Interpreting virtual photon interactions in terms of parton distribution functions

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2. **PDF of the virtual photon: who needs them?**
3. **World of SaSGAM**
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Why virtual photon?

because virtuality dependence of (the structure) of the photon provides information on several aspects of QCD:

- distinction **structure** vs **interaction**
- separation **perturbtive** vs **nonperturbative**
- structure/interactions of the **longitudinal** photon

Beware:

In QFT it is difficult to distinguish the effects of structure from those of interactions

Standard Model:

fundamental particles:

(quarks, leptons, gauge bosons, Higgs)
associated with fields in $\mathcal{L}_{\mathrm{SM}}$ but not necessarily eigenstates of $\mathcal{H}_{\mathrm{SM}}$

composite particles: (hadrons, atoms)
eigenstates of $\mathcal{H}_{\mathrm{SM}}$, but no fields in $\mathcal{L}_{\mathrm{SM}}$

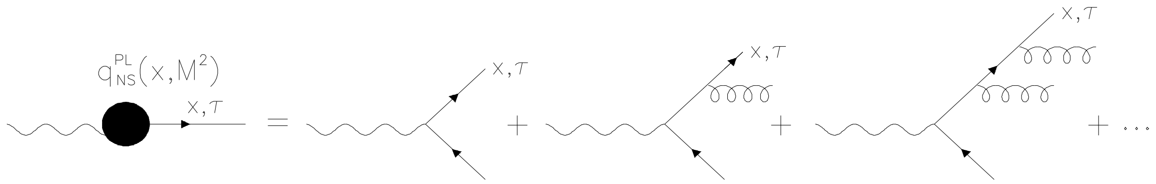
Structure in terms of **parton distribution functions** **natural** for composite particles, but very **useful** also for some fundamental ones, in particular the **photon**

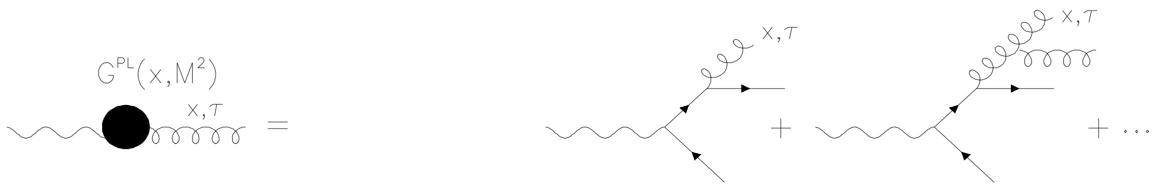
PDF of the virtual photon: who needs them?

Real photon: PDF satisfy inhomogenous evolution equations. Their solutions, for both quarks and gluons, can written as sums

$$f_{p/\gamma}(x,P^2,M^2) = f^{\mathrm{PL}}_{p/\gamma}(x,P^2,M^2) + f^{\mathrm{HAD}}_{p/\gamma}(x,P^2,M^2)$$

of a particular solution of the full inhomogenous EE, **pointlike** part, and general solution of the corresponding homogenous EE, **hadronic** or VDM, part.





$$\begin{aligned} q^{\mathrm{PL}}_{\mathrm{NS}}(x,M_0^2,M^2) &= \frac{\alpha}{2\pi} 3e_q^2(x^2+(1-x)^2)\ln\frac{M^2}{M_0^2} + \cdots \\ &= \frac{\alpha}{2\pi} a^{\mathrm{AP}}(x,M)\ln\frac{M^2}{M_0^2} \end{aligned}$$

BUT: the separation is ambiguous as there is infinite number pointlike solutions differing in initial condition:

$$f^{\mathrm{PL}}_{\mathrm{NS}}(x,M_0^2,M_0^2) = 0$$

Asymptotic pointlike: $a^{\mathrm{AP}}(x) = \lim_{M\to\infty} a(x,M)$

Evolution equations for the photon

$$\begin{aligned}
\frac{\mathrm{d}\Sigma(M^2)}{\mathrm{d}\ln M^2} &= k_q + P_{qq}\otimes\Sigma + P_{qG}\otimes G, \\
\frac{\mathrm{d}G(M^2)}{\mathrm{d}\ln M^2} &= k_G + P_{Gq}\otimes\Sigma + P_{GG}\otimes G, \\
\frac{\mathrm{d}q^i_{\mathrm{NS}}(M^2)}{\mathrm{d}\ln M^2} &= \sigma^i_{\mathrm{NS}} k_q + P_{\mathrm{NS}}\otimes q^i_{\mathrm{NS}},
\end{aligned}$$

splitting function expanded in powers of $\alpha_s(M)$

$$\begin{aligned}
k_q(x,M) &= \frac{\alpha}{2\pi}\left[k_q^{(0)}(x) + \frac{\alpha_s(M)}{2\pi}k_q^{(1)}(x) + \left(\frac{\alpha_s(M)}{\pi}\right)^2 k_q^{(2)}(x) + \cdots\right] \\
k_G(x,M) &= \frac{\alpha}{2\pi}\left[\frac{\alpha_s(M)}{2\pi}k_G^{(1)}(x) + \left(\frac{\alpha_s(M)}{\pi}\right)^2 k_G^{(2)}(x) + \cdots\right] \\
P_{ij}(x,M) &= \frac{\alpha_s(M)}{2\pi}P_{ij}^{(0)}(x) + \left(\frac{\alpha_s(M)}{2\pi}\right)^2 P_{ij}^{(1)}(x) + \cdots,
\end{aligned}$$

where

$$k_q^{(0)} = 3e_q^2(x^2 + (1-x)^2), \quad P_{ij}^{(0)}$$

are **unique**, but all higher order splitting functions

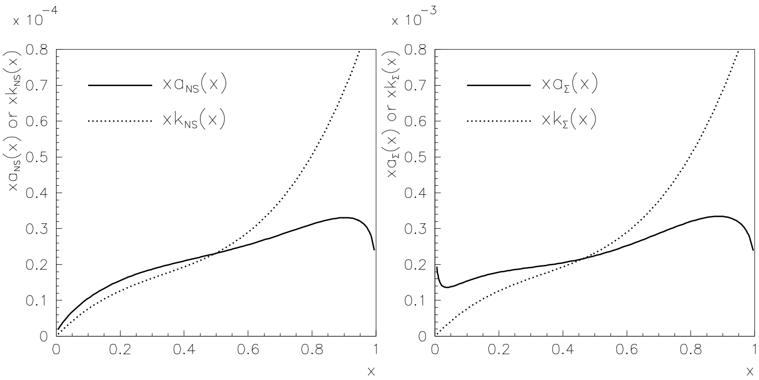
$$k_q^{(j)}, k_G^{(j)}, P_{kl}^{(j)}, j \geq 1$$

depend on the choice of **factorization scheme**

- Evolution equations can be used for $P^2 > 0$ as well but the whole framework based on PDF meaningful only so long as (Q^2 denotes a hard scale)

$$P^2 \ll Q^2$$

- hadronic part **necessary** for theoretical consistency at $P^2 = 0$, contains **nontrivial** information on nonperturbative properties of hadrons,
- hadronic part and thus also the **ambiguity PL vs HAD** important only at low P^2 and x.
- pointlike part calculable in perturbation theory and thus seemingly "trivial", but still very useful **phenomenologically**
- important effects icorporated in PDF
  - **softening** of **pointlike quarks**



  - **appearance** of **pointlike gluons**

World of SaSgam

SaS parametrizations provide excellent "laboratory" illustrating quantitatively basic features of photonic PDF

- **Ambiguity** of the separation into HAD and PL
- **Role** of the splitting term in $q^{\rm PL}$
- **Scale** dependence of HAD and PL
- Predictions for **physical quantities**
- **Virtuality** dependence of both PL and HAD

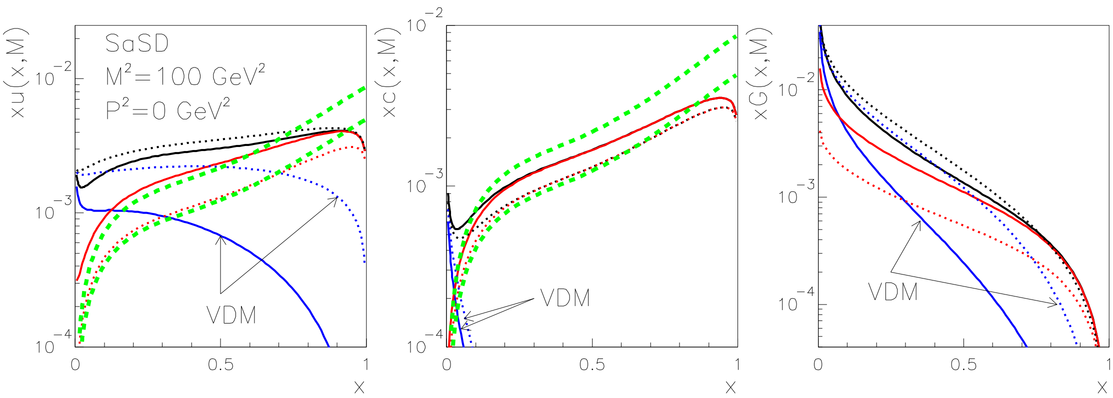


Figure 1: The x–dependence of u and c quark and gluon distribution functions of the real photon for SaS1D (upper solid curves) and SaS2D (upper dotted curves).

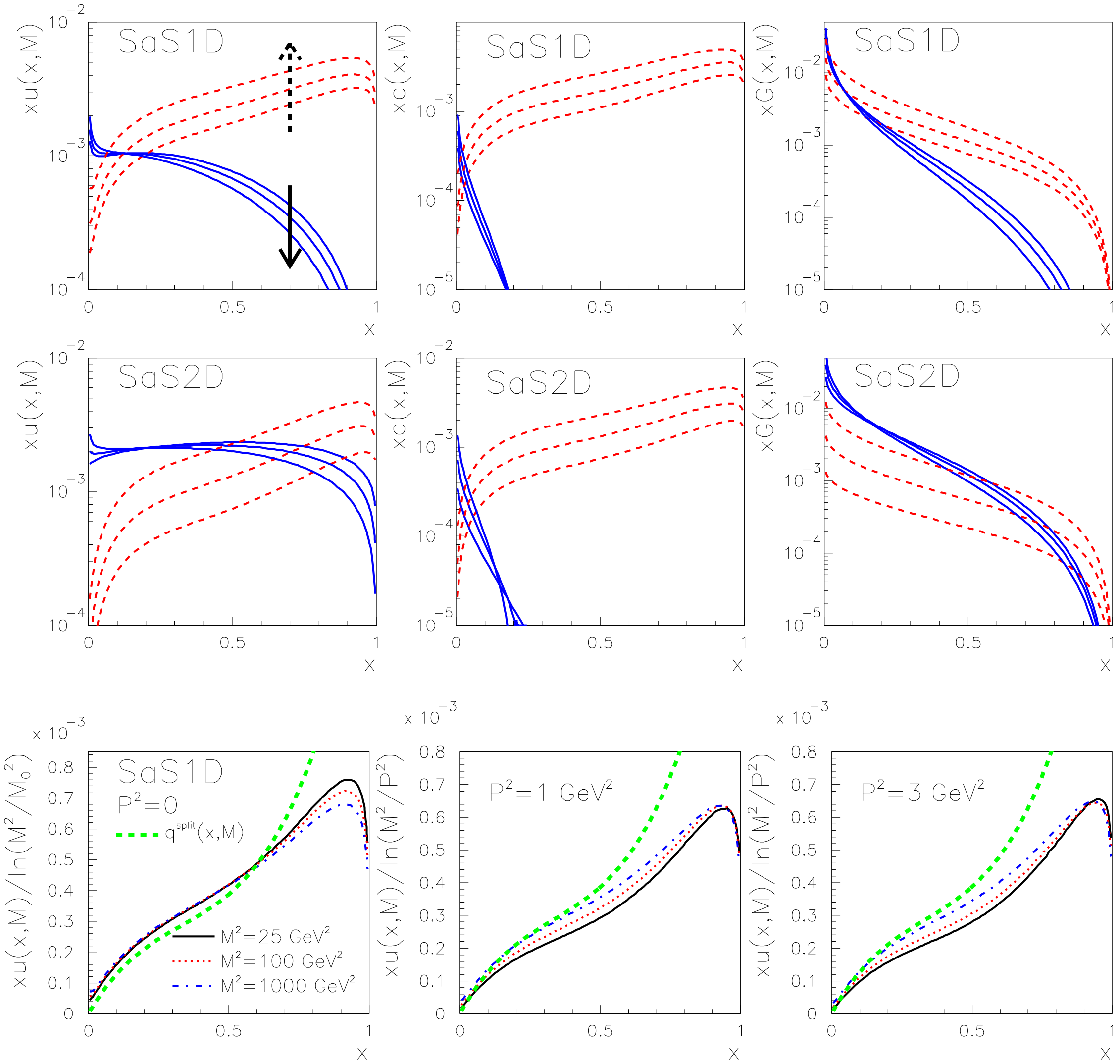


Figure 2: Factorization scale dependence of parton distributions functions $u(x,M), c(x,M)$ and $g(x,M)$ of the real photon. The dashed curves correspond pointlike, the solid to VDM parts of these distributions at $M^2 = 25, 100$ and 1000 GeV^2, in the order indicated by the arrows. The indicated pattern of scale dependence is the same for all parton distributions. In the lower part quark distribution $xu(x,M^2,P^2)$ scaled by $\ln(M^2/M_0^2)$ for the real photon (left) and by $\ln(M^2/P^2)$ for the virtual one, are plotted and compared to the predictions of the splitting term.

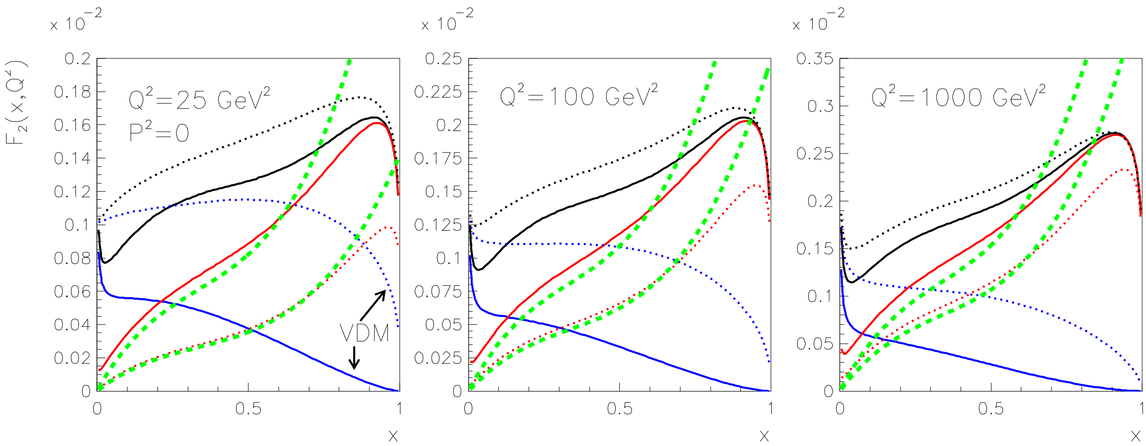


Figure 3: $F_2^\gamma(x,Q^2)$ as a function of x for $Q^2 = 25, 100, 1000$ GeV^2 as given by SaS1D (solid curves) and SaSD2 (dotted curves) parametrizations. The full results correspond to the upper, the VDM part to the lower curves. The dashed curves describe the splitting terms, corresponding to $M_0 = 0.6$ GeV for SaS1D and $M_0 = 2$ GeV for SaS2D.

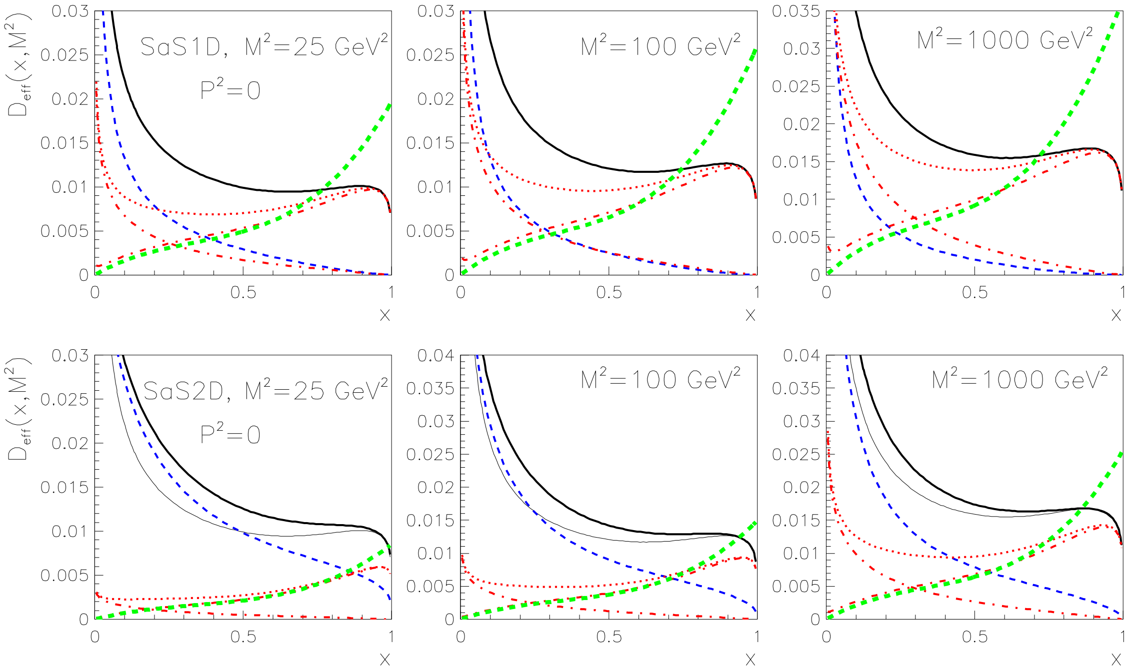


Figure 4: $D_{\rm eff}(x,M^2)$ as a function of x for $M^2 = 25, 100, 1000$ GeV^2 for the real photon as given by SaS1D and SaSD2 parametrizations. Solid curves show the full results, dashed ones the VDM and dotted ones the pointlike parts and the two dash–dotted curves correspond to the gluon (those peaking at low x) and quark contributions to the pointlike component. Thick dashed curves are given by the simple $\gamma \to q\bar{q}$ splitting term.

New features at $P^2 \geq 1$ GeV^2

The **PL** and **HAD** parts exhibit

- **Different P^2 dependence**
- **Different patterns** of scaling violations

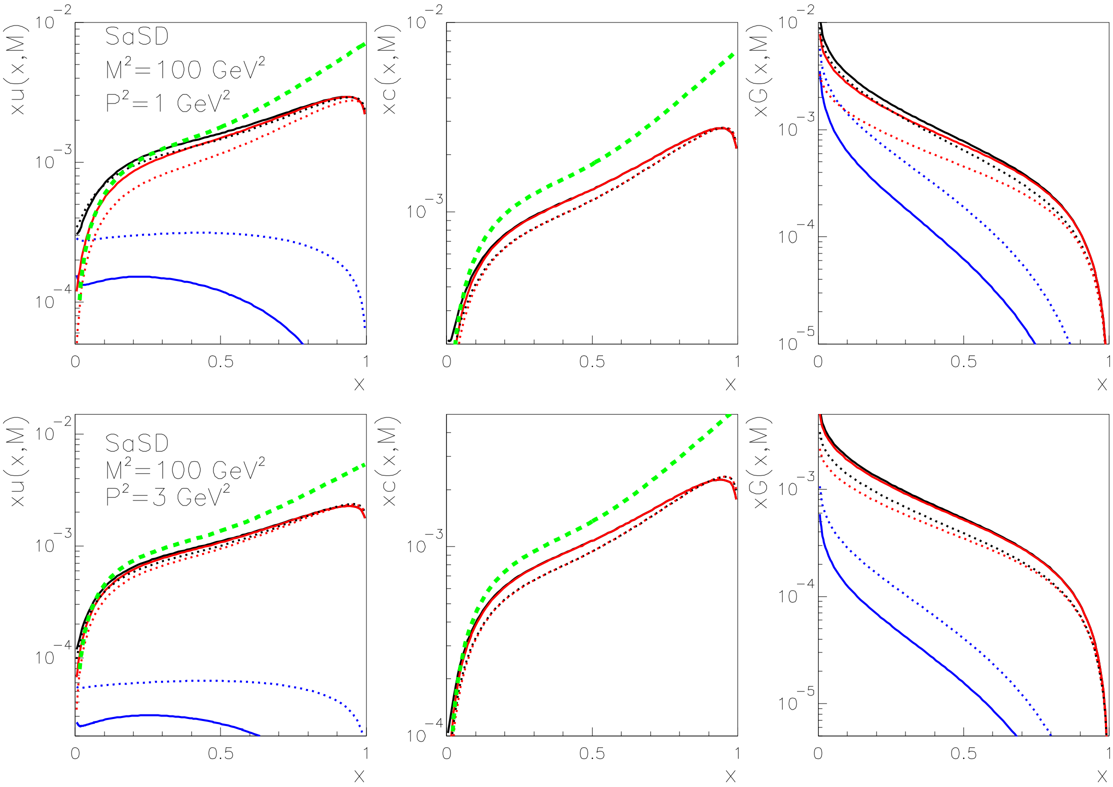


Figure 5: The same as in Fig. 1 but for virtual photon with virtualities $P^2 = 1$ and $P^2 = 3$ GeV^2.

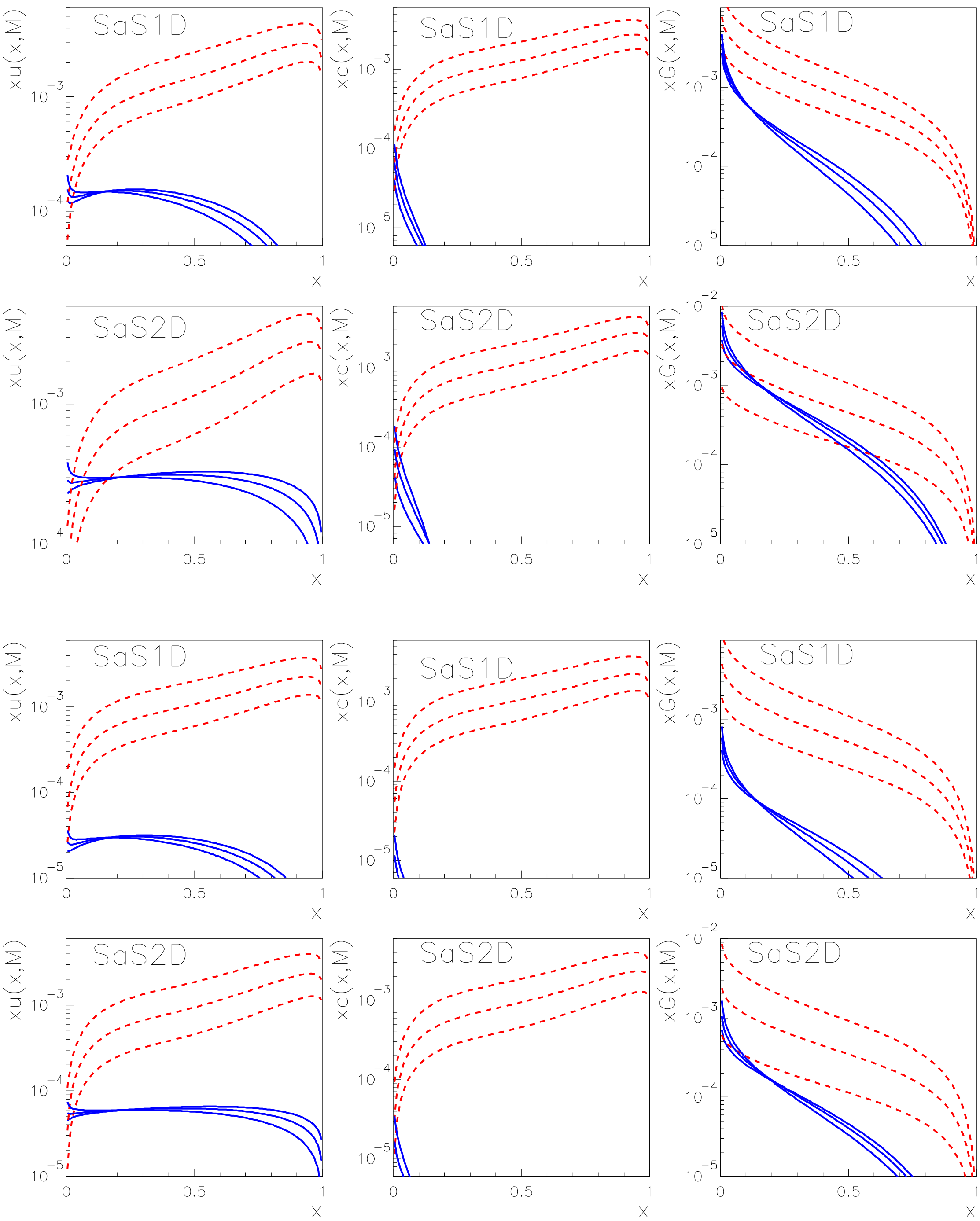


Figure 6: The same as in Fig. 2, but for virtual photon with $P^2 = 1$ (upper six plots) and $P^2 = 3$ (lower six plots) GeV^2.

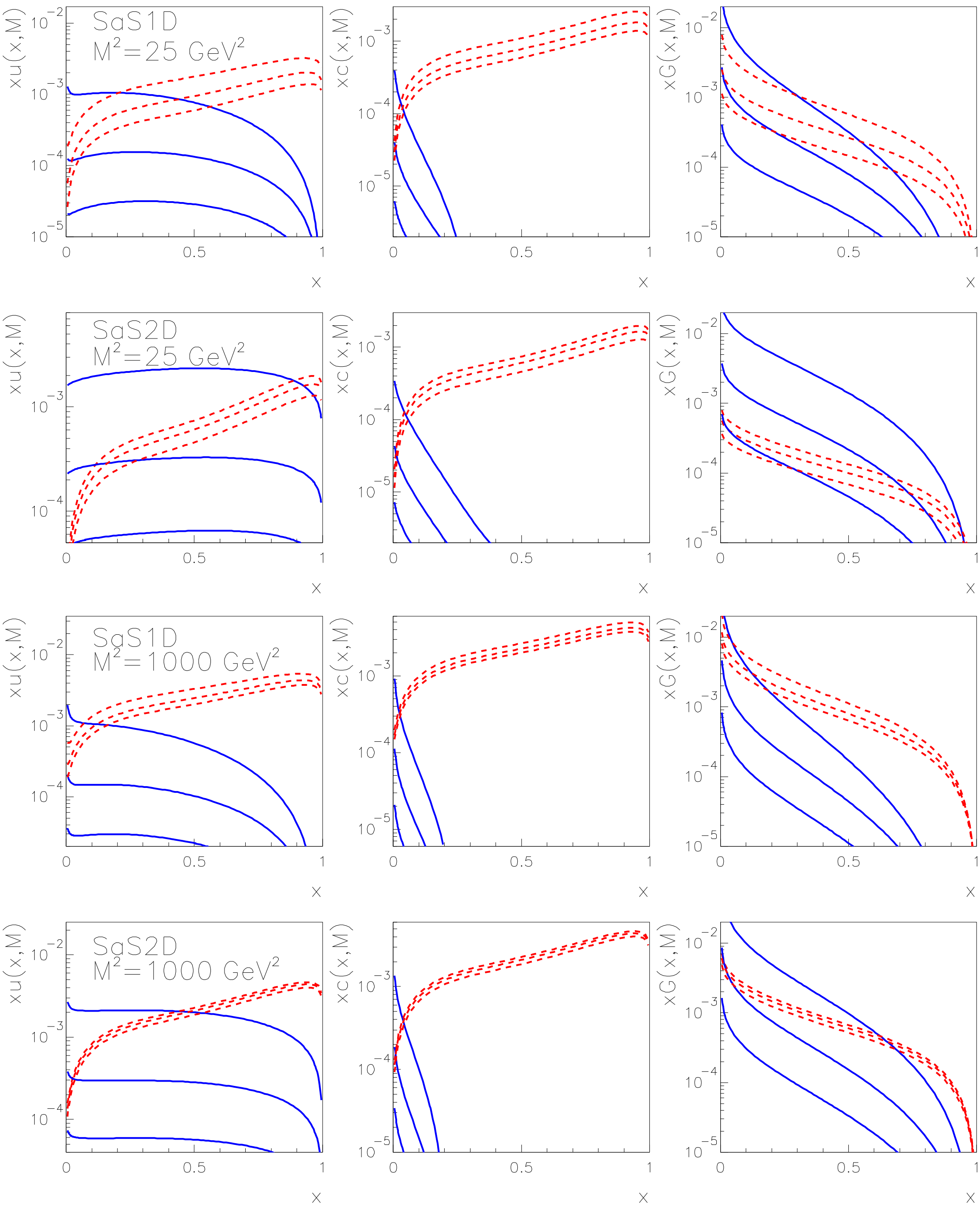


Figure 7: The virtuality dependence at $Q^2 = 25$ and $Q^2 = 1000$ GeV^2. The dashed curves correspond to pointlike and the solid ones to VDM parts of PDF, from above at $P^2 = 0, 1, 3$ GeV^2.

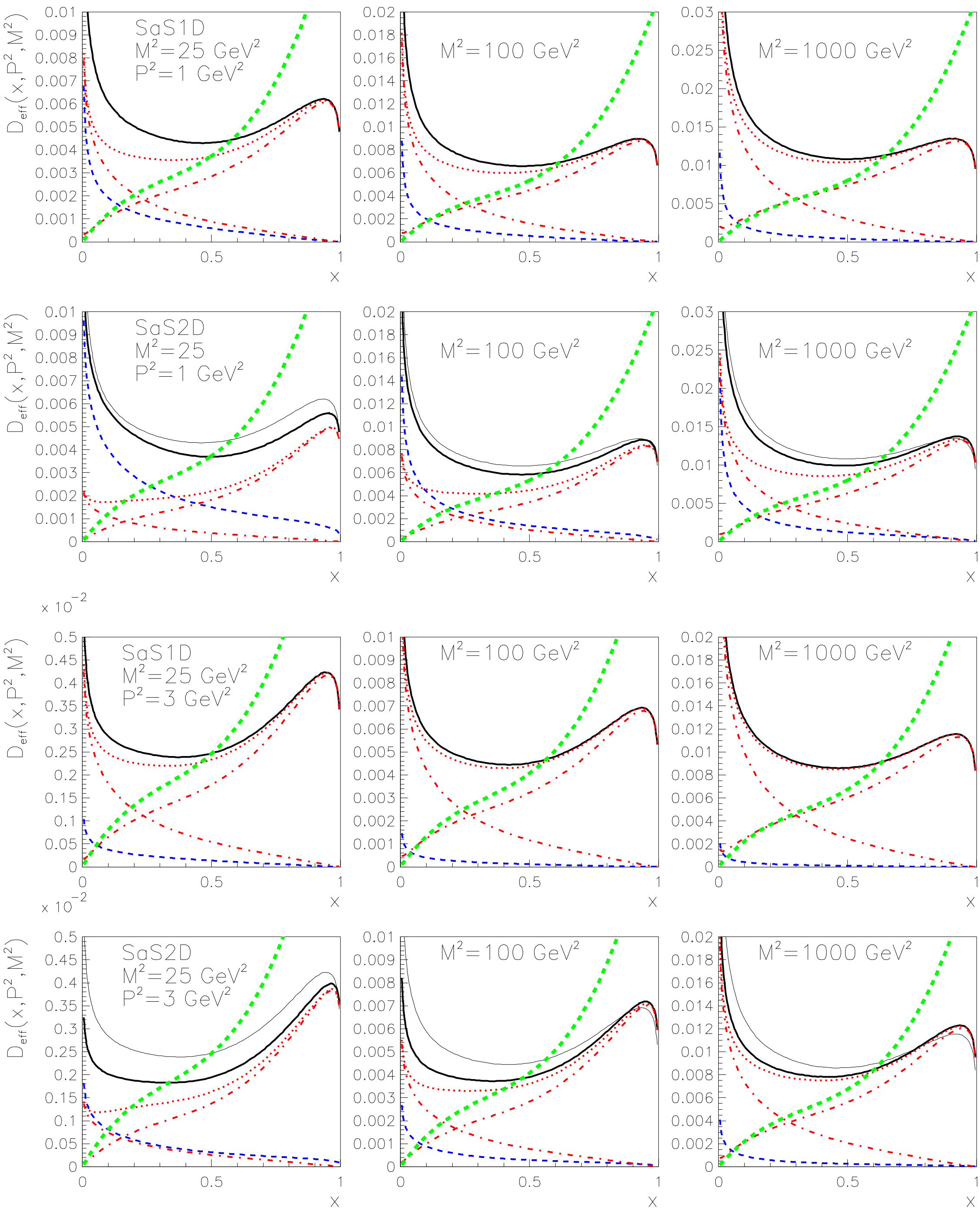


Figure 8: $D_{\rm eff}(x, P^2, M^2)$ as a function of x for $M^2 = 25, 100, 1000$ GeV^2 and $P^2 = 1, 3$ GeV^2. Notation as in Fig. 4, with thin solid curve in SaS2D plots representing the results of the corresponding SaS1D parametrizations for comparison. In the splitting term we set $M_0^2 = P^2$.

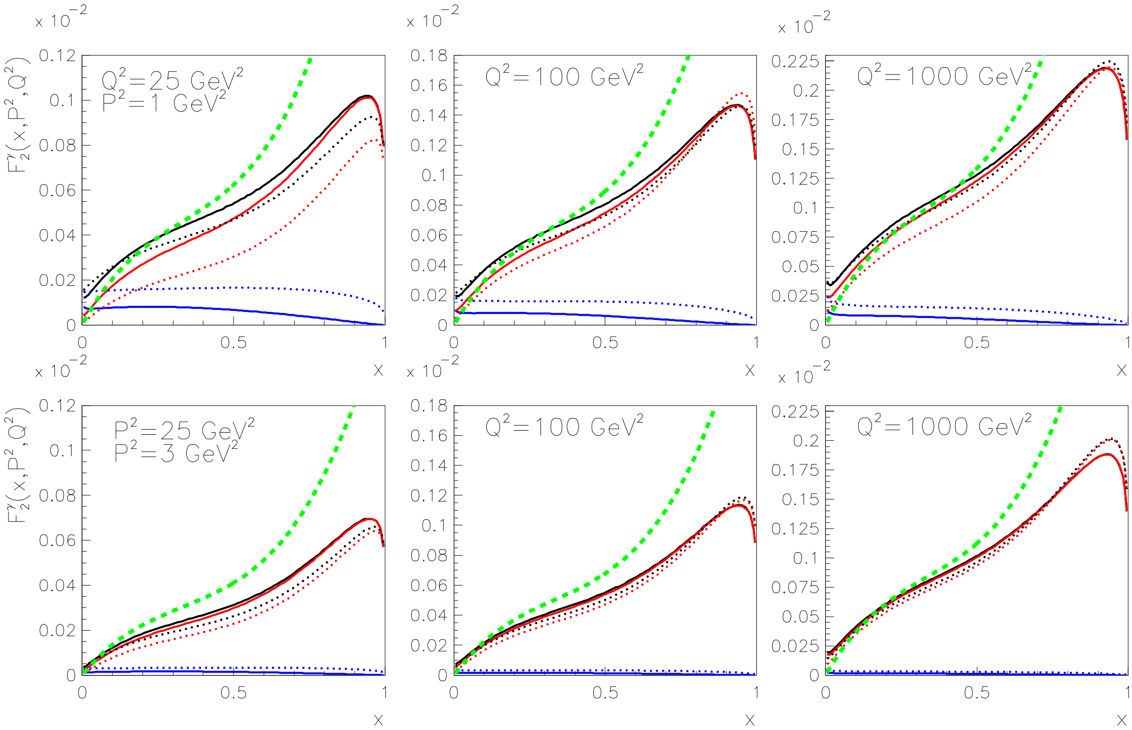


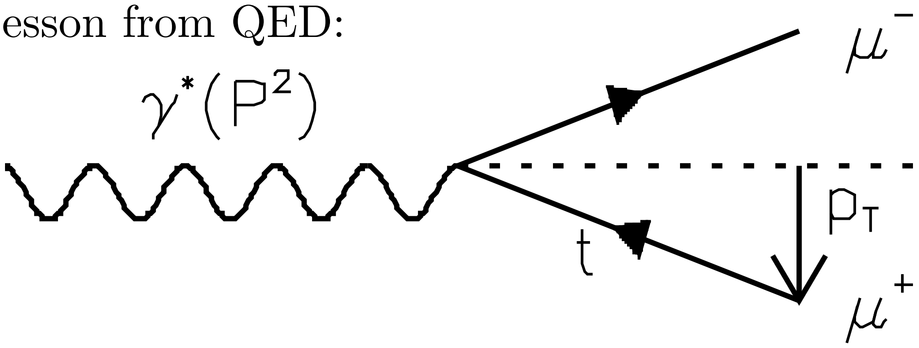
Figure 9: The same as in Fig. 3 but for virtual photon with $P^2 = 1, 3$ GeV^2.

Conclusion: jets in the region $x_\gamma \leq 0.5$, $P^2 \geq 1$ GeV^2 offer an **ideal place** to observe **nontrivial aspects** of photonic PDF. The resolved contribution to jet XS

- is dominated by the **pointlike gluons** at **small to medium** x_γ, where it leads to an **excess** of DIR+RES calculations over the DIR$_{\rm uns}$ ones
- while at x **close to** $x_\gamma = 1$ **pointlike quarks** take over, leading to **opposite** effect

Should we care about γ_L^*?

Lesson from QED:



$$f_{\mu/\gamma^*}(x,m^2,P^2,Q^2) \equiv \frac{\alpha}{2\pi}\int_{-Q^2}^{t_{max}} \frac{W(x,m^2,P^2)}{(t-m^2)^2}\mathrm{d}t$$

$$W(x,m^2,P^2) = f(x)\frac{p_T^2}{1-x} + g(x)m^2 + h(x)P^2$$

Integrating ovet dt we get in units of $\alpha/2\pi$

$$f_{\mu/\gamma}(x,m^2,P^2,Q^2) = f(x)\ln\frac{Q^2}{\kappa^2} - f(x)\left(1-\frac{\kappa^2}{Q^2}\right) + \frac{g(x)m^2+h(x)P^2}{\kappa^2}\left(1-\frac{\kappa^2}{Q^2}\right)$$

where $\kappa^2 \equiv xP^2 + m^2/(1-x)$ and

$$f_T(x) = x^2+(1-x)^2, \quad g_T(x) = \tfrac{1}{1-x}, \quad h_T(x) = 0$$
$$f_L(x) = 0, \quad g_L(x) = 0, \quad h_L(x) = 4x^2(1-x)$$

$\Downarrow$

transition between real and virtual γ governed by P^2/m^2

Compare PM predictions for $\gamma^*_{\rm L}$ with $\gamma^*_{\rm T}$(SaS1D):

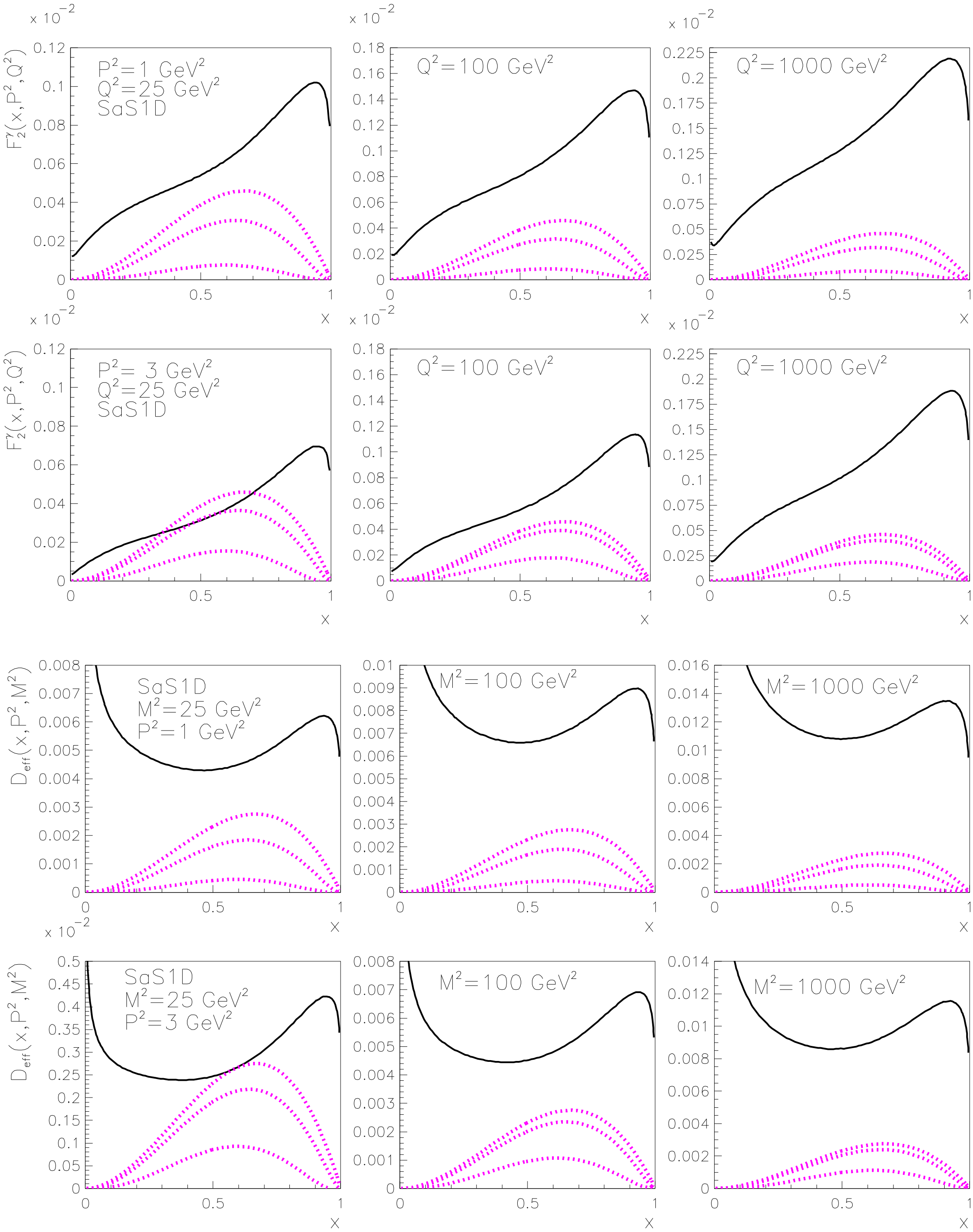


Figure 10: $F_2^\gamma(x,P^2,Q^2)$ and $D_{\rm eff}(x,P^2,M^2)$ for SaS1D parametrizations including the contribution of the longitudinal photon (dash-dotted curves).

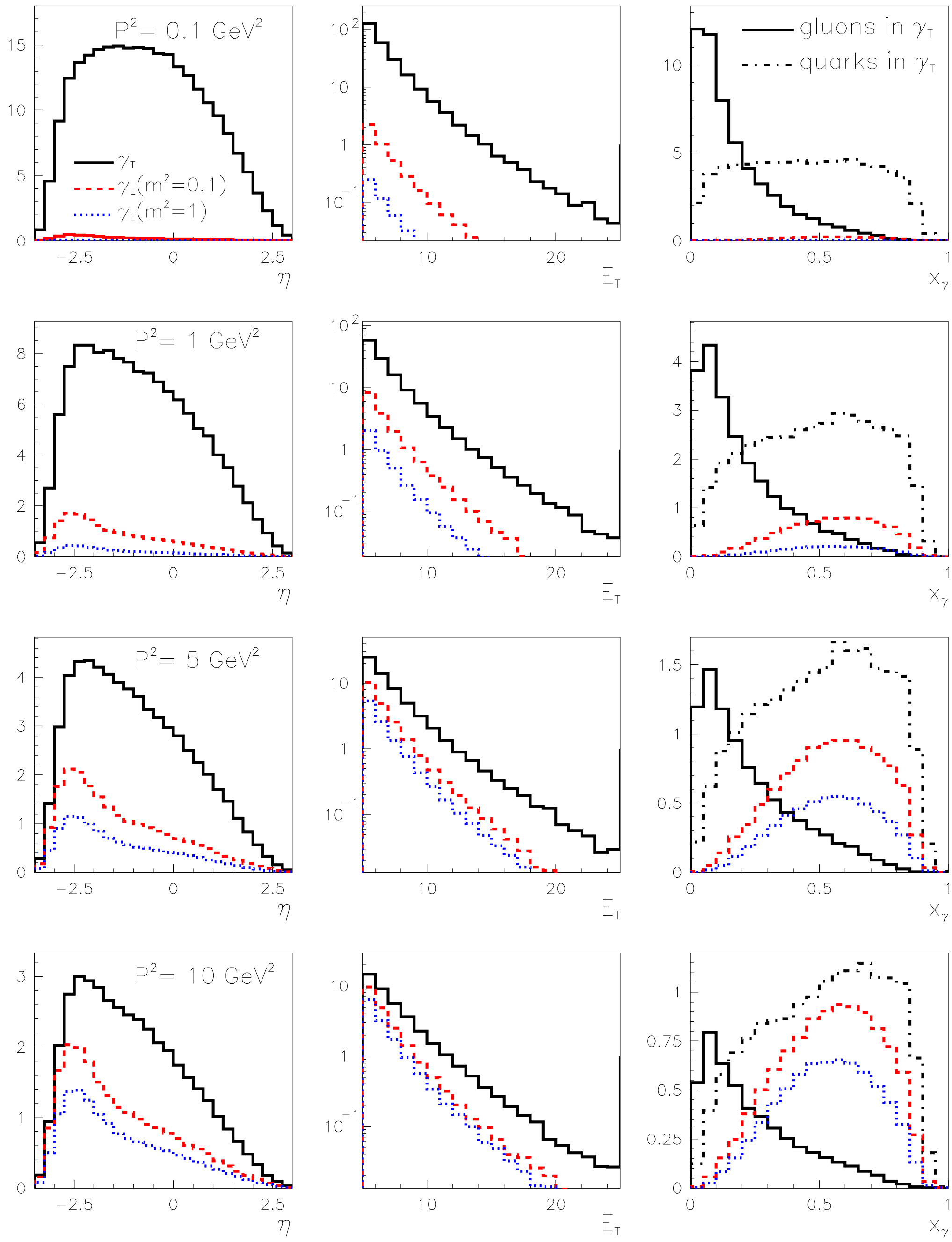


Figure 11: Contributions of γ_L^* to dijet production at $P^2 = 0.1, 1, 5, 10$ GeV^2 for $m^2 = 0.1, 1$ GeV^2.

PDF in NLO calculations

For virtual photons JETVIP can be run in two modes:

DIR$_{\rm uns}$: only the NLO unsubtracted direct photon calculations are performed without introducing the concept of virtual photon structure, i.e. like **DISENT**, **MEPJET** and **DISASTER**

DIR+RES: employs the concept of PDF of the virtual photon and gives the jet cross–sections as sums of subtracted direct (DIR) and resolved photon (RES) contributions, only **JETVIP**

Choice of PDF: CTEQ4M (proton) and SAS1D (γ^*)

Factorization scale dependence:

$$M = E_T^{(1)}/2, E_T^{(1)}, 2E_T^{(1)}.$$

Renormalization scale dependence: $\mu = M$.

Jet algorithm ambiguities: $R_{\rm sep} = R, 2R$.

$$\Delta R_{ij} = \sqrt{(\Delta\eta_{ij})^2 + (\Delta\phi_{ij})^2} \leq \frac{E_{T_i} + E_{T_j}}{\max(E_{T_i}, E_{T_j})} R.$$

$$\Delta R_{ij} \leq \min\left[\frac{E_{T_i} + E_{T_j}}{\max(E_{T_i}, E_{T_j})} R, R_{\rm sep}\right]$$

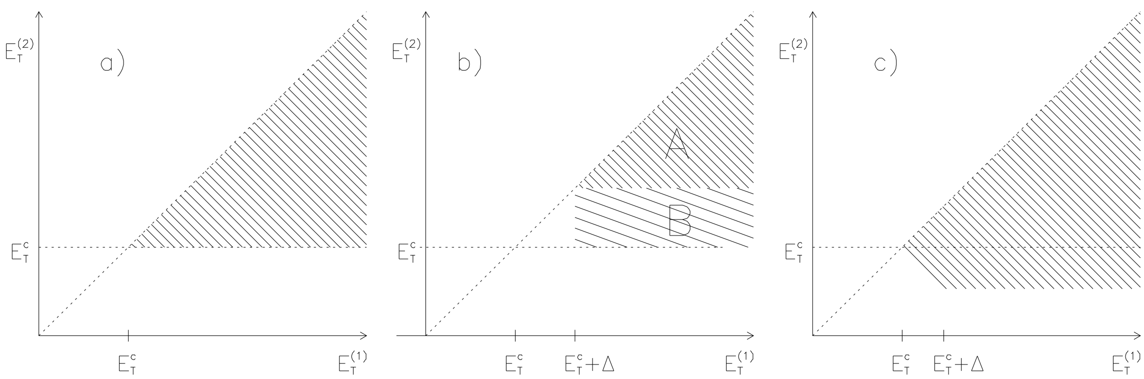
Hadronization corrections: **crucial**, particularly for jets with moderate E_T, but **not simple** to define and strongly η–dependent. Using standard definition leads to restriction

$$-2.5 \leq \eta^{(i)}, \ i = 1, 2$$

where corrections flat in η and $\leq$ a few percent.

Selected kinematical region

Jet E_T: $E_T^{(1)} \geq 7$ GeV, $E_T^{(2)} \geq 5$ GeV;

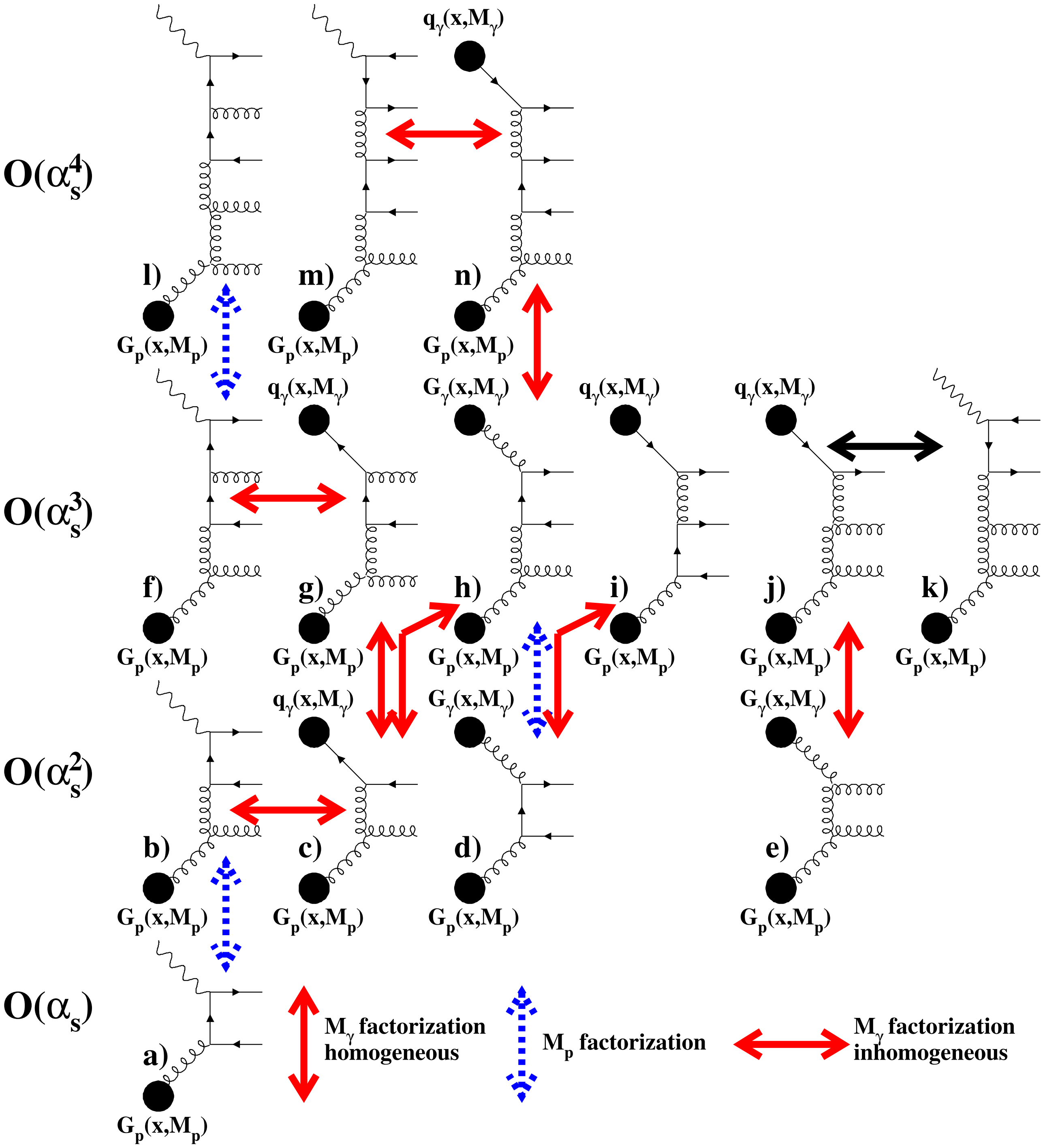


Photon virtuality:

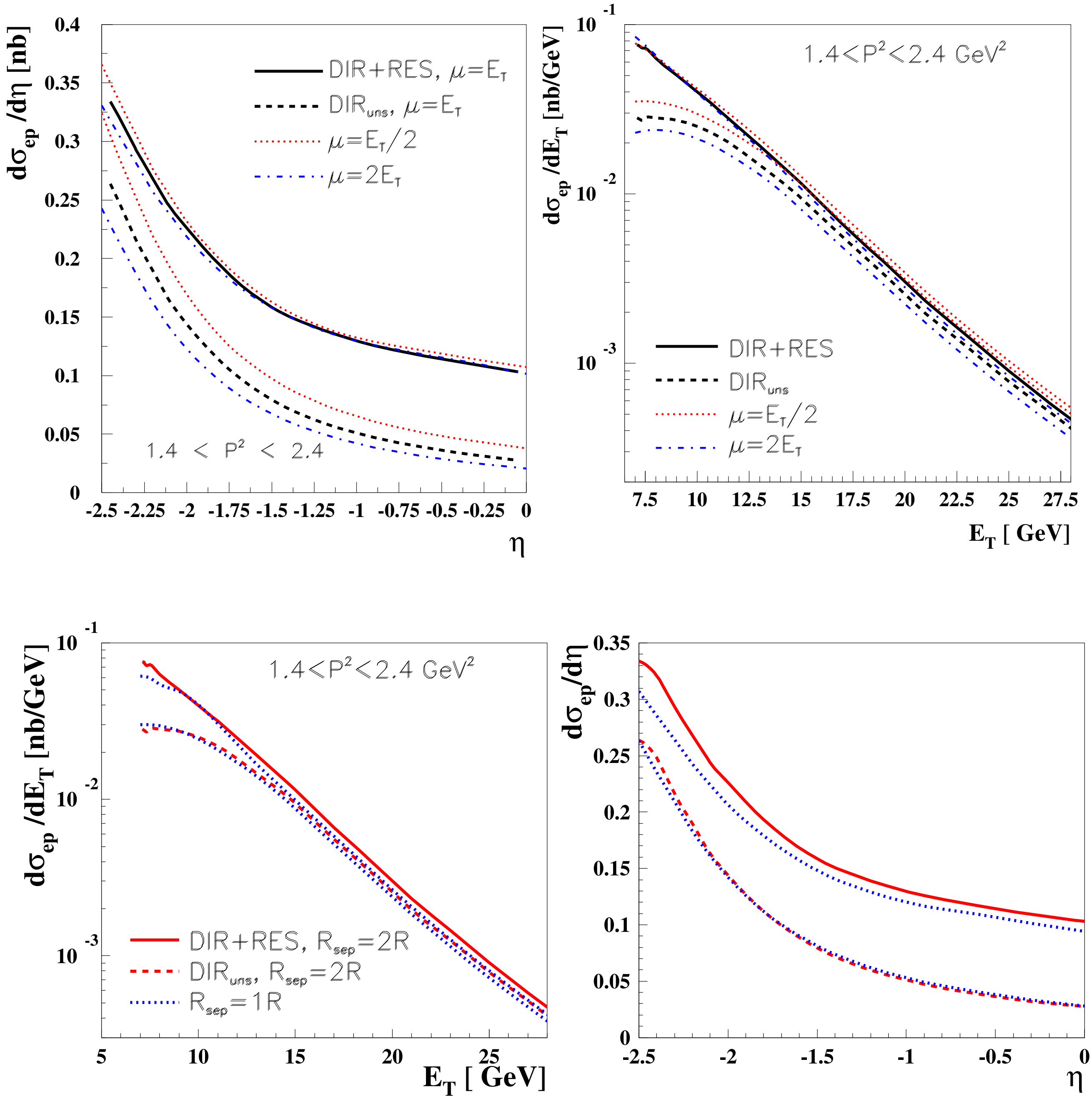
$1.4 \leq P^2 \leq 2.4$; $2.4 \leq P^2 \leq 4.4$; $4.4 \leq P^2 \leq 10$; $10 \leq P^2 \leq 25$

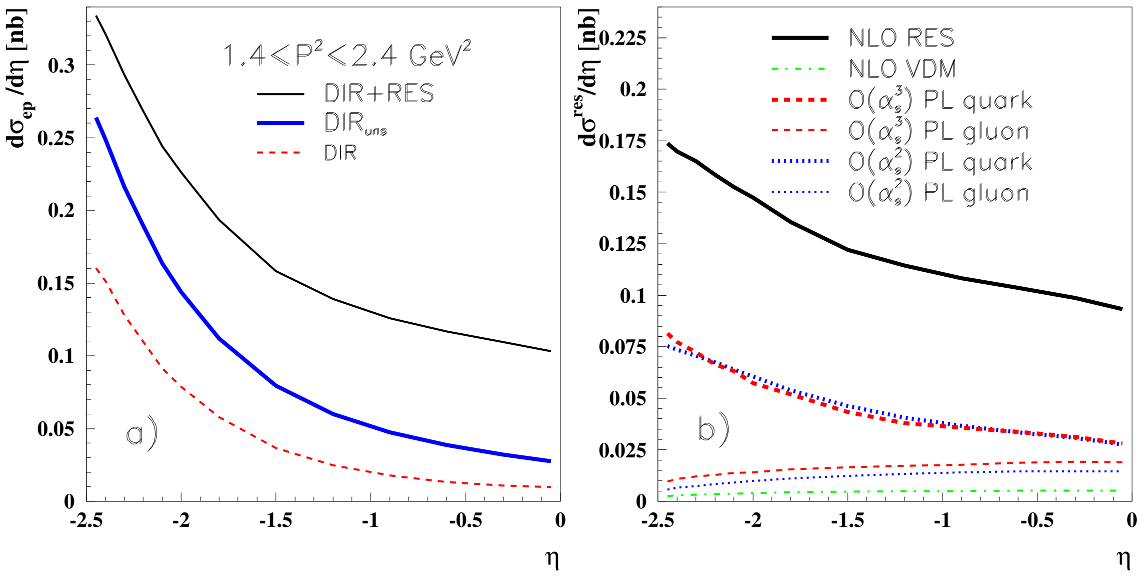
Jet pseudorapidities in γ^*p CMS: $-2.5 \leq \eta^{(i)} \leq 0$

Factorization scale dependence



JETVIP

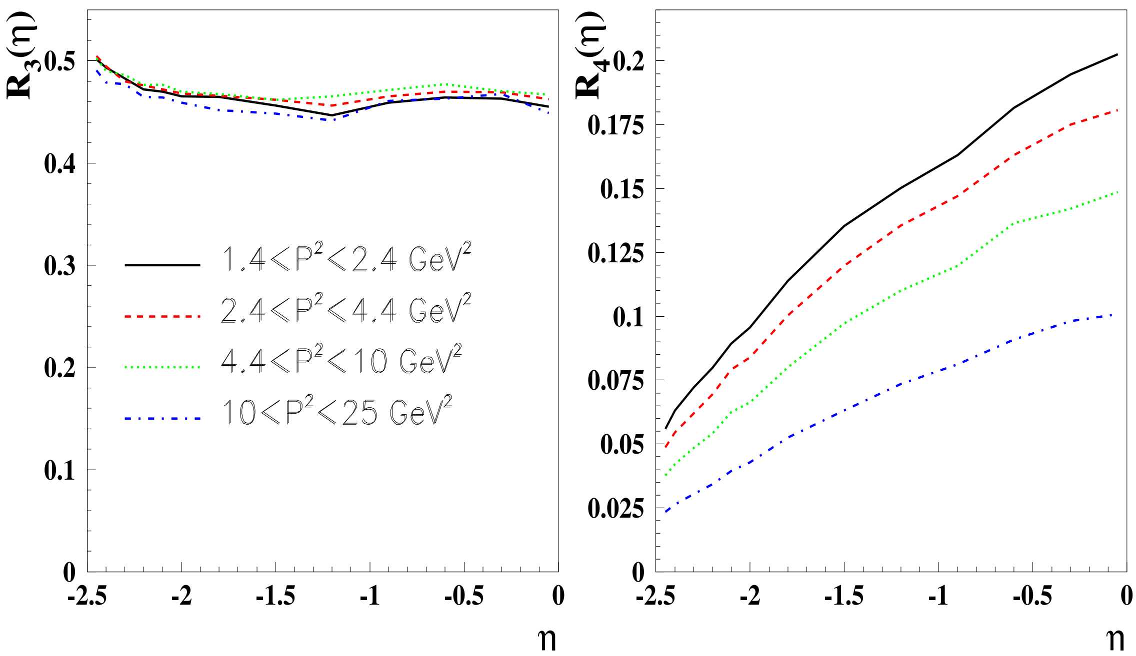

dσ_ep /dη [nb]
DIR+RES, μ=E_T
DIR_uns, μ=E_T
μ=E_T/2
μ=2E_T
1.4 < P² < 2.4
η
dσ_ep /dE_T [nb/GeV]
1.4<P²<2.4 GeV²
DIR+RES
DIR_uns
μ=E_T/2
μ=2E_T
E_T [GeV]
dσ_ep /dE_T [nb/GeV]
1.4<P²<2.4 GeV²
DIR+RES, R_sep=2R
DIR_uns, R_sep=2R
R_sep=1R
E_T [GeV]
dσ_ep/dη
η

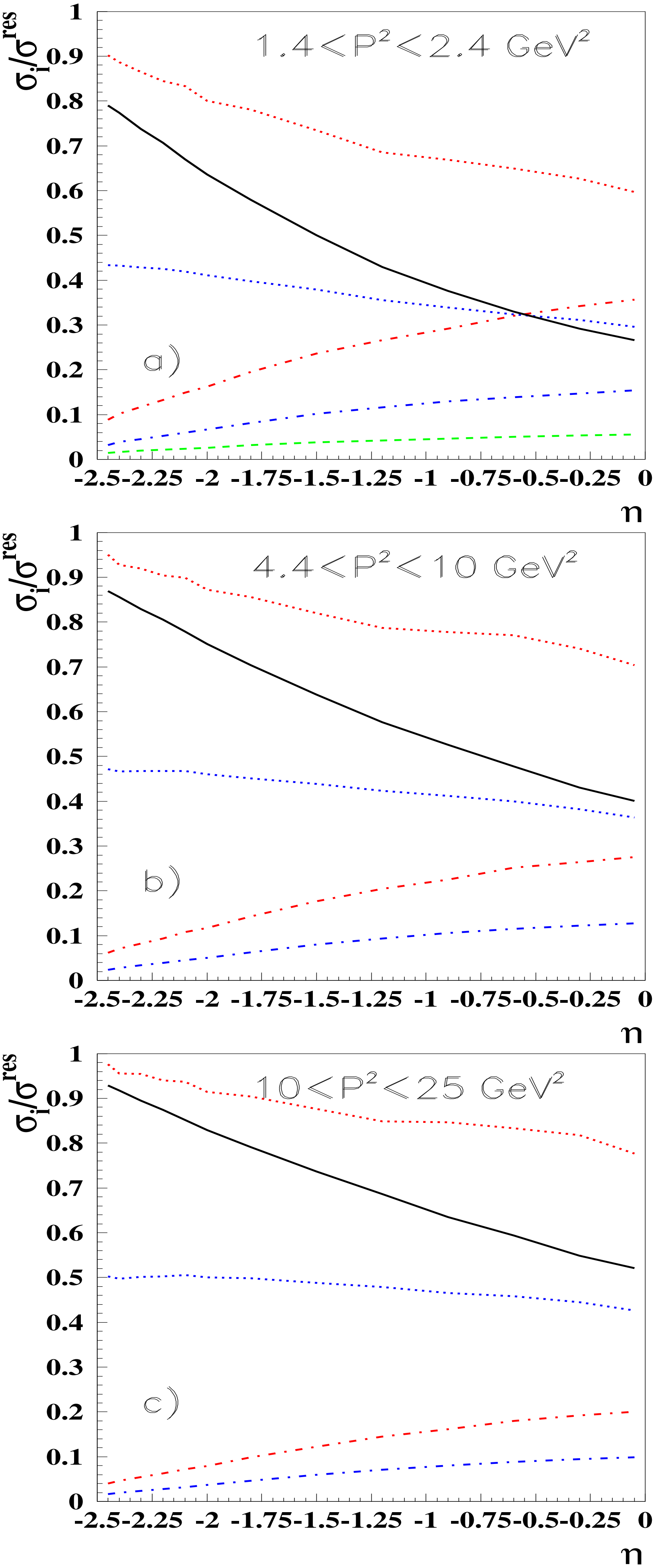


Nontrivial fractions

$$R_3 \equiv \frac{q^{\rm PL} \otimes \sigma_q^{\rm res}(O(\alpha_s^3)) + G^{\rm PL} \otimes \sigma_G^{\rm res}(O(\alpha_s^2))}{\sigma^{\rm res}}$$

$$R_4 \equiv \frac{G^{\rm PL} \otimes \sigma_G^{\rm res}(O(\alpha_s^3))}{\sigma^{\rm res}}$$




σ_i/σ^{res}
$1.4 < P^2 < 2.4$ GeV^2
a)
η
σ_i/σ^{res}
$4.4 < P^2 < 10$ GeV^2
b)
η
σ_i/σ^{res}
$10 < P^2 < 25$ GeV^2
c)
η
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
-2.5 -2.25 -2 -1.75 -1.5 -1.25 -1 -0.75 -0.5 -0.25 0

Conclusions for $P^2 \geq 1$ GeV^2:

- The contribution of the **VDM very small**, perceptible only at $P^2 \leq 3$ GeV^2 and close to $\eta = 0$.
- $O(\alpha_s^3) \doteq O(\alpha_s^2)$ resolved photon **numerically very important** for all η.
- **PL quarks dominate** $\mathrm{d}\sigma^{\mathrm{res}}/\mathrm{d}\eta$ at $\eta \approx -2.5$, while as $\eta \to 0$ **PL gluons rise** to $\approx 40\%$.
- As P^2 increases
  - $\mathrm{DIR}_{\mathrm{uns}}$ represents **increasing fraction** of full NLO results.
  - Relative contribution (PL gluons/PL quarks) **decreases**.
  - The nontriviality factor R_4 (which comes entirely from pointlike gluons) **decreases**, whereas R_3, which is dominated by pointlike quarks and flat in η, is practically **independent of P^2**.

$$\Downarrow$$

The relevance of PDF governed by P^2/M^2

nontrivial effects included in PDF persist for arbitrarily large P^2 provided $P^2 \ll M^2$.

Conclusions

In describing interactions of (sufficiently) virtual photon

- **Parton distribution functions**
  - **in principle not needed** but
  - **in practice very useful**
- **longitudinal photon should be** taken into account in phenomenological analyses of experimental data and its PDF **deserve serious theoretical investigation** within pQCD
- The data accessible at HERA via jet production offer **promising opportunity** to identify the **nontrivial aspects** of PDF of the virtual photon