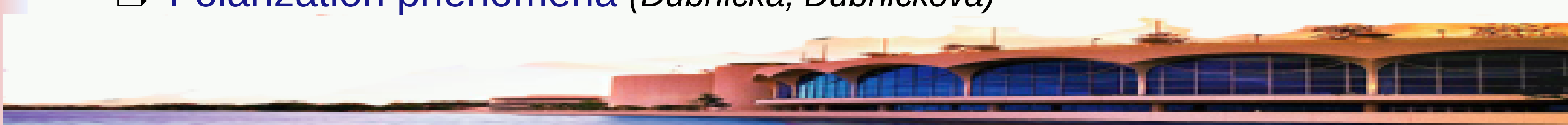
Hadronic Final States Working group: theory talks

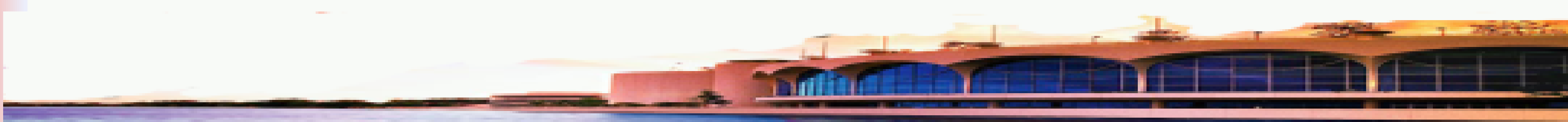
Pavel Nadolsky (Argonne National Laboratory)

- Perturbative QCD *(Klasen, Kniehl, Sassot)*
- Monte-Carlo generators *(Frixione)*
- Resummations *(Andersen, Kidonakis, Kyrieleis, Olness)*
- Photon structure *(Levy)*
- Unitarity at high energy & small x *(Marquet, Weiss)*
- Pentaquarks *(Szczepaniak)*
- Polarization phenomena *(Dubnicka, Dubnickova)*



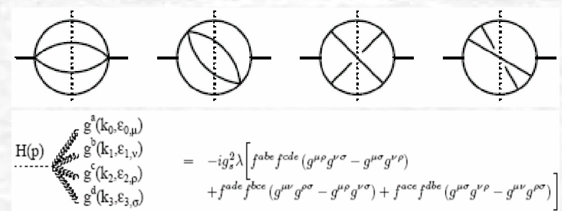
Status of NNLO calculations
(M. Klasen)

- Inclusive processes:
  - NNLO calculation completed for $F_{1,2,3}$ → first NNLO fits
  - NNLO calculation completed for Higgs and DY production
- Less inclusive processes:
  - $e^+e^- \to$ 3 jets: 1 → 4 subtraction terms partially completed
    → First (preliminary and partial) result for average thrust
  - $e^+e^- \to$ QQ : 1 → 2 vector and axial-vector vertex @ 2-loop
    → Subtraction terms still missing
  - p p → 2 jets: 2 → 2 quark helicity amplitudes completed
    → Subtraction terms still missing
- Multi-particle processes: Twistor methods
  - Tree-level: Works for non-SUSY, non-MHV, also fermions
  - Loop-level: Works for N=4 SYM @ 1-loop, extension unclear



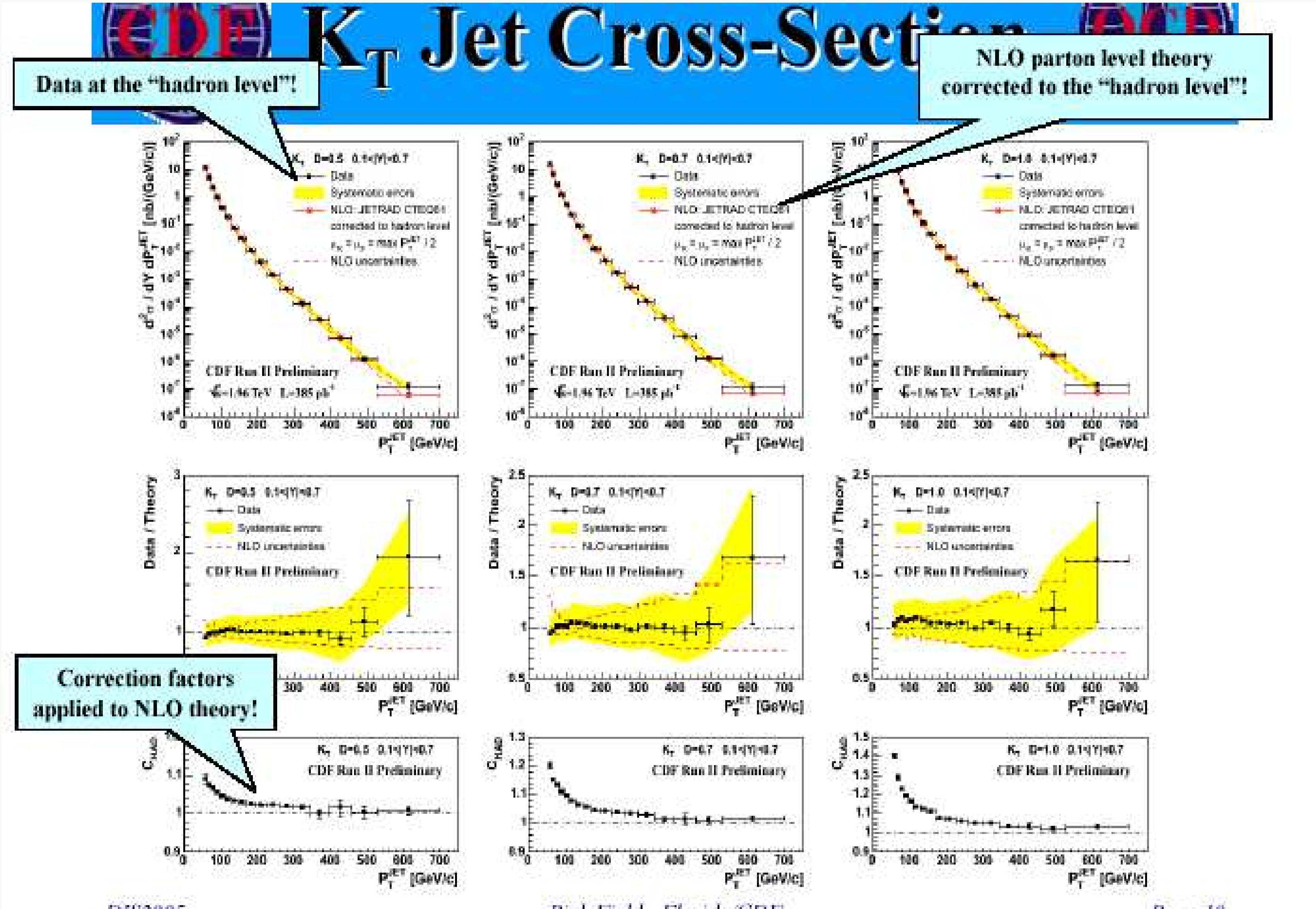
Jets (2)

- Ingredients:
  - 1 → 3 @ 2-loop: Inteference with 1 → 3 @ 0-loop √
  - 1 → 4 @ 1-loop: Single soft and/or collinear regions √
  - 1 → 5 @ 0-loop: Double soft … triple collinear regions √
- Methods:
  - Optical theorem: 3-loop propagators
  - Subtraction terms: Antenna functions



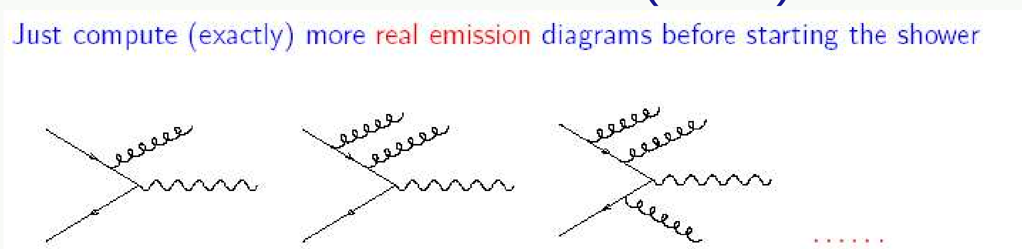
- First (preliminary) numerical result:
  - Average thrust: $\langle 1-T\rangle = \int (1-T)\frac{1}{\sigma_0}\frac{d\sigma}{dT} = C_F\left[\left(\frac{\alpha_s}{2\pi}\right)A + \left(\frac{\alpha_s}{2\pi}\right)^2 B + \left(\frac{\alpha_s}{2\pi}\right)^3 C + \ldots\right]$
  - A = 1.57, B = 32.3, C = (-20.4±4) C_F^2 + …
  - A. Gehrmann, T. Gehrmann, N. Glover, LL 2004

Future NNLO cross sections for $p + p \to jets + X$ needed for the full NNLO PDF analysis

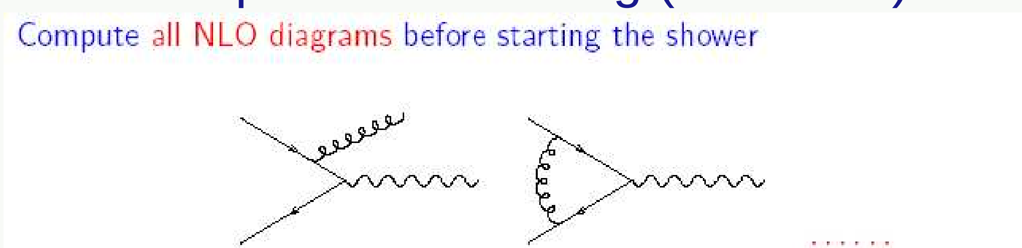


Monte-Carlo event generators *(S. Frixione)*

- Adequate Monte-Carlo showering models are crucially important for many measurements (including jet cross sections)
- To what extend can we combine powerful features of perturbative calculations and Monte-Carlo methods in a single formalism?
  - Matrix-element corrections (MEC)

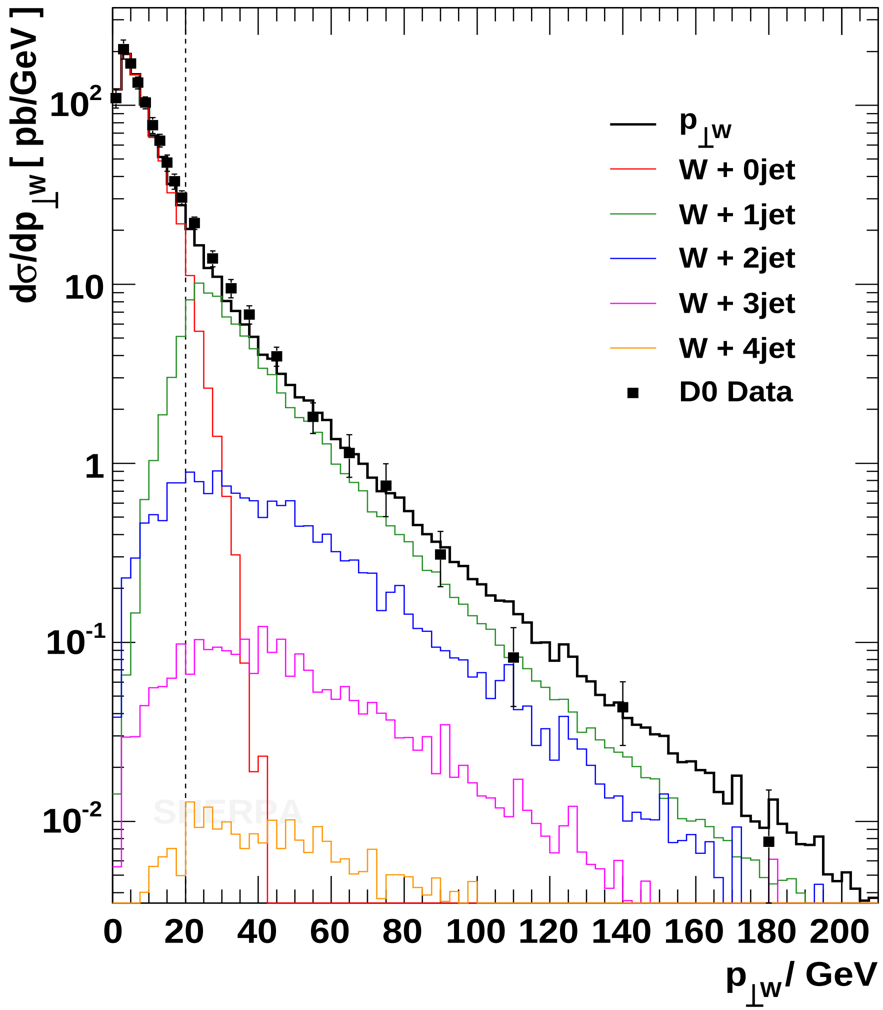


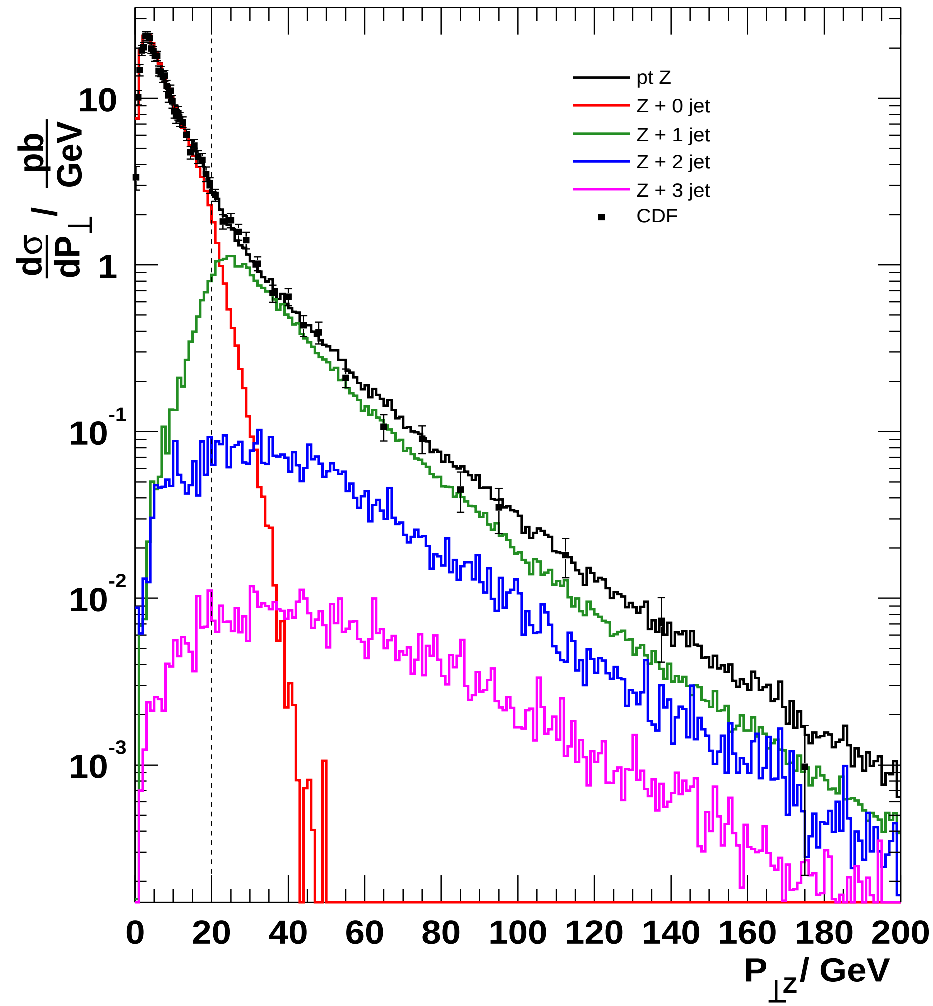
  - NLO with parton showering (NLOwPS)



▷ pros and cons of two methods

Using MEC



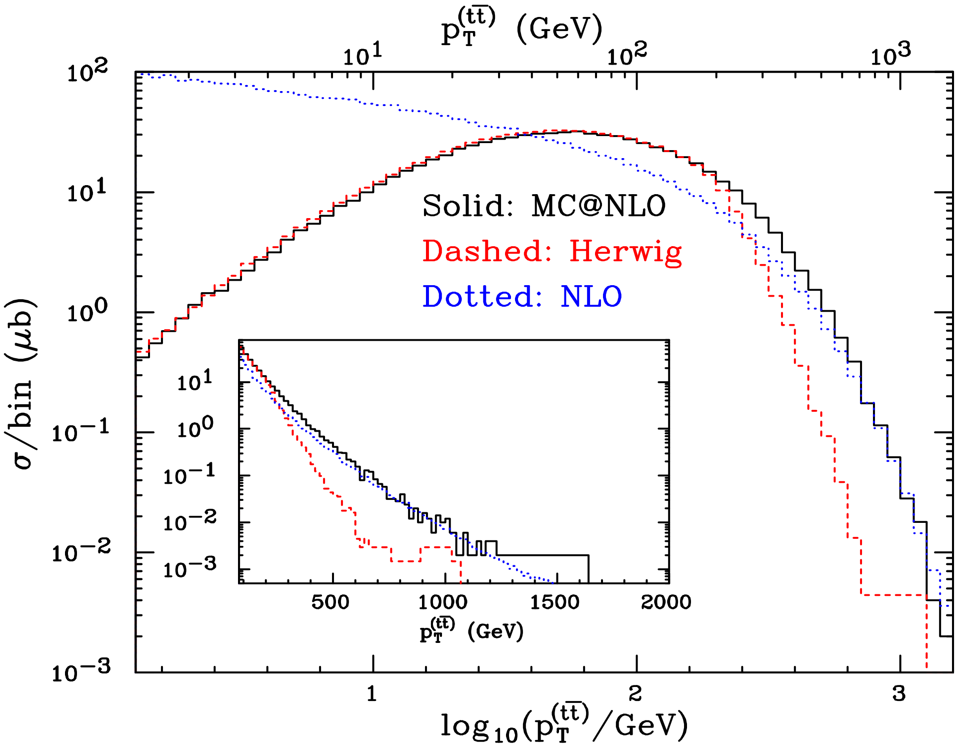


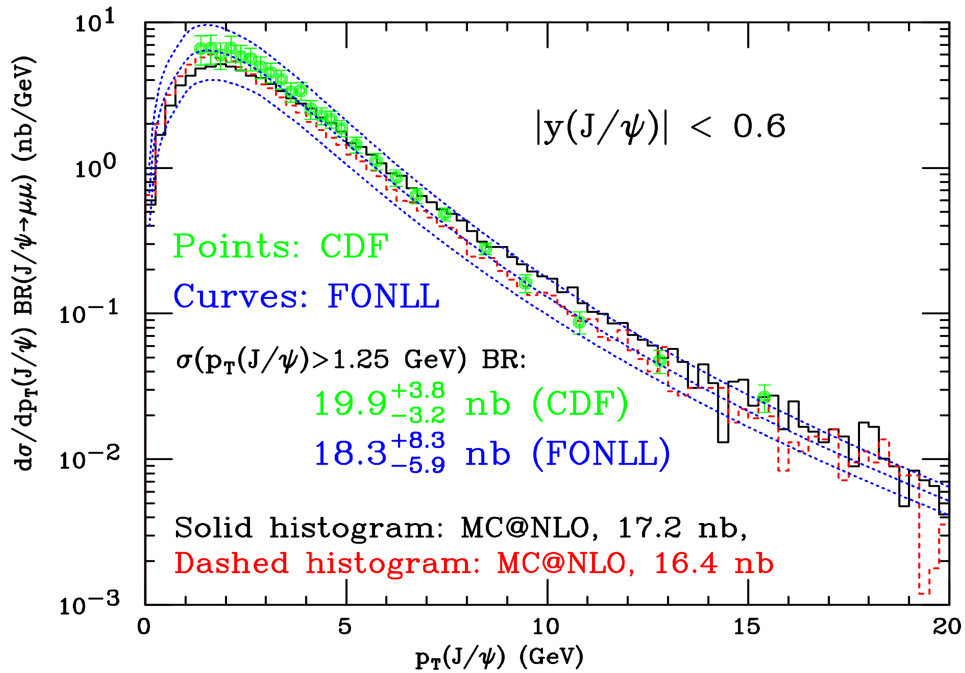
SHERPA (from hep-ph/0409122) – CKKW is built in

Different partonic subprocesses cooperate to give the physical result

- How about the δ_{sep} dependence?

What to expect from an NLOwPS (here MC@NLO)





- MC@NLO rate = NLO rate $\Longrightarrow$ K-factors are included consistently
- MC@NLO- and MC-predicted shapes are identical where MC does a good job
- $\mathcal{S}$+0 jet and $\mathcal{S}$+1 jet treated exactly, $\mathcal{S}+n$ jets ($n > 1$) better than in MC's
- No dependence on δ_{sep} $\Longrightarrow$ tuning is the same as in ordinary MC's
- Some negative-weight events, to be subtracted (rather than added) from histograms

NLOwPS versus MEC

- Why is the definition of NLOwPS's much more difficult than MEC?

  The problem is a serious one: KLN cancellation is achieved in standard MC's through unitarity, and embedded in Sudakovs. This is no longer possible: IR singularities do appear in hard ME's

IR singularities are avoided in MEC by cutting them off with δ_{sep}. This must be so, since only loop diagrams can cut off the divergences of real matrix elements

NLOwPS's are better than MEC since:

+ There is no δ_{sep} dependence (i.e., no merging systematics)
+ The computation of total rates is meaningful and reliable

NLOwPS's are worse than MEC since:

− The number of hard legs is smaller
− There are negative weights (i.e., more running time required)

- MEC programs: AcerMC, ALPGEN, AMEGIC++, CompHEP, Grace, MadEvent

- NLOwPS programs: MC@NLO, Φ-veto, grcNLO

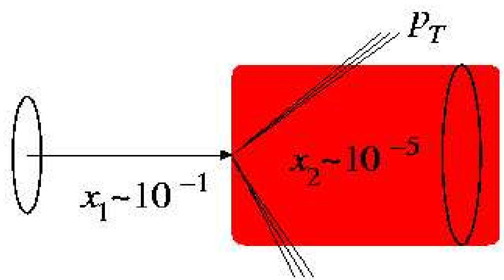
... and a lot of ongoing theoretical activity

Underlying event at hadron colliders

- under active investigation
- requires a serious study and Monte-Carlo tuning at the Tevatron
  (R. Field)
- Current models for LHC fall in the “plug and pray” category
  (S. Frixione)
  - unknown dependence on $\sqrt{S}$
  - not well-understood at high luminosities and parton densities
  - will require substantial tuning in the first years of LHC
- pp data from RHIC ($\sqrt{S} = 200$ GeV) can help constrain the energy dependence $\Rightarrow$ *Jiangyong Jia’s talk*

Black–body limit in central pp/pA collisions at LHC

L. Frankfurt (Tel Aviv), M. Strikman (Penn State), Ch. Weiss (JLab)
DIS2005, April 27 – May 1, 2005



- Interaction of large–x_1 partons with small–x_2 gluons approaches "black–body" (unitarity) limit

→ large $p_\perp \gg \Lambda_{\text{QCD}}$

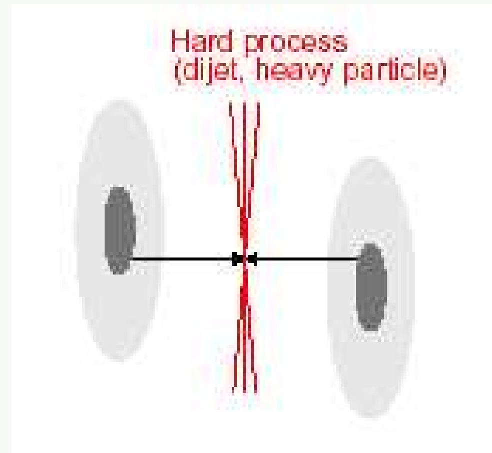
→ modified forward hadron production

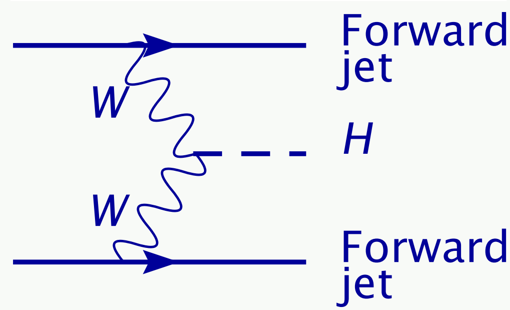
→ affects pp events with new particle production (Higgs)

- Ingredients: HERA data on $G(x, Q^2)$, transverse size
  QCD factorization (DGLAP) $\longleftrightarrow$ dipole picture

Black-body limit at the LHC II

- may affect forward-rapidity hadronic activity in central pp/pA collisions
- e.g., in production of massive particles or jet systems at small rapidities (Higgs production in vector boson fusion)





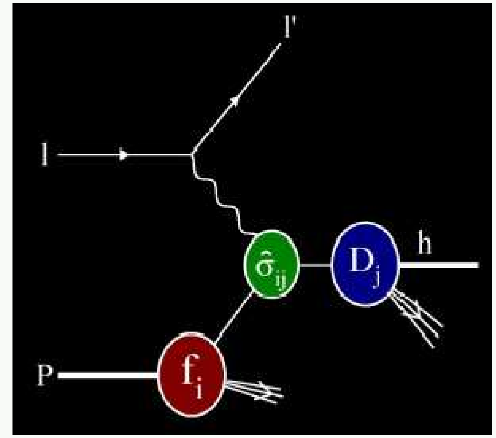
Signatures:

- lost coherence of parton radiation (“shattered” projectiles)
- leading-energy hadrons have suppressed multiplicity and large p_T w.r.t. to the jet
- increased soft particle multiplicities at central rapidities

Not implemented yet in Monte-Carlo generators

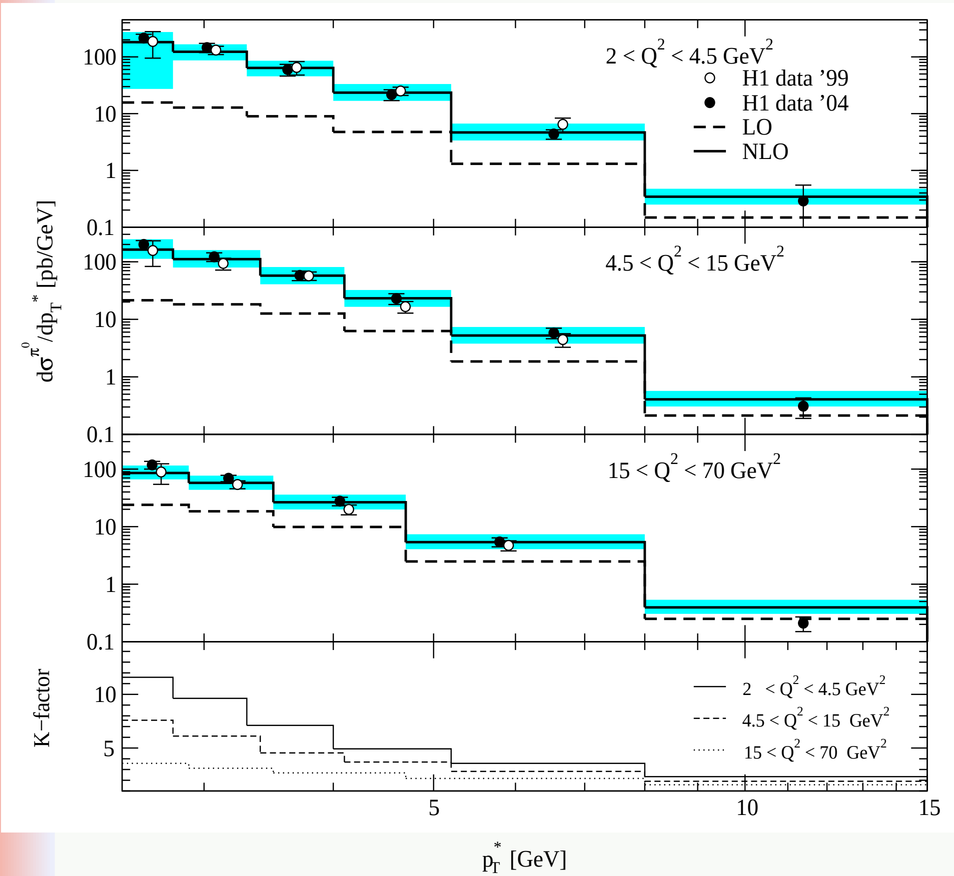
$\mathcal{O}(\alpha_s^2)$ corrections to semi-inclusive DIS at high p_T (B. Kniehl, R. Sassot)

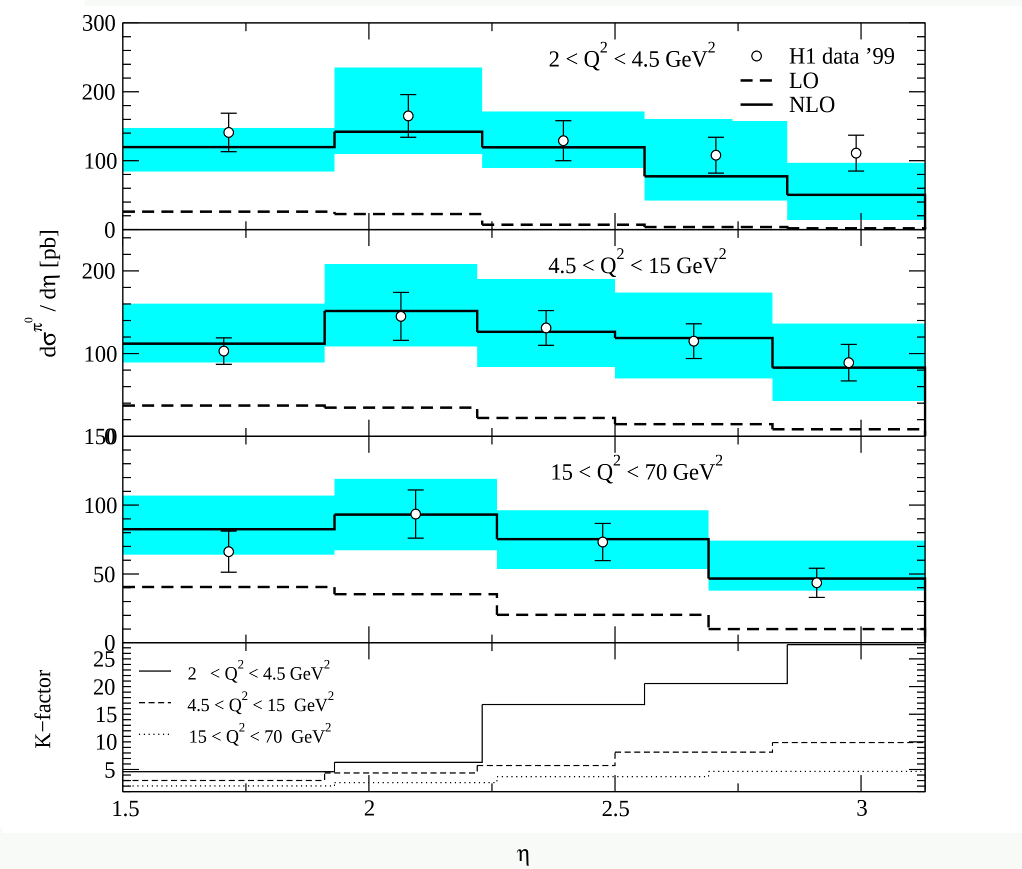
- Completed recently by several groups
  - 0-loop real emission: $\gamma \overset{(-)}{q} \to \overset{(-)}{q} gg$, $\gamma g \to q\bar{q}g$, etc.
  - 1-loop virtual corrections: $\gamma \overset{(-)}{q} \to \overset{(-)}{q} g$, $\gamma g \to q\bar{q}$



- Agrees with most of the HERA data within uncertainties; at the same time,
  - $K = \sigma_{NLO}/\sigma_{LO}$ is in the range $\sim 1 - 25$
    K increases at smaller Q, x, p_T^*, or large η
  - Scale uncertainty of $\sim 100\%$
  - Substantial dependence on fragmentation functions

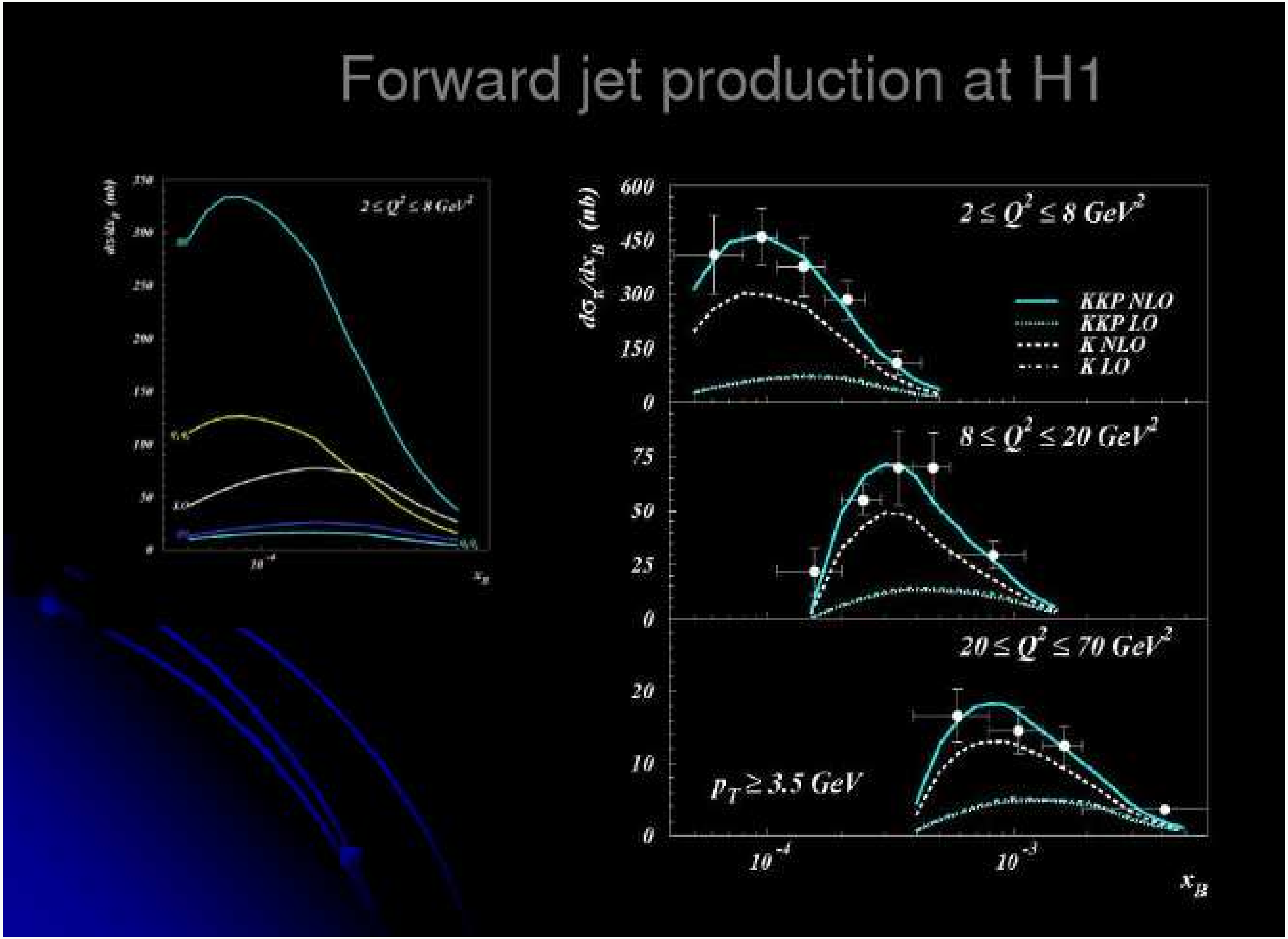
(a) π^0 mesons in the forward region (H1)





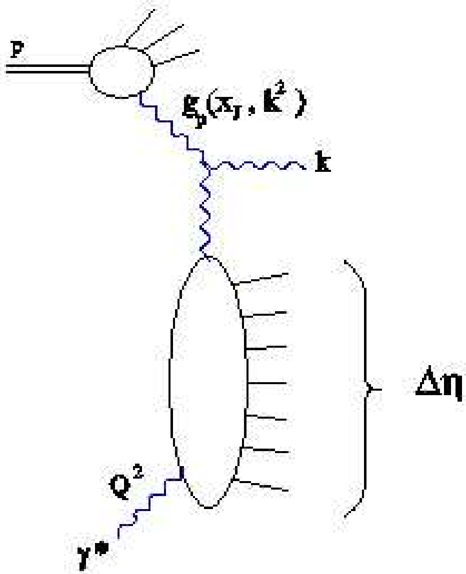
p_T^*

$\eta = -\ln\tan(\theta/2)$


Forward jet production at H1
$2 \le Q^2 \le 8\ GeV^2$
x_B
$d\sigma_{jet}/dx_B$ (nb)
600
450
300
150
0
$2 \le Q^2 \le 8\ GeV^2$
KKP NLO
KKP LO
K NLO
K LO
75
50
25
0
$8 \le Q^2 \le 20\ GeV^2$
20
10
0
$20 \le Q^2 \le 70\ GeV^2$
$p_T \ge 3.5\ GeV$
10^{-4}
10^{-3}
x_B

The forward-jet cross-section

in LL BFKL with saturation (C. Marquet)



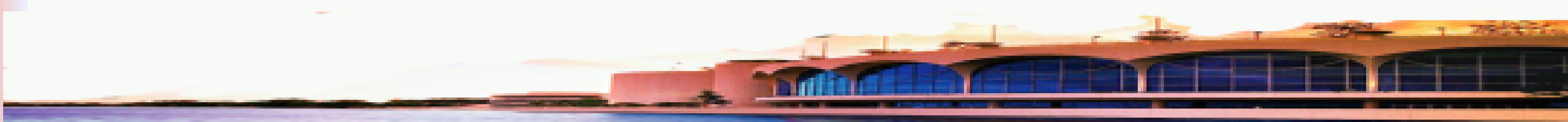
- x, y, Q_2 : usual kinematic variables of DIS
- x_J, k : longitudinal and transverse momentum of the jet

∀ $\Delta\eta = \log(x_J/x)$: rapidity interval

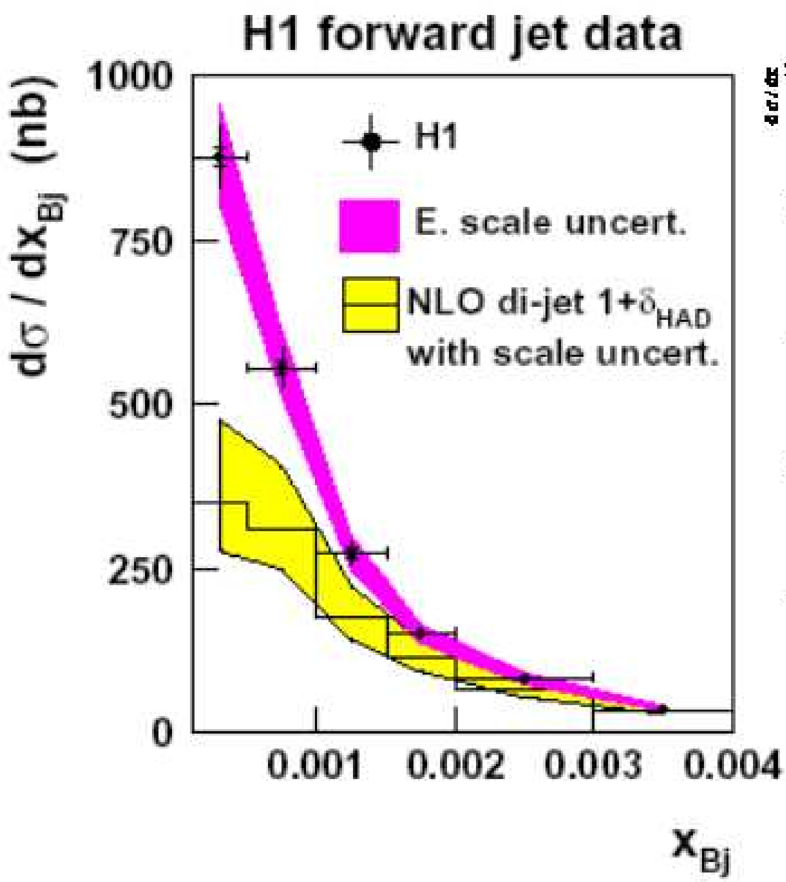
$$\frac{d\sigma}{dx\,dQ^2dx_J dk^2} = \frac{\alpha\, g_p(x_J, k^2)}{2xk^2Q^2}\left\{\frac{y^2}{2}\frac{d\sigma_T}{dk^2} + (1-y)\left(\frac{d\sigma_T}{dk^2} + \frac{d\sigma_L}{dk^2}\right)\right\}$$

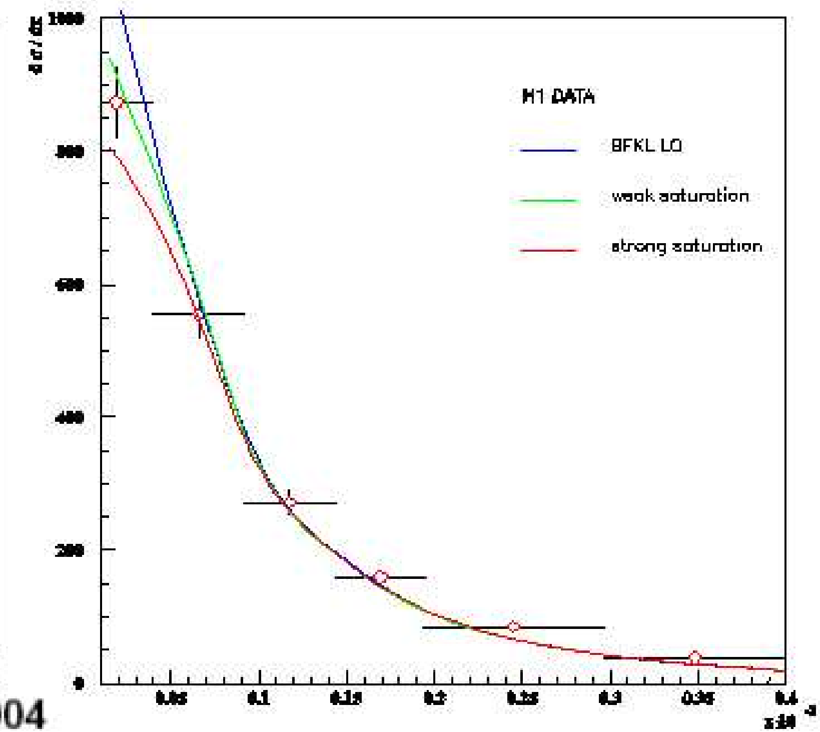
with the hard cross-section given by

$$\frac{d\sigma_{T,L}}{dk^2} = \int d^2r_1\, d^2r_2 \left|\psi_{T,L}(r_1, Q^2)\right|^2 \frac{J_0(kr_2)}{2\pi r_2}\frac{\partial}{\partial r_2} r_2 \frac{\partial}{\partial r_2}\sigma_{(gg)d}(\Delta\eta, r_1, r_2)$$



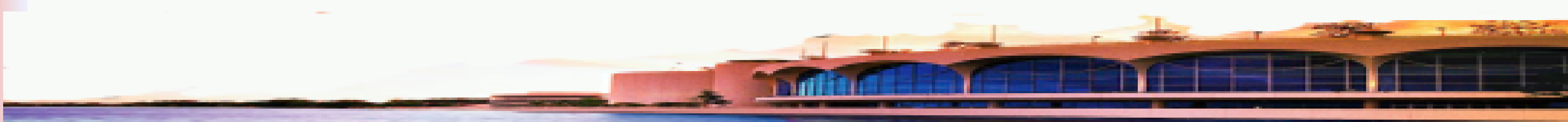
Predictions for H1 preliminary data





Resummations

Methods for systematic calculation
of perturbative cross sections
depending on several momentum scales



Computation of NNNLO-NLL logarithms in threshold resummation (N. Kidonakis)

NNNLO master formula

$$
\begin{aligned}
\hat{\sigma}^{(3)} = {} & \sigma^B \frac{\alpha_s^3(\mu_R^2)}{\pi^3} \frac{1}{8} c_3^3 \, \mathcal{D}_5(s_4) \\
& + \sigma^B \frac{\alpha_s^3(\mu_R^2)}{\pi^3} \left\{ \frac{5}{8} c_3^2 c_2 - \frac{5}{2} c_3 X_3 \right\} \mathcal{D}_4(s_4) + \frac{\alpha_s^{d_{\alpha_s}+3}(\mu_R^2)}{\pi^3} \frac{5}{8} c_3^2 A^c \, \mathcal{D}_4(s_4) \\
& + \sigma^B \frac{\alpha_s^3(\mu_R^2)}{\pi^3} \left\{ c_3 c_2^2 + \frac{c_3^2}{2} c_1 - \zeta_2 c_3^3 + (\beta_0 - 4c_2) X_3 + 2c_3 X_2 - \sum_j C_j \frac{\beta_0^2}{48} \right\} \mathcal{D}_3(s_4) \\
& + \frac{\alpha_s^{d_{\alpha_s}+3}(\mu_R^2)}{\pi^3} \left\{ \frac{1}{2} c_3^2 T_1^c + \left[2 c_3 c_2 - \frac{\beta_0}{2} c_3 - 4 X_3 \right] A^c + c_3 F^c \right\} \mathcal{D}_3(s_4) \\
& + \sigma^B \frac{\alpha_s^3(\mu_R^2)}{\pi^3} \left\{ \frac{3}{2} c_3 c_2 c_1 + \frac{1}{2} c_2^3 - 3 \zeta_2 c_3^2 c_2 + \frac{5}{2} \zeta_3 c_3^3 + \left(-3 c_1 + \frac{27}{2} \zeta_2 c_3 \right) X_3 \right. \\
& \quad + (3 c_2 - \beta_0) X_2 - \frac{3}{2} c_3 X_1 - \sum_i C_i \frac{\beta_1}{8} + \sum_j \frac{\beta_0^2}{16} B'^{(1)}_j + \sum_j \frac{3}{32} C_j \beta_1 \\
& \quad \left. + \sum_j C_j \frac{\beta_0}{16} \left[\beta_0 \ln\left(\frac{\mu_R^2}{M^2} \right) + 2K \right] \right\} \mathcal{D}_2(s_4) \\
& + \frac{\alpha_s^{d_{\alpha_s}+3}(\mu_R^2)}{\pi^3} \left\{ \left(\frac{3}{2} c_3 c_2 - 3 X_3 \right) T_1^c + \frac{3}{2} \left[c_2 + c_3 \ln\left(\frac{M^2}{s} \right) \right] F^c \right. \\
& \quad + \left[\frac{3}{2} c_2^2 + \frac{3}{2} c_3 c_1 - 3 \zeta_2 c_3^2 + 3 X_2 + \frac{\beta_0^2}{4} - \frac{3}{4} \beta_0 \left(c_2 - \frac{c_3}{2} \ln\left(\frac{\mu_R^2}{M^2} \right) \right) \right. \\
& \quad \left. \left. - \frac{3\beta_0}{8} c_3 \ln\left(\frac{M^2}{s} \right) \right] A^c + \frac{3}{2} c_3 G^c + \frac{1}{2} K_3^c \right\} \mathcal{D}_2(s_4) \quad + \cdots
\end{aligned}
$$

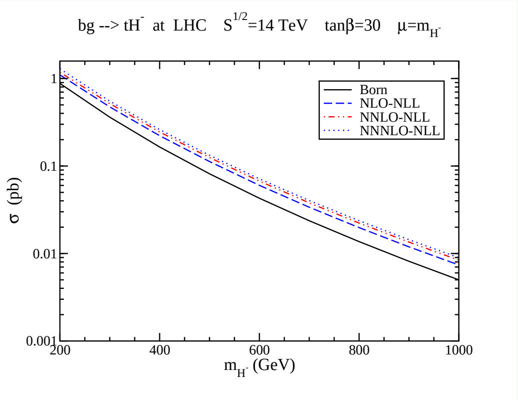
Here $X_3 = (\beta_0/12) c_3 - \sum_j C_j \beta_0/24$

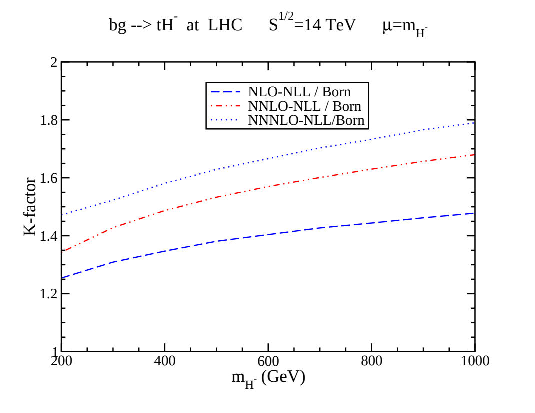
$X_2 = -(\beta_0/4) T_2 + (\beta_0/8) c_3 \ln(\mu_R^2/M^2) + c_3 K/4 - \sum_j (\beta_0/8) B'^{(1)}_j$

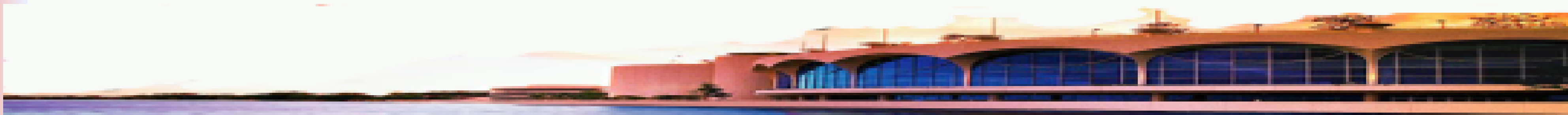
$X_1 = c_2 c_1 - \zeta_2 c_3 c_2 + \zeta_3 c_3^2 + (\beta_0/4) \zeta_2 c_3 - \sum_j C_j (\beta_0/8) \zeta_2 - C^{(2)}_{D_0}$

$$
\begin{aligned}
K_3^c = {} & \mathrm{tr} \left[H^{(0)} \left(\Gamma'^{(1)\dagger}_S \right)^3 S^{(0)} + H^{(0)} S^{(0)} \left(\Gamma'^{(1)}_S \right)^3 \right. \\
& \left. + 3 H^{(0)} \left(\Gamma'^{(1)\dagger}_S \right)^2 S^{(0)} \Gamma'^{(1)}_S + 3 H^{(0)} \Gamma'^{(1)\dagger}_S S^{(0)} \left(\Gamma'^{(1)}_S \right)^2 \right]
\end{aligned}
$$

NNNLO soft-gluon corrections for charged Higgs production



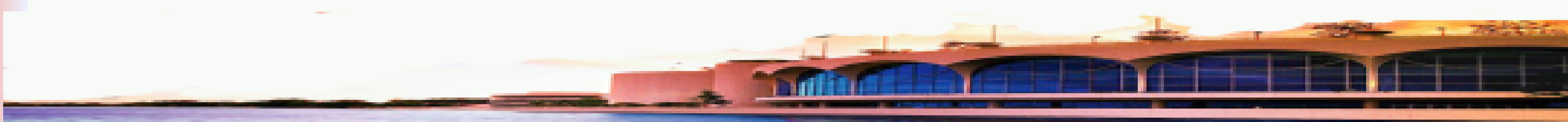




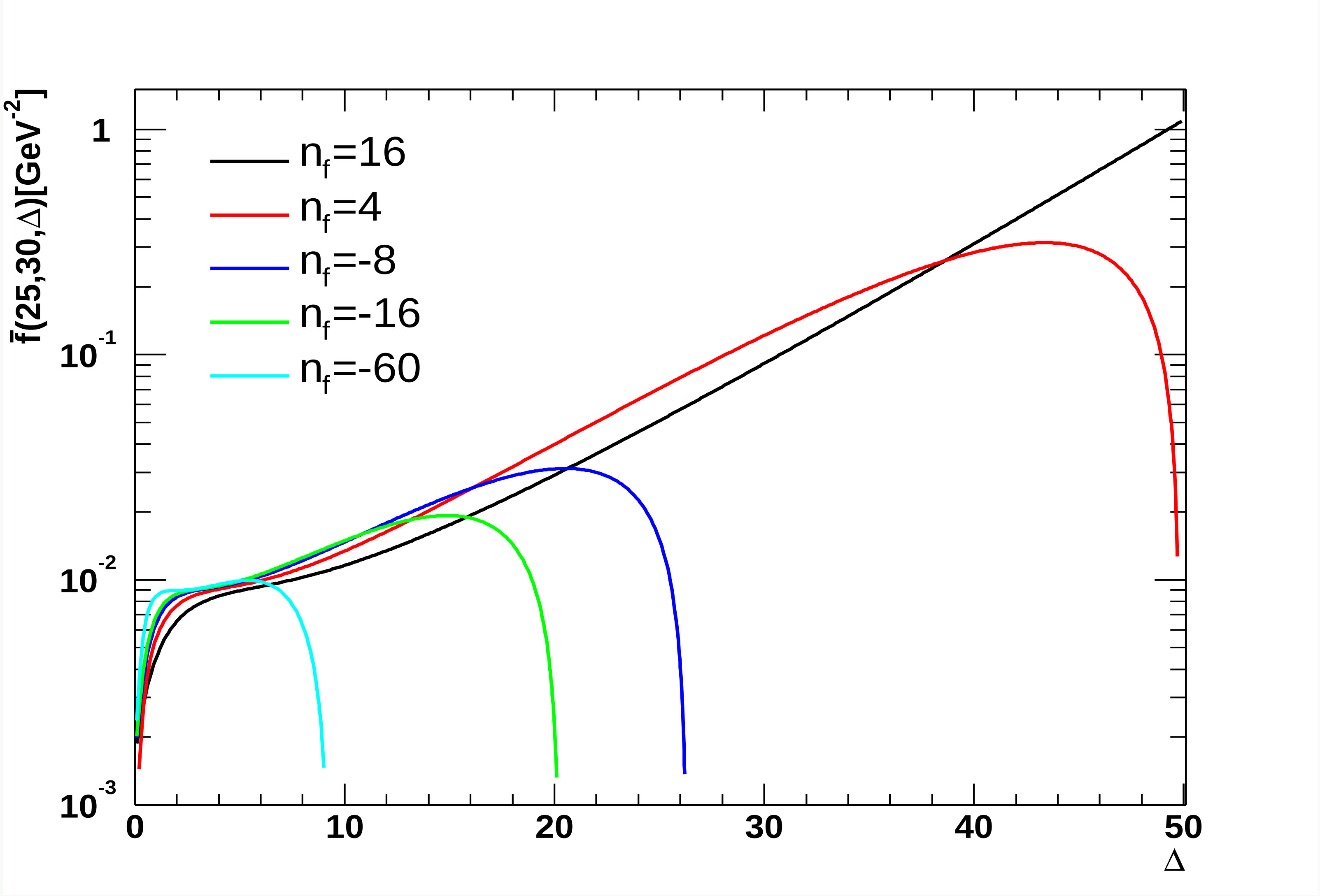
Solving NLL BFKL by iteration
(J. Andersen)

We propose an iterative approach to the BFKL equation at NLLA that solves the equation with *no approximations*

- Directly in the physical rapidity and transverse momentum space
  (avoids the use of the troublesome Mellin transform completely)
- The right language for use of impact factors (physics predictions!)
- Hopeful in extending the approach to final state studies like at LL
- Expresses the solution in terms of effective vertices and no-emission probabilities (physical insight into the BFKL solution at NLLA!)



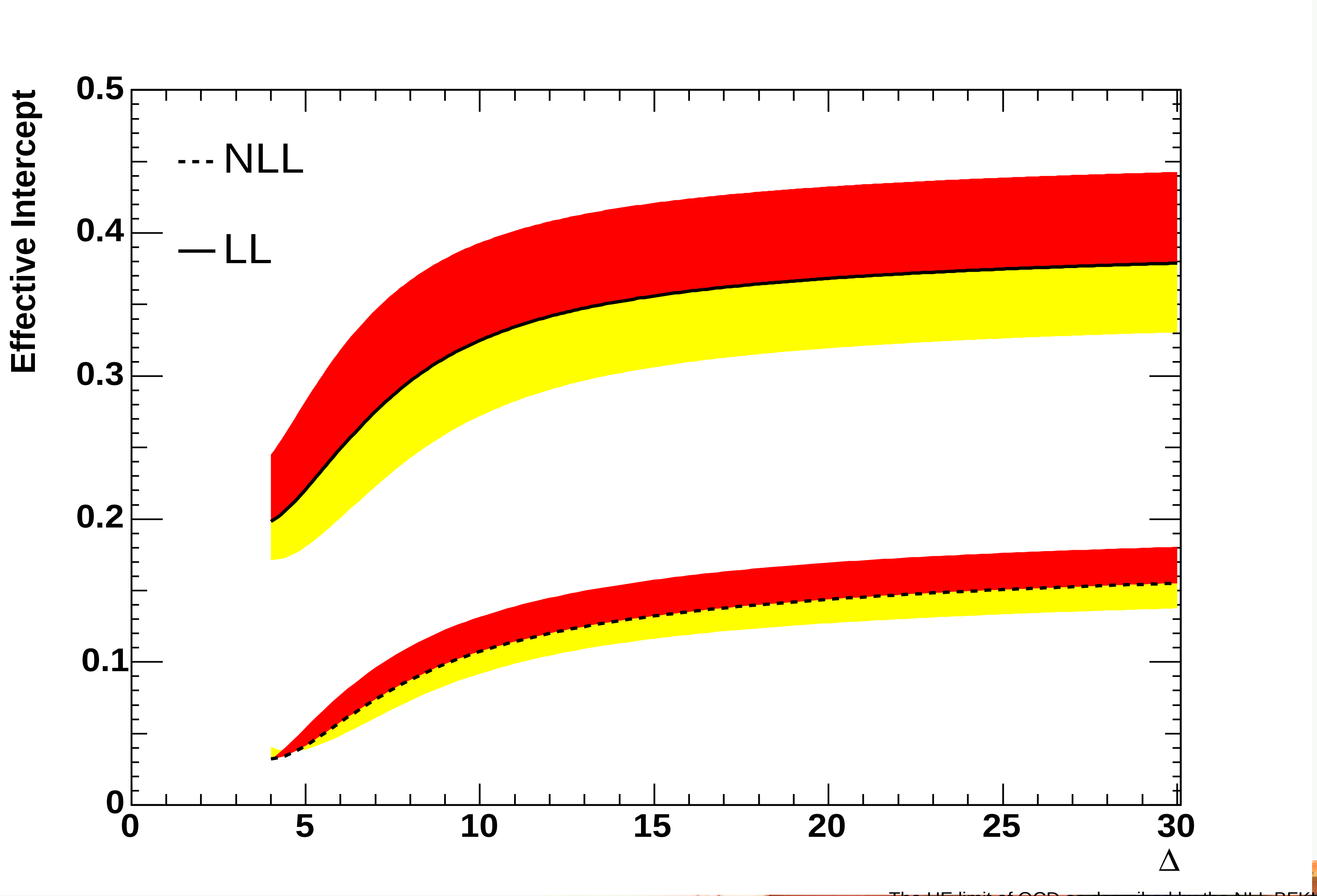
Leading Log tools at NLL



!!this would be a major catastrophe!!

BFKL Intercept

QCD, $n_f = 4$, one loop running



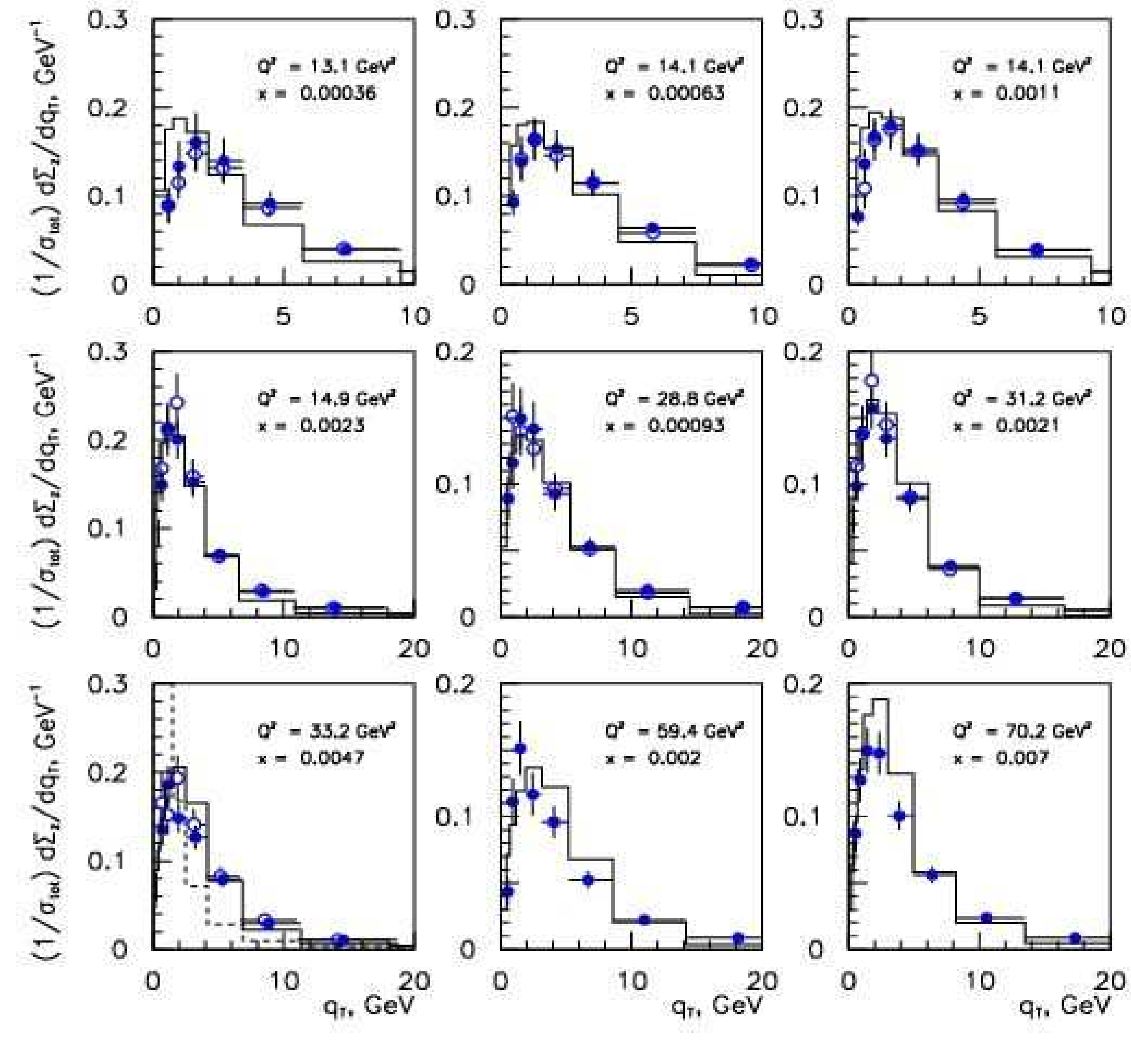
Transverse momentum resummation at small x

(F. Olness, in collaboration with S. Berge, P. N., and C.-P. Yuan)

Universality of soft-gluon resummation at small q_T in the Drell-Yan process and current region of SIDIS

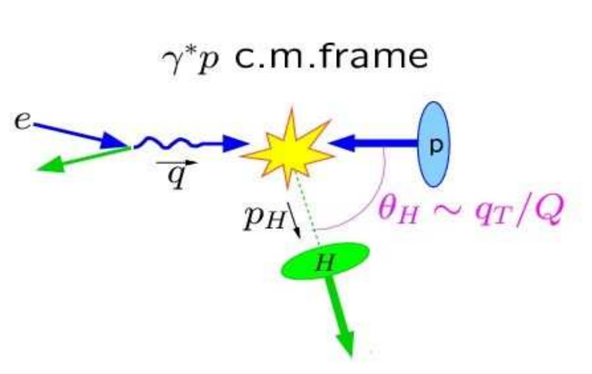
$\Rightarrow$predictions for Drell-Yan q_T distributions at $x < 10^{-2}$ based on HERA E_T data

Differential energy flow at small-x???



$$\frac{d\Sigma_z}{dx\,dQ^2\,dq_T}$$

$$d\Sigma_z = \int z \frac{d\sigma}{dz}$$

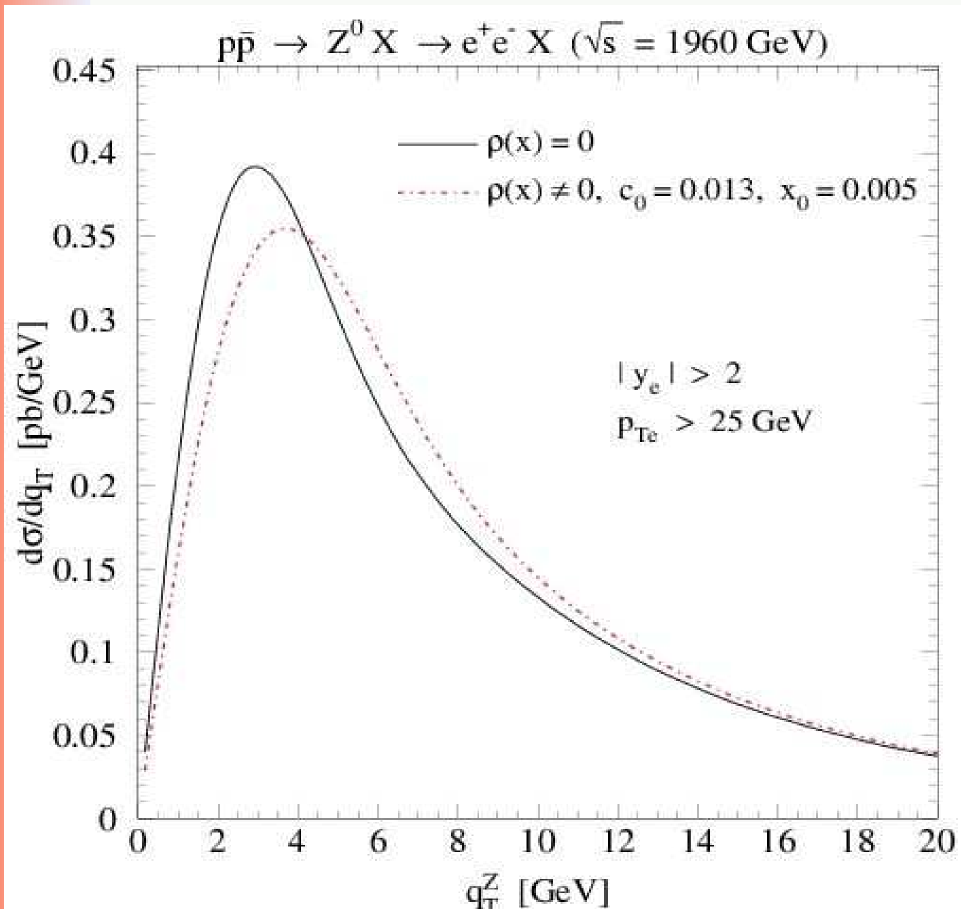


Extra q_T broadening for $x<10^{-2}$

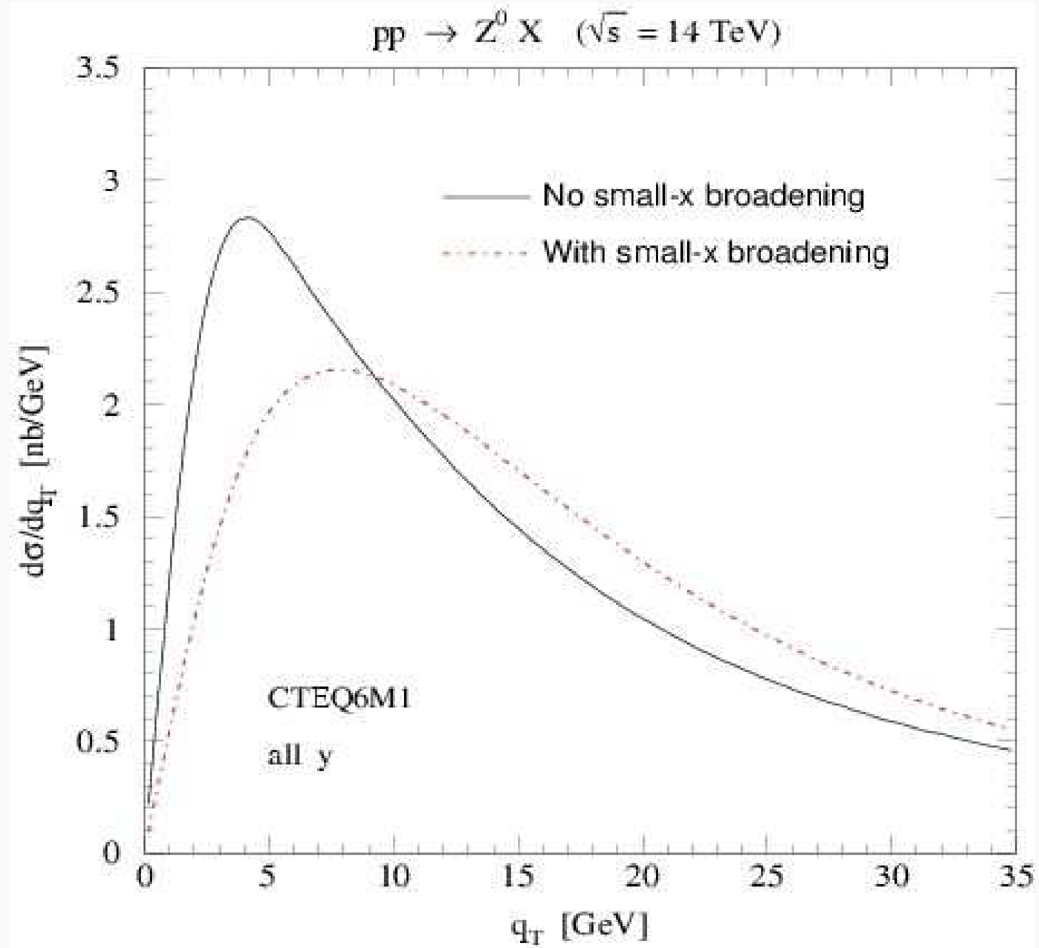
H1 Collaboration,
PL B356, 118 (1995)
EPJ C12,595 (2000)

Z Production: Tevatron & LHC

Tevatron



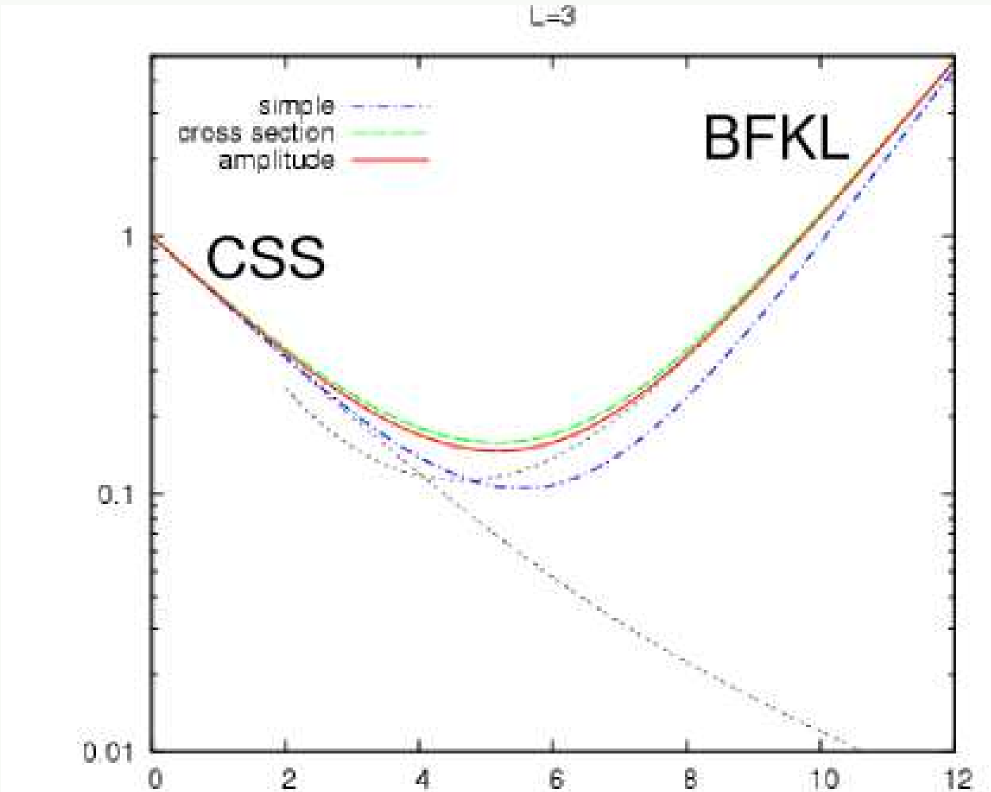
LHC

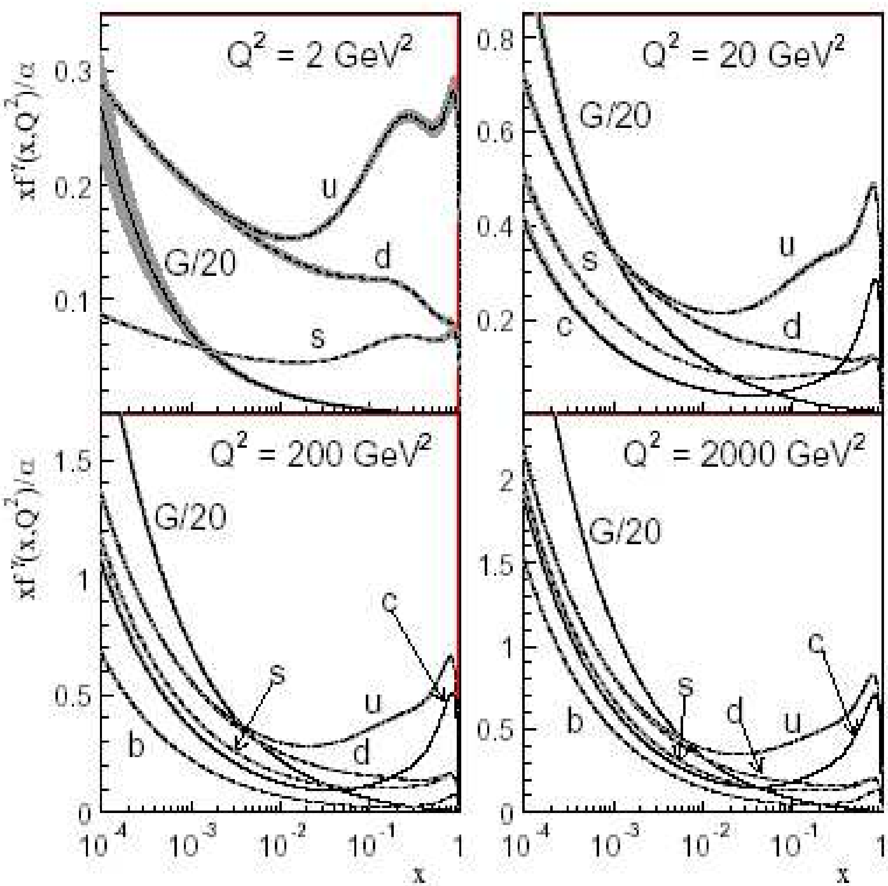


With cuts on y_e and p_{Te}

No y cut necessary !!!

Merging CSS and BFKL resummations for interjet particle production at high energies (A. Kyrieleis)





SAL PDFs

The bands mark the fit uncertainty.

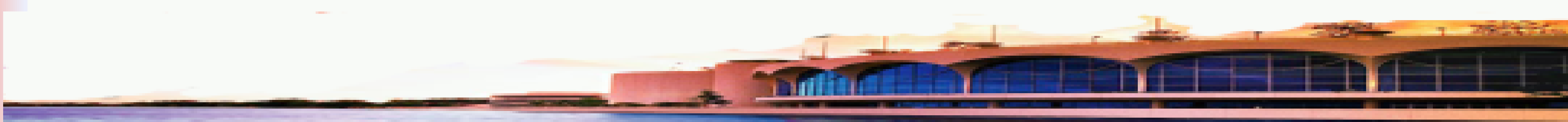
New parametrization of photon PDF's from ee and ep data (A. Levy)

Pentaquarks:

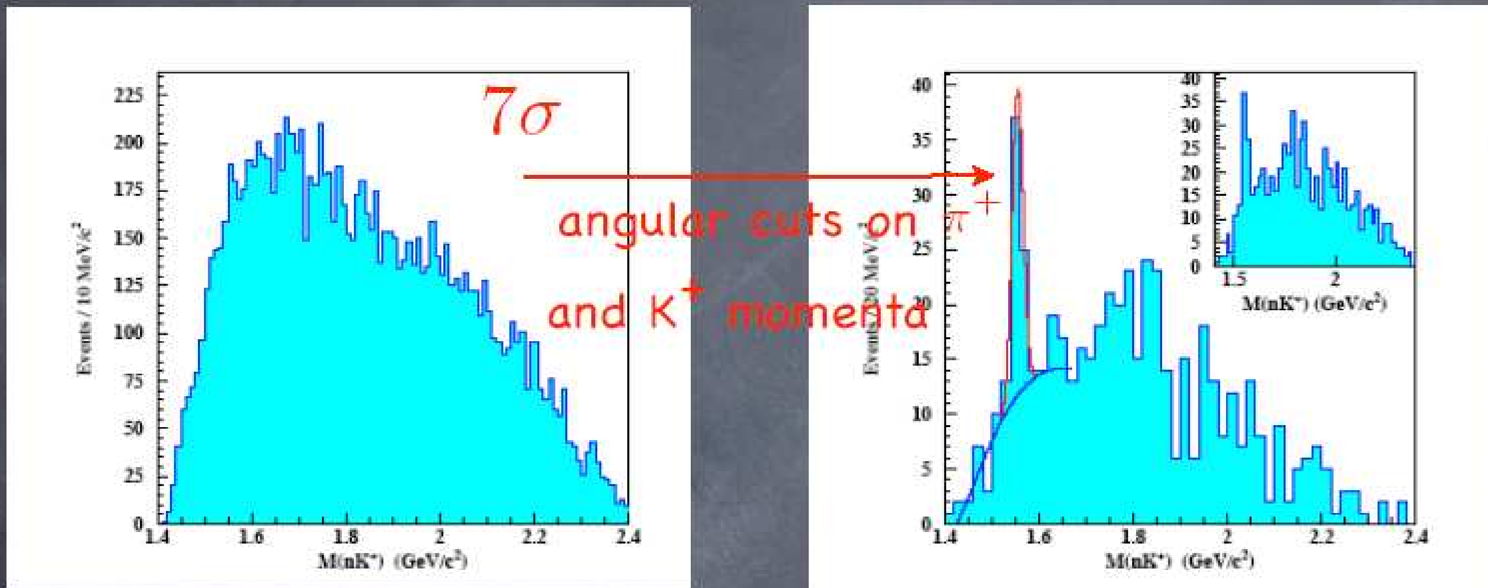
critical examination of the (absence) of the evidence

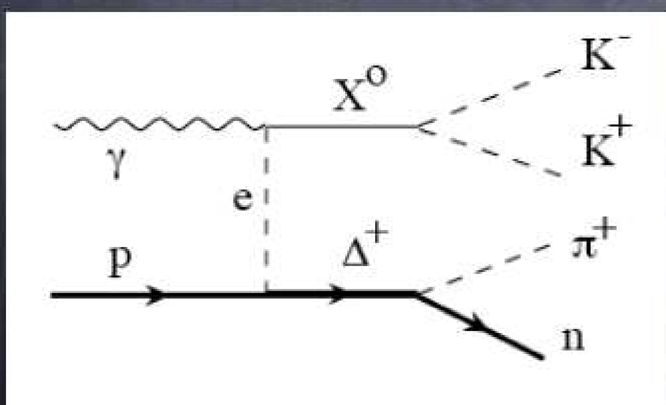
(A. Szczepaniak, based on hep-ex/0412077 with A. Dzierba and C. Mayer)

- Statistical significance of the discovery reports
- Conventional sources of spurious peaks
  - Kinematical reflections
  - Hidden particle exchanges
  - Kinematical cuts



CLAS (proton) $\gamma p \rightarrow \pi^+ K^- K^+ n$



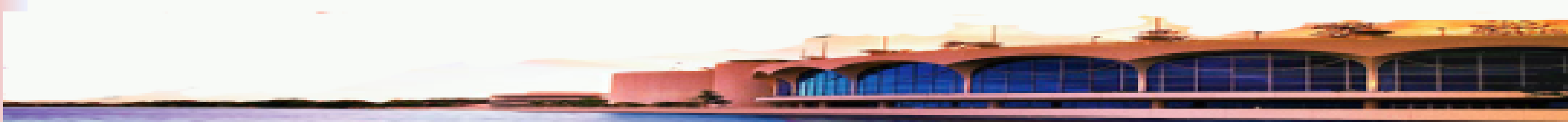


Can generate resonance-like structure in K^+K^-n spectrum and π^+ momentum cut enhances kinematic reflections from decays of K^+K^- resonances

not an explanation of the actual pentaquark data!

Pentaquark sightings come from low statistics, low resolution, low-energy experiments with kinematically constrained final states after complicated cuts are imposed.

High resolution, high statisitcs, experiments with both low- and high- particle multiplicity do not report the pentaquarks.



DIS 2005 April 27-May 1, 2005 Madison, Wisconsin U.S.A.

New possible insight into JLab proton polarization data puzzle by DIS

A. Z. Dubničková[1],

S. Dubnička[2],

Proton is compound of **quarks** $\Rightarrow$ **non-pointlike** - in EM interactions it **manifests EM structure** to be described (equally well neutron EM structure) by **two independent scalar functions (form factors FF's) of one variable** $t = -Q^2$, the squared four-momentum transferred by the exchanged virtual photon.

There is some **freedom in the choice of proton EM FF's**.

The most suitable in extracting of experimental information are **Sachs electric** $G_{Ep}(t)$ and **magnetic** $G_{Mp}(t)$ FF's, giving in the Breit frame the **charge and magnetization distributions** within the proton, respectively.

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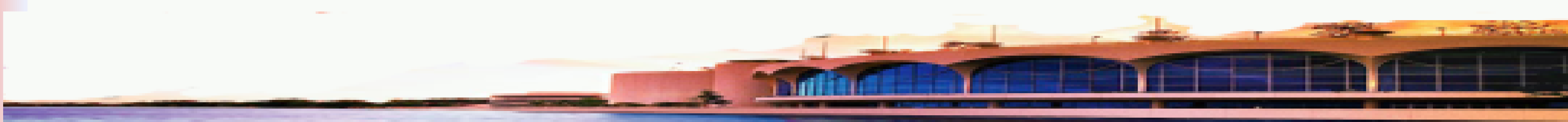

Conclusions

- Progress is made towards understanding of various aspects of hadroproduction
- Many questions remain, especially related to QCD physics at energies accessible at the LHC
- Systematic study of perturbative corrections, resummations, and non-perturbative models must go on in order to meet objectives of the LHC physics program