MC4LHC Workshop, CERN, July 2006

Heavy Particles & Hard Jets:

from ttbar at the Tevatron to SUSY at the LHC

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with

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& T. Sjöstrand (CERN & Lund U),

Approximations to QCD

1. <u>Fixed order matrix elements: Truncated expansion in α_S ➔</u>
   - Full intereference and helicity structure to given order.
   - Singularities appear as low-p_T log divergences.
   - Complexity increases rapidly with final state multiplicity ➔ in practice limited to 2 → 5/6.

2. <u>Parton Showers: infinite series in α_S (but only singular terms = collinear approximation).</u>
   - 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?

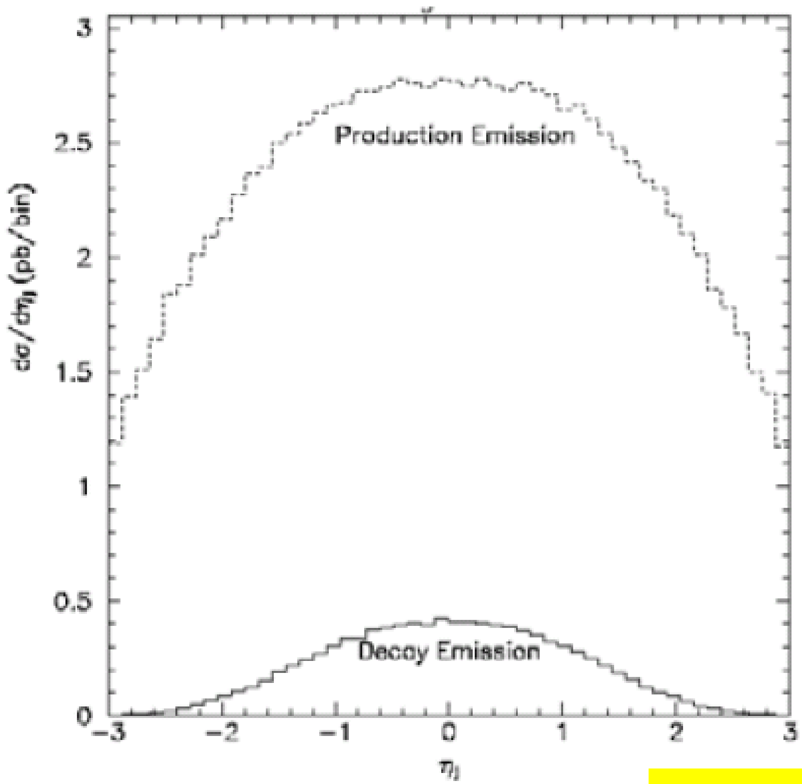
- Matrix Elements correct for 'hard' jets
- Parton Showers correct for 'soft' ones.

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

- And to what extent is it realistically possible to construct and/or tune showers to describe hard radiation?

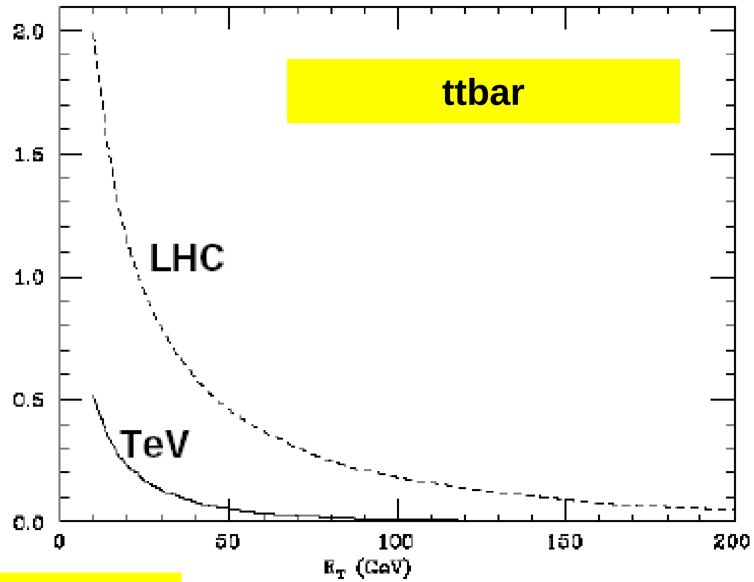
Stability of PT at Tevatron & LHC

- Most radiation in production:



- And lots of it!

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



E_T, GeV

Slide from Lynne Orre
Top Mass Workshop

LHO, Stelzer, Stirling, PRD 1997

(S)MadGraph Numbers

sps1a

T = 600 GeV top

LHC

	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!

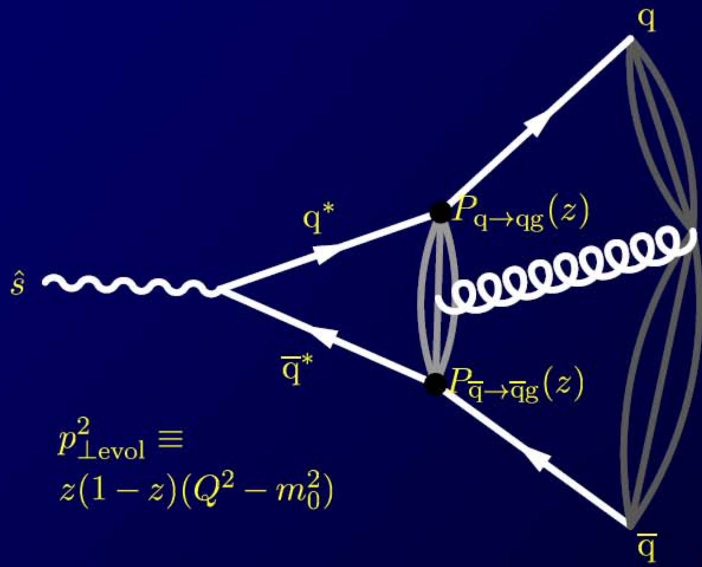
2) Extra 50 GeV jets - ??? No control → We only know ~ a lot!

Rainwater, Plehn & PS : hep-ph/0510144 + hep-ph/0511306

Pythia 6.3+ : p_T-ordered showers

Merged with X + 1 jet Matrix Elements (by reweighting) for: h/γ/Z/W production, and for most EW, top, and MSSM decays!

Exclusive *kinematics* constructed inside dipoles based on Q^2 and z, assuming yet unbranched partons on-shell

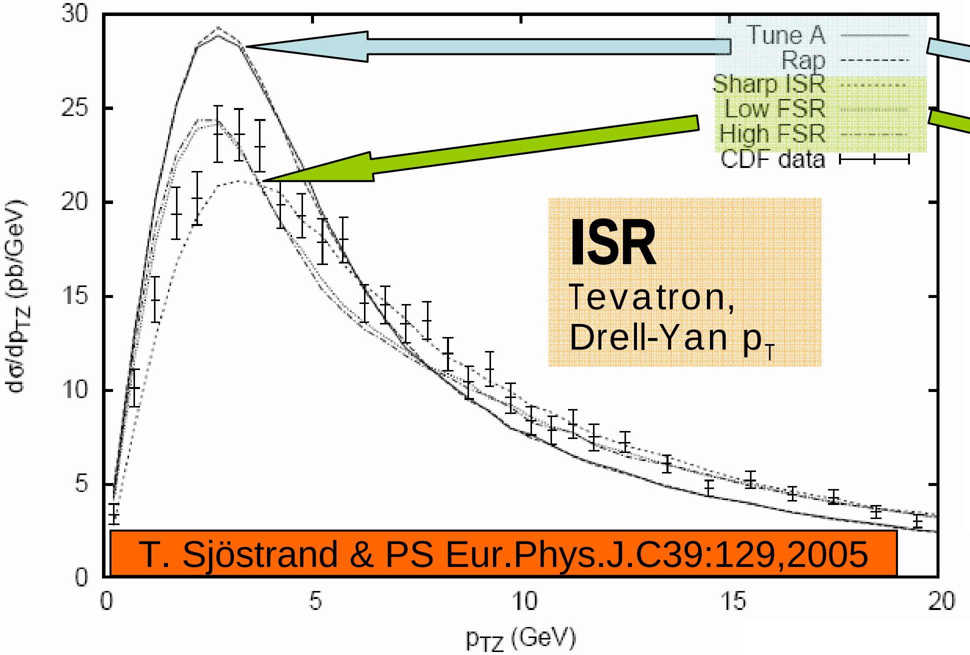


Iterative application of Sudakov factors...

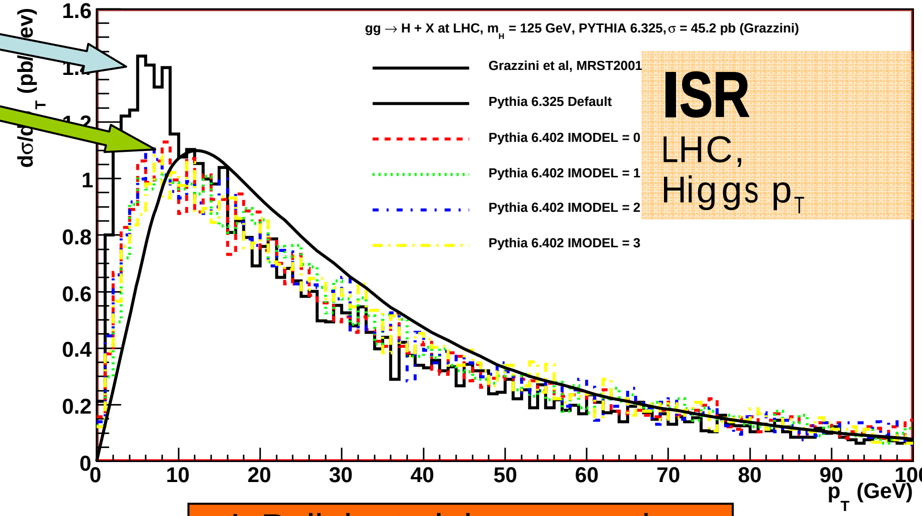
$\Rightarrow$ One combined sequence $p_{\perp max} > p_{\perp 1} > p_{\perp 2} > \ldots > p_{\perp min}$

NB: Choice of $p_{\perp max}$ non-trivial and *very* important for hard jet tail $\leftrightarrow$ wimpy vs power showers...

Pythia 6.3+ : p_T-ordered showers



T. Sjöstrand & PS Eur.Phys.J.C39:129,2005

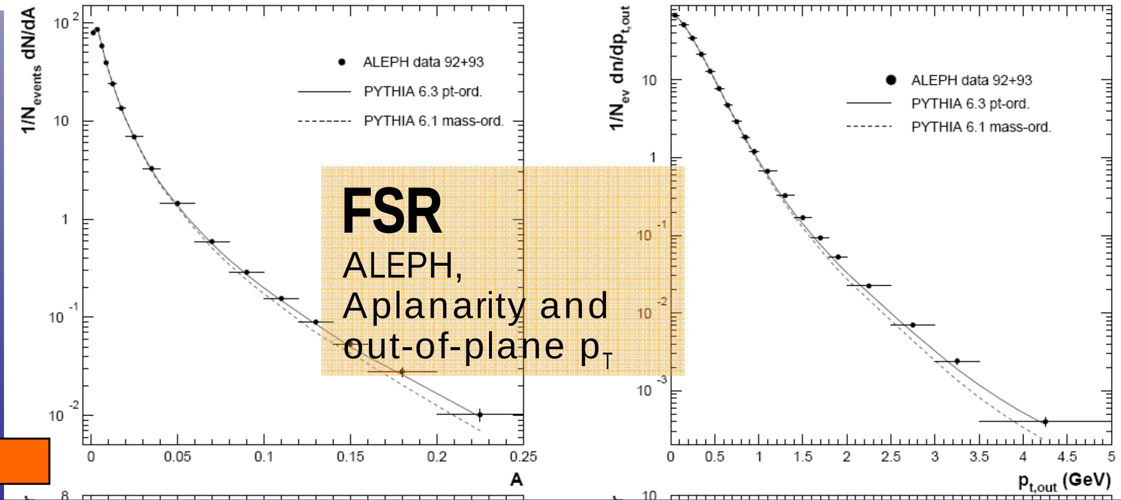


I. Puljak et al, in preparation

Sample tunes available as new subroutine: PYTUNE(ITUNE)

http://www.thep.lu.se/~torbjorn/pythia/main75.f (for Pythia 6.402+)

(incl. detailed comments on each tune)



G. Rudolph (ALEPH, 2004)

Rainwater, Plehn & PS : hep-ph/0510144 + hep-ph/0511306

To Quantify:

- 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)** $\rightarrow \infty$ **PARP(67)**
  - '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)** **New in 6.3**

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

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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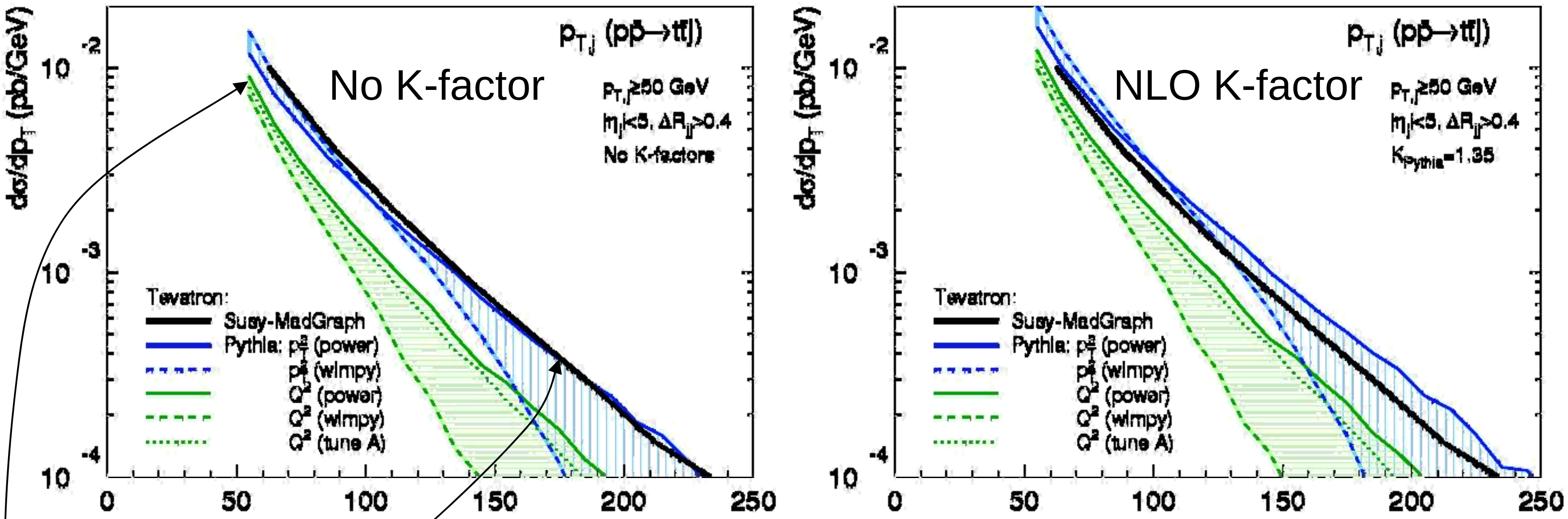

<u>Hard tails</u>:

- 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)

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]
$s = (14000)^2$
$Q^2_{Hard} \sim (175+\ldots)^2$
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ttbar + jets @ LHC

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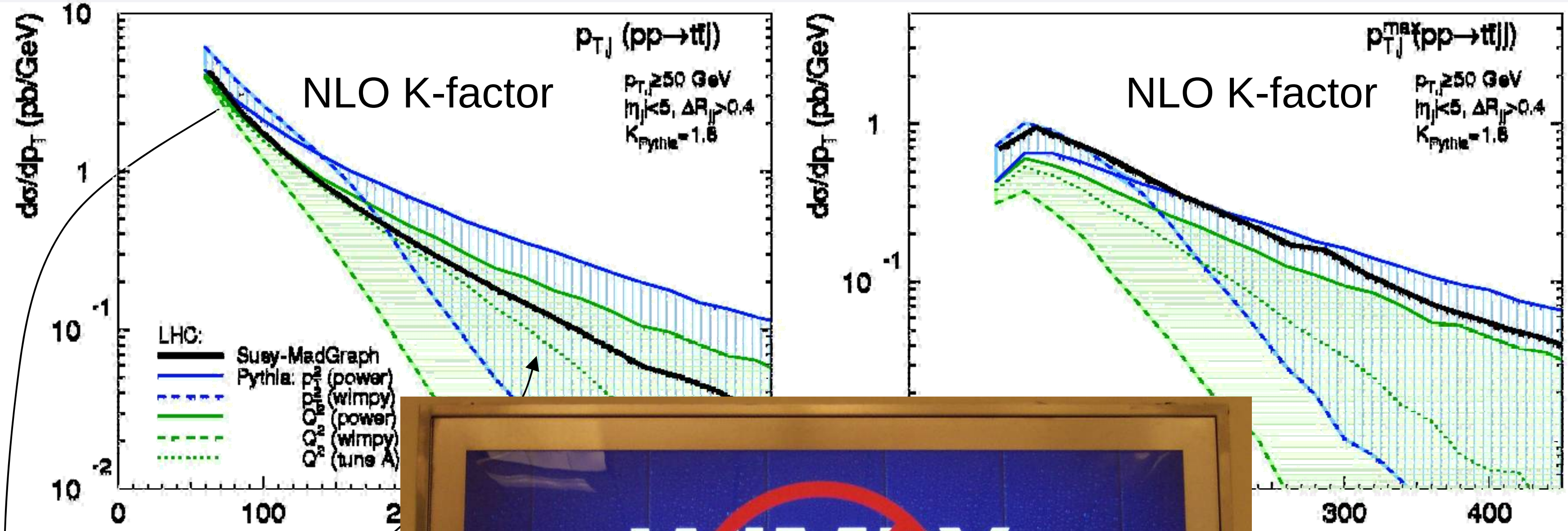


Hard tails: More
• Power Showers
• Wimpy Showers ... mass.

• 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

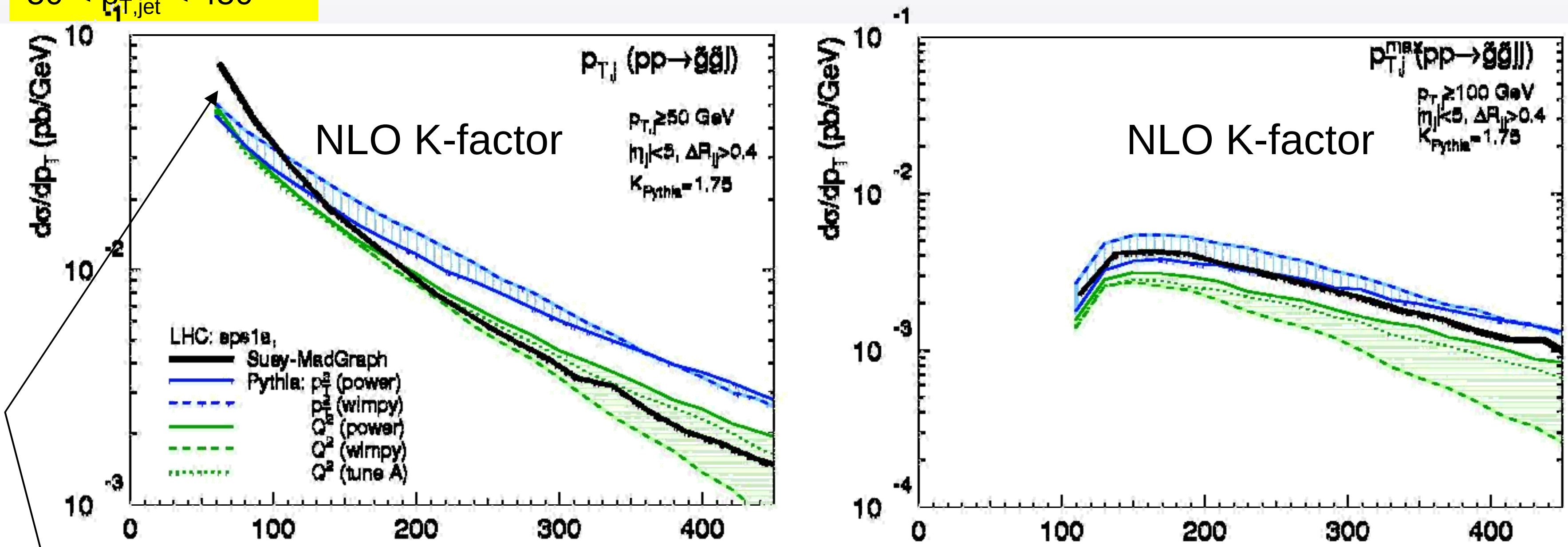
$Q^2_H/s = (0.05)^2$

$1/10 < p_T / Q_H < 1$

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

SUSY + jets @ LHC

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



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

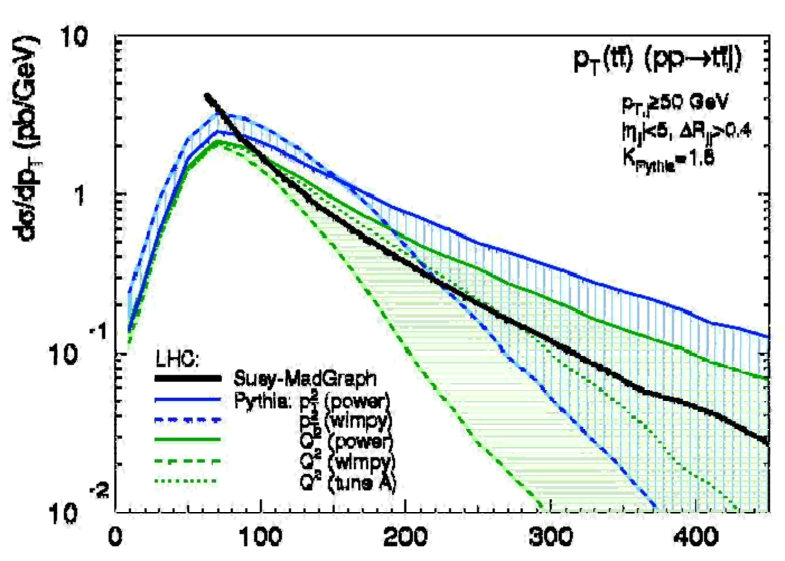
• <u>Soft peak</u>: fixed order breaks down for ~ 100 GeV jets. Reconfirmed by parton showers → universal limit below 100 GeV.

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)

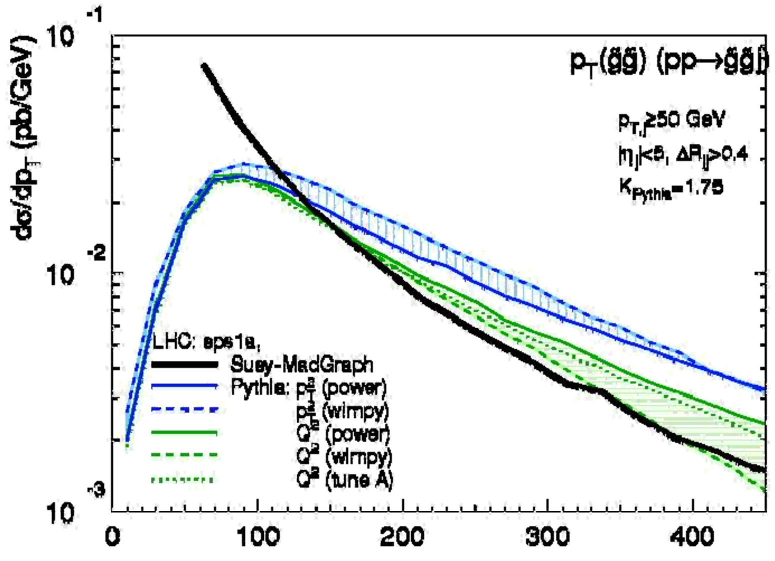
ttbar + 1 jet @ LHC

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 Comparisons to PYTHIA Q^2- and p_T^2- ordered showers → New illustrations of old wisdom:
  - Hard jets (= hard in comparison with signal scale)
    - Parton showers *can* produce realistic rates
    - They can also produce completely wrong rates
    - Use matrix elements with explicit jets when possible
  - Soft jets (= soft in comparison with signal process, but still e.g. 100 GeV for SPS1a)
    - fixed order not reliable, due to large logarithms from QCD singularities → use resummation / parton showers.

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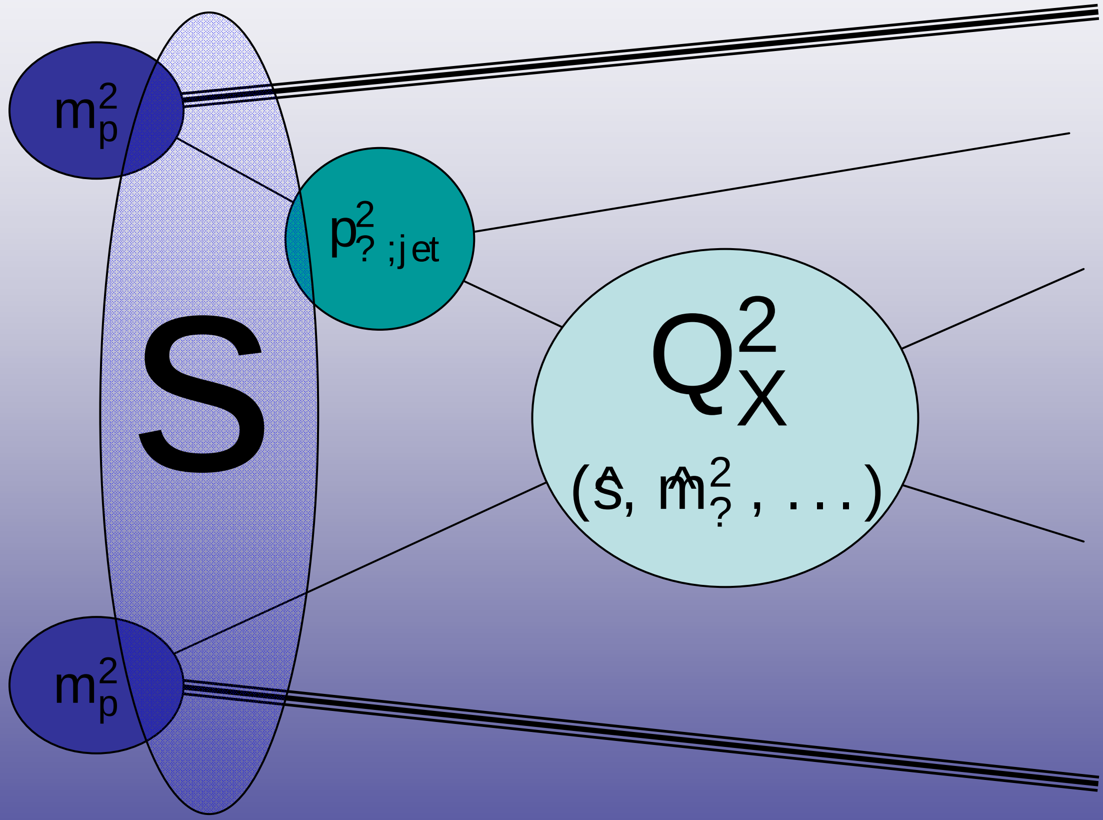
		**KRIPTON FOUNTAINS. SINGLE JET NOZZLES HIGH JET** **Design/Application Data** : The "Kripton Fountains" High jet Nozzle is Special Nozzle that is used to achieve greater Fountain Height, preferred in Floating and lake fountains
		**KRIPTON FOUNTAINS SINGLE JET NOZZLES (Adj. clear stream type)** **Design / Application Data:** Small tapered Adjustable clear stream nozzle develops display with a minimum of distortion. Designed for precision use with spray ring, spray bars or other installations where precision vertical columns or trajectory patterns are desired.
		**KRIPTON FOUNTAINS MULTIJET NOZZLES [A] VULCAN ADJUSTABLE JETS** **Design / Application Data** : A sparkling and unique triple tiered effect of clear streams. Ideal for small and medium sized displays. No constant water level is required.
	Three-Tier Nozzles  	**KRIPTON FOUNTAINS SCULPTURE JET / 3TIER NOZZLES** **Design / Application Data** : A sparkling and unique triple / 4Row tiered effect of clear streams. Ideal for small and medium sized displays. No constant water level is required.

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?

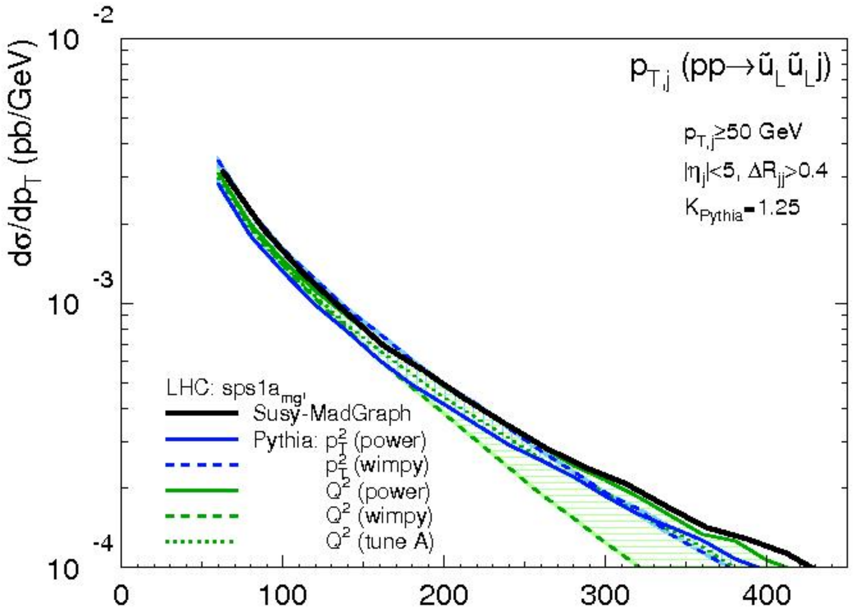
- Handwavingly, leading logs are:

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

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

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

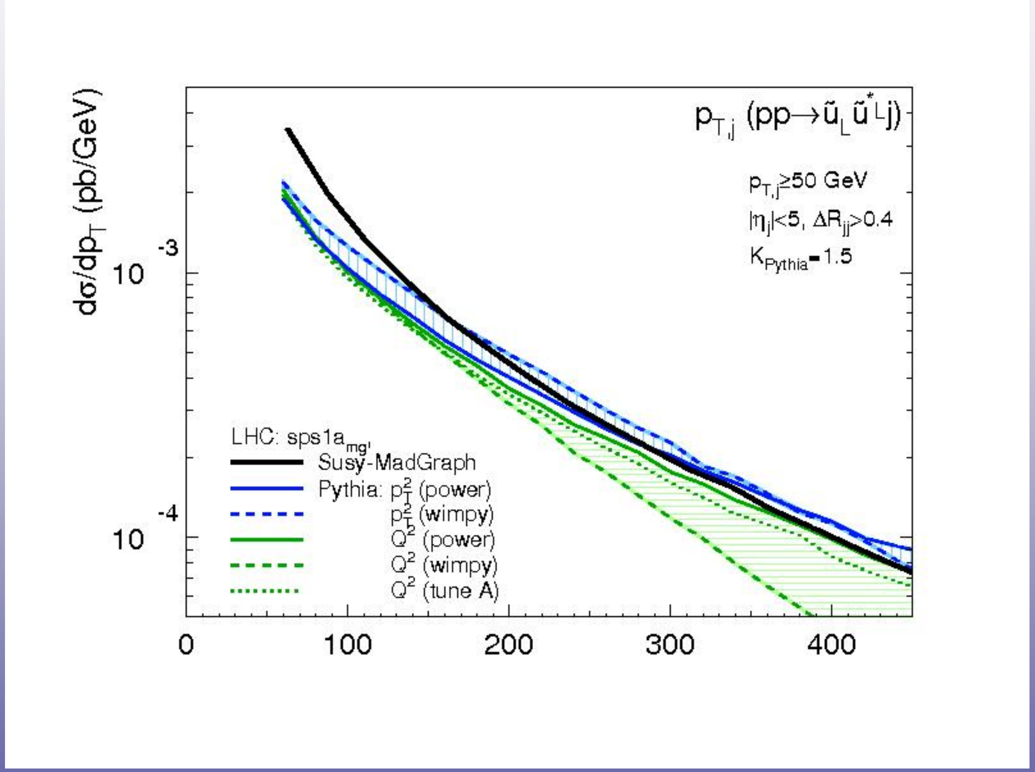
More SUSY: $\sim u_L \sim u_L$



ME Divergence much milder than for ~g~g !

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

More SUSY: $\tilde{u}_L \tilde{u}_L^*$



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