Exercises

Make teams

- Teams of ~5 students
- Choose a name of your team
- You will need a pen and a piece of paper and python for some short calculations

Example: collider

$(E_1, 0, 0, p_z^1)$ $\quad$ $(E_2, 0, 0, p_z^2)$

Electron-positron colliding with the same energy, i.e. 45 GeV like at LEP

$$s = (p_1 + p_2)^2 = p_1^2 + p_2^2 + 2(p_1 \cdot p_2)$$
$$s = m_e^2 + m_e^2 + 2(E_1 \cdot E_2 - \vec{p_1} \cdot \vec{p_2})$$
$$s \simeq 2(E_1 \cdot E_2 - (E_1 \cdot (-E_2)) \simeq 4E_1 \cdot E_2$$

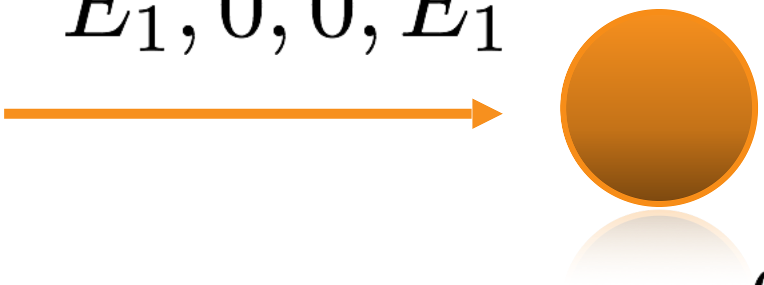
Where I have neglected the electron masses and where p_2 has the component Z in the direction –z ~ $-E_2$.

$$\boxed{\sqrt{s} = 2 \cdot E_{beam}}$$

For equal beam energies:
The c.m. energy of a collider grows linearly with the beam energy

Example: fixed target

$$E_1, 0, 0, E_1$$



$$m_2, 0, 0, 0$$

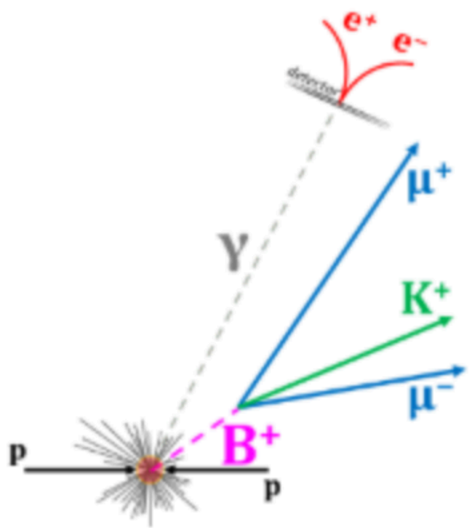
$$s = (p_1 + p_2)^2 = m_1^2 + m_2^2 + 2E_1 \cdot m_2$$
$$\sqrt{s} = \sqrt{2E_1 \cdot m_2}$$

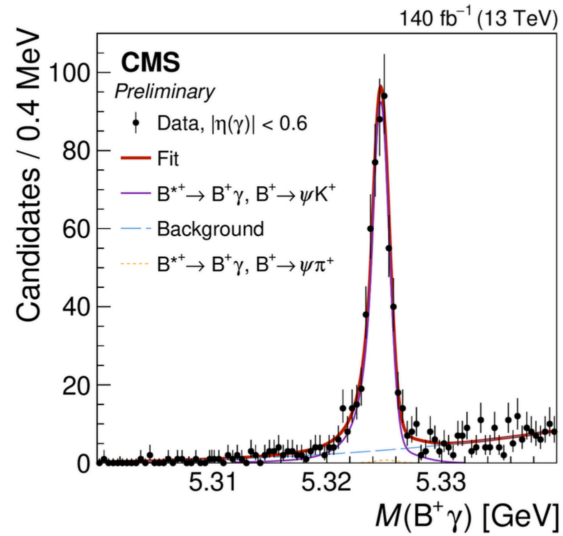
In fixed target the c.m. energy increases only with the sqrt of the beam energy. To double the c.m. energy, I need 4X beam energy, not very efficient.

Is there an advantage anyway? Why do I want higher c.m. energy usually?

Event display

B* mesons are excited to (finally) show up!

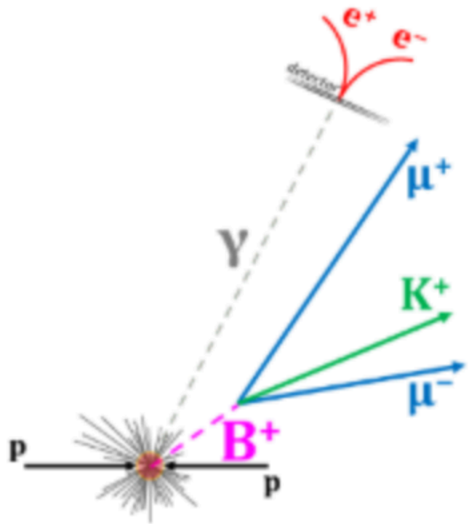


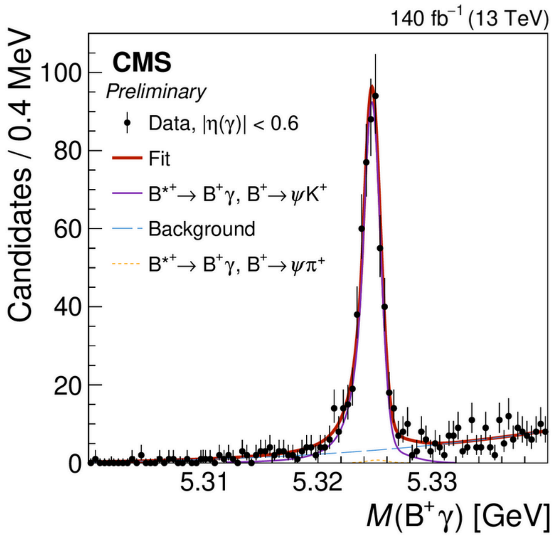


How do these tracks looks like in The CMS detector?

Event display

B* mesons are excited to (finally) show up!





How do these tracks looks like in The CMS detector?

https://cds.cern.ch/record/2933467/files/animatedMP4.mp4

General on Particles

Fill at least 3 rows

Particle	Charge	L_e	L_μ	L_τ	Mass (MeV)
e^-					
ν_e					
μ^-					
ν_μ					
τ^+					
$\bar{\nu}_\tau$					
u					
d					
s					
c					
b					
t					
$\bar{u}$					
$\bar{d}$					

General on Forces

Forces	charge cons.	P cons.	C cons.	Flavour cons.	CP cons.	Coupling
electromagnetic						
weak NC						
weak CC						
strong						

where cons.=conservation

Kinematics

The electron-proton collider HERA had a c.m. energy of 319 GeV, when colliding electrons of 27.6 GeV with protons of 920 GeV. If the protons were a fixed target, which energy should the electron beam have to obtain the same c.m. energy?

Bonus: Comment on the result, if such a linear accelerator would exist.

Feynman diagrams

Draw the Feynman diagrams of the following processes, at the lowest order and at the quark level and write down which interaction is involved:

- 1) $\pi^+ \to \mu^+ \nu_\mu$

- 2) $n \to p^+ e^- \bar{\nu}_e$

- 3) $e^+ e^- \to \mu^+ \mu^-$

Feynman diagrams

- 6) $\Lambda \rightarrow p^+\pi^-$

- 7) $\pi^+ \rightarrow \mu^+\nu_\mu$

- 8) $K^+ \rightarrow \mu^+\nu_\mu$

Processes

- Which of the processes are forbidden and why?

- 1) $p^+ \to \pi^+\pi^0$
- 2) $\mu^+ \to e^+\pi^0$
- 3) $J/\Psi \to D^+D^-$
- 4) $\Lambda^0 \to p^+\pi^-$
- 5) $\Lambda^0 \to p^+\pi^0$

Discovery of W and Z

- The W and Z bosons were discovered in $p\bar{p}$ collisions at CERN in 1983. Considering:

  - a theoretical cross section $\sigma(p\bar{p} \to W \to e\nu_e)$ of 530 pb;
  - a c.m. energy of 540 GeV;
  - a detection efficiency of 50%
  - an integrated time for running of 1 year (10^7 seconds)

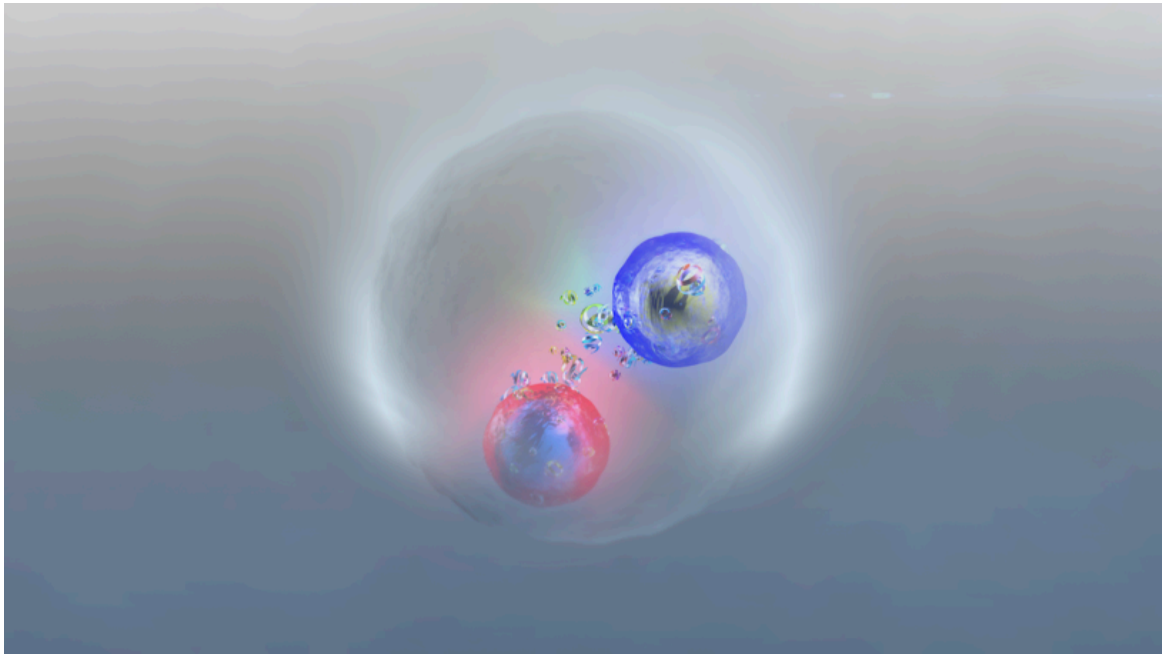
  calculate which instantaneous lumoniosity the $p\bar{p}$ collider had to achieve to achieve 25 W events.

  Do you know how such intensity was achieved at that time? Do you know how the center-of-mass energy was decided at that time?

Compounds states?

Is there a toponium?

- DESY Seminar today at 4 PM in the DESY Auditorium

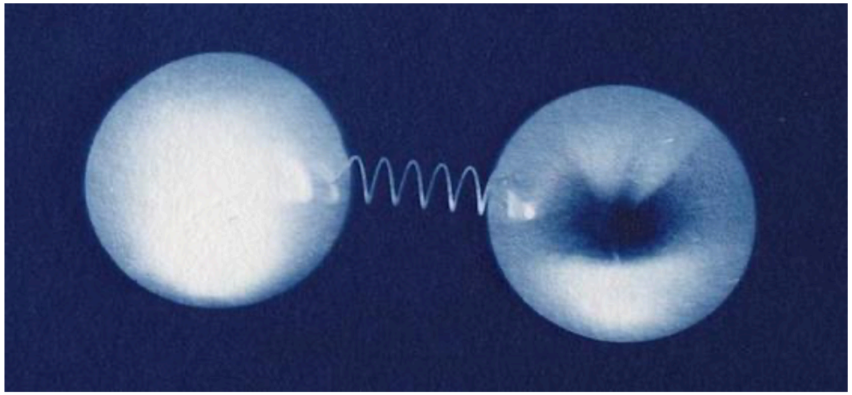


Is there a toponium?

Observation of an excess at the top-quark-pair production threshold.

Special Quantum Universe Colloquium

Katharina Behr (DESY),
Maria Vittoria Garzelli (Universität Hamburg),
Alexander Grohsjean (Universität Hamburg)



Abstract: An enhancement in top quark-antiquark ($t\bar{t}$) production near threshold was observed by the CMS Collaboration at the end of last year. A similar observation has now been reported by the ATLAS Collaboration, as highlighted in the CERN press release of July 8th. Both measurements focus on dileptonic $t\bar{t}$ final states and are based on the full Run 2 datasets in proton-proton collisions at $\sqrt{s}$ = 13 TeV. The observed enhancements are consistent with the formation of quasi-bound $t\bar{t}$ states, so-called toponium, as predicted by non-relativistic quantum chromodynamics. These results rely on state-of-the-art theoretical inputs and detailed systematic modeling, yet they also point to the need to improve the description of higher-order off-shell, and bound-state effects. In this special colloquium, we will present the latest experimental findings from both the CMS and ATLAS experiments, and discuss progress of theory calculations, including future directions needed to sharpen our understanding of this threshold region

QCD in e^+e^-

QCD in e^+e^-

Additional confirmation of the theory of strong interactions came from experiments at electron-positron colliders (SPEAR, DESY, PETRA, LEP).

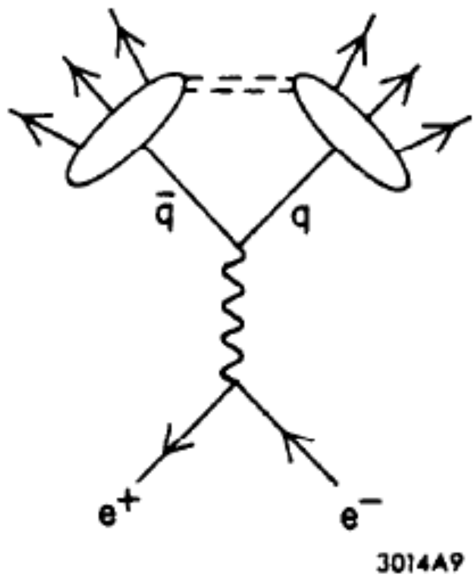


Fig. 9. Quark-parton model picture of production of hadrons in e^+e^- annihilation.

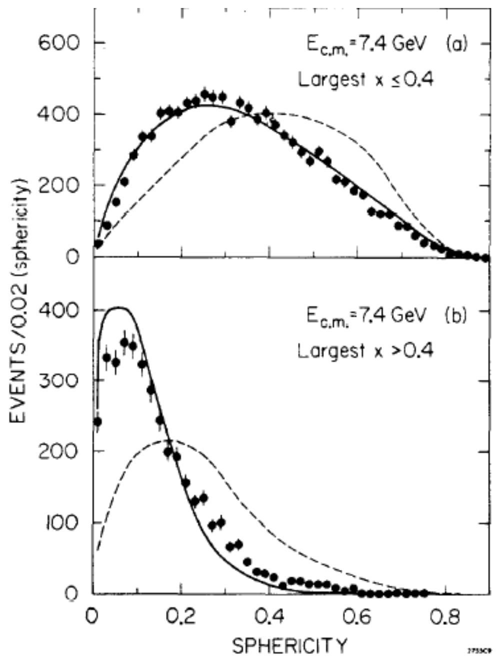
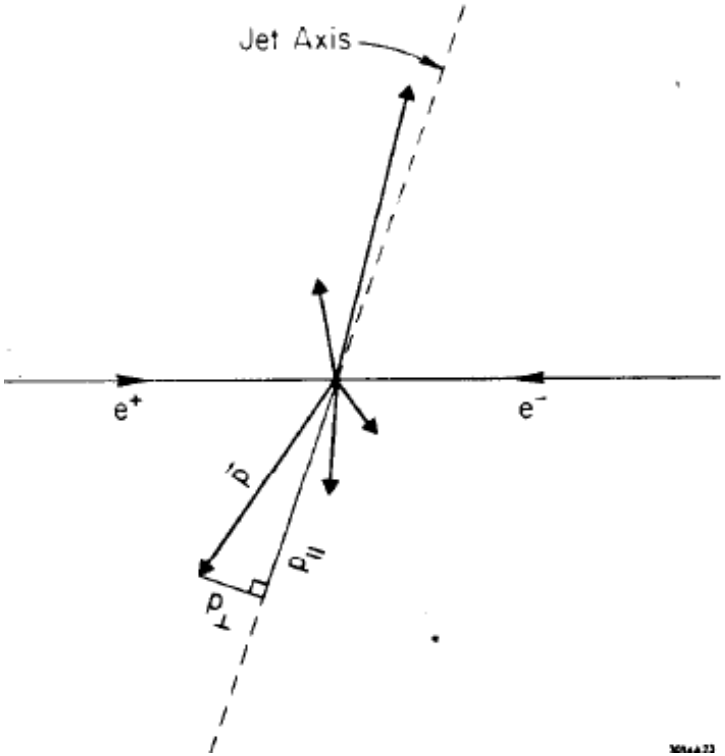
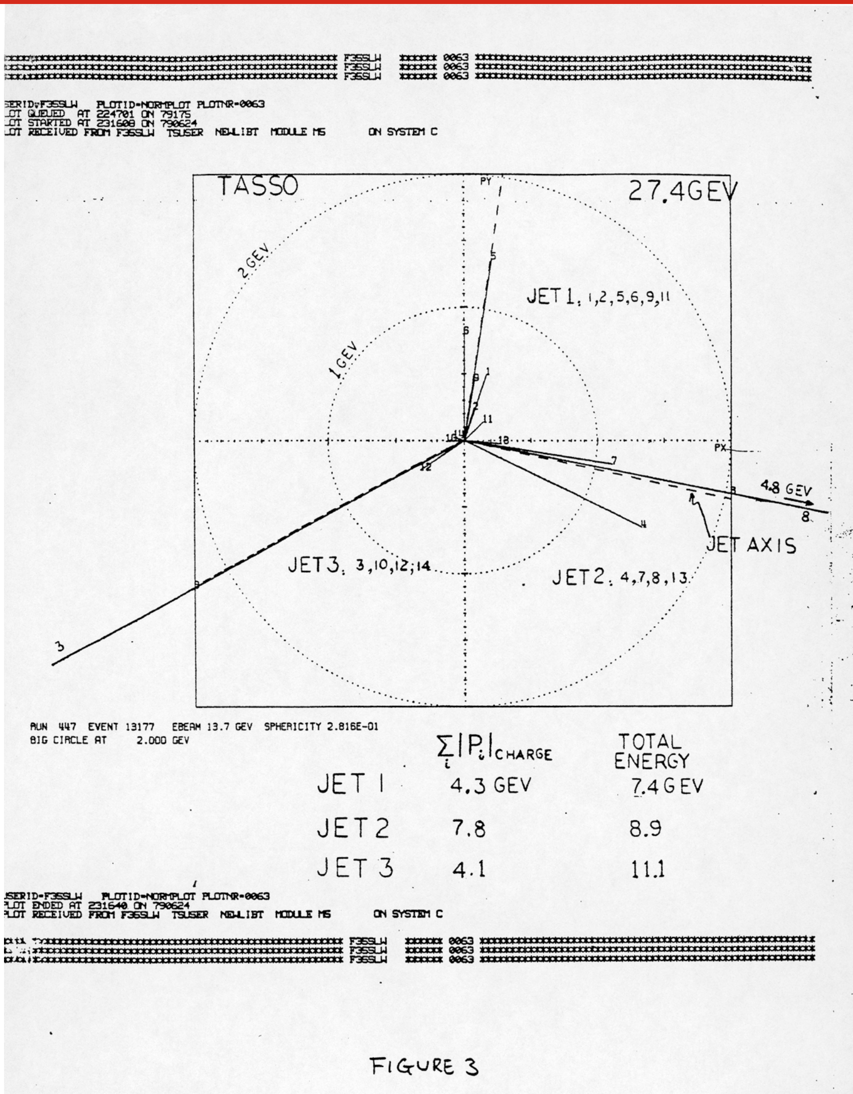


Fig. 16. Observed sphericity distributions at $E_{c.m.} = 7.4$ GeV for data, jet model (solid curves), and phase-space model (dashed curves) for (a) events with largest $x \leq 0.4$ and (b) events with largest $x > 0.4$.

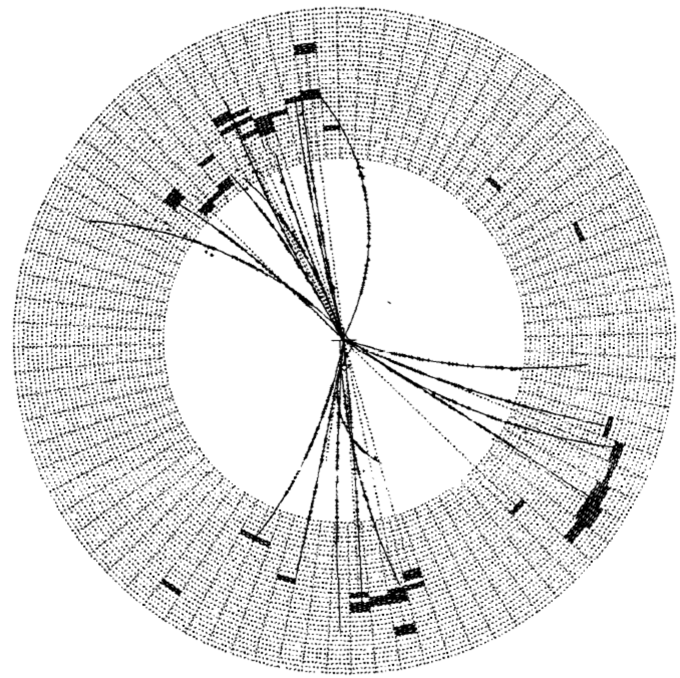


Font: SLAC-PUB-1814, SPEAR observation of 2 jets

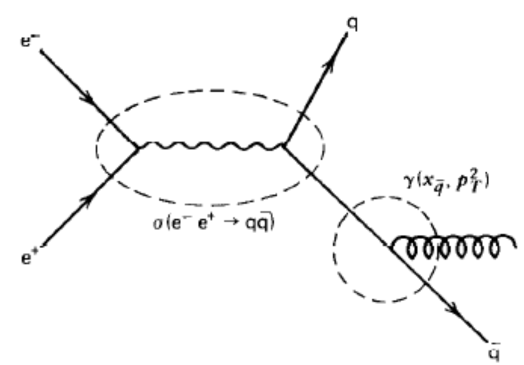
Three-jet event at PETRA



First event by TASSO (1979), DESY



JADE experiment, DESY



Measurement of alphas

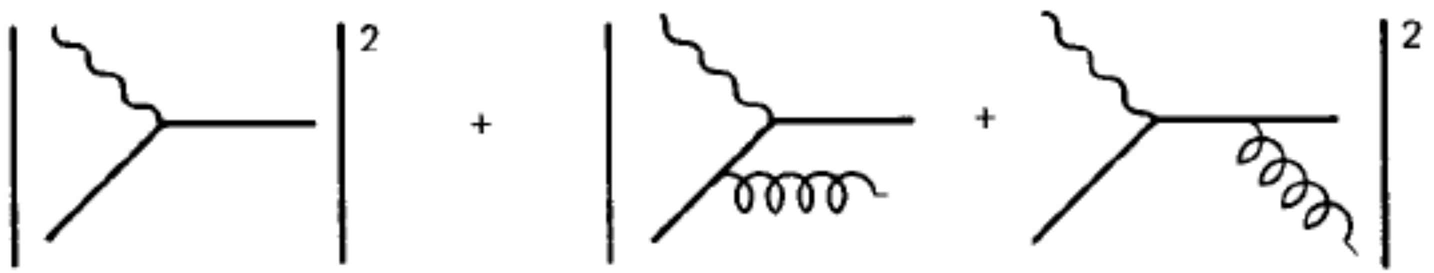
Let's suppose I have an electron-positron collider, at high energy enough to produce jets. How can I measure alphas?

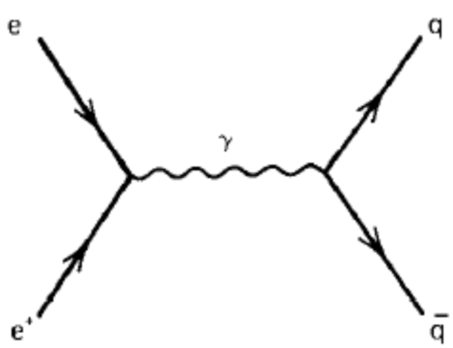
NLO and perturbation theory

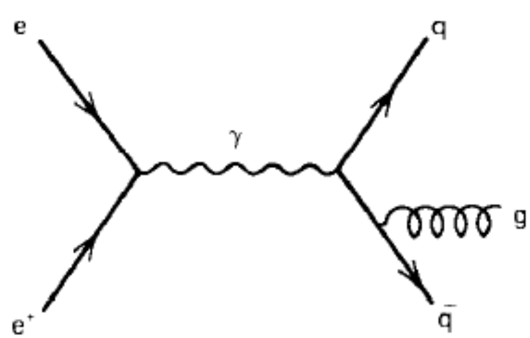
Thanks to the fact that α_S is small at high energy, we can apply perturbative calculations (pQCD)

ME = LO + NLO + NNLO + ...

2 examples:

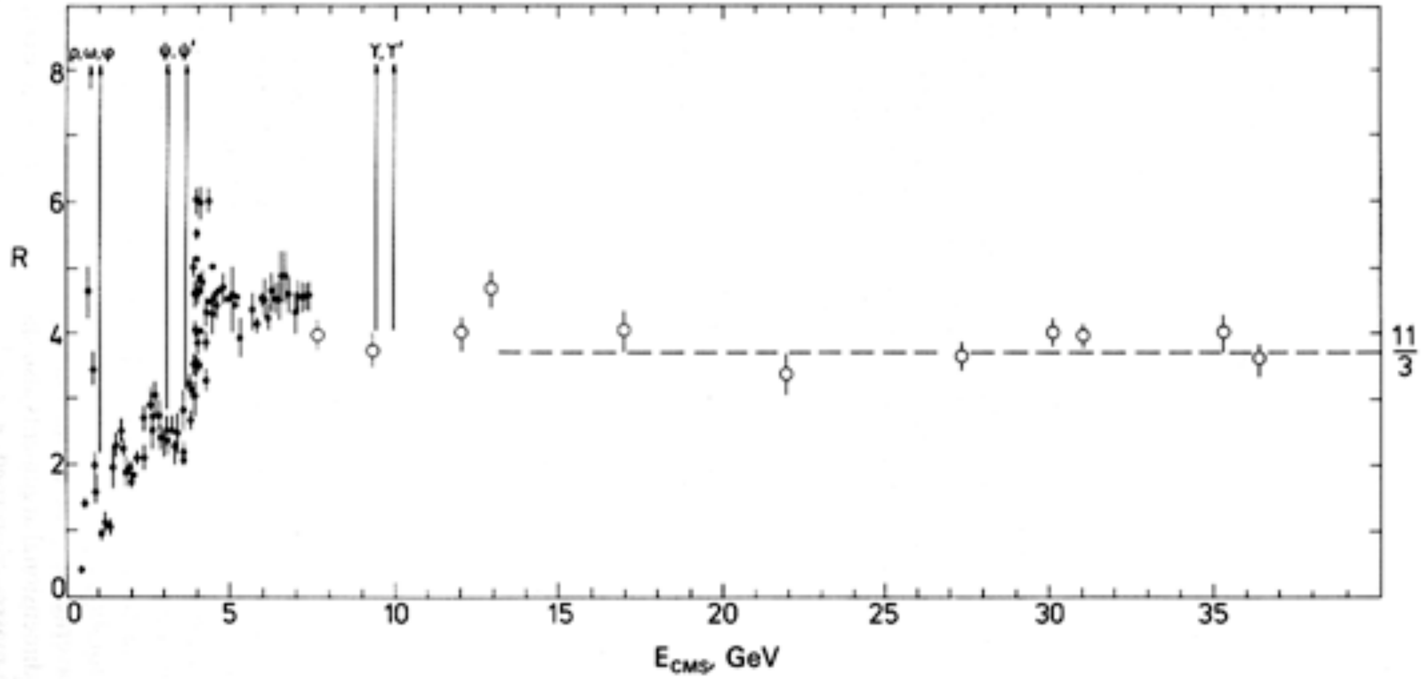






$$\boxed{R = 3\sum_q e_q^2\left[1 + \frac{\alpha_s(Q^2)}{\pi}\right].}$$

Ratio R in e^+e^-



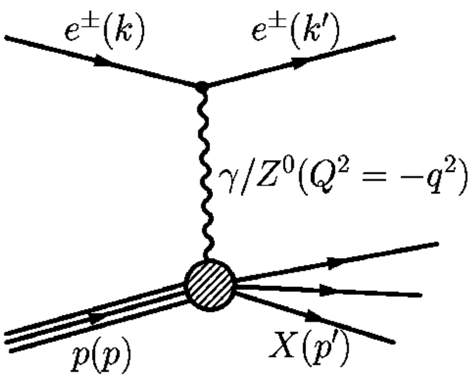
$$
\begin{aligned}
R &= 3\left[\left(\tfrac{2}{3}\right)^2 + \left(\tfrac{1}{3}\right)^2 + \left(\tfrac{1}{3}\right)^2\right] = 2 && \text{for } u, d, s, \\
&= 2 + 3\left(\tfrac{2}{3}\right)^2 = \tfrac{10}{3} && \text{for } u, d, s, c, \\
&= \tfrac{10}{3} + 3\left(\tfrac{1}{3}\right)^2 = \tfrac{11}{3} && \text{for } u, d, s, c, b
\end{aligned}
$$

What happens at 380 GeV?

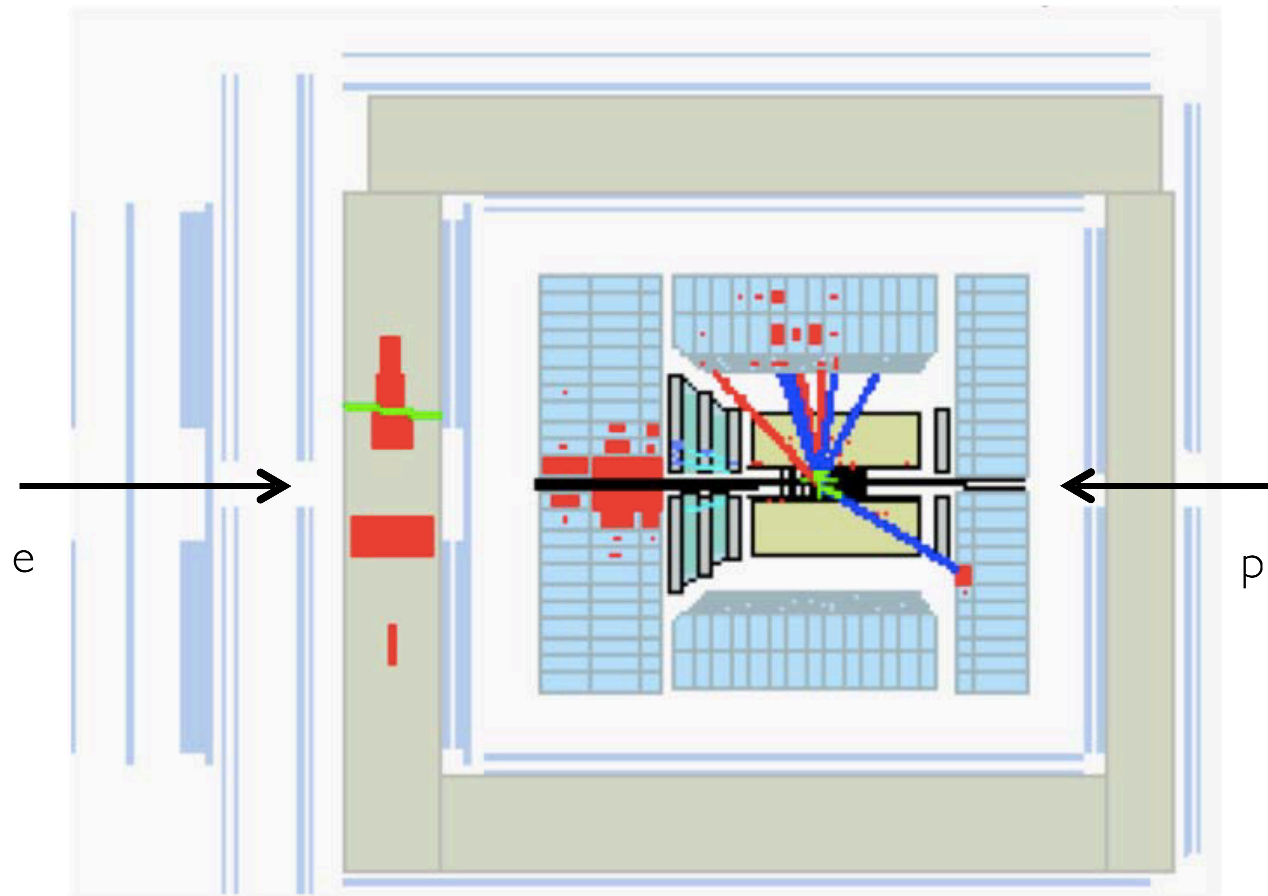
Have we measured the ratio R at 380 GeV?

DIS

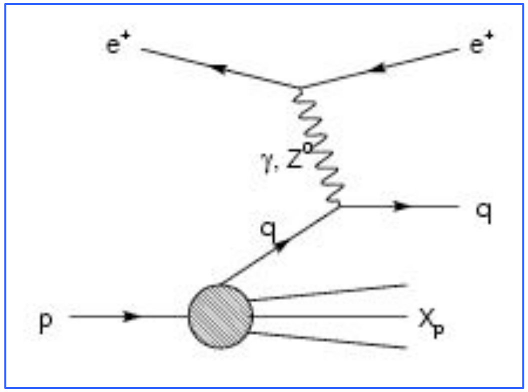
HERA

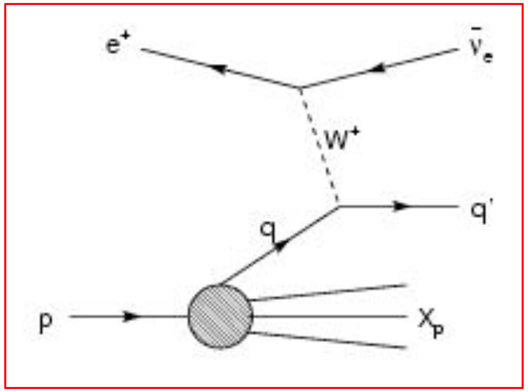


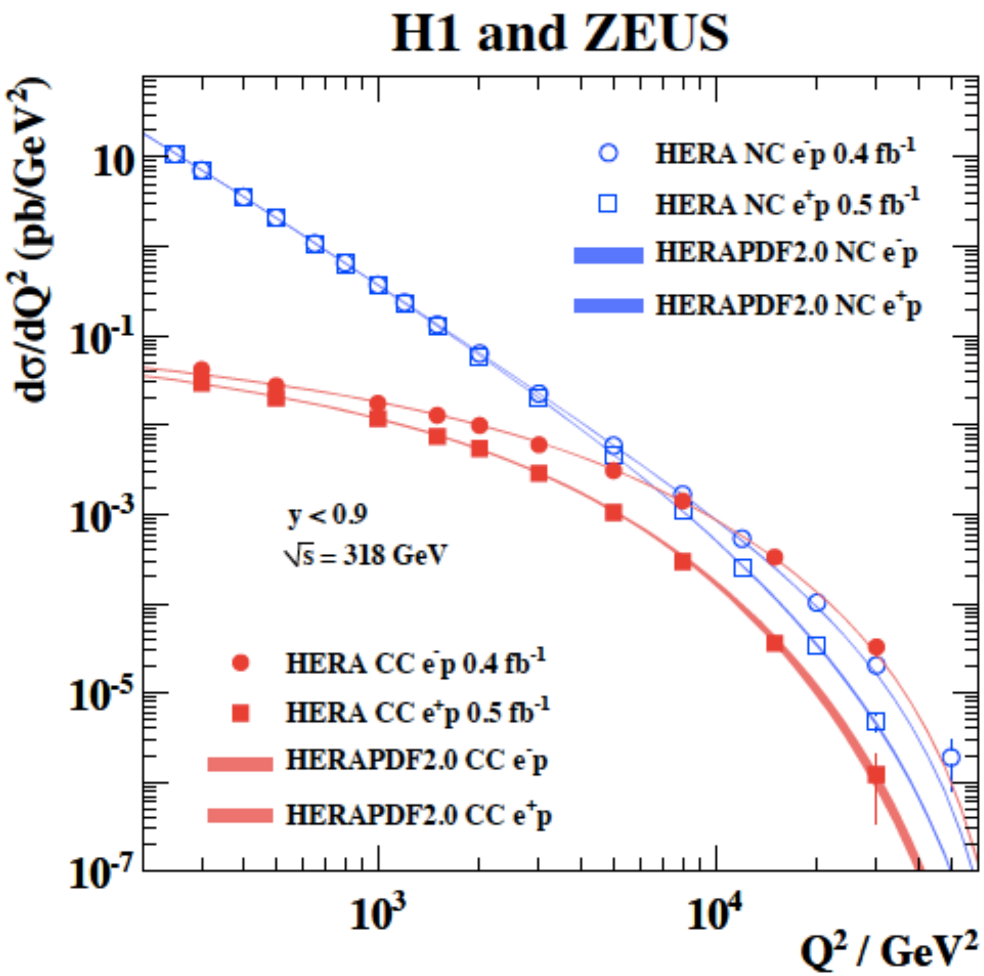
$$Q^2 = -q^2 = 4EE' \sin^2 \frac{\theta}{2}$$



HERA tests of SM



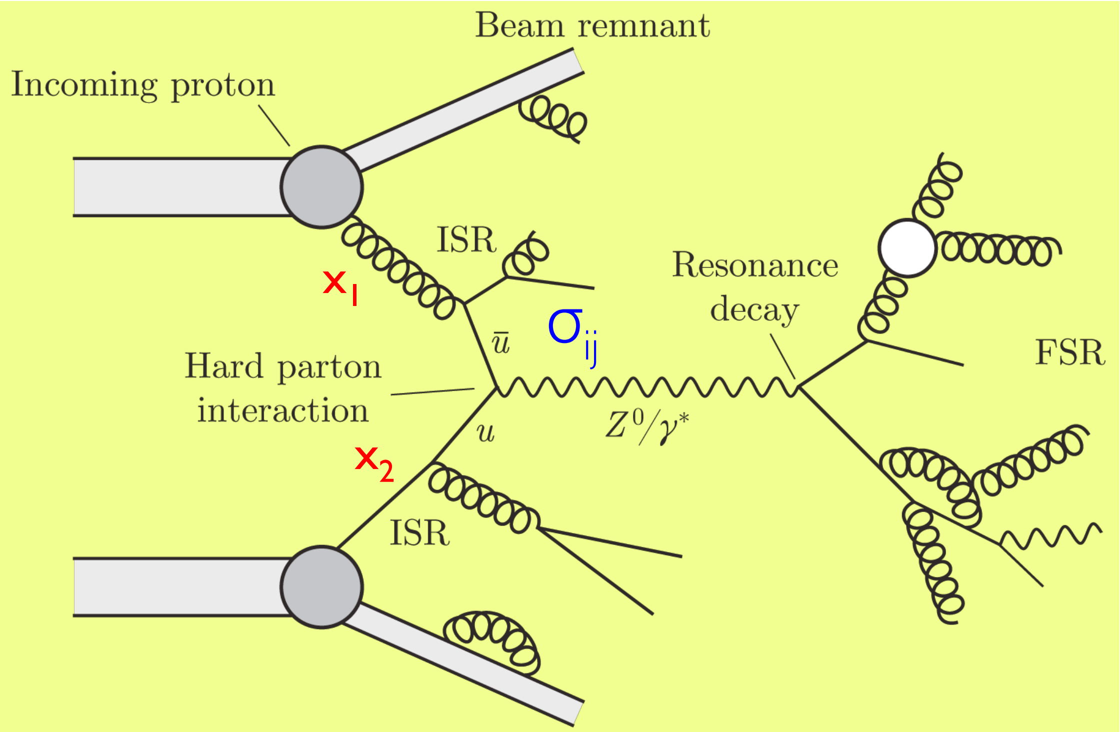




Why is this plot famous?

QCD in pp

A pp interaction



The cross section can be factorized as (factorization theorem in QCD):

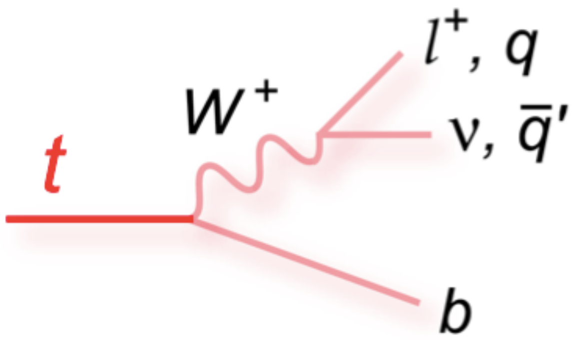
$$d\sigma_{h_1 h_2} = \sum_{i,j} \int_0^1 dx_i \int_0^1 dx_j \sum_f \int d\Phi_f \boxed{f_{i/h_1}(x_i, \mu_F^2)\, f_{j/h_2}(x_j, \mu_F^2)} \boxed{\frac{d\hat{\sigma}_{ij \to f}}{dx_i\, dx_j\, d\Phi_f}}$$

Non-perturbative, parton densities functions (PDFs), universal, from fit to exps. data

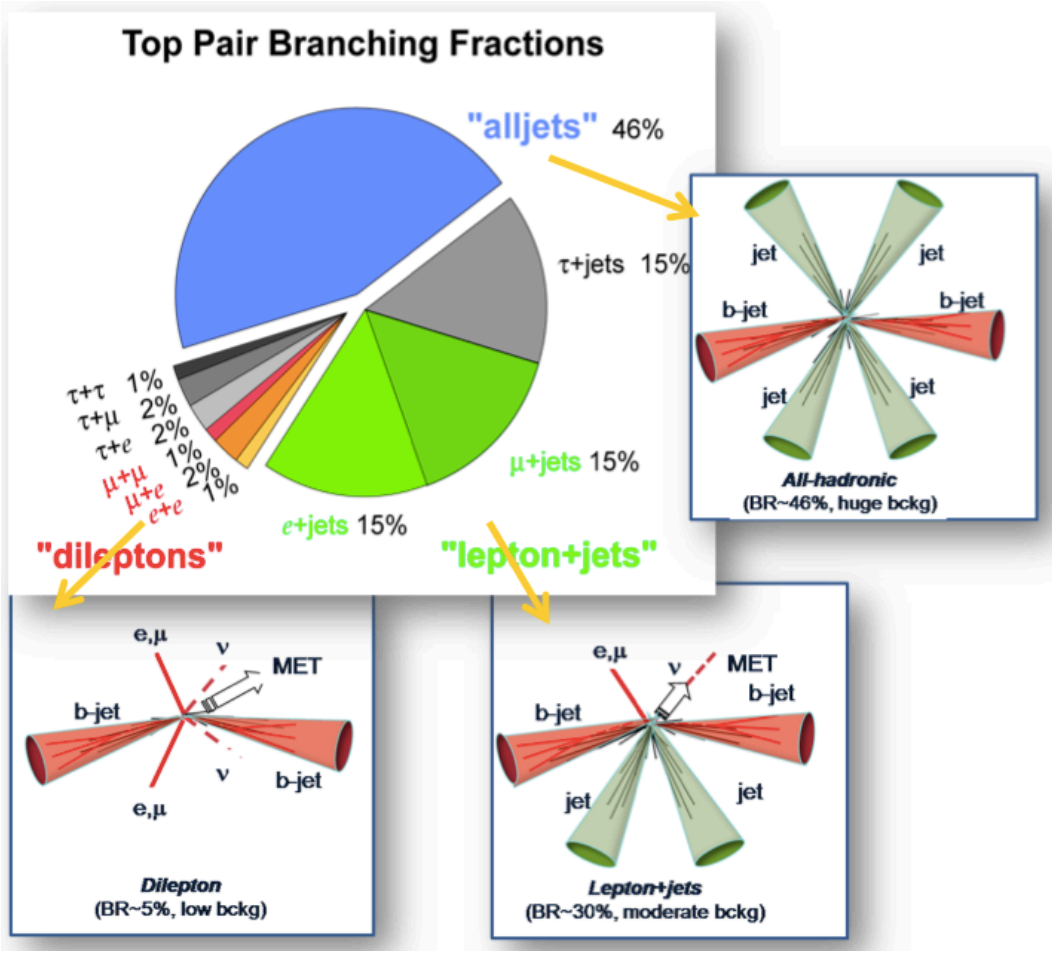
Perturbative process, calculable in pQCD

μ_F=factorization scale

Top decays



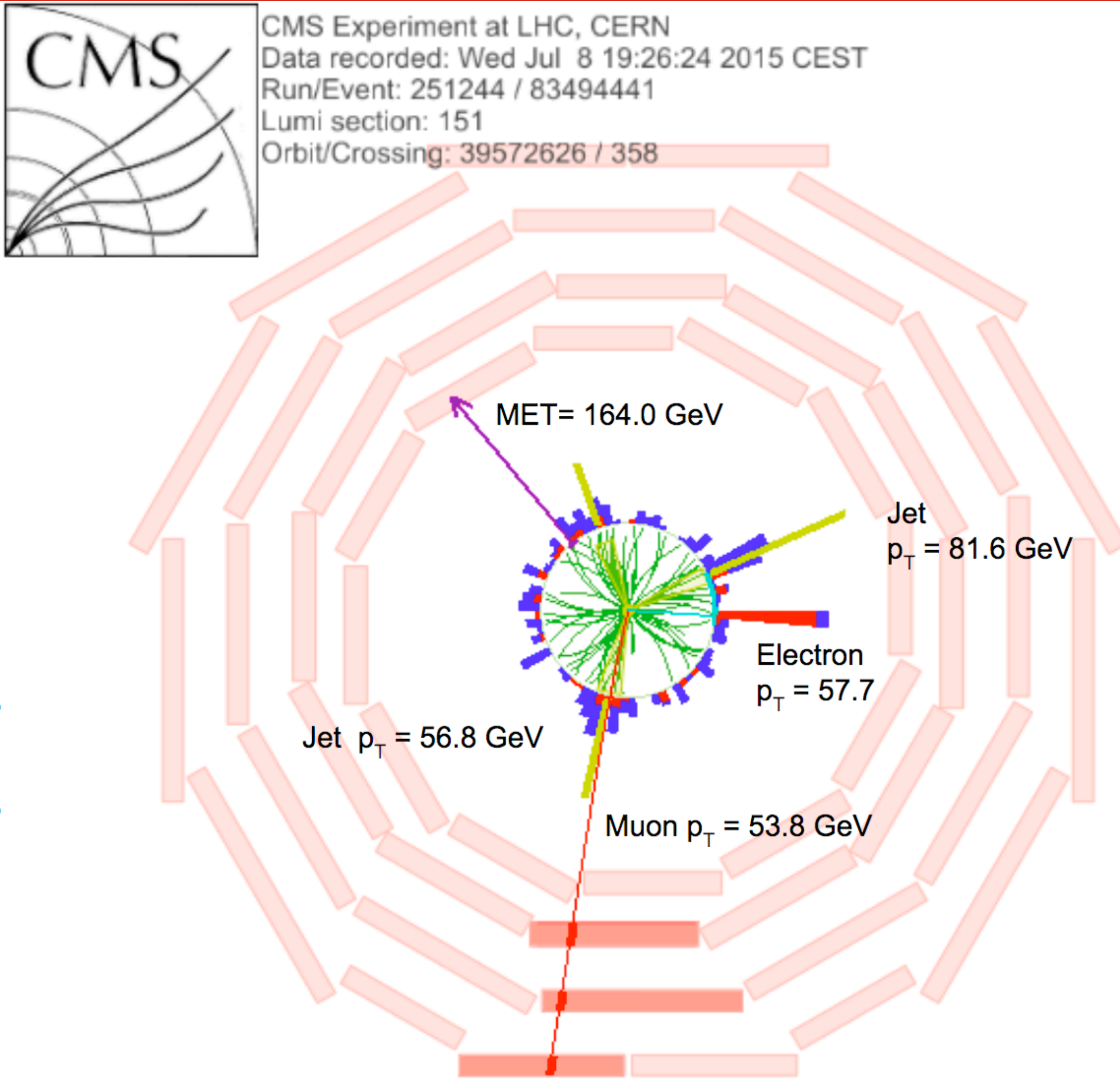
l^+, q
W^+
$\nu, \bar{q}'$
t
b

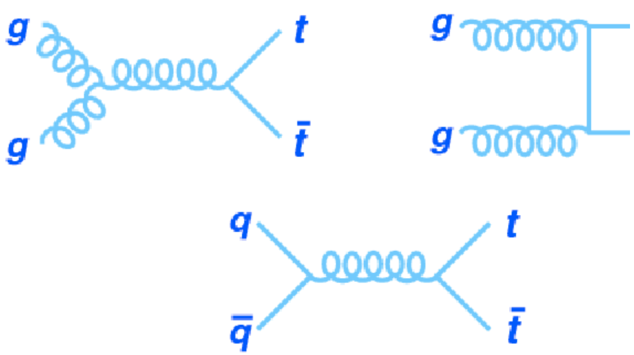


Top Pair Branching Fractions
"alljets" 46%
τ+jets 15%
μ+jets 15%
e+jets 15%
τ+τ 1%
τ+μ 2%
τ+e 2%
μ+μ 1%
μ+e 2%
e+e 1%
"dileptons"
"lepton+jets"
jet
b-jet
All-hadronic
(BR~46%, huge bckg)
e,μ
ν
MET
Dilepton
(BR~5%, low bckg)
Lepton+jets
(BR~30%, moderate bckg)

Top quark at the LHC

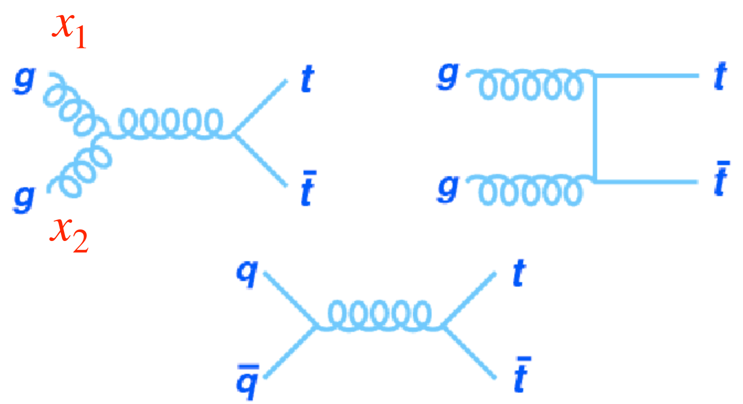
By now at the LHC we have millions top pair produced





Which production mode is higher at the LHC and why?

Top pair production at the LHC



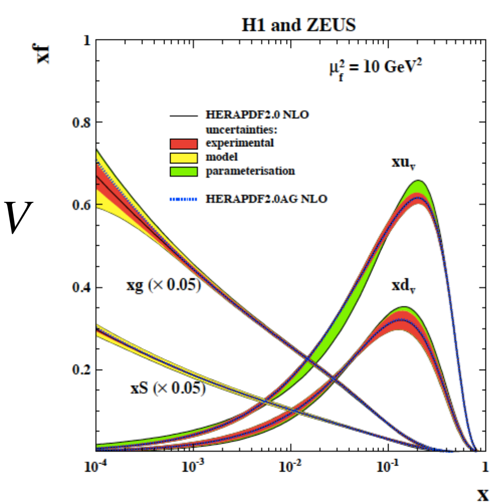
Each quark would have ~x of the beam energy, so the effective c.m. energy sqrt(s) becomes:

$$(2m_{top})^2 = 4x_1E_{\bar{p}}x_2E_p = x_1x_2s$$

$$2Xm_{top} \simeq x \cdot \sqrt{s} \quad , m_{top} = 172\ GeV, \sqrt{s} = 13{,}000\ GeV$$

$$x \simeq 0.02$$

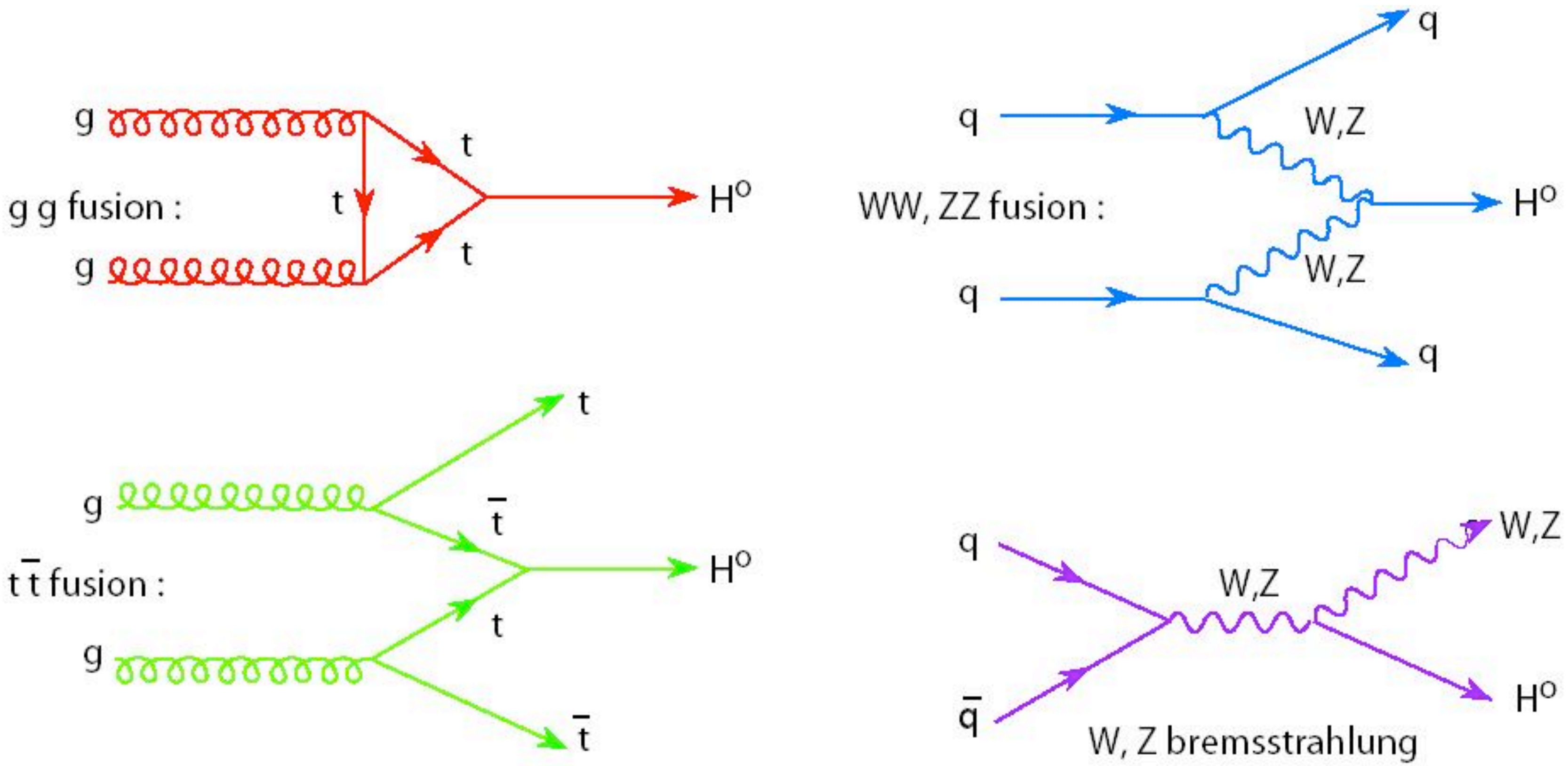
In gluon region



Font: Bettini

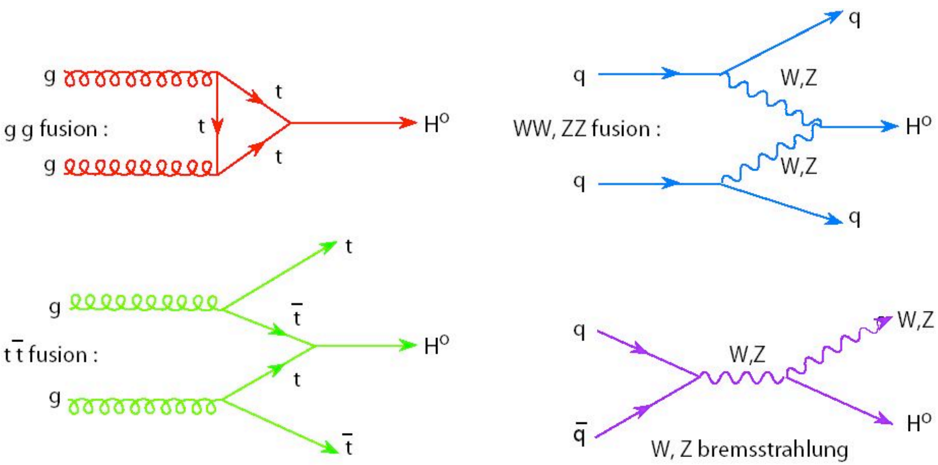
Higgs

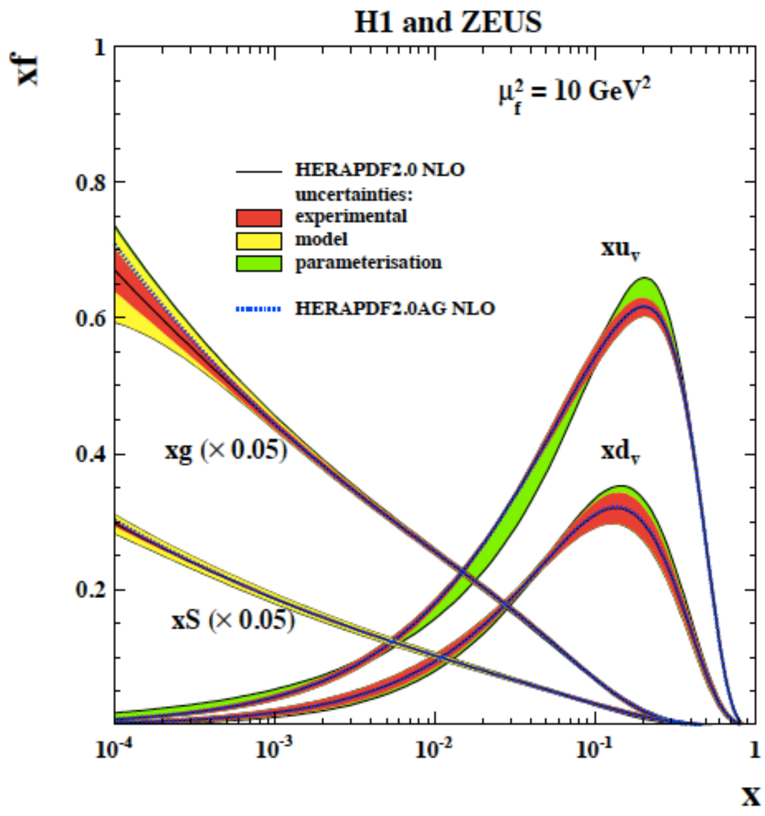
i.e. Higgs production



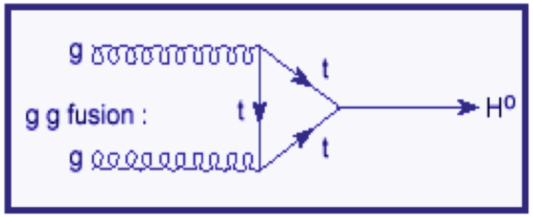
Which production mode is higher at the LHC and why?

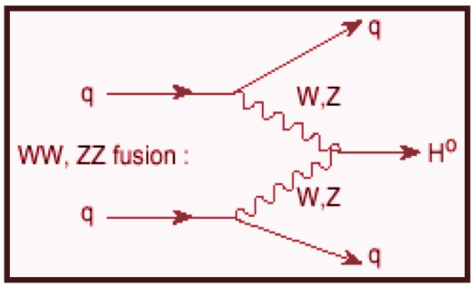
Higgs production

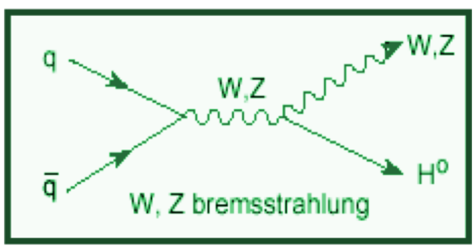


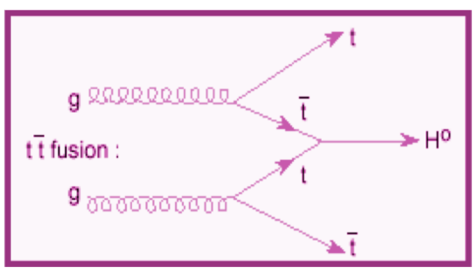


Higgs production



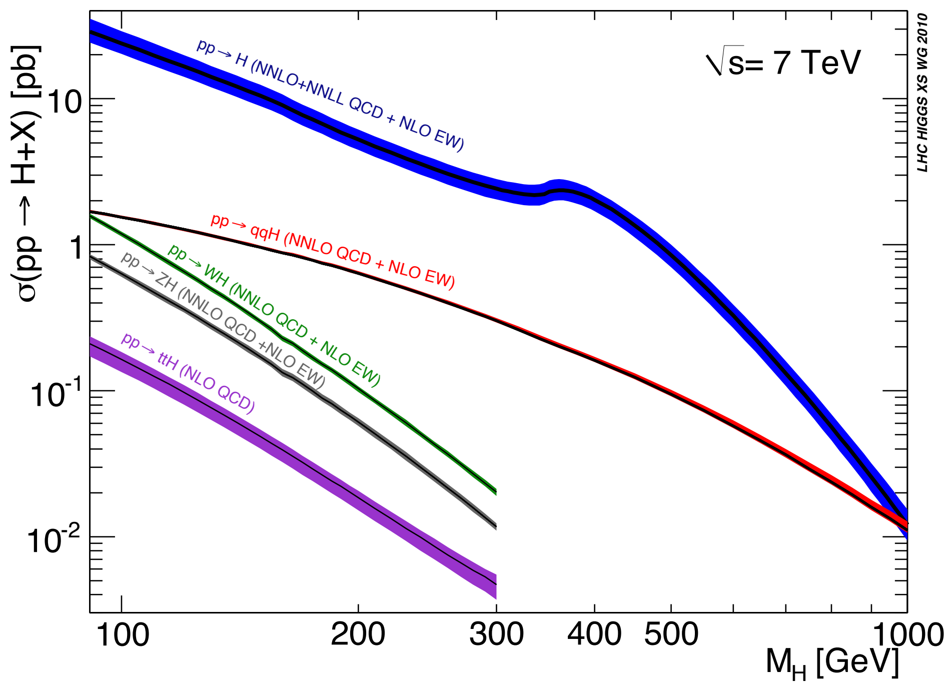






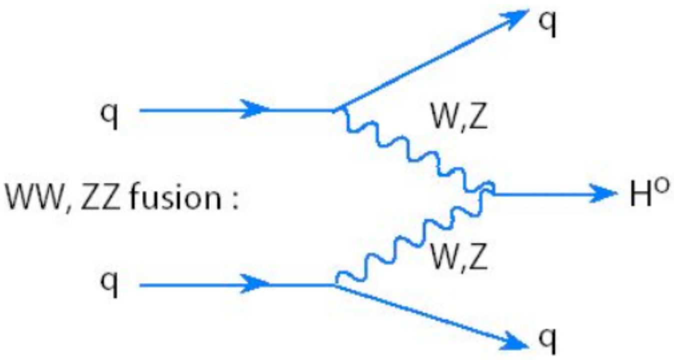
The Higgs boson can be produced in pp collisions through 4 main diagrams.

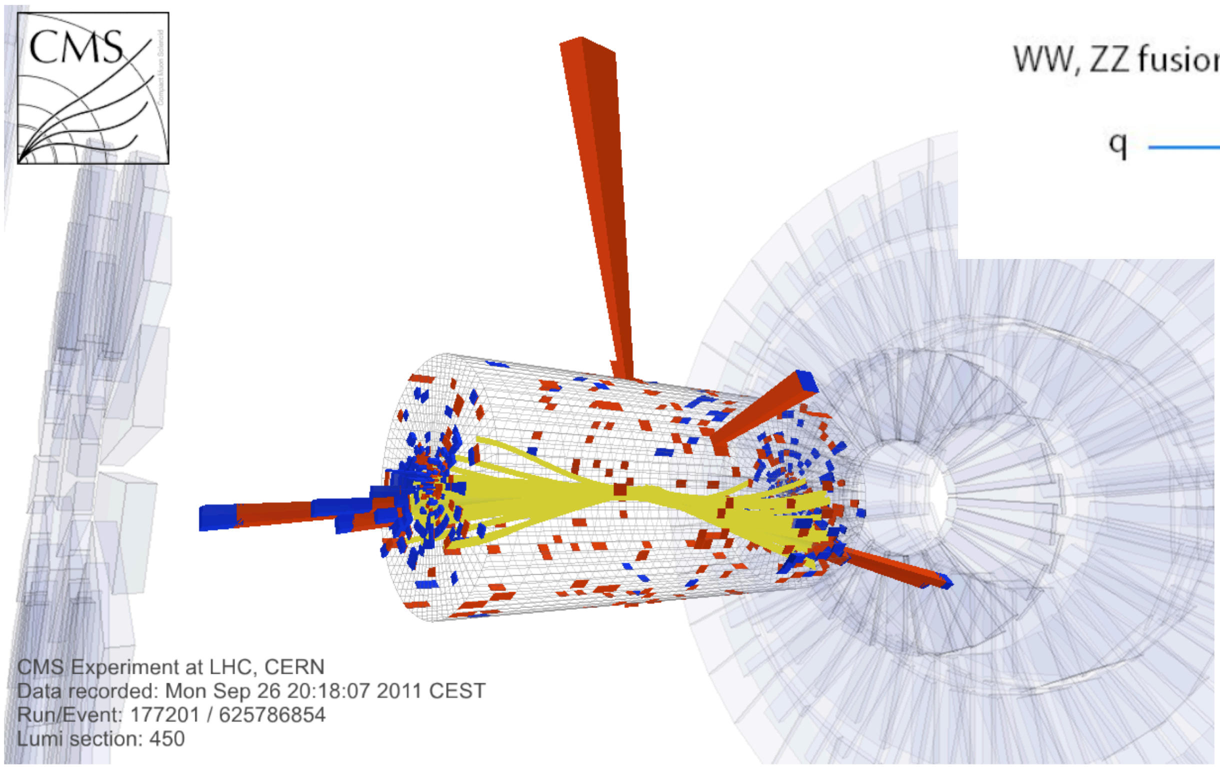
The cross sections are shown as a function of the Higgs boson mass below, here plotted at 7 TeV



The bands represent the theo uncertainties as calculated at the time of the discovery

VBF topology





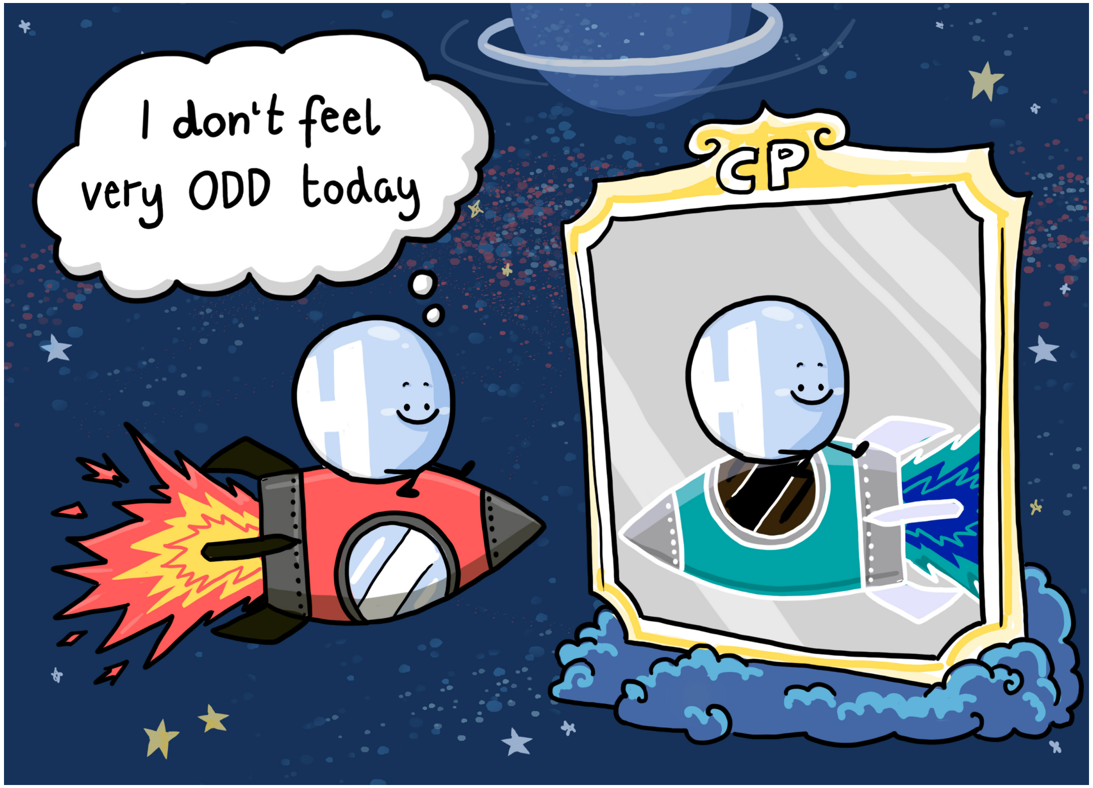
VBF topology

The cross section ratio between Higgs production and Drell Yan (Z) at the LHC is higher when two jets are present compared to no jet:

$$\frac{\sigma(VBF)(H + 2jets)}{\sigma(Z + 2jets)} > \frac{\sigma(H)}{\sigma(Z)}$$

- Draw the Feynman diagrams for the 4 processes in which the H or Z decay into two tau leptons
- Explain why this is the case
- Which implications could it have for an analysis looking for Higgs decaying Into two tau leptons?

A scalar particle



Can somebody interpret this picture?