# Probing the Higgs sector with Peripheral Collisions

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# Outline

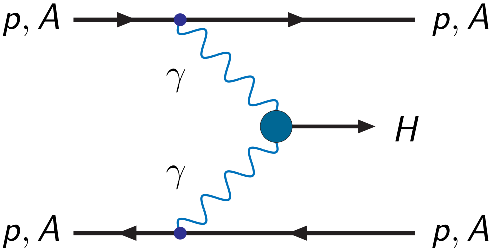
- Motivation
- Diffractive Higgs production
  - $\gamma\gamma$ annihilation
  - Double Pomeron Exchange (DPE)
- Deeply Virtual Compton Scattering (DVCS)
- Photoproduction approach: DPE in DVCS
- Higgs production in Peripheral Collisions
- Results
- Summary

# Motivation

- The existence of the Higgs boson is an open question in Particle Physics.
- LHC will reach the highest machine energy, which will enable the study of several processes in a new kinematical regime.
  - Higgs physics: the experimentalists expect that the $pp$ collisions will be able to produce the Higgs boson.
- Some hadron-hadron collisions will occur with **no** strong interaction.
  - There are predictions for $Z^0$ production in Peripheral Collisions at the Tevatron and LHC.
  - These processes allow the study of the Higgs boson production in $pp(AA)$ collisions at LHC.
- 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 $\to$ $\gamma\gamma$ **annihilation**
- **2007**: Miller — arXiv:0704.1985[hep-ph]
  - Contribution from **Electroweak boson loops** to the $\gamma\gamma \to H$.

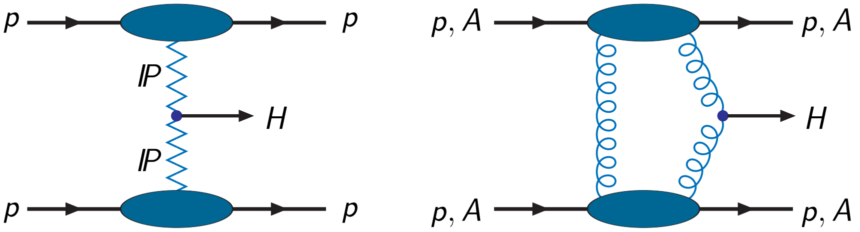



$M_H = 150$ GeV, $\sqrt{s} = 3.5$ TeV/A: **CJ**: $\sigma_{\text{PbPb}} = 7.0$ pb; **MS**: $\sigma_{\text{PbPb}} \sim 100$ pb

$M_H = 120$ GeV, $\sqrt{s} = 14$ TeV: **M**: $\sigma_{\text{pp}} =$ **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
  **2008**: Levin and Miller — arXiv:0801.3593[hep-ph]
  - QCD Pomeron → **hard-gluon exchange**




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

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

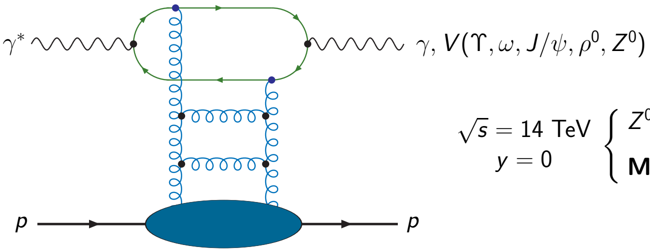
# Diffractive processes within Dipole picture

## Deeply Virtual Compton Scattering

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

## Vector meson production

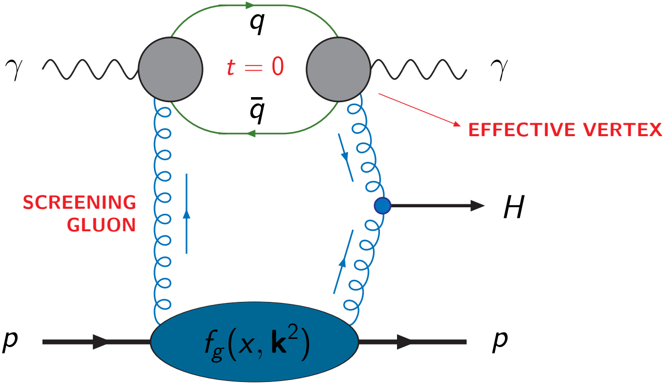
- **2001**: Munier, Staśto and Mueller ($\gamma^* p \to Vp$) — NPB **603** (2001) 427
  **2008**: Motyka and Watt ($\gamma p \to Vp$) — PRD **78** (2008) 014023




$\sqrt{s} = 14$ TeV, $y = 0$:
- $Z^0$ production at LHC
- **MW** : $\sigma^{\gamma p} \simeq$ **40 fb**

# Diffractive Higgs photoproduction

- **Proposal**: Apply the **DPE** to the **DVCS** in *pp* collision.

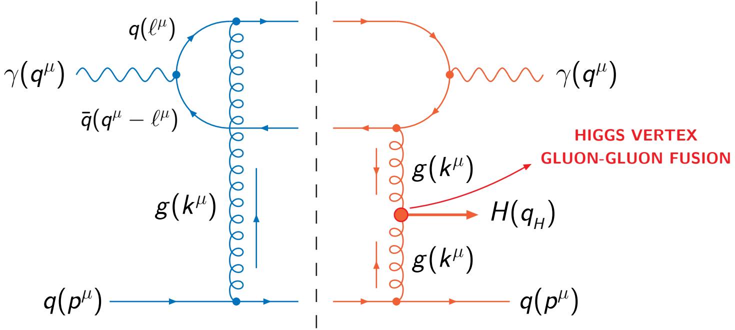



- The loop is treated in **impact factor formalism** at $t = 0$.
- <u>$H\gamma$ final state</u>: permits the study of the *b*-quark density in the proton.

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

# Scattering amplitude

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




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

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

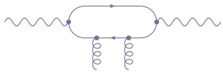
# Applying the rules

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

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

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

**THE OTHER CONTRIBUTIONS**



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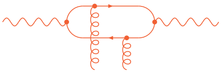
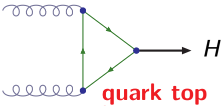


- For a **not too heavy Higgs** ($M_H \lesssim 200$ GeV), the $ggH$ vertex reads

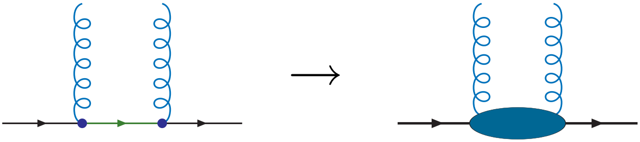



**quark top loop**

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

Forshaw, hep-ph/0508274

# Parton $\rightarrow$ Hadron



- To compute the event rate, we replace the *gq* vertices to consider the hadron coupling 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: $x \sim 0.01$.

# Phenomenology inside

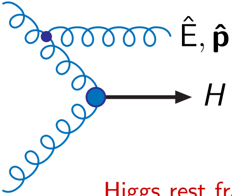
## Gluon Radiation

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

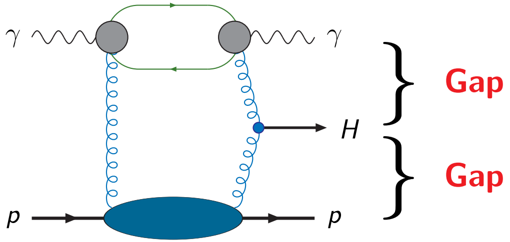
**Rapidity Gaps** KMR, EPJC **18** (2000) 167; Gotsman, Levin, Maor, arXiv:0708.1506[hep-ph]

- 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 normalization factor at $\Omega = 0$.

- $S^2_{\text{gap}}$ 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 ($y_H = 0$)

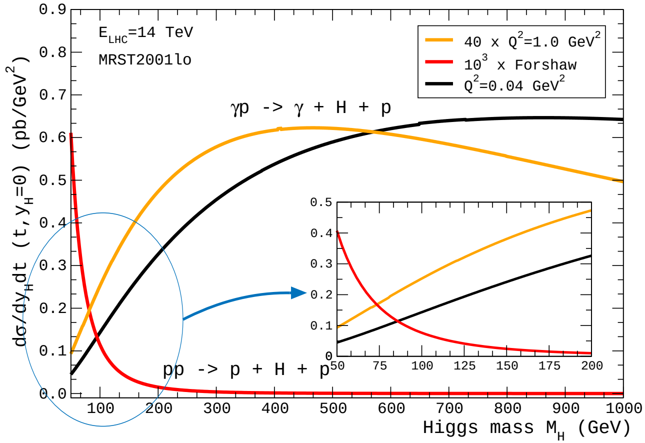
$$\left.\frac{d\sigma}{dy_H\, dt}\right|_{y_H,t=0} = \frac{S^2_{gap}}{2\pi B}\left(\frac{\alpha_s^2 \alpha M_H^2}{3N_c \pi v}\right)^2 \left(\sum_q e_q^2\right)^2 \left[\int_{\mathbf{k}_0^2}^{\infty} \frac{d\mathbf{k}^2}{\mathbf{k}^6}\, e^{-S(\mathbf{k}^2, M_H^2)}\, f_g(x,\mathbf{k}^2)\, \mathcal{X}(\mathbf{k}^2,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

- Quark contribution[1]: $\alpha_s C_F/\pi \quad \rightarrow \quad f_g(x,\mathbf{k}^2) = \mathcal{K}\, \partial_{(\ell n\, \mathbf{k}^2)}\, xg(x,\mathbf{k}^2)$
- 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 gluon-proton form factor: $B = 5.5$ GeV$^{-2}$

[1] Khoze, Martin, Ryskin, EJPC **14** (2000) 525
[2] Khoze, Martin, Ryskin, EJPC **18** (2000) 167
[3] Forshaw, hep-ph/0508274

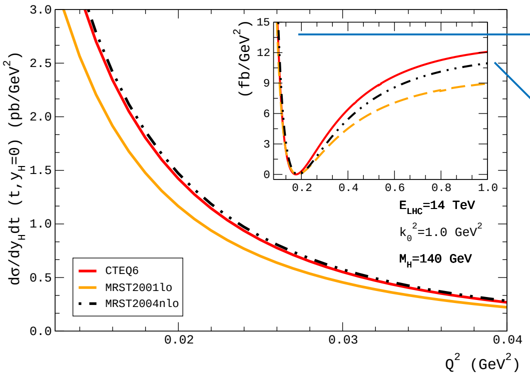
# Results: *pp* vs. $\gamma p$ process

- **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.

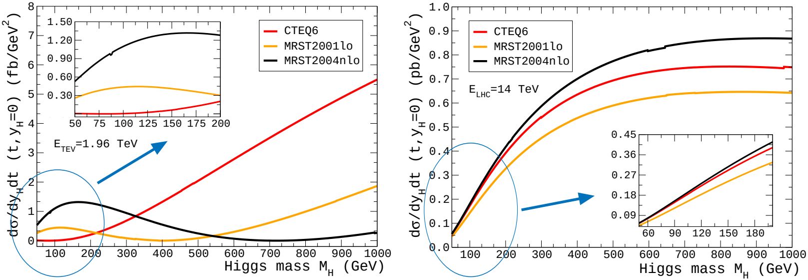



Peripheral photons

Perturbative region

$Q^2 = 0.04$ GeV$^2$

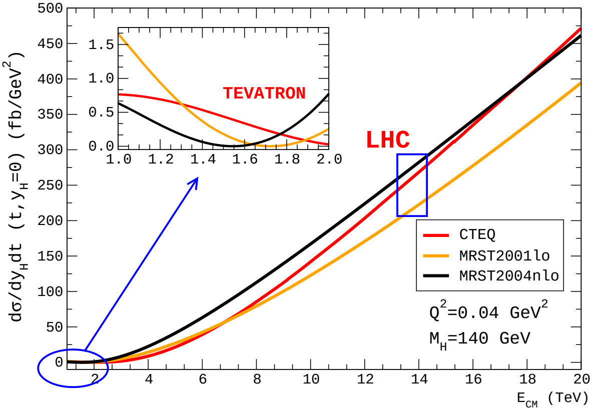
# Results: Gluon distribution functions




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

# Results: Energy dependence • PDFs

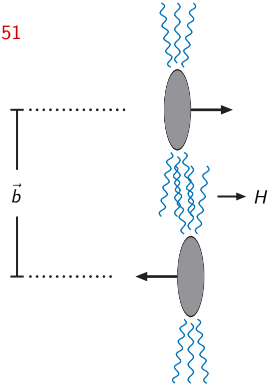
- Significative distinction among the **LO** and **NLO** distributions:
  - **Same** difference in the region $\underbrace{\sqrt{s} \gtrsim 12\ \text{TeV}}_{\textbf{includes LHC}}$



# The photoproduction in Peripheral Collisions

- The $\gamma p$ process is a subprocess in peripheral *pp* collisions

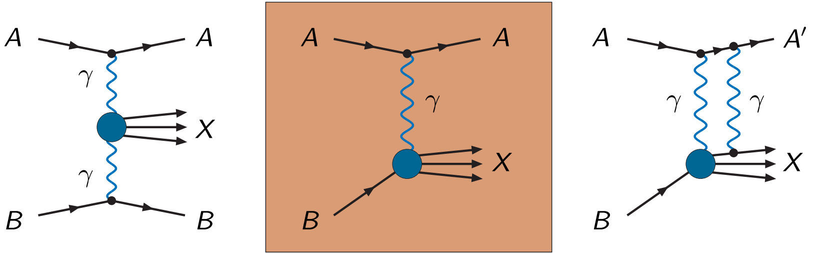
C.A. Bertulani
Heavy Ion Phys. **14** (2001) 51




- **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**: $Q^2 \lesssim 10^{-2}\ \text{GeV}^2$.

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

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

# The photon flux

Motyka and Watt, PRD **78** (2008) 014023

- To compute the peripheral $pp$ collision, one introduces the photon flux

$$\frac{dn}{dk} = \frac{\alpha_{em}}{2\pi k}\left[1+\left(1-\frac{2k}{\sqrt{s}}\right)^2\right]\left(\ln A - \frac{11}{6} + \frac{3}{A} - \frac{3}{2A^2} + \frac{1}{3A^2}\right)$$

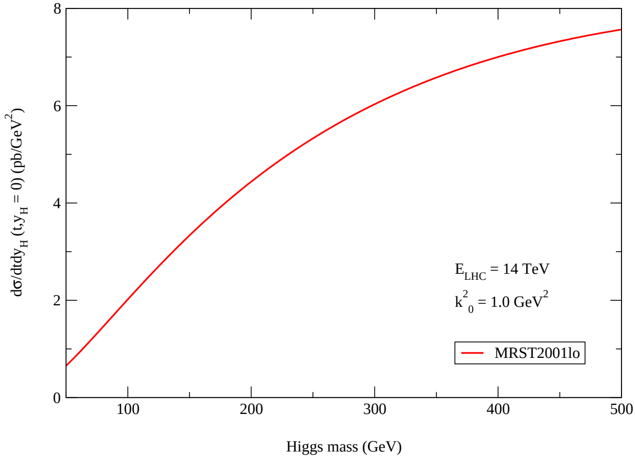
where $A = 1 + (0.71\ \mathrm{GeV}^2)/Q^2_{min}$ and $Q^2_{min} \simeq k^2/\gamma_L^2$.

- Integrating the $\sigma^{\gamma p}$ with the $dn/dk$ over the photon energy, one finds

$$\sigma(pp \to p + E + p) = 2\int dk\, \frac{dn}{dk}\, \sigma(\gamma p \to E + p)$$

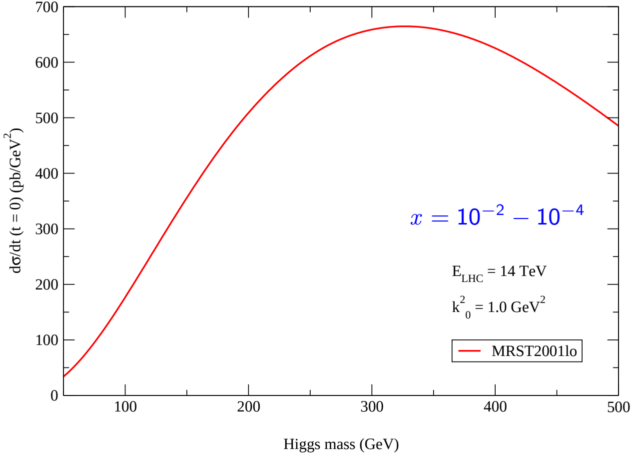
- The kinematical variables are defined as
  - Photon virtuality: $q^2 = -Q^2 = -k^2/(\gamma_L^2\beta_L^2) - q_\perp^2$
  - Lorentz factor of a single beam: $\gamma_L = (1-\beta_L^2)^{-1/2} = \sqrt{s}/(2m_p)$
  - The $\gamma p$ CM energy squared: $W^2 \simeq 2k\sqrt{s}$
  - Higgs rapidity: $x = \frac{M_H}{\sqrt{s}}\exp(\pm y_H)$

# Results: *pp* cross section




- *pp* **collisions**: The results have the **same** shape as the $\gamma p$ ones.

# Results: $pp$ cross section • $y_H$ integrated




- **Suppression** in the high mass limit. (above ∼ 325 GeV)

# Summary

- With the $\gamma p$ approach, we compute the event rate for **Higgs boson production** in $pp$ processes for Peripheral Collisions at LHC:

  - $$\frac{d\sigma}{dtdy_H} \sim 2.0 \text{ pb/GeV}^2$$

- In the LHC kinematical regime, the results with NLO distributions are **15%** higher than the LO ones.
  - It assigns the importance of the **gluon recombination effects** (if the non-perturbative effects are small).
- These results are **three times** less sensitive to the integration cuts if compared to the KMR approach.
  - The next step is to produce a comprehensive phenomenological analysis of the $pp$ collision as in the $\gamma p$ case.
    (much more processing time!)
- The $pp$ results predict an **enhanced signal** for the Higgs detection at LHC.