Polarization Puts a New Spin on Hadronic Physics

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@

International Workshop on Structure and Spectroscopy, Freiburg

Outline of Topics

- Overview of nucleon spin decomposition:
  - Theoretical ideas:
    - Naïve quark model vs chiral soliton model
  - Experimental status of the spin of the nucleon
    - Gluons and strange quarks
  - Other probes of nucleon spin:
    - Nucleon-antinucleon annihilation, (anti-)Λ polarization
- Looking for new physics:
  - Search for dark matter
  - Spin effects at the LHC
    - Discriminating supersymmetry from extra dimensions

Decomposition of the Nucleon Spin?

Proton spin sum rule:

$$\tfrac{1}{2} = \tfrac{1}{2}.\Delta\Sigma + \Delta G + L_z$$

Total quark spin (cf singlet axial charge a_0)

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

Net quark spin contributions Δq

Net strange quark spin Δs

Net gluon spin ΔG

Orbital angular momentum L_z

Models of Nucleon Structure

- Naïve quark model
- $M_Q \sim 300$ MeV
- Wave function QQQ
- Sea of extra qqbar pairs generated perturbatively
- Usual SU(3) multiplets
- Explains OZI rule
- Proton spin = Sum of valence quark spins
- Sum of quark spins = ½
- Few intrinsic ssbar

- Chiral soliton model
- $M_{U,D} \sim$ few MeV,
- $M_S \sim 100$ MeV
- Intrinsic qqbar pairs in nucleon wave function
- Exotic SU(3) multiplets?
- Evasions of OZI rule
- Proton spin = Orbital angular momentum
- Sum of quark spins = 0
- Many polarized ssbar

Proton Spin in Chiral-Soliton Model

- Proton spin sum rule:

  $\frac{1}{2} = \frac{1}{2}(\Delta u + \Delta d + \Delta s) + \Delta G + L_z$

- χSM → small sum of quark contributions to spin:

  $\Delta u + \Delta d + \Delta s = 0$

- χSM → proton spin due to orbital angular momentum:

  $L_z = \frac{1}{2}$

- χSM → small gluon contribution to spin:

  $\Delta G = 0$

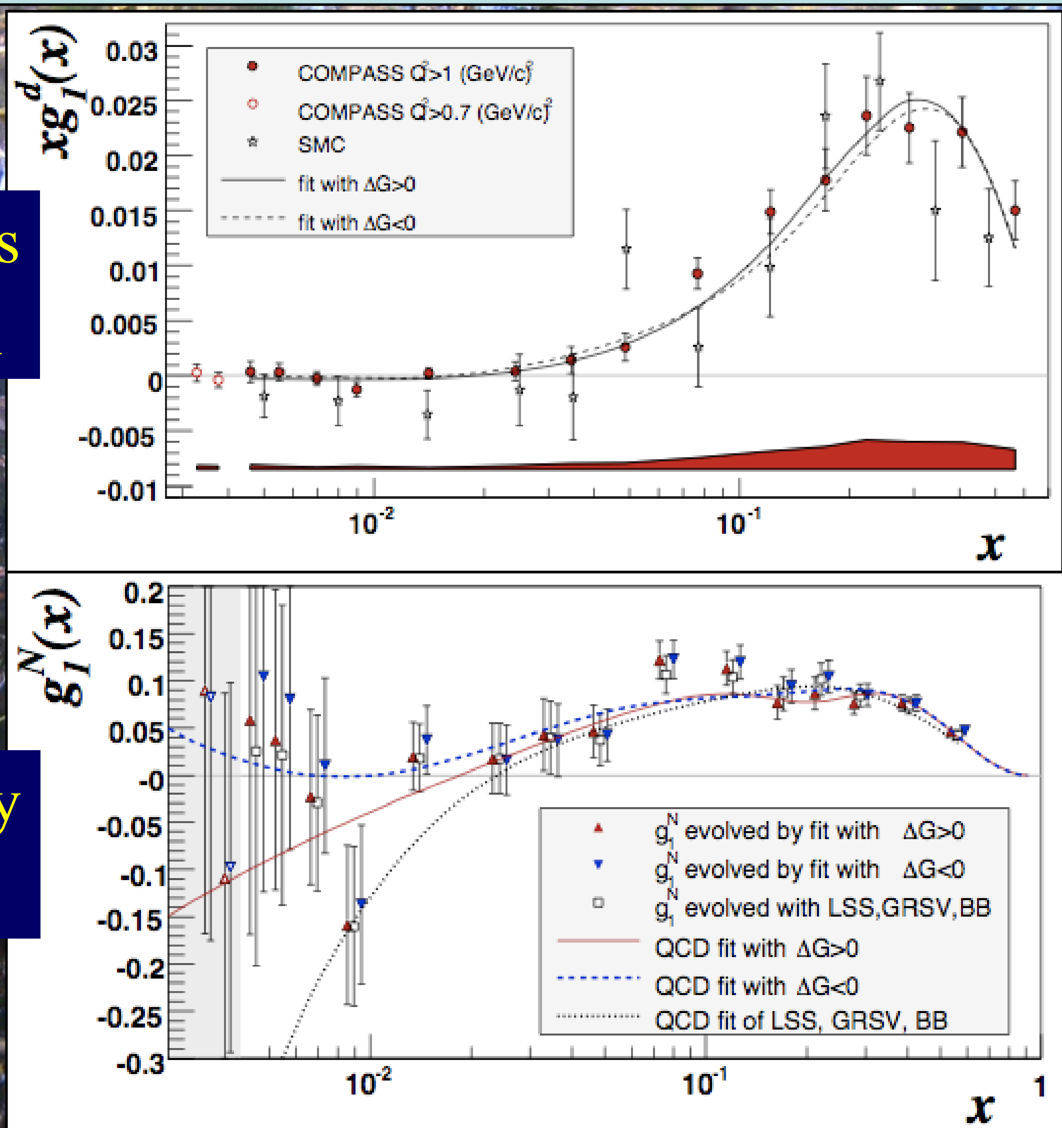
  in simple extension of χSM to include gluons

  Predictions subject to $1/N_c$, m_s corrections ~ 30%?

New COMPASS Data on g_1^d

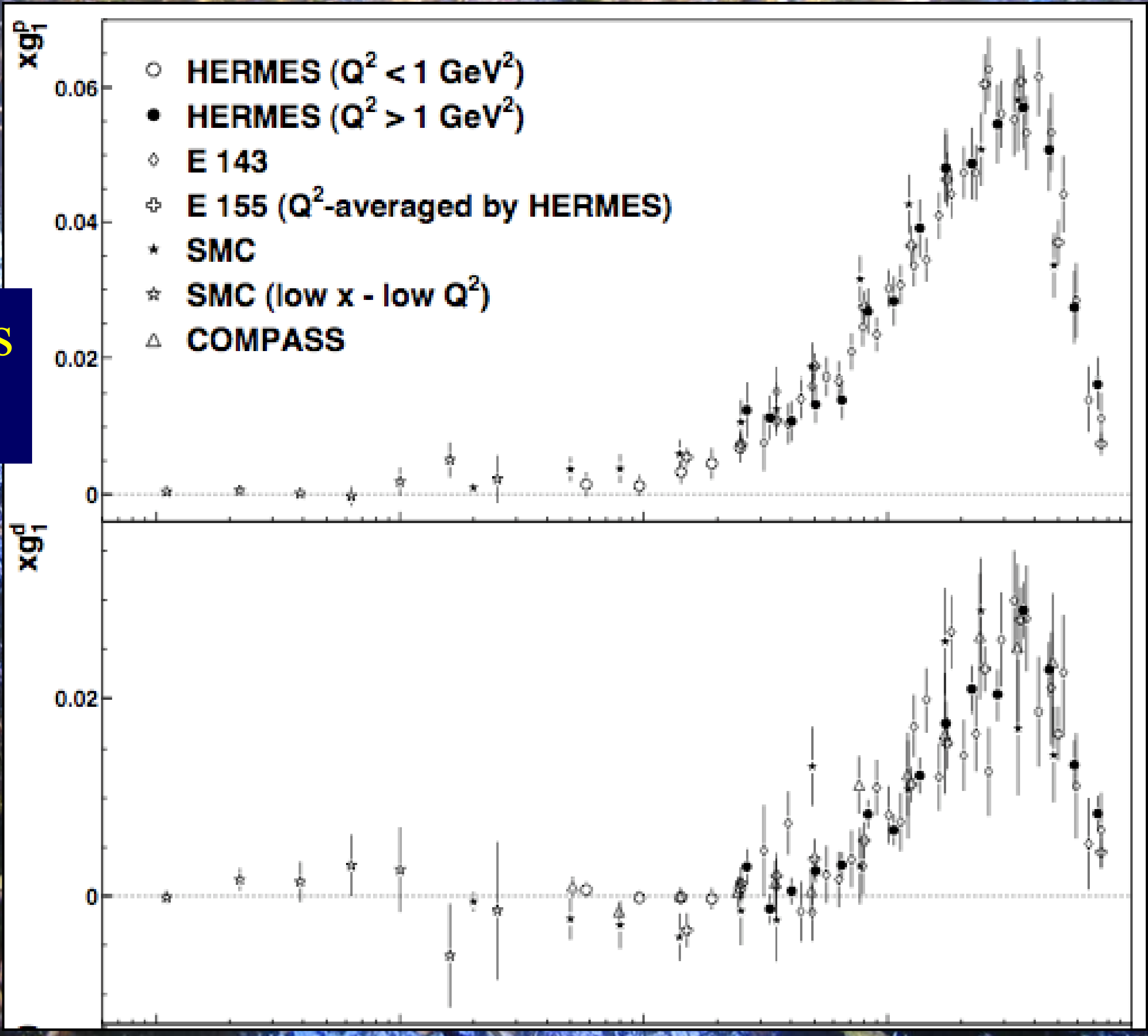
Improved measurements - particularly at small x

Interesting sensitivity to ΔG



New HERMES Data on g_1^p & g_1^d

Improved measurements
- particularly at large x

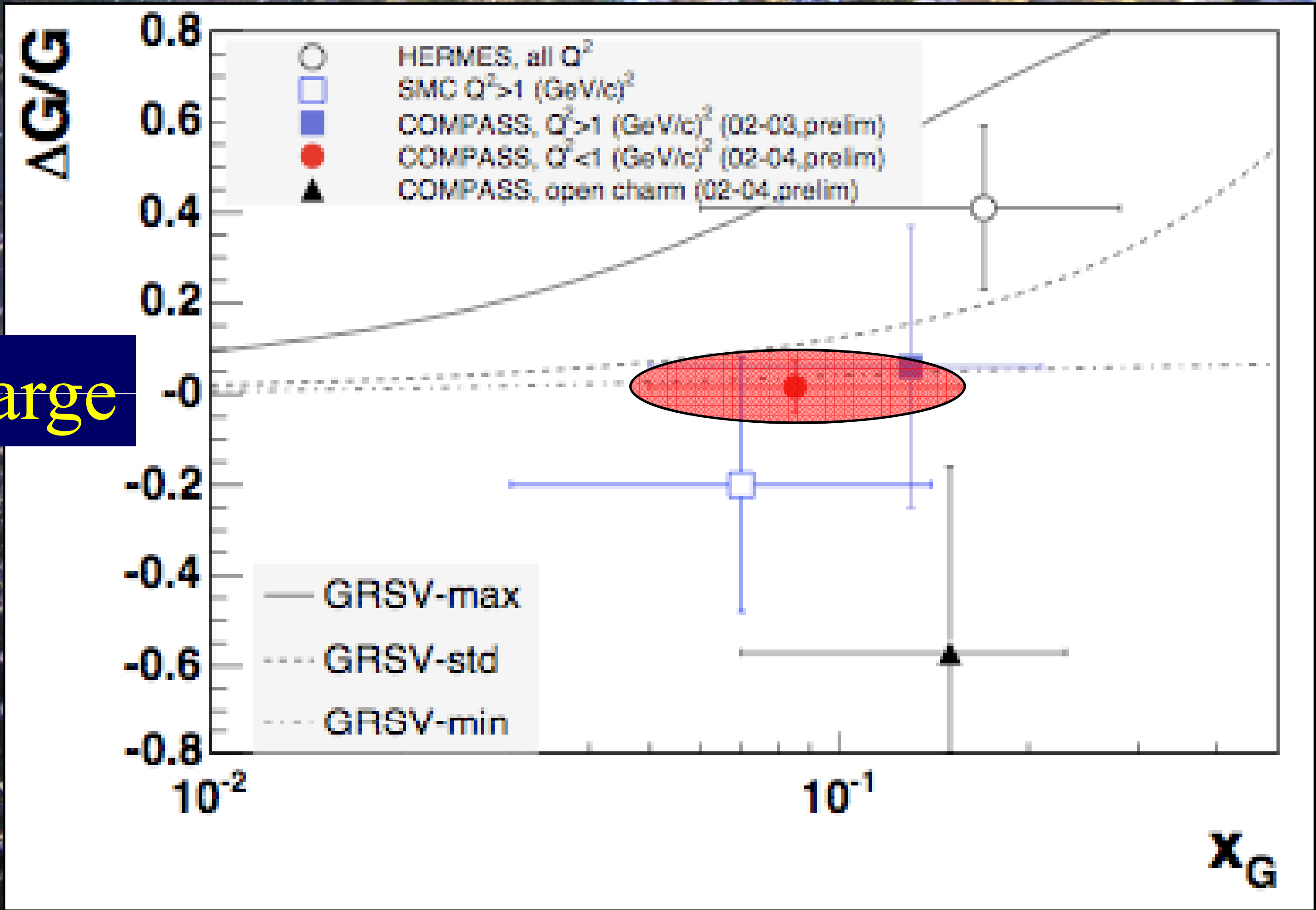


Emerging Consensus on Nucleon Spin Decomposition?

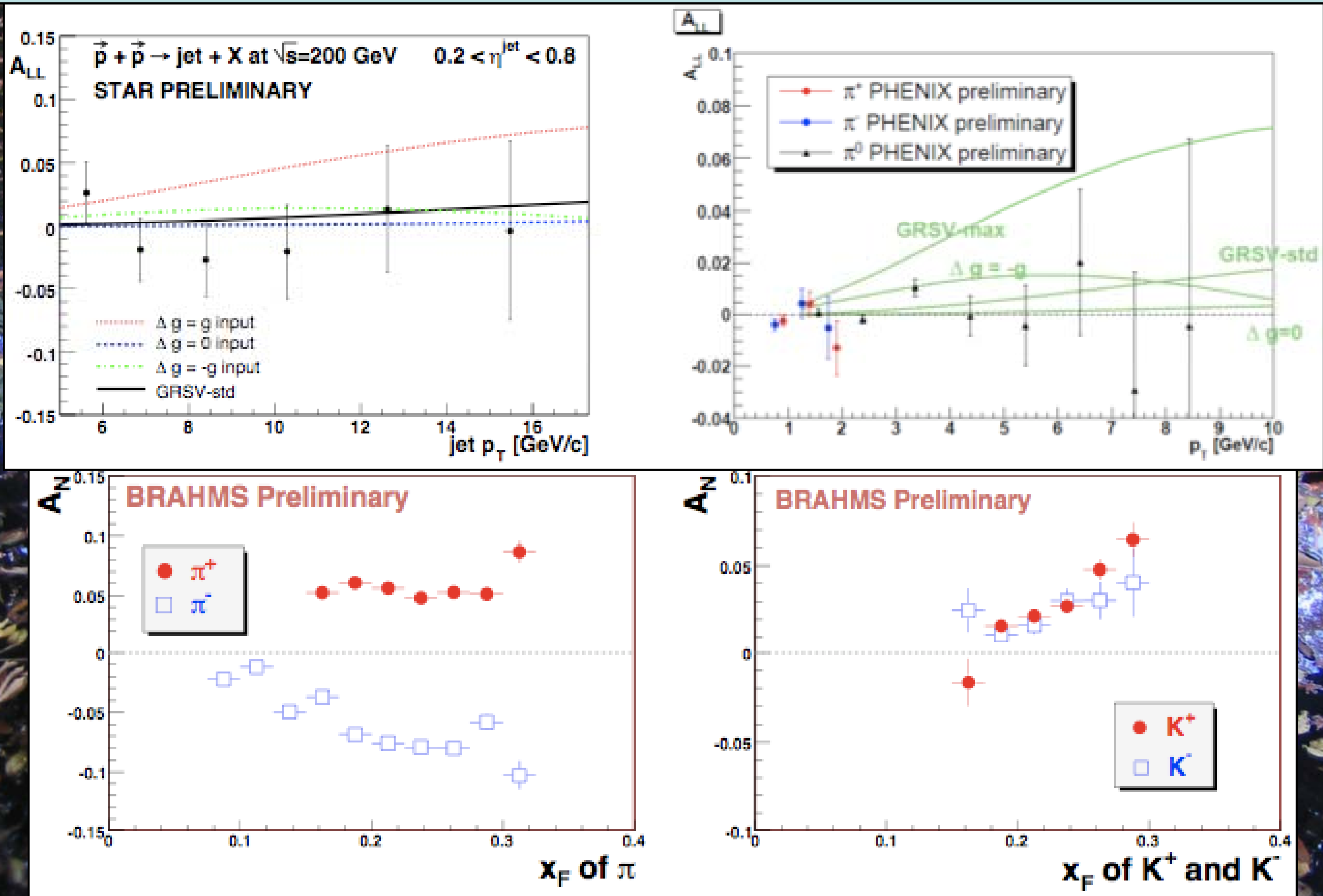
- Small quark contribution to nucleon spin:
  - COMPASS: $a_0(Q^2\!=\!3\,(\mathrm{GeV}/c)^2) \;=\; 0.35 \pm 0.03(stat.) \pm 0.05(syst.)$
  - HERMES: $\mathbf{a_0}(Q^2 = 5\,\mathrm{GeV}^2) = \mathbf{0.330} \pm \mathbf{0.011}(\mathrm{theo.}) \pm \mathbf{0.025}(\mathrm{exp.}) \pm \mathbf{0.028}(\mathrm{evol.})$
- Net negative polarization of strange quarks:
  - COMPASS: $(\Delta s + \Delta\bar{s})_{Q^2\to\infty} \;=\; \frac{1}{3}(\hat{a}_0 - a_8) \;=\; -0.08 \pm 0.01(stat.) \pm 0.02(syst.).$
  - HERMES: $\Delta s + \Delta\bar{s} = -0.085 \pm 0.013(\mathrm{theo.}) \pm 0.008(\mathrm{exp.}) \pm 0.009(\mathrm{evol.})$
- Gluon polarization small, probably positive?

COMPASS Constraints on ΔG

ΔG not large

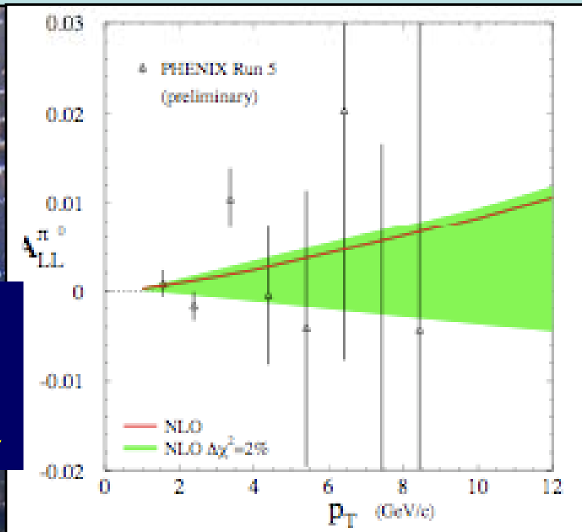


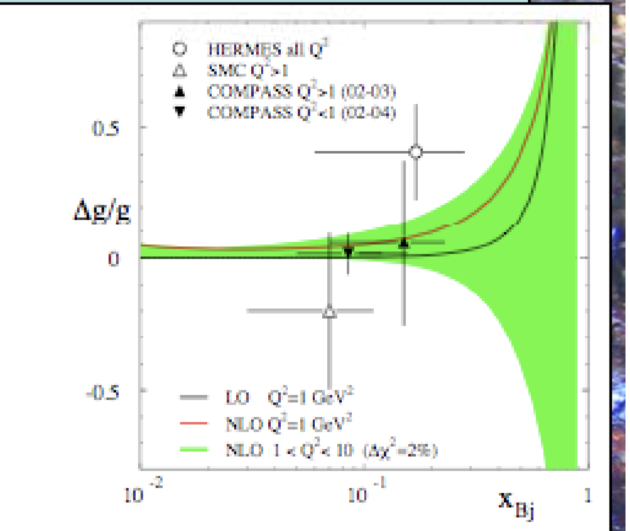
Production Asymmetries @ RHIC

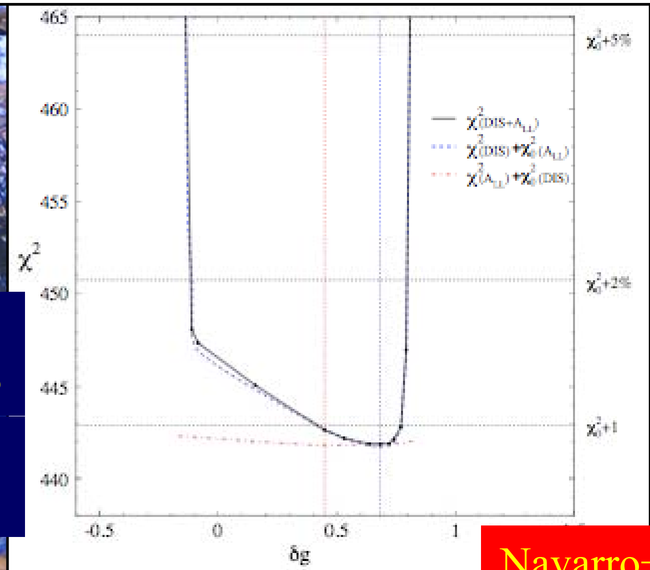


Combined Fit including Positivity, RHIC Data

Comparison with
PHENIX, COMPASS data



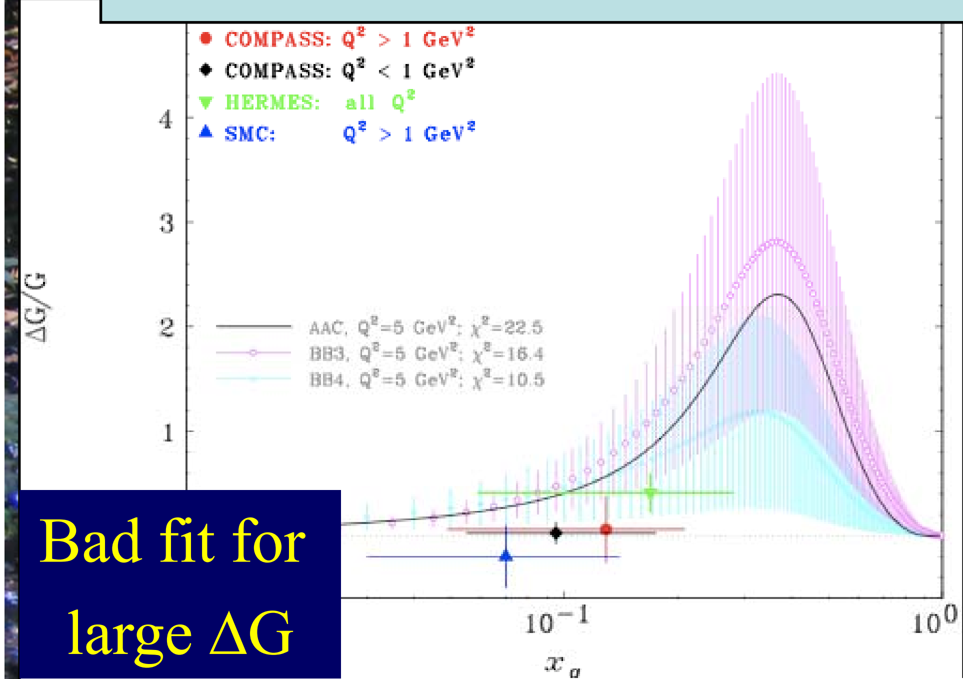




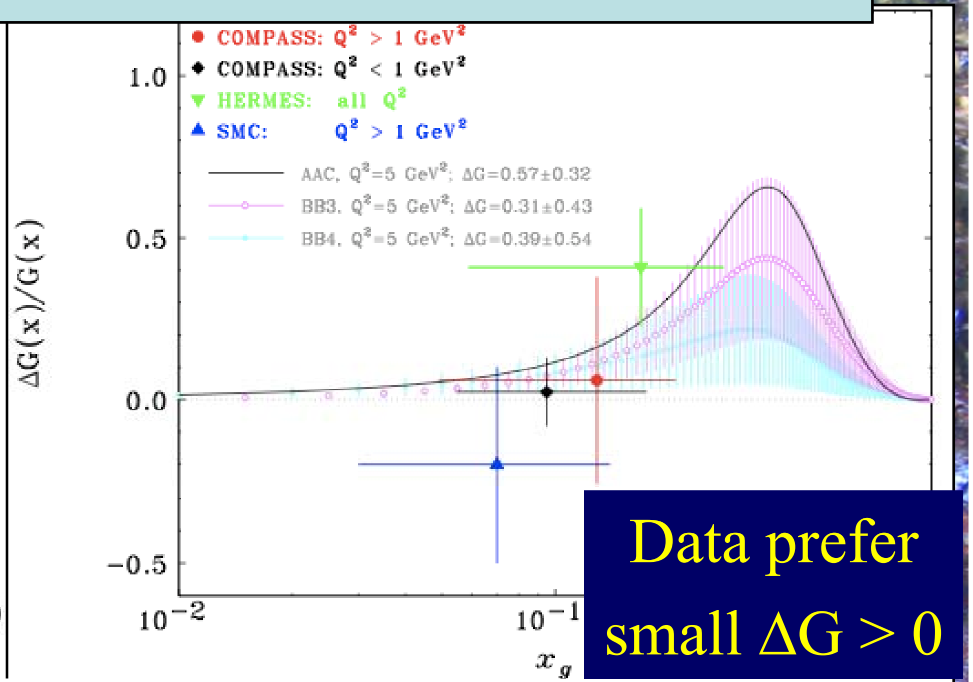
Positivity prevents large |ΔG|,
probably ΔG > 0

Navarro+Sassot

Indications that ΔG cannot be large



Bad fit for large ΔG



Data prefer small ΔG > 0

Q^2 GeV^2	BB4			BB3			AAC		
	ΔG	χ^2 best fit	χ^2 for ΔG=2	ΔG	χ^2 best fit	χ^2 for ΔG=2	ΔG	χ^2 best fit	χ^2 for ΔG=2
1.5	0.31±0.40	1.6	19.7	0.46±0.44	1.0	13.4	0.58±0.31	2.2	22.8
2.0	0.33±0.43	1.5	16.5	0.33±0.37	1.2	21.2	0.57±0.31	2.3	23.4
5.0	0.39±0.54	1.5	10.5	0.31±0.43	1.1	16.4	0.57±0.32	2.5	22.5
10.0	0.43±0.62	1.5	6.5	0.30±0.48	1.1	13.5	0.58±0.33	2.6	20[illegible]

JE+Karliner

Impact of New Polarized RHIC Data

Double longitudinal polarization asymmetry

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

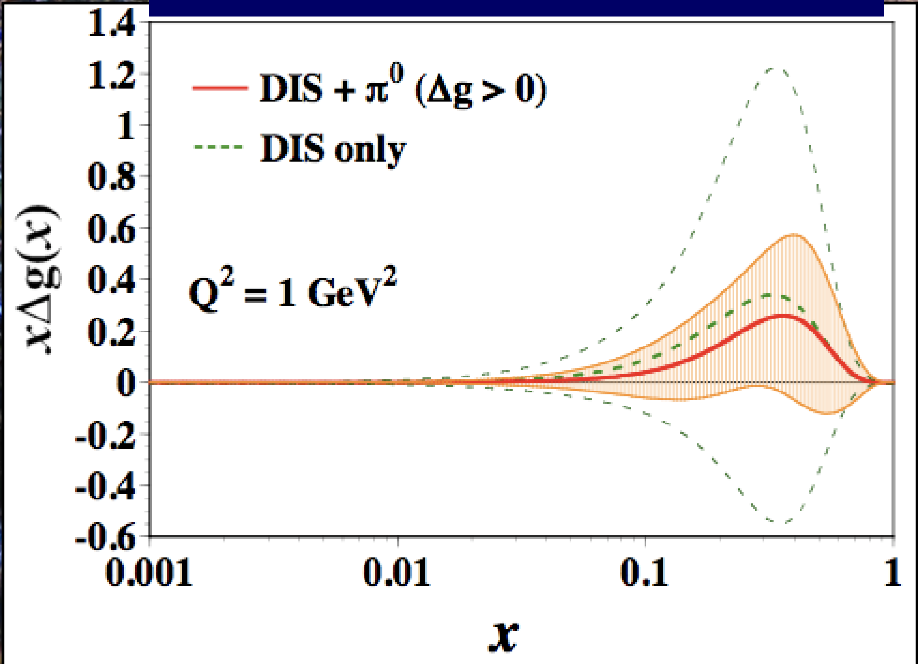
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

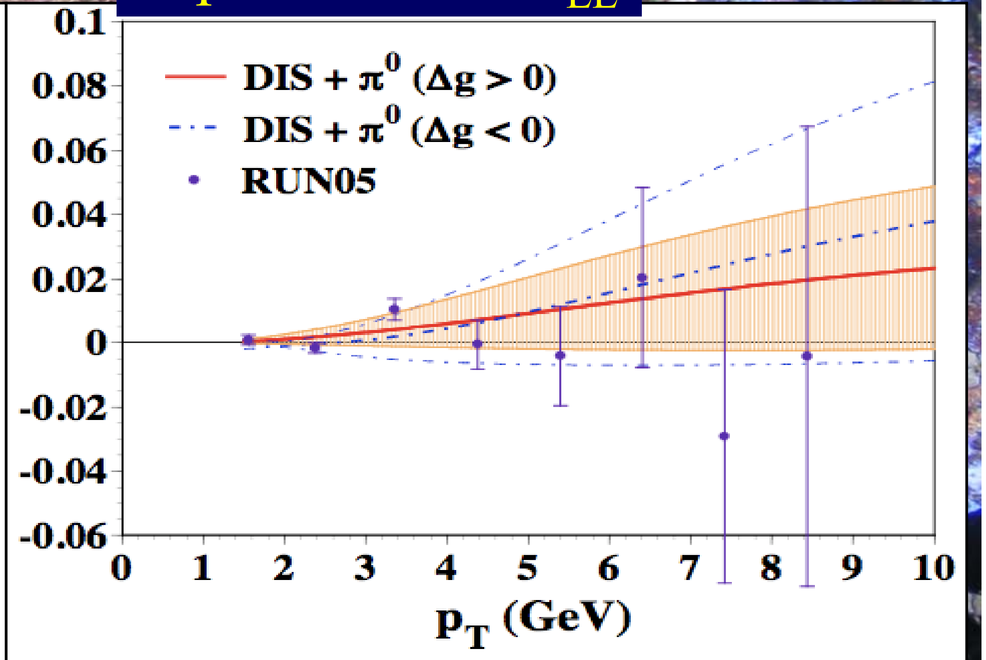
Hirai, Kumano & Saito

Comparison with Deep-Inelastic Data

Refine estimate of Δg from DIS structure functions …

… but quadratic dependence of A_{LL}

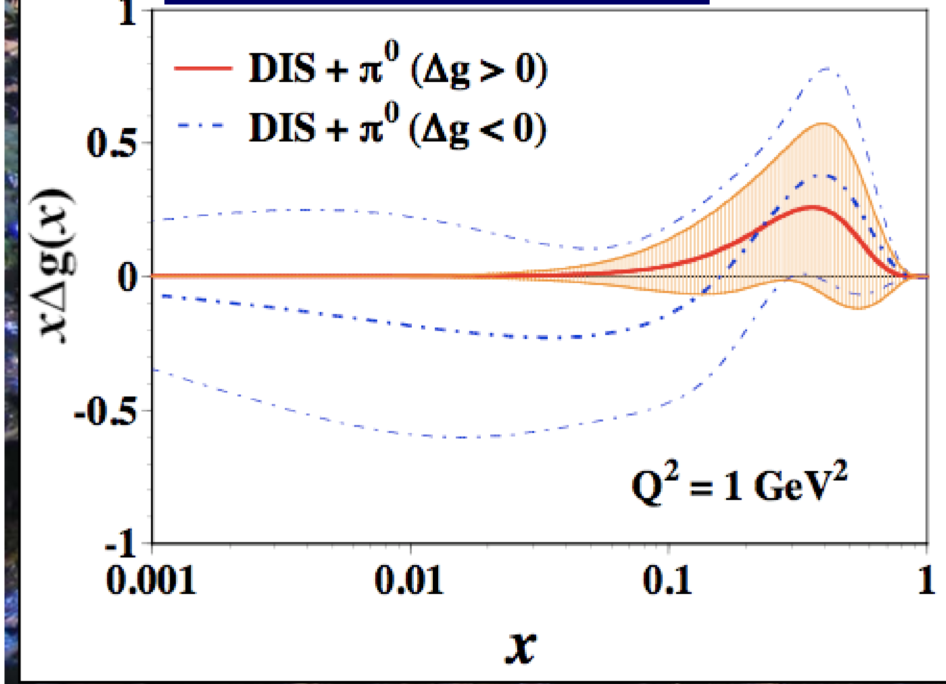




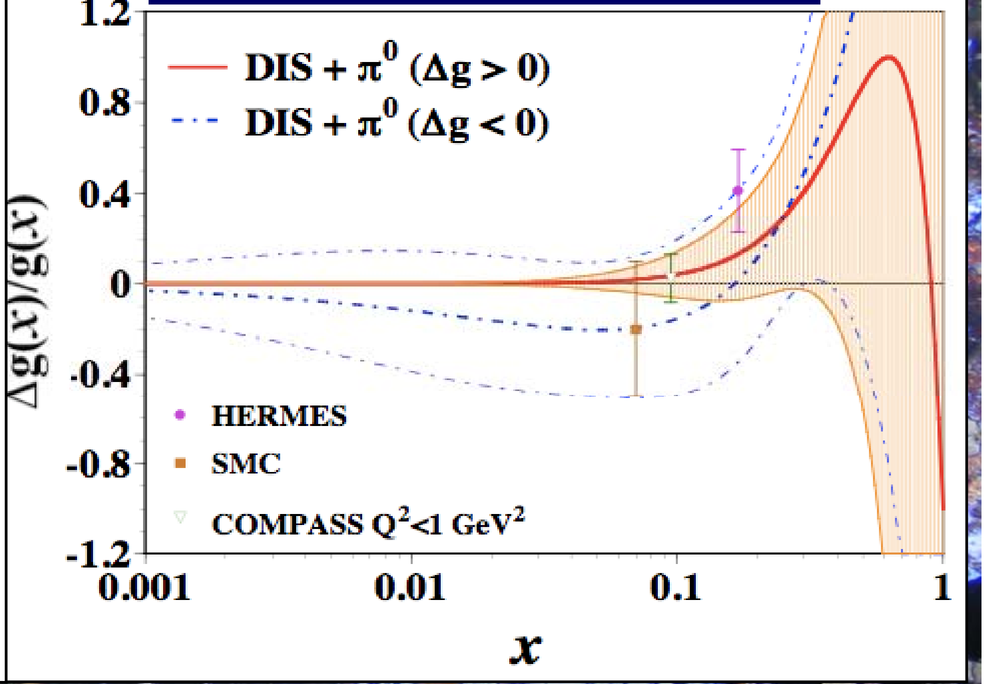
Hirai, Kumano & Saito

Comparison with Deep-Inelastic Data

Ambiguity between
$\Delta g > 0$ and $\Delta g < 0$



Comparison with DIS
production asymmetries



Hirai, Kumano & Saito

Questions for the Future

- Direct confirmation that $\Delta s < 0$?
- Is ΔG a large fraction of the nucleon spin?
- How large are the orbital angular momentum components?
- Connections with other spin-dependent observables?
  - Proton-antiproton annihilation
  - Λ polarization

Λ Polarization in Quark & Diquark Fragmentation

Λ polarization from **quark** fragmentation

$$P_\Lambda^q(B) = -C_q^\Lambda(B) P_q,$$

Table 1: Spin correlation coefficients in SU(6) and BJ models

Λ's parent	C_u^Λ		C_d^Λ		C_s^Λ	
	SU(6)	BJ	SU(6)	BJ	SU(6)	BJ
quark	0	-0.18	0	-0.18	1	0.63
Σ^0	-2/9	-0.12	-2/9	-0.12	1/9	0.15
Ξ^0	-0.15	0.07	0	0.05	0.6	-0.37
Ξ^-	0	0.05	-0.15	0.07	0.6	-0.37
Σ^*	5/9	5/9	5/9	5/9	5/9	5/9

SU(6): nonrelativistic SU(6) wave functions

BJ: flavor SU(3) & polarized DIS data for baryon octet:

$$\Delta u_\Lambda \approx \Delta d_\Lambda \approx -0.2$$
$$\Delta s_\Lambda \approx 0.6$$

Λ polarization from **diquark** fragmentation

$$P_\Lambda^{\nu\, d}(prompt; N) = P_\Lambda^{\bar\nu\, u}(prompt; N) =$$
$$P_\Lambda^{l\, u}(prompt; N) = C_{sq} \cdot P_q,$$

$$P_\Lambda^{\nu\, d}(\Sigma^0; n) = P_\Lambda^{\bar\nu\, u}(\Sigma^0; p) =$$
$$P_\Lambda^{l\, u}(\Sigma^0; p) = P_\Lambda^{l\, d}(\Sigma^0; n) = \frac{1}{3} \cdot \frac{2 + C_{sq}}{3 + 2C_{sq}} \cdot P_q,$$

$$P_\Lambda^{\nu\, d}(\Sigma^{*0}; n) = P_\Lambda^{\nu\, d}(\Sigma^{*+}; p) =$$
$$P_\Lambda^{\bar\nu\, u}(\Sigma^{*0}; p) = P_\Lambda^{\bar\nu\, u}(\Sigma^{*+}; n) =$$
$$P_\Lambda^{l\, u}(\Sigma^{*0}; p) = P_\Lambda^{l\, d}(\Sigma^{*0}; n) =$$
$$P_\Lambda^{l\, d}(\Sigma^{*+}; p) = P_\Lambda^{l\, u}(\Sigma^{*-}; n) = -\frac{5}{3} \cdot \frac{1 - C_{sq}}{3 - C_{sq}} \cdot P_q.$$

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Results for Λ Polarization @ NOMAD

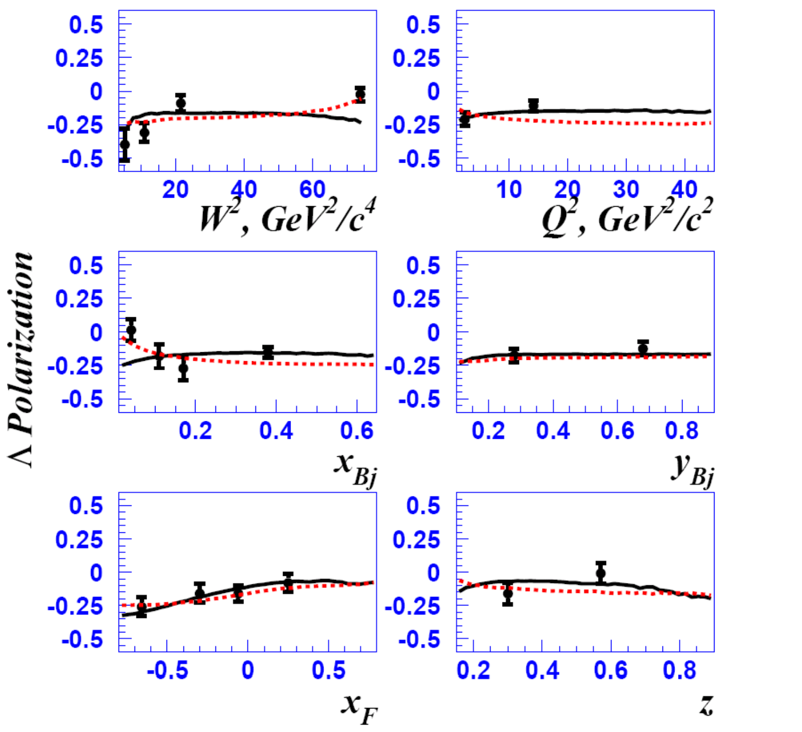

Figure 5: Our model predictions (model A - solid line, model B - dashed line) for polarization of Λ hyperons produced in ν_μ charged current DIS interactions off nuclei as functions of W^2, Q^2, x_{Bj}, y_{Bj}, x_F and z (at $x_F > 0$). The points with error bars are from NOMAD.

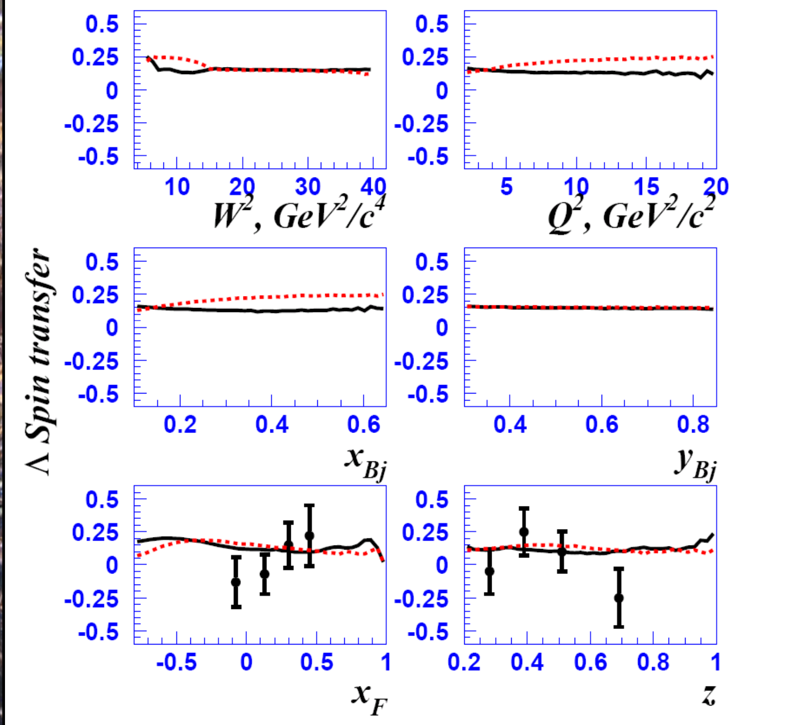

Figure 6: Our model predictions (model A - solid line, model B - dashed line) for the spin transfer of Λ hyperons produced in e^+ DIS interactions off nuclei as functions of W^2, Q^2, x_{Bj}, y_{Bj}, x_F and z (at $x_F > 0$). ($E_e = 27.5$ GeV) The points with error bars are from HERMES

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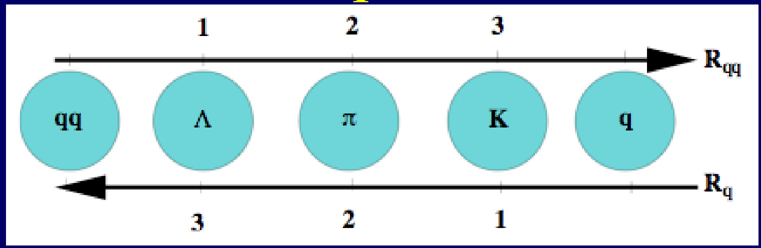
Spin Transfer to (anti-)Λ Hyperons

- We use Lund string fragmentation model incorporated in LEPTO 6.5.1 and JETSET 7.4
- Order particles by ranks R_q, R_{qq}



- We consider two extreme cases when polarization transfer is nonzero:
  - **model A:**
    - the hyperon contains the stuck quark: $R_q = 1$
    - the hyperon contains the remnant diquark: $R_{qq} = 1$
  - **model B:**
    - transfer from struck quark if $R_q < R_{qq}$
    - transfer from remnant diquark if $R_{qq} < R_q$

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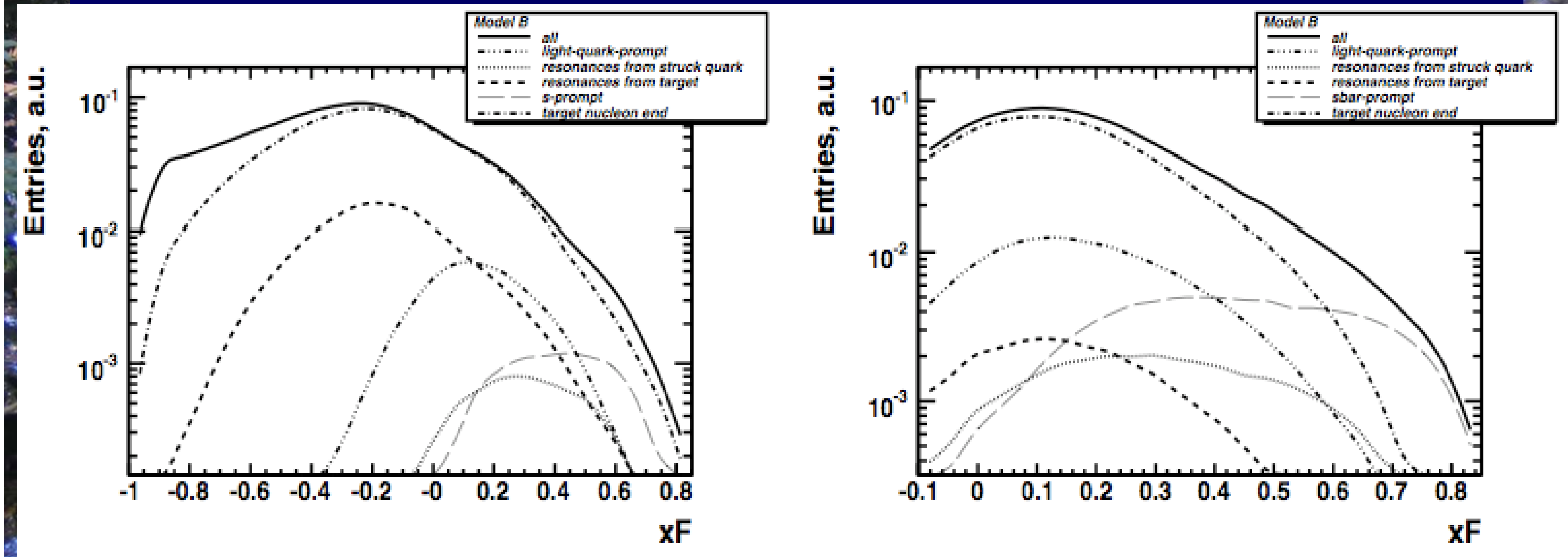
Λ, anti-Λ Production at COMPASS

- Comparison of production mechanisms



- Production off s, anti-s in nucleon dominate at large x_F
- Particularly for anti-Λ production

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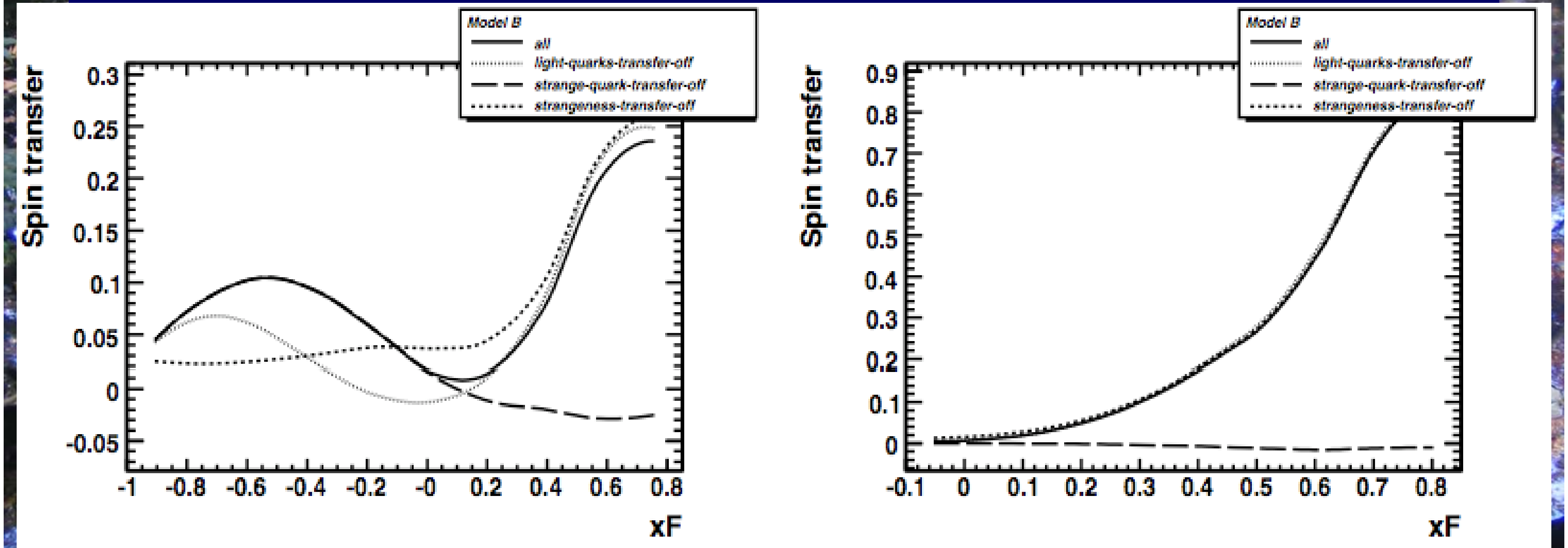
Spin Transfers to Λ, anti-Λ at COMPASS

- Contributions to Λ, anti-Λ polarization



- Domininated by s, anti-s polarization at large x_F
- Particularly for anti-Λ polarization

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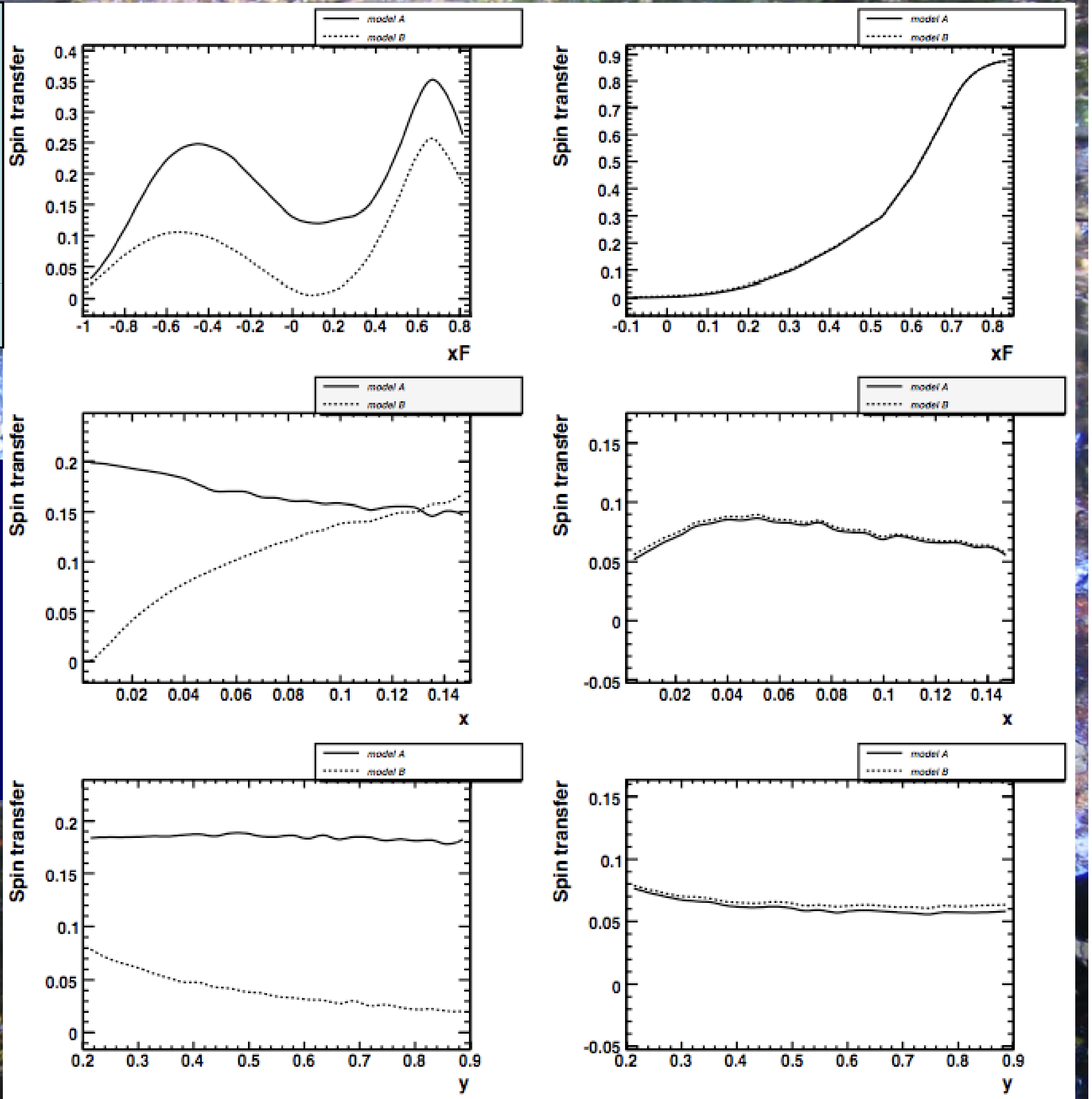
Predictions for Λ, anti-Λ Polarization

- Model dependence
- Dependences on x, x_F, y



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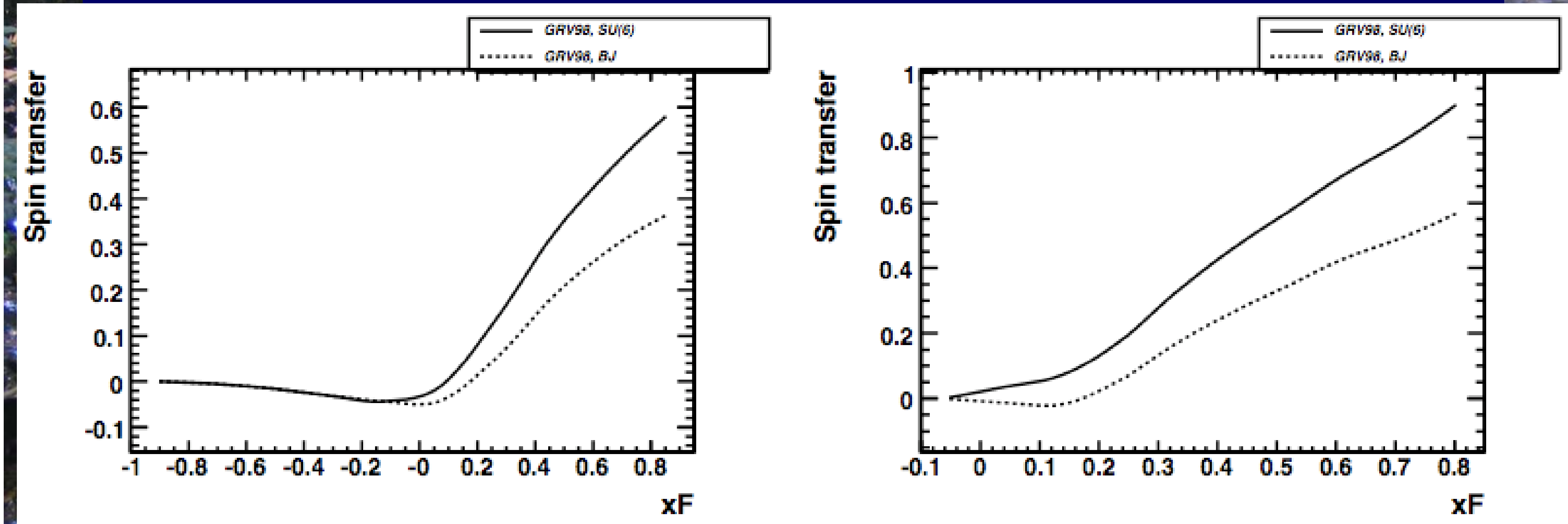
Predictions for HERA Experiments

- Clear qualitative prediction for spin transfers at $x_F > 0$



- Details depend on model for spin structure

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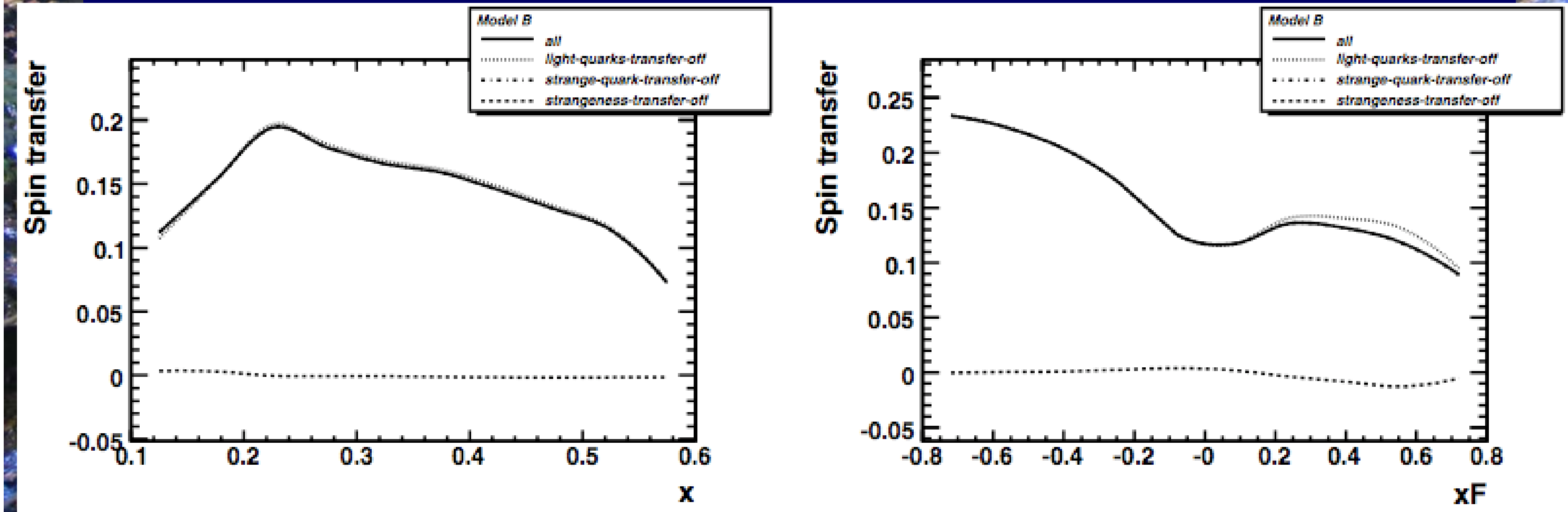
Predictions for JLAB Experiments

- Dominated by spin transfer from nucleon remnant



- Sensitive to remnant's memory of struck quark

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Outline of Topics

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  - Other probes of nucleon spin:
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    - Discriminating supersymmetry from extra dimensions

Open Questions beyond the Standard Model

- What is the origin of particle masses?

  due to a Higgs boson? + supersymmetry?

  solution at energy < 1 TeV (1000 GeV)

- Why so many types of matter particles?

  matter-antimatter difference?

- Unification of the fundamental forces?

  at very high energy ~ 10^{16} GeV?

  probe directly via baryon decay, neutrino physics, indirectly via masses, couplings

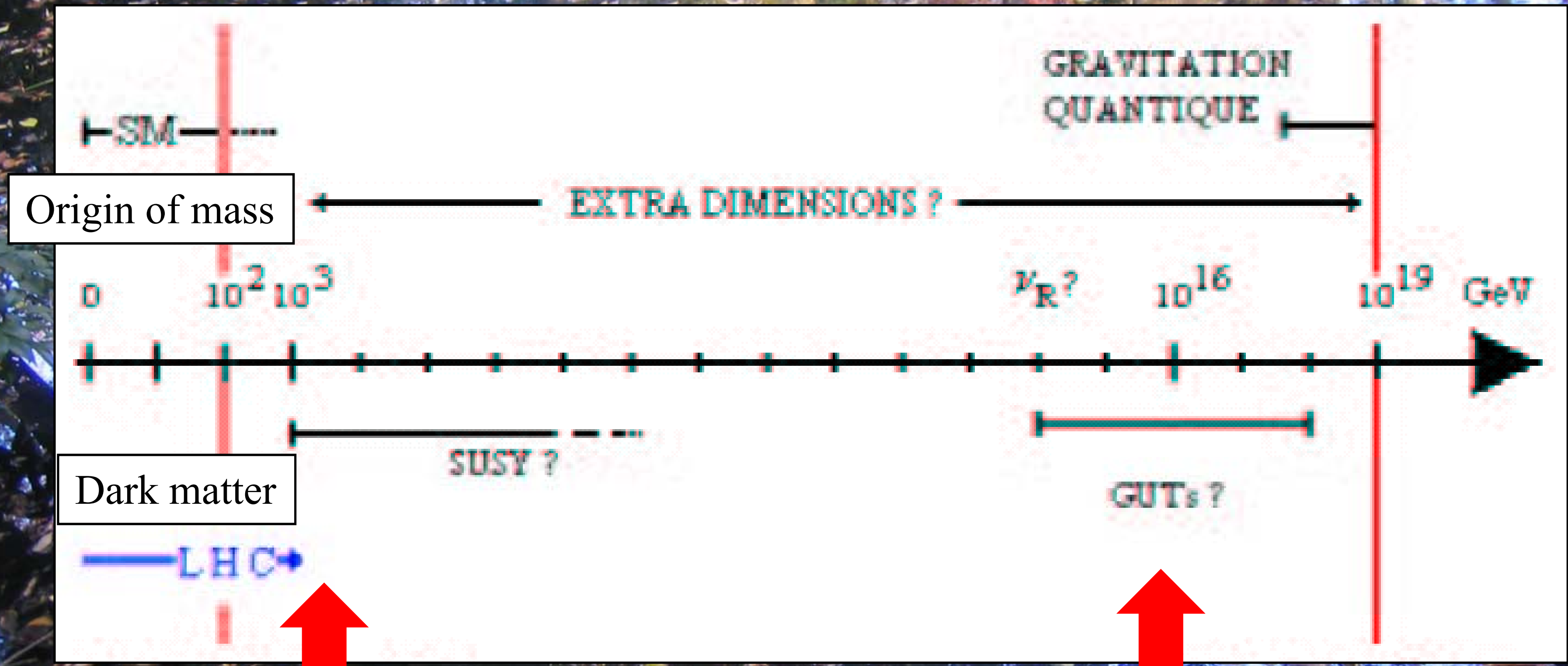
- Quantum theory of gravity?

  (super)string theory: extra space-time dimensions?

Spin

Spin

At what Energy is the New Physics?



Roles for spin physics

Accessible only indirectly: Astrophysics and cosmology?

Dark Matter in the Universe

Astronomers say that most of the matter in the Universe is invisible Dark Matter

‘Supersymmetric’ particles ?

We shall look for them with the LHC

Strategies for Detecting Supersymmetric Dark Matter

- Annihilation in galactic halo

  $\chi - \chi \rightarrow$ antiprotons, positrons, …?
- Annihilation in galactic centre

  $\chi - \chi \rightarrow \gamma + \ldots?$
- Annihilation in core of Sun or Earth

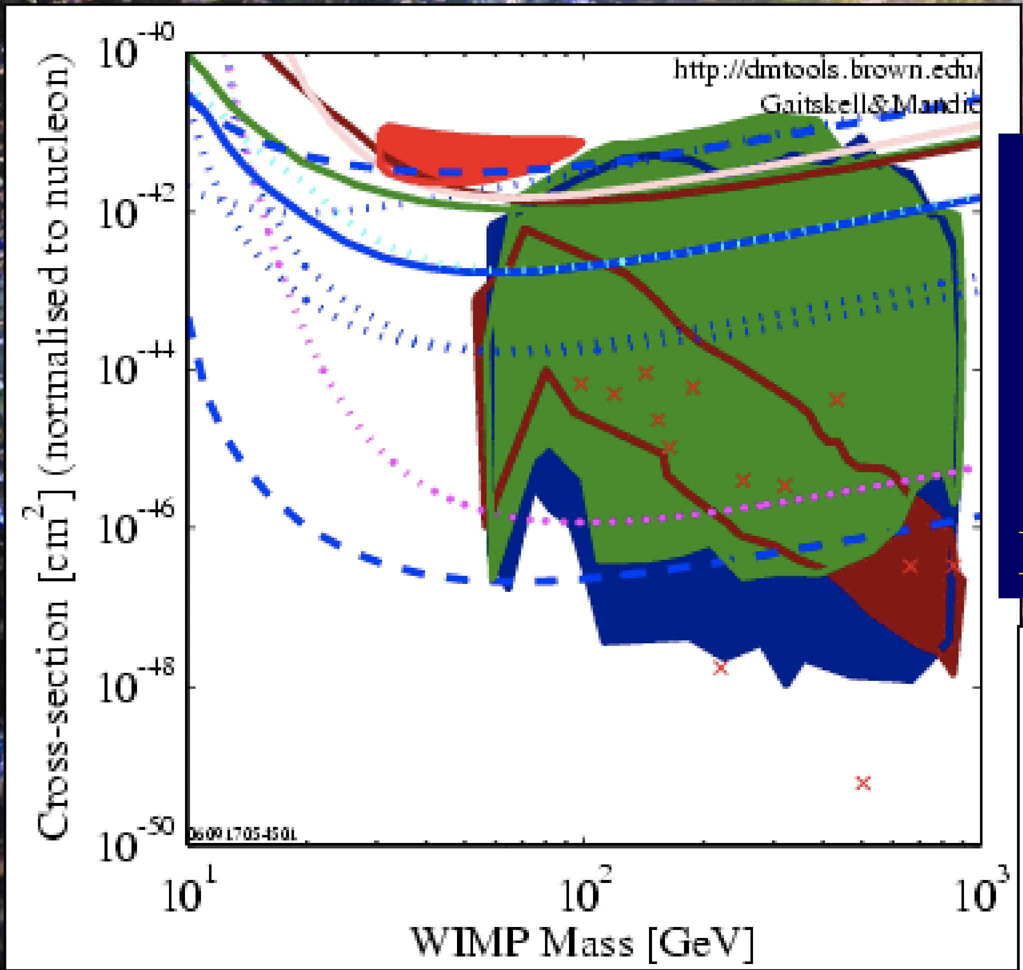
  $\chi - \chi \rightarrow \nu + \ldots \rightarrow \mu + \ldots$
- Scattering on nucleus in laboratory

  $\chi + A \rightarrow \chi + A$

Sensitive to Δs

Sensitive to Δs

Search for Supersymmetric Dark Matter



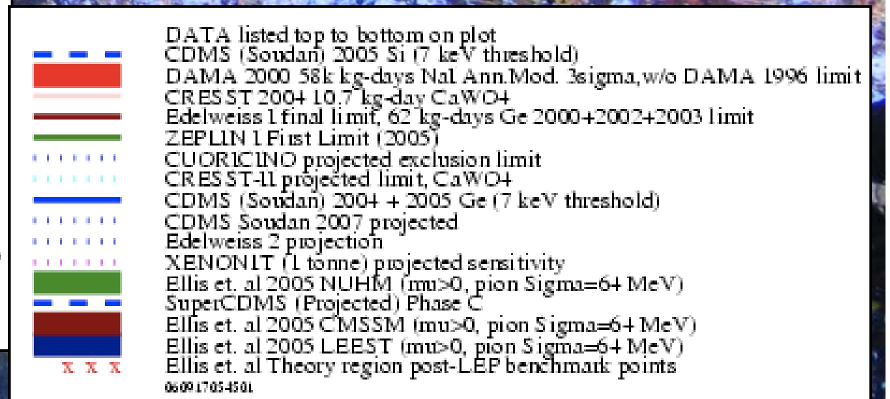
Limits on

spin-independent

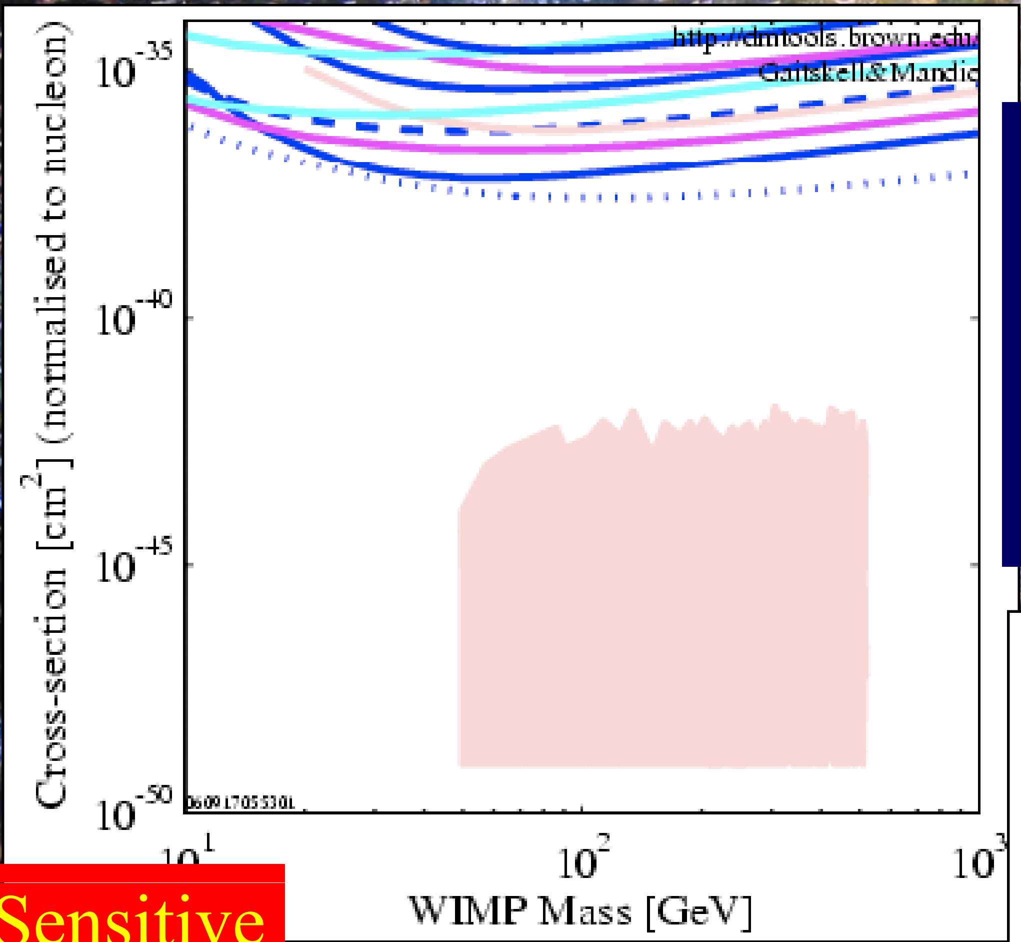
scattering of dark matter

vs

Predictions in some susy models



Search for Supersymmetric Dark Matter



Limits on
spin-dependent
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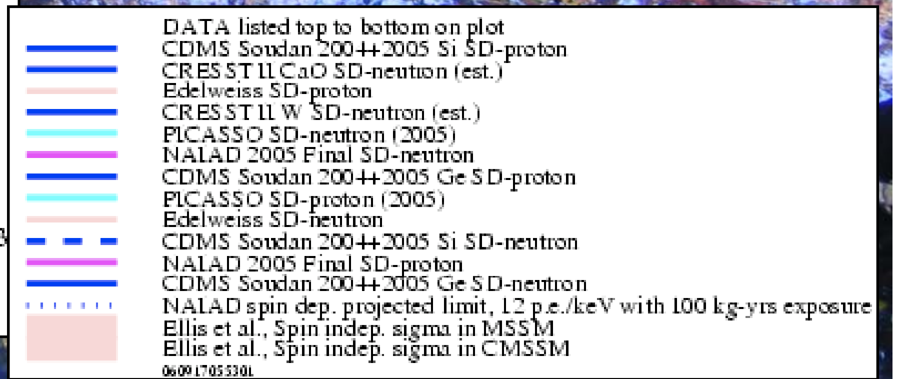
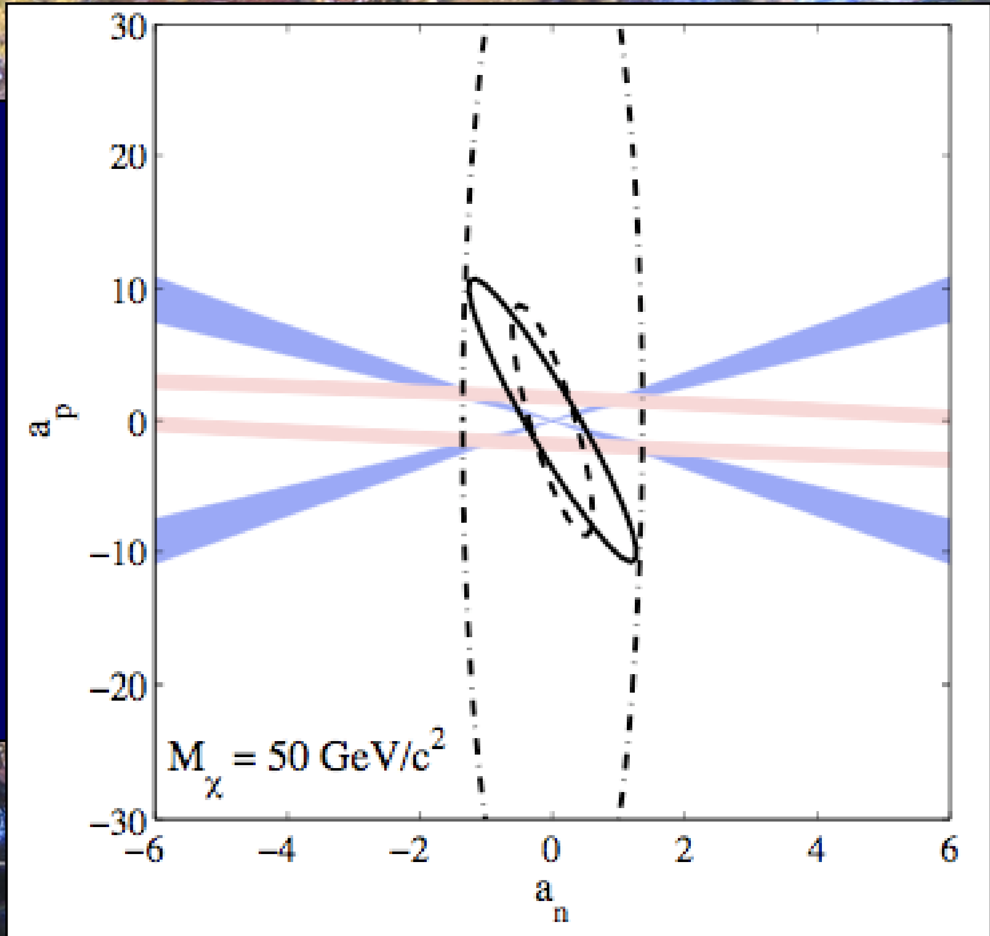
Predictions in some susy models



Sensitive to Δs

Scattering on Protons and Neutrons

- Constraints from CDMS experiment on spin-dependent couplings to p, n
- Depend on Δs

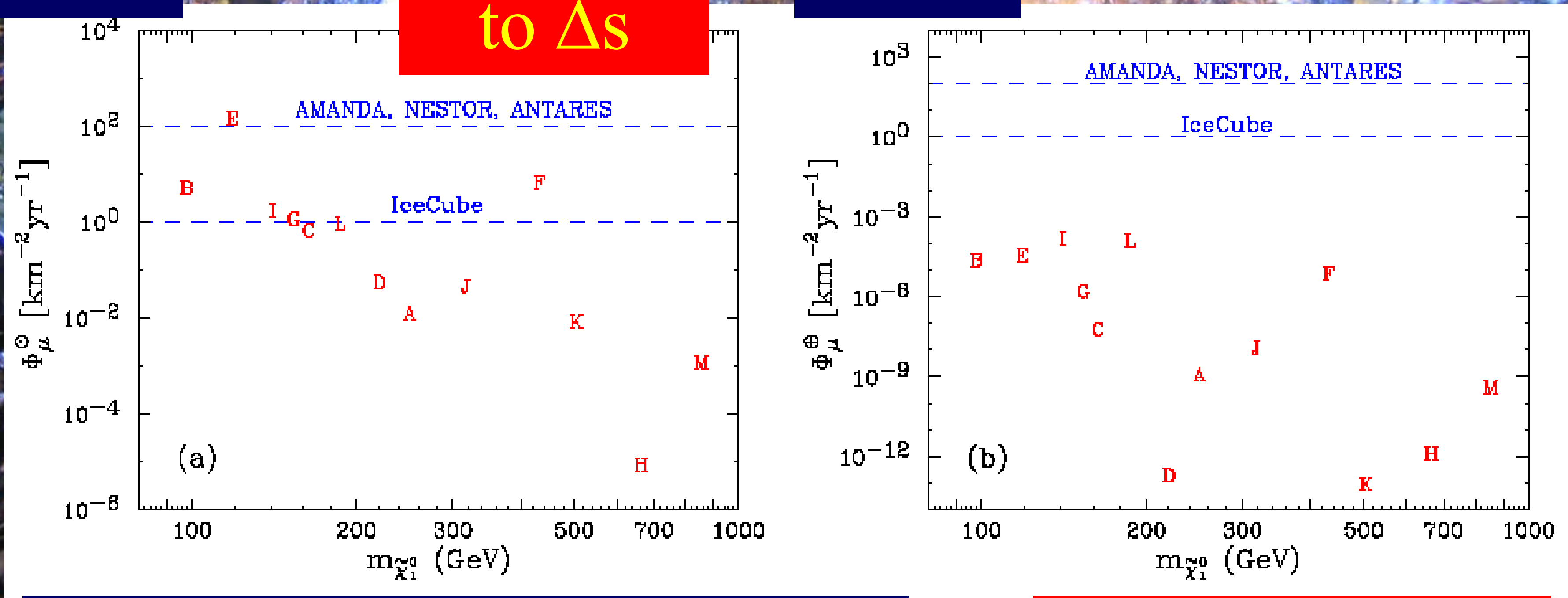


Annihilations in Solar System

Sensitive to Δs

… Sun

… Earth



Prospective experimental sensitivities

Benchmark scenarios

JE + Feng + Ferstl + Matchev + Oli

The Large Hadron Collider (LHC)

Proton- Proton Collider

7 TeV + 7 TeV

1,000,000,000 collisions/second

First exploration of the TeV energy scale

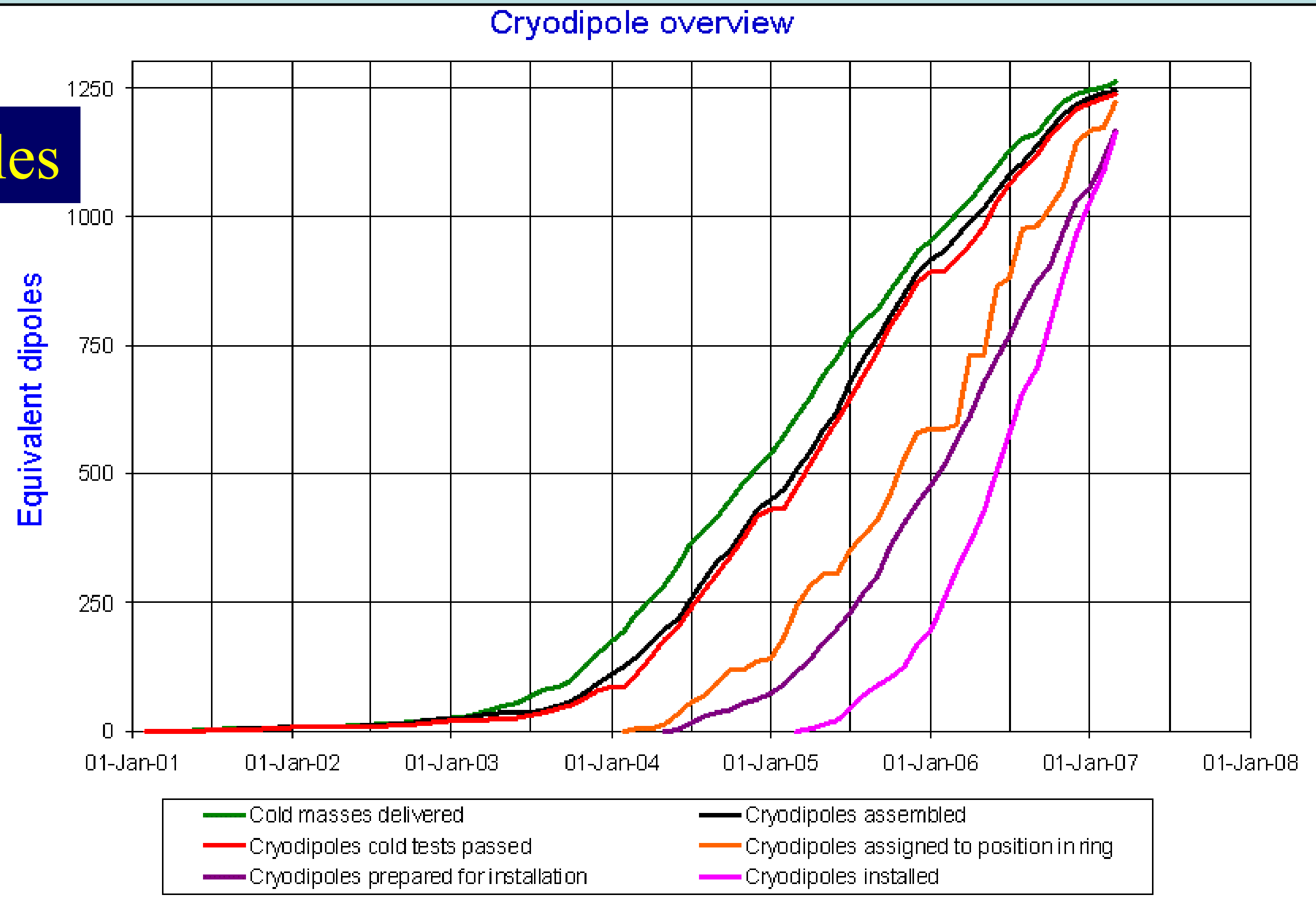
Primary targets:

- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

Underground

LHC Progress Dashboard

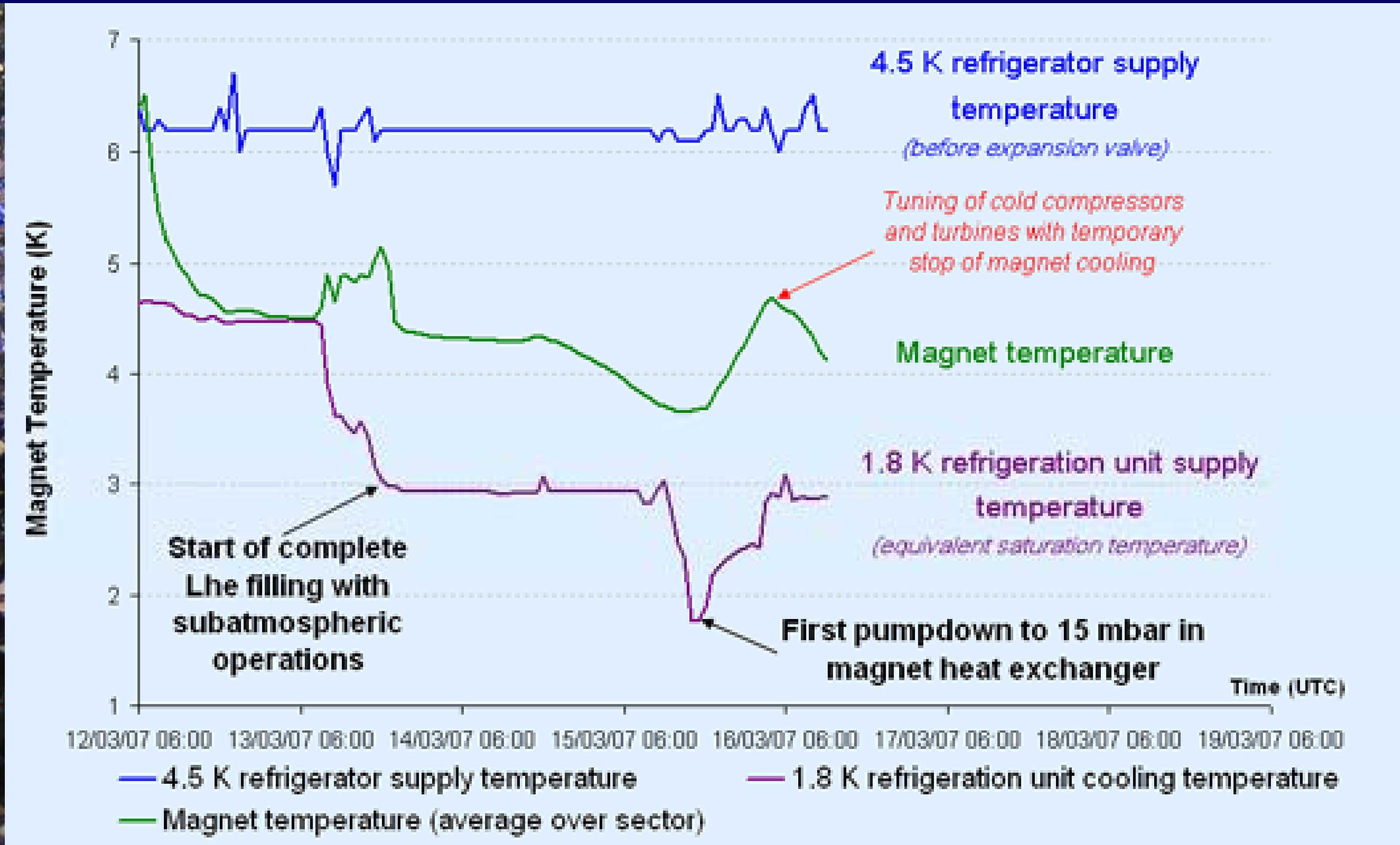
Main dipoles



Accelerator to be completed in Summer 2007,
First collisions November 2007

Cooling Sector 78 of the LHC

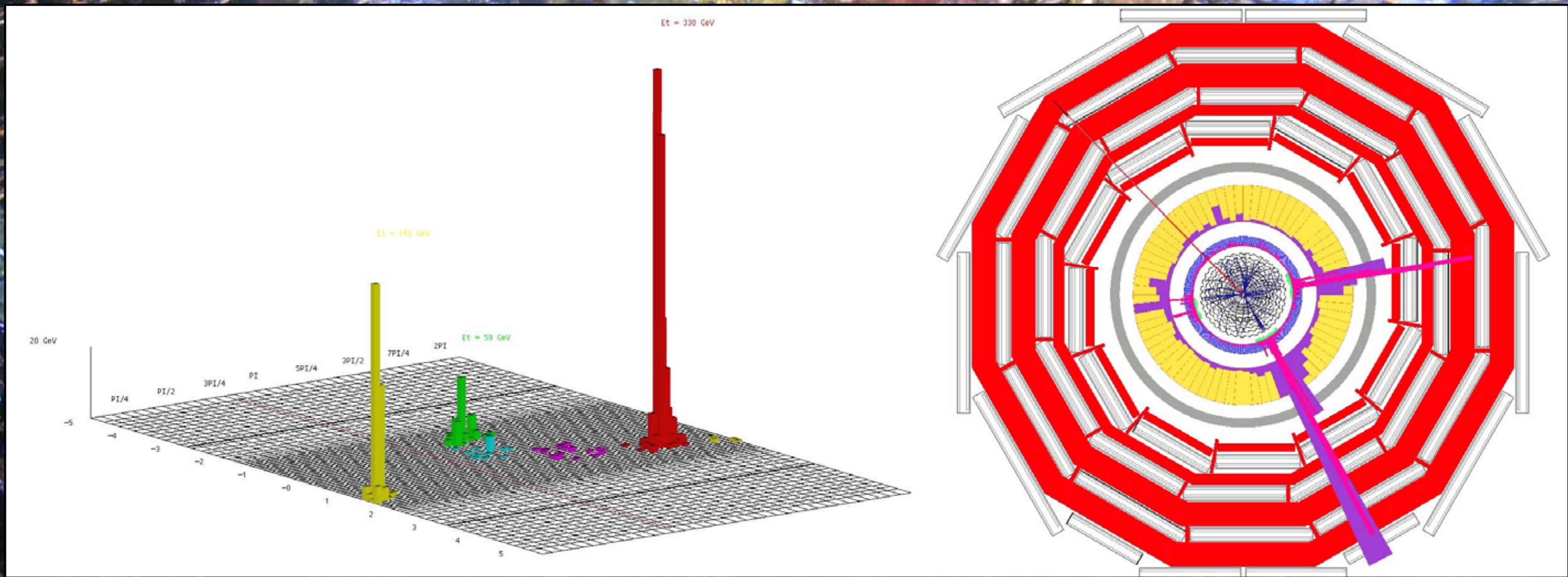
Magnets to be powered when temperature stable @ 1.9K



Plan for LHC Commissioning

- Sectors 7-8 and 8-1 will be fully commissioned up to 7 TeV in 2006-2007. If we continue to commission the other sectors up to 7 TeV, we will not get circulating beam in 2007
- The other sectors will be commissioned up to the field needed for de-Gaussing.
- **Initial operation in Nov. 2007 at 900 GeV (CM) with a static machine (no ramp, no squeeze) to debug machine and detectors**
- Full commissioning up to 7 TeV will be done in the winter 2008 shutdown

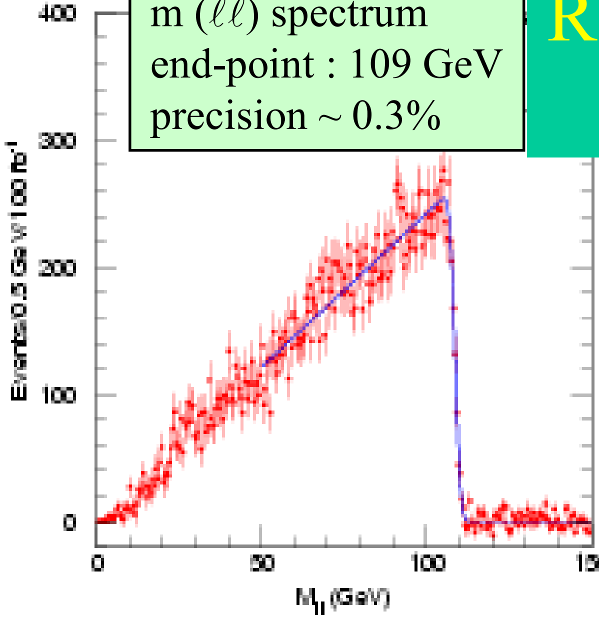
Classic Supersymmetric Signature



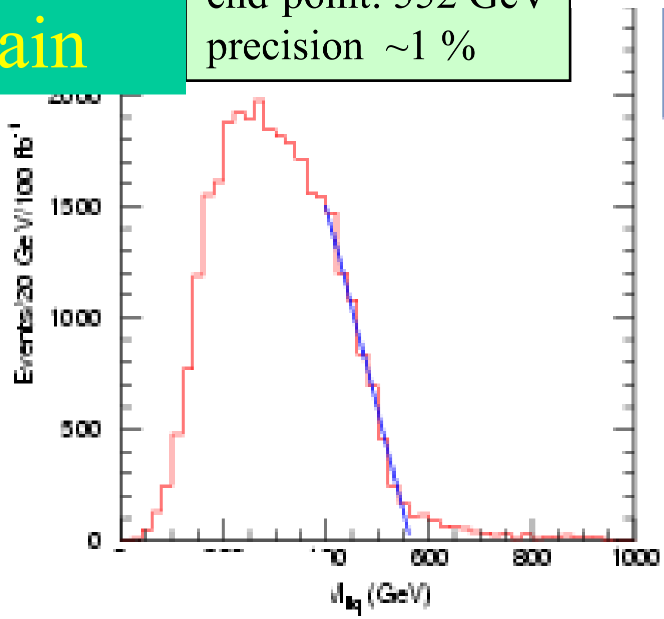
Missing transverse energy
carried away by dark matter particles

Reconstruction of `Typical' Sparticle Decay Chain

m ($\ell\ell$) spectrum
end-point : 109 GeV
precision ~ 0.3%

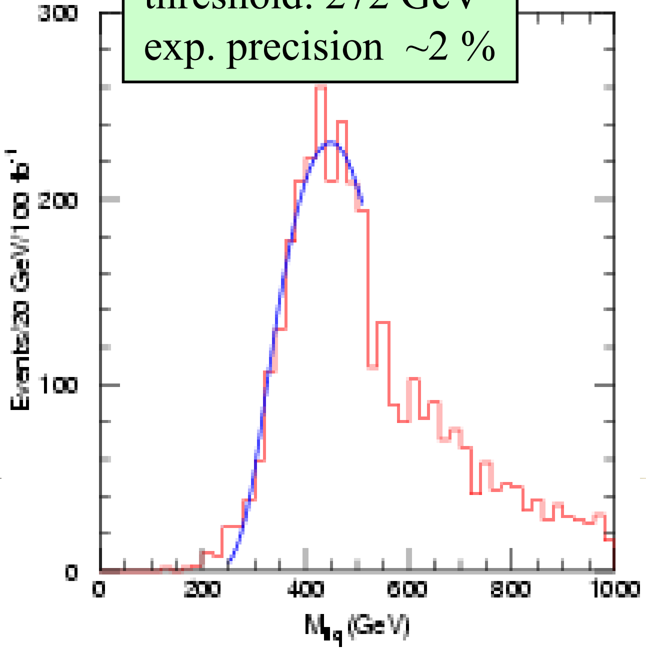


m ($\ell\ell$j)^{min} spectrum
end-point: 552 GeV
precision ~1 %



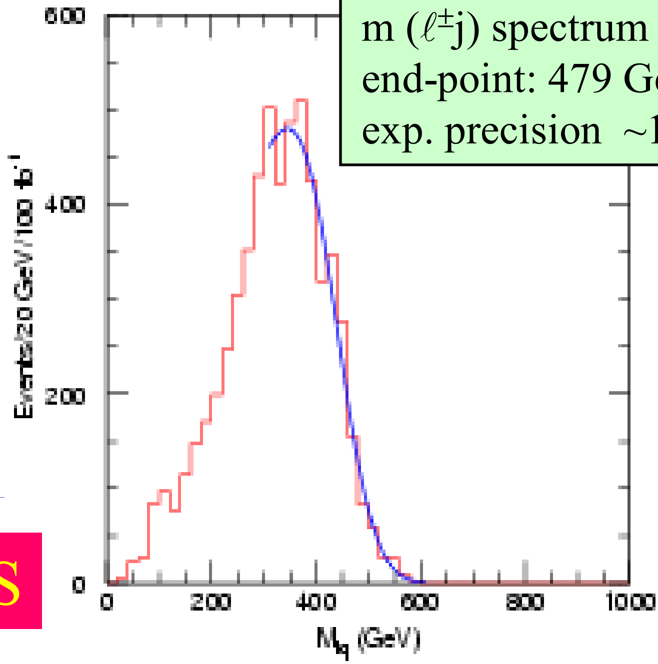
$$\tilde{q}_L \rightarrow q\, \chi^0_2$$
$$\hookrightarrow \tilde{\ell}_R\, \ell$$
$$\hookrightarrow \ell\, \chi^0_1$$

m ($\ell\ell$j)^{max} spectrum
threshold: 272 GeV
exp. precision ~2 %



M_{squark} = 690
$M_{\chi'}$ = 232
$M_{slepton}$ = 157
M_{χ} = 121
(GeV)

m ($\ell^{\pm}$j) spectrum
end-point: 479 GeV
exp. precision ~1 %

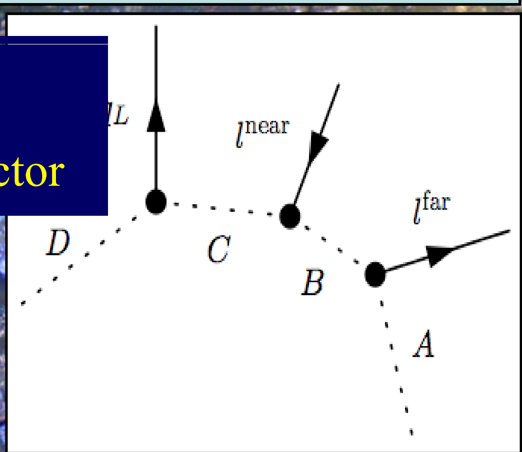


ATLAS

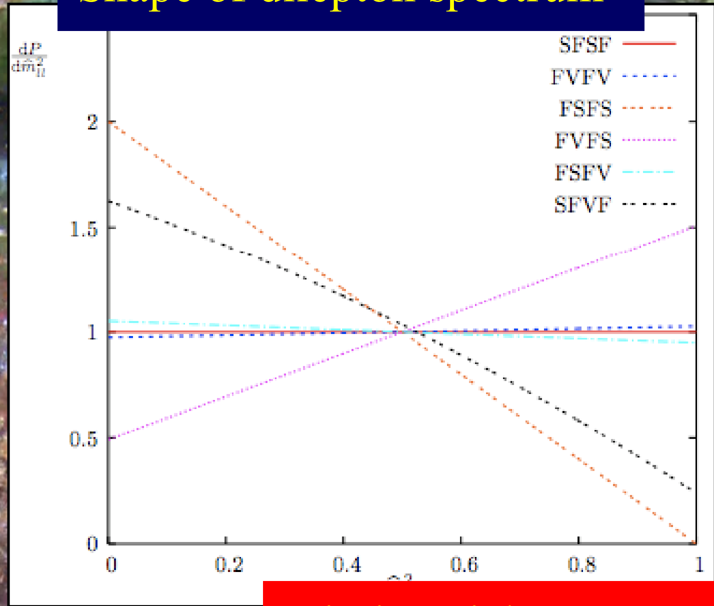
Spin Effects in Decay Chains

Chain DCBA:

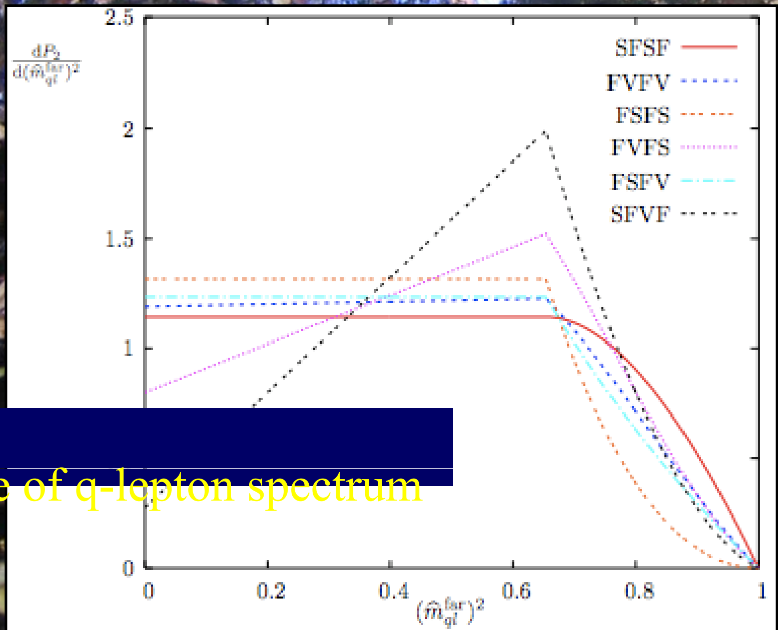
Scalar/Fermion/Vector



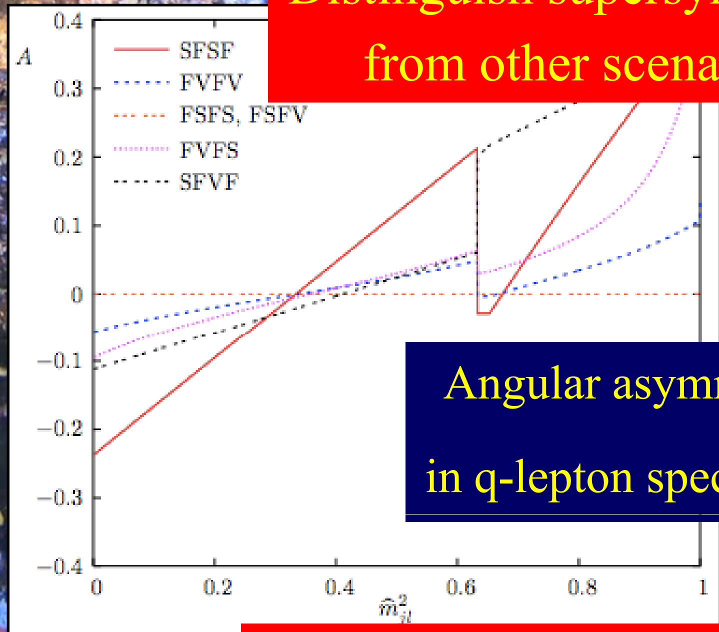
Shape of dilepton spectrum



Distinguish supersymmetry from other scenarios



Shape of q-lepton spectrum



Angular asymmetry in q-lepton spectrum

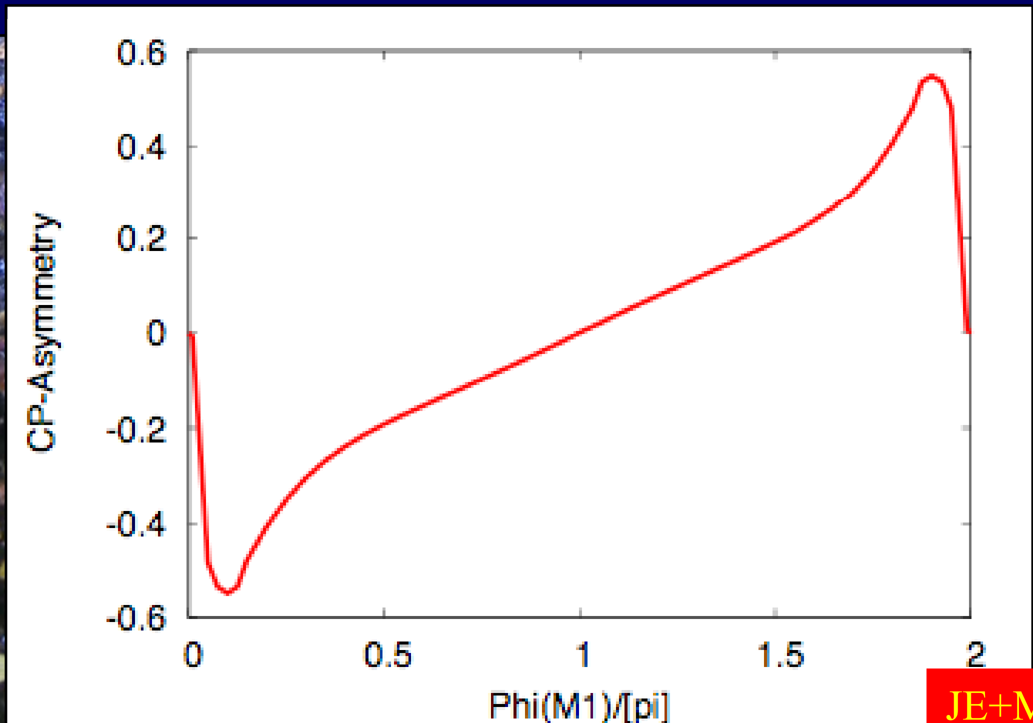
Athanasiou+Lester+Smillie+Webber

CP-Violating Asymmetry in Sparticle Decay

- Look for lepton asymmetry in the decay chain:

$$gg \to \tilde{t}_1 \tilde{t}_1, \quad \tilde{t}_1 \to t \tilde{\chi}_2^0, \quad \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 e^+ e^-$$

- Sensitive to supersymmetric phase Θ:



JE+Moortgat+Moortgat-Pick

The Power of Polarization

- Dissects what we think we know …
  - … and often finds surprises
    - Nucleon spin
- Delicate probe for new physics:
  - New observables
  - Suppresses backgrounds
  - Enhances signals
- **These are complementary:**
  - **We must understand SM to probe beyond it**