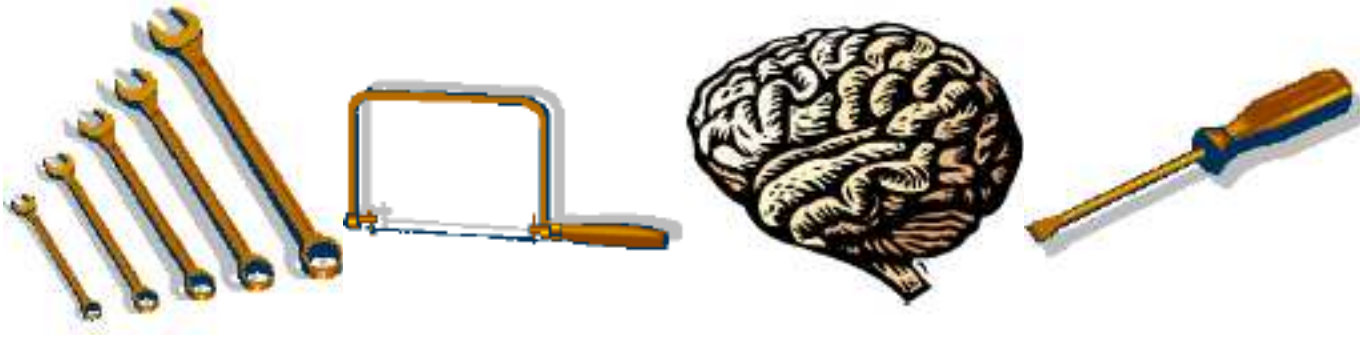
reSummation® tools



of the Q_T kind

A Csaba Balázs presentation @ Fermilab, Run2 MC Workshop 4/19/2001
In collaboration with: J.Collins, D.Soper, J.Huston, I.Puljak & C.-P.Yuan
Available: www.phys.hawaii.edu/~balazs/Physics/Talks/2001/Fermilab

Factorization and soft gluon reSummation™

- Factorization, transverse momentum, reSummation™
- Matching of low and high Q_T

Numeric implementations

- Application to various processes
- various approaches, codes

Parton showers

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The first expert of **S**ummation ...

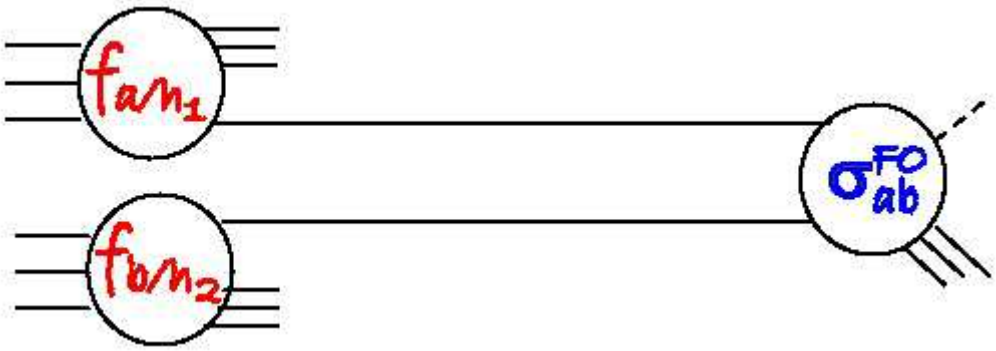
Rene Descartes: "Cogito ergo sum"

(This picture was probably painted before his death...)

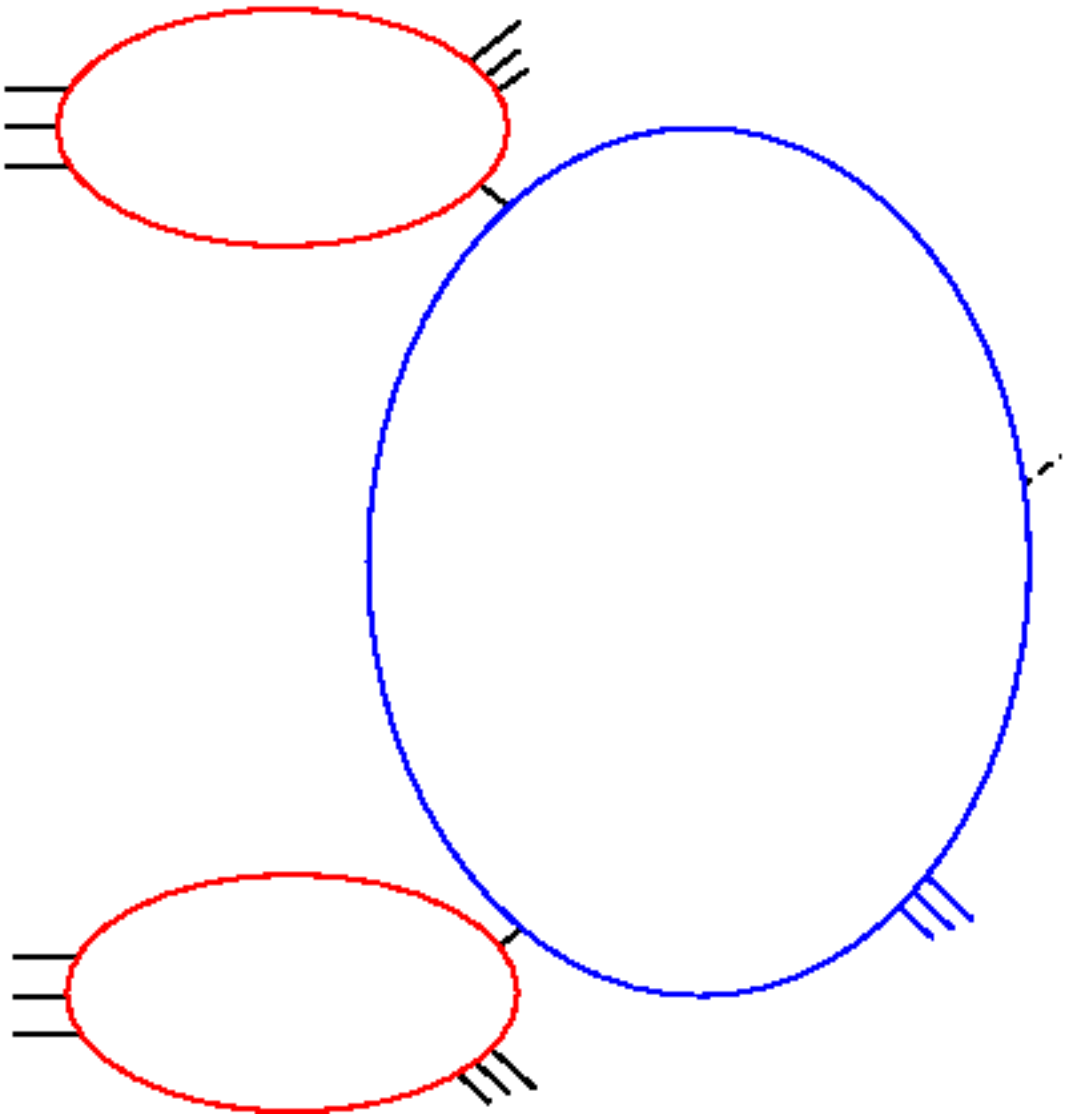
In the Run 2 era: Cogito ergo re sum

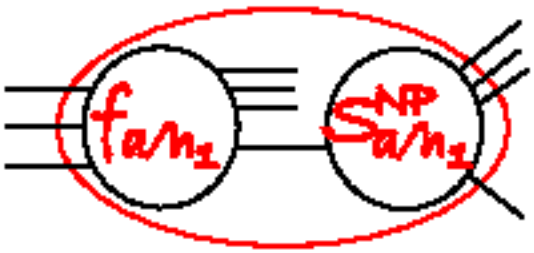
Factorization

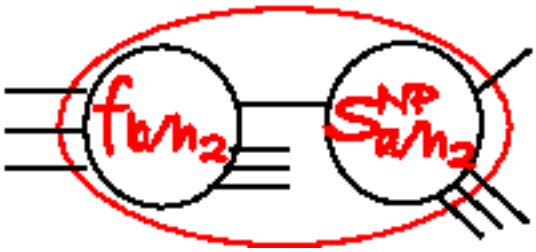
Standard hadronic factorization



Low Q_T factorization

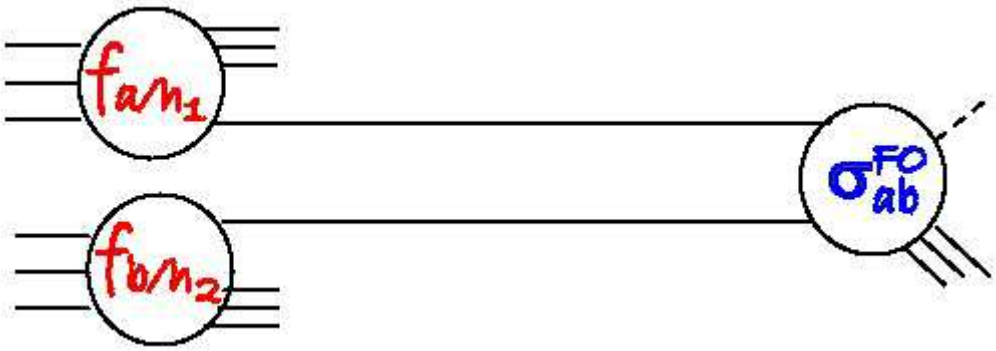



f_{a/n_1}
S^{NP}_{a/n_1}

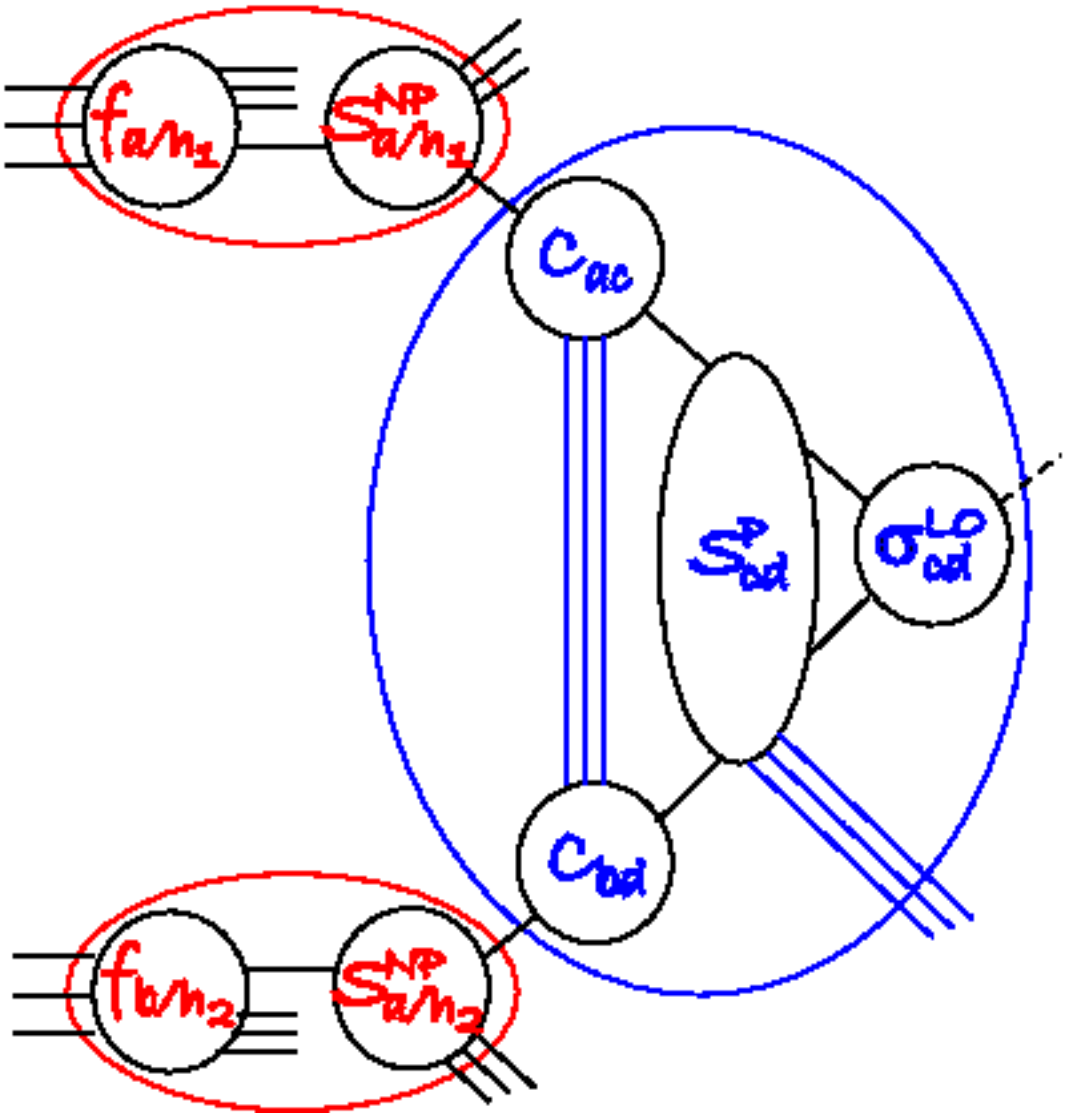

f_{a/n_2}
S^{NP}_{a/n_2}

Factorization

Standard hadronic factorization



Low Q_T factorization



Factorization and Q_T

The story of the "Big Bad Log". D.Soper

Factorization theorem

— For $h_1 h_2 (gg) \to HX$, the fully differential cross section is factorized (m_F = Q inv. mass):

$$d\sigma \sim f(x_1, Q) \, f \, H(Q, Q_T, x_1, x_2) \, f \, f(x_2, Q)$$

• At LO $Q_T = 0$ ⇒ $\sigma^{LO} \sim \delta(Q_T)$ "kinematic" singularity

— In fixed order QCD corrections, after the cancellation of the IR singularities, the Q_T dist'n contains $L = \ln\left(\frac{Q^2}{Q_T^2}\right)$

$$\frac{d\sigma}{dQ_T^2} \underset{Q_T \to 0}{\propto} \frac{\alpha_s^n}{Q_T^2} c_{n,m} L^m + O\left(\frac{1}{Q_T^2}\right), \quad 0 \le m \le 2n-1$$

• Each log is due to the emission of a soft gluon (double logs ⇐ soft & collinear gluons)

• Factorization is proven for, and works when, $Q_T \sim Q$ or Q_T is integrated over ("one scale problem")

• When the two scales, Q and Q_T, are different, $\alpha_s L > 1$ and the perturbative expansion of $H(Q, Q_T, x_1, x_2)$ doesn't converge ⇒ breakdown of factorization

Low Q_T factorization

Collins, Soper, PRL48 655, NPB193 381, NPB197 446 (`83)

Collins, Soper, Sterman, NPB250 199 (`85)

Modified factorization theorem

$$\frac{d\sigma}{dQ_T} = W(Q_T, Q) + Y(Q_T, Q)$$

$$W(Q_T, Q) = \int d^2 k_T \, C(\vec{k}_T, Q) \, H(Q, Q_T) \, C(\vec{Q}_T - \vec{k}_T, Q)$$

- The idea is to iteratively (order by order in α_S) absorb the kinematic singularity into a PDF-like object
- $C(\vec{k}_T, Q)$ are k_T dependent "parton densities"
- No need for "intrinsic k_T"
- W is simpler in transverse position (b) space

$$W(Q_T, Q) = \frac{1}{2\pi} \int d^2 b \, e^{i \vec{Q}_T \cdot \vec{b}} \tilde{W}(b, Q)$$

$$\tilde{W}(b, Q) = \tilde{C}_{a/h_1}(b, Q) \, \tilde{H}(b, Q) \, \tilde{C}_{b/h_2}(b, Q)$$

— Why b-space? Parisi, Petronzio, NPB154 427 ('79)

- multi-gluon phase-space factorizes
- cross section factorizes $\leftrightarrow f(f \otimes g) = f(f) f(g)$
- transverse momentum conservation is explicit
- RG invariance is preserved

Low Q_T vs. standard factorization ...

Standard factorization	Low Q_T factorization
initial logarithmic singularity	
$\ln(m_q/\mathbf{m})$	$\ln(Q/Q_T)$
associated perturbative kernel	
Splitting functions	Sudakov exp., Wilson coeff.
governing the perturbative evolution (RGE)	
DGLAP	CSS
iterative solution Æ reSummation™	
"collinear" singularities	"soft" (& double) singularities
including non-perturbative sector	
$f(x, Q_0)$	$f(x, Q_0)\, S_{NP}(b_0)$

- In this spirit your #1 hadronic resummation tool is the CTEQ PDF evolution package

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Partial Summation of perturbative series

"'Resummation' suggests that you summed it but screwed up, and you have to sum it again..." D.Soper

— $\tilde{W}$ satisfies the RGE:

$$\partial_{\ln Q^2}\,\tilde{W}(b,Q) = \left(\int_{c_1^2/b^2}^{c_2^2 Q^2}\frac{d\mu^2}{\mu^2}\,A(\alpha_s(\mu))\right) - B(Q)\,\tilde{W}(b,Q)$$

• The solution is easy as ABC:

$$\tilde{H}(b,Q) = e^{-S(b,Q)}$$

leads to the Sudakov exponent, which reSums the logs:

$$S(b,Q) = \int_{c_1^2/b^2}^{c_2^2 Q^2}\frac{d\mu^2}{\mu^2}\,A(\alpha_s(\mu))\,\ln\left(\frac{c_2^2 Q^2}{\mu^2}\right) - B(\alpha_s(c_2 Q))$$

• Logs under control : A, B, and C can be calculated in PT

$$A(\alpha_s(\mu)) = \sum_{i=1}\left(\frac{\alpha_s(\mu)}{\pi}\right)^i A^{(i)}, \text{ etc. for } B \text{ and } C$$

— The modified "PDFs"

$$\tilde{C}_{a/h_1}(b,Q) = C_{ab}(b)\otimes f_{b/h_1}\,e^{S_{NP}(b,Q)/2}$$

$$S_{NP}(b,Q) = g_1 b^2 + g_2 b^2 \ln\left(\frac{Q}{Q_0}\right) + g_1 g_3 b \ln(100\, x_1 x_2)$$

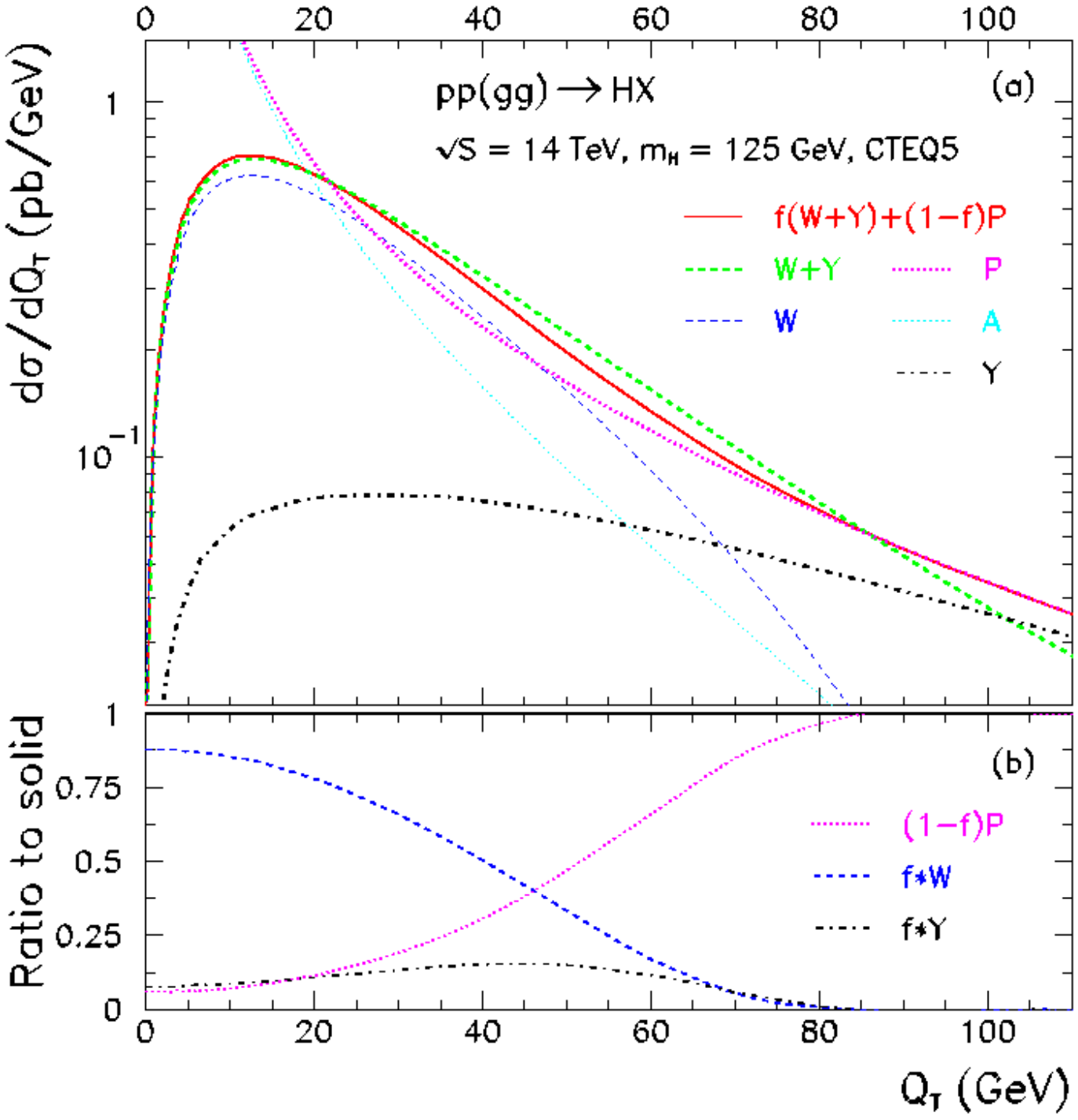
• A, $B^{(1)}$ and g_2 are universal

B, $C_{ab}(b)$ and g_1 are process dependent

• The non-perturbative function S_{NP} carries the transverse information, (further) "smearing" the cross section at low Q_T

Low Q_T factorization — in one picture

— The full story of the re**S**ummation of $\log(Q/Q_T)$



Matching

Plan A

— QCD corrections to the Q_T dist'n contain log's:

$$\frac{ds}{dQ_T^2} \quad \frac{\text{æ}}{Q_T \text{Æ} 0} \quad \frac{\text{Æ}}{Q_T^2} \quad a_s^n \, c_{n,m} \, L^m + O \quad \frac{\text{Æ}}{Q_T} \quad M$$

FxO = Singular (Asy) + Regular (Y)

Y ∫ FxO - Asy

— After exponentiation of the singular pieces:

$$ds = W + Y$$

$$= W + FxO - Asy$$

W ∫ "1 - e^{-Asy}"

• At low Q_T: Logs large fi FxO ª Asy fi ds ª W

— Here's how matching works:

• At high Q_T: Logs small fi W ª Asy fi ds ª FxO

The correct high Q_T behavior is built into the formalism

Improved matching

"Plan B." Folklore

— Problem: W contains reSummed logs and Asy is calculated up to some fixed order in a_s **fi** the orders of W and Asy mismatch **fi** at high Q_T matching has problems

— Solution: switch from reSummed to fixed order when W **+** Y becomes unreliable

- Switch at some arbitrary point: generates discontinuity
- Switch where reSummed and fixed orders cross: generates a kink
- Switch over an extended region in Q_T (this is done presently in ResBos): results in smooth Q_T dist'n

— Modify W **+** Y such that it matches FxO better at high Q_T

Applications of low Q_T factorization

Extract from the HEPWebster's:

Res.Bos */'rez,bɔuz/* ***1 n AmE*** Monte Carlo event generator for "***Res***summed ***Bos***on production", implementing the low trans verse momentum hadronic factorization formalism; calculates QCD corrections to the inclusive processes hadrons Ø boson(s) + X Ø decay products (when applicable), for boson(s) = photon, Z^0, $W^{\leq}$, H^0, diphoton, Z^0-pair or gluon. ***2 v*** To use the computer code ResBos.

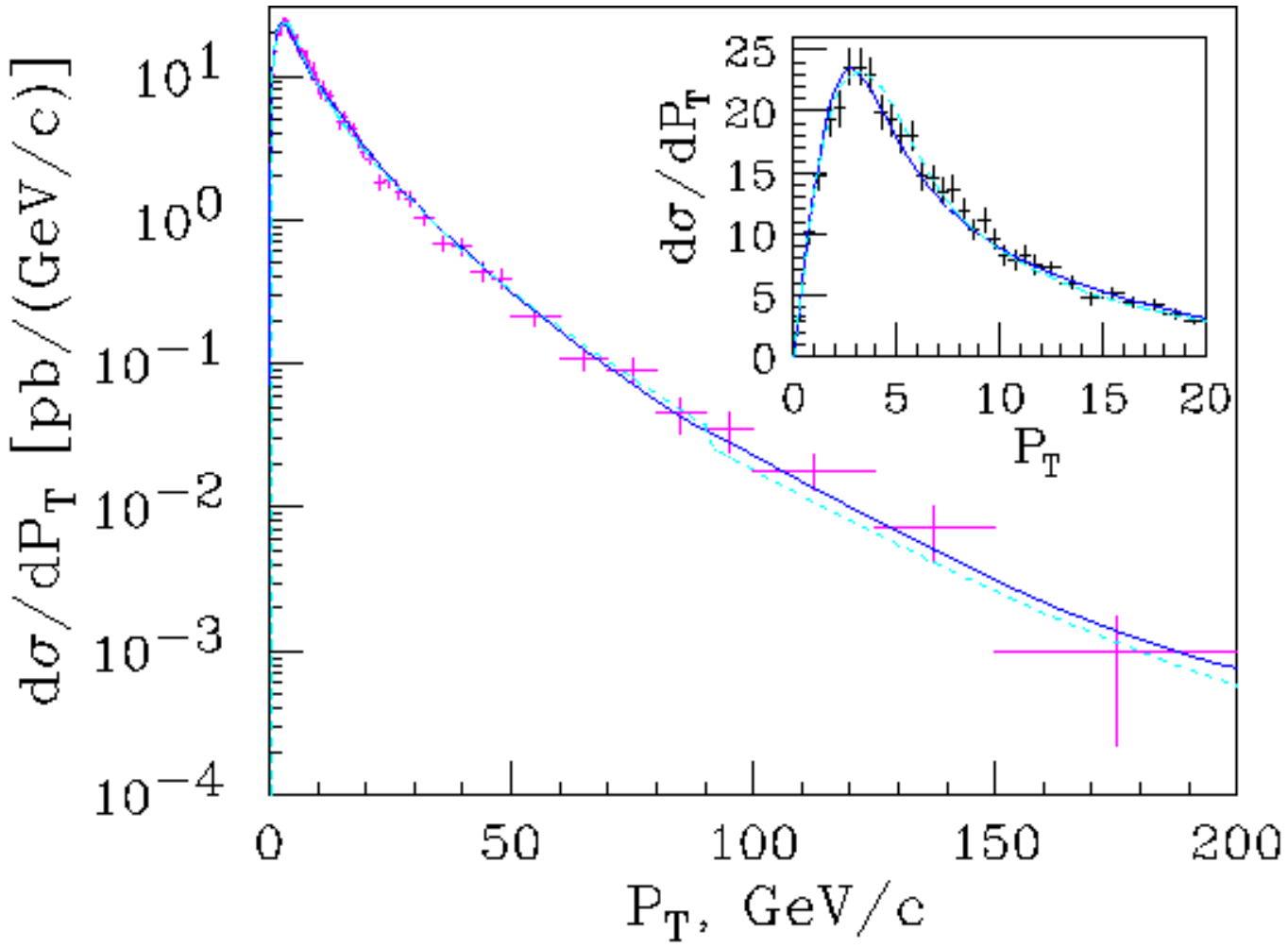
VBP */'víbípí/* ***1 n AmE*** Analytic style implementation of resummed QCD corrections for ***V***ector ***B***oson ***P***roduction in qt- and b-spaces (orig.: Fermilab).

"Stirling-Kulesza" */'stirling-kulesza/* ***1 n BrE*** Re-summed $W^{\leq}$ and Z^0 production implementation in both spaces (orig.: Durham).

Why should I believe any of this at all?

— Experiments for various E_{CM}, initial states and hard processes agree well with the formalism

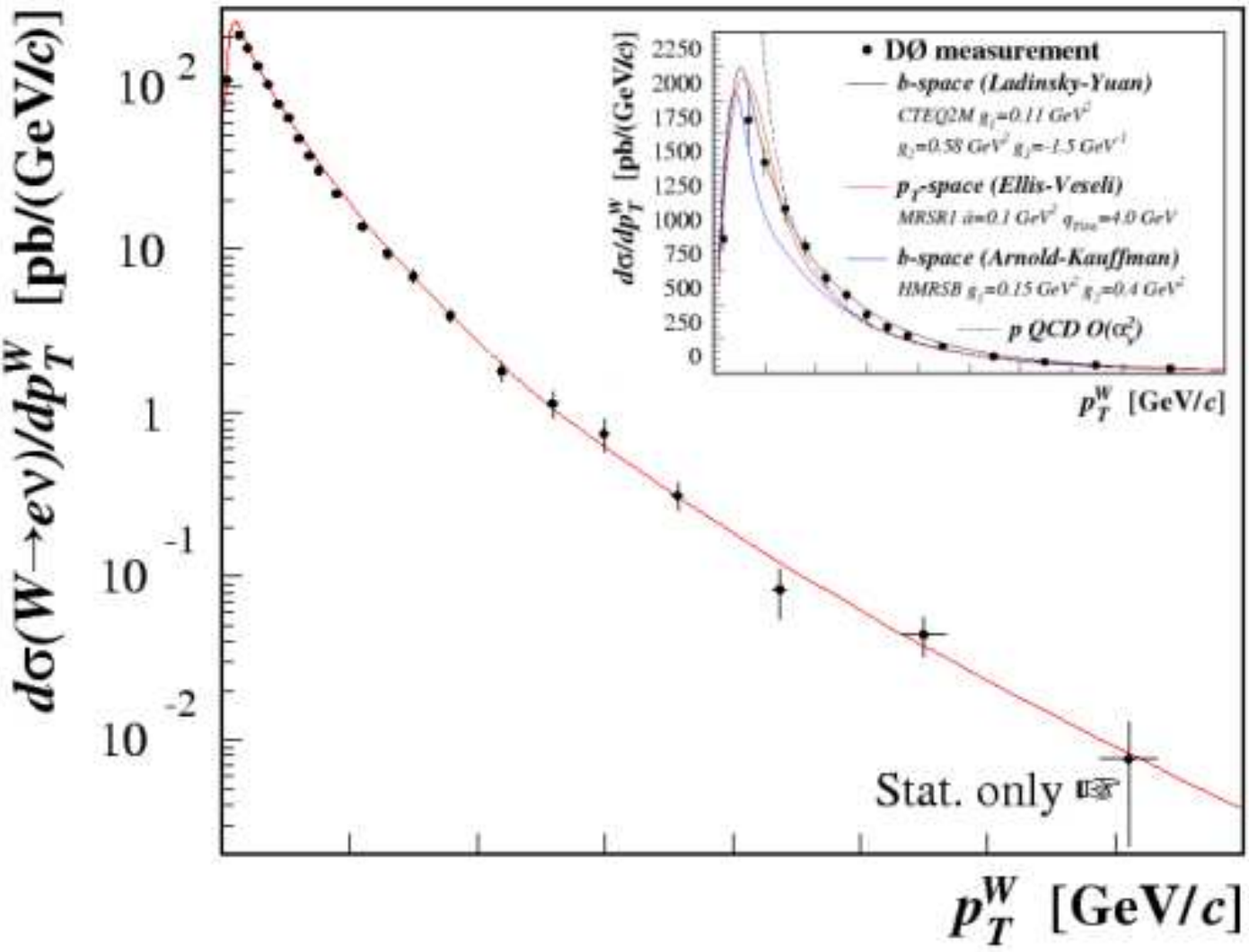
— Z^0 production at CDF



www-cdf.fnal.gov/physics/ewk/ptz.html

- Solid: ResBos, dash: VBP
- Expt. contact: W. Sakumoto

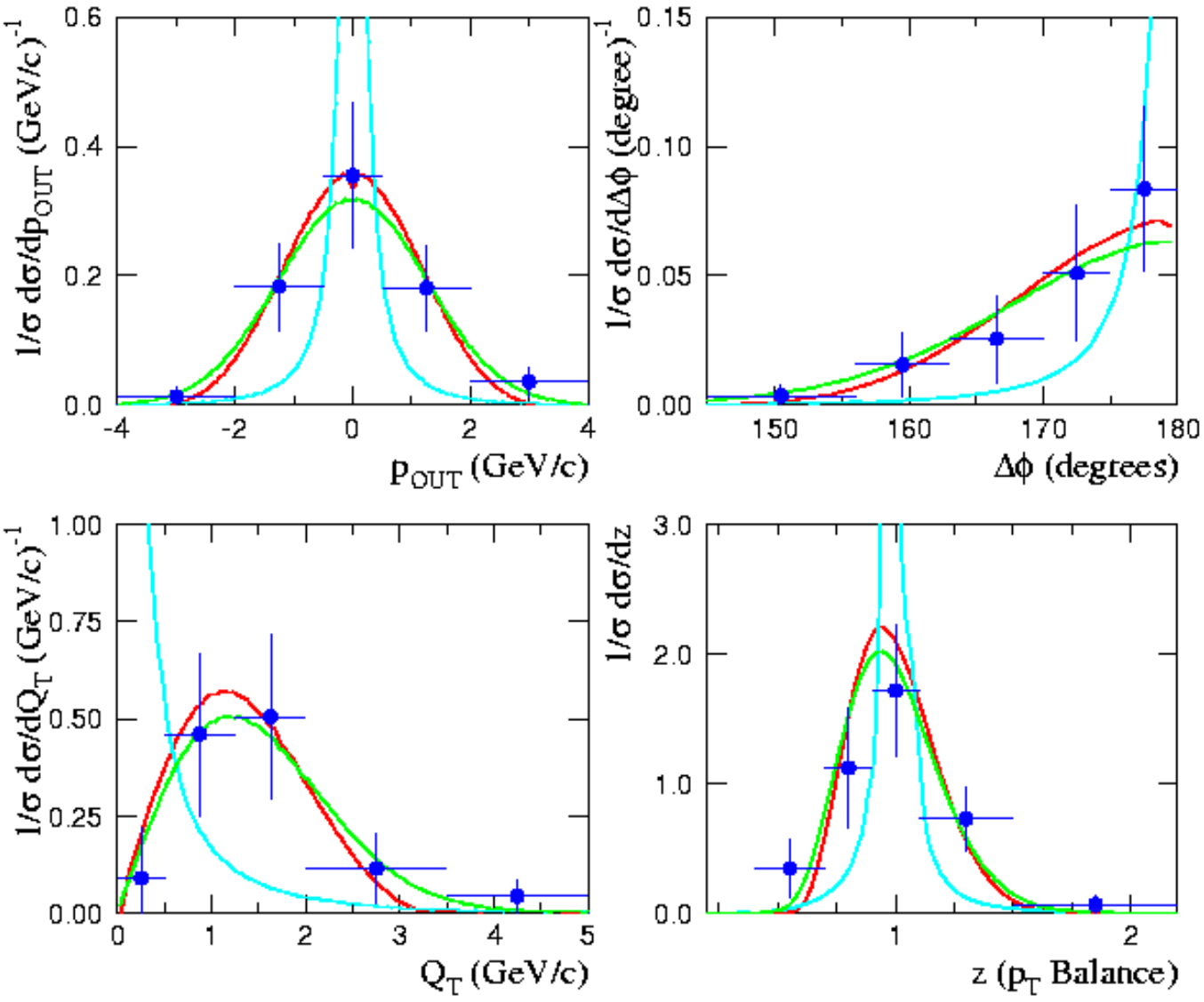
— $W^{\pm}$ production at DØ



www-d0.fnal.gov/public/wz/wzqcd/pt/pt.html

- Red: ResBos (Inset — black: ResBos, red: VBP, blue: AK)
- Expt. contact: D. Casey or C. Gerber

$p^- Be \rightarrow \gamma\gamma X$



www-d0.fnal.gov/~flattum/Public/RunII/MarchMeeting/Photons/marek.ps

- Red: ResBos, green: PYTHIA, blue: NLO (Bailey et al.)
- Expt. contact (E706): M. Zielinsky

"Q_T-space" approach

"To b or not to b?" K.Ellis

Ellis, Veseli, NPB511 (`98)

— Recognized problems: (i) breakdown of W + Y at large Q_T (ii) lack of explicit matching (Q_T) (iii) "need for speed"

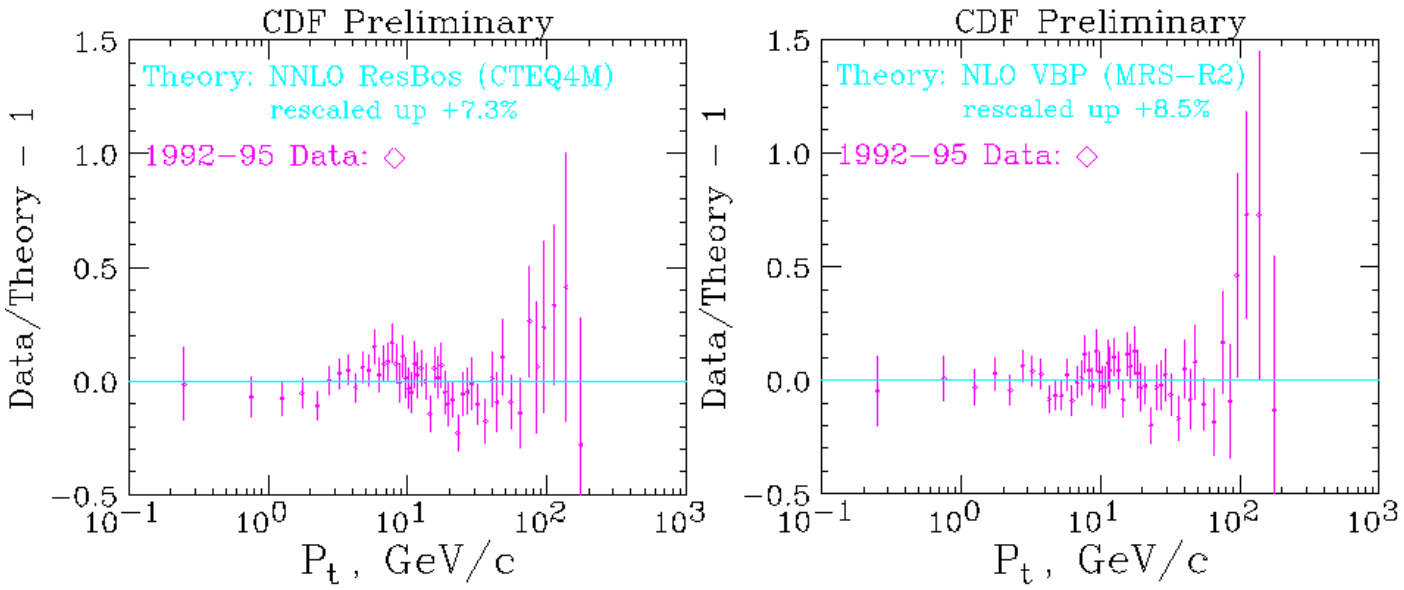
— Calculate the Fourier transform of the b-space cross section; obtain an approximate (NNNLL) expansion, in a closed form in Q_T-space:

$$W\mathbf{H}Q_T, Q\mathbf{L} = H_{ab}\mathbf{H}Q_T, Q\mathbf{L} * \int_{dQ_T} \mathbf{H}C_{a\hat{e}h_1}\mathbf{H}Q_T, x_1\mathbf{L} \,\mathbf{,,}\, {}^{T\mathbf{H}Q,Q_T\mathbf{L}}\, C_{b\hat{e}h_2}\mathbf{H}Q_T, x_2\mathbf{LL}$$

• Final result is elegant, similar to the original DDT (Dokshitzer-Diakonov-Troian) formula

• Reintroduce the k_T dependent component of the PDF's, and include Y for the high Q_T region

• Numerical implementation: VBP (K.Ellis, S.Veseli)



http://www-cdf.fnal.gov/physics/ewk/ptz.html

More "Q_T-space" approaches

— "Q_T-space" approach #2

Frixione, Nason, Ridolfi, NPB542 (`99)

• Starting from the b-space re**S**ummation formula, analytically perform the b integral, keeping NLL accuracy

• Result exhibits singularities at high Q_T

• Y piece and matching are not considered

— "Q_T-space" approach #3

Stirling, Kulesza, NPB555 (`99), JHEP 0001:016 (`00),

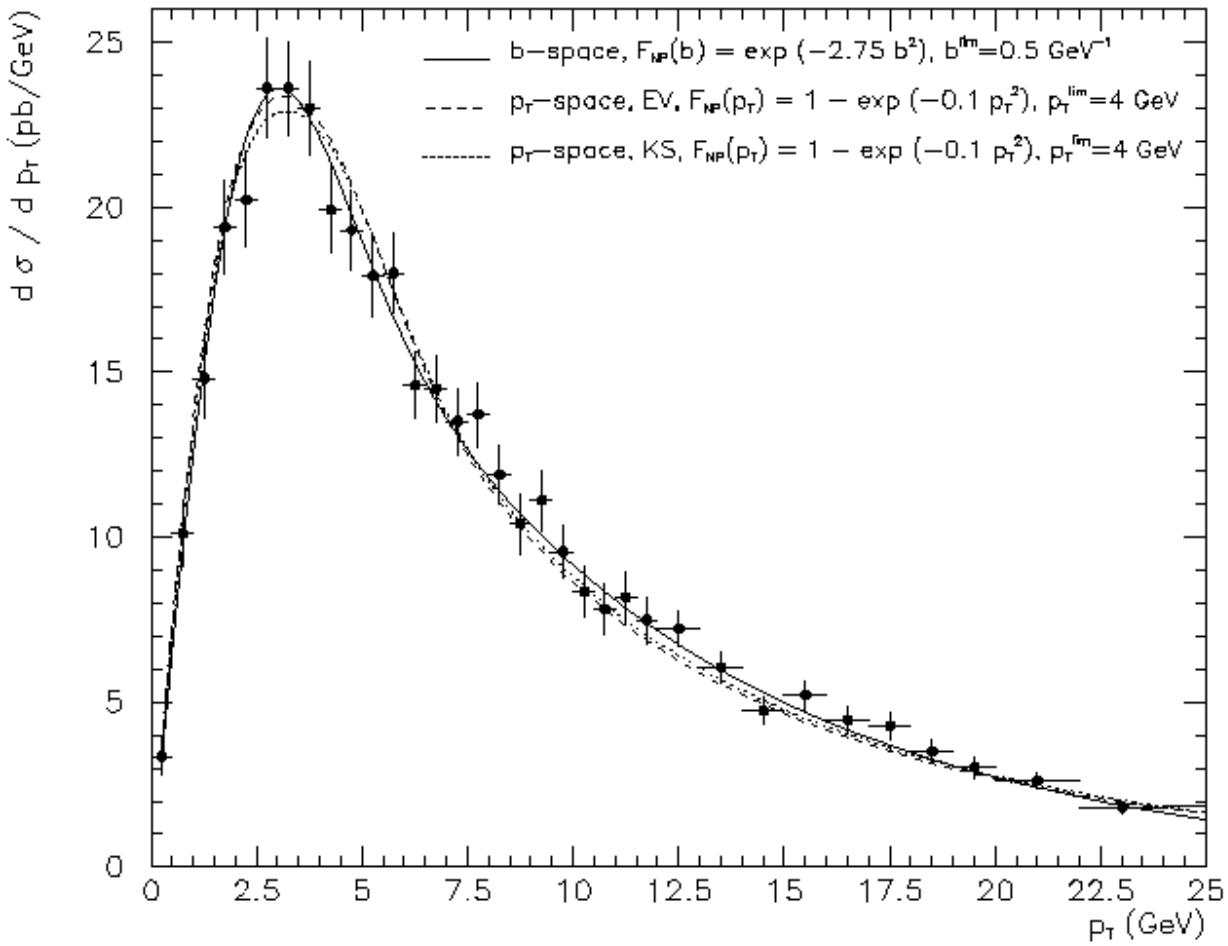
hep-ph/0103089

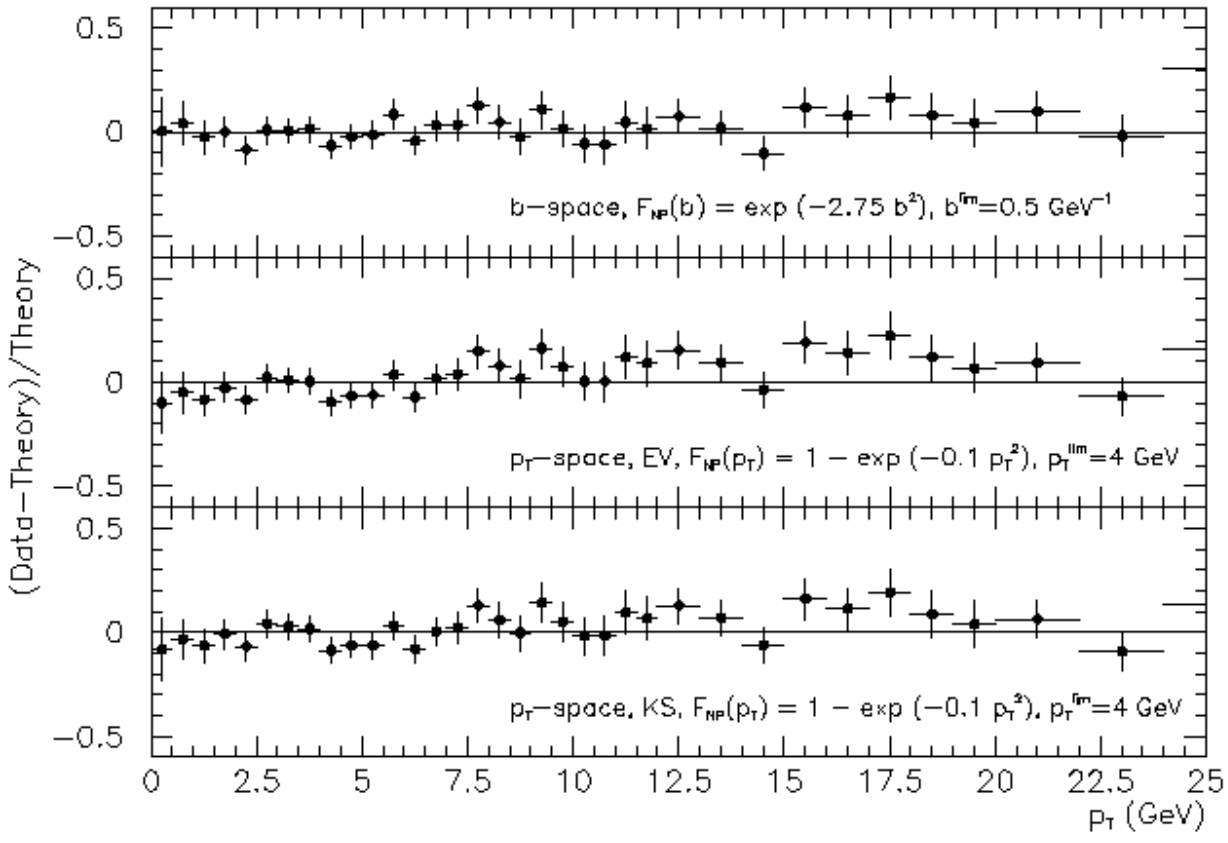
• Expanding the b-space cross section, the b-integral is evaluated term-by-term

• The cross section is approximated by terms of an asymptotic series in Q_T space — simple and elegant

• Numerically implemented for $W^{\pm}$ and Z^0 production

• Example: Z^0 production at Run 1


d σ / d pT (pb/GeV)
b−space, FNP(b) = exp (−2.75 b²), bfm=0.5 GeV⁻¹
pT−space, EV, FNP(pT) = 1 − exp (−0.1 pT²), pTlim=4 GeV
pT−space, KS, FNP(pT) = 1 − exp (−0.1 pT²), pTfm=4 GeV
pT (GeV)


(Data−Theory)/Theory
b−space, FNP(b) = exp (−2.75 b²), bfm=0.5 GeV⁻¹
pT−space, EV, FNP(pT) = 1 − exp (−0.1 pT²), pTlim=4 GeV
pT−space, KS, FNP(pT) = 1 − exp (−0.1 pT²), pTfm=4 GeV
pT (GeV)

Parton showers as tools of resummation

"Why not just run PYTHIA?" The unknown experimentalist

Balazs, Huston, Puljak, PRD63 014021 (`00)

— Showers include soft gluon effects, resumming logs generated by real emission off the initial partons **fi**

• Showering is process independent **Æ** its Sudakov can only include terms equivalent to $A^{(1)}$ & $B^{(1)}$ (by default)

• Part of $B^{(1)}$ is included in HERWIG and PYTHIA due to kinematic corrections

• Virtual corrections are not included **Æ** the total rate is the lowest order

• Modification of the PDF's is not included **Æ** no equivalent of $C^{(1)}$ (but cf. S.Mrenna)

• Gaussian non-perturbative smearing is included **Æ** non-perturbative treatment is only empirical

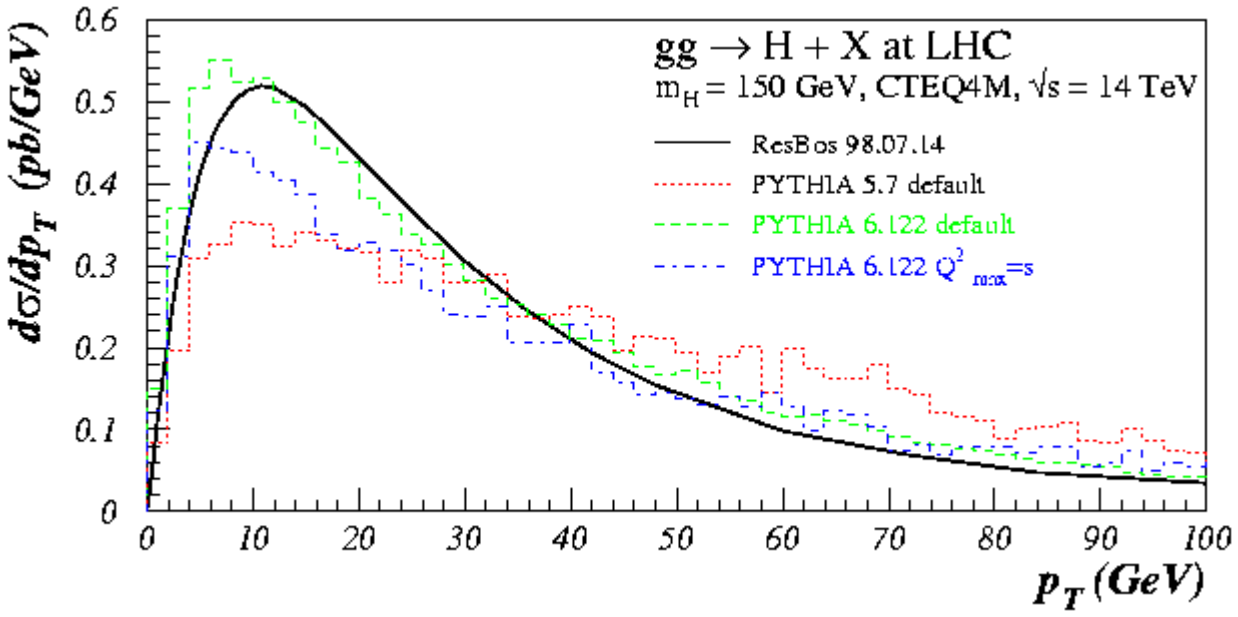
• High Q_T matrix elements and matching are not included by default, but cf. ME corrs.

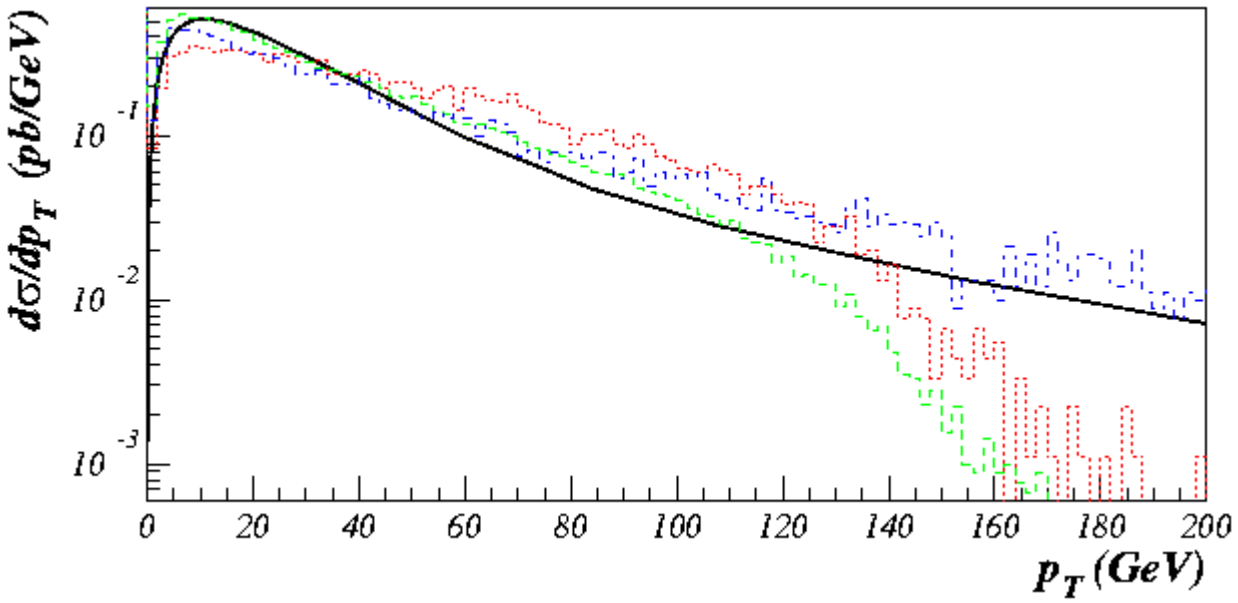
— These lead to potential differences in rate and shape between ResBos and PYTHIA/HERWIG/ISAJET/etc.

Comparison of ResBos and PYTHIA

Balazs, Huston, Puljak, PRD63 014021 (`00)

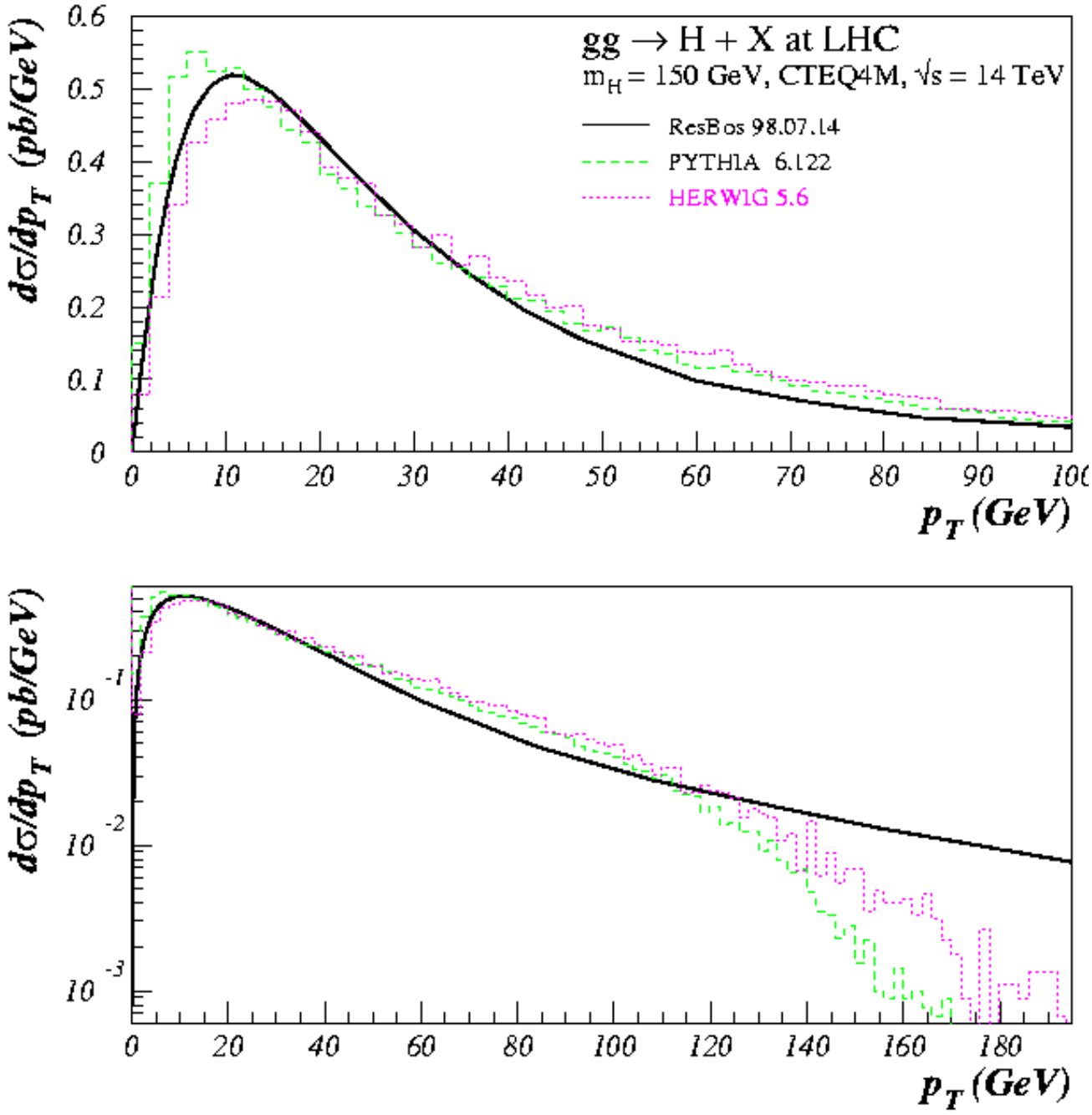
— The reliability of parton showers can be tested by comparing them to analytic calculations





- Reasonable agreement in low Q_T
- Have to work on ME corrections to the parton showers

Comparison of ResBos and HERWIG

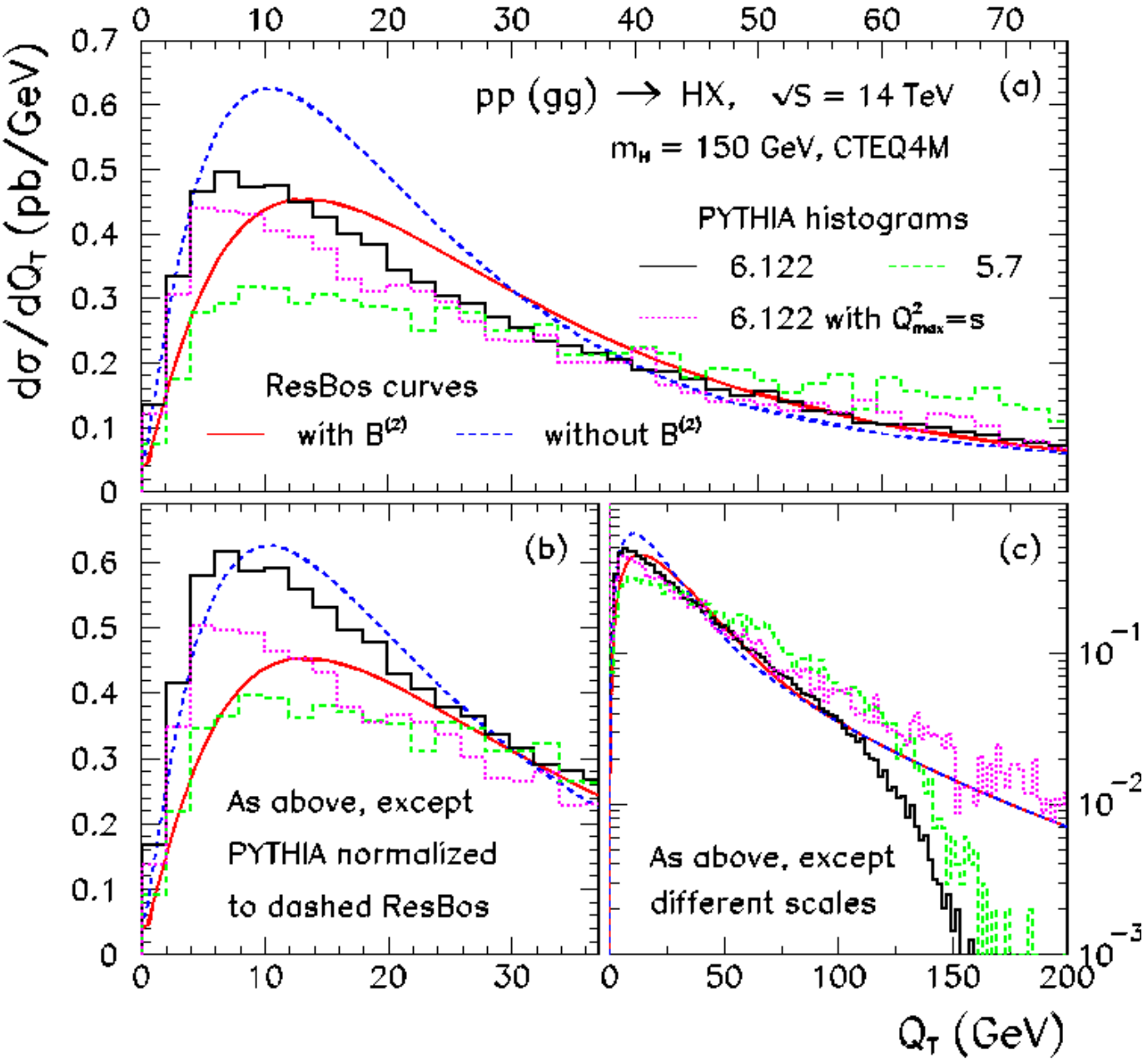


Balazs, Huston, Puljak, PRD63 014021 (`00)

- ResBos between PYTHIA and HERWIG at low Q_T
- Similar conclusions as in the case of PYTHIA

In the meanwhile back in Europe...

— New NNLO corrections to Higgs production enabled us to improve the Sudakov for this process in ResBos ...



Balazs, Huston, Puljak, Yuan, in preparation

... leading to disagreement between ResBos and PYTHIA 6.122/-HERWIG 5.6

Other tools of resummation

Here's what I left out:

Your Name Here, hep-ph/yymmnnn

...

...

...

— Description of your code here

...

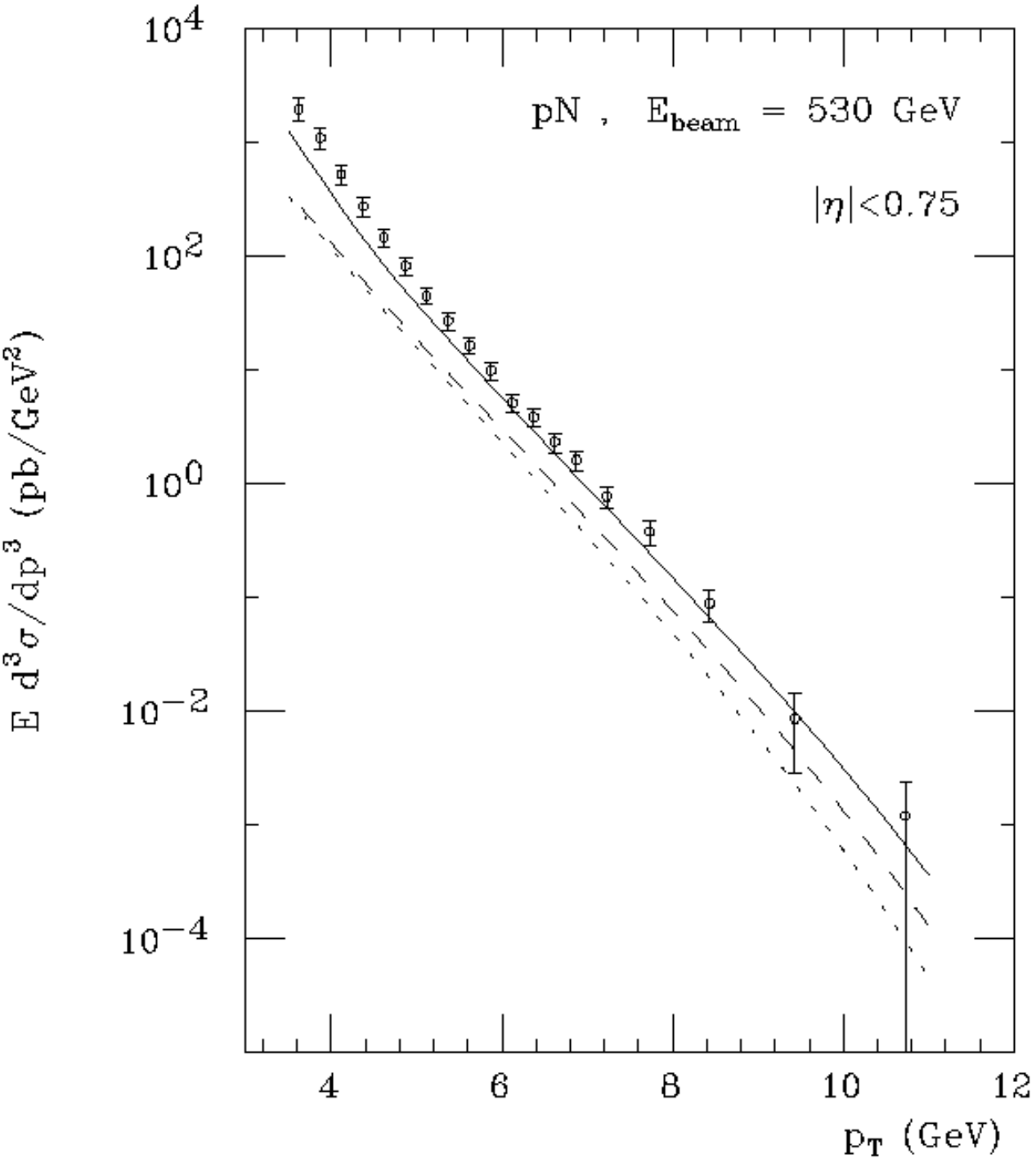
...

...

reSummation+factorization=refactorization

Laenen, Sterman, Vogelsang, hep-ph/0002078, ...

— Combination of Q_T and threshold reSummation



- Results for E706 are encouraging
- Numerical implementation: limited only for fixed target

Conclusions and outlook

"Be careful what you say: it may wind up on other people's transparencies." C.Balazs

Conclusions

Factorization, soft-gluon re**S**ummation and transverse momentum are inseparable, and important issues for hadronic production of Higgs and vector bosons

— Several numerical implementations: "b-space", "q_T-space"

• Each contains different amount of physics (assumptions, approximations, orders in α_s, non-pert., etc.)

• Results agree with experiments for various hard processes, CM energies, initial hadrons, and with parton showers

• CDF, DO, ATLAS and CMS experimentalists already use numeric implementations to exploit the state of the art theoretical predictions

Outlook

— Formalism: improved matching

— Application to Higgs production

• Inclusion of full QCD background, calculated at the same (re**S**ummed) order

— Update ResBos MC generator