Particle Physics II
(LPHY2133)

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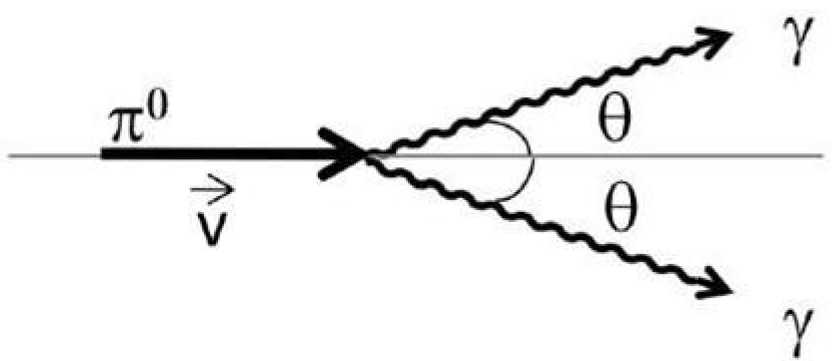
Neutral pion background
(from last week)

The π^0 has a lifetime of ~10^{-16} s and a mass of 135 MeV.



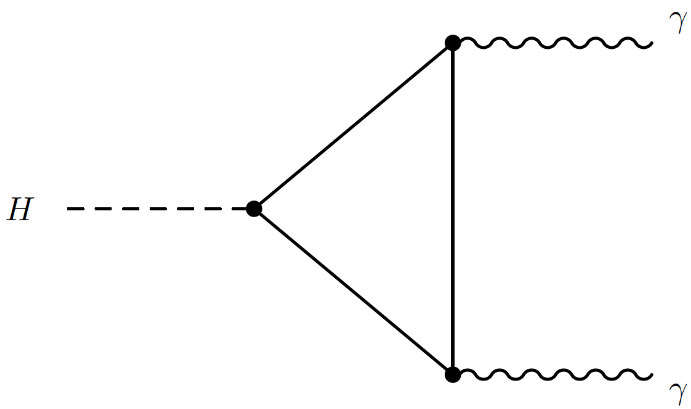
Exercise 1: calculate the decay length for E_π = 60 GeV; compare with the inner radius of CMS tracker (4 cm) and EM cal. (1.3 m).

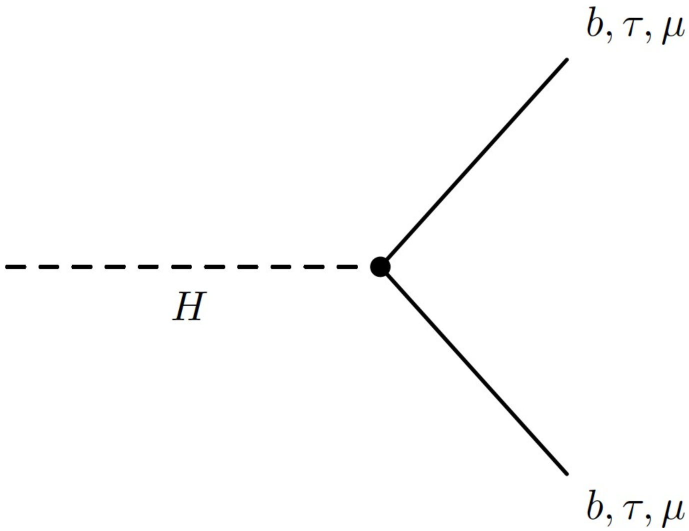
Exercise 2: calculate the angle θ, for E_π = 60 GeV; compare with the angular acceptance of an ECAL cell 2 cm wide.

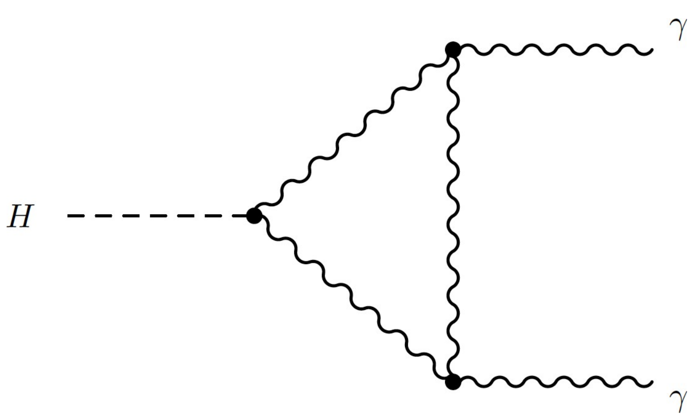
Section 5

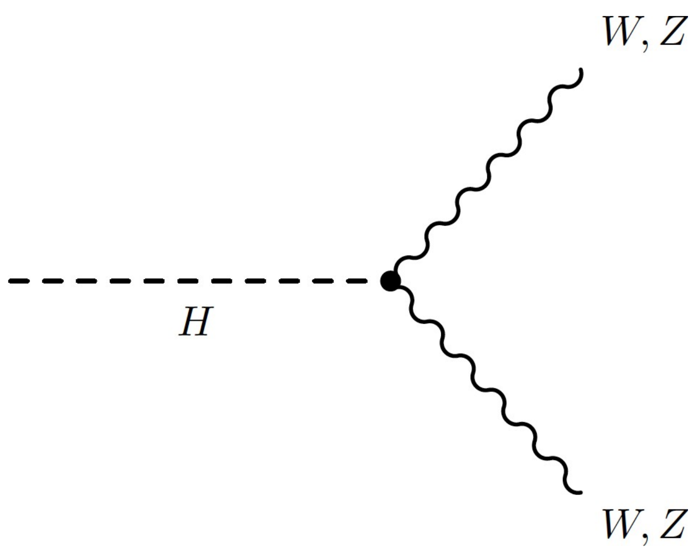
The search for the Higgs boson in the WW, $\tau\tau$, $b\bar{b}$ channels

Higgs decays

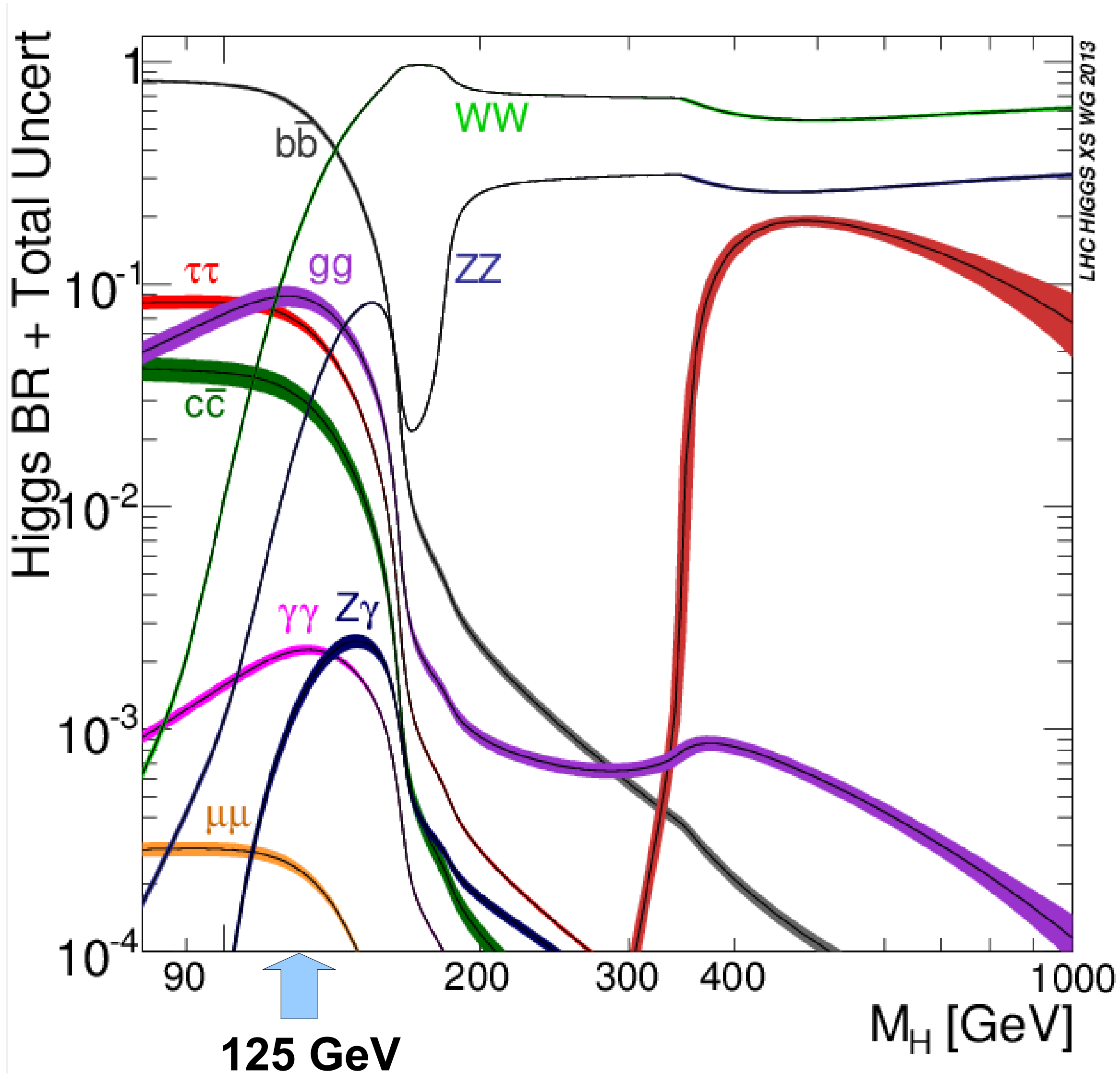




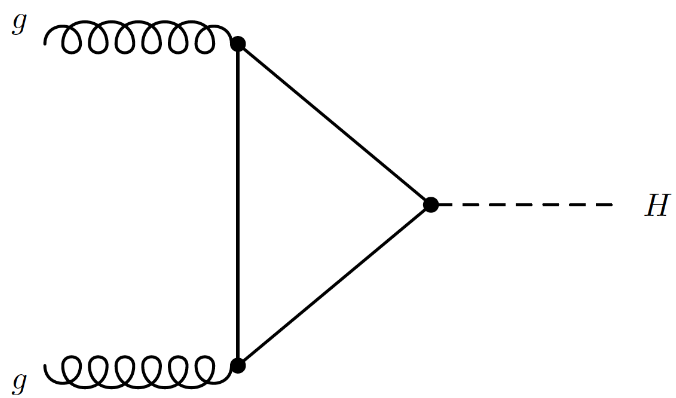




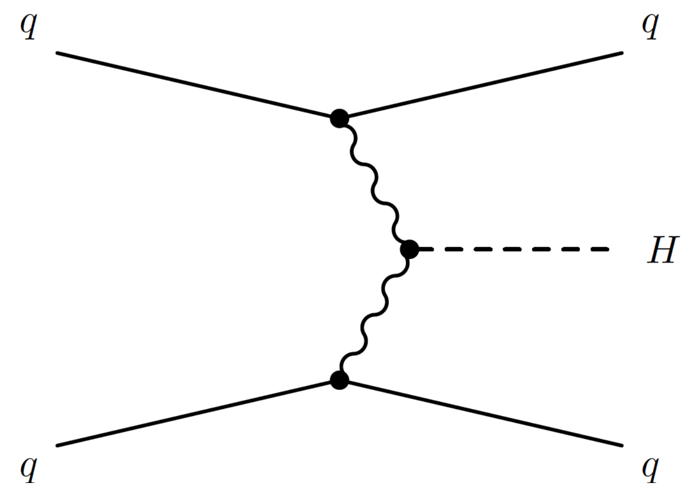
Branching ratios vs mass



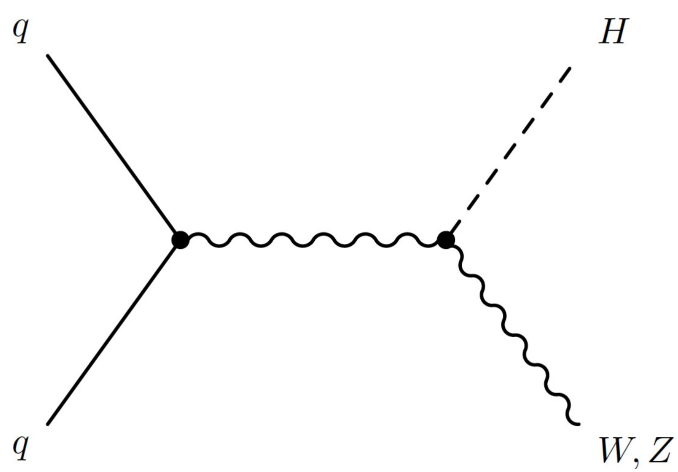
How to produce a Higgs boson



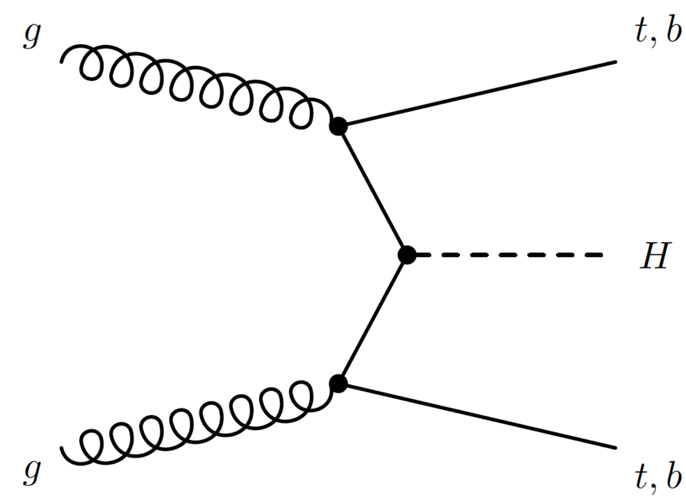
Gluon-gluon fusion



Vector-boson fusion

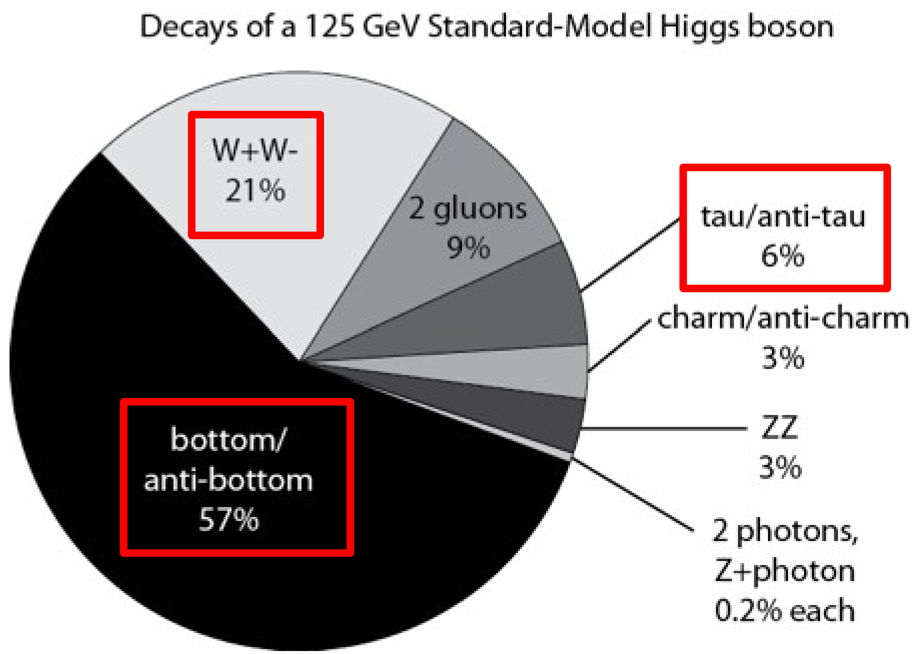


Higgs-strahlung



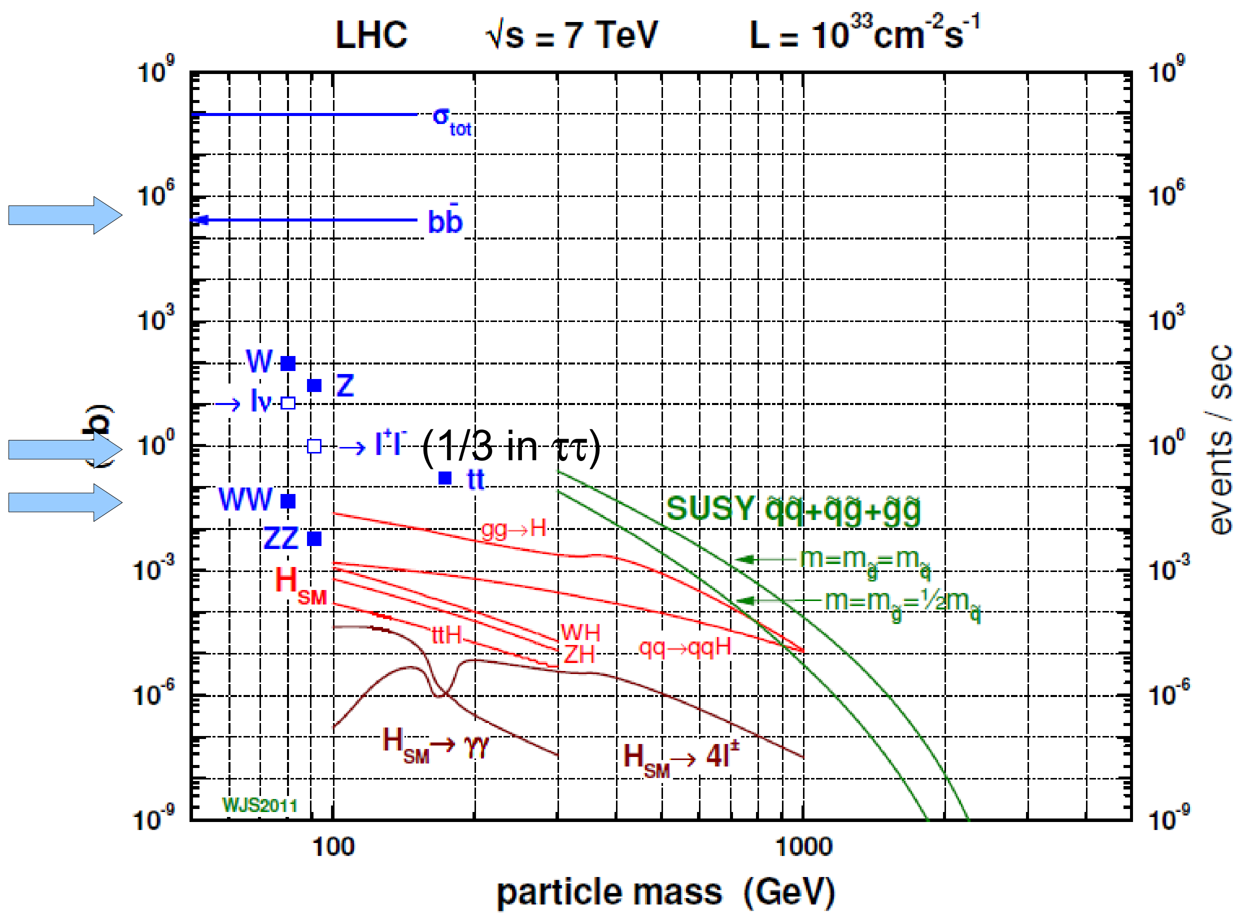
Top(bottom)-associated

Branching ratios @ 125 GeV

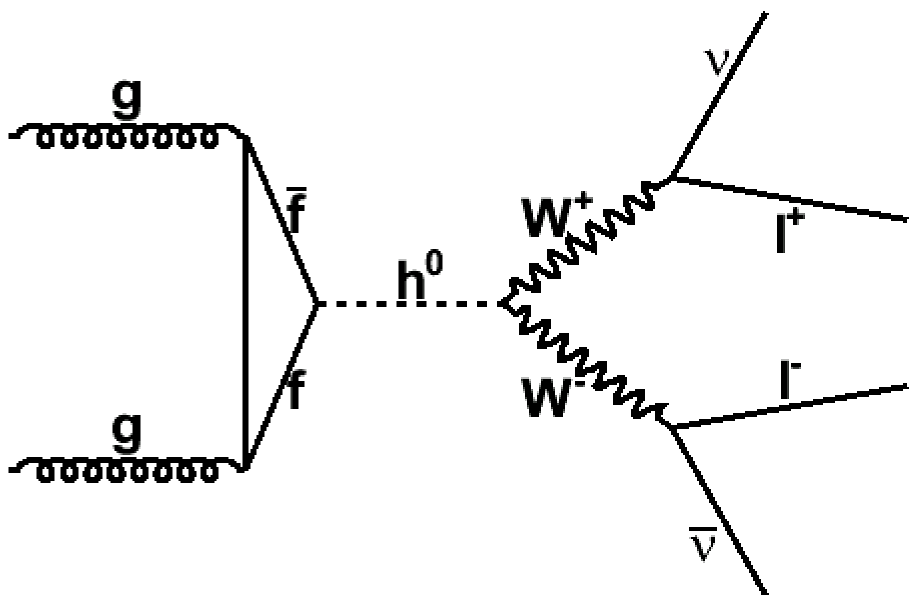


Today we talk about the 1st, 2nd and 4th most abundant decay channels (the 3rd, gg, is considered hopeless because of QCD di-jet background at LHC)

Event rates of their irreducible backgrounds



$H \to W^+W^- \to l^+l^-\nu\bar{\nu}$ ($l=e,\mu$) channel



Quiz: branching ratios of the W

- A property of the weak interactions is "universality": W and Z couple equally to all fermion doublets
- Based only on this fact, predict the branching ratio of:
  - $W \to e\nu_e$
  - $W \to \mu\nu_\mu$
  - $W \to \tau\nu_\tau$
  - $W \to qq'$

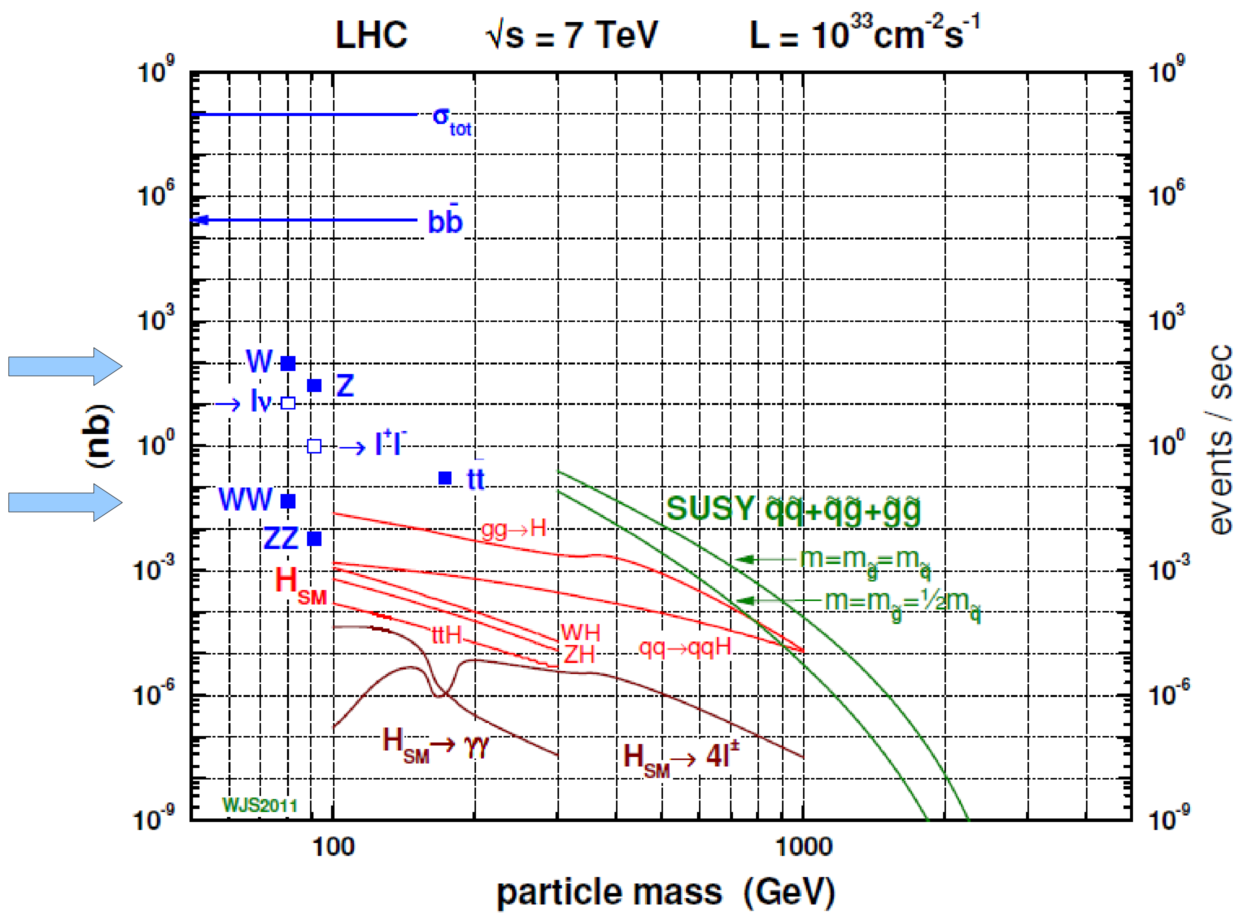
Solution

W^+ DECAY MODES		Fraction (Γ_i/Γ)
$\ell^+\nu$	[b]	(10.86 ± 0.09) %
$e^+\nu$		(10.71 ± 0.16) %
$\mu^+\nu$		(10.63 ± 0.15) %
$\tau^+\nu$		(11.38 ± 0.21) %
hadrons		(67.41 ± 0.27) %

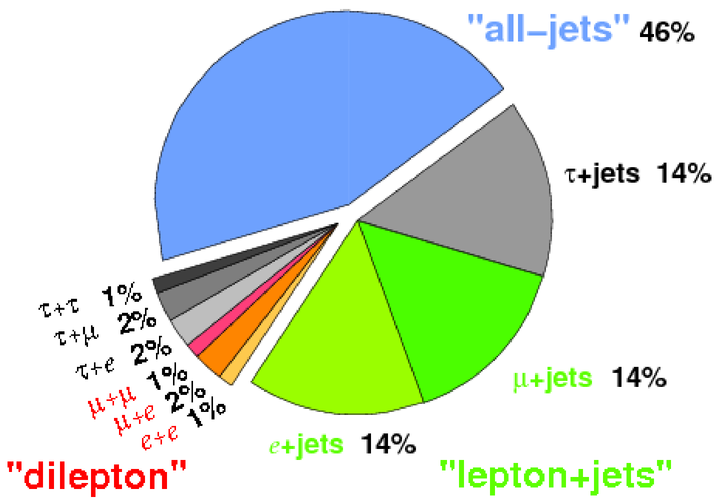
From the PDG

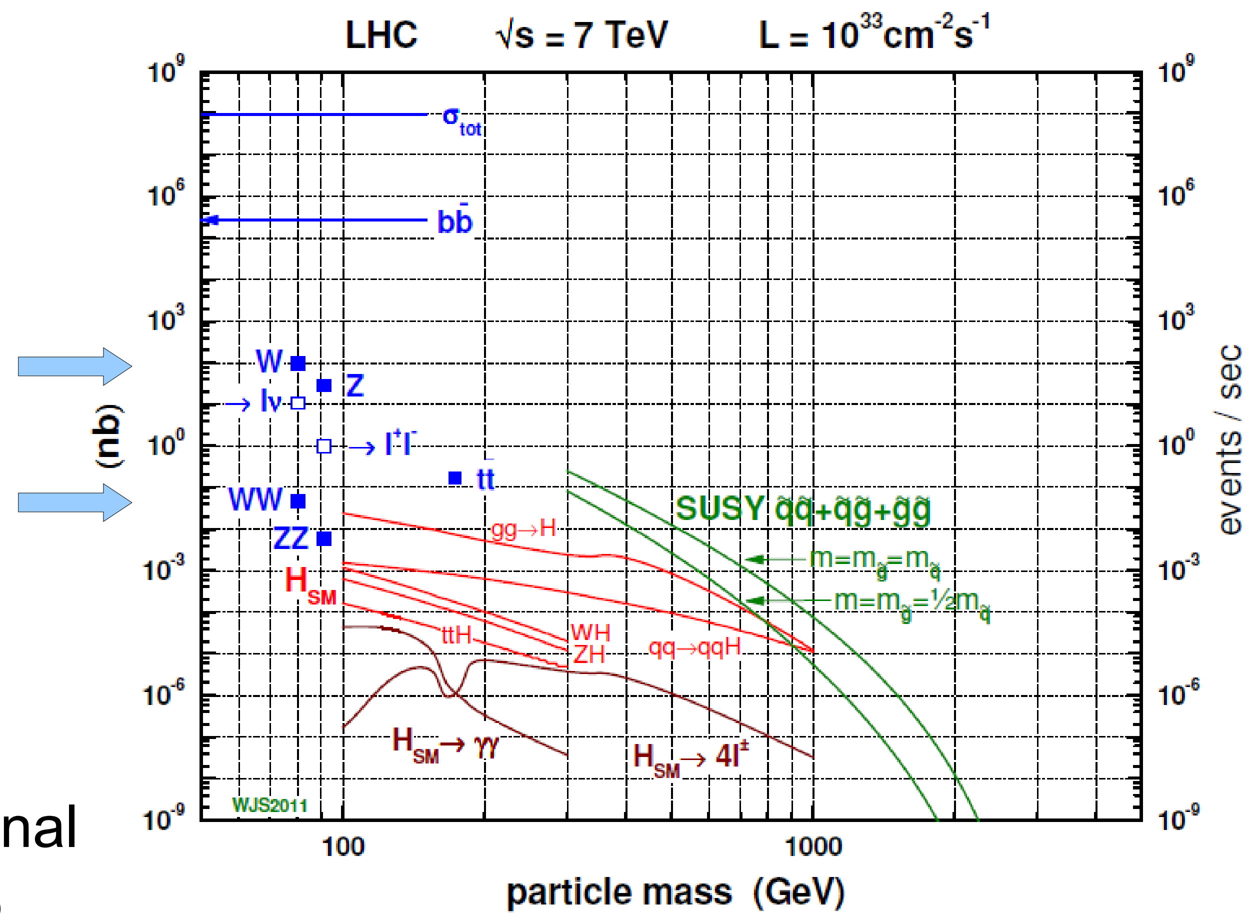
- At first order, BR ~ 1/9 (11.11%) for each lepton channel
- In fact, each quark has 3 degrees of freedom, because of the *color* quantum number
- No $W \rightarrow tb$ because of $M_t + M_b > M_W$
- The small deviations from 1/9 come from perturbative corrections (QCD loops affecting the decays into quarks)

W(+jets) vs WW backgrounds



Low statistics but high purity

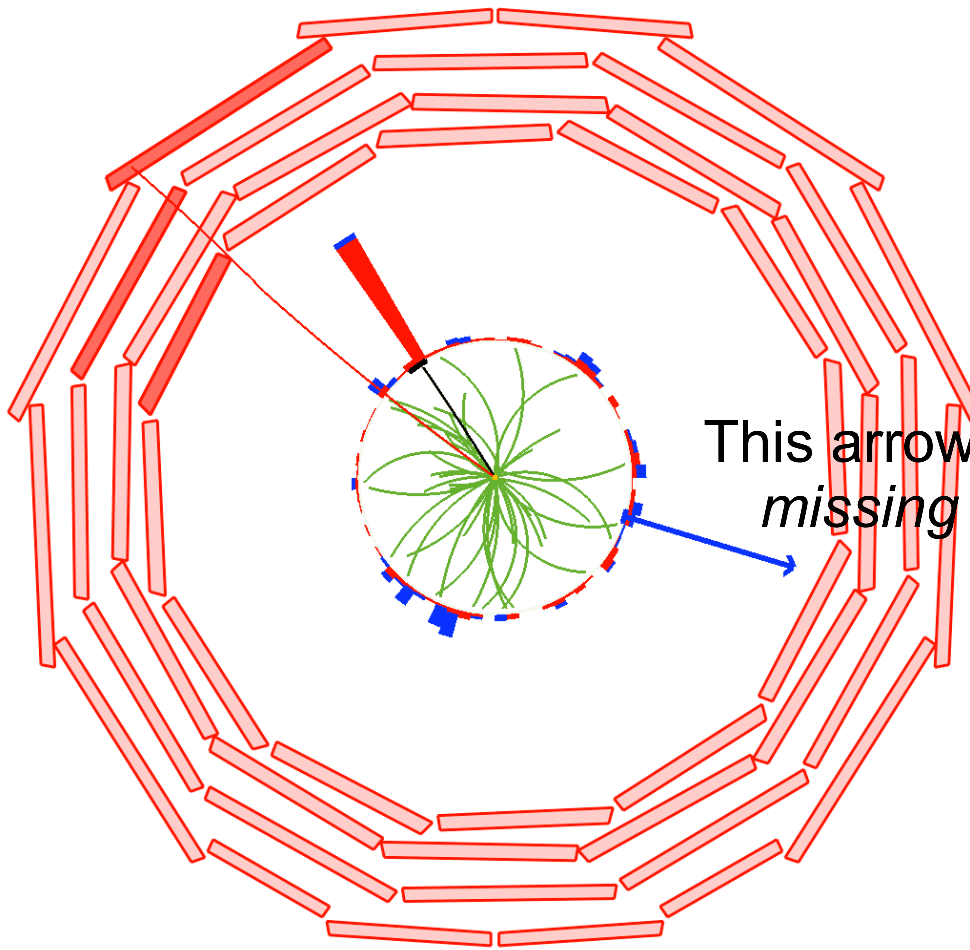




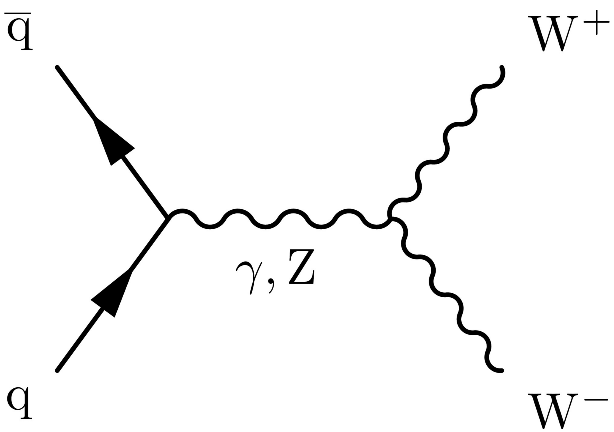
H→WW→lνjj is 28% of the signal while H→WW→llνν is only 4%

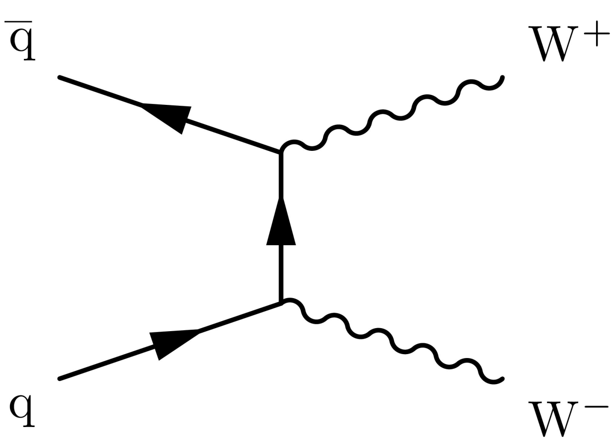
but W+jet, which is an irreducible background in the first case (reducible in the second case) is 3 orders of magnitude larger than WW

An $e\mu\nu\bar{\nu}$ candidate

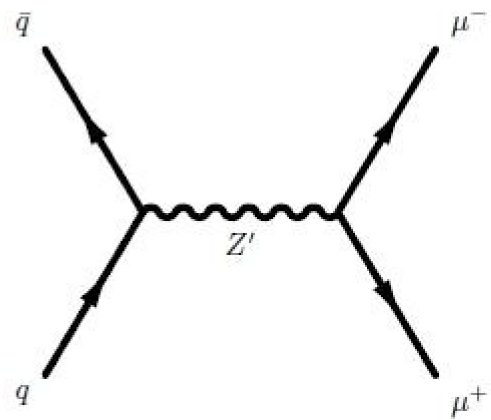


Backgrounds with 2 real leptons

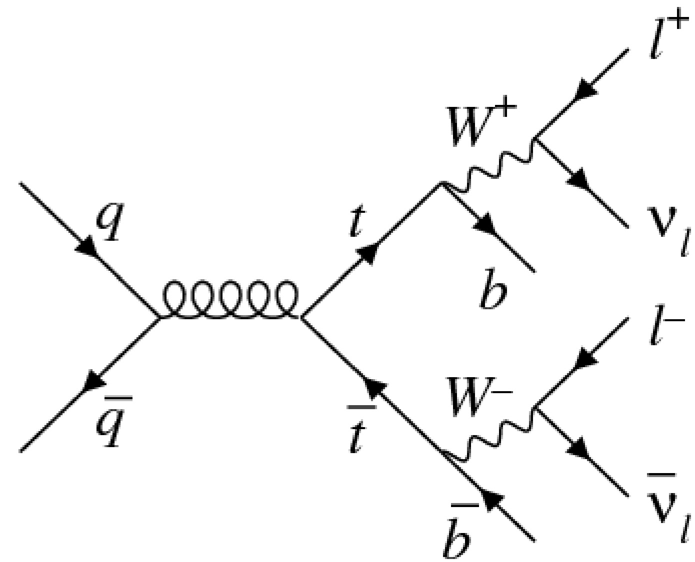




Irreducible background



Z background in ee, μμ:
Main difference is the absence of neutrinos (leptons are back-to-back); mostly reduced by cutting around the Z mass peak



Top background:
Main difference is the presence of jets

(Another important background is W+jets, where a lepton is real and one is fake)

Transverse missing energy (MET)

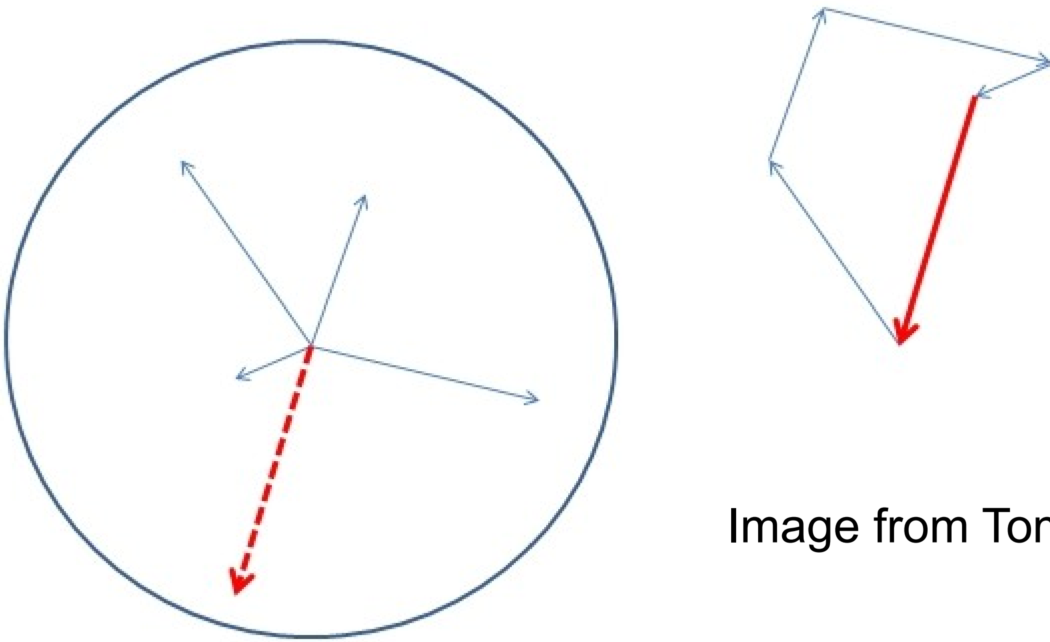
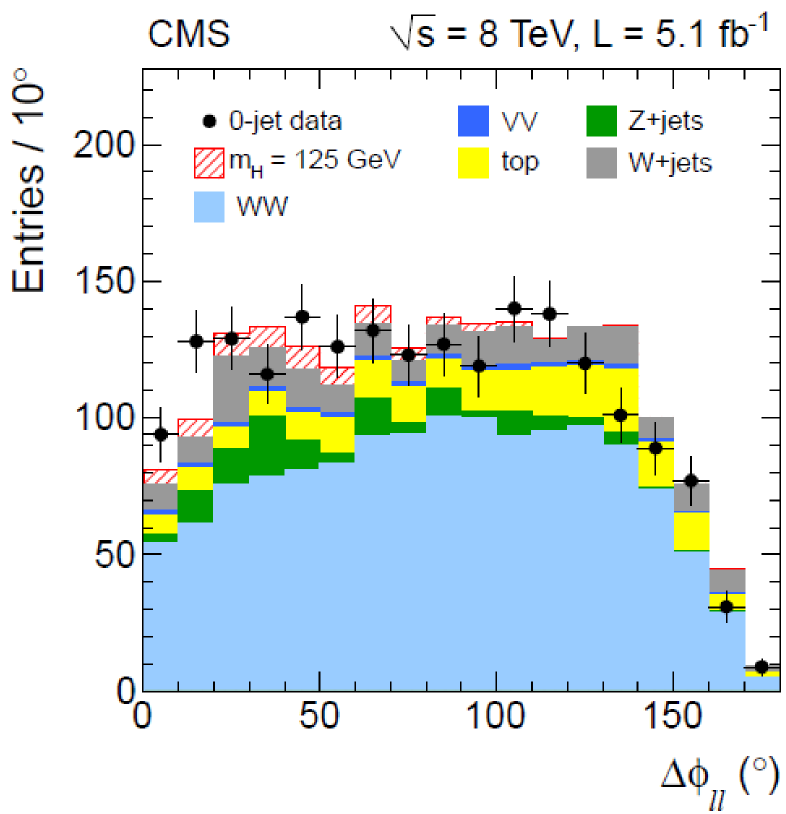
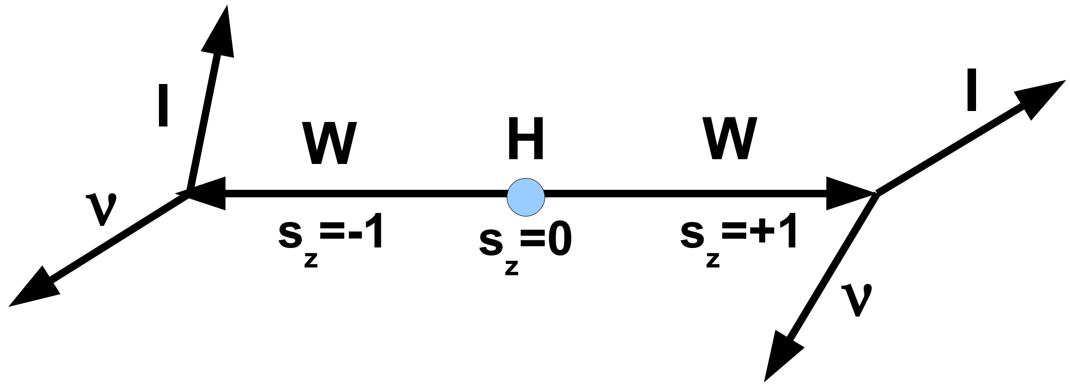


Image from Tommaso Dorigo

A threshold is applied on MET to reduce the Z boson background (and in general the processes with no neutrinos). MET can be used as a rough approximation of transverse neutrino momentum; but it is very imprecise because not 100% of the other particles are detected.

Angular distribution



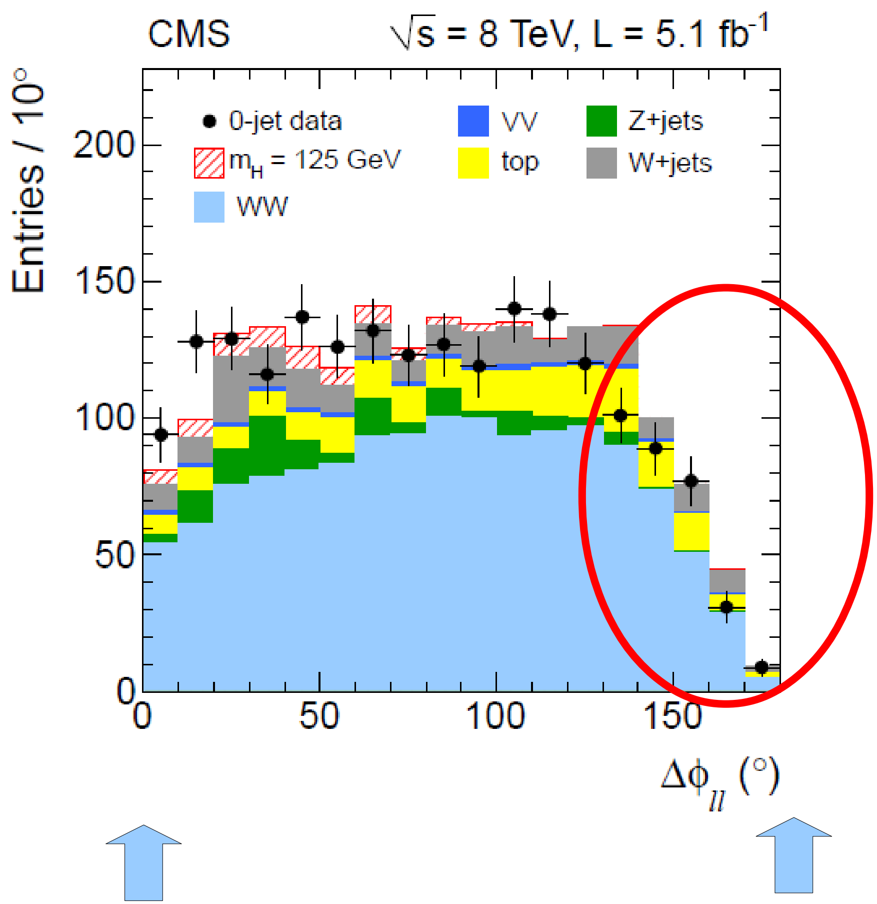


The two W bosons must have opposite spin vectors, to sum the total spin to 0, and opposite momentum (if H at rest), so they must have the same helicity (h=s·p/|p|). The W can only decay to left-handed particles or right-handed anti-particles ⇒ leptons tend to fly in the same direction

$\Delta\phi \sim 0$: the two leptons are close

$\Delta\phi \sim \pi$: they are back-to-back

Quiz

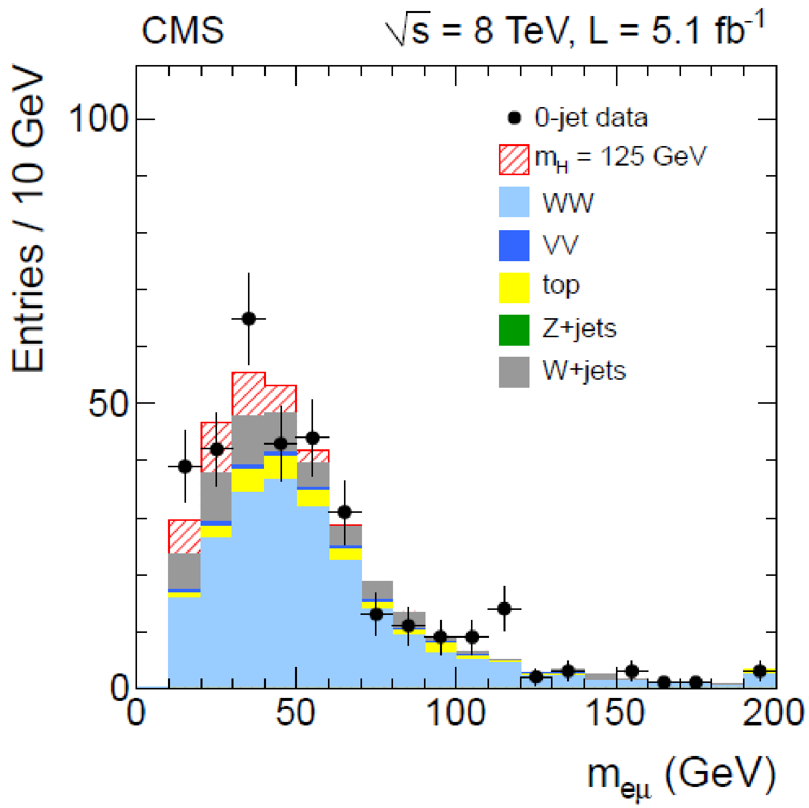


Why this sudden drop in population close to π?

$\Delta\phi \sim 0$: the two leptons are close

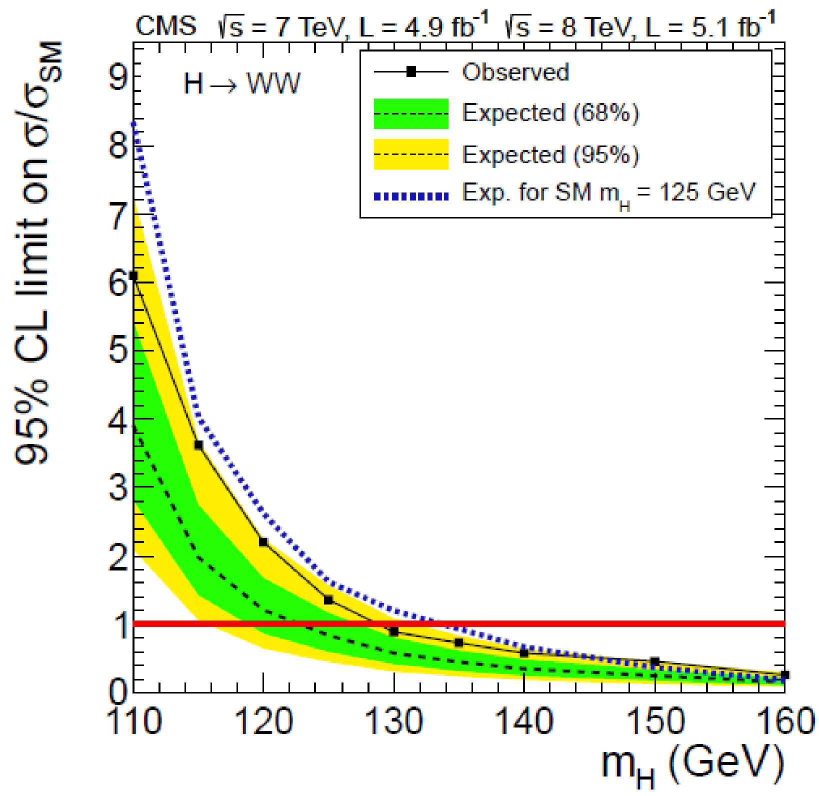
$\Delta\phi \sim \pi$: they are back-to-back

Dilepton invariant mass



Unfortunately because of the two escaping neutrinos we have no direct access to the H mass; but we can use variables correlated with it, like the dilepton mass

Results (CMS 2012)



Observed ~2 sigma deviation from the background-only hypothesis over a broad range of masses (because of poor mass sensitivity), compatible with the signal observed in the previous channels (γγ & 4l) which have the advantage of a precise mass determination

H→$\tau^+\tau^-$ channel

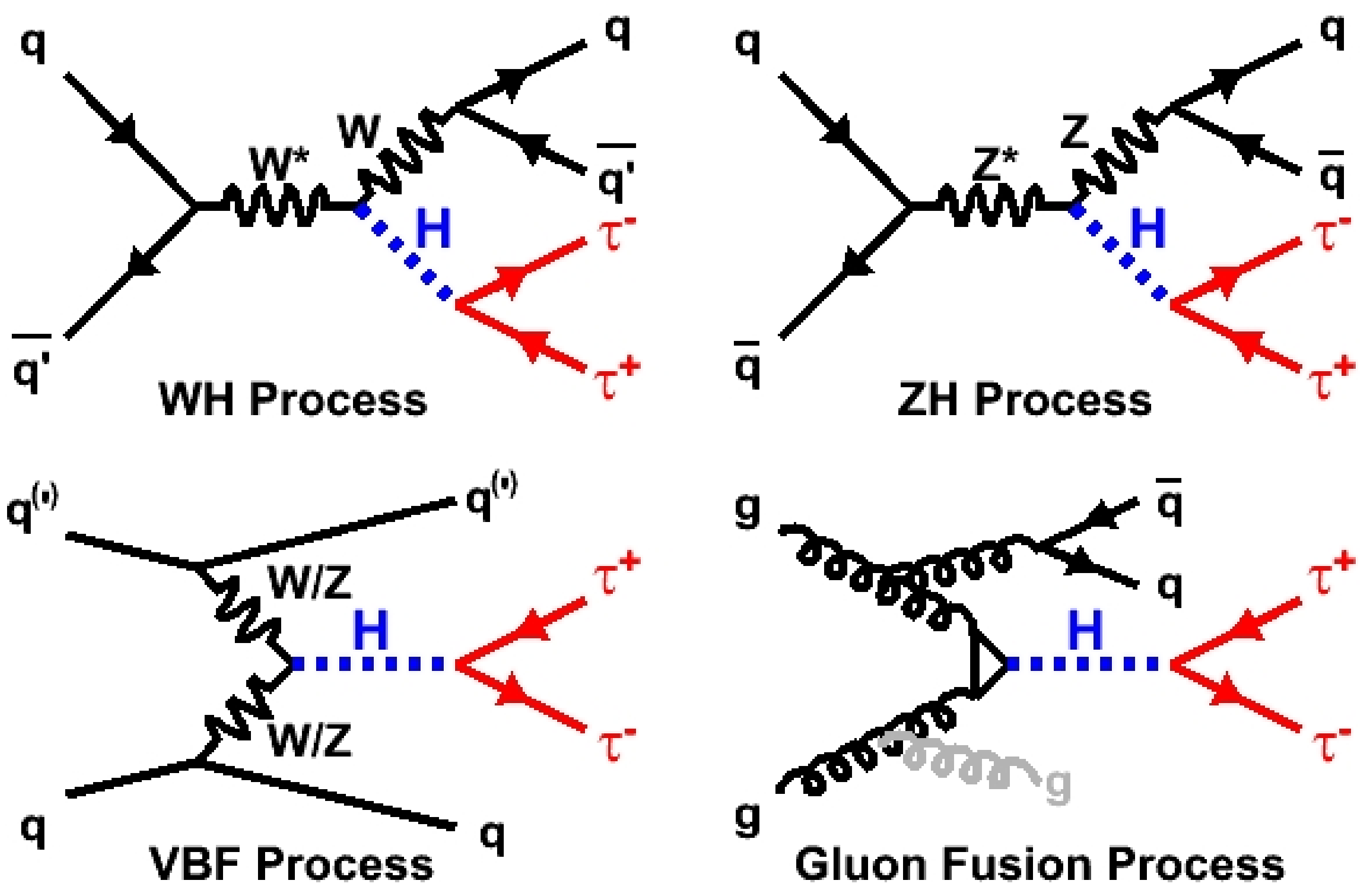
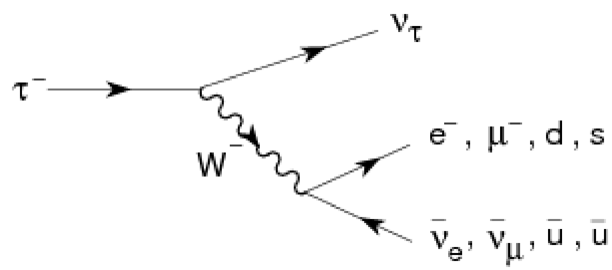


Image from here

Quiz: branching ratios of the tau



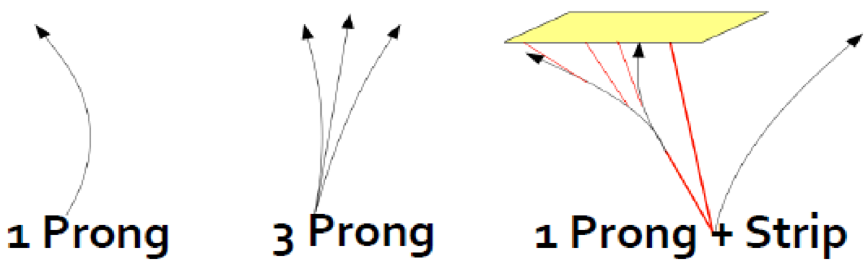
- Neglecting the masses of the decay particles, what is the branching ratio of:
  - $\tau \rightarrow e \nu_e \nu_\tau$
  - $\tau \rightarrow \mu \nu_\mu \nu_\tau$
  - $\tau \rightarrow q q' \nu_\tau$

Solution

- BR ~ 1/5 (= 20%) per channel, ignoring $\tau\to cs\nu_\tau$
  - M_τ ~ 1.777 GeV
  - Mass of the lightest charmed hadron (D^0): 1.865 GeV
- From the PDG:
  - (17.82±0.04)% $\tau\to e\nu_e\nu_\tau$
  - (17.39±0.04)% $\tau\to\mu\nu_\mu\nu_\tau$
  - The rest goes into $\tau\to qq'\nu_\tau$

Q: why smaller for the muon?

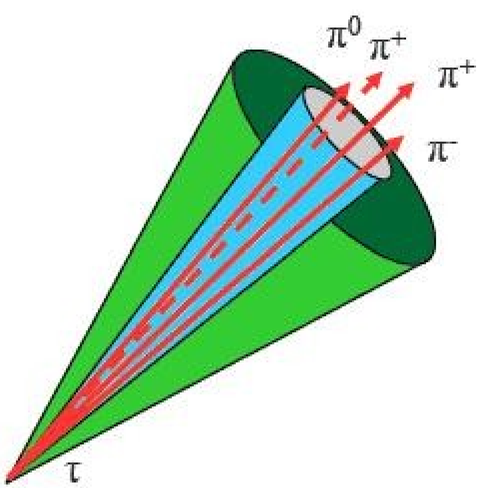
Hadronic tau modes



In most of the $\tau \rightarrow qq'\nu_\tau$ decays, the qq' system hadronizes in very few particles, looking like a narrow jet.

The number of charged hadrons (*prongs*) can only be odd (*Q: why?*) and more than 3 are very rare.
The tau-jet can contain, or not, signal in the EM calorimeter due to π^0's.

Tau-jet isolation: based on sum of momenta in ring around the tau-jet direction. It is the main property distinguishing it from q/g jets



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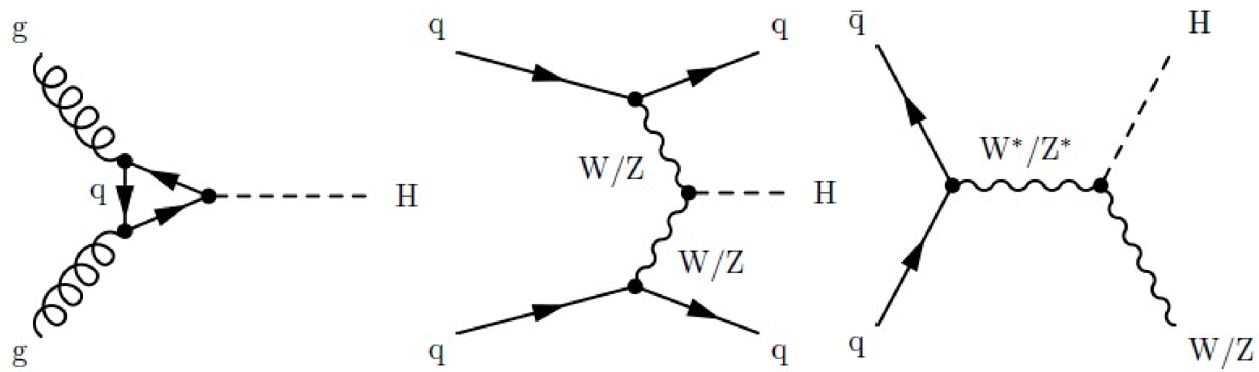
CMS analysis with full Run-1 data

(arXiv:1401.5041 [hep-ex]; J. High Energy Phys. 05 (2014) 104)

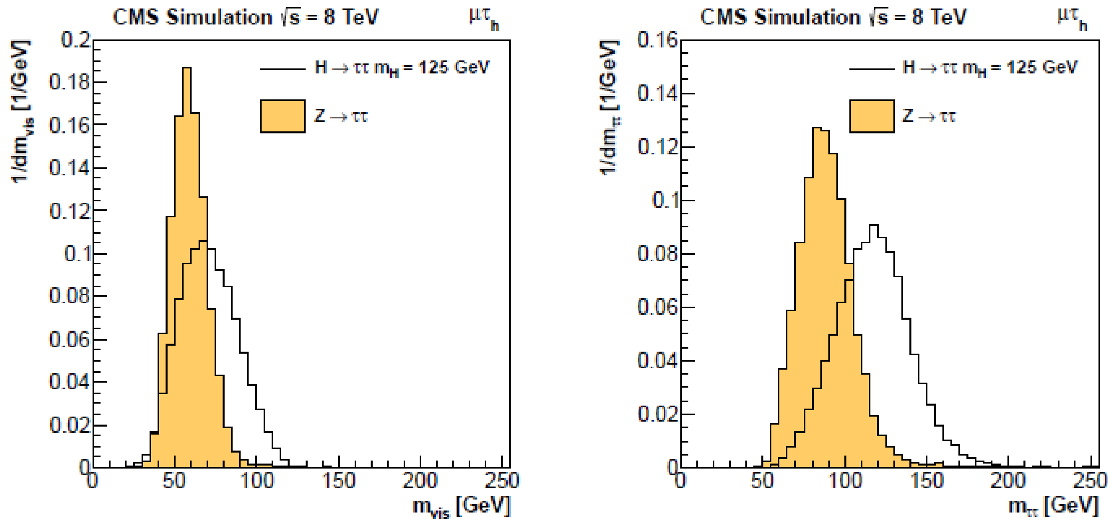


Gluon-fusion, the most abundant process and thus the most sensitive in all the channels that we saw so far, is much less sensitive in $\tau\tau$:

tau-jets are contaminated by q/g-jets, leptonic decays of the taus are clean but a lot of energy is carried away by two neutrinos.

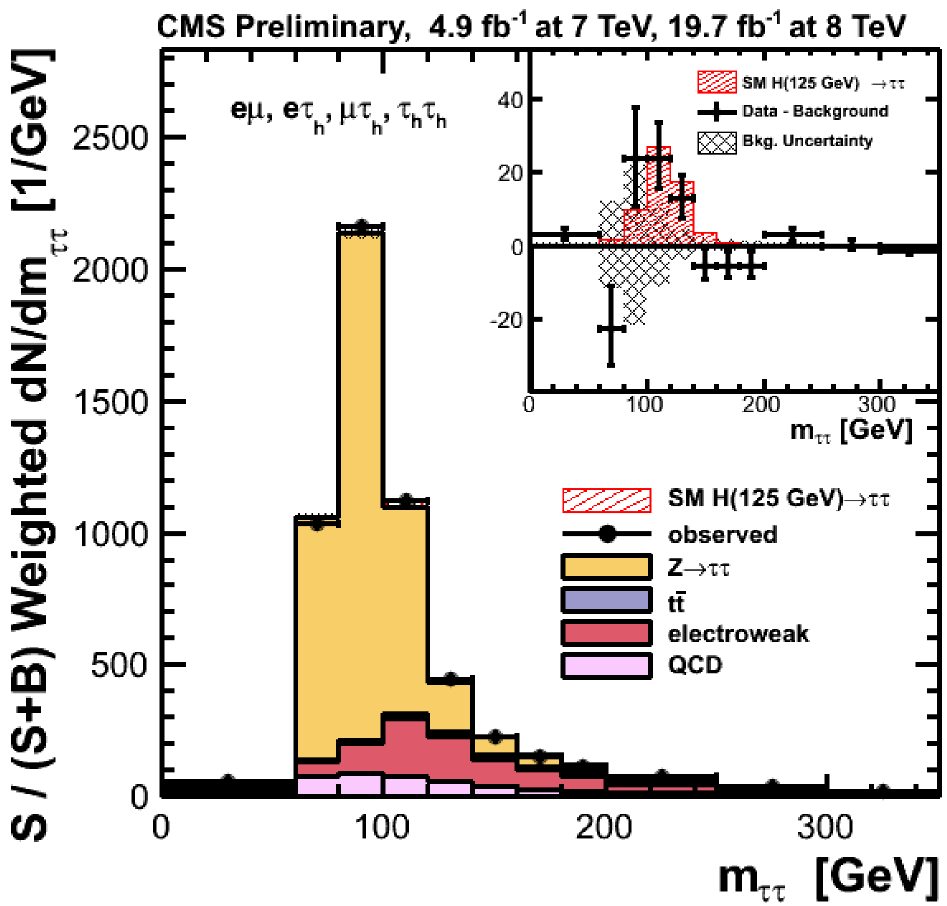
In this decay channel the less abundant VBF and VH signals are crucial, thanks to the reduction of backgrounds caused by the extra objects (forward jets in VBF, light leptons in VH)

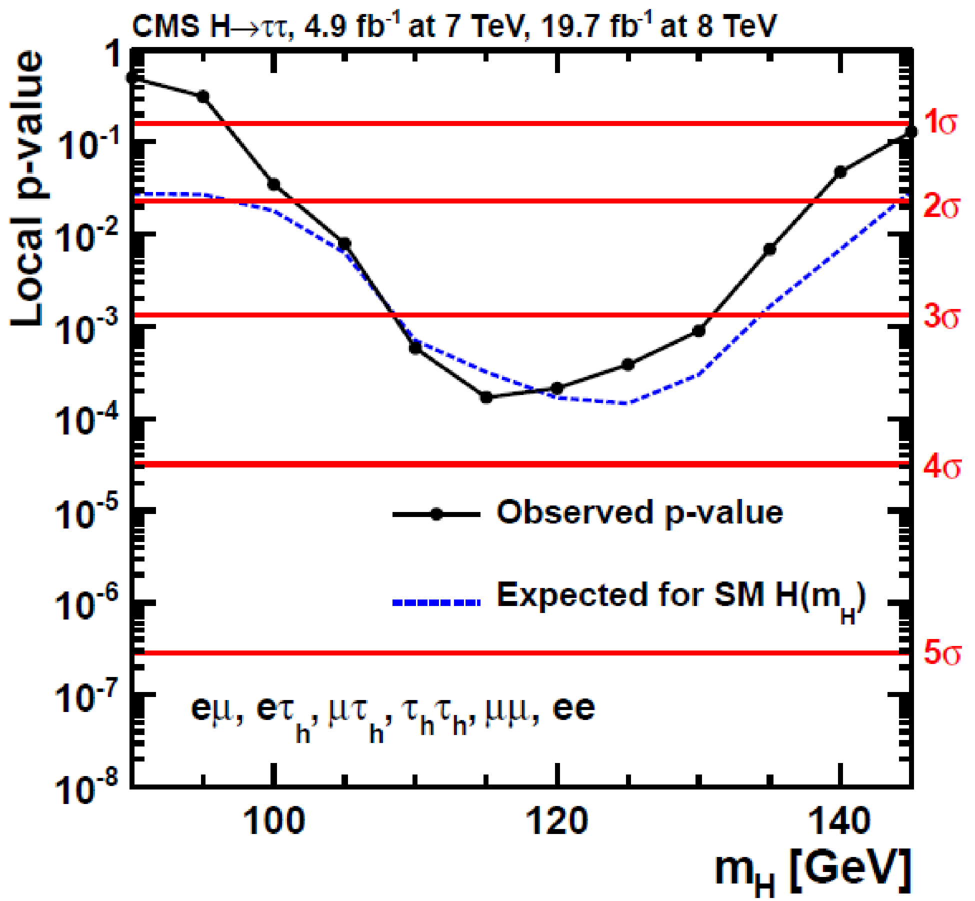
Mass reconstruction



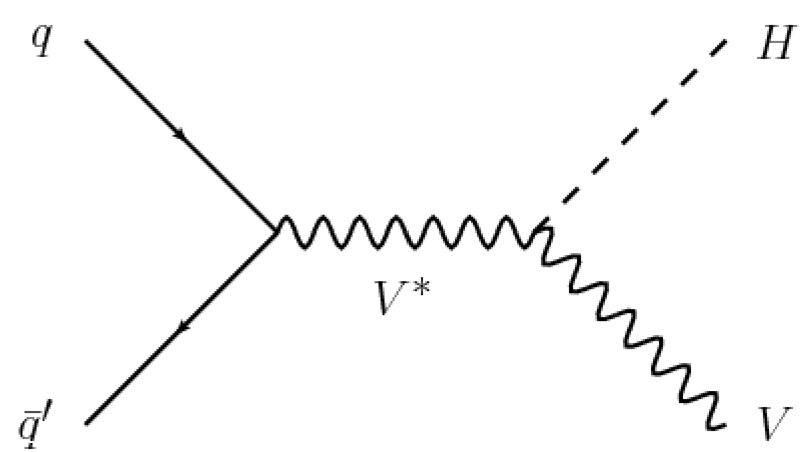
- *Visible mass*: invariant mass of all the particles identified as coming from the two taus, which does not include the neutrinos
- *Fitted mass*: a maximum likelihood fit is performed to extract the most likely mass, assuming the predicted kinematics of the Higgs and tau decays; inputs include the transverse missing energy in the event, the visible mass, relative angles of the visible decay products

Result


CMS Preliminary, 4.9 fb-1 at 7 TeV, 19.7 fb-1 at 8 TeV
eμ, eτh, μτh, τhτh
S / (S+B) Weighted dN/dmττ [1/GeV]
mττ [GeV]
SM H(125 GeV)→ττ
Data - Background
Bkg. Uncertainty
SM H(125 GeV)→ττ
observed
Z→ττ
tt̄
electroweak
QCD

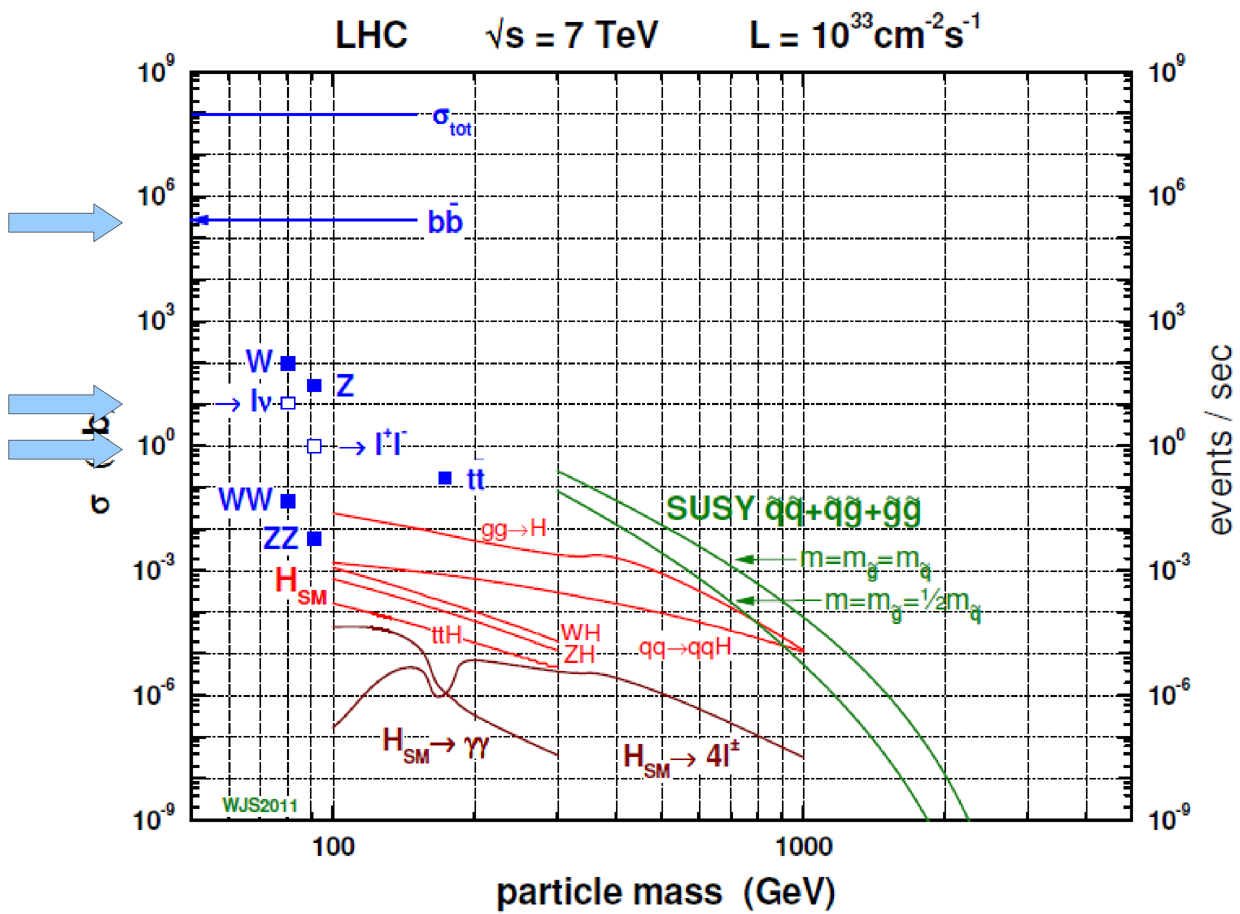

CMS H→ττ, 4.9 fb-1 at 7 TeV, 19.7 fb-1 at 8 TeV
Local p-value
mH [GeV]
1σ
2σ
3σ
4σ
5σ
Observed p-value
Expected for SM H(mH)
eμ, eτh, μτh, τhτh, μμ, ee

$H \rightarrow b\bar{b}$ channel

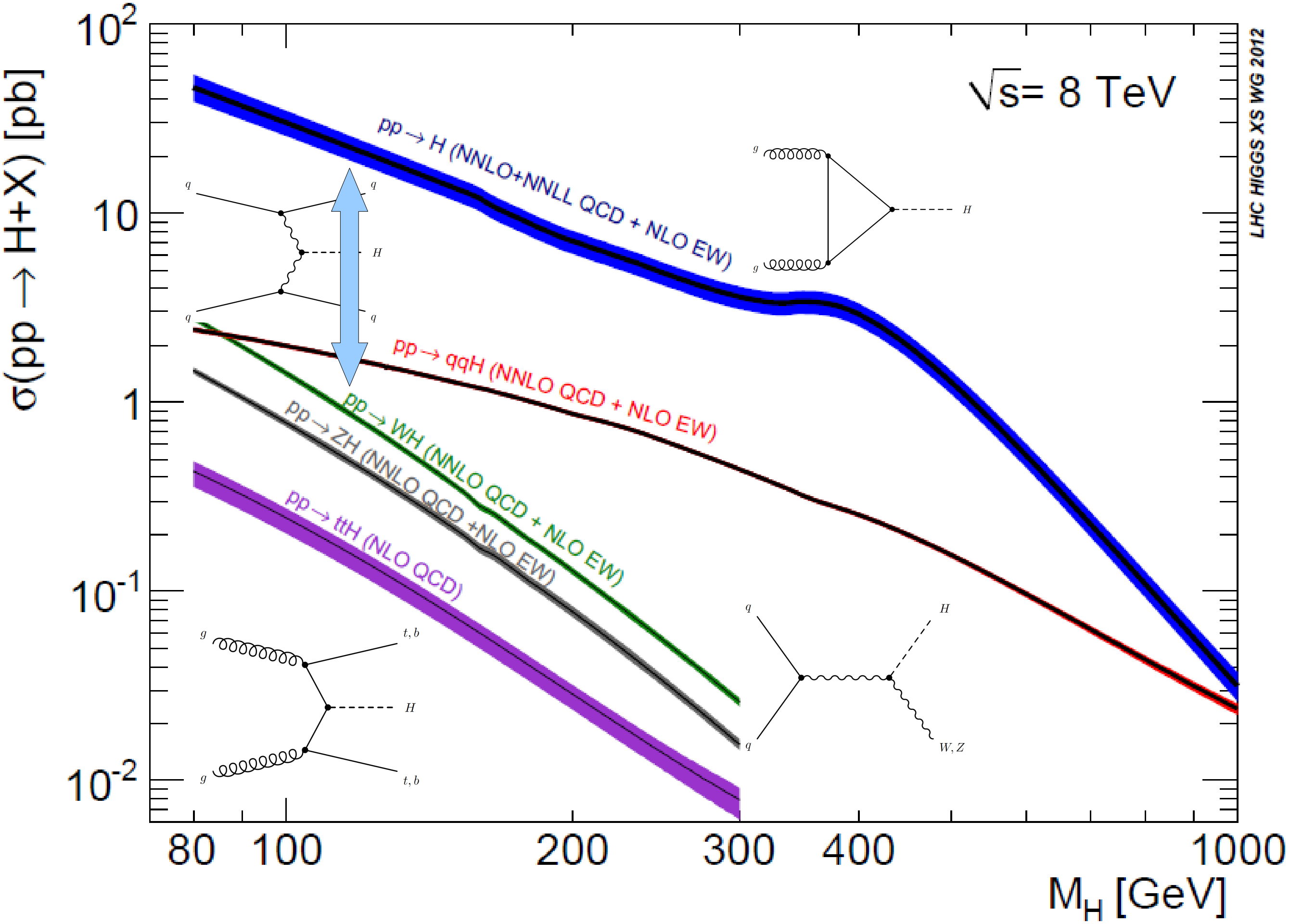


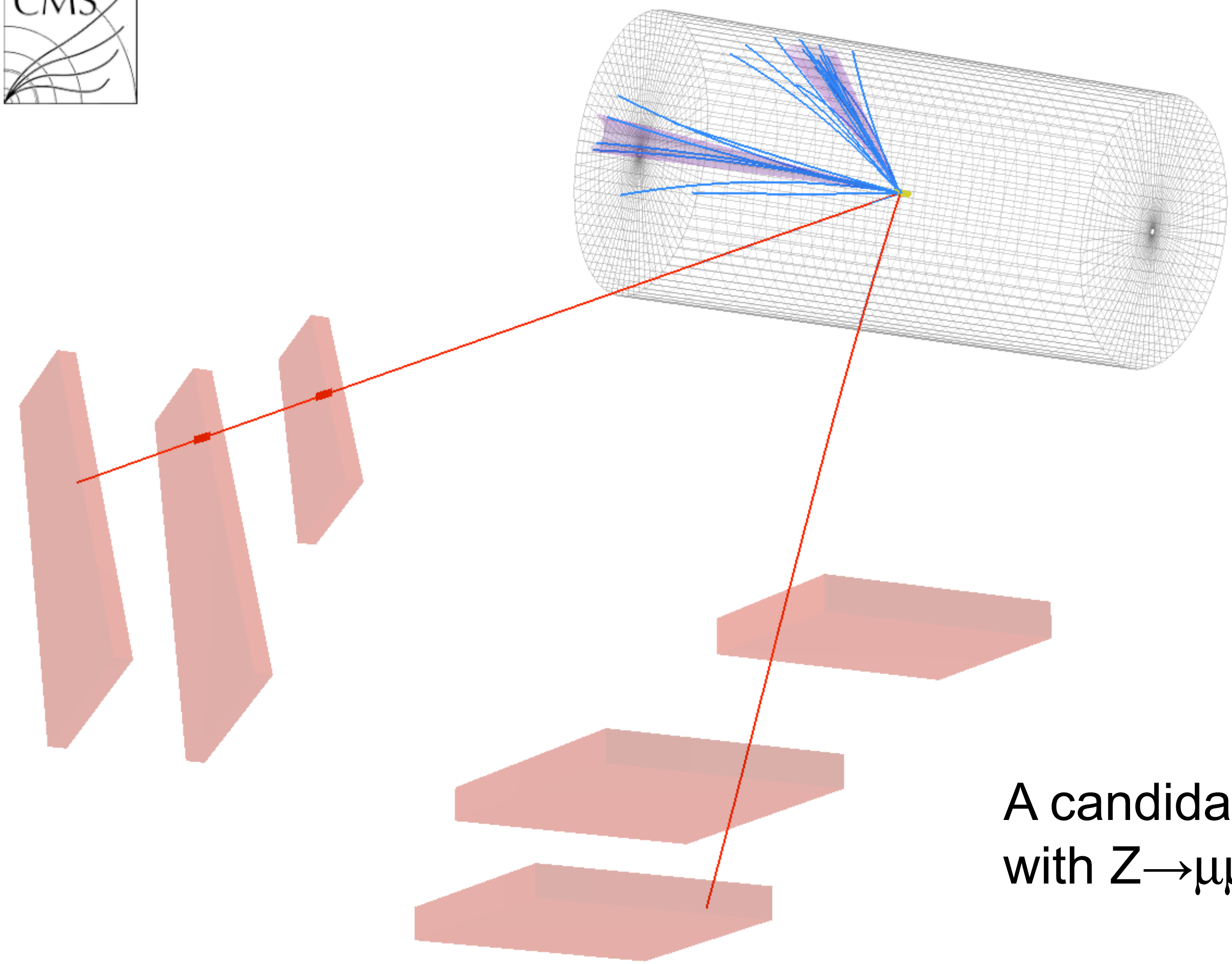
Idea: gain orders of magnitude in purity by restricting the search to the VH production mechanism, with V(=W/Z)→1l/2l

$b\bar{b}$ vs W/Z(+jets) backgrounds



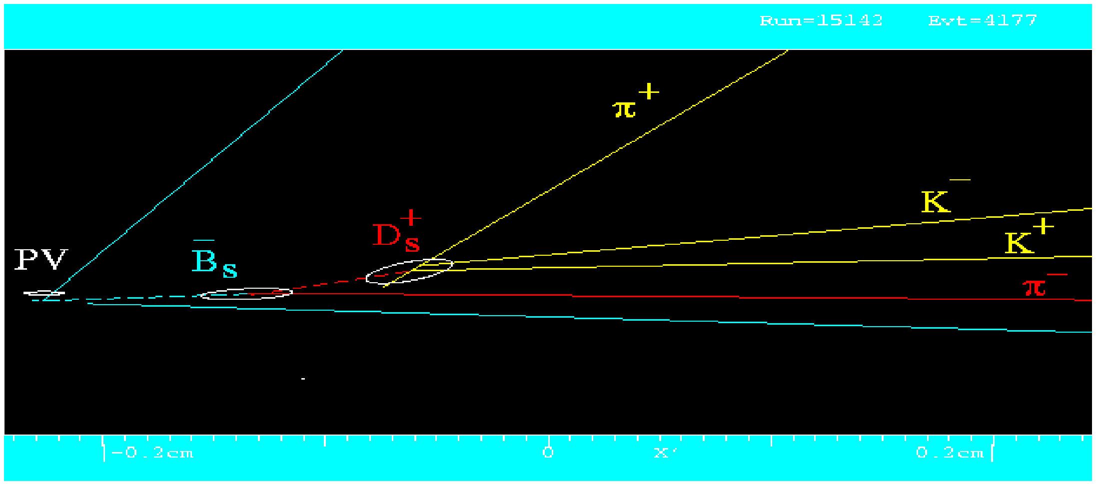
The cost in signal statistics

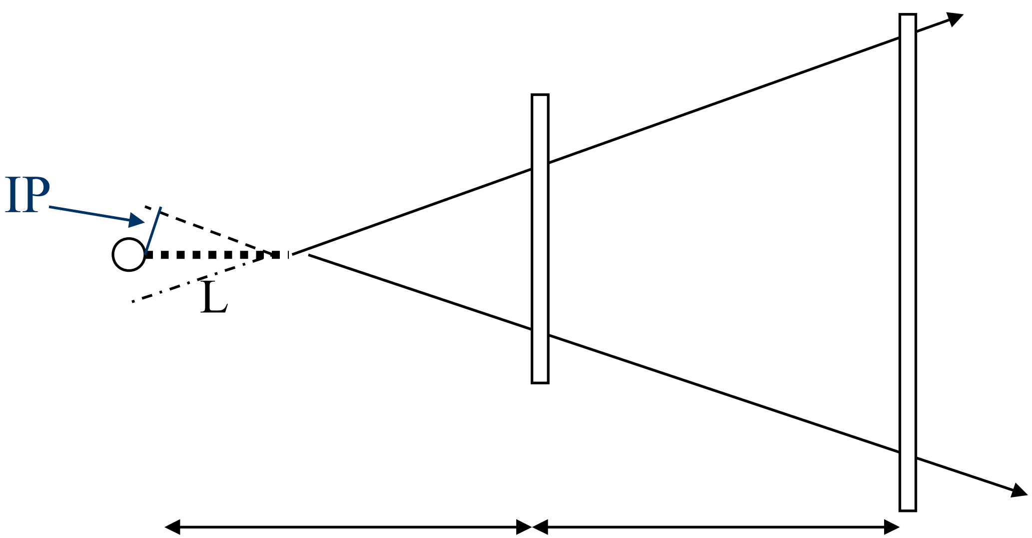




A candidate ZH event, with $Z \to \mu\mu$ and $H \to b\bar{b}$

B tagging





In CMS, the first tracking layer is at 4 cm

Basic idea: B hadrons have relatively long lifetimes; their decay vertex has a distance from the production vertex that can be measured with very precise tracking detectors whose first layers are close enough to the center.

In practice we often prefer to use the Impact Parameter (IP). The IP is invariant by boost:

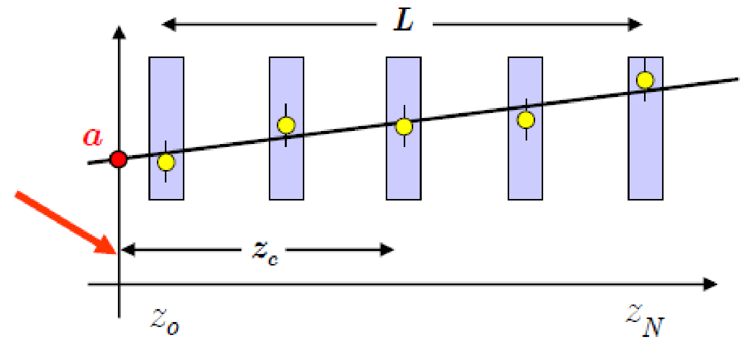
$$IP \approx L \cdot \frac{1}{\gamma} \approx c\tau\gamma \cdot \frac{1}{\gamma} = c\tau$$

$c\tau$, B ~ 500 μm

$c\tau$, D & τ ~ 100 μm

Impact parameter

Consider a tracking detector with (for simplicity of calculation) equally spaced layers, all with the same hit position uncertainty (σ)



$$ip = f(-z_c) = a - bz_c$$

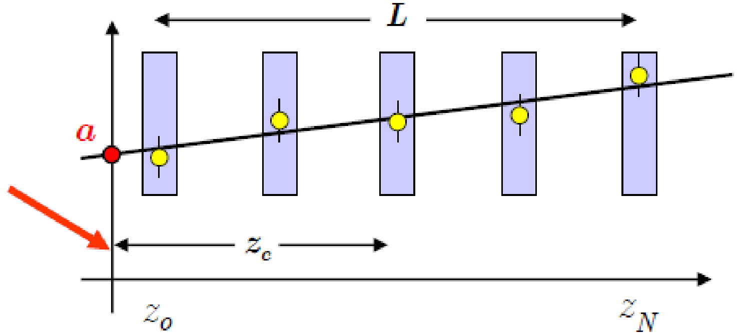
$$L = z_N - z_o \qquad z_c = \frac{z_N + z_o}{2}$$

Consider a straight-line fit (e.g., valid for the r-z plane in a solenoidal magnetic field), for example a least-squares fit (*do it as homework!*) The uncertainties on the intercept (a) and slope (b) are:

$$\sigma_a^2 = \left[1 + 12\frac{N}{N+2}\frac{z_c^2}{L^2}\right]\frac{\sigma^2}{N+1} \qquad \sigma_b^2 = \frac{\sigma^2}{(N+1)L^2}\frac{12N}{(N+2)}$$

$$\sigma_{ip}^2 = \sigma_a^2 + z_c^2\sigma_b^2 \;\Rightarrow\; \sigma_{ip}^2 = \frac{\sigma^2}{N+1} + \frac{\sigma^2}{N+1}\frac{12N}{N+2}\frac{z_c^2}{L^2}$$

Impact parameter precision



$$L = z_N - z_o \qquad z_c = \frac{z_N + z_o}{2}$$

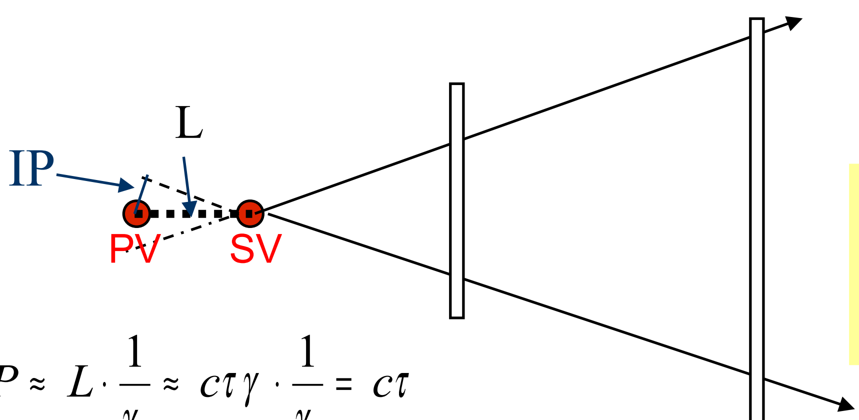
$$\sigma_{ip}^2 = \frac{\sigma^2}{N+1} + \frac{\sigma^2}{N+1}\frac{12N}{N+2}\frac{z_c^2}{L^2}$$

To get a precise impact parameter measurement (⇒ good separation between primary and secondary vertex ⇒ between long-lived, short-lived and stable particles) we need:

- Precise tracking detectors: small σ
- Many layers: large N
- A big detector overall: large L
- Layers as close as possible to the origin: small z_c

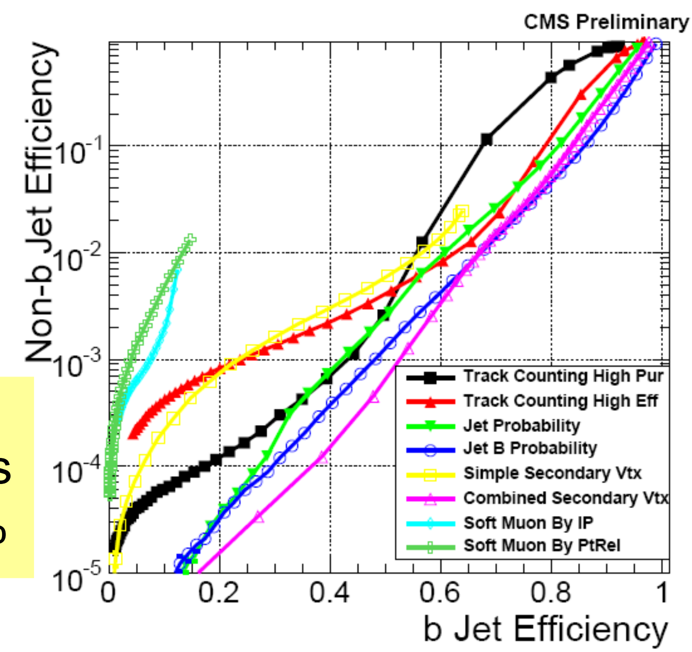
Types of b tagging

- Based on Impact Parameter (IP)
  - "Track counting": require at least N tracks with IP/σ_{IP}>cut
  - Combination of the IP's incompatibility with 0 of all the tracks in the jet
- Based on "soft" leptons
  - BR(b→e/μ+X)~20%, but e/μ not isolated, therefore not so clean
- Based on secondary vertex (SV) reconstruction
  - Explicit search for the b decay point



$$IP \approx L \cdot \frac{1}{\gamma} \approx c\tau\gamma \cdot \frac{1}{\gamma} = c\tau$$

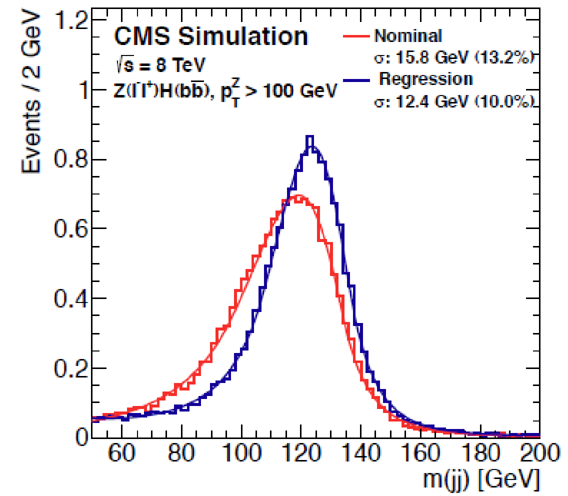
Requiring a rejection factor of 100 for light jets usually gives ε_b~50-70%

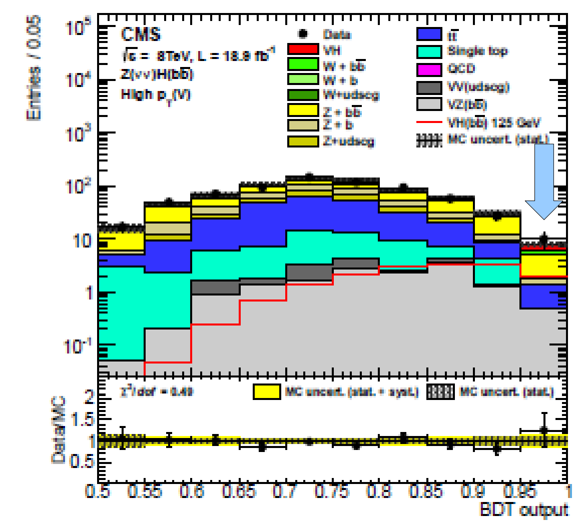


CMS analysis with full Run-1 data

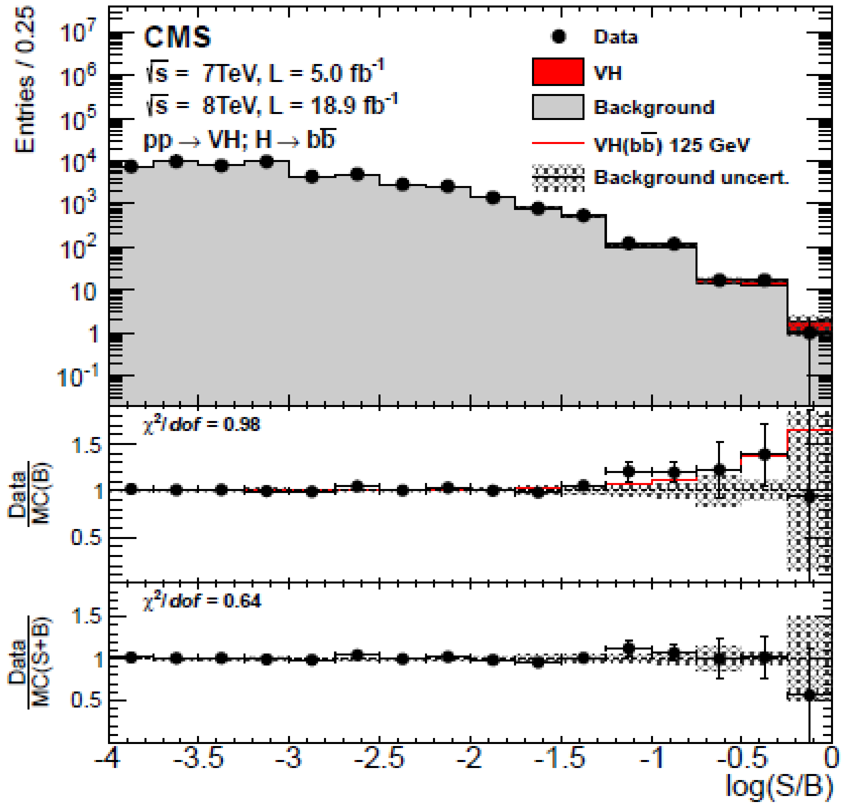
(arXiv:1310.3687 [hep-ex]; Phys. Rev. D 89, 012003 (2014))

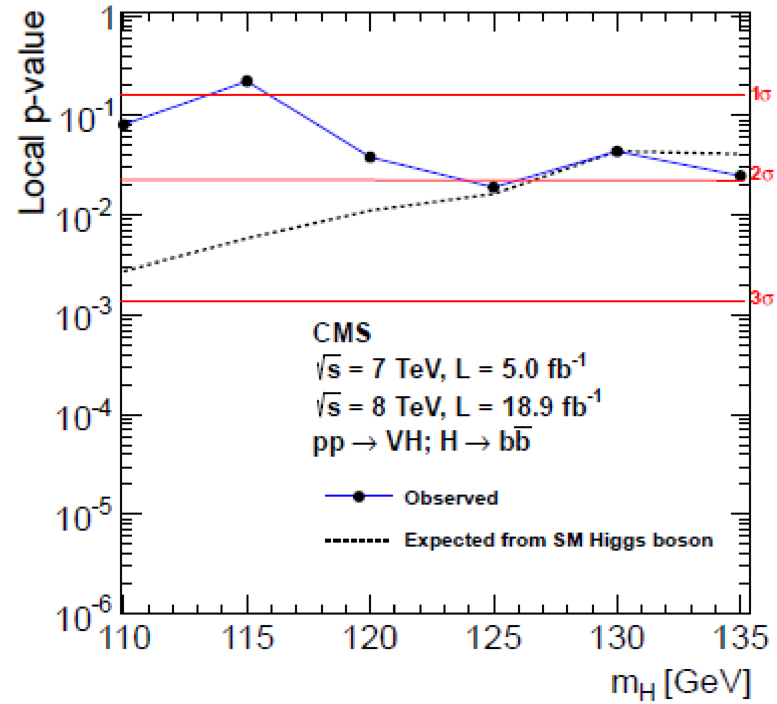
- Classified by the decay channel of W or Z:
  - W→eν,μν: single-lepton triggers
  - W→τν: tau trigger based on 1-prong hadronic decay (cleaner against q/g-jets) and large MET
  - Z→ee,μμ: di-lepton/single-lepton triggers
  - Z→νν: large MET triggers
- An MVA is applied to b-jets to correct their energy ⇒ improve m_{bb} resolution
- In each category of events, MVA classifiers were trained to discriminate signal vs background, and fitted





Results

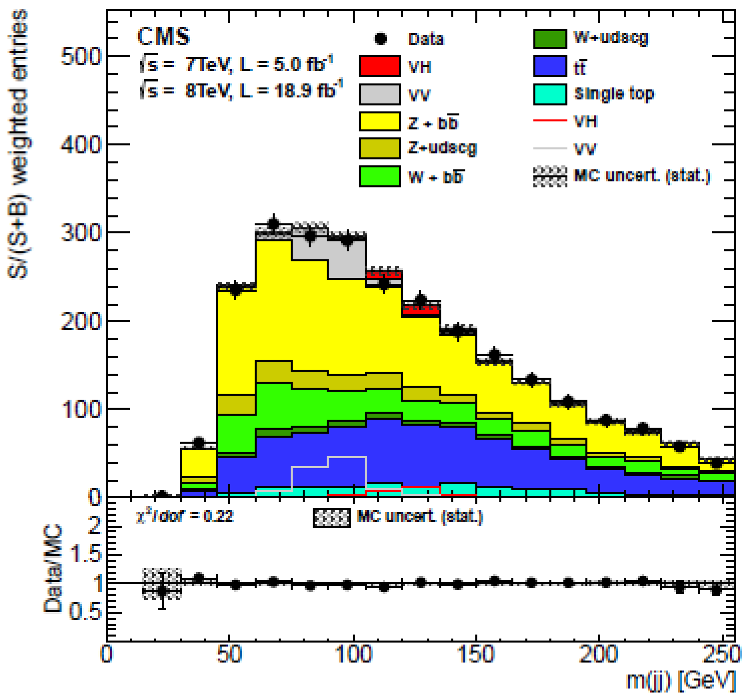


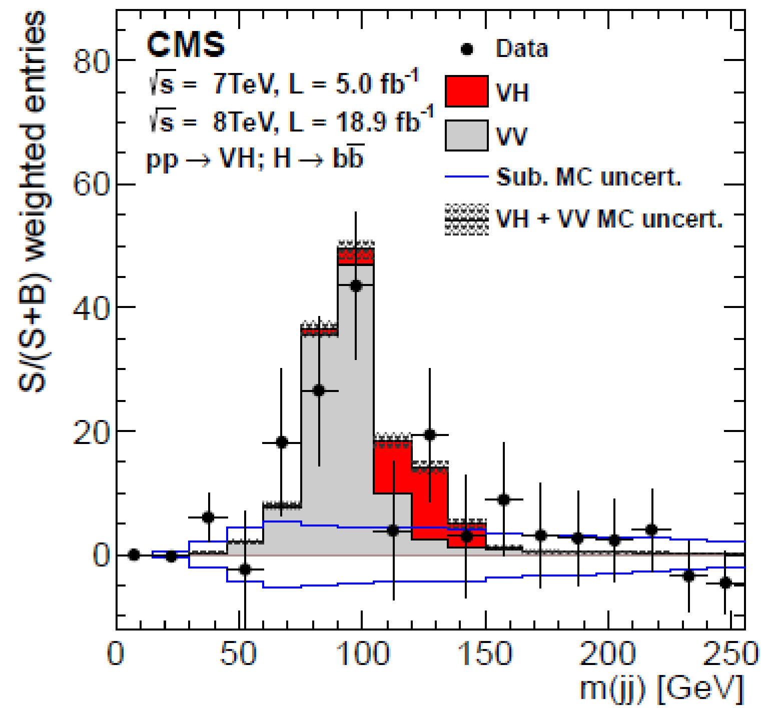


This histogram is formed by putting together all bins in all MVA distributions for all channels, ordered by their purity. The two ratios at the bottom are with respect to B-only and B+S hypotheses.

Result confirms the finding in other channels, but only at 2s. Combined with ττ channel, this result confirmed that H interacts with fermions

Cross check analysis





- As cross-check, also performed a fit on m_{bb}
  - Also the VV background has a recognizable peak in m_{bb}, so the VV prediction is used to verify that analysis is correct
  - Here "background" means all minus VH and VV

Rest of this course

- 16/3 and 30/3: top-Higgs connection
- 23/3: mid-term evaluation
  - I am circulating four scientific articles about a different particle (the top quark)
  - Each of you has to choose one, and on 23/3 you will present in 15' (+15' Q&A) what you understand of it
  - In case of failure, it doesn't count in negative for your final evaluation; in case of success, it will count in positive
  - I will give individual feedback
- 27/4: start of the detector part of this course

For the mid-term evaluation

- Paper #1: $t\bar{t}\rightarrow 2l$ ($l=e,\mu$), CMS @ 7 TeV (early data), link
- Paper #2: $t\bar{t}\rightarrow 1l$ ($l=e,\mu$), CMS @ 7 and 8 TeV, link
- Paper #3: $t\bar{t}\rightarrow \tau+l$ ($l=e,\mu$), CMS @ 8 TeV, link
- Paper #4: $t\bar{t}\rightarrow 0l$, CMS @ 7 TeV, link
- Do not hesitate to contact me in case of doubts or difficulties. If I am not in the office (3rd floor), send a mail.

Questions?

Decay width

(reminder from the 2nd lecture)

- $\Gamma \propto$ |amplitude|^2·(phase space volume)
- So even if the coupling is large (amplitude is large), decay rate can be small if there is little phase space available (e.g., $m_A \sim m_B + m_C$)

Fermi G.R. example: consider the isotropic decay of a neutral spin-0 particle into two massless daughters

$$A \to B + C.$$

The Fermi G.R. gives the decay rate as

$$\begin{aligned} \Gamma &= 2\pi |V_{fi}|^2 \frac{dN}{dE_f} \\ &= 2\pi |V_{fi}|^2 \frac{4\pi p_B^2}{(2\pi)^3} \frac{dp_B}{dE_f} \mathcal{V}. \end{aligned}$$

Since all decay angles are equally probable, the integrals over the angles contributes 4π. The decay products have momentum $|\mathbf{p_B}| = E_f/2$ so $\frac{dp_B}{dE_f} = \frac{1}{2}$. Normalising to one unstable particle per unit volume gives $\mathcal{V} = 1$, and results in a decay rate

$$\begin{aligned} \Gamma &= \frac{1}{2\pi} |V_{fi}|^2 p_B^2 \\ &= \frac{1}{8\pi} |V_{fi}|^2 m_A^2. \end{aligned}$$

http://www-pnp.physics.ox.ac.uk/~barra/teaching/resonances.pdf

Caractérisation globale d'une collision hadronique, les variables cinématiques utilisées

$$p_T = p_\perp = \sqrt{p_x^2 + p_y^2} = p \sin\theta$$ **Moment transversal**

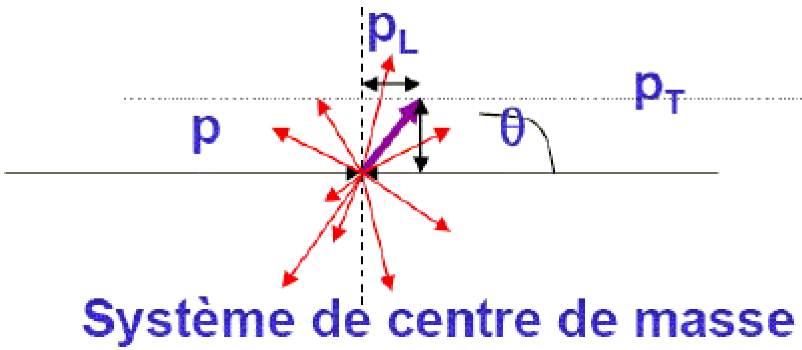
Section efficace invariant

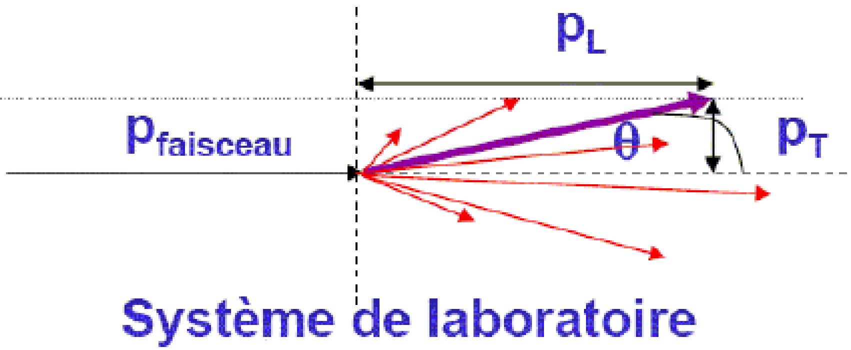
$$E\frac{d^3\sigma}{dp^3} = E\frac{d^3\sigma}{dp_x dp_y dp_z} = \frac{1}{2\pi}\frac{d^2\sigma}{p_T dp_T d\left(p_L/E\right)} \sim \underbrace{F\left(p_T\right)F'\left(p_L\right)}$$

(Feynman scaling)

$$F\left(p_T\right) \sim e^{-bp_T} \; ; \; < p_T >_{\text{particules sécondaires}} \approx 0.3 - 0.5 \; GeV/c \; \approx \frac{\hbar}{R}$$

$$E_T = \sum_{i=\text{part.sécondaires}} E_i \sin\theta_i$$ **Energie transversal**





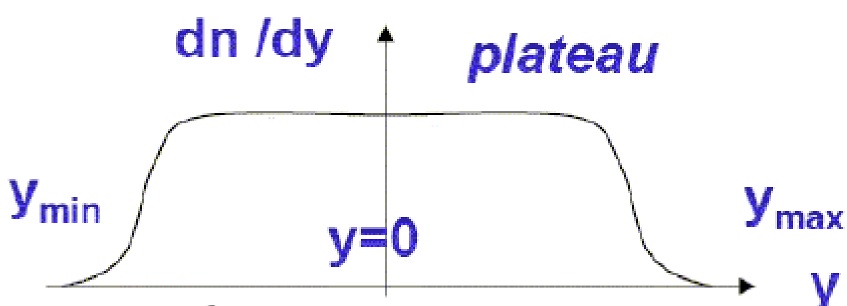
$$x_F = p_L / p_L^{\max} = p_L / \left(\sqrt{s}/2\right) \quad \text{(Feynman "}x\text{")}$$

Rapidité *y*, « invariante » de Lorentz

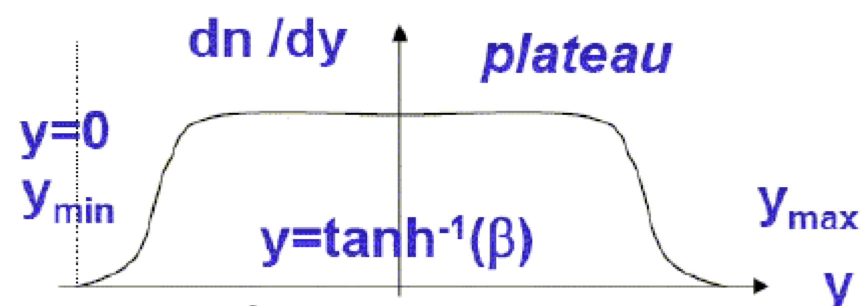
$$y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right) \overset{\beta\to 1,\, m\to 0}{\approx} \eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

***η*, pseudo-rapidité**

$$y \to y + \tanh^{-1}(\beta) \qquad y_{\max} = \frac{1}{2}\ln\left(\frac{s}{m^2+p_T^2}\right)$$



Système de centre de masse



Système de laboratoire

38.5.2. ***Inclusive reactions:*** Choose some direction (usually the beam direction) for the z-axis; then the energy and momentum of a particle can be written as

$$E = m_T \cosh y \ , \ p_x \ , \ p_y \ , \ p_z = m_T \sinh y \ , \tag{38.35}$$

where m_T is the transverse mass

$$m_T^2 = m^2 + p_x^2 + p_y^2 \ , \tag{38.36}$$

and the rapidity y is defined by

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$$

$$= \ln \left(\frac{E + p_z}{m_T} \right) = \tanh^{-1} \left(\frac{p_z}{E} \right) \ . \tag{38.37}$$

Under a boost in the z-direction to a frame with velocity β, $y \to y - \tanh^{-1} \beta$. Hence the shape of the rapidity distribution dN/dy is invariant. The invariant cross section may also be rewritten

$$E \frac{d^3\sigma}{d^3p} = \frac{d^3\sigma}{d\phi \, dy \, p_T \, dp_T} \Longrightarrow \frac{d^2\sigma}{\pi \, dy \, d(p_T^2)} \ . \tag{38.38}$$

For $p \gg m$, the rapidity [Eq. (38.37)] may be expanded to obtain

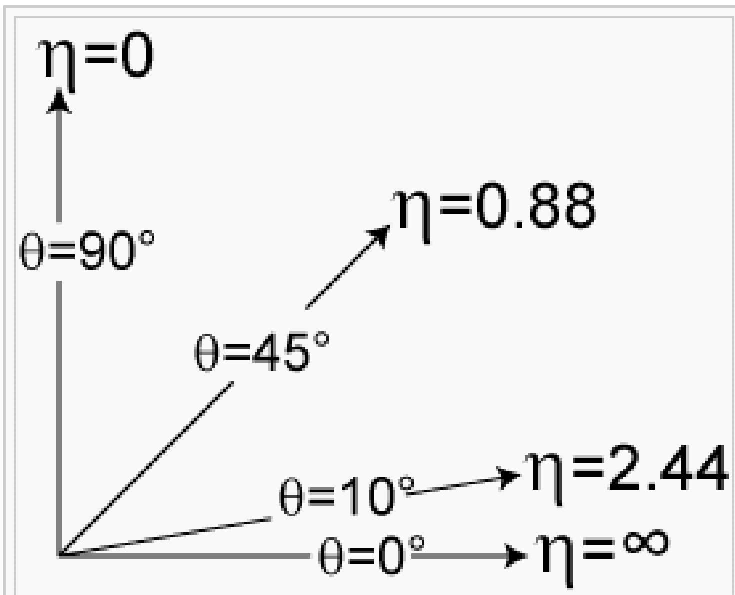
$$y = \frac{1}{2} \ln \frac{\cos^2(\theta/2) + m^2/4p^2 + \ldots}{\sin^2(\theta/2) + m^2/4p^2 + \ldots}$$

$$\approx -\ln \tan(\theta/2) \equiv \eta \tag{38.42}$$

where $\cos\theta = p_z/p$. The pseudorapidity η defined by the second line is approximately equal to the rapidity y for $p \gg m$ and $\theta \gg 1/\gamma$, and in any case can be measured when the mass and momentum of the particle is unknown. From the definition one can obtain the identities

$$\sinh \eta = \cot \theta \ , \quad \cosh \eta = 1/\sin \theta \ , \quad \tanh \eta = \cos \theta \ . \tag{38.43}$$

Pseudo-rapidity



$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

EM interactions

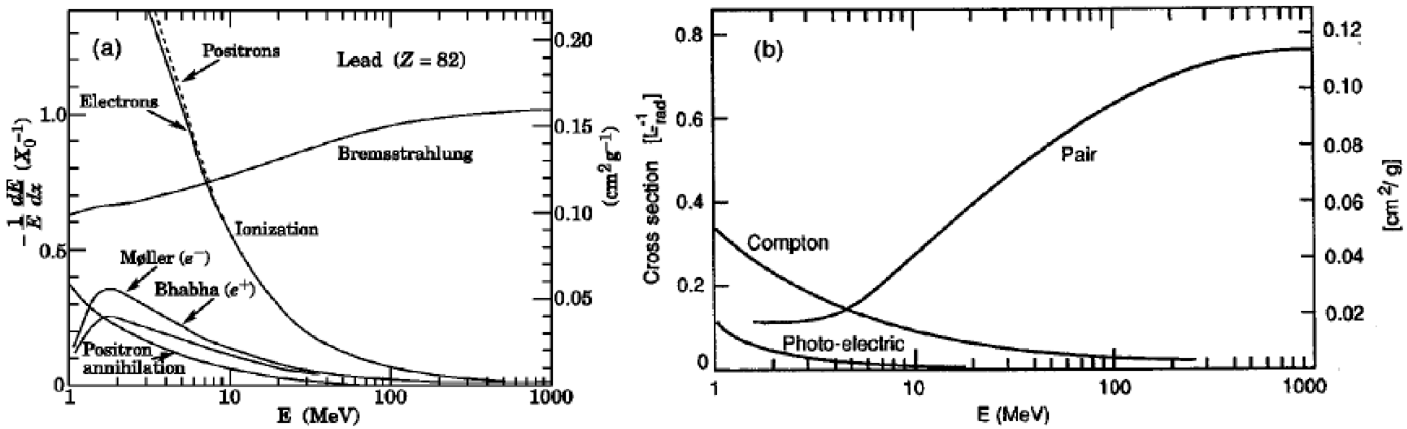


FIG. 1. (a) Fractional energy lost in lead by electrons and positrons as a function of energy (Particle Data Group, 2002). (b) Photon interaction cross section in lead as a function of energy (Fabjan, 1987).

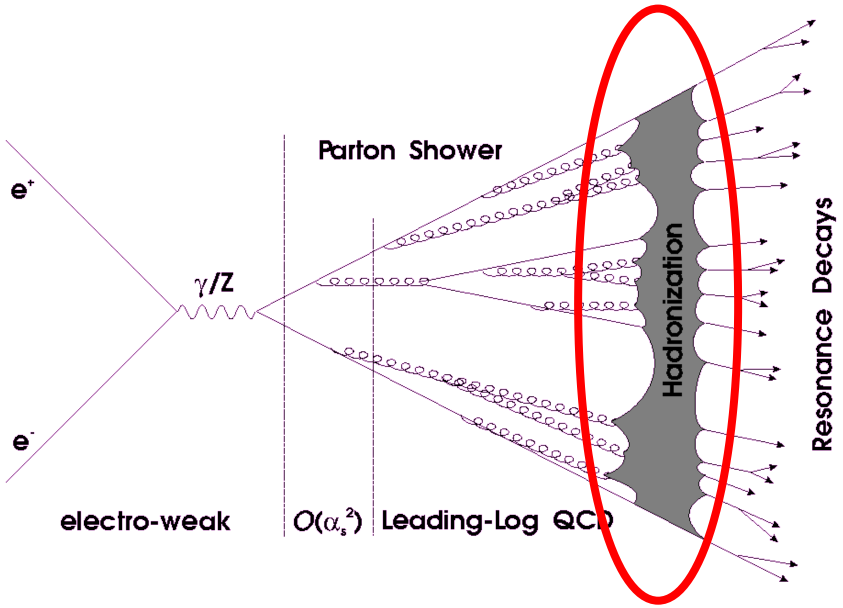
To know more on calorimetry:

REVIEWS OF MODERN PHYSICS, VOLUME 75, OCTOBER 2003

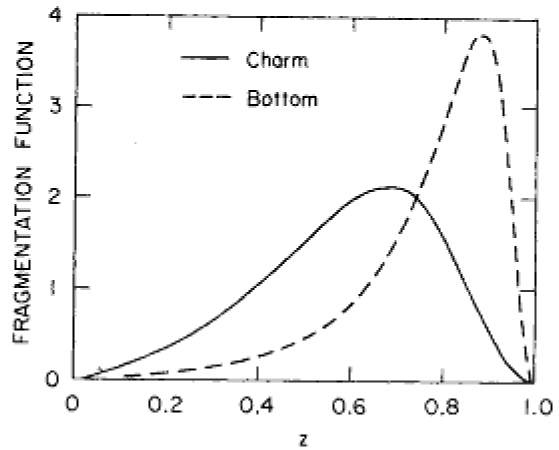
Calorimetry for particle physics

Christian W. Fabjan and Fabiola Gianotti

Fragmentation function



$$z = \frac{(E + p_{||})_{hadron}}{(E + p_{||})_{quark}}$$



$$x_B = \frac{E_{hadron}}{E_{beam}}$$

Peterson's function for heavy quarks:

$$D_Q^H(z) = \frac{N}{z[1-(1/z)-\epsilon_Q/(1-z)]^2} .$$