LUND UNIVERSITY

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$\gamma\gamma$ Interactions
from Real to Virtual Photons

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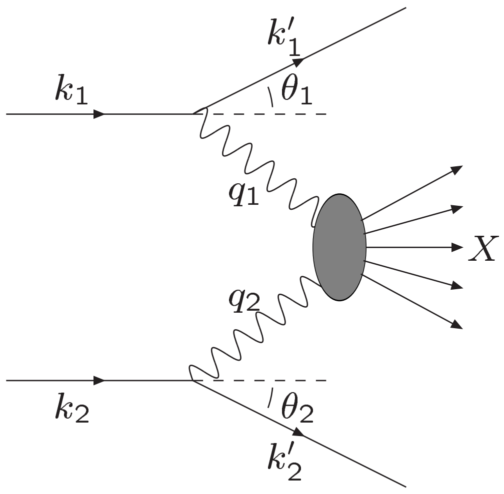
based on C. Friberg and TS,
Eur. Phys. J. C13 (2000) 151 (hep-ph/9907245),
JHEP 09 (2000) 10 (hep-ph/0007314),
LU TP 00-31 (hep-ph/0009003) $\Rightarrow$ Phys. Lett. B

Objective: "complete" framework for $\gamma\gamma/\gamma^*\gamma/\gamma^*\gamma^*$ interactions at all Q_i^2, especially $Q_i^2 \sim m_\rho^2$

Why? (1) physics challenge
(2) important background, e.g. SUSY search

Where? fully from PYTHIA 6.152

The photon flux (bremsstrahlung)



$$W^2 = (q_1 + q_2)^2$$
$$Q_i^2 = -q_i^2$$
$$y_i = \frac{q_i k_j}{k_i k_j} \quad j{=}2(1) \text{ for } i{=}1(2)$$
$$x_i = \frac{q_i(k_1 + k_2)}{k_i(k_1 + k_2)}$$
$$y_i \approx x_i + \frac{Q_i^2}{s}$$

$$Q_i^2 \approx \frac{x_i^2}{1 - x_i} m_i^2 + (1 - x_i)s \sin^2(\theta_i/2)$$

$$\mathrm{d}\sigma(\mathrm{ee} \to \mathrm{ee}X) = \sum_{\xi_1,\xi_2=\mathrm{T,L}} \int \mathrm{d}y_1\, \mathrm{d}Q_1^2\, \mathrm{d}y_2\, \mathrm{d}Q_2^2$$

$$\times\, f_{\gamma/\mathrm{e}}^{\xi_1}(y_1, Q_1^2)\, f_{\gamma/\mathrm{e}}^{\xi_2}(y_2, Q_2^2)\, \mathrm{d}\sigma(\gamma^*_{\xi_1}\gamma^*_{\xi_2} \to X)$$

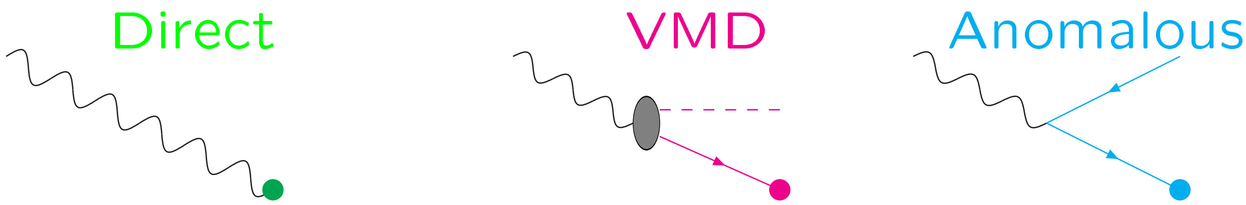
with

$$f_{\gamma/\mathrm{e}}^{\mathrm{T}}(y, Q^2) = \frac{\alpha_{\mathrm{em}}}{2\pi}\left(\frac{(1 + (1 - y)^2}{y}\frac{1}{Q^2} - \frac{2m_{\mathrm{e}}^2 y}{Q^4}\right)$$

$$f_{\gamma/\mathrm{e}}^{\mathrm{L}}(y, Q^2) = \frac{\alpha_{\mathrm{em}}}{2\pi}\frac{2(1 - y)}{y}\frac{1}{Q^2}$$

Beamstrahlung: real photons $\Rightarrow$ no news

Photoproduction / $\gamma\gamma$



Direct: point-like   Resolved: hadronic state

$\gamma\gamma$: $3 \times 3 = 9$ combinations (+ subdivisions)

Spectrum of fluctuations $\gamma \leftrightarrow \mathrm{q\overline{q}} \propto \mathrm{d}k_\perp^2/k_\perp^2$

alt. $m \simeq 2k_\perp$; $\mathrm{d}m^2/m^2$

$\star$ $k_\perp < k_0 \simeq 0.5$ GeV: nonperturbative $\gamma \to \mathrm{q\overline{q}}$
hadronic physics $\Rightarrow$ VMD
(Vector Meson Dominance)
parameterized couplings to ρ^0, ω, ϕ, J/ψ
$\sigma_{\mathrm{tot}}^{\gamma\to\rho} = \mathcal{P}(\gamma \to \rho) \cdot \sigma_{\mathrm{tot}}^{\rho}$
PDF $f_i^{\gamma\to\rho}(x, \mu^2)$, $\sigma_{\mathrm{jet}}^{\gamma\to\rho} = \ldots$
beam remnants, multiple interactions, ...

$\star$ $k_\perp > k_0$: perturbative $\gamma \to \mathrm{q\overline{q}}$
PDF calculable: anomalous part of γ
but $\sigma_{\mathrm{tot}}^{\mathrm{q\overline{q}}}$ not $\Rightarrow$ GVMD (Generalized VMD)
geometric scaling ansatz $\sigma_{\mathrm{tot}}^{\mathrm{q\overline{q}}} \propto k_V^2/k_\perp^2$,
$k_V \simeq m_\rho/2$ for light quarks
again hadronic character: beam remnants, ...

Photon 'high-$p_\perp$' processes

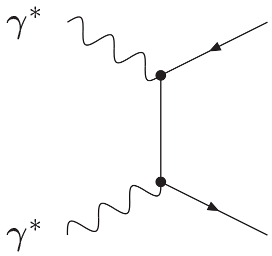
Three main 'high-$p_\perp$' jet process classes:

1. direct×direct

$\gamma^*_\mathrm{T}\gamma^*_\mathrm{T} \to \mathrm{q\overline{q}}$

$\gamma^*_\mathrm{T}\gamma^*_\mathrm{L} \to \mathrm{q\overline{q}}$

$\gamma^*_\mathrm{L}\gamma^*_\mathrm{L} \to \mathrm{q\overline{q}}$



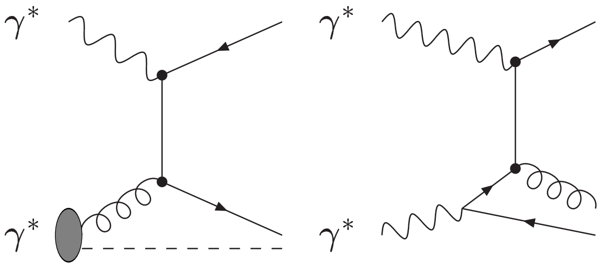
2. direct×resolved , resolved = VMD or anomalous

$\gamma^*_\mathrm{T}\mathrm{g} \to \mathrm{q\overline{q}}$

$\gamma^*_\mathrm{L}\mathrm{g} \to \mathrm{q\overline{q}}$

$\gamma^*_\mathrm{T}\mathrm{q} \to \mathrm{qg}$

$\gamma^*_\mathrm{L}\mathrm{q} \to \mathrm{qg}$



etc.

3. resolved×resolved

$\mathrm{qq'} \to \mathrm{qq'}$

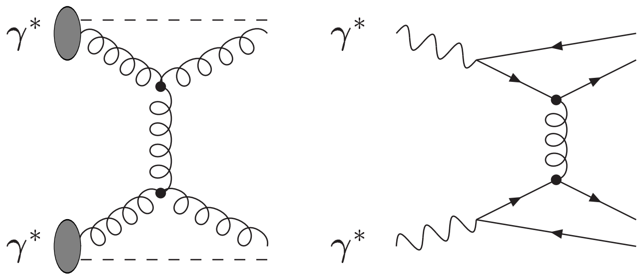
$\mathrm{q\overline{q}} \to \mathrm{q'\overline{q}'}$

$\mathrm{q\overline{q}} \to \mathrm{gg}$

$\mathrm{qg} \to \mathrm{qg}$

$\mathrm{gg} \to \mathrm{gg}$

$\mathrm{gg} \to \mathrm{q\overline{q}}$



etc.

$$\mathrm{d}\sigma(\gamma^*\gamma^* \to X) = \left(\int \mathrm{d}\hat{x}_1 \, f_i^{\gamma^*}(\hat{x}_1, \mu^2, Q_1^2) \right)$$

$$\times \left(\int \mathrm{d}\hat{x}_2 \, f_j^{\gamma^*}(\hat{x}_2, \mu^2, Q_2^2) \right) \int \mathrm{d}\hat{t} \, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}(\hat{s} = \hat{x}_1 \hat{x}_2 W^2)$$

Deeply Inelastic Scattering / $\gamma^*\gamma$

Virtual photon: $\gamma^*\mathrm{q} \to \mathrm{q}$, e.g. q in (VMD) ρ^0

$$\sigma_{\mathrm{tot}}^{\gamma^*\rho} \simeq \frac{4\pi^2\alpha_{\mathrm{em}}}{Q^2} F_2^{\rho}(x,Q^2) \simeq \frac{4\pi^2\alpha_{\mathrm{em}}}{Q^2} \sum_{\mathrm{q},\overline{\mathrm{q}}} e_{\mathrm{q}}^2\, x q(x,Q^2)$$

but $F_2 \to 0$ for $Q^2 \to 0$ by gauge invariance,
+ limit doublecounting with photoproduction

$$\sigma_{\mathrm{DIS}}^{\gamma^*\rho} \simeq \left(\frac{Q^2}{Q^2+m_\rho^2}\right)^2 \frac{4\pi^2\alpha_{\mathrm{em}}}{Q^2} \sum_{\mathrm{q},\overline{\mathrm{q}}} e_{\mathrm{q}}^2\, x q(x,Q^2)$$

where $q(x,Q^2)$ frozen for $Q^2 < Q_0^2$;
and prefactor ensures $\sigma_{\mathrm{DIS}} \to 0$ for $Q^2 \to 0$

$$\mathcal{O}(\alpha_{\mathrm{s}})\ \mathrm{DIS} = \left\{ \begin{array}{c} \mathrm{QCDC}\ \gamma^*\mathrm{q} \to \mathrm{qg} \\ \mathrm{BGF}\ \gamma^*\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}} \end{array} \right\} = \mathrm{dir} \times \mathrm{res}$$

$$\sigma_{\mathrm{LO\ \ DIS}}^{\gamma^*\rho} = \sigma_{\mathrm{DIS}}^{\gamma^*\rho} - \sigma_{\mathrm{dir}\times\mathrm{res}}^{\gamma^*\rho} \to \sigma_{\mathrm{DIS}}^{\gamma^*\rho} \exp\left(-\frac{\sigma_{\mathrm{dir}\times\mathrm{res}}^{\gamma^*\rho}}{\sigma_{\mathrm{DIS}}^{\gamma^*\rho}}\right)$$

corresponds to Sudakov form factor

$\gamma\gamma$:	9	combinations = (dir+VMD+GVMD)^2
$\gamma^*\gamma^*$:	+ 4	combinations = 2 sides×(VMD+GVMD)
	13	!!

From Real to Virtual Photons

Direct photon: Q^2 in ME expression

Resolved photon:
total cross section $\sigma_{\mathrm{tot}}^{\gamma \to i}$ dampened by dipole

$$\left(\frac{m^2}{m^2 + Q^2} \right)^2 \quad \text{(fewer fluctuations, smaller size)}$$

VMD: $m = m_\rho, m_\omega, m_\phi, m_{\mathrm{J}/\psi}$
GVMD: $m \simeq 2k_\perp$; in total

$$\int_{k_0^2} \frac{\mathrm{d}k_\perp^2}{k_\perp^2} \frac{k_V^2}{k_\perp^2} \left(\frac{4k_\perp^2}{4k_\perp^2 + Q^2} \right)^2$$

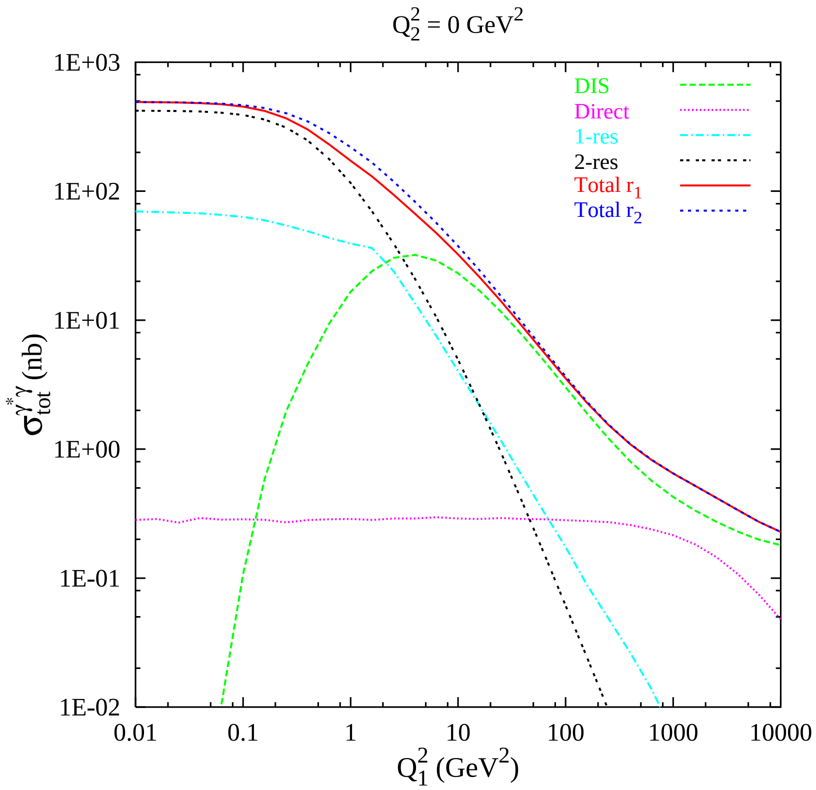
$f_i^{\gamma^*_\mathrm{T}}(x, \mu^2, Q^2)$: SaS 1D (also dipole-based)
$f_i^{\gamma^*_\mathrm{L}}(x, \mu^2, Q^2)$: simple multiplicative factor
or Chýla (hep-ph/0006232)

Putting it all together, res $=$ VMD $+$ GVMD:

$$\begin{aligned} \sigma_{\mathrm{tot}}^{\gamma^*\gamma^*}(W^2, Q_1^2, Q_2^2) &= \sigma_{\mathrm{DIS}\times\mathrm{res}}^{\gamma^*\gamma^*} \exp\left(- \frac{\sigma_{\mathrm{dir}\times\mathrm{res}}^{\gamma^*\gamma^*}}{\sigma_{\mathrm{DIS}\times\mathrm{res}}^{\gamma^*\gamma^*}} \right) + \sigma_{\mathrm{dir}\times\mathrm{res}}^{\gamma^*\gamma^*} \\ &+ \sigma_{\mathrm{res}\times\mathrm{DIS}}^{\gamma^*\gamma^*} \exp\left(- \frac{\sigma_{\mathrm{res}\times\mathrm{dir}}^{\gamma^*\gamma^*}}{\sigma_{\mathrm{res}\times\mathrm{DIS}}^{\gamma^*\gamma^*}} \right) + \sigma_{\mathrm{res}\times\mathrm{dir}}^{\gamma^*\gamma^*} \\ &+ \sigma_{\mathrm{dir}\times\mathrm{dir}}^{\gamma^*\gamma^*} + \left(\frac{W^2}{Q_1^2 + Q_2^2 + W^2} \right)^3 \sigma_{\mathrm{res}\times\mathrm{res}}^{\gamma^*\gamma^*} \end{aligned}$$

$(1 - x)^3$ reduces doublecounting at large x

Process composition



$W_{\gamma^*\gamma^*} = 100$ GeV

Direct = dir×dir

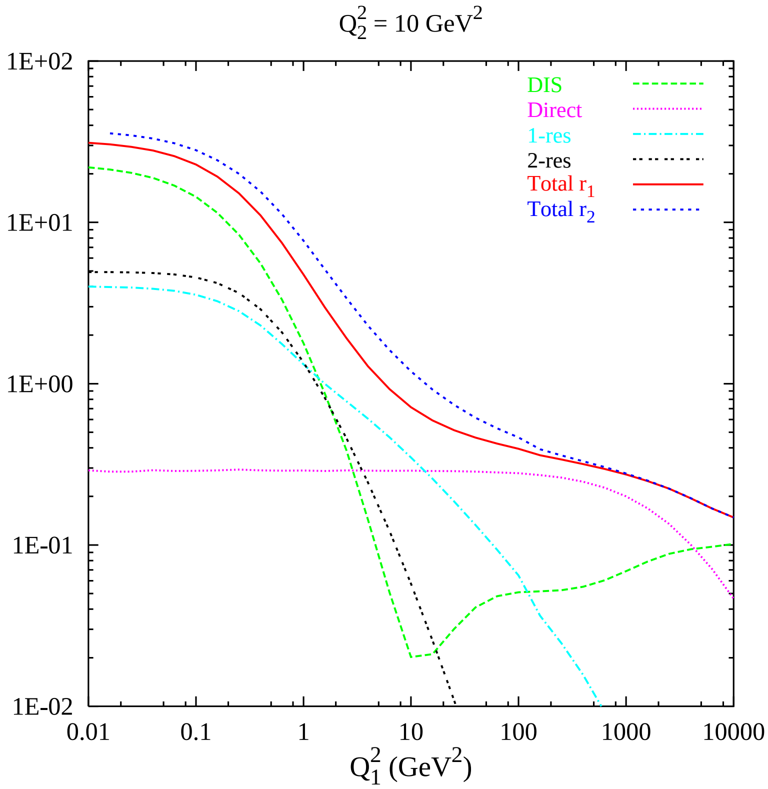
1-res = dir×res

2-res= res×res

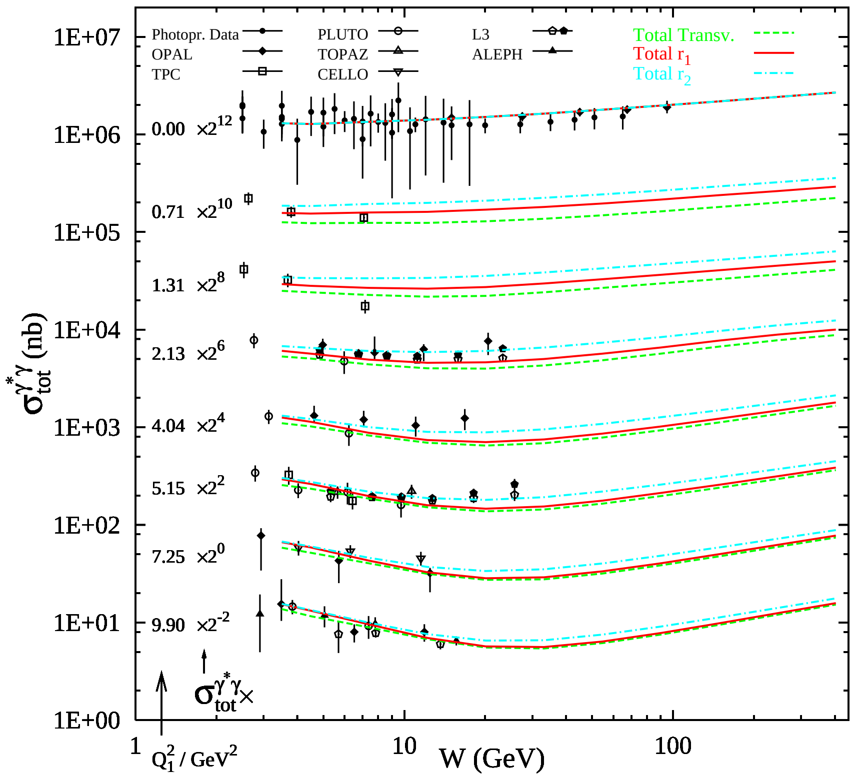
$f_i^{\gamma_L^*}/f_i^{\gamma_T^*}$:

$$r_1 = \frac{2m^2Q^2}{(m^2+Q^2)^2}$$

$$r_2 = \frac{2Q^2}{m^2+Q^2}$$



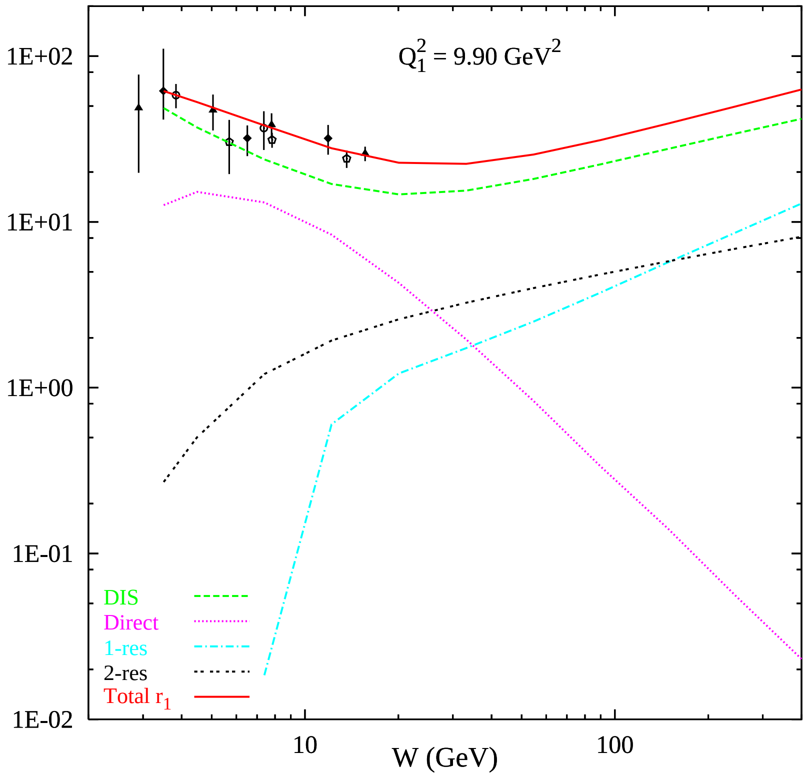
Energy dependence



$f_i^{\gamma^*_\mathrm{L}} / f_i^{\gamma^*_\mathrm{T}}$:

$$r_1 = \frac{2m^2Q^2}{(m^2+Q^2)^2}$$

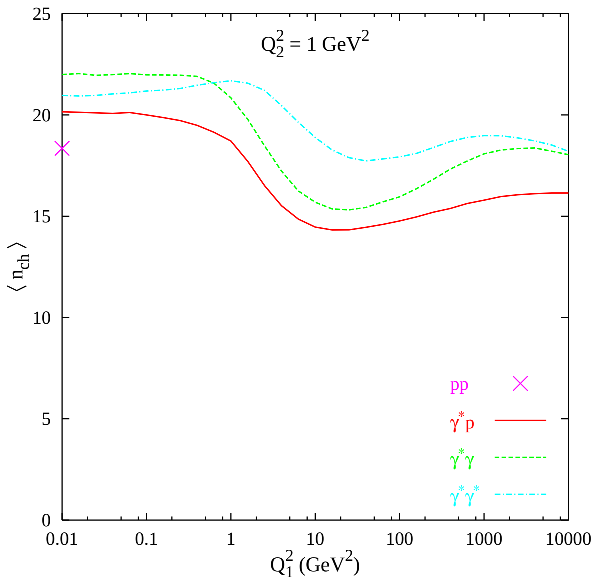
$$r_2 = \frac{2Q^2}{m^2+Q^2}$$

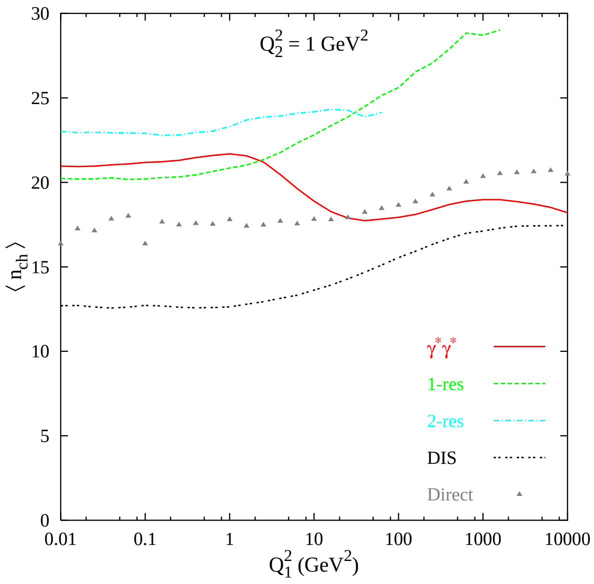


Event properties

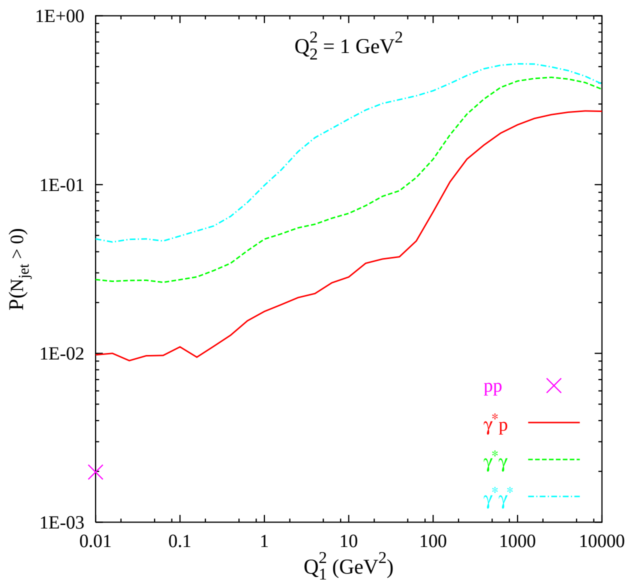
$W_{\gamma^*\gamma^*} = 100$ GeV

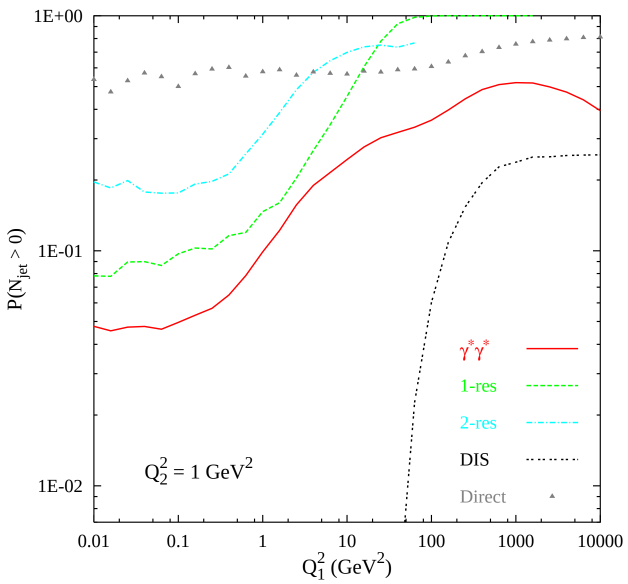
average charged multiplicity:



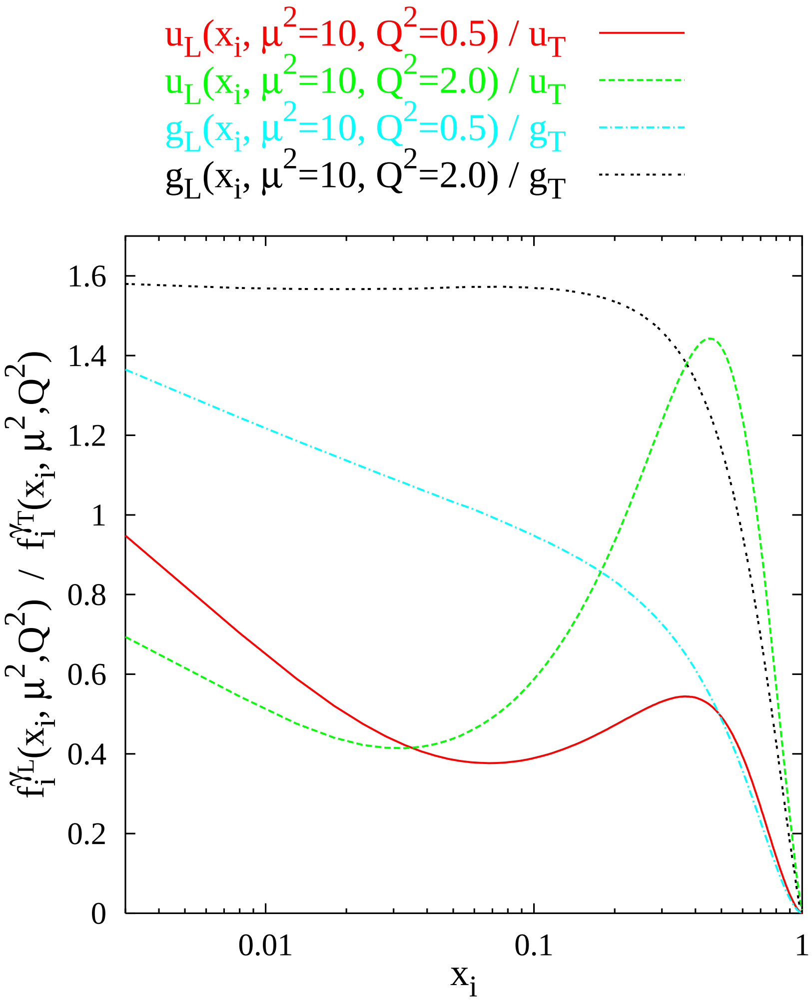


probability to have a jet with $E_\perp > 5$ GeV inside a cone $R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} < 1$:



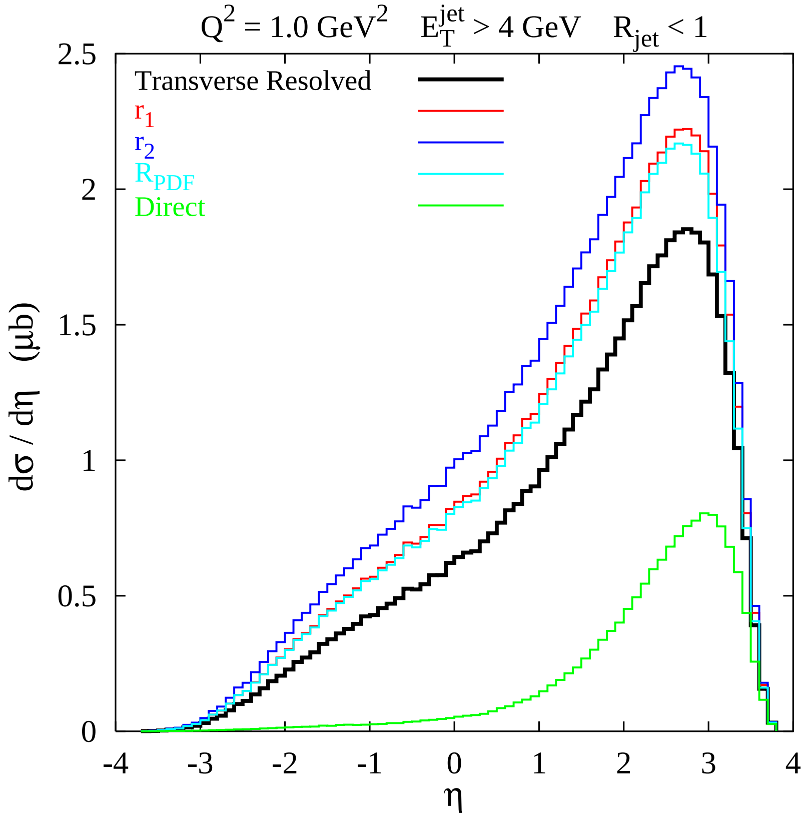


Effects of longitudinal photons



γ^*_L: Chýla

γ^*_T: SaS 1D



$$r_1 = \frac{2m^2Q^2}{(m^2+Q^2)^2}$$

$$r_2 = \frac{2Q^2}{m^2+Q^2}$$

$$R_{\mathrm{PDF}} = \frac{f_i^{\gamma^*_L}(x,\mu^2,Q^2)}{f_i^{\gamma^*_T}(x,\mu^2,Q^2)}$$

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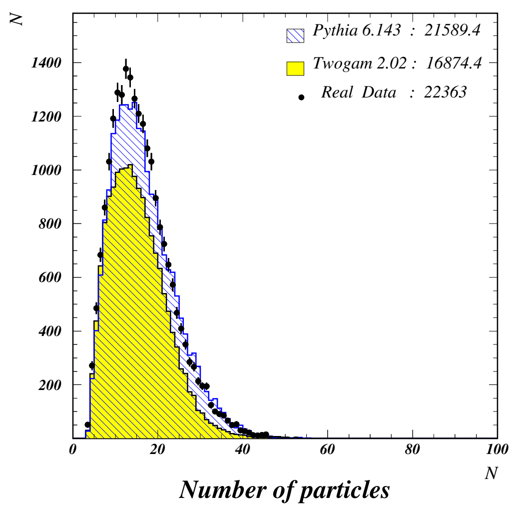
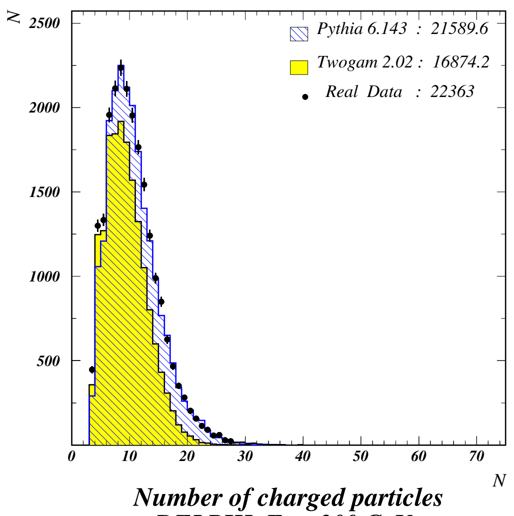
$E_{\perp}^{\mathrm{ch}} \leq 20$ GeV. Preliminary!

DELPHI E_{cm}=200 GeV



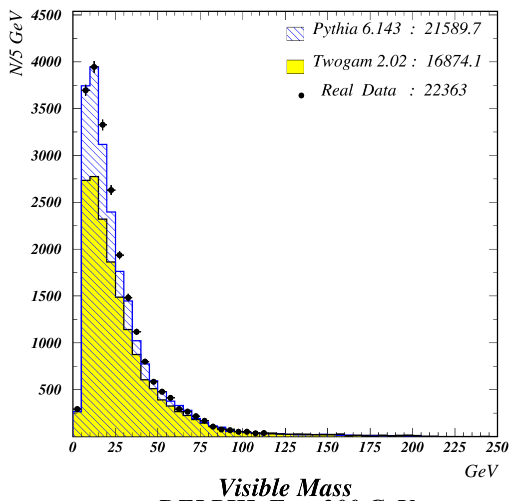
Number of particles

DELPHI E_{cm}=200 GeV



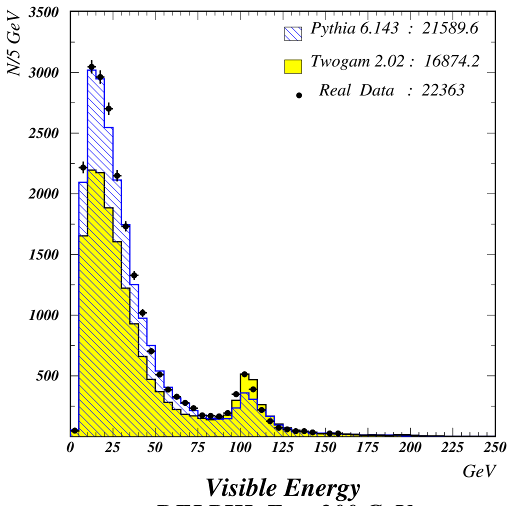
Number of charged particles

DELPHI E_{cm}=200 GeV



Visible Mass

DELPHI E_{cm}=200 GeV



Visible Energy

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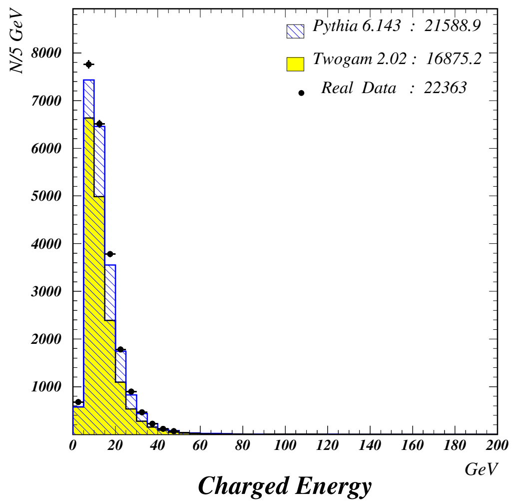
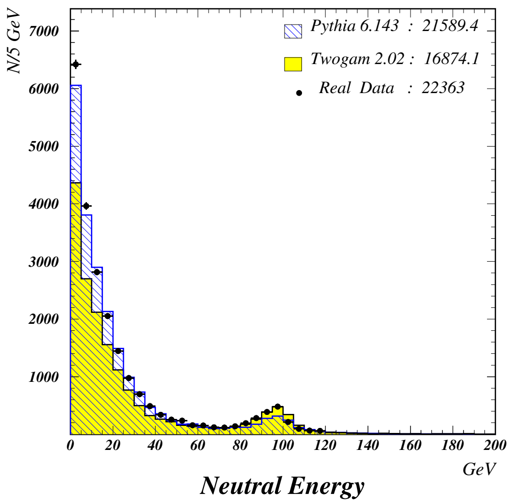


Charged Energy

DELPHI E_{cm}=200 GeV



Neutral Energy

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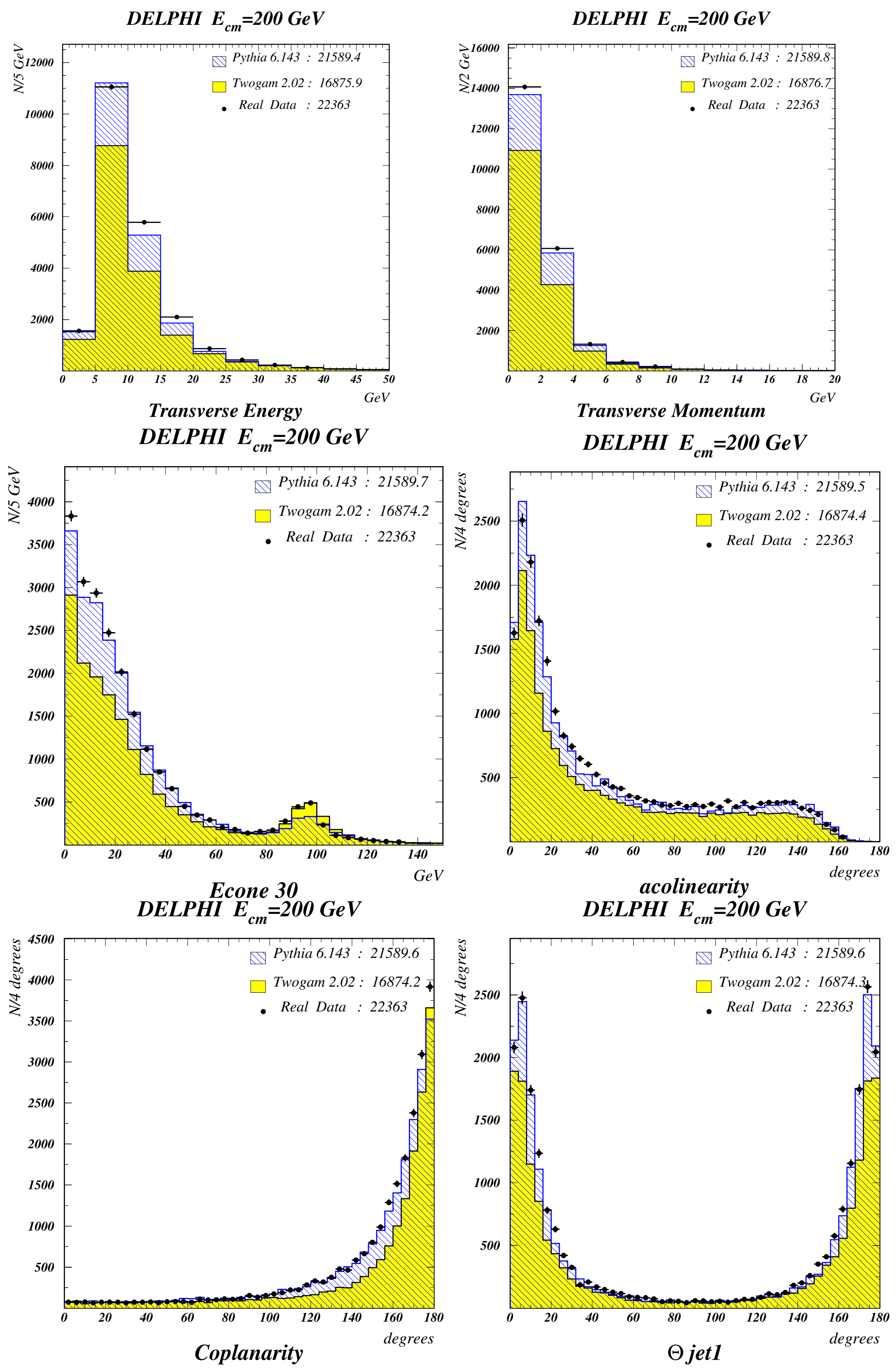
$E_{\perp}^{\text{ch}} \leq 20$ GeV. Preliminary!



Program particulars

To access new γ^* flux convolution:
`CALL PYINIT('cms','gamma/e-','gamma/e+',200D0)`

Also possible to have $\gamma^*\gamma^*$ collisions directly:
`CALL PYINIT('five','gamma','gamma',100D0)`
with `P(1,J)` and `P(2,J)` defining momenta and virtualities (`P(I,5) < 0` for spacelike ones).

Photon character regulated by `MSTP(14)`:
= 10 : mix direct/VMD/anomalous for real photons; d×V = V×d etc. ⇒ 6 classes.
= 30 : (new default) mix dir/VMD/GVMD and DIS for virtual photons; ⇒ 13 classes.
= other numbers : individual classes.
Warning : $\gamma^*\gamma^* \to \ell^+\ell^-$ included in dir×dir if not switched off (automatic when mixing).

`MSEL = 1, CKIN(3) > 2` : jets with $p_\perp >$`CKIN(3)`
`MSEL = 1, CKIN(3) = 0` : jet + low-$p_\perp$
`MSEL = 2, CKIN(3) = 0` : + diffractive + elastic

Possible to specify cuts on x_i, y_i, Q_i^2, θ_i, W^2 in `CKIN(61) - CKIN(78)`.
Phase space sampled according to

$$\prod_i (\mathrm{d}Q_i^2/Q_i^2)\,(\mathrm{d}x_i/x_i)\,\mathrm{d}\varphi_i$$

⇒ full efficiency for x_i and Q_i^2 cuts.