Looking for the light Higgs boson at the LHC

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Motivation

- What is matter?
- How does it behave?

Leptons		Quarks$_C$		
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	e_R	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	u_R	d_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	μ_R	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	c_R	s_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	τ_R	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	t_R	b_R

- Standard Model (*Weinberg, Glashow, Salam*)
  $\Leftrightarrow$ spontaneously broken gauge theory

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \xrightarrow{H} SU(3)_C \otimes U(1)_{em}$$

- renormalisable (*t'Hooft, Veltman*)
  $\rightarrow$ radiative corrections well definied $\rightarrow$ precise predictions!

"There appears to be some hope that [...] the combination of spontaneous symmetry breakdown with the gauge principle may provide the basis for an understanding of the broken symmetries of high–energy physics."

[P.W. Higgs, Phys. Rev. 145:1156 (1966)]

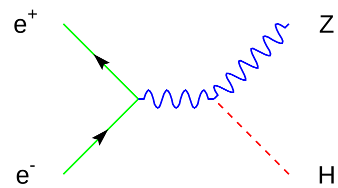
P.W. Higgs, Phys. Lett. 12 (1964), Phys. Rev. Lett. 13 (1964), Phys. Rev. 145 (1966).

F. Englert, R. Brout, Phys. Rev. Lett. 13 (1964).

G.S. Guralnik, C.R. Hagen, T.W. Kibble, Phys. Rev. Lett. 13 (1964).

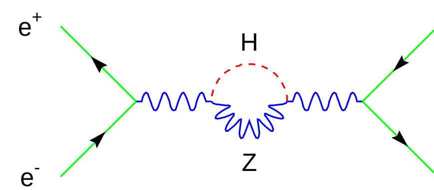
The situation after LEP

- Direct limit:

  Dominant process at LEP 

  $\sqrt{s} > M_Z + M_H \Rightarrow$ $M_H \geq 114.3$ GeV (95% c.l.)

- Indirect limit

  Observables are modified by quantum corrections 

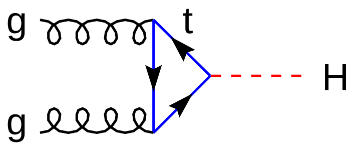
  $\mathcal{O}_{NLO} - \mathcal{O}_{LO} \sim \alpha \log(M_H) \Rightarrow M_H = 81^{+52}_{-33}$ GeV

  $M_H < 193$ GeV (95% c.l.)

  [!!! if the Higgs sector is minimal and perturbative !!!]

Situation for the LHC

- The Tevatron has a chance to discover a light Higgs boson $M_H < 125$ GeV
- Dominant process at the LHC: gluon fusion



- The most promising signature for 80 GeV $< M_H <$ 140 GeV:

$$gg \to H \to \gamma\gamma$$

- The experimental studies do not include K factors!
  $L = 100\,\mathrm{fb}^{-1} \Rightarrow S/B \sim 5\%,\ S \sim 1000,\ B \sim 20000$
- Corrections for the signal (NLO) of order 100% (!)
  NNLO corrections ($M_{Top} \to \infty$) are calculated, resummations to account for soft gluon effects are performed $\Rightarrow$ The signal is theoretically under control!

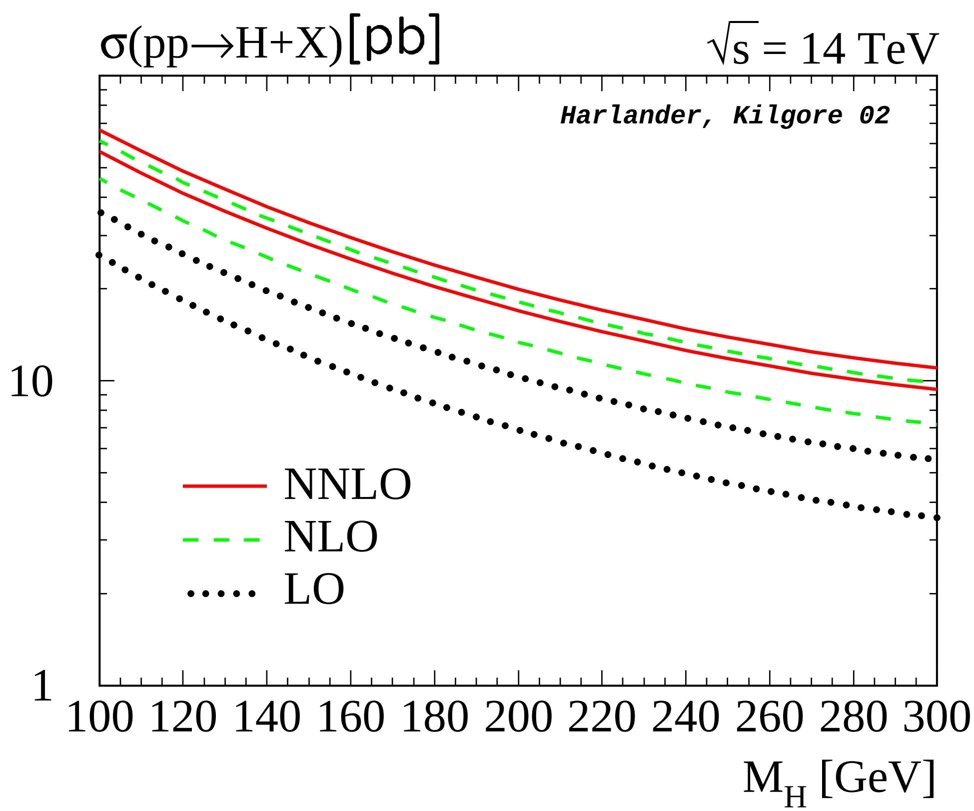
How big are the radiative corrections for the background?

Higher order corrections for the signal

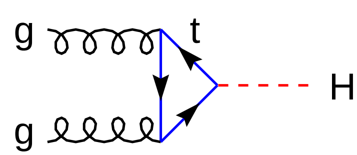
NLO: Spira, Djouadi, Graudenz, Zerwas 1997

NNLO ($M_{top} \to \infty$): Harlander, Kilgore and Anastasiou, Melnikov 2002

NNLO result for LHC



$$\mu = M \in [M_H/2, 2\, M_H]$$

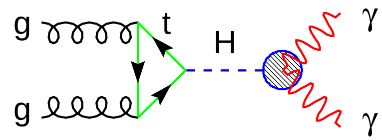


$$\sigma \sim \sigma_0\,(1 + 0.8 + 0.3)\,,\ \delta\sigma/\sigma \sim 15$$

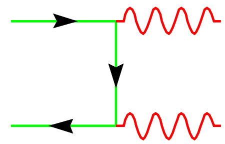
$$B(H \to \gamma\gamma) \sim 2 \times 10^{-3}$$

Photon pairs at the LHC

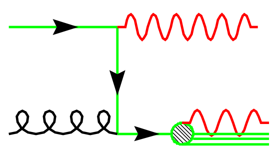
Apart from the signal:

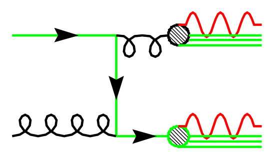


I Direct Photons: The photons are produced through point–like interactions

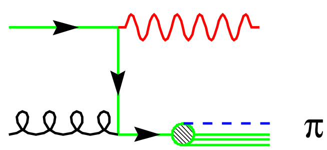


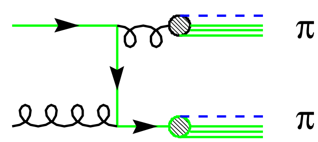
II Photons from fragmentation: At least one photon is produced in the hadronisation of partons





III Meson decay: $\pi^0, \eta, \ldots$ decay into photon paires. If $p_T(\pi^0)$ is big the two photons are misidentified as a single photon in the detector $\Rightarrow$ "Fake Photons"



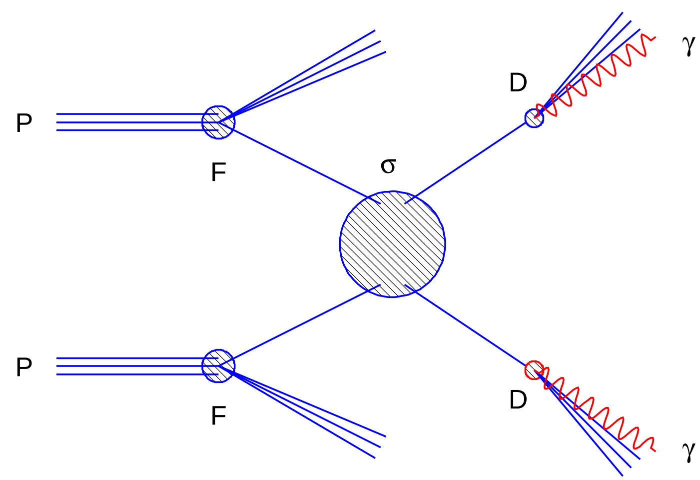


Physics of γ's $\Leftrightarrow$ Physics of π^0's

The parton model and collinear fragmentation

$$\sigma[PP \to \gamma\gamma] = \sum_{p_j} \int F_{p_1/P}(M) F_{p_2/P}(M)$$
$$\otimes \sigma[p_1 p_2 \to p_3 p_4](\mu) \otimes D_{\gamma/p_3}(M_f) D_{\gamma/p_4}(M_f)$$

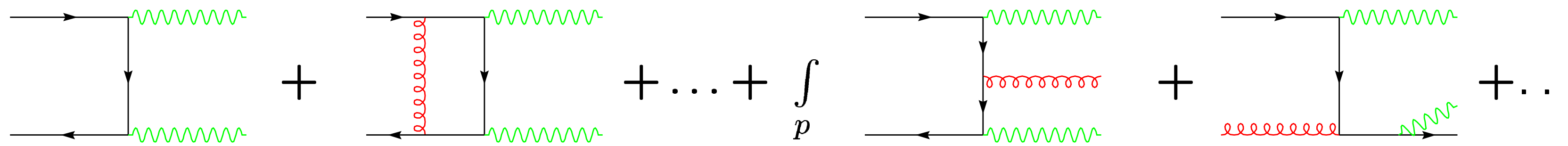
- Direct Photons $D_{\gamma/p_j} \leftrightarrow \delta(1-z)$
- Pion production $D_{\gamma/p_j} \leftrightarrow D_{\pi^0/p_j}$



$\Rightarrow$ at leading order predictions are very sensitive on variations of the scales μ, M, M_f

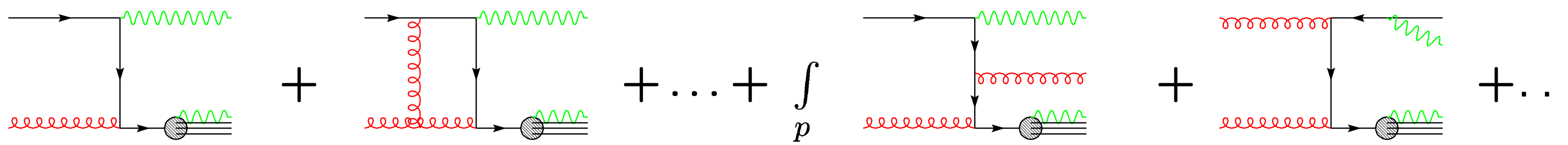
$\gamma\gamma$ production beyond the leading order

Contribution direct/direct:

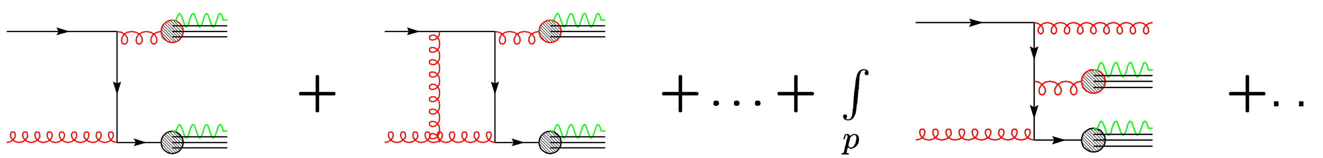


LO NLO virtual NLO real

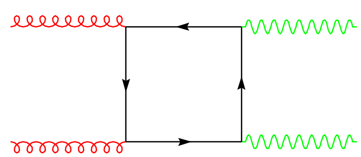
Contribution direct/fragmentation:



Contribution fragmentation/fragmentation:



The box contribution:



The program DIPHOX

- All contributions are calculated and included in a flexible FORTRAN code: DIPHOX

  [T.B., J.P. Guillet, E. Pilon, M. Werlen, EPJ C16 (2000)]

- Describes the production of photon pairs, photon+hadron and hadron pairs in hadronic collisions at NLO

- Allows to study effects due to experimental cuts

- Allows to compare existing data with NLO QCD

- Allows to make predictions for photon pair rates at the LHC

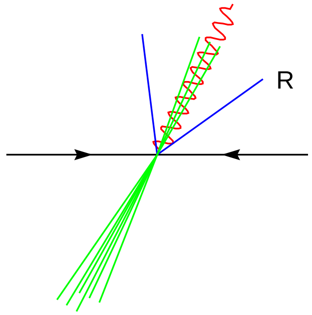
Comparison with Tevatron data

Tevatron: $P\bar{P}$ collider at Fermilab, Run I: $\sqrt{s} = 1.8$ TeV

Experimental cuts:

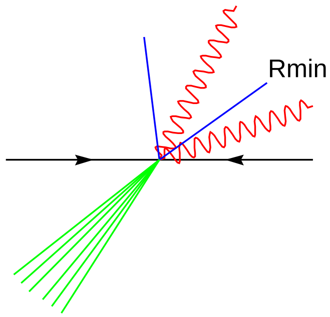
- Cut on transverse momenta and rapidity:

$$p_T(\gamma_1) > 14.9 \text{ GeV}$$
$$p_T(\gamma_2) > 13.9 \text{ GeV}$$
$$|y(\gamma_{1,2})| < 1$$



- Isolation cut:

$$E_{T\,hadronic} < E_{T\,max} = 2 \text{ GeV}$$
$$R = \sqrt{(y - y_\gamma)^2 + (\phi - \phi_\gamma)^2} < 0.4$$



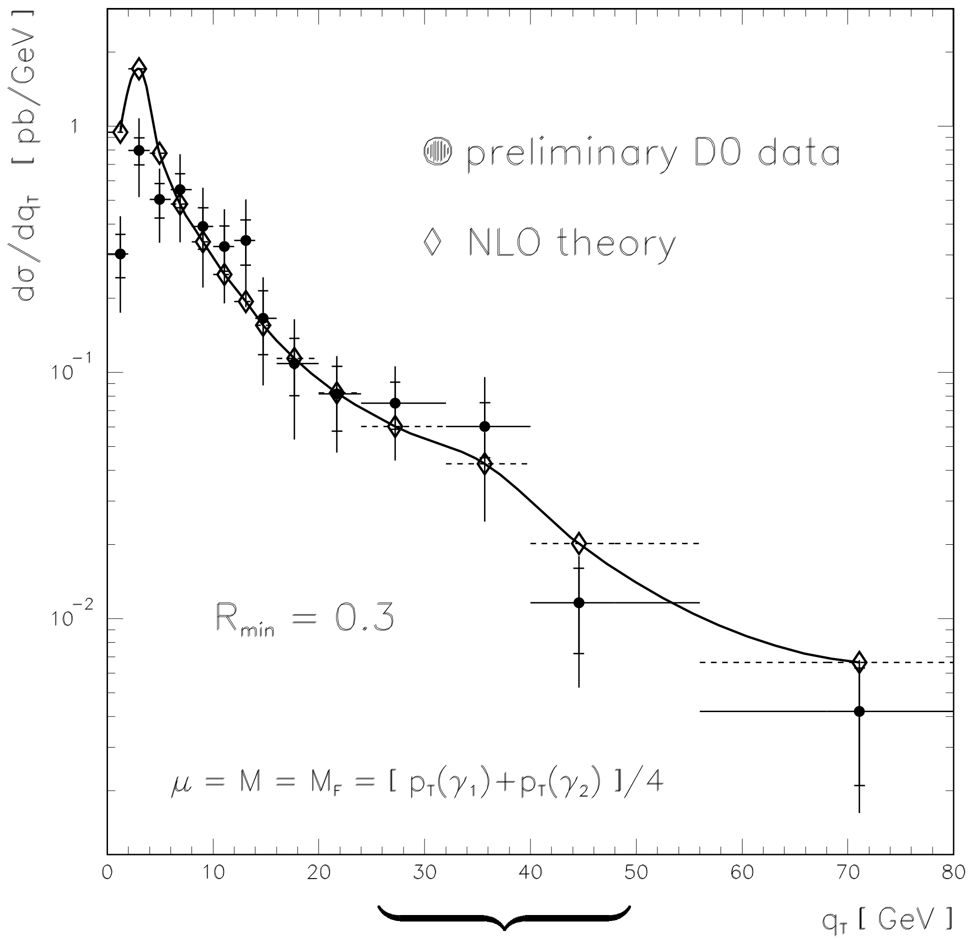
- Separation cut for the photons:

$$R_{min} = \sqrt{(y_{\gamma_1} - y_{\gamma_2})^2 + (\phi_{\gamma_1} - \phi_{\gamma_2})^2} > 0.3$$

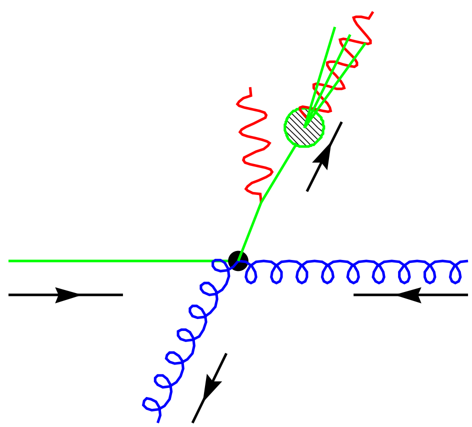
The q_T distribution at the Tevatron

[T.B., J.P. Guillet, E. Pilon, M. Werlen, Phys. Rev. D63 (2001)]

higher orders important $\rightarrow$ resummation !!!



$$q_T = |\vec{p}_T(\gamma_1) + \vec{p}_T(\gamma_2)|$$



small shoulder visible $\Rightarrow$ collinear effect in the final state

$\Rightarrow$ NLO effect in the fragmentation part !!!

Predictions for the LHC

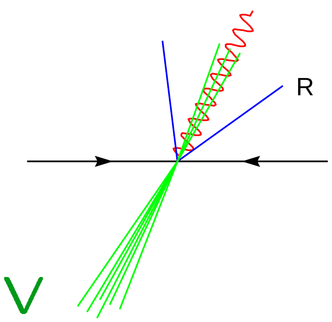
[T.B., J.P. Guillet, E. Pilon, M. Werlen, EPJdirect C7 (2002)]

LHC: PP collider at CERN: $\sqrt{s} = 14$ TeV, start $2007 + x$

- Cuts on transverse momenta, rapidity and invariant mass:

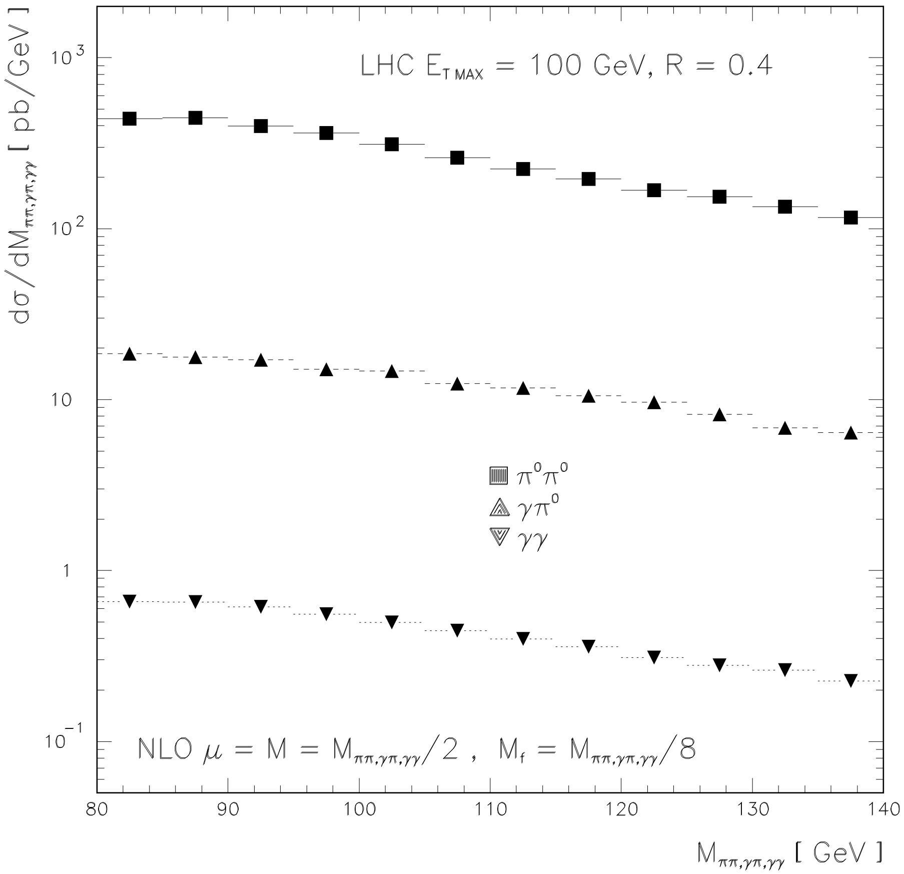
$$p_T(\gamma_1, \pi_1) > 40 \text{ GeV}$$
$$p_T(\gamma_2, \pi_2) > 25 \text{ GeV}$$
$$|y(\gamma_{1,2}, \pi_{1,2})| < 2.5$$
$$80 \text{ GeV} < M_{\gamma\gamma,\gamma\pi,\pi\pi} < 140 \text{ GeV}$$

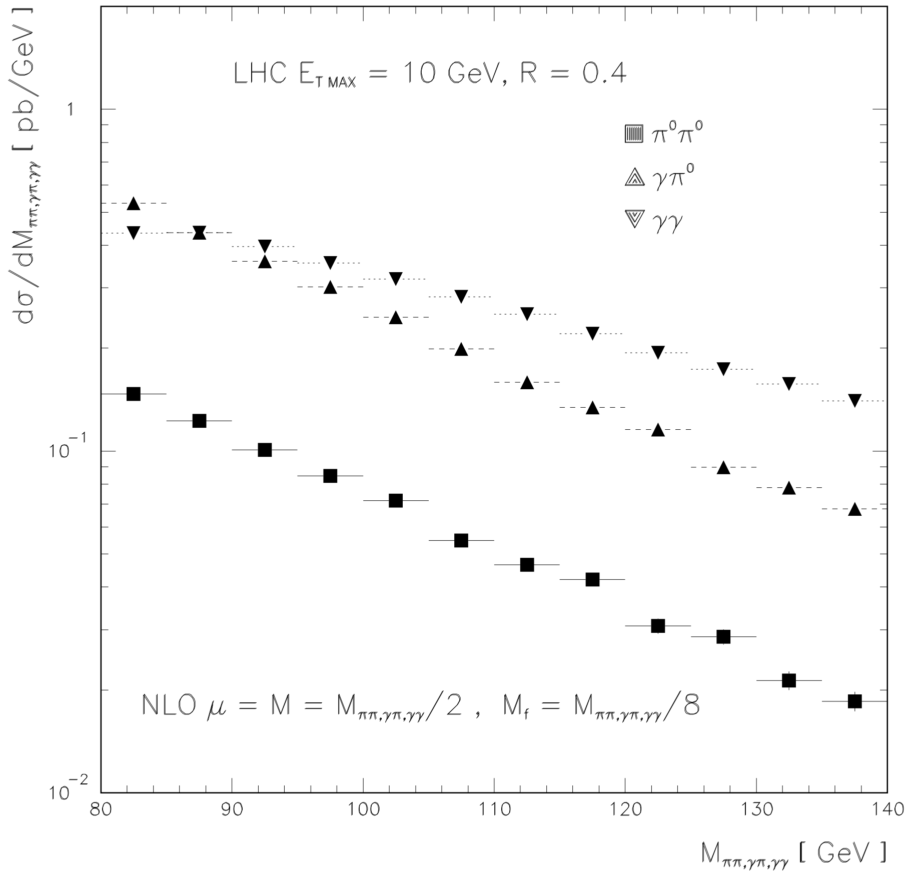
- Isolation cuts:



$$E_{T\,hadronic} < E_{T\,max} = 5, \ldots, 15 \text{ GeV}$$
$$R = \sqrt{(y - y_\gamma)^2 + (\phi - \phi_\gamma)^2} < 0.4$$

The rates for $\gamma\gamma$, $\gamma\pi^0$, $\pi^0\pi^0$ at the LHC





To suppress the pions ($\rightarrow$ "fake photons") and the photons of the fragmentation part severe isolation cuts have to be applied

!!! reduction factors of order $\mathcal{O}(1000)$!!!

Problems due to strict isolation cuts

severe isolation cuts $\Rightarrow$

$$z = \frac{E_T(\pi^0)}{E_T(Had) + E_T(\pi^0)} \;,\; E_T(Had) = \frac{1-z}{z} E_T(\pi^0)$$

$$\Rightarrow \quad 1 \geq z \geq z_{min} = \frac{p_{T\,min}}{p_{T\,min} + E_{T\,max}}$$

$$E_T(\pi^0) > p_{T\,min} = 25 \text{ GeV}$$

$$E_T(Had) < E_T(max) \sim 10 \text{ GeV}$$

$$\Rightarrow \qquad z > z_{min} \sim 0.7$$

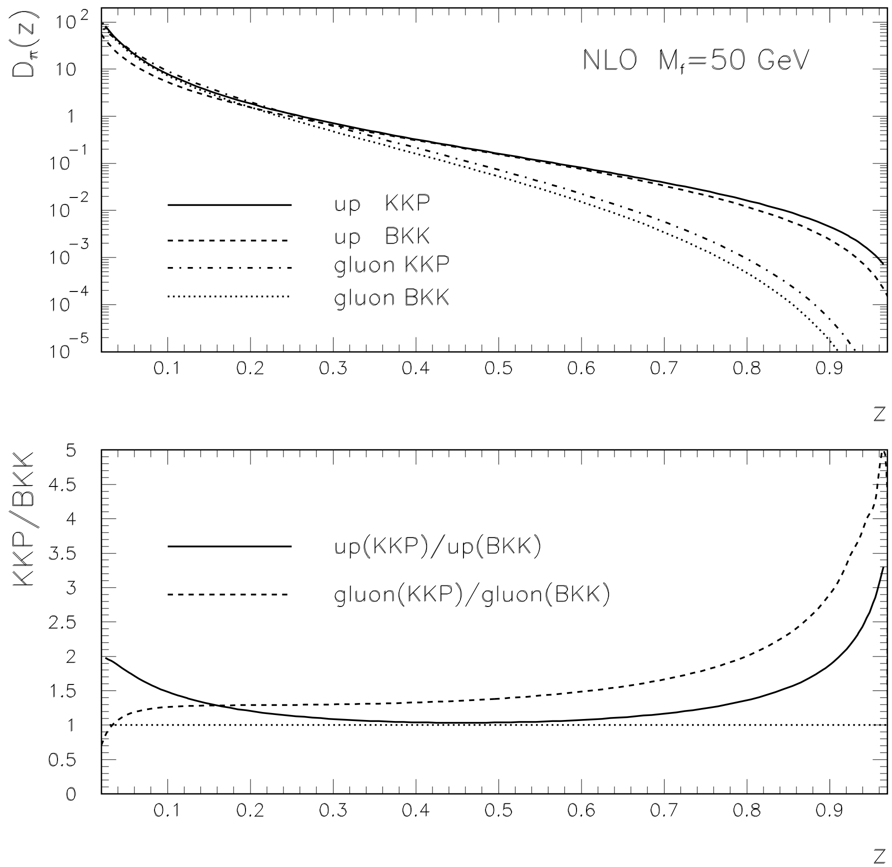
Fragmentation models are tested at high z, $z \sim 1$

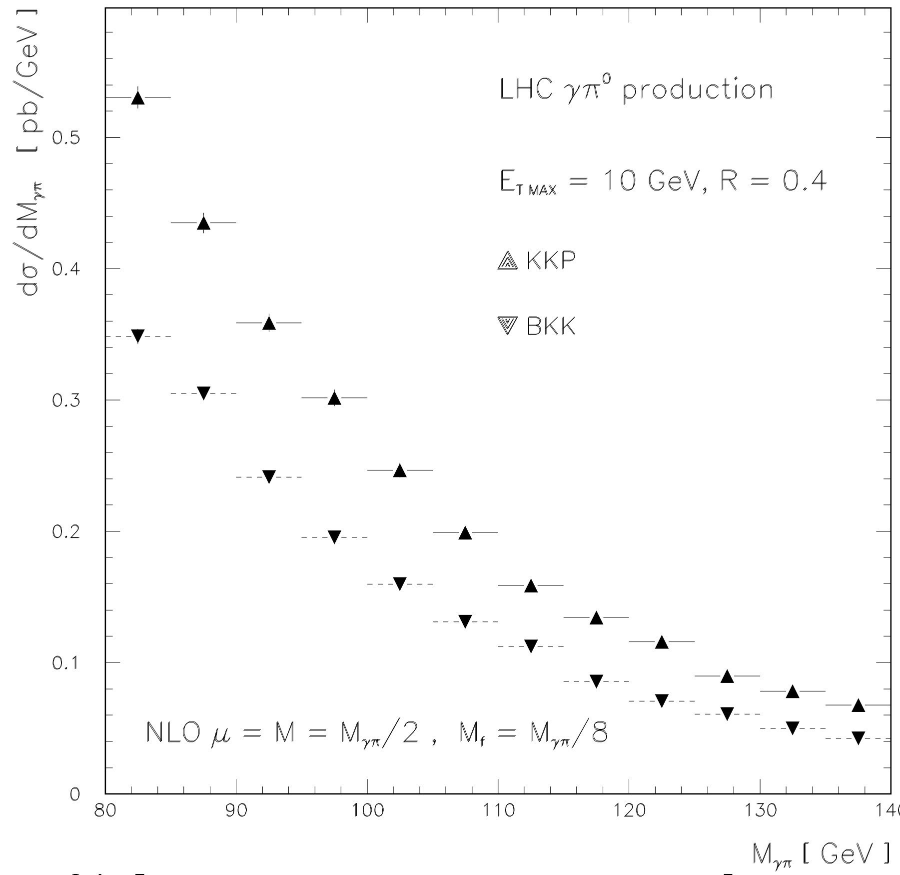
$D_{\pi/q,g}(z)$ is only constrainte for $0.1 < z < 0.7$!!!

Danger of large logarithms $\log(1-z)$

$\sigma \sim A \log^2(1 - z_{min}) + B \log(1 - z_{min}) + \ldots \rightarrow$ resummation !!!

Uncertainty for $\gamma\pi^0$ due to fragmentation functions





Contribution of the fragmentation part $\sim 10\%$ $[E_{T\,max} = 10$ GeV, $R = 0.4]$

Uncertainties due to higher order effects $\sim \pm 40 - 50\%$

Uncertainty due to fragmentation functions $\sim \pm 50\%$ (???)

!!! Measurement of high p_T pions at Tevatron necessary !!!

Higgs discovery potential including NLO corrections

[see also: Bern, Dixon, Schmidt, Phys. Rev. D66 (2002)]

combine DIPHOX background with $gg \to H \to \gamma\gamma$ at NLO
(interference effects negligible, $\Gamma_H << M_H$)

Example: $M_H = 118$ GeV, 116 GeV $< M_{\gamma\gamma} <$ 120 GeV

standard cuts + cone isolation: $R = 0.4$, $E_{T max} = 15$ GeV

$$L = 30 \text{ fb}^{-1} \Rightarrow \begin{cases} S \sim 1000 \\ B \sim 20000 \end{cases} \Rightarrow \frac{S}{\sqrt{B}} \sim 7$$

⇒ NLO corrections increase discovery potential
⇒ Beware of uncertainties in π^0 rates
⇒ "Precise" $S/\sqrt{B}$ analysis needs full experimental set–up

Summary:

- Higgs physics near a decision !!!
  - ⇒ Tevatron: sensitivity, LHC: discovery 2007+x
  - ⇒ ... keep an eye on an extended Higgs sector and heavy Higgs scenarios

- Signal and background for $H \to \gamma\gamma$ known beyond LO !!!
  - ⇒ DIPHOX code: full $H \to \gamma\gamma$ background at NLO
  - ⇒ DIPHOX describes all available data
  - ⇒ main uncertainty from $D_{\pi/q}(z)$ for $z > 0.7$ (measureable at Tevatron!)
  - ⇒ NLO corrections increase Higgs discovery potential

Only a profound knowledge of the Standard Model will allow us to understand new and unexpected phenomena !!!