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Heavy Particles, Hadron Collisions, & Hard Jets

News in Pythia 6.3 and SUSY-MadGraph

(Butch Cassidy and the Sundance Kid)

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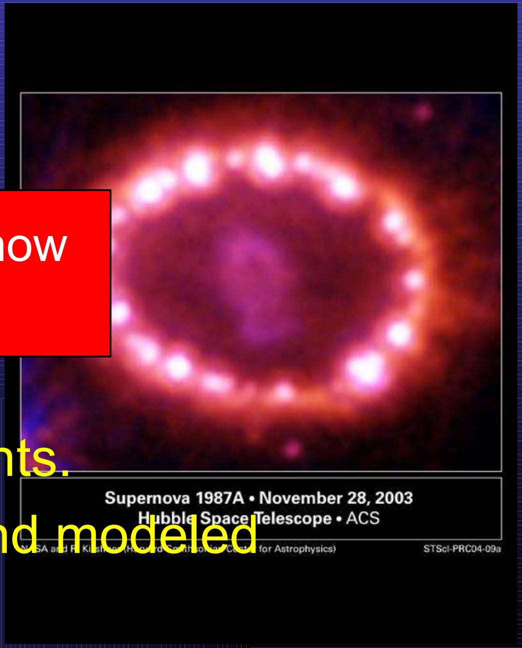
Why Study Supernovae?

- 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

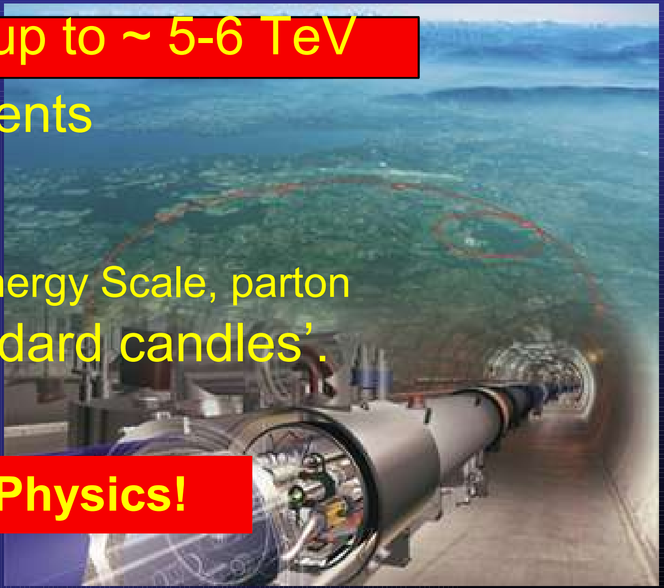


✂→ Much can be done even in complex environments.

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

Why Study Hadron Collisions?

- Tevatron (2 TeV, Fermilab, running)
  - 4 – 8 fb^{-1} by LHC turn-on (1fb^{-1} on tape now)
  - Large Z, W, and ttbar samples (including hard tails !)
  - Always: Potential discoveries...

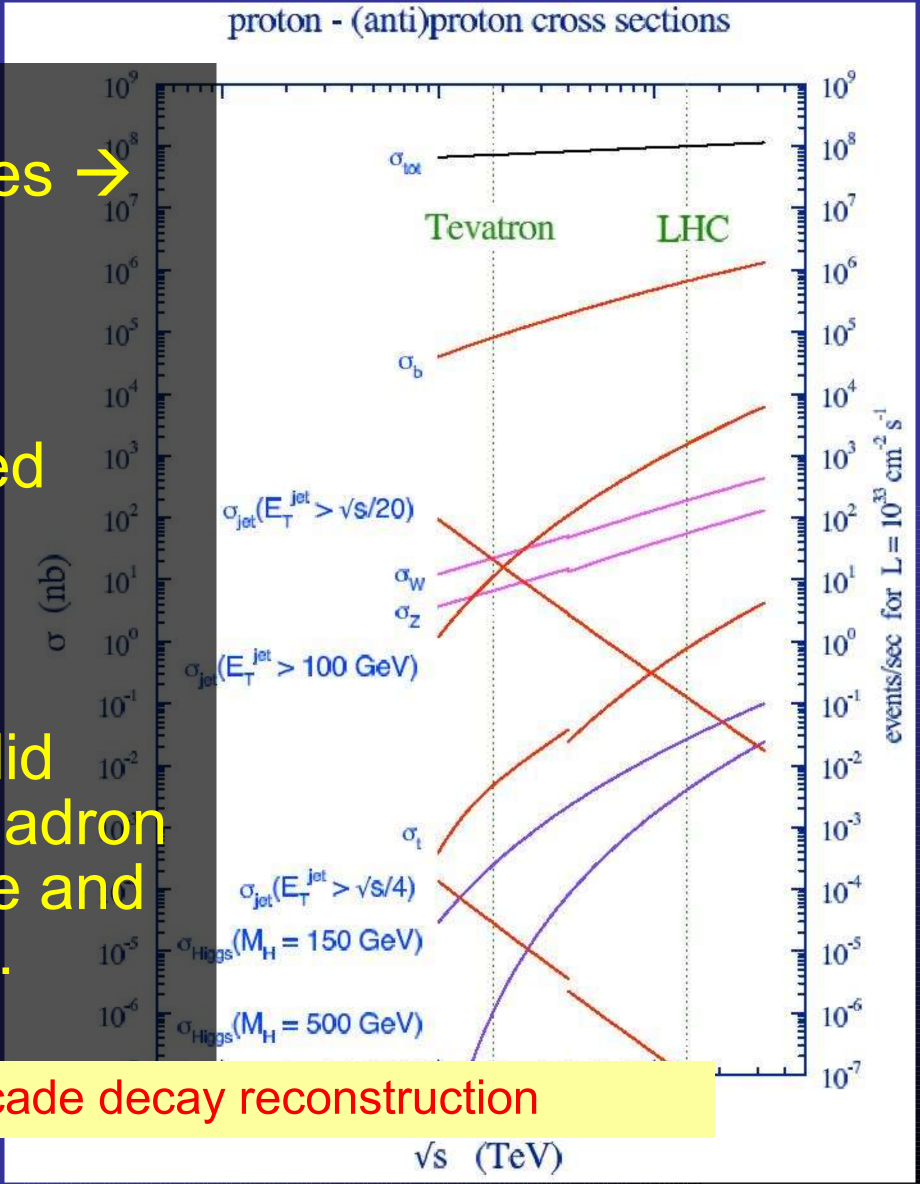


- LHC (14 TeV, CERN, start 2007(?))
  - Explore EWSB / Probe New Physics up to ~ 5-6 TeV
  - 10 fb^{-1} → more than 10^7 Z,W, ttbar events
  - ➔ $\sigma_{stat} << 1\%$
  - Improved systematics (Luminosity, Jet Energy Scale, parton distributions, …) with high-statistics ‘standard candles’.

→**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

- Quantum Chromodynamics @ high energy
- A new parton/dipole shower and underlying-event model in Pythia
- Top production at the Tevatron
- Top production at the LHC
- Supersymmetry pair production at the LHC

QUANTUM CHROMODYNAMICS

- 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 ☺ e.g. parton showers
    - 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.

1. Parton Showers: infinite series in α_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]

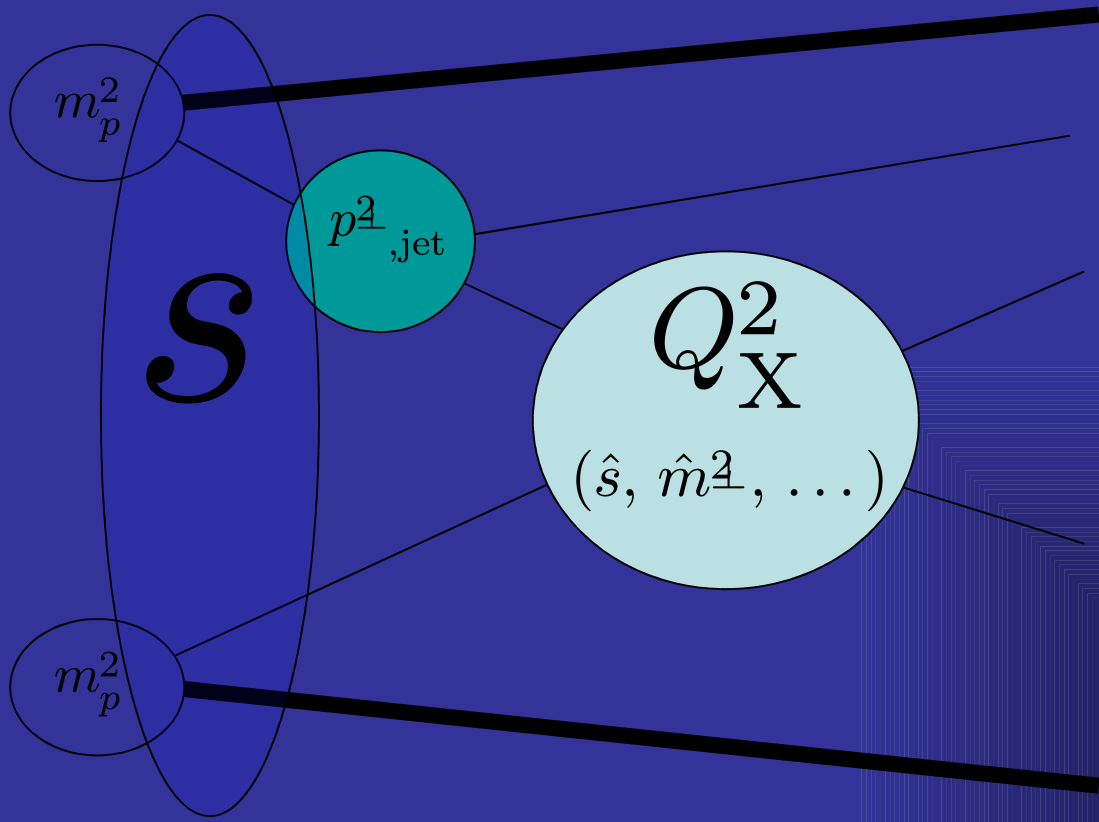
What's what?

- 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:

- 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?

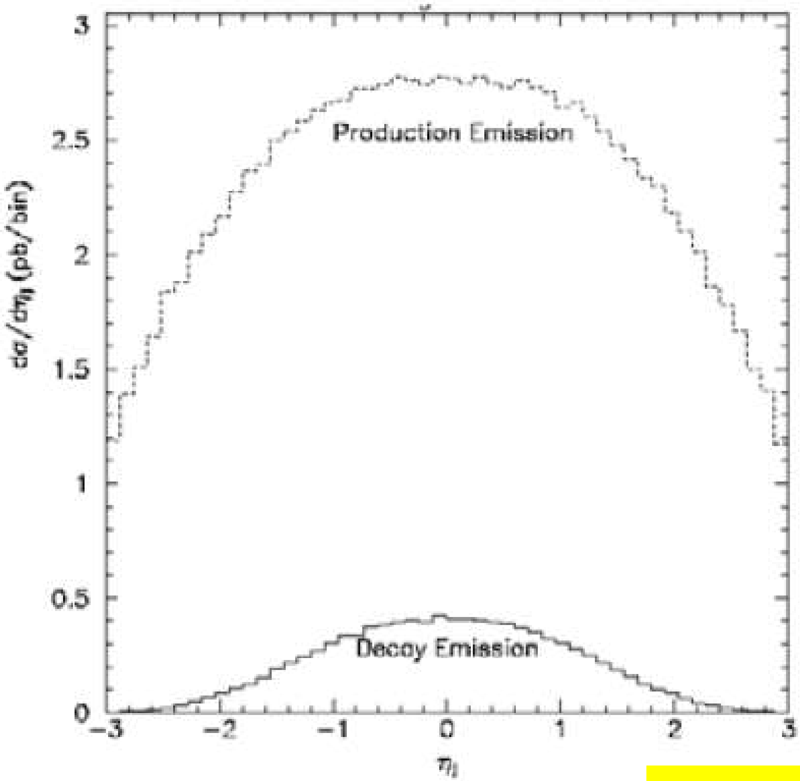
- Handwavingly, leading logs are:

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

✂➔ very roughly, logarithms become large for jet p_T around 1/6 of the hard scale.

Stability of PT at Tevatron & LHC

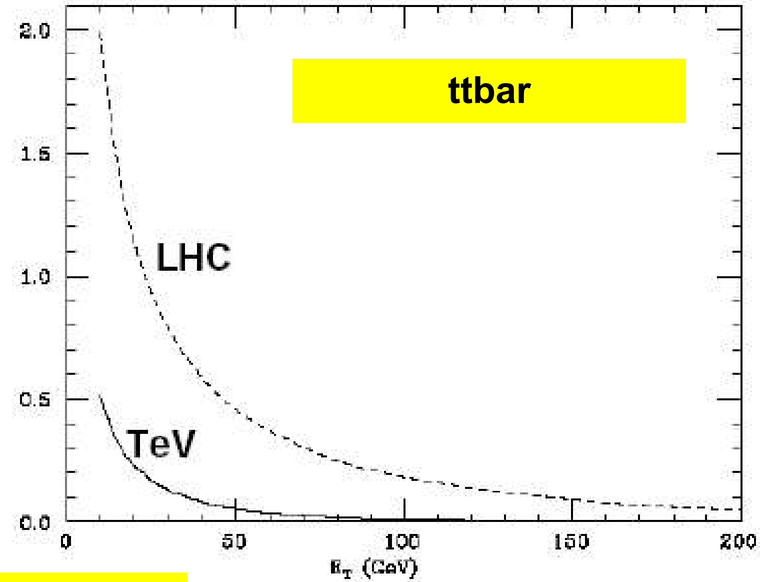
- Most radiation in production:



LHO, Stelzer, Stirling, PRD 1997

- And lots of it!

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



E_T, GeV

Slide from Lynne Orre

Top Mass Workshop

Overview

- QCD @ high energy
- A new QCD parton/dipole shower
- Top pairs at the Tevatron and the LHC
- SUSY pairs 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:

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

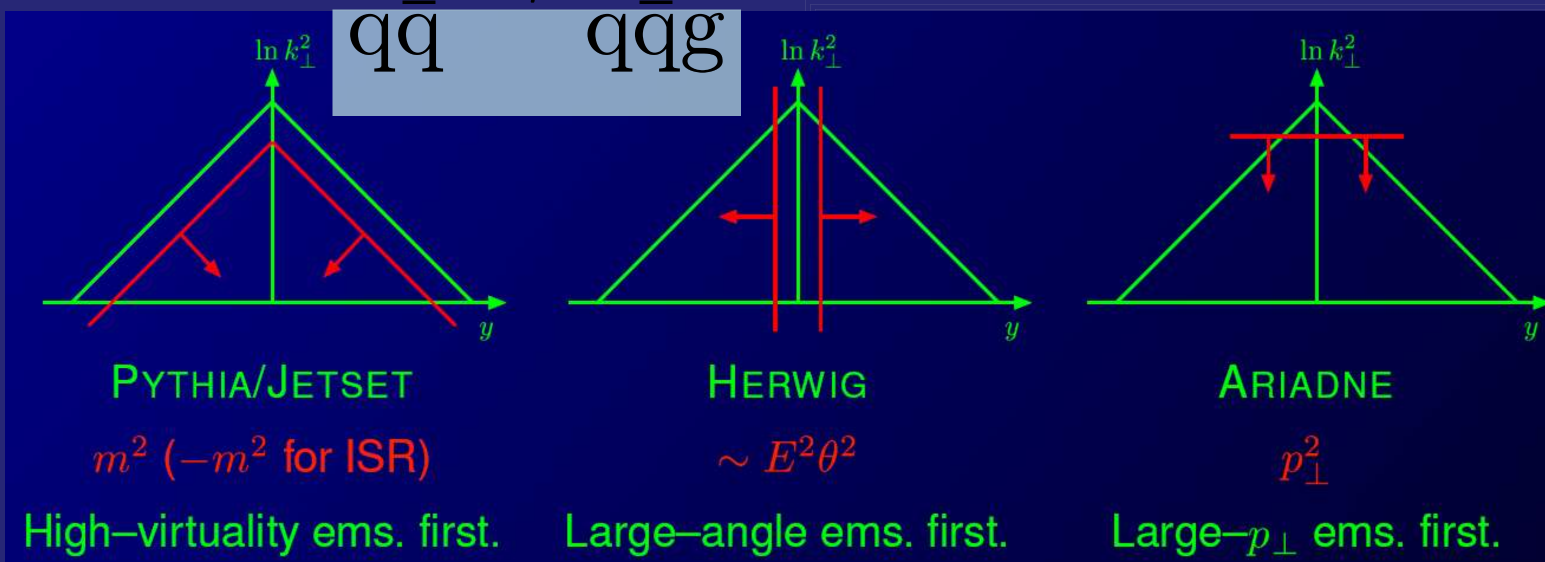
Sudakov Form Factor
= 'no-branching' probability

  - **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

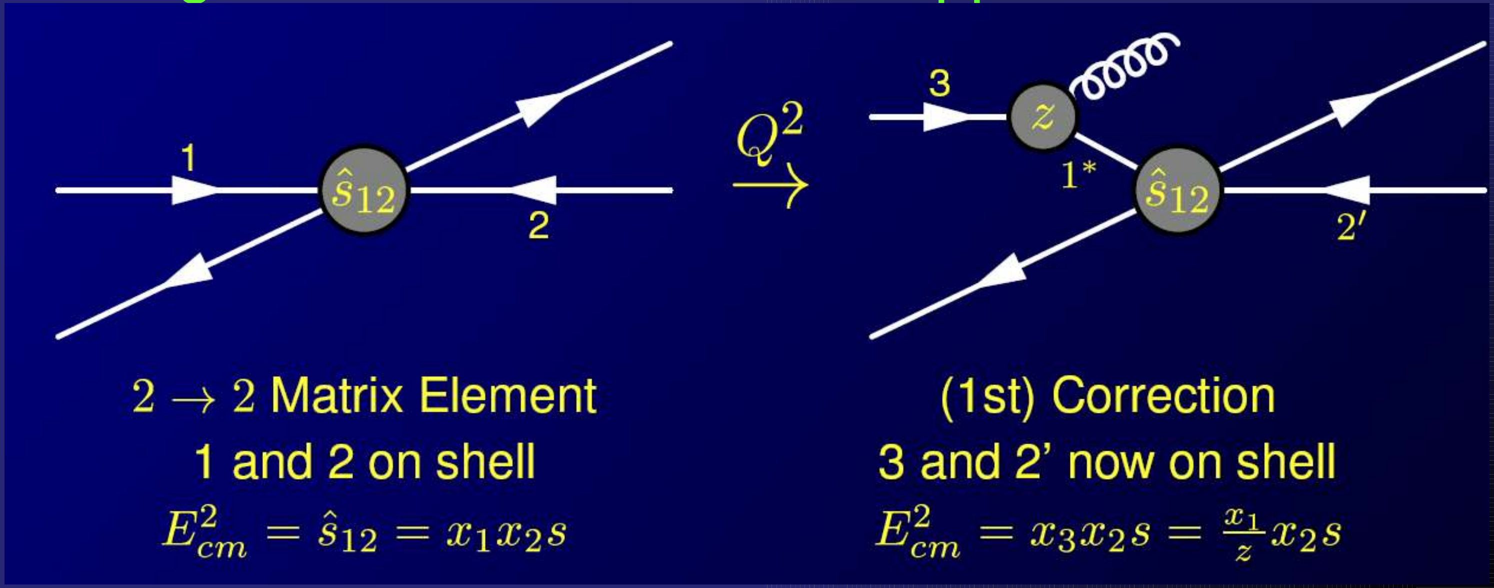
- Today, basically 2 approaches to showers:
  - Parton Showers (e.g. HERWIG, PYTHIA)
  - and Dipole Showers (e.g. ARIADNE).
- Essential Difference: Ordering Variable

$$q\bar{q} \rightarrow q\bar{q}g$$



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.

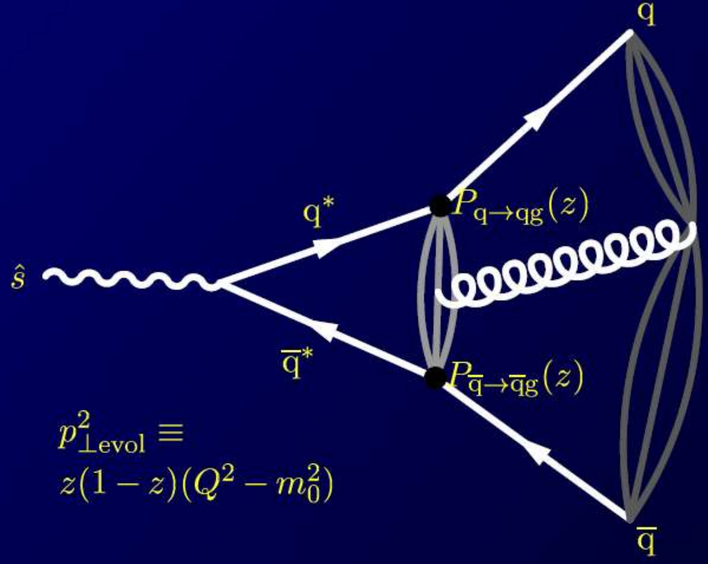
- **Finally, while these all describe LEP data well, none are perfect.**

  ➔ 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/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...

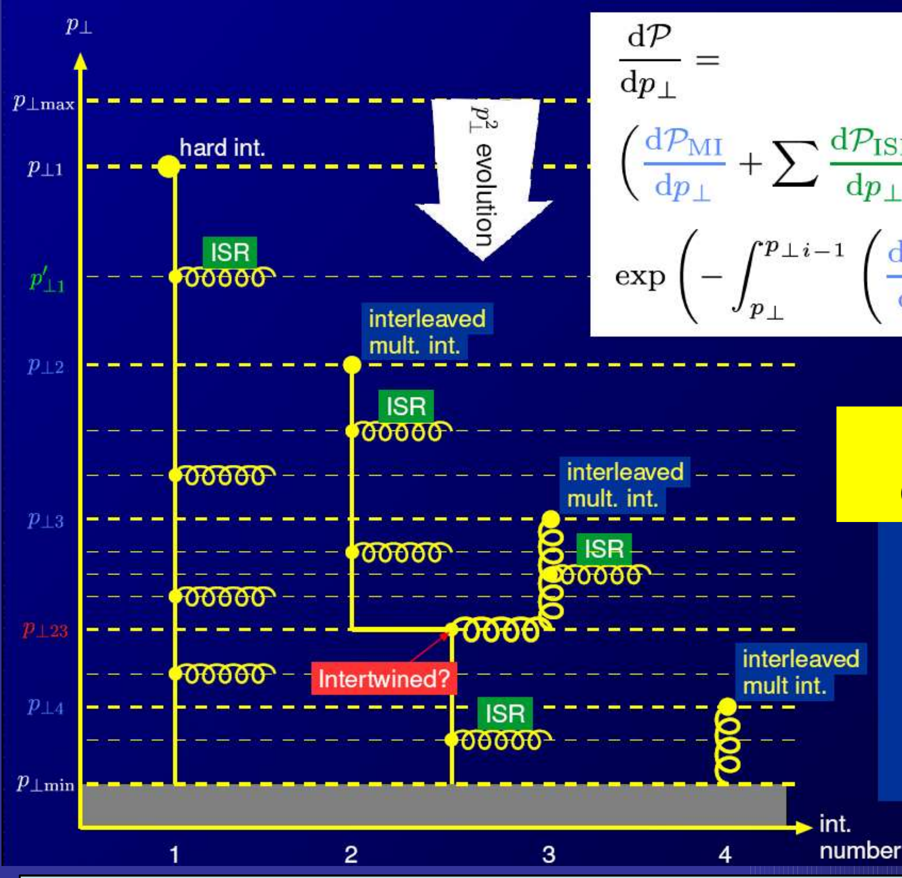
$\Rightarrow$ One combined sequence $p_{\perp\max} > p_{\perp1} > p_{\perp2} > \ldots > p_{\perp\min}$

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.



Pythia 6.3

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

→Underlying Event
(separate LARGE topic now …)

∼ "Finegraining"

→ correlations between
all perturbative activity
at successively smaller scales

T. Sjöstrand & PS - Eur.Phys.J.C39(2005)129 + JHEP03(2004)053

Overview

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

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 ('Wimpy Q^2-ordered'), $\to\infty$ ('Power Q^2-ordered'), =4 ('Tune A')

New in 6.3 ('Wimpy p_T-ordered', 'Power p_T-ordered')

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

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	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

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

$1/4 < p_T / Q_H < 2$

SCALES [GeV]

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TTBAR + JETS @ TEVATRON

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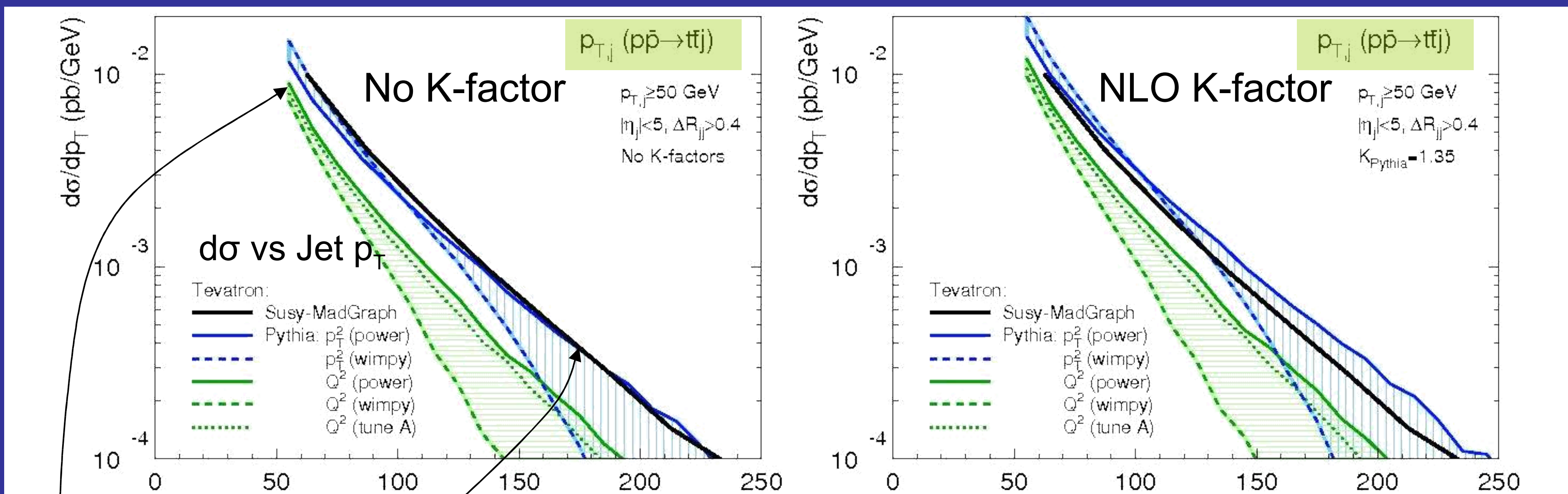


<u>Hard tails</u>:

- 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)

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:

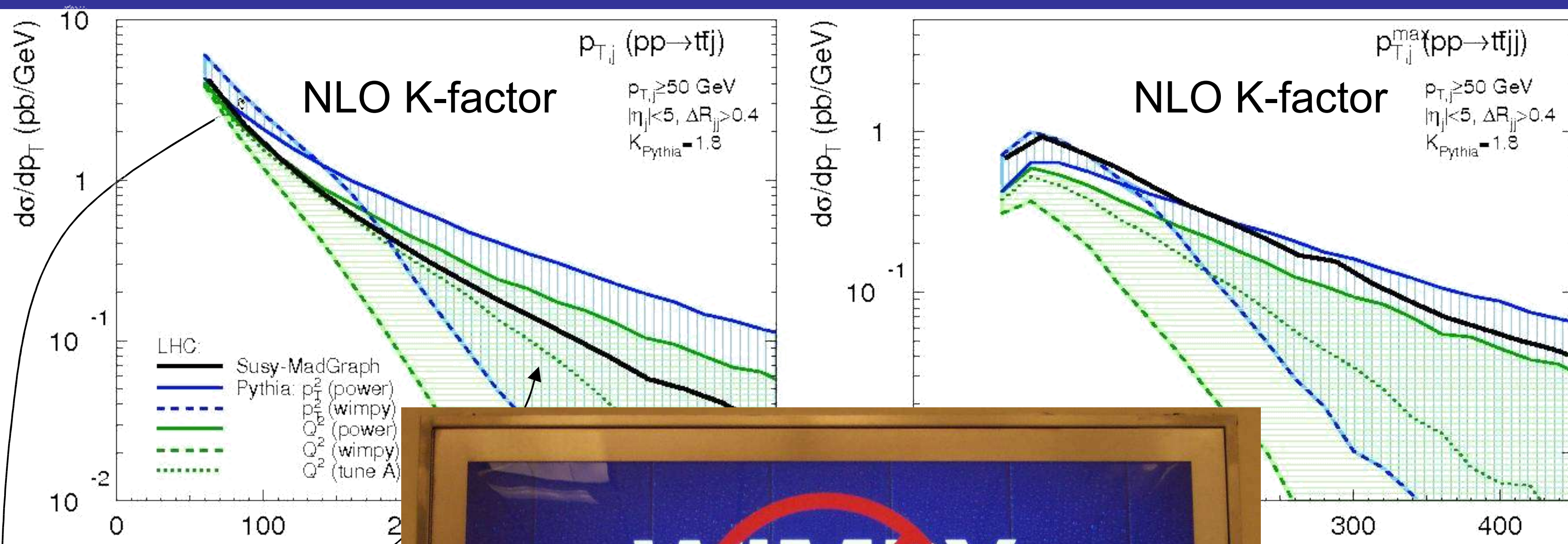
$Q^2_H/s = (0.02)^2$

$1/5 < p_T / Q_H < 2.5$

TTBAR + JETS @ LHC

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

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



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

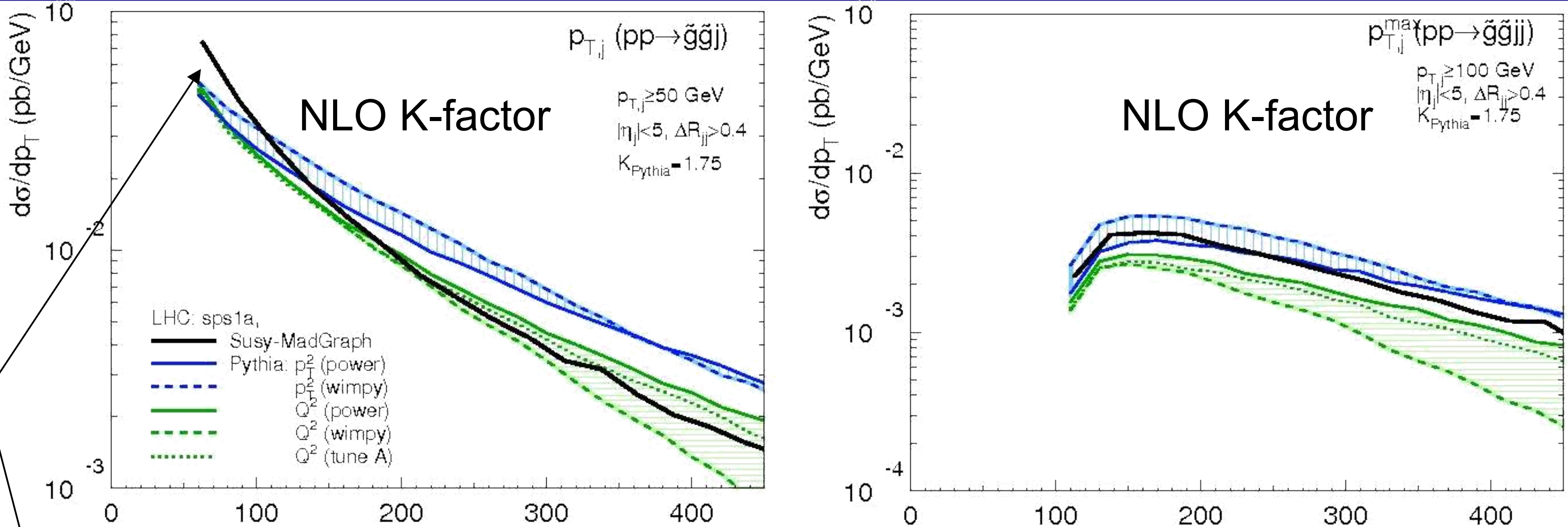
$Q^2_H/s = (0.05)^2$

$1/10 < p_T / Q_H < 1$

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

SUSY + JETS @ LHC

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



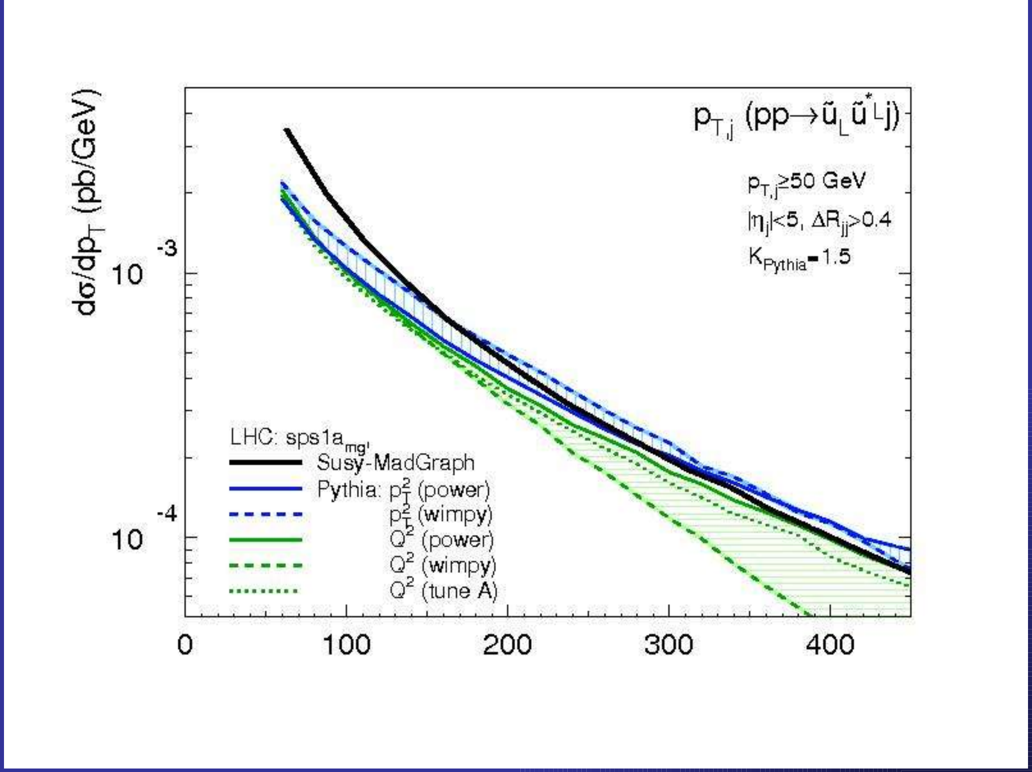
Hard tails: Still a lot of radiation (p_T spectra have moderate slope)

- 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.

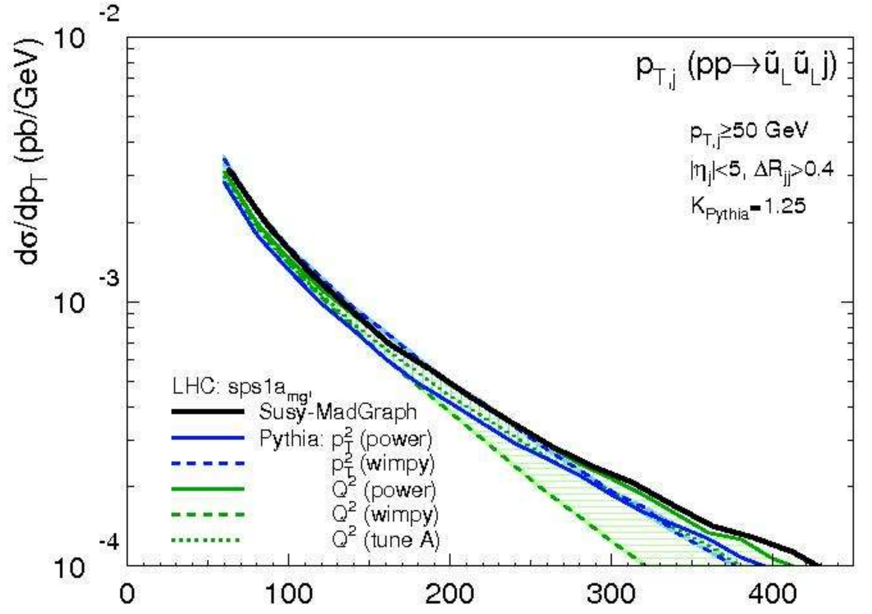
No description is perfect everywhere!
→ To improve, go to ME/PS matching (CKKW / MC@NLO / …)

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



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 fixed-order P.T. (if available)
    - If P.S., handle with care! (i.e. vary phase space, ordering variable etc to at least estimate uncertainty)
  - Soft jets (= soft in comparison with signal process, but still e.g. 100 GeV for SPS1a)
    - → low-pT real readiation pole gives large logarithms
    - → singular terms must be resummed
- 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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