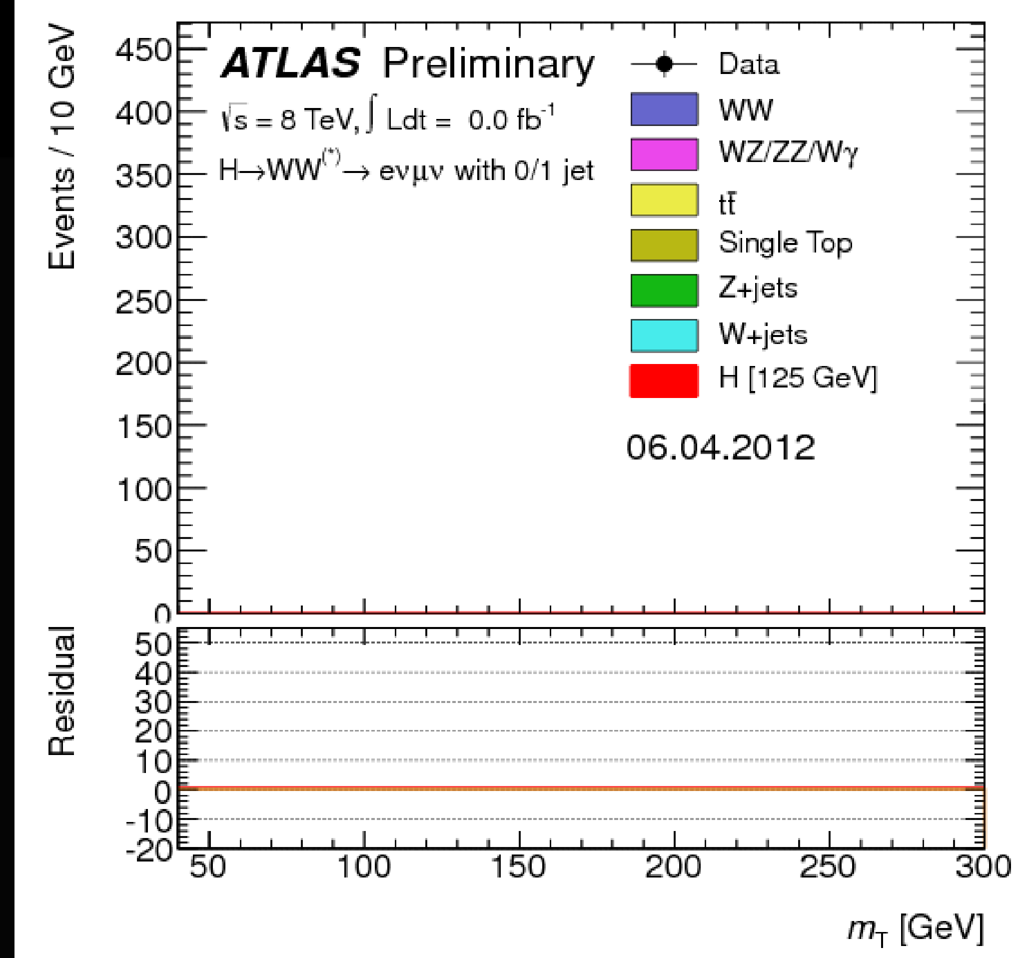


Understanding of "background" is important

- Most of which is due to important physics at the heart of the gauge structure / symmetry of electroweak interaction
- Higgs showed up between 2 relatively busy regions!

$H \rightarrow WW^* \rightarrow l\nu l\nu$



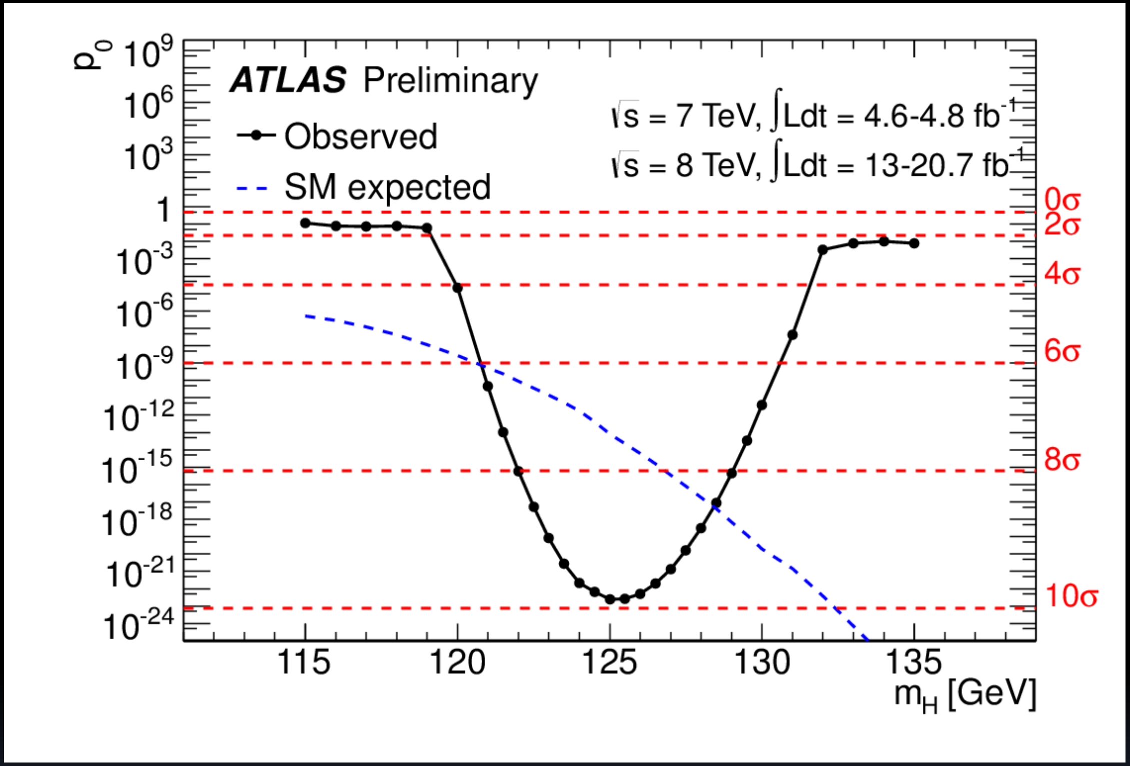


$$m_{\rm T} = \sqrt{(E_{\rm T}^{\ell\ell} + E_{\rm T}^{\rm miss})^2 - (\mathbf{P}_{\rm T}^{\ell\ell} + \mathbf{P}_{\rm T}^{\rm miss})^2}$$

- Understanding of background is crucial
  - Most of which is due to important physics
  - at the heart of the gauge structure / symmetry of electroweak interaction

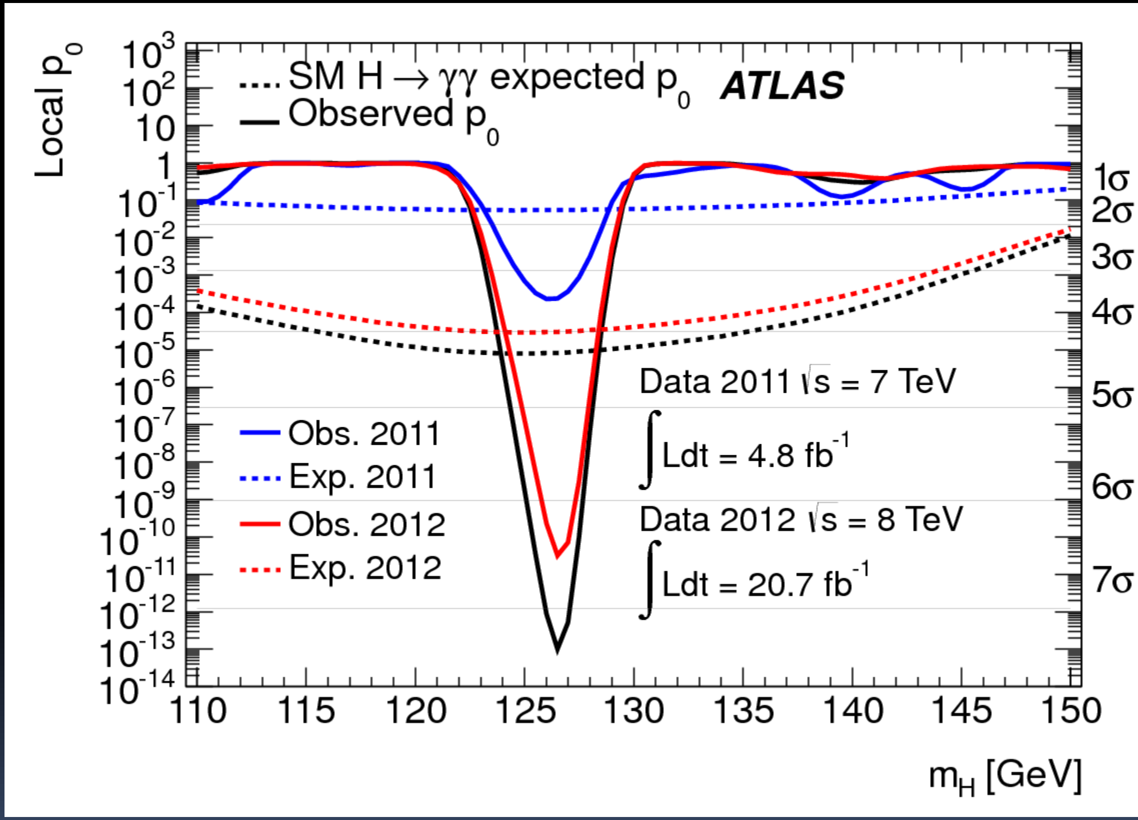
A new particle discovered

- Local probability p_o for a background-only experiment to be more signal-like than the observation as a function of m_H
- Combination of all channels
  - $\tau\tau$ and bb not all included yet



- 10σ signal @ M~125.5 GeV
- Probability of background fluctuation: ~10^{-23}

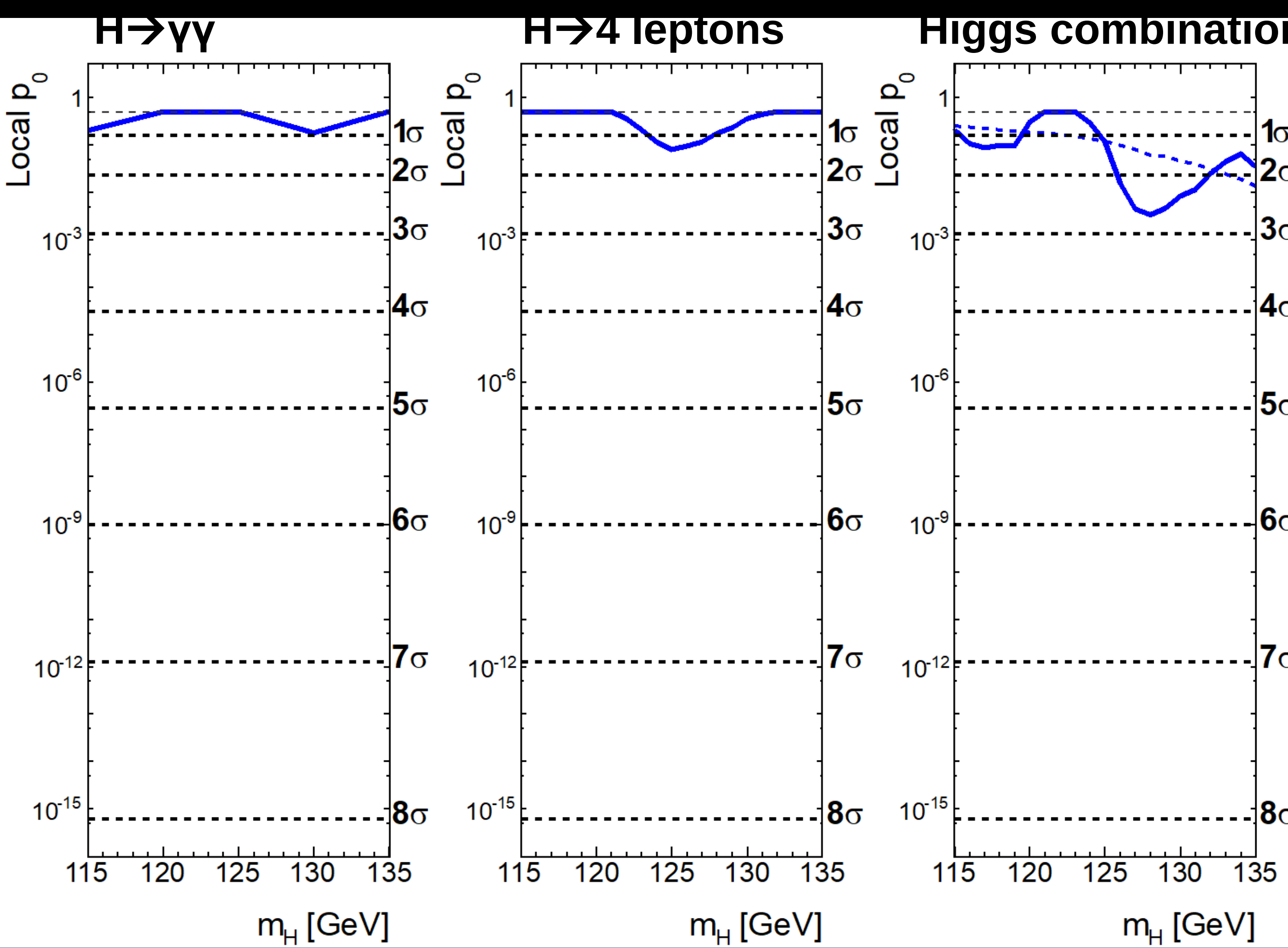
- Observed local p_0 as a function of the Higgs boson mass m_H for the $\sqrt{s}$ = 7TeV data(blue), the $\sqrt{s}$ = 8TeV data (red) and their combination (black)



From excess to discovery (ATLAS)

progressive significance(p0) plots

Local p_0: probability that the background fluctuates to the observed data (or higher)

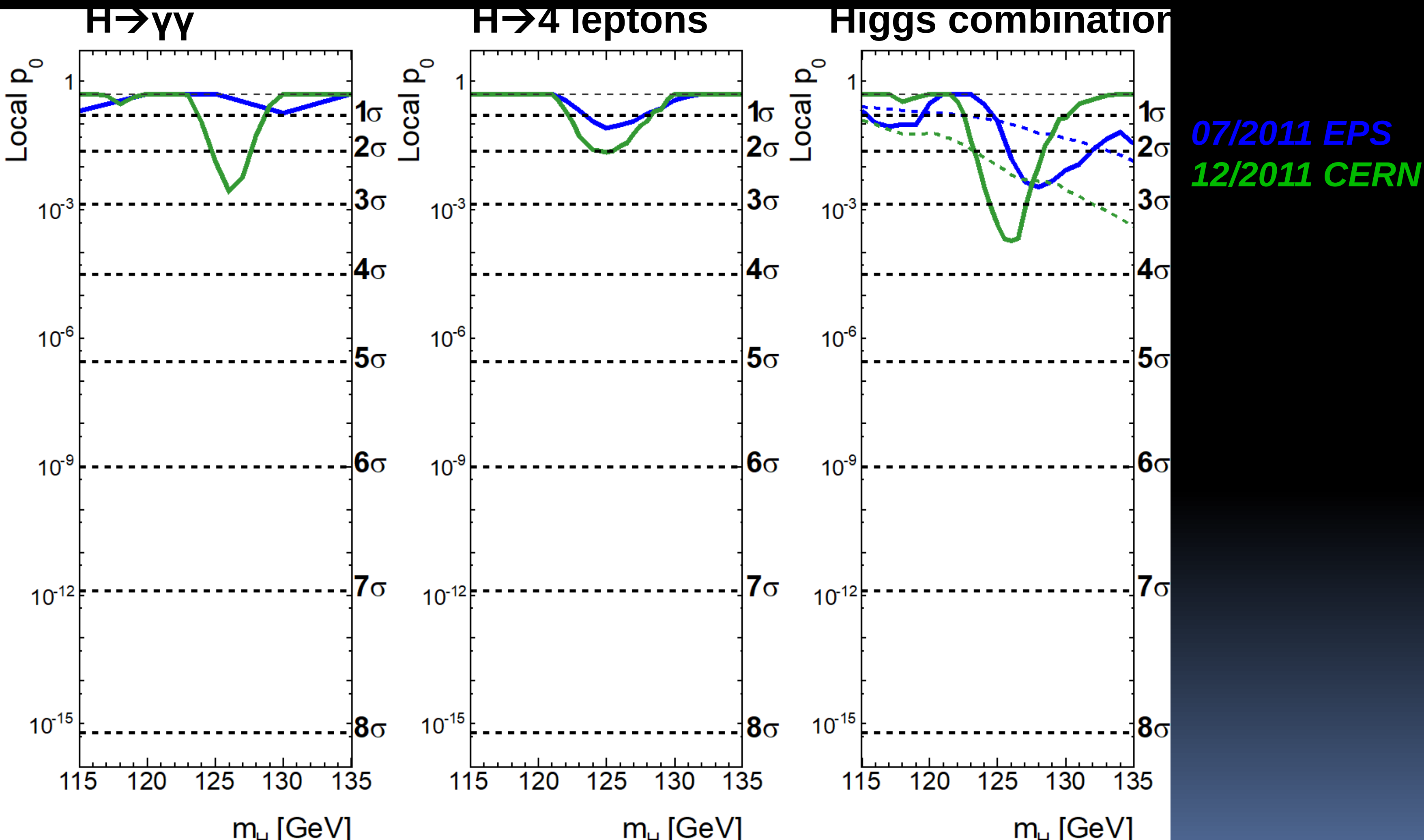


07/2011 EPS

From excess to discovery (ATLAS)

progressive significance(p0) plots

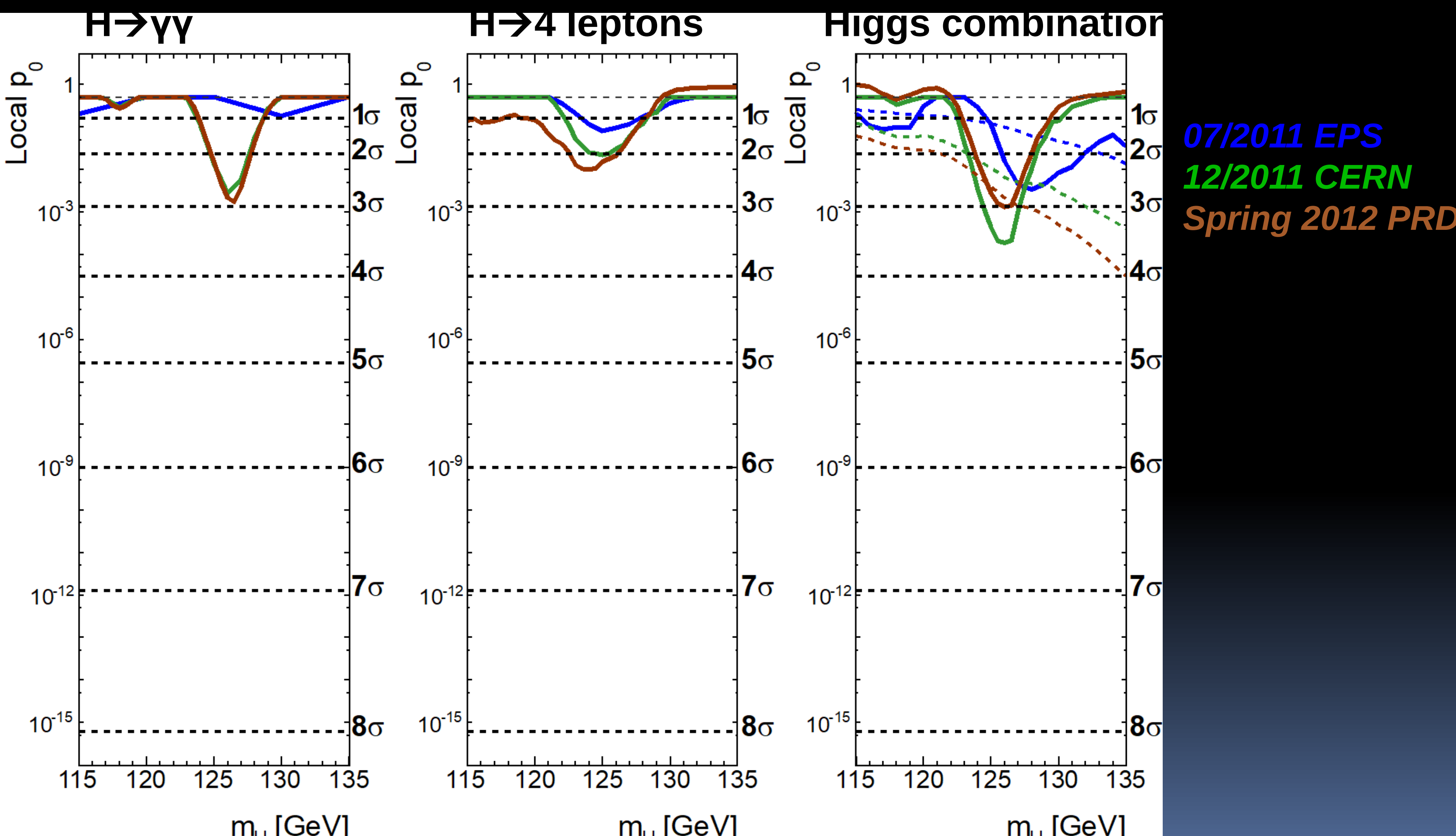
Local p_0: probability that the background fluctuates to the observed data (or higher)



From excess to discovery (ATLAS)

progressive significance(p0) plots

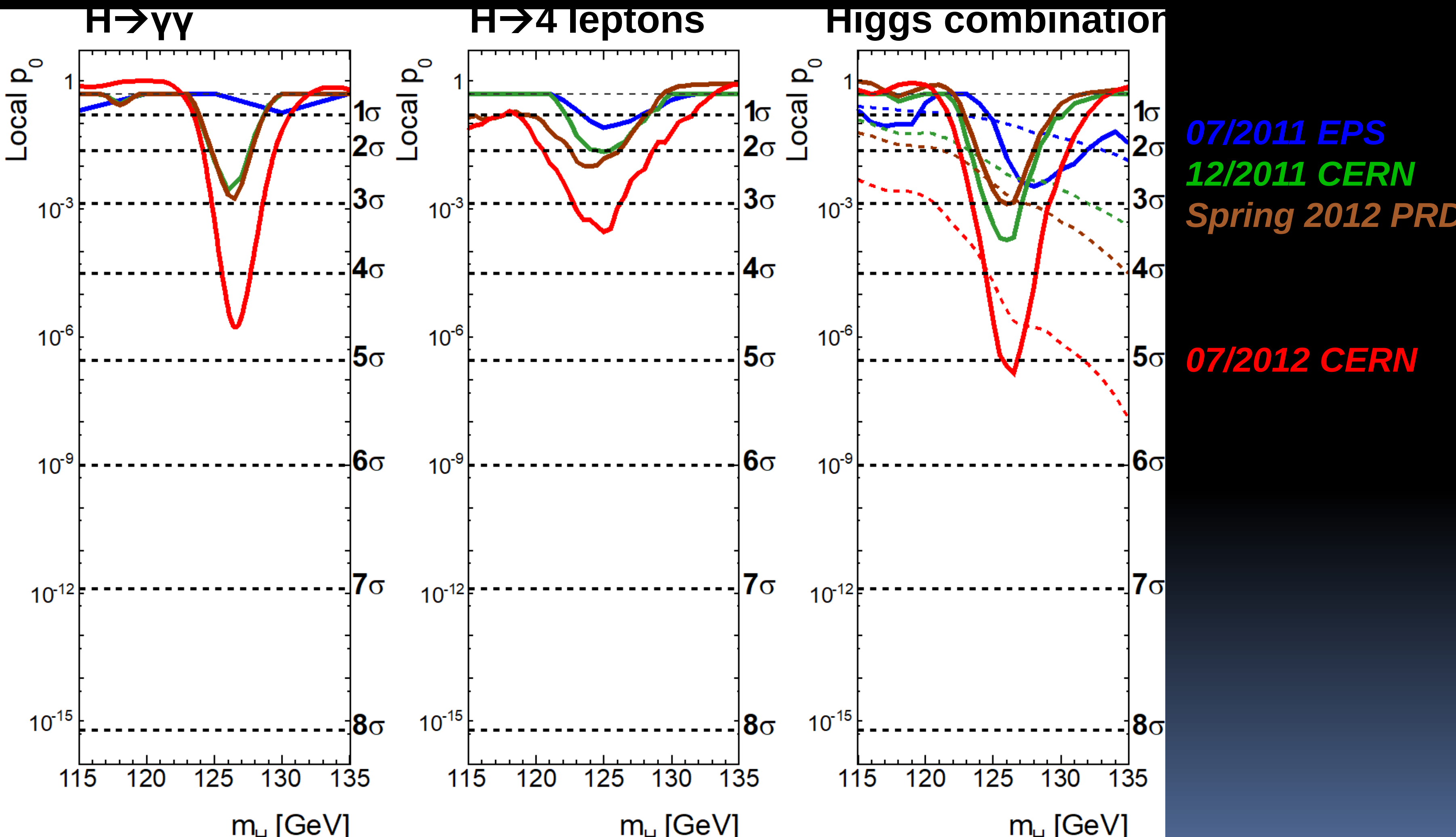
Local p_0: probability that the background fluctuates to the observed data (or higher)



From excess to discovery (ATLAS)

progressive significance(p0) plots

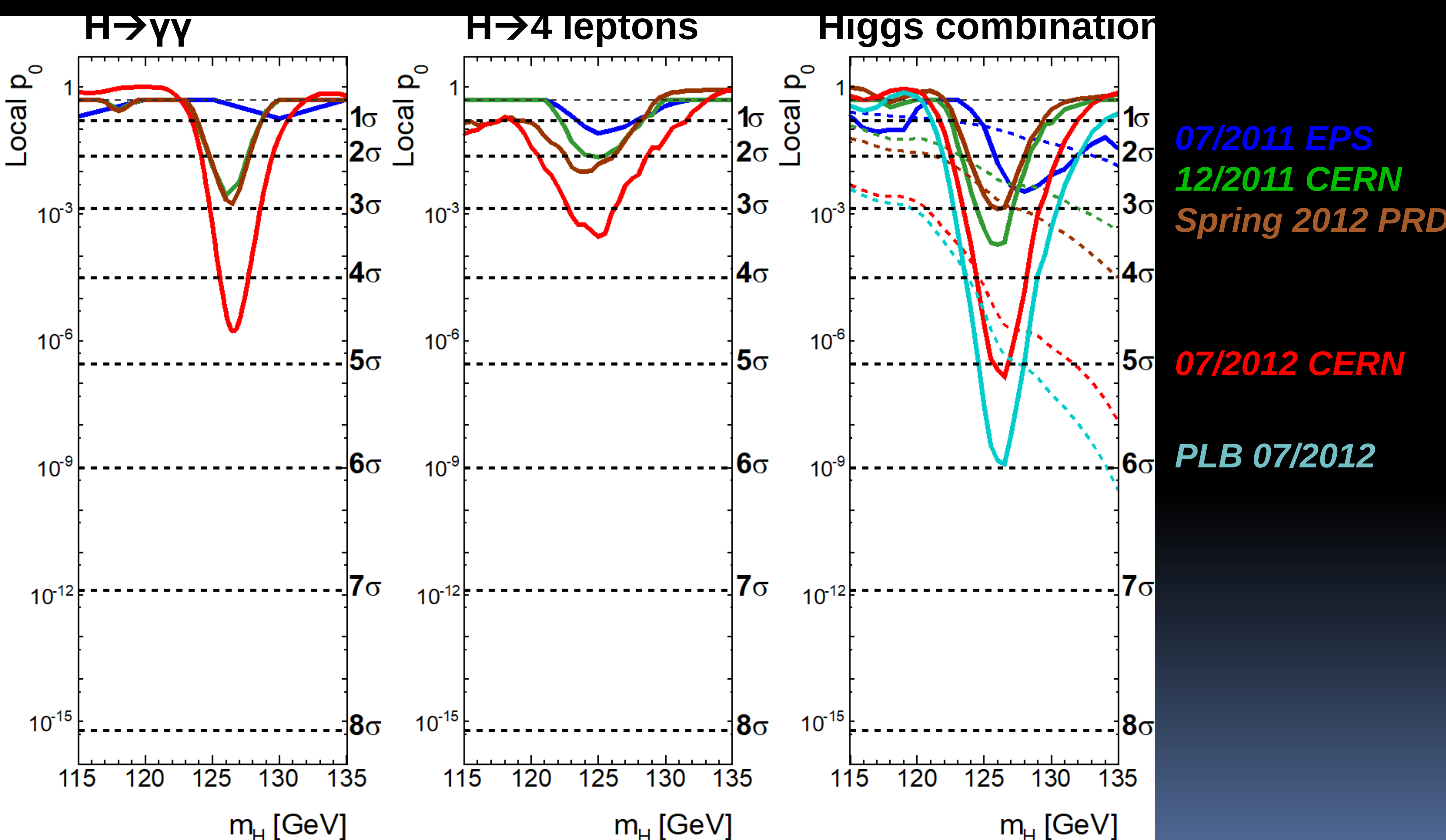
Local p_0: probability that the background fluctuates to the observed data (or higher)



From excess to discovery (ATLAS)

progressive significance(p0) plots

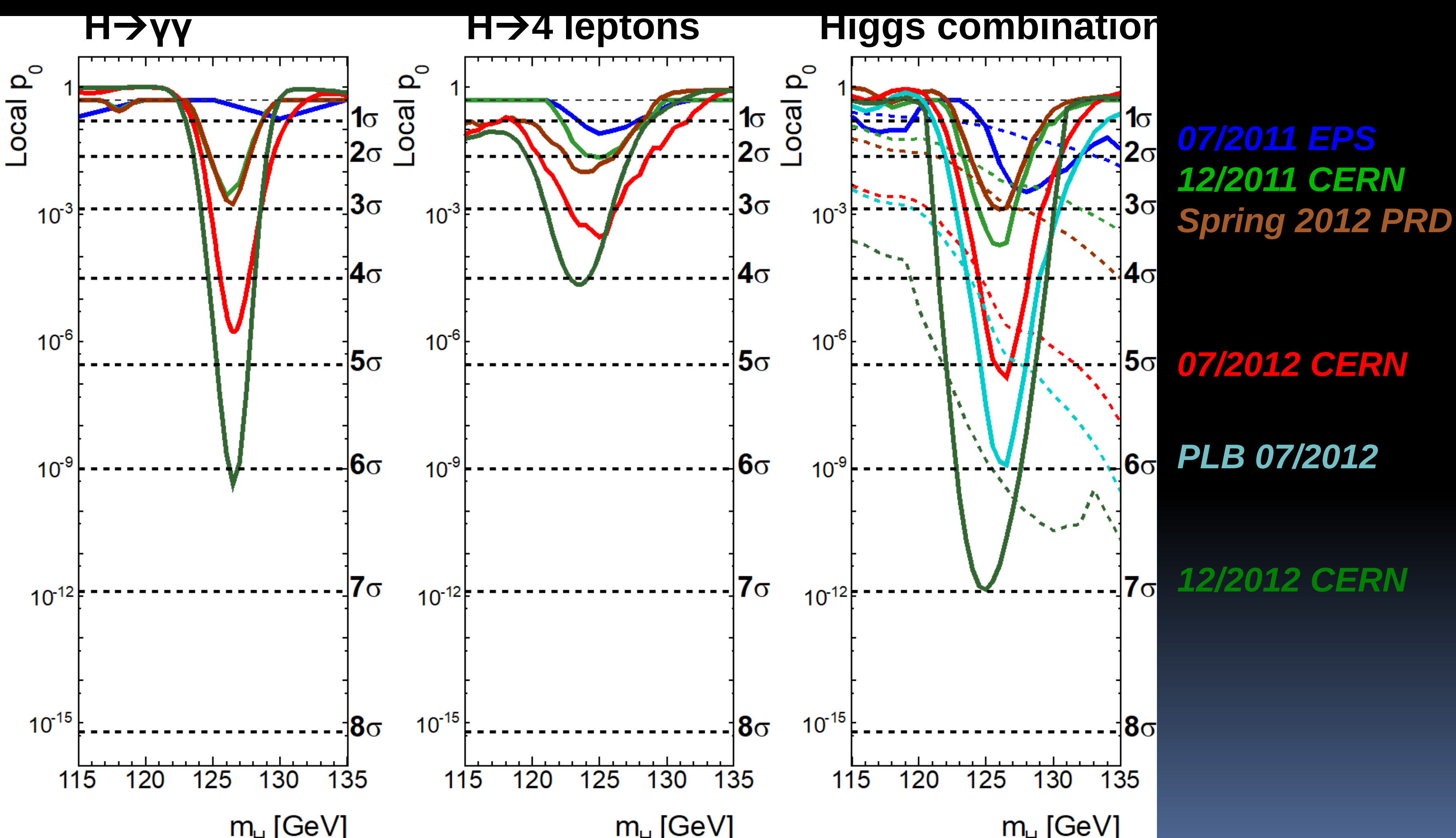
Local p_0: probability that the background fluctuates to the observed data (or higher)



From excess to discovery (ATLAS)

progressive significance(p0) plots

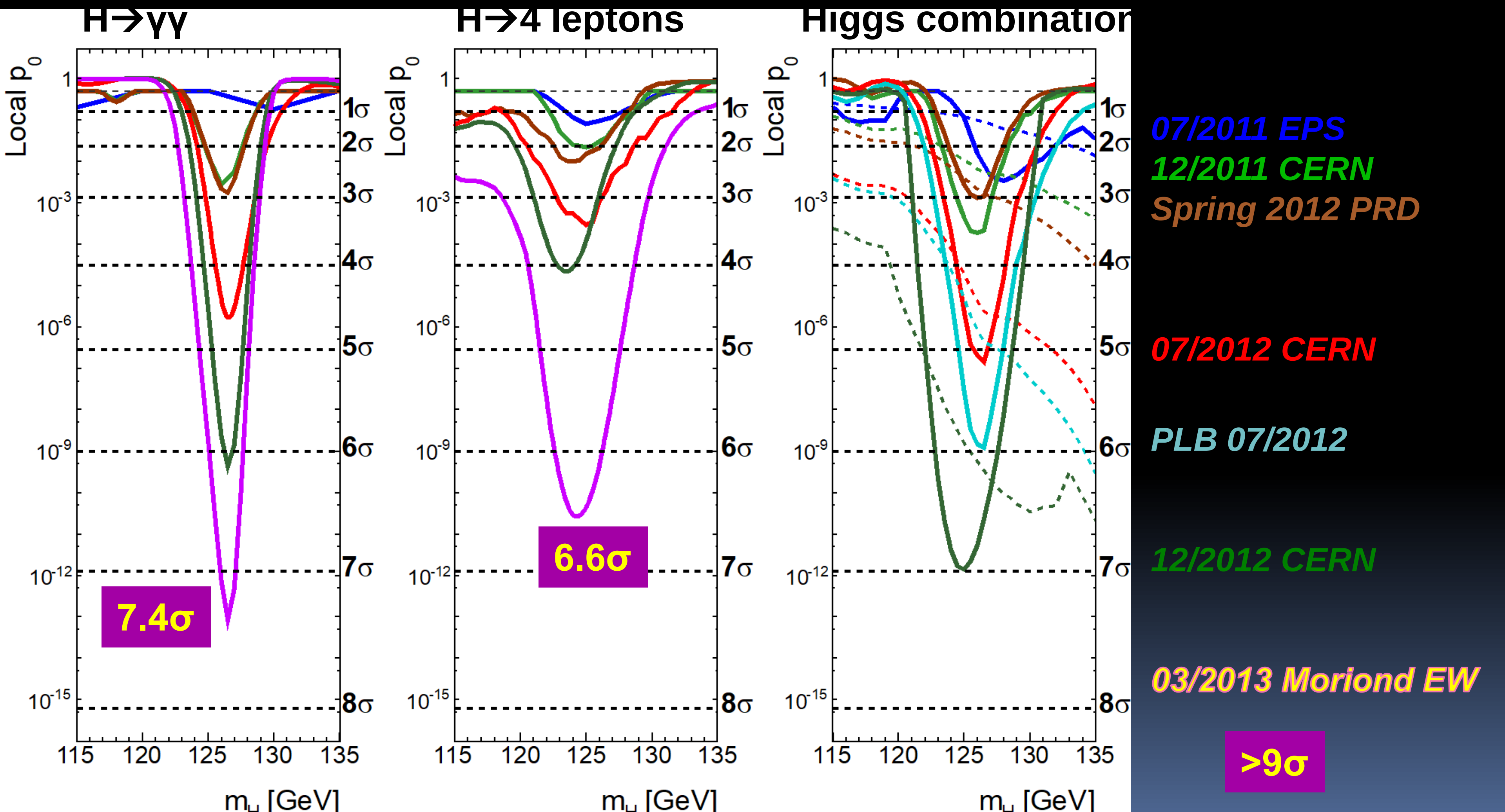
Local p_0: probability that the background fluctuates to the observed data (or higher)



From excess to discovery (ATLAS)

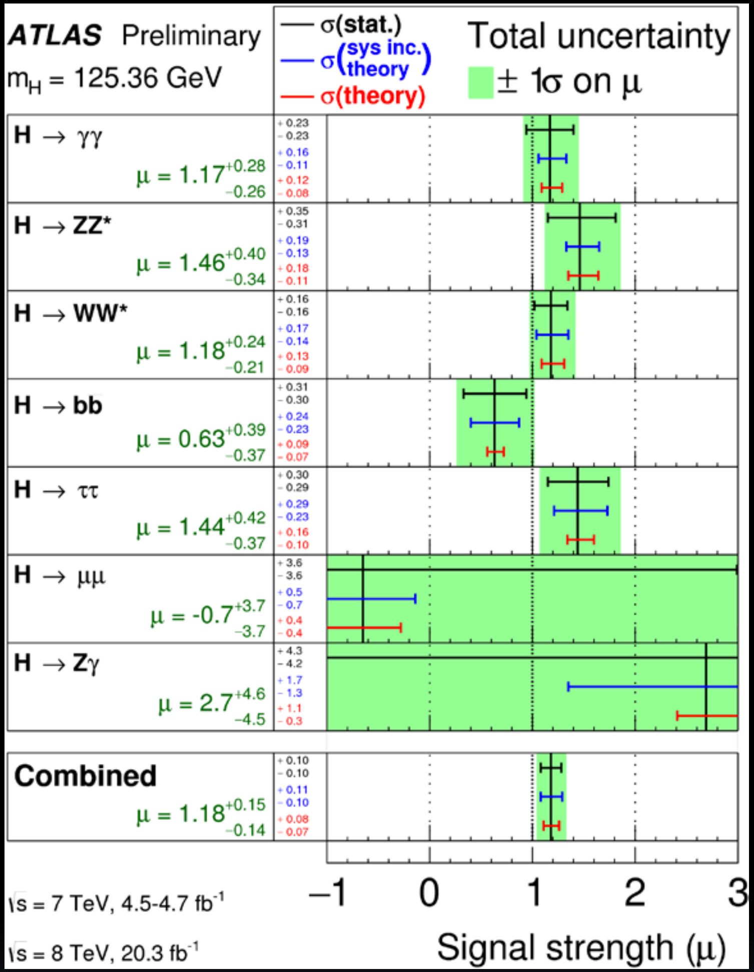
progressive significance(p0) plots

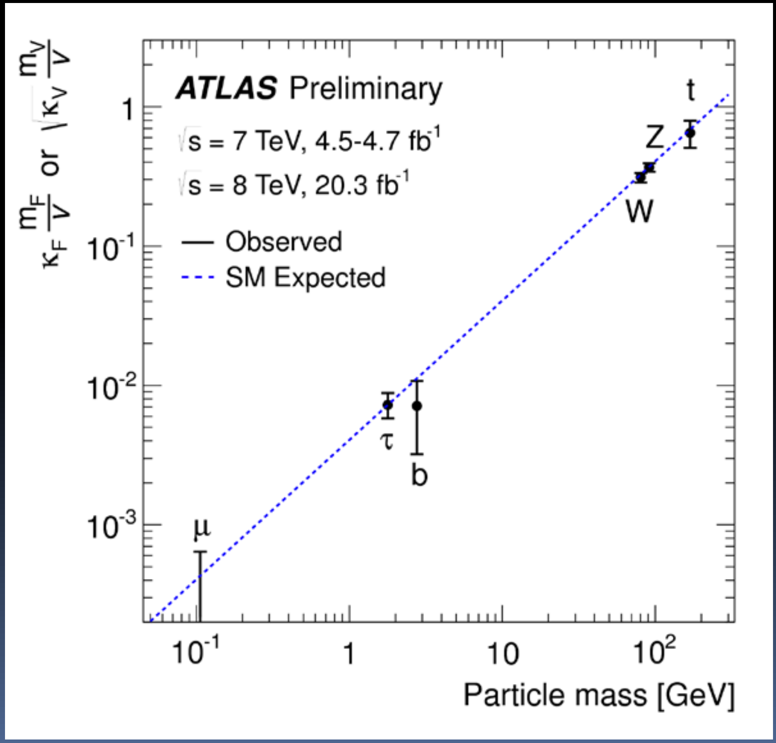
Local p_0: probability that the background fluctuates to the observed data (or higher)



Decays to bosons and fermions established, not yet μμ, …

- Measurements of the signal strength parameter μ for m_H =125.36 GeV for the individual channels and their combination
- Combination of all channels
- Consistency with SM: $1.18^{+0.15}_{-0.14}$
- Quantum numbers consistent with Scalar: $J^{PC}=0^{++}$

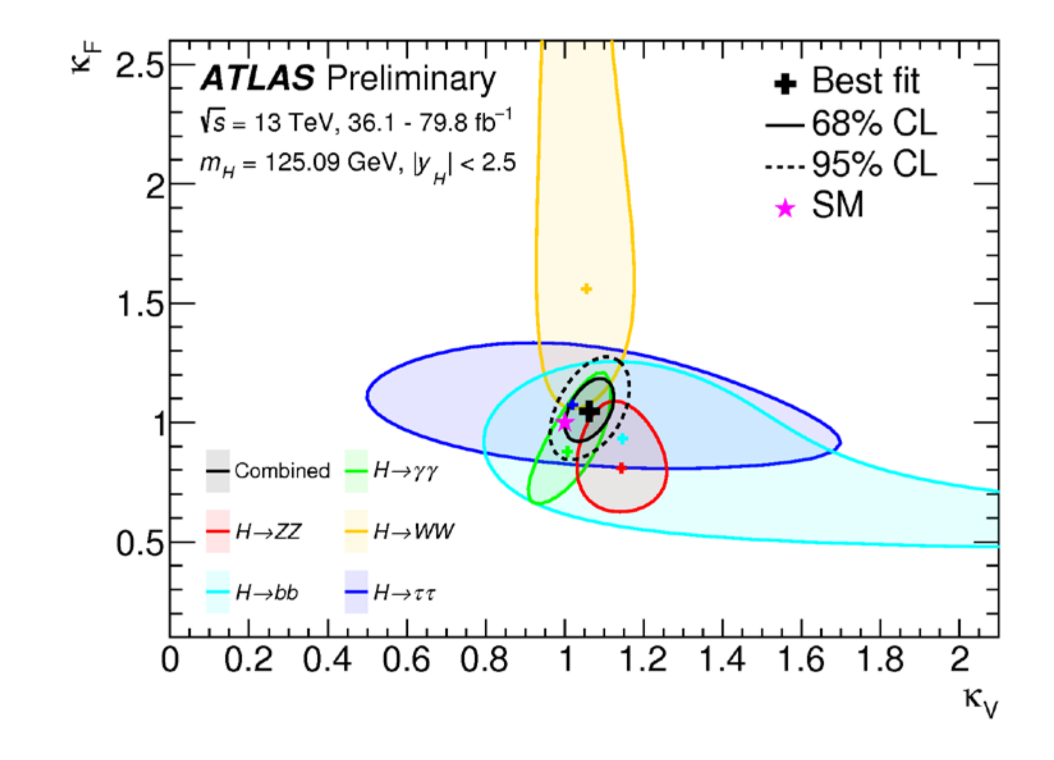


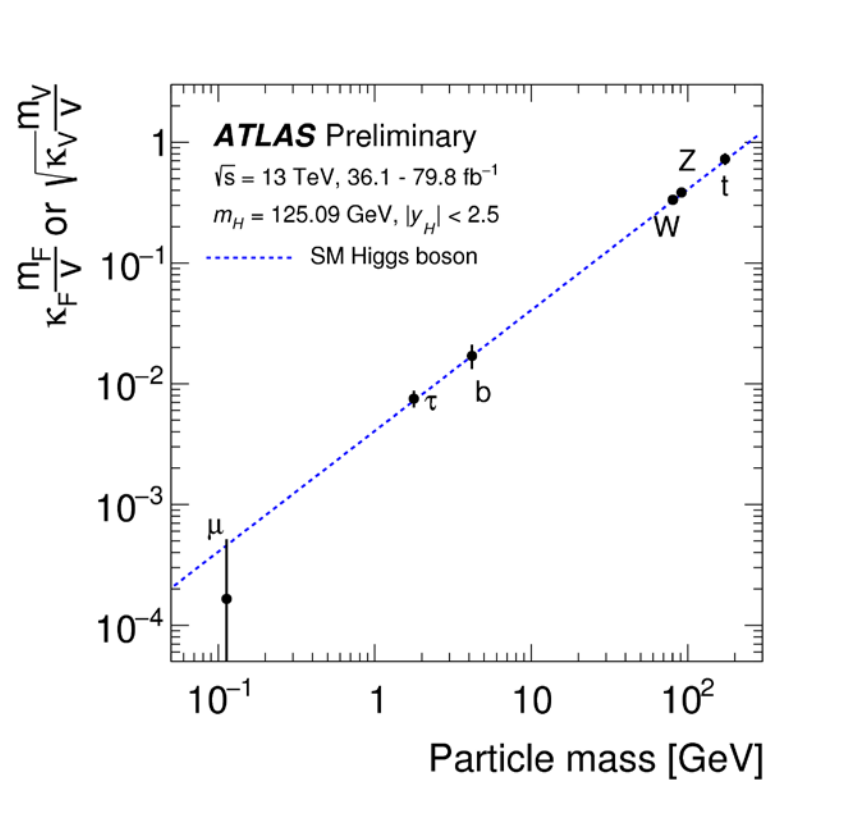


- Decays to fermions – difficult channels with high background – are a priority, especially bb (B~57%!)
- Searches for rare decays started: Zγ, μμ, …. Hidden decays, …
- Reduced coupling consistent with SM

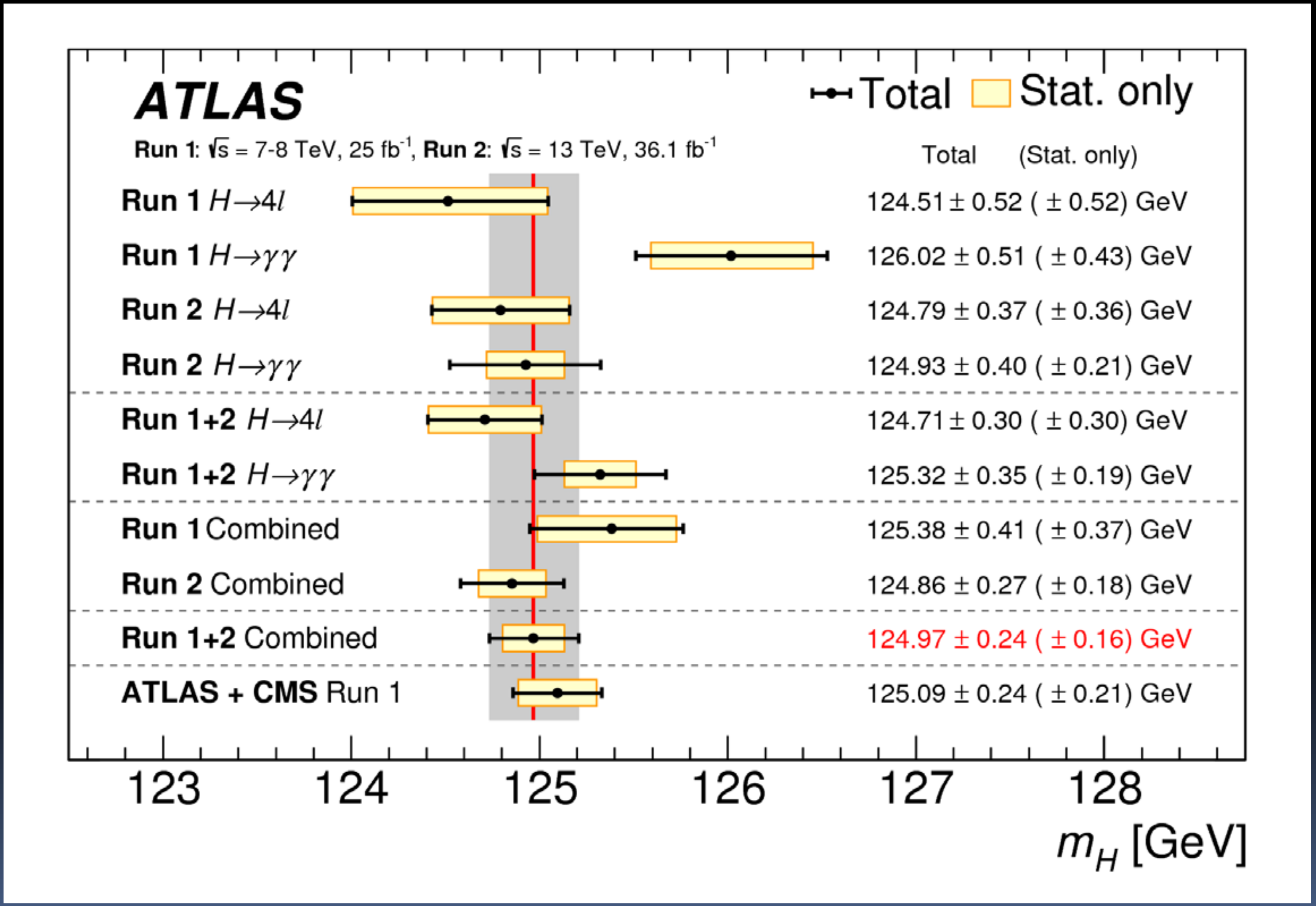
Higgs to Fermions and bosons

▪



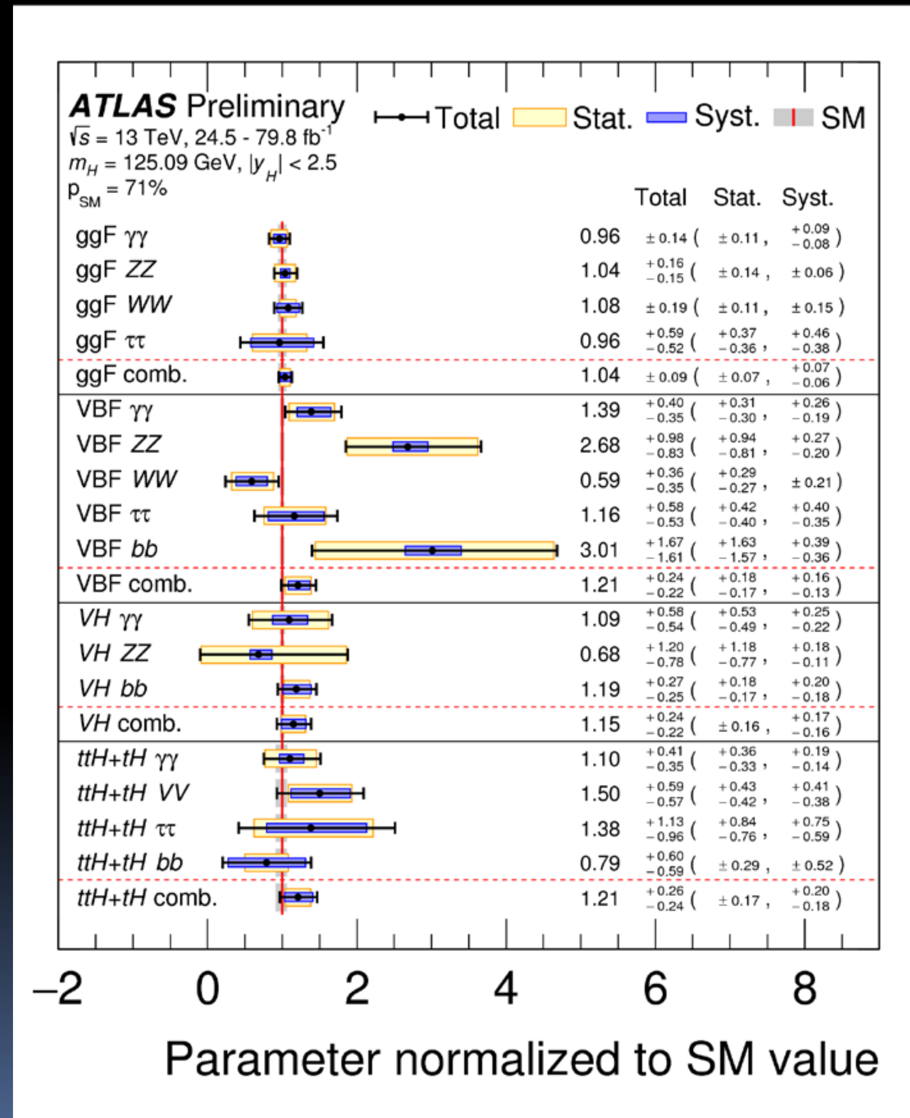


Higgs boson mass

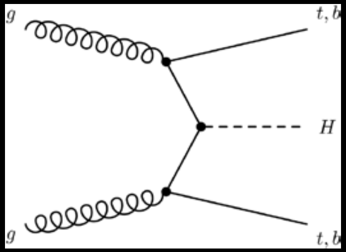


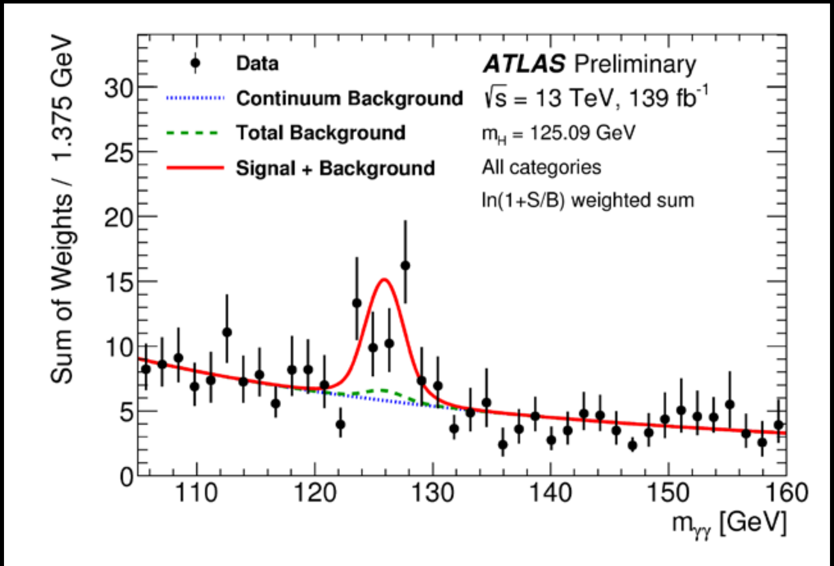
Cross sections time branching fraction

- Cross sections time branching fraction for the main Higgs production modes at the LHC (ggF, VBF, VH and ttH+tH) in each relevant decay mode (γγ, WW, ZZ, ττ, bb).
- All values normalized to SM predictions
- In addition, combined results for each production cross-section are also shown, assuming SM values for the BRs into each decay mode

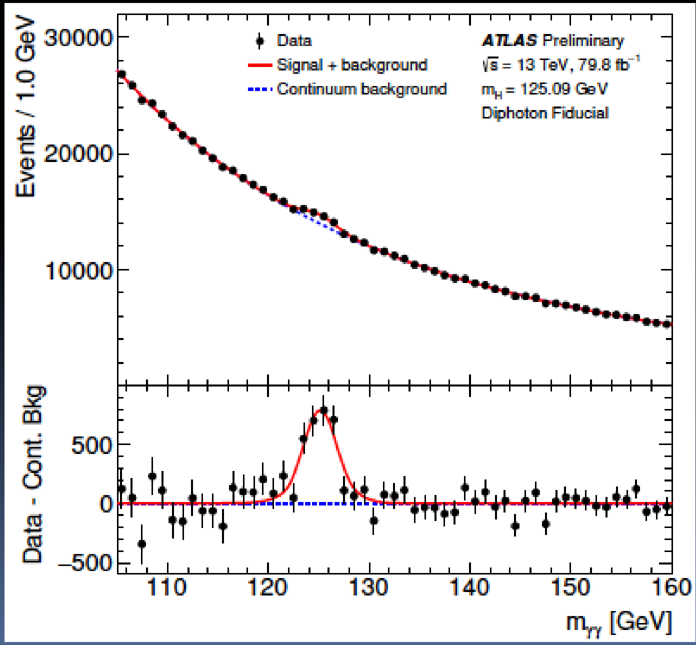


ttH signal in diphoton invariant mass spectrum





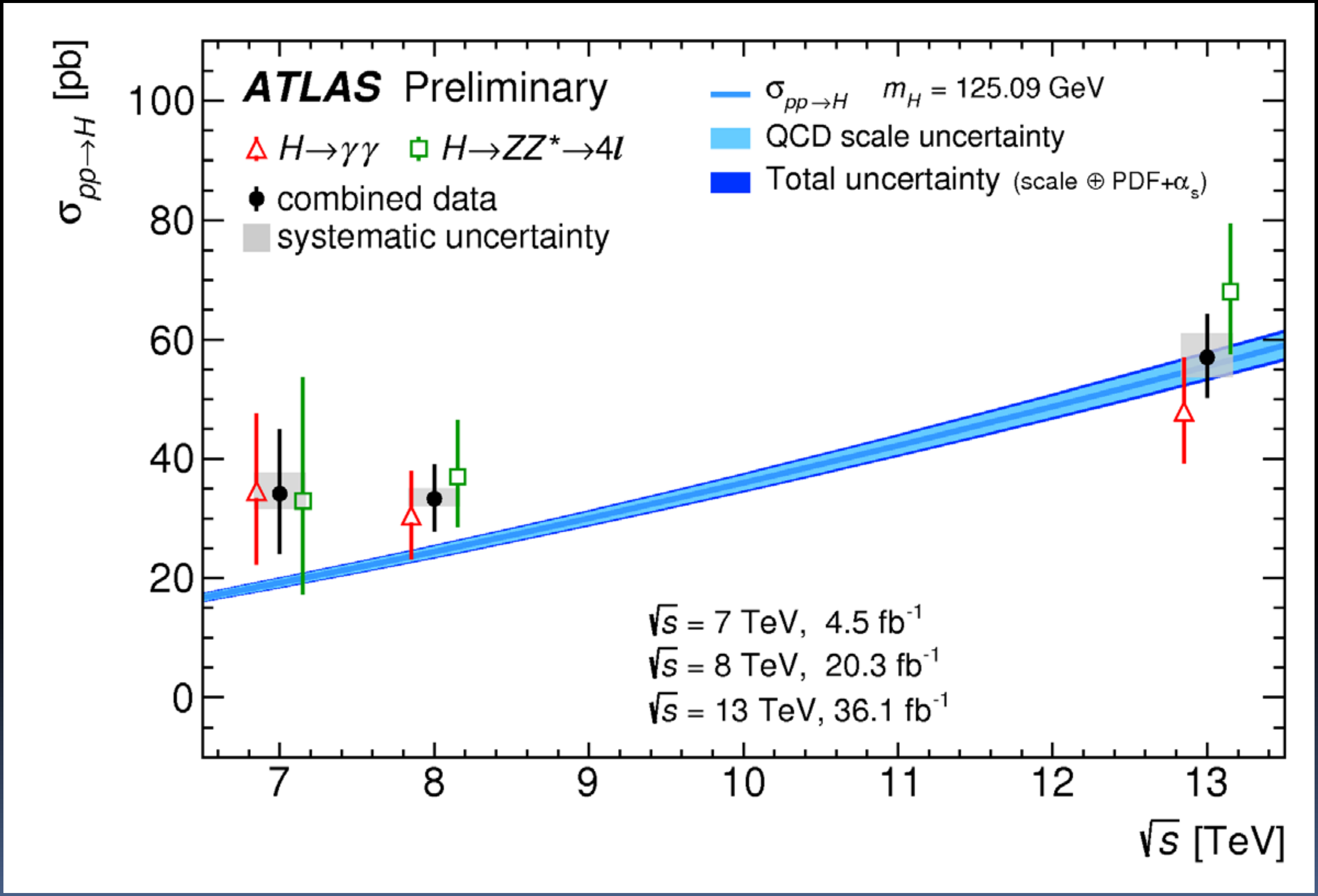
- Assume theoretical prediction, at 139 fb^{-1}, LHC should have produced
- ~ 7,000,000 Higgs bosons
- ~ 70,000 via ttH production
- ~ 160 in the ttHγγ channel ATLAS



The signal strength (obs/SM) is measured to be

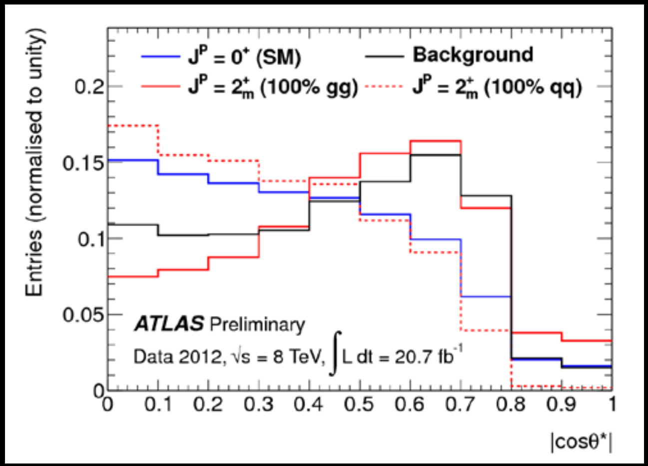
$$\mu_{t\bar{t}H} = 1.38\,^{+0.41}_{-0.36} = 1.38\,^{+0.33}_{-0.31}\,(\text{stat.})\,^{+0.13}_{-0.11}\,(\text{exp.})\,^{+0.22}_{-0.14}\,(\text{theo.})$$

Higgs cross-section at LHC

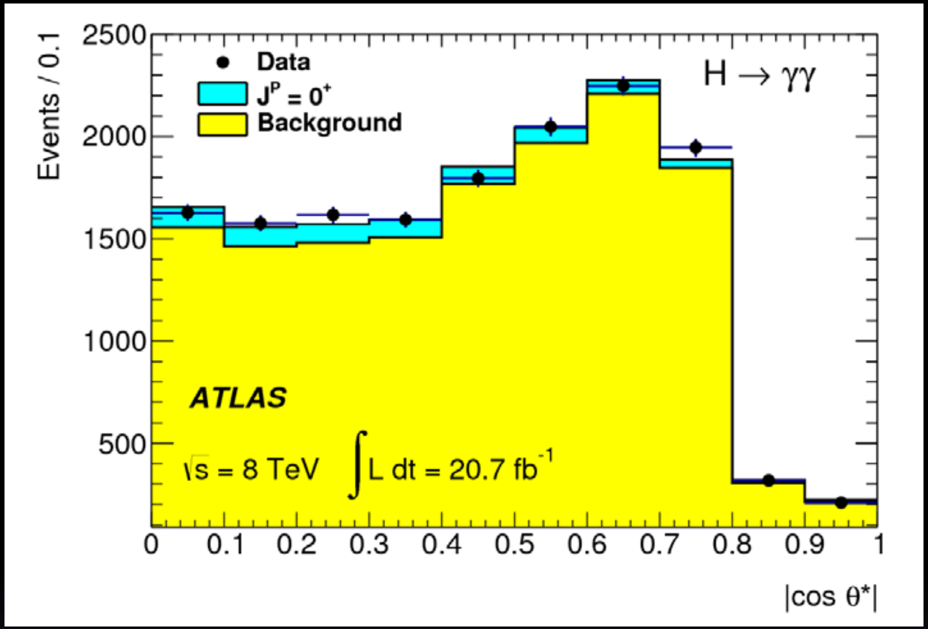


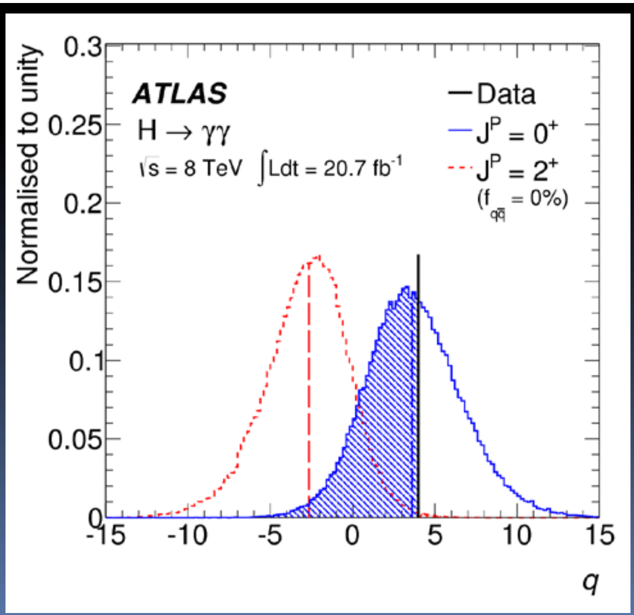
Is the new boson a Higgs?

- Measure its quantum numbers! Spin, parity, c-parity: J^{PC}=? If Higgs: 0^{++}
- Decay angle of H→γγ
  - Expected



data (background not subtracted)





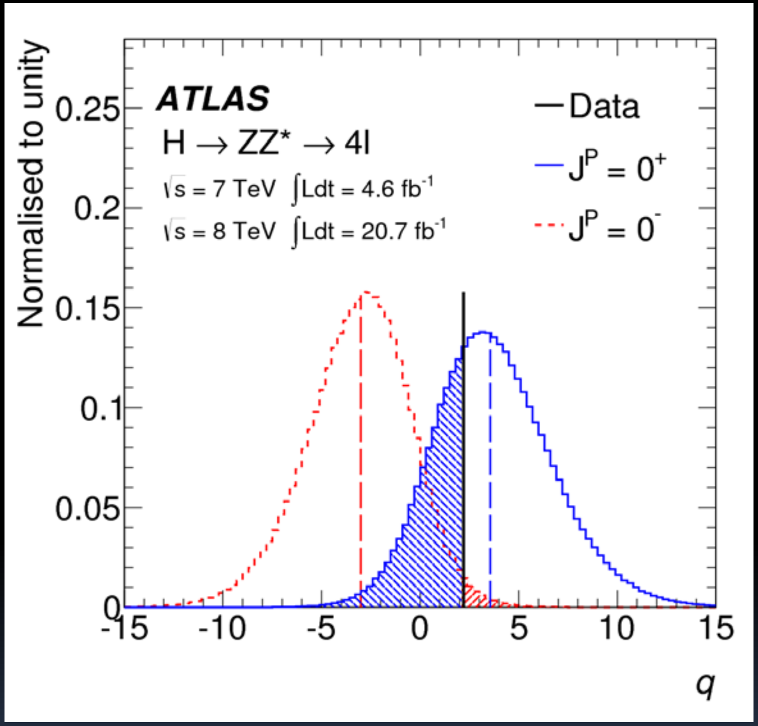
- "The hypothesis of a spin-2 particle (Graviton-like) produced by gluon fusion is excluded at 99% CL"

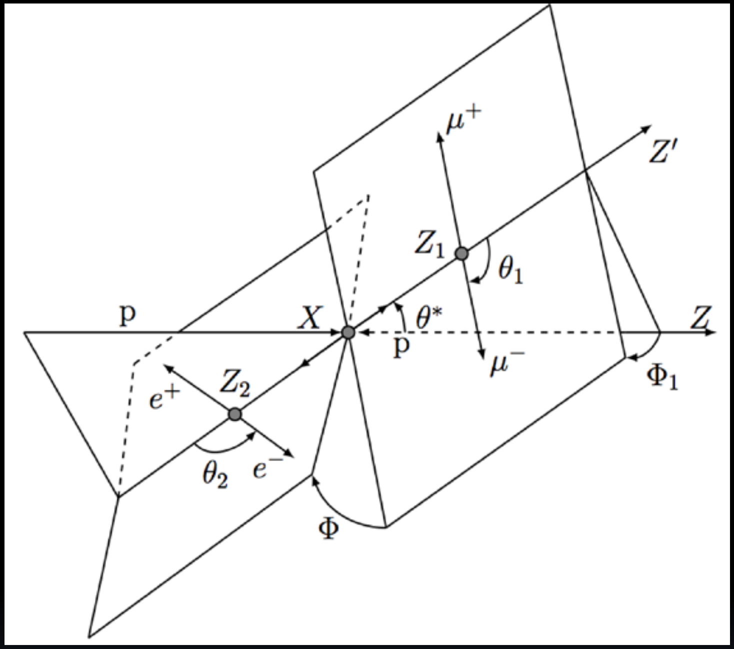
- Spin 1 cannot decay to γγ

Is the new boson a Higgs?

- Define production & decay angle for $H \rightarrow ZZ \rightarrow 4l$
  - Beam axis in the lab frame, the Z_1 and Z_2 in X rest frame and leptons in their corresponding parent rest frames

- Likelihood ratio for various hypotheses

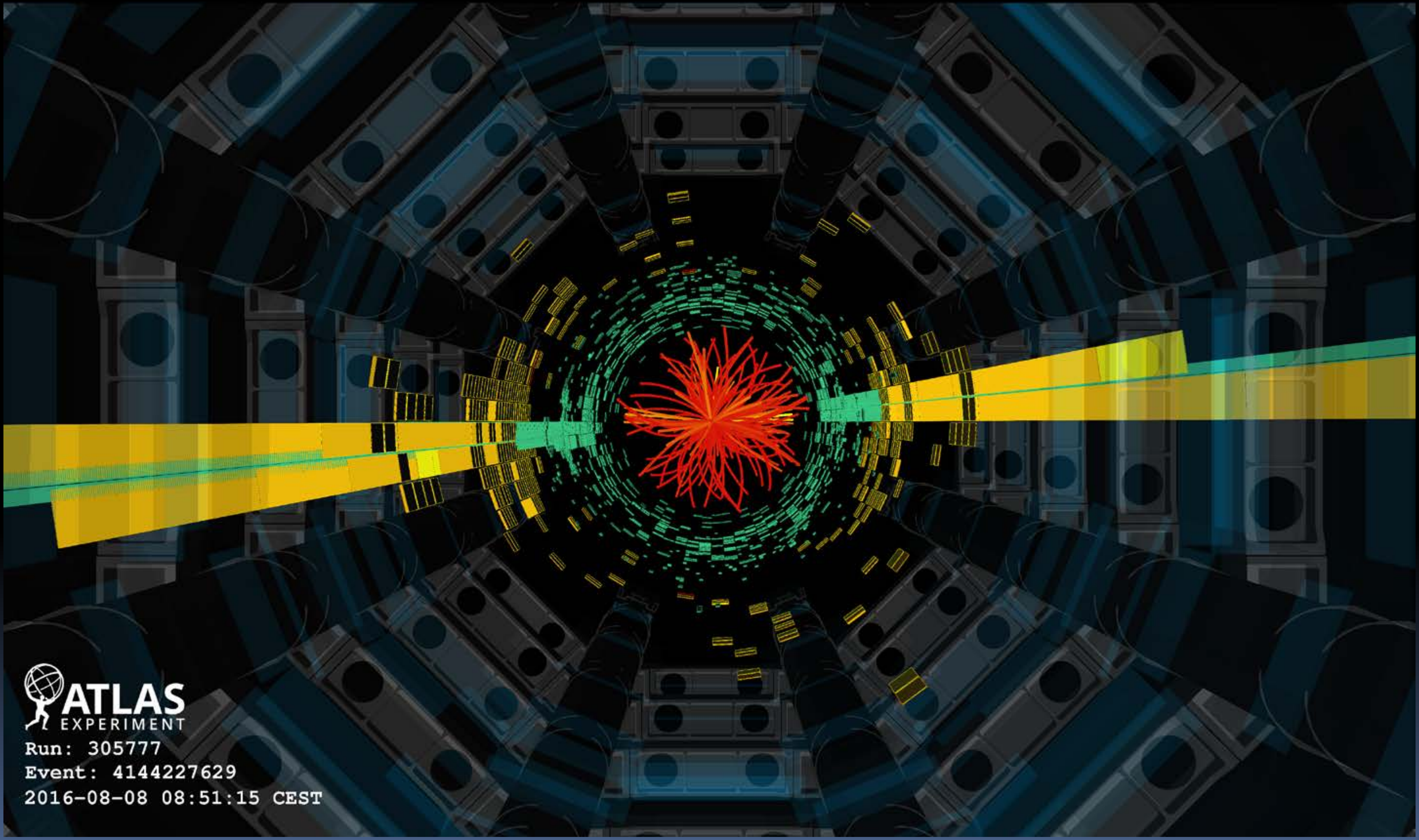




- Higgs-like boson found to be compatible with SM expectation of 0^+ when compared pair-wise with 0− , 1+ , 1− , 2+ , and 2−
- 0^- and 1^+ states are excluded at the 97.8% C.L.
- WW analysis leads to similar conclusions

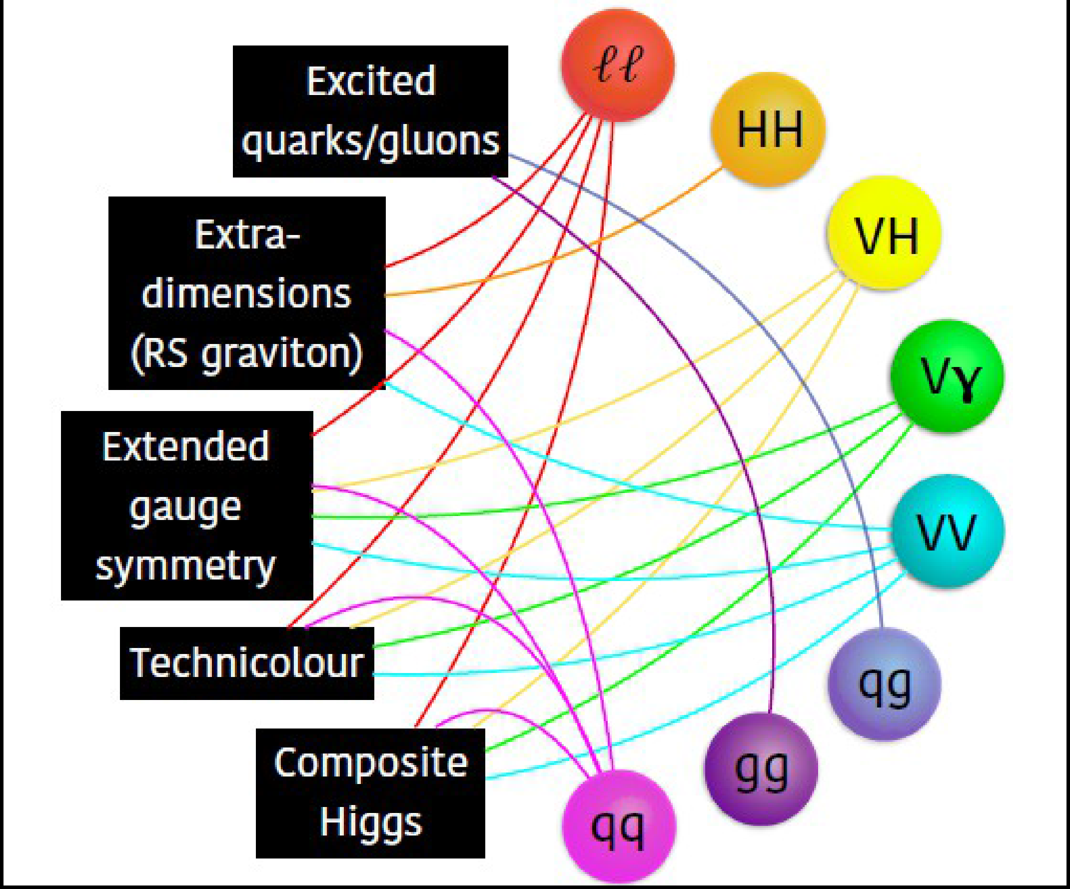
Any New Physics out there?

8.2 TeV-Mass di-jet event



What & How?

- Heavy gauge bosons, Z′ and W′,
  - From higher symmetry (e.g. E6) breaking, and more
- Composite models for quarks, q*, and leptons, l*
  - with substructure scale Λ
- Randal-Sundrum gravitons, G* and
- G*$_{bulk}$, from warped extra dimensions
- Low-scale strings with large EDs,
  - and TeV⁻¹ Kaluza-Klein excitations of ©/Z
- Technicolor, Chiral bosons (W*/Z*)
- Quantum black holes, ADD, Contact Interactions (non resonant) …



- "Simple"
  - ll, γγ, ZZ, WW, …
- Traditional
  - Jets or Rutherford – Hammer method
  - Missing
- Mix
  - "Leptons-quarks-gauge bosons-missing"
- Innovate
  - "Lepton-jets"

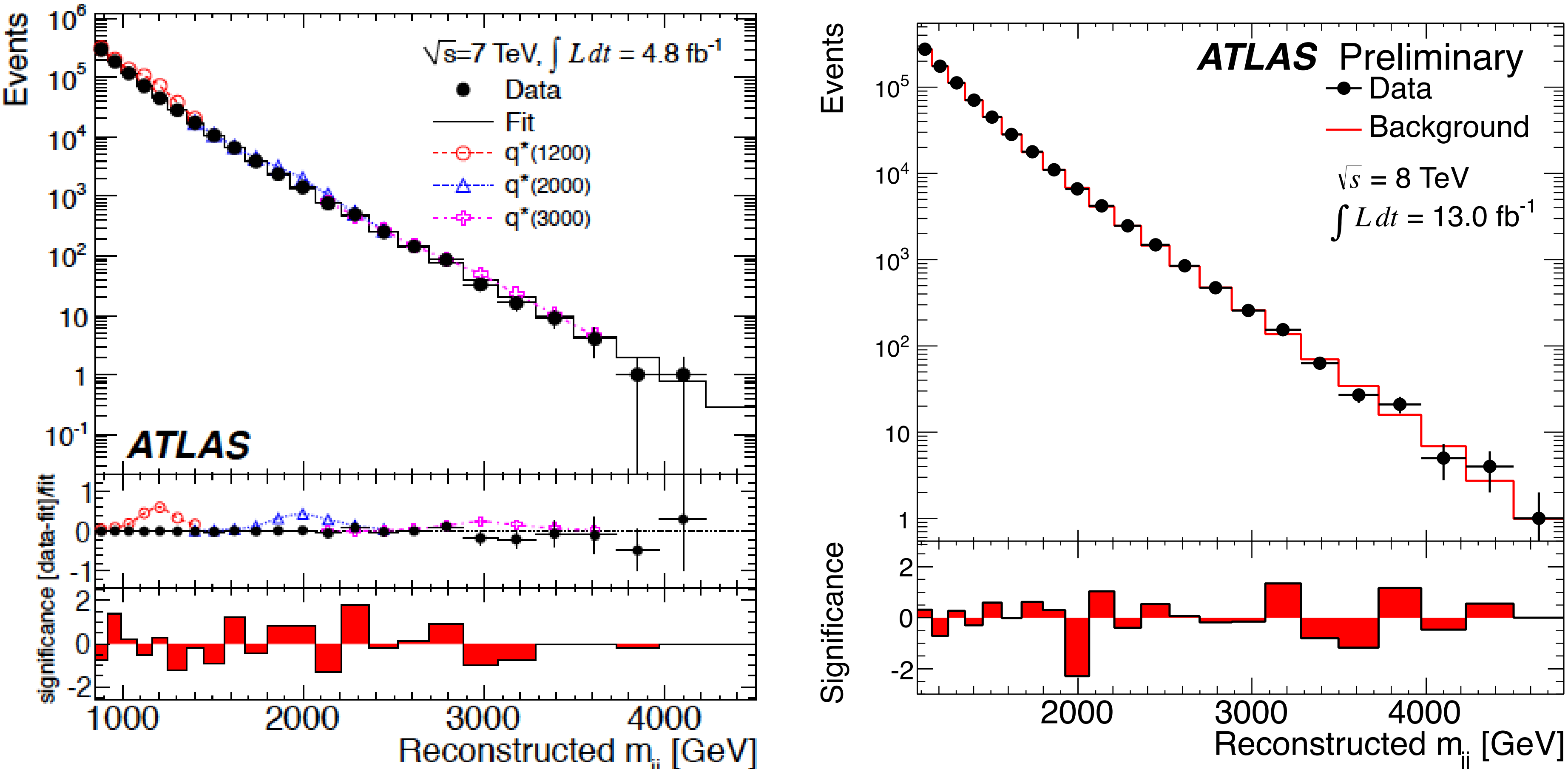
New phenomena in di-jets

- New physics
  - new particles could be produced,
  - new interactions between particles could manifest themselves,
  - interactions resulting from the unification of SM with gravity could appear in the TeV range
  - probe the structure of the fundamental constituents of matter at the smallest distance scales
    - Modification of di-jet mass and angular distributions
    - experimental test of the size of quarks, excited quarks

Di-jet invariant mass

- Anti-kT jet algorithm
- Background fit

$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln x}$$



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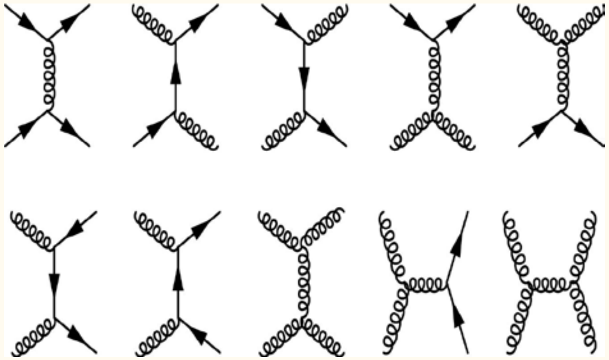
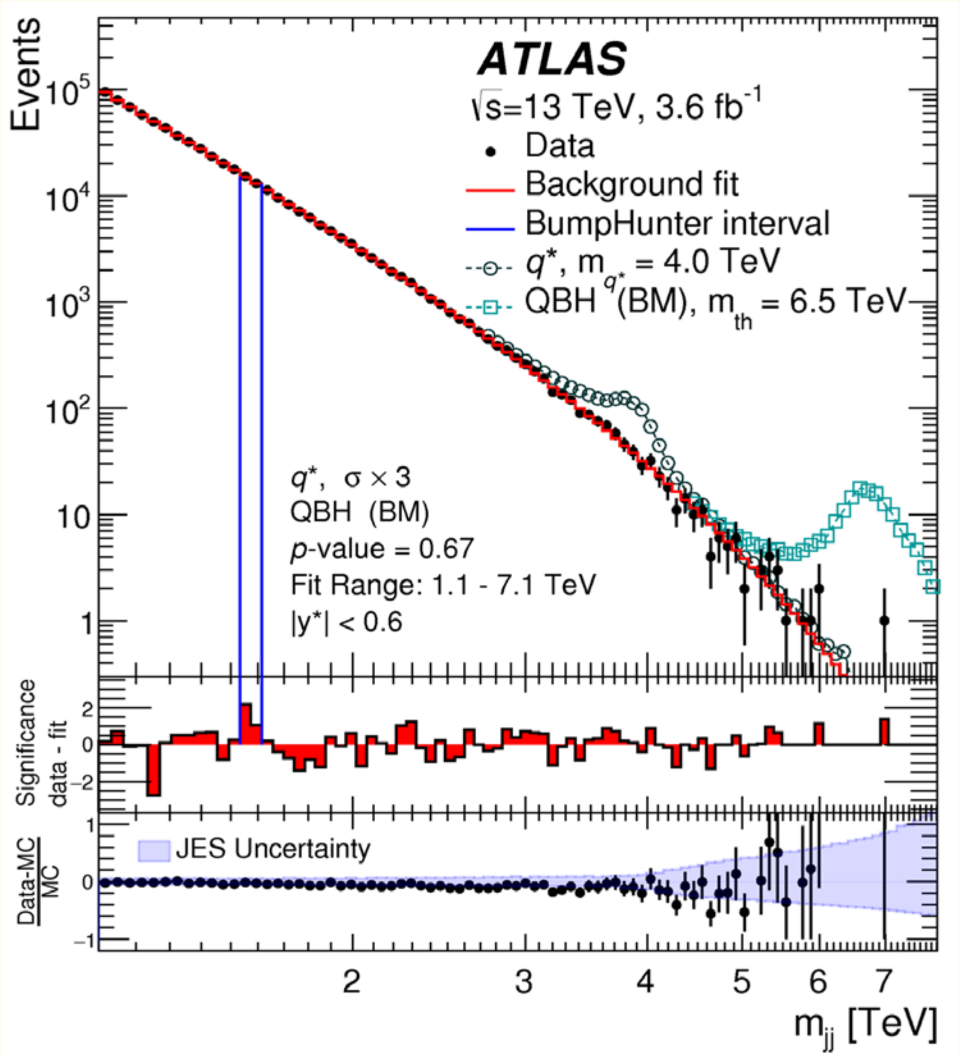
Search for new phenomena in dijet mass and angular distributions

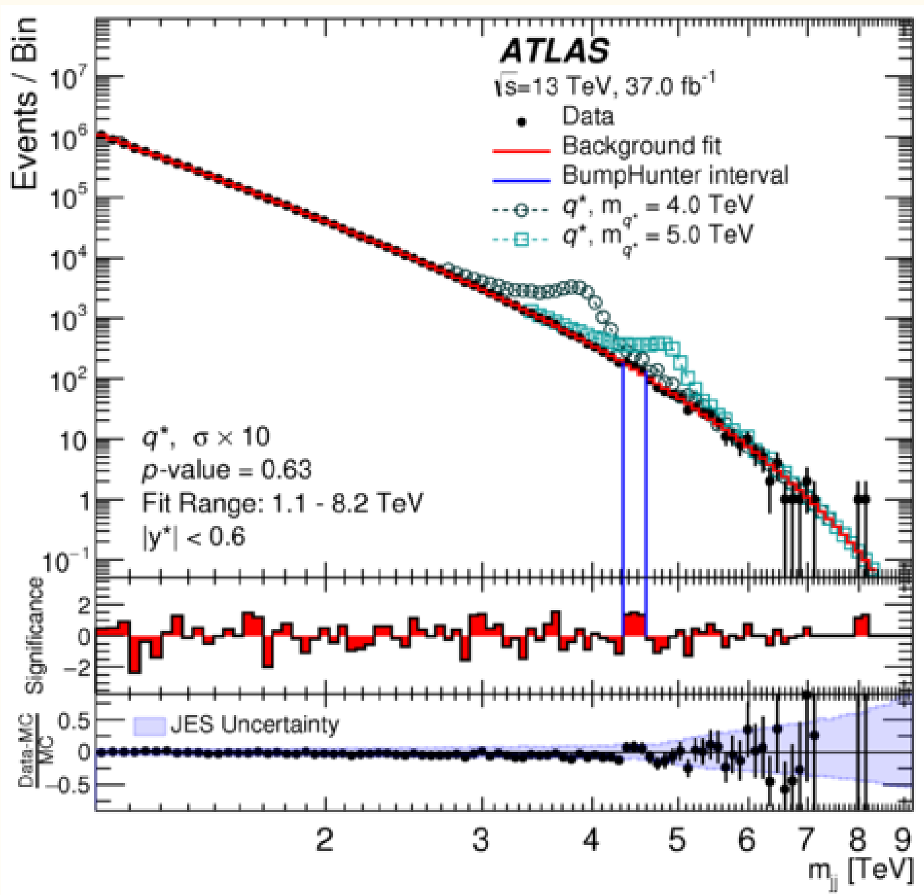
- ❖ Di-jet production dominated by t-channel gluon exchange
  - ➢ Steeply falling di-jet mass

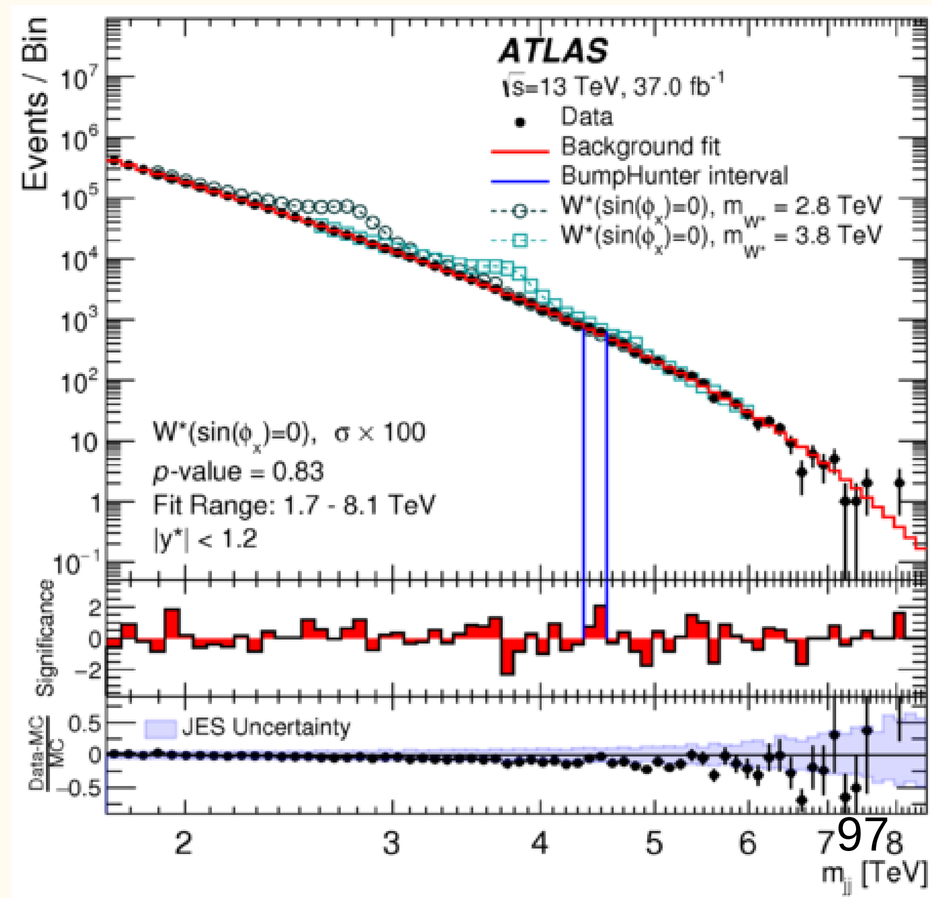


- ❖ Standard Model QCD background
  - ➢ $f(z) = p_1 (1-z)^{p2} / z^{p3}$: $z=m_{jj}/\sqrt{s}$
- ❖ Angular distributions, b-quark jets (appendix)



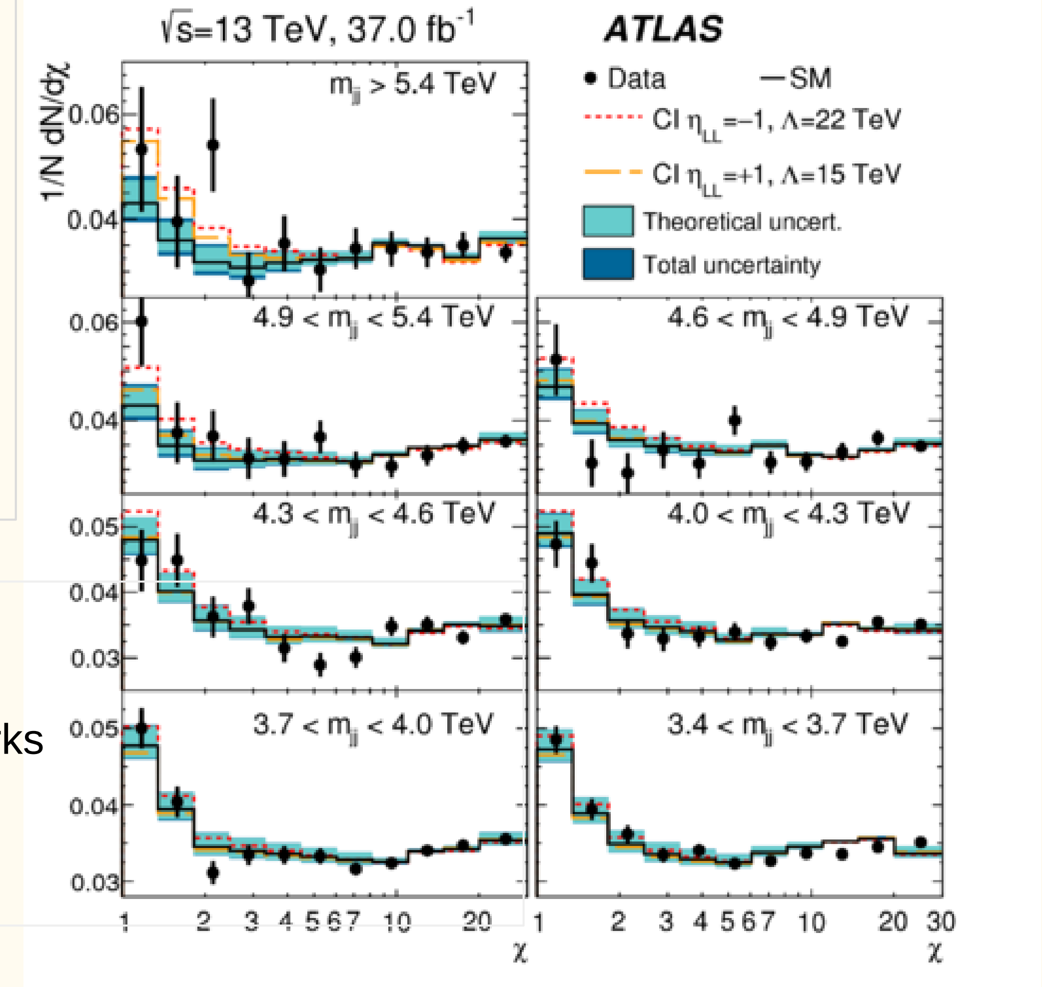
Di-jet results at 13 TeV





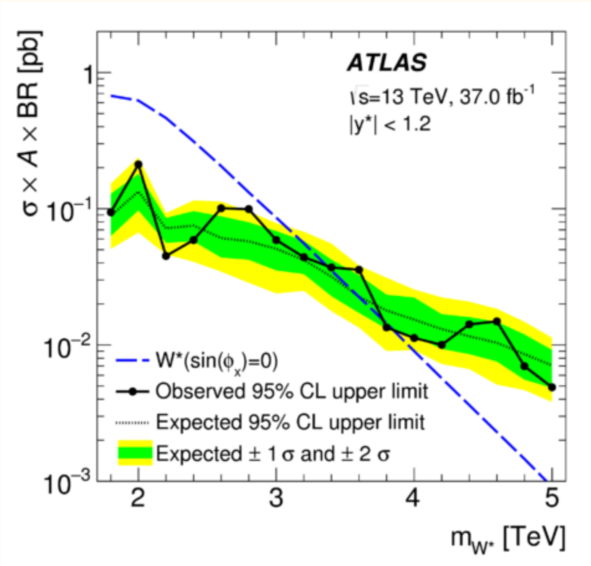
Search for new phenomena in dijet angular distributions

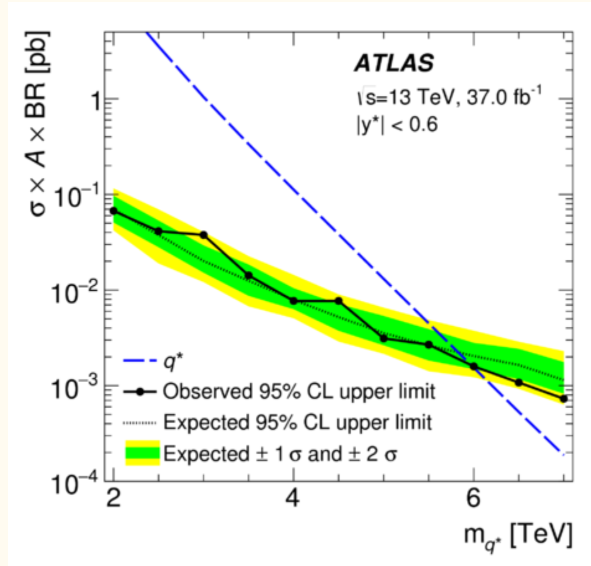
- Di-jet production dominated by t-channel gluon exchange
  - Angular distribution peaked at $|\cos\theta^*|=1$
- Variable $\chi=e^{2|y^*|} \sim (1+\cos\theta^*)/(1-\cos\theta^*)$ in bins of m_{jj} $y^*=(y_3-y_4)/2$

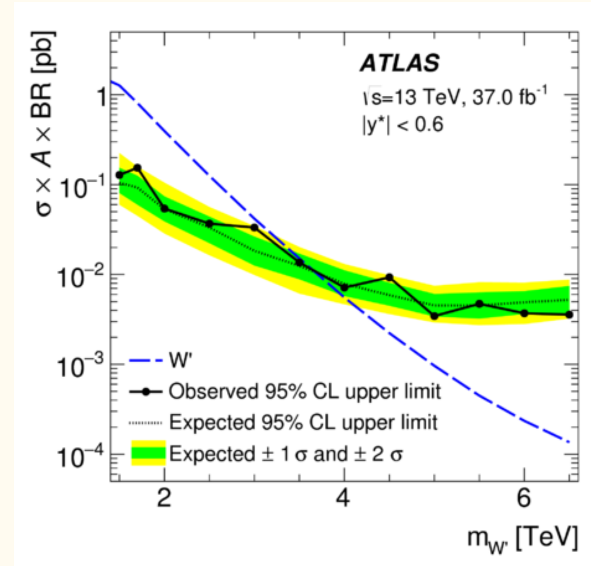


- Sensitivity to BSM scenarios
  - Contact interaction – excited quarks
  - Quantum Black Hole
  - Extended gauge sector (W', Z')
- Data agree with Next to Leading Order (NLO) predictions

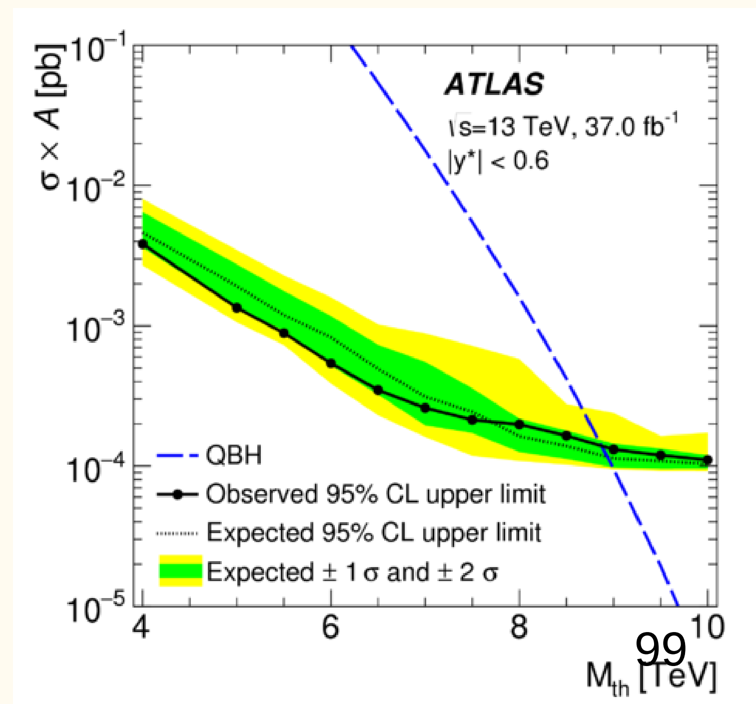
Search for new phenomena in dijet mass and angular distributions







Model	95% CL exclusion limit	
	Observed	Expected
Quantum black hole	8.9 TeV	8.9 TeV
W'	3.6 TeV	3.7 TeV
W^*	3.4 TeV 3.77 TeV – 3.85 TeV	3.6 TeV
Excited quark	6.0 TeV	5.8 TeV
Z' $(g_q = 0.1)$	2.1 TeV	2.1 TeV
Z' $(g_q = 0.2)$	2.9 TeV	3.3 TeV
Contact interaction $(\eta_{\rm LL} = -1)$	21.8 TeV	28.3 TeV
Contact interaction $(\eta_{\rm LL} = +1)$	13.1 TeV 17.4 TeV – 29.5 TeV	15.0 TeV



New di-lepton resonances?