Theory summary: what I would like to understand

Jiří Chýla, Institute of Physics, Prague

Often difficult to distinguish between theory/phenome- and experiment. **A lot of comparison** of older calculations with new data, as well as **new calculations**.

Overview on direct photons: Heinrich
Total cross sections: Pancheri,
GPD's & related: Friot, Landsberg, Pire, Wallon, Szymanowski
Unintegrated PDF: Szczurek, Hautman
Standard PDF: JC, Hejbal, Sasaki
Power corrections: Hautman
Scales, schemes: Geiser, Grindhammer
QED processes: Serbo, Da Silva

I will not attempt to summarize what the speakers actually said, but **will attach** to each of the topics **comments/questions**, the latter mostly reflecting my ignorance of the respective subjects, but which, nevertheless, might be interesting to answer.

Prompt Photon Production

in γ p, e p and hadronic collisions

Gudrun Heinrich

University of Edinburgh

Photon 2007, La Sorbonne, Paris, 10.07.07

PHOX programs

The PHOX Family

NLO Monte Carlo programs (partonic event generators) to calculate cross sections for the production of large-p_T photons, hadrons and jets

http://wwwlapp.in2p3.fr/lapth/PHOX_FAMILY/main.html

P. Aurenche, T. Binoth, M. Fontannaz, J.Ph. Guillet, GH, E. Pilon, M. Werlen

- DIPHOX

  $h_1\, h_2 \to \gamma\ \gamma\ + X$, $h_1\, h_2 \to \gamma\ h_3\ + X$, $h_1\, h_2 \to h_3\, h_4\ + X$

- JETPHOX

  $h_1\, h_2 \to \gamma$ jet $+ X$, $h_1\, h_2 \to \gamma\ + X$

  $h_1\, h_2 \to h_3$ jet $+ X$, $h_1\, h_2 \to h_3 + X$

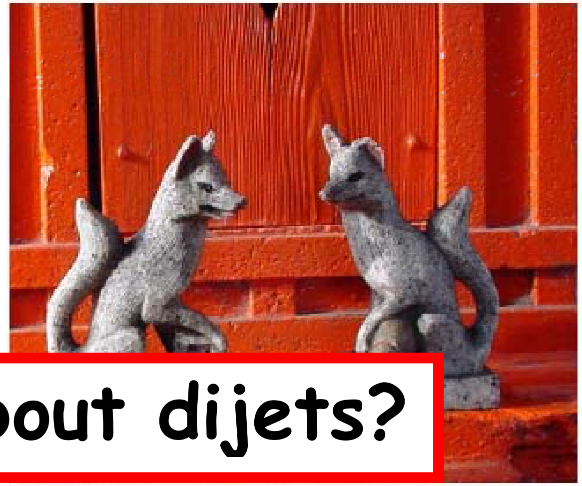
- EPHOX

  $\gamma\, p \to \gamma$ jet $+ X$, $\gamma\, p \to \gamma\ + X$

  $\gamma\, p \to h$ jet $+ X$, $\gamma\, p \to h + X$

- TWINPHOX

  $\gamma\gamma \to \gamma$ jet $+ X$, $\gamma\gamma \to \gamma\ + X$



What about dijets?

Prompt photons in hadronic collisions

theory efforts: resummation for $x_T = 2p_T/\sqrt{s} \to 1$:

Laenen, Oderda, Sterman '98

Catani, Mangano, Nason, Oleari, Vogelang '99

Kidonakis, Owens 2000

Sterman, Vogelsang 2001

De Florian, Vogelsang 2005 (frag)

effect of resummation extends down to $x_T \gtrsim 10^{-1} \Rightarrow$ covers fixed target range

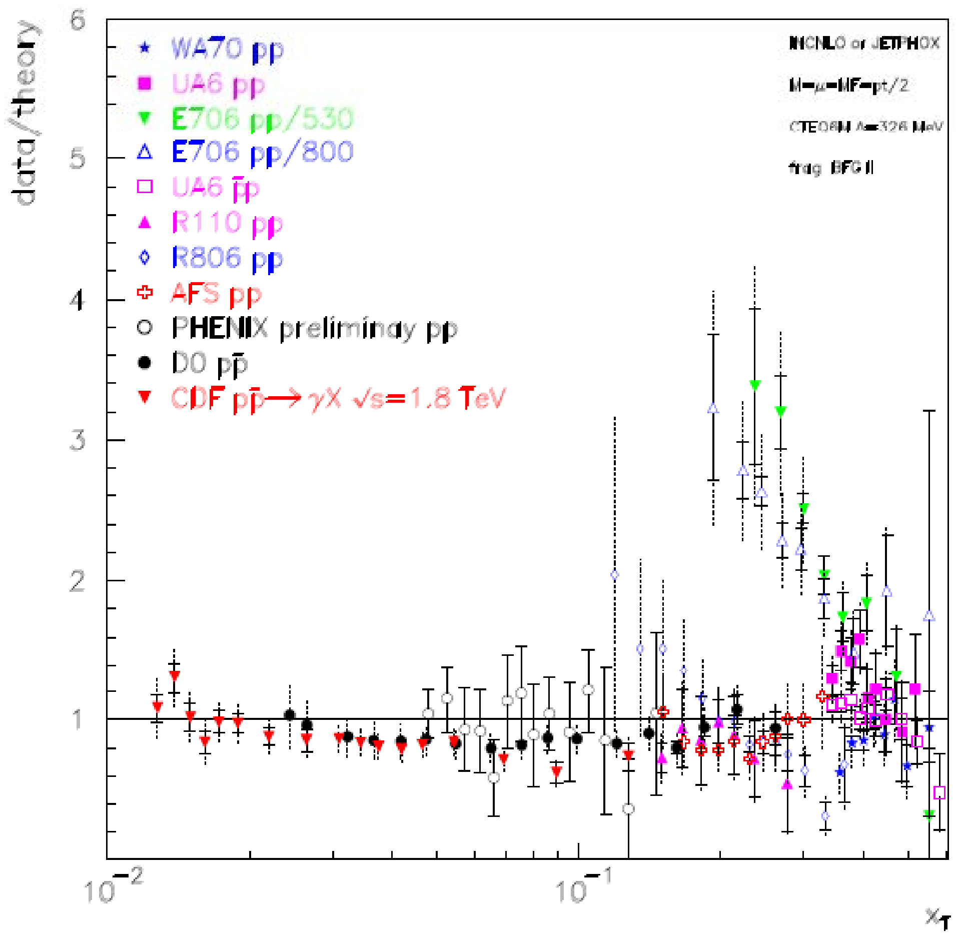
joint resummation of threshold and recoil effects (multiple soft-gluon emission): Sterman, Vogelsang 2005

result:

- scale dependence considerably reduced
- recoil effects in inclusive γ production relatively small
- agreement with almost all prompt photon data

Prompt photons in hadronic collisions

data/theory from fixed target to collider energies



significant achievement!

Aurenche, Fontannaz, Guillet, Pilon, Werlen 06

Total cross sections

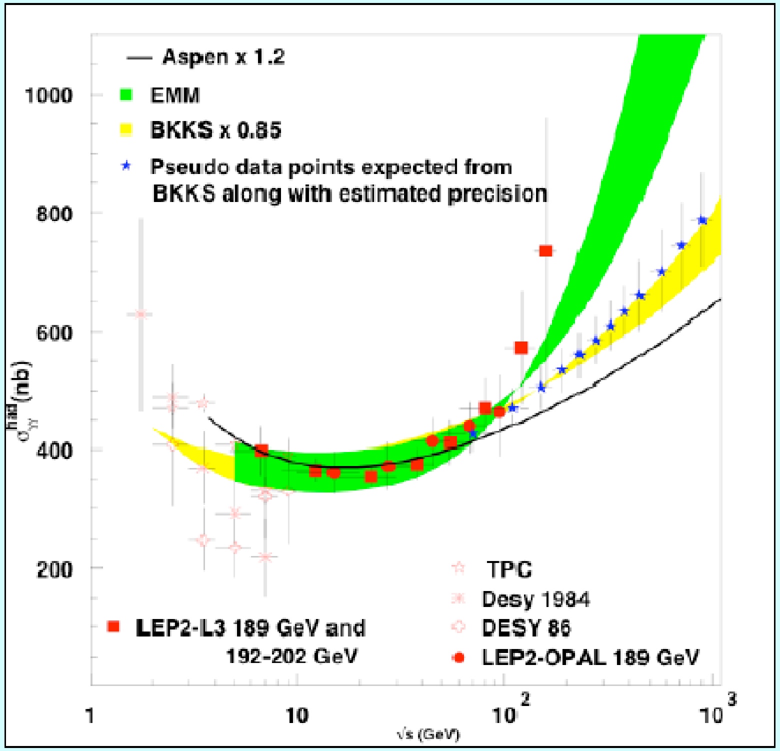
s^{ε} : Should ε be the same for all hadronic cross-sections?

G. Pancheri:

- Yes if the model
  - is based on Regge poles and a universal Pomeron pole exchange

    $\sigma = Bs^{-\eta} + As^{\varepsilon}$

- Not necessarily if
  - The model has some connection with QCD and parton densities play a role

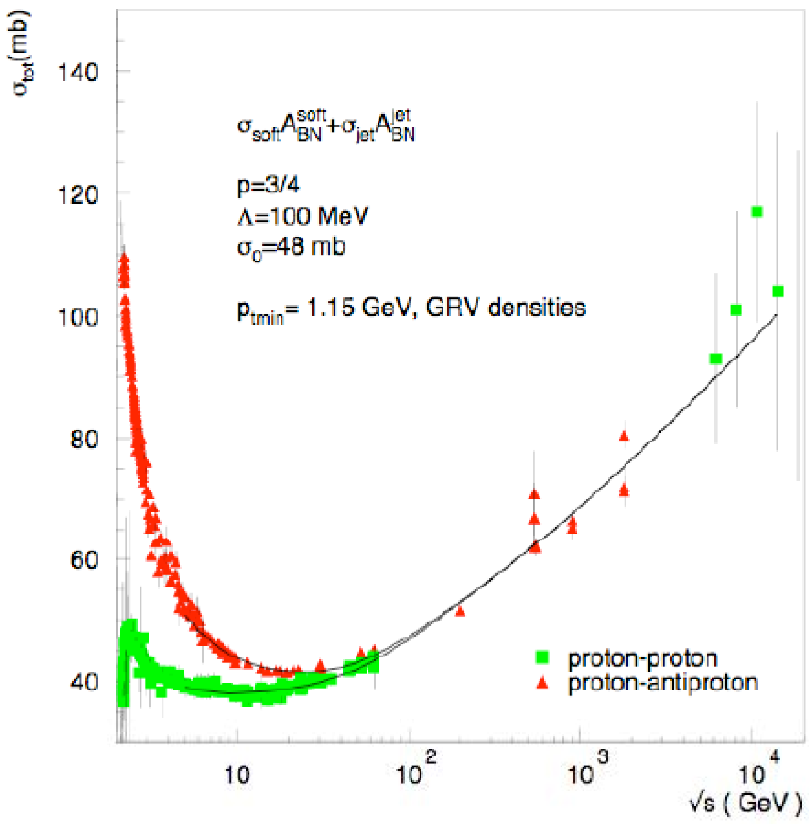


What drives the rise of the total cross sections?

G. Pancheri has the answer:

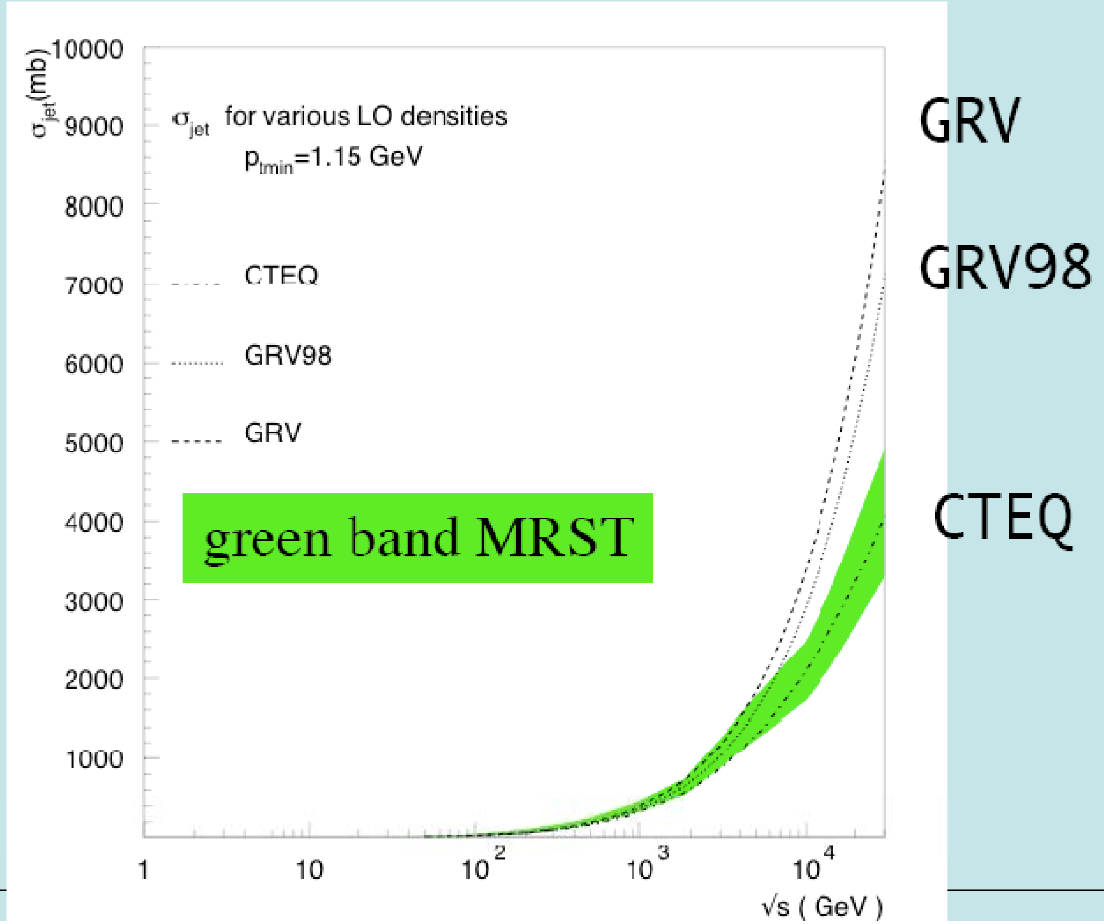
minijet production driven by the rise of PDF at low x

σ_{tot}=102 mb
at LHC



GRV

σ_{jet} for p_{tmin}=1.15 GeV



To get the rise she needs **very small lower cut off** on minijet, or better, produced parton, tranverse momentum

$$p_T^{\min} \cong 1\, GeV$$

But as such low transverse momenta:

- lowest order partonic cross sections **are unreliable and highly ambiguous** (scales!).
- These XS **grow rapidly** at low p_T and thus the rise of the total XS is **very sensitive** to the choice of p_T^{min}
- I do not understand how one can use in minijet models PDF extracted from **genuine hard processes**.

Generalized PDF and similar quantities

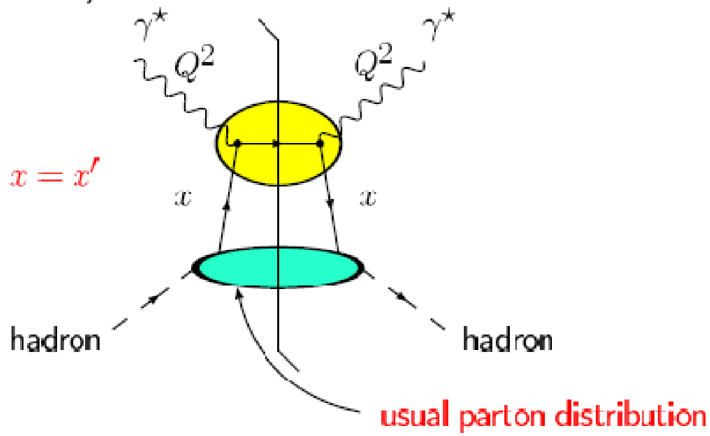
From Wallon's talk:

- DIS: inclusive process $\longrightarrow$ forward amplitude ($t = 0$)

Factorization on the level of partonic cross sections

Structure Function

= Coeffi cient Function (hard) $\otimes$ Parton Distribution Function (soft)

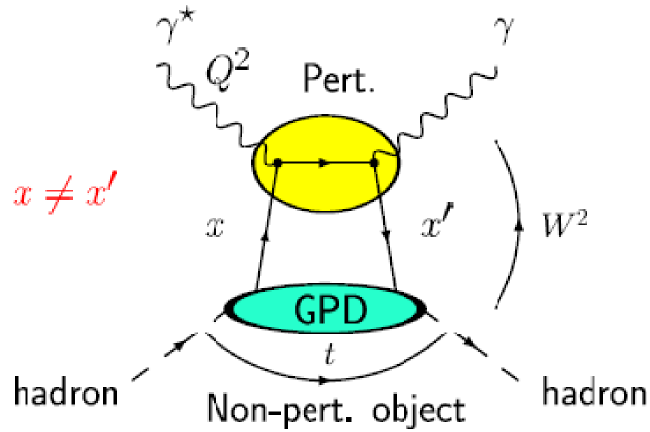


- DVCS: exclusive process $\longrightarrow$ non forward amplitude ($-t \ll s = W^2$)

Factorization on the level of partonic amplitudes

Amplitude

= Coeffi cient Function (hard) $\otimes$ Generalized Parton Distribution (soft)

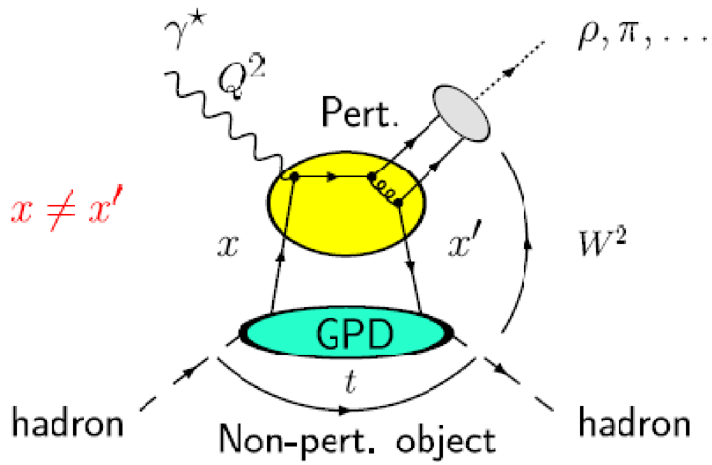


Extensions:

- Meson production: γ replaced by $\rho, \ \pi, \cdots$

Amplitude

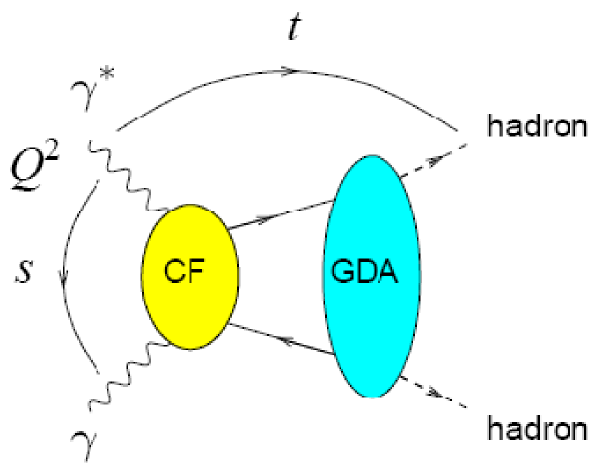
= GPD (soft) $\otimes$ CF (hard) $\otimes$ Distribution Amplitude (soft)



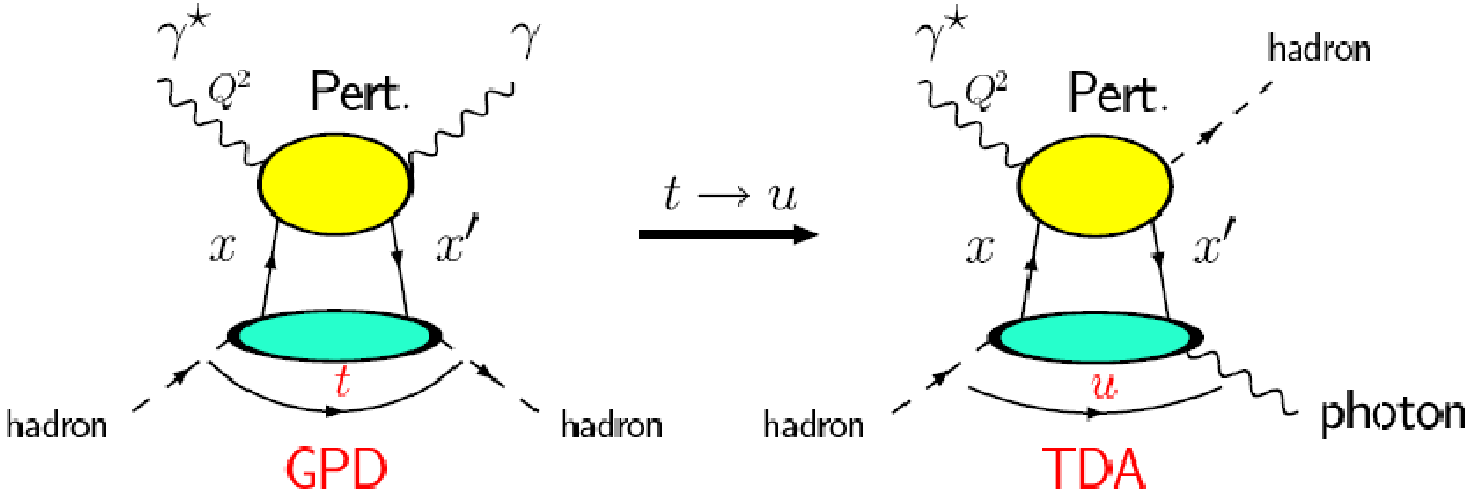
- Crossed process: $s \ll -t$

Amplitude

= Coeffi cient Function (hard) $\otimes$ Generalized Distribution Amplitude (soft)



- starting from usual DVCS, one allows initial hadron $\neq$ final hadron
  example:



which can be further extended by replacing the outoing γ by any hadronic state

Amplitude	=	Transition Distribution Amplitude (soft)	$\otimes$	CF (hard)	$\otimes$	DA (soft)

Great, but **factorization implies ambiguities**, scales and schemes, which at least for inclusive processes, play very important phenomenological role.

I would expect them to play **analogous role in GPD's** and related quantities as well. **Is that true?**

If yes, there must a mechanism to guarantee independence of physical quantities of these ambiguities, similarly as in inclusive processes:

compensation

$$F^p(Q) = A\left(\alpha_s(M)\right)^{\frac{-2P^{(0)}}{\beta_0}} \exp\left[-\frac{\alpha_s(M)}{2\pi}\left(C_q^{(1)}-\kappa\right)\right]\left(1+\frac{\alpha_s(\mu)}{2\pi}C_q^{(1)}(Q/M)\right)$$

Choice of $C^{(1)}$ here

is compensated by change of $C^{(1)}$ here

Mechanism guaranteeing **factorization scale and scheme invariance** of proton structure function

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Hard exclusive electroproduction of a pion in the backward region

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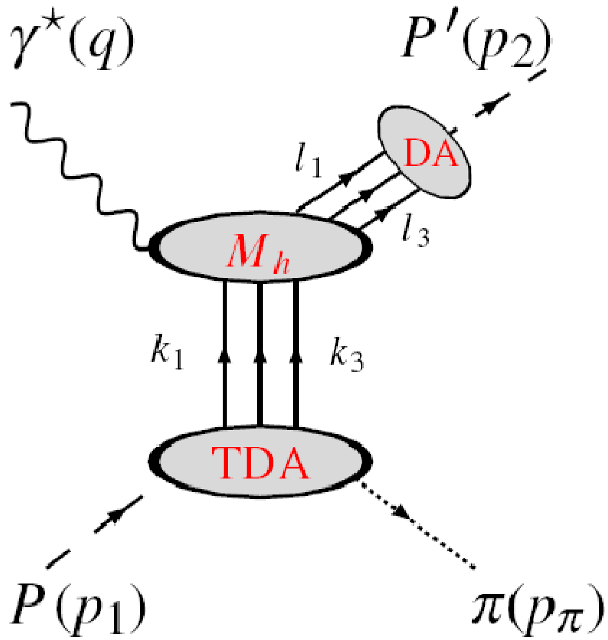


$\alpha_s^2(\mu)$

$$\mathcal{M}^{\lambda}_{s_1 s_2} = -i\frac{(4\pi\alpha_s)^2\sqrt{4\pi\alpha_{\rm em}}f_N^2}{54 f_\pi Q^4}\Bigg[\underbrace{\bar{u}(p_2,s_2)\not\varepsilon(\lambda)\gamma^5 u(p_1,s_1)}_{\mathcal{S}^{\lambda}_{s_1 s_2}}\underbrace{\int_{-1+\xi}^{1+\xi} d^3x \int_0^1 d^3y\Big(2\sum_{\alpha=1}^{7} T_\alpha + \sum_{\alpha=8}^{14} T_\alpha\Big)}_{\mathcal{I}}$$

$$-\underbrace{\varepsilon(\lambda)_\mu \Delta_{T,\nu}\bar{u}(p_2,s_2)(\sigma^{\mu\nu}+g^{\mu\nu})\gamma^5 u(p_1,s_1)}_{\mathcal{S}'^{\lambda}_{s_1 s_2}}\underbrace{\int_{-1+\xi}^{1+\xi} d^3x \int_0^1 d^3y\Big(2\sum_{\alpha=1}^{7} T'_\alpha + \sum_{\alpha=8}^{14} T'_\alpha\Big)}_{\mathcal{I}'}\Bigg],$$

DA:

$$V^p(x_i) = \varphi_{as}[11.35(x_1^2 + x_2^2) + 8.82x_3^2 - 1.68x_3 - 2.94],$$

$$A^p(x_i) = \varphi_{as}[6.72(x_2^2 - x_1^2)],$$

$$T^p(x_i) = \varphi_{as}[13.44(x_1^2 + x_2^2) + 4.62x_3^2 + 0.84x_3 - 3.78],$$

TDA:

$$V^{p\pi^0} = \frac{\varphi_{as}}{8}\left[\frac{11.35}{4}(x_1^2 + x_2^2) + \frac{8.82}{4}x_3^2 - \frac{1.68}{2}x_3 - 2.94\right],$$

$$A^{p\pi^0} = \frac{\varphi_{as}}{8}\left[\frac{6.72}{4}(x_2^2 - x_1^2)\right],$$

$$T^{p\pi^0} = \frac{3\varphi_{as}}{8}\left[\frac{13.44}{4}(x_1^2 + x_2^2) + \frac{4.62}{4}x_3^2 + \frac{0.84}{2}x_3 - 3.78\right]$$

Looks like the LO **purely perturbative** quantity

$$O = A\alpha_s^2(\mu)M_{LO} \overset{?}{+} B(M_f)\alpha_s^3(\mu)M_{NLO}(Q,\mu)$$

contain information on the structure of hadrons

No **unknown** nonperturbative input needed ?

No **factorization scale** introduced ?

How to choose μ ?

Unintegrated PDF

Used by **Szczurek** to describe data on inclusive **direct photon production** in hadronic collisions

standard collinear distributions and UPDFs

$$xp_i(x,\mu^2) = \int_0^{\mu^2} f_i(x,k_t^2,\mu^2)\frac{dk_t^2}{k_t^2}$$

Kwieciński UPDFs

meaning of this scale?

$$f_k(x,k_t^2,\mu^2) = \int_0^{\infty} db\, bJ_0(k_t b)\tilde{f}_k(x,b,\mu^2)$$

$$\tilde{f}_k(x,b,\mu^2) = \int_0^{\infty} dk_t\, k_t J_0(k_t b) f_k(x,k_t^2,\mu^2)$$

Kimber-Martin-Ryskin for $k_t^2 > k_{t,0}^2$

$$f_q(x, k_t^2, \mu^2) = T_q(k_t^2, \mu^2)\frac{\alpha_s(k_t^2)}{2\pi}$$

$$\cdot \int_x^1 dz \left[P_{qq}(z)\frac{x}{z}q(\frac{x}{z}, k_t^2)\Theta(\Delta - z) + P_{qg}(z)\frac{x}{z}g(\frac{x}{z}, k_t^2)\right]$$

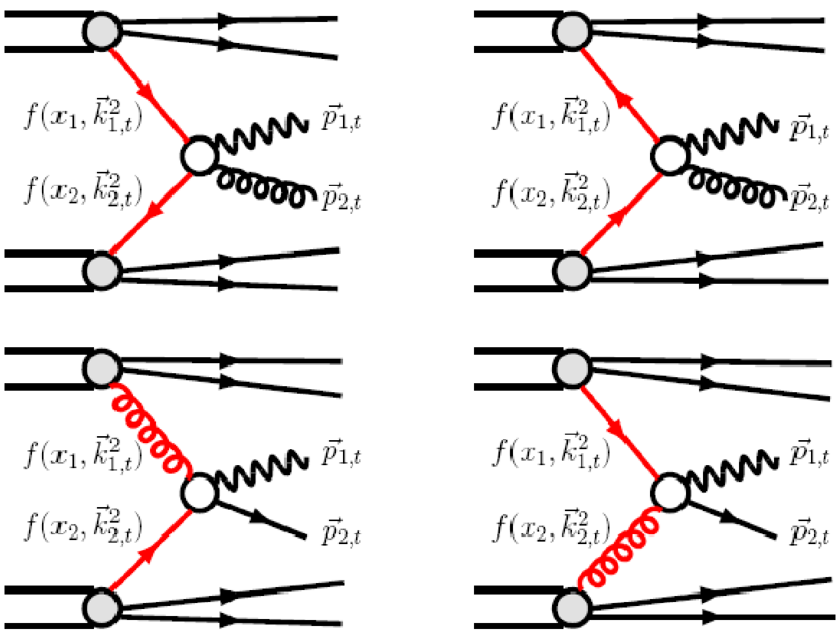
$$f_g(x, k_t^2, \mu^2) = T_g(k_t^2, \mu^2)\frac{\alpha_s(k_t^2)}{2\pi}$$

$$\cdot \int_x^1 dz \left[P_{gg}(z)\frac{x}{z}g(\frac{x}{z}, k_t^2)\Theta(\Delta - z) + \sum_q P_{gq}(z)\frac{x}{z}q(\frac{x}{z}, k_t^2)\right]$$

UPDFs and photon production

$$\frac{d\sigma(h_1h_2 \to \gamma, parton)}{d^2p_{1,t}d^2p_{2,t}} = \int dy_1 dy_2 \frac{d^2k_{1,t}}{\pi}\frac{d^2k_{2,t}}{\pi}\frac{1}{16\pi^2(x_1x_2s)^2}\sum_{i,j,k}\overline{|M(ij \to \gamma k)|^2}$$

$$\cdot\, \delta^2(\vec{k}_{1,t} + \vec{k}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}) f_i(x_1, k_{1,t}^2) f_j(x_2, k_{2,t}^2)$$



but where is μ?

$$(i, j, k) = (q, \bar{q}, g), (\bar{q}, q, g), (g, \bar{q}, q), (q, g, q)$$

standard collinear formula

$$f_i(x_1, k_{1,t}^2) \to x_1 p_i(x_1)\delta(k_{1,t}^2)$$

$$f_j(x_2, k_{2,t}^2) \to x_2 p_j(x_2)\delta(k_{2,t}^2)$$

I miss the mechanism by which the dependence of UPDF's on the scale μ is cancelled. In the standard integrated PDF's this cancellation is provided is by the explicit dependence of hard scattering cross sections on μ.

So the off-shell cross sections **should depend** on it as well, and one would probably need NLO QCD calculation of these cross sections to get the cancellation mechanism.

At the present time the **scale dependence** of calculations involving UPDF's **is therefore large**.

But perhaps, I am wrong....

Standard, integrated PDF and structure of the photon

<u>**Real photon**</u>: alternative organization of finite order QCD approximations to photon structure function

Plea: apply the terms "LO", "NLO" etc to **QCD contributions** only

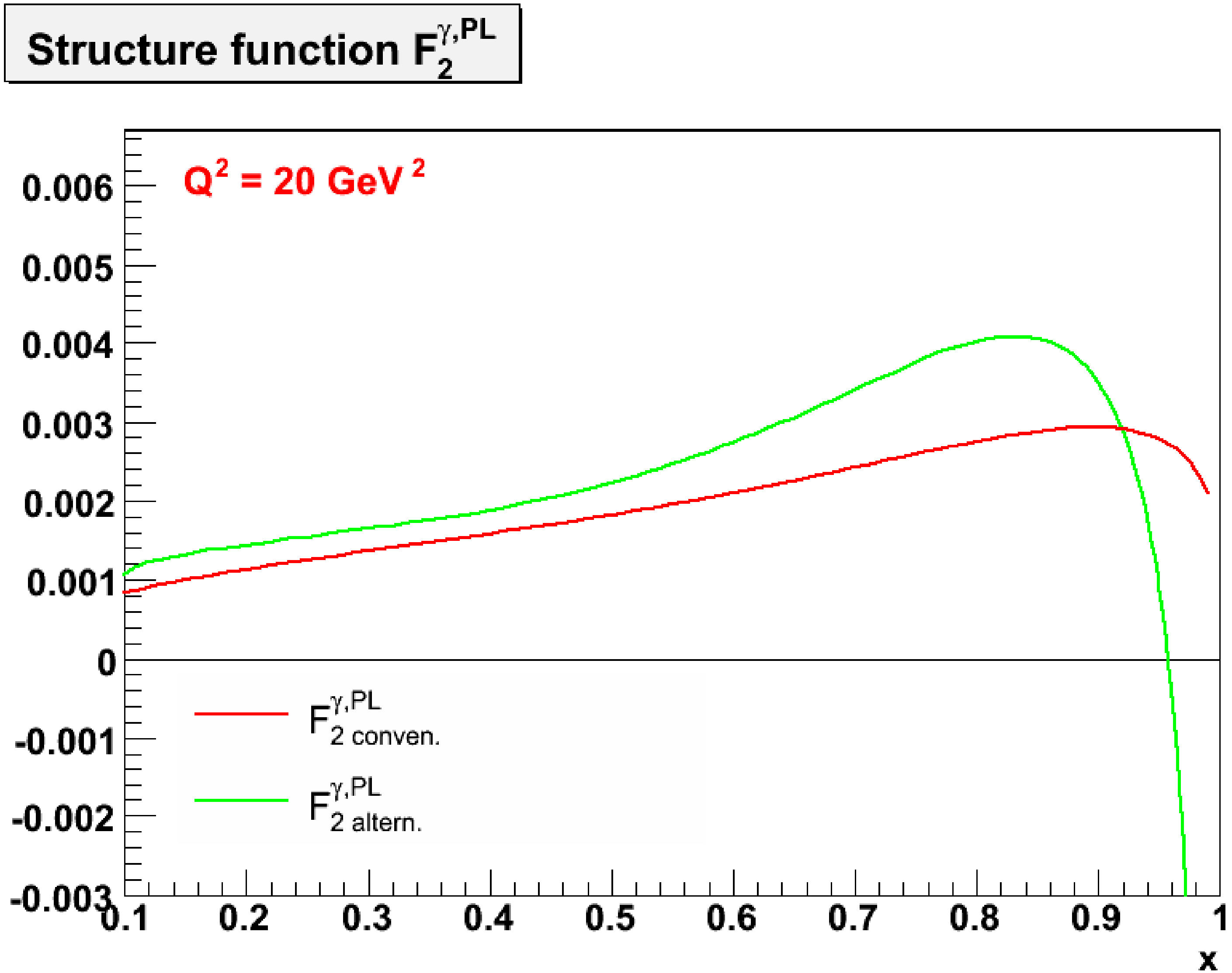
Basic message: parton distribution functions of the photon **do not behave like**

$$D(M) \approx \alpha / \alpha_s(M)$$

Together with the plea above this implies **significantly different** definitions of LO and NLO approximations to

$F_2^{\gamma}(x,Q)$ as well as other photon induced processes.

Numerical differences between standard and alternative approaches and their phenomenological relevance shown by J. Hejbal:



Virtual photon: new NNLO (in the standard definition) calculations of the

Virtual Photon Structure functions to NNLO in QCD

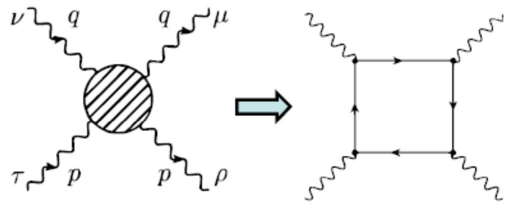
Ken Sasaki (Yokohama National U.)

"Order" defined in terms of **high Q^2 behavior** of the structure function, as understood in the pioneering papers of **Witten, De Witt et al. and Llewelyn-Smith.**

Ken Sasaki F_2^γ in Perturbative QCD

- For real photon target $(P^2 \approx 0)$ $P^2 \ll Q^2$

Simple parton model



$$F_2^\gamma(x,Q^2) = \alpha\left[\frac{1}{\alpha_s(Q^2)}A + B + B' + \mathcal{O}(\alpha_s)\right]$$

(LO) (NLO) Hadronic piece

Point-like contribution dominates $\sim \ln Q^2$

$\sim \ln \frac{Q^2}{\Lambda^2}$

OPE+RGE
lowest order in α

Witten (1977)
Bardeen-Buras (1979)

Walsh-Zerwas (1973)

⇒ NNLO extension Moch-Vermaseren-Vogt (2002, 2006)

- For highly virtual photon target $(\Lambda^2 \ll P^2 \ll Q^2)$

$$F_2^\gamma(x,Q^2,P^2) = \alpha\left[\frac{1}{\alpha_s(Q^2)}\tilde{A} + \tilde{B} + \mathcal{O}(\alpha_s)\right]$$

Λ : QCD scale parameter

(LO) (NLO) Uematsu-Walsh (1981,1982)

Hadronic piece can also be dealt with perturbatively
Definite prediction of F_2^γ , its shape and magnitude, is possible

- We extend the analysis to NNLO ($\alpha\alpha_s$)

- Summarized as

Ken Sasaki

$$\int_0^1 dx\, x^{n-2} F_2^\gamma(x, Q^2, P^2)$$

LO ($\alpha\alpha_s^{-1}$)

for even n

$$= \frac{\alpha}{4\pi}\frac{1}{2\beta_0}\left\{ \frac{4\pi}{\alpha_s(Q^2)} \sum_i \mathcal{L}_i^n \left[1 - \left(\frac{\alpha_s(Q^2)}{\alpha_s(P^2)}\right)^{d_i^n+1}\right]\right.$$

NLO (α)

$$+ \sum_i \mathcal{A}_i^n \left[1 - \left(\frac{\alpha_s(Q^2)}{\alpha_s(P^2)}\right)^{d_i^n}\right] + \sum_i \mathcal{B}_i^n \left[1 - \left(\frac{\alpha_s(Q^2)}{\alpha_s(P^2)}\right)^{d_i^n+1}\right] + \mathcal{C}^n$$

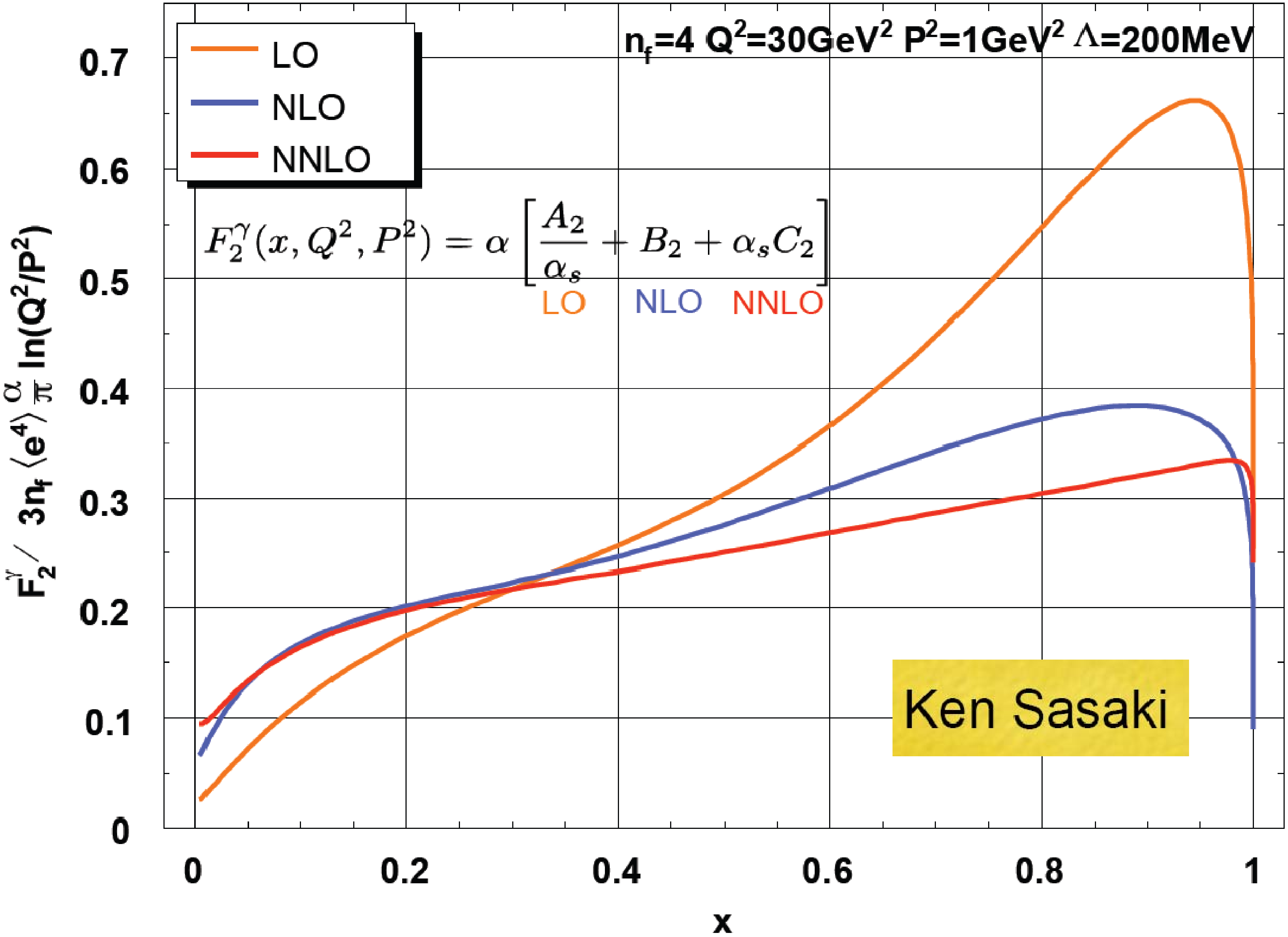
$$+ \frac{\alpha_s(Q^2)}{4\pi}\left(\sum_i \mathcal{D}_i^n \left[1 - \left(\frac{\alpha_s(Q^2)}{\alpha_s(P^2)}\right)^{d_i^n-1}\right] + \sum_i \mathcal{E}_i^n \left[1 - \left(\frac{\alpha_s(Q^2)}{\alpha_s(P^2)}\right)^{d_i^n}\right]\right.$$

$$\left.\left. + \sum_i \mathcal{F}_i^n \left[1 - \left(\frac{\alpha_s(Q^2)}{\alpha_s(P^2)}\right)^{d_i^n+1}\right] + \mathcal{G}^n \right) + \mathcal{O}(\alpha_s^2) \right\}$$

apart from the last term behaves as

NNLO ($\alpha\alpha_s$)

$\alpha\alpha_s^2(Q^2)\ln(Q^2/P^2)$ for $\Lambda_{QCD} \to \infty$


LO
NLO
NNLO
n_f=4 Q^2=30GeV^2 P^2=1GeV^2 Λ=200MeV
$F_2^\gamma(x,Q^2,P^2) = \alpha\left[\frac{A_2}{\alpha_s} + B_2 + \alpha_s C_2\right]$
LO NLO NNLO
Ken Sasaki
$F_2^\gamma / 3n_f \langle e^4\rangle \frac{\alpha}{\pi} \ln(Q^2/P^2)$
x
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
0 0.2 0.4 0.6 0.8 1

Scales, schemes

Boring, frustrating but inevitable perturbation theory ambiguities. We can ignore them, but to our own peril.

Achim Geiser:
How well do we understand choice of QCD scales?

These ambiguities are inevitable consequence of renormalization and factorization procedures **and truncation** of PT to any fixed order.

Contrary to conventional view, they **do not go away** when we go to higher orders, as at each order of PT **new free parameters** defining renormalized/factorized quantities do appear.

There is **no genuine "resolution"** of these ambiguities, just a few **recipes** how to fix the scales and schemes.

Achim Geiser's

remarks on QCD scale dependence

- Ideally (calculation to all orders) QCD predictions should not depend on the choice of **renormalization and factorization scales** μ_r, μ_f
  => **not physical parameters** => can not be determined from data

- In practice, finite order calculations **do** depend on choice of these scales
  = reference points for perturbative expansion (Taylor expansion)

- **Choice of scale is to large extent arbitrary.**
  Best solution is case by case evaluation of sensible scales, and detailed study of behaviour of cross section with respect to variation of these scales.

- In practice often replaced by **simple recipes**. Overinterpretation might lead to premature conclusions that data/QCD predictions do not agree.

- If recipes at all, at least try to use the "best"
  => try to evaluate performance

Common recipes for scale choice

Common sense criterion/try to minimize occurrence of large logs:

- => 1. choose "natural" scale of process involved $(m, Q^2, E_T, \ldots)$
  but subscales (e.g. subdominant gluon radiation) often lower

nowadays often only criterion used

Two other textbook criteria from the late 80ies: **time for a revival?**

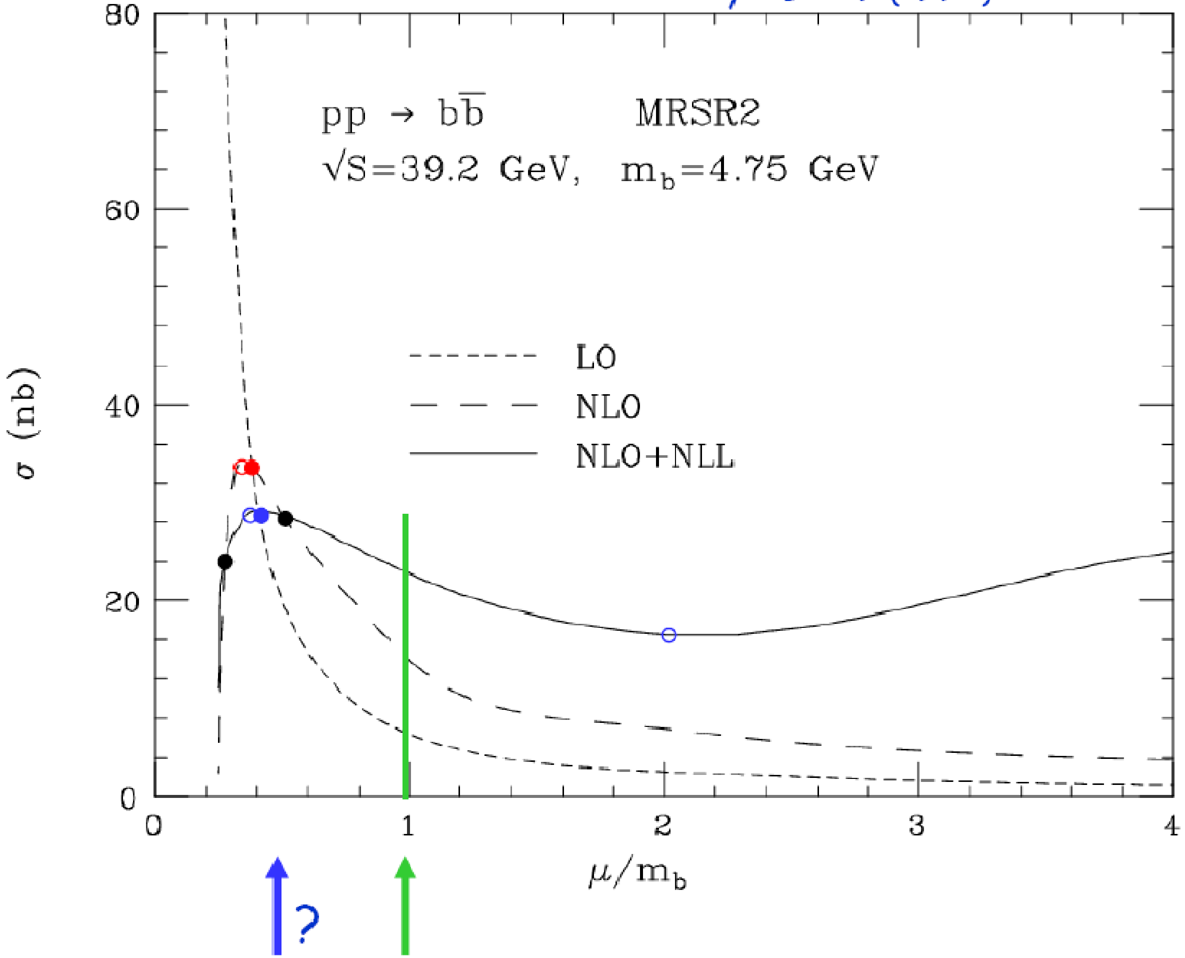
- principle of fastest apparent convergence: choice of scales such that, ideally, cross sections will not change when higher order corrections are included
  => 2. best bet: NLO = LO => hope: NNLO = NLO **check!**
- principle of minimal sensitivity: minimize sensitivity to scale variations
  => 3. best bet: $d\sigma/d\mu = 0$ => hope: minimize NLO corrections

- range of variation of scale is supposed to be a measure of theoretical error for uncalculated higher orders

- evaluate all three criteria to determine a "reasonable" choice

Achim Geiser's example: total b cross section at HERA-B

Bonciani, Catani, Mangano, Nason
Nucl. Phys. B 529 (1998) 424



NLO stability:

- • NLO = LO
- ∘ $d\sigma_{NLO}/d\mu = 0$

NLO+NLL stability:

- • NLO+NLL = LO
- • NLO+NLL = NLO
- ∘ $d\sigma_{NLO+NLL}/d\mu = 0$

"natural" scale

in many cases, such solutions do not exist

=> consider only those cases where they do

I generally agree with Achim's strategy, but want to emphasize two points:

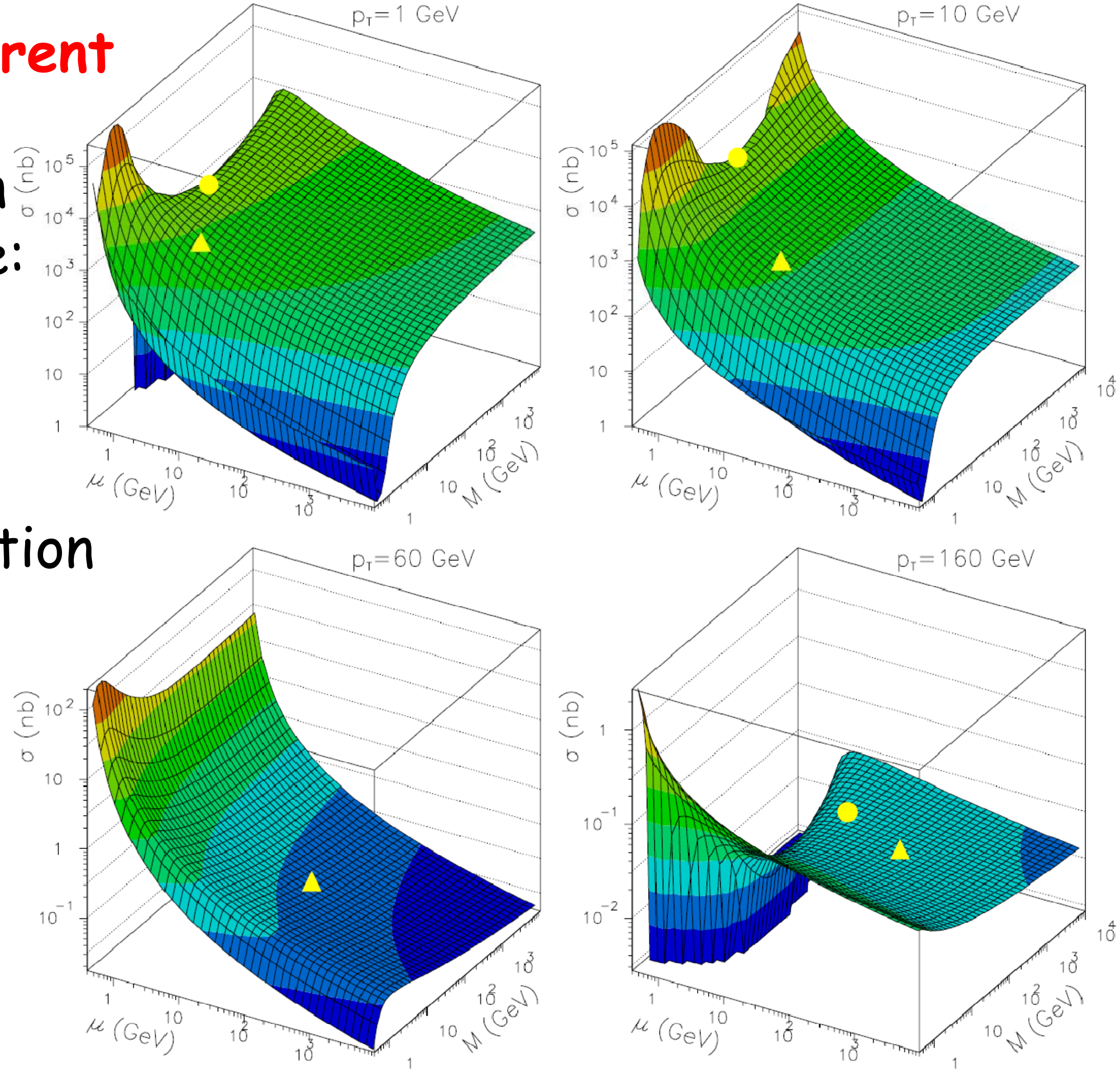
- ❑ **Renormalization schemes** **are equally important** as **renormalization scales**. We can fix one and very the other or the other way round.

  The number **"1/2"** in Achim's suggested new default scale **corresponds to the standard MS_{bar} RS**. In other RS it will be different and **could easily be 1**.

- ❑ The renormalization and factorization scales **should not be identified** (as usually done).

Reply to Samuel Wallon: **BLM** scale setting method **cannot be applied** to quantities involving **factorization scale.**

Example of **different** renormalization and factorization scale dependence:



NLO calculation of bbbar production at the Tevatron

The Renormalization Scale Problem

- No renormalization scale ambiguity in QED
- Running Gell Mann-Low QED Coupling sums all Vacuum Polarization Contributions
- QED Scale Identical to Photon Virtuality
- Examples: Lamb Shift, muonic atoms, g-2
- No renormalization scale ambiguity in EW theory

PHOTON05
9-3-05

BLM Scale Setting

Stan Brodsky, SLAC

Chyla (Photon 2005)

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 $\overline{\text{MS}}$ RS and FS.

Dependence on scales has a clear interpretation, but their choice is insufficient to specify perturbative calculations.

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

has no justification apart from simplicity (Politzer 87).

Chyla (Photon 2005)

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

The conventional procedure which assumes working in $\overline{\mathrm{MS}}$ is thus based on entirely ad hoc choice of RS.

Choice of scales and schemes should be done in more sophisticated way. This means keeping

μ and M_p, M_γ, M_F independent

and investigating the dependence of perturbative results on these free parameters, looking for regions of local stability.

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

Conventional renormalization scale-setting method:

- Guess arbitrary renormalization scale and take arbitrary range. Wrong for QED and Precision Electroweak.
- Prediction depends on choice of renormalization scheme
- Variation of result with respect to renormalization scale only sensitive to nonconformal terms; no information on genuine (conformal) higher order terms
- Conventional procedure has no scientific basis.
- FAC and PMS give unphysical results; have no validity.
- Renormalization scale not arbitrary! Sets # active flavors

Factorization scale

$$\mu_{\text{factorization}} \neq \mu_{\text{renormalization}}$$

- Arbitrary separation of soft and hard physics
- Dependence on factorization scale not associated with beta function - present even in conformal theory
- Keep factorization scale separate from renormalization scale $$\frac{d\mathcal{O}}{d\mu_{\text{factorization}}} = 0$$
- Residual dependence when one works in fixed order in perturbation theory.

Power corrections and low x physics

Low-x gluon density and rescattering effects

F. Hautmann

I. Parton distributions at $x \ll 1$

II. Parton picture, s-channel picture,
and a "dictionary" to connect them

III. Power corrections from rescattering

4. Power corrections from rescattering

$$\frac{dF_2}{d\ln Q^2} = \left(\frac{dF_2}{d\ln Q^2}\right)_{\rm LP} + \sum_{n=1}^{\infty} R_n \,\frac{\lambda^2(n)}{(Q^2)^n}$$

$\diamondsuit$ R_n calculated to order α_s from lightcone wavefunctions

$\diamondsuit$ λ^2 nonperturbative moments of matrix elements Ξ:

$$\lambda^2(-v) = \frac{1}{\Gamma(v)} \int \frac{d\boldsymbol{z}}{\pi \boldsymbol{z}^2} \,(\boldsymbol{z}^2)^{v-1} \int d\boldsymbol{b}\; \Xi(\boldsymbol{z},\boldsymbol{b})$$

But: **separation of perturbative part and power corrections is ambiguous** and the numerical relevance of the latter thus depends on the choice of free parameters (scales, schemes) of perturbative calculations.

Example: **Klaus Hammacher** at **ICHEP 2002** in Amsterdam

Data and Corrections

Talk is based on: DELPHI Coll., R. Reinhardt et al.,
A study of the energy evolution of event shape distributions and their means with the DELPHI detector at LEP

- Data
  - DELPHI data from LEP1 and LEP2 (E_{CM} =89 to 202 GeV)
  - DELPHI radiative Z events at E_{CM} =45, 66 and 76 GeV
  - low energy data from various experiments (PETRA, PEP, TRISTAN)

- Observables
  - mean values of Thrust, C-Param., Major, jet–broadenings; ($\int$EEC, $\int$JCEF)
  - means of jet–masses ($M^2_{h/s}/E^2_{vis}$) in alternative definitions ("E-scheme")

Theoretical Predictions - Power Corrections

$\mathcal{O}(\alpha_s^2)$ perturbative expansion for shape means reads:

$$\langle f_{pert}\rangle = A \cdot \frac{\alpha_s(\mu)}{2\pi} + \left(A \cdot 2\pi b \ln \frac{\mu^2}{E_{cm}^2} + B\right)\left(\frac{\alpha_s(\mu)}{2\pi}\right)^2$$

A,B perturbative parameters given in $\overline{MS}$-scheme.
Non-perturbative hadronisation $\longrightarrow$ mean values modified by a term $\propto 1/E_{\rm cm}$:

$$\langle f\rangle = \langle f_{\rm pert}\rangle + c_f \mathcal{P}$$

Dokshitzer and Webber et al.

$$\mathcal{P} = \frac{4C_F}{\pi^2}\mathcal{M}\frac{\mu_I}{E_{\rm cm}}\left[\alpha_0(\mu_I) - \alpha_s(\mu) - \left(b \cdot \log\frac{\mu^2}{\mu_I^2} + \frac{K}{2\pi} + 2b\right)\alpha_s^2(\mu)\right]$$

$\alpha_0(\mu_I)$ is a universal non-perturbative parameter $(\alpha_0 = \langle\alpha_s(k)\rangle|_{k<\mu_I})$.
c_f f dependent perturbative parameter known for resummable f's.
Assess all observables $\langle f\rangle$ using simple power corrections:

$$\langle f\rangle = \langle f_{\rm pert}\rangle + \frac{C_1^{(f)}}{E_{\rm cm}}$$

Renormalisation Group Invariant (RGI) Perturbation Theory

Basic idea: use observable $R = \langle f \rangle / A$ as expansion parameter; require R to fulfil RGE:

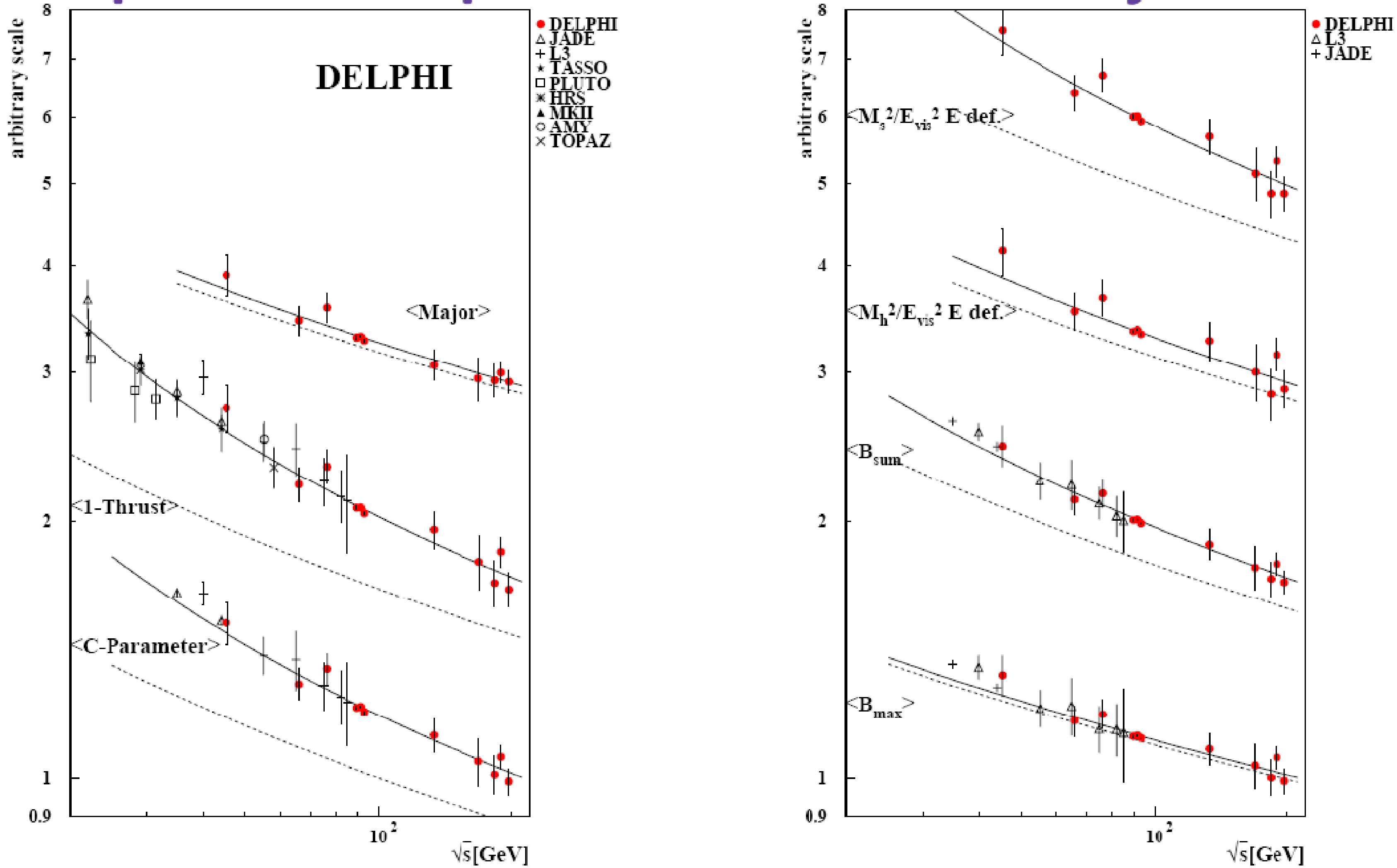
$$Q\frac{dR}{dQ} = -\frac{\beta_0}{2}R^2(1 + \rho_1 R + \rho_2 R^2 + \ldots) = \frac{\beta_0}{2}\rho(R) \quad .$$

β_0, $\rho_1 = \beta_1/2\beta_0$ are universal, ρ_i scheme invariant ($\longrightarrow$ name of the method).

$$\frac{\beta_0}{2}\ln\frac{Q}{\Lambda_R} = \frac{1}{R} - \rho_1 \ln\left(1 + \frac{1}{\rho_1 R}\right) + \underbrace{\int_0^R dx \left(\frac{1}{\rho(x)} + \frac{1}{x^2(1+\rho_1 x)}\right)}_{\text{vanishes in second order}}$$

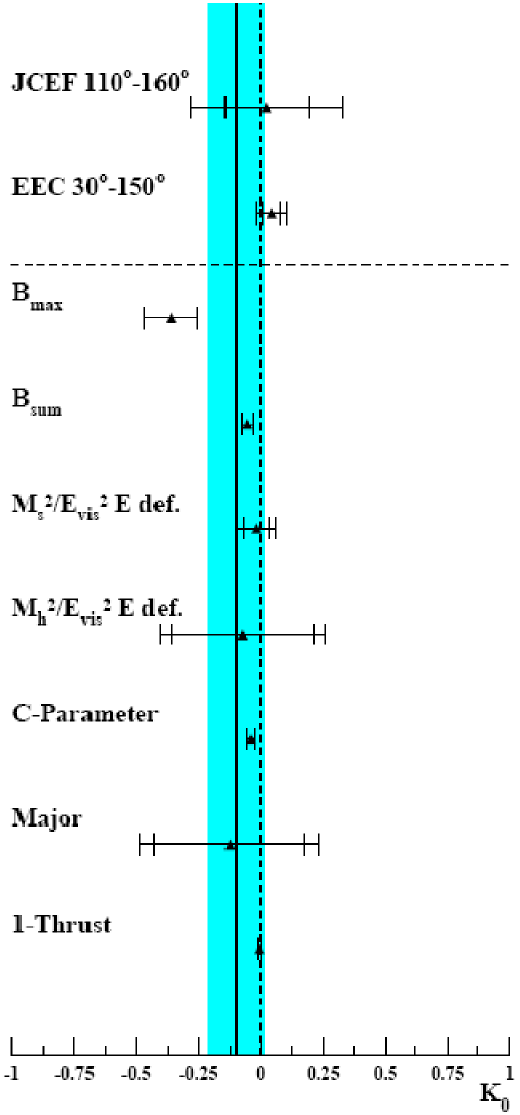
Simple RGI applies to observables depending on a single energy scale.
RGI resums UV log. terms. Numerically RGI=ECH.

Description of Shape Observable Means by RGI



RGI (full line) – $\overline{MS}$ with same $\alpha_s(M_Z)$ (dotted) $= \overline{MS}$ power correction.

No Significant Power Corrections Needed with RGI



Fitting RGI with power–corrections to a large set of observables:

$\longrightarrow$ Observe power terms $K_0 \sim 0$!

This should be viewed as a virtue of both: RGI and inclusiveness of mean values.

$\longrightarrow$ Power terms in $\overline{MS}$-analysis are due to missing higher order corrections.

Presence of genuine power suppressed terms for means unclear so far!

Possible contribution:
only $\sim 3\%$ (relative) at Z energies.

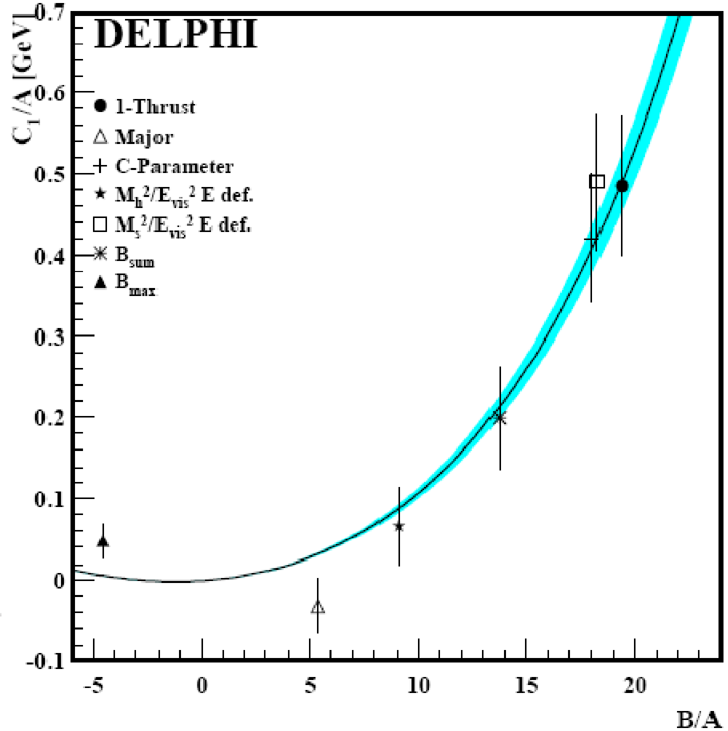
"Predict" $\overline{MS}$ Power Terms using RGI

Set RGI = Power Model; solve for α_0 or C_1.

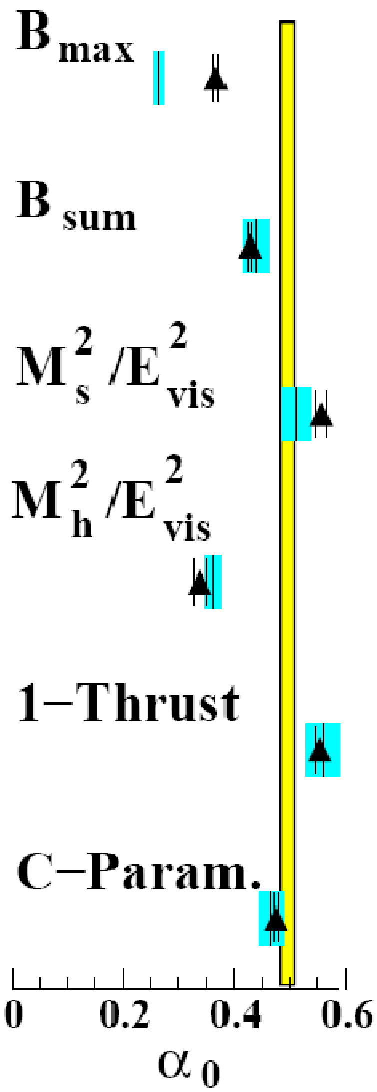
$$\langle R \rangle_{RGI} \cdot A = \langle f \rangle_{pert} + \langle f \rangle_{pow}$$

Plot: size of power corr. $\leftrightarrow$ size of 2^{nd} order term

$\Lambda_{\overline{MS}} = 220 MeV$



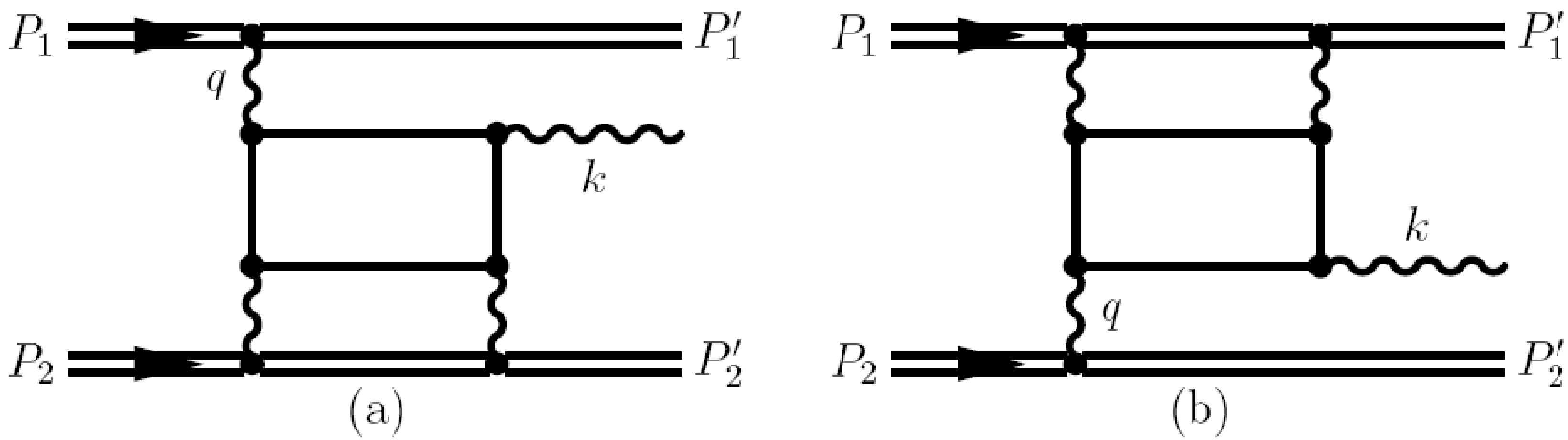
α_0 agrees better than any presumed universal value $\sim 0.5.\longrightarrow$



QED processes are not boring

V. Serbo: Large contribution of the Delbruck scattering into process of a photon emission in collisions of relatistic nuclei.

In the present report we consider not the Compton subprocess, but another one – **the Delbrück scattering subprocess** — which can given an essential contribution to emission of photons at the nuclear collisions without excitation of the final nuclei (see Fig. 2).



At first sight, this is a process of **a very small cross section** since

$$\sigma \propto \alpha^7 .$$

But at second sight, we should **add a very large factor**

$$Z^6 \sim 10^{11}$$

and take into account that the cross section **scale** is

$$1/m_e^2 \, .$$

And the last, but not the least, we will show that this cross section has **an additional logarithmic enhancement** of the order of

$$L^2 \gtrsim 100 \, , \quad L = \ln\left(\gamma^2\right) .$$

As a result, the discussed cross section for the LHC collider is

$$\boxed{\sigma \sim \frac{(Z\alpha)^6 \, \alpha}{m_e^2} L^2 \sim \mathbf{50 \ \ barn} \, .}$$

Da Silva: Four fermion two pair production from gamma-gamma collisions: from PLC to LHC

1. Introduction
   - Four fermions two pairs production
   - Computation and analytic results
2. Monte-Carlo Generator
   - Cross section computation
   - LHC
3. Deal with Mixed QED and QCD
   - $\gamma g \to q\bar{q}Q\bar{Q}$ case
   - $gg \to q\bar{q}Q\bar{Q}$ case

Motivation
- Need for a reference process for luminosity measurement at a PLC
- QED and QCD back-ground source to rare processes
- Only a realistic Monte-Carlo can give a correct result

But these processes are of great interest for heavy quark production in $\gamma\gamma$ collisions!

Au revoir in 2009 at DESY