Collider Physics

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March 29, 2006

Second part: Probing the Standard Model

- I. $\mathbf{Z}$ production
- II. $\mathbf{W}^{\pm}$ production
- III. Other useful variables
- IV. Top quark production at the LHC
- V. Higgs production at the LHC

I. $\mathbf{Z}$ production

Invariant mass variable

- Consider an unstable particle ($\mathbf{X = Z,\ W^{\pm},\ t}$) decaying $\mathbf{X \to ab\ldots}$

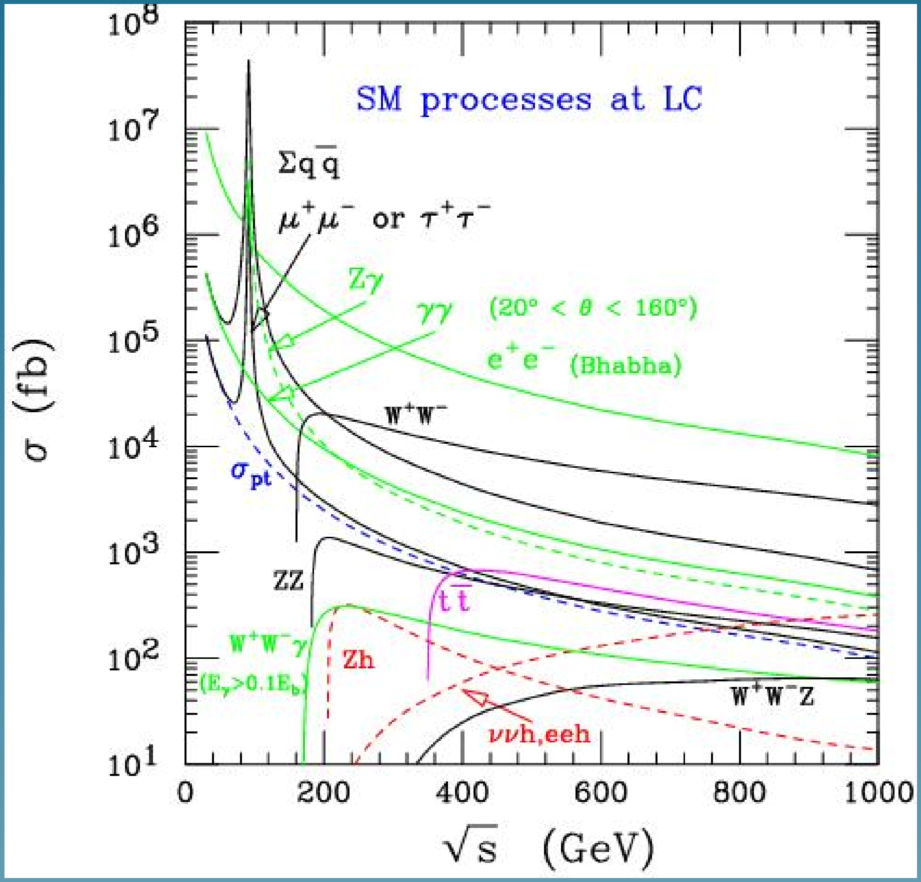
$$\frac{\mathbf{d\sigma}}{\mathbf{dM_{ab\ldots}}} \propto \frac{\mathbf{1}}{\mathbf{(M^2_{ab\ldots} - M^2_V)^2 + \Gamma^2_V M^2_V}}$$

and exhibits a peak for $\mathbf{M^2_{ab\ldots} = (p_a + p_b + \ldots)^2 = (\ \sum_i^n p_i\ )^2 \approx M^2_V}$

- For the same reason the production $\mathbf{ab \to X+}$ anything exhibits a peak for $\mathbf{M^2_{ab} \simeq M^2_V}$

- If the decays products are observable $\implies$ we can reconstruct $\mathbf{M_{ab\ldots}}$, e.g. $\mathbf{Z \to e^+e^-,\ b\bar{b},\ \ldots}$

$\mathbf{e^+e^- \to Z}$: in this case $\mathbf{M_{e^+e^-} = \sqrt{s}}$



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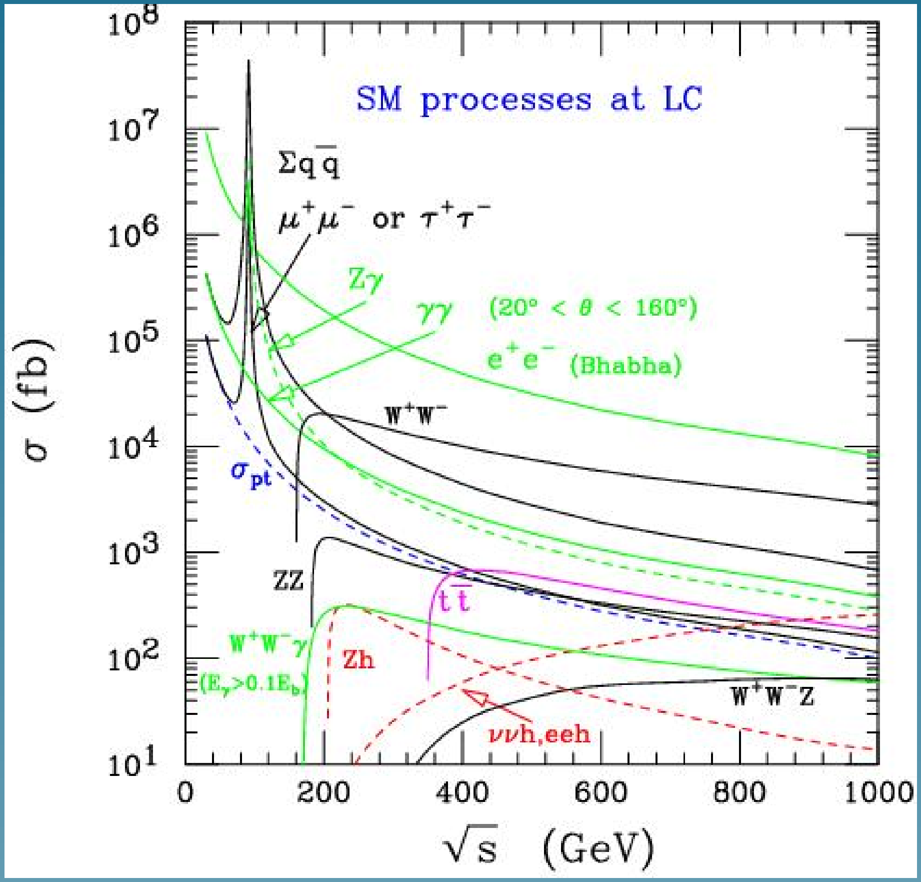

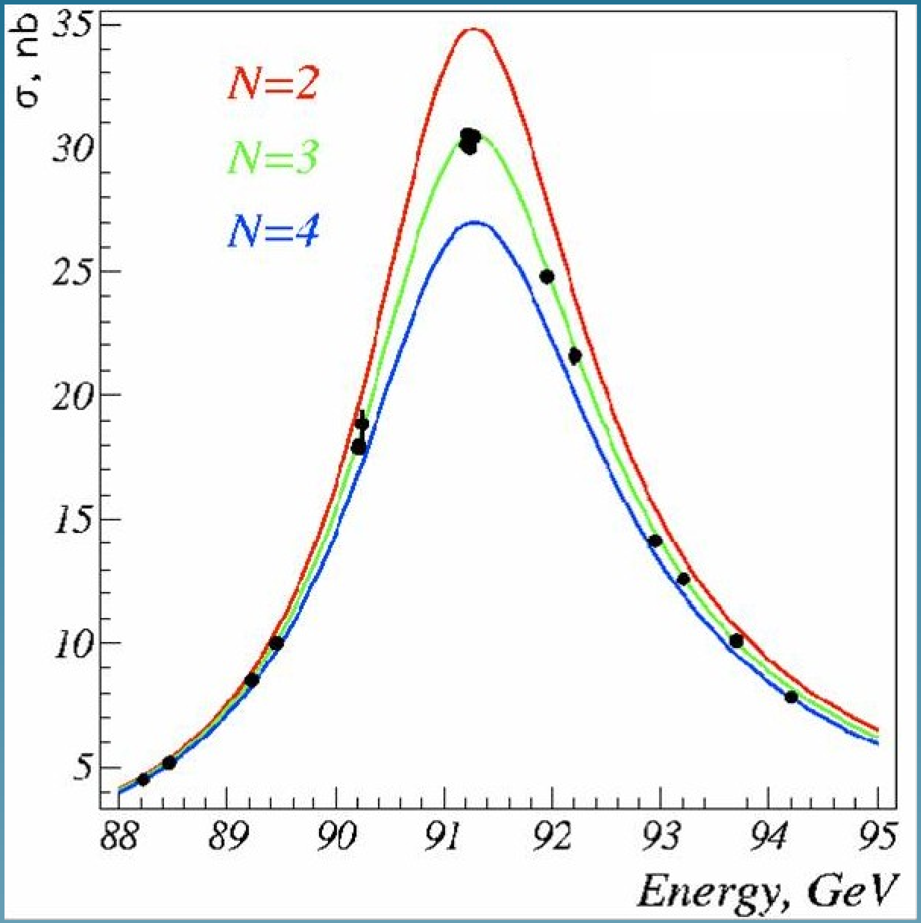

- At the Tevatron $p\bar{p} \rightarrow \mathbf{Z} + \mathbf{X}$

- $\mathbf{Z} \rightarrow \mathbf{e^+ e^-}$ at DØ
- $\sigma(\mathbf{Z}) \simeq$ few nb
- The background is small
- basic cuts: $|\eta| < \mathbf{2.5}$ and $\mathbf{E_T} > \mathbf{25}$ GeV

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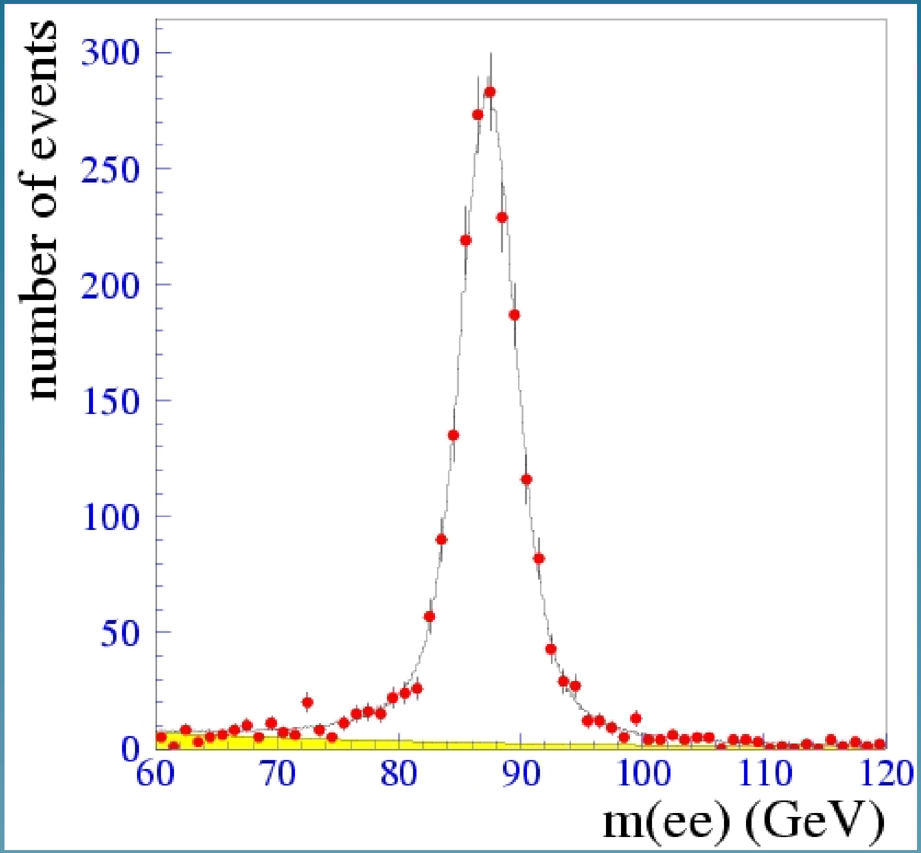

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❄ Br$(\mathbf{Z \rightarrow b\bar{b}})$/BR$(\mathbf{Z \rightarrow e^+e^-}) \simeq \mathbf{3.5}$

❄ There are large QCD backgrounds:

$$\mathbf{gg\ (q\bar{q}) \rightarrow b\bar{b}}$$

with $\sigma \gtrsim \mu$b

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- $P_T^\mu > 7.5$ GeV
- 2 SVX tags
- $\Delta\phi_{b\bar{b}} > 3$
- $\sum_3 E_T < 10$ GeV

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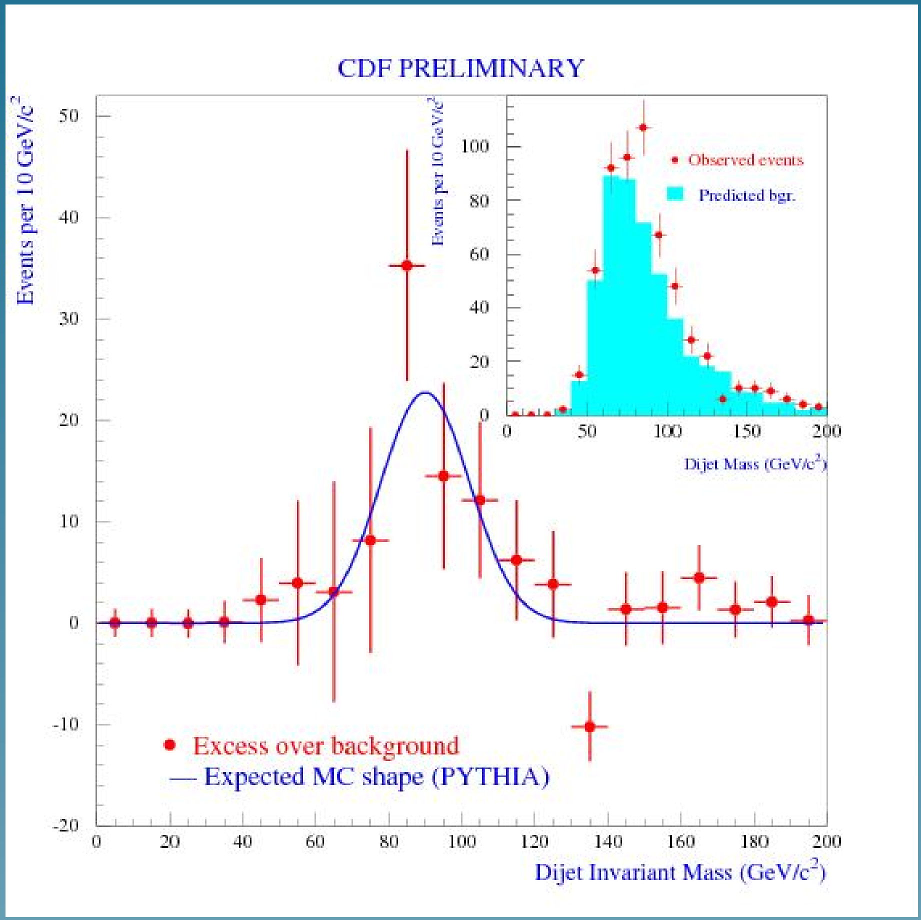
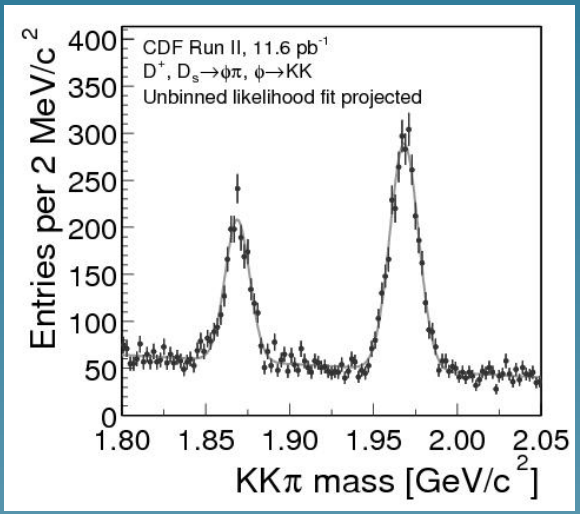
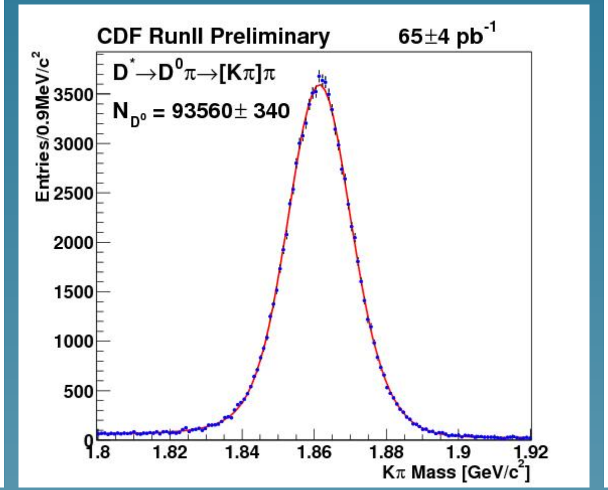
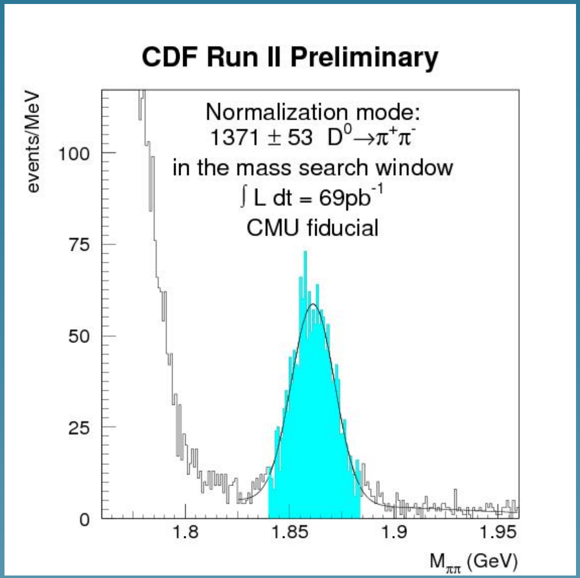


Much more can be done

(hep-ex/0309026)







II. $W^{\pm}$ production

Hadronic colliders: transverse mass variable

- Consider the process $\mathbf{p\bar{p} \to WX \to e\nu X}$

$$\mathbf{m^2_{e\nu} = (E_e + E_\nu)^2 - (\vec{p}_{eT} + \vec{p}_{\nu T})^2 - (p_{ez} + p_{\nu z})^2} \; .$$

However, $\vec{\mathbf{p}}_\nu$ is not observable.

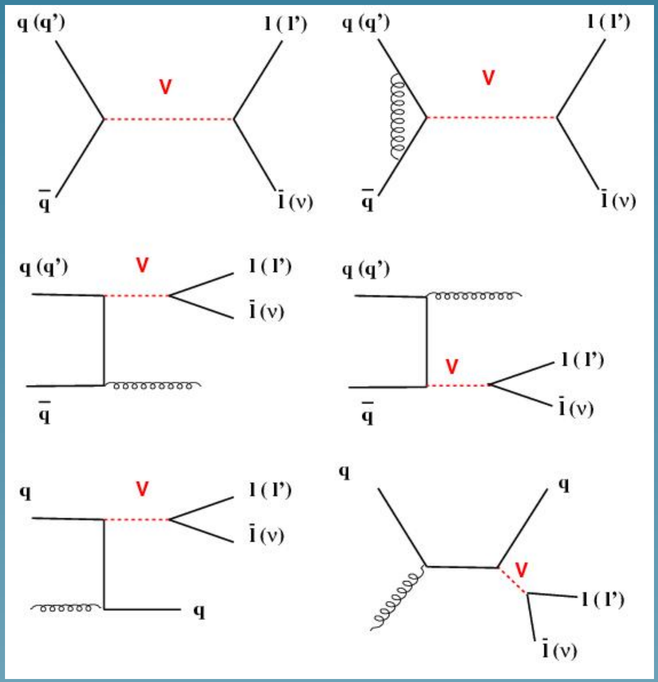
- We can infer $\vec{p}_{\nu T} \simeq \vec{\not{p}}_T = -\sum \mathbf{\vec{p_T}}$ (observed). Analogously $\not{E}_T = \mathbf{E}_\nu$
- We define transverse mass

$$\mathbf{m^2_{e\nu T} \equiv (E_{eT} + E_{\nu T})^2 - (\vec{p}_{eT} + \vec{p}_{\nu T})^2 \approx 2\vec{p}_{eT} \cdot \vec{p}_{\nu T} \approx 2E_{eT}\not{E}_T \, (1 - \cos\phi_{e\nu})}$$

- In general $\mathbf{0 \leq m_{e\nu T} \leq m_{e\nu}}$ (Prove it!)

- For $q\bar{q}' \to W^* \to e\nu$ there is a Jacobian peak.

$$\frac{d\hat{\sigma}}{dm^2_{e\nu,T}} \propto \frac{\Gamma_W M_W}{(m^2_{e\nu} - M^2_W)^2 + \Gamma^2_W M^2_W} \frac{1}{\sqrt{m^2_{e\nu} - m^2_{e\nu,T}}}.$$



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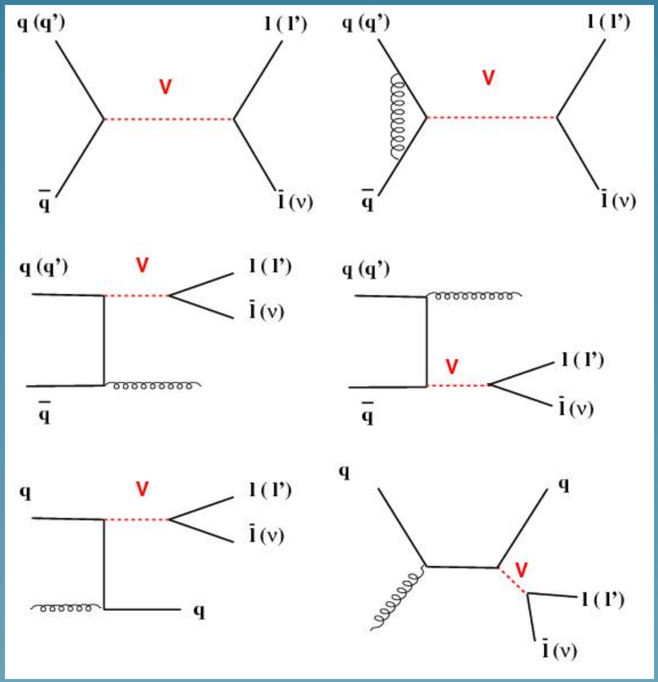
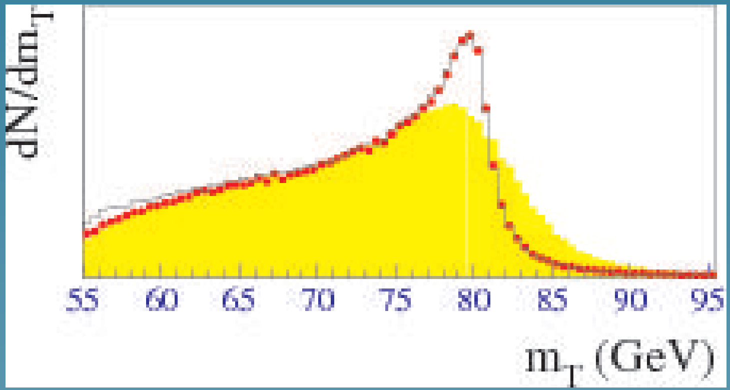
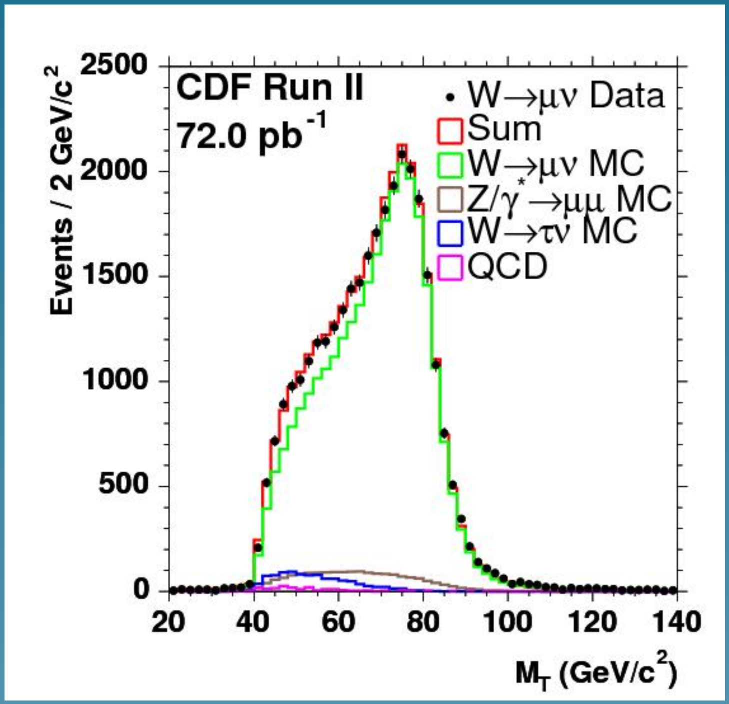




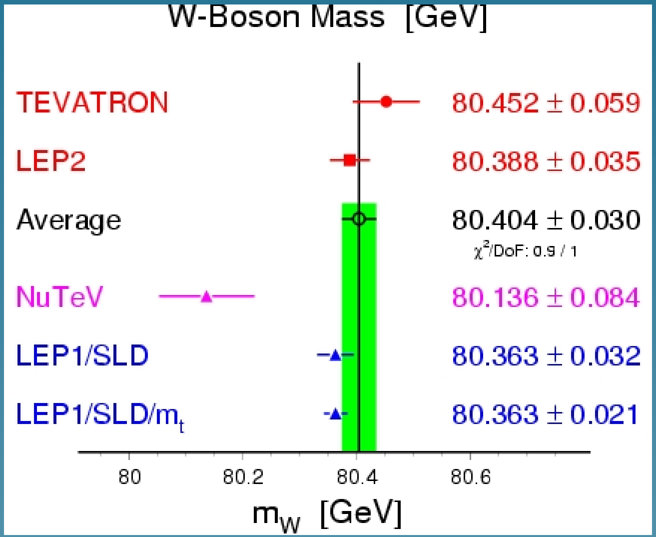
❄ Rather insensitive to $\vec{\mathbf{p}}_{\mathbf{W}}$

❄ $\mathbf{m_T}$ has a significant resolution sensitivity

❄ rather easy to obtain the $\mathbf{W}$



❄ Fitting the data leads to $\mathbf{M_W}$, and, $\mathbf{\Gamma_W}$ (hep-ph/0311039)



❄ We can get $\mathbf{\Gamma_W}$ from

$$\mathbf{R} \equiv \frac{\sigma_\mathbf{W} \cdot \mathbf{Br}(\mathbf{W} \to \mathbf{e}\nu)}{\sigma_\mathbf{Z} \cdot \mathbf{Br}(\mathbf{Z} \to \mathbf{ee})} = \frac{\sigma_\mathbf{W}}{\sigma_\mathbf{Z}} \frac{\mathbf{\Gamma_Z}}{\mathbf{\Gamma}(\mathbf{Z} \to \mathbf{ee})} \frac{\mathbf{\Gamma}(\mathbf{W} \to \mathbf{e}\nu)}{\mathbf{\Gamma_W}}$$

Second method: $\mathbf{p_T}$ distributions

❄ In the CMS $\mathbf{p_{eT} = p_e} \sin\theta^*$. For a $\mathbf{2 \to 2}$ process

$$\frac{\mathbf{d}\hat{\sigma}}{\mathbf{dp_{eT}}} = \frac{\mathbf{4p_{eT}}}{\hat{\mathbf{s}}\sqrt{\mathbf{1 - 4p_{eT}^2/\hat{s}}}} \frac{\mathbf{d}\hat{\sigma}}{\mathbf{d}\cos\theta^*}$$

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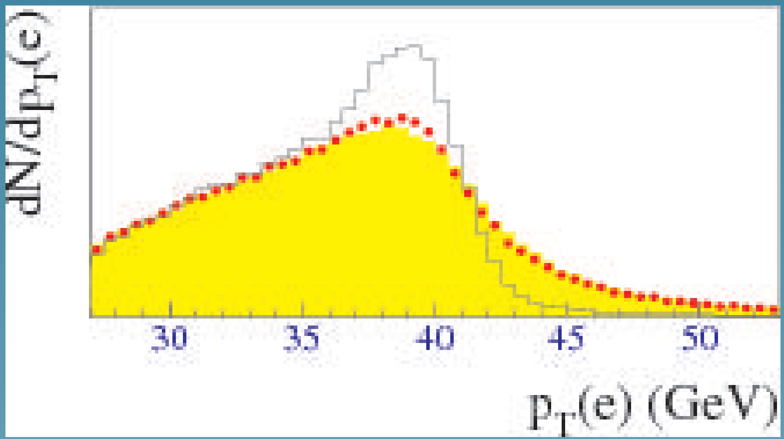

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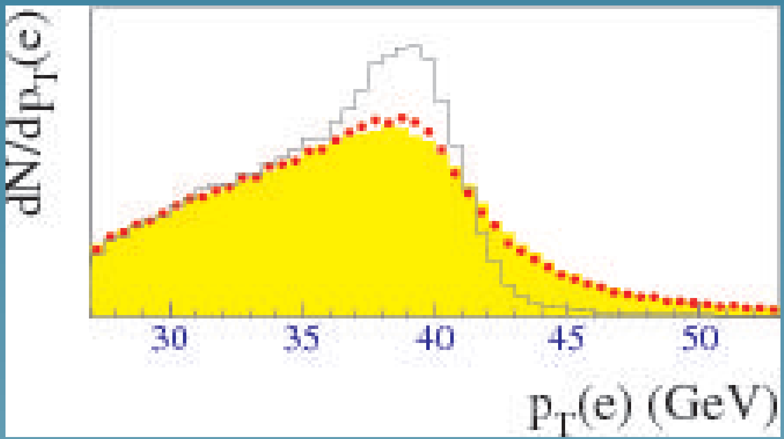

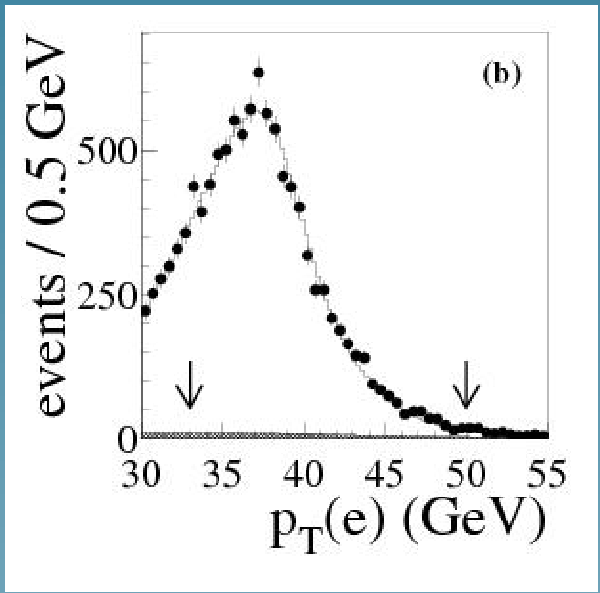

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$\mathbf{M_W}$ at LEP2

❋ At LEP2 $\mathbf{e^+e^-} \rightarrow \mathbf{W^+W^-}$: $\mathbf{M_W}$ is reconstruct from the decay products

❋ $qqqq$ (46%)

- the largest background is $Z^* \rightarrow qq$ ($\simeq 10\times$)
- require 4 jets
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❋ $qq\ell\nu$ (44%)

- some backgrounds Zee and Z^*
- require 2 jets and a high momentum, isolated lepton
- purity $\simeq$ efficiency $\simeq 80$%

❋ Advantage: CM (=lab) energy is know $\Longrightarrow$ we can perform kinematical constraints!

❋ For $qq\ell\nu$ energy and momentum conservation:

$$\begin{aligned} \vec{p}_\nu &= -E_\ell \vec{\mathrm{e}_\ell} - E_i \vec{\mathrm{e}_i} - E_j \vec{\mathrm{e}_j} \\ E_i + E_j &= E_\mathrm{b} \\ E_\ell + E_\nu &= E_\mathrm{b}, \end{aligned}$$

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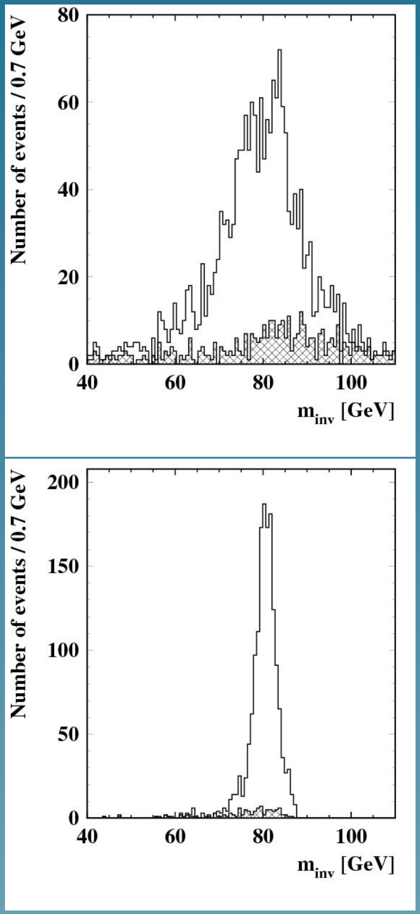


III. Other useful variables

❁ $\mathbf{H \to W_1 W_2 \to q_1 \bar{q}_2\ e\nu}$: A natural choice is

$$\mathbf{M'^2_{T,WW}} = \left(\sqrt{\mathbf{p^2_{T,jj} + m^2_{jj}}} + \sqrt{\mathbf{p^2_{T,e\nu} + m^2_{e\nu T}}} \right)^{\mathbf{2}} - (\vec{\mathbf{p}}_{\mathbf{T,jje}} + \vec{\not{p}}_T)^{\mathbf{2}}$$

since the $\mathbf{W}$ can be offshell

❁ $\mathbf{H \to Z_1 Z_2 \to e^+ e^-}\ \nu\bar{\nu}$: in this case

$$\begin{aligned} M^2_{T,ZZ} &= (E_{T,Z_1} + E_{T,Z_2})^2 - (\vec{p}_{T,Z_1} + \vec{p}_{T,Z_2})^2 \\ &= \left(\sqrt{p^2_{T,ee} + M^2_Z} + \sqrt{\not{p}_T{}^2 + M^2_Z} \right)^2 - (\vec{p}_{T,ee} + \vec{\not{p}}_T)^2 \end{aligned}$$

if $\mathbf{p^H_T = 0}$ then $\mathbf{M_{T,ZZ} \approx 2\sqrt{p^2_{T,ee} + M^2_Z}}$

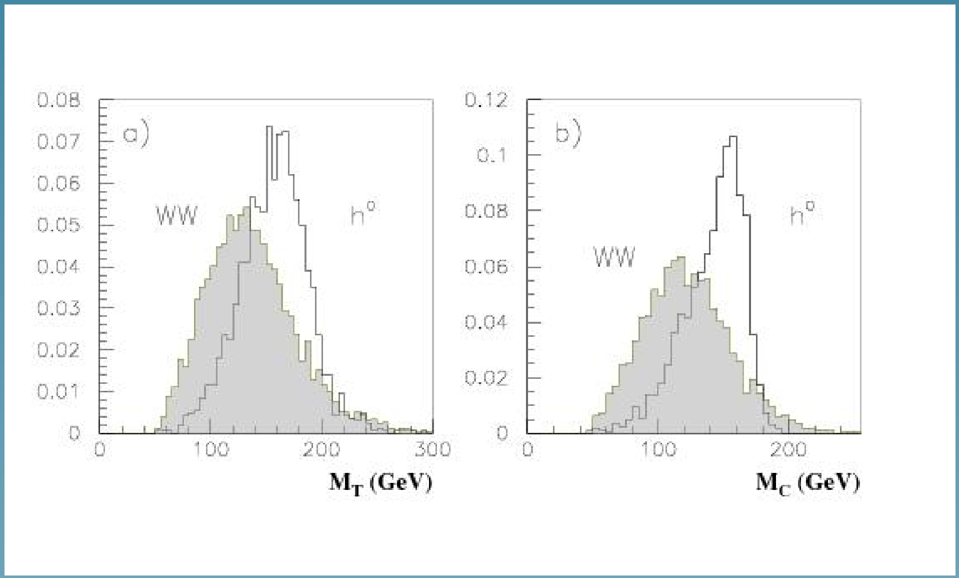
❁ $\mathbf{H} \rightarrow \mathbf{W_1 W_2} \rightarrow \ell_1\nu_1\ \ell_2\nu_2$:

$$M^2_{C,WW} = \left(\sqrt{p^2_{T,\ell\ell} + M^2_{\ell\ell}} + \not{p}_T\right)^2 - (\vec{p}_{T,\ell\ell} + \vec{\not{p}}_T)^2$$

an alternative is

$$M_{T,WW} \approx 2\sqrt{p^2_{T,\ell\ell} + M^2_{\ell\ell}}$$

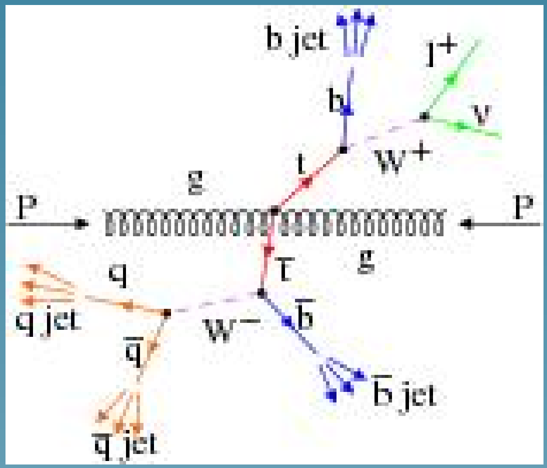
❁ For $M_H = 170$ GeV at the Tevatron



IV. Top quark production at the LHC

- $\mathbf{t}$ is produced by $\mathbf{q\bar{q}} \to \mathbf{t\bar{t}}$ (90%) and $\mathbf{gg} \to \mathbf{t\bar{t}}$ (10%) with $\sigma(\mathbf{t\bar{t}}) \simeq \mathbf{830}$ pb
- For $\mathcal{L}= \mathbf{10}$ fb^{-1} $\Longrightarrow$ $10^7\ \mathbf{t\bar{t}}$ $\Longrightarrow$ LHC is a top factory!
- This is good to measure $\mathrm{M_t}$ but it is also a background!
- In the SM $\mathbf{t} \to \mathbf{W^+b}$ $\Longrightarrow$ $\mathbf{t} \to \ell\nu\mathbf{b}$ (32 %) or $\mathbf{t} \to \mathbf{qq'b}$ (68 %) so

  - $\mathbf{t\bar{t}} \to \mathbf{jjb\ jj\bar{b}}$ (44%)
  - $\mathbf{t\bar{t}} \to \mathbf{jjb}\ (\mathbf{e}/\mu)\nu\mathbf{b}$ (30%)
  - $\mathbf{t\bar{t}} \to (\mathbf{e}/\mu)\mathbf{b}\ (\mathbf{e}/\mu)\nu\mathbf{b}$ (5%)



Top mass measurement in $\mathbf{t\bar{t}} \to \mathbf{jjb}\ (\mathbf{e}/\mu)\nu\mathbf{b}$

- Main background and their size

Process	σ (pb)
signal	250
$\mathbf{bb} \to \ell\nu +$ jets	$\mathbf{2.2 \times 10^6}$
$\mathbf{W} +$ jets $\to \ell\nu +$ jets	$\mathbf{7.8 \times 10^3}$
$\mathbf{Z} +$ jets $\to \ell^+\ell^- +$ jets	$\mathbf{7.8 \times 10^3}$
$\mathbf{WW} \to \ell\nu +$ jets	$\mathbf{17.1}$
$\mathbf{WZ} \to \ell\nu +$ jets	$\mathbf{3.4}$
$\mathbf{ZZ} \to \ell^+\ell^- +$ jets	$\mathbf{9.2}$

- $\mathbf{S/B \simeq 10^{-4}}$ This is not as bad as it looks.

Event selection

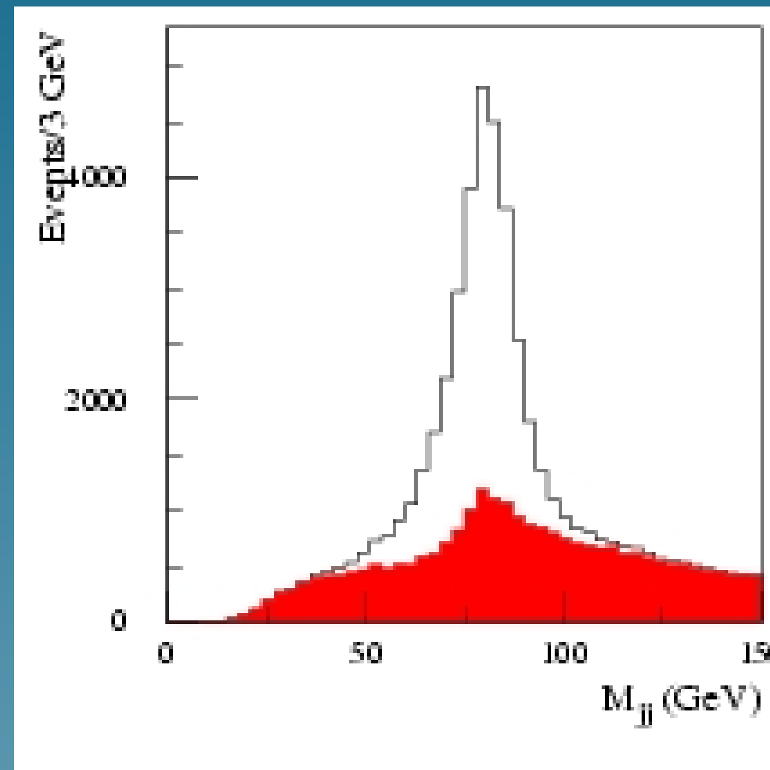
- 1 isolated $\mathbf{e}^{\pm}$ or $\mu^{\pm}$ with $\mathbf{p_T} > \mathbf{20}$ GeV and $|\eta| < \mathbf{2.5}$
- $\not{E}_T > \mathbf{20}$ GeV
- 2 tagged $\mathbf{b}$ quarks with $\mathbf{p_T} > \mathbf{40}$ GeV and $|\eta| < \mathbf{2.5}$
- 2 light jets with $\mathbf{p_T} > \mathbf{40}$ GeV and $|\eta| < \mathbf{2.5}$

Process	Cross-section (pb)	Total efficiency (%)
$t\bar{t}$ signal	250	3.5
$b\bar{b} \to l\nu + jets$	2.2×10^6	3×10^{-8}
$W + jets \to l\nu + jets$	7.8×10^3	2×10^{-4}
$Z + jets \to l^+l^- + jets$	1.2×10^3	6×10^{-5}
$WW \to l\nu + jets$	17.1	7×10^{-3}
$WZ \to l\nu + jets$	3.4	1×10^{-2}
$ZZ \to l^+l^- + jets$	9.2	3×10^{-3}

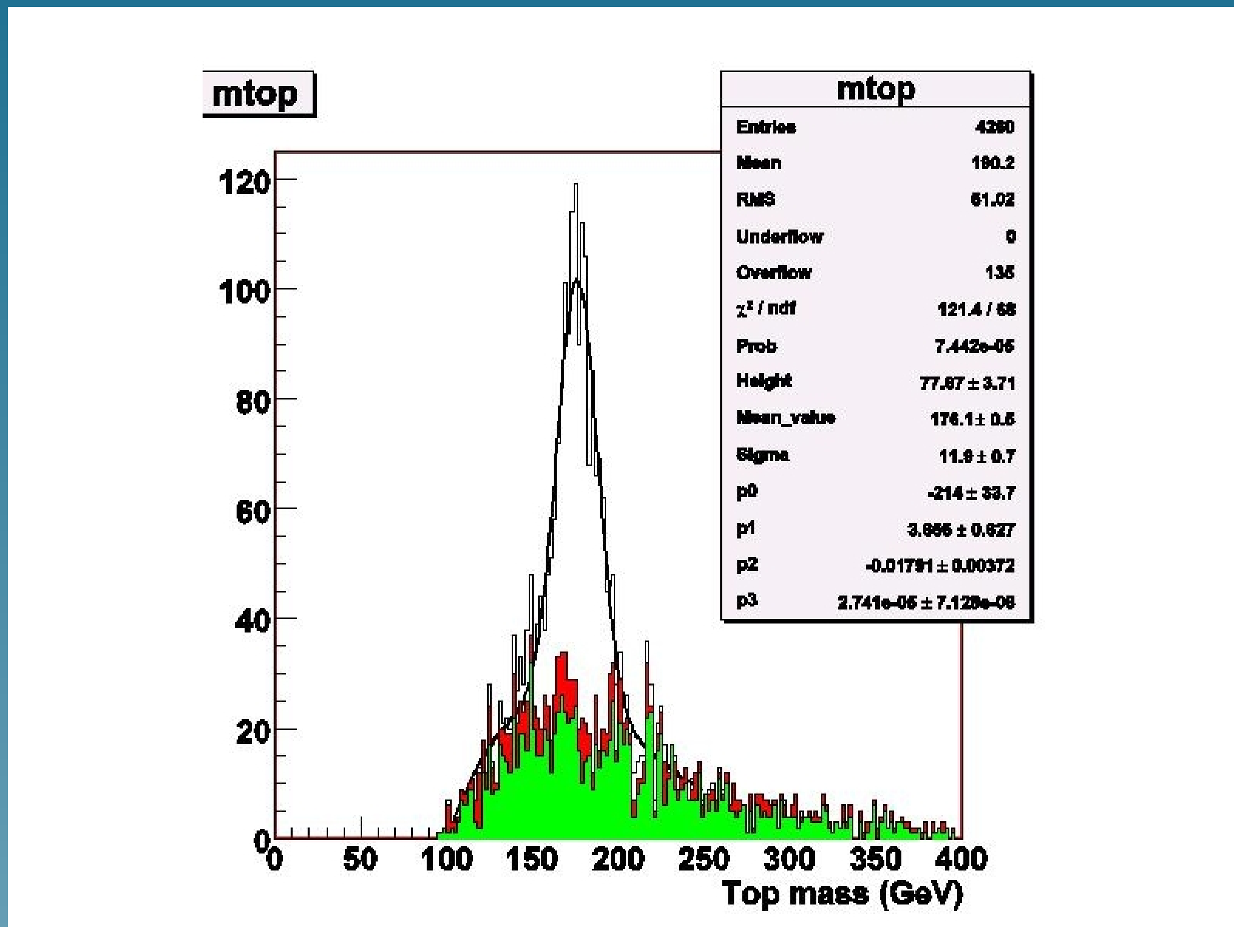
- After cuts $\mathbf{S/B \simeq 78}$
- 87k events for 10 fb^{-1}

Top quark mass from $\mathbf{t \to bjj}$

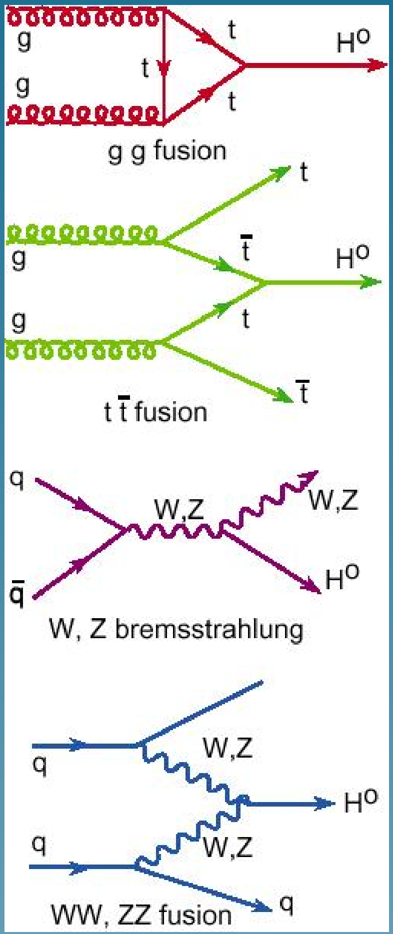
- The event present ≥ 4 jets (ISR and FSR)
- First recontruct the W: $|\mathbf{M_{jj}} - \mathbf{M_W^{PDG}}| < \mathbf{20}$ GeV (66%)
- choose the $\mathbf{b}$–tagged jet leading to highest $\mathbf{p_T^{top}}$ (81%)



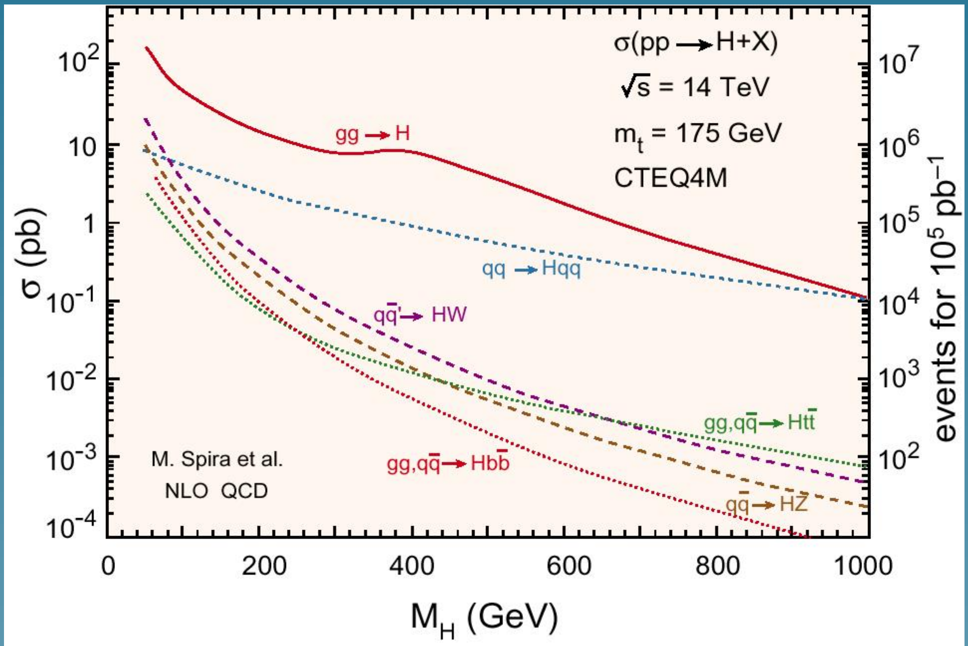
- Possible to measure $\mathrm{M_t}$ with a precision $\simeq 1.3$ GeV (systematic) for 10 fb^{-1}



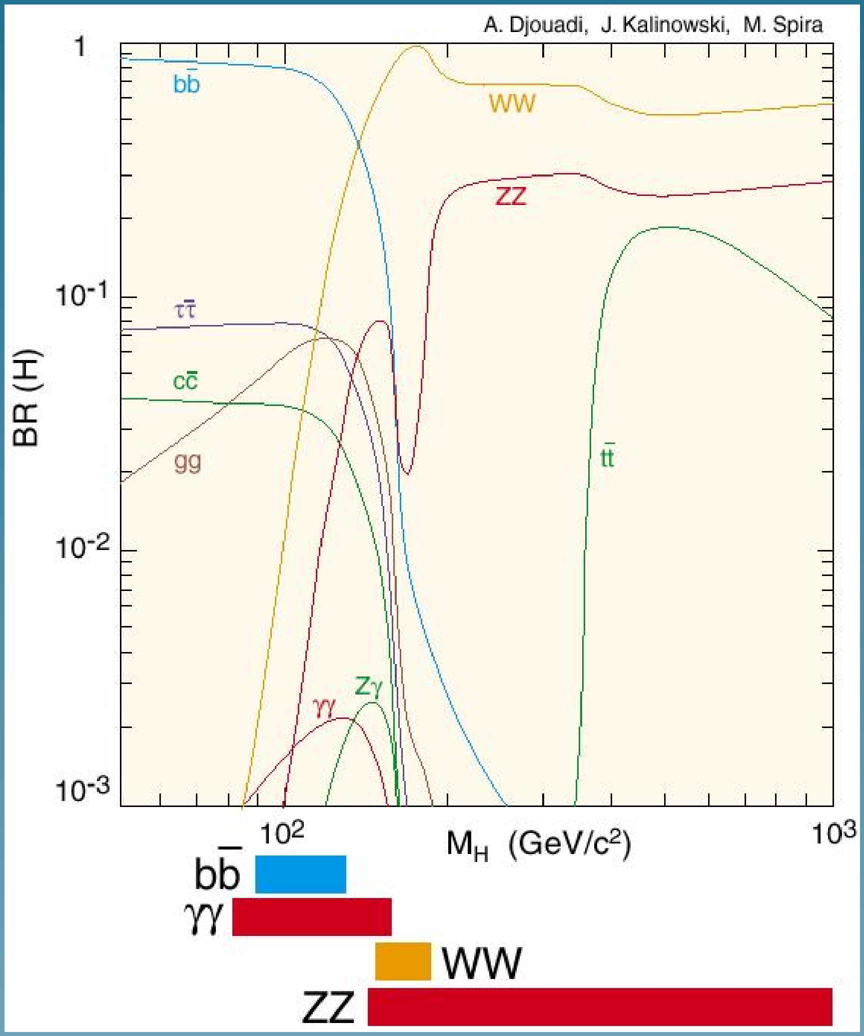
V. Higgs production at the LHC



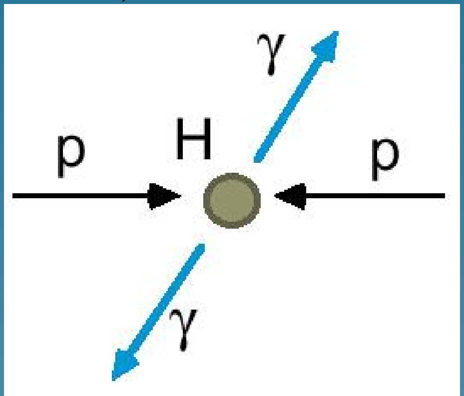
- Production mechanisms

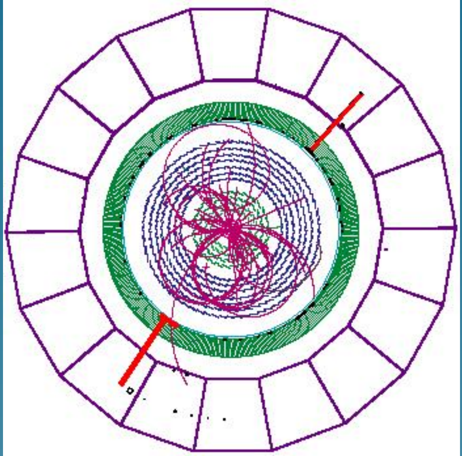


❇ The possible decay channels are



- Large QCD backgground $\sigma(\mathbf{b\bar{b}}) \simeq \mathbf{200}\mu$m $\Longrightarrow$ Let's start with $\mathbf{H_l} \to \gamma\gamma$
- $\mathbf{M_{H_l}} \lesssim \mathbf{150}$ GeV
- Br$(\mathbf{H_l} \to \gamma\gamma) \simeq \mathbf{10^{-3}}$





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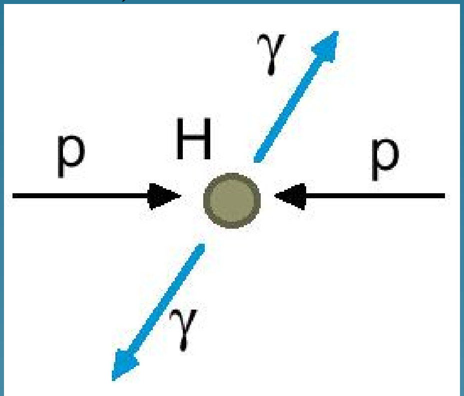

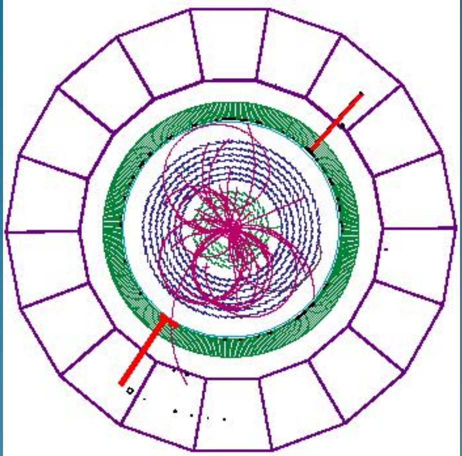

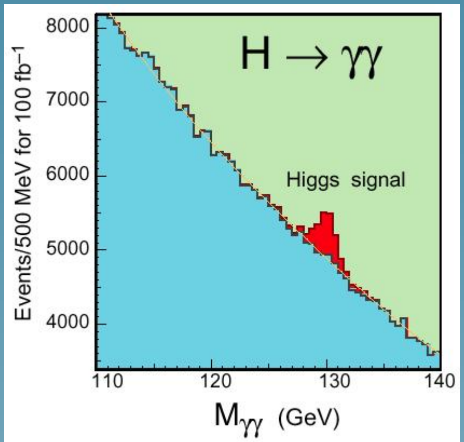

❇ Requires a good ECAL performance: $\sigma \simeq 1$ GeV

❇ $\mathbf{S/B \simeq 1:20}$

❇ Background extracted from data

Light Higgs production via WBF

- We can tag the final state jets in $\mathbf{qq} \to \mathbf{Hqq} \to \mathbf{Hjj}$
- Let's focus on $\mathbf{H} \to \tau^+\tau^- \to \mathbf{e}^\mp\mu^\pm \not{p}_T$
- The main backgrounds are
  - $\mathbf{t\bar{t}} + \mathbf{n}$ jets with $n = 0,\ 1,\ 2$. The extra jet is a tagging jet.

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❇ The main cuts are:

- Rapidity gap and acceptance cuts

$$p_{T_j} \geq 20 \text{ GeV}\,, \quad |\eta_j| \leq 5.0\,, \quad \triangle R_{jj} \geq 0.7\,,$$

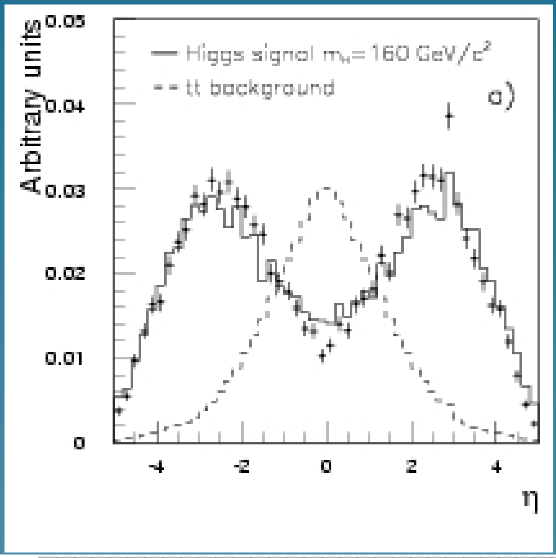
$$p_{T_\ell} \geq 10 \text{ GeV}\,, \quad |\eta_\ell| \leq 2.5\,, \quad \triangle R_{j\ell} \geq 0.7\,.$$

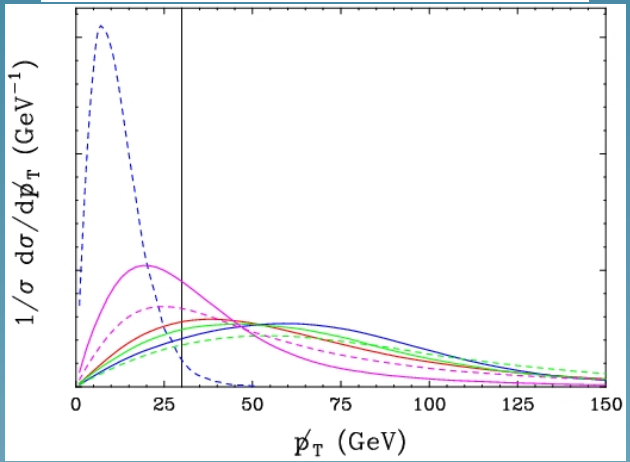
$$\triangle R_{e\mu} \geq 0.4\,.$$

$$\eta_{j,min} + 0.7 < \eta_{\ell_{1,2}} < \eta_{j,max} - 0.7\,,$$

$$\eta_{j_1} \cdot \eta_{j_2} < 0$$

$$\triangle\eta_{tags} = |\eta_{j_1} - \eta_{j_2}| \geq 4.4\,,$$





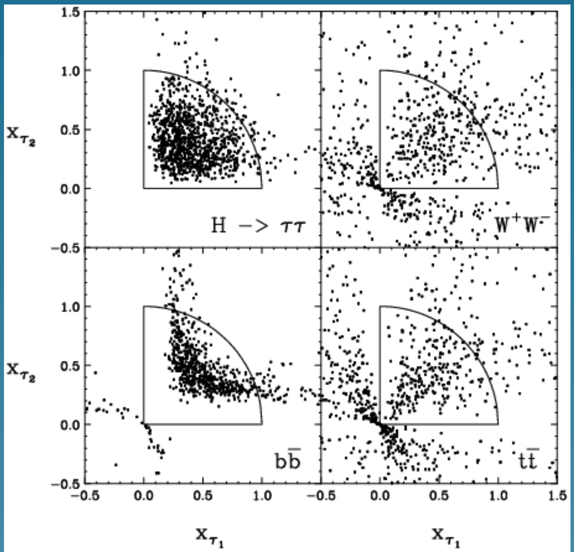
- b–veto:
  $\mathbf{p_{T_b} > 20}$ GeV $, \quad \boldsymbol{\eta_{j,min} < \eta_b < \eta_{j,max}}\,.$

- Missing transverse momentum $\not{p}_T > \mathbf{30}$ GeV

- $\mathbf{M_{jj} > 800}$ GeV

- $\tau\tau$ reconstruction: $\mathbf{M}_{\tau\tau} = \mathbf{m}_{\mathbf{e}\mu}/\sqrt{\mathbf{x}_{\tau_1}\mathbf{x}_{\tau_2}}$

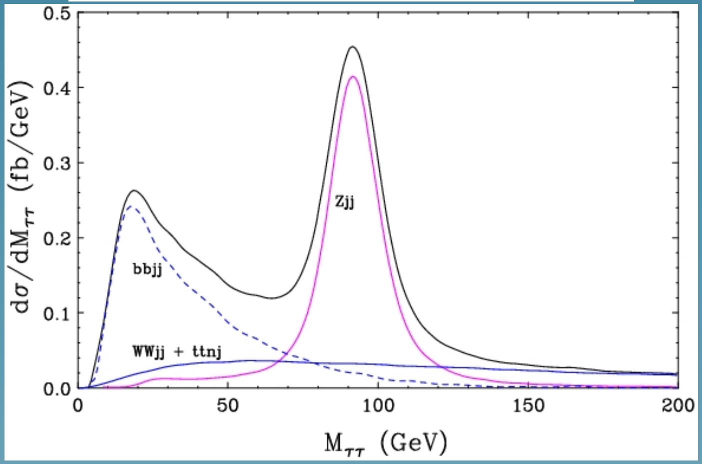
$$\cos\phi_{e\mu} > -0.9 \; .$$
$$x_{\tau_1},\; x_{\tau_2} > 0 \; ,$$
$$x_{\tau_1}^2 + x_{\tau_2}^2 < 1 \; .$$

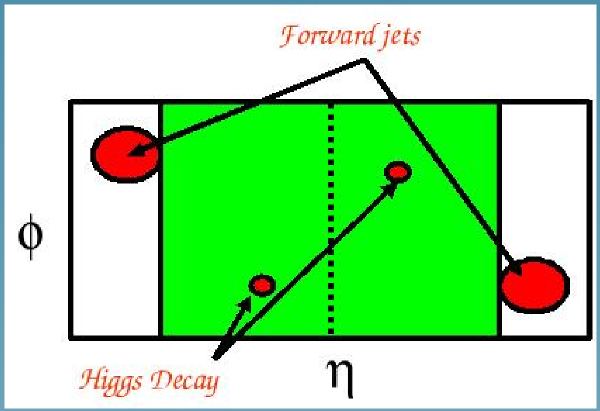


- Lepton correlations: $\triangle\mathbf{R}_{\mathbf{e}\mu} < \mathbf{2.6}$

- minijet veto:

$$\mathbf{p}_{\mathbf{Tj}}^{\text{veto}} > \mathbf{p}_{\mathbf{T},\text{veto}} \; ; \; \eta_{\mathbf{j},\mathbf{min}}^{\text{tag}} < \eta_{\mathbf{j}}^{\text{veto}} < \eta_{\mathbf{j},\mathbf{max}}^{\text{tag}}$$





❇ Effect of the cuts for $\mathbf{M_H = 120}$ GeV and a bins $\pm\mathbf{10}$ GeV

cuts	$H \to \tau\tau$ signal	QCD $\tau\tau jj$	EW $\tau\tau jj$	$t\bar{t} + jets$	$b\bar{b}jj$	QCD $WWjj$	EW $WWjj$	S/B
forward tags	1.34	4.7	0.18	45	8.2	0.18	0.11	1/44
+ b veto				2.6				1/12
+ $\not{p}_T$	1.17	2.3	0.12	2.0	0.28	0.12	0.08	1/4.1
+ M_{jj}	0.92	0.67	0.10	0.53	0.13	0.049	0.073	1/1.7
+ non-τ reject.	0.87	0.58	0.10	0.09	0.10	0.009	0.012	1/1
+ $\triangle R_{e\mu}$	0.84	0.52	0.086	0.087	0.028	0.009	0.011	1.1/1
+ ID effic. ($\times\ 0.67$)	0.56	0.34	0.058	0.058	0.019	0.006	0.008	1.1/1
$P_{surv,20}$	$\times 0.89$	$\times 0.29$	$\times 0.75$	$\times 0.29$	$\times 0.29$	$\times 0.29$	$\times 0.75$	-
+ minijet veto	0.50	0.100	0.043	0.017	0.006	0.002	0.006	2.7/1

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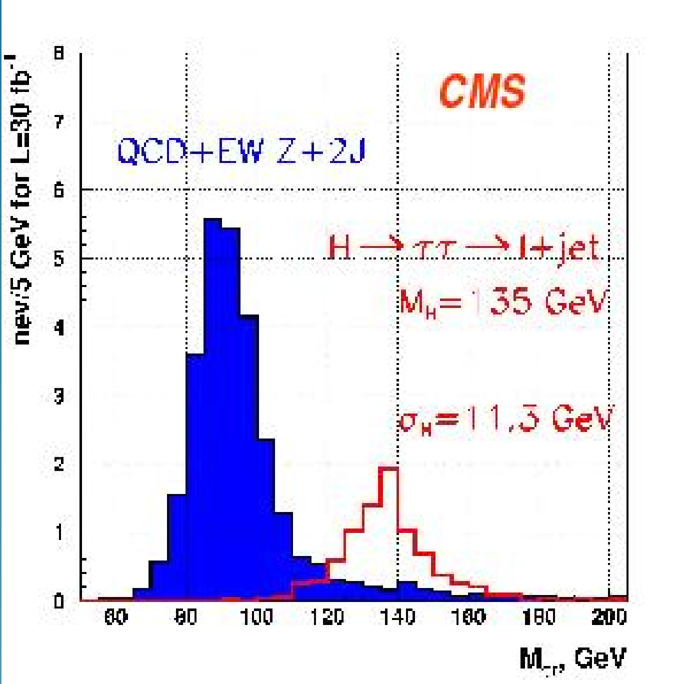
❇ Contamination from $\mathbf{H \to WW}$

M_H	115	120	125	130	135	140	145	150
B($H \to \tau\tau$)$\cdot\sigma$ (fb)	0.93	0.84	0.74	0.62	0.51	0.39	0.27	0.19
B($H \to WW$)$\cdot\sigma$ (fb)	0.015	0.024	0.034	0.045	0.057	0.067	0.072	0.076

- Even after full simulation the Higgs signal is nice

- $\tau\tau$ channel



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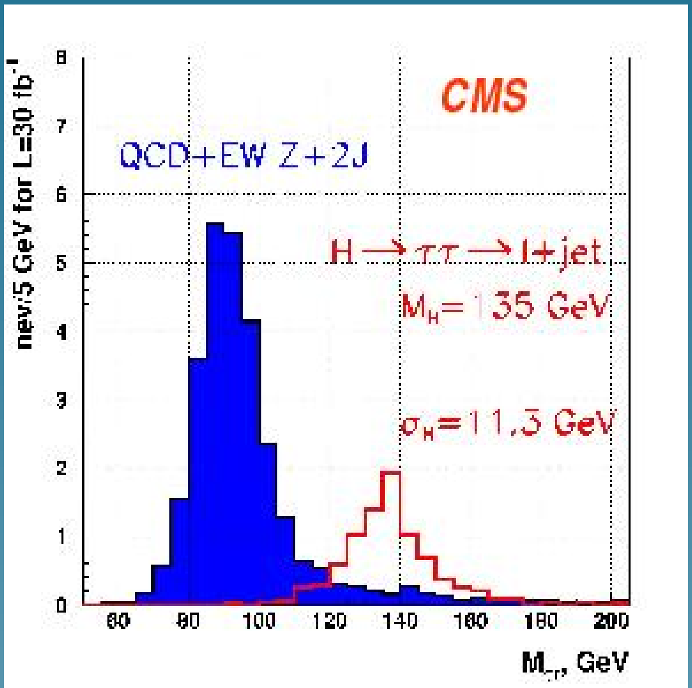
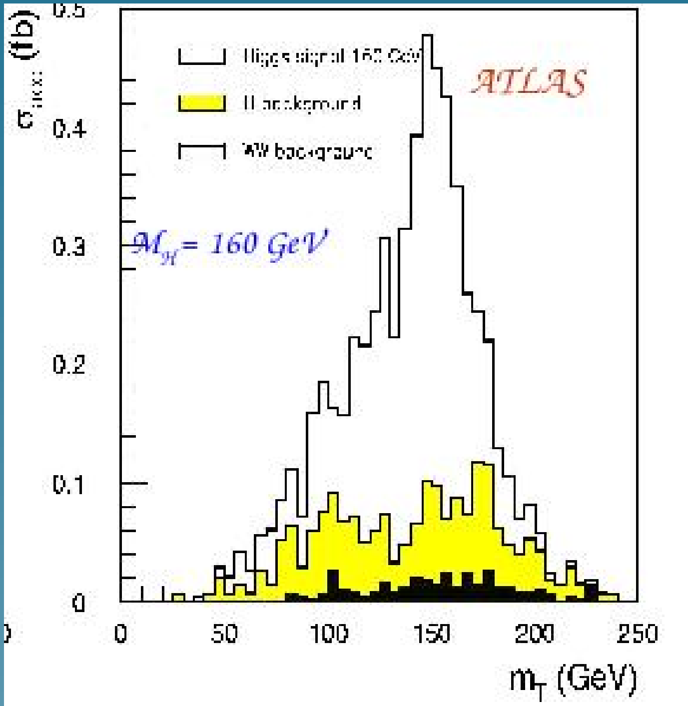
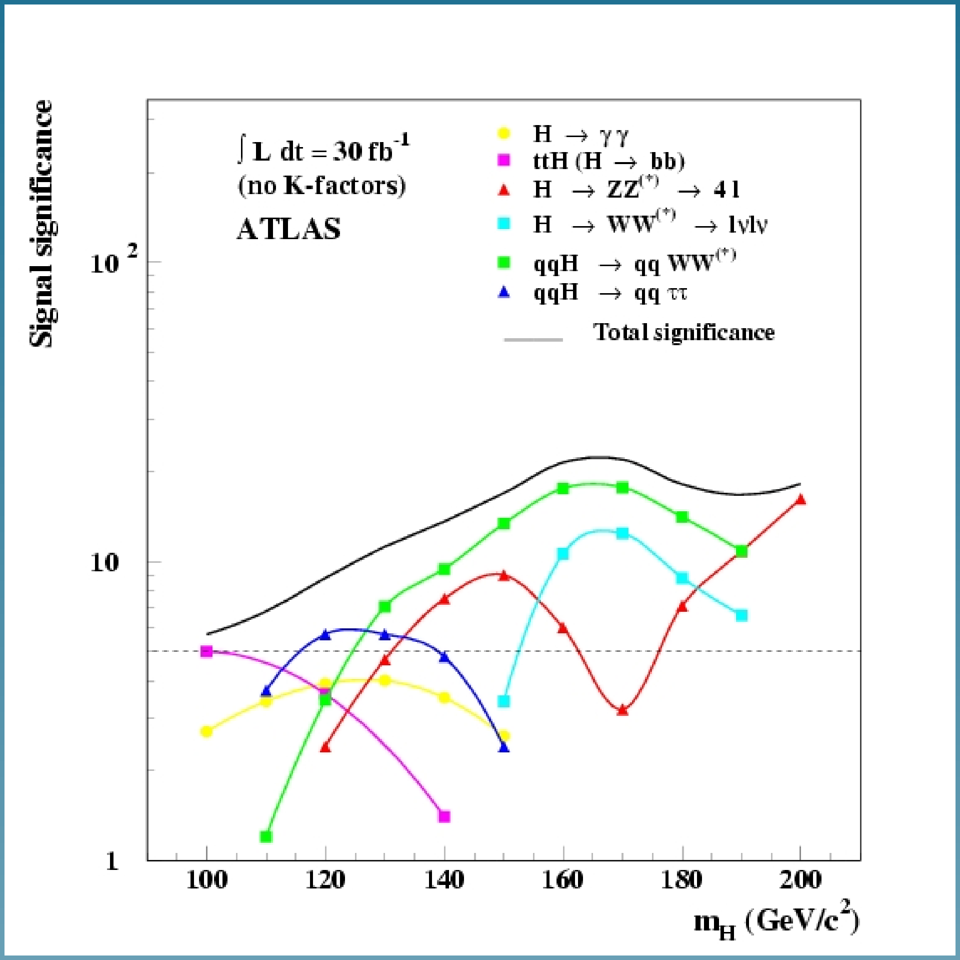


❇ $\mathbf{WW}$ channel



❇ What happens when we add all the channels for the SM Higgs?



❇ combining both detectors