Central Higgs photoproduction in photon-proton processes

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Outline

- Motivation;
- Diffractive processes;
  - Deeply Virtual Compton Scattering (DVCS);
  - Vector boson production.
- Diffractive Higgs production;
  - $\gamma\gamma$ annihilation;
  - Double Pomeron Exchange (DPE).
- The Khoze-Martin-Ryskin approach;
- Photoproduction approach: DPE in DVCS;
- Results;
- Summary.

Motivations

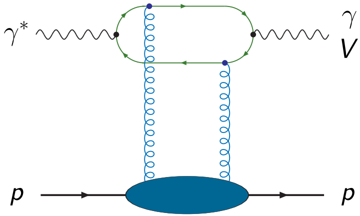
- The Higgs detection is the major plan of the CERN for the next year.
- LHC will explore a new regime $\begin{cases} \sqrt{s_{pp}} = 14 \text{ TeV} \\ \sqrt{s_{pA}} = 8.8 \text{ TeV/A} \\ \sqrt{s_{AA}} = 5.5 \text{ TeV/A} \end{cases}$ to observe:
  - Saturation regime;
  - Supersymmetry;
  - Quark-Gluon plasma, ...
  - **Higgs sector**.

- Some hadron-hadron collisions will occur with **no** strong interaction.
  - **Peripheral collisions** by photon exchange in pp/pA/AA collisions;
  - Another way to hunt the Higgs boson in heavy-ion collisions.
- Other processes of Higgs production are under study.
  - Pomeron exchange provides the Higgs production in diffractive processes.

Diffractive processes

Deeply Virtual Comptom Scattering and Vector meson production

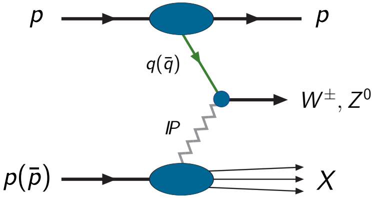
- **1991**: Ji
  PRD **55** (1997) 7114
- **2001**: Munier, Staśto and Mueller
  NPB **603** (2001) 427



$Q^2 = 27$ GeV^2, $x \sim 10^{-3}$ { ρ^0-meson at **HERA**; **MSM**: $\frac{d\sigma_L}{dt}\Big|_{t=0} =$ **20 nb/GeV^2** }

Pomeron flux in Single Diffraction Vector boson production

- **2007**: Gay Ducati, Machado and Machado
  PRD **75** (2007) 114013

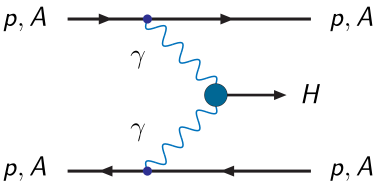


$x_{I\!P} = 0.003$, $\sqrt{s} = 1.8$ TeV, $\eta_e = 0$ { **GDMM:** $\frac{d\sigma^{\text{inc}}}{d\eta_e} = 100$ pb; $\frac{d\sigma^{\text{diff}}}{d\eta_e} =$ **10 pb** }

Diffractive Higgs production in *pp* collisions

Electromagnetic production

- **1990**: Cahn and Jackson
  PRD **42** (1990) 3690
  Müller and Schramm
  PRD **42** (1990) 3699
- **2007**: Miller
  arXiv:0704.1985[hep-ph]



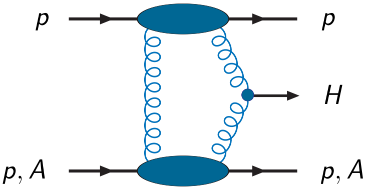
$M_H = 150$ GeV, $\sqrt{s} = 3.2$ TeV/A: **CJ**: $\sigma_{\rm PbPb} = 7.0$ pb; **MS**: $\sigma_{\rm AA} \sim 100$ pb

$M_H = 120$ GeV, $\sqrt{s} = 14$ TeV: **M**: $\sigma_{\rm pp} =$ **0.1 fb**

Double Pomeron Exchange

- **1991**: Bialas and Landshoff
  PLB **256** (1991) 540
- **1997**: Khoze, Martin and Ryskin
  PLB **401** (1997) 330

  2008: Levin and Miller
  arXiv:0801.3593[hep-ph]



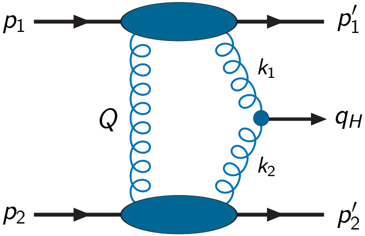
$M_H = 150$ GeV, $\sqrt{s} = 16$ TeV: **BL**: $\sigma_{\rm pp} = 0.1$ pb

$M_H = 120$ GeV, $\sqrt{s} = 14,\ 5.5(8.8)$ TeV/A: **KMR**: $\sigma_{\rm pp}^{\rm exc/inc} \sim$ **1.0**/300 fb; **LM**: $\sigma_{\rm pA(AA)} = 100(3.9)$ pb

Close looking to the KMR approach

Khoze, Martin and Ryskin
PLB **401** (1997) 330

- The hadronic processes at high energies can be phenomenologically described by the exchange of **pomerons** in the t-channel.
- **Higgs**: the protons can exchange pomerons to produce the Higgs **centrally**.
- The KMR approach is described by the Feynman diagram



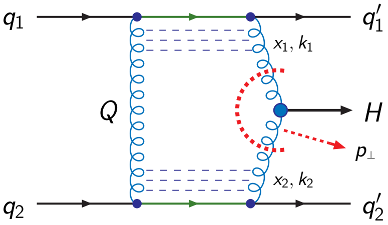
Khoze, Martin and Ryskin
EPJC **14** (2000) 525

- Color charge is **not** exchanged between the protons.
  - The gluon vertices do **not** change the quantum numbers of the protons.
    - The left line **neutralizes** the color charge of the interaction.

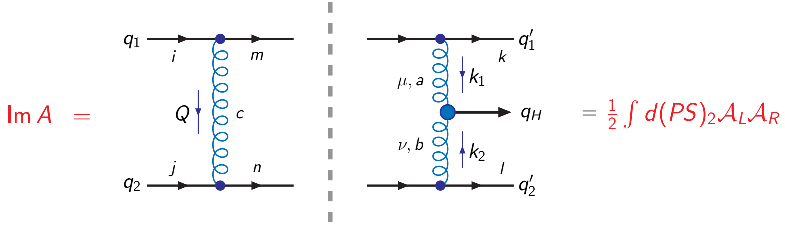
Parton level

Forshaw
hep-ph/0508274 (2005)

- Considering the partonic process, the gluons are exchanged between the quark content of the protons.
- As the Higgs is a heavy particle, its production is computed in the high-s limit.
  - The quark exchange in the t-channel is **suppressed** by a factor $\ln(1/s)$.
- To compute the pp collision, the gluon evolution is represented by a gluon ladder coupled to the protons (dashed lines).
- The **gluon radiation** need be suppressed from the ggH vertex since it can populate the final state. (dotted lines)



Scattering amplitude



- The scattering amplitude is computed by the Cutkosky rules

$$\mathrm{Im}\,A^{ik}_{jl} = \frac{1}{2}\int d(PS)_2\,\delta([q_1-Q]^2)\,\delta([q_2+Q]^2)\,\mathbf{2}\left[\frac{2gq_1^{\alpha}\,2gq_{2\alpha}}{Q^2}\,\frac{2gq_1^{\mu}}{k_1^2}\,\frac{2gq_2^{\nu}}{k_2^2}\right]\left(\tau^c_{im}\tau^c_{jn}\tau^a_{mk}\tau^b_{nl}\right)\,V^{ab}_{\mu\nu}$$

  - $d(PS)_2$: volume element of the 2-body phase space $= \frac{s}{2}\int \frac{d^2\mathbf{Q}}{(2\pi)^2}\,d\alpha d\beta$
  - $\delta([\ldots]^2)$: four-momentum conservation in the cut line;
  - τ^a_{mn}: Gell-Mann color matrices;
  - $V^{ab}_{\mu\nu}$: $gg \to H$ vertex mediated by a top-quark loop.
  - 2: Higgs produced in both sides of the cut.

Sudakov parametrization

Forshaw
hep-ph/0508274 (2005)

- The gluon four-momentum is decomposed under two base vectors q_1 and q_2

$$Q^\mu = \alpha q_1^\mu + \beta q_2^\mu + Q_\perp^\mu \qquad Q^2 \approx -\mathbf{Q}^2 \qquad \begin{cases} q_i^2 = 0 & q_1 \cdot q_2 = s/2 \\ Q_\perp = (0, Q_x, Q_y, 0) \equiv (0, \mathbf{Q}, 0) \end{cases}$$

- The delta functions present in the scattering amplitude are defined under the **on-mass shell condition** of the quark lines

$$(q_1 - Q)^2 = 0 \quad \therefore \quad q_1^2 - 2q_1 \cdot Q + Q^2 \approx -\beta s - \mathbf{Q}^2 = 0 \quad \therefore \quad \beta = -\mathbf{Q}^2/s \ll 1$$

$$(q_2 + Q)^2 = 0 \quad \therefore \quad q_2^2 + 2q_2 \cdot Q + Q^2 \approx \alpha s - \mathbf{Q}^2 = 0 \quad \therefore \quad \alpha = \mathbf{Q}^2/s \ll 1$$

- The other two gluon lines can be parametrized in the same way

$$k_i = x_i q_i + k_\perp,$$

which determines the **transfer momentum**

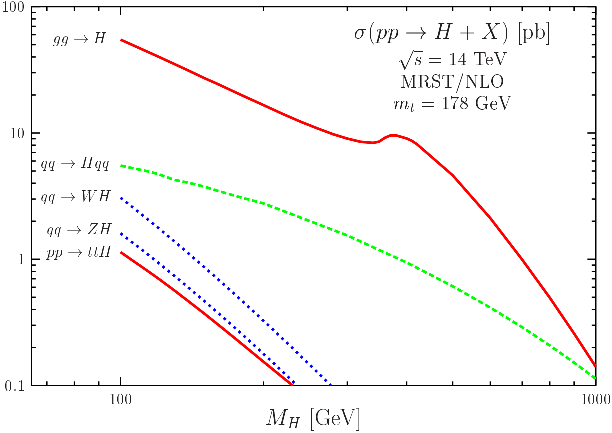
$$t = (k_1 - k_2)^2 \approx 2k_1 \cdot k_2 \approx x_1 x_2 s \approx M_H^2$$

and $x_i = M_H/\sqrt{s}$.

Higgs production

A. Djouadi
Czech. J. Phys. Suppl. **54** (2004) A1

- The *gg* **fusion** has the highest cross section for Higgs production in LHC

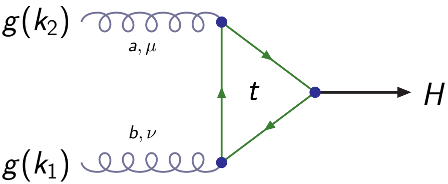


$\sigma_H =$ **10 - 100 pb** $\to$ $M_H =$ **100 - 300 GeV**

The effective vertex

Kniehl
Phys. Rept. **240** (1994) 211

- The Higgs production through gg fusion is mediate by a **top-quark loop**



- Through perturbative QCD, this vertex is given by

$$V_{\mu\nu}^{ab} = F\left(\frac{M_H^2}{m_t^2}\right)\left[g_{\mu\nu} - \frac{k_{2\mu}k_{1\nu}}{k_1 \cdot k_2}\right]\delta^{ab}$$

- Considering the mass range expected to detect the Higgs boson, the function F can be approximated as

$$F\left(\frac{M_H^2}{m_t^2}\right) \approx \frac{2}{3}\frac{M_H^2\alpha_s}{4\pi v}$$

Forshaw
hep-ph/0508274 (2005)

for $M_H \lesssim 200$ GeV.

Experimental accessibility

Forshaw
hep-ph/0508274 (2005)

- The two fusing gluons are transversely polarized, i.e.

$$\varepsilon_i \sim k_{i\perp}$$

- Considering that the outgoing quarks have **no** transverse momentum, one concludes that

$$Q_\perp = -k_{1\perp} = k_{2\perp}$$

thus

$$\varepsilon_1 = -\varepsilon_2$$

- **Conclusion**: Higgs does not has z-component of angular momentum if

$$q'^2_{i\perp} \ll Q^2_\perp$$

i.e., the quarks scatter through **zero angle**.

- Consequence: the Higgs decay in a $b\bar{b}$ pair is now **viable**, since
  - The LO $b\bar{b}$ background is **suppressed** by a factor of $\sim m_b^2/M_H^2 \sim 10^{-5}$.

Scattering amplitude

- Performing the products, one gets the imaginary part of the amplitude as

$$\frac{\mathrm{Im}\,\mathcal{A}}{s} \approx \left(\frac{4C_F}{3N_c}\,\frac{\alpha_s^3}{4\pi\upsilon}\right)\int d^2\mathbf{Q}\left[-\frac{\mathbf{k}_1\cdot\mathbf{k}_2}{\mathbf{Q}^2\mathbf{k}_1^2\mathbf{k}_2^2}\right]$$

- The cross section reads

$$\frac{d\sigma}{d^2\mathbf{q}_1'\,d^2\mathbf{q}_2'\,dy_{\mathrm{H}}} \approx \left(\frac{4C_F}{3N_c}\right)^2\frac{\alpha_s^6\,G_F}{2\sqrt{2}\,\pi}\left[\int\frac{d^2\mathbf{Q}}{(2\pi)^3}\,\frac{\mathbf{k}_1\cdot\mathbf{k}_2}{\mathbf{Q}^2\mathbf{k}_1^2\mathbf{k}_2^2}\right]^2$$

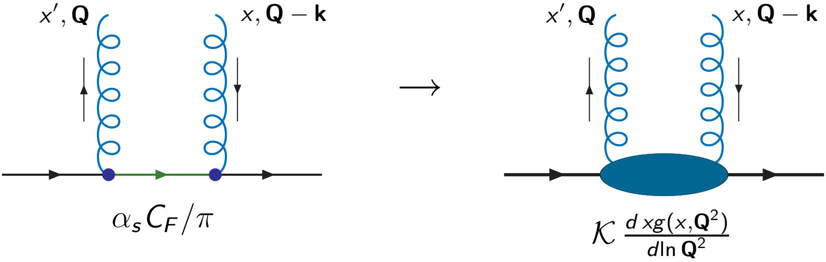
- Reminding the scattering of the protons in **zero angle**, only the forward amplitude is important and leaves one to approximate

$$\frac{\mathbf{k}_1\cdot\mathbf{k}_2}{\mathbf{Q}^2\mathbf{k}_1^2\mathbf{k}_2^2} \approx -\frac{1}{\mathbf{Q}^4}$$

- Finally, the **partonic** cross section for diffractive Higgs production reads

$$\frac{d\sigma}{d\mathbf{q}_1'^2\,d\mathbf{q}_2'^2\,dy_{\mathrm{H}}} \approx \frac{1}{9}\,\frac{\alpha_s^2\,G_F}{128\sqrt{2}\pi}\left[\int\frac{d^2\mathbf{Q}}{\mathbf{Q}^4}\left(\frac{\alpha_s C_F}{\pi}\right)\left(\frac{\alpha_s C_F}{\pi}\right)\right]^2$$

Parton → Hadron



- The hadron coupling is represented by a **non-diagonal** PDF

$$\frac{\alpha_s C_F}{\pi} \longrightarrow f_g(x,\mathbf{Q}^2) = \mathcal{K}\left(\frac{\partial[xg(x,\mathbf{Q}^2)]}{\partial \ln \mathbf{Q}^2}\right)$$

Khoze, Martin and Ryskin
PLB **401** (1997) 330

- The $\mathcal{K}$ factor takes into account the non-diagonality of the PDF.
  - It is equal to unit if $x = x'$ and $\mathbf{k} = 0$: **diagonal limit**

Proton-Pomeron coupling

Shuvaev *et al*
PRD **60** (1999) 014015

- The KMR approach states that

$$x' \ll x \quad \text{and} \quad \mathbf{k}^2 \ll \mathbf{Q}^2$$

  and the non-diagonality is approximated by a multiplicative factor

$$\mathcal{K} = (1.2)\exp(-B\,\mathbf{q}_i'^2/2)$$

  where the slope is $B = 5.5\ \text{GeV}^{-2}$.

  - The cross section is **enhanced** by a factor of $(1.2)^4 \approx 2$.

- Proton-pomeron coupling: coupling of the gluon ladder to the proton.

- $t = 0$ is **not** a sufficient condition to identify the gluon distribution $f_g(x, \mathbf{Q}^2)$.

  - The gluon ladder exchanges longitudinal momentum $(\mathbf{k}^2)$
  - Observing that $|t_{\min}| = m_p^2 x^2 \sim 0$ and taking

$$x = \frac{M_H}{\sqrt{s}} \sim 0.01$$

    one can identify the unintegrated distribution $f_g(x, \mathbf{Q}^2)$.

The cross section

- Including the phenomenological aspects, the cross section reads

$$\frac{d\sigma}{d\mathbf{q}_1' d\mathbf{q}_2' dy_{\mathrm{H}}} \approx \frac{(1.2)^4}{9} \left(\frac{\alpha_s^2 \, G_F}{128\sqrt{2}\pi} \right) e^{-2B(\mathbf{q}_1'^2 + \mathbf{q}_2'^2)} \left[\int \frac{d^2\mathbf{Q}}{\mathbf{Q}^4} f_g(x_1, \mathbf{Q}^2) f_g(x_2, \mathbf{Q}^2) \right]^2$$

- Integrating over the momenta $\mathbf{q}_i'^2$, one gets

$$\left.\frac{d\sigma}{dy_{\mathrm{H}}}\right|_{y_H=0} \approx \frac{1}{256\pi B^2} \frac{\alpha_s^2 \, G_F \sqrt{2}}{9} \left[\int \frac{d^2\mathbf{Q}}{\mathbf{Q}^4} f_g(x_1, \mathbf{Q}^2) f_g(x_2, \mathbf{Q}^2) \right]^2$$

- The event rate is accounted for central production ($y_H = 0$).
- The integrand is infrared divergent in the limit of low momentum ($\mathbf{Q}^2 \to 0$)
  - This effect occurs since the virtual diagrams were not accounted which contribute with terms of

$$\ln\left(\frac{\mathbf{Q}}{M_H}\right)$$

which has a high contribution as $\mathbf{Q} \to 0$.

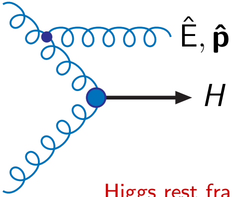
Phenomenology inside

Gluon Radiation Forshaw, hep-ph/0508274

- The real gluon emission from the ggH vertex needs to be **suppressed**.
  - Summation of virtual graphs that include terms like $\ell n\,(\mathbf{Q}/M_H)$.
- The emission probability of 1-gluon is computed by **Sudakov form factors**

$$S(\mathbf{Q}^2, M_H^2) = \frac{N_c}{\pi}\int_{\mathbf{k}^2}^{M_H^2/4}\frac{\alpha_s(\hat{\mathbf{p}}^2)}{\hat{\mathbf{p}}^2}\,d\hat{\mathbf{p}}^2\int_{\hat{\mathbf{p}}}^{M_H/2}\frac{d\hat{\mathrm{E}}}{\hat{\mathrm{E}}} = \frac{3\alpha_s}{4\pi}\,\ell n^2\left(\frac{M_H^2}{4\mathbf{Q}^2}\right)$$

- Real emissions are **not suppressed** if the gluon color neutralization **fails**.
- Suppressing many gluons emission:
  - It is included a factor e^{-S} to the cross section.
    - Emissions below $\mathbf{Q}^2$ are **forbidden**.
  - As $\mathbf{Q}^2 \to 0$ the non-emission probability goes to zero **faster** than any power of $\mathbf{Q}$, like $\mathbf{Q}^{-4}$.



Higgs rest frame

The final event rate

- Multiple emissions exponentiate and the non-emission probability is included in the cross section

$$\frac{d\sigma}{dy_H} \approx \frac{1}{B^2}\left[\int \frac{d\mathbf{Q}^2}{\mathbf{Q}^4} f_g(x_1,\mathbf{Q}^2) f_g(x_2,\mathbf{Q}^2)\, e^{-S(M_H^2,\mathbf{Q}^2)}\right]^2$$

- As $\mathbf{Q}$ reaches the infrared limit the exponent diverges and e^{-S} vanishes faster than any power of $\mathbf{Q}$.
  - **The integral becomes finite**.
- If one considers the **running coupling constant**, the non-emission probability includes **single** logarithms

$$e^{-S(M_H^2,\mathbf{Q}^2)} = \exp\left(-\int_{\mathbf{Q}^2}^{M_H^2/4} \frac{d\hat{\mathbf{p}}^2}{\hat{\mathbf{p}}^2}\frac{\alpha_s(\hat{\mathbf{p}}^2)}{2\pi}\int_0^{1-2\hat{\mathbf{p}}/M_H} dz\left[zP_{gg}(z)+\sum_q P_{qg}(z)\right]\right)$$

  - $P_{ij}(z)$: DGLAP splitting functions.
- Hence, the non-emission probability is included in the unintegrated distribution

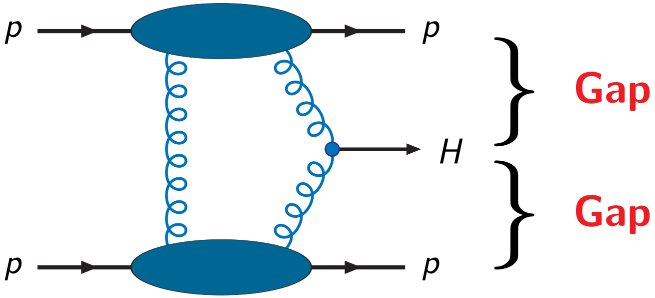
$$\tilde{f}(x,\mathbf{Q}^2) = \frac{\partial}{\partial \ln \mathbf{Q}^2}\left[e^{-S/2} xg(x,\mathbf{Q}^2)\right]$$

Phenomenology inside

Rapidity Gaps KMR, EPJC **18** (2000) 167; Gotsman, Levin, Maor, arXiv:0708.1506[hep-ph]

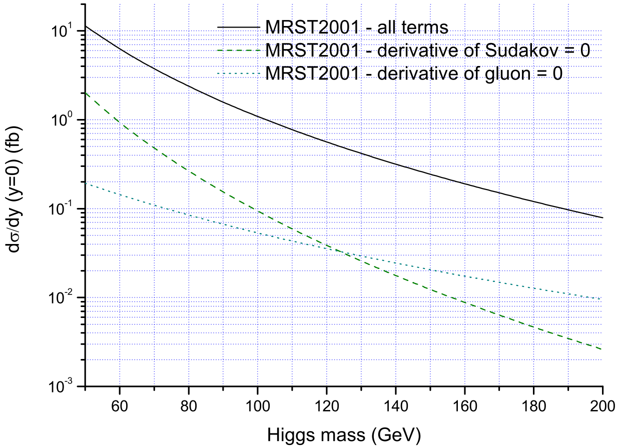
- The **Rapidity Gap Survival Probability** is calculated by

$$S^2_{\text{gap}} = \frac{\int |\mathcal{A}(s,b)|^2 \, e^{-\Omega(b)} \, d^2\mathbf{b}}{\int |\mathcal{A}(s,b)|^2 \, e^{-\Omega_0} \, d^2\mathbf{b}} = \begin{cases} 5\% \text{ Tevatron} \\ 2.7 - 3\% \text{ LHC} \end{cases}$$



Results: cross section for central rapidity

- The cross section for $y_H = 0$ is obtained considering $\begin{cases} x\partial g(x, Q^2)/\partial Q^2 = 0 \\ \partial S/\partial Q^2 = 0 \end{cases}$

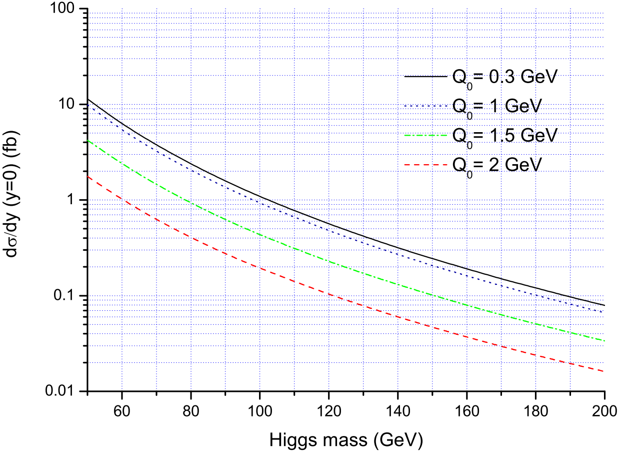


$Q_0^2 = 0.3$ GeV

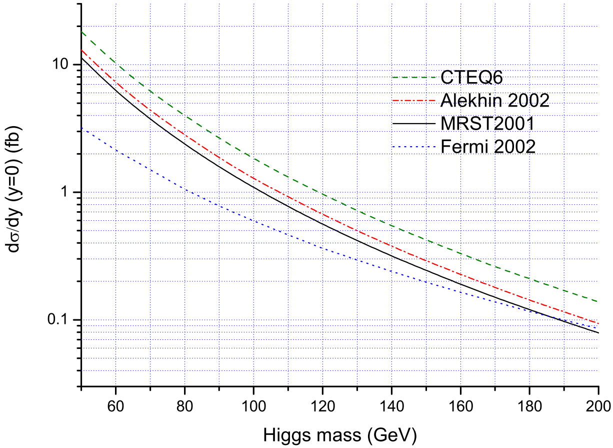
- **Single logarithms**: a enhancement of a factor $\sim$ **30** in the cross section.

Results: the cutoff sensibility

- The cross section is almost insensitive to a cutoff $Q_0^2 < 1$ GeV.
- However, for $Q_0^2 = 2$ GeV the results are **5x** lower than for $Q_0^2 = 1$ GeV.

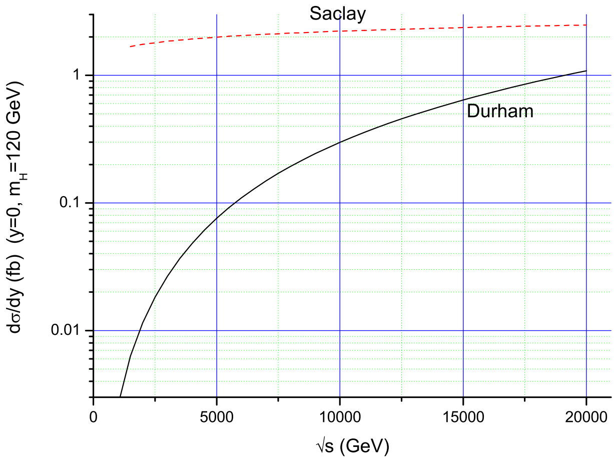


Results: Global fits



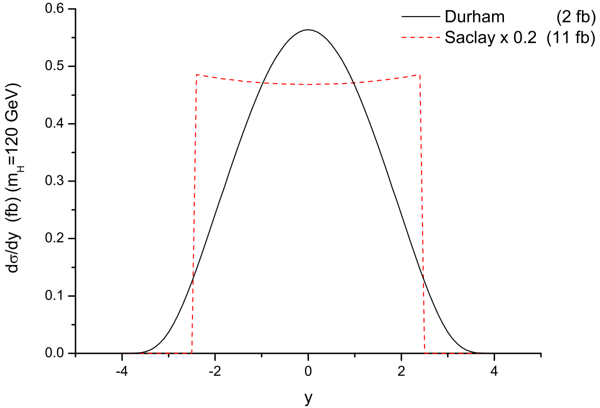
- All PDFs are evolved from an initial scale: $Q_0^2 = 0.3$ GeV.
- CTEQ6 and Fermi2002 above and over the MRST results, respectively.

Results: Energy dependence



- The Saclay approach computes the cross section with a **soft pomeron exchange**.

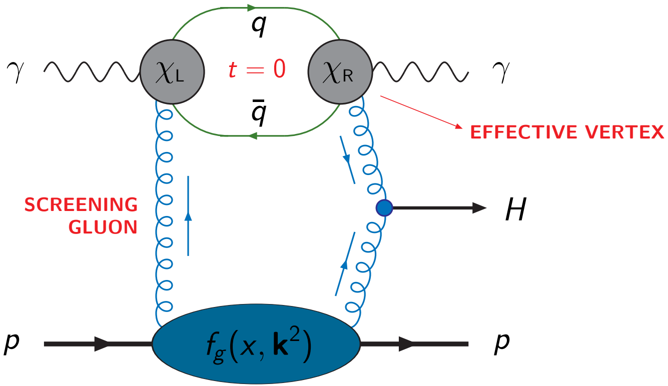
Results: Rapidity distribution



- The dependence on the rapidity y_H is present in $x_i = \left(M_H/\sqrt{s}\right)\exp(\pm y_H)$.
- The Durham prediction **falls** as y_H increases since a larger value of x is probed.
- Saclay: almost y_H-**independent** with a cutoff in any integration over rapidity.

Diffractive Higgs photoproduction

- **Proposal**: γp process by **DPE** in pp collision.



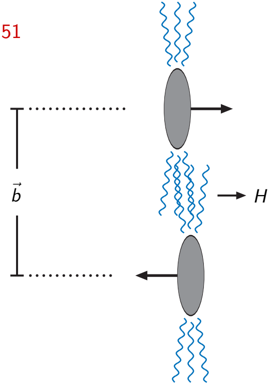
- The loop is treated in **impact factor formalism** at $t = 0$.
- $H\gamma$ final state: study the b-quark density in the proton.

Gabrielli, Mele and Rathsman, PRD **77** (2008) 015007

Higgs production in Peripheral Collisions

- The γp process is a subprocess in peripheral *pp* collisions

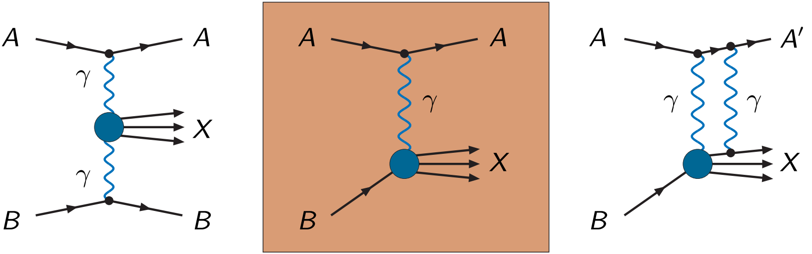
C.A. Bertulani
Heavy Ion Phys. **14** (2001) 51



- **Impact parameter**: $|\vec{b}| > 2R$ → **NO STRONG INTERACTION!**
- Only EM force acts in the second proton → **REAL PHOTONS**

Peripheral photons

Baur, Hencken and Trautman
J. Phys. **G24** (1998) 1657



- The **photon virtuality** is related to the nucleus radius: coherent action of the charged particles

$$Q^2 \lesssim 1/R^2$$

  - In the **proton case**: $Q^2 \lesssim 10^{-2}$ GeV^2.

COHERENCE CONDITION

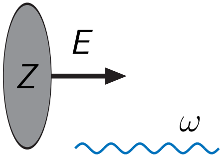
- **Uncertainty principle**: upper limit to the photon transverse momentum

$$\mathbf{Q} \lesssim \frac{1}{R} \approx \begin{cases} 28 \text{ MeV, Pb beam} \\ 330 \text{ MeV, proton beam} \end{cases}$$

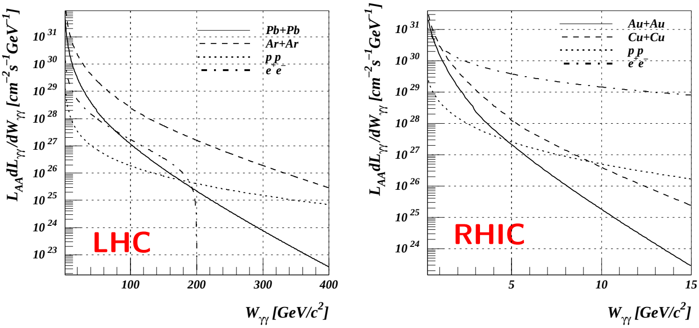
Photon spectra

Hencken *et al*, PRept. **458** (2008) 1

- The energy fraction of the photon related to the the incident nucleus obey the **coherence condition**



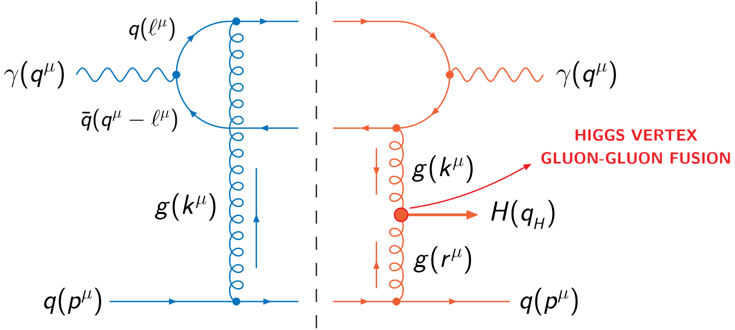
$$x_\gamma = \frac{\text{photon energy}}{\text{beam energy}} = \frac{\omega}{E} \begin{cases} x_\gamma \lesssim 10^{-3}, \text{Ca} \\ x_\gamma \lesssim 10^{-4}, \text{Pb} \end{cases}$$



- The photon distribution is **strongly** suppressed at high energies.

Scattering amplitude

- **Partonic process**: $\gamma q \to \gamma + H + q$



- The scattering amplitude is obtained by the **Cutkosky Rules**

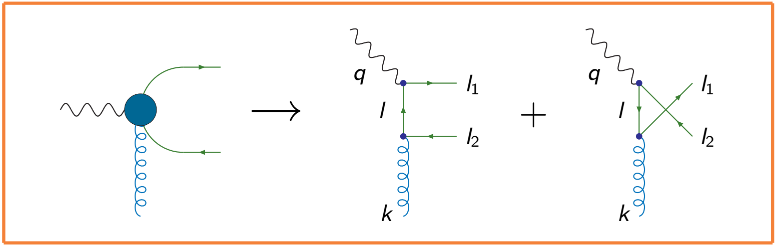
$$\mathrm{Im}\,\mathcal{A} = \frac{1}{2}\int d(PS)_3\, \mathcal{A}_{(left)}\, \mathcal{A}_{(right)}$$

Photon impact factor

- The color dipole is composed of two effective vertices to the γg coupling

$$\chi_L^{\mu\nu} = -ig_s\, ee_q\, t^a \left\{ \gamma^\mu \left[\frac{\not{l}_1 - \not{q}}{(l_1 - q)^2} \right] \gamma^\nu - \gamma^\nu \left[\frac{\not{l}_1 - \not{k}}{(l_1 - k)^2} \right] \gamma^\mu \right\}$$

$$\chi_R^{\lambda\eta} = -ig_s\, ee_q\, t^b \left\{ \gamma^\lambda \left[\frac{\not{k} - \not{l}_2}{(k - l_2)^2} \right] \gamma^\eta - \gamma^\eta \left[\frac{\not{q} - \not{l}_2}{(q - l_2)^2} \right] \gamma^\lambda \right\}$$



- Photon polarization vectors for $t = 0$:

$$\epsilon_\mu^L \epsilon_\nu^L = \frac{4Q^2}{s} \frac{p_\mu p_\nu}{s} \quad \text{and} \quad \sum \epsilon_\mu^T \epsilon_\nu^{T*} = -g_{\mu\nu} + \frac{4Q^2}{s} \frac{p_\mu p_\nu}{s}$$

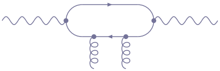
Applying the rules

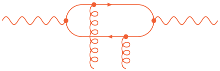
- Performing the product of the two sides of the cut one gets

$$\mathcal{A}_L\mathcal{A}_R = (4\pi)^3\,\alpha_s^2\,\alpha\left(\sum_q e_q^2\right)\left(\frac{\epsilon_\mu\epsilon_\lambda^*}{k^6}\right)\overbrace{\frac{V_{\sigma\eta}^{ba}}{N_c}}^{\text{ggH}}\left(t^b t^a\right)\overbrace{4p_\nu p^\sigma}^{\text{eikonal}}$$

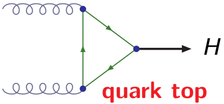
$$\times\ 2\left\{\frac{\mathrm{Tr}\left[(\not{q}-\not{l})\gamma^\mu\not{l}\gamma^\nu(\not{k}+\not{l})\gamma^\eta\not{l}\gamma^\lambda\right]}{l^4}+\frac{\mathrm{Tr}\left[(\not{q}-\not{l})\gamma^\nu(\not{k}+\not{l}-\not{q})\gamma^\mu(\not{k}+\not{l})\gamma^\eta\not{l}\gamma^\lambda\right]}{l^2(k+l+q)^2}\right\}$$

OTHER POSSIBILITIES





- For a **non-heavy Higgs** ($M_H \lesssim 200$ GeV), the ggH vertex reads



quark top loop

$$V_{\mu\nu}^{ab} \approx \frac{2}{3}\frac{M_H^2\alpha_s}{4\pi v}\left(g_{\mu\nu}-\frac{k_{2\mu}k_{1\nu}}{k_1\cdot k_2}\right)\delta^{ab}$$

Forshaw, hep-ph/0508274

Vector decomposition

- The Sudakov parametrization gets to the following decomposed vectors

$$\begin{aligned} \ell^\mu &= \alpha_\ell q'^\mu + \beta_\ell p^\mu + \ell_\perp^\mu \\ k^\mu &= \alpha_k q'^\mu + \beta_k p^\mu + k_\perp^\mu \\ r^\mu &= \alpha_r q'^\mu + \beta_r p^\mu + r_\perp^\mu \end{aligned}$$

- The denominators in $\mathcal{A}_L \mathcal{A}_R$ can be rewritten as

$$l^2 = -\left[\frac{\alpha_\ell(1-\alpha_\ell)Q^2 + \mathbf{l}^2}{1-\alpha_\ell}\right] \equiv -\frac{D_1}{1-\alpha_\ell}$$

$$(l+k-q)^2 = -\left[\frac{\alpha_\ell(1-\alpha_\ell)Q^2 + (\mathbf{l}+\mathbf{k})^2}{\alpha_\ell}\right] \equiv -\frac{D_2}{\alpha_\ell}.$$

- Considering that the gluons are **purely** transverse, one has

$$k^2 \simeq -\mathbf{k}^2$$
$$r^2 \simeq -\mathbf{r}^2 \approx -\mathbf{k}^2$$

The implication of the δ functions

- The volume element of the **three-body phase space** reads

$$\int d(PS)_3 = \frac{1}{(2\pi)^5} \int d^4l\, d^4k\, \delta([q-\ell]^2)\, \delta([\ell+k]^2)\, \delta([p-k]^2)$$

which corresponds in the Sudakov parametrization

$$\begin{aligned} \int d(PS)_3 &= \int d\alpha_\ell\, d\beta_\ell\, d^2\mathbf{l} \int d\alpha_k\, d\beta_k\, d^2\mathbf{k} \\ &\times \delta\left[\beta_\ell + \frac{Q^2}{s} + \frac{\mathbf{l}^2}{s(1-\alpha_\ell)}\right] \delta\left[\beta_k + \frac{(\mathbf{l}+\mathbf{k})^2}{\alpha_\ell s} + \beta_\ell\right] \delta[\alpha_k s + \mathbf{k}^2]. \end{aligned}$$

- Performing the integration over the delta functions, one finds the coefficients of the **quark** and **gluon** four-vectors

$$l^\mu = \alpha_\ell q'^\mu - \left(Q^2 + \frac{\mathbf{l}^2}{1-\alpha_\ell}\right) \frac{p^\mu}{s} + l_\perp^\mu$$

$$k^\mu = -\frac{\mathbf{k}^2}{s} q'^\mu + \left[Q^2 + \frac{\mathbf{l}^2}{1-\alpha_\ell} + \frac{(\mathbf{l}+\mathbf{k})^2}{\alpha_\ell}\right] \frac{p^\mu}{s} + k_\perp^\mu$$

The amplitude in parton level

- The imaginary part of the amplitude has the form

$$\frac{\mathrm{Im}\,\mathcal{A}}{s} = -\frac{4}{9}\left(\frac{M_H^2\alpha_s^2\alpha}{N_c v}\right)\left(\sum_q e_q^2\right)\left(\frac{\alpha_s C_F}{\pi}\right)\int \frac{d\mathbf{k}^2}{\mathbf{k}^6}\,\mathcal{X}(\mathbf{k}^2, Q^2)$$

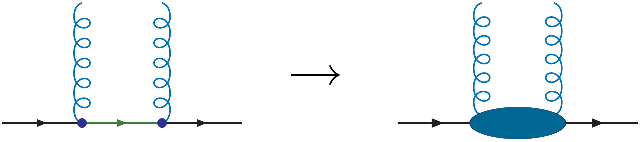
- **First remark**: dependence on $\mathbf{k}^{-6}$ due to the presence of the color dipole.
- Only the **quark contribution** $\rightarrow$ extension to the hadron coupling.
- The dependence on the photon virtuality reads

$$\mathcal{X}(\mathbf{k}^2, Q^2) \underset{Q^2\rightarrow 0}{\sim} 1 + \frac{\mathbf{k}^2}{Q^2} \rightarrow \infty$$

- Computing the event rate in central rapidity

$$\left.\frac{d\sigma}{dy_H\, d\mathbf{p}^2\, dt}\right|_{y_H,t=0} = \frac{1}{2}\left(\frac{\alpha_s^2\alpha M_H^2}{9\pi^2 N_c v}\right)^2\left(\sum_q e_q^2\right)^2\left[\frac{\alpha_s C_F}{\pi}\int \frac{d\mathbf{k}^2}{\mathbf{k}^6}\,\mathcal{X}(\mathbf{k}^2, Q^2)\right]^2.$$

Parton → Hadron



- The hadron coupling is represented by a **non-diagonal** PDF

$$\frac{\alpha_s C_F}{\pi} \longrightarrow f_g(x,\mathbf{k}^2) = \mathcal{K}\left(\frac{\partial[xg(x,\mathbf{k}^2)]}{\partial \ell n\, \mathbf{k}^2}\right)$$

Khoze, Martin and Ryskin
PLB **401** (1997) 330

- The non-diagonality is approximated by a multiplicative factor

$$\mathcal{K} = (1.2)\exp(-B\mathbf{p}^2/2)$$

Shuvaev *et al*
PRD **60** (1999) 014015

where $B = 5.5\ \mathrm{GeV}^{-2}$ is the slope of the gluon-proton form factor.

- To correctly compute the pomeron coupling to the proton: $x \sim 0.01$.

Cross section for central rapidity

- The cross section is calculated for central rapidity ($y_H = 0$)

$$\left.\frac{d\sigma}{dy_H\,dt}\right|_{y_H,t=0} = \frac{S^2_{gap}}{2\pi B}\left(\frac{\alpha_s^2\alpha M_H^2}{3N_c\pi v}\right)^2\left(\sum_q e_q^2\right)^2\left[\int_{\mathbf{k}_0^2}^{\infty}\frac{d\mathbf{k}^2}{\mathbf{k}^6}\,e^{-S(\mathbf{k}^2,M_H^2)}\,f_g(x,\mathbf{k}^2)\,\mathcal{X}(\mathbf{k}^2,Q^2)\right]^2$$

- Quark contribution[1]: $\alpha_s C_F/\pi \;\rightarrow\; f_g(x,\mathbf{k}^2) = \mathcal{K}\,\partial_{(\ell n\,\mathbf{k}^2)}\,xg(x,\mathbf{k}^2)$
- Gap Survival Probability[2]: $S^2_{gap} \rightarrow$ 3% (5%) for LHC (Tevatron)
- Gluon radiation suppression[3]: Sudakov factor $S(\mathbf{k}^2, M_H^2) \sim \ell n^2\left(M_H^2/4\mathbf{k}^2\right)$
- Cutoff $\mathbf{k}_0^2$: Necessary to avoid infrared divergencies :: $\mathbf{k}_0^2 = 1$ GeV^2.
- Electroweak vacuum expectation value: $v = 246$ GeV
- Slope of the proton-pomeron coupling: $B = 5.5$ GeV^{-2}

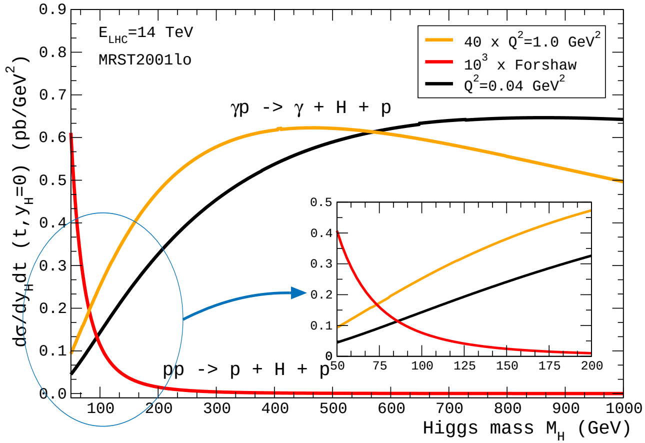
[1] Khoze, Martin, Ryskin, EJPC **14** (2000) 525

[2] Khoze, Martin, Ryskin, EJPC **18** (2000) 167

[3] Forshaw, hep-ph/0508274

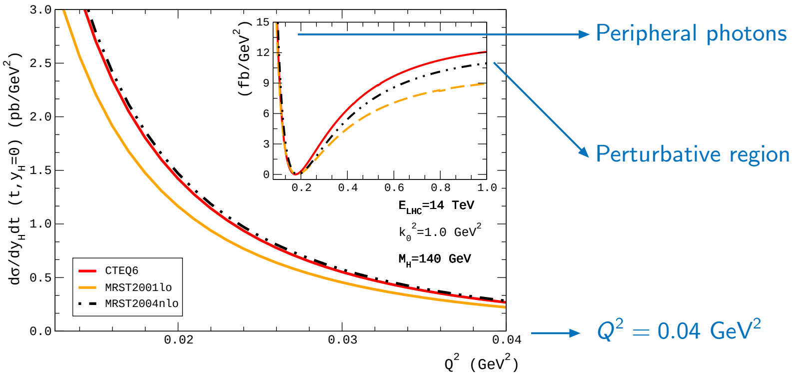
Results: pp vs. γp process

- **Higher** rate in the **mass region** expected for Higgs detection.

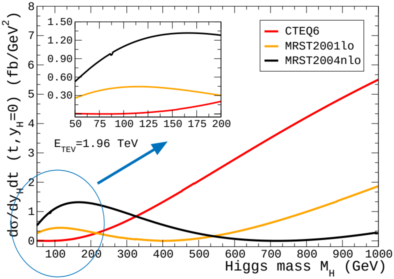


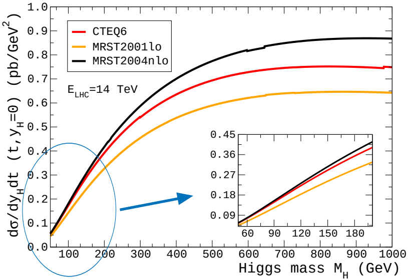
Results: Q^2-dependence

- Peripheral collisions: photon limit of $Q^2 = 0.04$ GeV^2
  - **Divergent region**: highest cross section for Higgs production
- Perturbative region: $Q^2 \sim 1$ GeV^2 KMR, hep-ph/0605189
  - **Smaller event rate**: range expected to its detection $\sigma_{exc} \sim 3$ fb.



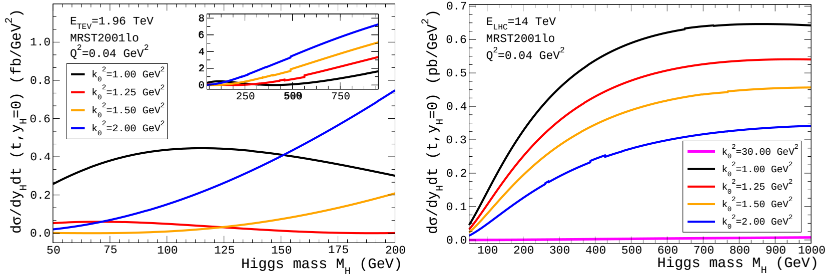
Results: Gluon distribution functions





- **Tevatron**: **Distinct** behaviors for the **LO** and **NLO** distributions;
  - Leading contribution $\begin{cases} \textbf{NLO} \rightarrow & M_H \lesssim 200 \text{ GeV} \\ \textbf{LO} \;\;\rightarrow & M_H \gtrsim 400 \text{ GeV} \end{cases}$
- **LHC**: NLO distributions show a **higher** contribution than the LO ones.

Results: Cutoff sensitivity

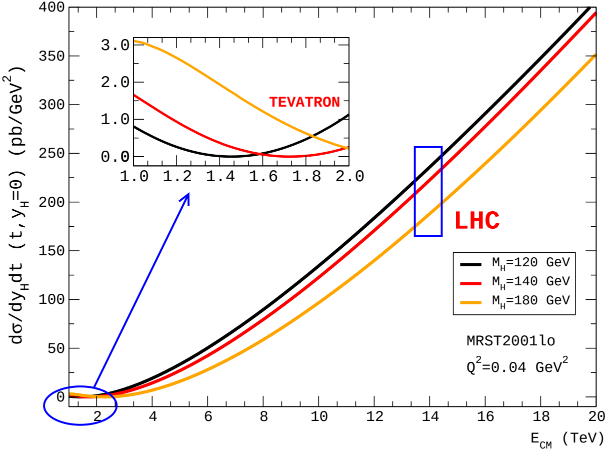


- The event rate is **3x** less sensivite on the cut $\mathbf{k}_0^2$ if compared to the previous approaches.
- The results for LHC vanishes as $\mathbf{k}_0^2$ increases:

$$\frac{d\sigma}{dt dy_H}(30\ \text{GeV}^2) \to 0$$

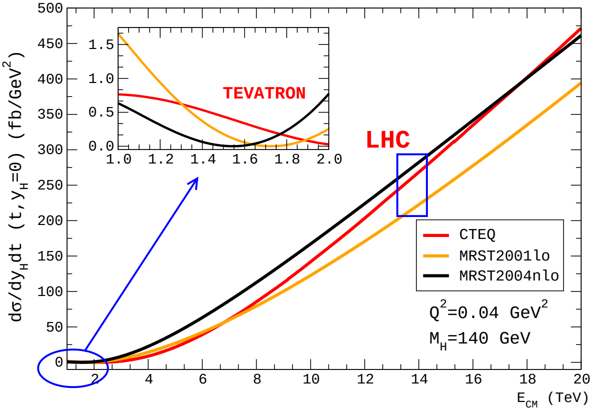
Results: Energy dependence • Higgs mass

- **Non-uniform** behavior of the event rate at Tevatron.
- Uniform and **Small** dependence on Higgs mass at LHC.



Results: Energy dependence • PDFs

- Significative distinction among the **LO** and **NLO** distributions:
  - **Same** difference in the region $\underbrace{\sqrt{s} \gtrsim 12 \text{ TeV}}_{\textbf{includes LHC}}$



Summary

- The event rate is computed for **Higgs boson production** in γp process for Peripheral Collisions at LHC:

  - $$\frac{d\sigma}{dtdy_H} \sim 600 \text{ fb/GeV}^2$$

- The event rate is **15x** higher than the rate predicted by previous results.
  - Comparison: to study the rate for pp and AA collisions.
  - A preliminary result for pp collision: $d\sigma/dy_H \sim 15$ fb ($M_H = 120$ GeV).
    - Previously: $d\sigma/dy_H \lesssim$ **1 fb**, $\sigma_{I\!PI\!P}^{\text{exc}} \sim 3.0$ fb and $\sigma_{\gamma\gamma}^{\text{exc}} = 0.1$ fb.
- It is shown a clear difference of **15%** between LO and NLO distributions in the kinematic region of LHC:
  - It assigns the importance of the **gluon recombination effects** (if the non-perturbative effects are small).
- The calculation is **3x** less sensitive to the integration cuts if compared to the KMR results.