Diffractive Higgs boson photoproduction in *pp* collisions

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Outline

- Motivation
- Diffractive processes
  - Deeply Virtual Compton Scattering (DVCS)
  - Higgs boson production
    - $\gamma\gamma$ annihilation
    - Double Pomeron Exchange (DPE)
- Photoproduction approach: DPE in DVCS
- Peripheral Collisions
- Photoproduction at the Tevatron and LHC
- Summary

Motivation

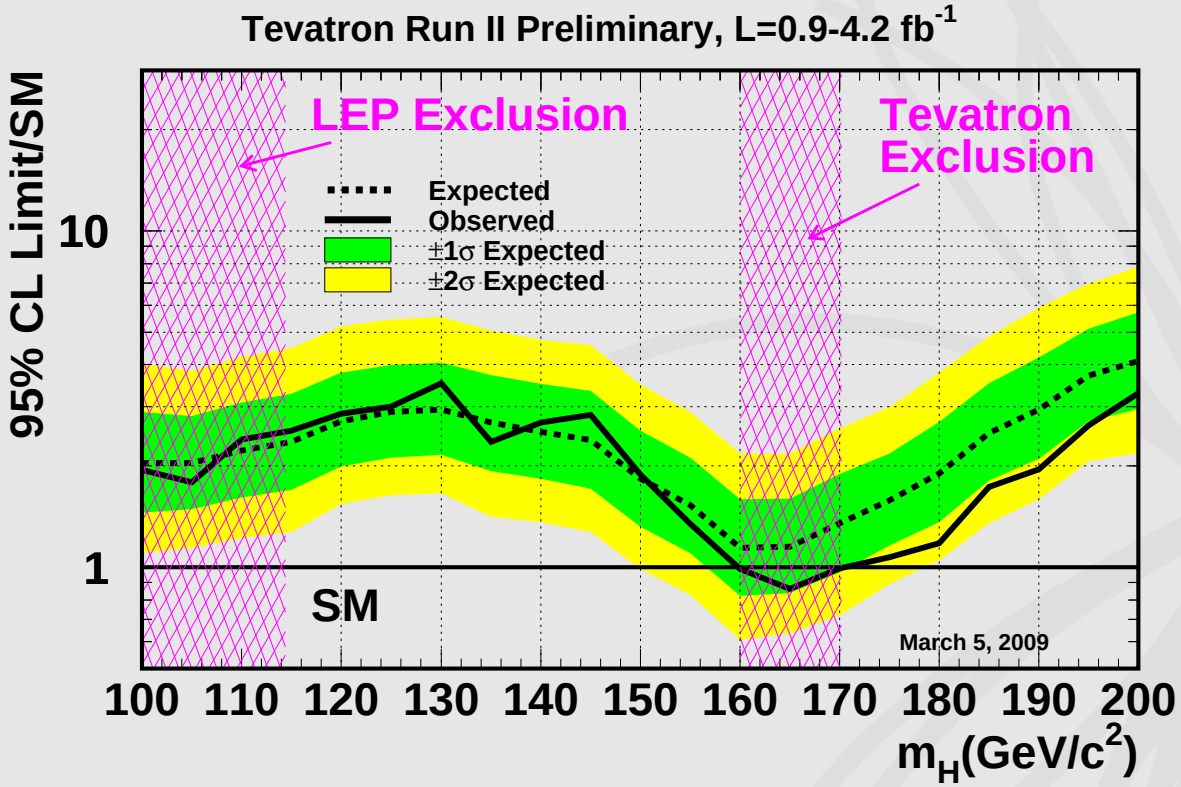
- LHC will allow to study a new kinematic region:
  - CM energy: 14 TeV $\rightarrow$ 7x Tevatron energy
  - Luminosity: 10-100 fb^{-1} $\rightarrow$ $\sim$10x Tevatron luminosity
  - Higgs physics: it is expected that the pp collisions will be able to produce the Higgs boson.
- Some hadron-hadron collisions 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.
- Evidences show another mass range **excluded** for Higgs boson production.

New results from the Tevatron

- Excluded range: The TEVNPH Working Group, arXiv:0903.4001[hep-ex]

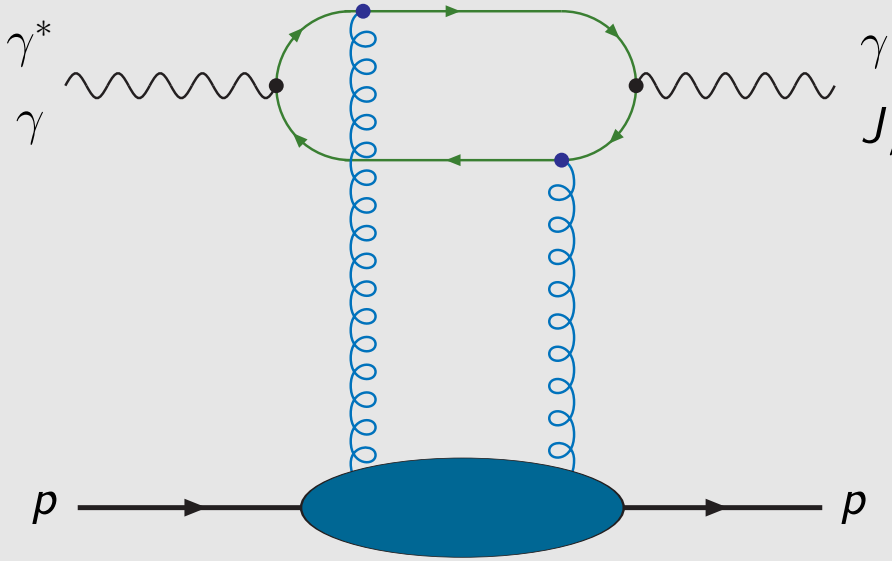
$$160 \text{ GeV} < M_H < 170 \text{ GeV}$$

- EW fits: $M_H = 116.3 \,^{+15.6}_{-1.30}$ GeV Goebel, arXiv:0905.2488[hep-ph]



Deeply Virtual Compton Scattering (DVCS)

- **1997**: Ji PRD **55** (1997) 7114
  - $\gamma^* p \to \gamma p$ by **Pomeron exchange** in ep collisions.
- **2001**: Munier, Staśto and Mueller NPB **603** (2001) 427
  - Vector meson production $\gamma^* p \to Vp$ with **GBW model**.
- **2008**: Motyka and Watt PRD **78** (2008) 014023
  - Vector particle production $\gamma p \to Ep$ in **Peripheral Collisions**.



$\gamma, \Upsilon, \omega, J/\psi, \rho^0$

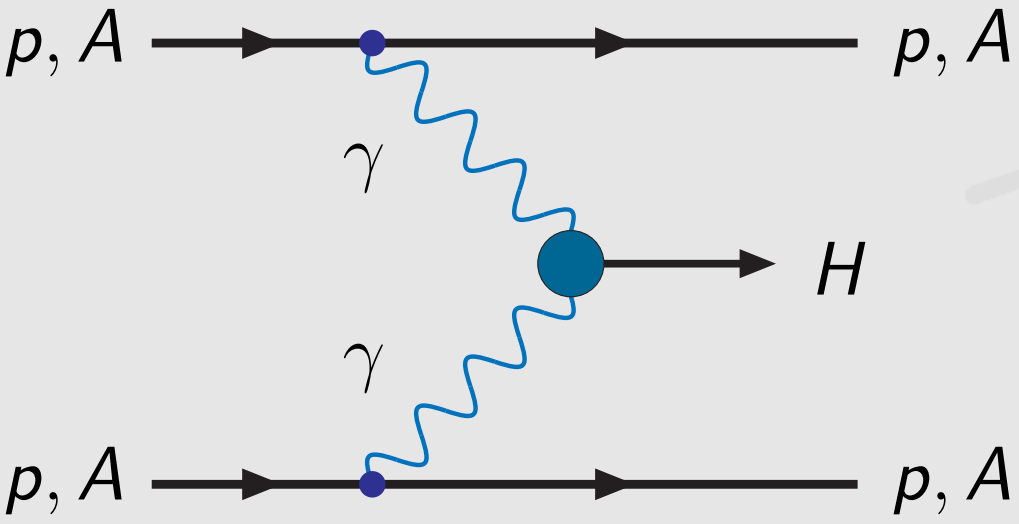
$J/\psi, \Upsilon, Z^0$

MW: Z^0 boson production

$$y = 0 \begin{cases} \sigma_{\gamma p} = \mathbf{4.2\ fb}\ , \text{ Tevatron} \\ \sigma_{\gamma p} = \mathbf{37\ fb}\ , \text{ LHC} \end{cases}$$

Electromagnetic Higgs production

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

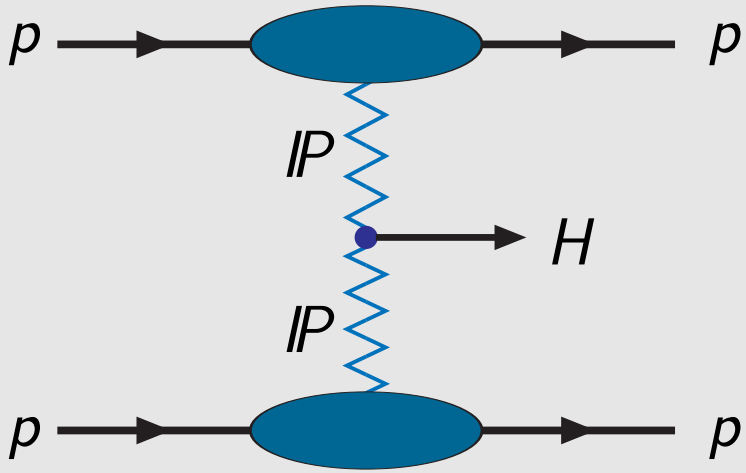


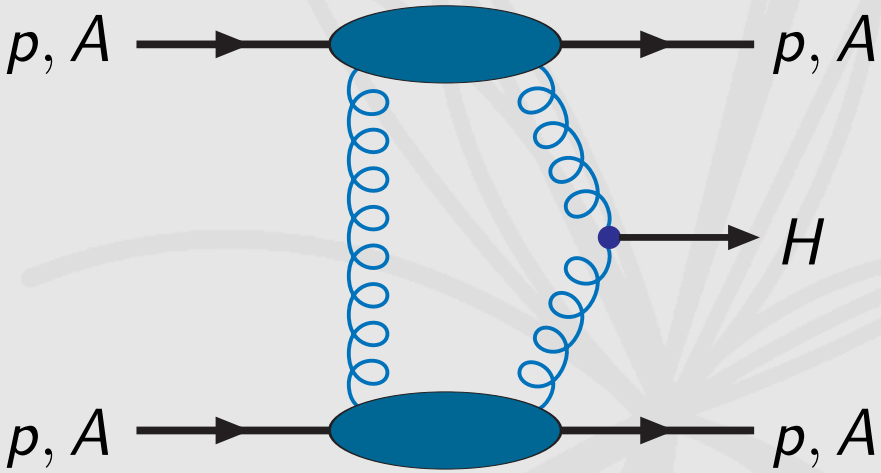
$M_H = 150$ GeV, $\sqrt{s} = 3.5$ TeV/A: **CJ**: $\sigma_{\rm PbPb} = 7.0$ pb; **MS**: $\sigma_{\rm AA} \sim 100$ pb

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

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**



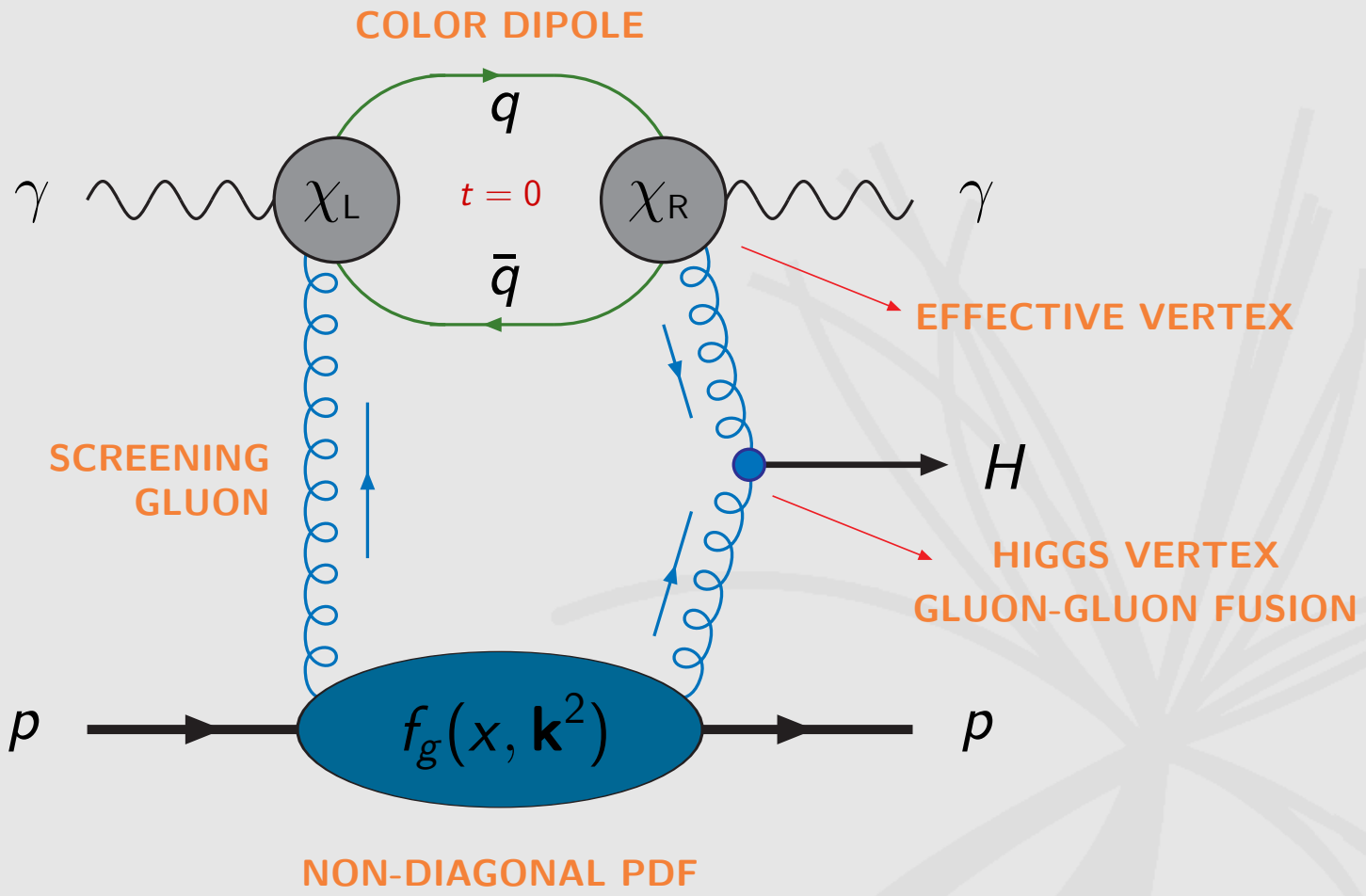


$M_H = 150$ GeV, $\sqrt{s} = 16$ TeV: **BL** : $\sigma_{pp} = 0.1$ pb

$M_H = 120$ GeV, $\sqrt{s} = 14$ / 8.8 (5.5) TeV/A: **KMR** : $\sigma_{pp}^{exc/inc} \sim$ **1 fb**/300 fb; **LM** : $\sigma_{pA(AA)} = 0.64$ pb (3.9 nb)

Diffractive Higgs photoproduction

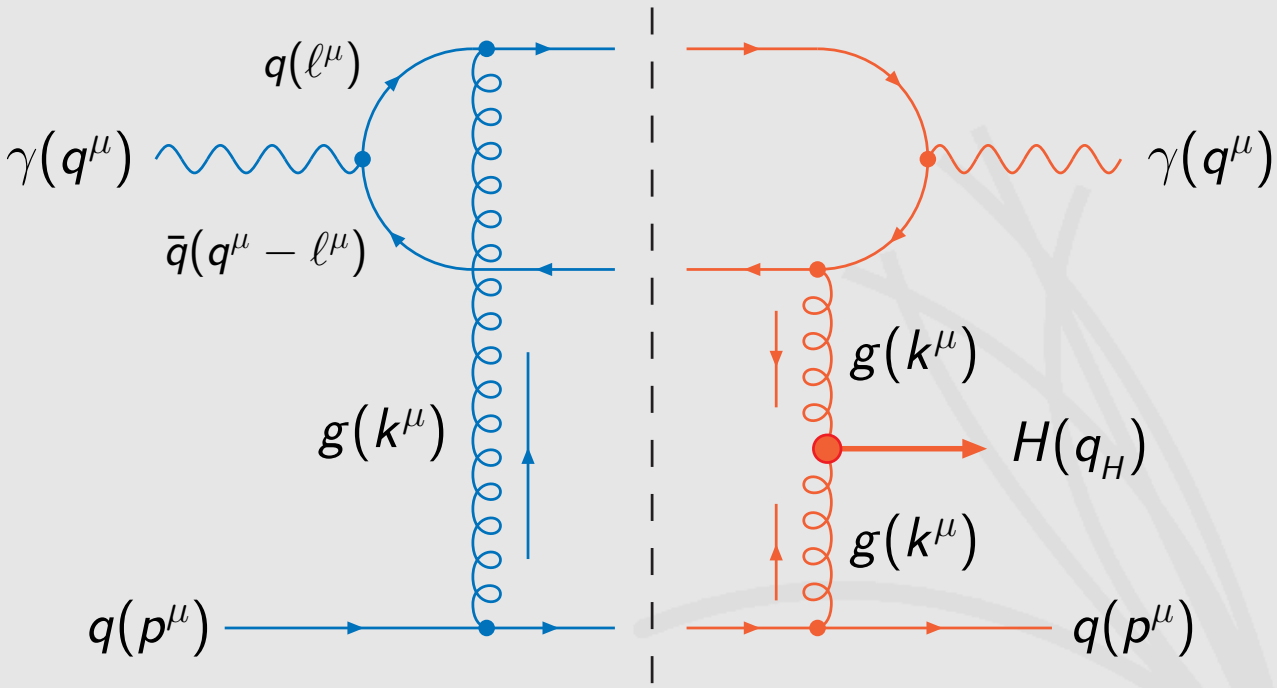
- **Proposal**: γp process by **DPE** in pp collision.



- The loop is treated in **impact factor formalism** at $t = 0$.

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

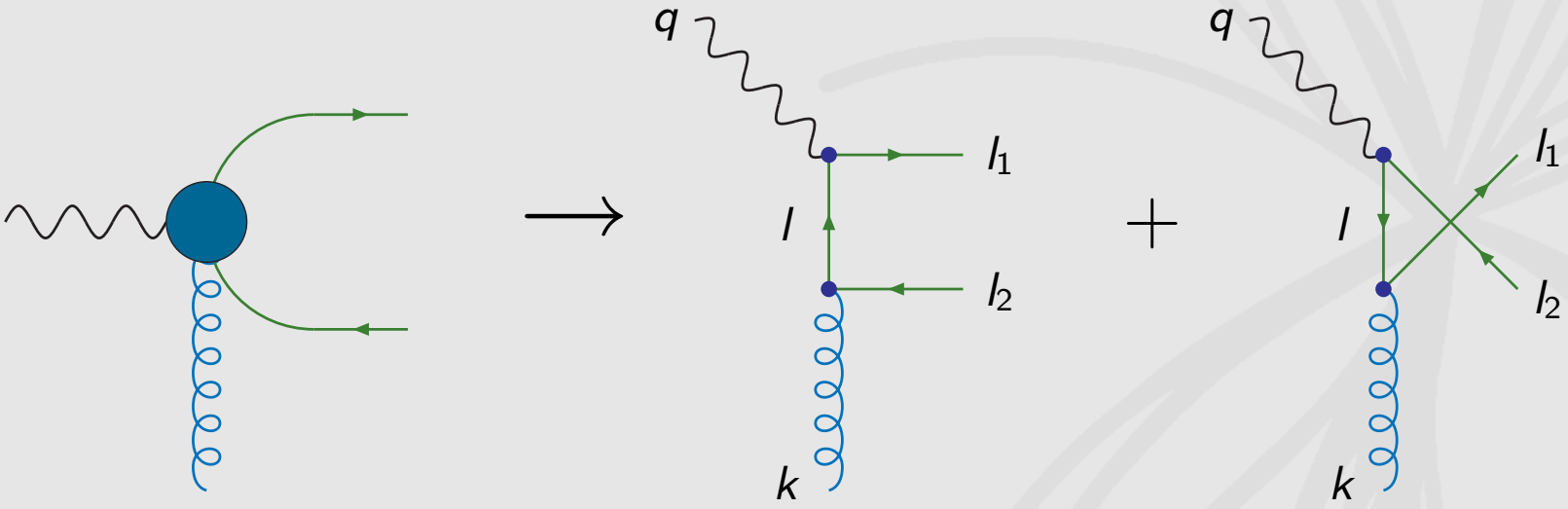
- The color dipole is composed of two effective vertices to the γg coupling

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

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

- Photon polarization vectors for $t = 0$:

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



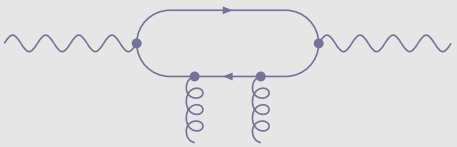
Applying the rules

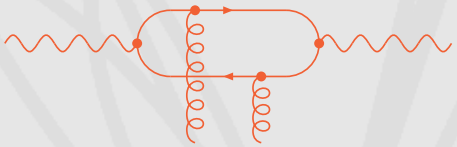
- Performing the product of the two sides of the cut one gets

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

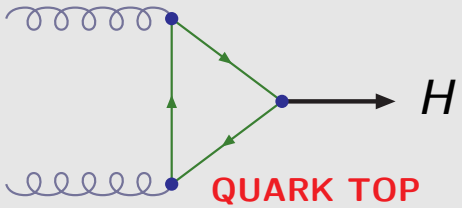
$$\times\ 2\left\{\frac{\mathrm{Tr}\left[(\not q-\not l)\gamma^\mu\not l\gamma^\nu(\not k+\not l)\gamma^\eta\not l\gamma^\lambda\right]}{l^4}+\frac{\mathrm{Tr}\left[(\not q-\not l)\gamma^\nu(\not k+\not l-\not q)\gamma^\mu(\not k+\not l)\gamma^\eta\not l\gamma^\lambda\right]}{l^2(k+l+q)^2}\right\}$$

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

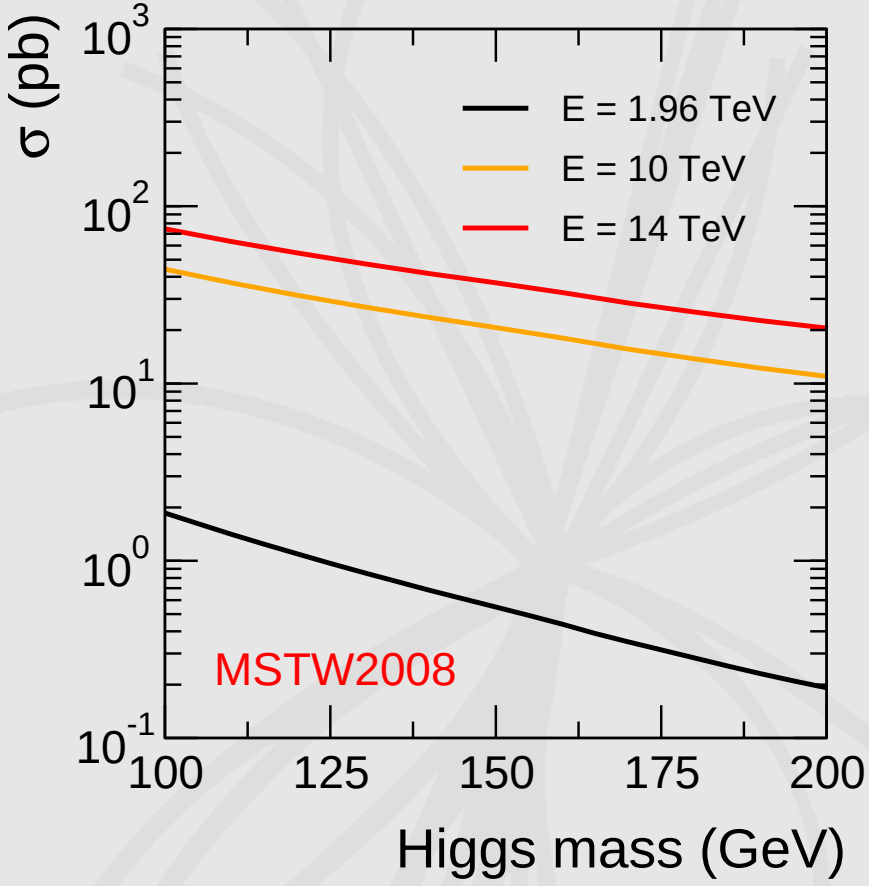
Updates on $gg \to H$ cross section

De Florian and Grazzini
PLB **674** (2009) 291

- Most recent advances taken into account:
  - NNLL soft-gluon resummation;
  - NLO bottom-quark contribution;
  - 2-loop EW effects.
- Significant improvements in LHC.

TEVATRON $\begin{cases} +9\% \to M_H = 115 \text{ GeV} \\ -9\% \to M_H = 200 \text{ GeV} \end{cases}$

LHC $\begin{cases} +30\% \to M_H = 115 \text{ GeV} \\ +9\% \to M_H = 300 \text{ GeV} \end{cases}$



The amplitude in parton level

- The imaginary part of the amplitude has the form

$$\frac{\mathrm{Im}\,\mathcal{A}}{s} = -\frac{4}{9}\left(\frac{M_H^2\alpha_s^2\alpha}{N_c v}\right)\left(\sum_q e_q^2\right)\left(\frac{\alpha_s C_F}{\pi}\right)\int\frac{d\mathbf{k}^2}{\mathbf{k}^6}\int_0^1 d\tau\int_0^1 d\rho\,\mathcal{X}(\mathbf{k}^2,Q^2)\,,$$

with

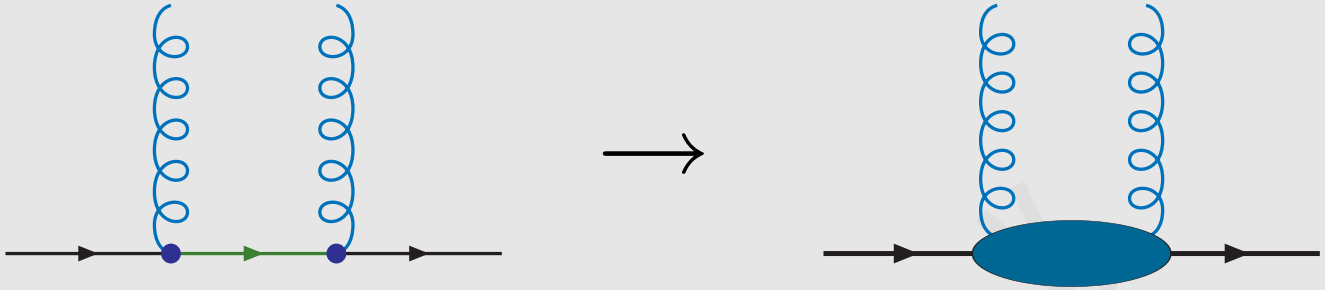
$$\mathcal{X}(\mathbf{k}^2,Q^2) = \frac{\mathbf{k}^2\left[\tau^2+(1-\tau)^2\right]\left[\rho^2+(1-\rho)^2\right]}{Q^2\rho(1-\rho)+\mathbf{k}^2\tau(1-\tau)}.$$

- **First remark**: dependence on $\mathbf{k}^{-6}$ due to the presence of the color dipole.
- Computing the event rate in central rapidity

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

- Only the **quark contribution** $\rightarrow$ extension to the hadron coupling.

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

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

Phenomenology inside

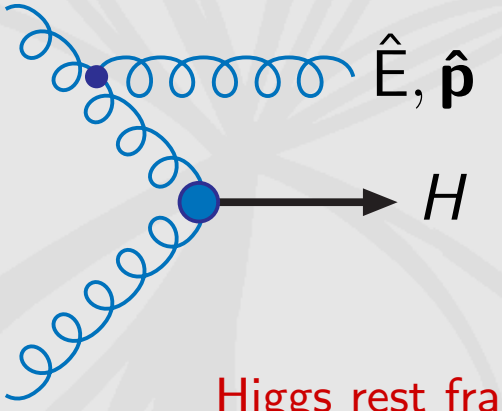
Gluon Radiation

Forshaw, hep-ph/0508274

- The real gluon emission from the ggH vertex needs to be **suppressed**.
  - Sum the virtual graphs that include terms like $\ell n\left(M_H/\mathbf{k}^2\right)$.
- 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

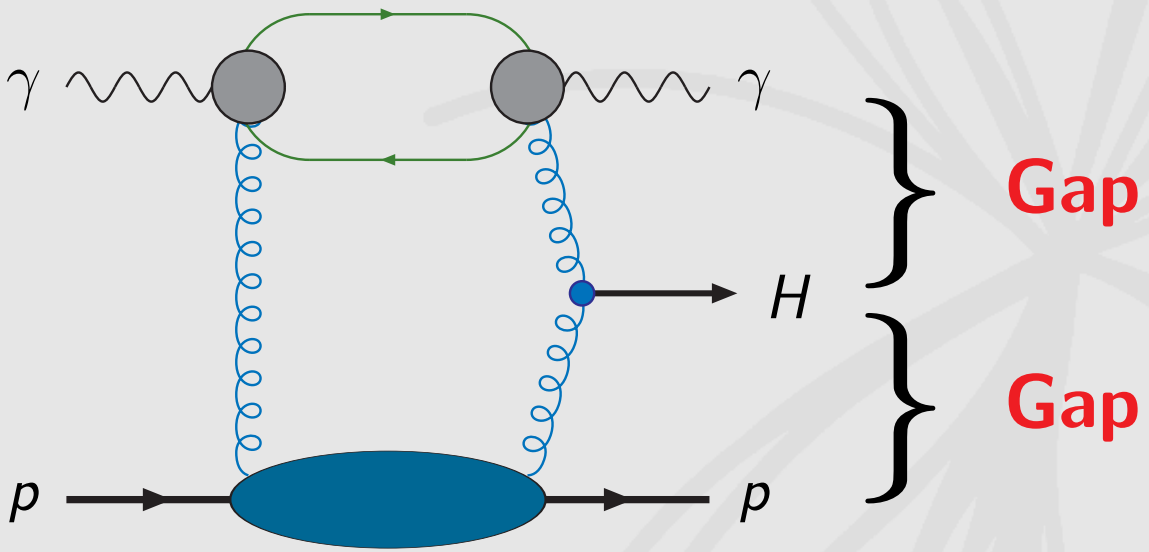
Rapidity Gaps KMR, EPJC **18** (2000) 167; Gotsman, Levin, Maor, arXiv:0708.1506[hep-ph]

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

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

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

- Pomeron loops: Higgs boson production with $S^2_{gap} = 0.4\%$ Miller EPJC **56** (2008) 39 arXiv:0908.3450[hep-ph]



Cross section for central rapidity

Gay Ducati and Silveira PRD **78** (2008) 113005

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

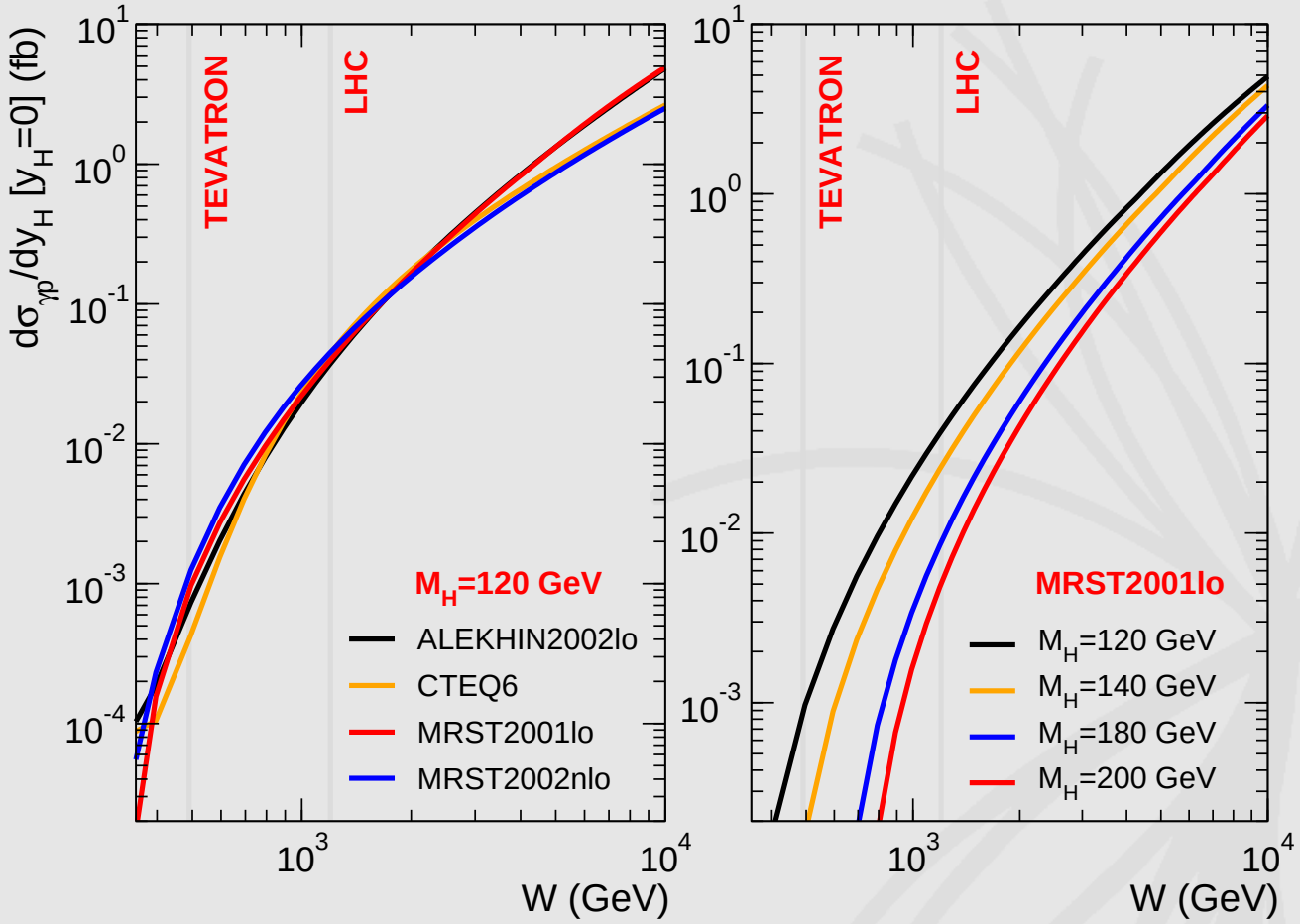
$$\left.\frac{d\sigma}{dy_H\, dt}\right|_{y_H,t=0} = \frac{S^2_{gap}}{2\pi B}\left(\frac{\alpha_s^2 \alpha M_H^2}{3N_c \pi v}\right)^2 \left(\sum_q e_q^2\right)^2 \left[\int_{\mathbf{k}_0^2}^{\infty} \frac{d\mathbf{k}^2}{\mathbf{k}^6}\, e^{-S(\mathbf{k}^2, M_H^2)}\, f_g(x,\mathbf{k}^2)\, \mathcal{X}(\mathbf{k}^2,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

- Proton content[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}

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

Results: predictions for the γp process

- The predictions for different PDF's are close in LHC
- **Tevatron**: restricted to $M_H < 140$ GeV (reason: $x > 0.01$)



Results: gluon PDF parametrizations

- All parametrizations start the distribution evolution from

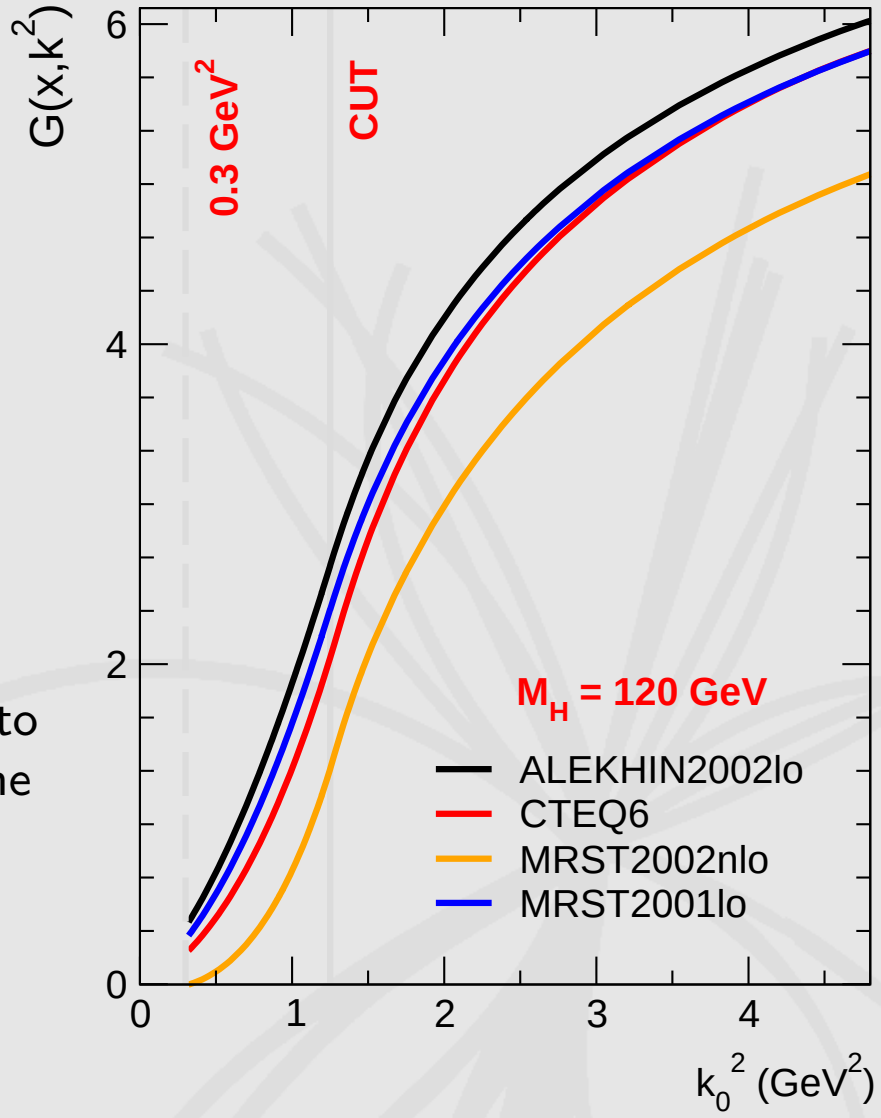
$$\mathbf{k}_0^2 \sim 1.25 \text{ GeV}^2$$

- One can extrapolate the distribution for $\mathbf{k}^2 \to 0$

$$k_{\leftarrow}^2 \sim k^{4+2(\gamma+2)\mathbf{k}^2}$$

- For each parametrization one needs to compute the parameters to match the **function** and its **derivative** in the correct value.

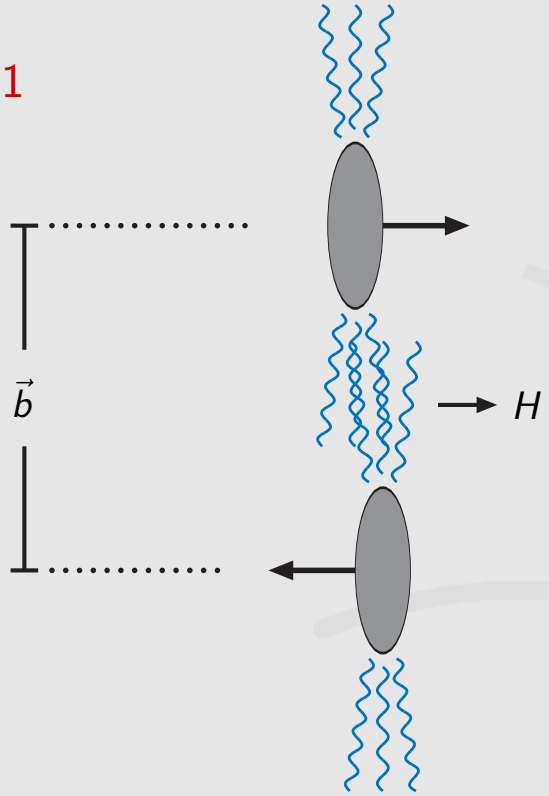
MRST2001lo $\to \gamma = 1.987455222$



Higgs production in Peripheral Collisions

- The γp process is a subprocess in peripheral pp collisions

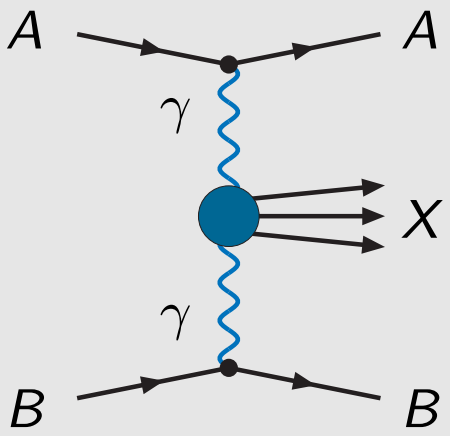
Hencken *et al*
Phys. Rept. **458** (2008) 1

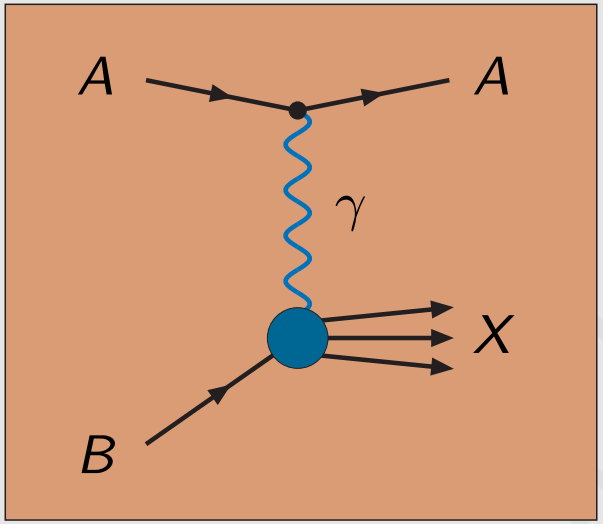


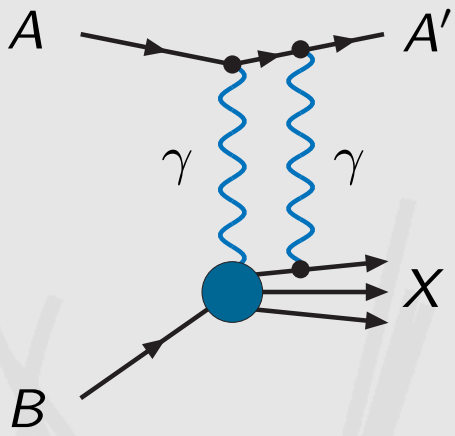
- **Impact parameter**: $|\vec{b}| > 2R \rightarrow$ **NO STRONG INTERACTION!**
- Only EM force acts in the second proton $\rightarrow$ **REAL PHOTONS**

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.

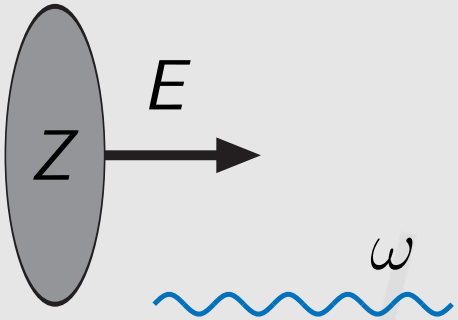
- **Uncertainty principle**: upper limit to the photon transverse momentum

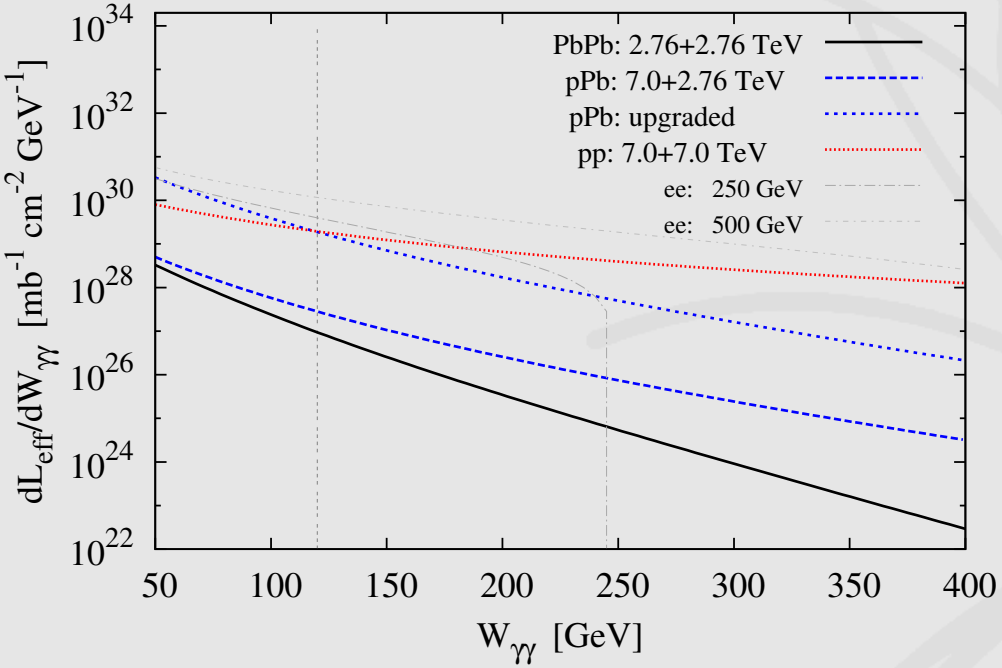
$$\mathbf{Q} \lesssim \frac{1}{R} \approx \begin{cases} 28 \text{ MeV, Pb beam} \\ 330 \text{ MeV, proton beam} \end{cases}$$

Photon spectra

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

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





d'Enterria and Lansberg
arXiv:0909.3047[hep-ph]

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

Hadronic cross section

- For pp collisions, $\sigma_{\gamma p}$ is convoluted with the photon flux

$$\sigma(pp \to p + H + p) = 2 \int_{\omega_0}^{\sqrt{s}/2} \frac{dn}{d\omega}\, \sigma_{\gamma p}(\omega, M_H)\, d\omega,$$

where the photon flux is given by

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

with $A \simeq 1 + (0.71\,\mathrm{GeV}^{-2})\sqrt{s}/2\omega^2$.

- The parametrization allows one to write the virtuality as

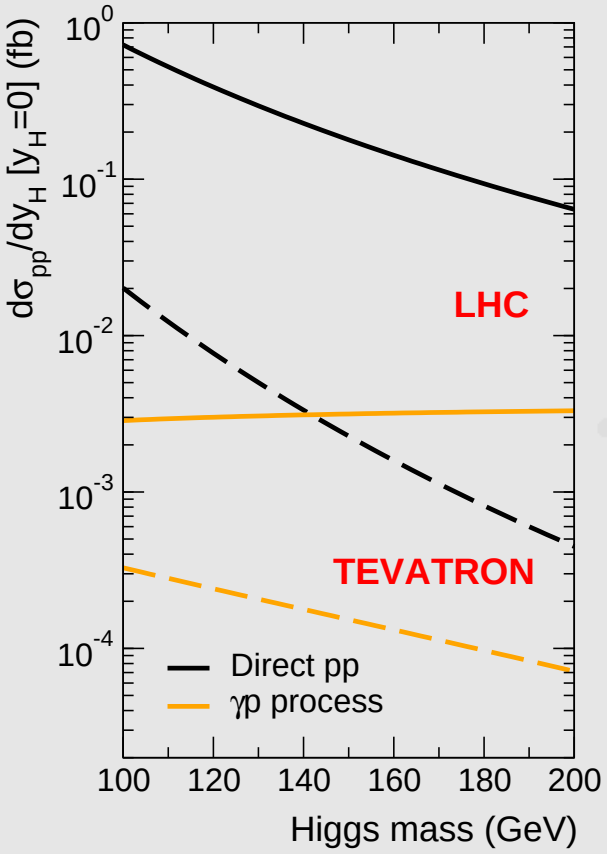
$$Q^2 = -\omega^2/(\gamma_L^2 \beta_L^2) - q_\perp^2$$

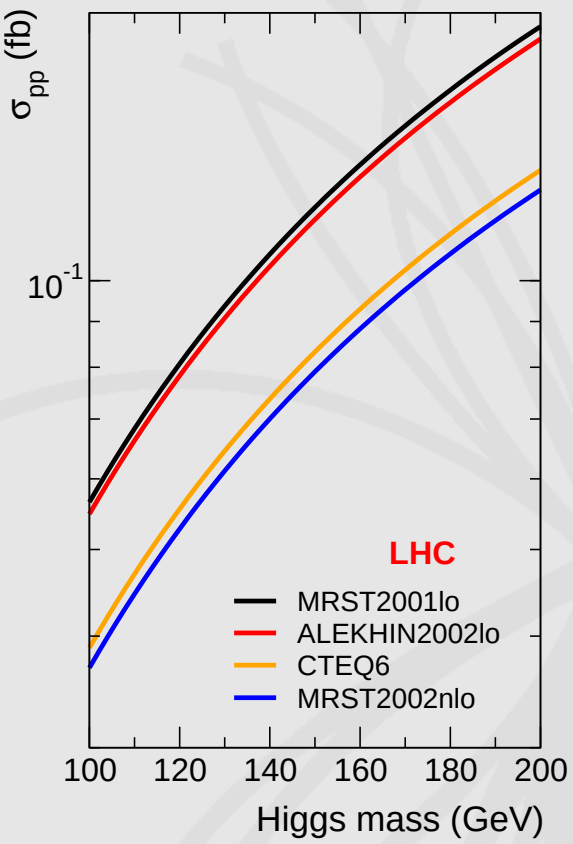
with $\gamma_L = (1 - \beta_L^2)^{-1/2} = \sqrt{s}/2m_p$.

- The γp center-of-mass energy: $W^2 = 2\omega\sqrt{s}$.

Results: Higgs boson in UPCs

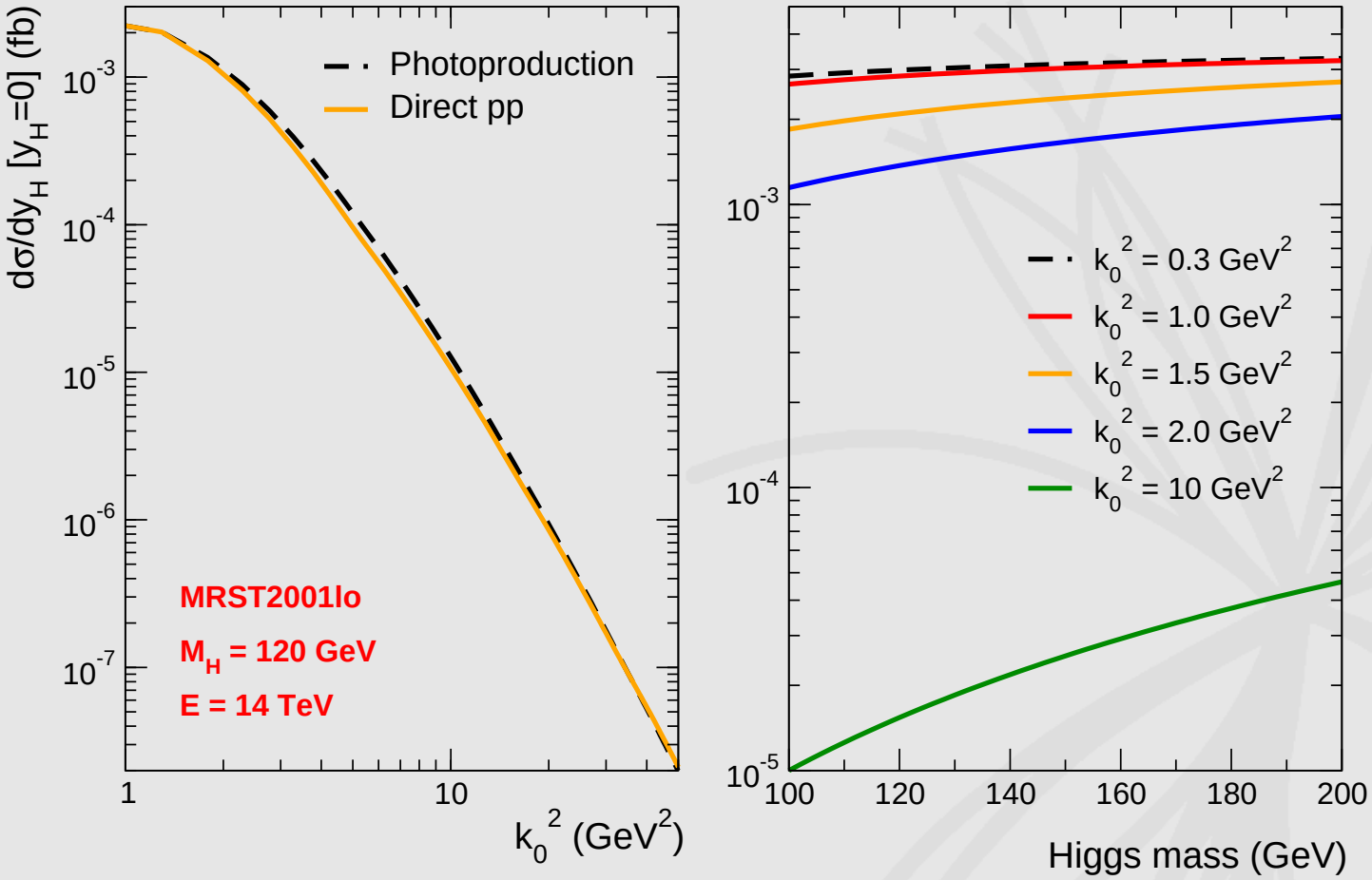
- Similar to those from $\gamma\gamma$ process (10^{-1} fb).
- Clear distinction among the predictions in LHC for different PDF's.
- The event rate is obtained from the relation $\frac{d\sigma_{pp}}{dy_H} = 2\int_{\omega_0}^{\sqrt{s}/2} \frac{dn}{d\omega} \frac{d\sigma_{\gamma p}}{dy_H}\, d\omega.$





Results: Cutoff sensitivity

- The main contribution comes from the range $\mathbf{k}_0^2 < 30$ GeV^2.
- Sensitivity: almost the same behavior than the direct *pp* process.



Summary

- We compute the event rate for **Higgs boson production** in Peripheral Collisions at LHC:

$$\sigma_{pp} \sim 0.1 \text{ fb}$$

- The computed total cross section is lower than the direct pp process, however,
  - The Rapidity Gap Survival Probability (GSP) is not appropriated to the γp process (3%).
  - **We must compute the GSP for the γp collsions.**

Subprocess	GSP (%)	σ_{pp} (fb)
$I\!P I\!P$	2.3	2.7
$I\!P I\!P$	0.4	0.47
$\gamma\gamma$	100	0.1
γp	3.0	**0.08**

- The predictions can be analysed in a data sample of **non-central collisions**.
  - Will be less competitive than direct pp processes if analysed separetely.

Perspectives

- Study this approach in nucleus-nucleus collsions: pA and AA.
- More phenomenology:
  - More precise predictions for the GSP;
  - Include updates on the ggH cross section;
  - ...
- Inclusion of QCD and Electroweak-theory corrections:
  - Compute the impact factor for $\gamma \to \gamma^*$;
  - ...
- and more.