Higgs boson @ LHC

• the diffractive opportunity •

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work with G.G. Silveira arXiv:0809.0425 [hep-ph]

Outline

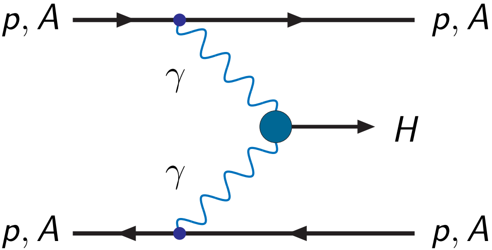
- Motivation
- Diffractive Higgs production
  - $\gamma\gamma$ annihilation
  - Double Pomeron Exchange (DPE)
- Deeply Virtual Compton Scattering (DVCS)
- Peripheral Collisions
- The KMR model
- Photoproduction approach: DPE in DVCS
- Results
- Summary

Motivation

- The existence of the Higgs boson is an open question in Particle Physics.
- LHC will allow to study a new kinematic region:
  - Center-of-mass energy: $\sqrt{s_{pp}} = 14$ TeV and $\sqrt{s_{AA}} = 5.5$ TeV/A.
  - Rapidity (CMS): $|\eta_{jets}| < 6.6$, $|\eta_{\gamma, e^{\pm}}| < 3$ and $|\eta_{\mu}| < 2.5$.
  - Luminosity : $\mathcal{L}_{pp} \sim 10^{34}$ fb^{-1} and $\mathcal{L}_{AA} \sim 10^{26}$ fb^{-1}.
  - Bjorken-x: $x \sim 10^{-4}$.
  - Higgs physics: it is expected that the pp collisions will be able to produce the Higgs boson.
- Some hadron-hadron collisions will occur with **no** strong interaction.
  - The peripheral collisions are a new way to study the Higgs boson production in $pp(AA)$ collisions.
- Other processes of Higgs production are under study to allow its detection in hadron colliders.
  - DPE allows the Higgs boson production through the leading ggH vertex mainly in the mass range $M_H \sim 115 - 200$ GeV.

Electromagnetic Higgs production

- **1990**: Cahn and Jackson — PRD **42** (1990) 3690
  Müller and Schramm — PRD **42** (1990) 3699
  - Peripheral heavy-ion collision → $\gamma\gamma$ **annihilation**
- **2007**: Miller — arXiv:0704.1985[hep-ph]
  - Contribution from **Electroweak boson loops** to the $\gamma\gamma \to H$.

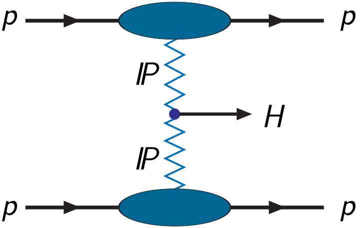


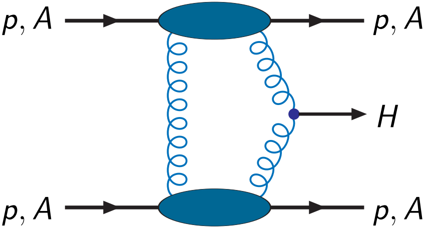
$M_H = 150$ GeV, $\sqrt{s} = 3.5$ TeV/A
- **CJ**: $\sigma_{\mathrm{PbPb}} = 7.0$ pb
- **MS**: $\sigma_{\mathrm{AA}} \sim 100$ pb

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

Diffractive Higgs production in *pp* and *AA* collisions

- **1991**: Bialas and Landshoff PLB **256** (1991) 540
  - Regge Theory → **non-perturbative gluons**
- **1997**: Khoze, Martin and Ryskin PLB **401** (1997) 330
  2007: Levin and Miller arXiv:0801.3593[hep-ph]
  - QCD Pomeron → **hard-gluon exchange**





$$\begin{matrix} M_H = 150 \text{ GeV} \\ \sqrt{s} = 16 \text{ TeV} \end{matrix} \left\{ \textbf{BL} : \sigma_{\text{pp}} = 0.1 \text{ pb} \right.$$

$$\begin{matrix} M_H = 120 \text{ GeV} \\ \sqrt{s} = 14 \ / \ 5.5 \ (8.8) \text{ TeV/A} \end{matrix} \begin{cases} \textbf{KMR} : \sigma_{\text{pp}}^{\text{exc/inc}} \sim \mathbf{1 \ fb}/300 \text{ fb} \\ \textbf{LM} : \sigma_{\text{pA(AA)}} = 100 \ (3.9) \text{ pb} \end{cases}$$

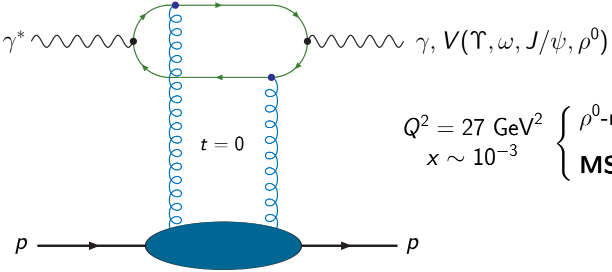
Diffractive processes within Dipole picture

Deeply Virtual Compton Scattering

- **1997**: Ji PRD **55** (1997) 7114
    - $\gamma^* p \to \gamma p$ by **Pomeron exchange** in *ep* collisions.

Vector meson production

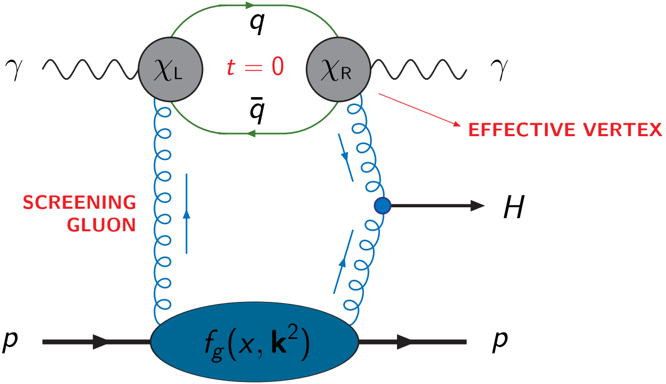
- **2001**: Munier, Staśto and Mueller NPB **603** (2001) 427
    - $\gamma^* p \to Vp$ with **GBW model**.



$$Q^2 = 27 \text{ GeV}^2 \quad x \sim 10^{-3} \quad \begin{cases} \rho^0\text{-meson at HERA} \\ \textbf{MSM} : \left.\frac{d\sigma_L}{dt}\right|_{t=0} = \mathbf{20\ nb/GeV^2} \end{cases}$$

Diffractive Higgs photoproduction

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



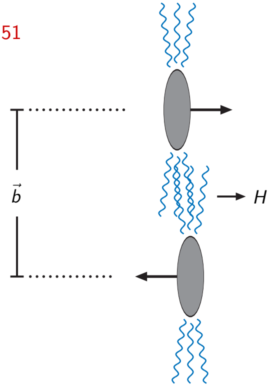
- The loop is treated in **impact factor formalism** at $t = 0$.
- $H\gamma$ final state: study the b-quark density in the proton.

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

Higgs production in Peripheral Collisions

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

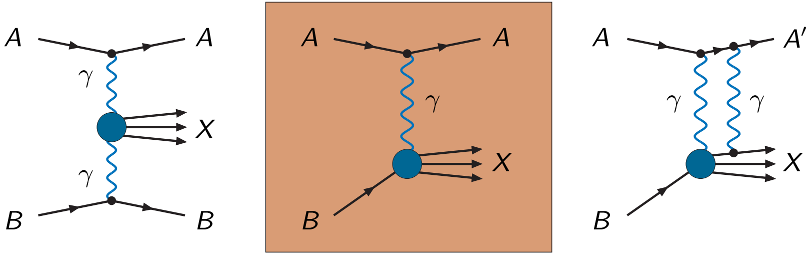
C.A. Bertulani
Heavy Ion Phys. **14** (2001) 51



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

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

COHERENCE CONDITION

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

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

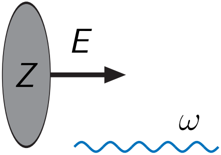
$$\mathbf{Q} \lesssim \frac{1}{R} \approx \begin{cases} 28 \text{ MeV, Pb beam} \\ 330 \text{ MeV, proton beam} \end{cases}$$

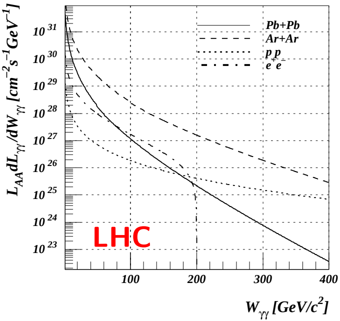
Photon spectra

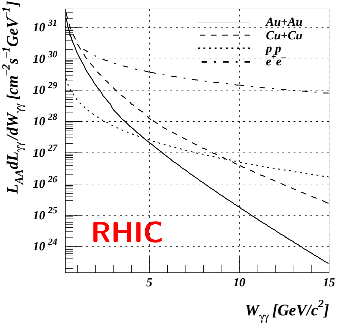
Hencken *et al*, PRept. **458** (2008) 1

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

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



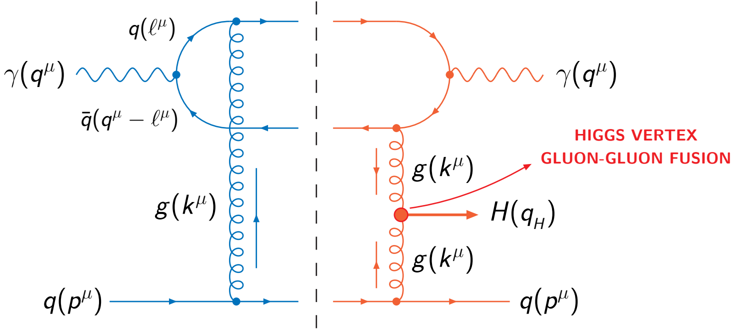




- The photon distribution is **strongly** suppressed at high energies.

Scattering amplitude

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



- 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

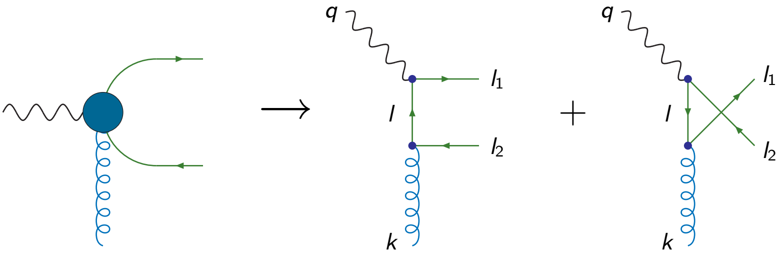
- The color dipole is composed of two effective vertices to the γg coupling

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

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

- 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

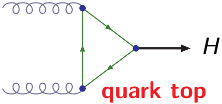
- Performing the product of the two sides of the cut one gets

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

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

OTHER POSSIBILITIES

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



quark top loop

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

Forshaw, hep-ph/0508274

The amplitude in parton level

- The imaginary part of the amplitude has the form

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

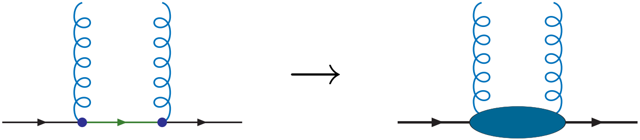
- **First remark**: dependence on $\mathbf{k}^{-6}$ due to the presence of the color dipole.
- Only the **quark contribution** → extension to the hadron coupling.
- The dependence on the photon virtuality reads

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

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

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

Phenomenology inside

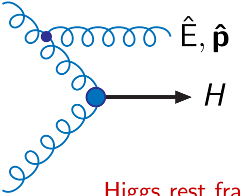
Gluon Radiation

Forshaw, hep-ph/0508274

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

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

- 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 $\mathbf{k}^2$ are **forbidden**.
  - As $\mathbf{k}^2 \to 0$ the non-emission probability goes to zero **faster** than any power of $\mathbf{k}$, like $\mathbf{k}^{-6}$.



Higgs rest frame

Phenomenology inside

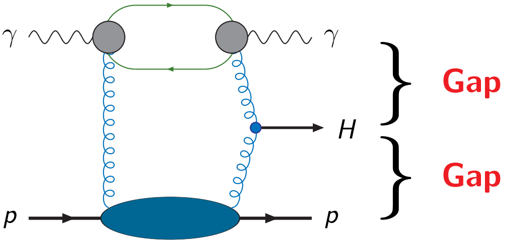
Rapidity Gaps KMR, EPJC **18** (2000) 167; Gotsman, Levin, Maor, arXiv:0708.1506[hep-ph]

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

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

  where $N = e^{-\Omega_0}$ is the relevant opacity at $\Omega = 0$.

- S^2_{gap} depends on the spatial distribution of the proton.
  - It is **controlled** by the B-slope of the gluon-proton form factor.



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
- gluon-proton form factor: $B = 5.5$ GeV^{-2}

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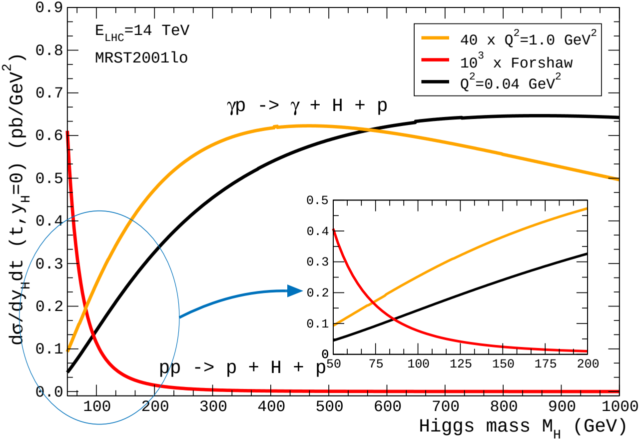
[1] Khoze, Martin, Ryskin, EJPC **14** (2000) 525

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

[3] Forshaw, `hep-ph/0508274`

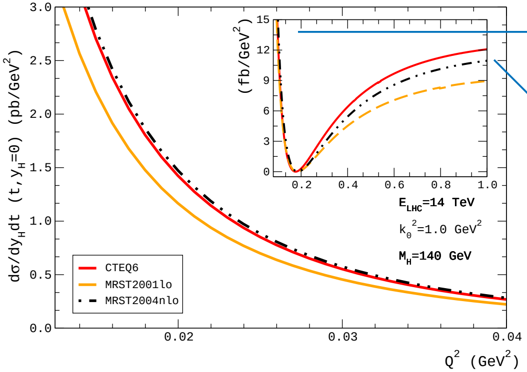
Results: *pp* vs. γp process

- **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 $\sigma_{\text{exc}} \sim 3$ fb.

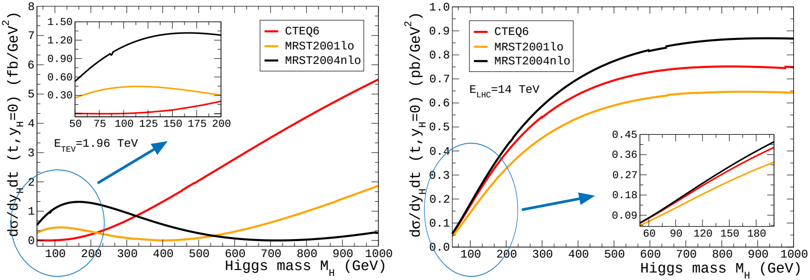


Peripheral photons

Perturbative region

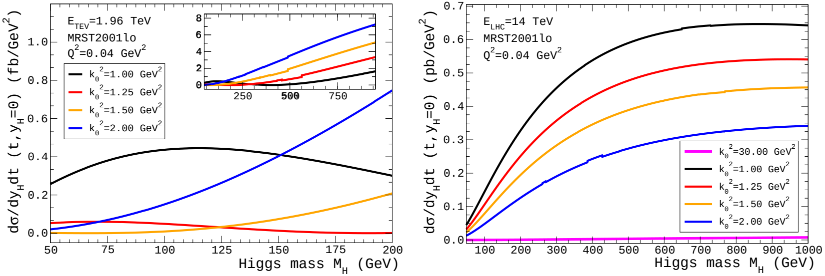
$Q^2 = 0.04$ GeV^2

Results: Gluon distribution functions



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

Results: Cutoff sensitivity



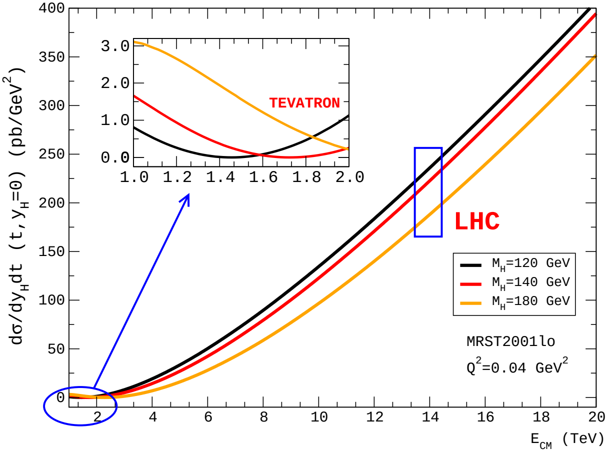
- The event rate is **5x** less sensivite on the cut $\mathbf{k}_0^2$ if compared to the previous approaches.

- The results for LHC vanishes as $\mathbf{k}_0^2$ increases:

$$d\sigma/dtdy_H(30\ \mathrm{GeV}^2) \rightarrow 0$$

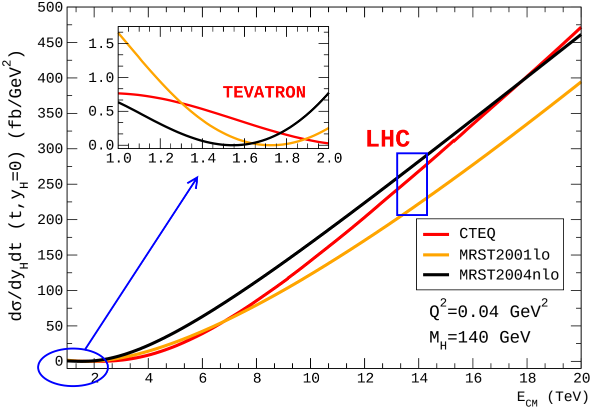
Results: Energy dependence • Higgs mass

- **Non-uniform** event-rate behavior 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

- We compute the event rate for **Higgs boson production** in γp process for Peripheral Collisions at LHC:
  - $\dfrac{d\sigma}{dtdy_H} \sim 600$ fb/GeV^2
- The event rate is **fifteen** times higher than the rate predicted by previous results in pp collisions.
  - To compare effectively we need to study this rate for $pp(AA)$ 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, $\sigma^{\text{exc}}_{I\!\!P I\!\!P} \sim 3.0$ fb and $\sigma^{\text{exc}}_{\gamma\gamma} = 0.1$ 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 **five times** less sensitive to the integration cuts if compared to the KMR approach.

Perspectives

- Study this approach in hadron-hadron collsions: *pp*, *pA* and *AA*.
- Introduction of the photon distribution of the proton (or nucleus).
- To extend the phenomenology analysis:
  - More precise predictions for the GSP;
  - ...
- Inclusion of QCD and Electroweak-theory corrections:
  - Color dipole;
  - Higgs vertex;
  - ...
- and more.