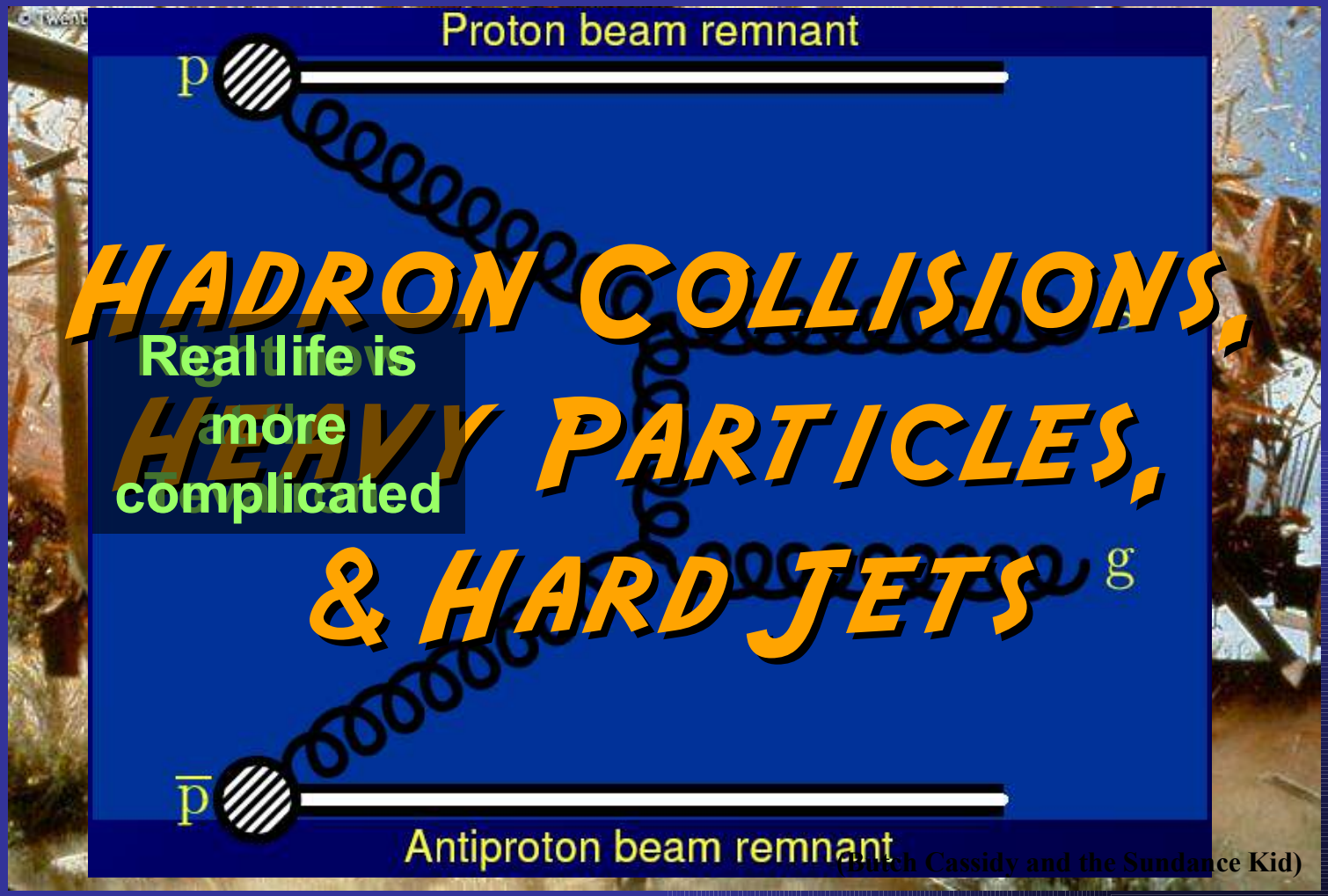
SEMINAIRE, MONTEPELLIER, NOVEMBRE 2005




# Hadron Collisions, Heavy Particles, & Hard Jets

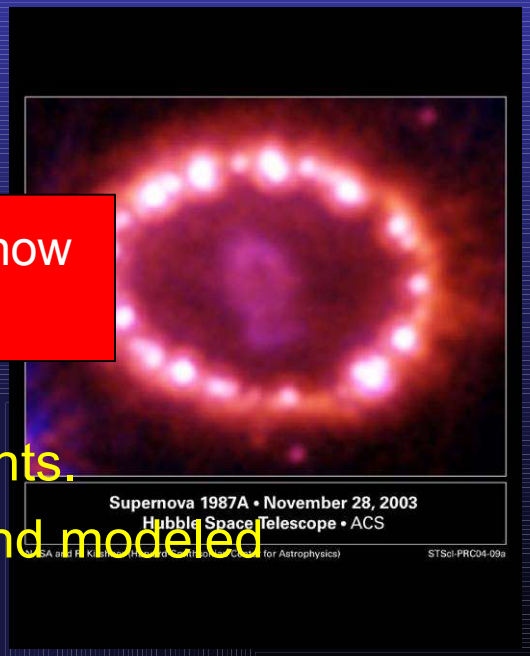
Real life is more complicated

(Butch Cassidy and the Sundance Kid)

Peter Skands (Fermilab) with T. Plehn (MPI Munich), D. Rainwater (U Rochester), & T. Sjöstrand (CERN & Lund U)

# Why Study Supernovae?

- They are the highest energy explosions in the universe
- They give us clues to other physics
  - Type Ia = large-distance standard candles  distance/redshift relation
  - Cosmological constant problem
- SN1987a
  - → neutrino physics,
  - Cooling → limits on light/weak particles
  - + much much more ...




PRICE: Extremely Complicated Dynamics ←→ They are now <u>almost</u> making them explode in simulations

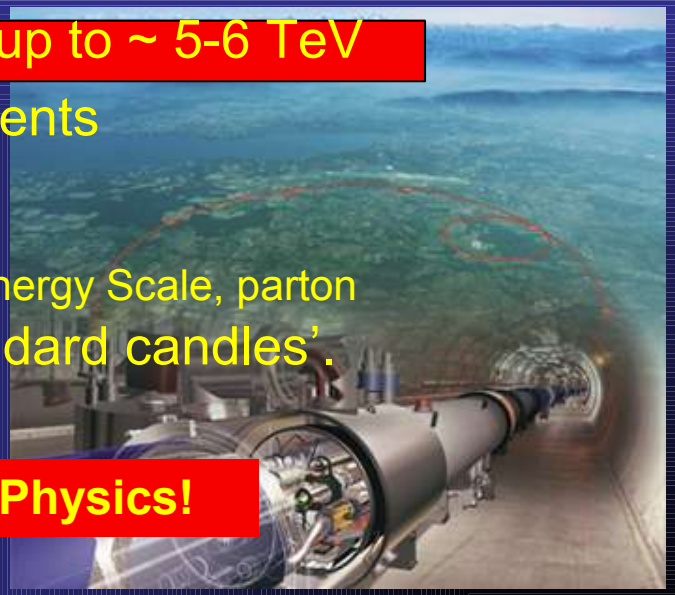
✂→ Much can be done even in complex environments.

•*More* if the complex dynamics can be understood and modeled

# Why Study Hadron Collisions?

- Tevatron
  - 4 – 8 $fb^{-1}$ by LHC turn-on (1$fb^{-1}$ on tape now)
  - Large Z, W, and ttbar samples (including hard tails !)
  - Always: Potential discoveries...

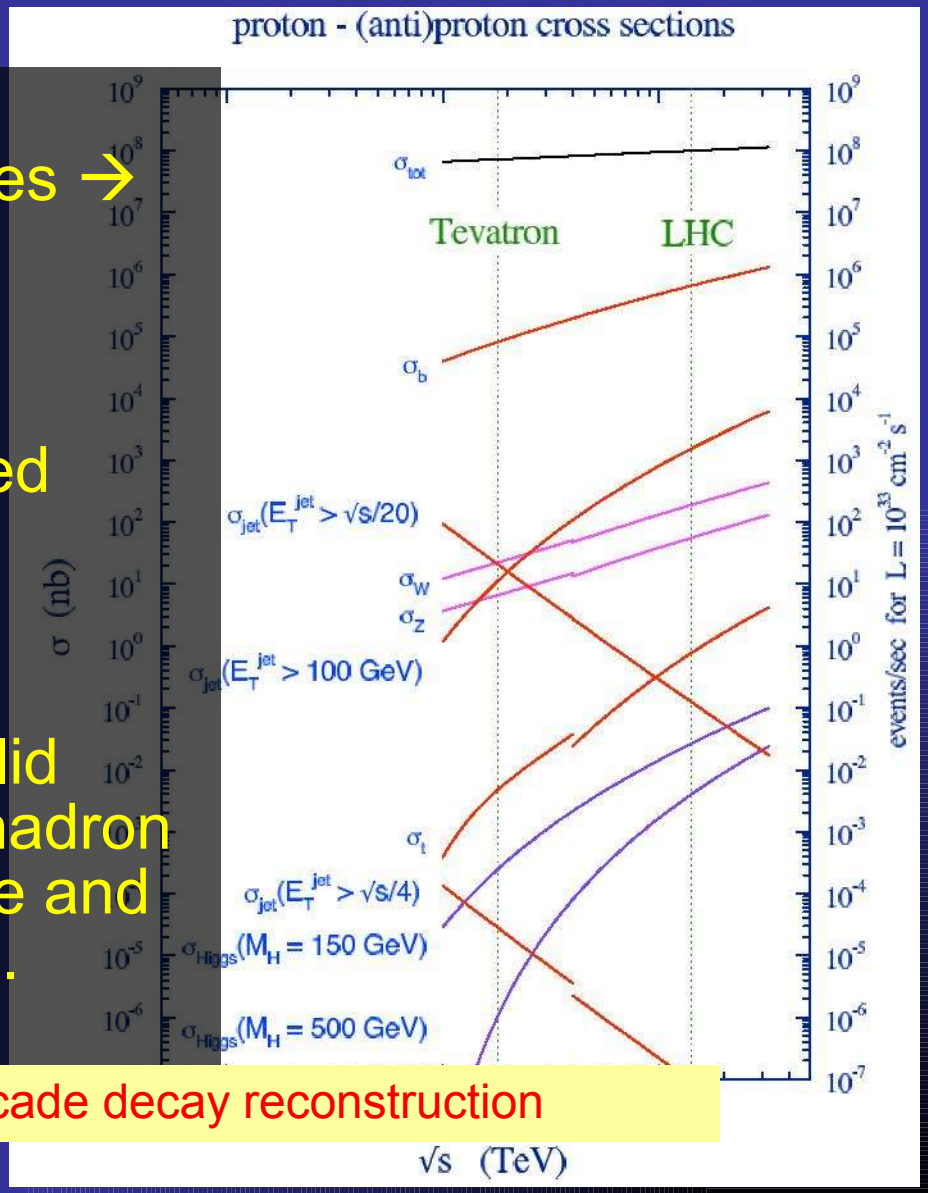
- LHC
  - Explore EWSB / Probe New Physics up to ~ 5-6 TeV
  - 10 $fb^{-1}$ → more than $10^7$ Z,W, ttbar events
  - → $\sigma_{stat} << 1\%$
  - Improved systematics (Luminosity, Jet Energy Scale, parton distributions, …) with high-statistics 'standard candles'.



**→Large discovery potential + Percent level Physics!**

# But No Free Lunch

- Not all discovery channels produce dramatic signatures → Need theoretical control of shapes, backgrounds, uncertainties, ...
- Scattering at LHC≠ rescaled scattering at Tevatron.
- Aiming for percent level measurements, PDFs, luminosities, jets etc ➔ solid understanding of QCD in hadron collisions, both perturbative and non-perturbative, is crucial.




E.g.: precision in SUSY cascade decay reconstruction

# Overview

- QCD @ high energy
- A new QCD parton/dipole shower
- Top production at the Tevatron
- Top production at the LHC
- Supersymmetry pair production at the LHC
- Outlook …

# 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 $\alpha_s$ ➔

- 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.

1. Parton Showers: infinite series in $\alpha_s$ (l
collinear approximation).

Marriage Desirable!

- 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.

# Tools – What's There...

X=Anything (e.g. ttbar)
PS=Parton Shower

## Hard & Soft

Marriage Desireable!

- Several different ceremonies:

1) **Merging** (correcting first jet in X+PS to X+jet matrix element)

- PYTHIA: many ee →X + jet, pp → (h,V) + jet and most top, EW & MSSM decays
- HERWIG: many ee →X + jet (incl VV), DIS, pp → (V,h) + jet, top decay

2) **LO Matching** (combining LO X, X+jet, X+2jets, ... with PS)

- SHERPA: "CKKW" matching for e+e- → n jets, pp → (V,VV) + jets
- PATRIOT: Pre-prepared ME/PS matched samples (using MADGRAPH with PYTHIA, stored in MCFIO format) for (W, Z) + jets (≤ 4) , for Tevatron
- ARIADNE: Vetoed Shower matching (interface to MADGRAPH) for e+e- → n jets and pp → W + jets (DIS underway)

3) **NLO Matching** (matching NLO matrix elements with PS)

- MC@NLO: NLO + HERWIG for: pp → (h,V,VV,QQ,ll) + jets

[+ MCFM: NLO (no PS) for pp → (V,h)+jets, VV,Vh, WBF, single top]

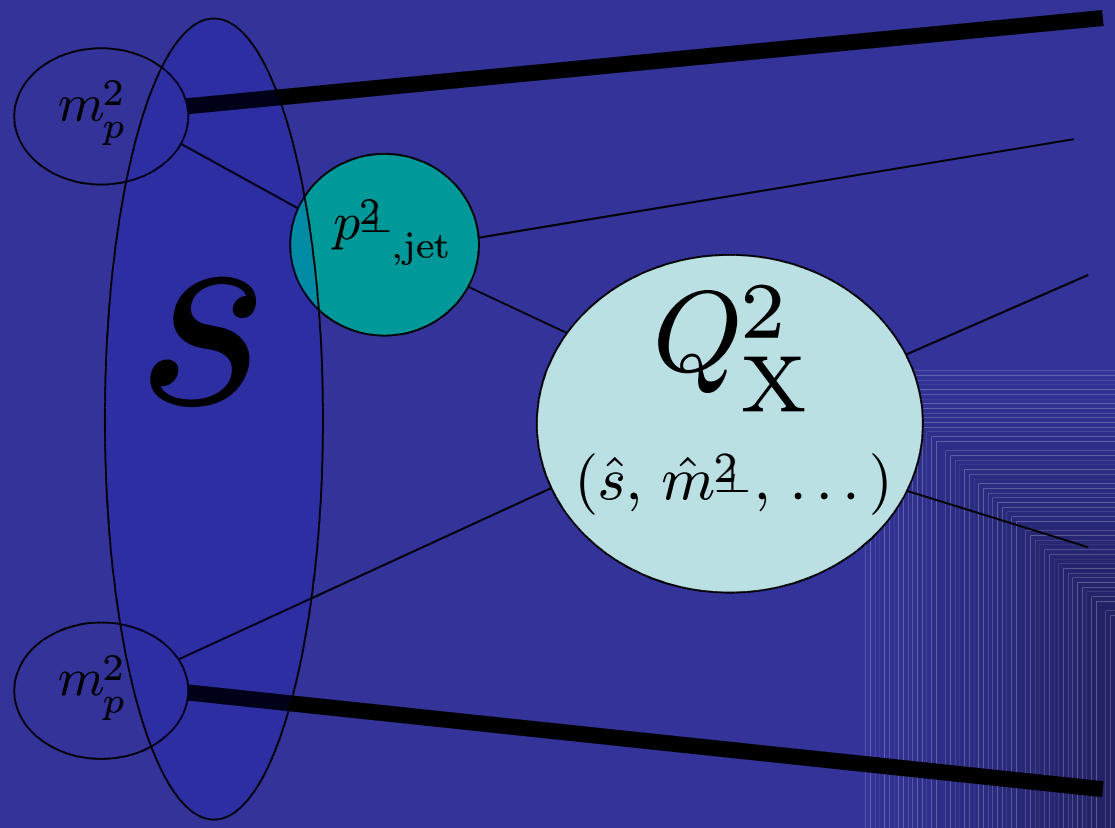
# What's what?

- 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:

- $\Gamma$ : decay widths
- $m_p$ : beam mass
- $\Lambda_{QCD}$ : hadronisation
- $m_i$ : small rest masses

## + "ARBITRARY" SCALES:

- $Q_F$ , $Q_R$ : Factorisation & Renormalisation

# A HANDWAVING ARGUMENT

- Quantify: what is a soft jet?

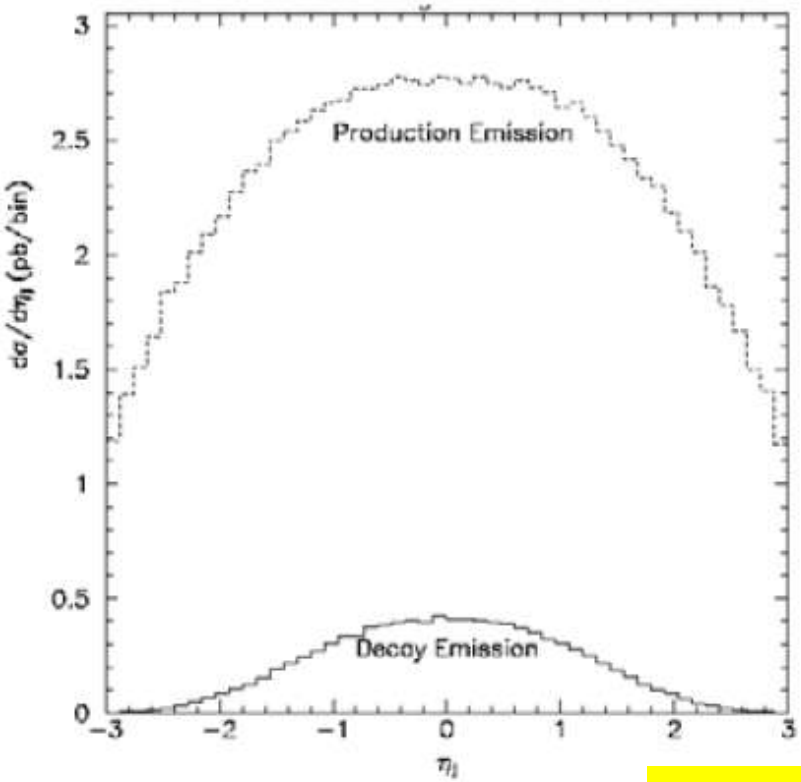
- Handwavingly, leading logs are:

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

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

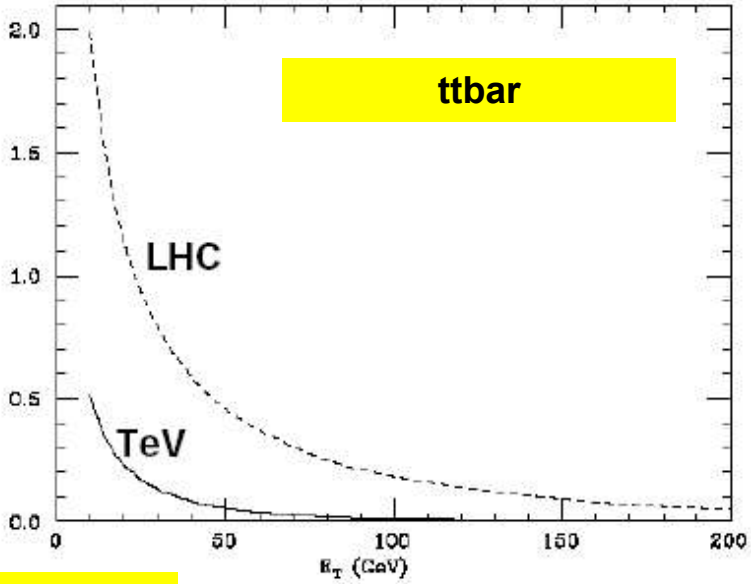
# Stability of PT at Tevatron & LHC

- Most radiation in production:




- 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

LHO, Stelzer, Stirling, PRD 1997

# Overview

- QCD @ high energy
- A new QCD parton/dipole shower
- Top production at the Tevatron
- Top production at the LHC
- SUSY pair production at the LHC
- Outlook …

# Parton Showers: the basics

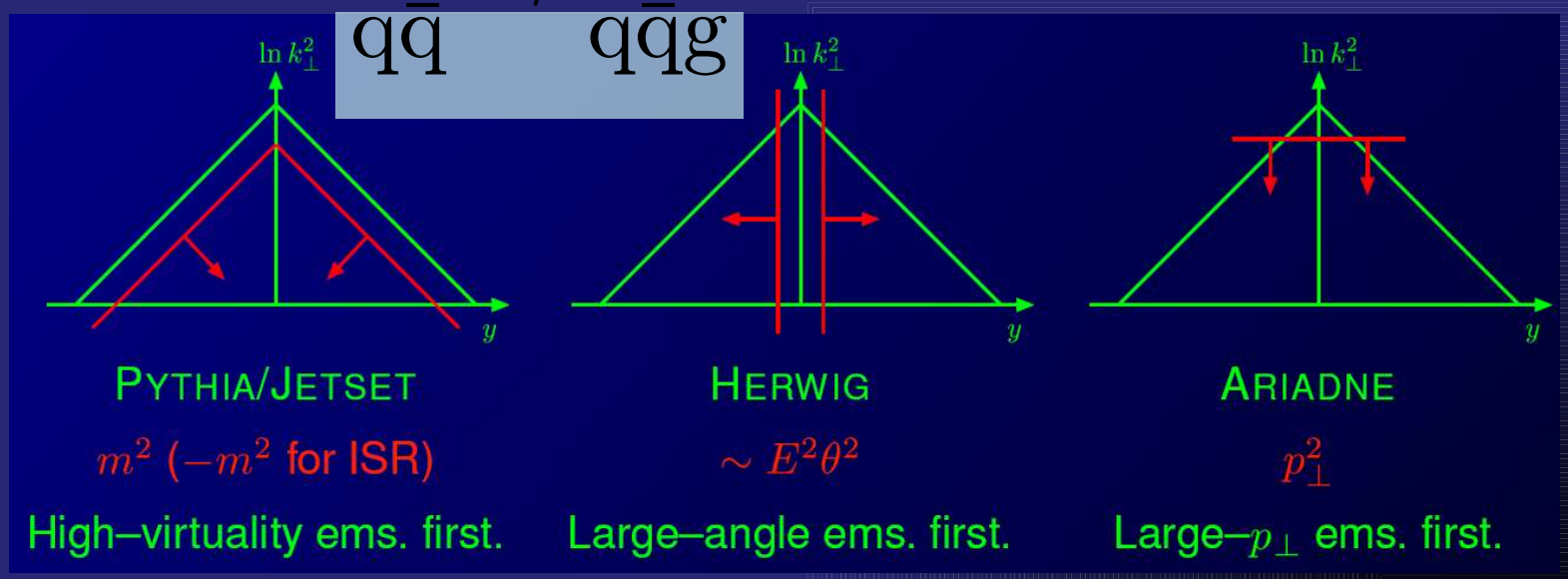
- Today, basically 2 approaches to showers:
  - Parton Showers (e.g. HERWIG, PYTHIA)
  - and Dipole Showers (e.g. ARIADNE).
- Basic Formalism: Sudakov Exponentiation:

$$\mathrm{d}\mathcal{P}_a = \frac{\mathrm{d}X^2}{X^2}\,\frac{\alpha_s(X^2)}{2\pi}\,P_{a\to bc}(z)\,\mathrm{d}z\,\exp\left(-\int_X^{X_{\max}}\cdots\right)$$

  - **X = Some measure of hardness ($Q^2$, $p_T^2$, … )**
  - **z: energy-sharing**
  - **Resums leading logarithmic terms in P.T. to all orders**
  - **Depends on (universal) phenomenological params (color screening cutoff, ...) → determine from data (compare eg with form factors) ~ `tuning'**
  - **Phenomenological assumptions→ some algorithms `better' than others.**

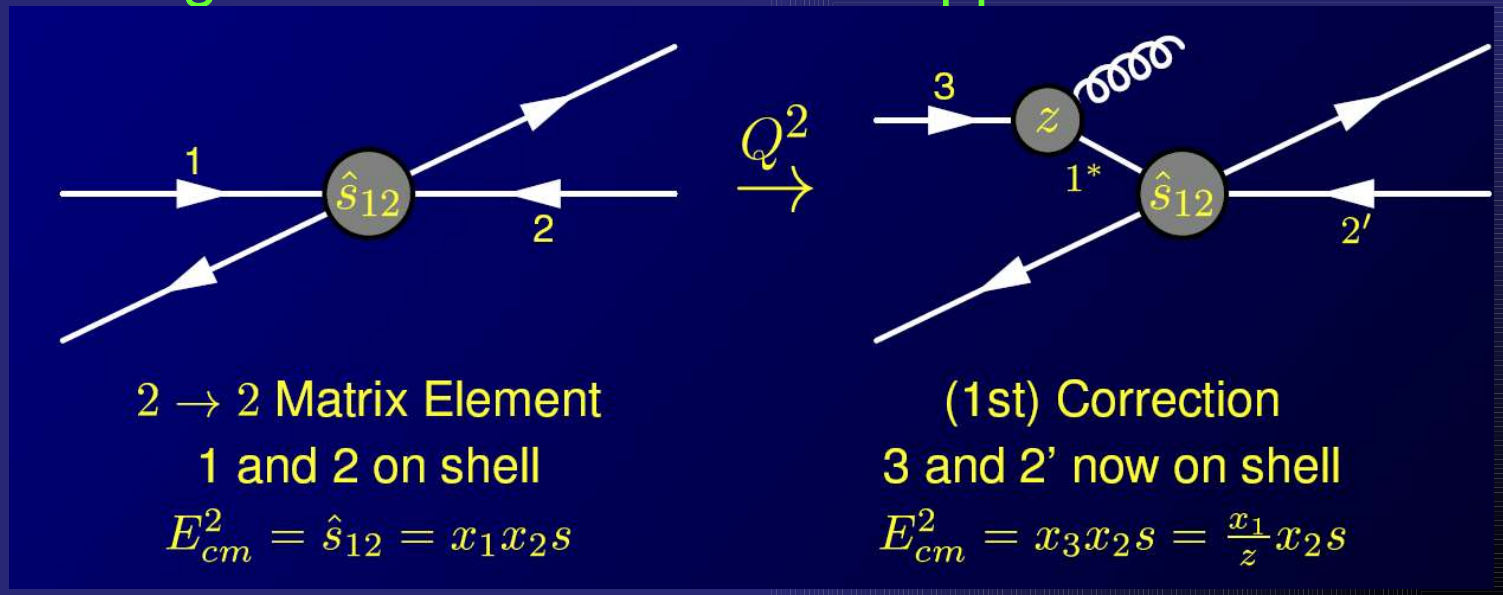
# Parton Showers: the basics

- Today, basically 2 approaches to showers:
  - Parton Showers (e.g. HERWIG, PYTHIA)
  - and Dipole Showers (e.g. ARIADNE).
- Essential Difference: Ordering Variable



# Parton Showers: the basics

- Today, basically 2 approaches to showers:
  - Parton Showers (e.g. HERWIG, PYTHIA)
  - and Dipole Showers (e.g. ARIADNE).
- Another essential difference: kinematics construction, i.e. how e.g. 2→2 kinematics are 'mapped' to 2→3.



# New Parton Shower – Why Bother?

- Today, basically 2 approaches to showers:
  - Parton Showers (e.g. HERWIG, PYTHIA)
  - and Dipole Showers (e.g. ARIADNE).

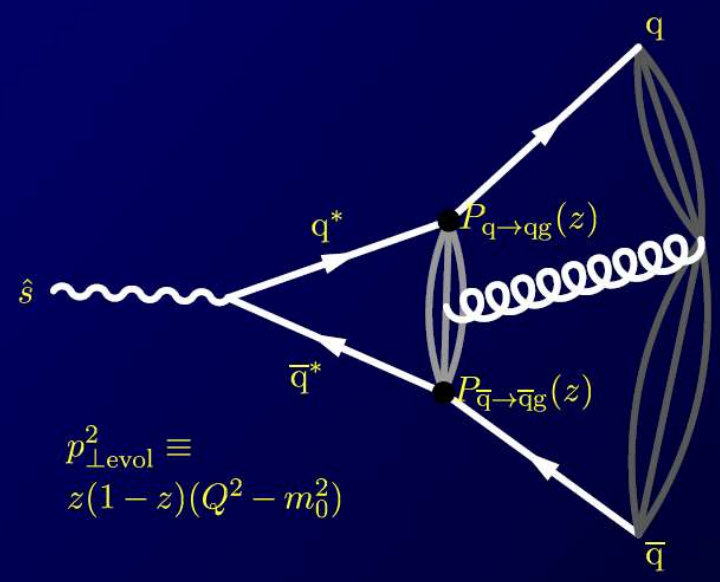
- **Each has pros and cons, e.g.:**
  - In PYTHIA, ME merging is easy, and emissions are ordered in some measure of (Lorentz invariant) hardness, but angular ordering has to be imposed by hand, and kinematics are somewhat messy.
  - HERWIG has inherent angular ordering, but also has the (in)famous 'dead zone' problem, is not Lorentz invariant and has quite messy kinematics.
  - ARIADNE has inherent angular ordering, simple kinematics, and is ordered in a (Lorentz Invariant) measure of hardness, but is primarily a tool for FSR, and g→qq is 'articial' in dipole formalism.
- **Finally, while all of these describe LEP data very well, none are perfect.**

➔ Try combining the virtues of each of these while avoiding the vices?

# PYTHIA 6.3 : $P_T$-ORDERED SHOWERS

Merged with $X$ + 1 jet Matrix Elements (by reweighting) for:
h/$\gamma$/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...

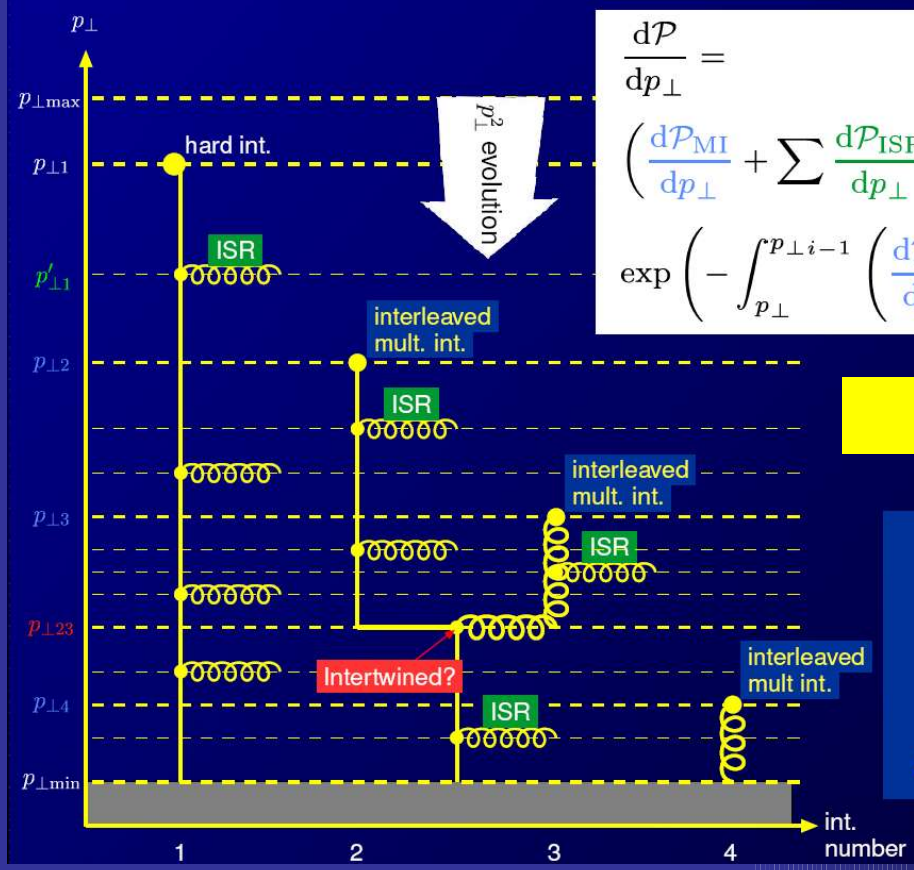
$\Rightarrow$ One combined sequence $p_{\perp\max} > p_{\perp 1} > p_{\perp 2} > \ldots > p_{\perp\min}$

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

# 'Interleaved evolution' with multiple interactions

The new picture: start at the most inclusive level, $2 \to 2$.

Add exclusivity progressively by evolving *everything* downwards.




$$\frac{d\mathcal{P}}{dp_\perp} = \left(\frac{d\mathcal{P}_{MI}}{dp_\perp} + \sum \frac{d\mathcal{P}_{ISR}}{dp_\perp} + \sum \frac{d\mathcal{P}_{JI}}{dp_\perp}\right) \times \exp\left(-\int_{p_\perp}^{p_{\perp i-1}} \left(\frac{d\mathcal{P}_{MI}}{dp'_\perp} + \sum \frac{d\mathcal{P}_{ISR}}{dp'_\perp} + \sum \frac{d\mathcal{P}_{JI}}{dp'_\perp}\right) dp'_\perp\right)$$

→ Underlying Event

$\sim$ "Finegraining"

$\to$ correlations between all perturbative activity at successively smaller scales

# Overview

- QCD @ high energy
- A new QCD parton/dipole shower
- Top production at the Tevatron
- Top production at the LHC
- SUSY pair production at the LHC
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# 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 < $Q_F$)**
  - 'Power $Q^2$-ordered' **(PHASE SPACE LIMIT = s)**
  - 'Tune A' ($Q^2$-ordered) **(PHASE SPACE LIMIT ~ $Q_F$)**
  - 'Wimpy $p_T$-ordered' **(PHASE SPACE LIMIT = $Q_F$)**
  - 'Power $p_T$-ordered' **(PHASE SPACE LIMIT = s)**

**PARP(67)**: =1, →∞, =4

**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 $3p_T$**

# CS)MadGraph Numbers

**LHC**

sps1a

T = 600 GeV top

| | $\sigma_{\rm tot}$[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 | $\sigma_{0j}$ | 4.83 | 5.65 | 0.286 | 0.502 | 1.30 |
| | $\sigma_{1j}$ | 2.89 | 2.74 | 0.136 | 0.145 | 0.73 |
| | $\sigma_{2j}$ | 1.09 | 0.85 | 0.049 | 0.039 | 0.26 |
| $p_{T,j} >$ 50 GeV | $\sigma_{0j}$ | 4.83 | 5.65 | 0.286 | 0.502 | 1.30 |
| | $\sigma_{1j}$ | 5.90 | 5.37 | 0.283 | 0.285 | 1.50 |
| | $\sigma_{2j}$ | 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**

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

$1/4 < p_T / Q_H < 2$

**SCALES [GeV]**

$s = (2000)^2$

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

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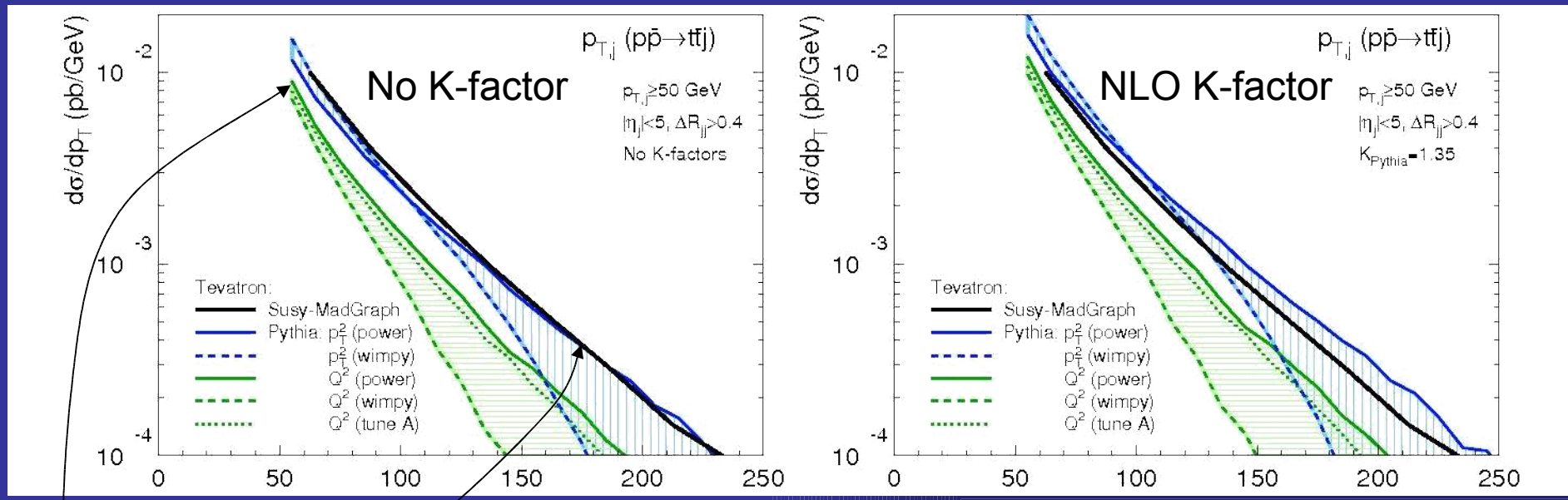
# TTBAR + JETS @ TEVATRON




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 hard, in comparison with hard scale ~ top mass, but is 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]**

$s = (14000)^2$

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

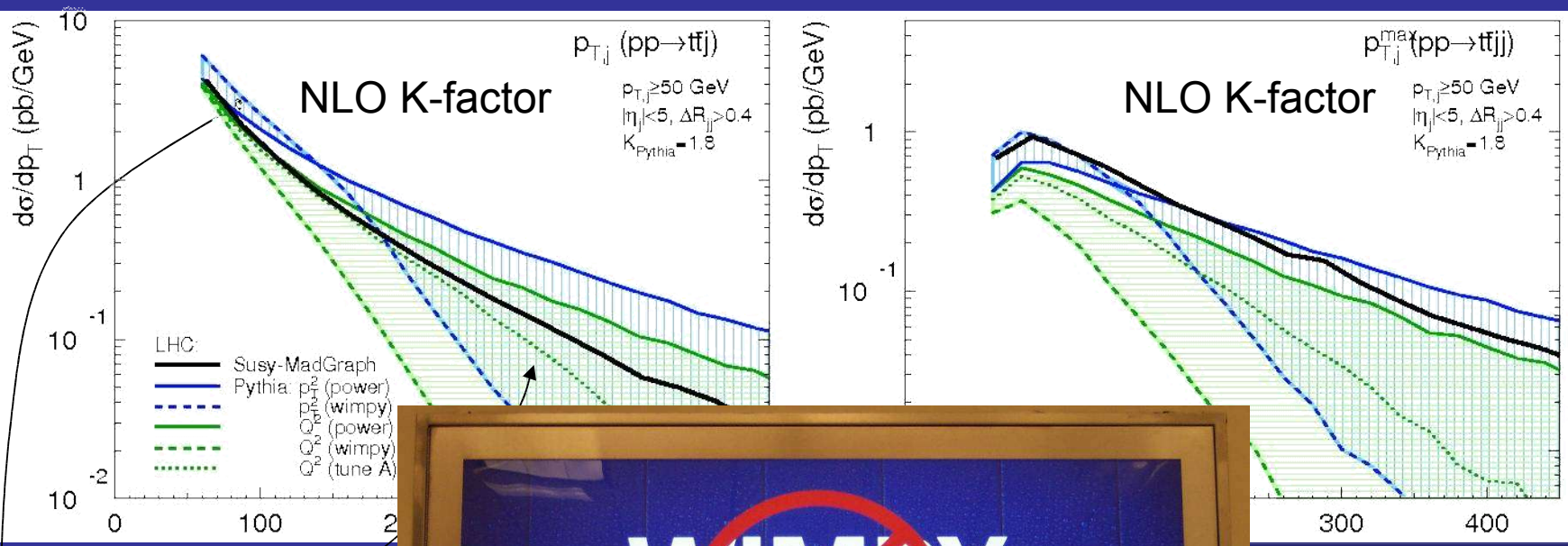
$50 < p_{T,jet} < 450$

# 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 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]**

$s = (14000)^2$

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

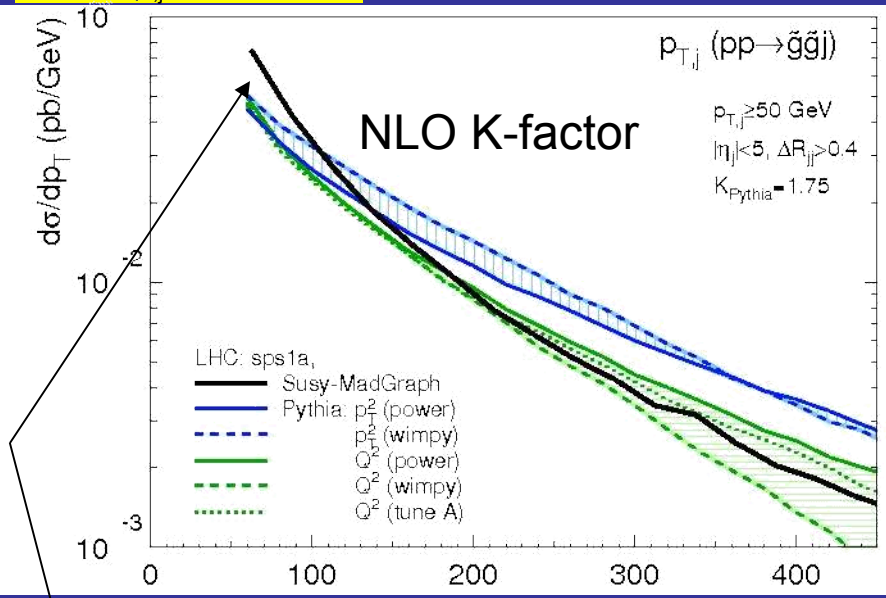
$50 < p_{T,jet} < 450$

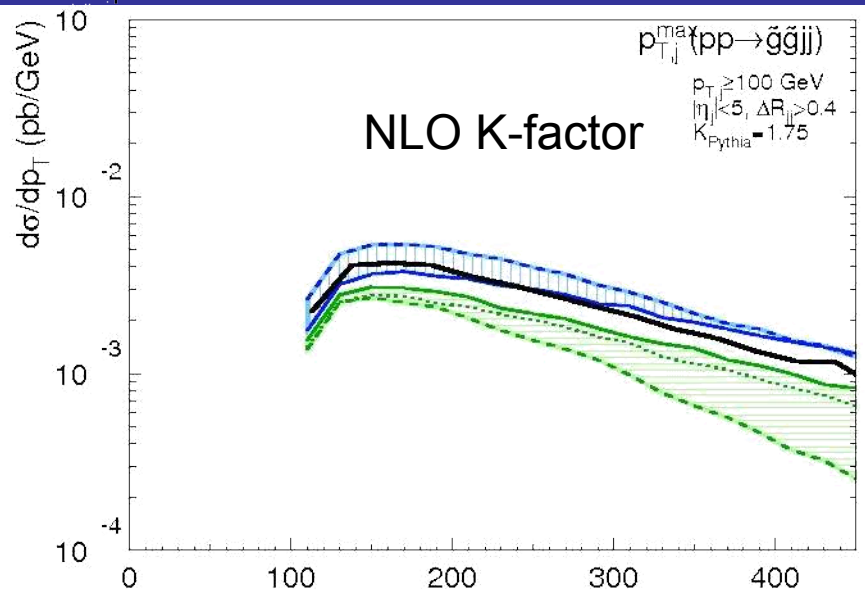
# SUSY + JETS @ LHC

**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)

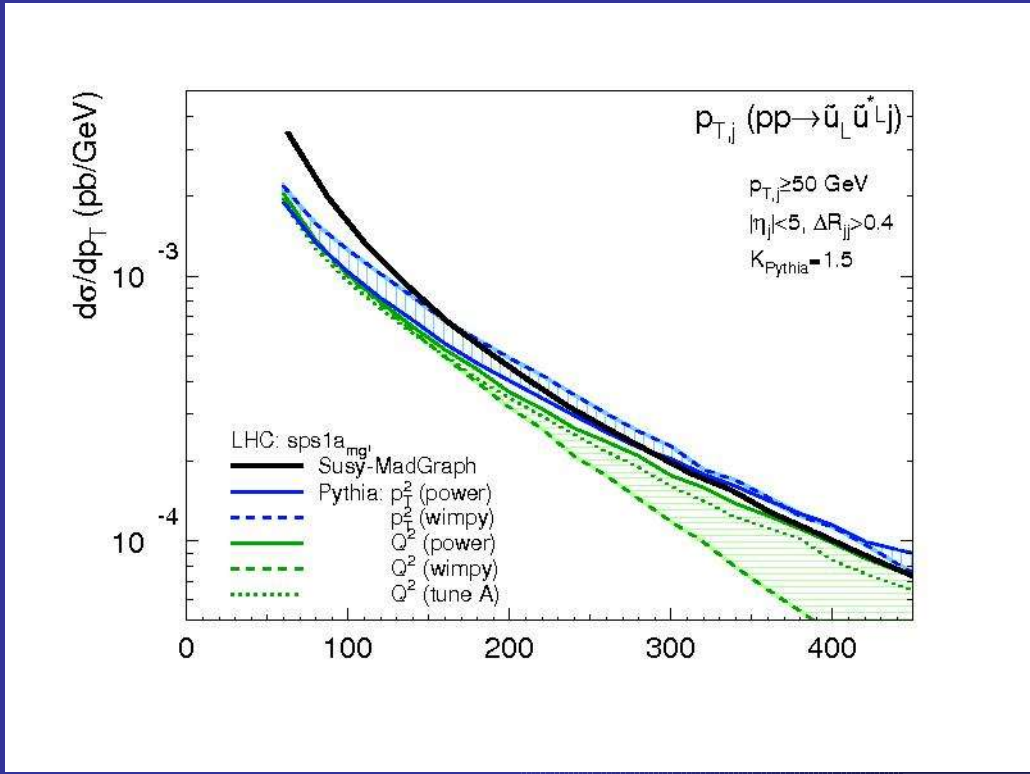
- Parton showers less uncertain, due to higher signal mass scale.

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

**No description is perfect everywhere!**

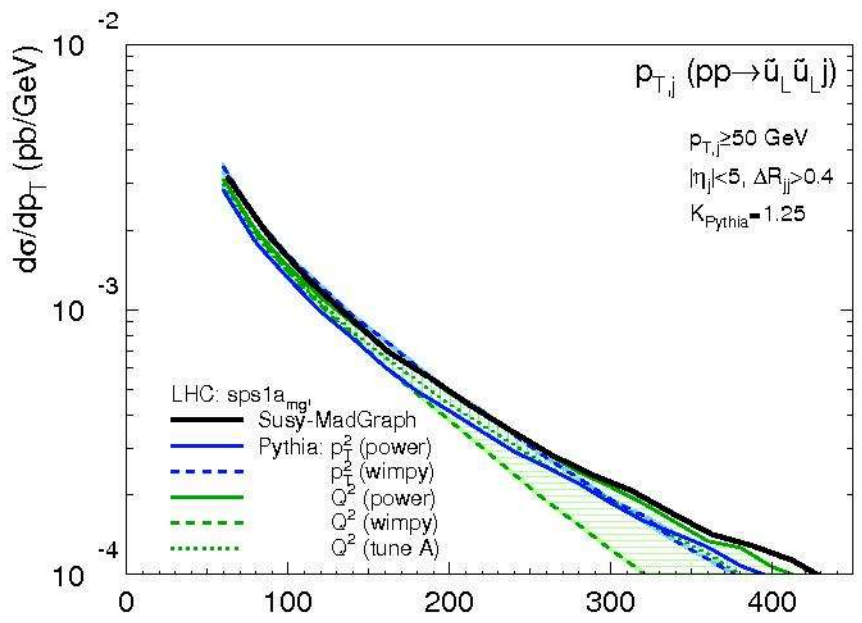
**→ To improve, go to ME/PS matching (CKKW / MC@NLO / …)**

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




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

# 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.

# Conclusions

New!

- 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 e.g. wimpy vs power, $Q^2$ vs $p_T$, → gives possibility for systematic variation ☺
- Important for precision measurements, e.g. in SUSY cascade decays with squarks & gluinos – but probably even more so for other BSM!

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| | | |
| | | **KRIPTON FOUNTAINS**<br>**SCULPTURE JET / 3TIER NOZZLES**<br><br>**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. |