HERA and the LHC 2007 —
Summary of MC&Tools (WG5)

Stefan Gieseke

CERN/Universität Karlsruhe

with Paolo Bartalini (CERN/U Florida), Thomas Kluge (DESY), Frank Krauss (IPPP Durham)

Talks in WG5

23 talks under roughly 5 headings. 8 in joint session with WG2.

- **k_T–factorization approach**
  3 talks
  (1 with WG 2)
- **New ideas for parton showers**
  5 talks
  (1 with WG 2)
- **Confrontation with data**
  6 talks
- **Multiple interactions**
  5 talks
  (all with WG 2)
- **More final state studies**
  4 talks
  (1 with WG 2)

k_T–factorization approach

- Magnus Hansson:
  Unintegrated PDFs

- Hannes Jung:
  Status of Cascade

- Francesco Hautmann:
  k_T*–dependent parton distributions*

Why $k_\perp$-factorization?

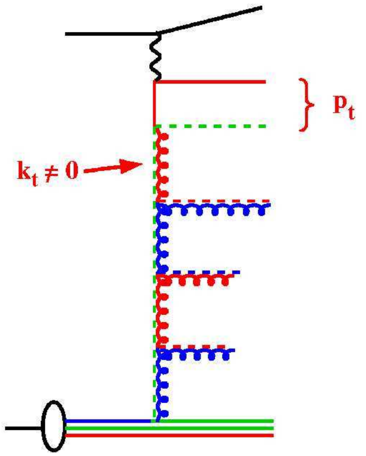
More correct treatment of kinematics

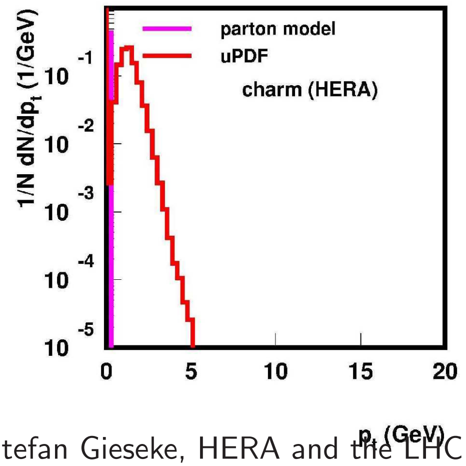
J.Collins, H.Jung hep-ph/0508280

⇒ More physical distributions already in LO

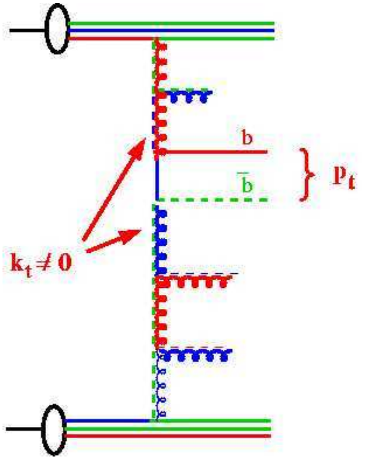
⇒ Smaller NLO corrections

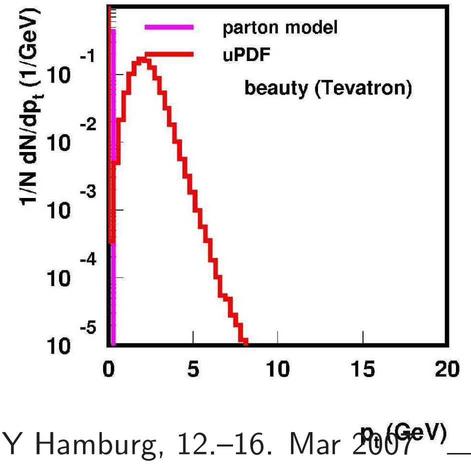
Heavy Quarks at HERA



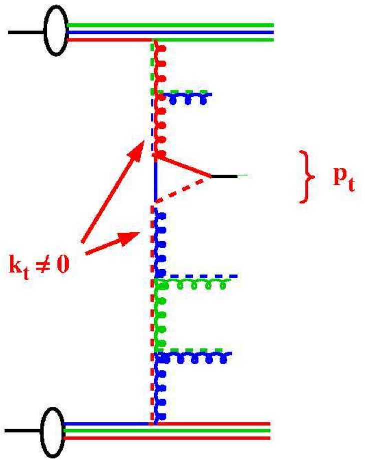


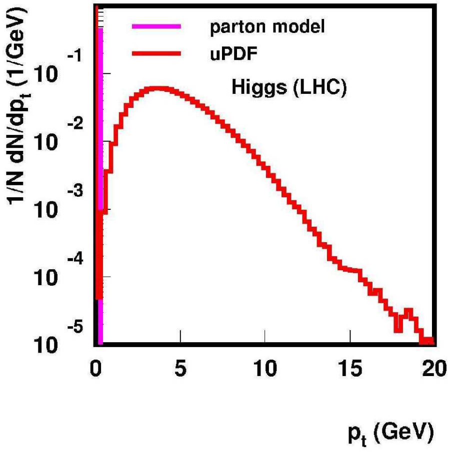
Heavy Quarks at *pp*



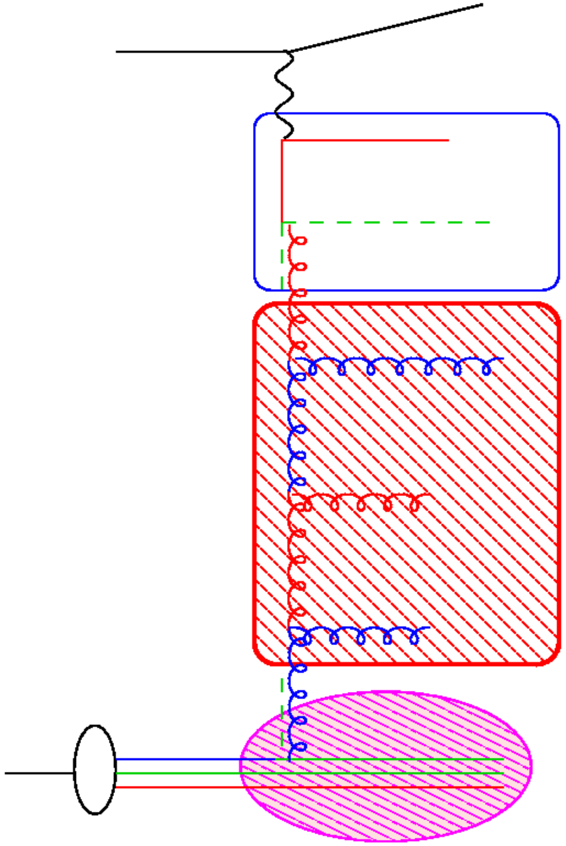


Higgs at *pp*





CASCADE - C_{atani}C_{iafaloni}F_{iorani}M_{archesini} evolution

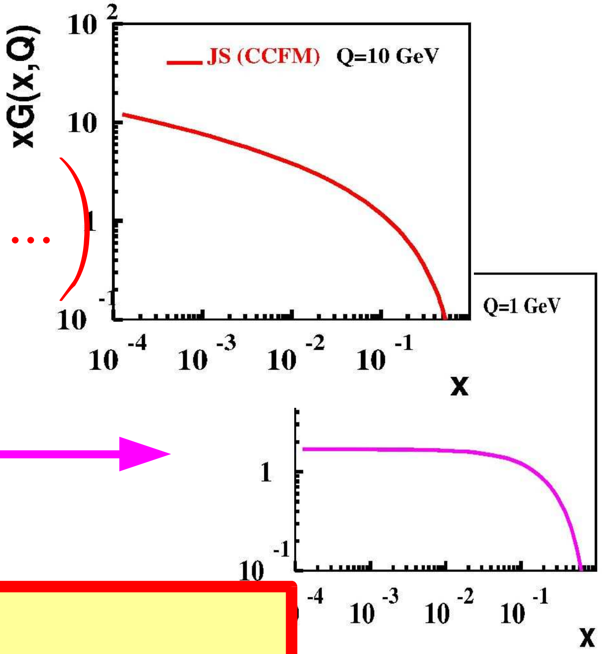


BGF matrix element
off shell

CCFM (all loops)
- angular ordering
- non - Sudakov Δ_{ns}

evolution of parton
cascade:

$$\tilde{P} = \bar{\alpha}_s \left(\frac{1}{1-z} + \frac{1}{z}\Delta_{ns} + \dots \right)$$



initial distribution
~ flat

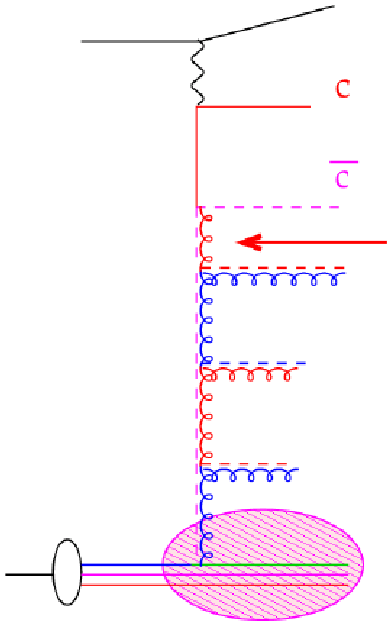
$$\sigma(ep \to e'q\bar{q}) = \int \frac{dy}{y} d^2Q \frac{dx_g}{x_g} \int d^2k_t \hat{\sigma}(\hat{s}, k_t, Q) x_g \mathcal{A}(x_g, k_t, \bar{q})$$

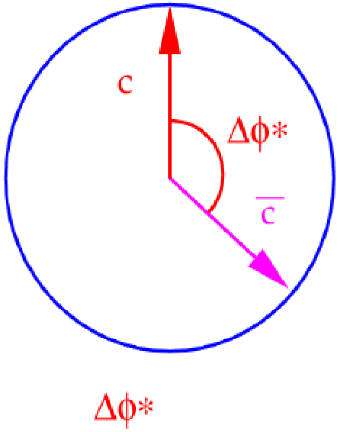
$$\int d^2k_t x_g \mathcal{A}(x_g, k_t, \bar{q}) \simeq x_g G(x_g, Q^2)$$

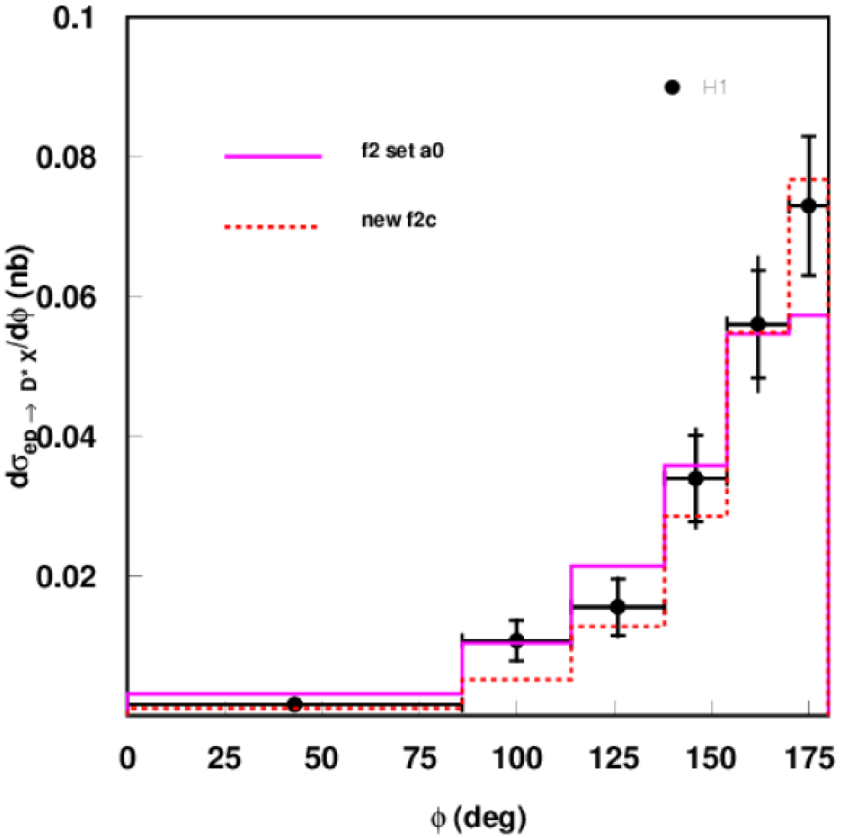
Application to D* + jets

- Photoproduction at HERA:

$\gamma p \to c\bar{c}X \to D^* + jet + X$







- uPDF obtained from same evolution as used in CASCADE simulation
- consistent treatment ... no matching problem as in collinear case !!!

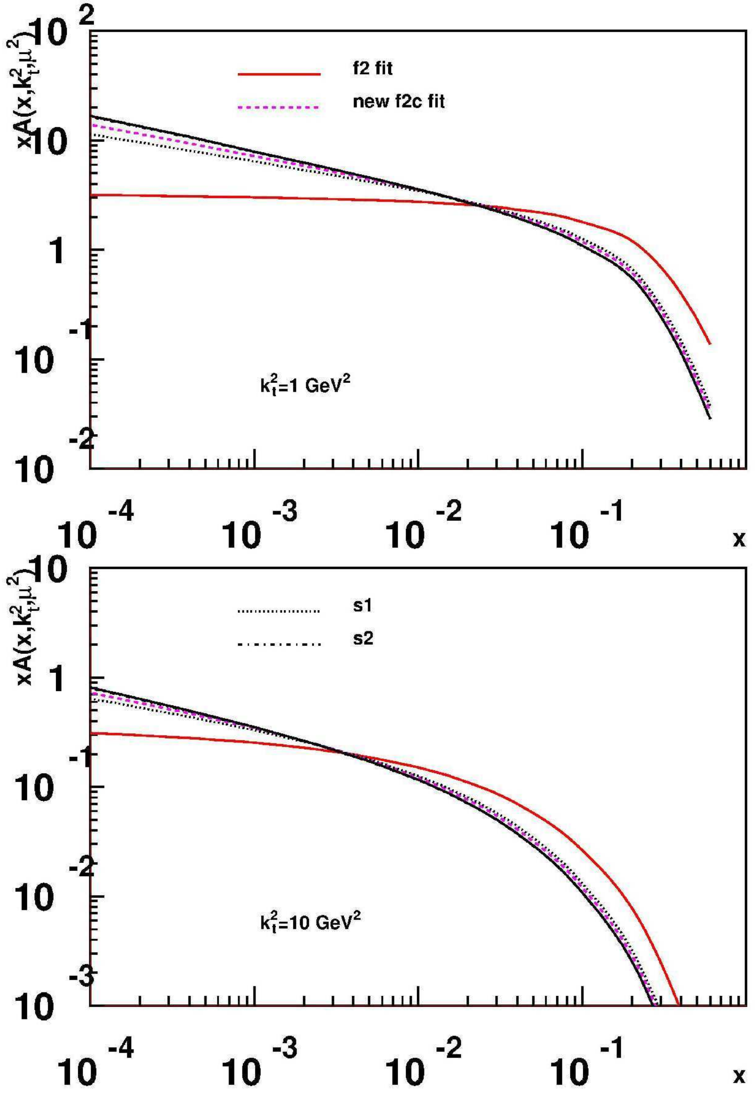
Future of CASCADE

- Extension of CASCADE towards a **multipurpose event generator** applying kt-factorization
- Inclusion of new processes ... matrix element calculations needed ...
- Extension of "CASCADE" collaboration:
  M. Deak, K. Kutak,
  J. Bartels, S. Baranov,
  A. Kotikov, A. Lipatov, N. Zotov

- Inclusion of new processes ...
  - $pp \to b\bar{b} + X$
  - $pp \to J/\psi + X$
  - $pp \to W^{\pm} + X$
  - $pp \to W^{\pm} + jets + X$
  - $pp \to Z^0 + X$
  - $pp \to Z^0 + jets + X$
  - $pp \to l^+ + l^- + X$ (Drell Yan)
  - $pp \to \gamma + jets + X$ (prompt photon)
  - $pp \to \gamma + \gamma + X$
  - $pp \to H^0 + X$
  - $pp \to H^0 + jets + X$

Previous Fits: F_2 and F_2^c

- H. Jung *et al.* hep-ph/0611093
- Fits to F_2 and F_2^c suggest different uPDFs
- Fit to $F_2 \Rightarrow$ flat uPDF for small x
- Fit to $F_2^c \Rightarrow$ steep rise of uPDF for small x



Fit Procedure I

Use Fit Program by H. Jung:

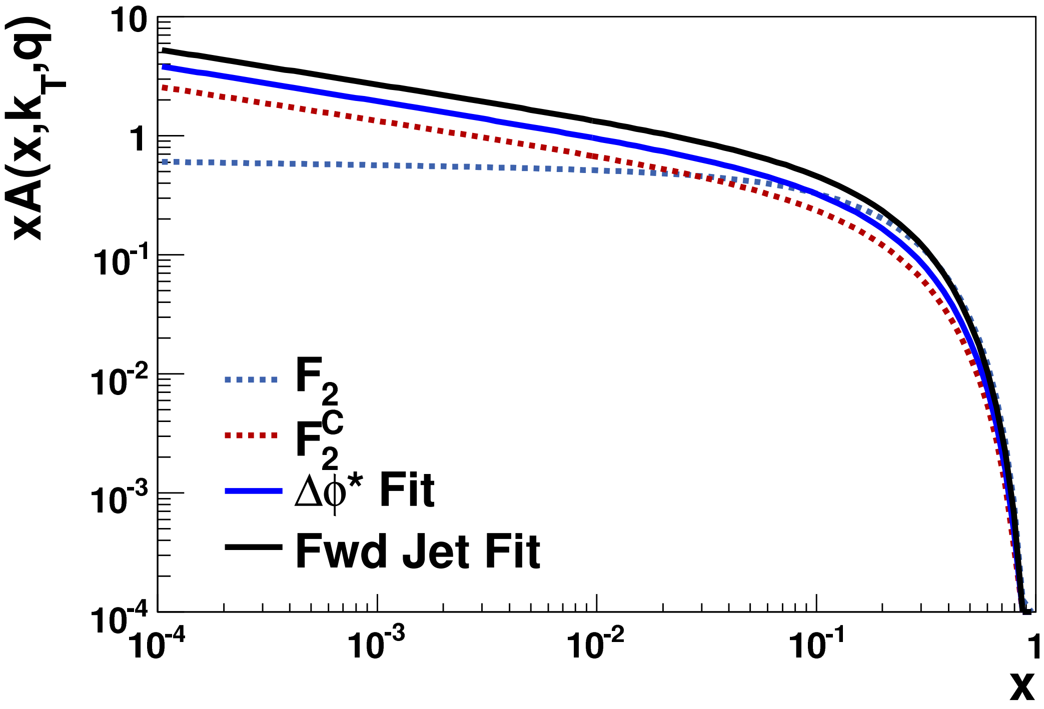
- Only use gluon densities
- Select starting distribution $x\mathcal{A}_0(x, k_\perp, \bar{q}_0)$
- Simulate events using Cascade MC generator, uPDF is evolved using CCFM according to

$$x\mathcal{A}(x, k_\perp, \bar{q}) = \int dx' \mathcal{A}_0(x', k_\perp, \bar{q}_0) \cdot \frac{x}{x'} \tilde{\mathcal{A}}(\frac{x}{x'}, k_\perp, \bar{q})$$

- Minimize χ^2 by varying parameters in starting distribution $x\mathcal{A}_0(x, k_\perp, \bar{q}_0)$ using HZTOOL and MINUIT

Fit to Forward Jet Data (H1)

	N	B
F_2	0.4695	0.0278
F_2^c	0.1860	0.2860
$\Delta\phi^*$ Fit	0.2502	0.2976
Fwd Jet Fit	0.3551	0.2940



Summary & Conclusions

- Unintegrated gluon density fitted to jet data using CASCADE, HZTOOL and MINUIT

- Fit to H1 preliminary jet data ($\Delta\phi^*$)
  $\Rightarrow$ Good description at low x
  $\Rightarrow$ Improvement compared to F_2 and F_2^c

- Fit to H1 forward jet data
  $\Rightarrow$ Improvement compared to F_2 and F_2^c
  $\Rightarrow$ ...but no good χ^2

- Fits to dijet and forward jet data suggest similar gluon as obtained from F_2^c

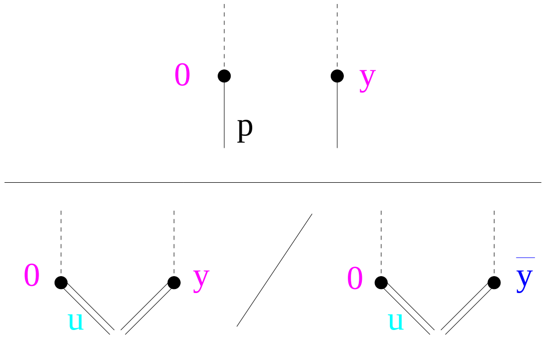
III. Updf's with subtractive regularization

Subtractive method: more systematic. Widely used in NLO calculations.

Formulation suitable for operator matrix elements: Collins & H, 2001.

- gauge link still evaluated at n lightlike, but multiplied by "subtraction factors"

$$\widetilde{f}^{(\mathrm{subtr})}(y^-, y_\perp) = \frac{\overbrace{\langle P|\overline{\psi}(y)V_y^\dagger(n)\gamma^+V_0(n)\psi(0)|P\rangle}^{\text{original matrix element}}}{\underbrace{\langle 0|V_y(u)V_y^\dagger(n)V_0(n)V_0^\dagger(u)|0\rangle \;/\; \langle 0|V_{\bar{y}}(u)V_{\bar{y}}{}^\dagger(n)V_0(n)V_0^\dagger(u)|0\rangle}_{\text{counterterms}}}$$



$\bar{y} = (0, y^-, 0_\perp)$; u = auxiliary non-lightlike eikonal

◇ u serves to regularize the endpoint; drops out of distribution integrated over $k_\perp$

H, hep-ph/0702196

$$P(x,k_\perp,q_\perp) = \frac{\alpha_s}{2\pi} \left(\frac{q_\perp^2}{q_\perp^2 + x(1-x)k_\perp^2} \right)^2 \left[\frac{x^2 + (1-x)^2}{2} + 2\ x^2\ (1-x)^2\ \frac{k_\perp^2}{q_\perp^2} \right]$$

- ▷ positive-definite splitting function
- ▷ including full transverse-momentum dependence
- ▷ universality (short-distance, process-independent)

Ciafaloni & al., 2006

Catani & H, 1994

⟶ to be implemented in MC with u-pdfs?

New ideas for parton showers

- Emil Avsar:
  Dipole Model with energy conservation and swing

- Phil Stephens:
  Matching Constrained Monte Carlo at NLO

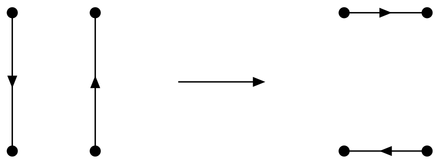
- Stanislaw Jadach:
  General constrained Monte Carlo algorithm for single hadron

- André van Hameren:
  Propagation of uncertainty in a parton shower

- Korinna Zapp:
  A MC model for jet quenching

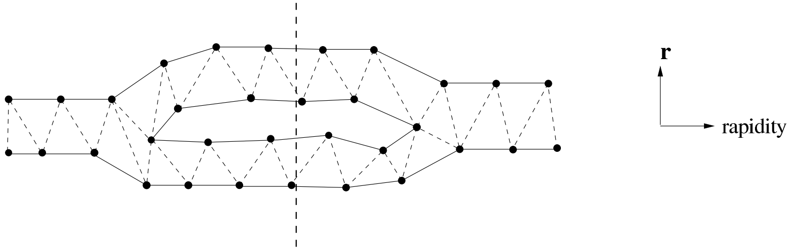
Saturation and Frame Independence

- Mueller’s cascade include saturation effects only from multiple collisions. No loops in cascade evolution.
- $\Rightarrow$ formalism not frame independent.
- Need colour suppressed effects also during evolution.
- Dipole swing: $2 \rightarrow 2$ transition.

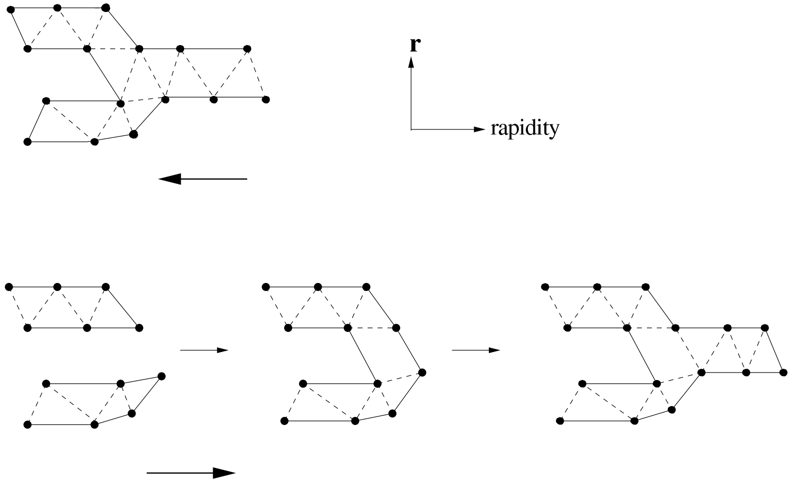


- Gives almost frame independent formalism. hep-ph/0610157, JHEP 01(2007)012.

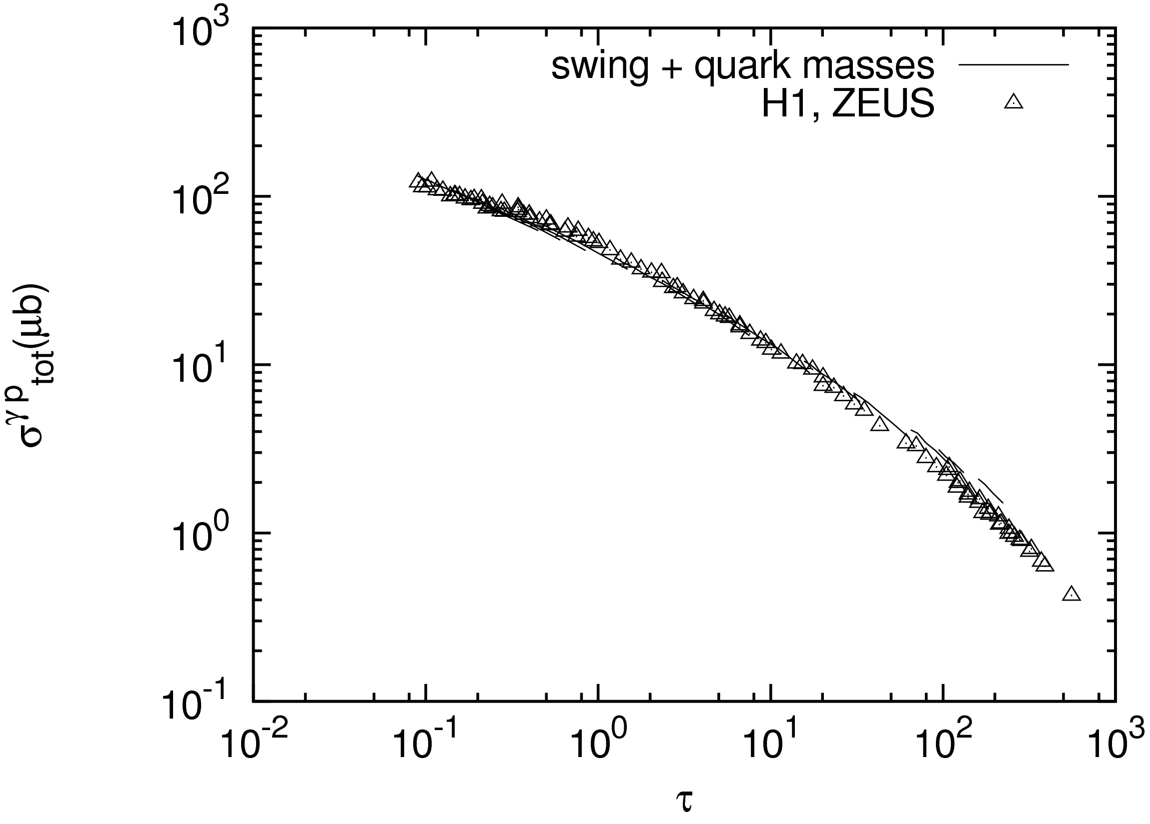
Generating the Loops



- Loops can be generated by $1 \rightarrow 2$ splitting $+2 \rightarrow 2$ “swing”.



Full Results



- $\tau \equiv Q^2/Q_s^2(x)$, $Q_s^2(x) = (x_0/x)^{0.3}$, $x_0 = 3 \cdot 10^{-4}$. Effective light quark mass $=$ 60MeV and m_c $=$1.4GeV.

CAMTOPH-Krakow project 2004-08

- **People involved:**
  K. Golec-Biernat*, A. van Hameren, S. Jadach*, M. Jeżabek, G. Nanava, W. Płaczek*, E. Richter-Wąs, M. Skrzypek*, P. Sawicki, P. Stephens, Z. Wąs*
- **Papers* on QCD MC evolution and new parton shower MCs:**
  hep-ph/0312355, NP Proc. 135:138(04), hep-ph/0504205, hep-ph/0509178, hep-ph/0504263, hep-ph/0603031, NP Proc. 157:241(06), hep-ph/0701174 and more in preparation.
- **The aim is dedicated MC (parton shower) for W/Z production at LHC, with NLO QCD and 1-st order EW/QED corrections from SANC group (Dubna)**
- **Other LHC related MC projects at IFJ-PAN:**
  TAUOLA, PHOTOS, WINHAC.

Three types of kernels

Bremsstrahlung kernels of (A), (B) and (C) type:

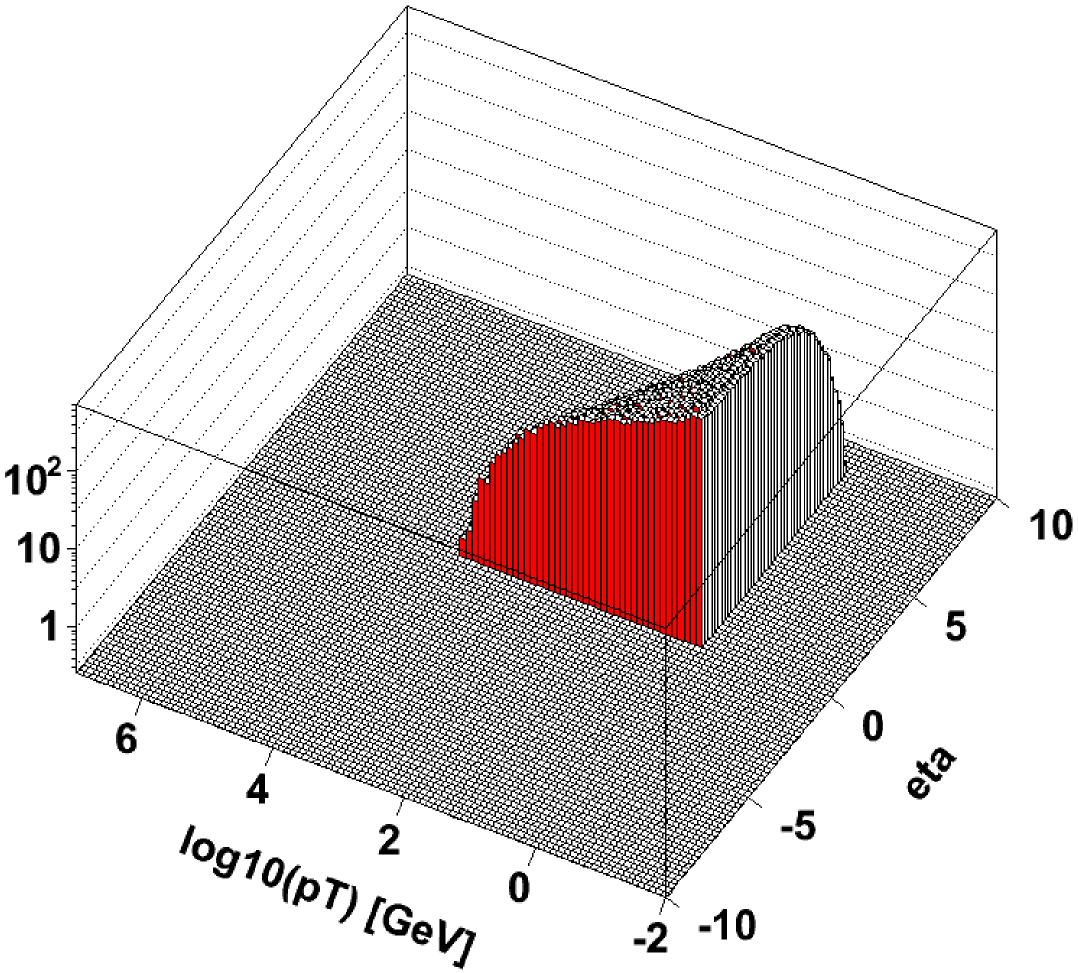
$$\mathcal{K}^{(A)\theta}_{ff}(t,x,u) = \frac{\alpha_S(e^t)}{\pi}\frac{1}{u}P_{ff}(x/u)\;\theta_{u-x\geq u\epsilon},$$
$$\mathcal{K}^{(B)\theta}_{ff}(t,x,u) = \frac{\alpha_S((1-x/u)e^t)}{\pi}\frac{1}{u}P_{ff}(x/u)\;\theta_{u-x\geq u\lambda e^{-t}},$$
$$\mathcal{K}^{(C)\theta}_{ff}(t,x,u) = \frac{\alpha_S((u-x)e^t)}{\pi}\frac{1}{u}P_{ff}(x/u)\theta_{u-x\geq \lambda e^{-t}}.$$

Inclusion of quark-gluon transitions, $X = A, B, C$:

$$x\mathcal{K}^{\theta(X)}_{f'f}(t,x,u) = \delta_{f'f}\; x\mathcal{K}^{\theta(X)}_{f'f}(t,x,u) + (1-\delta_{f'f})\frac{\alpha_S(e^t)}{\pi}F_{f'f}(z)\theta_{1-z>\epsilon}\;,$$

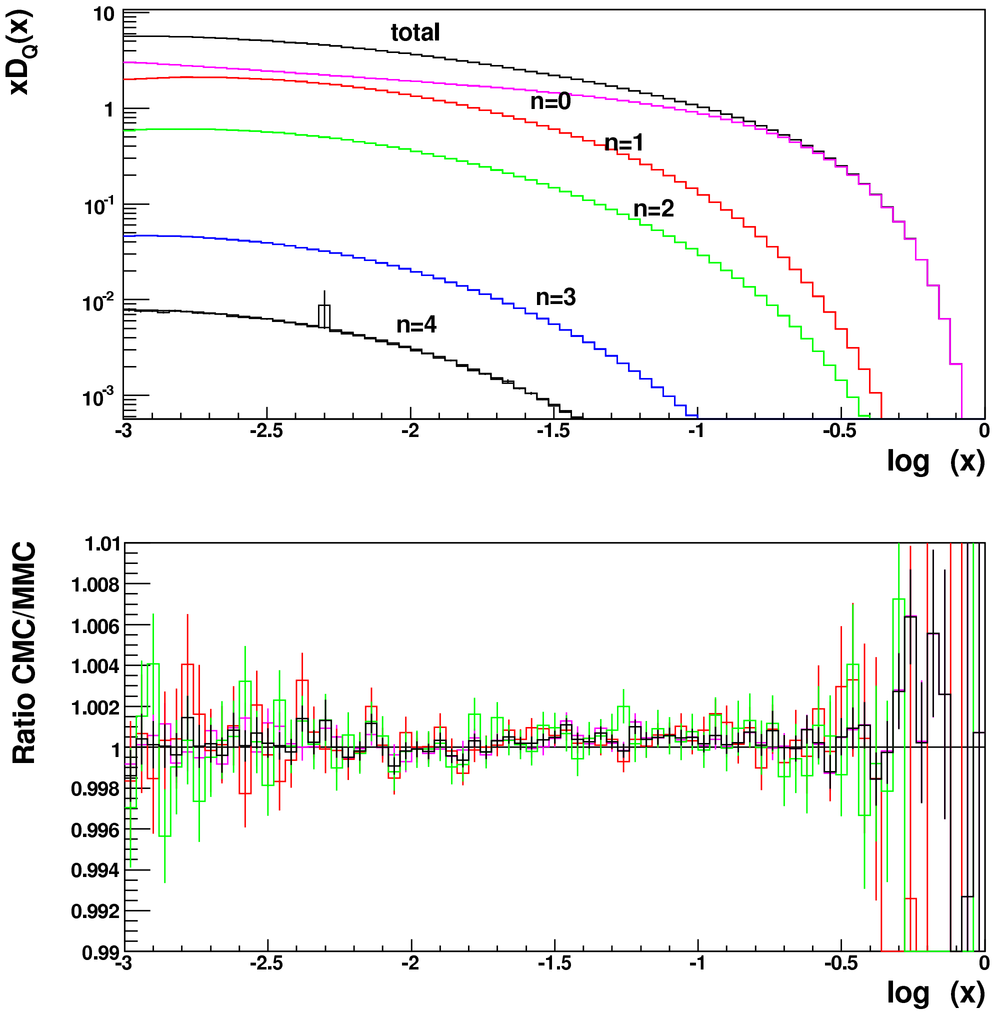
Case (A) is LL DGLAP,
case (C) is CCFM without non-Sudakov formfactor.

CMC kernel (C), numerical results



Distribution of rapidity and log of k^T from CMC for $2E_h = 1000$GeV and $\lambda = 1$GeV, for kernel type (C), pure bremsstrahlung.

CMC kernel (C); Example numerical results



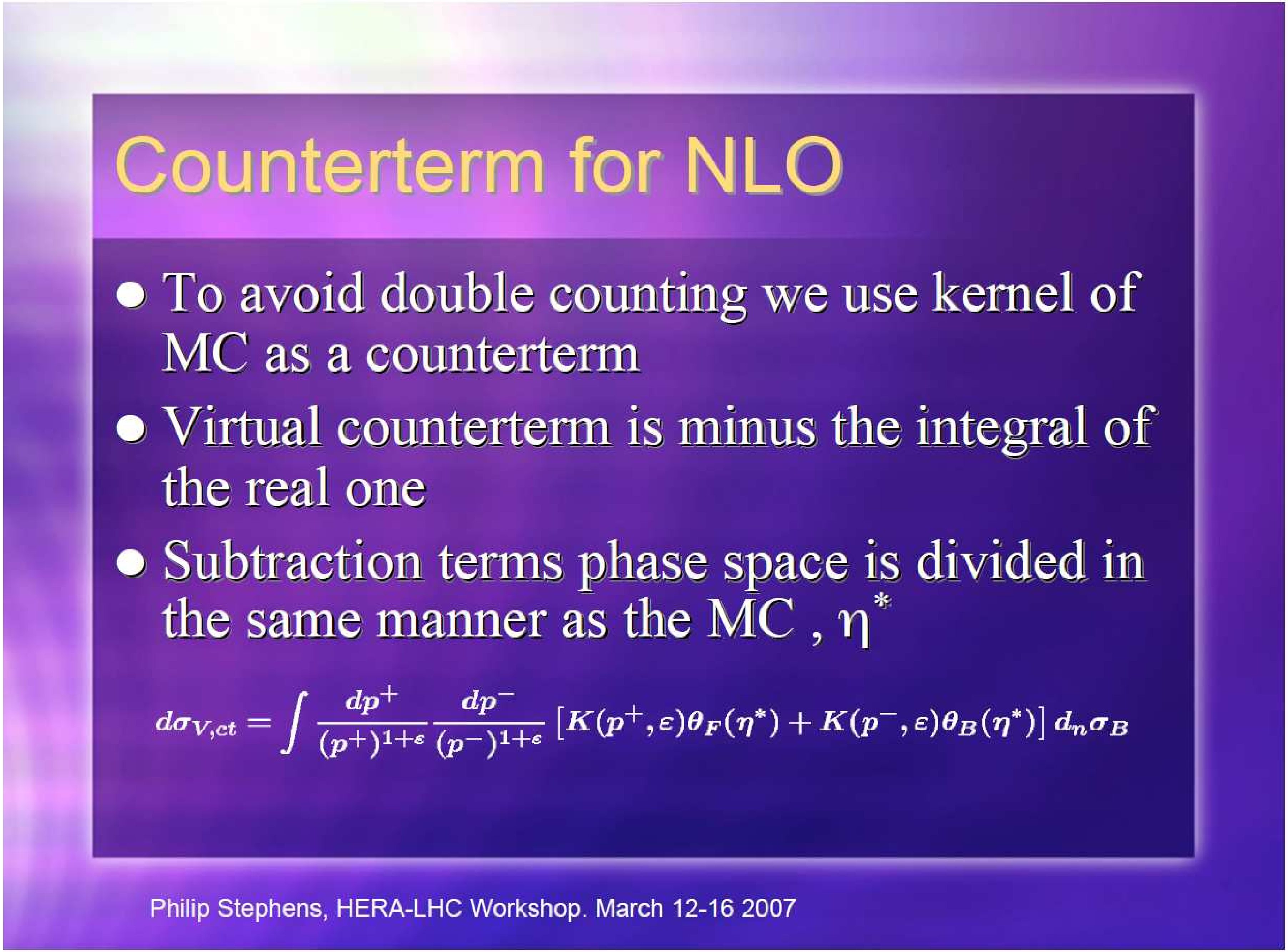
NEW!!! Quark distribution from CMC and MMC for evolution with kernel (C'), $\lambda = 1$GeV and $e^{t_{\max}} = 2E_h = 1$TeV. Contributions from fixed number of the quark-gluon transitions $n = 0, 1, 2, 3, 4$ are also shown. The ratios CMC/MMC in the lower plot are separately for the total result and for the number of quark-gluon transition $n = 0, 1, 2$. MC statistics is 10^{10} weighted events for both CMC and MMC.

NLO Matrix Element

- NLO calculation (from Feynman diagrams) is generally of the form (in 4-2ε dimensions)

$$\begin{aligned}
d_{n+1}\sigma_V &= \left[\left(\frac{A_V}{\varepsilon^2}+\frac{B_V}{\varepsilon}\right)d_n\sigma_B + d_n\sigma_{V,reg}\right]\delta(p^+)\delta(p^-)dp^+dp^- \\
d_{n+1}\sigma_R &= d_{n+1}\sigma_F + \frac{\delta(p^+)\delta(p^-)}{\varepsilon^2}d_n\sigma_S dp^+dp^- \\
&\quad + \frac{dp^+dp^-}{\varepsilon}\left(d_n\sigma_{c+}(p^+)\delta(p^-) + d_n\sigma_{c-}(p^-)\delta(p^+)\right)
\end{aligned}$$

  - Angular variable is implicit
  - p^+ and p^- are light-cone components of gluon emission



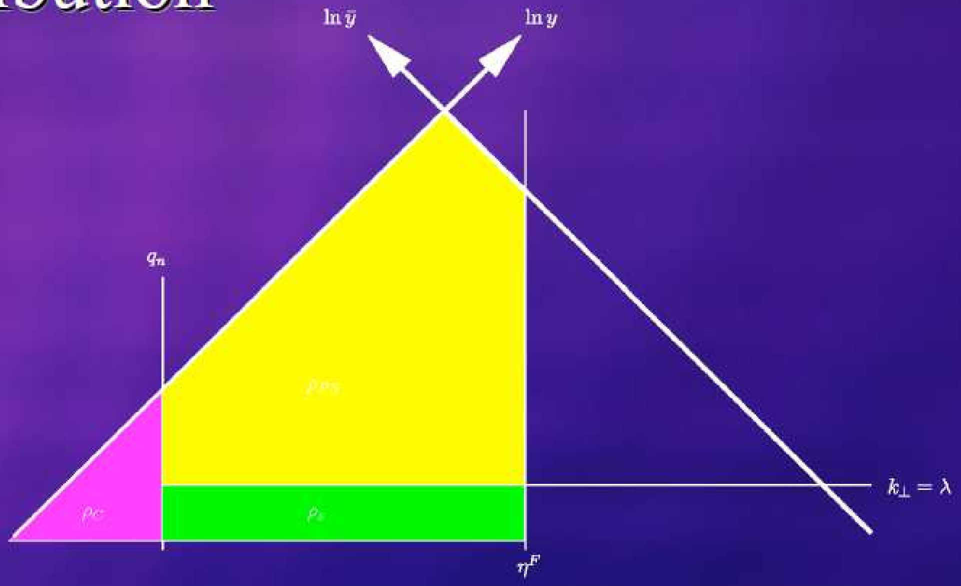
Counterterm for NLO

- To avoid double counting we use kernel of MC as a counterterm
- Virtual counterterm is minus the integral of the real one
- Subtraction terms phase space is divided in the same manner as the MC , η^*

$$d\sigma_{V,ct} = \int \frac{dp^+}{(p^+)^{1+\varepsilon}} \frac{dp^-}{(p^-)^{1+\varepsilon}} \left[K(p^+,\varepsilon)\theta_F(\eta^*) + K(p^-,\varepsilon)\theta_B(\eta^*)\right] d_n\sigma_B$$

Subtraction Term vs. Parton Shower

- Due to ordering and IR regulator the subtraction term differs from PS contribution



Conclusion

- Currently implementing $W^+ W^-$ at NLO
- Remaining issues
  - Must implement quark-gluon transitions in parton shower for two hemispheres
  - Must fit initial parton distributions to DIS data
  - Would like to use matched NLO DIS for fits
- Once working for one process should be quick to implement additional processes

Method

The basic building block of a parton-shower is the a probability distribution of the type

$$\mathcal{P}[\boldsymbol{\varphi}(\vec{y})] = F_R[\boldsymbol{\varphi}(\vec{y})] \exp\left(-\int^{\xi(\vec{y})} d^n\vec{y}\,' F_V[\boldsymbol{\varphi}(\vec{y}\,')]\right) ,$$

where φ is a vector of functional components representing the variable quantities within the shower, for example

- coupling constant;
- kernel;
- ...,

and $\vec{y}$ represents evolution variables, the splitting variables, ...

Method

Varying this distribution following $\varphi \mapsto \varphi + \delta\varphi$ we find

$$\frac{\mathcal{P}[\varphi + \delta\varphi]}{\mathcal{P}[\varphi]} = \left(1 + \frac{\delta F_R[\varphi]}{F_R[\varphi]}\right) \exp\left(-\int^{\xi(\vec{y})} d^n\vec{y}\,' \, \delta F_V[\varphi(\vec{y}\,')]\right) \ ,$$

where

$$\delta F_{R/V}[\varphi] = F_{R/V}[\varphi + \delta\varphi] - F_{R/V}[\varphi] \ .$$

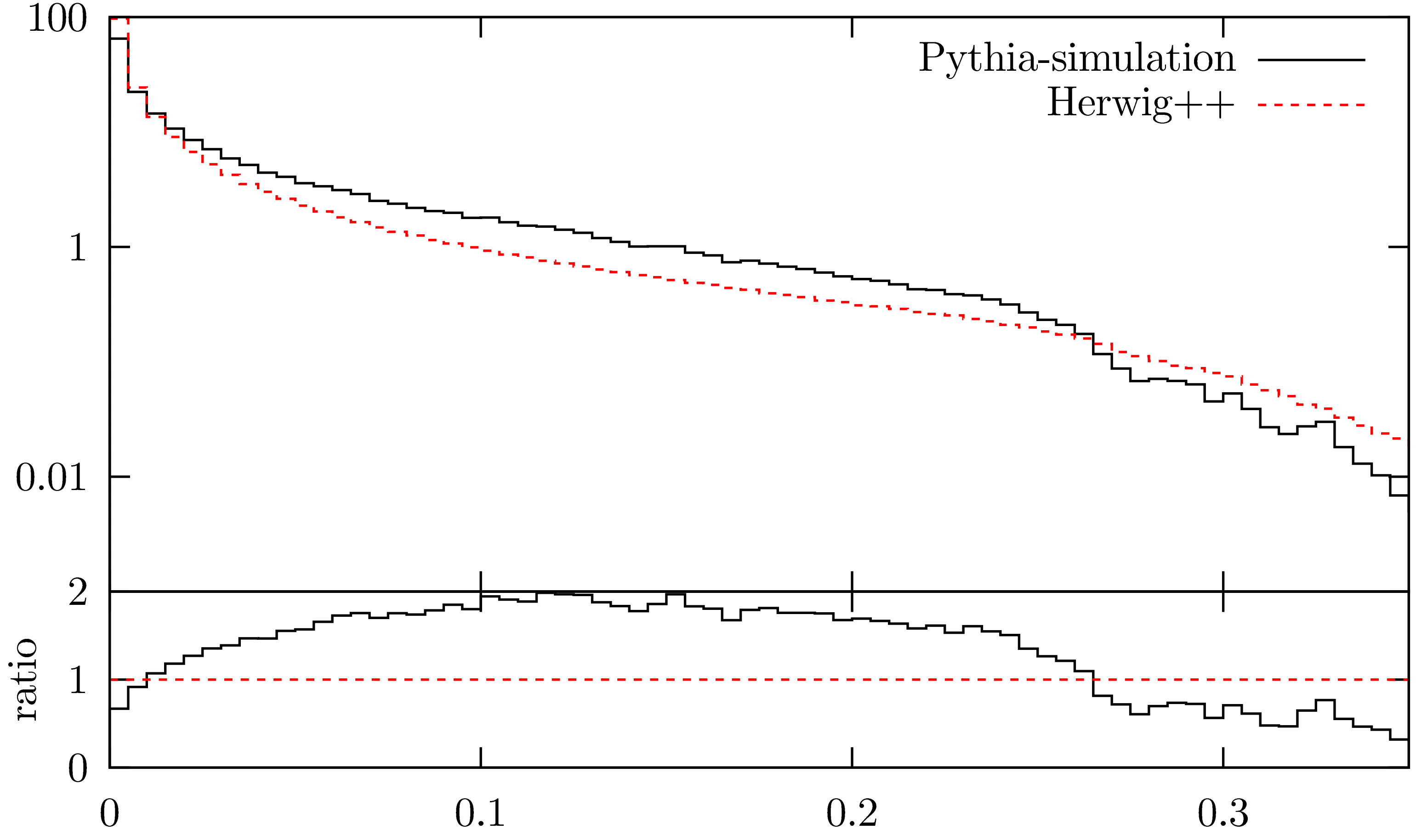
In order to mimick the effect of the variation, the generation stage is reweighted by

$$1 + \frac{\delta\mathcal{P}[\varphi]}{\mathcal{P}[\varphi]} := \frac{\mathcal{P}[\varphi + \delta\varphi]}{\mathcal{P}[\varphi]} \ .$$

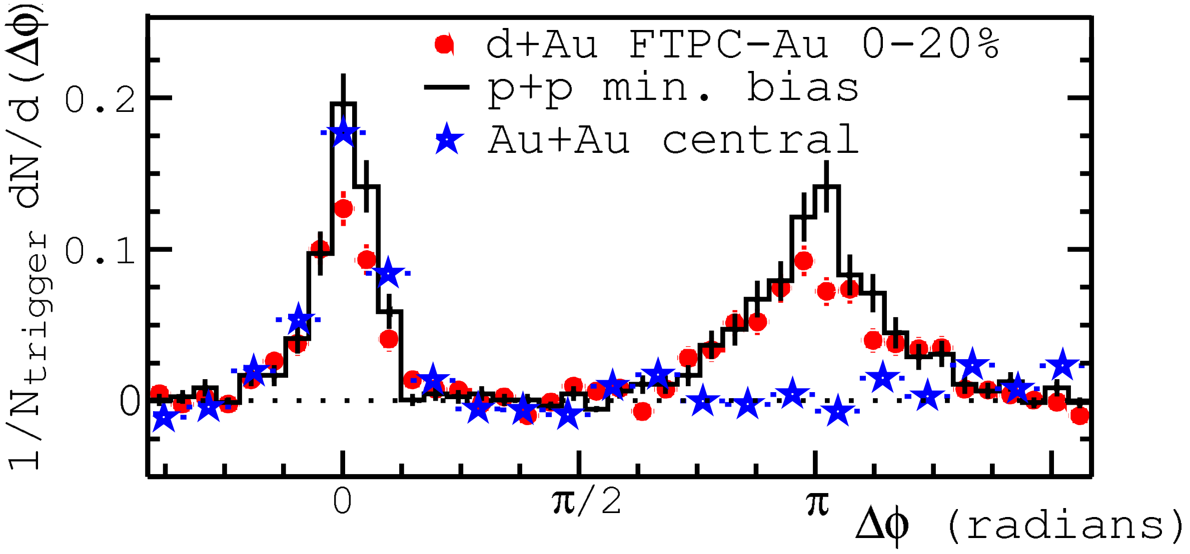
The full event is reweighted by a product of these weights.

Change of Kinematics

Distribution of $1 - T$ with thrust $T = \max_{n} \frac{\sum_{i=1}^{N} |\mathbf{p}_i \cdot \mathbf{n}|}{\sum_{i=1}^{N} |\mathbf{p}_i|}$.



Disappearance of the away-side jet

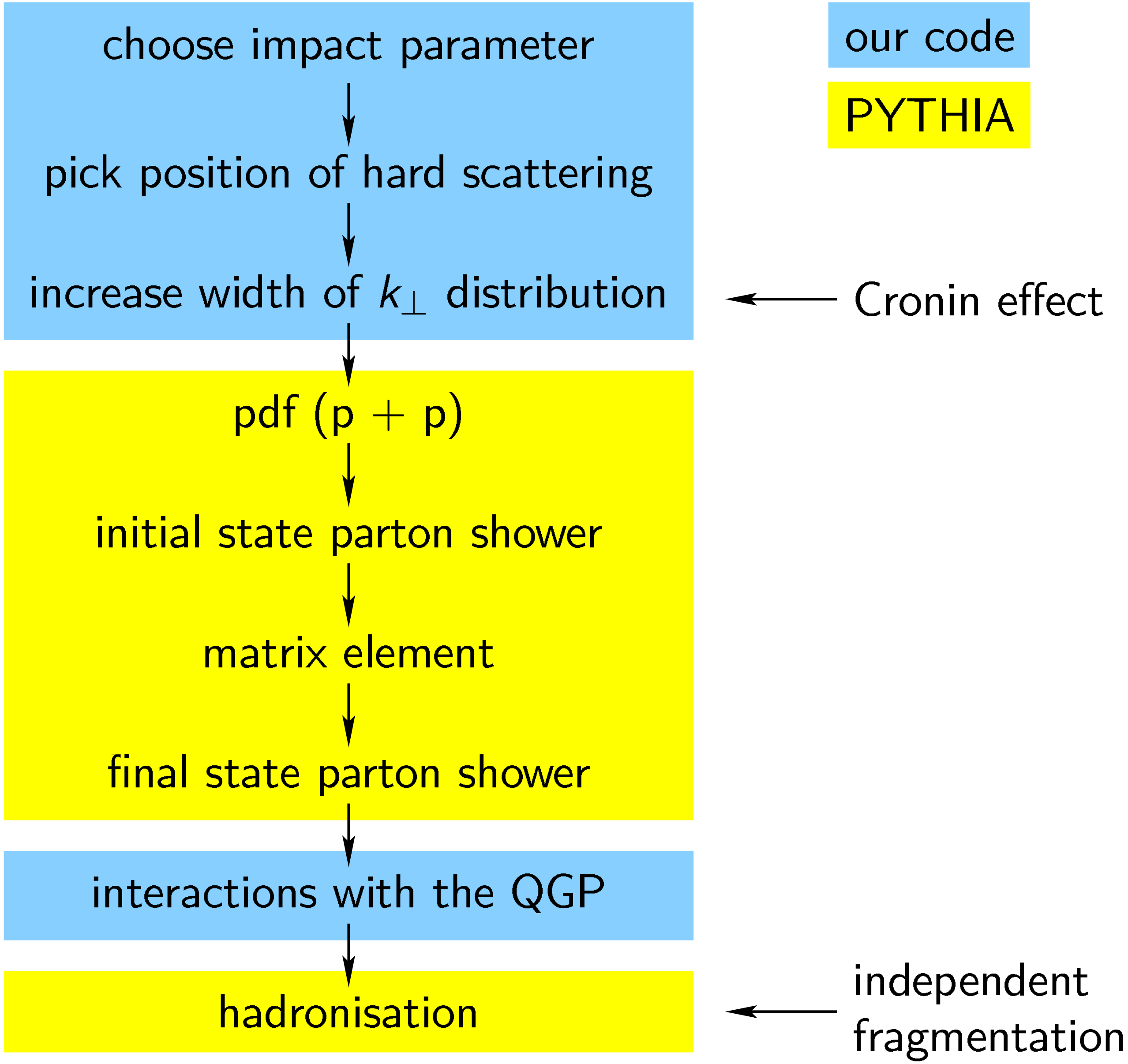


Adams *et al.*, STAR Collaboration, PRL **91** (2003) 072304

trigger particles: $4\,\text{GeV} < p_\perp < 6\,\text{GeV}$
associated particles: $2\,\text{GeV} < p_\perp < p_\perp(\text{trig})$

- disappearance of the away-side jet in central Au + Au collisions
- again no suppression in d + Au

Overview



choose impact parameter

pick position of hard scattering

increase width of $k_\perp$ distribution

pdf (p + p)

initial state parton shower

matrix element

final state parton shower

interactions with the QGP

hadronisation

our code

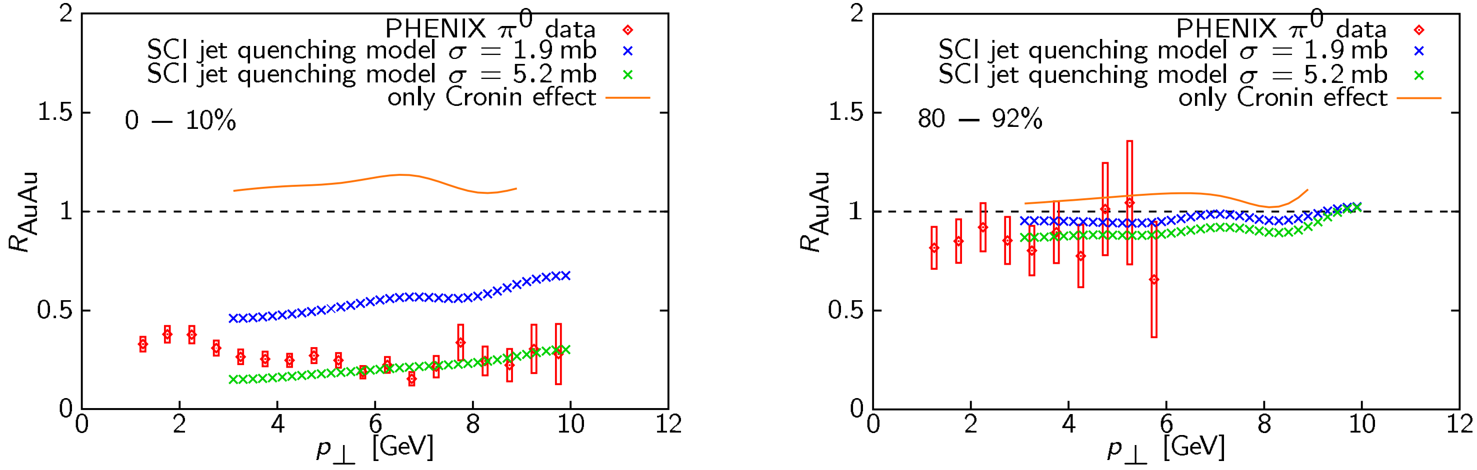
PYTHIA

Cronin effect

independent fragmentation

Nuclear Modification Factor

π^0 suppression

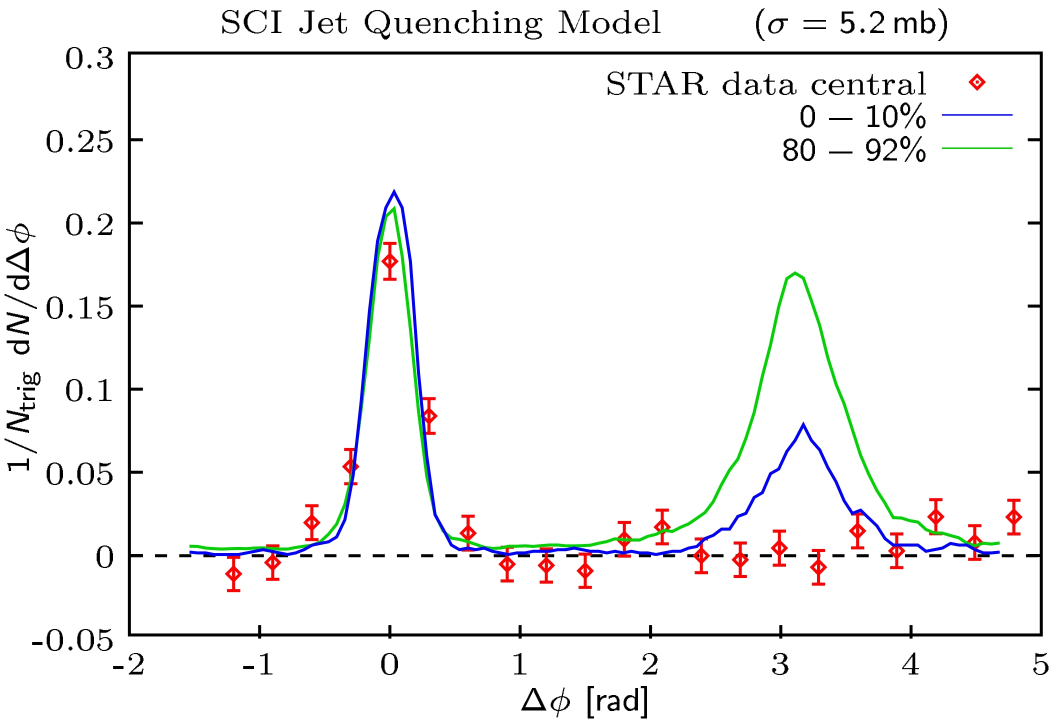


- most central collisions: large cross section scenario consistent with data
- most peripheral collisions: two scenarios are similar and in agreement with data

Adler *et al.*, PHENIX Collaboration, PRL **91** (2003)

Azimuthal Correlation

trigger particles: $4\,\text{GeV} < p_\perp < 6\,\text{GeV}$
associated particles: $2\,\text{GeV} < p_\perp < p_\perp(\text{trig})$



- We see a suppression of the away-side jet but no disappearance.

Adams *et al.*, STAR Collaboration, PRL **91** (2003) 072304

Confrontation with data

- Michiel Botje:
  NNLO upgrade of the QCDNUM DGLAP evolution program
- Steve Mrenna:
  Using the Vista of high–p_T data to validate event generators
- Leif Lönnblad:
  Status of Rivet
- Hannes Jung:
  Announcement of the new HZTool release
- Sergej Chekanov:
  Update on the RunMC project
- Sergej Chekanov:
  Status of jHEPWork

$\longrightarrow$ Thomas Kluge

Multiple interactions

- Daniele Treleani:
  Parton correlations and multi–parton exclusive cross sections
- Mark Strikman:
  Multiple interactions and energy loss
- Sakar Osman:
  Mulitple interactions in DIS
- Lluis Marti:
  Multiple interactions in photoproduction
- Arthur Moraes:
  Underlying event tunings for the LHC

⟶ Claire Gwenlan (summary of WG2)

The integrand $\frac{1}{N!}\Big(\int_{p_t^c} D(x)f(b)\hat{\sigma}(x,x')D(x')f(b-\beta)d^2b\,dx\,dx'\Big)^N$ is dimensionless

and *after normalization* it may be understood as the probability to have *N* parton collisions:

$$\frac{\big(\sigma_S F(\beta)\big)^N}{N!}e^{-\sigma_S F(\beta)} = \mathrm{P}_N(\beta) \qquad \sigma_S F(\beta) = \int_{p_t^c} D(x)f(b)\hat{\sigma}(x,x')D(x')f(b-\beta)d^2b\,dx\,dx'$$

One may hence express the hard cross section σ_H (namely the contribution to σ_{inel} of all events with *at least* one parton collision) as

$$\boxed{\sigma_H = \sum_{N=1}^{\infty}\int d^2\beta \frac{\big(\sigma_S F(\beta)\big)^N}{N!}e^{-\sigma_S F(\beta)} = \int d^2\beta\Big[1-e^{-\sigma_S F(\beta)}\Big]}$$

Differently form σ_S and σ_D, σ_H is always smaller that σ_{inel} and one may write

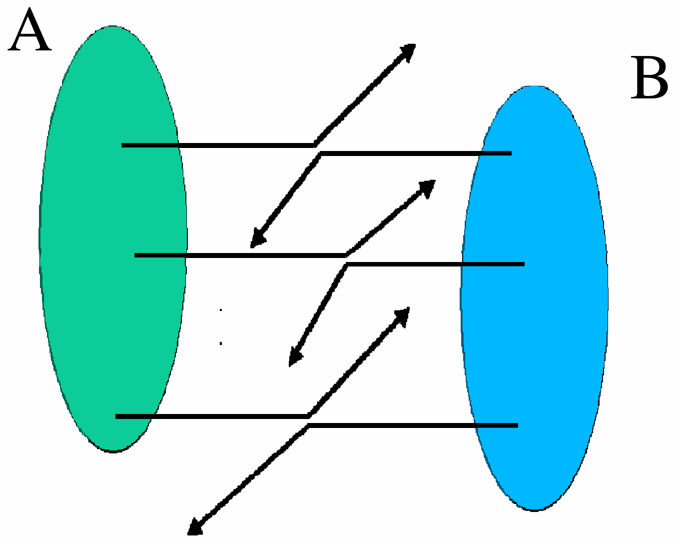
$$\boxed{\sigma_{inel} = \sigma_{soft} + \sigma_H}$$

While σ_S is divergent when p_t^c goes to zero, σ_H and all contributions to σ_H with a given number *N* of parton collisions are, on the contrary, finite when p_t^c goes to zero

This expression for σ_H includes all possible interaction (with on-shell intermediate states) between any configuration with n partons of hadron A and any configuration with m partons of hadron B. The cross section complies with the AGK cutting rules.

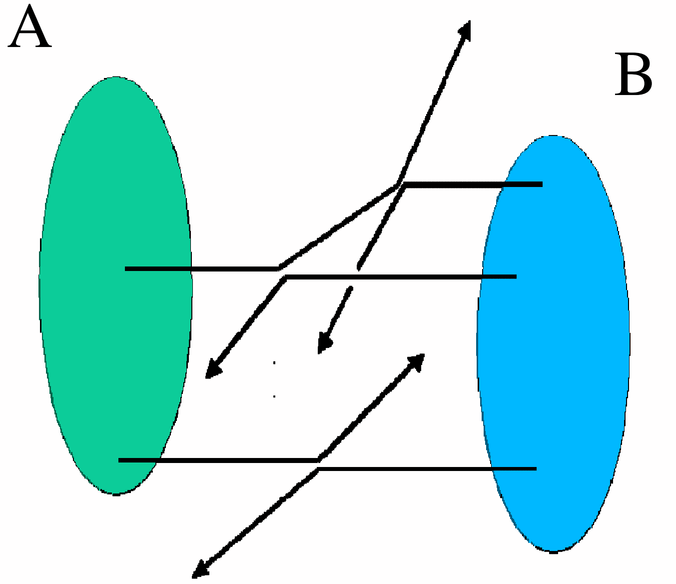
Both

disconnected collisions



and

rescatterings



are included in σ_H

What to be measured ?

All relations above are easily adapted to different choices of final state cuts

The *inclusive cross sections* are the moments of the distribution in the number of collisions. Hence e.g. triple, quadruple etc. parton interactions contribute to the inclusive double parton scattering cross section σ_D, once taken into account with the proper multiplicity factor.

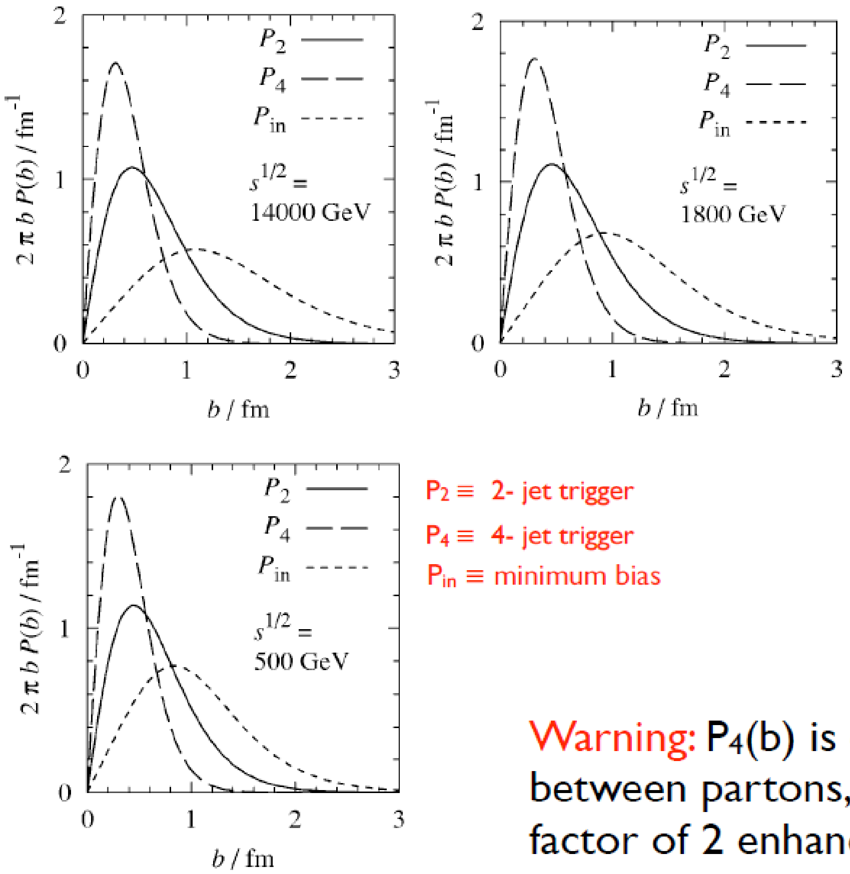
One may obtain further information on the interaction dynamics by measuring, in addition to the inclusive cross sections, also the *exclusive cross sections* (including σ_H itself) in different phase space intervals.

All exclusive cross sections are well defined experimental quantities (corresponding to events with a given number of parton interactions only) and are well behaved in the infrared region

Explicit expressions, including all effects of the two-body parton correlations, are available both for the *inclusive* and the *exclusive cross sections*

Implications for LHC - impact parameters for collisions with new particle production are much smaller than for generic inelastic collisions.

Using HERA data and fits to elastic pp data we can quantify this.



P_2 ≡ 2- jet trigger

P_4 ≡ 4- jet trigger

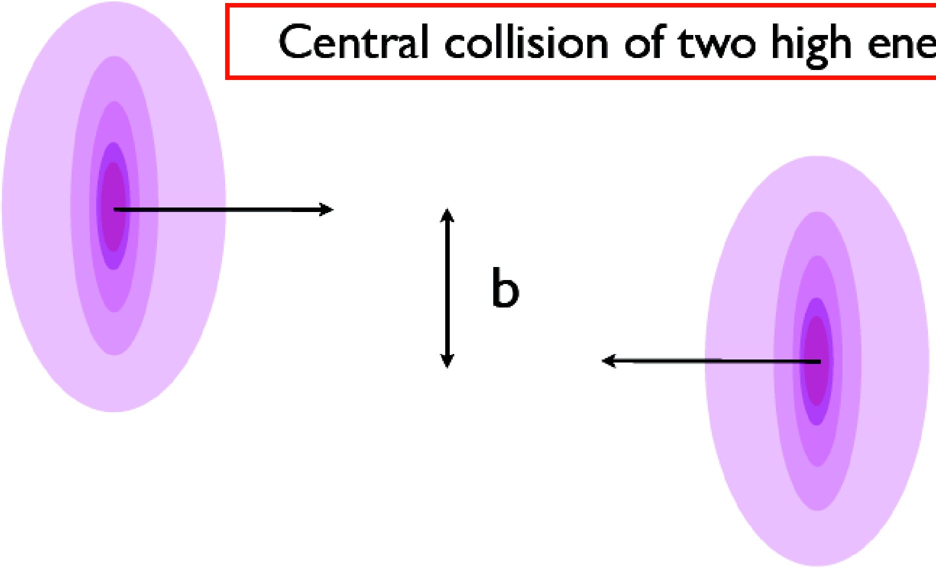
P_{in} ≡ minimum bias

Distribution over b for different triggers

Difference between b-distributions for minimal bias and dijet, four jet events strongly increases with increase of incident energy. *Solid lines:* b–distributions for the dijet trigger, $P_2(b)$, with $q_\perp = 25\,GeV$, as obtained from the dipole–type gluon ρ–profile. *Long–dashed line:* b–distribution for double dijet events, $P_4(b)$. *Short–dashed line*: b–distribution for generic inelastic collisions.

Warning: $P_4(b)$ is calculated assuming that there are no transverse correlations between partons, while our analysis of CDF 3jet +photon data suggests a factor of 2 enhancement due to the transverse correlations. If so, the change of b distribution between 2 jet and 4 jet trigger is a factor of 2 smaller.

Central collision of two high energy protons



Valence quarks/gluons of the protons are interacting with probability ~ one, loosing energy and getting large transverse momenta growing with energy. Soft interactions are suppressed - minimal scale/virtuality of strong interaction is few GeV and growing with energy. Gross suppression of particle production in fragmentation region, much higher rate of hadron production away from the fragmentation region.

Final state studies

- Simon Albino:
  Fragmentation at HERA

- Oldrich Kepka:
  Report on the DPEMC Generator

- Kenneth Lessnof:
  Tuning Pythia for the LHCb

- Nelli Pukhaeva:
  Jets study and comparison of different generators

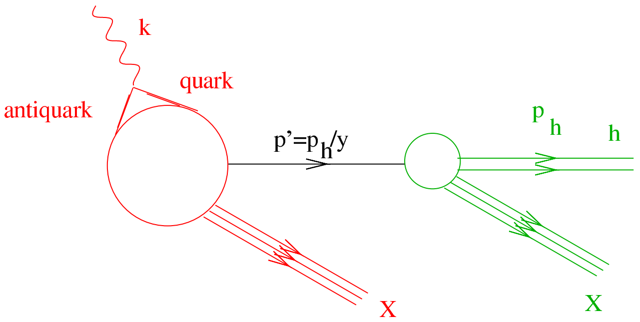
⟶ Thomas Kluge

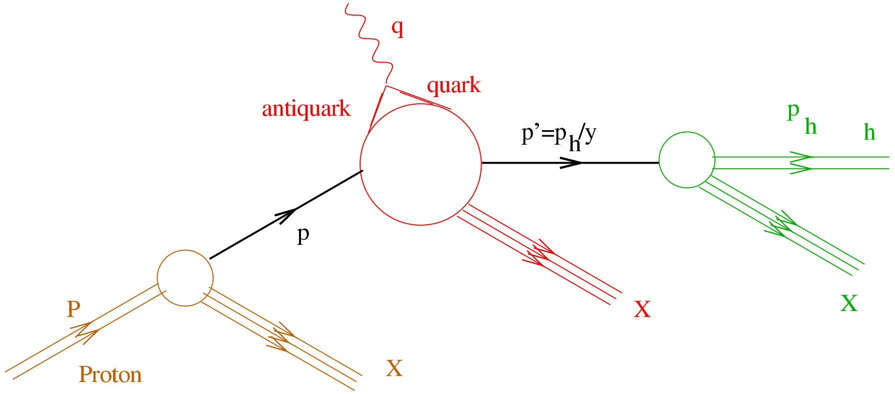
⟶ Claire Gwenlan (summary of WG2)

Factorization in $e^+e^- \;/\; ep \to h + X$

e^+e^-: $x_p = \frac{2p_h}{\sqrt{s}},\ s = k^2$ ep: $x_p = \frac{2p_h \cdot q}{q^2} (= \frac{2p_h}{Q} \text{ Breit}), x = \frac{Q^2}{2P\cdot q}, Q^2 = -q^2$

$\frac{d\sigma^h}{dx_p}(x_p, s)$: $\frac{\frac{d}{dx_p}\int_{\text{cuts}} dQ^2 dx \frac{d^2\sigma^h}{dx dQ^2}}{\int_{\text{cuts}} dQ^2 dx \frac{d^2\sigma^h}{dx dQ^2}}$:





perturbative ⊗ FFs PDFs ⊗ perturbative ⊗ FFs

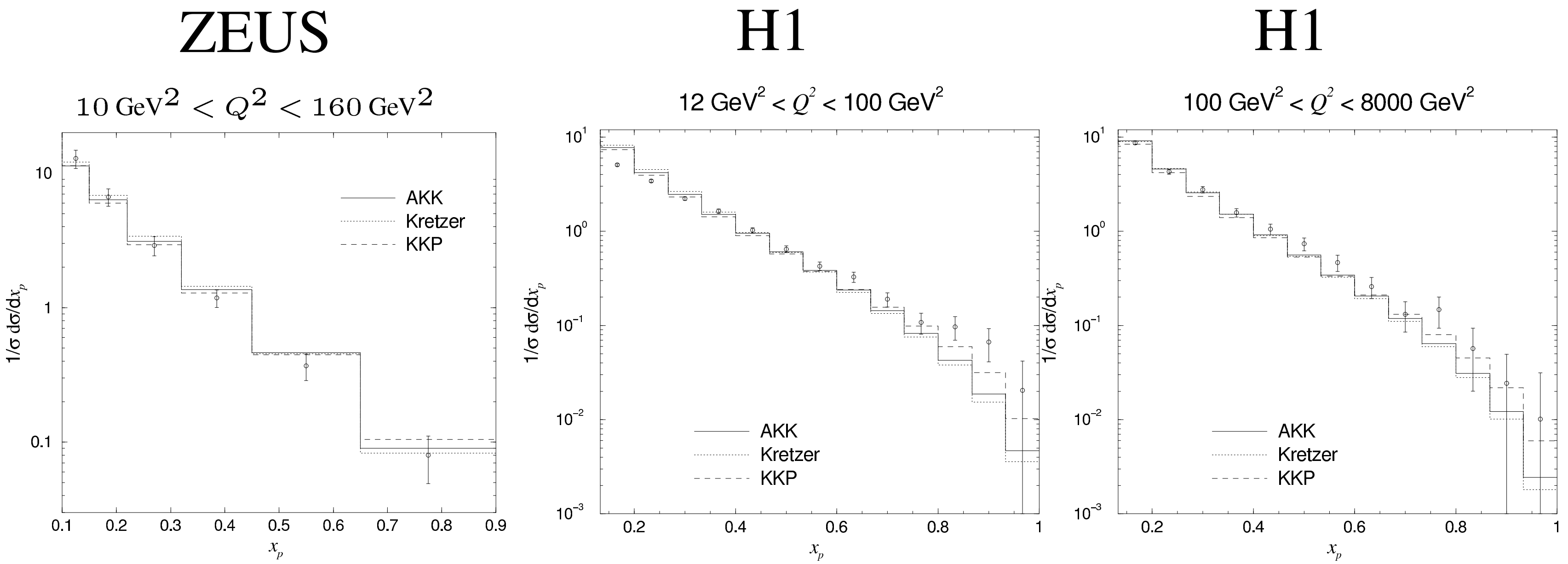
$G_I = 1$ G_I from Ith PDF

$$\frac{d\sigma^h}{dx_p}(x_p, s \text{ or } Q^2) = \sum_i \int_{x_p}^1 \frac{dy}{y} \frac{d\sigma^i}{d(x_p/y)}\left(\frac{x_p}{y}, s \text{ or } Q^2, \mu_f^2\right) D_i^h(y, \mu_f^2)$$

$$\text{LO}: \quad \approx \sum_I e_{q_I}^2 (Q^2) G_I(Q^2) D_I^h(x_p, Q^2)$$

$$\text{DGLAP}: \quad \frac{d}{d\ln\mu_f^2} D_i^h(x, \mu_f^2) = \int_x^1 \frac{dy}{y} \sum_j P_{ij}\left(\frac{x}{y}, a_s(\mu_f^2)\right) D_j^h(y, \mu_f^2)$$

x_p distributions vs. FFs



Large x_p: Inadequate e^+e^- data → FF discrepancies

AKK $\simeq$ Kretzer

Low Q

- H1:
  small x_p bad (small exp. errors, various theory issues)
  large x_p undershoot: resummation?
- ZEUS: General agreement

High Q (H1)

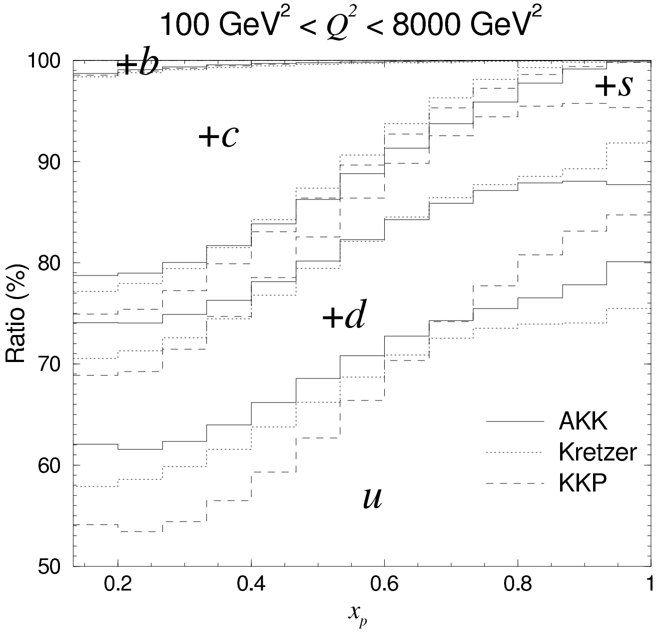
General agreement

(smaller pred. errors)

Quark tagging (H1)

Identify quark flavour at e.w. vertex

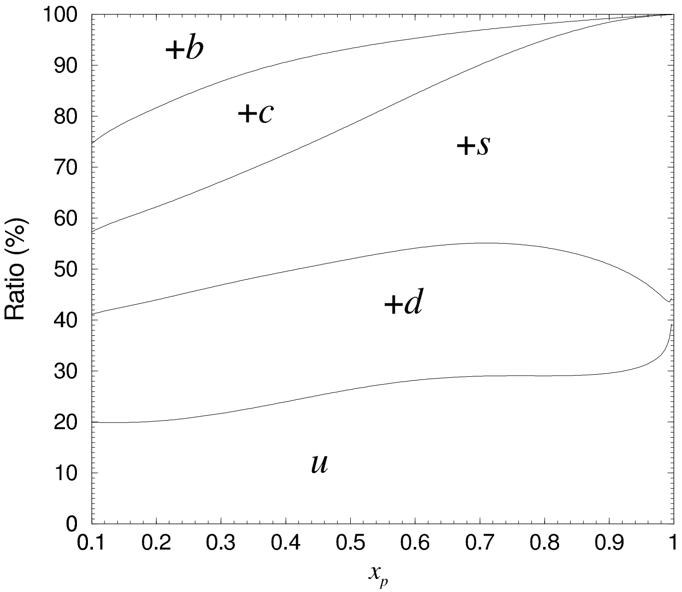
$ep \longrightarrow h + X$



Proton is good source of u

$e^+e^- \longrightarrow h + X$

$\sqrt{s} = 91$ GeV



s relatively large

In principle, ep and e^+e^- together can separate uds FFs

Summary

- Very interesting sessions.

- Interesting contributions pointing into new directions.
  New parton showers being developed.
  k_T–factorization based MCs give interesting results.
  My comment: "old" MCs are ready.
  New MCs (Pythia8, Herwig++/Sherpa) will not be used much for first data.
  Physics/new data will drive this into new direction soon, I guess.
- Multiple Interactions. Challenging, active field.
  My comment: More understanding is necessary and desirable.
  Tuning one model does not necessarily mean understanding the data.

- *Thanks a lot to the speakers for their contributions to WG5!*

Commercial break

- New EU Marie Curie RTN *MCnet*
  - CERN
  - Durham
  - Karlsruhe
  - Lund
  - UCL (userlink)
- ∼20 short term studentships (∼3 months, like internship).
- 2 long–term studentships for combined PhD at Karlsruhe/Durham, Durham/UCL.
- Experiments may send us young students to learn about our MC programs.

`http://www.montecarlonet.org`