Central Exclusive Production at the LHC

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Exclusive Production

Diffractive production of any central system X

For both proton-antiproton (Tevatron) and proton-proton (LHC) collisions

↓

No break-up of the proton(s) or antiproton

$$pp \to p + X + p$$

Part of well-known diffractive processes at HERA but now also observed at CDF (2006)

2006: First clear evidence of exclusive interaction at Tevatron by CDF

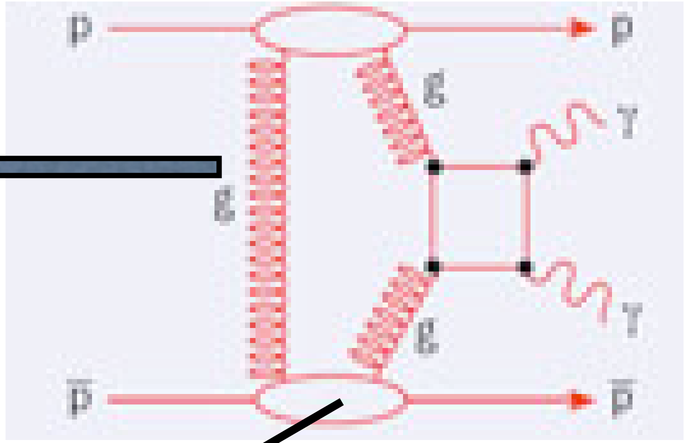
↓

High energy photon pairs in the central rapidity (barrel) region of detector (and nothing else down to 0.1^0 from the beam (± 7.4 units of (pseudo)rapidity))

⇒ consistent with gg fusion process

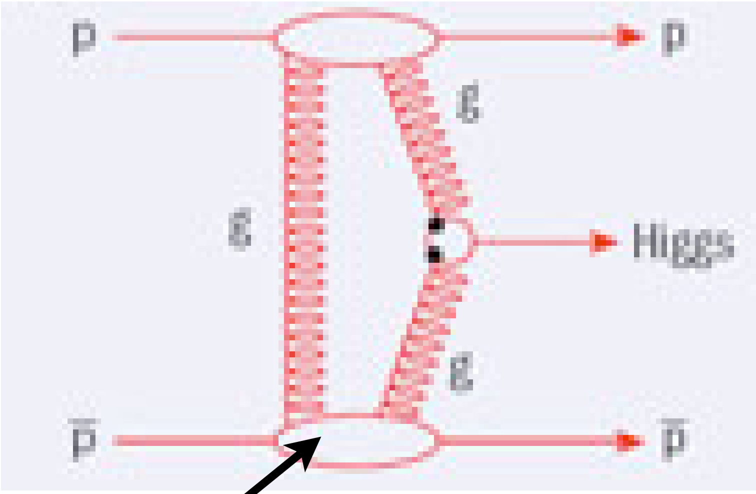
Screening gluon

("Pomeron process")



Gluons produced directly from protons

Exclusive Production was originally proposed in 2001 (Durham group) as a 'clean' channel' for Higgs production

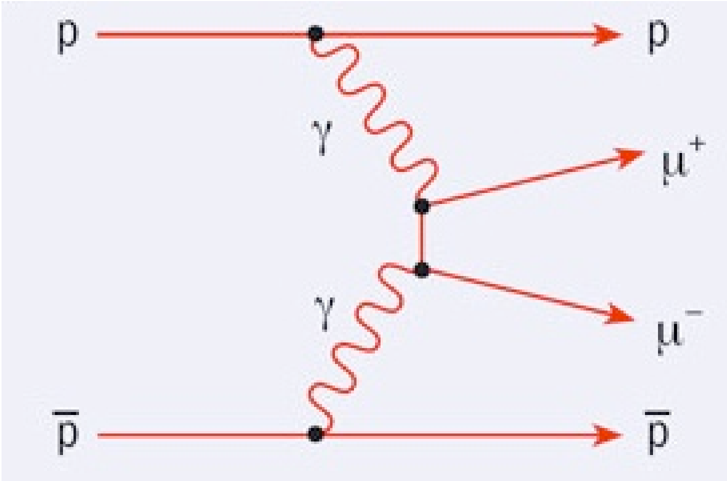


"Exciting the vacuum to produce the Higgs in a glancing collision of p and p-(bar)"

Predictions of the Durham model tested using two photon process and used for Higgs production

Many other processes consistent with QED predictions observed

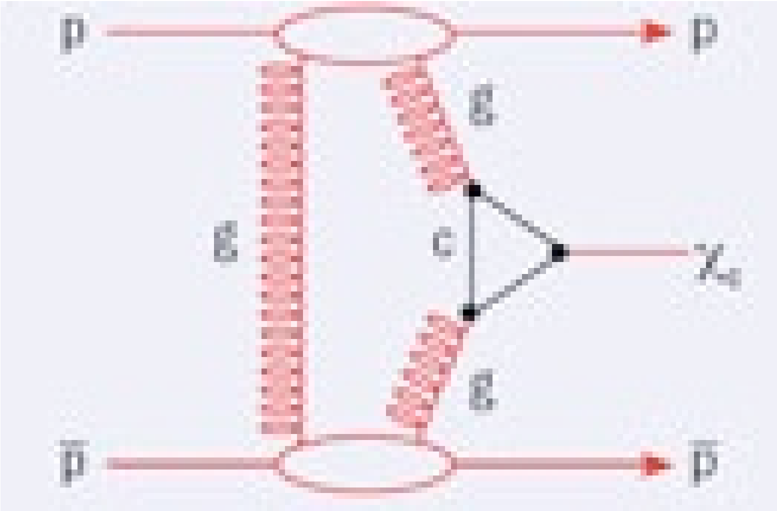
$\gamma\gamma \longrightarrow e^+e^- , \mu^+\mu^-$

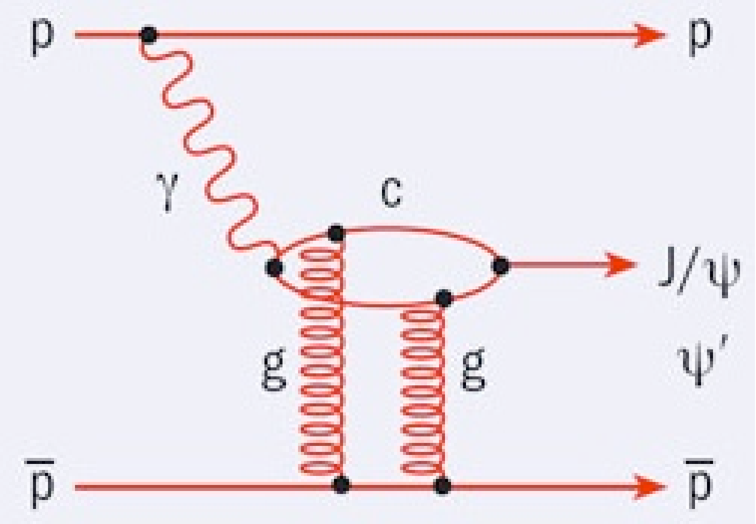


Not a pomeron process but here Tevatron acts as a photon collider and helps in calibration of momentum scale and resolution of forward proton spectrometers for ATLAS and CMS

Exclusive production of

$J/\Psi, \Psi(2S) \longrightarrow \mu^+ \mu^-$, $\chi_c^0 \longrightarrow \mu^+ \mu^- +$ soft photons



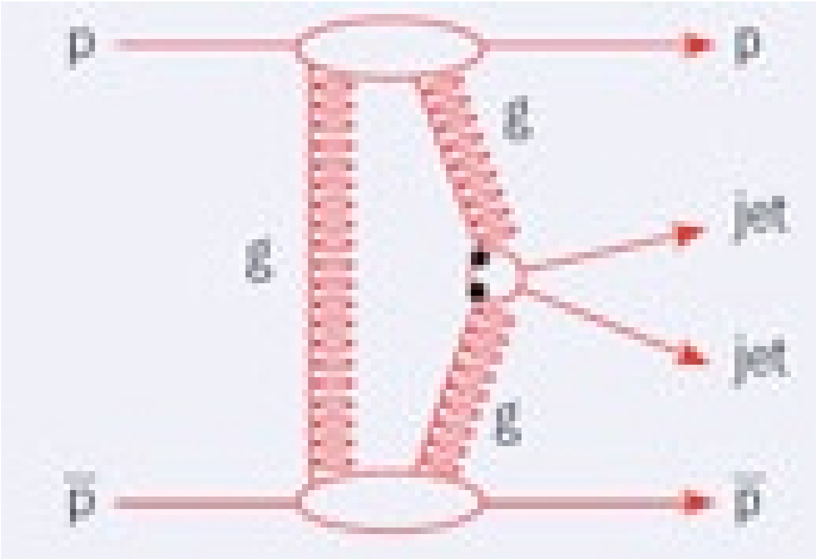


"pomeron-photon collider"

All of these are produced through a diffractive process

⟶ large region of rapidity region is empty ("gap")

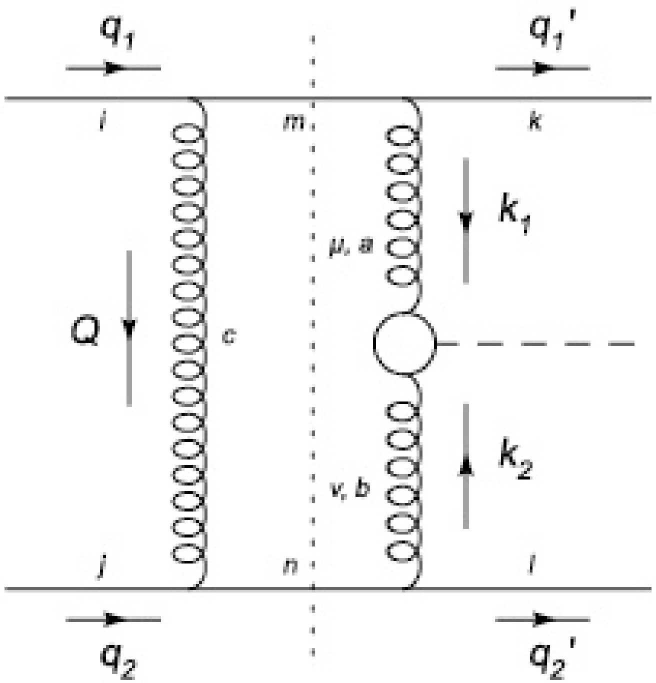
CDF, 2008: Dijet events seen



All of these diffractive processes are describable through a perturbative QCD based “Durham” model

Theoretical Approach - the Durham Model

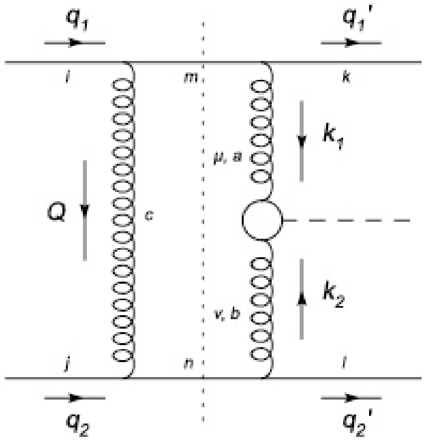
-- Khoze, Martin and Ryskin, 2000



$$qq \longrightarrow q + H + q$$

Strategy:

- Higgs produced by top quark loop
- Two gluons needed for no colour exchange
- Quark exchange suppressed by inverse power of beam energy
- Calculate only Im part of amplitude (Cutkosky rules) - (real part negligible for asymptotically high CM energy), quarks scattered to small angles and Higgs produced centrally



two diagrams

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

cutting rules

eikonal form for qqg vertex

Forshaw 2005...

$$d(PS)_2 = \frac{s}{2} \int \frac{d^2\mathbf{Q_T}}{(2\pi)^2}\, d\alpha d\beta$$

$Q = \alpha q_1 + \beta q_2 + Q_T$ and

$\alpha \approx -\beta \approx \mathbf{Q}_T{}^2/s \ll 1$ (cut quark lines)

$$V^{ab}_{\mu\nu} = \delta^{ab}\left(g_{\mu\nu} - \frac{k_{2\mu}k_{1\nu}}{k_1 \cdot k_2}\right) V$$

$$V = m_H^2 \alpha_s/(4\pi v) F(m_H^2/m_t^2)$$

- - - -

$$\frac{d\sigma}{d^2\mathbf{q_{1T}}' d^2\mathbf{q_{2T}}' dy} \approx \left(\frac{N_c^2 - 1}{N_c^2}\right)^2 \frac{\alpha_s^6}{(2\pi)^5} \frac{G_F}{\sqrt{2}} \left[\int \frac{d^2\mathbf{Q_T}}{2\pi} \frac{\mathbf{k_{1T}} \cdot \mathbf{k_{2T}}}{\mathbf{Q_T}^2 \mathbf{k_{1T}}^2 \mathbf{k_{2T}}^2} \frac{2}{3}\right]^2$$

rapidity of the Higgs

Some immediate consequences of this structure

Using $k_i = x_i q_i + k_{iT}$

$$q_1^\mu V_{\mu\nu}^{ab} q_2^\nu \approx \frac{k_{1T}^\mu}{x_1} \frac{k_{2T}^\nu}{x_2} V_{\mu\nu}^{ab} \approx \frac{s}{m_H^2} k_{1T}^\mu k_{2T}^\nu V_{\mu\nu}^{ab}$$

- as if the gluons which fuse to form the Higgs are transversely polarised

- if outgoing quarks carry no transverse momenta, $Q_T = -k_{1T} = k_{2T}$

$$\epsilon_1 = -\epsilon_2$$

Centrally produced system should have $J_z = 0$ in the limit protons scatter through small angles

HIggs decay to b-quarks is viable because for massless quarks the lowest order q-qbar bgd vanishes (not at NLO) so LO b b-bar bgd is suppressed by a factor m_b^2/m_H^2

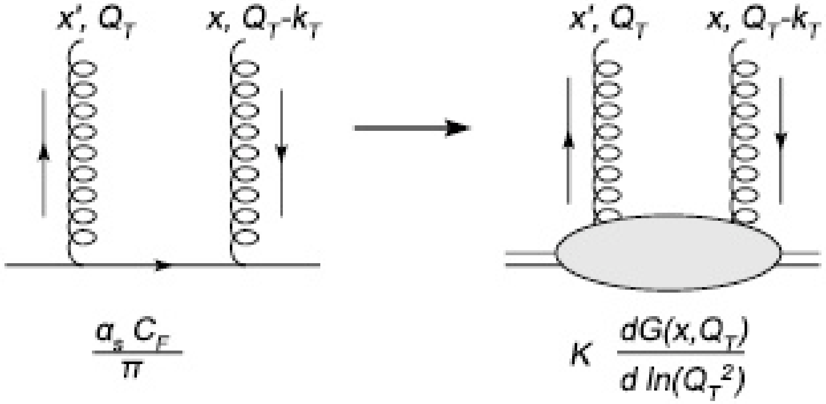
In the forward scattering limit

$$\frac{\mathrm{k_{1T}} \cdot \mathrm{k_{2T}}}{\mathrm{Q_T}^2 \mathrm{k_{1T}}^2 \mathrm{k_{2T}}^2} \approx -\frac{1}{\mathrm{Q_T}^4}.$$

$$\left[\int \frac{d^2\mathrm{Q_T}}{2\pi} \frac{\mathrm{k_{1T}} \cdot \mathrm{k_{2T}}}{\mathrm{Q_T}^2 \mathrm{k_{1T}}^2 \mathrm{k_{2T}}^2} \frac{2}{3}\right]$$ is infrared divergent

Two problems need to be solved:

- The Q_T integral is divergent
- Need to convert quark lines to proton lines



This needs "*off diagonal parton distributions*"

Durham prescription: Replace as above (other than the K) which is derivable from DGLAP equation, and for $x' \ll x, \;\; k_T^2 \ll Q_T^2$

The off-diagonality can be approximated by a multiplicative factor K for $x' \ll x, k_T^2 < Q_T^2$

After integrating over the transverse momenta of the scattered protons

$$\frac{d\sigma}{dy} \approx \frac{1}{256\pi b^2} \frac{\alpha_s G_F \sqrt{2}}{9} \left[\int \frac{d^2\mathbf{Q_T}}{\mathbf{Q_T}^4} f(x_1, Q_T) f(x_2, Q_T) \right]^2$$

$$f(x, Q) \equiv \partial G(x, Q) / \partial \ln Q^2$$

The K factor for a 120 GeV Higgs is estimated to be

$$K \sim 1.2 \times e^{-b k_T^2 / 2}$$

Thus off-diagonality itself provides an enhancement of $(1.2)^4 \approx 2$ in the cross section

Uncertainty in the slope parameter b can be reduced by using results from diffractive J/ψ production

To return to the first problem

The Q_T integral is IR divergent

This is fixed through a well known ladder summation

Lowest order diagram is not enough. Higher order graphs contain logarithms of Q_T/m_H

$$\frac{C_A\alpha_s}{\pi}\int_{Q_T^2}^{m_H^2/4}\frac{dp_T^2}{p_T^2}\int_{p_T}^{m_H/2}\frac{dE}{E}\sim\frac{C_A\alpha_s}{4\pi}\ln^2\left(\frac{m_H^2}{Q_T^2}\right).$$

Real gluon emissions into the final state are suppressed

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Real gluon emissions into the final state are suppressed

And multiple real emissions exponentiate

Sudakov Physics

The non-emission probability

$$e^{-S} = \exp\left(-\frac{C_A \alpha_s}{\pi} \int_{Q_T^2}^{m_H^2/4} \frac{dp_T^2}{p_T^2} \int_{p_T}^{m_H/2} \frac{dE}{E}\right).$$

$Q_T \to 0$: the non emission probability vanishes faster than any power of Q_T

$$\int \frac{dQ_T^2}{Q_T^4} f(x_1, Q_T) f(x_2, Q_T)\, e^{-S}$$

(Leading double logs)

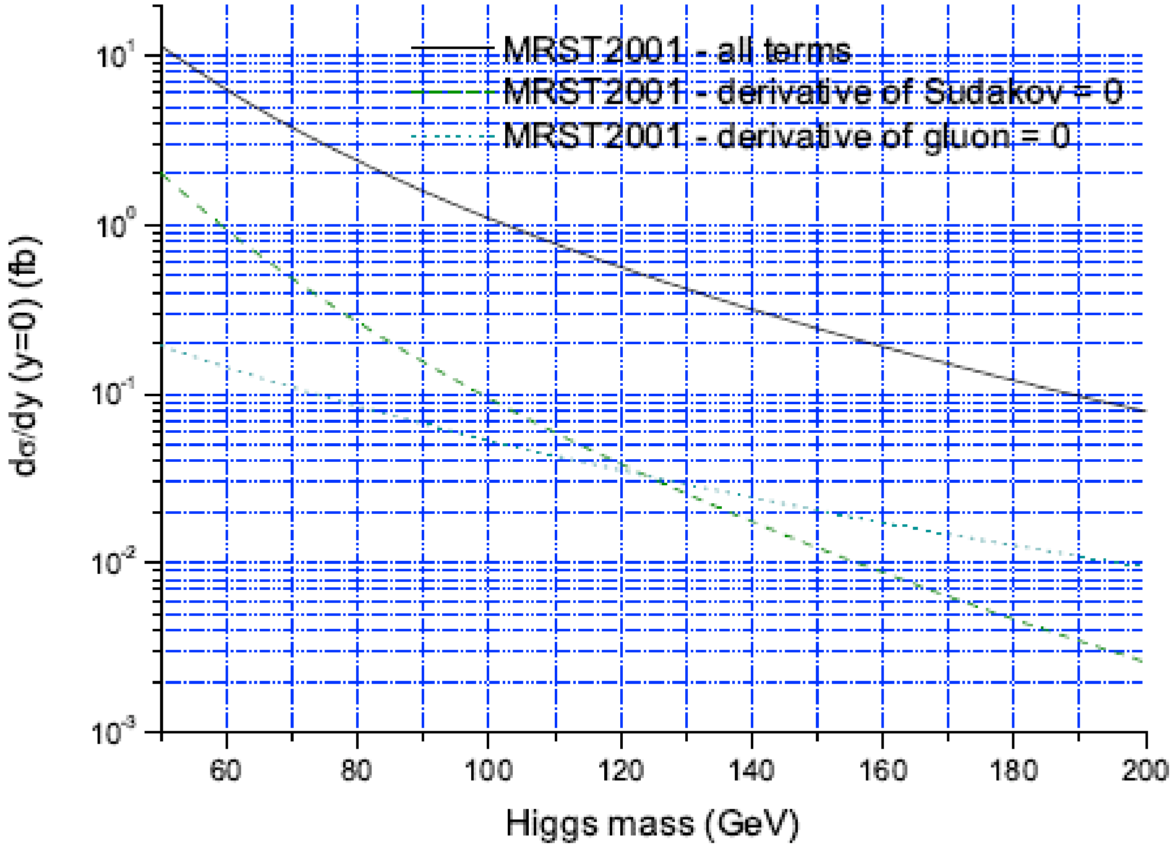
Single logs: running α_s, and quark emission

$$e^{-S} = \exp\left(-\int_{Q_T^2}^{m_H^2/4} \frac{dp_T^2}{p_T^2} \frac{\alpha_s(p_T^2)}{2\pi} \int_0^{1-\Delta} dz\, [z P_{gg}(z) + \sum_q P_{qg}(z)]\right)$$

Q_T integral:

$$\int \frac{dQ_T^2}{Q_T^4} \tilde{f}(x_1, Q_T) \tilde{f}(x_2, Q_T) \qquad \tilde{f}(x, Q_T) = \frac{\partial}{\partial \ln Q_T^2} \left(e^{-S/2} G(x, Q_T) \right).$$

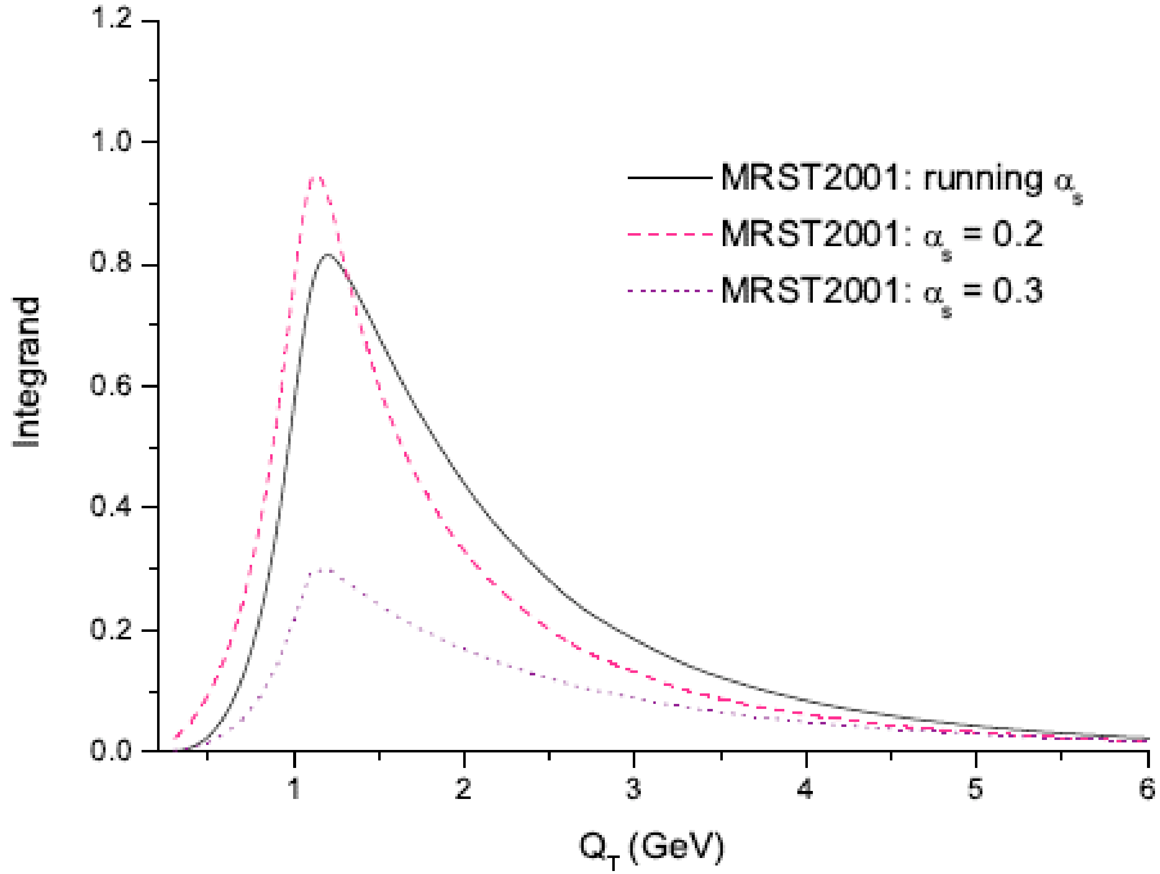
Sudakov suppression factor



Forshaw 2005

Single log effect very large ~ 30 for $m_H \sim$ 120 GeV

Are we justified in using perturbative QCD in this treatment?



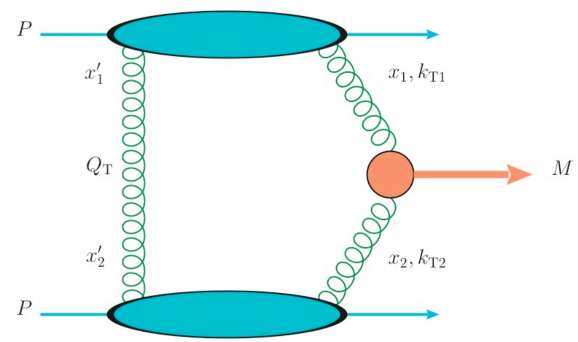
Integral peaks around 1 GeV and Sudakov suppression gets better with increasing α_s

We have looked at CEP of

- Graviton
- leptogluons and leptoquarks
- squark pair, gluino pair production
- ......
- production of

$$\chi_c^{2+}, \chi_b$$

Graviton contribution is zero !

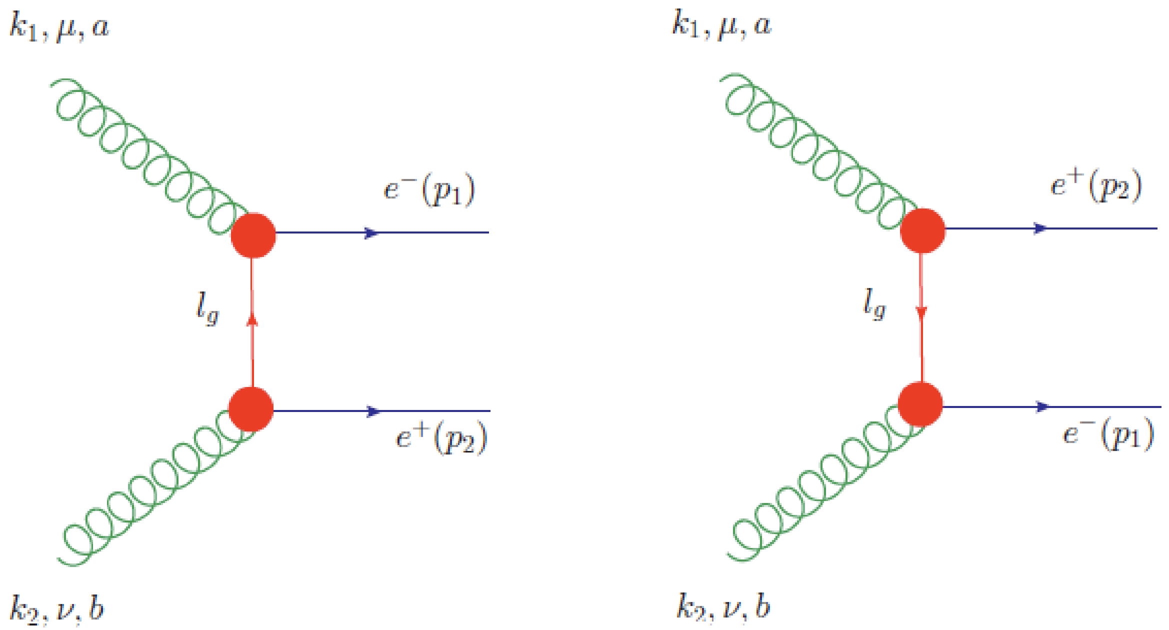


The 0^{++} ($J_z = 0$, C,P even) selection rule forbids exclusive spin-2 graviton production

gluons can only couple to the scalar component *h*

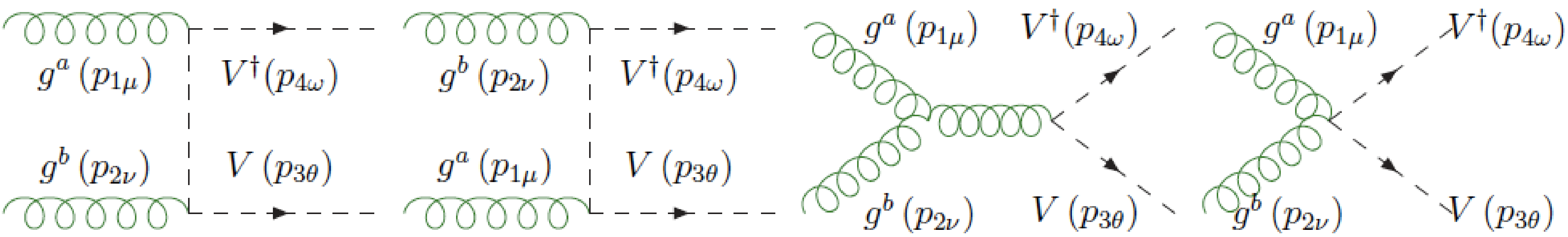
Leading order coupling of *h* to two gluons is zero (for massless gluons)

Lepto gluon



$$\mathcal{L}_{\rm eff} = \frac{g_s}{\Lambda}\left[\lambda_L \bar{e}_L \sigma^{\mu\nu} L_g{}^a_R + \lambda_R \bar{e}_R \sigma^{\mu\nu} L_g{}^a_L\right] G^a_{\mu\nu} + h.c.,$$

Vector lepto quark



$$\mathcal{L} \;=\; \frac{1}{2}\,(D_\mu\,V_\nu - D_\nu\,V_\mu)^\dagger\,(D^\mu\,V^\nu - D^\nu\,V^\mu) - m^2\,V_\mu\,V^\mu$$

V_μ :Vector lepto quark

FP420 R&D project: arXiv:0806.0302

Installation of forward proton detectors, 420m from the interaction point of ATLAS and CMS

↓

Detect both outgoing protons that have lost < 2% of their longitudinal momentum along with associated centrally produced system

$$pp \to p + \phi + p$$

ϕ can be a single particle (H) or more than one

CEP particularly attractive for heavy new particles

- The di-gluon system obeys a $J_z = 0$, C-even, P-even selection

↓

allows clean determination of quantum numbers of the new particle/ resonance

-- the process is exclusive

↓

energy loss of the outgoing protons directly related to the invariant mass of the central system

-- For Higgs boson production and other particles, large signal/background ratios (~1 or better) is possible

Broad QCD and EW physics program

- By tagging both protons, the LHC is effectively turned into a gluon-gluon, photon-proton, photon-photon collider
- In QCD detailed studies of diffractive scattering, unintegrated gluon densities, rapidity gap survival probabilities, properties of gluon jets, dilepton production, quarkonia, can be carried out
- Observing Higgs boson in SM, MSSM, NMSSM in W, tau and b quark decay channels
- Can use b-bar decay channel of Higgs (normally it has overwhelming backgrounds)
- ....