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Heavy Partons & Hard Jets:

from ttbar at the Tevatron to SUSY at the LHC

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with

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Overview

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

QCD

- Known Gauge Group and Lagrangian
- Rich variety of dynamical phenomena, not least confinement.
- Large coupling constant also means perturbative expansion tricky.
- To calculate higher perturbative orders, 2 approaches:
  - Feynman Diagrams
    - Complete matrix elements order by order ☺
    - Complexity rapidly increases ☹
  - Resummation
    - In certain limits, we are able to sum the entire perturbative series to infinite order ☺ parton showers are examples of such approaches.
    - Exact only in the relevant limits ☹

Approximations to QCD

1. Fixed order matrix elements: Truncated expansion in α_S ➔
   - Full intereference and helicity structure to given order.
   - Singularities 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 + ambiguous phase space → large uncertainties away from singular regions.

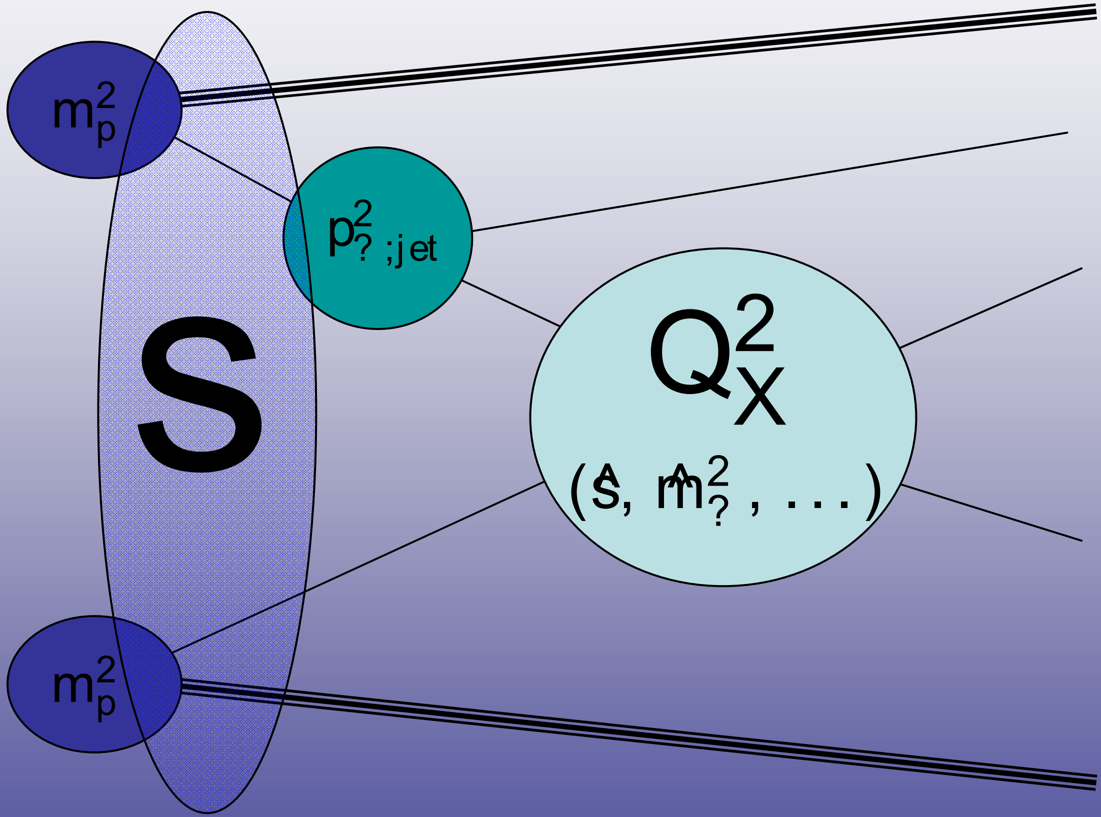
What's what?

- Matrix Elements correct for 'hard' jets
- Parton Showers correct for 'soft' ones.

So what *is* 'hard' and
what is 'soft'?

- And to what extent can showers be constructed and/or tuned to describe hard radiation? (PS: I'm not talking about matching here)

Collider Energy Scales



HARD SCALES:

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

A handwaving argument

- Quantify: what is a soft jet?
- Handwavingly, leading logs are:

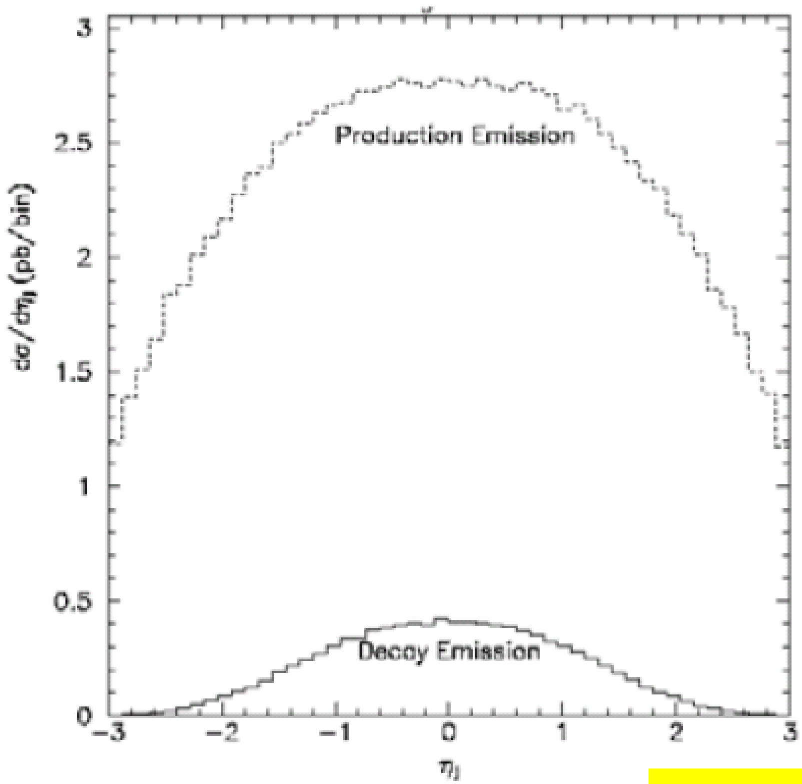
$$\alpha_s \log^2(Q_F^2 / p_{\perp,jet}^2)$$

$$\rightarrow \quad O(1) \text{ for } \frac{Q_F}{p_{\perp,jet}} \sim 6$$

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

Stability of PT at Tevatron & LHC

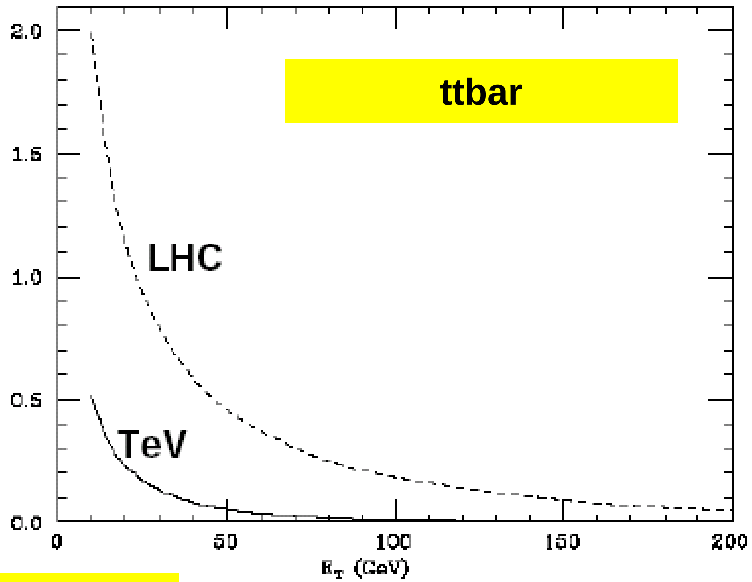
- Most radiation in production:



LHO, Stelzer, Stirling, PRD 1997

- And lots of it!

$$\frac{\sigma}{\sigma_0} = \frac{\sigma(ttj,\ E_T{}^j > E_T\ cut)}{\sigma_{(tt)}}$$



E_T, GeV

Slide from Lynne Orre
Top Mass Workshop

To Quantify:

Last Week: D. Rainwater, T. Plehn & PS - hep-ph/0510144

- Compare MadGraph (for ttbar, and SMadGraph for SUSY), with 0, 1, and 2 explicit additional jets to:
- 5 different shower approximations (Pythia):
  - 'Wimpy Q^2-ordered' **(PHASE SPACE LIMIT < Q_F)** =1
  - 'Power Q^2-ordered' **(PHASE SPACE LIMIT = s)** →∞
  - 'Tune A' (Q^2-ordered) **(PHASE SPACE LIMIT ~ Q_F)** =4
  - 'Wimpy p_T-ordered' **(PHASE SPACE LIMIT = Q_F)**
  - 'Power p_T-ordered' **(PHASE SPACE LIMIT = s)**

PARP(67)

New in 6.3

p_T-ordered showers: T. Sjöstrand & PS - Eur.Phys.J.C39:129,2005

NB: Renormalisation scale in p_T-ordred showers also varied, between $p_T/2$ and $3p_T$

(S)MadGraph Numbers

sps1a

T = 600 GeV top

	σ_{tot}[pb]	$\tilde{g}\tilde{g}$	$\tilde{u}_L\tilde{g}$	$\tilde{u}_L\tilde{u}_L^*$	$\tilde{u}_L\tilde{u}_L$	TT
$p_{T,j} >$ 100 GeV	σ_{0j}	4.83	5.65	0.286	0.502	1.30
	σ_{1j}	2.89	2.74	0.136	0.145	0.73
	σ_{2j}	1.09	0.85	0.049	0.039	0.26
$p_{T,j} >$ 50 GeV	σ_{0j}	4.83	5.65	0.286	0.502	1.30
	σ_{1j}	5.90	5.37	0.283	0.285	1.50
	σ_{2j}	4.17	3.18	0.179	0.117	1.21

1) Extra 100 GeV jets are there ~ 25%-50% of the time!

2) Extra 50 GeV jets - ??? No control → We only know ~ a lot!

ttbar + jets @ Tevatron

Process characterized by:

• 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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ttbar + jets @ Tevatron

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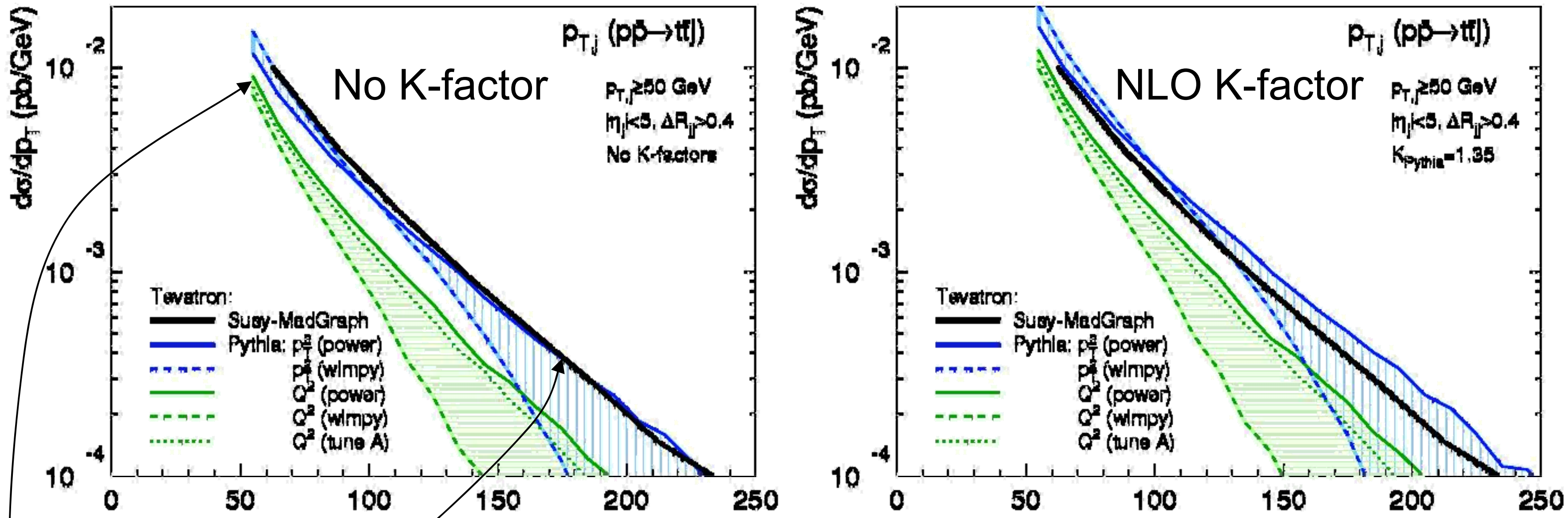

<u>Hard tails</u>:
- Power Showers (solid green & blue) surprisingly good (naively expect *collinear* approximation to be worse!)
- Wimpy Showers (dashed) drop rapidly around top mass.

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

SCALES [GeV]

$s = (2000)^2$

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

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

ttbar + jets @ Tevatron

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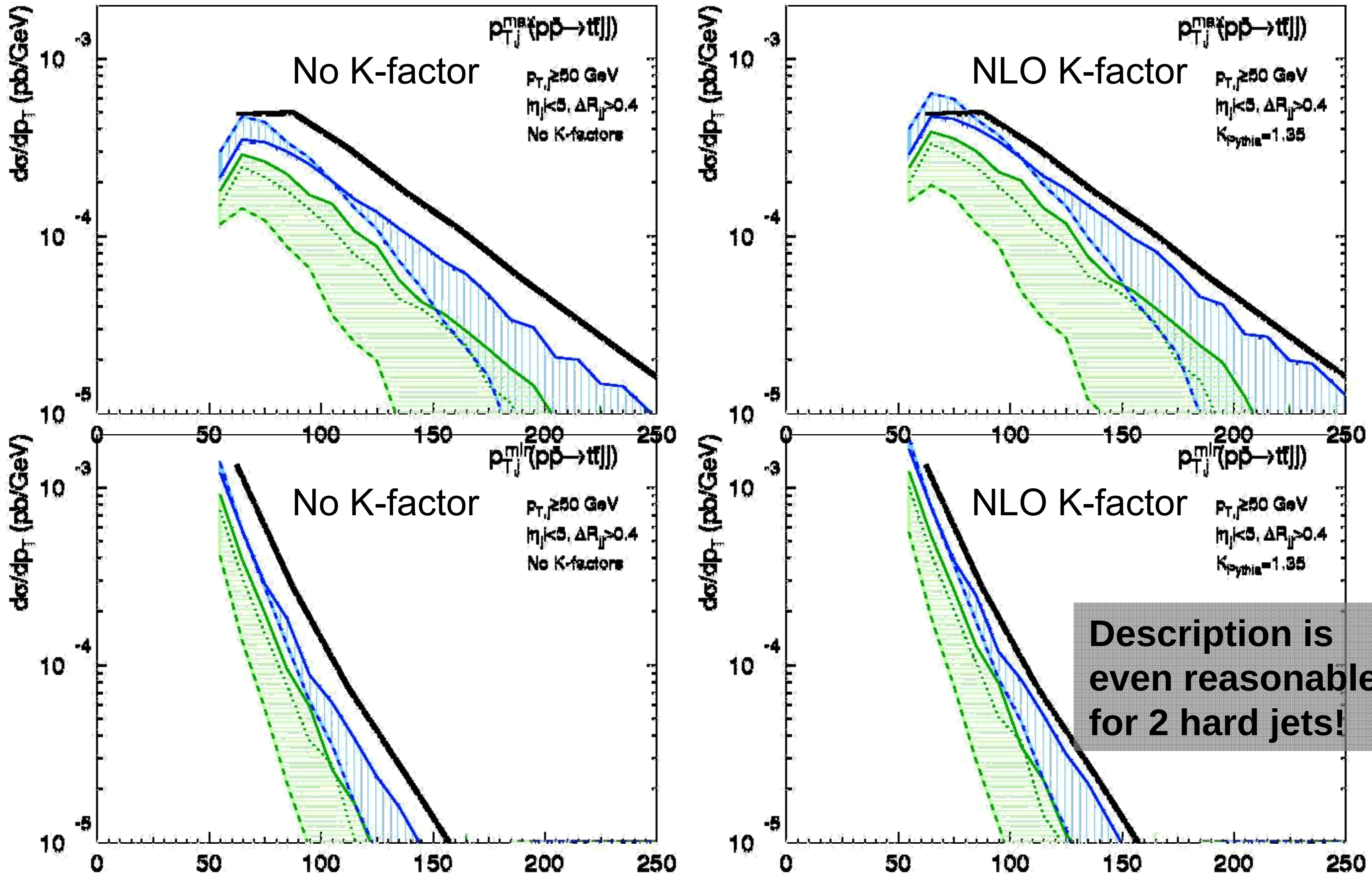


Description is even reasonable for 2 hard jets!

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:

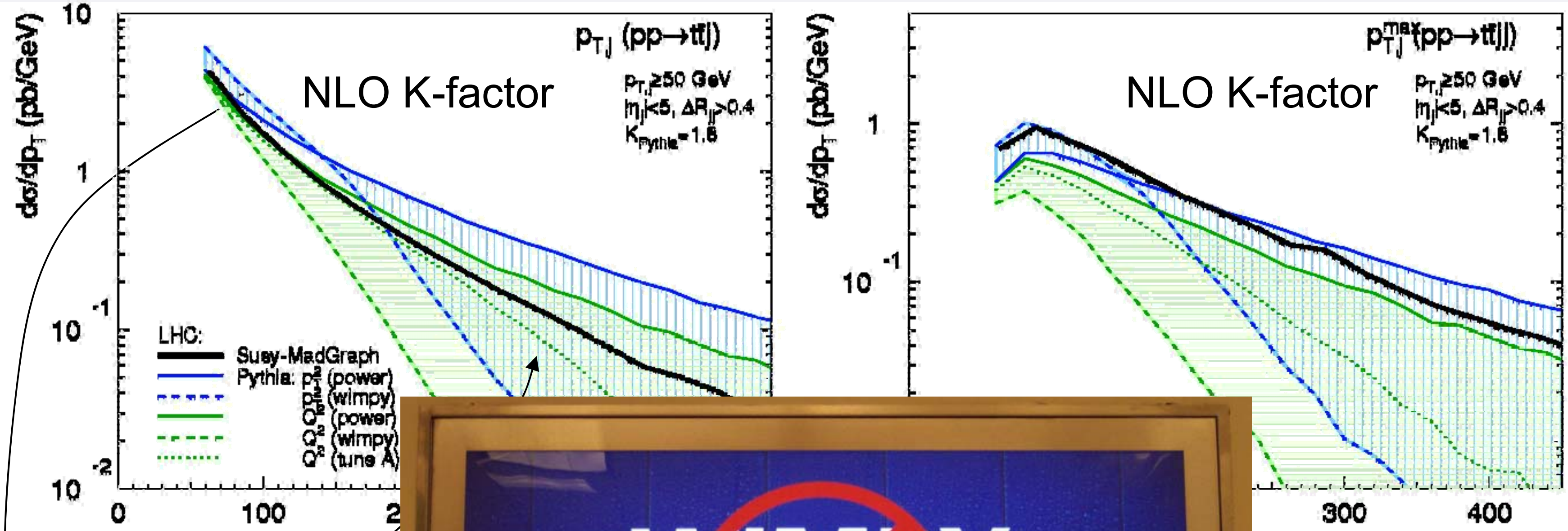
$Q^2_H/s = (0.02)^2$

$1/5 < p_T / Q_H < 2.5$

SCALES [GeV]
$s = (14000)^2$
$Q^2_{Hard} \sim (175+\ldots)^2$
$50 < p_{T,jet} < 450$

ttbar + jets @ LHC

RATIOS
$Q^2_H/s = (0.02)^2$
$1/5 < p_T / Q_H < 2.5$



Hard tails: More
- Power Showers
- Wimpy Showers ... mass.

- Soft peak: logs ... not threshold dominated here) ... jets.

SUSY + jets @ LHC

Process characterized by: (SPS1a → m_{gluino}=600GeV)

- 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

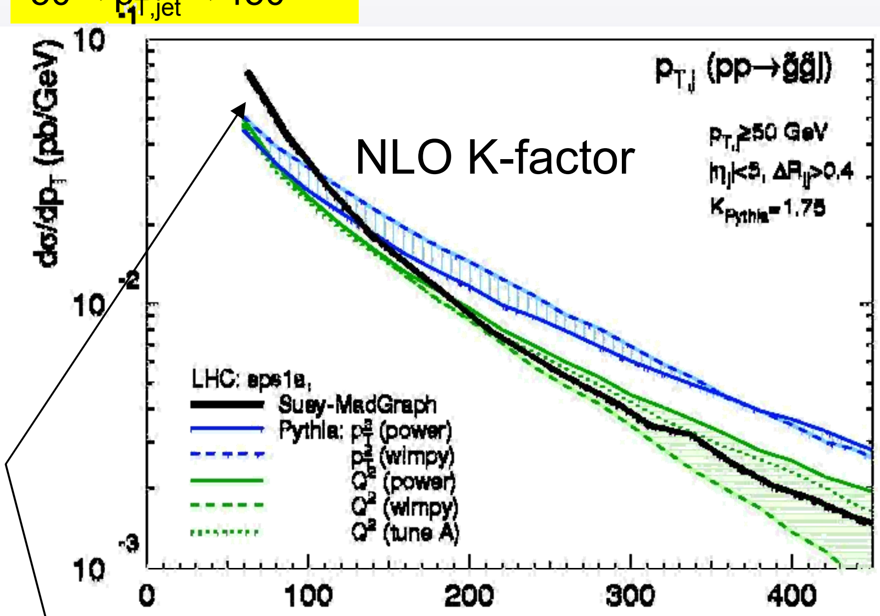
$Q^2_H/s = (0.05)^2$

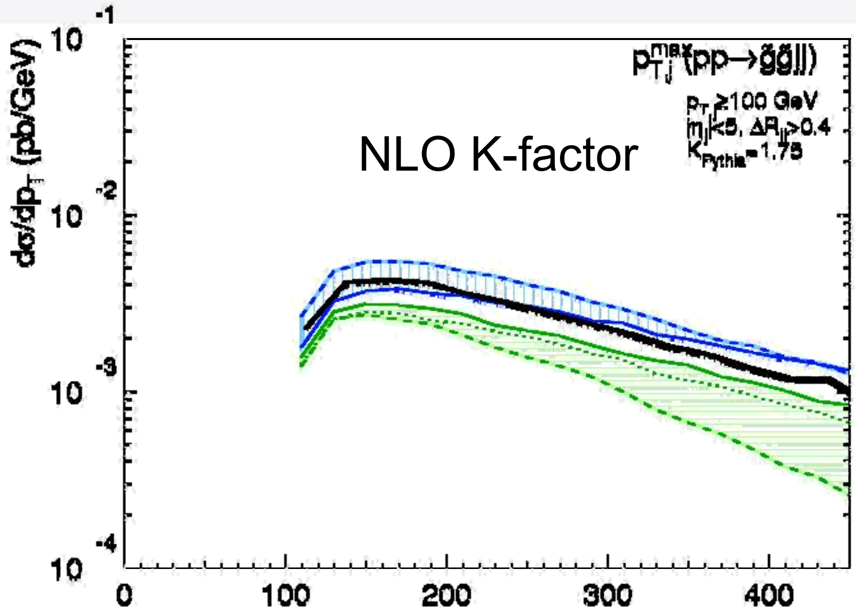
$1/10 < p_T / Q_H < 1$

SCALES [GeV]
$s = (14000)^2$
$Q^2_{Hard} \sim (600)^2$
$50 < p_{T,jet} < 450$

SUSY + jets @ LHC

RATIOS
$Q^2_H/s = (0.05)^2$
$1/10 < p_T / Q_H < 1$





Hard tails: Still a lot of radiation (p_T spectra have moderate slope)
• Parton showers less uncertain, due to higher signal mass scale.

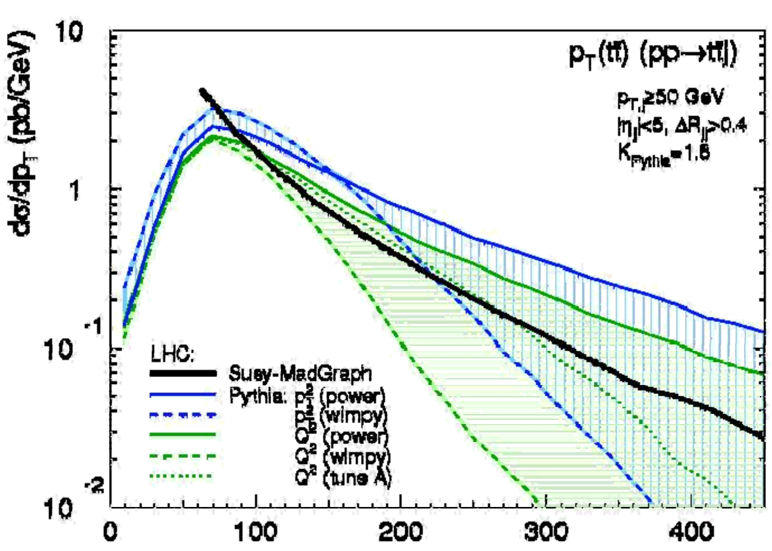
• Soft peak: fixed order breaks down for ~ 100 GeV jets. Reconfirmed by parton showers → universal limit below 100 GeV.

No description is perfect everywhere!
→ To improve, go to ME/PS matching (CKKW / MC@NLO / …)

p_T of hard system
(Equivalent to $p_{T,Z}$ for Drell-Yan)

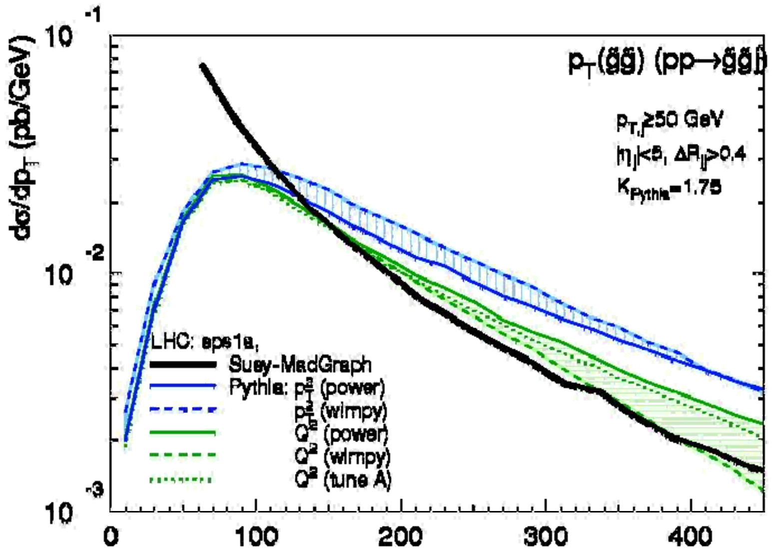
ttbar + 1 jet @ LHC

p_T of (ttbar) system



~g~g + 1 jet @ LHC

p_T of (~g~g) system



→ 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)
    → singularities give large logarithms
    → use resummation / parton showers to resum logs to all orders.

Conclusions

- SUSY at LHC is more similar to top at Tevatron than to top at LHC, owing to similar *ratios* of scales involved
- (but don't forget that ttbar is still mainly qq-initiated at the Tevatron).

- Parton Showers *can* produce realistic rates ☺ for hard jets, though not perfectly ☹
- Ambiguities in hard region ☹ between different approximations (e.g. wimpy vs power, Q^2 vs p_T) → gives possibility for systematic variation ☺
- Better showers = good ☺ Matched approaches better! ☼

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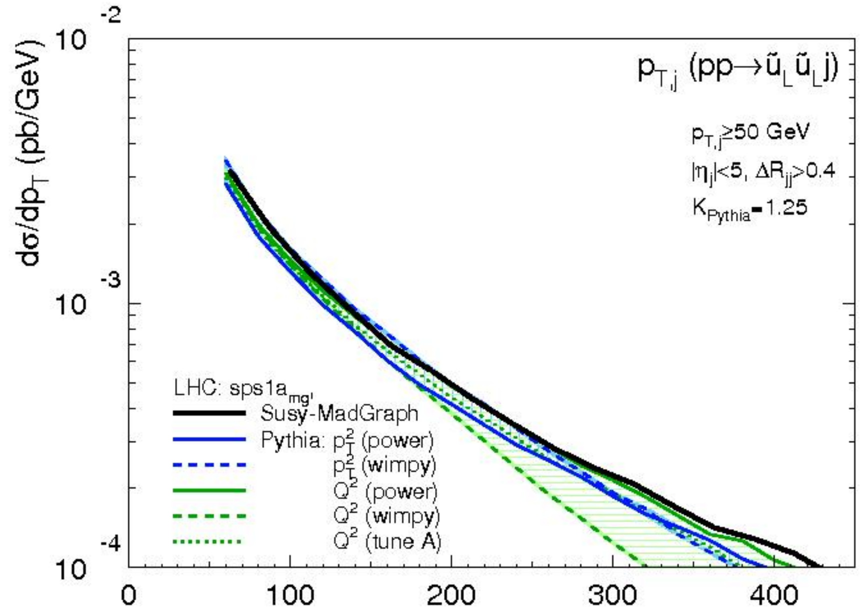
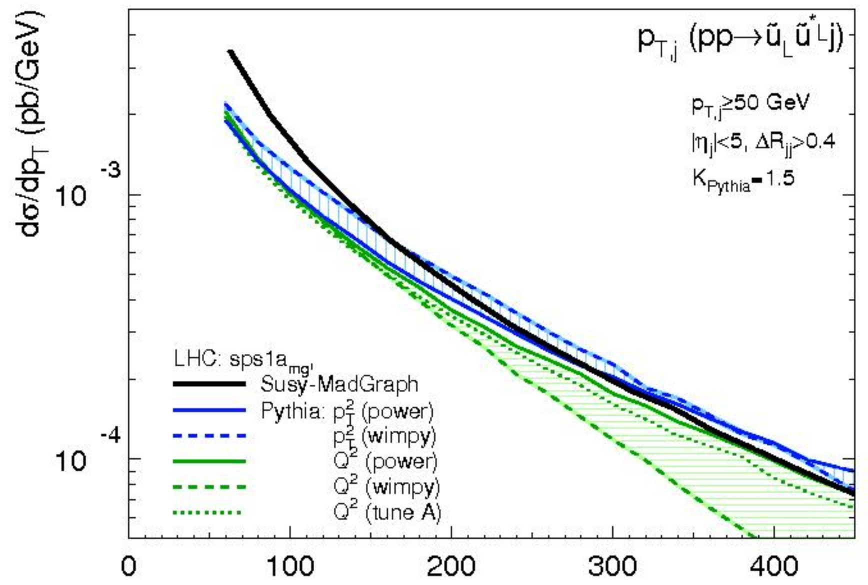
More SUSY: $\tilde{}u_L\tilde{}u_L$



ME Divergence much milder than for ~g~g !

Possible cause: qq-initiated valence-dominated initial state
→ less radiation.

More SUSY: $\sim u_L \sim u_L^*$



Other sea-dominated initial states exhibit same behaviour as ~g~g