Jets and inclusive hadronic processes in photon induced collisions: a theoretical overview

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Variety of related hard processes

- Jet production
- Inclusive particle production
- Jets + inclusive particles production
- Prompt photon + jet production
- Heavy quark production

just a remark

involving either (quasi)real or virtual photons in

$\boxed{\gamma \mathrm{p}, \quad \gamma\gamma}$ or hadron-hadron collisions.

I will restrict myself to the photoproduction-like region and will give a overview of the relevant theory with emphasize on

- current status of relevant QCD calculations
- recent progress in phenomenological applications
- potential problems in describing data.

I will concentrate on discussion of theoretical uncertainties of various QCD calculations because

these uncertainties are often bigger than experimental errors and thus prevent an unambiguous interpretation of the comparison of theory with data.

Basic concepts and notation

Evolution equations for PDF of the photon

$$\frac{\mathrm{d}\Sigma(x,M)}{\mathrm{d}\ln M^2} = \delta_\Sigma k_q + P_{qq}\otimes\Sigma + P_{qG}\otimes G\,,$$

$$\frac{\mathrm{d}G(x,M)}{\mathrm{d}\ln M^2} = k_G + P_{Gq}\otimes\Sigma + P_{GG}\otimes G\,,$$

$$\frac{\mathrm{d}q_{\mathrm{NS}}(x,M)}{\mathrm{d}\ln M^2} = \delta_{\mathrm{NS}} k_q + P_{\mathrm{NS}}\otimes q_{\mathrm{NS}}\,,$$

Pure QED

where

$$k_q(x,M) = \frac{\alpha}{2\pi}\left[\boxed{k_q^{(0)}(x)} + \frac{\alpha_s(M)}{2\pi}k_q^{(1)}(x) + \left(\frac{\alpha_s(M)}{2\pi}\right)^2 k_q^{(2)}(x) + \ldots\right]$$

$$k_G(x,M) = \frac{\alpha}{2\pi}\left[\frac{\alpha_s(M)}{2\pi}k_G^{(1)}(x) + \left(\frac{\alpha_s(M)}{2\pi}\right)^2 k_G^{(2)}(x) + \ldots\right]$$

$$P_{ij}(x,M) = \left[\boxed{\frac{\alpha_s(M)}{2\pi}P_{ij}^{(0)}(x)} + \left(\frac{\alpha_s(M)}{2\pi}\right)^2 P_{ij}^{(1)}(x) + \ldots\right]$$

General solution (in NS channel)

$$\boxed{D(x,M) = D^{\mathrm{PL}}(x,M) + D^{\mathrm{HAD}}(x,M)}$$

pointlike

hadronlike

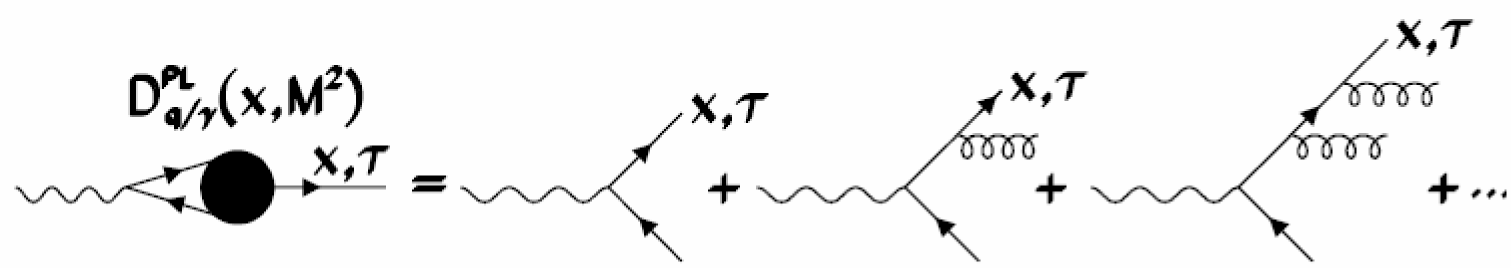
separation inherently ambiguous

$$\boxed{a_{\mathrm{NS}}(n) \equiv \frac{\alpha}{2\pi\beta_0} \frac{k_{\mathrm{NS}}^{(0)}(n)}{1 - 2P_{qq}^{(0)}(n)/\beta_0}}$$

example of the pointlike part

$$q_{\mathrm{NS}}^{\mathrm{PL}}(n, M_0, M) = \frac{4\pi}{\alpha_s(M)} \left[1 - \left(\frac{\alpha_s(M)}{\alpha_s(M_0)} \right)^{1-2P_{qq}^{(0)}(n)/\beta_0} \right] a_{\mathrm{NS}}(n)$$

which results from the resummation of the diagrams



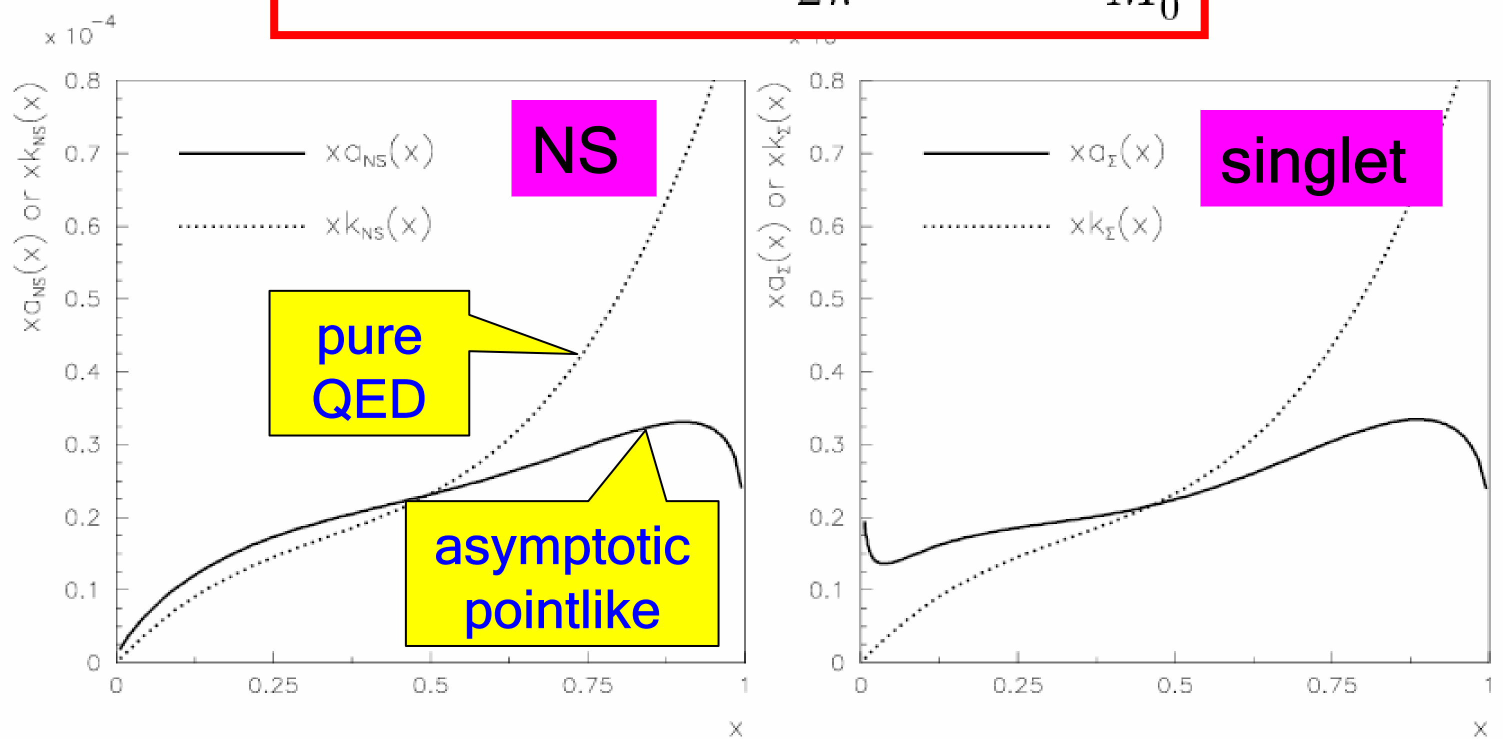
the fact that for $M \to \infty$

asymptotic pointike

$$q_{\rm NS}^{\rm PL}(x, M_0, M) \longrightarrow \frac{4\pi}{\alpha_s(M)} a_{\rm NS}(x) \equiv q_{\rm NS}^{\rm AP}(x, M) \propto \ln \frac{M^2}{\Lambda^2}$$

does not imply $q_{NS}^{PL} \propto \alpha / \alpha_s$ because when $\Lambda_{QCD} \to 0$

$$\boxed{q_{\rm NS}^{\rm PL}(x, M, M_0) \longrightarrow \frac{\alpha}{2\pi} k_{\rm NS}^{(0)}(x) \ln \frac{M^2}{M_0^2}}$$



Semantics (sometimes) matters

What do we mean under "LO" or "NLO"?

Recall:

QED

$$R_{e^+e^-}(Q) \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \left(3\sum_{i=1}^{n_f} e_i^2\right)(1 + r(Q))$$

QCD correction

$$r(Q) = \underbrace{\frac{\alpha_s(M)}{\pi}}_{\text{Leading order (LO)}}\left[1 + \underbrace{\frac{\alpha_s(M)}{2\pi} r_1(Q/M)}_{\text{Next-to Leading order (NLO)}} + \cdots\right]$$

Always subtract pure QED contributions and keep the terms LO and NLO for QCD effects only!

Unfortunately, in some photon induced hard processes this convention is not observed, leading to unnecessary confusion.

Phenomenological input

colour coupling

$$\alpha_s(\mu, RS)$$

renormalization scheme

renormalization scale

factorization scale

PDF of the proton

GRV98, CTEQ6
MRST02

$$D_p(M_p, FS_p)$$

factorization scheme

PDF of the photon (γ_T)

AGF94, GRV92, SaS96,
GRS99, CJKL03, AFG05

$$D_\gamma(M_\gamma, FS_\gamma)$$

FF

BKK96, KKP2000,
BFGW2001, Kretzer01

$$D_p^h(M_h, FS_h)$$

Scales and schemes appear due to ambiguities in the treatment of singularities at

short distances: μ and renormalization scheme

long distances: M_p, M_γ, M_F and factorization schemes

Freedom in the choice of renormalization and factorization schemes almost unexploited and phenomenological applications calculations done mostly in $\mathrm{MS}_{\mathrm{bar}}$ RS and MS FS.

Dependence on scales has a clear intuitive interpretation, but their choice is not sufficient to define unambiguously perturbative QCD calculations.

Common practice: $\mu = M_p = M_\gamma = M_F$ = "natural scale"

But there is no good reason for such assumption (Politzer 87)

Factorization: XS of physical processes can be written as convolutions of PDF, FF and partonic hard cross sections

$$\sum_{a,b,c} D_{a/A}(M_a) \otimes D_{b/B}(M_b) \otimes \sigma^{hard}_{ab\to c+..}(M_a, M_b) \otimes D^h_c(M_h)$$

The renormalization scale enters only when partonic hard scattering cross section is expanded in PQCD

$$\sigma^{hard}_{ab\to c+..} = \alpha_s^k(\mu)\sigma^{LO} + \alpha_s^{k+1}(\mu)\sigma^{NLO}(M_a, M_b, \mu)$$

k=0: DIS, Drell-Yan, jets in direct $\gamma\gamma$
k=1: jets in direct ep
k=2: jets in hadron-hadron

In defining perturbative calculation the order of all PDF, FF and hard scattering cross sections must be specified.

Note: NLO in $\sigma^{hard}_{a+b\to c}$ requires k≥1.

The same choice of the renormalization scale gives different results in different RS! In fact the schemes are as important as scales, but there no "natural" RS or FS!

The conventional procedure which implicitly assumes working in MS_{bar} is thus based on entirely ad hoc choice of RS.

I think the choice of scales and schemes should be done more in a more sophisticated and educated way.

This means keeping μ and M_p, M_γ, M_F independent

and investigating the stability of perturbative results on these free parameters looking for regions of

local stability - Principle of Minimal Sensitivity (PMS)

fastest apparent convergence - Effective Charges (EC)

Such investigation makes sense even if one does not subscribe to PMS or EC!!

Theoretical "uncertainty" of perturbative calculations

conventionally comprises several components:

- dependence on PDF and FF
- hadronization effects
- scale and scheme variation

two uncertainties with reasonably good meaning.

ill-defined

Conventional way of estimating theoretical uncertainty due to scale choice, i.e. identifying all scales with some "natural scale" Q and plotting the band of results corresponding to

$$Q/2 \leq \mu \leq 2Q$$

arbitrary number

makes little sense because it

- depends on selected scheme
- is actually misleading

Take the LO where

$$\frac{\alpha_s(\mu/2)-\alpha_s(2\mu)}{\alpha_s(\mu)} \doteq \beta_0\alpha_s(\mu)\ln 4 \to 0 \text{ as } \mu \to \infty$$

so the LO QCD predictions would appear to have very small "uncertainty" at short distances, which is nonsense.

Because of the way the "uncertainty" due to scale/scheme choice is conventionally defined it should not be mixed with the other sources of genuine theoretical uncertainty.

We should make a choice of scales and schemes, based on some general idea, and look whether it leads to meaningful phenomenology for wide range of processes.

To make a judicious choice we should spend computer time on investigation of scale dependence as mentioned above.

Ambiguities do not decrease at higher orders

The usual claim that at higher orders the ambiguities of finite order perturbative approximations decrease is not true, because at each order of perturbation theory additional new free parameters, like

higher order β-function coefficients and splitting functions

do appear. We can ignore them and continue to work in the conventional (renormalization and factorization) schemes, which reflect our preference for dimensional regularization, but this does not make the mentioned claim true.

Note, that technically, it makes no sense to compare functions of different number of variables.

Hadronization corrections and related effects

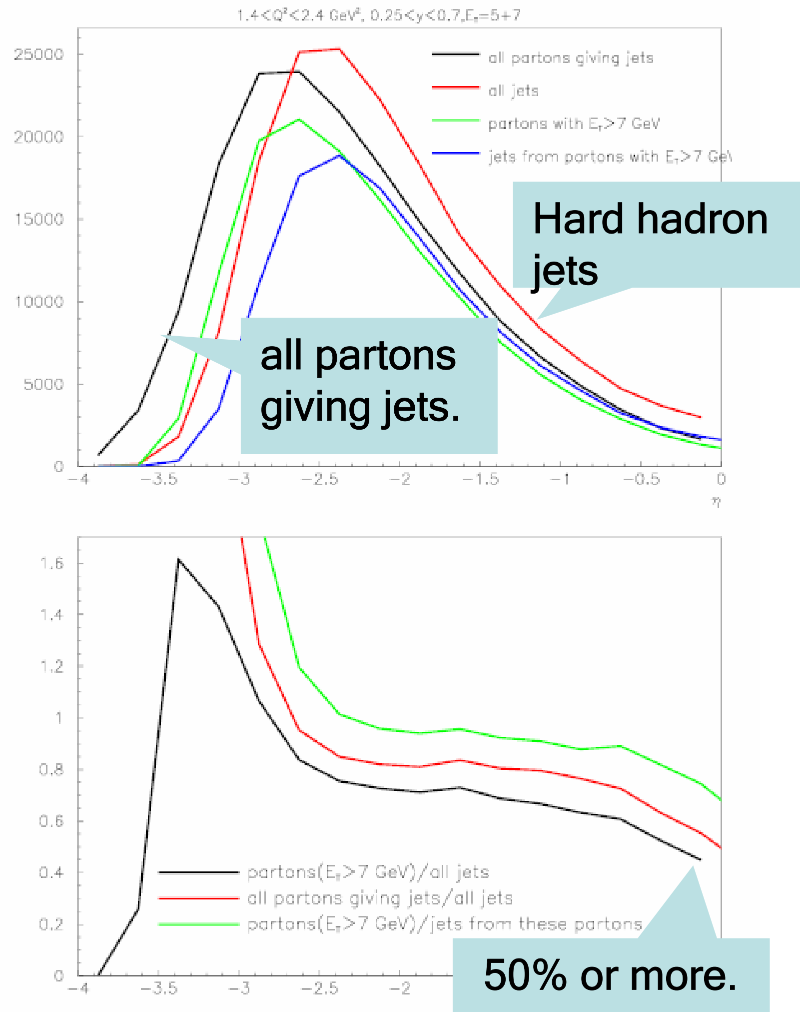
What we want to correct?

Standard way of estimating hadronization corrections to jet observables, i.e.

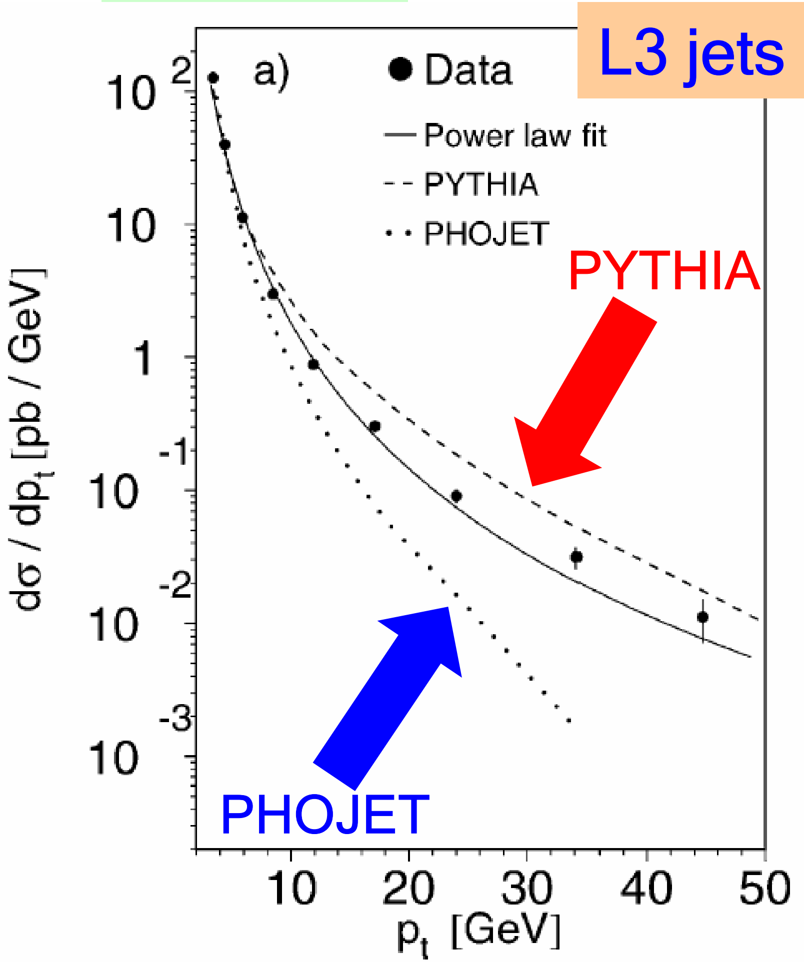
$$\frac{\text{jet algo on hadrons } (\eta, p_T)}{\text{jet algo on partons } (\eta, p_T)}$$

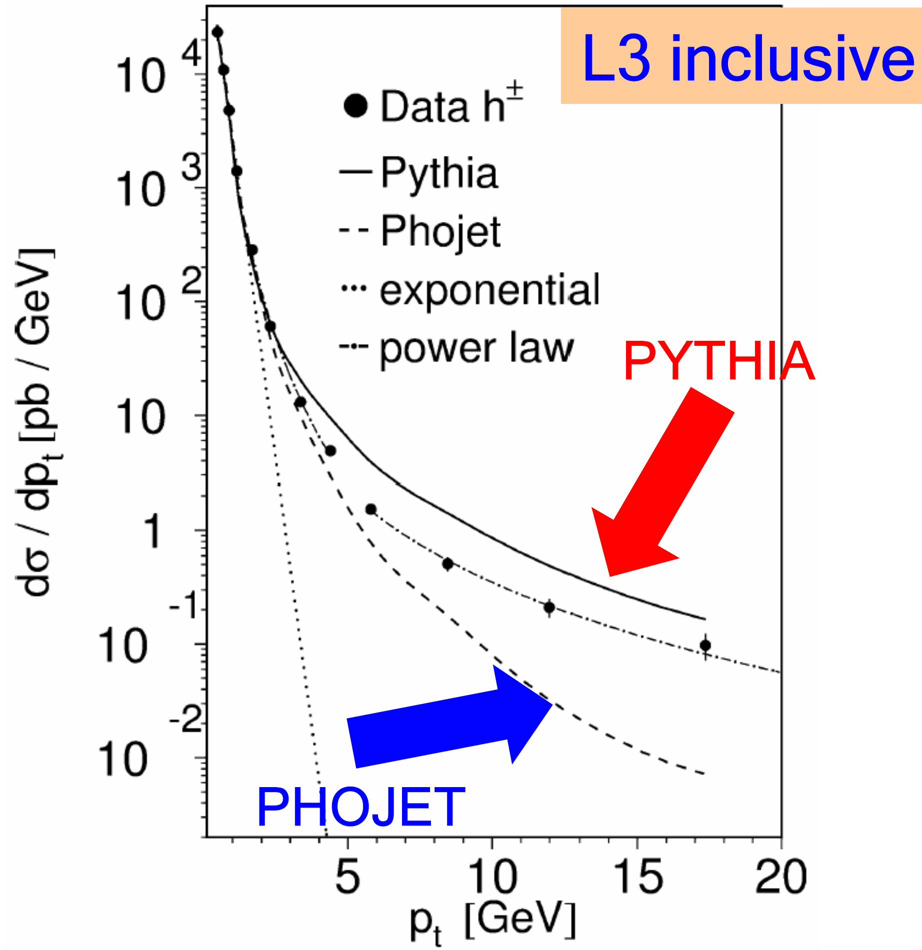
has little relevance for correcting NLO parton level calculations.

For that purpose all effects, absent in hard partonic calculations, should be included.



Example:





PYTHIA and PHOJET use the same QED XS, which domina-tes at large E_T, so what makes such a dramatic difference?

MC event generators vs NLO parton level calculations

Some of the features of full NLO QCD effects are mimicked within MC event generators, which use only LO partonic cross sections, by means of parton showers and noncollinear kinematics of initial state partons.

But LO MC also use different input (LO PDF and α_s), which were extracted in global analysis from data, and so have a chance to describe also other data as well.

To identify genuine NLO effects is thus not simple.

Jet production in γp collisions

Complete framework for quasireal photons laid out in

Frixione, Ridolfi (97)
Klasen, Kramer, Kleinwort (98)
Aurenche, Bourhis, Fontannaz, Guillet (00)

and recently reviewed in Klasen: RMP 74 (2002), 1221

Differences in regularization method: slicing vs subtraction

Suitable cuts on dijets developed

- Single jets
- Dijets
- Multijets
- Jets in diffraction

Closely related to dynamics of jet + prompt photon

Structure of calculations

direct subtracted

Direct contribution: $\alpha\alpha_s$ + $\alpha\alpha_s^2$

Resolved contribution: $\alpha\alpha_s^2$ + $\alpha\alpha_s^3$

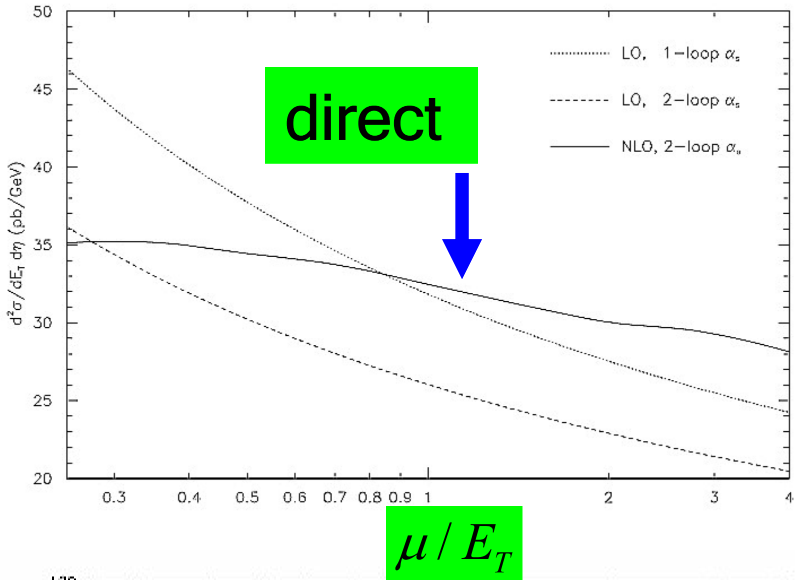
Not necessary to order $\alpha\alpha_s^2$

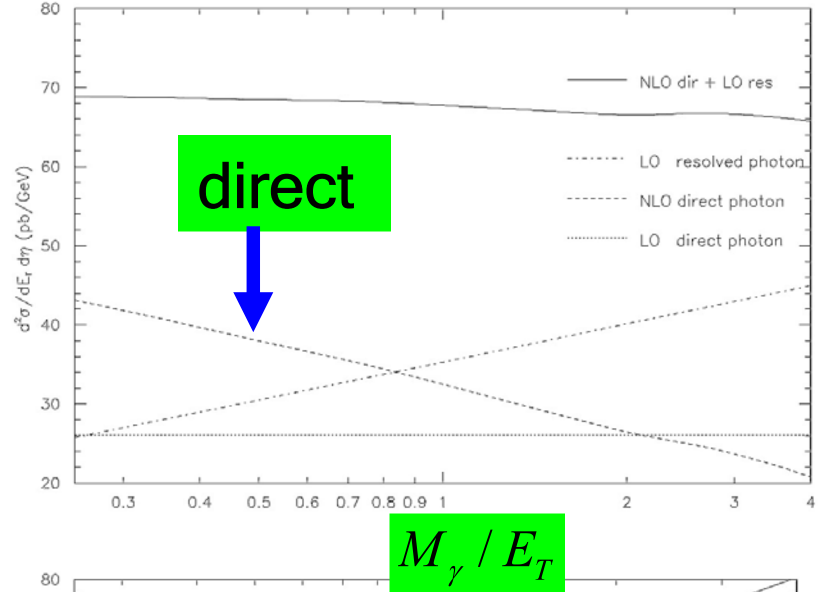
For full consistency to order $\alpha\alpha_s^3$
also direct photon contribution to that order needed!

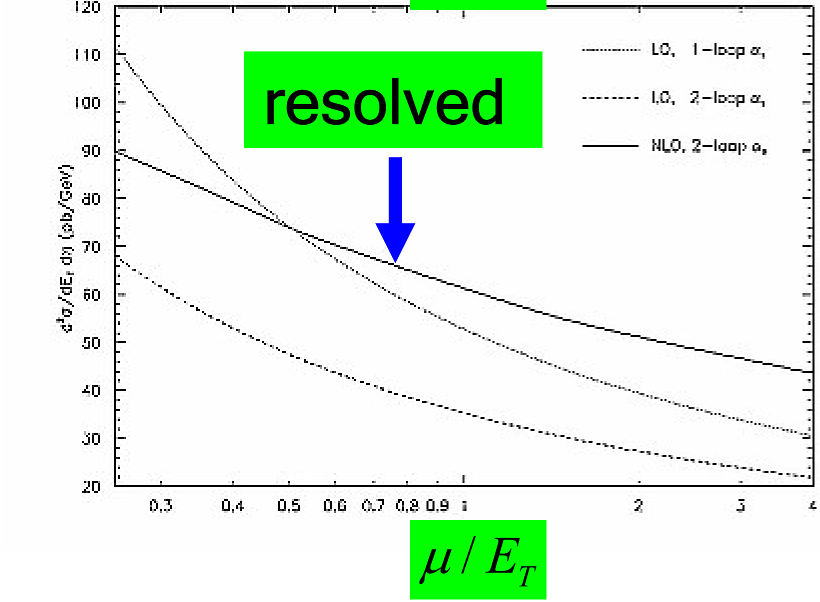
Extensive application to HERA data lead in general

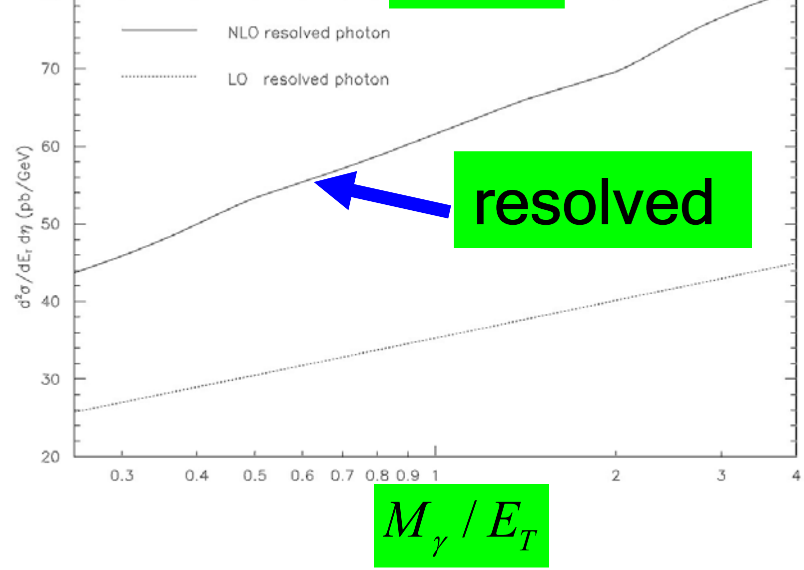
- to reasonable agreement, except for some IR sensitive quantities
- but suffers from non-negligible scale dependence of many QCD calculations.
- Concept of the resolved photon indispensable.

Klasen, Kramer, Kleinwort (99): single jets for $E_T = 20$ GeV, η=1

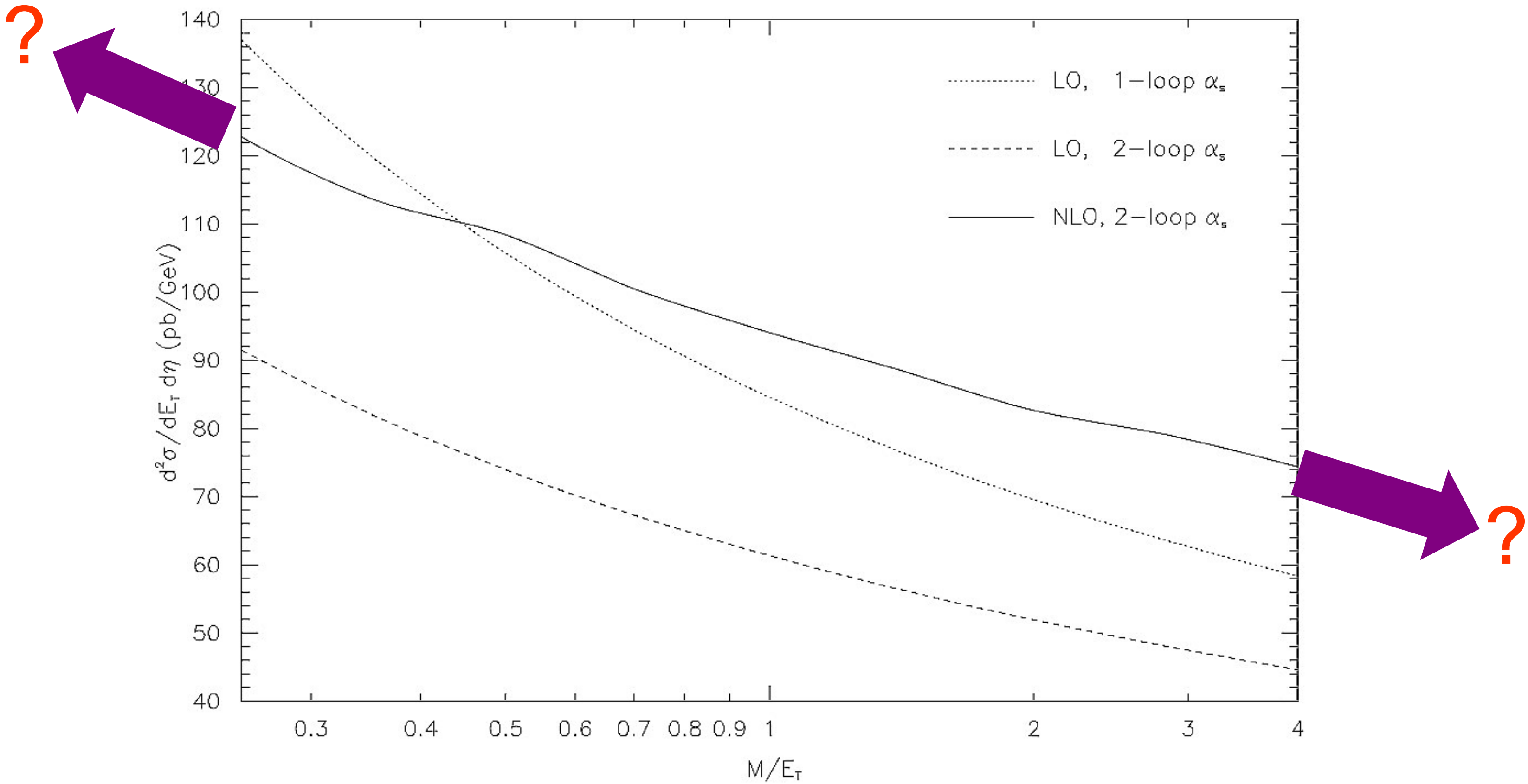








Direct + resolved calculation

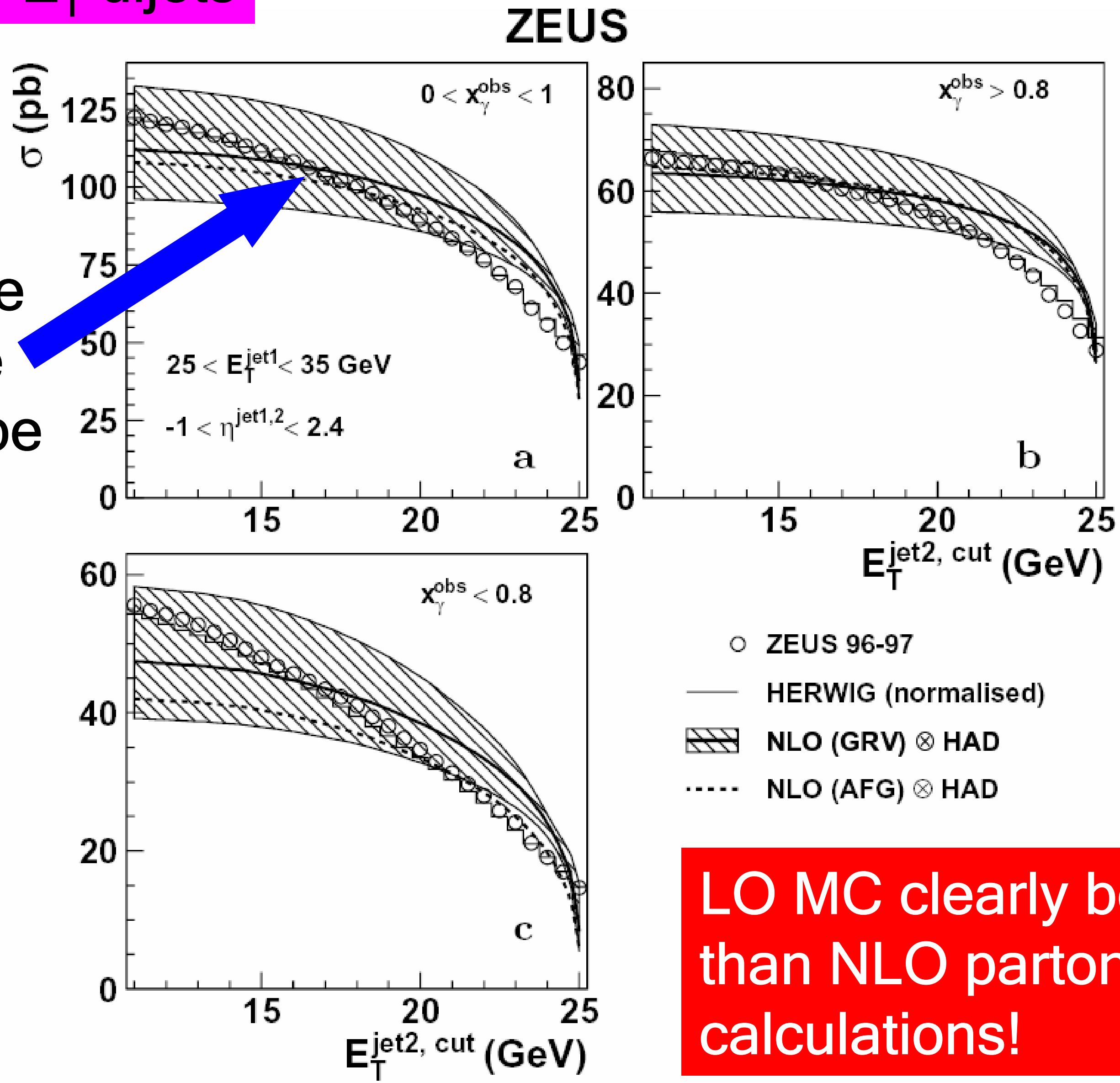


All scales identified and set equal to M.

What so these plots indicate? (In)stability?

Large E_T dijets

Note the shape



LO MC clearly better than NLO parton level calculations!

Jet production in γ^*p collisions

Many people contributed to theory and phenomenology of hard collisions of virtual photons

Kramer, Klasen, Pötter, GRV, Sjöstrand, Friberg, J.Ch., Taševský, Aurenche, Fontannaz, Guillet, Heinrich, De Florian, Sassot, ….sorry for any omission

Of particular interest the region of transition between photo-production (where E_T sets the scales) and genuine DIS, where Q^2 is unquestionably the hard scale.

In this region the concept in resolved (virtual) photon does not have to be introduced, but it turns out to be very useful phenomenologically. But not everybody agrees.

But, in this region playing with scales

does wonders and fakes (almost) everything else.

NLO parton level Monte Carlos: (black: no longer attended)

MEPJET (Mirkes, Zeppenfeld)
DISENT (Catani, Seymour)
DISASTER (Graudenz)
JETVIP (Pötter), may be resuscited by Klasen
NLOJET (Nagy, Troczsanyi)
plus possibly other.

Only JETVIP includes resolved γ^*

The only NLO generator for genuine 3-jet region

In principle JETVIP most general, but

- has problem with stability of NLO RES
- disagrees with other MC in NLO DIR

MC event generators: resolved virtual photons available in

PYTHIA: γ_T as well as γ_L
HERWIG: γ_T and in H1 version also γ_L
RAPGAP: γ_T only

Processes:

- Single jets
- Dijets
- Multijets
- Forward jets

Of great theoretical interest because of potential implications for identifying BFKL dynamics.

The region of interest: $Q^2 \leq E_T^2$ or even better $Q^2 \ll E_T^2$

where:

- the concept of resolved virtual photon is relevant
- jet E_T provides the only natural scale and
- photon virtuality Q^2 enters only through PDF of $\gamma_{T,L}$

However, in most analyses of HERA data only the weaker condition $1/\kappa \leq Q^2/E_T^2 \leq \kappa$ typically with $\kappa=2$ demanded.

JETVIP direct unsubtracted for asymmetric E_T cuts:

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

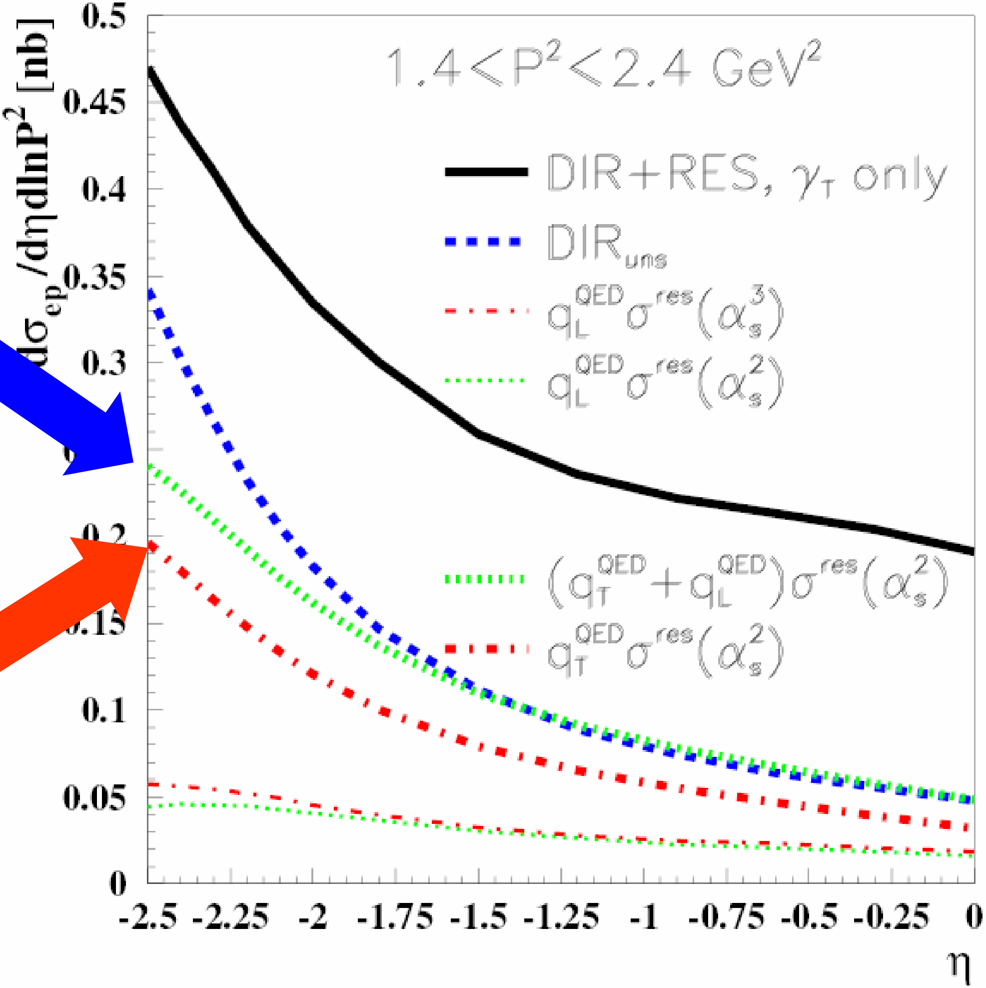
Resolved in direct

NLO direct is well approximated by

LO DIR+ LO RES

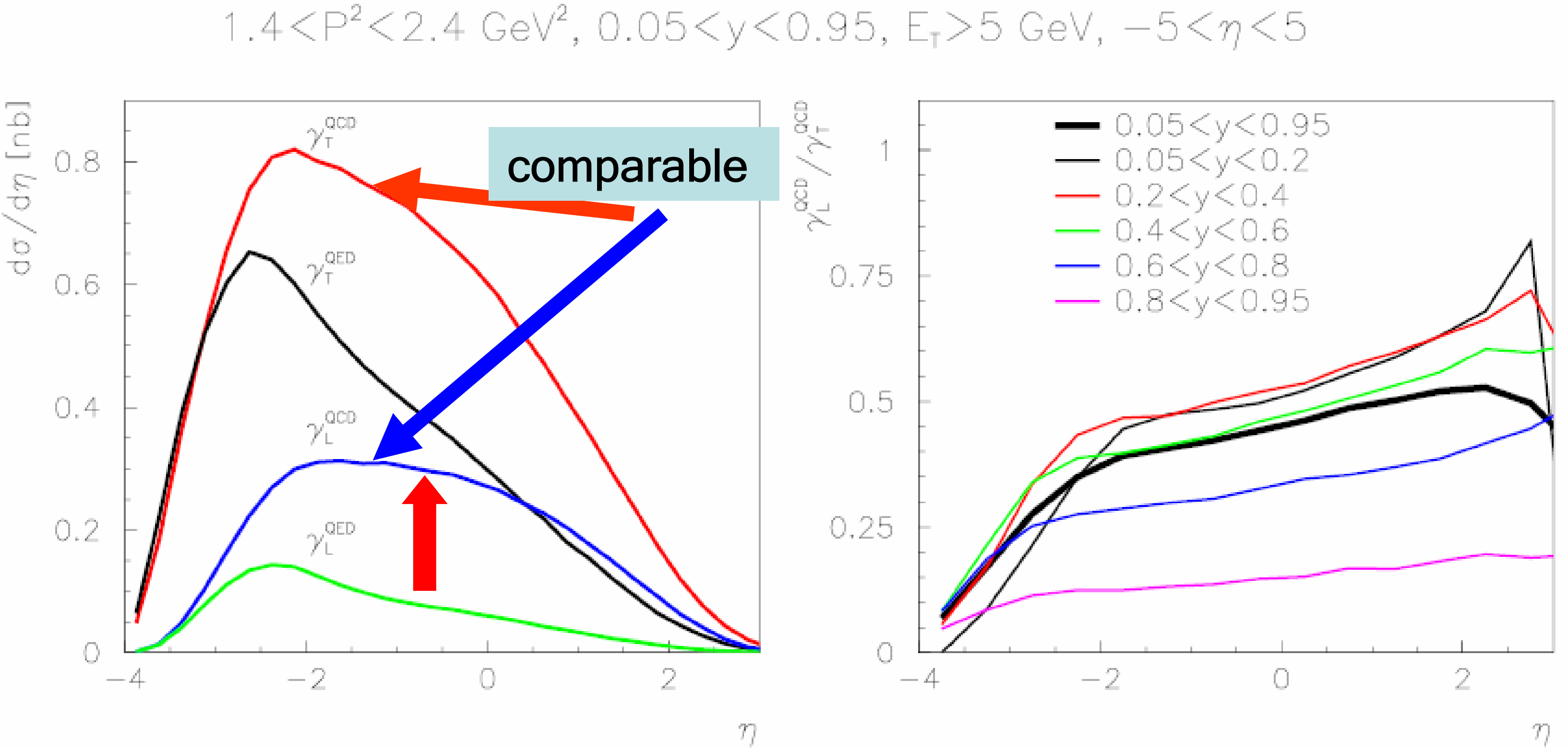
with QED PDF of the virtual photon

provided also the contribution of γ_L is included.



Relevance of resolved γ_L

HERWIG MC simulations:



Similar calculations with PYTHIA.

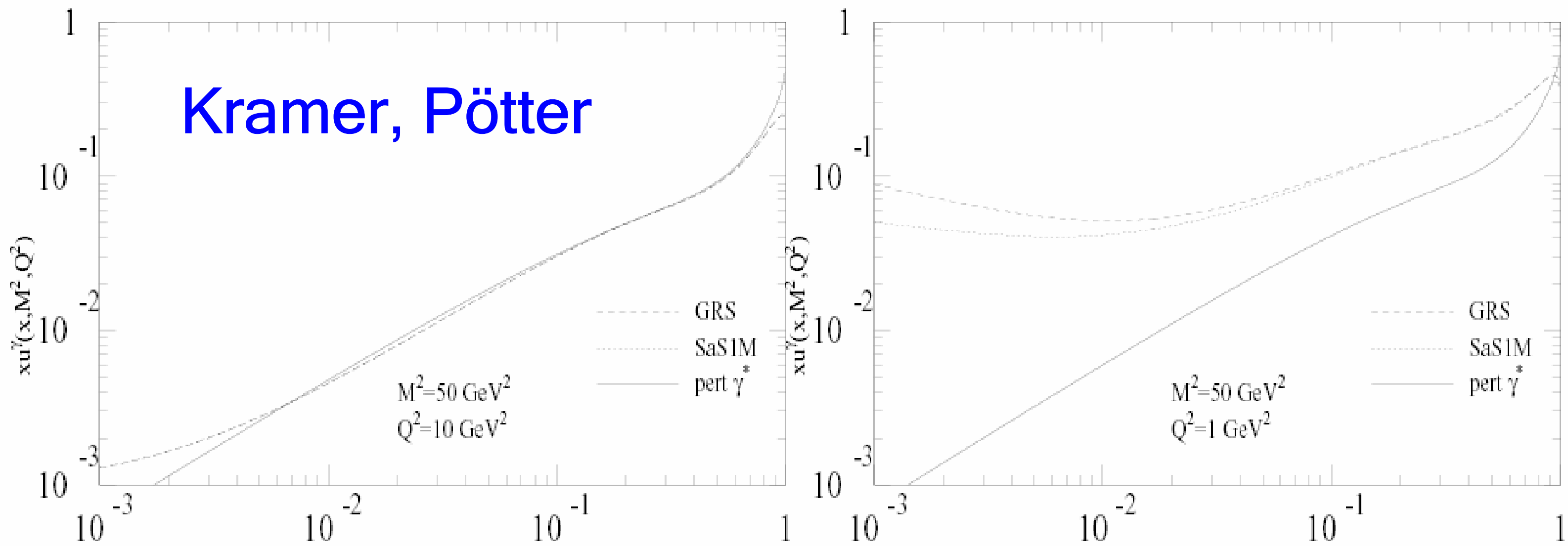
PDF of virtual γ_T and γ_L

γ_T: GRV, GRS, SaS, AFG $\quad$ γ_L: J.Ch.

Virtuality dependence of PDF very different for the point-like and hadron-like components

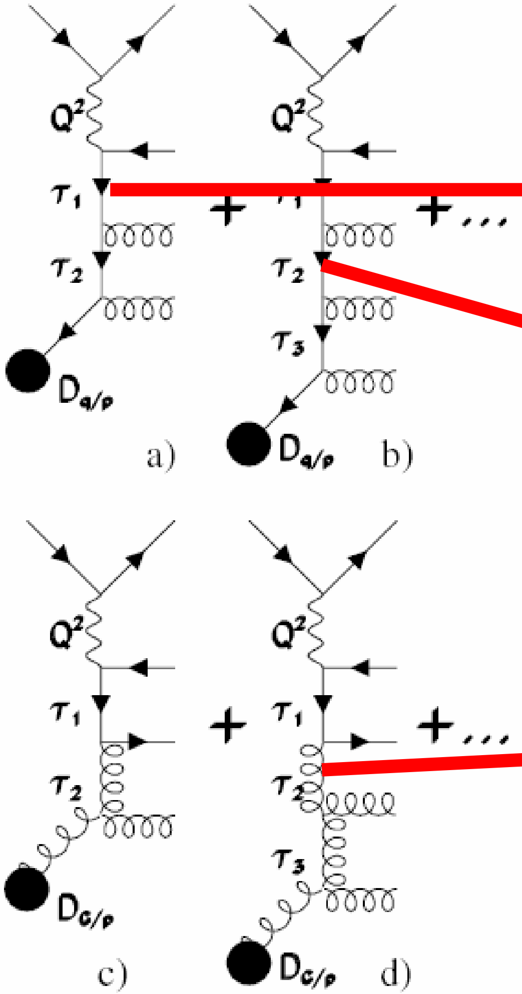
In most of practical circumstances modest QCD evolution

Kramer, Pötter



Crucial improvement over DIRECT unresolved: the inclusion of NLO resolved contribution

Resolved virtual photon as approximate method for including higher order direct photon terms



NLOJET in 3-jet mode allows us to investigate this idea quantitatively.

correspond to QED plus first QCD term of quark d.f. of resolved γ^*

gluon d.f.

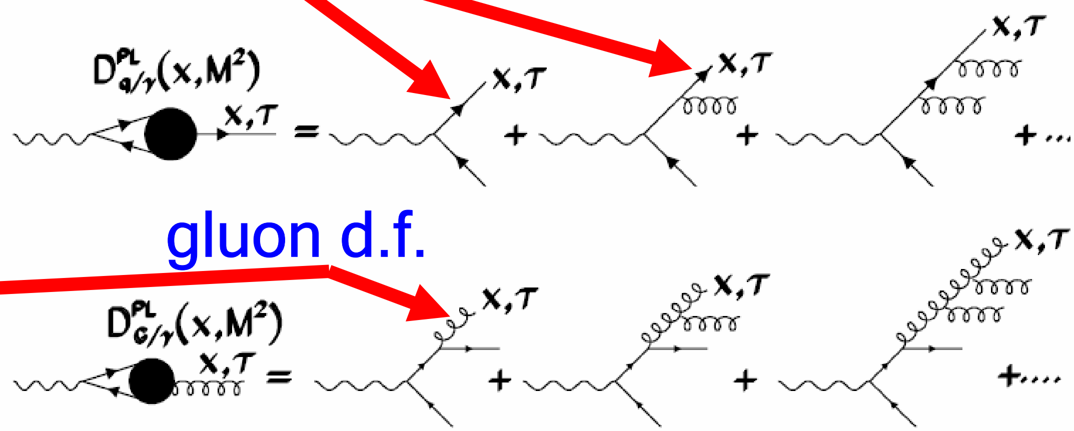


Fig. 2. Graphs contributing to the definition of the pointlike part of quark and gluon distribution functions of the photon

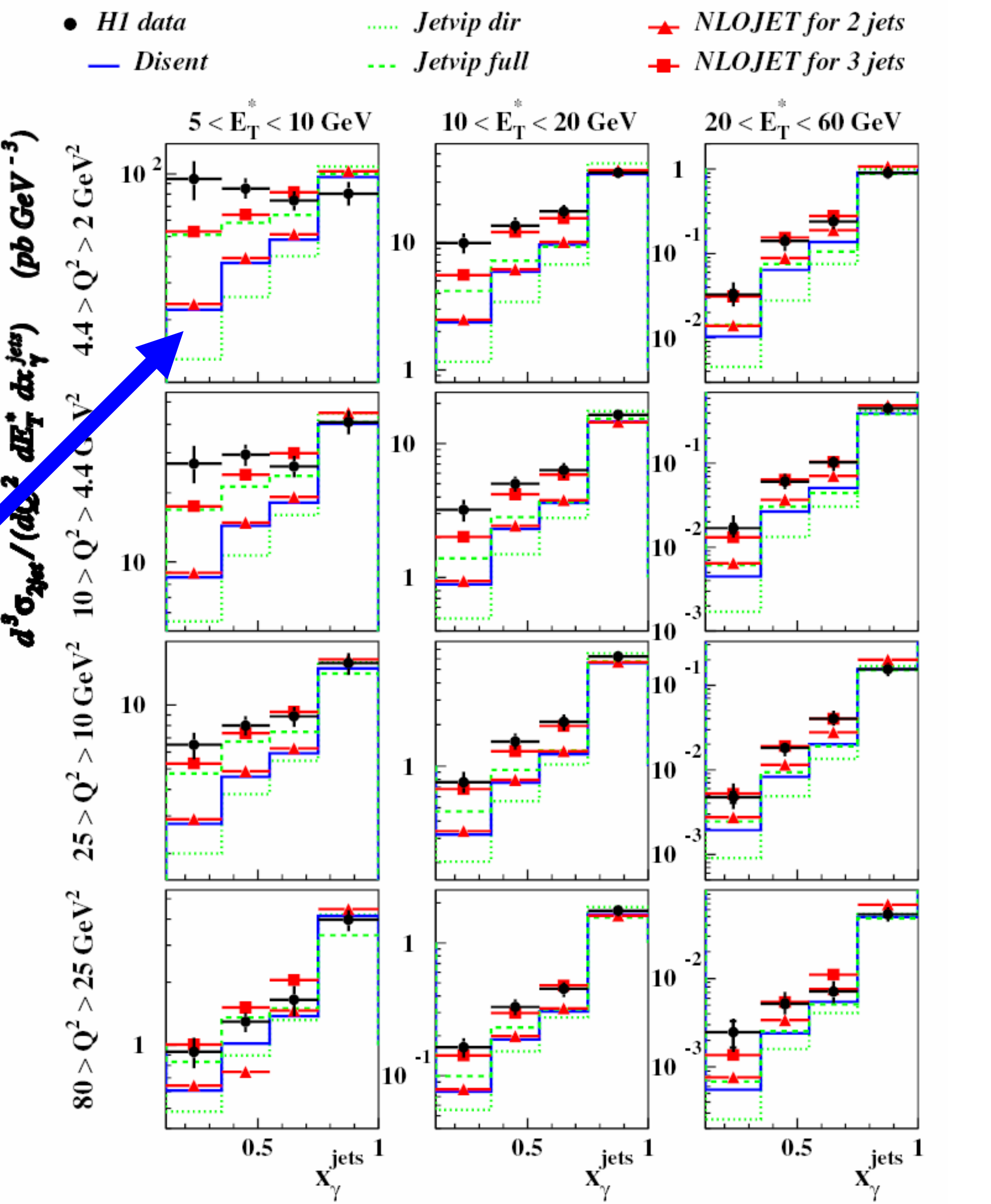
Example:

QCD analysis of dijet production at low Q^2 at HERA

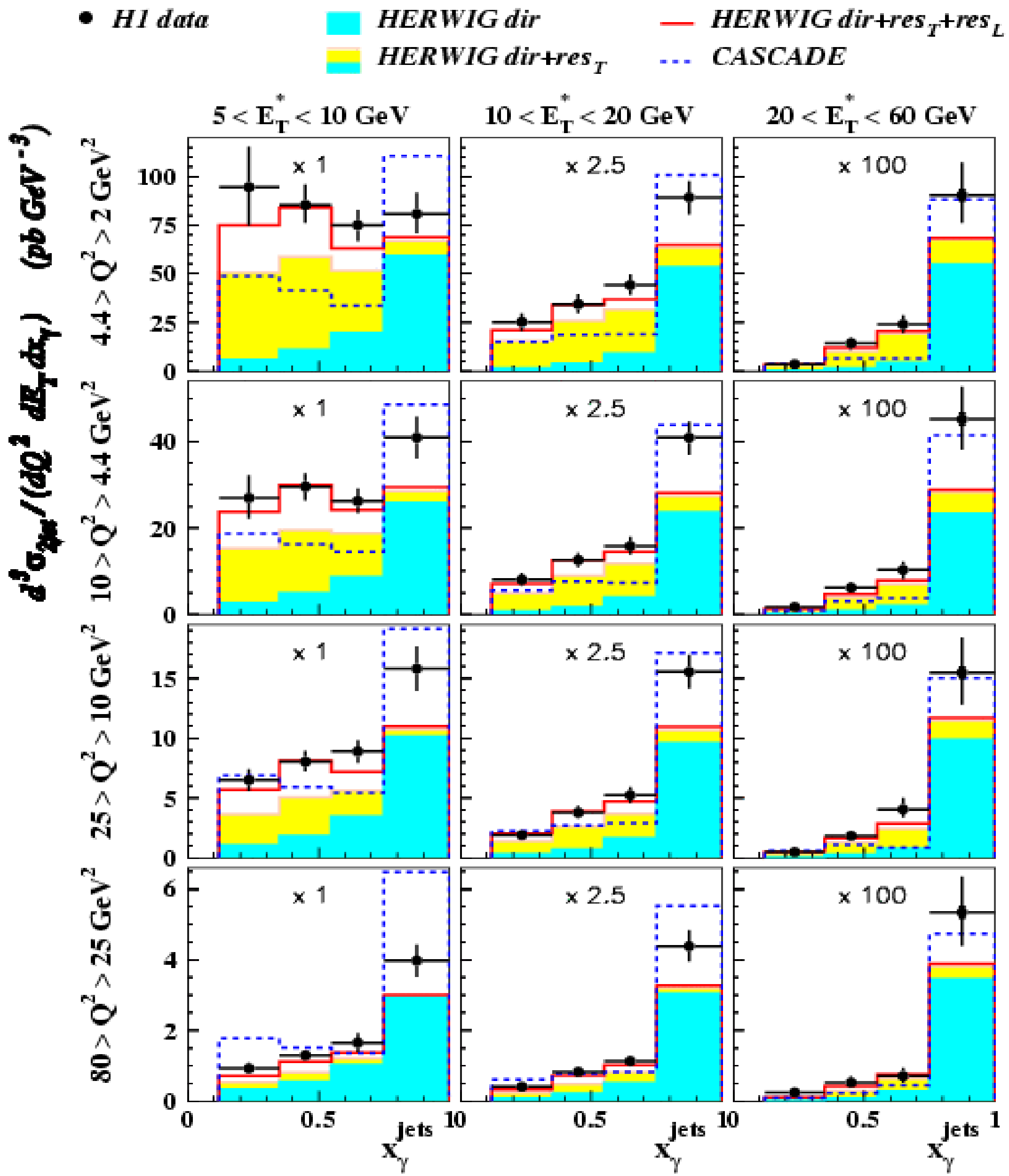
(J. Ch., J. Cvach, K. Sedlák, M. Taševský 05)

Note the disagreement between JETVIP DIR a DISENT/NLOJET

Still higher order direct terms, effectively included in resolved γ^*, will hopefully fill the remaining gap to data.



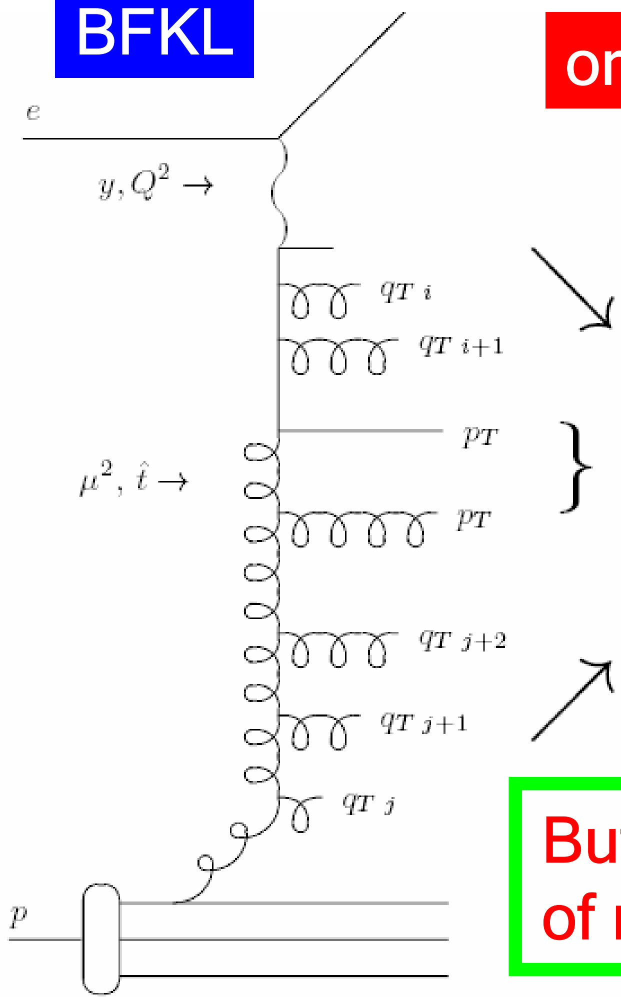
Note: the data are described very well by HERWIG with both γ_T and γ_L!



Forward jets at HERA

Mueller 92: best place to look for BFKL effects.

BFKL

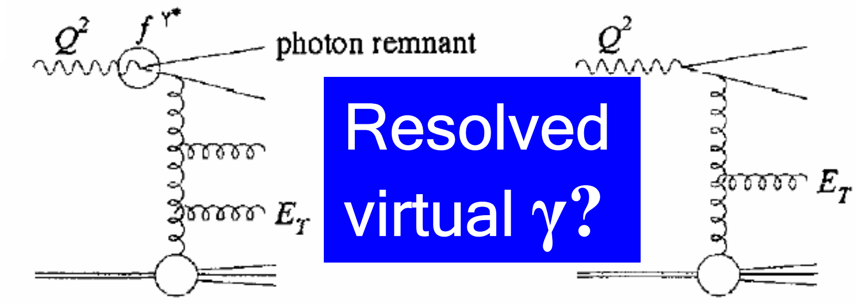


$x_\gamma f(x_\gamma, \mu^2, Q^2)$ γ - DGLAP

$qg \to qg$
hard scattering

$x_p f(x_p, \mu^2)$ p - DGLAP

or



Resolved virtual γ?

But difficult to distinguish from effects of resolved virtual photon!

Forward jet production at small x in NLO QCD

Kramer, Pötter 99

DIR alone
below data

Inclusion of NLO RES leads to nice agreement!

However:
scale choice crucial!

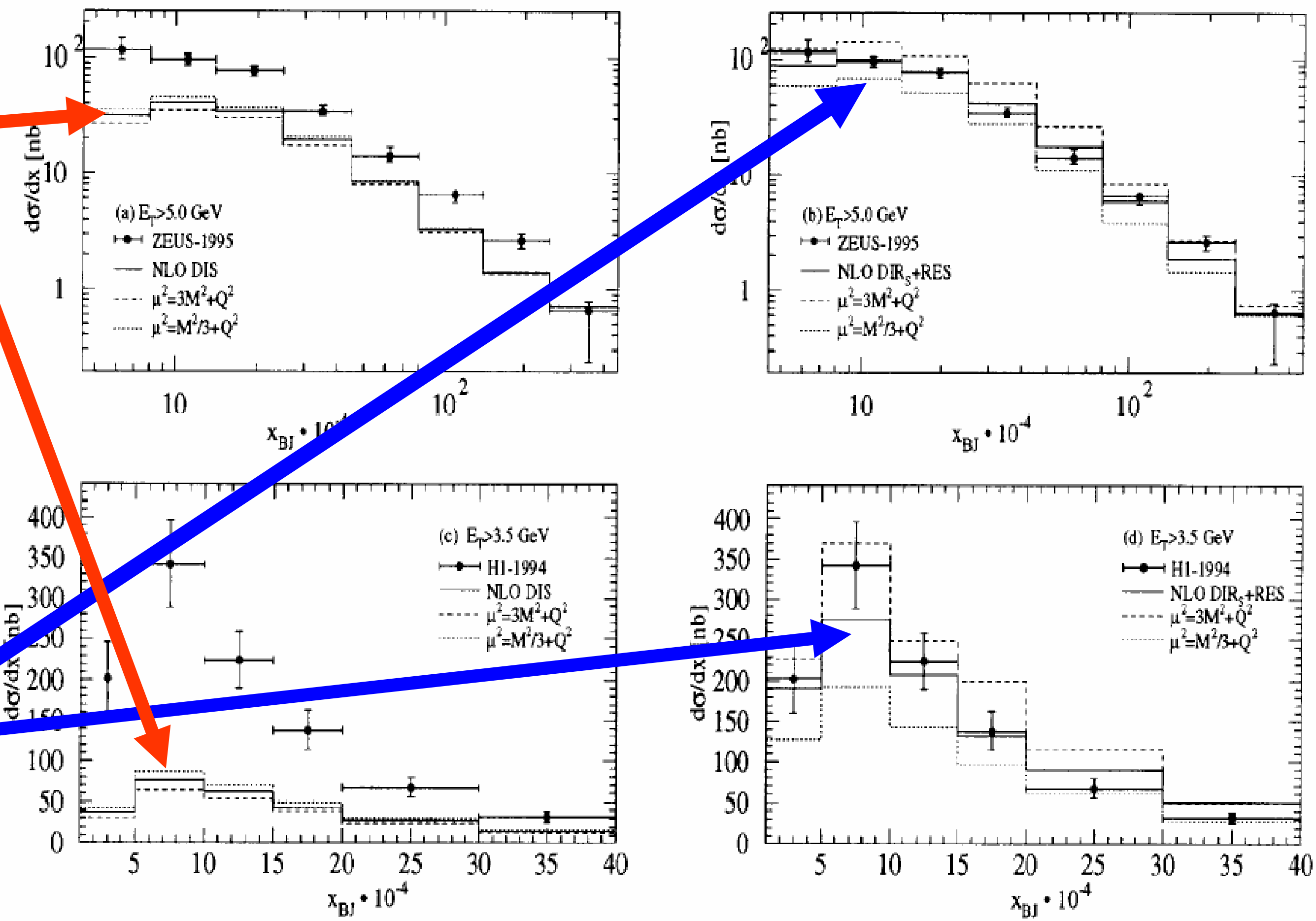


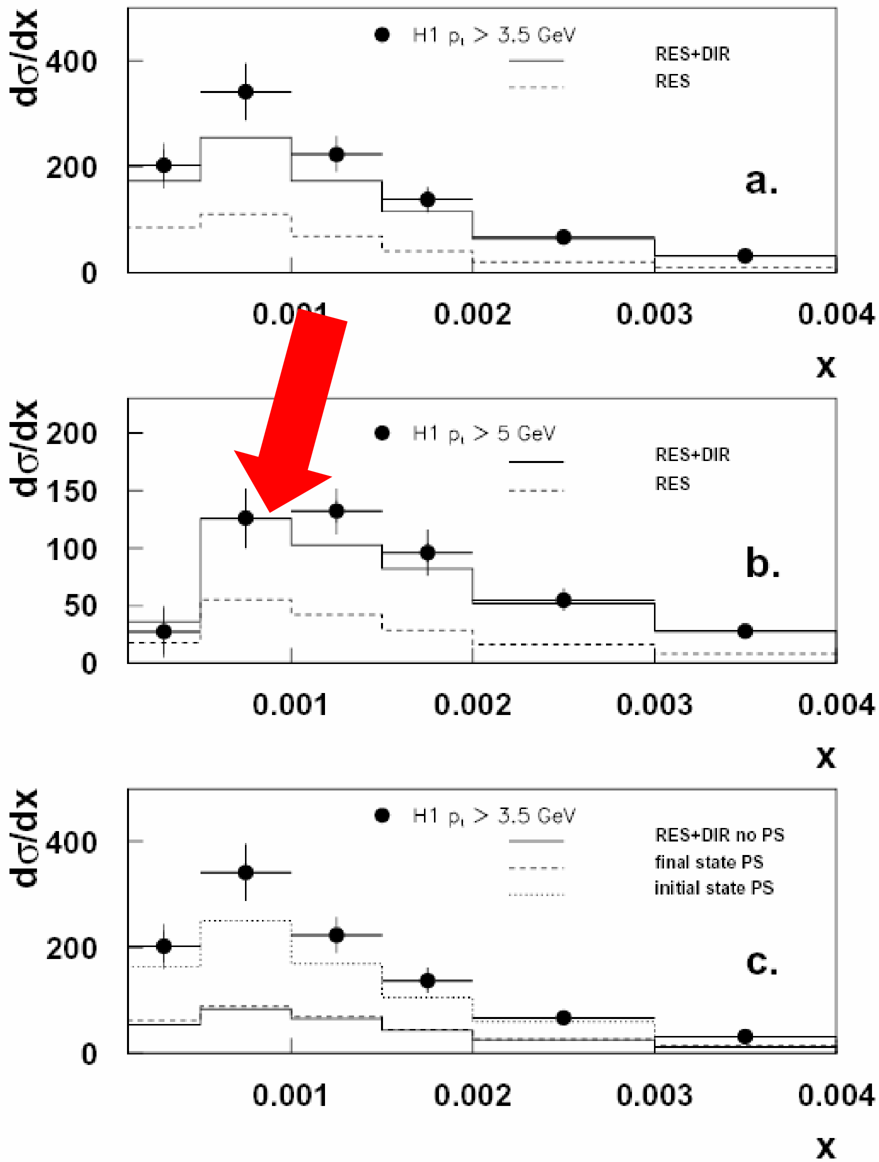
Figure 1. Dijet cross section in the forward region compared to HERA data: (a) and (b) ZEUS; (c) and (d) H1. (a) NLO DIS, $E_T > 5$ GeV; (b) NLO DIR$_S$+RES, $E_T > 5$ GeV; (c) NLO DIS, $E_T > 3.5$ GeV; (d) NLO DIR$_S$+RES, $E_T > 3.5$ GeV.

But are NLO resolved terms really important?

Jung, Jönsson, Küster 99:

NLO calculations including contributions from direct as well as resolved photons, are similar to using LO matrix elements for both the photon and the proton with the addition of parton showers, as implemented in the RAPGAP generator. This indicates that

higher order contributions are well simulated by the inclusion of parton showers in LO Monte Carlo generators.



Inclusive particle production in $\gamma^* p$ collisions

Aurenche, Fontannaz, Basu, Godbole, Daleo, De Florian, Sassot, Kramer, Kniehl, Maniatis,Gordon,....

Recently most attention to forward pions to search for BFKL

Situation even more ambiguous and puzzling than for jets:

BFKL or merely direct γ or resolved γ needed?

Systematic investigation of scale dependence crucial for proper choice of four scales! (Aurenche et al.)

Conventional choice

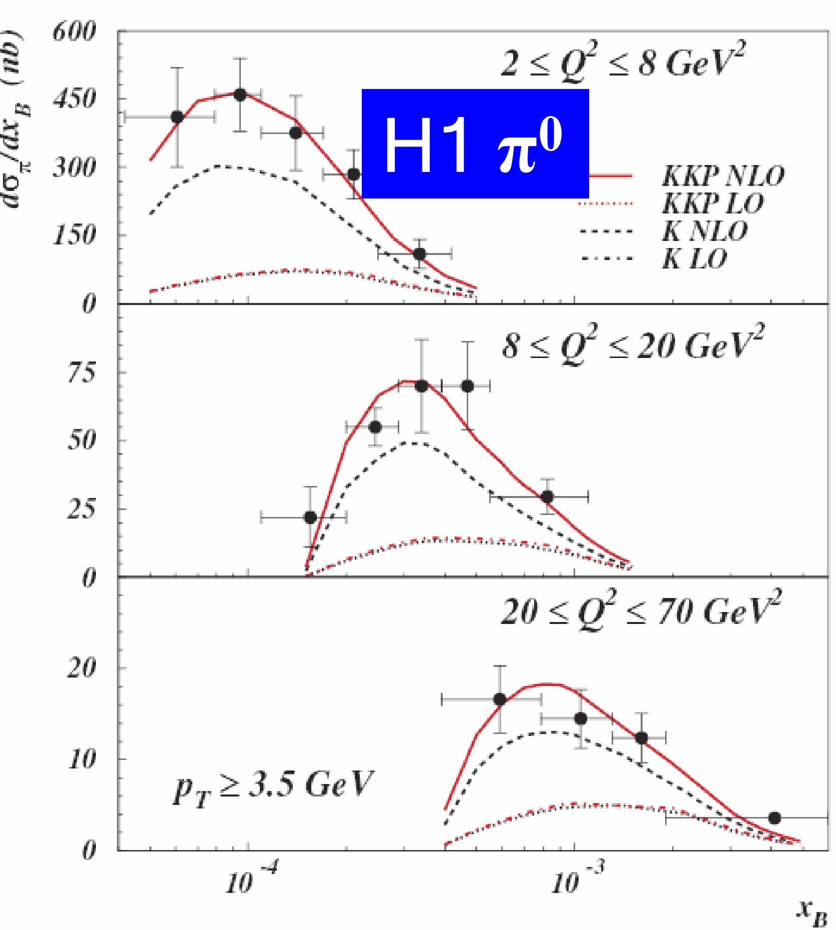
$$\mu^2 = M_p{}^2 = M_\gamma{}^2 = M_h{}^2 = \kappa^2 (Q^2 + E_T^2)$$

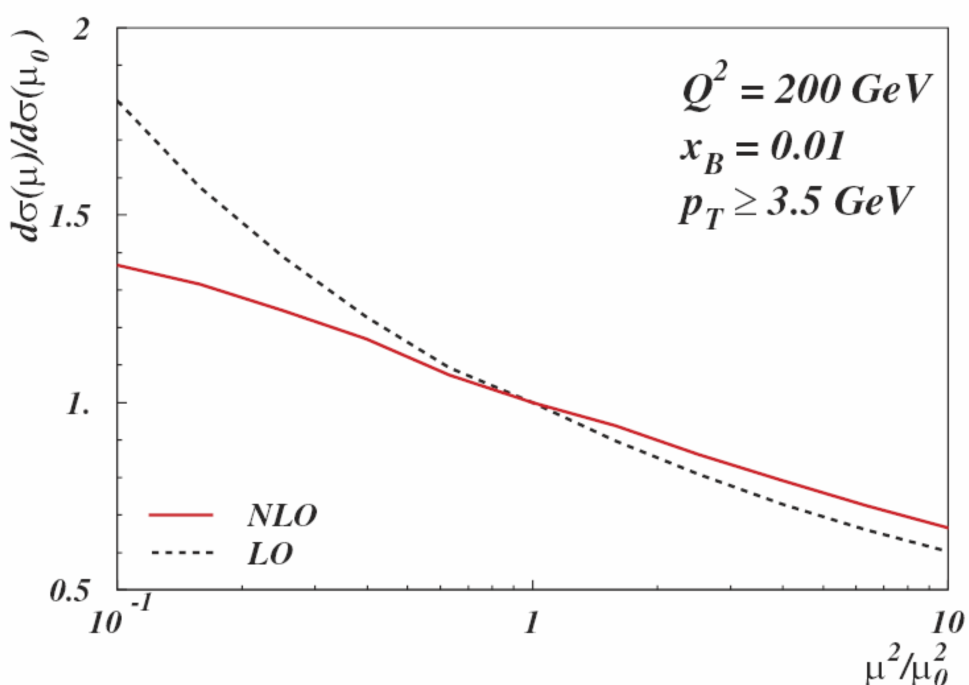
even less justified than for jets!

It results in resolved contribution even for $Q^2 \gg E_T^2$!!

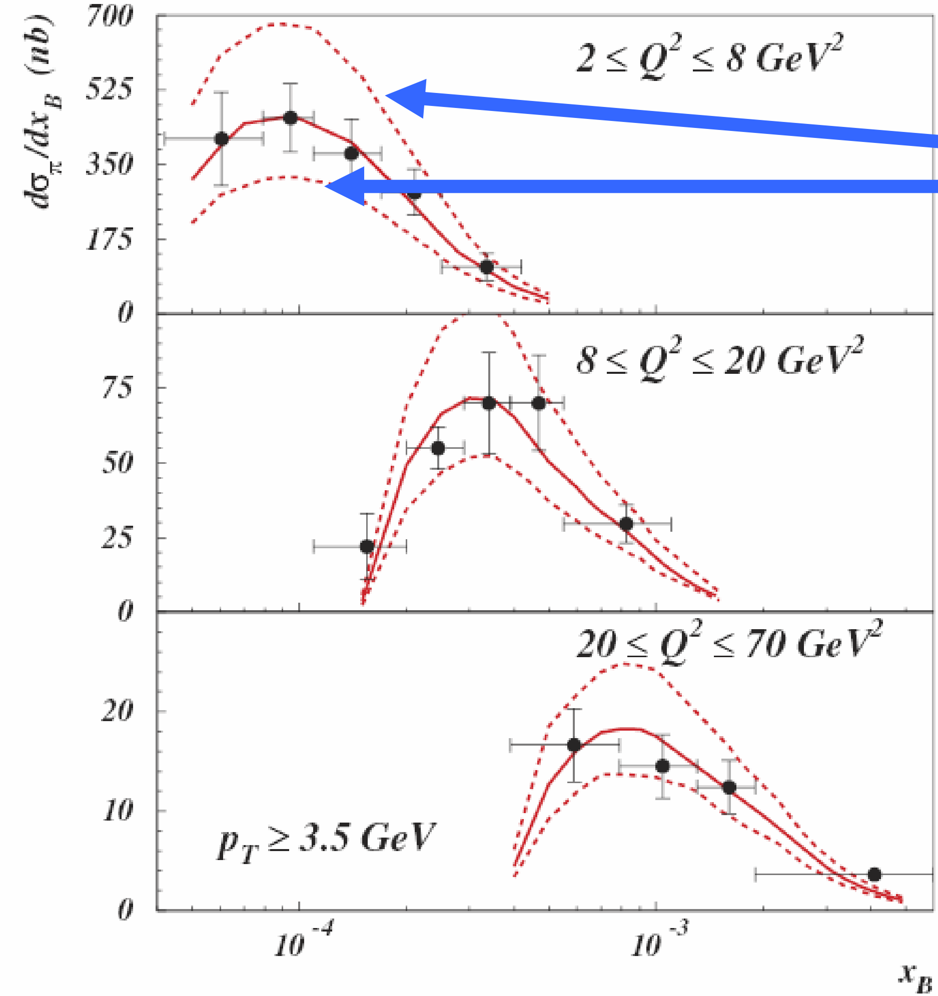
Daleo, de Florian, Sassot 04: only direct photon contribution

KKP as well as Kretzer FF, setting $M^2 = (Q^2 + E_T^2)/2$





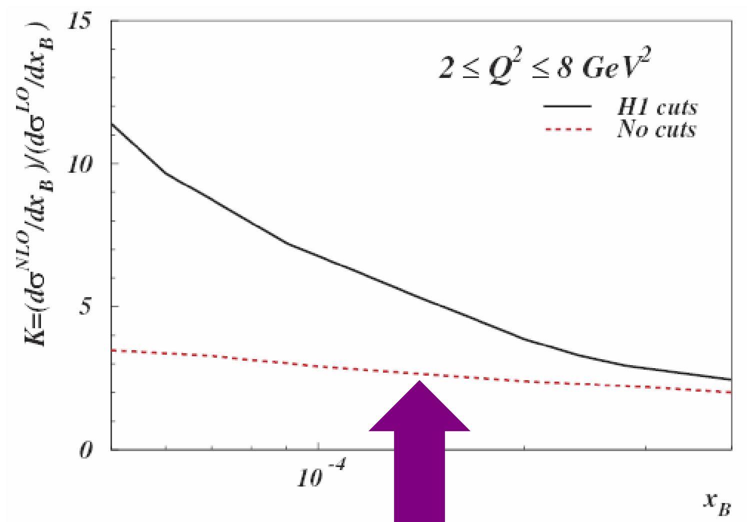
Sizable dependence on both FF and common scale!



The central (solid) line corresponds to setting the factorization and renormalization scales to $(Q^2 + p_T^2)/2$ and the upper and lower (dashed) ones to $(Q^2 + p_T^2)/4$ and $Q^2 + p_T^2$ respectively.

Difference by a factor of more than 2 for narrower range of scales!!

Decreases only slowly with increasing Q^2



Large K-factors!

Their conclusion:

In spite of the reasonable agreement between data and the NLO DGLAP estimate, the rather large K-factors and the significant factorization scale dependence,..., suggest the presence of non-negligible NNLO effects....

These rather large uncertainties in their (and my) view

hide any potential disagreement between the data and the DGLAP prediction, restraining, for the moment, any empirical suggestion of dynamics different to plain DGLAP evolution.

Note: basically the same perturbative partonic cross sections as for jets, so the explanation should be applicable to both.

Kniehl, Kramer and Maniatis 05

Same scale choice and FF as in previous analysis

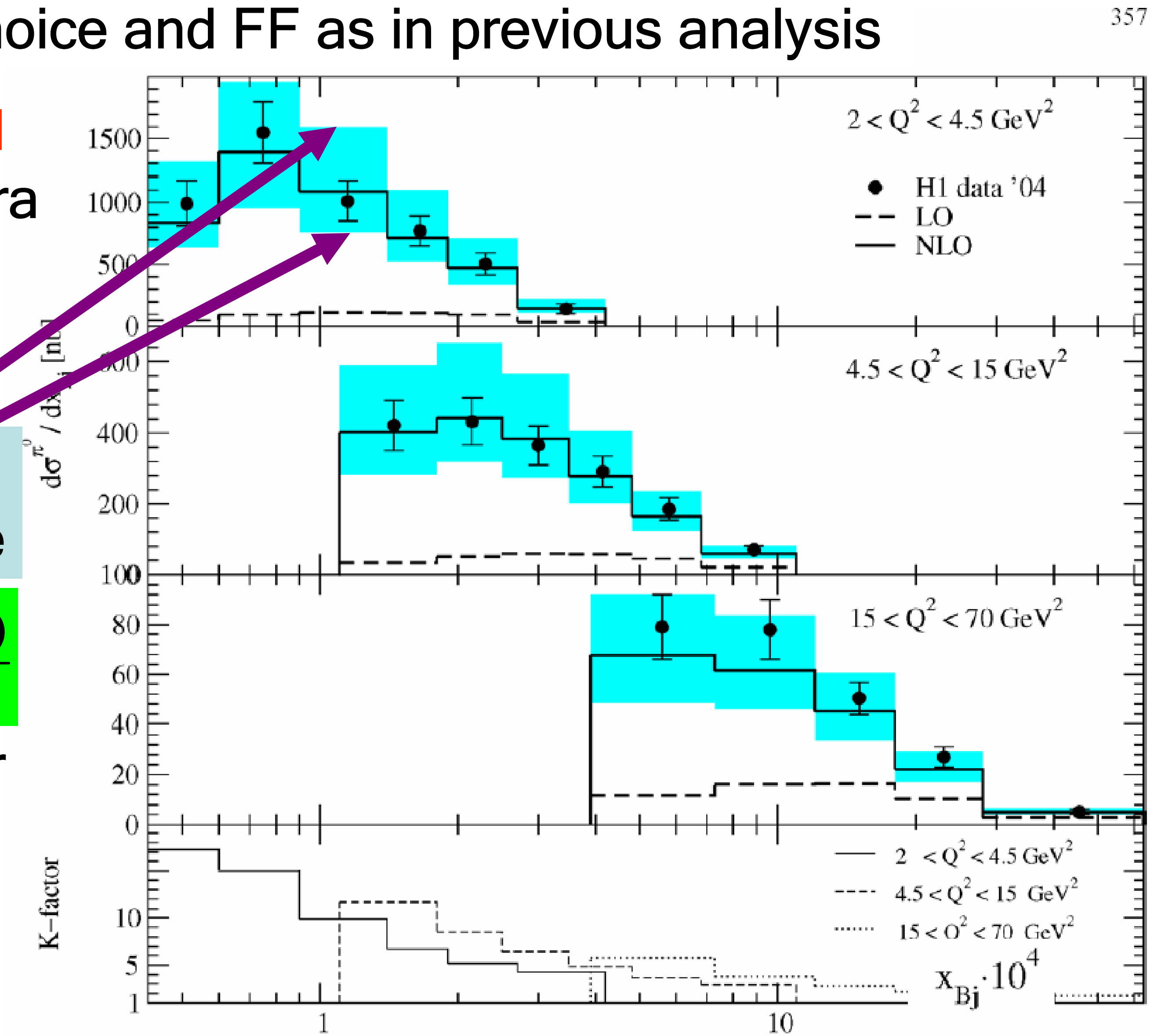
π^0 and charged hadrons spectra compared to H1(99) data.

Again a factor of 2 difference

$$M^2 = \xi \frac{(Q^2 + E_T^2)}{2}$$

Agreement for $\xi = 1$

range $1/2 \le \xi \le 2$



Compared to Daleo et al. they are more optimistic in the interpretation of the H1 data:

NLO correction is found to produce a sizeable enhancement in cross section, of up to one order of magnitude,

bringing the theoretical prediction to good agreement with recent measurements for neutral pions and charged hadrons at HERA.

But they obviously put (too?) much faith in their choice of scales

Our default predictions, endowed with theoretical uncer-ainties estimated by moderate unphysical scale variations led to a satisfactory description of the HERA data in the preponderant part of the accessed phase space.

The most recent analysis of the same H1 data on forward π^0 done by Aurenche, Basu, Fontannaz and Godbole

taking into account the resolved virtual photon as well.

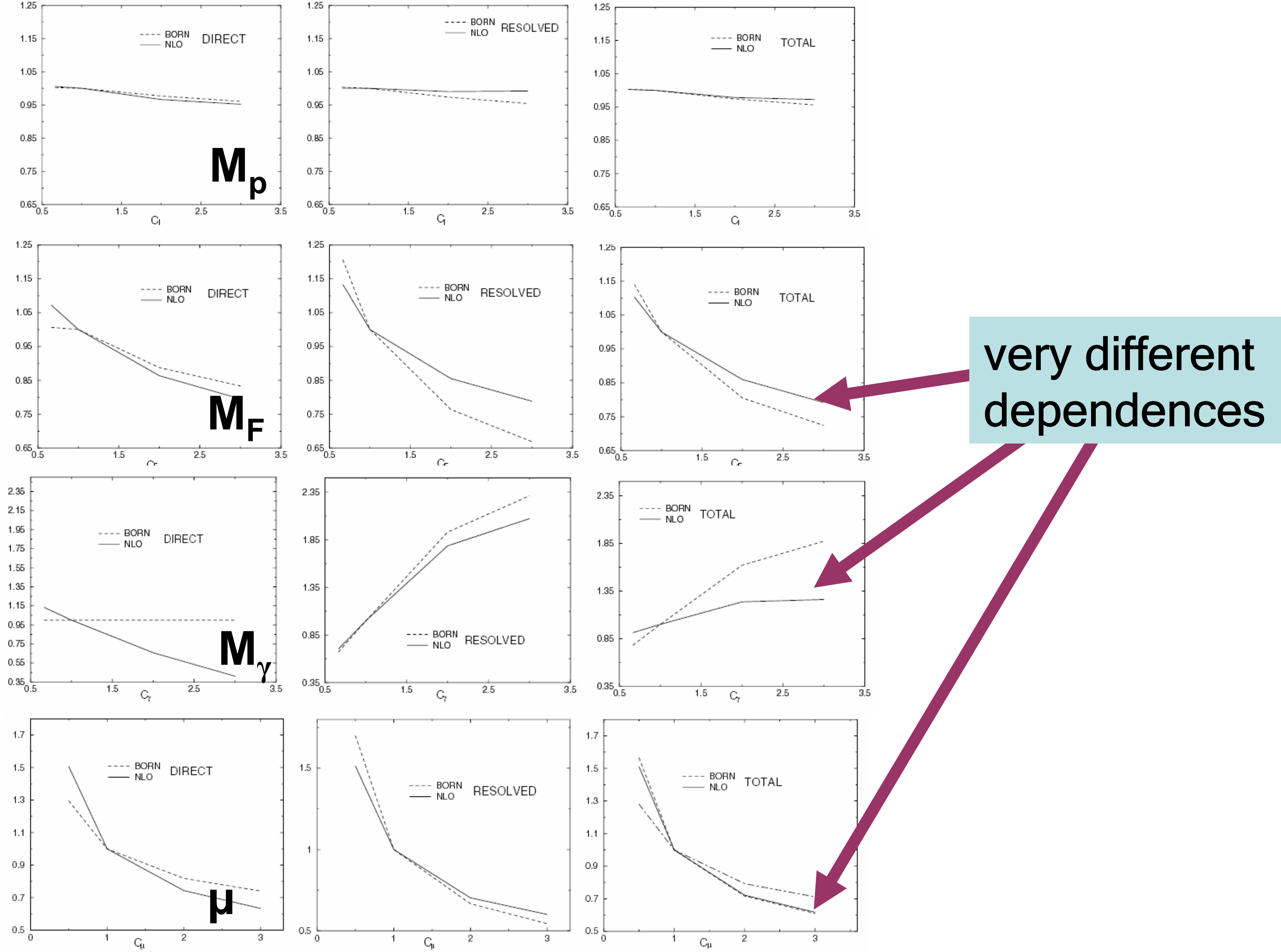
Includes up to now the most detailed analysis of the separate dependence on different scales finding very different dependence on the renormalization factorization, fragmentation and factorization scales.

Default calculations done for the common scale set to

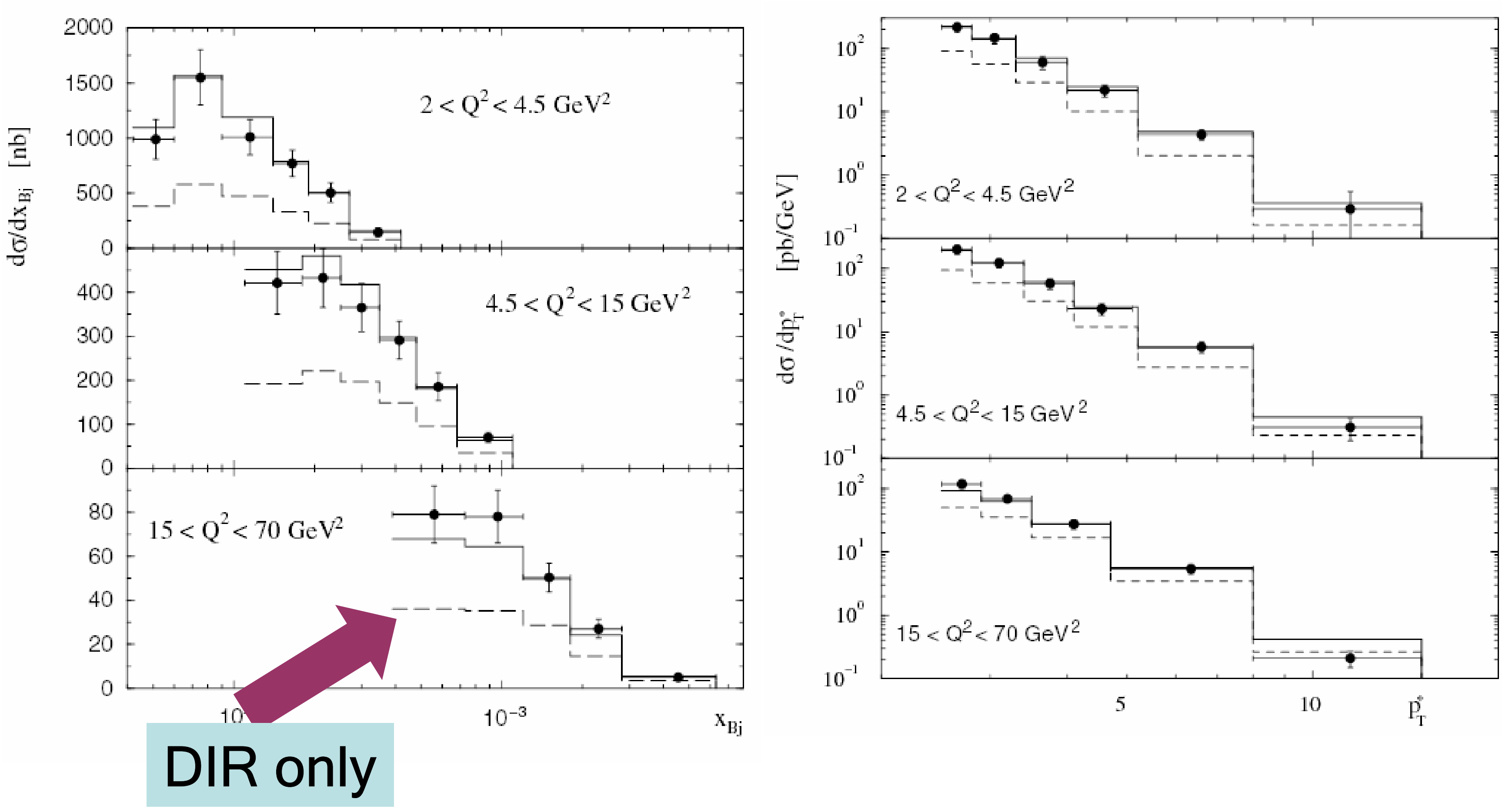
$$M^2 = (Q^2 + E_T^2)$$

Compared to Daleo et al. and Kniehl et al. the common scale is twice bigger and thus the NLO direct substantially smaller!

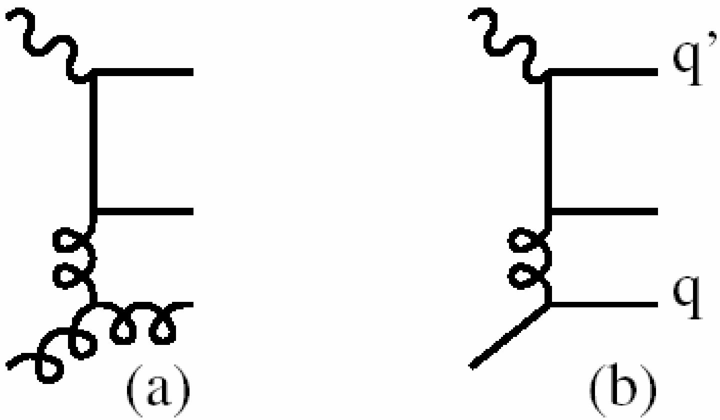
Consequently, also the conclusions are very different.

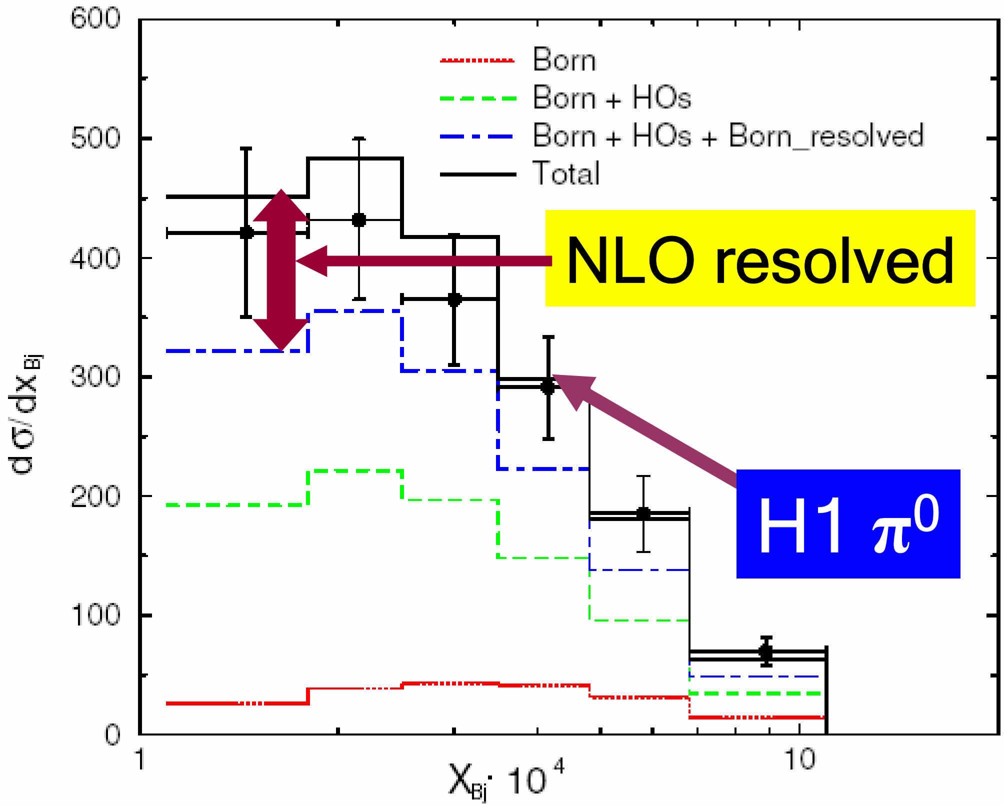


BORN
NLO
DIRECT
RESOLVED
TOTAL
Mp
MF
Mγ
μ
very different dependences



dσ/dx_Bj [nb]
2 < Q² < 4.5 GeV²
4.5 < Q² < 15 GeV²
15 < Q² < 70 GeV²
x_Bj
10⁻³
dσ/dp*_T [pb/GeV]
p*_T
DIR only





The agreement between theory and data achieved for $\mu^2 = M^2 = Q^2 + E_T^2$

Variations under the proton and photon factorization scales are under control. However a large instability is observed when varying independently the renormalization and fragmentation scales.

This prevents a really quantitative prediction for the single pion inclusive distribution in the forward region.

Inclusive particle production in γγ collisions

Problems with inclusive particle production are not new recall

Gordon 94:

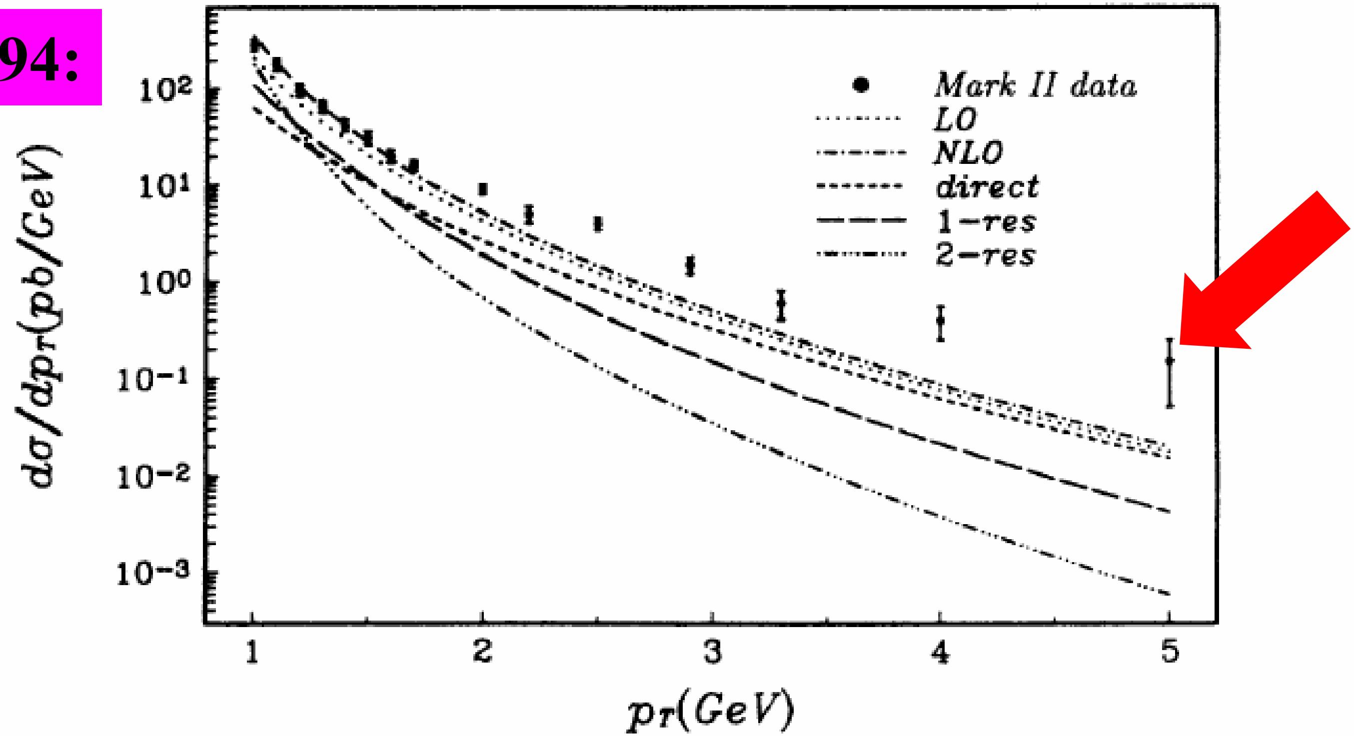


FIG. 16. Comparison of the LO and NLO predictions using the GRV photon distributions and the new charged hadron fragmentation functions of Ref. [40] with the Mark II data.

Binnewies, Kniehl, Kramer 96

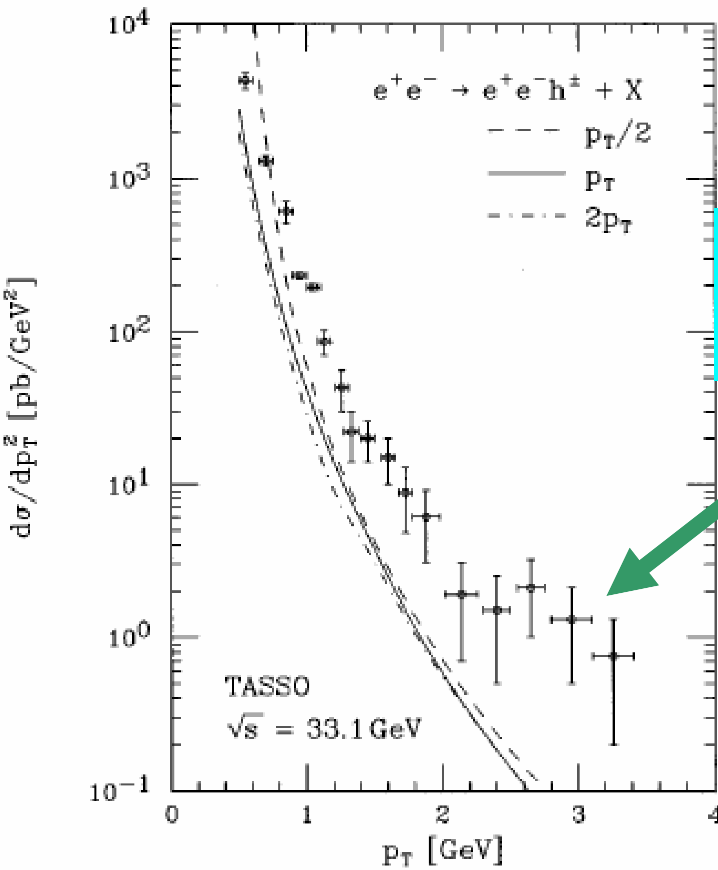


FIG. 1. Cross section $d\sigma/dp_T^2$ of inclusive charged-hadron production in single-tagged $\gamma\gamma$ collisions. The TASSO data [15] ($\sqrt{s}=33.1$ GeV on average) are compared with our corresponding NLO calculations for scale choices $\xi=1/2$, 1, and 2.

The same message

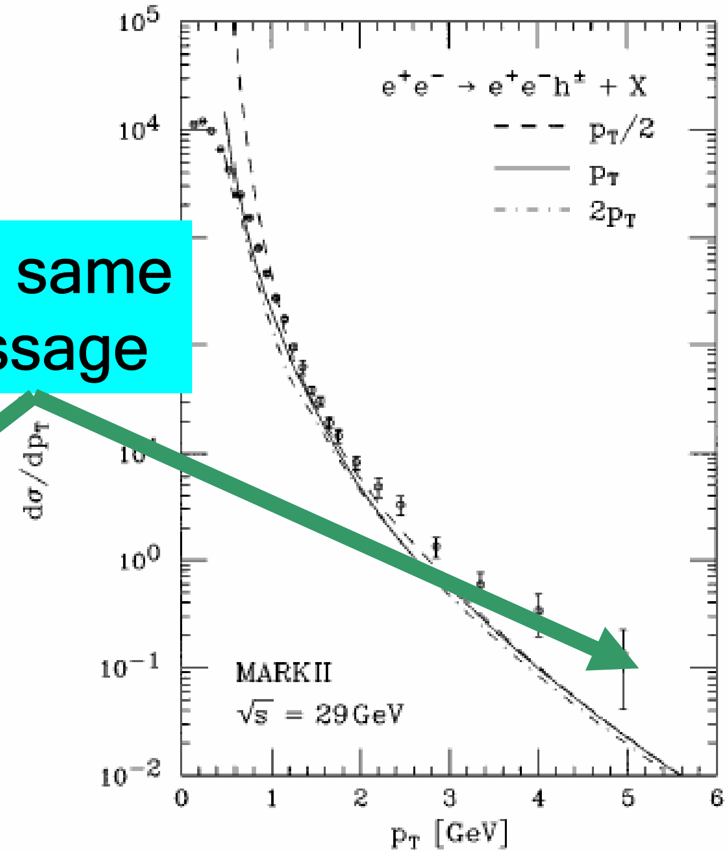


FIG. 2. Cross section $d\sigma/dp_T$ of inclusive charged-hadron production in single-tagged $\gamma\gamma$ collisions. The MARK II data [16] ($\sqrt{s}=29$ GeV) are compared with our corresponding NLO calculations for scale choices $\xi=1/2$, 1, and 2.

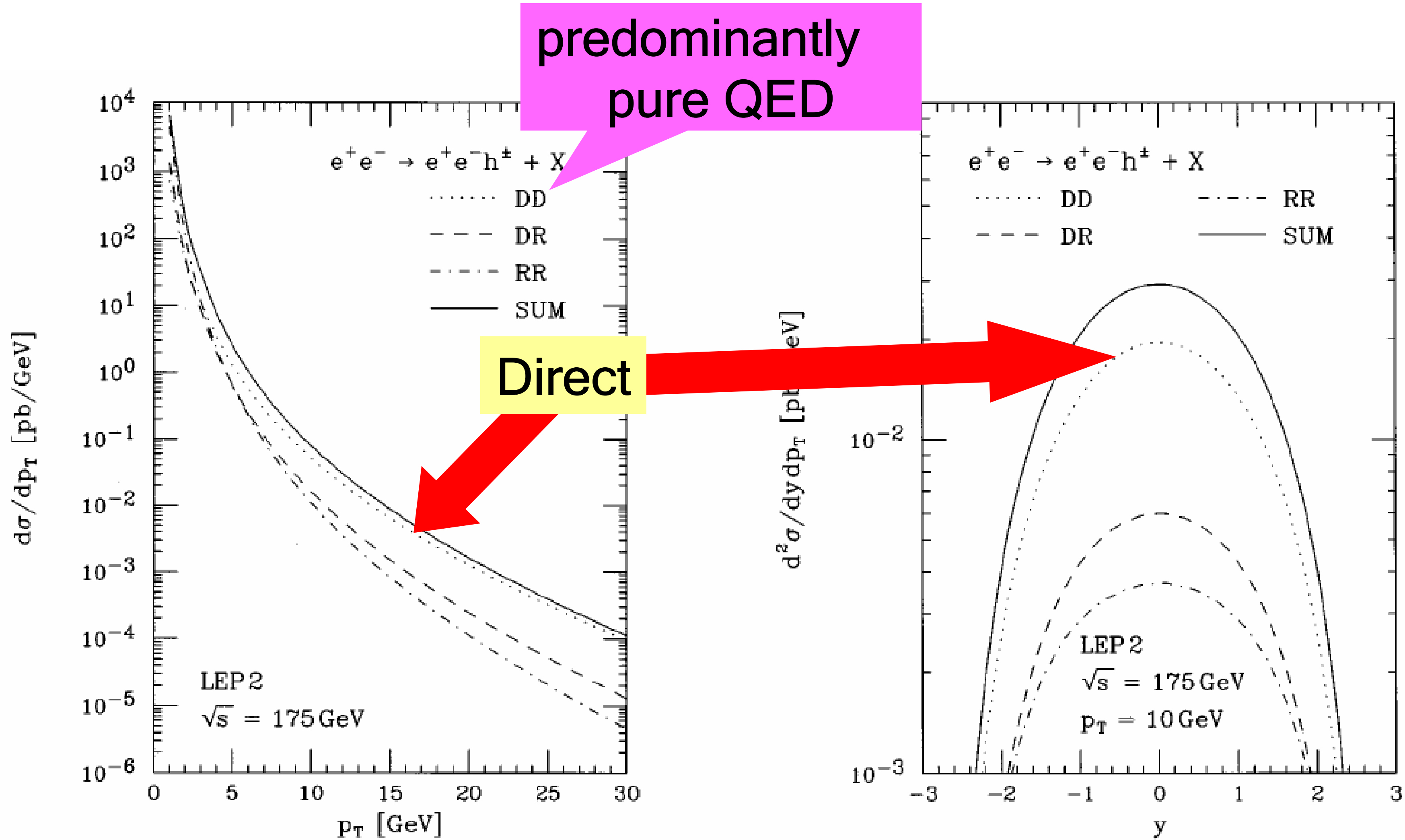


FIG. 4. NLO cross section $d\sigma/dp_T$ of inclusive charged-hadron production in double-tagged $\gamma\gamma$ collisions at LEP2 ($\sqrt{s}=175$ GeV). The DD, DR, and RR components are also shown.

FIG. 5. Same as in Fig. 4 for the y dependence $d^2\sigma/dy\, dp_T$ at $p_T=10$ GeV.

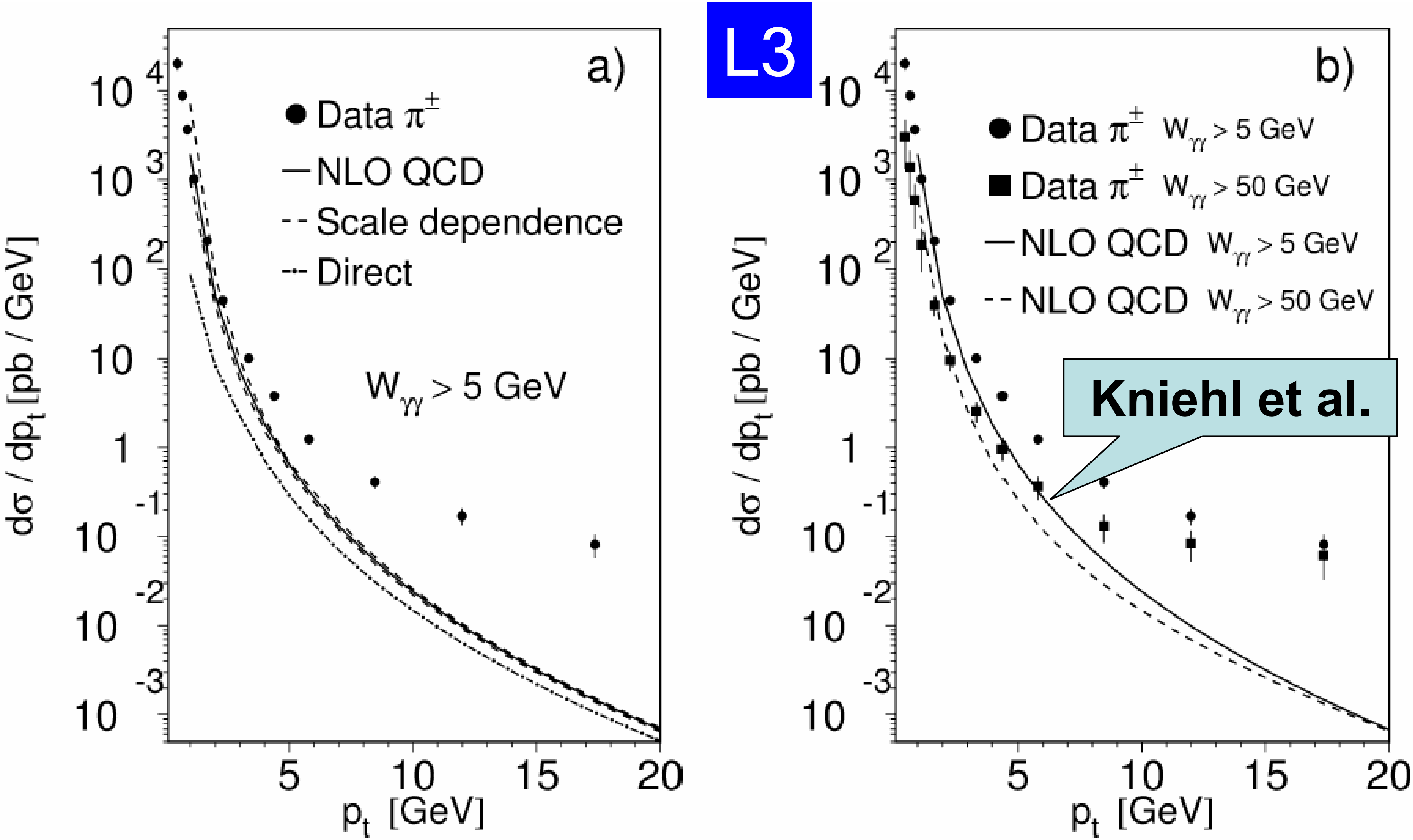
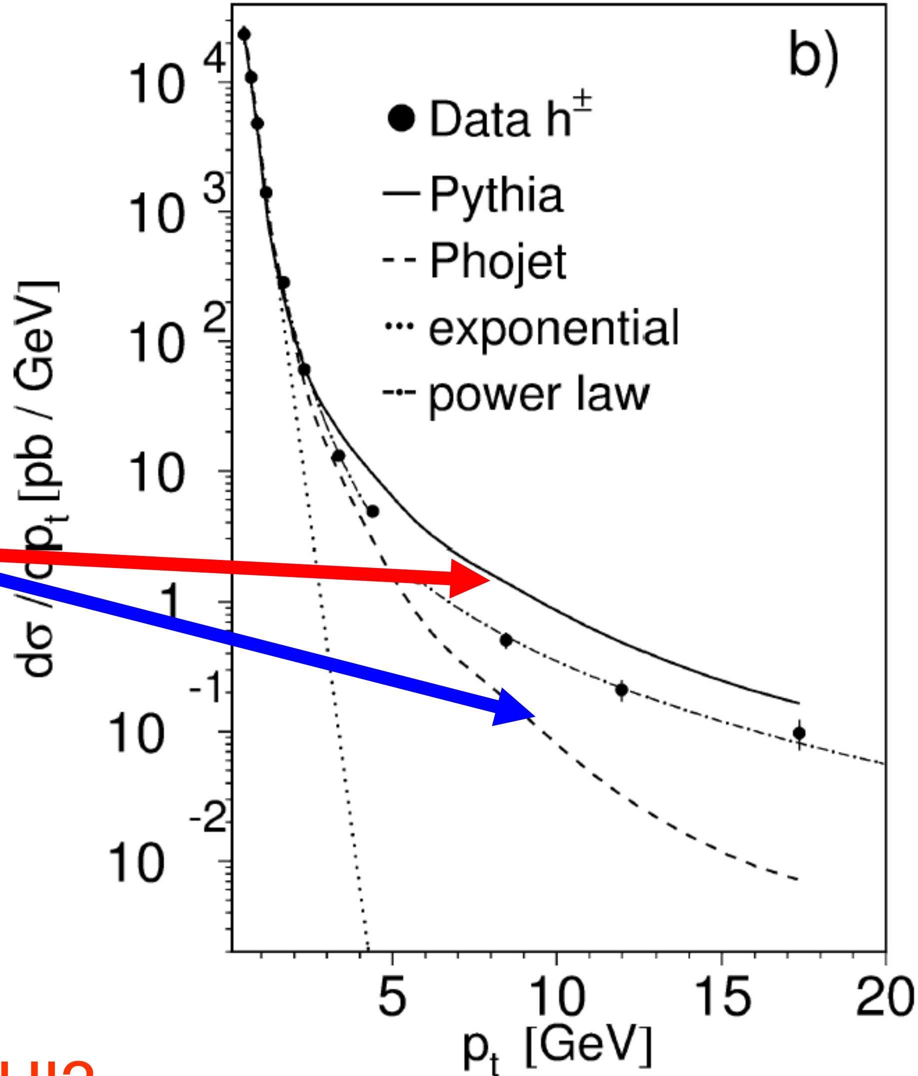


Fig. 4. (a) Inclusive $\pi^{\pm}$ differential cross section $d\sigma/dp_t$ compared to NLO QCD calculations [19] for $W_{\gamma\gamma} > 5$ GeV. The dashed-dotted lin corresponds to the direct subprocess. The dashed lines represent the scale uncertainty of the calculations. (b) Inclusive $\pi^{\pm}$ differential cros section $d\sigma/dp_t$ with different $W_{\gamma\gamma}$ cuts. The average p_t value of each bin, $\langle p_t \rangle$, is used.

Difficult to understand as for large p_T hadrons the pure QED contribution should overhwelmingly dominate!

But maybe, we just do not understand hadronization?

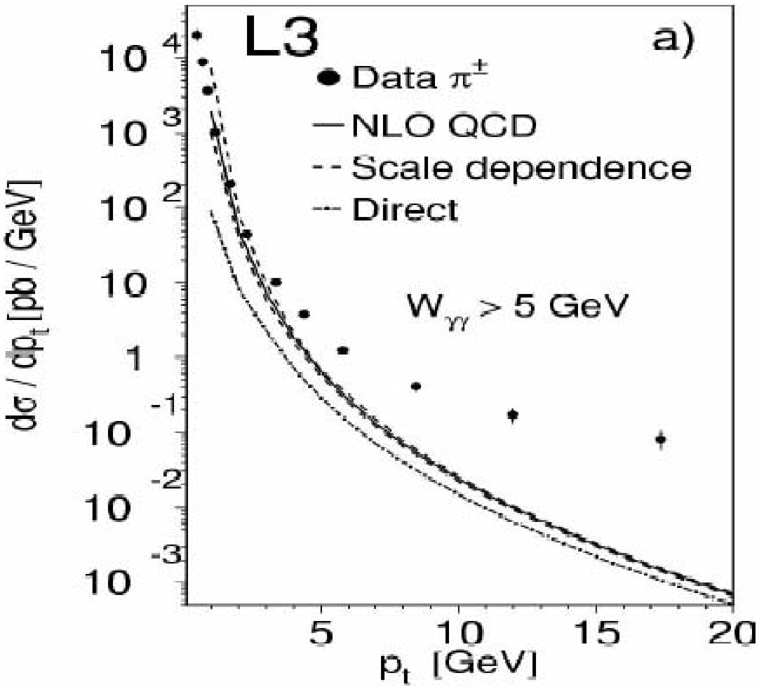
Must have the same reasor as excess in jet production observed by L3 as well.



LP05 Uppsala:
Trivial explanation by DELPHI?

Do we really know QCD this well?

- 2003: L3 $\gamma\gamma$ results show weird discrepancy at high transverse momentum
- Similar effect in both charged hadrons (shown) and in jets
- Scale dependence (theory error) certainly doesn't account for it!

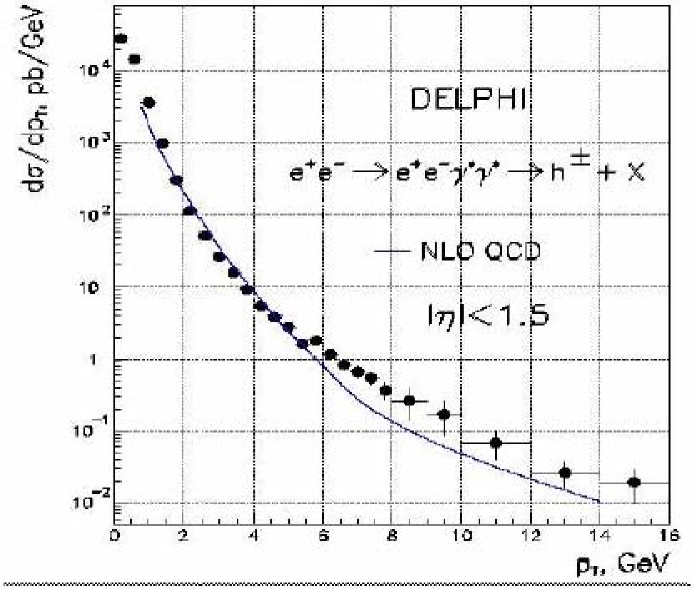


- If true, a real surprise & a big problem for QCD

Single Particle Inclusive Cross Section in $\gamma\gamma$ events

DELPHI:738

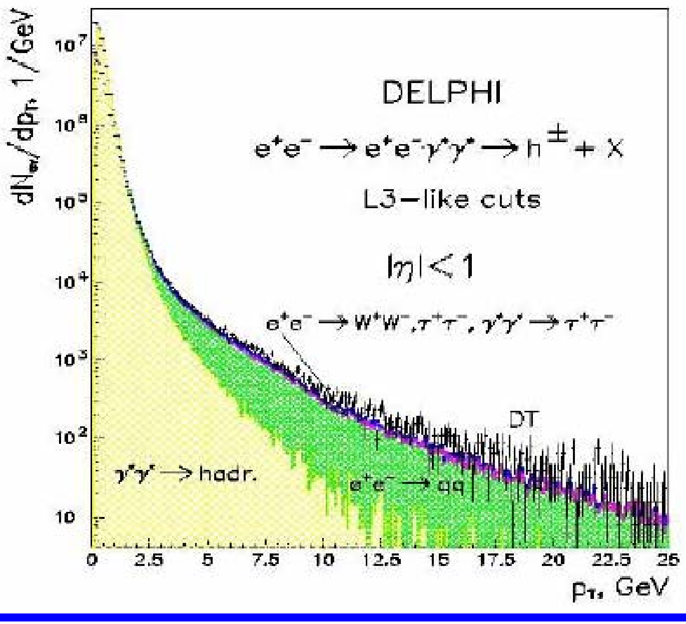
- New DELPHI result (this conference)
- Shows good agreement with QCD.

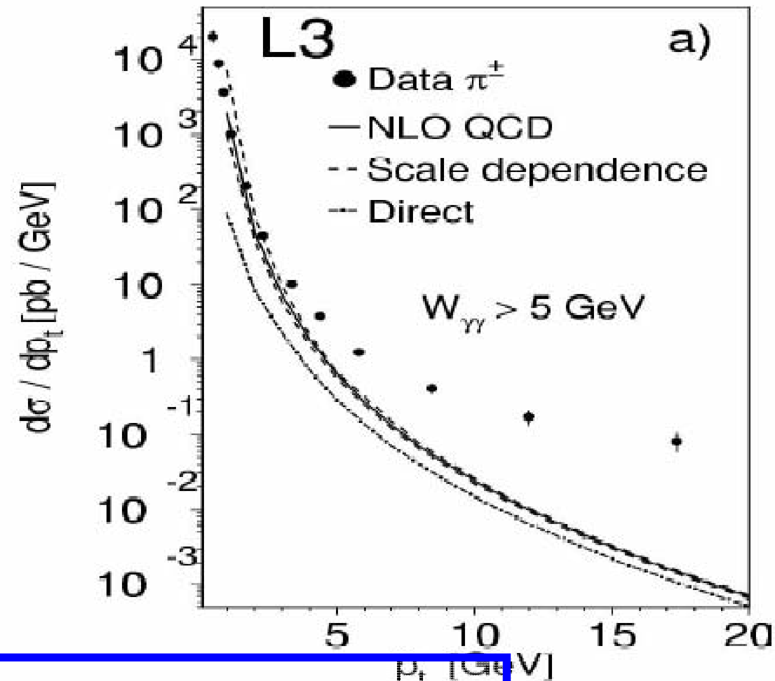


Single Particle Inclusive Cross Section in $\gamma\gamma$ events

DELPHI:738

- Use L3 cuts, let in annihilation background.

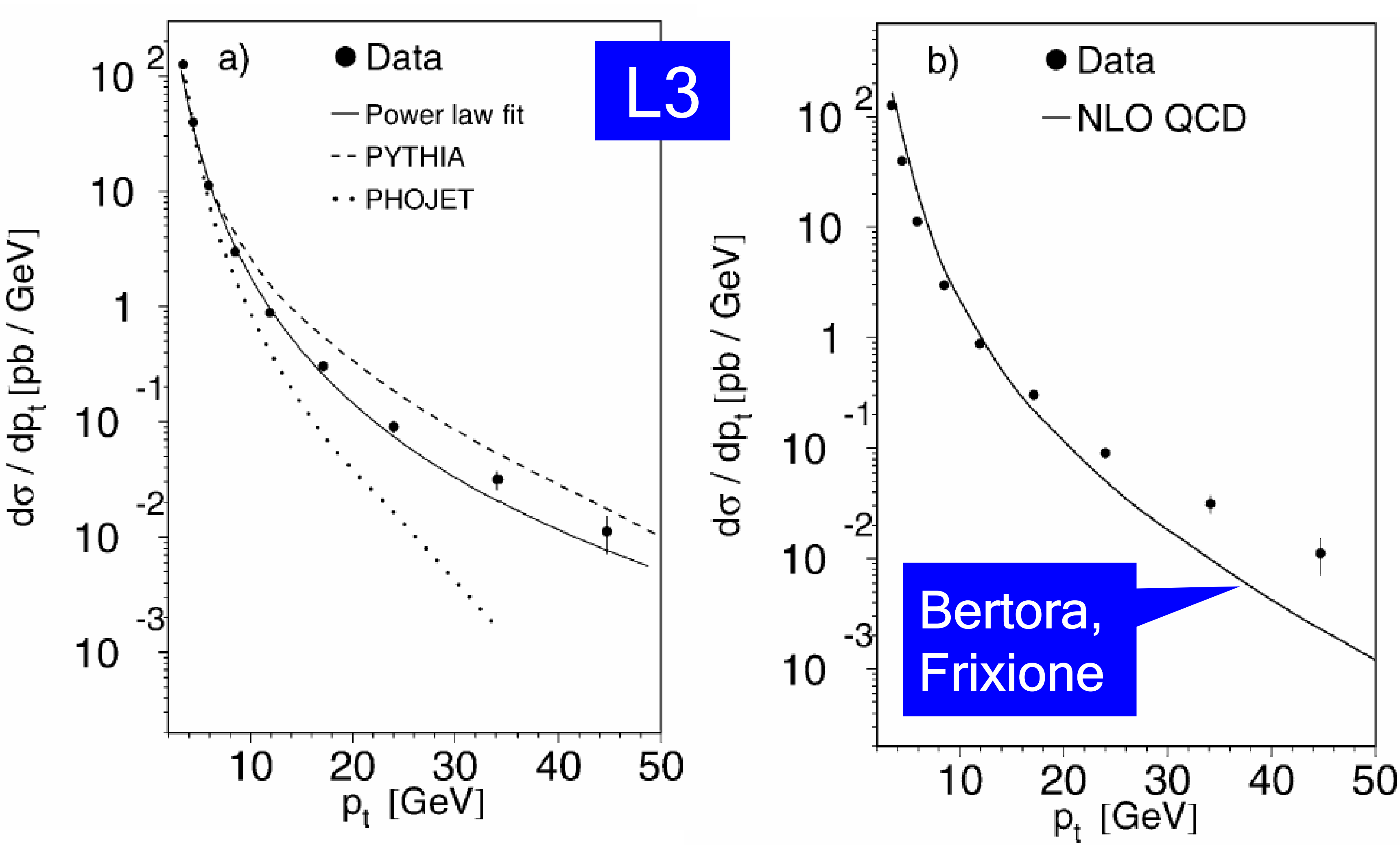




Jon: Seems to be resolved. QCD wins again!

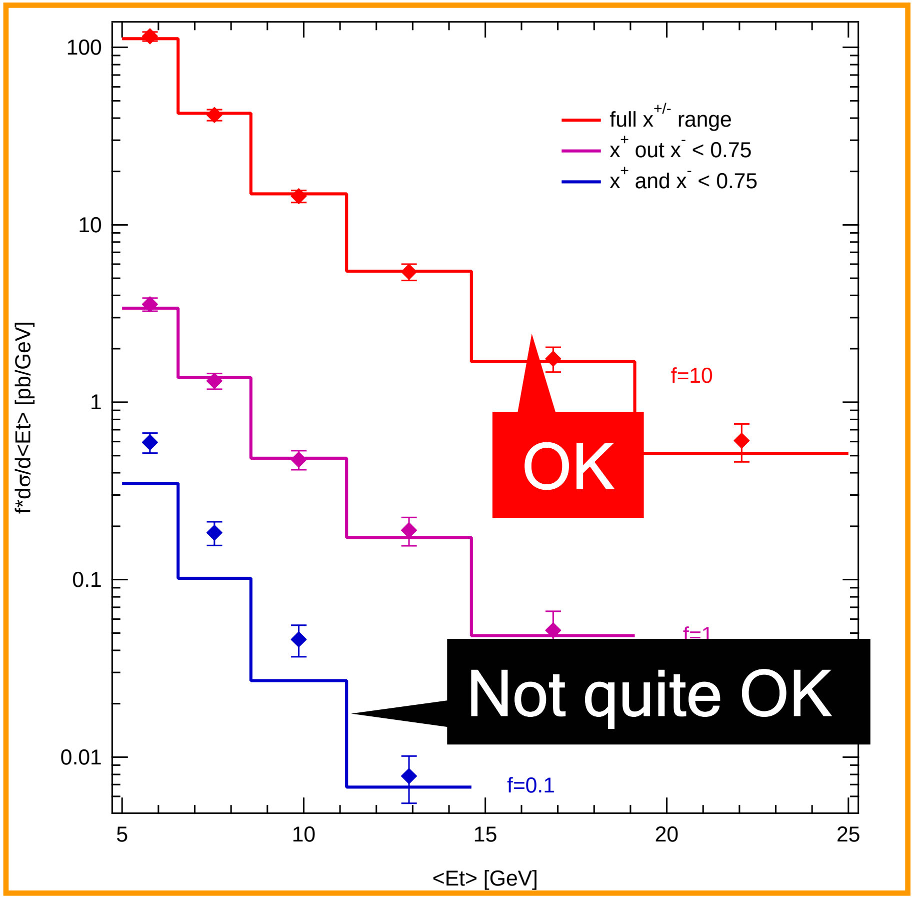
Really?

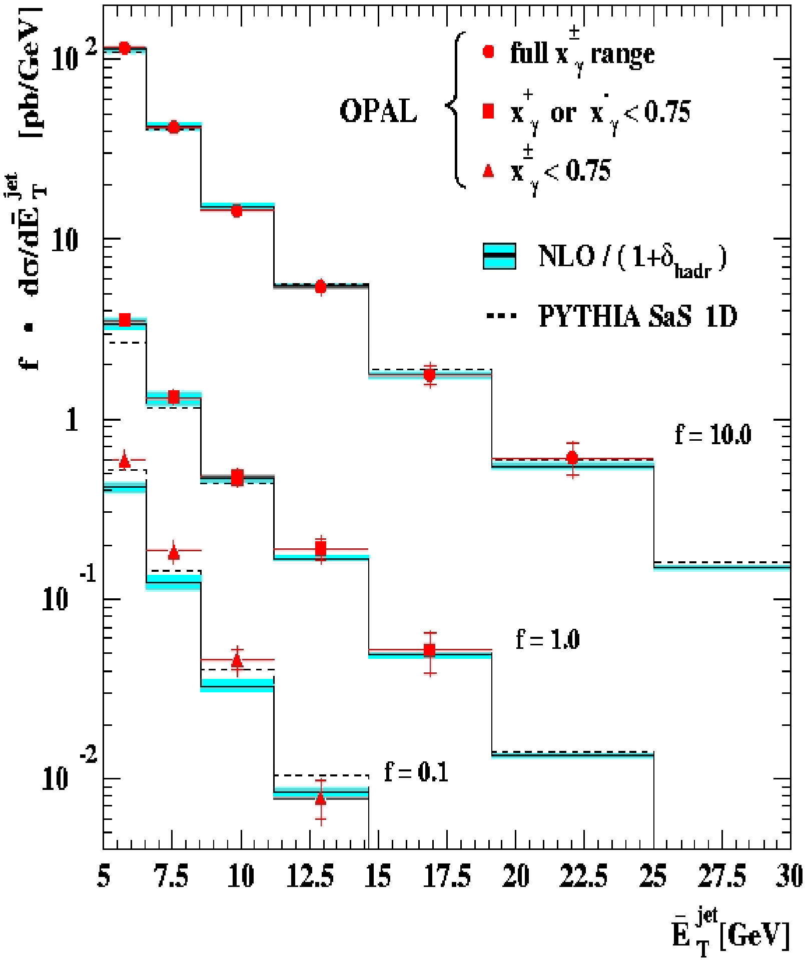
Puzzling $\gamma\gamma$ collisions: and now also jets



L. Bertora at PHOTON03, DIS04

Results: Theo.vs.Opal



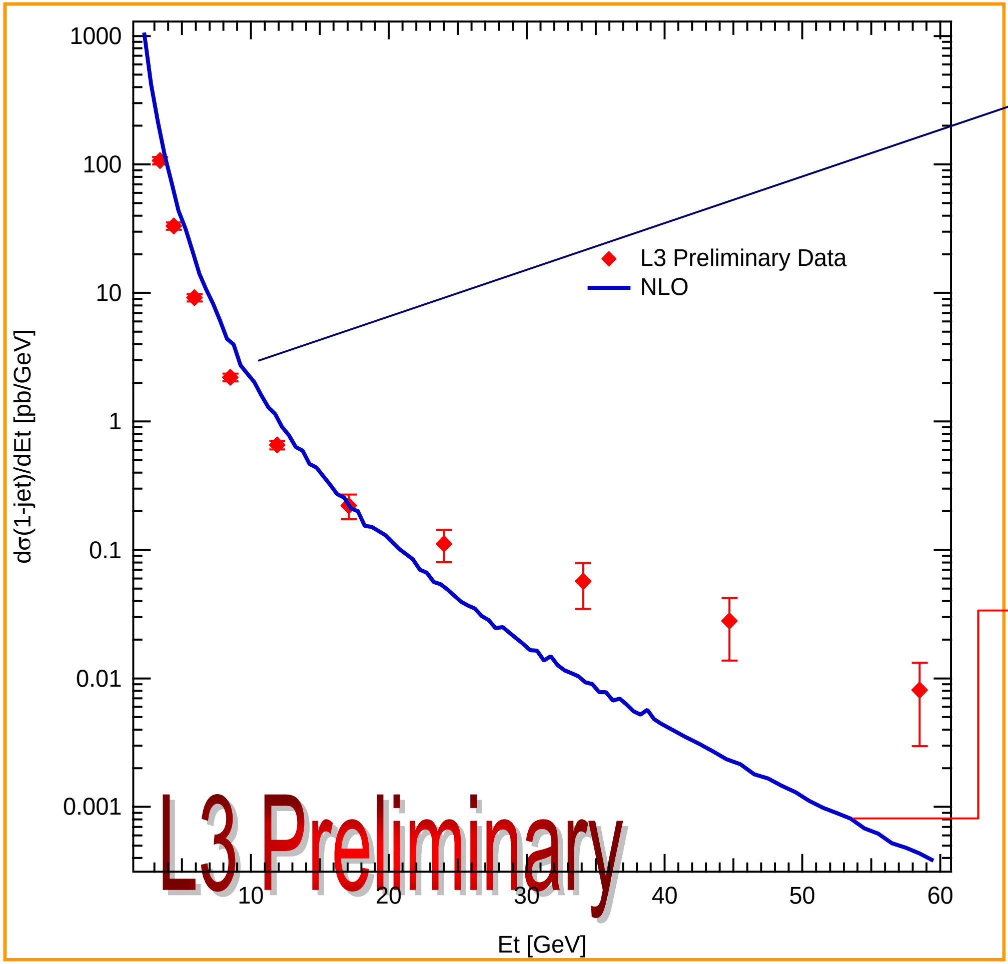


Data from Di-Jet Production in photon-photon collisions at sqrt(s) from 189 to 209 GeV

OPAL coll., hep-ex/0301013

L. Bertora at
PHOTON03, DIS04

Results: Theo. vs. L3



Good shape,
but not really good
normalization

Wrong shape and
normalization:
Preliminary data seem
to confirm L3-hadron
production discrepancy
with NLO prediction

Remarks on theory:

At large p_T:

- direct $\gamma\gamma$ contribution dominant (as for hadrons)
- QED part dominates direct $\gamma\gamma$ contribution
- QCD contribution does not represent full NLO but cannot be expected to close the gap
- threshold resummation may be important
- Hadronization effects should be looked into

Direct contribution: $\alpha^2 + \alpha^2\alpha_s + \alpha^2\alpha_s^2$ missing

Single resolved: $\alpha^2\alpha_s + \alpha^2\alpha_s^2$

Double resolved: $\alpha^2\alpha_s^2 + \alpha^2\alpha_s^3$

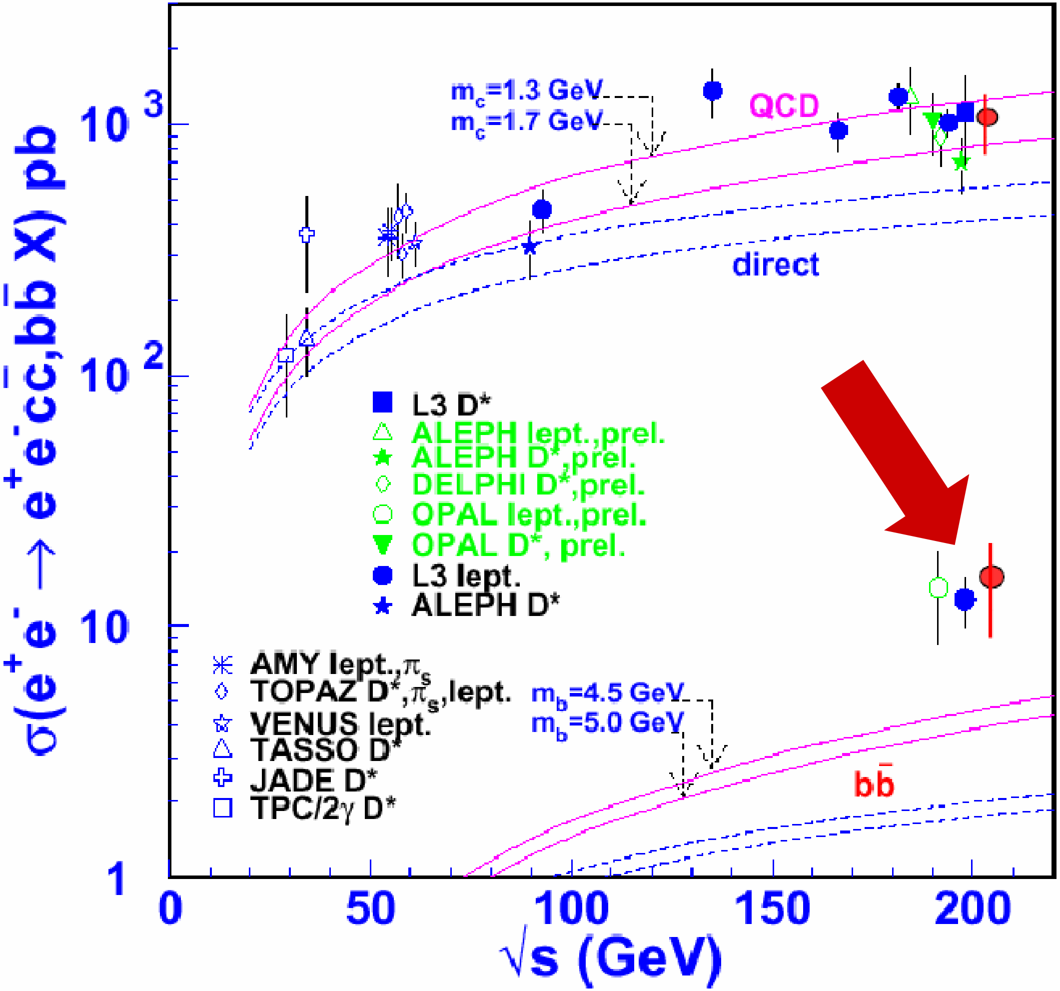
Needed for full consistency to order $\alpha^2\alpha_s^2$

Moreover:

the same problem in $b\bar{b}$ production in $\gamma\gamma$ collisions!

New L3 analysis confirms their older result which is in excellent agreement with those of OPAL and DELPHI.

So, I think we still have a problem.



Prompt photon + jet production

Bawa, Stirling, Gordon, Wogelsang, Krawczyk, Zembruski, Fontannaz, Heinrich,...

Two approaches differing

by counting of orders of α_s

Neither included

A:

Direct contribution:	α^2 +	$\alpha^2\alpha_s$ +	$\alpha^2\alpha_s^2$ +	$\alpha^2\alpha_s^3$
Single resolved:		$\alpha^2\alpha_s$ +	$\alpha^2\alpha_s^2$ +	$\alpha^2\alpha_s^3$
Double resolved:			$\alpha^2\alpha_s^2$ +	$\alpha^2\alpha_s^3$

B:

Direct contribution:	α^2 +	$\alpha^2\alpha_s$ +	$\alpha^2\alpha_s^2$	(box)
Single Resolved:		$\alpha^2\alpha_s$		
Double Resolved:			$\alpha^2\alpha_s^2$	

Conclusions

In the interesting transition region between photoproduction and DIS the scale and other uncertainties prevent us from calculating with (in)accuracy better than a factor of 2, potentially masking signals of "new physics" like BFKL.

Calls for NNLO calculations should be accompanied with systematic investigation of scale and scheme ambiguities of existing LO/NLO calculations.

We should also understand better the relation between LO MC event generators and NLO partonic calculations. Way forward: MC&NLO.

In theoretically seemingly clean case of jet, inclusive hadrons and heavy quark production in photon-photon collisions we face serious disagreement with (some?) data which we do not understand.