Informal thesis presentation
October 6, 2004
Lund

PHENOMENOLOGICAL STUDIES ON SUPERSYMMETRY AND THE STRONG FORCE

Ph.D. thesis by Peter Zeiler Skands
Advisor: Torbjörn Sjöstrand

Overview

1. The standard Zoology of particle physics.
2. So what's the problem(s) ?
3. Supersymmetry – Beyond the Standard Model.
4. The thesis work:
   - What I have been doing, fast overview.
   - Spotting speculative sparticles.
   - SuSy talk, and no mistake about it.
   - Interlude: neutrino masses ?
   - Proton collisions à la Pythia 6.3.
5. To summarise...

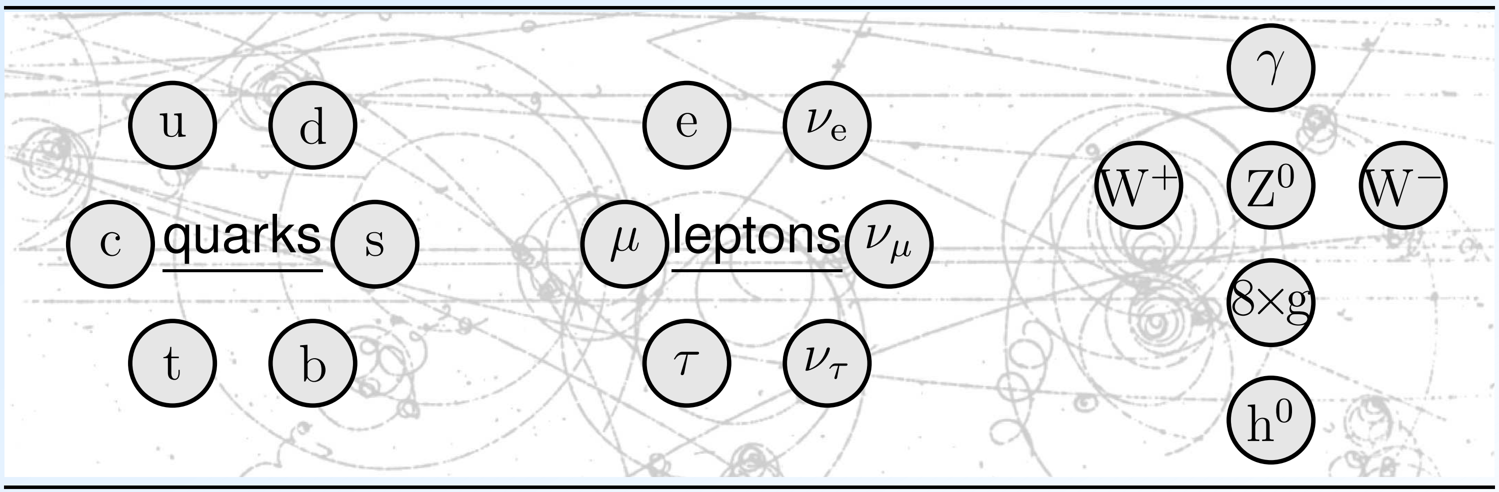
1. The Standard Zoology...

The Standard Zoology of Particle Physics

- Standard Model $\equiv$ Quantum Field Theory with:
  - 3 forces: $SU(3) \times SU(2) \times U(1)$ (+Higgs $\rightarrow$ mass).
  - $3_{\mathrm{gen}} \times 2_{\mathrm{iso}} \times 3_{\mathrm{col}} \times 2_{LR} = 36$ quarks.
  - $3_{\mathrm{gen}} \times 2_{\mathrm{iso}} \times 1_{\mathrm{col}} \times 1.5_{LR} = 9$ leptons. (Maybe 12?)

Fermions (matter particles)

Bosons (force particles)



- Works very nicely, so what's the problem?

2. So what’s the problem(s) ?

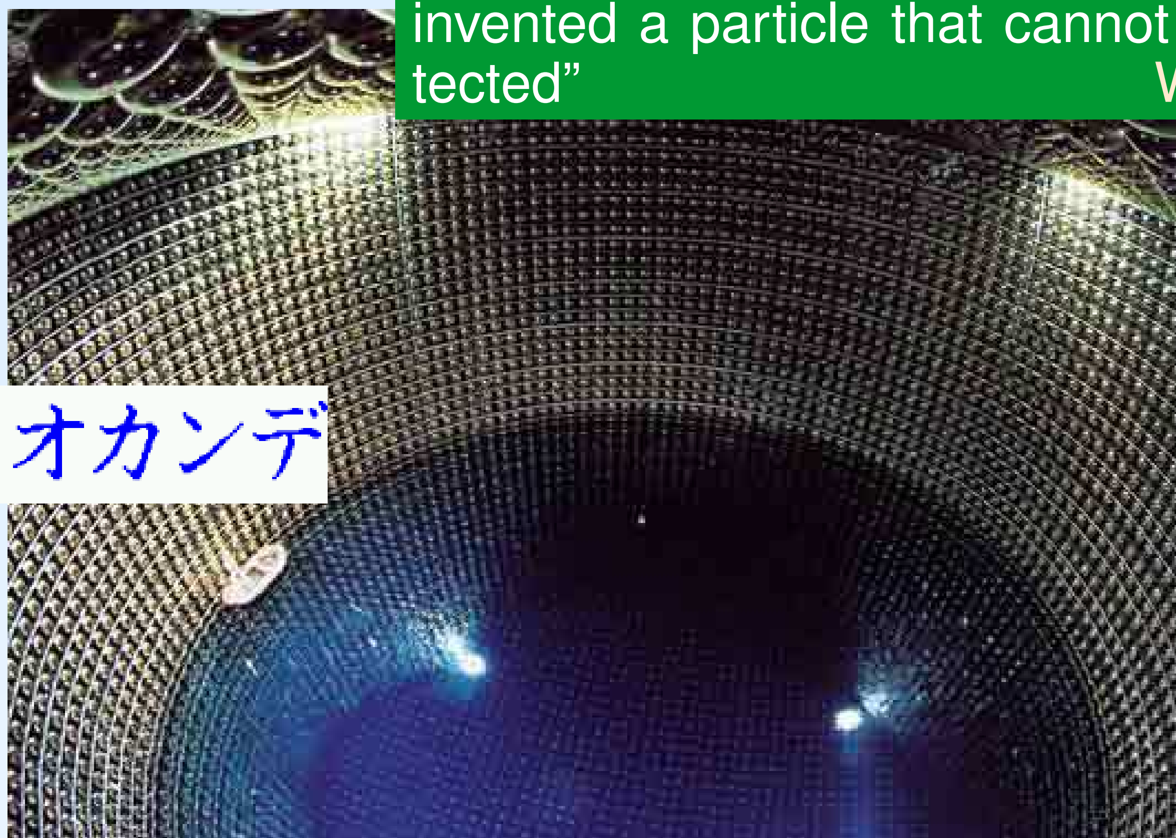
What's the problem?

- Some experiments...

What's the problem?

A few experiments:

"I have done a terrible thing, I have invented a particle that cannot be detected" W. Pauli



スーパーカミオカンデ

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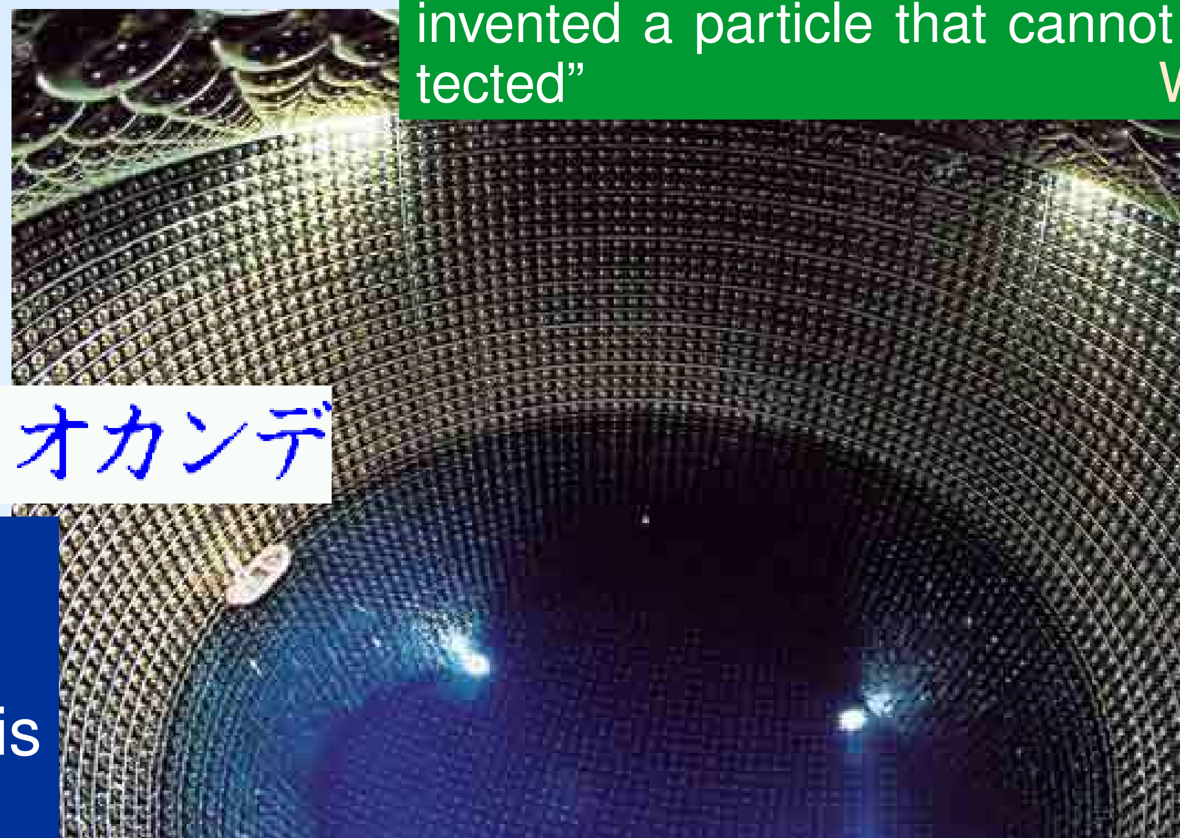

スーパーカミオカンデ

Masatoshi Koshiba

Raymond Davis Jr.

Nobel prize 2002: Neutrinos have mass!

What's the problem?

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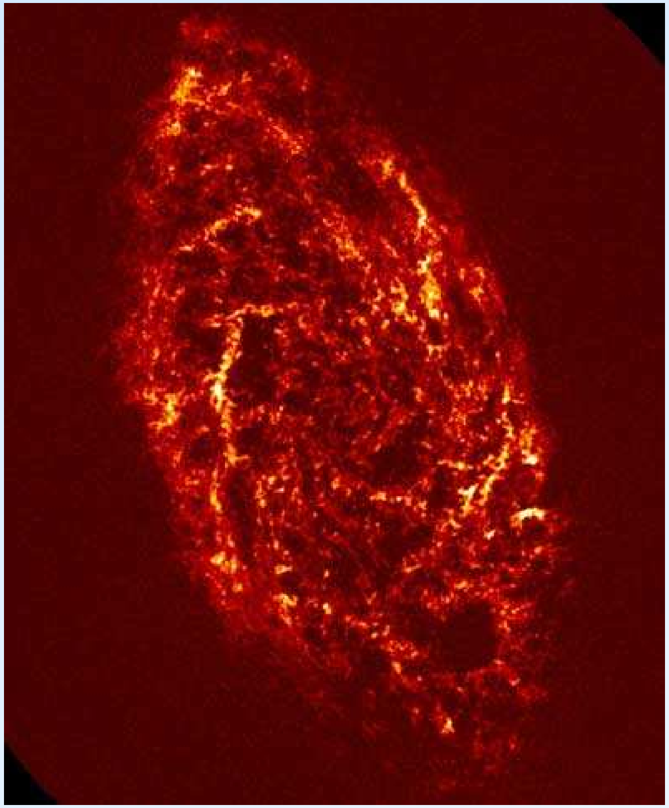

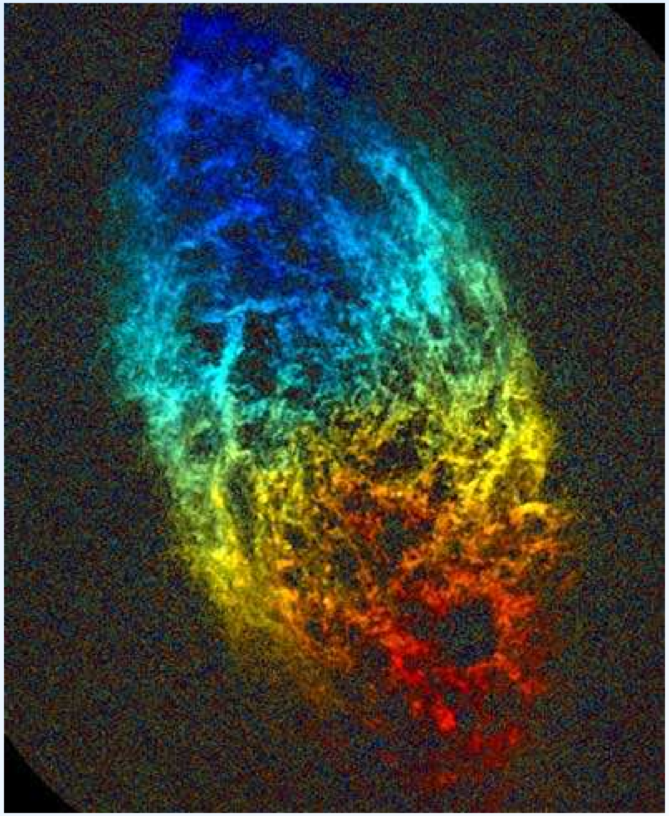

Doppler shifts $\rightarrow$ Rotation profiles of galaxies

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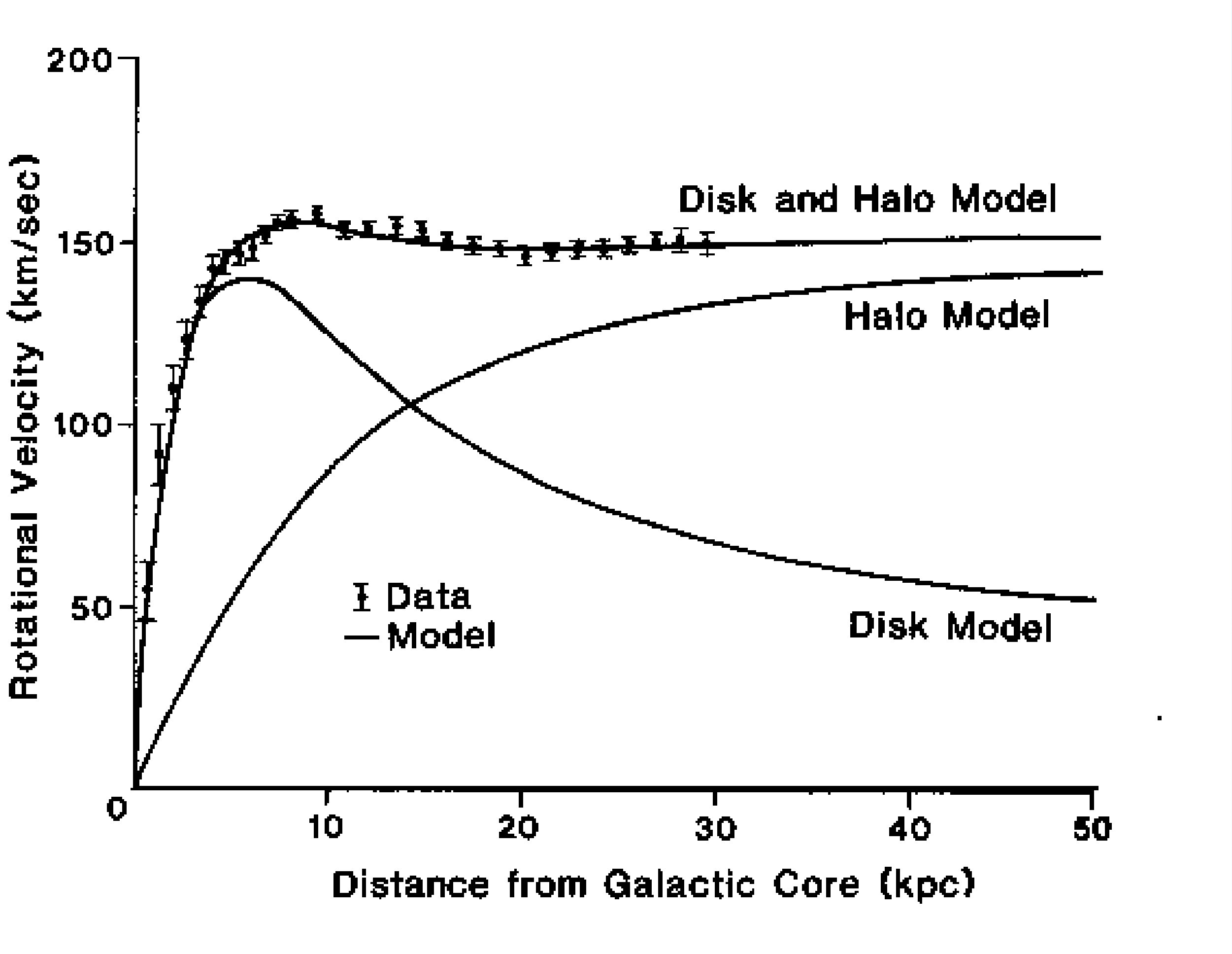

"It's a dark matter in cosmology... but then again, in that field most things are..." [A. Khodjamirian]

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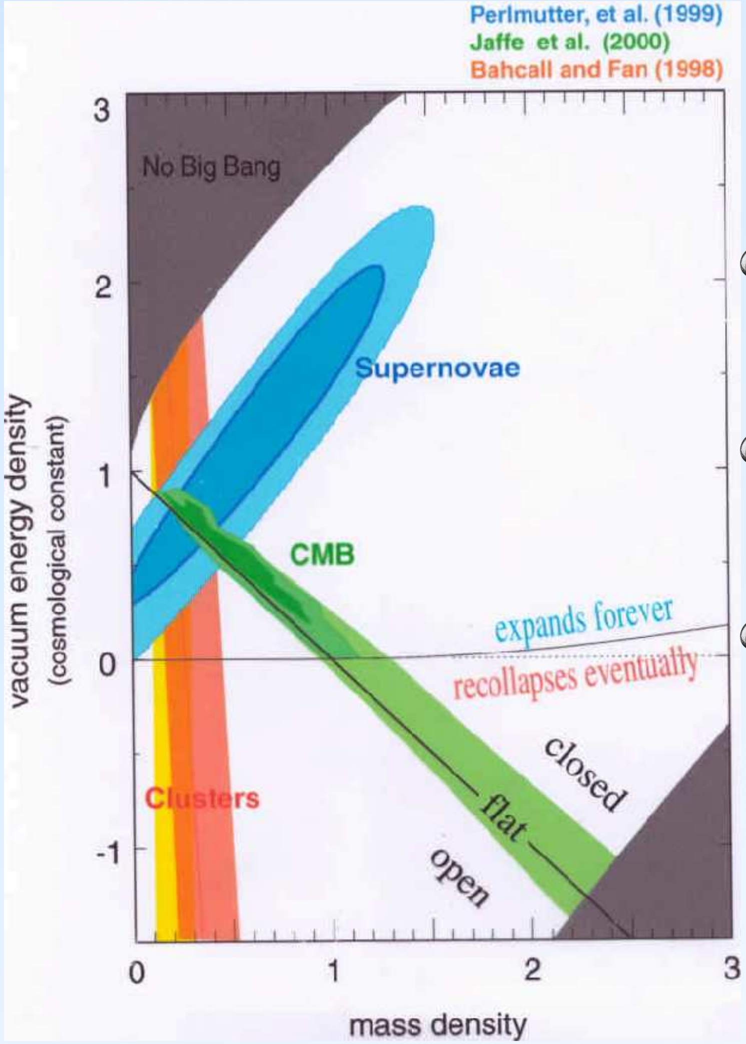

- Looks like Universe will expand forever.
- 30% matter (incl. the dark kind)
- 70% vacuum energy density (cosmological "constant")

What is Λ*?*

What's the problem?

- Some experiments...
  - How do Neutrino Masses fit in?
  - What is Dark Matter?
  - What is Dark Energy?

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Some mathematics:

- The Standard Model isn't natural!
  - The Higgs is special. It's the only scalar.
  - Its mass gets *huge* quantum corrections from higher energies, $m^2 = m_0^2 + \Delta m^2$, with $\Delta m \sim 10^{19}\ \frac{\mathsf{GeV}}{\mathsf{c}^2}$.

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The Standard Model has no explanation for this phenomenon, known as the *hierarchy problem*.

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Some mathematics:

- Gravity does not fit in the Standard Model
  - The graviton is special.
  - General Relativity: gravity is described by a tensor field: the metric $g_{\mu\nu}$, describing the curvature of space–time.
  - $\to$ a mixture of $\ell = 0$, $\ell = 1$, and $\ell = 2$ fields.

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  - $\rightarrow$ a mixture of $\ell = 0$, $\ell = 1$, and $\ell = 2$ fields.
  - Spin-2 fields are **non–renormalizable** in quantum field theory (basically, they don't make sense).
- $\rightarrow$ Gravity appears to be incompatible with Quantum Field Theory.

What's the problem?

Some mathematics:

- The Strong Force gives us headaches:
  - In QFT we can relatively easily handle
    - A handful (maybe two) of particles,
    - with small couplings $\ll 1$ (e.g. $\alpha_{\mathrm{em}} \sim 10^{-2}$)

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  - Hadronic physics and collisions always involve:
    - Potentially infinite no. of particles.
    - And couplings that may be $\gg$ large!
- So we devise phenomenological models, to describe the effective/measurable physics.
- Even so, long way still to go ...

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- Some experiments...
  - How do Neutrino Masses fit in?
  - What is Dark Matter?
  - What is Dark Energy?
- Some mathematics...
  - What to do about the hierarchy problem? (may be relevant for experiments...)
  - How to make a theory for quantum gravity (probably not relevant for experiments...)
  - How to solve (or just “solve”) QCD? (very relevant for experiments...)

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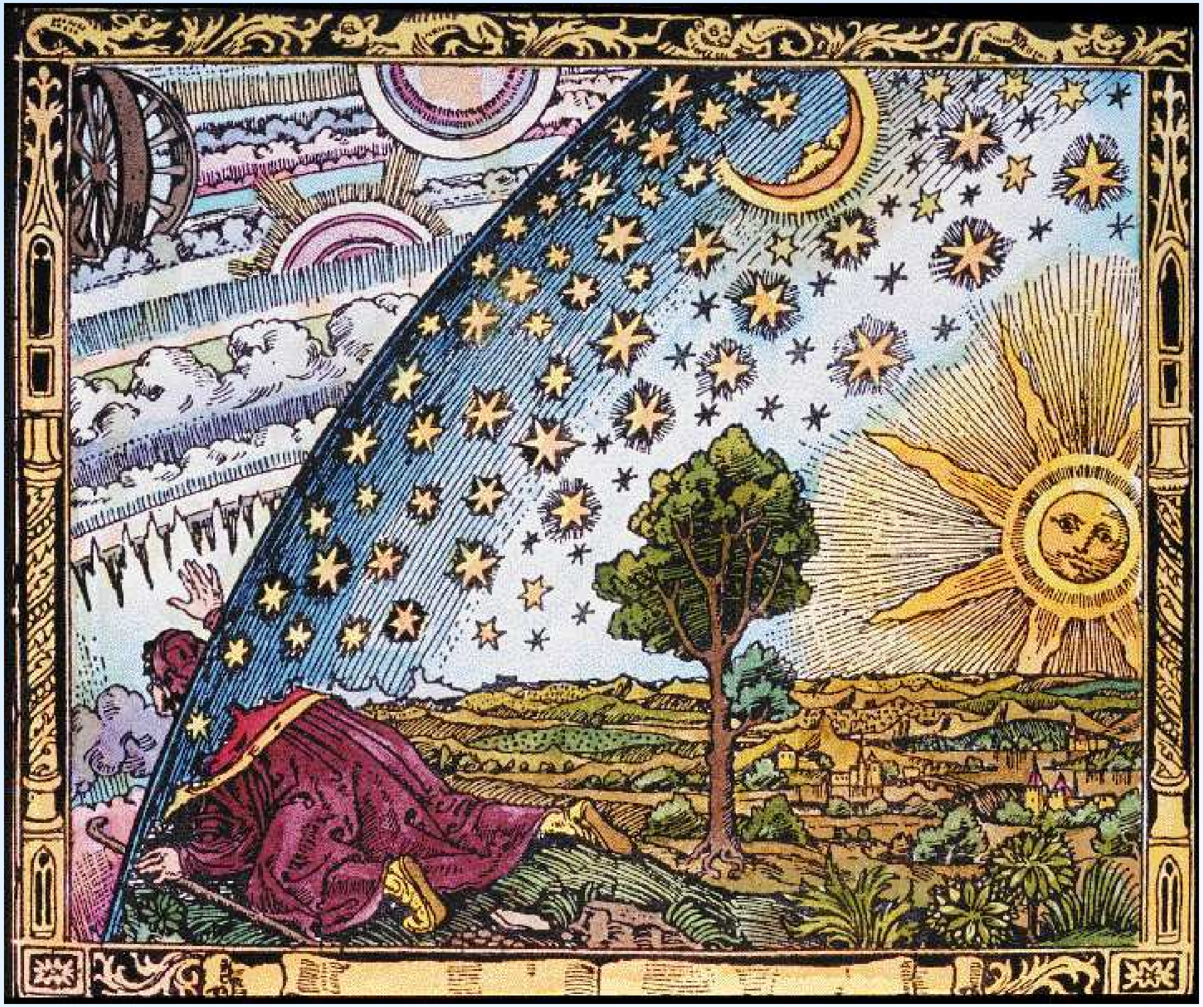
- Why 3 spatial dimensions?
- Could there be more space–time symmetries?
- Are the true fundamental objects in Nature really point-like, or are they strings, or even membranes?
- Could there be *one* fundamental theory of everything?

Spotting Speculative Sparticles



3. Supersymmetry — Beyond the Standard Model

So what is Supersymmetry?

SUPERSYMMETRY

For every boson, there is a fermion
For every fermion, there is a boson

6 leptons + 6 quarks — $S=\frac{1}{2}$

photon + $W^{\pm}$ and Z^0 + gluon — $S=1$

Higgs — $S=0$

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For every boson, there is a fermion
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6 leptons + 6 quarks	$S=\frac{1}{2}$
2×6 sleptons + 2×6 squarks	S=0
photon + $W^\pm$ and Z^0 + gluon	S=1
photino + Winos and Zino + gluino	$S=\frac{1}{2}$
Higgs	S=0
Higgsino	$S=\frac{1}{2}$

Supersymmetry.

- But what's the point?
  - Why should Nature respect this weird symmetry?
  - Instead of reducing the mess, we've *doubled* the spectrum of physical states!
- It makes sense because:
  - SUSY gives the largest possible space–time symmetry.

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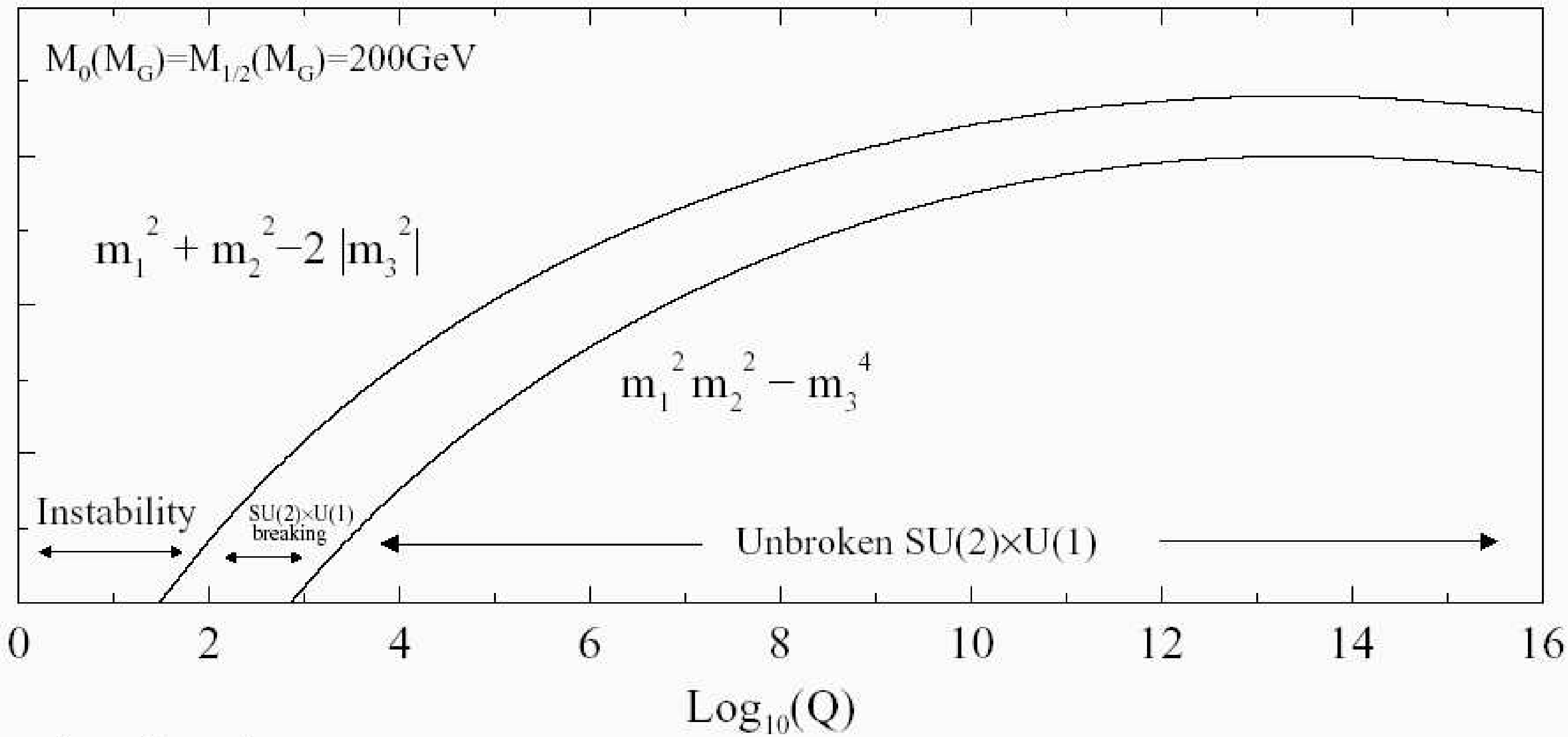

$[m_i^2 = m_{H_i}^2 + \mu^2]$

[Dedes]

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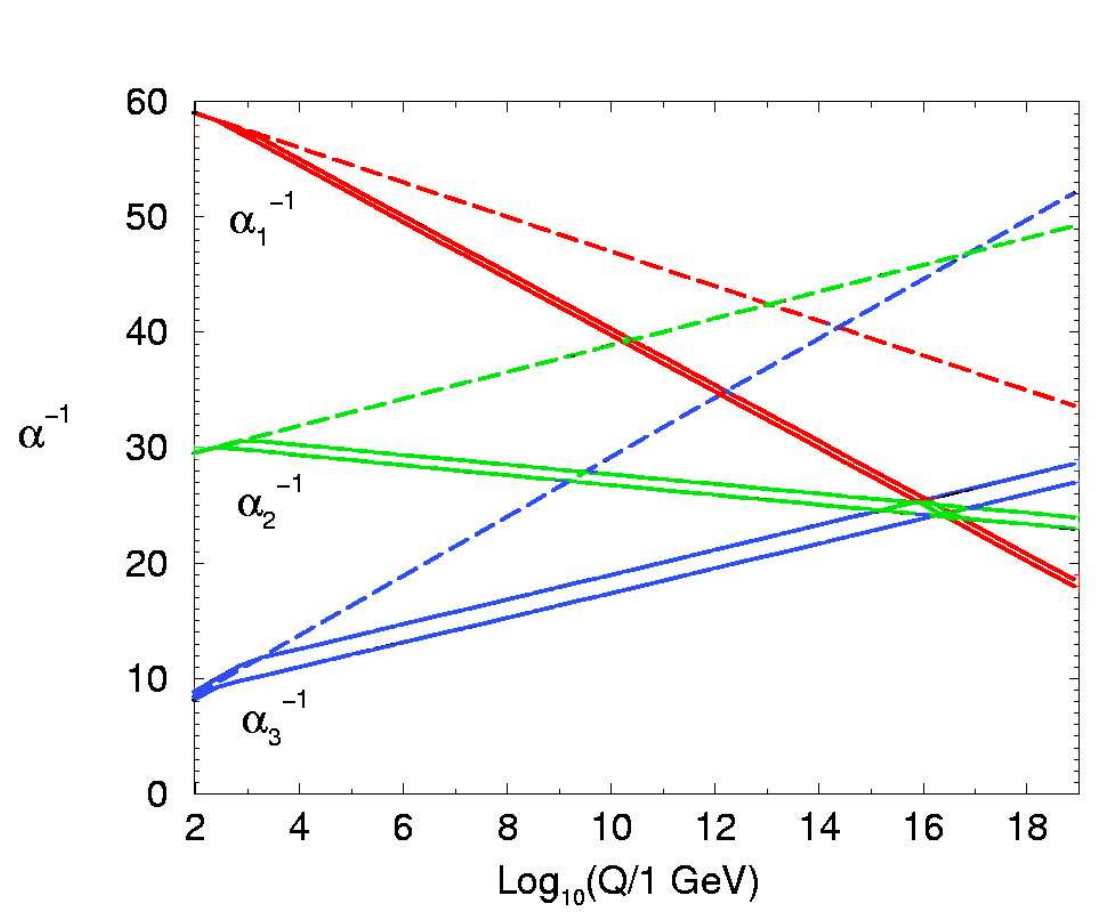
SUSY Leads to Grand Unification

- GUT's with only SM as underlying theory are ruled out, couplings don't unify.
- GUT's with SUSY can do wonderful things:



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  - SUSY leads to Grand Unification.
  - SUSY is the “super” in superstring theory.

4. The thesis work...

What I have been doing, fast overview

- lepton number violation (paper I),
- baryon number violation (paper II),
- supersymmetry calculations (paper III),
- neutrino masses (paper IV),
- proton collisions and hadronization (paper V),
- proton collisions and bremsstrahlung (paper VI).

Mix it together and you get . . . not pythipanna . . .

PYTHIA 6.3

Papers I and II

Spotting Speculative Sparticles

I "Searching for L-Violating Supersymmetry at the LHC".
By P. Skands.
LU TP 01-32, Oct 2001.
Published in European Physical Journal C23 (2002) 173.

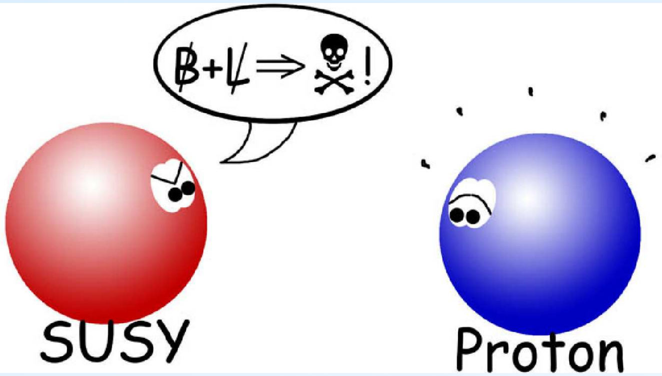
II "Baryon Number Violation and String Topologies".
By T. Sjöstrand and P. Skands.
LU TP 02-46, Dec 2002.
Published in Nuclear Physics B 659 (2003) 243.

Lepton and Baryon Number Violating SuSy

- Most general (MSSM) superpotential:

$$W = W_{\rm MSSM} + W_{\rm BNV} + W_{\rm LNV}$$

- But LNV+BNV makes bad cocktail!



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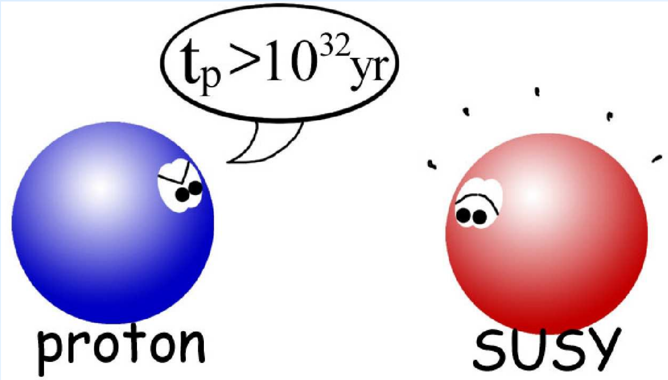

- To save proton, R, B, or L conservation imposed.
  - $\mathrm{R} \rightarrow$ CDM candidate, but no deep motivation.
  - B and L more robust against things outside MSSM.
  - No clear-cut answer.

Lepton Number Violating SuSy

- Paper I concerned Lepton Number Violating SuSy.
- More than 1200 decay channels of sparticles to particles were implemented in PYTHIA.
- Often many interfering amplitudes contributing to same process $\rightarrow$ big matrix element expressions and tricky phase space integrations (for the 3–body modes).
- In the end, the calculations were totally automized, using a just few generic routines.
- The second part was a study of trigger sensitivities and discovery potential for the LHC, using the augmented PYTHIA in combination with the ATLFAST detector simulation, and applying a technique based on neural networks to help separate signal-like events from background-like events.

Baryon Number Violating SuSy

- Paper II concerned Baryon Number Violating SuSy.
- This time, some 200 decay channels of sparticles to particles were implemented in PYTHIA.
- Again, these could have bothersome expressions etc.

$$\Gamma(\tilde\chi^0 \to \bar u_i \bar d_j \bar d_k) = \frac{1}{(2\pi)^3}\frac{1}{32M^3_{\tilde\chi^0}}\int \mathrm{d}m^2_{12}\int \mathrm{d}m^2_{23}\,|\overline{M}(\tilde\chi^0 \to \bar u_i \bar d_j \bar d_k)|^2$$

$$\frac{|\overline{M}(\tilde\chi^0 \to \bar u_i \bar d_j \bar d_k)|^2}{N_c!\lambda''^2_{ijk}} =$$

$$\sum_{\alpha=1}^{2}|Q^{2i-1}_{\alpha R}|^2 R(\tilde u^*_{i\alpha}, m^2_{jk})(m^2_{jk}-m^2_j-m^2_k)\left((a^2(\tilde u^*_{i\alpha})+b^2(\tilde u^*_{i\alpha}))(m^2_{\tilde\chi^0}+m^2_i-m^2_{jk})+4a(\tilde u^*_{i\alpha})b(\tilde u^*_{i\alpha})m_i m_{\tilde\chi^0}\right)$$
$$+\sum_{\alpha=1}^{2}|Q^{j}_{\alpha R}|^2 R(\tilde u^*_{j\alpha}, m^2_{ik})(m^2_{ik}-m^2_i-m^2_k)\left((a^2(\tilde u^*_{j\alpha})+b^2(\tilde u^*_{j\alpha}))(m^2_{\tilde\chi^0}+m^2_j-m^2_{ik})+4a(\tilde u^*_{j\alpha})b(\tilde u^*_{j\alpha})m_j m_{\tilde\chi^0}\right)$$
$$+\sum_{\alpha=1}^{2}|Q^{k}_{\alpha R}|^2 R(\tilde d_{k\alpha}, m^2_{ij})(m^2_{ij}-m^2_i-m^2_j)\left((a^2(\tilde d^*_{k\alpha})+b^2(\tilde d^*_{k\alpha}))(m^2_{\tilde\chi^0}+m^2_k-m^2_{ij})+4a(\tilde d^*_{k\alpha})b(\tilde d^*_{k\alpha})m_k m_{\tilde\chi^0}\right)$$
$$+2Q^i_{1R}Q^i_{2R}S(\tilde u^*_{i1},\tilde u^*_{i2},m^2_{jk},m^2_{jk})(m^2_{jk}-m^2_j-m^2_k)\Big((a(\tilde u^*_{i1})a(\tilde u^*_{i2})+b(\tilde u^*_{i1})b(\tilde u^*_{i2}))(m_{\tilde\chi^0}+m^2_i-m^2_{ik})$$
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$$+m_i m_{\tilde\chi^0} b(\tilde u^*_{j\beta})a(\tilde u^*_{i\alpha})\left(m^2_{jk}-m^2_k-m^2_j\right)+m_j m_{\tilde\chi^0} a(\tilde u^*_{j\beta})b(\tilde u^*_{i\alpha})\left(m^2_{ik}-m^2_i-m^2_k\right)$$
$$+b(\tilde u^*_{j\beta})b(\tilde u^*_{i\alpha})\left(m^2_{ik}m^2_{jk}-m^2_i m^2_j-m^2_{\tilde\chi^0}m^2_k\right)\Big)$$
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Dreiner, Richardson, and Seymour (hep-ph/9912407):

Baryon Number Violating SuSy

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- This time, some 200 decay channels of sparticles to particles were implemented in PYTHIA.
- Again, these could have bothersome expressions etc.
- But all that worked like before.

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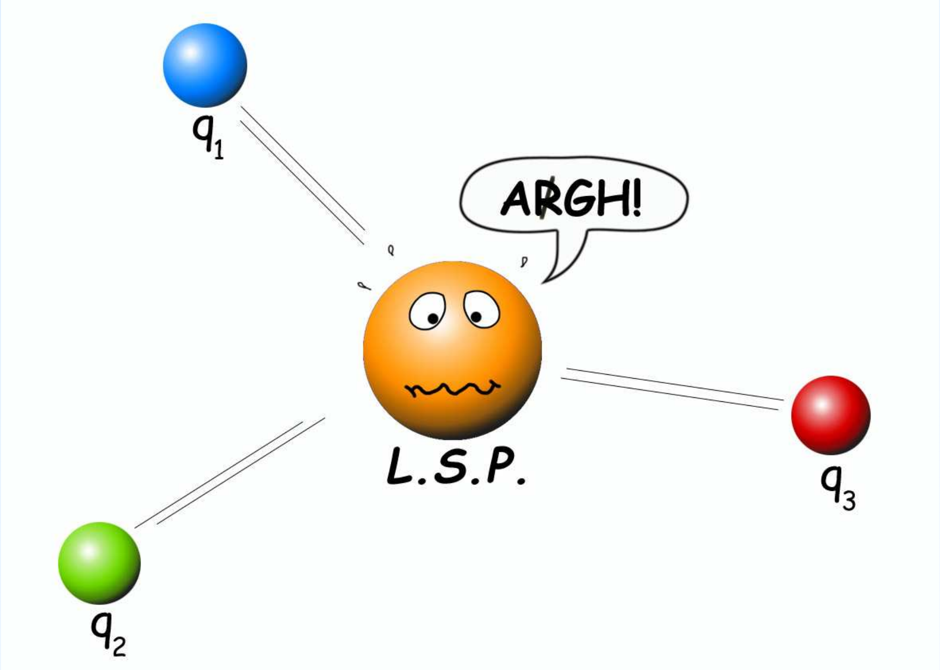
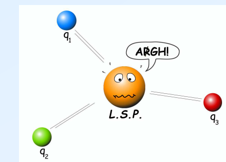
- But all that worked like before.
- The real challenge was the *colour flows!*

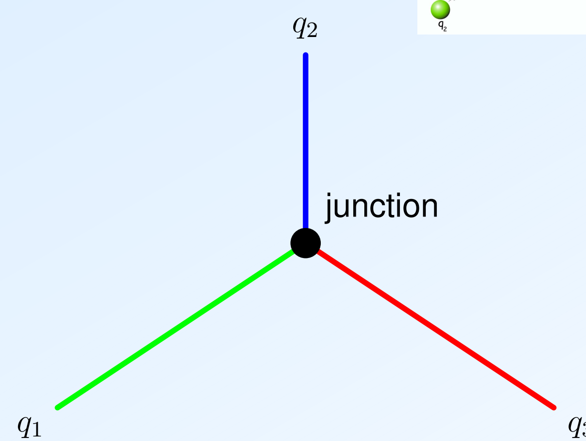


Baryon Number Violating SuSy

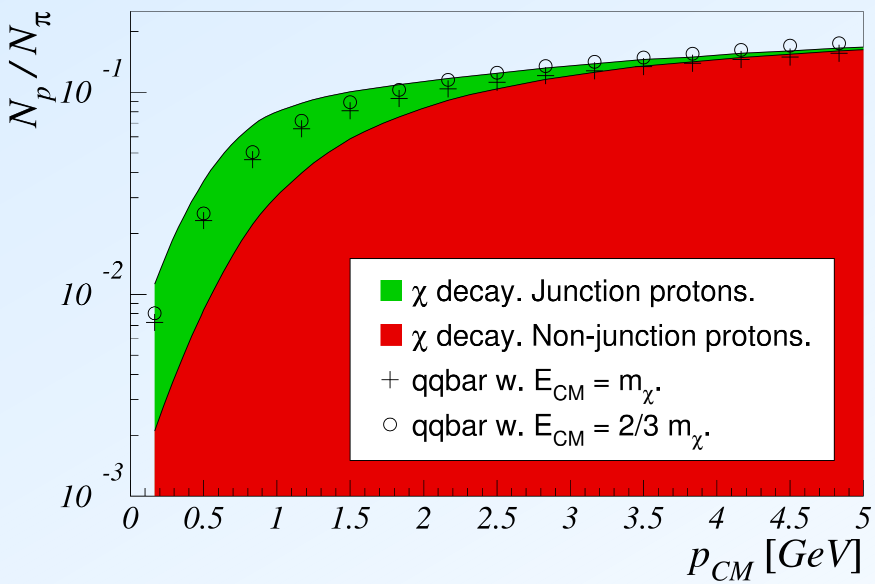
Special: creation of 3 colour carriers, antisymmetric in colour, at large momentum separation.

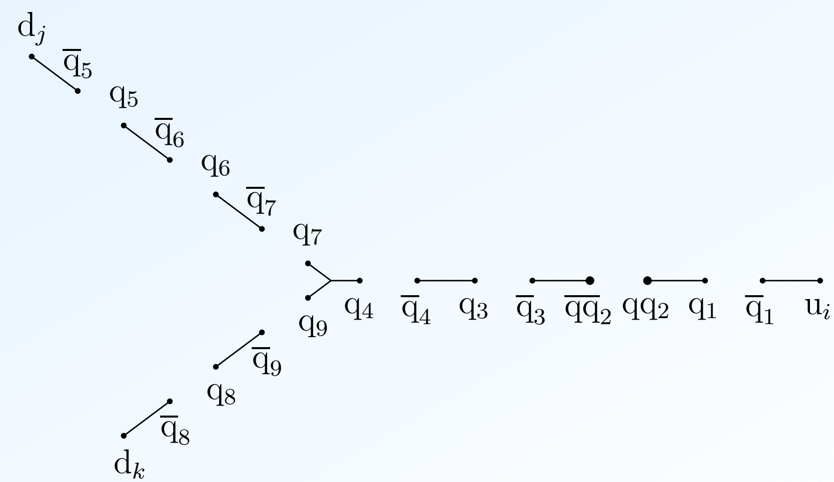
"Ordinary" string (e.g. $Z^0 \to q\bar{q}$):

"Baryonic" string (e.g. ):



$B \equiv$ string topologies w/ junction(s).





Paper III

SuSy talk, and no mistake about it.

III “SUSY Les Houches Accord: Interfacing SUSY Spectrum Calculators, Decay Packages, and Event Generators”.

By P. Skands, B.C. Allanach, H. Baer, C. Balázs, G. Bélanger, F. Boudjema, A. Djouadi, R. Godbole, J. Guasch, S. Heinemeyer, W. Kilian, J-L. Kneur, S. Kraml, F. Moortgat, S. Moretti, M. Mühlleitner, W. Porod, A. Pukhov, P. Richardson, S. Schumann, P. Slavich, M. Spira, G. Weiglein.

LU TP 03-39, Nov 2003.

Published in Journal of High Energy Physics 07 (2004) 036.

SuSy talk...

- Problem: lots of people doing SuSy calculations today!
  - Spectrum Calculators: $\sim$ 7 programs.
  - Relic Density Codes: $\sim$ 3 programs.
  - Dedicated Decay Packages: $\sim$ 3 programs.
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- This gave rise to some problems...
- So why not make an *Accord?* I.e. agree on a standard set of conventions for SuSy theories, with standard file structures $\rightarrow$ unambiguous communication.

SuSy talk...

- At the Les Houches meeting in 2003, the organisers had agreed to let me gather a lot of experts in a room, to discuss this. I made sure nobody could get out for some hours.
- Next day, we had another long meeting, and another one every day after that, for almost two weeks. Only a few people got out.
- At the end, everybody was tired and agreed.
- Then we had lots of mails, $\mathcal{O}(10^3)$, more meetings at CERN, at Montpellier, and latest at Durham.
- The result is the SuSy Les Houches Accord, which now is implemented in most of the relevant codes.

SuSy talk...

- At th ... anisers had a ... a room, to dis ... out for some
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- Ther ... ings at CER
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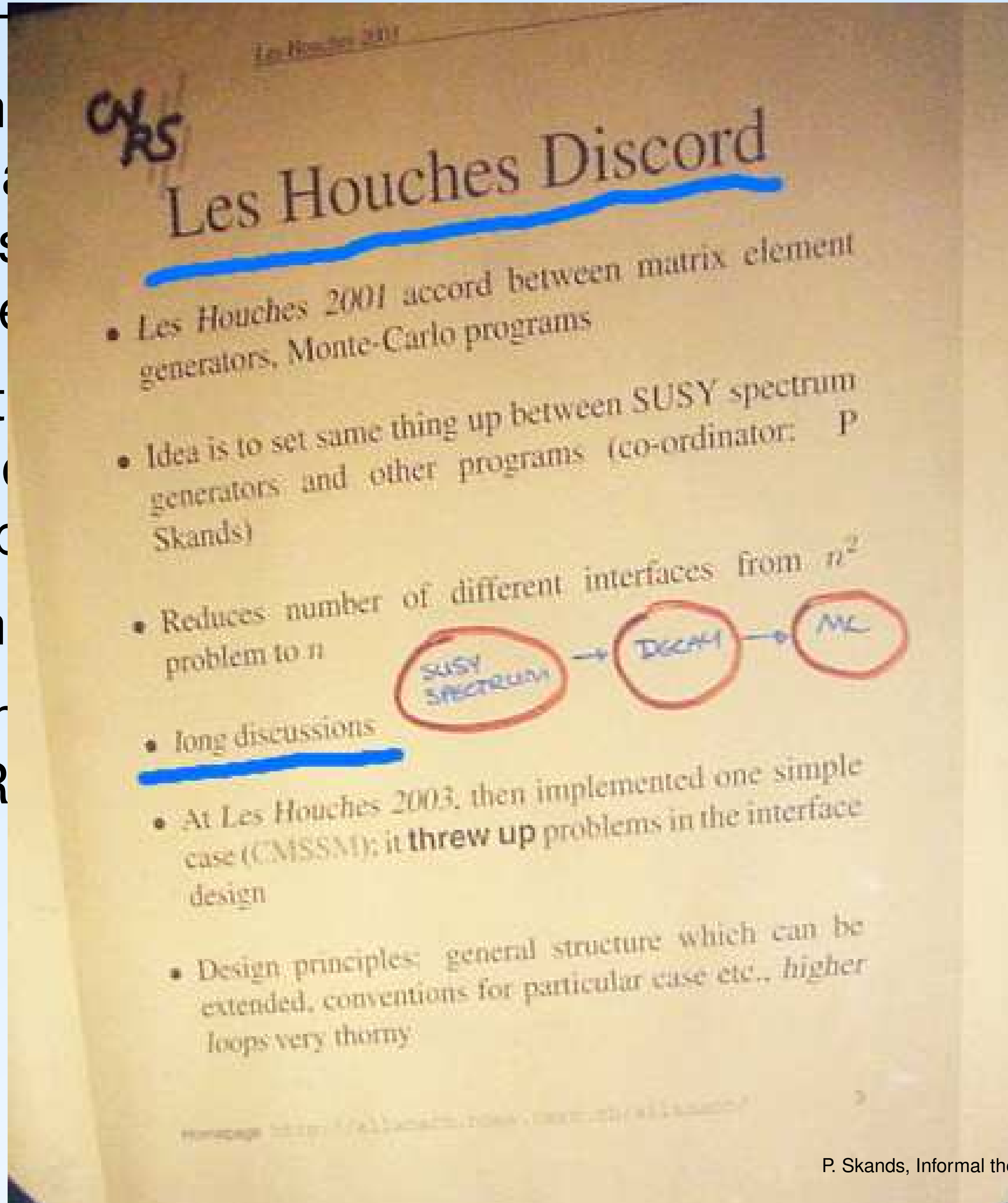


Paper IV

Interlude: neutrino masses ?

IV "Measuring Neutrino Mixing angles at LHC".

By W. Porod and P. Skands.

LU TP 03-50, ZU-TH 20/30, Jan 2004. [hep-ph/0401077]

In Beyond the Standard Model Working Group: Summary report, 3rd Les Houches Workshop: Physics at TeV Colliders, Les Houches, France, 26 May - 6 Jun 2003, B. C. Allanach *et al.* [hep-ph/0402295].

Neutrino Summary

Neutrino sector: a window to physics beyond SM?

1. Too few ν_μ from atmosphere, can be explained by oscillations into ν_τ: $\Delta m^2_{\mathrm{atm}} = m_3^2 - m_2^2 \sim 10^{-3} - 10^{-2}\,\mathrm{eV}^2$
2. Too few ν_e from Sun, can be explained by oscillations into ν_μ: $\Delta m^2_{\mathrm{sol}} = m_2^2 - m_1^2 \sim 10^{-5} - 10^{-4}\,\mathrm{eV}^2$
3. Bi-maximal mixing pattern: θ_{23} large, θ_{12} large, and θ_{13} small.

Explanations generally look like this:

$$\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$$

Bilinear R–violation

$$W_{\text{SUSY}} = W_{\text{MSSM}} + \epsilon_i L_i H_2$$

(Occurs e.g. when R–parity is broken spontaneously)

In context of neutrino masses, the important consequences are:

- EW symmetry is broken by Higgs *and* sneutrino vev's,

  $\langle \nu_i \rangle = v_i$ (i.e. $m_W^2 = \frac{1}{4} g^2 (v_d^2 + v_u^2 + v_1^2 + v_2^2 + v_3^2)$).

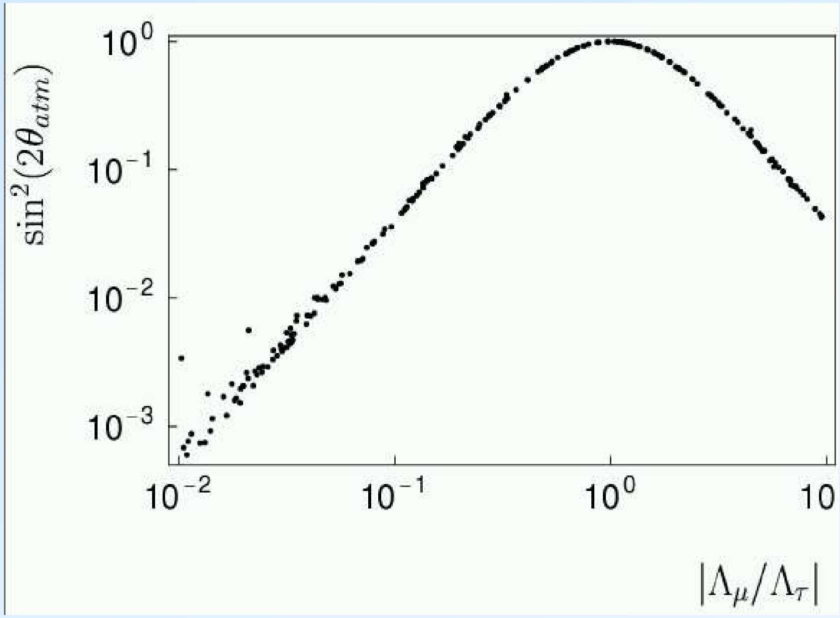
- Neutrinos mix with neutralinos $\to 7 \times 7$ mixing:

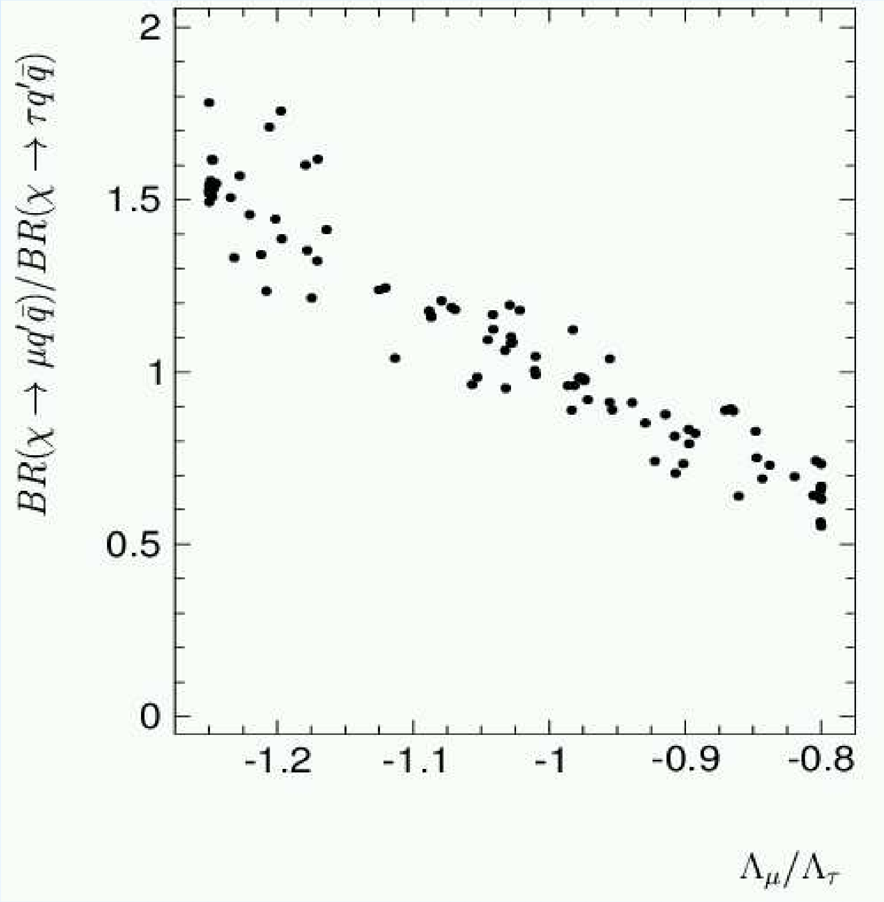
In block form: $M_N = \begin{pmatrix} 0 & m_{(3\times4)} \\ {m^T}_{(4\times3)} & M_{(4\times4)} \end{pmatrix}$

Measuring a ν angle...

Mixing depends on

$\Lambda_i = \mu v_i + v_d \epsilon_i$





- BRPV couplings also responsible for LSP decay.
- $\rightarrow$ Ratio of $\tilde{\chi}_1^0$ semileptonic branching ratios is strongly correlated with Λ_i/Λ_j!

Papers V and VI

Proton Collisions

V "Multiple Interactions and the Structure of Beam Remnants".
By T. Sjöstrand and P. Skands.
LU TP 04-01, Feb 2004.
Published in Journal of High Energy Physics 03 (2004) 053.

VI "Transverse-Momentum-Ordered Showers and Interleaved Multiple Interactions".
By T. Sjöstrand and P. Skands.
LU TP 04-29, Aug 2004.
To be submitted to the European Physical Journal C.

Proton Collisions...

1 hadron collision =

$(2 \rightarrow 2 \oplus \underbrace{\text{ISR} \oplus \text{FSR}} \oplus \text{UE}) \otimes$ hadronisation etc.

Eff. resum. of multiple (semi-)soft gluon emission effects

- $2 \rightarrow 2$: 'hard subprocess' (on–shell).
- ISR: Initial–State Radiation (spacelike).
- FSR: Final–State Radiation (timelike).
- UE: Underlying Event – any additional (perturbative) activity.

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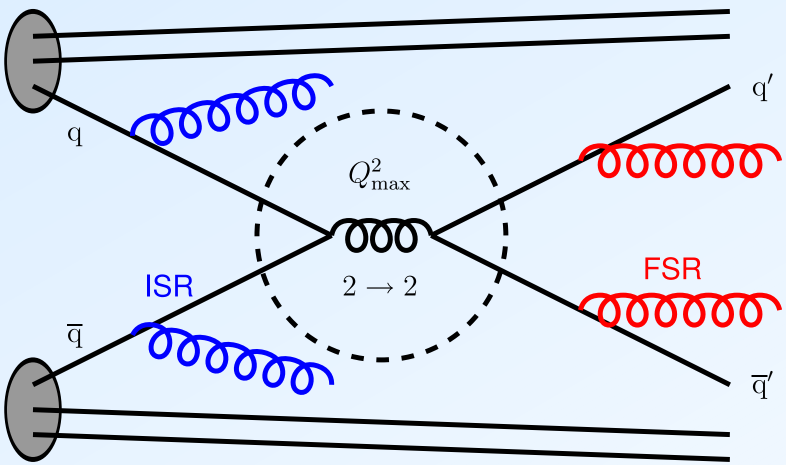

+ additional $2 \to 2$ scatterings
  = "multiple interactions"
+ hadronisation
+ hadron decays

Proton Collisions...

What we have done:

1. Developed a new complete model for multiple interactions in hadron-hadron collisions.
2. Developed a new (dipole) parton shower, both for final state and initial state radiation.

For both of these, we use transverse momentum as the “resolution” parameter.

Why Develop a New MI Model?

- Need to understand correlations and fluctuations. From QCD point of view:
  many interesting questions remain unanswered.
- Any reliable extrapolation to LHC energies will require a good understanding of the physics mechanisms.
  Simple parametrizations not sufficient.
- Random and systematic fluctuations in the underlying activity can impact precision measurements as well as New Physics searches:
  more reliable understanding is needed.
- Lots of fresh data from Tevatron:
  $\longrightarrow$ great topic for phenomenology right now!

Why Develop a New Shower?

- Incorporate several of the good points of the dipole formalism within the shower approach

  $\pm$ explore alternative $p_\perp$ definitions

  $+$ $p_\perp$ ordering $\Rightarrow$ coherence inherent

  $+$ Merging with Matrix Elements unproblematic.
  (unique $p_\perp^2 \leftrightarrow Q^2$ mapping; same z)

  $+$ $\mathrm{g} \rightarrow \mathrm{q}\overline{\mathrm{q}}$ natural

  $+$ kinematics constructed after each branching
  (partons explicitly on-shell until they branch)

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$+$ allows to combine $p_\perp$ evolutions of showers and multiple interactions $\rightarrow$ *common* (competing) evolution of ISR, FSR, and MI!

$\equiv$ 'Interleaved Multiple Interactions'

Proton Collisions... The New Picture

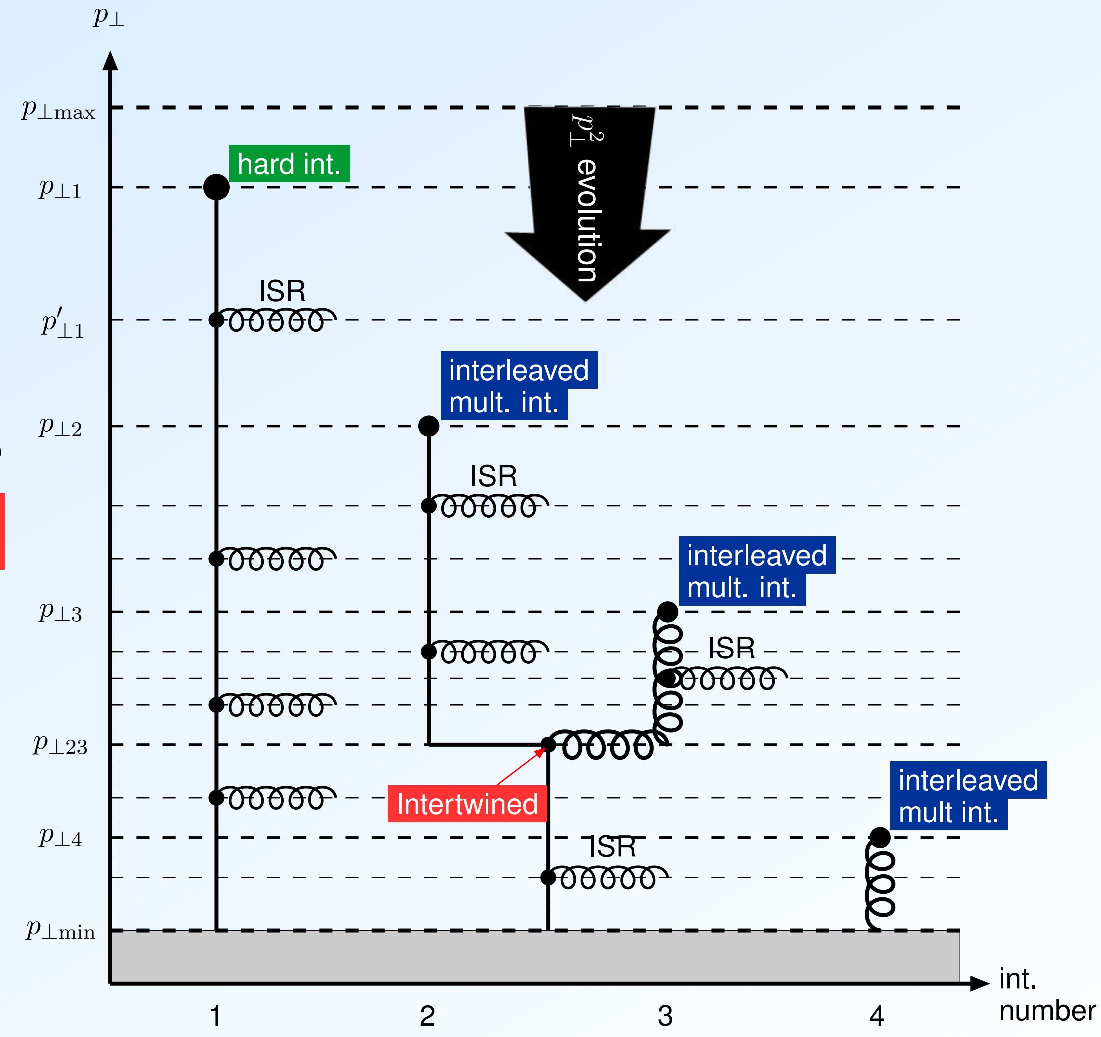
The building blocks:

- $p_\perp$–ordered initial–state parton showers. ✔
- $p_\perp$–ordered final–state parton showers. ✔
- $p_\perp$–ordered multiple interactions. ✔
- $p_\perp$ used as scale in α_s and in PDF's. ✔
- (Model for) correlated multi–parton densities. ✔
- Beam remnant hadronization model. ✔
- Model for initial state colour correlations. (✔ — but far from perfect!)
- Other phenomena? (e.g. colour reconnections (✔), ...)
- Realistic tunes to data (not yet!)

Proton Collisions... The New Picture

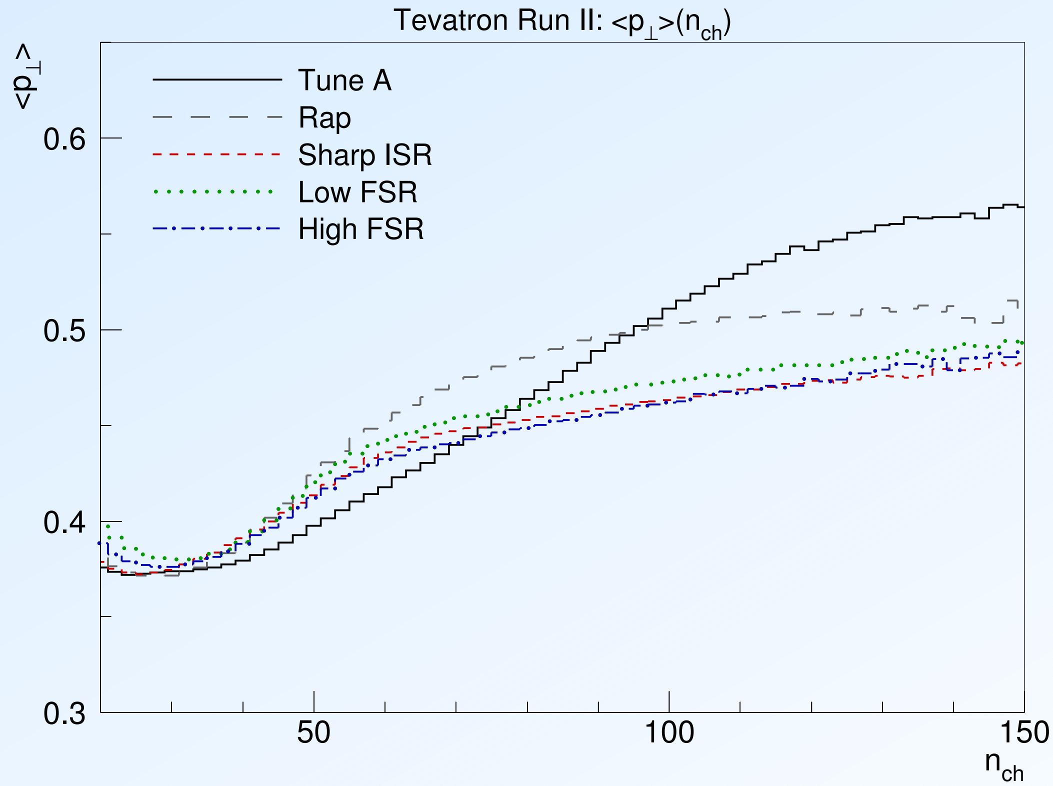
- The new picture: start at the most inclusive level, $2 \to 2$. Add exclusivity progressively by evolving *everything* downwards in *one* common sequence:
  $\to$ Interleaved evolution

- ($\to$ also possible to have interactions *intertwined* by the ISR activity?)



Proton Collisions... The New Picture

- The new description represents a new generation in terms of detail and sophistication of the physics description of hadron collisions.
- But there is still some way to go...



5. To Summarise...

Working in Lund

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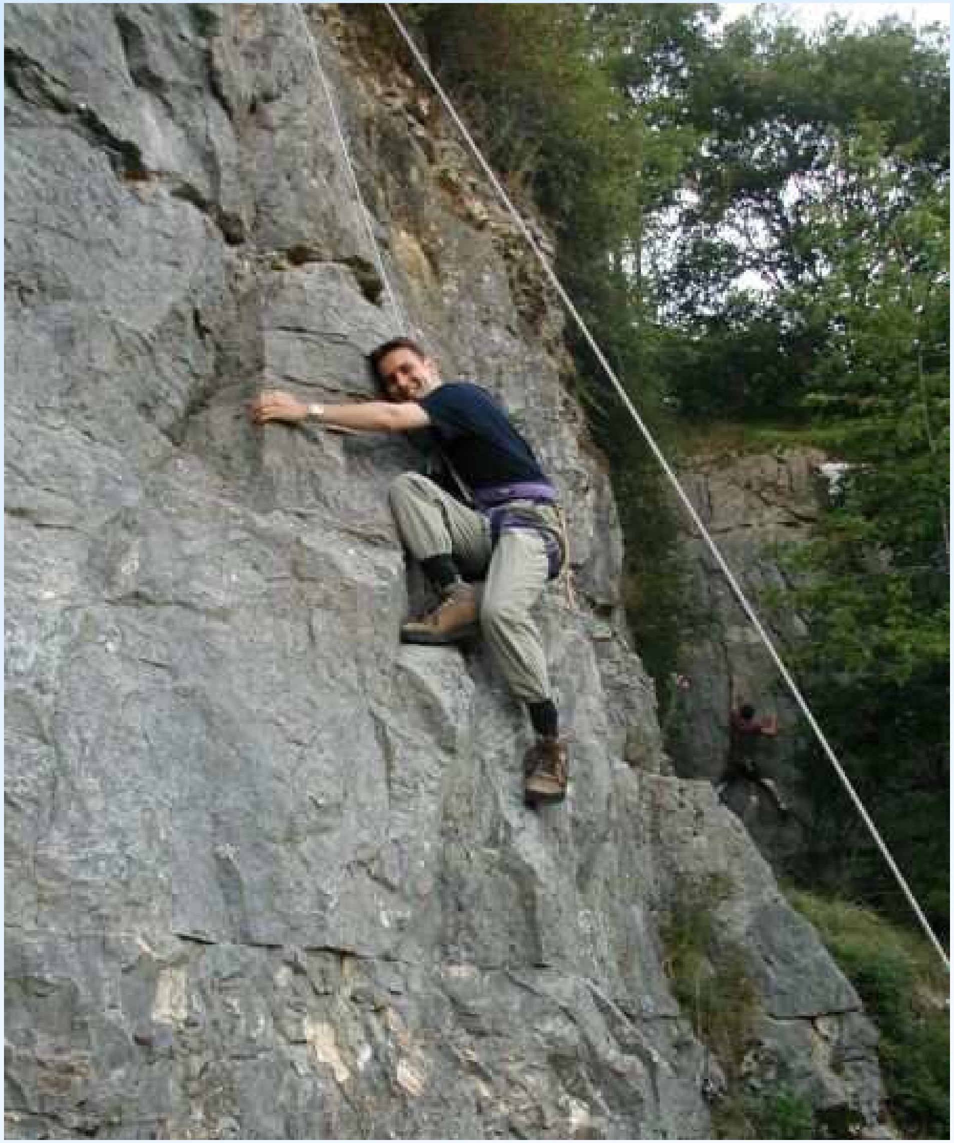
Has been an upward climb!



I have come a long way

I have come a long way

Not standing still...

Plans for the future

Plans for the future

...