C T E Q

ResBos
(Resummation for Bosons)
for Higgs Physics

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MCTP Higgs Symposium @ May 14, 2010

- What's it for?
- Where is it?
- For Higgs physics
- Limitations

ResBos

Initial state QCD soft gluon resummation
and
Final state QED corrections

In collaboration with

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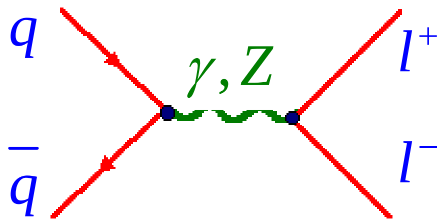
Carl Schmidt

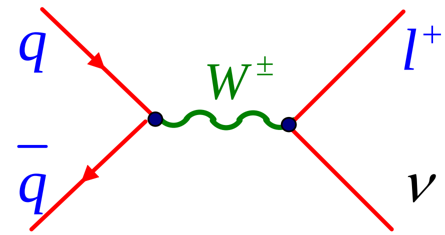
What’s it for? An Example

- Transverse momentum of

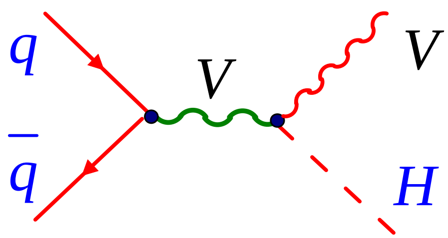
Drell-Yan



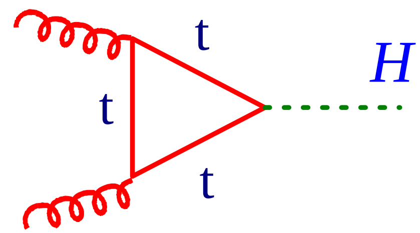
$W^\pm$



V H

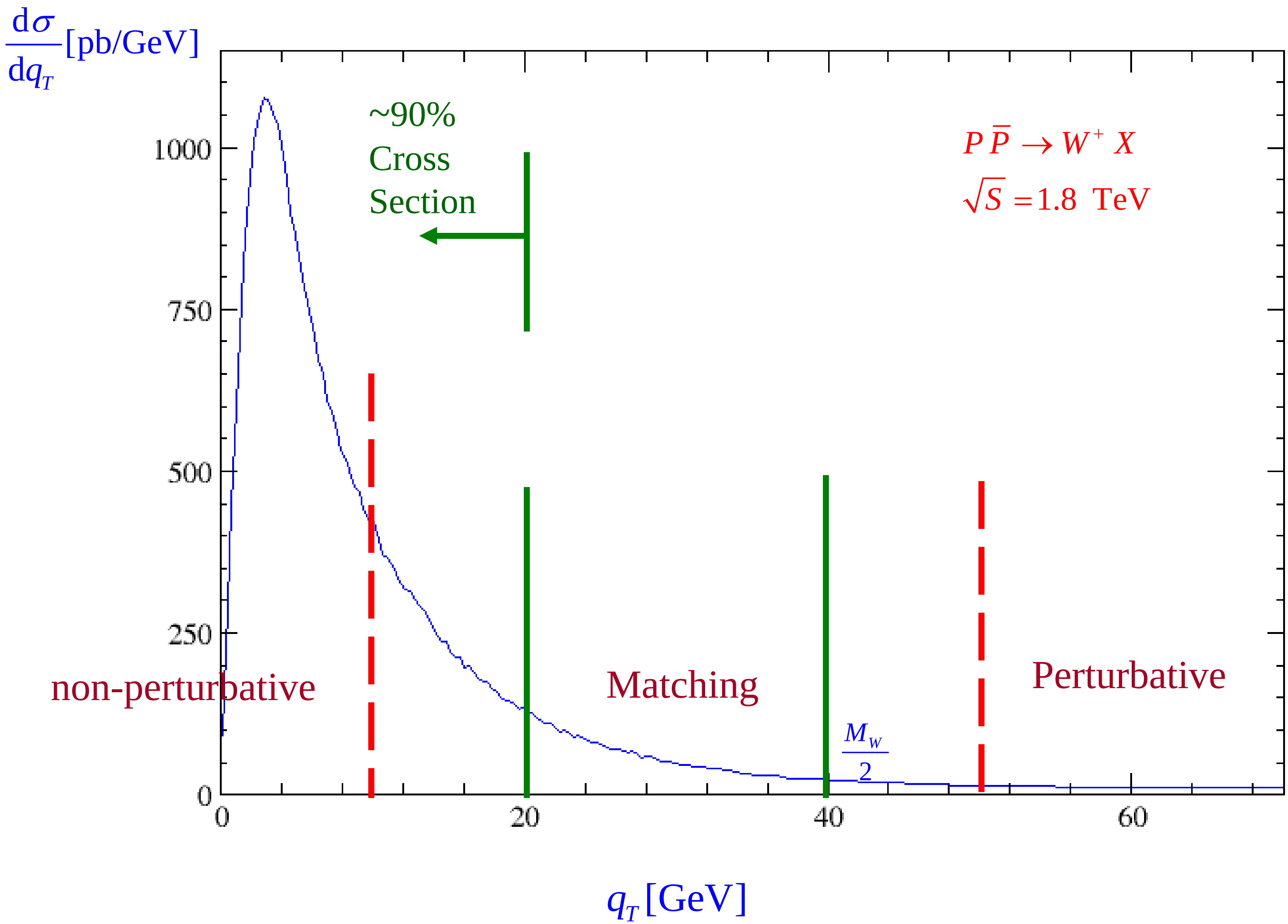


$g\,g \to H$



including QCD Resummations.

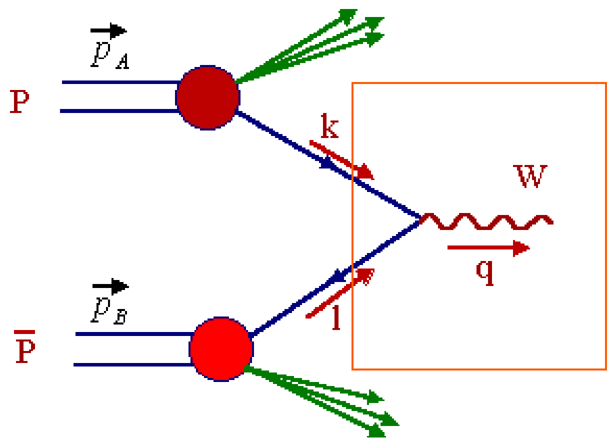
- Kinematics of Leptons from the decays
(Spin correlation included)



$\frac{d\sigma}{dq_T}$ [pb/GeV]
1000
750
500
250
0
0
20
40
60
~90%
Cross
Section
$P\bar{P} \rightarrow W^+ X$
$\sqrt{S} = 1.8$ TeV
non-perturbative
Matching
Perturbative
$\frac{M_W}{2}$
q_T [GeV]

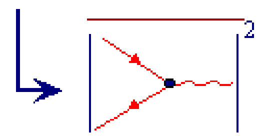
Fixed order pQCD prediction

$\alpha_S^{(0)}$



$$\sigma = \frac{1}{2S}\int \frac{d\xi_A}{\xi_A}\frac{d\xi_B}{\xi_B} f_{i/A}(\xi_A,\mu)\, f_{i/B}(\xi_B,\mu)\cdot d\hat{\sigma}$$

$$d\hat{\sigma} = \overline{|M|^2}\,(2\pi)^4\,\delta^{(4)}(q-k-l)\frac{d^3q}{(2\pi)^3\,2q_0}$$



$$s = (p_A + p_B)^2$$

$$k = \xi_A p_A$$

$$l = \xi_B p_B$$

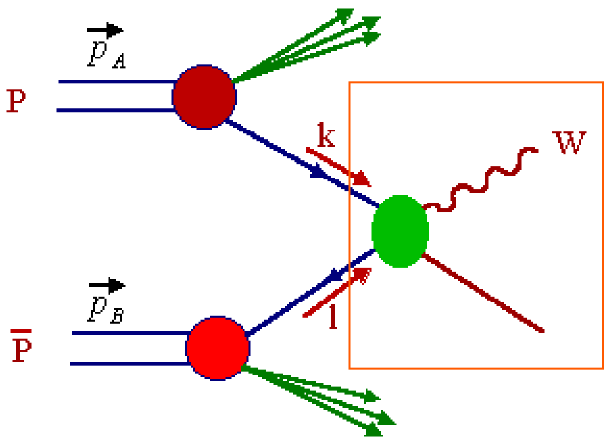
$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_T^2\,\mathrm{d}y\,\mathrm{d}Q^2} = \frac{1}{S}\int \frac{\mathrm{d}\xi_A}{\xi_A}\frac{\mathrm{d}\xi_B}{\xi_B} f_{i/A}(\xi_A,\mu)\, f_{i/B}(\xi_B,\mu)$$

$$\cdot\left(\frac{\pi^2}{Q^2}\right)\cdot\overline{|M|^2}\cdot\delta\left(1-\frac{x_A}{\xi_A}\right)\cdot\delta\left(1-\frac{x_B}{\xi_B}\right)$$

$$\cdot\delta\left(q_T^2\right)\cdot\delta\left(Q^2 - M_W^2\right)$$

$$Q \equiv \sqrt{Q^2} = \sqrt{q^2},\ \mu = Q = M_W,\ x_A = \frac{Q}{\sqrt{S}}e^{y},\ x_B = \frac{Q}{\sqrt{S}}e^{-y}$$

$\alpha_S^{(1)}$

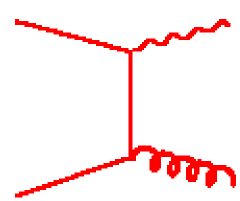
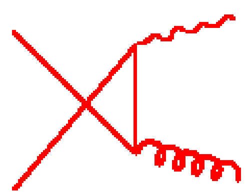


$$
\begin{aligned}
\frac{d\sigma}{dq_T^2\, dy\, dQ^2} = &\int \frac{d\xi_A}{\left(\xi_A S + U - Q^2\right)} \left(\frac{\hat{s}\, d\hat{\sigma}}{d\hat{t}}\right) \cdot f_{i/A}\left(\xi_A, \mu\right) \\
&\cdot f_{j/B}\left(\xi_B = \frac{-Q^2 - \xi_A\left(T - Q^2\right)}{\xi_A S + U - Q^2}, \mu\right) \cdot \delta\left(Q^2 - M_W^2\right) \\
&+ \int \frac{d\xi_B}{\left(\xi_B S + T - Q^2\right)} \left(\frac{\hat{s}\, d\hat{\sigma}}{d\hat{t}}\right) \cdot f_{j/B}\left(\xi_B, \mu\right) \\
&\cdot f_{i/A}\left(\xi_A = \frac{-Q^2 - \xi_B\left(U - Q^2\right)}{\xi_B S + T - Q^2}, \mu\right) \cdot \delta\left(Q^2 - M_W^2\right)
\end{aligned}
$$

$$
T = Q^2 - \sqrt{q_T^2 + Q^2}\sqrt{S}\; e^{-y}, \qquad \hat{s} = \xi_A \xi_B S
$$

$$
U = Q^2 - \sqrt{q_T^2 + Q^2}\sqrt{S}\; e^{y}, \qquad \hat{t} = \xi_A\left(T - Q^2\right) + Q^2
$$

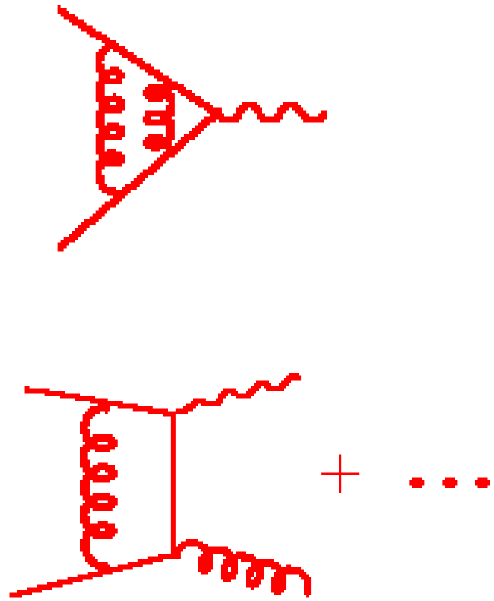
$$
\frac{\hat{s}\, d\hat{\sigma}}{d\hat{t}} = \frac{1}{16\pi^2}\overline{\left|M\right|^2}
$$

$M =$  + 

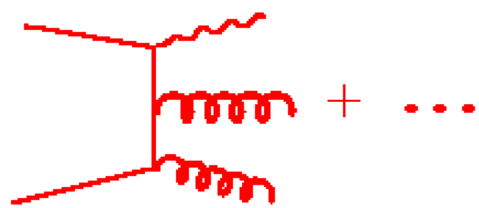
(For simplicity, only consider qq→Wg)

$\alpha_s^{(2)}$

- Virtual Corrections



- Real emission contributions



Perturbative Part:

- Higher order in $\alpha_S^{(n)}$
  ⇨ Less sensitive to Factorization Scale μ

- High q_T and smaller y (i.e. more central)
  ⇨ PDF (parton distribution function) better known

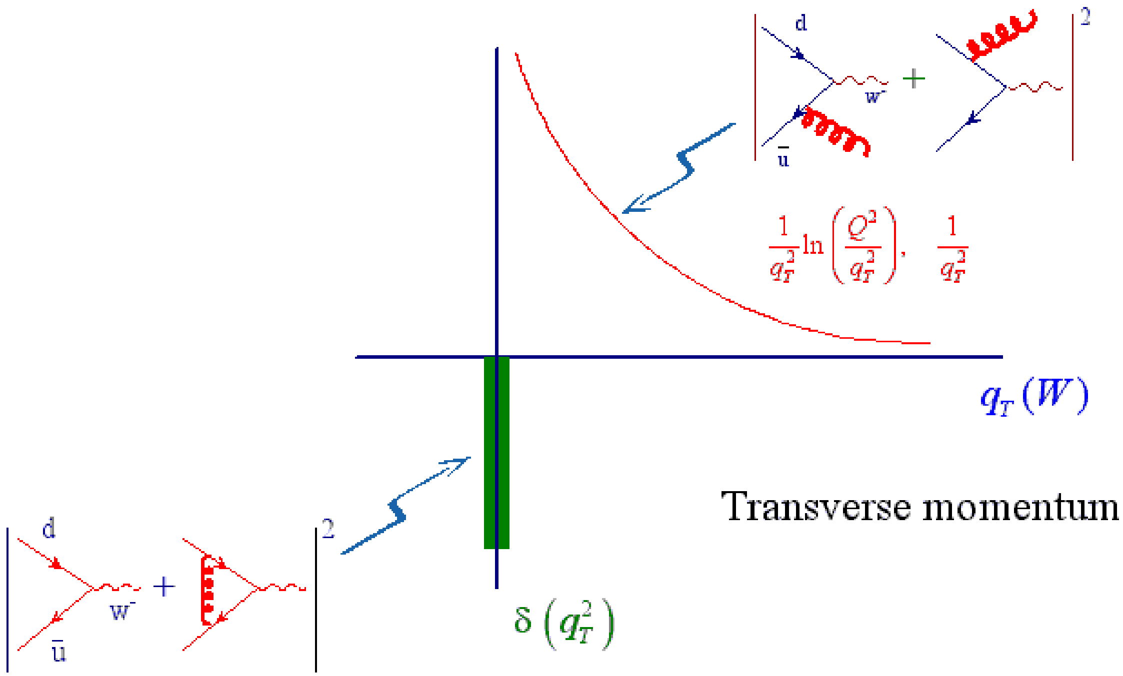
- With larger Luminosity
  ⇨ Test QCD in one large scale problem (i.e. $q_T \sim Q$)

- Up to now, most of the Data used in Testing QCD were
  One large scale observables, e.g., Jet-P_T.

- Observables involving Multiple Scales, e.g., q_T of W-Boson with mass M_W, can only be accurately described in QCD after including effects of Resummation.

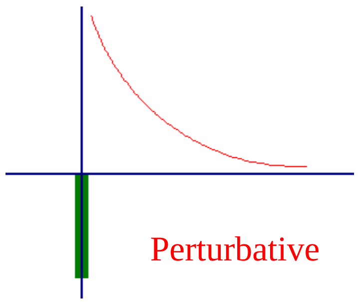
Shortcoming of fixed order calculation

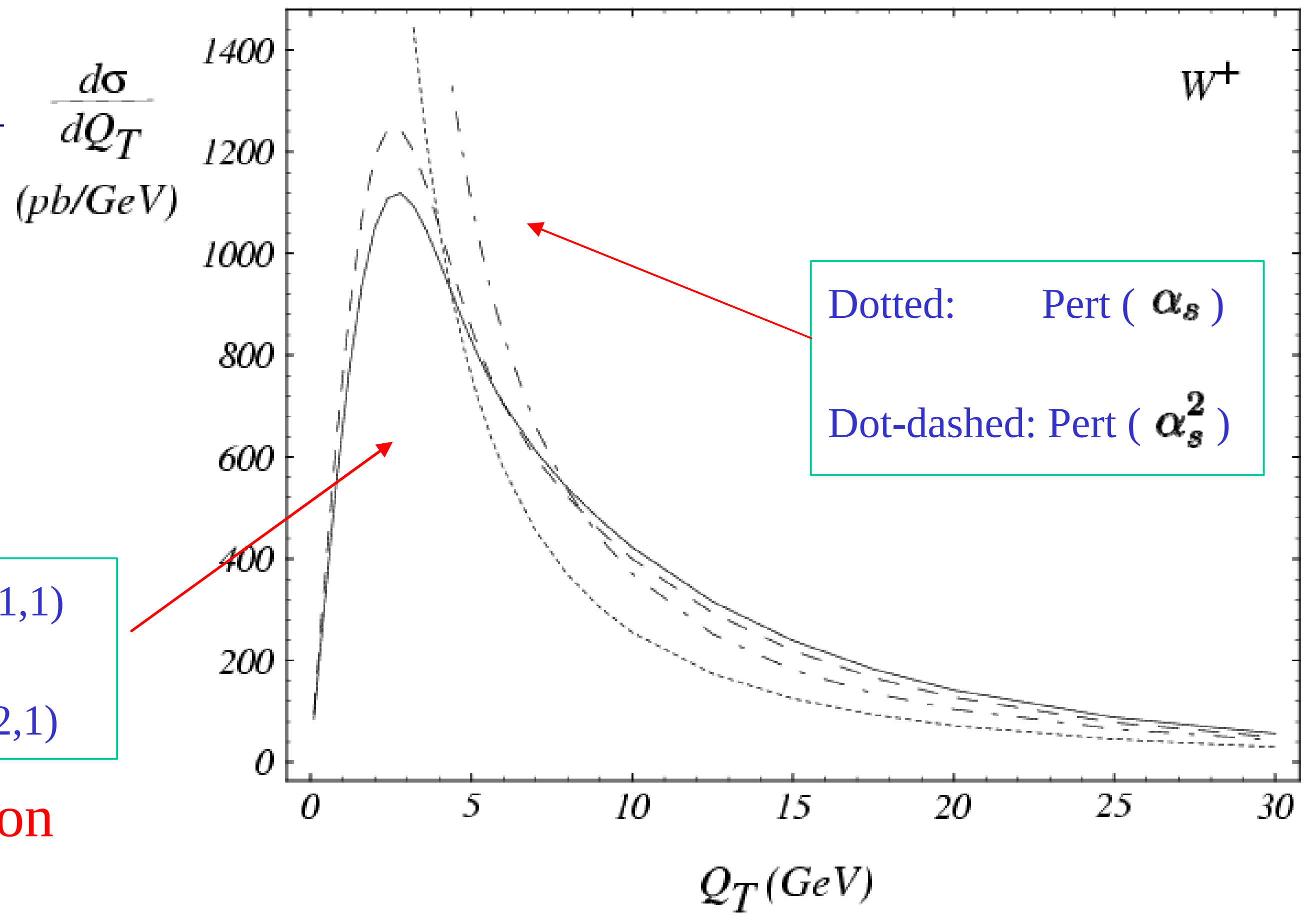
- Cannot describe data with small q_T of W-boson.
- Cannot precisely determine m_W at hadron colliders without knowing the transverse momentum of W-boson. Most events fall in the small q_T region.



(at NLO)

QCD Resummation is needed





Dotted: Pert (α_s)

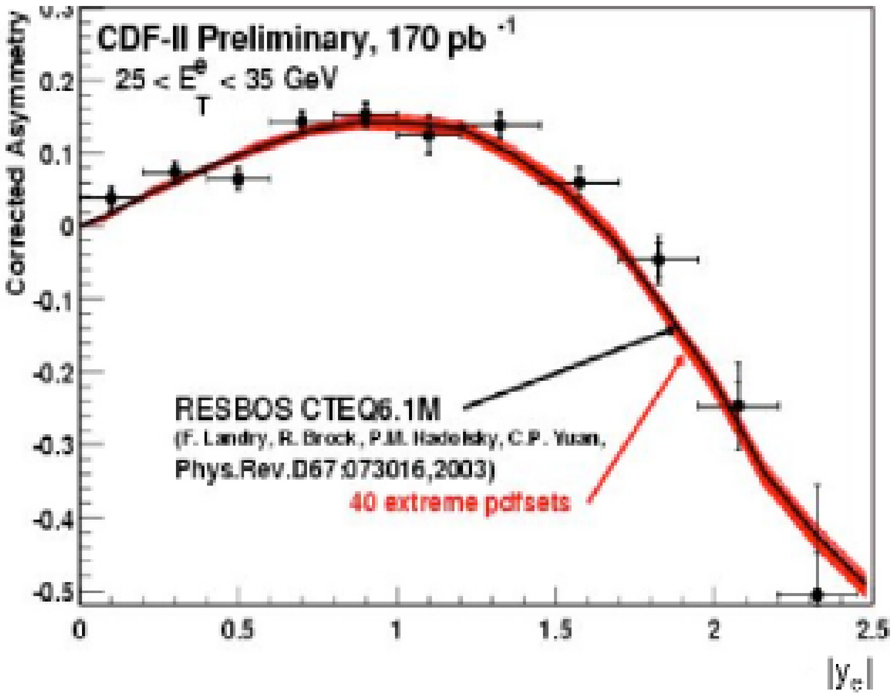
Dot-dashed: Pert (α_s^2)

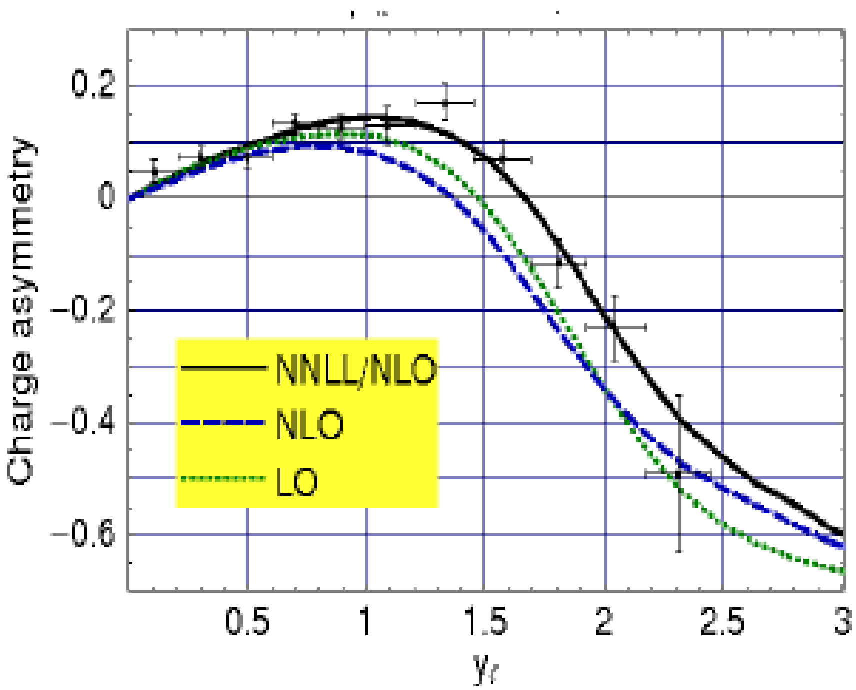
Dashed: CSS (1,1,1)

Solid: CSS (2,2,1)

Resummation

ResBos is also needed for Rapidity distributions





black curve is from ResBos calculation

What's QCD Resummation?

- Perturbative expansion

$$\frac{d\hat{\sigma}}{dq_T^2} \sim \alpha_S \left\{ 1 + \alpha_S + \alpha_S^2 + \cdots \right\}$$

- The singular pieces, as $\frac{1}{q_T^2}$ (1 or log's)

$$\frac{d\hat{\sigma}}{dq_T^2} \sim \frac{1}{q_T^2} \sum_{n=1}^{\infty} \sum_{m=0}^{2n-1} \alpha_S^{(n)} \ln^{(m)}\left(\frac{Q^2}{q_T^2}\right)$$

$$\sim \frac{1}{q_T^2} \{ \quad \alpha_S \left(\underline{L+1}\right)$$

$$+\alpha_S^2 \left(\underline{L^3 + L^2} + \underline{L+1}\right)$$

$$+\alpha_S^3 \left(\underline{L^5 + L^4} + \underline{L^3 + L^2} + \underline{L+1}\right)$$

$$+ \cdots \quad \}$$

$$L \equiv \ln\left(\frac{Q^2}{q_T^2}\right)$$

Resummation is to reorganize the results in terms of the large Log's.

Resummed results:

Determined by A(1) and B(1)

$$\frac{d\sigma}{dq_T^2} \sim \frac{1}{q_T^2}\Big\{ \left[\alpha_S(L+1) \quad + \alpha_S^2\left(L^3+L^2\right) + \alpha_S^3\left(L^5+L^4\right) \quad + \cdots \right]$$

$$+\left[\qquad + \alpha_S^2\left(L+1\right) \quad + \alpha_S^3\left(L^3+L^2\right) \quad + \cdots \right]$$

$$+\left[\qquad\qquad + \alpha_S^3\left(L+1\right) \qquad + \cdots \right]$$

$$+ \cdots \Big\}$$

Determined by A(2) and B(2)

Determined by A(3) and B(3)

→ QCD Resummation

In the formalism by Collins-Soper-Sterman, in addition to these perturbative results, the effects from physics beyond the leading twist is also implemented as

[non-perturbative functions].

CSS Resummation Formalism

$$\frac{d\sigma}{dq_T^2\,dy\,dQ^2} = \frac{\pi}{S}\sigma_0\delta\left(Q^2 - M_W^2\right)\cdot$$

$$\left\{\frac{1}{(2\pi)^2}\int d^2b \quad e^{i\vec{q}_T\cdot\vec{b}}\tilde{W}\left(b,Q,x_A,x_B\right)\cdot\text{[Non-perturbative functions]}\right.$$

$$\left. + Y\left(q_T,y,Q\right)\right\}$$

$$\tilde{W} = e^{-S(b)}\cdot C\otimes f\left(x_A\right)\cdot C\otimes f\left(x_B\right)$$

$$C\otimes f\left(x_A\right) \rightarrow \sum_j\int_{x_A}^1\frac{d\xi_A}{\xi_A}C_{qj}\left(\frac{x_A}{\xi_A},b,\mu\right)\cdot f_{j/A}\left(\xi_A,\mu\right)$$

$$C\otimes f\left(x_B\right) \rightarrow \sum_k\int_{x_B}^1\frac{d\xi_B}{\xi_B}C_{qk}\left(\frac{x_A}{\xi_A},b,\mu\right)\cdot f_{k/B}\left(\xi_B,\mu\right)$$

Sudakov form factor $S(b) = \int_{\left(\frac{b_0}{b}\right)^2}^{Q^2}\frac{d\bar{\mu}^2}{\bar{\mu}^2}\left[\ln\left(\frac{Q^2}{\bar{\mu}^2}\right)A\left(\bar{\mu}\right) + B\left(\bar{\mu}\right)\right]$

[Non-perturbative functions] are functions of (b,Q,x_A,x_B) which include QCD effects beyond Leading Twist.

- Example: for $W^{\pm}$

$$\sigma_0 = \left(\frac{4\pi^2\alpha}{3} \sum_{jj'} Q_{jj'}^{(W)} \right), \qquad Q_{jj'}^{(W)} = \frac{1}{4\sin^2\theta_W} \left(kM\right)_{jj'}^2$$

The couplings of gauge bosons to fermions are expressed in the way to include the dominant electroweak radiative corrections. The propagators of gauge bosons also contain energy-dependent width, as done in LEP precision data analysis.

Note:

$$A \equiv \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi} \right)^n \cdot A^{(n)}, \qquad B \equiv \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi} \right)^n \cdot B^{(n)},$$

$$C \equiv \sum_{n=0}^{\infty} \left(\frac{\alpha_S}{\pi} \right)^n \cdot C^{(n)}$$

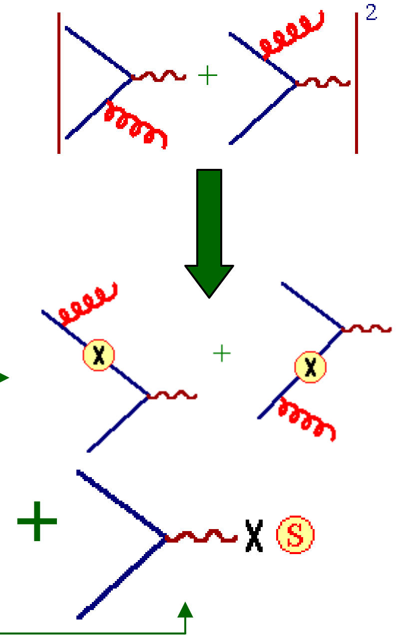
As $q_T \to 0$

$$\left.\frac{d\sigma}{dq_T^2\,dy\,dQ^2}\right|_{q_T\to 0} = \left(\frac{\pi}{s}\sigma_0\right)\cdot\delta\left(Q^2-M_W^2\right)\cdot\left(\frac{1}{2\pi q_T^2}\right)\left(\frac{\alpha_s(Q)}{\pi}\right)$$

$$\cdot\Big\{ f_{q/A}(x_A,Q)\left[P_{\bar q\leftarrow\bar q}\otimes f_{\bar q}\right]_{x_B,Q} + \left[P_{q\leftarrow q}\otimes f_q\right]_{x_A,Q} f_{\bar q/B}(x_B,Q)$$

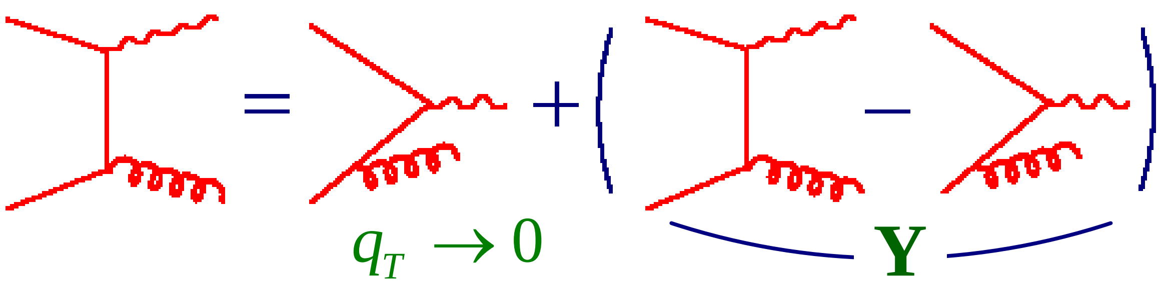
$$+ f_{q/A}(x_A,Q)\,f_{\bar q/B}(x_B,Q)\cdot\left[2\left(\frac{4}{3}\right)\ln\left(\frac{Q^2}{q_T^2}\right)+2(-2)\right]\Big\}$$

Diagramatically,

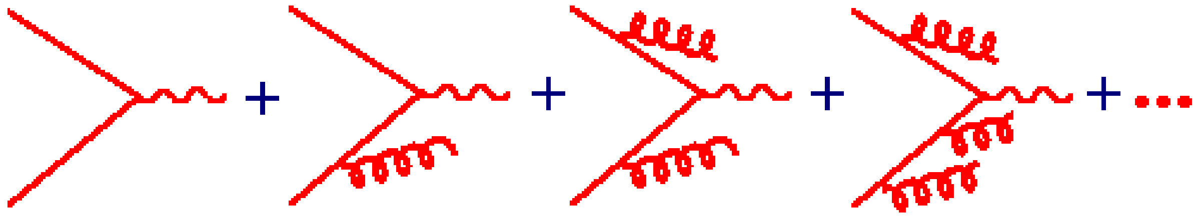


Exponentiate

To preserve transverse momentum conservation, we have to go to the impact parameter space (b-space) to perform resummation.



Diagramatically, Resummation is doing



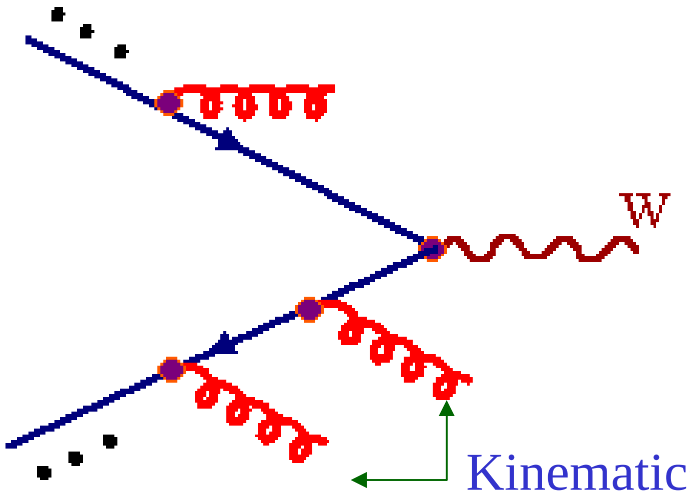
Resum large $\alpha_S^n \ln^m \left(\frac{Q^2}{q_T^2} \right)$ terms

$$\left. \frac{d\sigma}{dq_T^2 dy} \right|_{q_T \to 0} \sim \frac{1}{q_T^2} \sum_{n=1}^{\infty} \sum_{m=0}^{2n-1} \alpha_S^n \ln^m \left(\frac{Q^2}{q_T^2} \right) \cdot C_m^n$$

Monte-Carlo programs ISAJET, PYTHIA, HERWIG contain these physics.

(Note: Arbitrary cut-off scale in these programs to affect the amount of Backward radiation , i.e. Initial state radiation.)

Monte-Carlo Approach



Backward Radiation
(Initial State Radiation)

Kinematics of the radiated gluon, controlled by Sudakov form factor with some arbitrary cut-off. (In contrast to perform integration in impact parameter space, i.e., b space.)

➡ The shape of q_T (w) is generated. But, the integrated rate remains the same as at Born level (finite virtual correction is not included).

* Recently, there are efforts to include part of higher order effect in the event generator.

Event Generators (PYTHIA, HERWIG)

Note that the integrated rate is the same as the Born level rate ($\alpha_S^{(0)}$) even though the q_T – distribution is different (i.e., not $\delta\left(q_T^2\right)$ any more).

$$\sigma = \int \mathrm{d}q_T^2 \frac{\mathrm{d}\sigma}{\mathrm{d}q_T^2} \sim \int \mathrm{d}^2 b \underbrace{\int e^{i\vec{q}_T \cdot \vec{b}} \mathrm{d}^2 q_T}_{\delta^2(b)} \sigma_0 e^{-S(b)}$$

$$= \int \mathrm{d}^2 b \delta^2(b) \cdot \sigma_0 \cdot e^{-S(b)} \longrightarrow 1 \text{ at } b=0$$

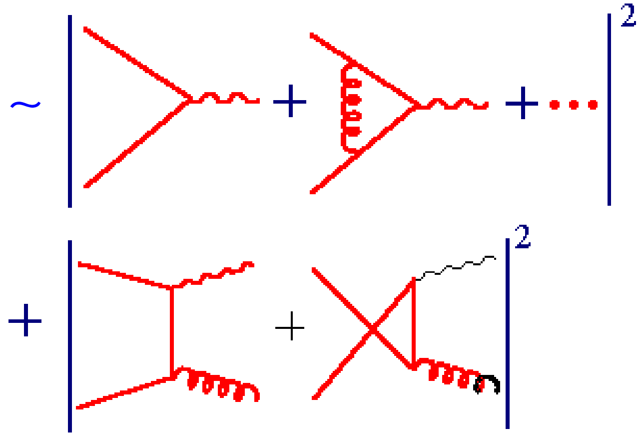
$$= \sigma_0$$

For C-Function = $\delta\left(1 - \frac{x_A}{\xi_B}\right)$

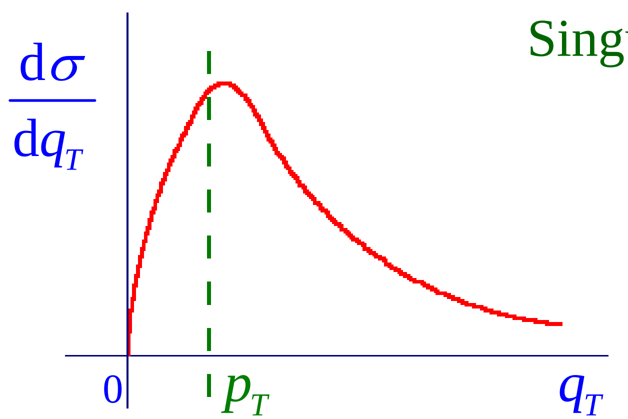
To recover the "K-factor" in the NLO total rate

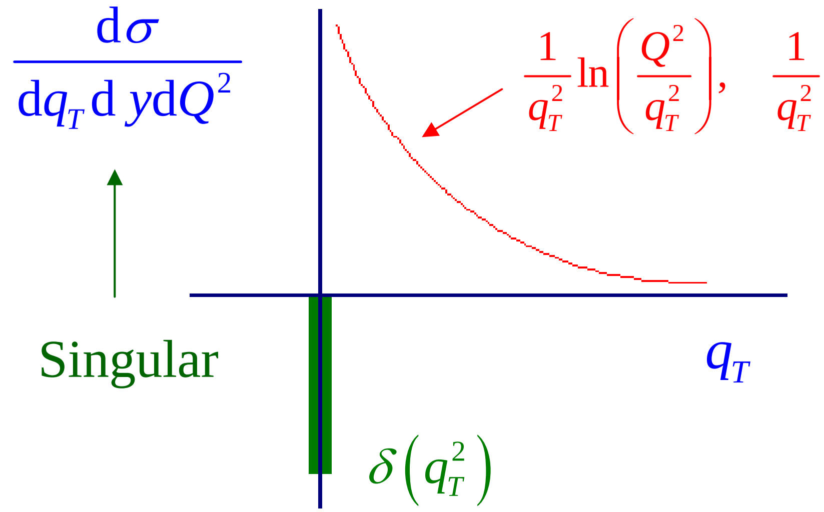
→ To include the C-Functions

$$\frac{d\sigma}{dQ^2 dy} \sim$$



Finite





→ The area under the q_T – curve will reproduce the total rate at the order $\alpha_S^{(1)}$ if Y term is calculated to $\alpha_S^{(1)}$ as well.

Include NNLO in high q_T region

- To improve prediction in high q_T region
- To speed up the calculation, it is implemented through K-factor table which is a function of (Q, q_T, y) of the boson, not just a constant value.

→ ResBos predicts both rate and shape of distributions.

[non-perturbative function] is a function of (b,Q,x_A,x_B), implemented to include effects beyond Leading Twist.

Until we know how to calculate QCD non-perturbatively, (Lattice Gauge Theory?), these functions can only be parameterized. However, the same functions should describe Drell-Yan, $W^{\pm}$, Z^0 data.

- Test QCD in problems involving multiple scales.
- Measuring these non-perturbative functions may help in understanding the non-perturbative part of QCD.

[non-perturbative functions] , dependent of Q, b, x_A, x_B, is necessary to describe q_T – distribution of Drell-Yan, $W^{\pm}$,Z^0 events.

$$\exp\left[-g_1 b^2 - g_2 b^2 \ln\left(\frac{Q}{2Q_0}\right) - g_1 g_3 b^2 \ln\left(100 x_A x_B\right)\right]$$

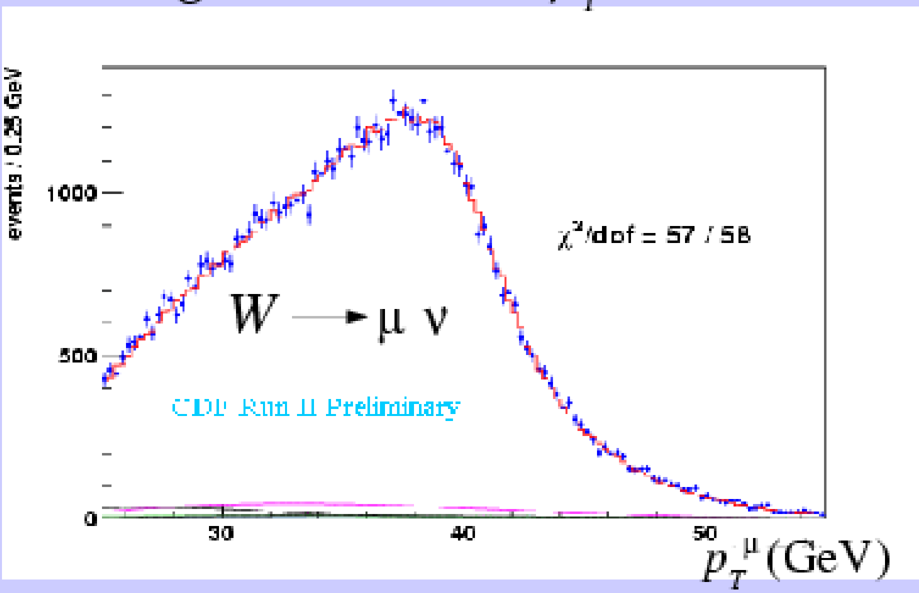
New term with x-dependence

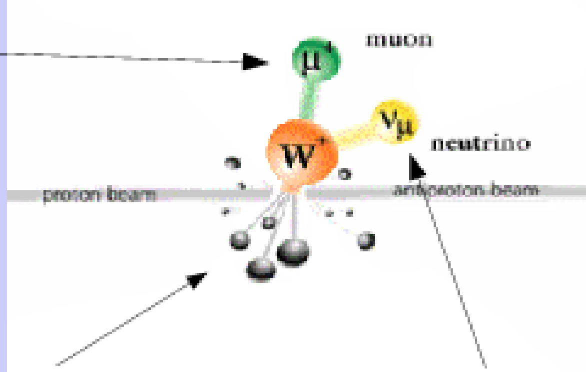
The coefficients g_1, g_2, g_3 need to be determined by existing data.

Effects of Resummation on *W* and *Z* Boson physics

Mass information comes primarily from lepton p_T

- Run 2 goal: calibrate p_T to ~0.01%

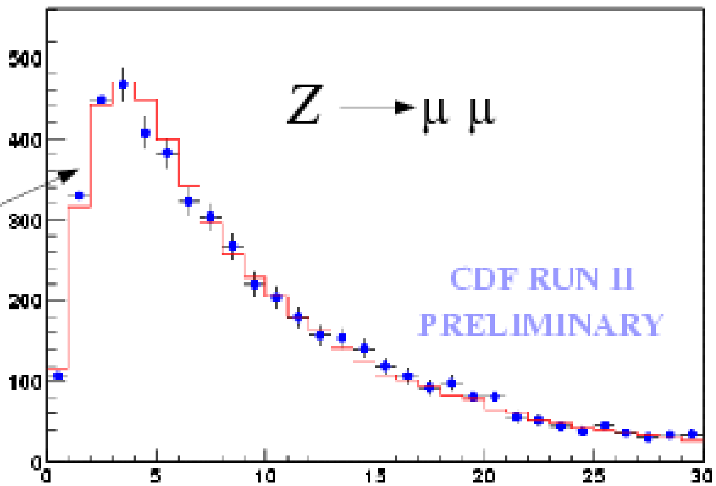




Additional information from ν p_T

(inferred through measurement of hadronic recoil energy)

Use Z decays to model boson p_T distribution, detector response to hadronic recoil energy



Combine lepton and neutrino p_T to form transverse mass (m_T) for best statistical power

Where is it?

- **ResBos**: http://hep.pa.msu.edu/resum/
- **Plotter**: http://hep.pa.msu.edu/wwwlegacy

ResBos-A (including final state NLO QED corrections)
http://hep.pa.msu.edu/resum/code/resbosa/
has not been updated.
Why? Because it was not used for Tevatron experiments.

The plan is to include final state QED resummation inside ResBos.

Physical processes included in ResBos

$W^{\pm}$

γ, Z

including gauge invariant set amplitude
for Drell-Yan pairs

H

$\gamma\gamma, ZZ, WW$

New physics: W', Z', H^{+}, A^{0}, H^{0} …

Physics processes inside ResBos

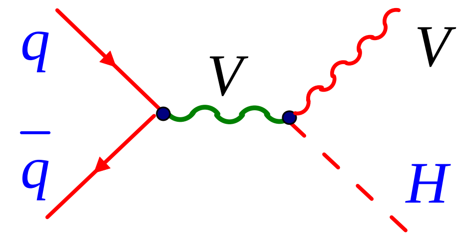
Process	$A^{(i)}$	$B^{(i)}$	$C^{(i)}$	order of Pert. part
$A+B \to W^+ \to l^+ + \nu + X$	3	2	1	NNLO
$A+B \to W^- \to l^- + \bar{\nu} + X$	3	2	1	NNLO
$A+B \to Z^0 \to l^- + l^+ + X$	3	2	1	NNLO
$A+B \to Z^0/\gamma^* \to l^+ + l^- + X$	3	2	1	NNLO
$A+B \to \gamma^* \to l^+ + l^- + X$	3	2	1	NNLO
$A+B \to gg \to H^0 \to \gamma\gamma + X$	3	2	1	NNLO
$A+B \to gg \to H^0 \to Z^0Z^0/W^+W^- \to 4l + X$	3	2	1	NNLO
$A+B \to W^{+*} \to W^+ + H^0 + X$	3	2	1	NNLO
$A+B \to W^{-*} \to W^- + H^0 + X$	3	2	1	NNLO
$A+B \to Z^{0*} \to Z^0 + H^0 + X$	3	2	1	NNLO
$A+B \to q\bar{q} \to \gamma\gamma + X$	3	2	1	NLO
$A+B \to gg \to \gamma\gamma + X$	3	2	1	NLO
$A+B \to q\bar{q} \to Z^0Z^0 + X$	3	2	1	NLO
$A+B \to W^+W^- + X$ (upcoming)	3	2	1	NLO

New Physics (upcoming)

Process	$A^{(i)}$	$B^{(i)}$	$C^{(i)}$	order of Pert. part
$A+B \to W' \to l^- + \bar{\nu} + X$	3	2	1	NNLO
$A+B \to Z' \to l^- + l^+ + X$	3	2	1	NNLO
$A+B \to bb \to A^0/H^0 + X$ (THDM)	3	2	1	NNLO
$A+B \to c\bar{s} \to H^+ + X$ (THDM)	3	2	1	NNLO

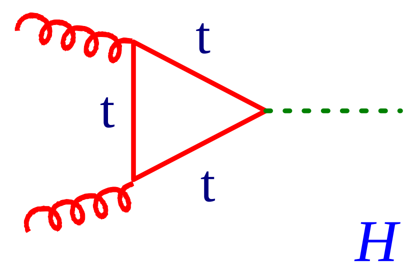
ResBos for Higgs Physics

Quark initiated processes:



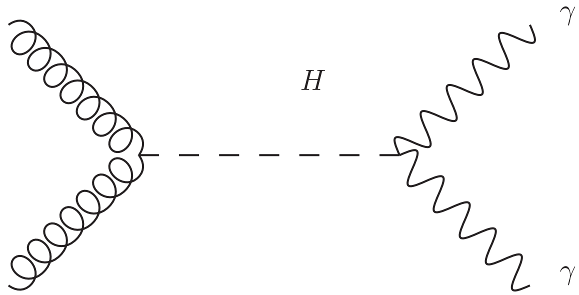
- Rate and shape:
  - ➢ at the same order of accuracy as Drell-Yan processes

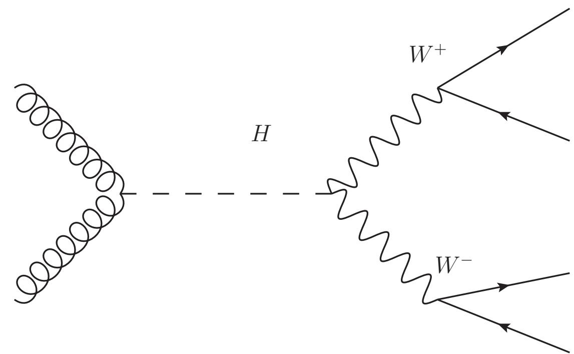
Gluon initiated processes:

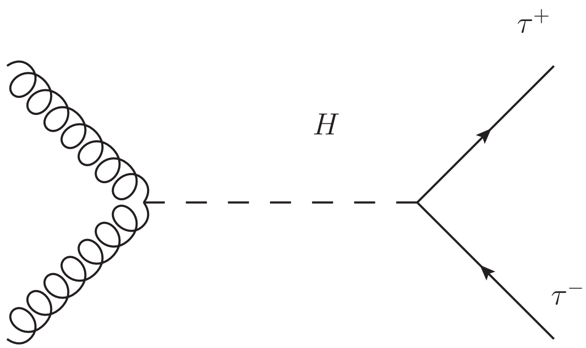


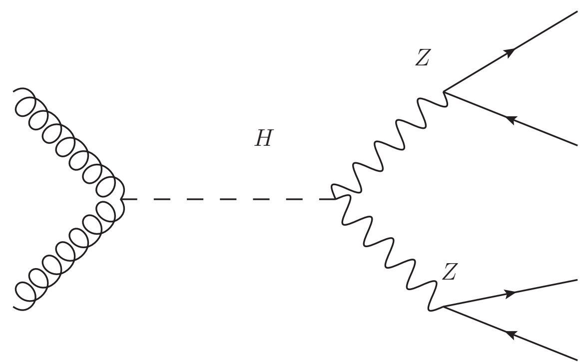
- Rate and shape:
  - ➢ at the same order of accuracy as Drell-Yan processes
  - ➢ consistent with NNLO QCD rate
  - ➢ include exact $\alpha_S^{(2)}$ contribution in high P_T

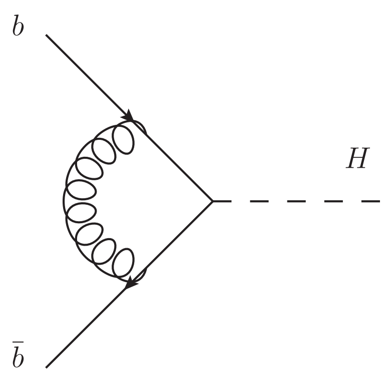
Gluon initiated processes for Higgs production in ResBos

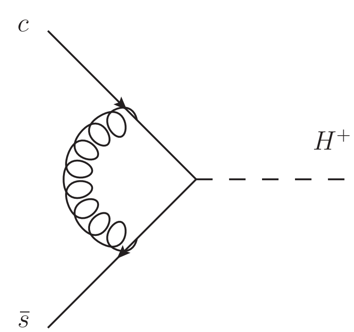




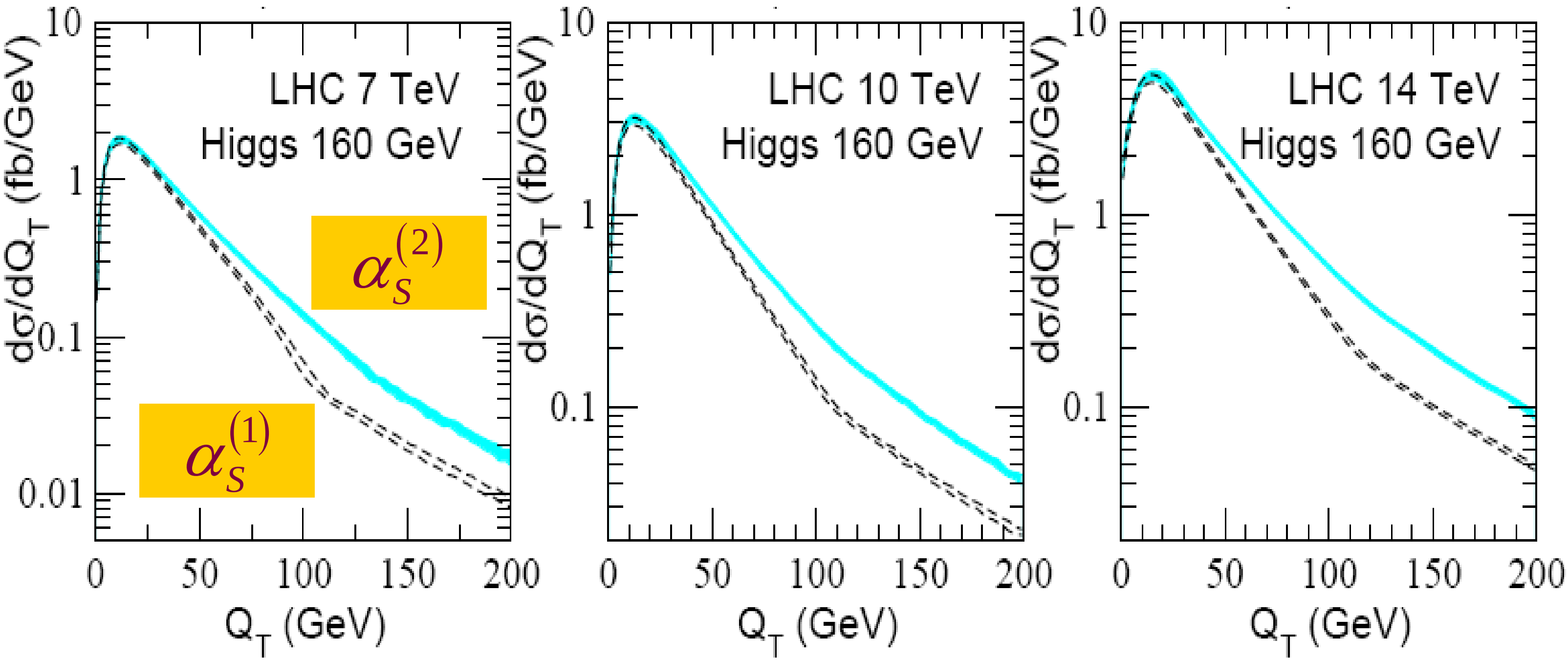


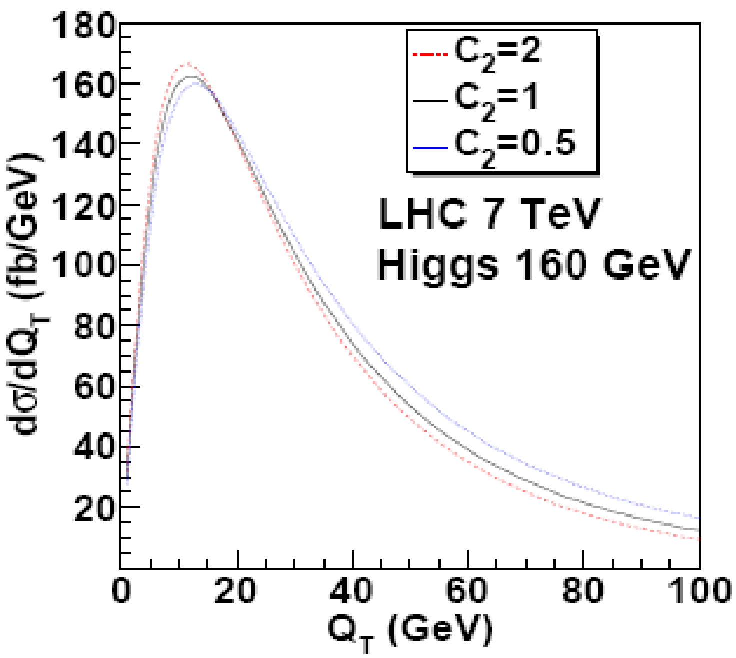


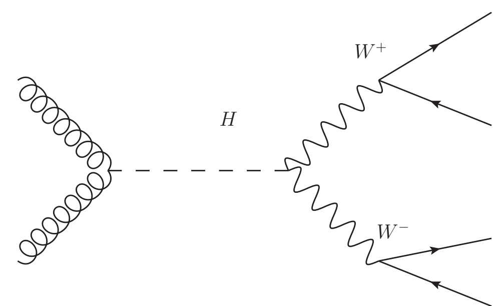




New Physics
(MSSM, THDM)







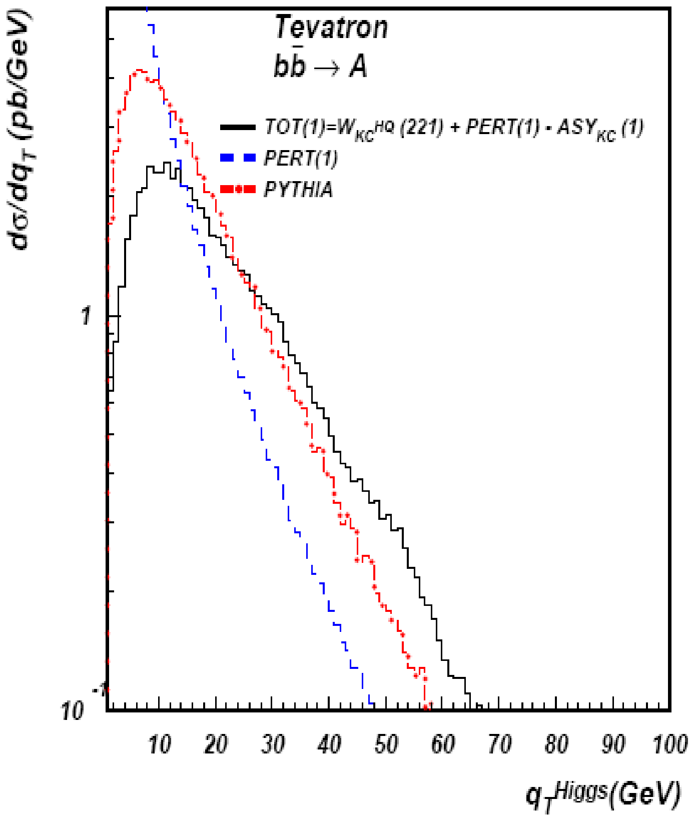
arXiv:0909.2305

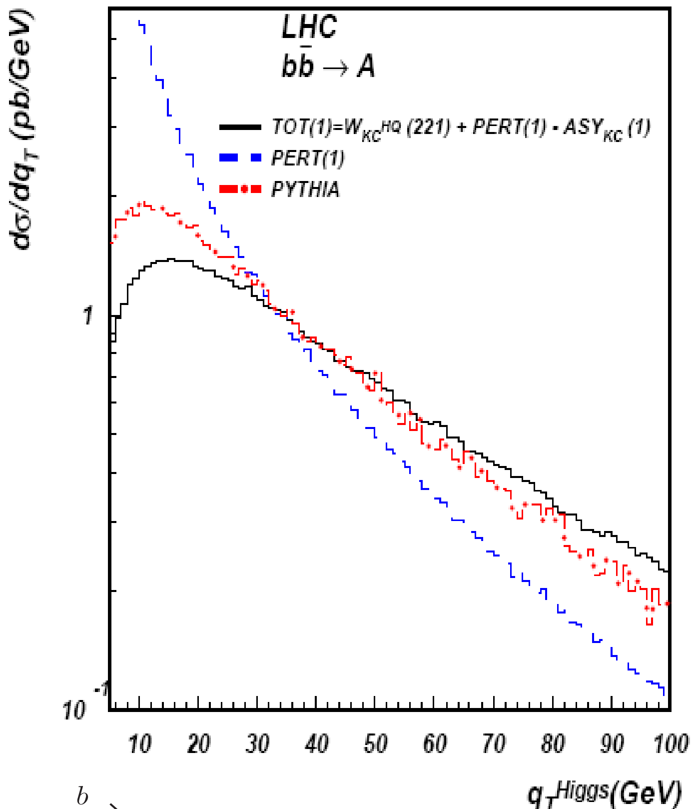
Shape changes from $\alpha_S^{(2)}$ and variation of scales

Predict different shape

ResBos vs PYTHIA vs NLO

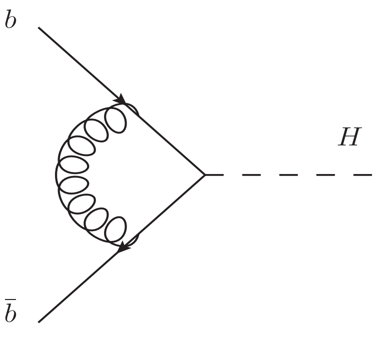
hep-ph/0509100





Consistent treatment of initial state parton mass with CTEQ6.6 PDFs, in GM scheme.

(see Sally Dawson's talk)



MSSM Higgs boson

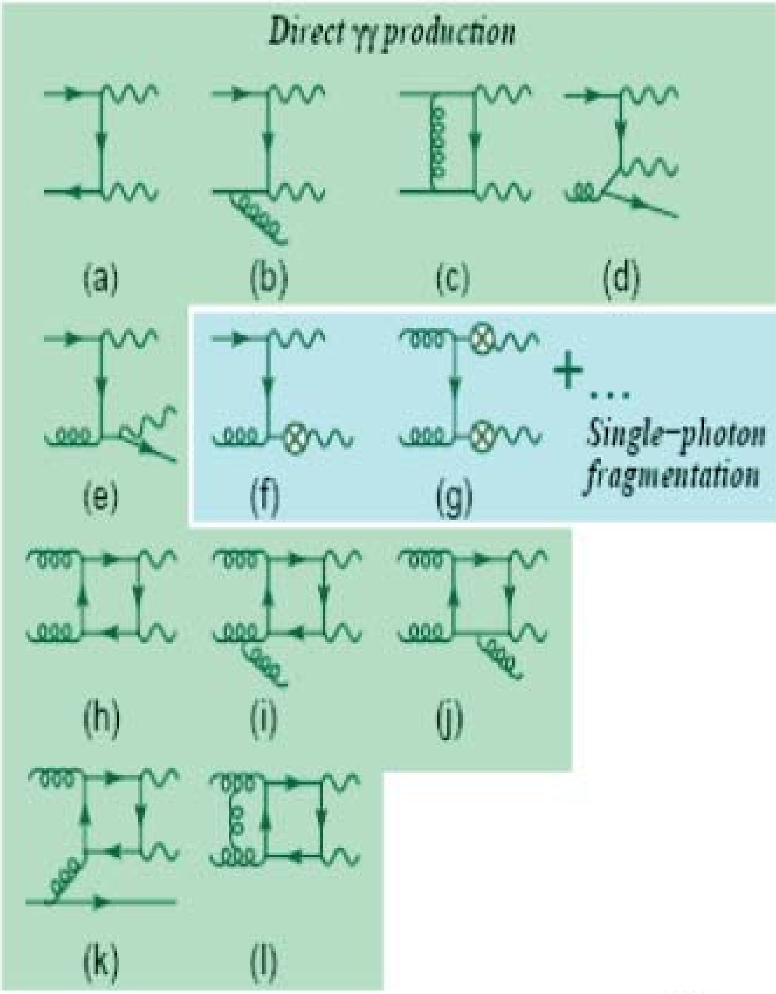
Di-Photon Productions

Theoretical predictions

PYTHIA
- $qq \rightarrow \gamma\gamma$ and $gg \rightarrow \gamma\gamma$ matrix elements.
- All-orders resummation to LL accuracy via parton shower.
- No fragmentation contributions included.

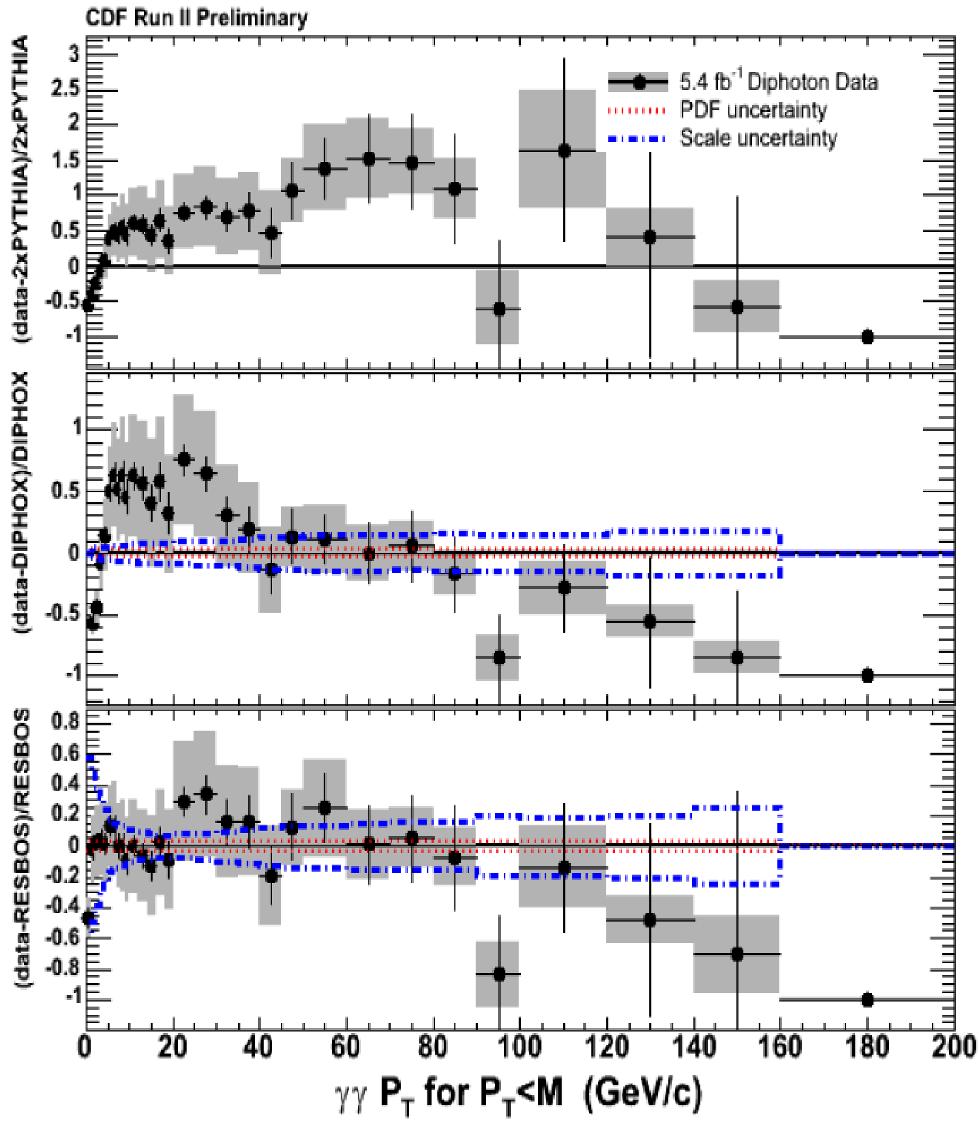
DIPHOX *Eur. Phys. J. C 16, 311 (2000)*
- Fixed-order NLO calculation (except for $gg \rightarrow \gamma\gamma$, which is at LO)
- No resummation:
  ➔ usually avoid divergence by requiring asymmetric $p_{T\gamma1}$-$p_{T\gamma2}$>0.
- Single-photon fragmentation (to NLO) included.

RESBOS *PRD 76, 013009 (2007)*
- All-orders resummation (to NNLL accuracy) matched to NLO.
- Single-photon fragmentation included via parameterization that approximates rate predicted by NLO fragmentation functions.



Compare to CDF Run-2 di-Photon data

Costas Vellidis
Pheno2010



The cut
$P_T < M$
is to suppress
fragmentation
contribution

(Data – theory)/theory vs. the diphoton transverse momentum for Higgs – like kinematics

Compare to CDF Run-2 di-Photon data

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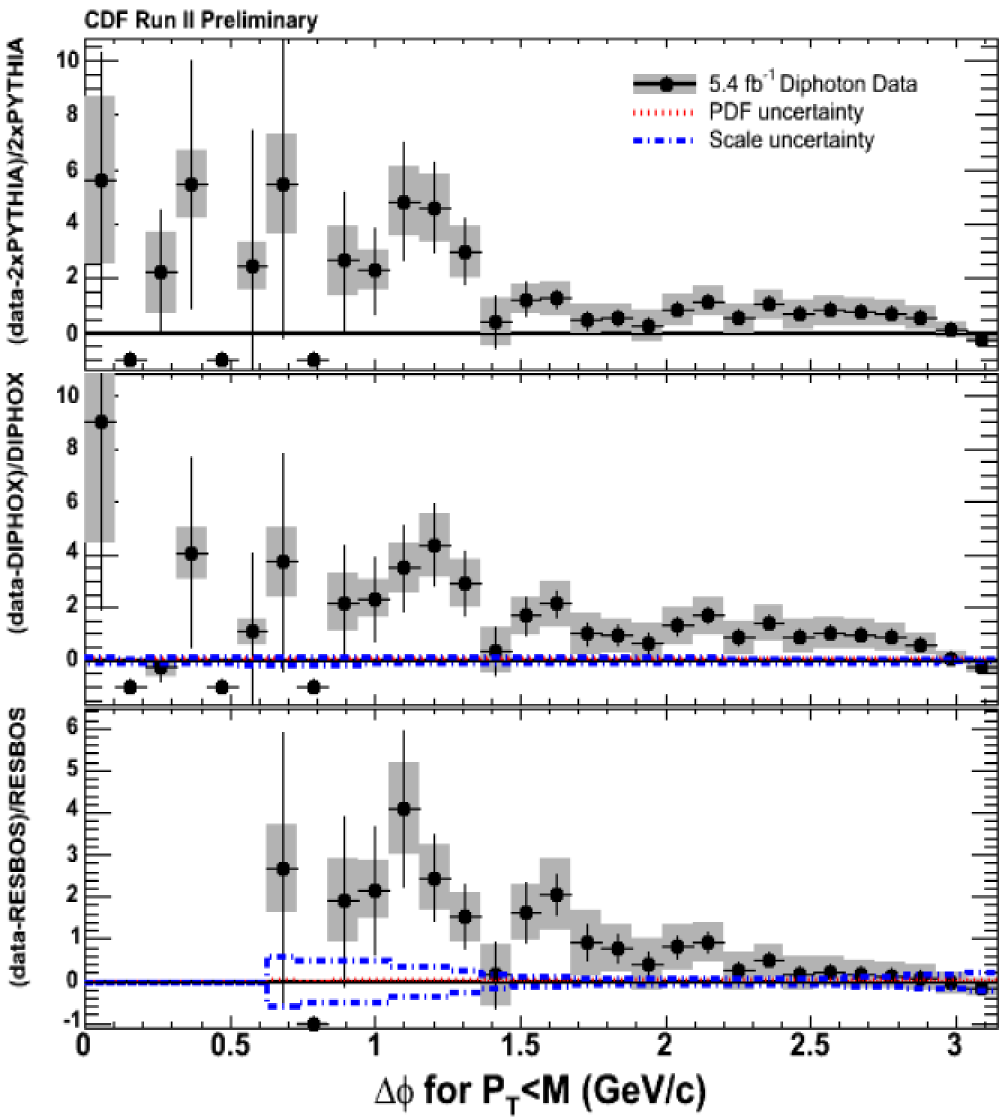
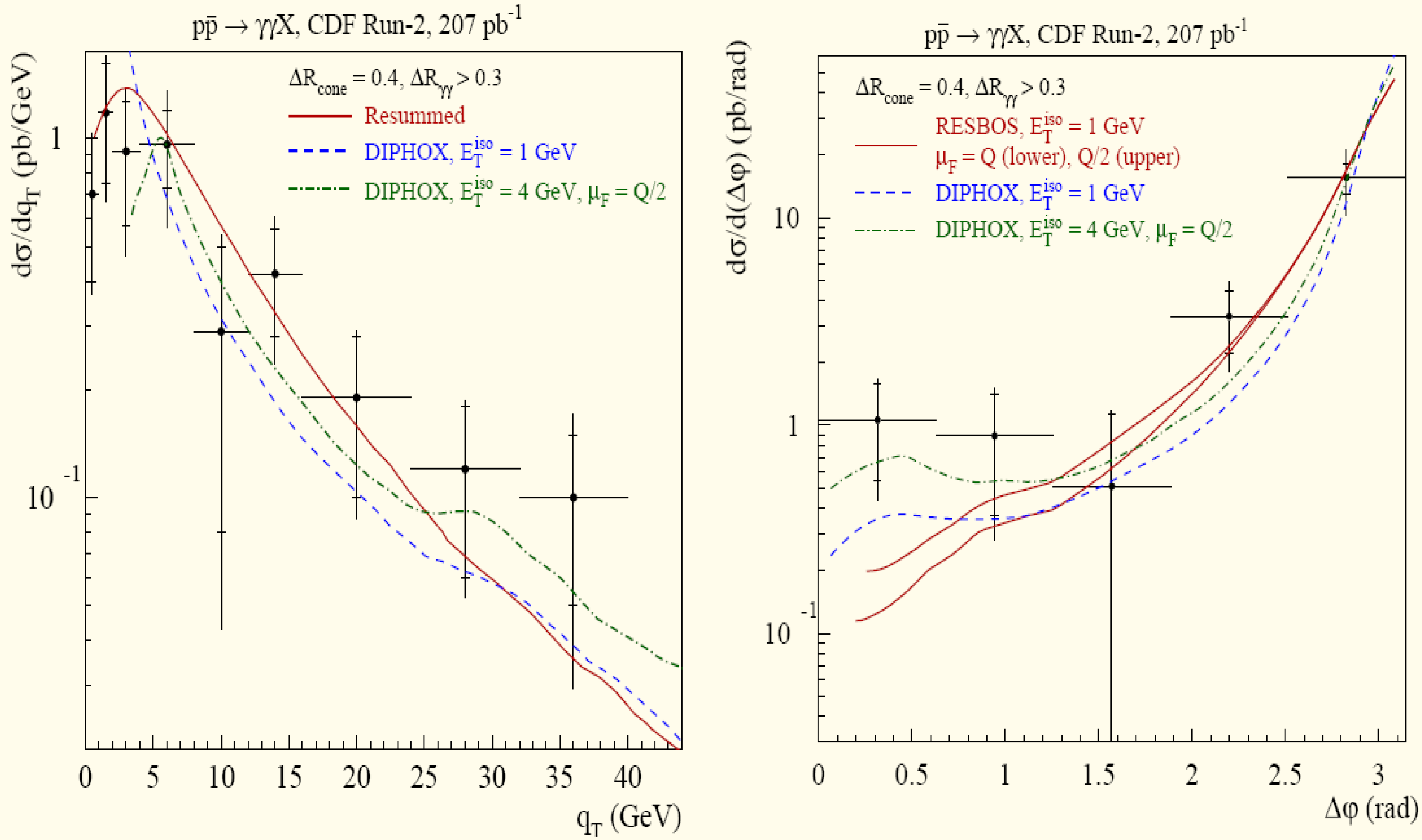


The cut
$P_T < M$
is to suppress
fragmentation
contribution

(Data – theory)/theory vs. the diphoton azimuthal distance for Higgs – like kinematics

Large theoretical uncertainty in fragmentation contribution

arXiv:0704.0001



- Theoretical uncertainties are large in the region $Q \lesssim 25$ GeV, $Q_T \gtrsim 27$ GeV, $\Delta\varphi < \pi/2$, not relevant for the LHC Higgs searches; uncertainties are suppressed by a $Q_T \leq Q$ cut

Limitations of ResBos

- Any perturbative calculation is performed with some approximation, hence, with limitation.
- To make the best use of a theory calculation, we need to know what it is good for and what the limitations are.

It does not give any information about the hadronic activities of the event.

⇨ It could be used to reweight the distributions generated by (PYTHIA) event generator, by comparing the boson (and it decay products) distributions to ResBos predictions.

This has been done for W-mass analysis by CDF and D0)

Potential of ResBos yet to be explored

- E.g., in the measurement of forward-backward asymmetry in Drell-Yan pairs.

ResBos can be used for Matrix Element Method by including resummed k_T-dependent parton distribution functions together with higher order matrix element contributions.

For example: The coefficients in front of the complete set of angular functions are given by ResBos

$$\mathcal{L}_0 = 1 + \cos^2\theta,\ \mathcal{A}_0 = \frac{1}{2}(1 - 3\cos^2\theta),\ \mathcal{A}_1 = \sin 2\theta \cos\phi,\ \mathcal{A}_2 = \frac{1}{2}\sin^2\theta\cos 2\phi,$$
$$\mathcal{A}_3 = 2\cos\theta,\ \mathcal{A}_4 = \sin\theta\cos\phi.$$

Conclusion

- ResBos is a useful tool for studying electroweak gauge bosons and Higgs bosons at the Tevatron and the LHC.
- It includes not only QCD resummation for low q_T region but also higher order effect in high q_T region, with spin correlations included via gauge invariant set of matrix elements.

If you use it, I will keep providing the service to our community. Please send the request to me.

Backup Slides

ResBos vs D0 Run-2 A_{FB} data