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Radiation in High-$\hat{s}$ Final States

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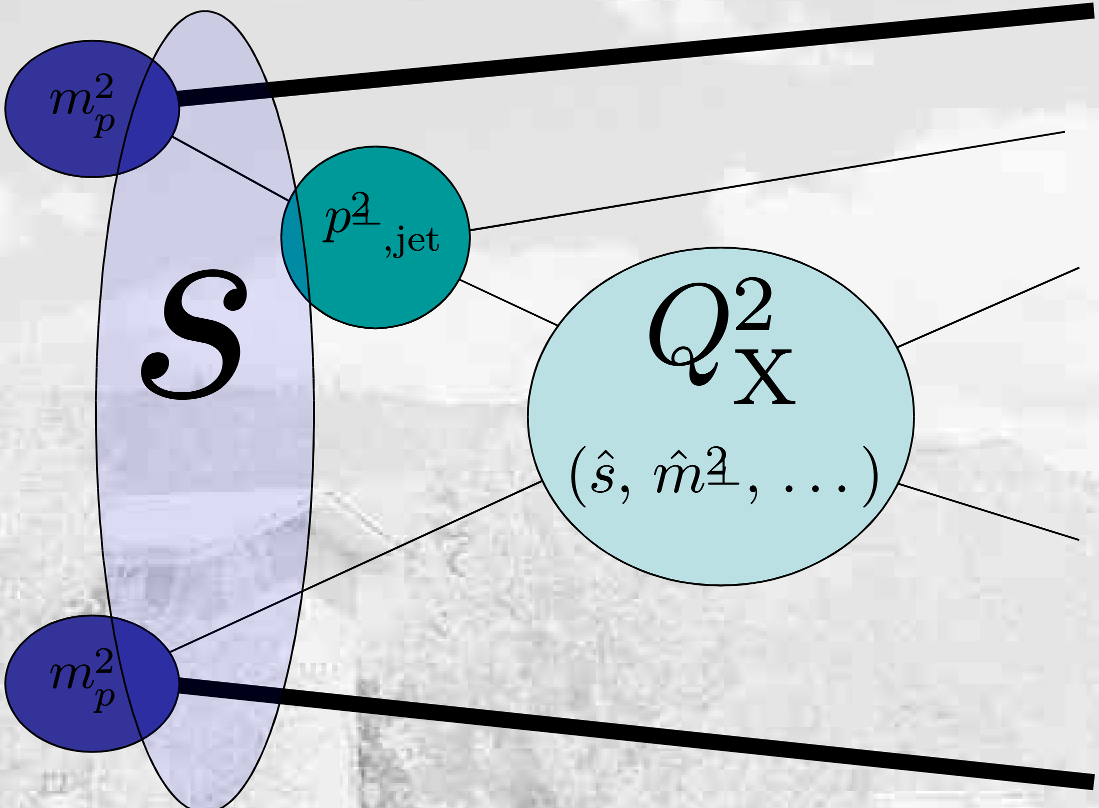
Overview

- QCD @ high energy:
  scales, logs & hands
- Tevatron: ttbar production
- LHC: ttbar production
- LHC: SUSY pair production

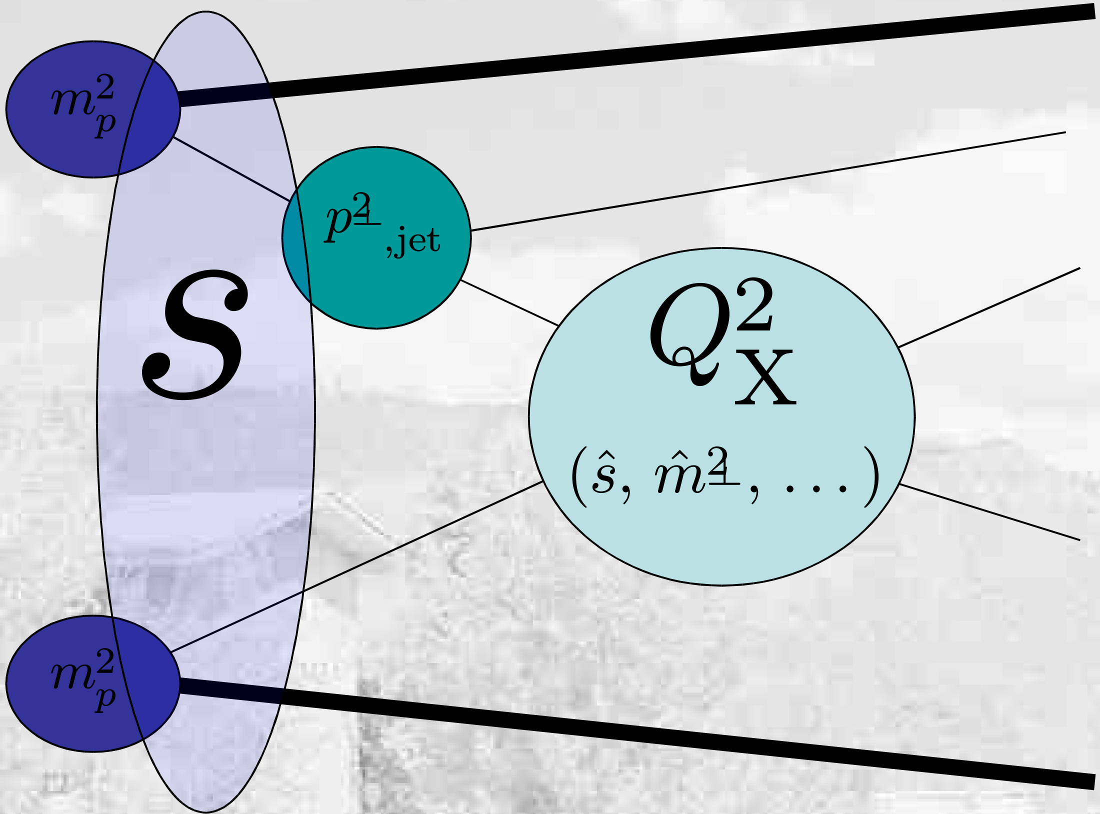
Collider Energy Scales



HARD SCALES:

- s : collider energy
- pT,jet : extra activity
- Q_X : signal scale (ttbar)
- m_X : large rest masses

Collider Energy Scales



HARD SCALES:

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- m_X : large rest masses

SOFT SCALES:

- Γ : decay widths
- m_p : beam mass
- Λ_{QCD} : hadronisation
- m_i : small rest masses

+ "ARBITRARY" SCALES:

- Q_F , Q_R : Factorisation & Renormalisation

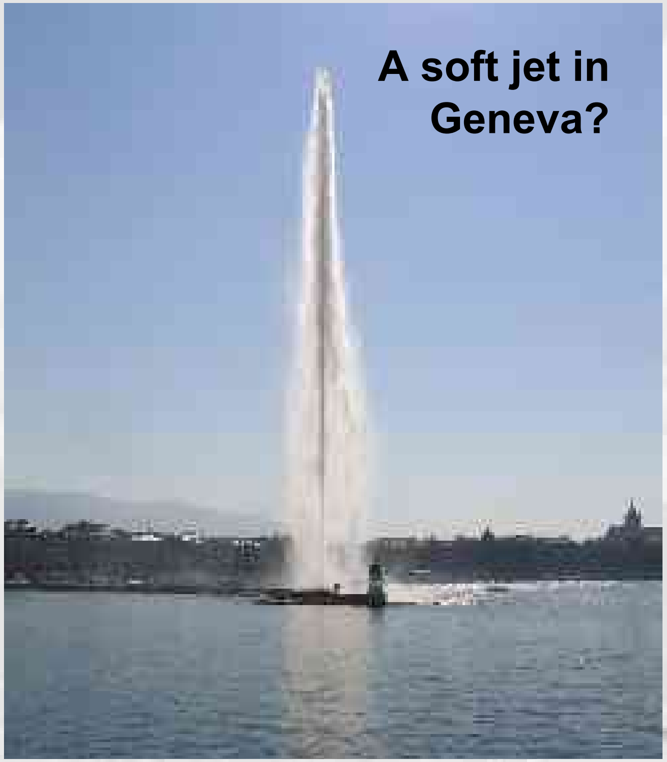
Approximations to QCD

1. Fixed order matrix elements: Truncated expansion in α_S ➔
   - Full intereference and helicity structure included to given order.
   - Divergences appear as low-p_T log divergences.
   - Difficulty (computation time) increases rapidly with final state multiplicity ➔ limited to 2 → 5/6.

2. Parton Showers: infinite series in α_S (but only singular terms = collinear approximation).
   - Resums logs to all orders → excellent at low p_T.
   - Factorisation → Exponentiation → Arbitrary multiplicity
   - Easy match to hadronisation models
   - Interference terms neglected + simplified helicity structure → large uncertainties away from singular regions.

A handwaving argument

- Quantify: what is a soft jet?



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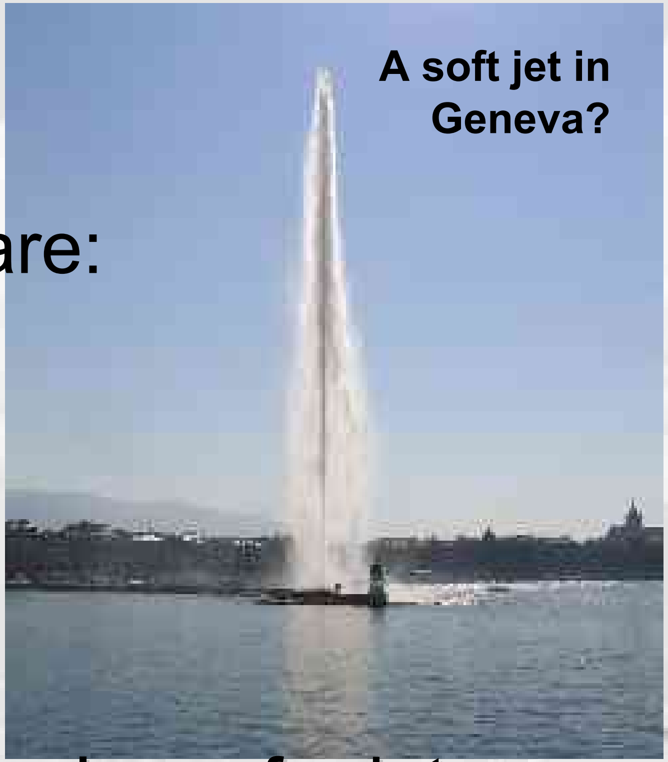

- Handwavingly, leading logs are:

$$\alpha_s \log^2(Q_F^2/p_{\perp,\mathrm{jet}}^2) \to \mathcal{O}(1) \text{ for } \frac{Q_F}{p_{\perp,\mathrm{jet}}} \sim 6$$

- So, very roughly, logs become large for jet p_T around 1/6 of the hard scale.

ttbar + jets @ Tevatron

<u>Process characterized by:</u>

- Threshold production (mass large compared to s)
- A 50-GeV jet is reasonably hard, in comparison with hard scale ~ top mass

SCALES [GeV]

$s = (2000)^2$

$Q^2_{Hard} \sim (175)^2$

$50 < p_{T,jet} < 250$

→ RATIOS

$Q^2_H/s = (0.1)^2$

$1/4 < p_T / Q_H < 2$

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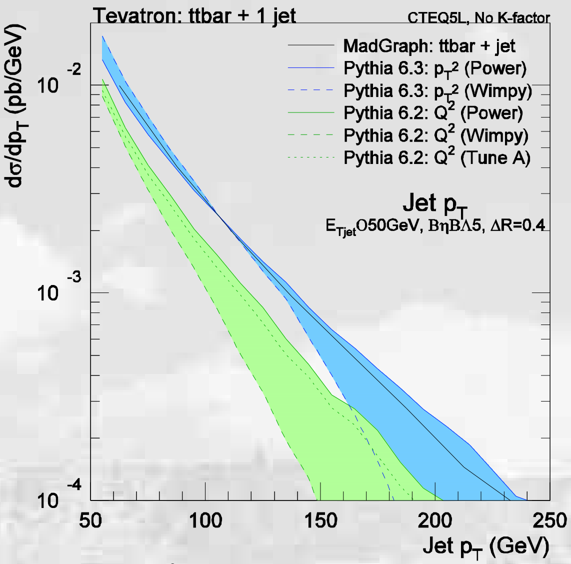
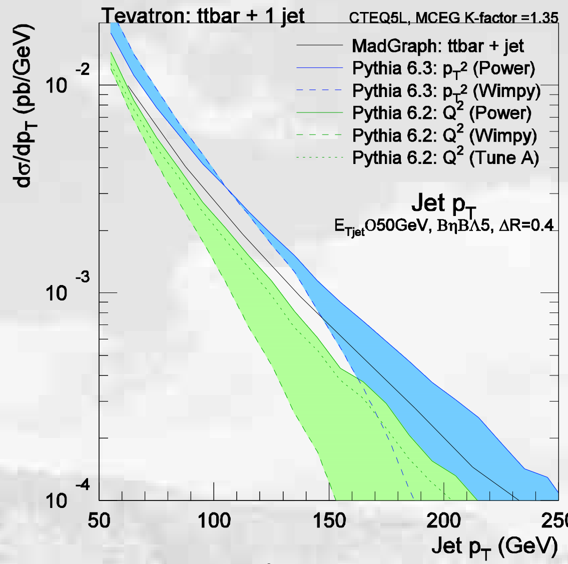
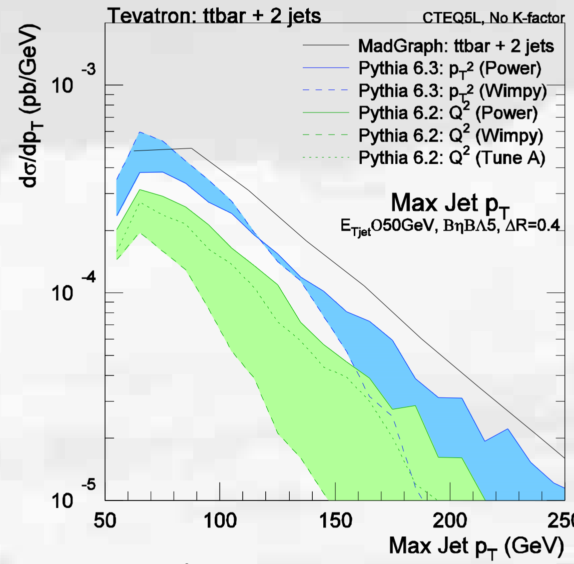


NO K-FACTOR



NLO K-FACTOR



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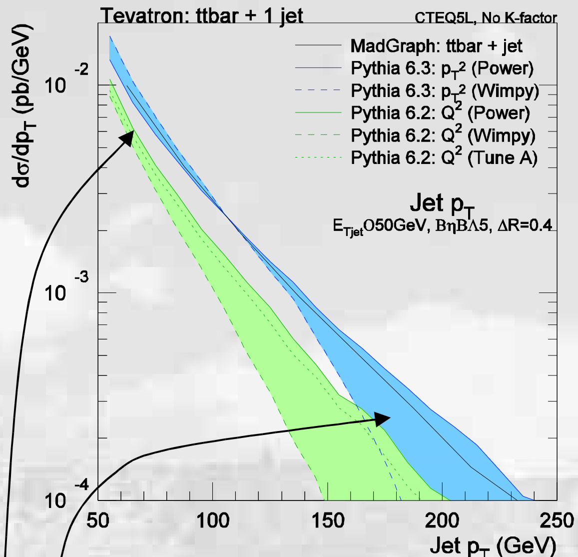

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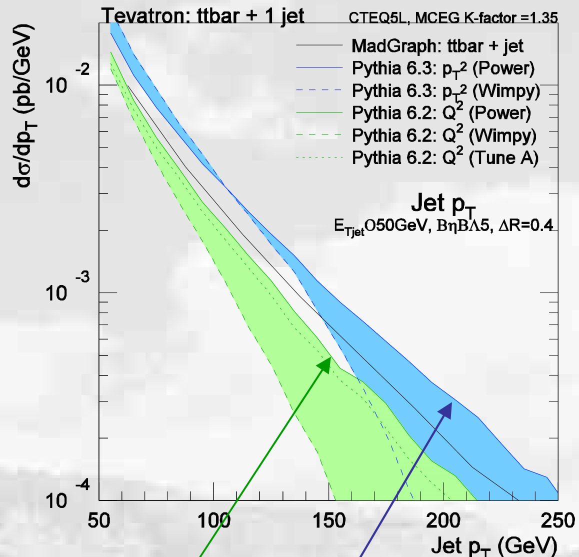

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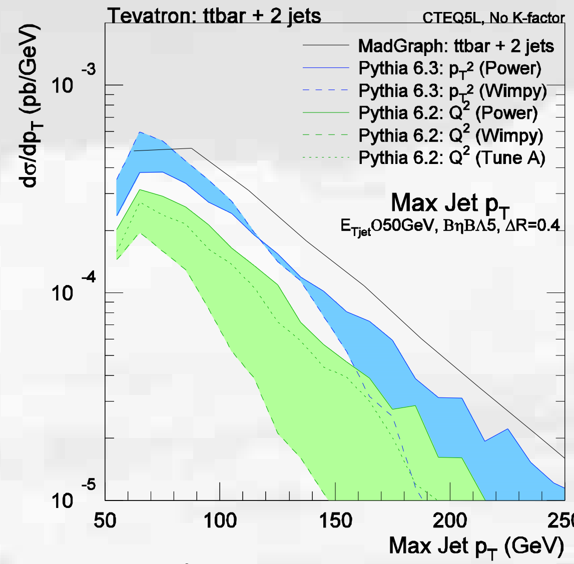

NO K-FACTOR

Hard tails:

- Power Showers (solid green & blue) surprisingly good (naively expect *collinear* approximation to be worse!)
- Wimpy Showers (dashed) drop rapidly around top mass.

Soft peak: logs large @ ~ mtop/6 ~ 30 GeV → fixed order still good for 50 GeV jets (did not look explicitly below 50 GeV yet)

ttbar + jets @ LHC

Process characterized by:

- Mass scale is small compared to s
- A 50-GeV jet is still hard, in comparison with hard scale ~ top mass, but is now soft compared with s.

SCALES [GeV]

$s = (14000)^2$

$Q^2_{Hard} \sim (175+\ldots)^2$

$50 < p_{T,jet} < 450$

RATIOS:

$Q^2_H/s = (0.02)^2$

$1/5 < p_T / Q_H < 2.5$

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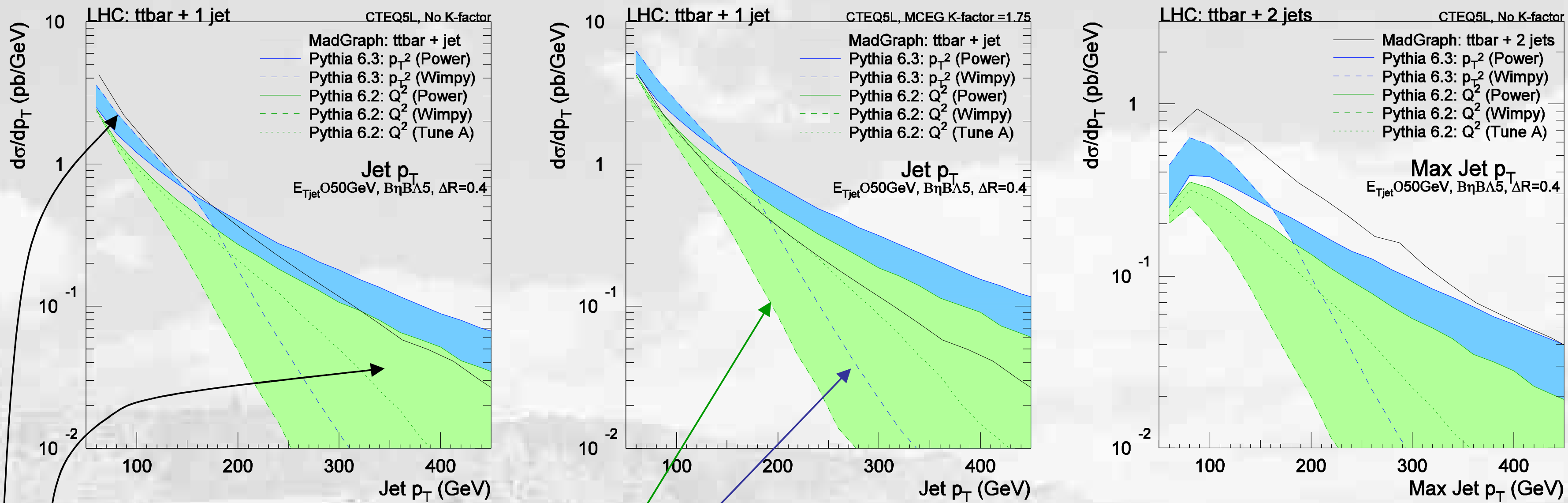

Hard tails: More phase space → more radiation.

- Power Showers still reasonable (but caution advised!)
- Wimpy Showers (dashed) drop catastrophically around top mass.

- Soft peak: logs slightly larger (scale larger than mtop, since not threshold dominated here) → but fixed order still reasonable for 50 GeV jets.

SUSY + jets @ LHC

Process characterized by: (SPS1a)

- Mass scale is again large compared to s
- But a 50-GeV jet is now soft, in comparison with hard scale ~ SUSY mass.

SCALES [GeV]

$s = (14000)^2$

$Q^2_{Hard} \sim (600)^2$

$50 < p_{T,jet} < 450$

RATIOS

$Q^2_H/s = (0.05)^2$

$1/10 < p_T / Q_H < 1$

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SUSY + jets @ LHC

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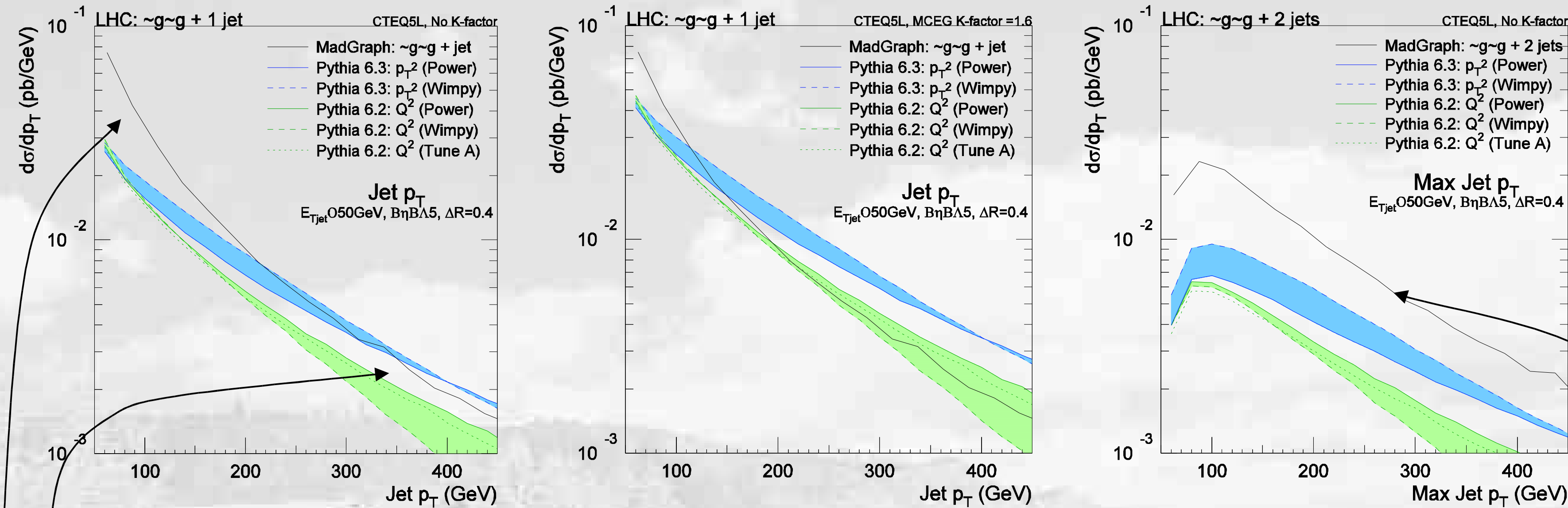


Hard tails: Still a lot of radiation (p_T spectra have moderate slope)

- Parton showers less uncertain, due to higher signal mass scale. Drop of wimpy showers happens later ~ 600 GeV.

- Soft peak: logs BIG: fixed order breaks down for ~ 100 GeV jets. Reconfirmed by parton showers → universal limit below 100 GeV.

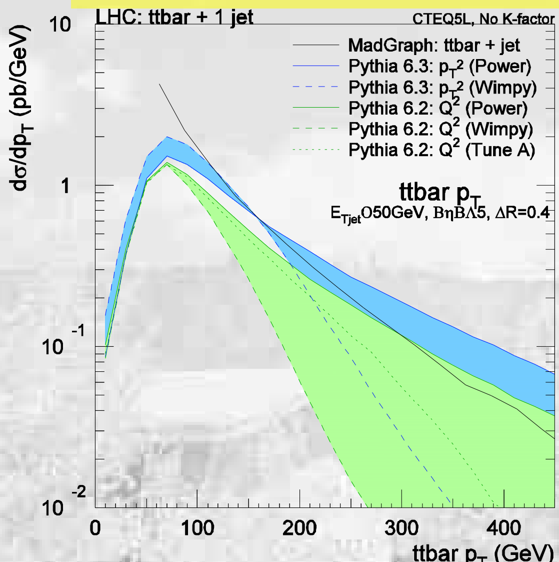
- (2 jet sample: matrix element blowing up → artificially large norm. difference?)

p_T of hard system

(Equivalent to $p_{T,Z}$ for Drell-Yan)

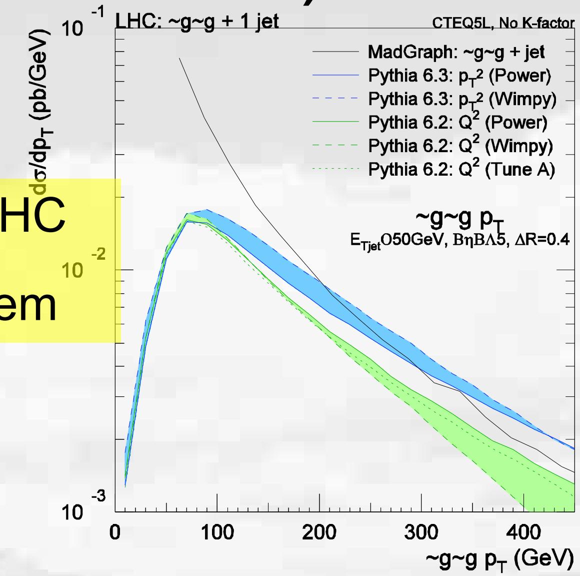
ttbar + 1 jet @ LHC

p_T of (ttbar) system



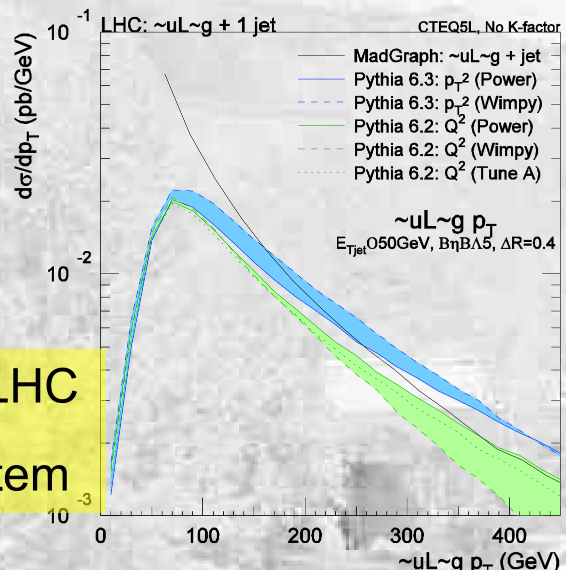
~g~g + 1 jet @ LHC

p_T of (~g~g) system



~uL~g + 1 jet @ LHC

p_T of (~uL~g) system



→ Resummation necessary

Bulk of cross section sits in peak sensitive to multiple emissions.

Conclusions

- SUSY-MadGraph soon to be public.
- Comparisons to PYTHIA Q^2- and p_T^2- ordered showers → New illustrations of old wisdom:
  - Hard jets (= hard in comparison with signal scale) → collinear approximation misses relevant terms → use matrix elements with explicit jets → interference & helicity structure included.
  - Soft jets (= soft in comparison with signal process, but still e.g. 100 GeV for SPS1a) → large logarithms → use resummation / parton showers to resum logs to all orders.

Co

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  showers ➔ New
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