A Role for Precision QCD?

Naturalness 2014

Weizmann Institute November 17, 2014

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Perturbative calculations and cuts

The WW test case

Resummation formalisms

What to do with many jets?

A perturbative frontier

When PDF uncertainties are “large”

Perturbative calculations and cuts

Signals & backgrounds start with generic (collinear) factorized cross sections

$$\sigma_{AB\to F+X} = \int dx_a dx_b f_{a/p}(x_a) f_{b/p}(x_b) \hat{\sigma}_{ab\to F+X}(x_a p_A, x_b p_B, M_F)$$

where $\hat{\sigma}_{ab\to F+X}$ is LO, NLO, NNLO ... and also (of course):

$$\sigma_{pp\to F+X} = \int d^2 p_{F\,T} \, \frac{d\sigma_{pp\to F+X}}{d^2 p_{F\,T}}$$

The calculation of $d\sigma_{pp\to F+X}/d^2 p_{F\,T}$ is qualitatively different than for $\sigma_{pp\to F+X}$ and generally requires a more elaborate factorization, for example (Laenen, GS, Vogelsang)

$$\frac{d\sigma_{ab\to V}}{dQ^2 d^2\mathbf{Q}_T} = \frac{1}{S}\sigma^{(0)}_{ab\to V}(Q^2) h^{(\mathrm{j})}_{ab}(\alpha_s(Q)) \int dx_a d^2\mathbf{k}_a \, \mathcal{R}_{a/a}(x_a, \mathbf{k}_a, Q) \int dx_b d^2\mathbf{k}_b \, \mathcal{R}_{b/b}(x_b, \mathbf{k}_b, Q)$$

$$\times \int dw_s d^2\mathbf{k}_s \, U_{ab}(w_s, Q, \mathbf{k}_s) \, \delta(1 - Q^2/S - (1-x_a) - (1-x_b) - w_s) \, \delta^2(\mathbf{Q}_T + \mathbf{k}_a + \mathbf{k}_b + \mathbf{k}_s) + Y_{\mathrm{j}}$$

A guide to resummation:

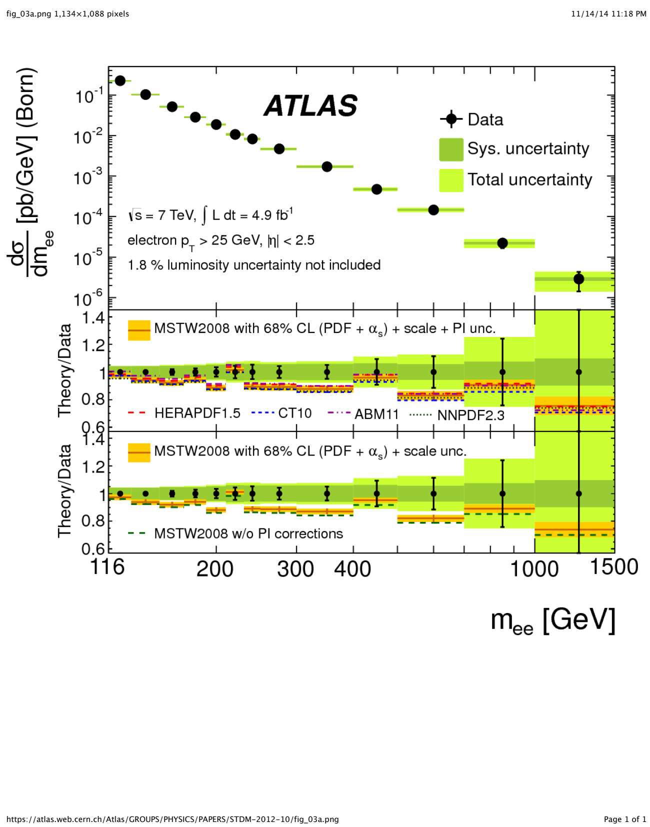
Every convolution (x, p_T or ΔY ...) leads to an evolution equation.

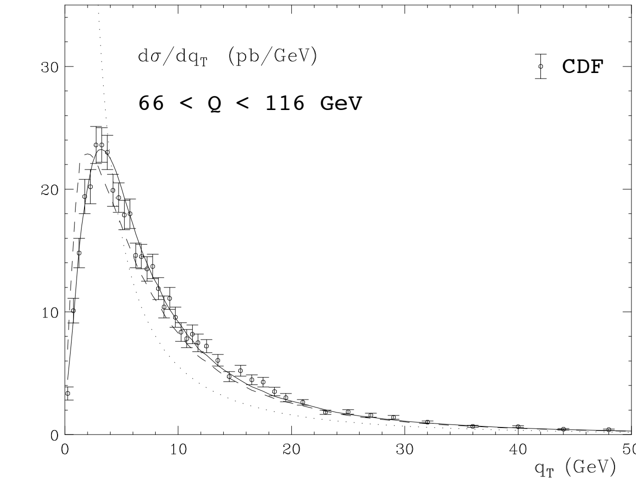
- **For collinear factorization in x, one (DGLAP) evolution equation $\Rightarrow$ exponentiation of single logs (in Q^2).**

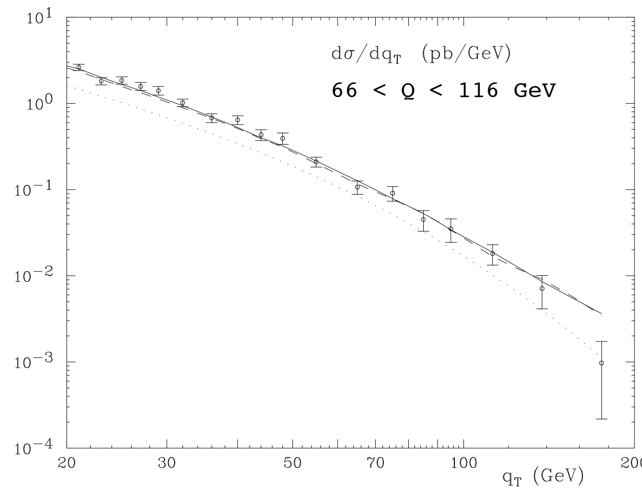
- **For k_T factorization, one (BFKL) evolution equation $\Rightarrow$ exponentiation of single logs (in s).**

- **For x and k_T together, two evolution equations (Collins-Soper, Sen) $\Rightarrow$ exponentiation of double logs (in p_T).**

Even when $\sigma_{pp\to F+X}$ is given by fixed order, $d\sigma_{pp\to F+X}/d^2p_{F\,T}$ (for example) is not a constant, and tends to pile up where there is more than one relevant scale $(Q \gg p_{T\,F} \gg \Lambda_{\rm QCD})$







The stability of the resumed differential cross section at $p_T = 0$ is an example of radiation-induced stability. Recently dubbed "Sudakov safety" (Larkowski, Thaler, 1307.1699).

But the situation may be more complex.

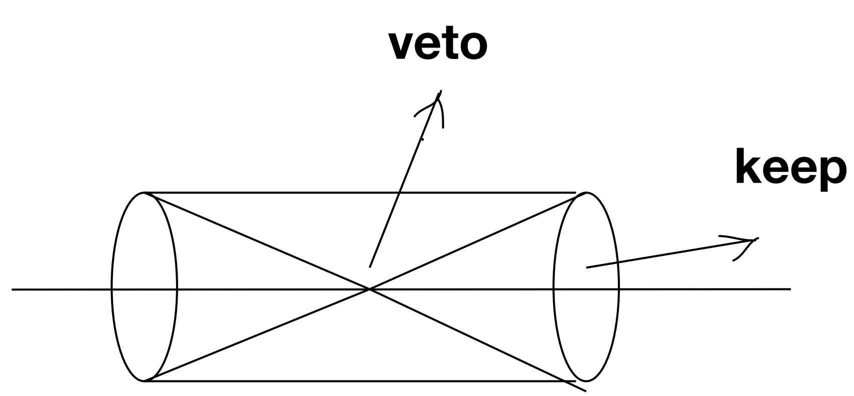
Break the calculation down: build up X = "anything" and the decay of F, the signal:

$$\sigma_{pp\to F+X} = \int d^3p_F \frac{1}{2S} \sum_{X'} \int d(PS)_{X'} \left|A_{AB\to FX'}(p_F)\right|^2 \int \sum_{F'} \left|A_{F\to F'}(p_F)\right|^2$$

$$\begin{aligned} \sigma_{pp\to F+X} &= \int d^3p_F \frac{1}{2S} \sum_{X'} \int d(PS)_{X'} \left|A_{AB\to FX'}(p_F)\right|^2 \left[\theta_v(X') + (1 - \theta_v(X'))\right] \\ &\quad \times \int \sum_{F'} \left|A_{F\to F'}(p_F)\right|^2 \left[\theta_a(F') + (1 - \theta_a(F'))\right] \end{aligned}$$

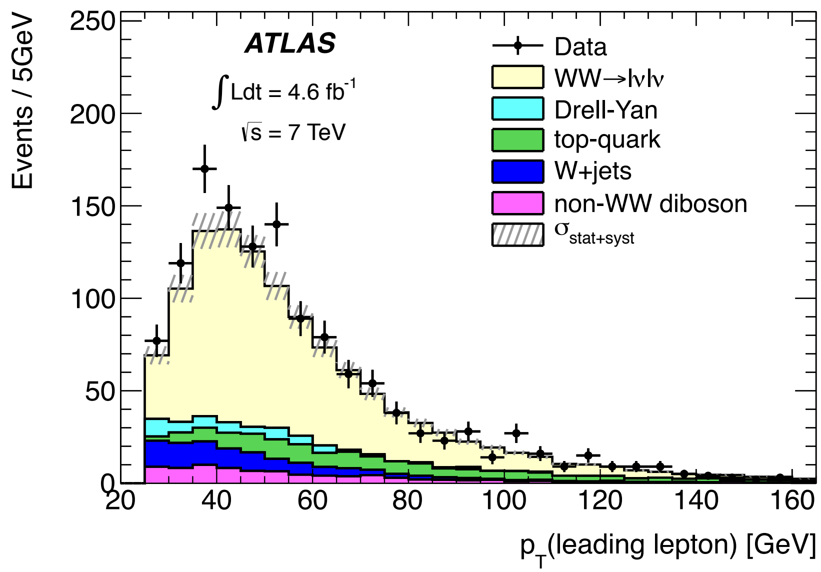
Can we calculate the effects of "acceptance" cuts $\theta_a(F')$ and the "veto" cuts $\theta_v(X')$?

A typical example is



The WW test case

An excess compared to expectations, but problematic at NLO because of jet veto.



Procedure of Meade, Ramani, Zeng 1407.4481

- **Generate events**
- **Reweight according to p_T-resummed cross section**
- **Impose jet vetos**
- **Plot and compare to un-reweighted and among different generators**

Moves in the right direction

. . . fills in a bit

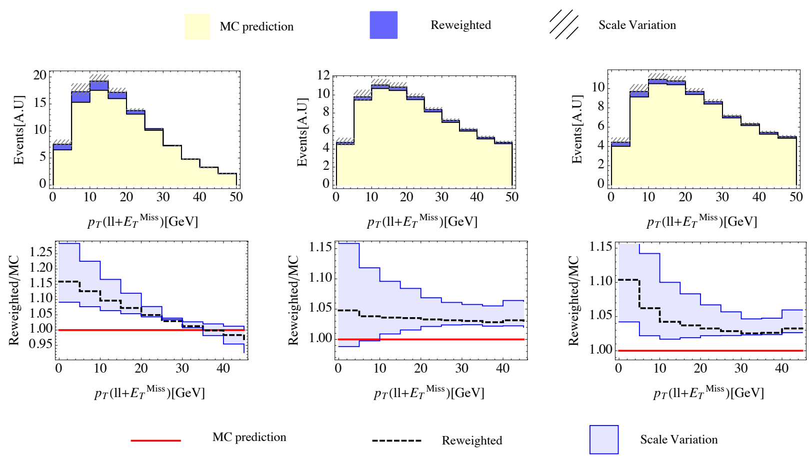


Figure 8: The top row shows the reweighting correction for left (Powheg+Pythia8), center (aMC@NLO+Herwig++), right (Powheg+Herwig++) to the $p_T(ll + E_T^{\text{miss}})$ observable. The bottom row has bin-by-bin percentage difference in events between reweighting and the MC + PS.

although the amount depends on the generator . . .

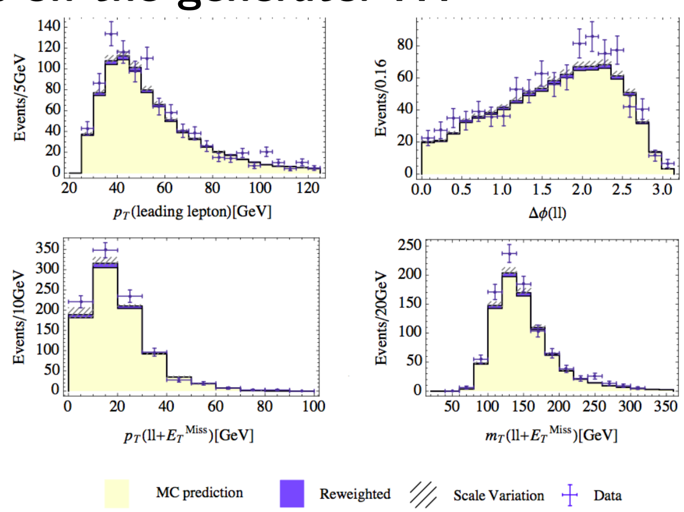


Figure 7: aMC@NLO+Herwig++ observables histogrammed for W^+W^- transverse momentum distribution for 7 TeV collisions and including the reweighting correction.

Resummation Formalisms

SCET has released the muse for factorizations that generalize p_T-factorization. We can apply these to WW with event cuts in "beam thrust", ($\mathcal{T} \sim \sum p_T e^{-|\eta|}$), p_T, etc..

- **Factorization of jet veto cross section a la Tackmann, Walsh, Zuberi, 1206.4312**

$$\sigma(\mathcal{T}^{\rm cut}) = \sigma_0 H_{gg}(m_H,\mu) \int dY\, B_g^{\rm jet}\left(m_H \mathcal{T}^{\rm cut}, x_a, \mu\right) \times B_g^{\rm jet}\left(m_H \mathcal{T}^{\rm cut}, x_b, \mu\right) S_{gg}^{\rm jet}(\mathcal{T}^{\rm cut},\mu)\,, \quad (31)$$

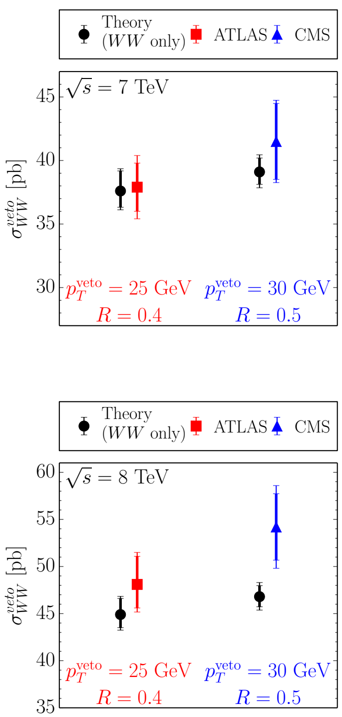
- **Factorization of jet veto cross section a la Becher, Neubert, 1205.3806**

$$d\sigma(p_T^{\rm veto}) = \sigma_0(\mu)\, C_t^2(m_t^2,\mu) \left|C_S(-m_H^2,\mu)\right|^2 \frac{m_H^2}{\tau s}\, dy\, \frac{d^2 q_\perp}{(2\pi)^2} \int d^2 x_\perp\, e^{-iq_\perp\cdot x_\perp} \times 2\mathcal{B}_c^{\mu\nu}(\xi_1, x_\perp, p_T^{\rm veto},\mu)\, \mathcal{B}_{\bar{c}\,\mu\nu}(\xi_2, x_\perp, p_T^{\rm veto},\mu)\, \mathcal{S}(x_\perp, p_T^{\rm veto},\mu)\,, \quad (10)$$

- **Adapted to W^+W^- by Okui and Jaiswal 1407.4537**

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M} = \frac{2(2\pi)^2}{4\pi M s} \int \frac{\mathrm{d}^3\vec{p}_3}{(2\pi)^3\, 2E_3}\, \mathrm{d}\eta\, \delta(M^2 - 2q_\parallel\cdot p_{3\parallel}) \sum_f \sum_{h=\pm1} C_f^{(h)}(\xi_1 P_1, \xi_2 P_2, p_{3+4\parallel}, p_{3-4}, \mu_{\rm f})\Big|_{p_4=q-p_3} \times \frac{1}{N_{\rm c}}\, \frac{1}{2\cdot 2}\Big[\mathcal{B}_{f/\mathrm{p}}(\xi_1, p_{\rm T}^{\rm veto}, \mu_{\rm f}, \nu)\, \mathcal{B}_{\bar{f}/\mathrm{p}}(\xi_2, p_{\rm T}^{\rm veto}, \mu_{\rm f}, \nu) + (f \leftrightarrow \bar{f})\Big]\,,$$

Suggests beyond-NLO corrections that help agreement, which has been confirmed by explicit NNLO in this case (Gehrmann et al., 1408.5243)



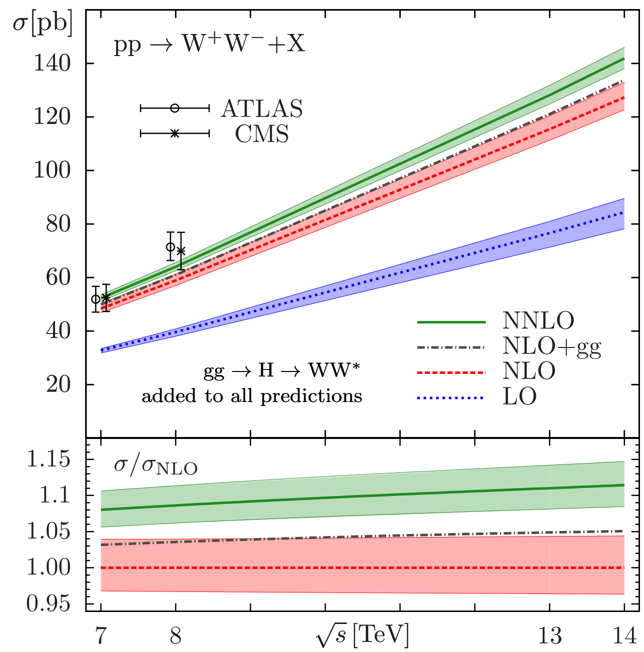
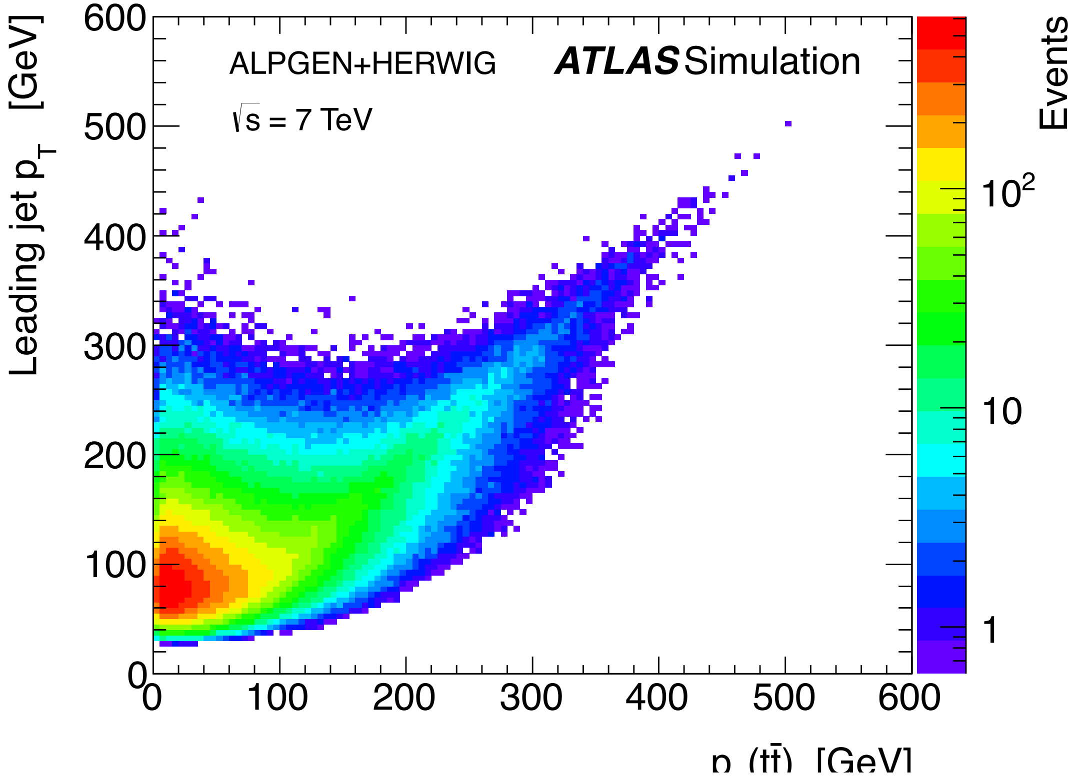


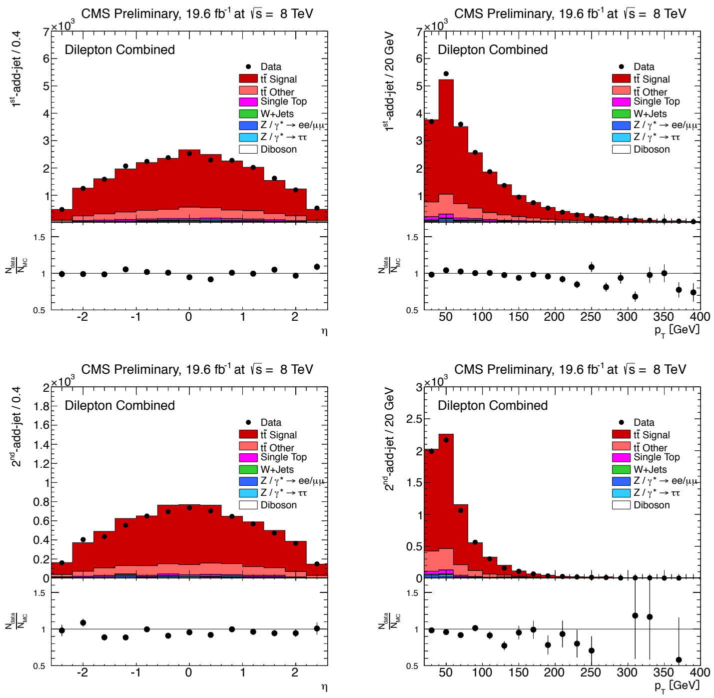
FIG. 1. The on-shell W^+W^- cross section in the 4FNS at LO (dots), NLO (dashes), NLO+gg (dot dashes) and NNLO (solid) combined with $gg \to H \to WW^*$ is compared to recent ATLAS and CMS measurements [5–8]. In the lower panel NNLO and NLO+gg results are normalized to NLO predictions. The bands describe scale variations.

What to do with many jets?

The information hidden in $t\bar{t}$ events is just astounding . . .



Distributions . . . in η, in p_T, in HT gap fractions . . . are only part of it



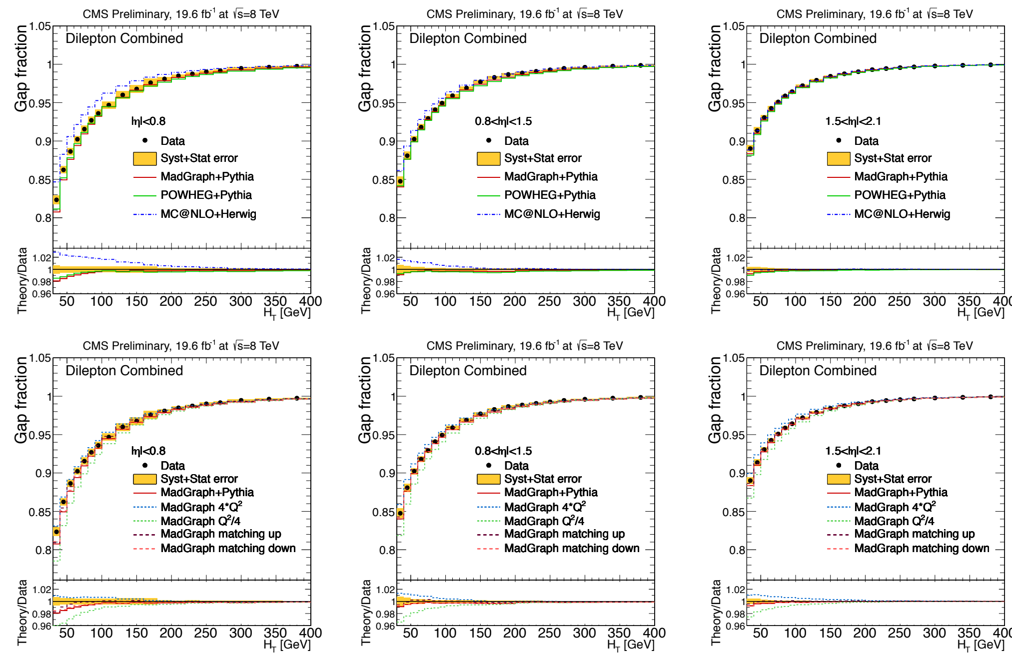
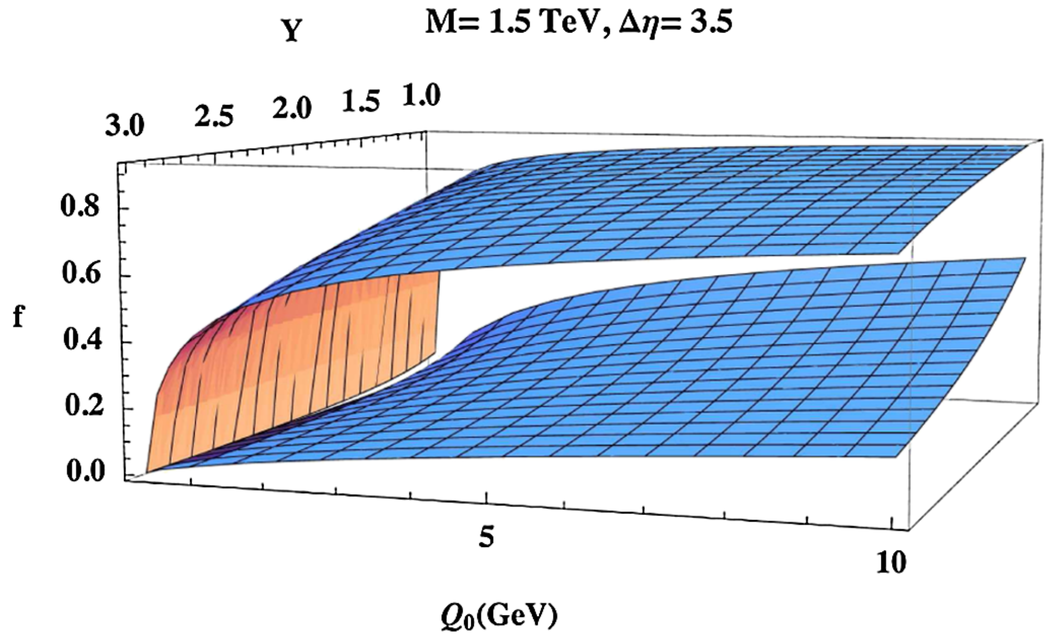


Figure 10: Measured gap fraction as a function of H_T in different η regions. Results in data are compared to the nominal MADGRAPH signal sample, POWHEG and MC@NLO (top) and to the samples with varied Q^2 scale and matching threshold (bottom). For each bin the threshold is defined at the value where the data point is. The errors on the data points indicate the statistical uncertainty. The shaded band corresponds to the statistical uncertainty and the total systematic uncertainty added in quadrature.

Unfold these data, look at pT and HT distributions as a function of rapidity . . .

Radiation into a gap is calculable as a function of energy – with important uncertainties (see below) –

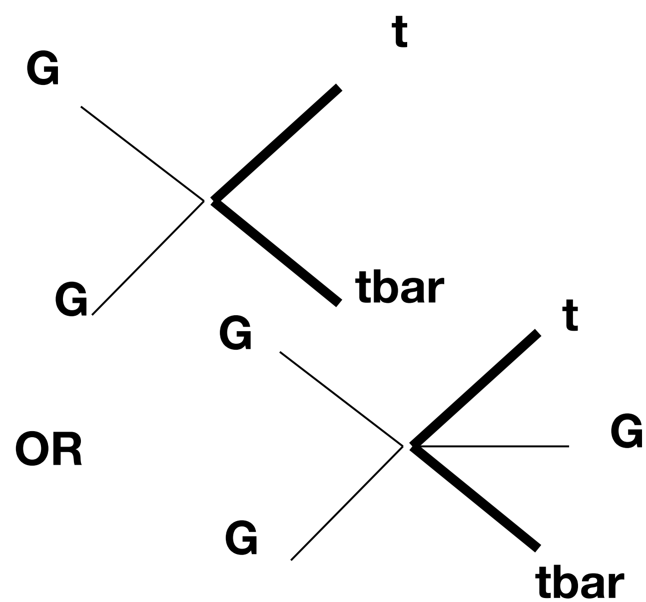


Gaps for heavy pairs of different color (Sung, 0908.3688)

So there is a program to check the QCD nature of radiation. Part of it is the "approximate scale invariance of QCD" but it's more than that . . .

Look in for radiation patterns and gap fractions from recoilless sources – consistent with radiation from LO top pair color flow? When is the color-coherent description of top pair plus leading jet a source necessary to describe lower-energy jets/net energy flow?

Soft functions: recoiless sources



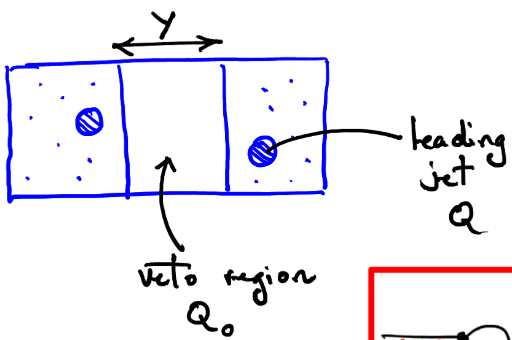
Each has a prediction for "gap" distributions in HT or total energy. But do they really factorize from the "beam function/PDFs"?

Novel jet substructure measures can be resummed starting with such sources (Larkowski, Thaler 1307.1699).

A pQCD frontier

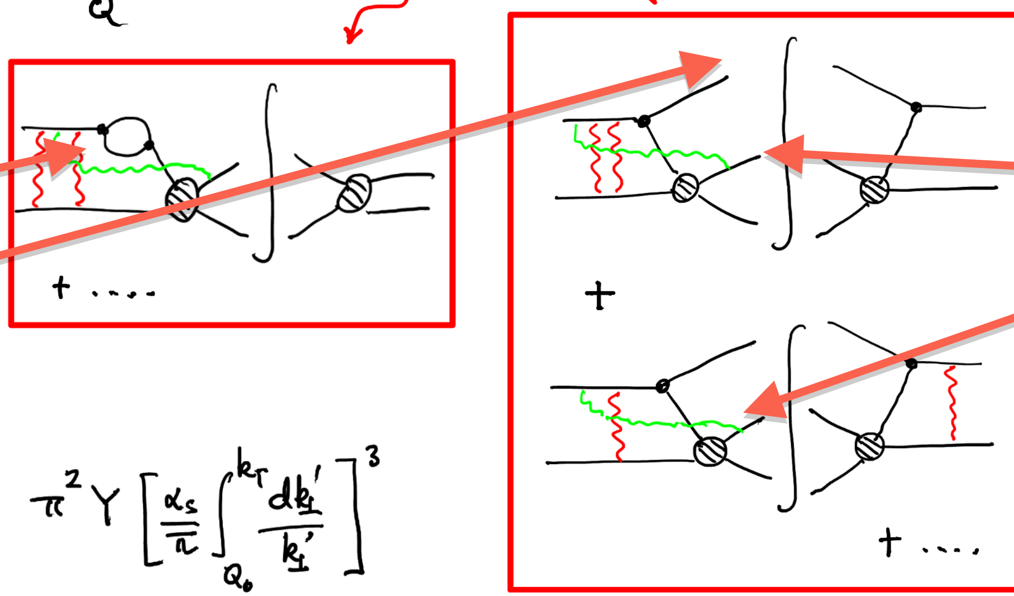
But: We need to improve the theory to get a better understanding of radiation with detected jets/colored particles in the final state. J. Forshaw at PSR 2014 Workshop:

Concrete example: "Gaps between Jets"



$$\sigma = \sigma_0 + \sigma_1 + \sigma_2 + \dots$$

$$\sigma_1 = \sigma_1^V - \sigma_1^R$$



. . . breaks real-virtual cancellation here.

Vetoing radiation here . . .

$$\sigma_1 \sim \frac{\alpha_s}{\pi}\int_{Q_0}^{Q}\frac{dk_\perp}{k_\perp}\int^{\ln Q/k_T} dy \times \pi^2 Y \left[\frac{\alpha_s}{\pi}\int_{Q_0}^{k_T}\frac{dk_\perp'}{k_\perp'}\right]^3$$

$$\times \left\{ t_1^2 \, [[t_t^2, \Delta_c], \Delta_c] - \right.$$

JF, Kyrieleis, Seymour hep-ph/0604094 ; 0808.1269

JF, Seymour, Siodmok 1206.6363

Catani, de Florian, Rodrigo 1112.4405

Also gluon reggeization fails at NNLL : del Duca, Duhr, Gardi, Magnea, White 1109.3581

Interpretation:

The basis of collinear (and k_T) factorization is the cancellation of "final state" interactions on space and time scales large compared to the final state interaction. Color "entanglements" are eliminated in this way, and Ward identities work.

"final state" = not causally connected to the localized hard scattering.

On the other hand . . .
Once the sum over final states becomes (sufficiently) exclusive, color exchange (entanglement?) at short times but over finite distances (size of the colliding systems) can survive.

This color coherence and incoherence may best be studied in a coordinate space picture of the scattering. (Erdogan, GS, to appear)

What to do when PDF uncertainties are "large"

Suppose we have "perfect" data and $\hat{\sigma}$ for some final state, so good that PDF uncertainties dominate.

Parameterization from Jun-Nadolsky "Meta-analysis" 1401.0013

$$f(x, Q_0; \{a\}) = e^{a_1} x^{a_2} (1-x)^{a_3} e^{\sum_{i \geq 4} a_i \left[T_{i-3}(y(x)) - 1\right]}$$

How do we minimize theoretical uncertainty given imperfect PDFs?

Consider collinear-factorized prediction for a range of rapidity Y, and then a subrange ΔY,

$$\boldsymbol{\sigma_H(Y) \ = \ \sigma_H(\Delta Y) \ + \ \sigma(Y - \Delta Y)}$$

Parameter a_1 is an overall normalization, which cancels in ratios. But can the data help at all?

Yes, re-analyze to rederive uncertainty in a_i, $i \neq 1$.

$$\boldsymbol{R\,(\Delta Y, \{a_i,\ i \neq 1\}) \ = \ \frac{\sigma(Y - \Delta Y)}{\sigma(Y)}}$$

Unless the uncertainty is all in a_1, this should improve theoretical uncertainty.

Some thoughts

- **If we are to find "stealth" or other hidden signals, it will require progress in the QCD background.**
- **The key may be in learning how color incoherence of incoming hadronic fragments (the set of "beam functions") emerges as we go from exclusive to inclusive final states. My own hopes are on a coordinate-space description (Erdogan + GS, to appear).**
- **The history of QCD jets and hadronization is there for the reading if we can only learn the language.**
- **Perhaps precision data can help reduce its own theoretical uncertainties.**