Les Houches Workshop:
TeV Scale Physics*

The future…

Where are we? Why the TeV scale?

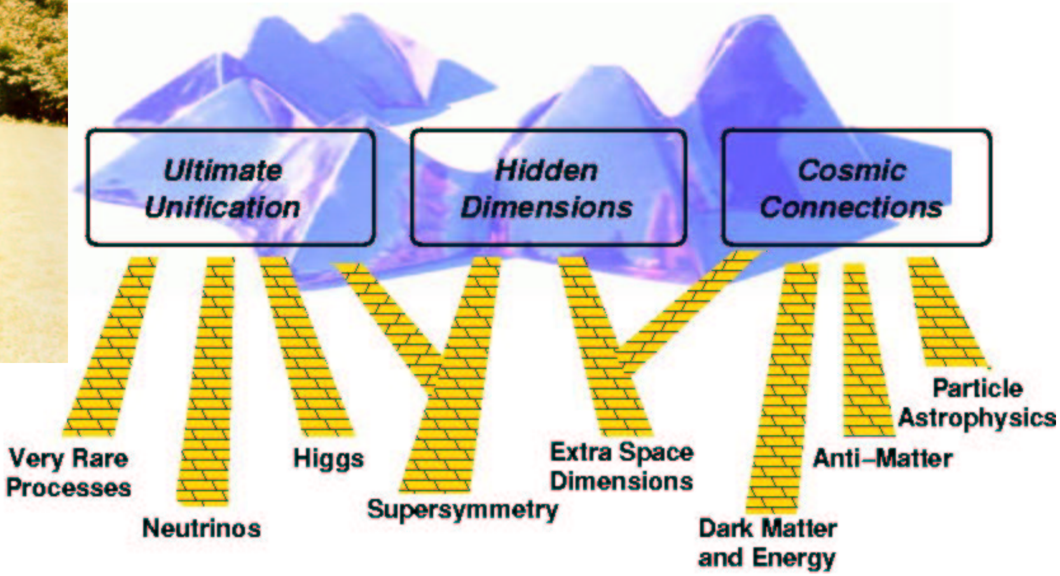
What physics should we be doing?

Sally Dawson
BNL
June 6, 2003

* NOT a summary….my personal views

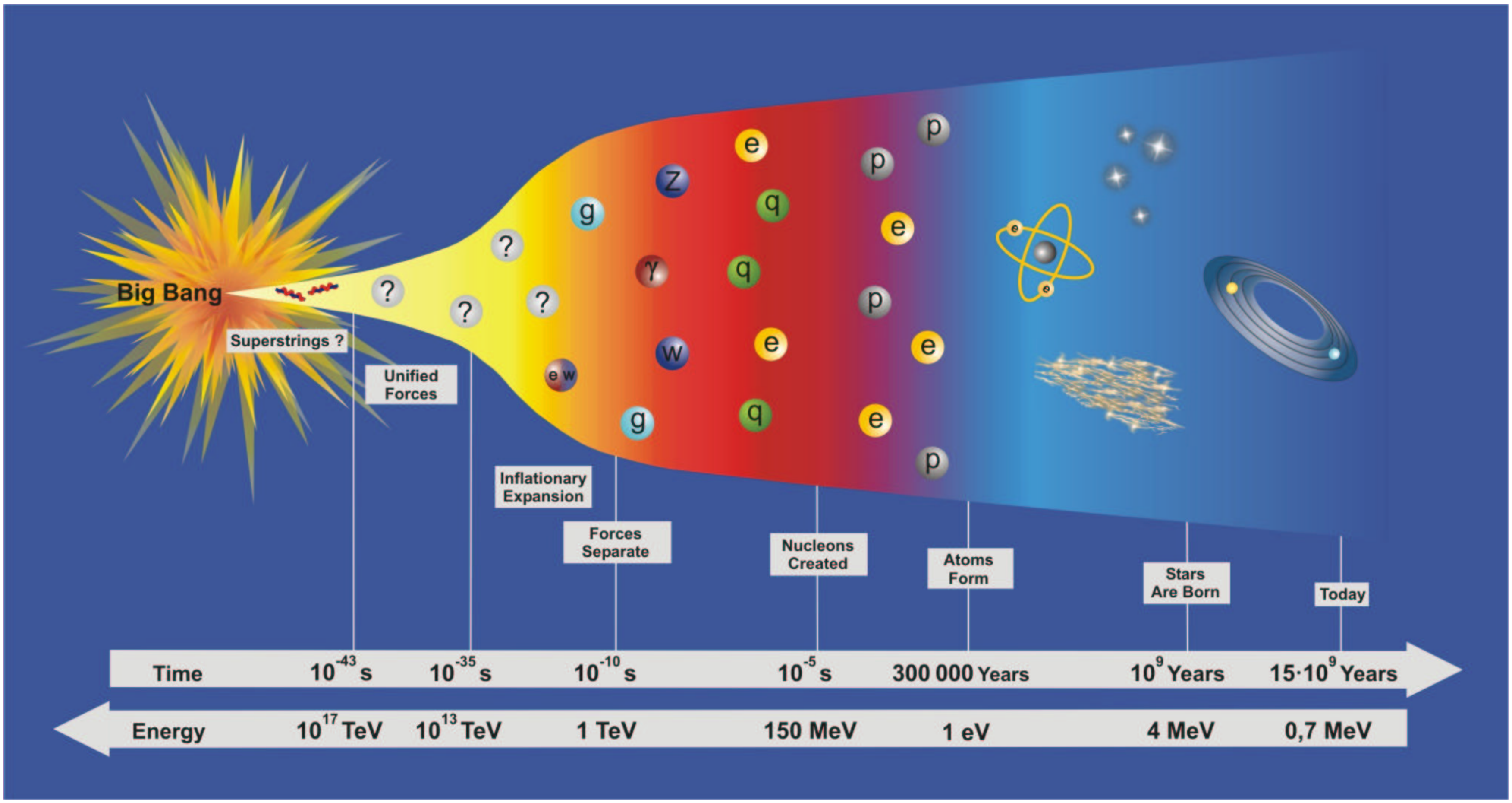
Scaling the Mountains…..

THANKS TO THE ORGANIZERS!



Broad definition of particle physics

The Challenge: Connecting the Energy Scales*



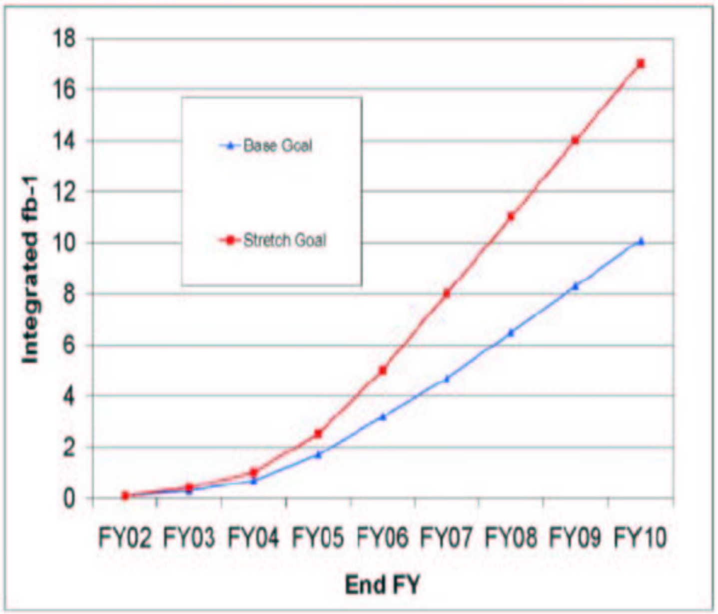
* US version is vertical

Much Progress last year

- Many new simulations reported here
- Many new tools
  - For Monte Carlos
  - For PDFs (uncertainties!)
  - For higher order corrections
  - For SUSY spectrum
  - For Higgs Properties
  - ……
- Many new ideas

Machines for Collider Physics

Tevatron



~ 9-15 fb^{-1} by Sept. 2009

10 fb^{-1} by 2007-2008

$\rightarrow$100 fb^{-1}

$\rightarrow$300 fb^{-1}

HERA

Linear Collider
20??

Looking towards 2007

W mass	**20 –30 MeV**	**LEP + Tevatron**
Top mass	**2 GeV**	**Tevatron**
Structure functions:*	**Few percent up to $Q^2 = 10^4$ GeV^2**	**HERA**
Higgs, SUSY	**Possible signal**	**Tevatron**

* Gluon PDFs critical at LHC

Physics landscape changes in 2007

Event Rates:

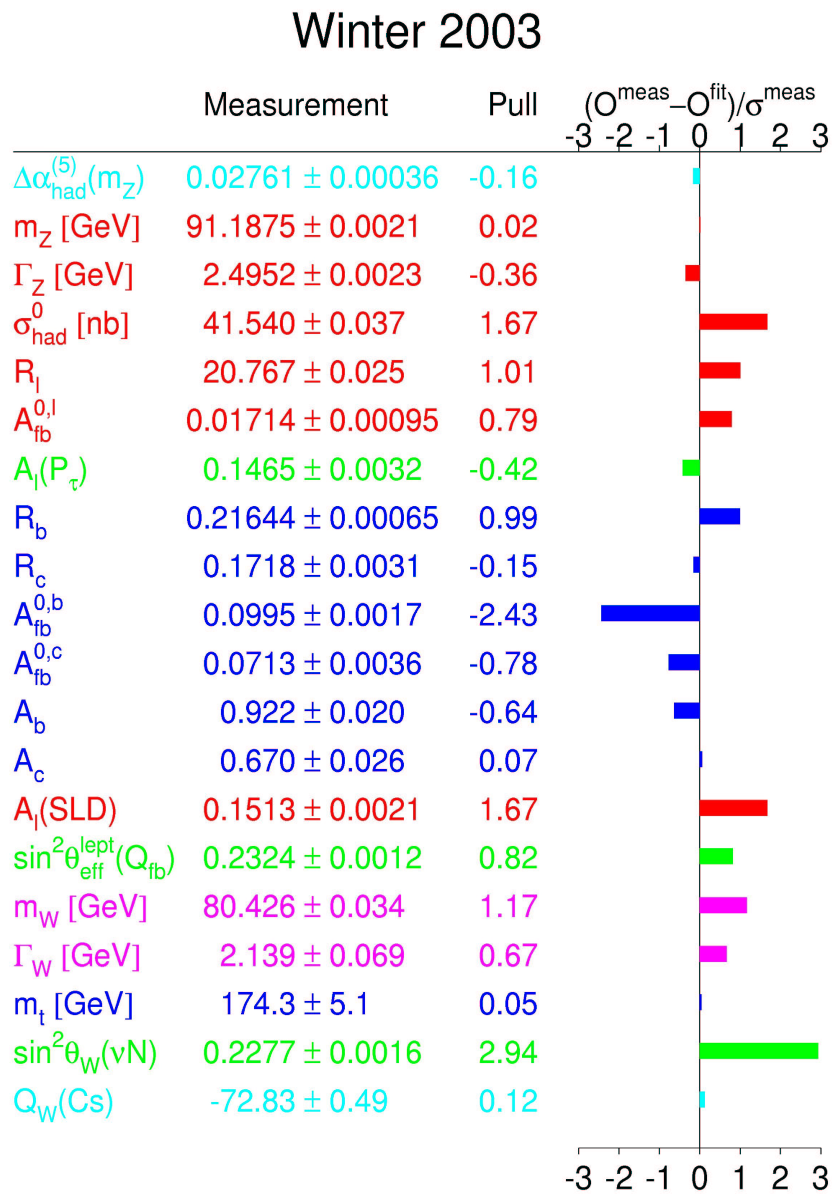
Process	10 fb^{-1} at LHC	Previous experiments
$W \to e\nu$	10^8	10^7 Tevatron
$Z \to e^+e^-$	10^7	10^7 LEP
$t\bar{t}$	10^7	10^4 Tevatron
$b\bar{b}$	10^{12}-10^{13}	10^9 B factories
Higgs, M_h=130 GeV	10^5	?
$\tilde{g}\tilde{g}$, m=1 TeV	10^4	--

Experimental successes of past decade put us on firm footing

We have a model

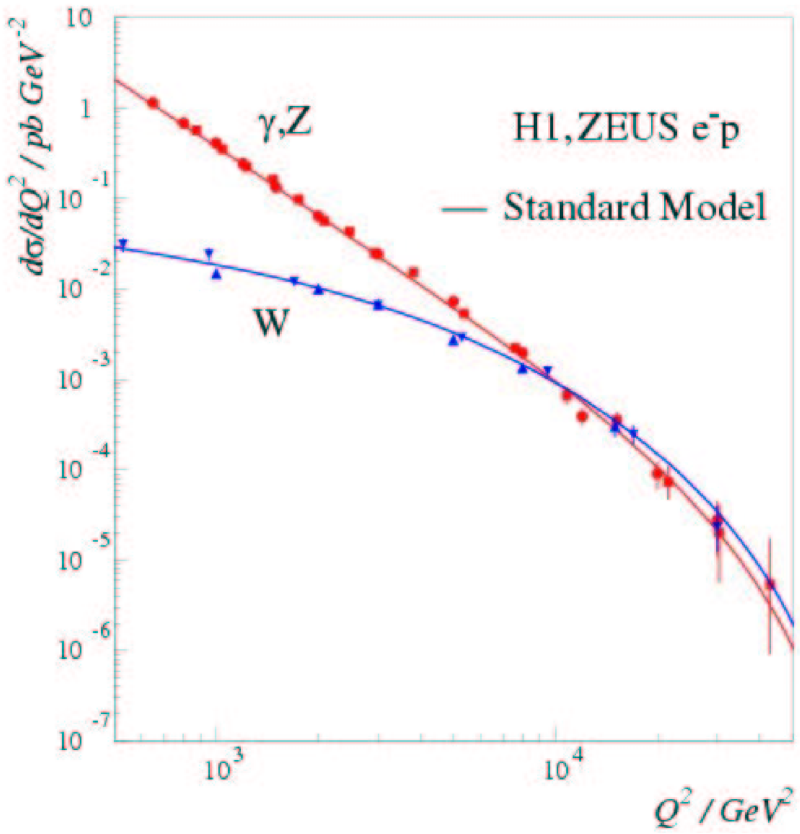
And it works to the 1% level

Gives us confidence to predict the future!



We’ve seen one example of gauge unification

HERA

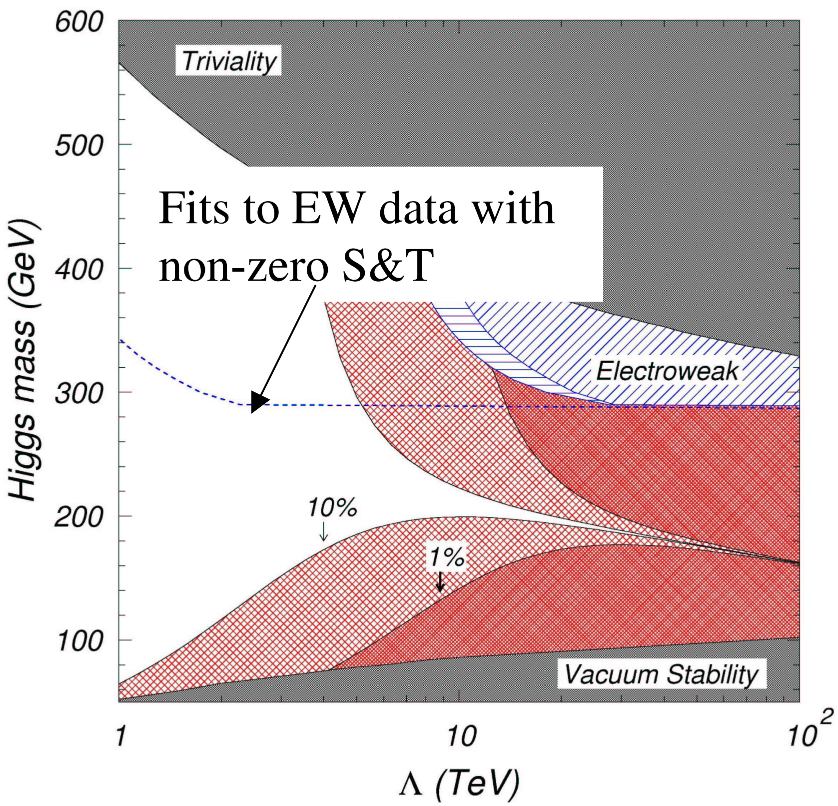


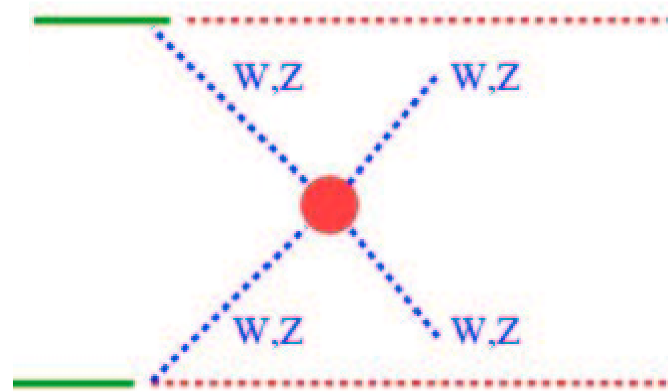
Charged and neutral currents unify at 100 GeV

Model requires Higgs boson or something like it for consistency!

Why the TeV Scale?
We expect new physics on very general grounds

Either a light Higgs, or strong WW Scattering





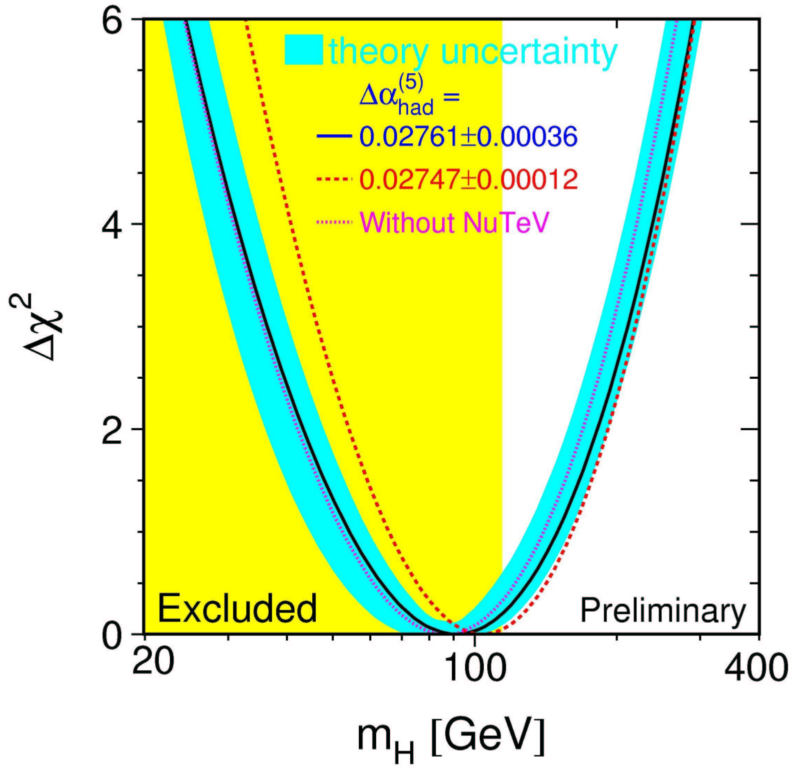
Standard Model inconsistent without Higgs unless new physics around 1.3 TeV

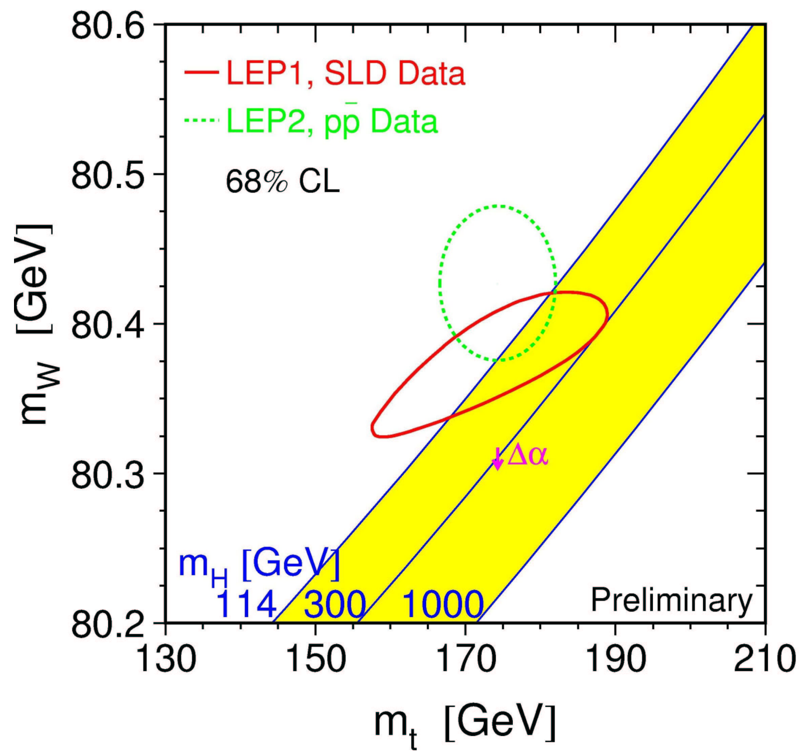
Kolda & Murayama, hep-ph/0003170

Is Mass due to a Higgs Boson?

$M_h < 211$ GeV

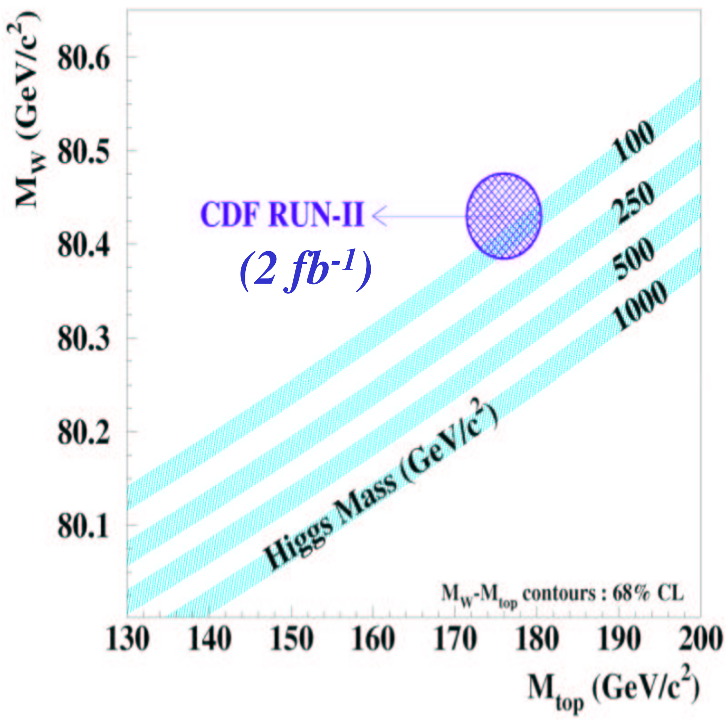
Precision EW Measurements:

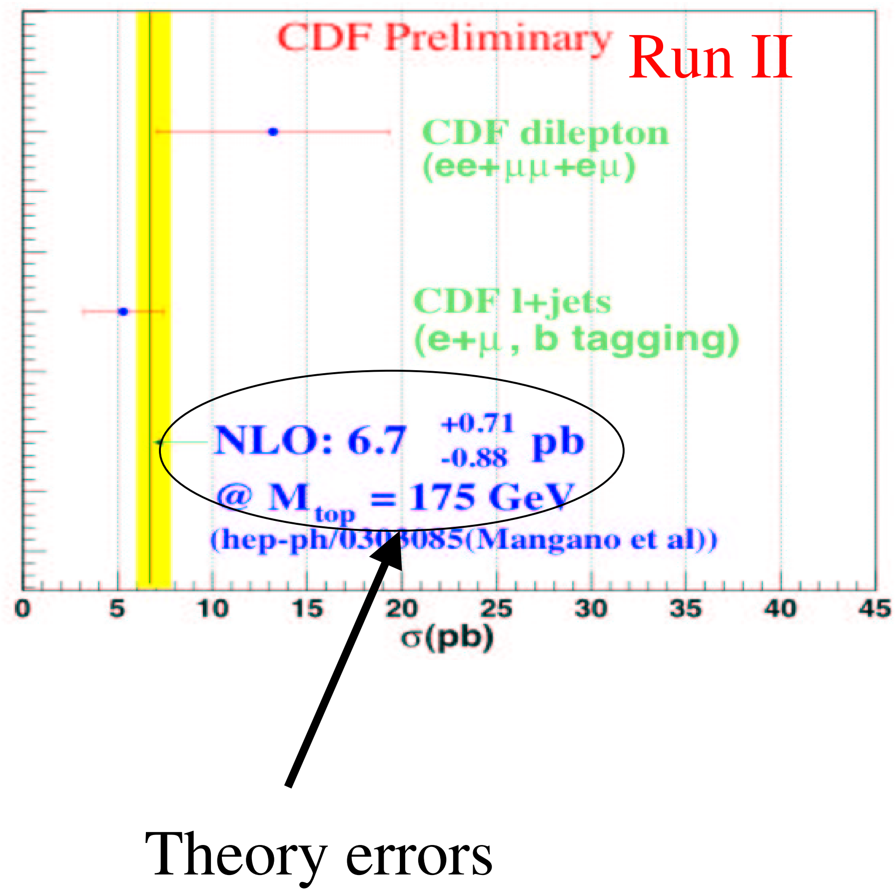




Note: Poor quality of fit

The Tevatron will point the way….

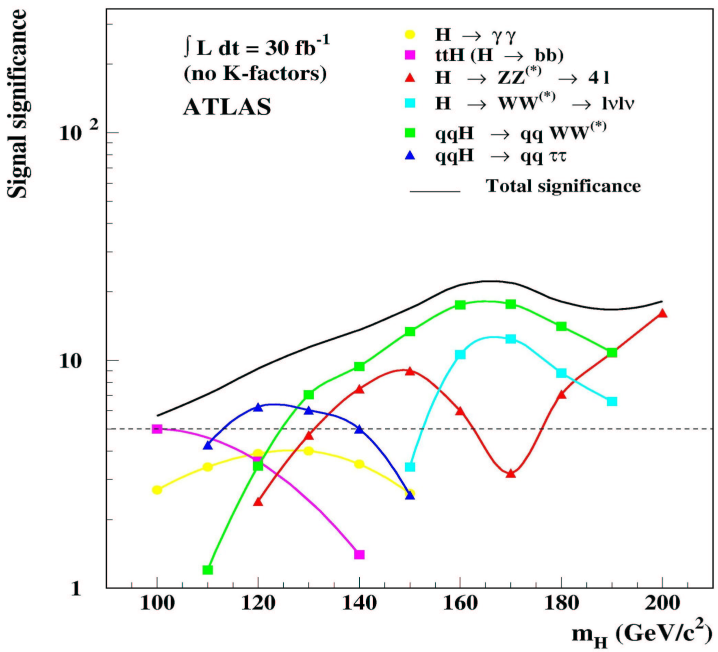




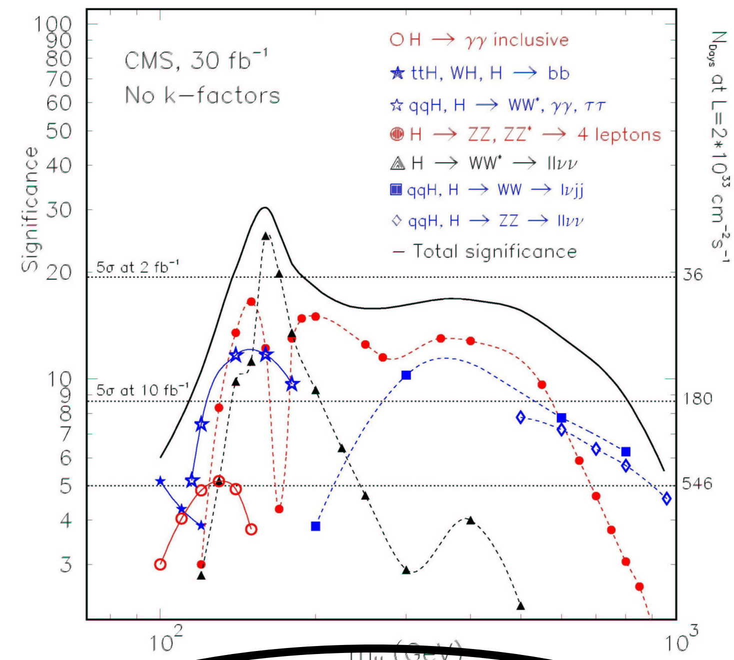
Increasing M_t increases M_h

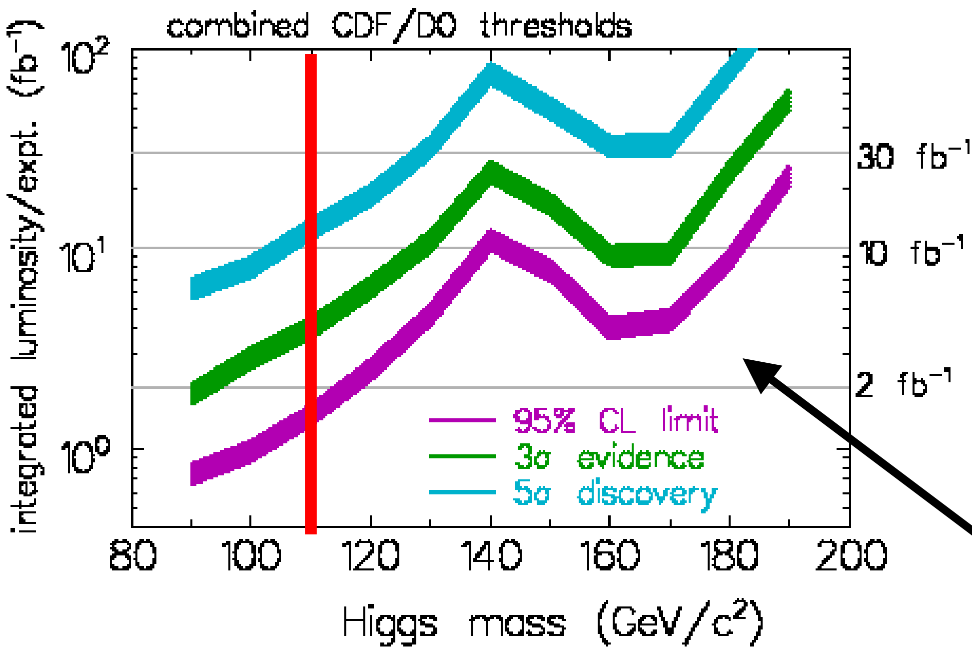
D0 preliminary:

M_t=180.1±3.6±4.0 GeV



If there is a light SM Higgs, we'll find it

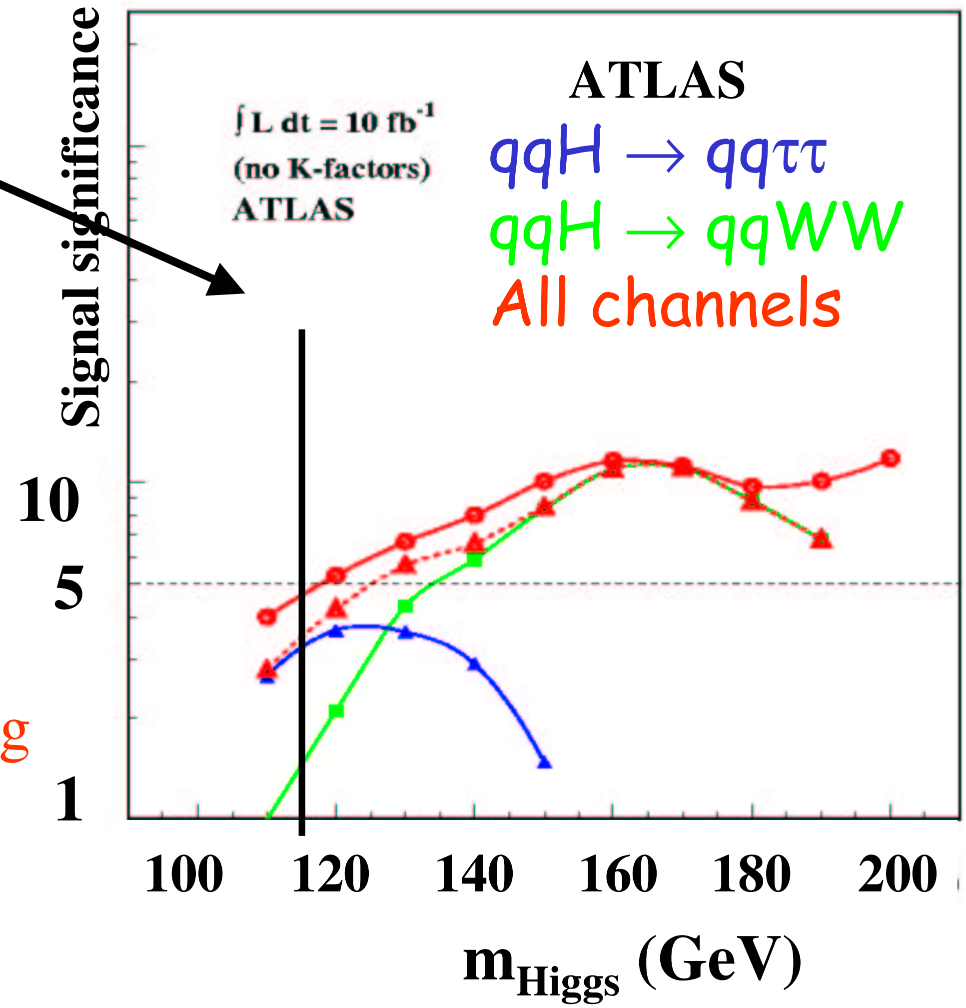




Conclusions "basically" confirmed by re-analysis

Progress in Vector Boson Fusion Studies

Note: 10 fb^{-1}



M_H= 115 GeV
combined significance ~ 5σ

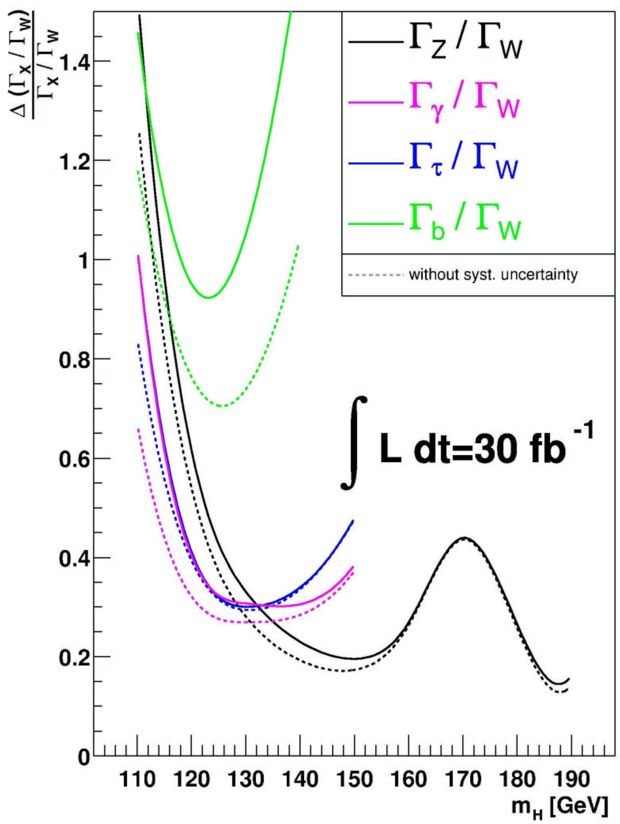
Promising channel for measuring couplings

PDF uncertainties ~±5%

Djouadi, Ferrag, Olieri

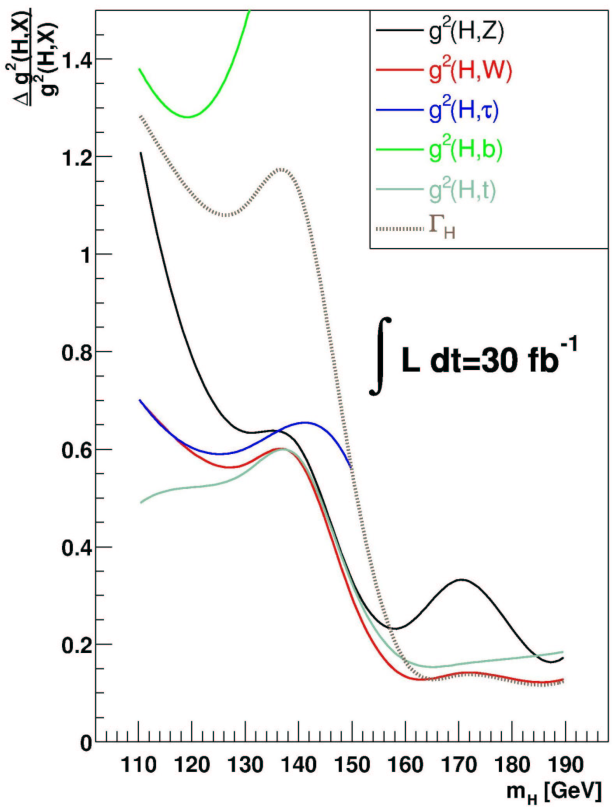
Coupling Constant Measurements

Ratios of coupling constants measured quite precisely



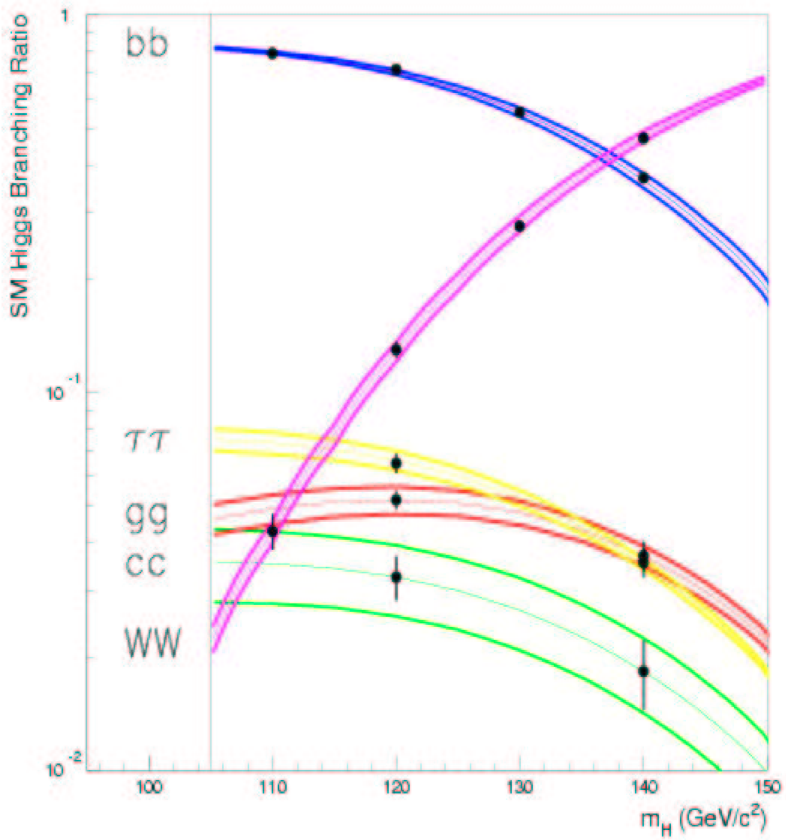
Duehrssen

ATLAS



Coupling constants less precisely (and with assumptions)

Coupling Constant Measurements at a Linear Collider



L=500 fb⁻¹, √s=350 GeV

Battaglia & Desch, hep-ph/0101165

Global fit to Higgs Couplings:

$\delta g_h/g_h$	
M_h=120 GeV	
bb	2.1%
$\tau^+\tau^-$	3.2%
W^+W^-	1.2%
cc	3.2%

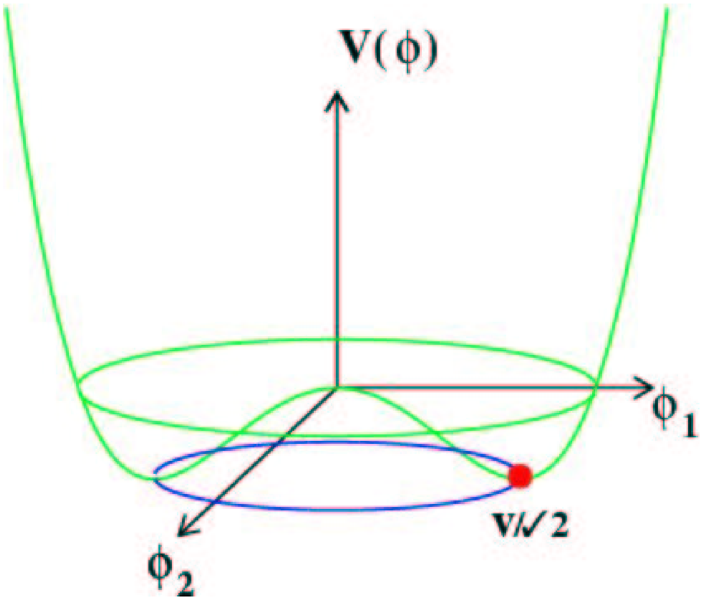
Largest error is theory!
(mostly from m_b)

Linear Collider is the place!

Can we reconstruct the Higgs potential?

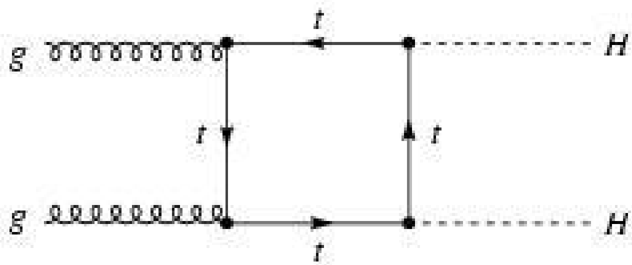
$$V = \frac{M_h^{\ 2}}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$

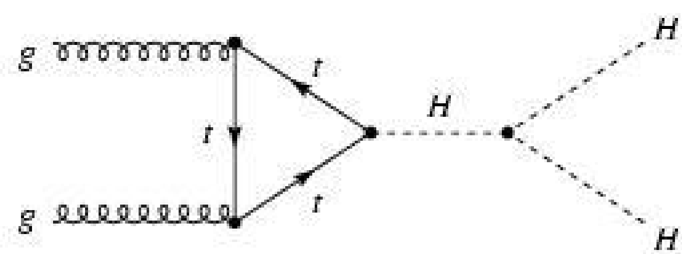
$$+ \sum_n C_n \frac{(h^2 - v^2)^n}{\Lambda^{(2n-4)}}$$



Fundamental test of model!

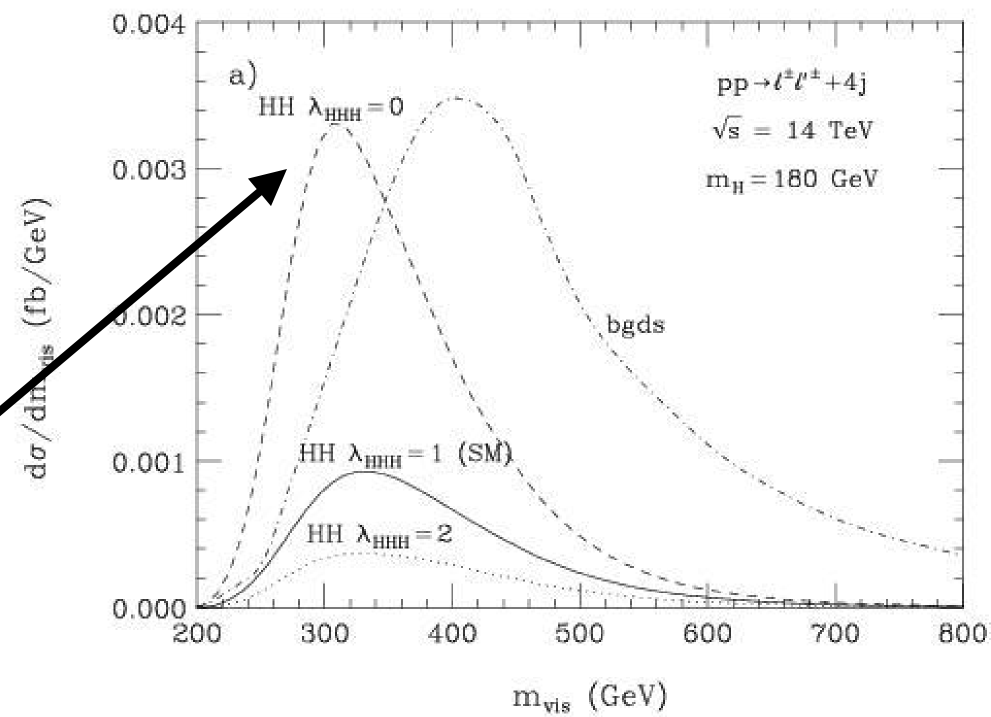
Reconstructing the Higgs potential





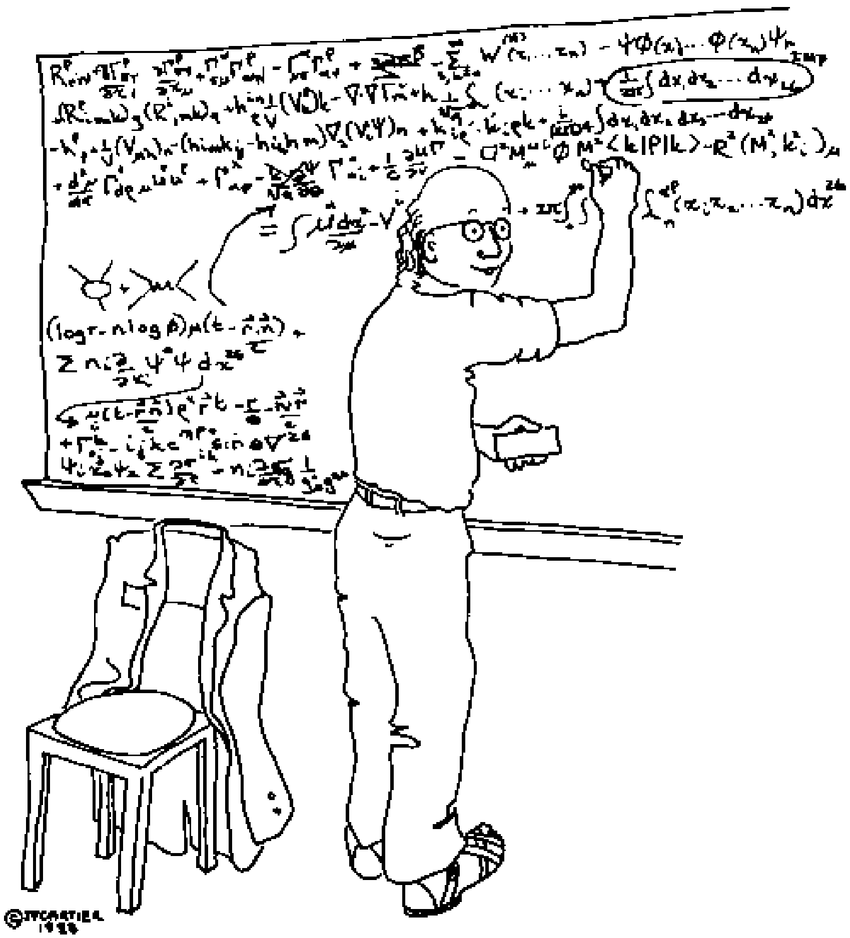
- λ_3 requires 2 Higgs production
- Depressing story
- No prospects for λ_4
- Hard at Linear collider too!

Can determine whether λ_3=0



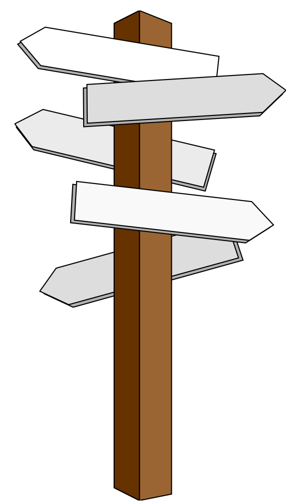
Baur, Plehn & Rainwater, hep-ph/0304015

What do Higgs couplings mean?
Can they tell us about new physics?



"At this point we notice that this equation is beautifully simplified if we assume that space–time has 92 dimensions."

Precision measurements versus direct observation of new particles



New Physics Searches require
Precision Calculations

- Is it new physics?
  - Extra dimensions
  - Little Higgs
  - SUSY
  - Something really new*.....
- Or is it QCD?

Effects typically $O(v^2/\Lambda^2)$

↓

Unless you see a new particle or resonance!

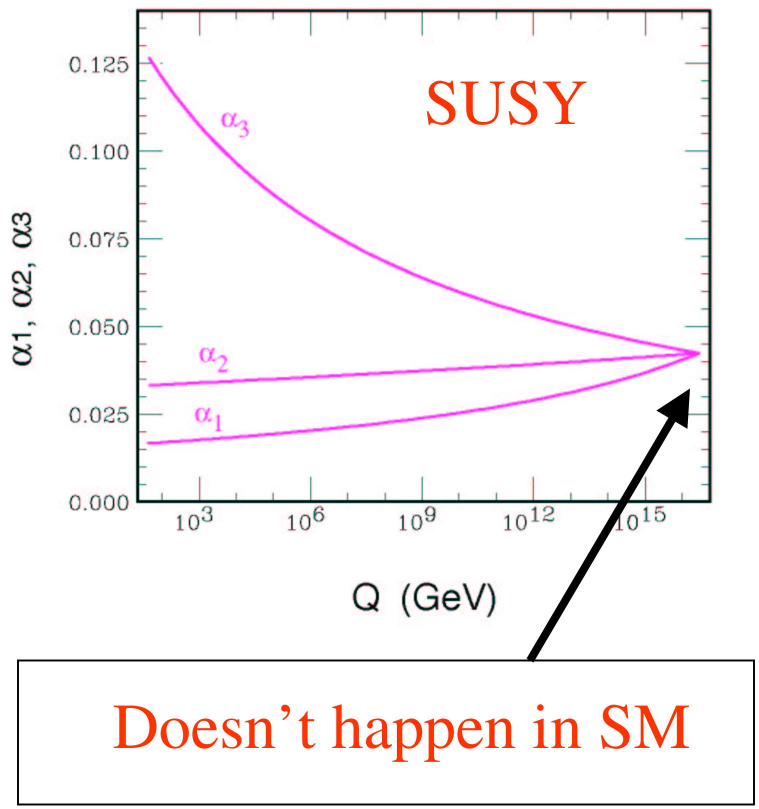
↓

QCD effects $O(\alpha_s)$

*Lots of theoretical progress

Of course….we all hope for physics beyond the Standard Model

- MSSM most studied variant of SM
- Motivated by coupling unification; Higgs mass renormalization
- Definite predictions



MSSM Higgs

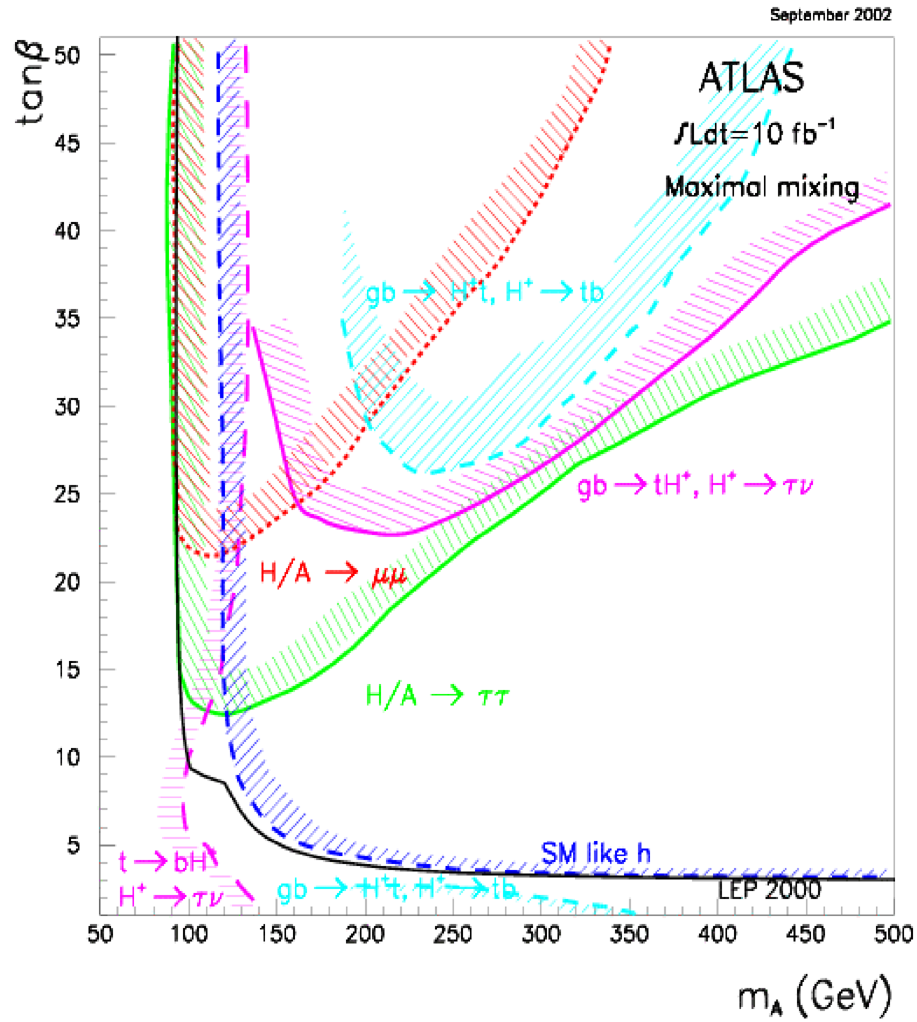
$M_A \rightarrow \infty$, light Higgs looks like SM

Focus on finding other Higgs bosons (signal for new physics beyond SM)

New decay channel $H/A \rightarrow \mu^+\mu^-$ covers much of region not excluded by LEP

New signature from $gb \rightarrow tH^+$, $H^+ \rightarrow \tau\upsilon$

$H/A \rightarrow \tau^+\tau^-$ important for intermediate tan β

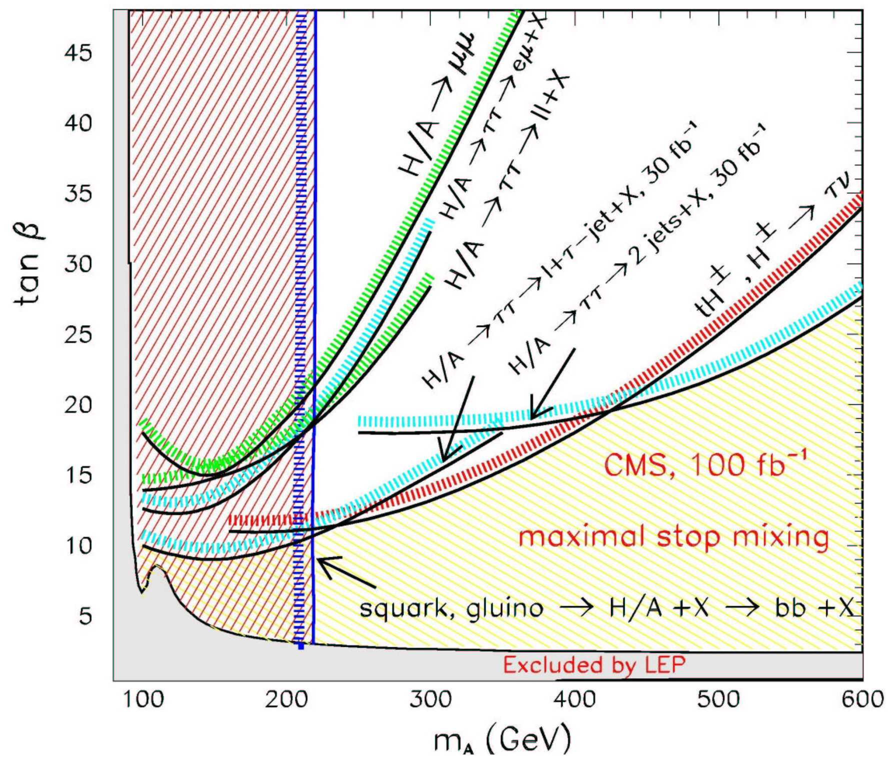


Emphasis on new signatures

One example:

- Cross section for pair production of squarks, gluinos large at LHC
- Look for complicated cascade decays
- Fills difficult low M_A, $\tan\beta$ region

$$\tilde{g}, \tilde{q} \rightarrow ..... \rightarrow \tilde{\chi}^{\pm}, \tilde{\chi}^{0} + h$$

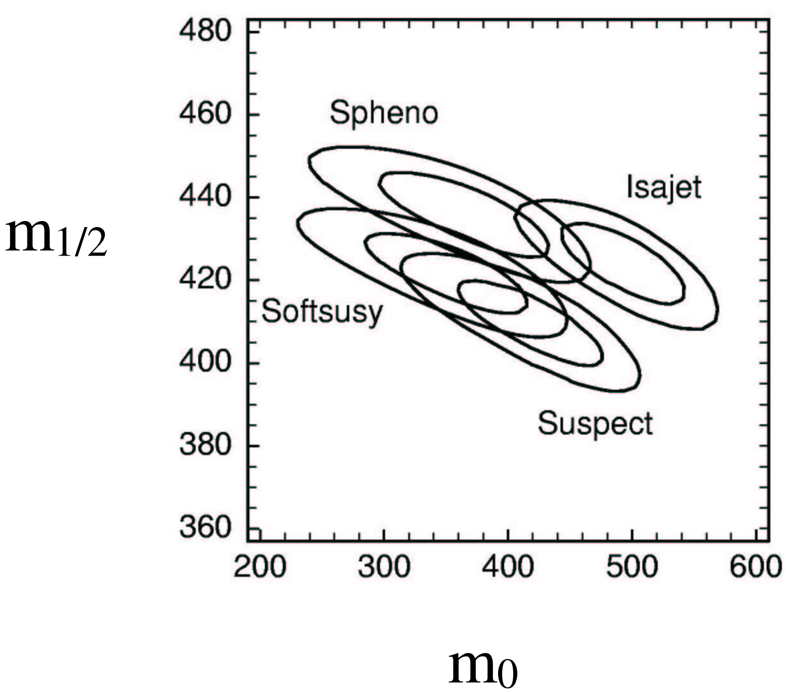


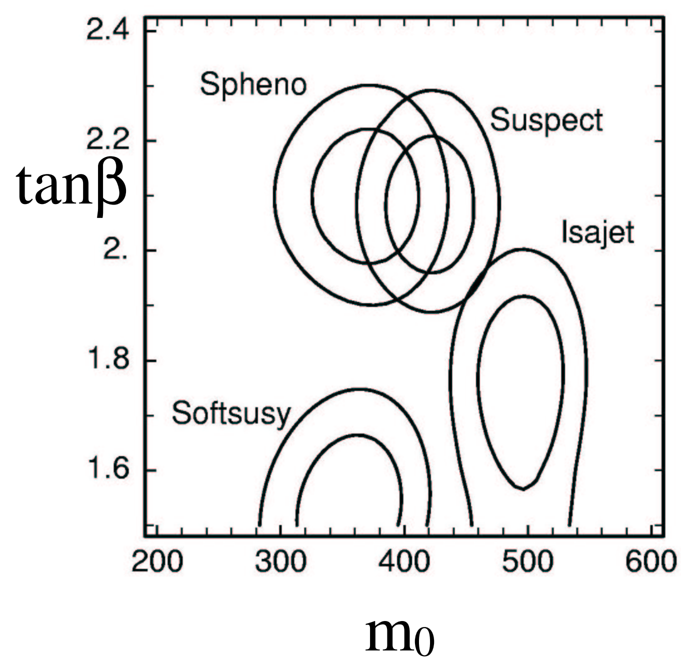
Datta, Djouadi, Guchait, Moortgat,

hep-ph/0303095

What does it all mean?

- If we measure SUSY masses at LHC, can we determine underlying SUSY theory?
- Extrapolate measured values with 300 fb^{-1} to M_{GUT}



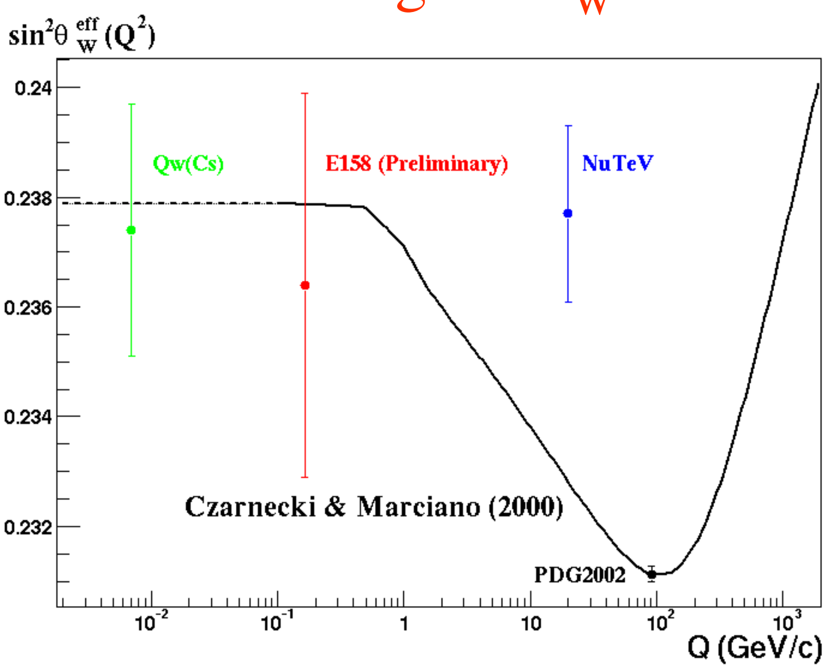


Allanach, Kraml, Porod, hep-ph0302102

We believe we understand parameters running with mass scales…..

Necessary ingredient for SUSY extrapolations

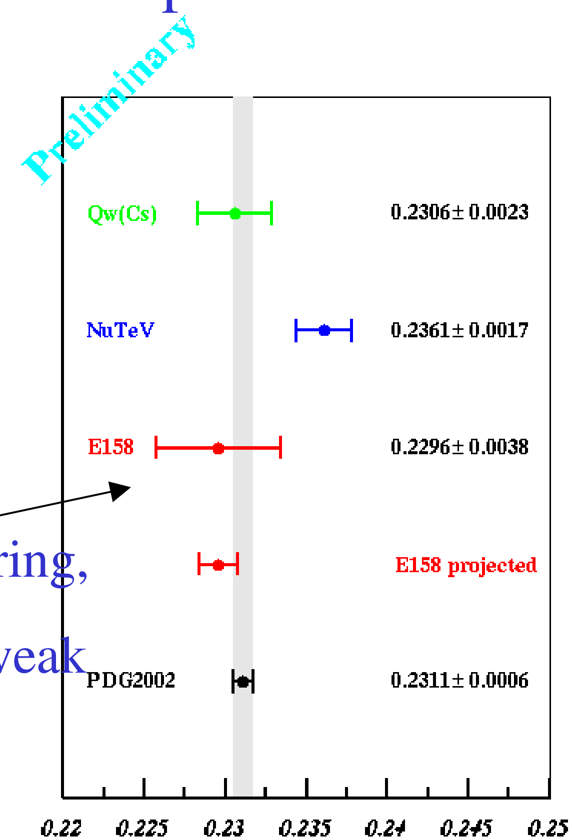
Running $\sin^2\theta_W^{eff}$



Czarnecki & Marciano

Moller Scattering,

Pure electroweak

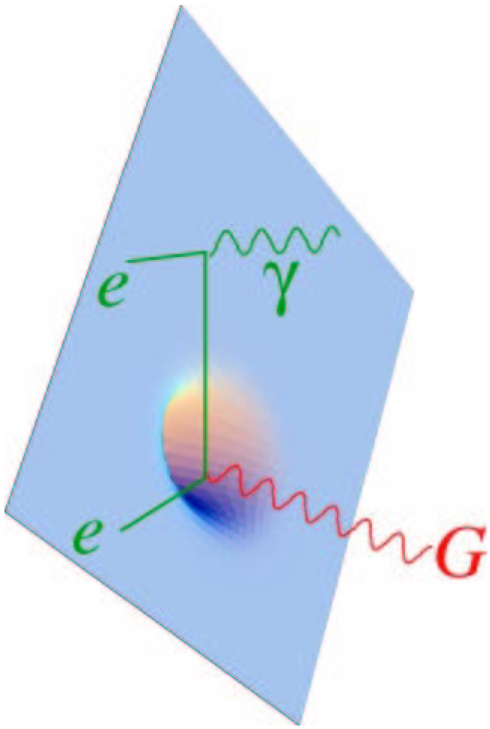


$\sin2\theta_W^{eff}(M_Z)$

Models with Extra Dimensions provide another good comparison point for SM

- Extra-D Models have towers of new Kaluza Klein Gravitons
- Graviton emission can measure the number of hidden dimensions
- Graviton exchange affects precision measurements,

  Drell-Yan production, missing E_T measurements….

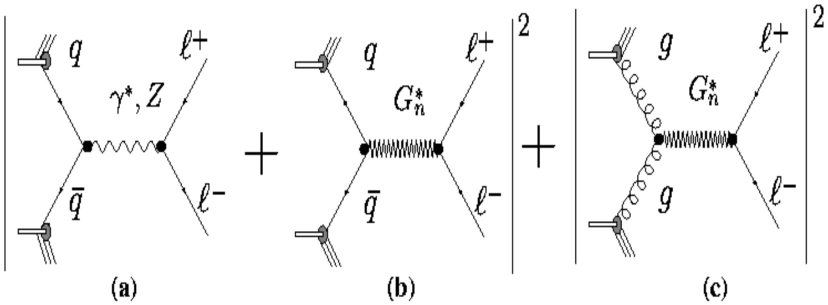


Large Extra Dimensions change angular, mass distributions of lepton pairs

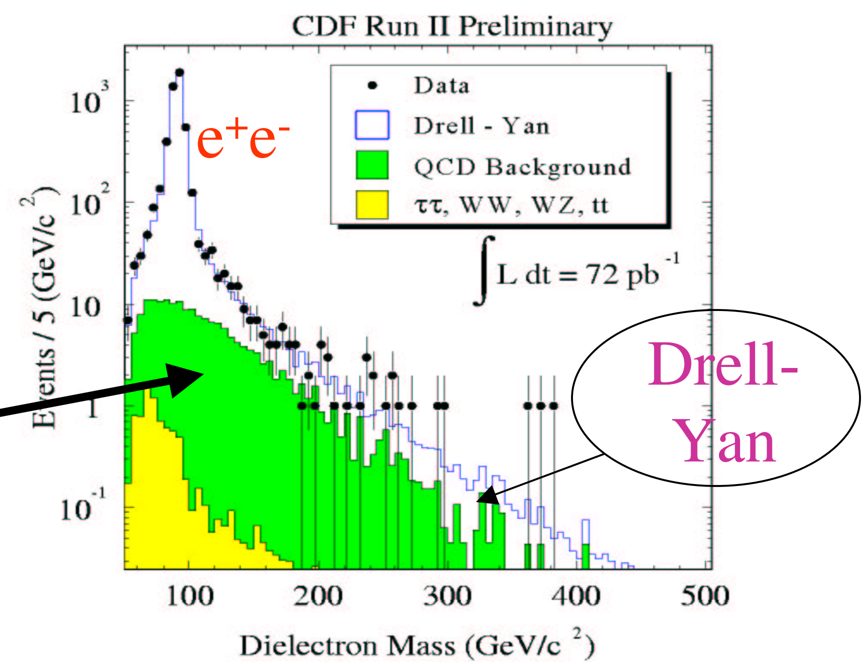
RunII search for high mass di-leptons

Sensitive to Z' and Randall-Sundrum Graviton

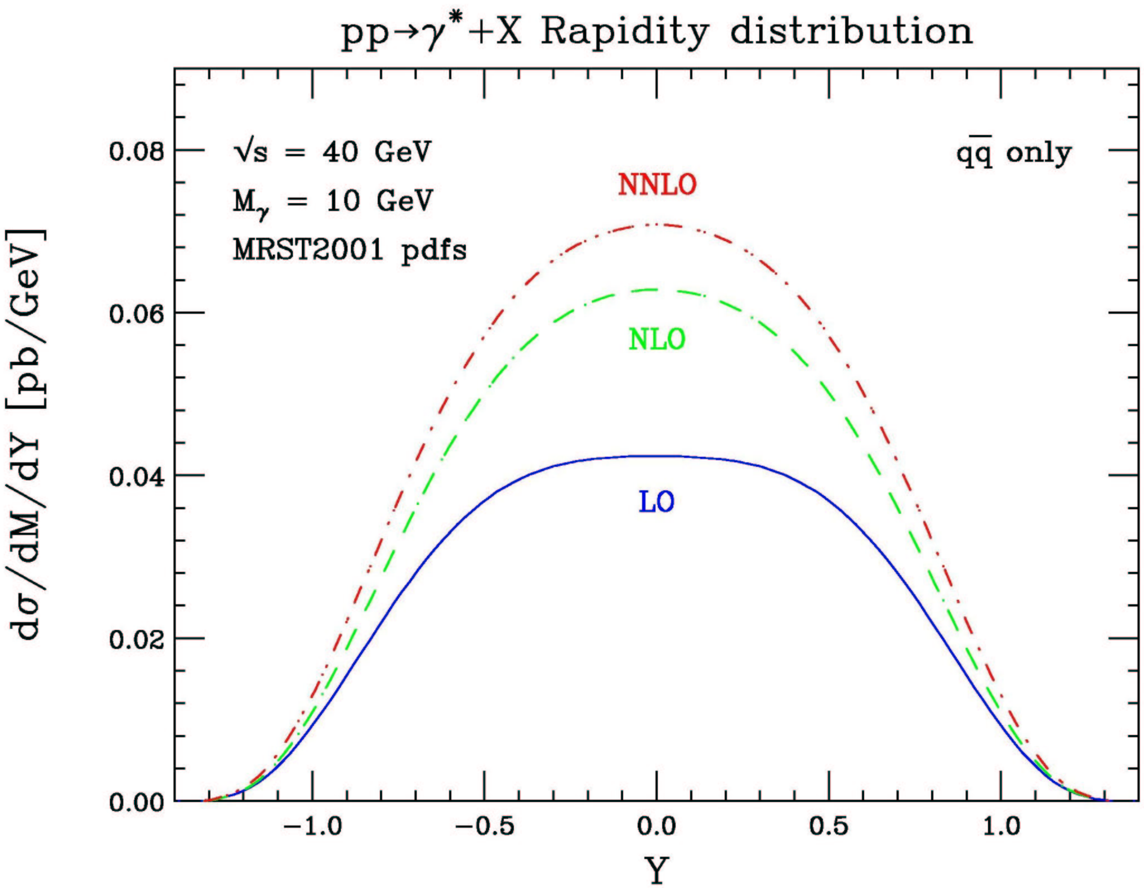
No excess observed



Note critical importance of understanding QCD backgrounds



First NNLO distribution: Drell Yan rapidity



Anastasiou,Dixon, Melnikov, Petriello (preliminary)

NLO, NNLO corrections significant at y=0

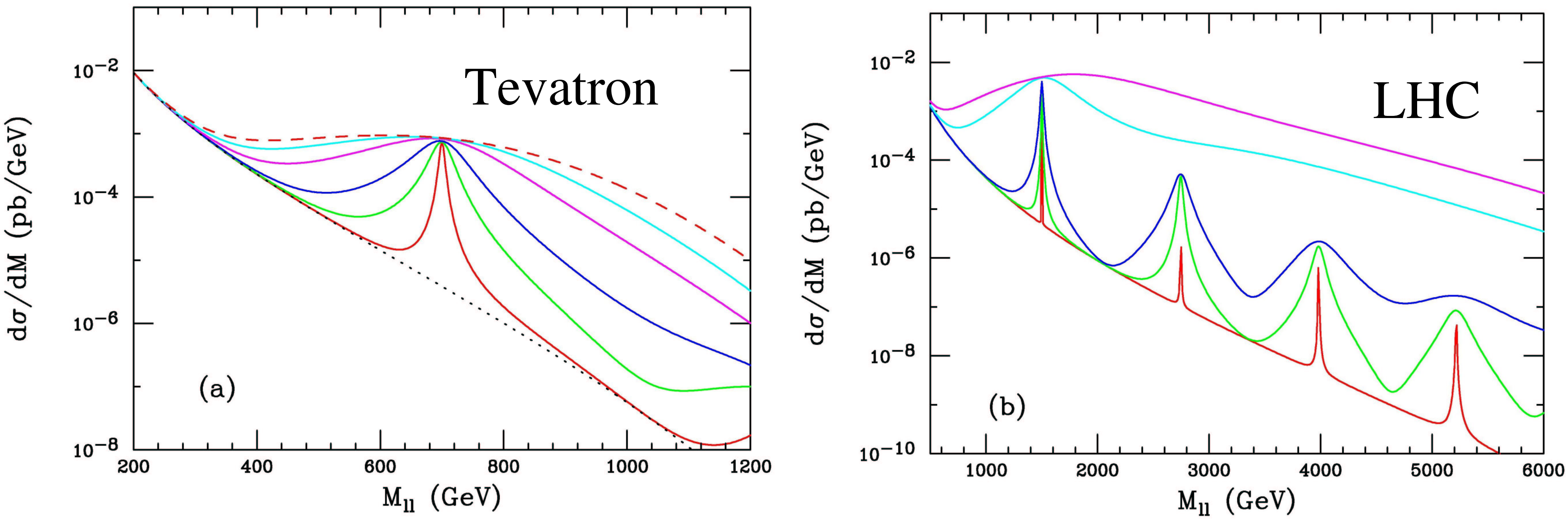
Calculation possible because of new techniques!

Nothing like direct production…

Drell-Yan production of KK Gravitons

in Randall-Sundrum Model

$pp \rightarrow$ Graviton KK $\rightarrow l^+l^-$



Davoudiasl, Hewett & Rizzo, hep-ph/0006041

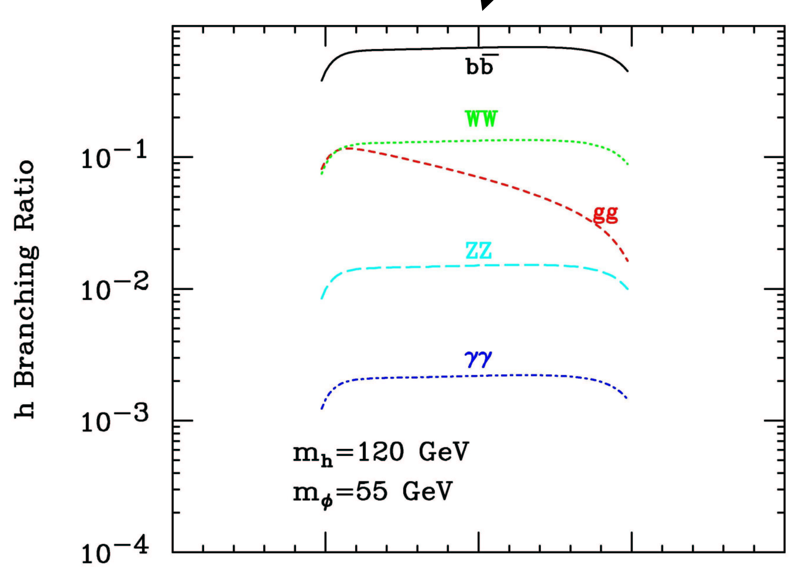
Once we find something, we want to know what it is….

Is it a Higgs or is it a radion?

- Randall-Sundrum model of extra dimensions has radion: ϕ
- ϕ couples like Higgs, but with strength ϕ/TeV instead of H/v
- Higgs-ϕ mixing suppresses standard channel, $gg \rightarrow h \rightarrow \gamma\gamma$
- How do you know it's a radion, not a SUSY Higgs?

(Have to find both Higgs & radion)

SM Limit



Higgs-Radion Mixing Parameter

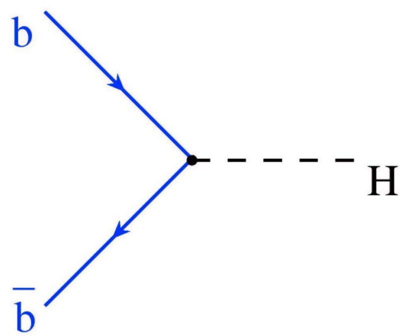
Battaglia, DeCurtis, DeRoeck, Dominici,& Gunion, hep-ph/030425

Dominici, Grzadkowski, Gunion, Toharia, hep-ph/0206192

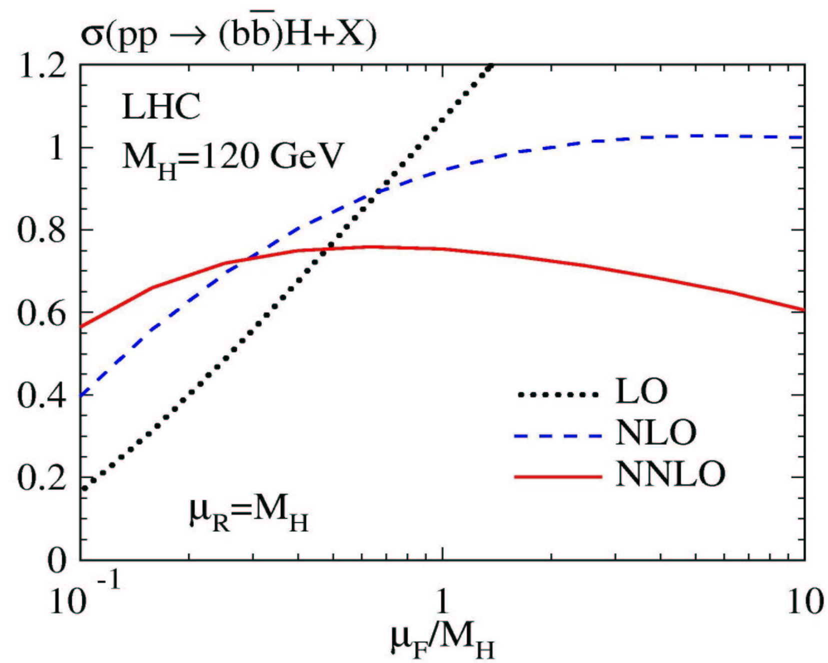
Hewett & Spiropulu, hep-ph/0205100

Need NLO, NNLO Results

bb→h



Reduced theoretical error from reduced μ dependence



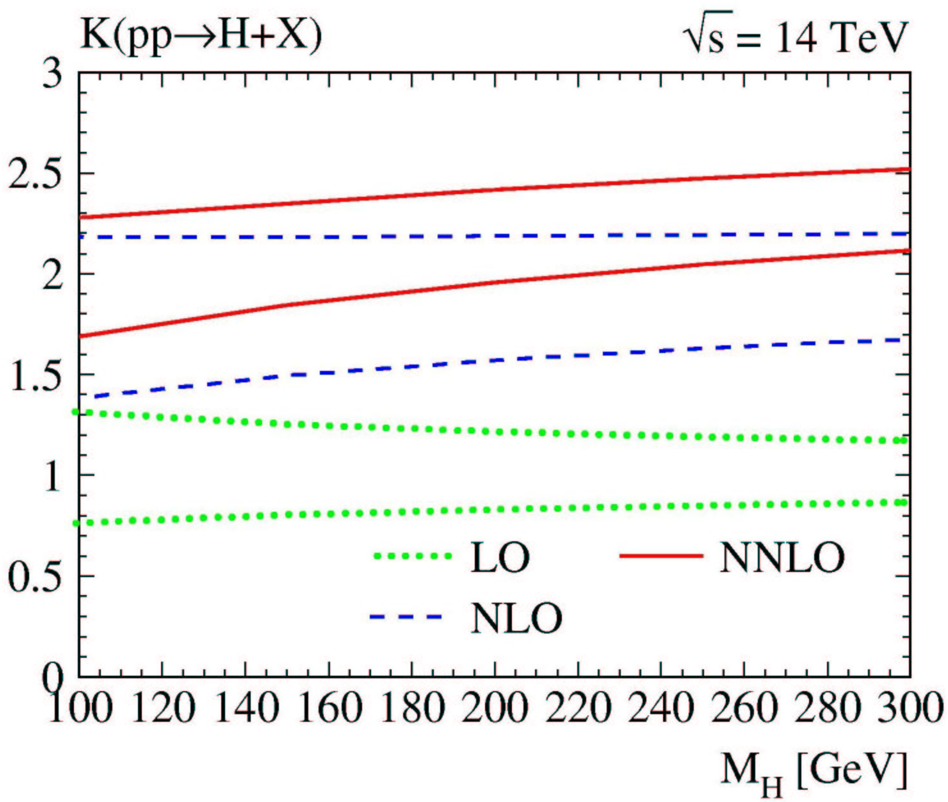
Only relevant in SUSY with large tan β

- When is the b quark a parton????
- Leads to new signatures with single b's: gb→bh

NLO: Maltoni, Sullivan, & Willenbrock, hep-ph/0301033

NNLO: Harlander & Kilgore, hep-ph/0304035

NNLO, gg→h



Bands show $.5M_h < \mu < 2\ M_h$

LO and NLO μ dependence bands don't overlap.

Need NNLO!

Resummation ↑ σ by 6% wrt NNLO [Grazzini]

NLO&NNLO results allow improved estimates of theoretical uncertainties

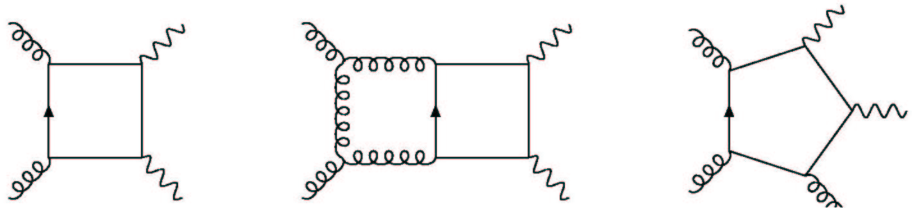
Harlander & Kilgore, hep-ph/0201202

Catani, deFlorian, Grazzini, hep-ph/0102227

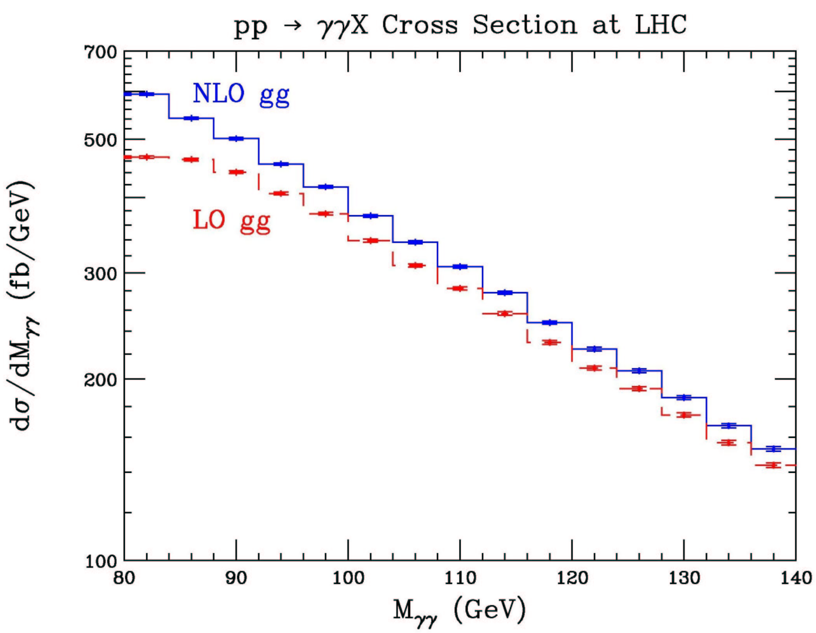
Anastasiou & Melnikov, hep-ph/0207004

Need backgrounds to Higher Order

- Background to h→γγ:
- qq→γγ
- gg→γγ



“NLO”



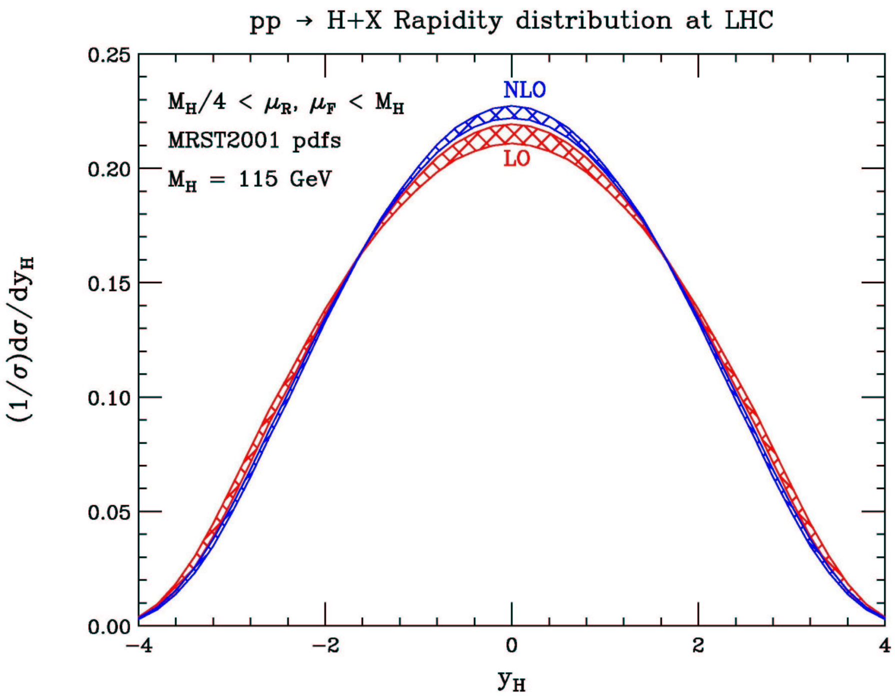
Bern, de Freitas, Schmidt, hep-ph/0206194

Previous estimates over-estimated γγ background

New ATLAS analysis of H→γγ with increased significance

More on higher order QCD

Higgs p_T spectrum at NLO QCD:



NLO corrections to shape small, 5% at y=0

Suggests using LO Monte Carlo, weighted by NNLO cross section

Need case by case study

Anastasiou, Dixon, &Melnikov, hep-ph/0211141

Glosser & Schmidt, hep-ph/0209248

Ravindran, Smith, & van Neervan, hep-ph/021114

deFlorian, Grazzini, & Kunszt, hep-ph/9902483

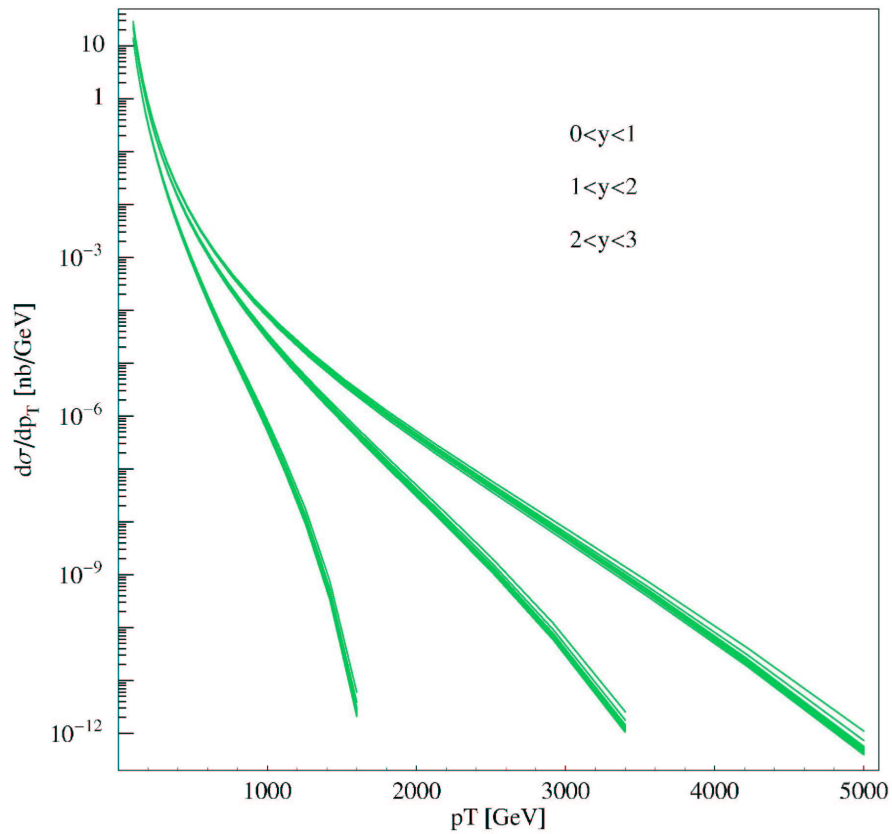
Progress in estimating theoretical errors

- CTEQ6 PDFs have errors
- NLO, NNLO have reduce scale dependence

Theoretical errors critical for extracting tan β….

PDF uncertainties decrease discovery reach for extra D's at LHC from 5 TeV →2 Tev [Ferrag]

Inclusive jet cross sections at LHC with PDF uncertainties (for fixed rapidity intervals)

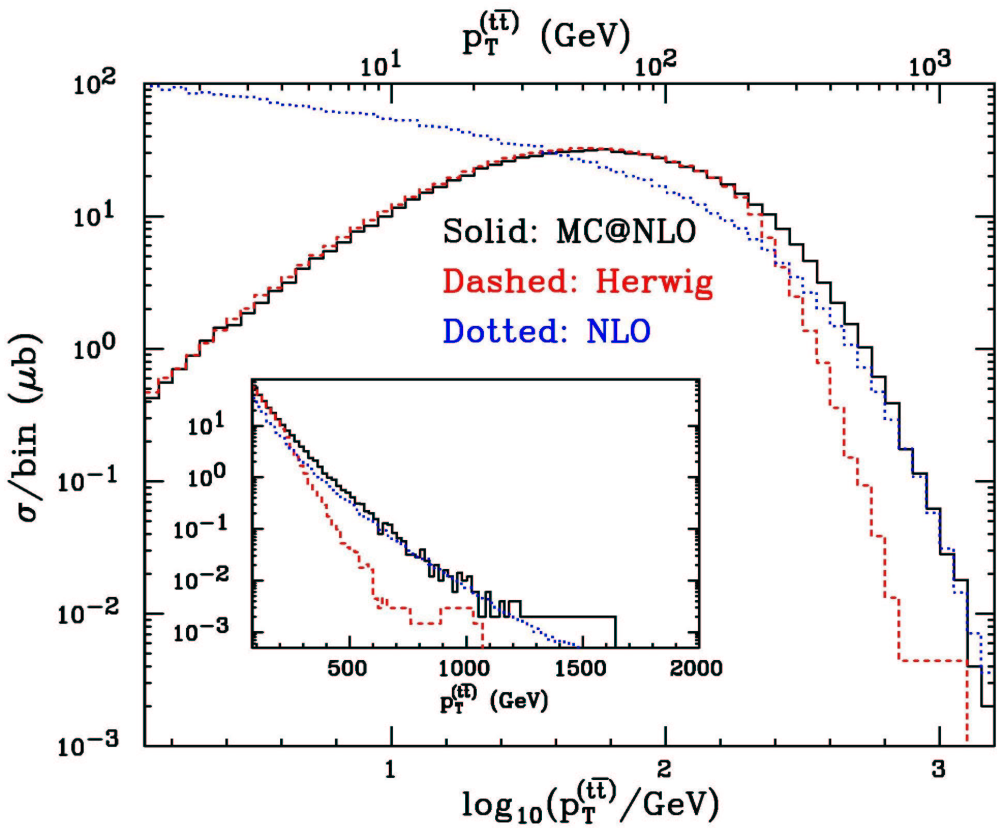


Stump, Huston…, hep-ph/030313

Need Monte Carlos which include NLO properly

$pp \to t\bar{t}$ at LHC

- Match NLO with parton shower
- Subtract terms which are included in parton shower from NLO result
  - At high p_T, NLO
  - At low p_T, MC



MC@NLO

Frixione, Nason & Webber, hep-ph/0305252

The bottom line:

To test models of new physics we need:

Precision calculations

Higher order Monte Carlos

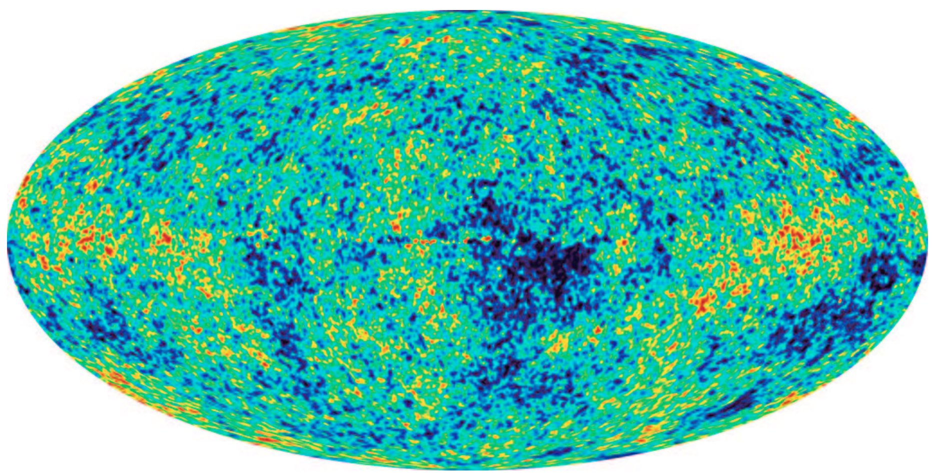
Much hard work remaining

The ASTRO/particle Connection

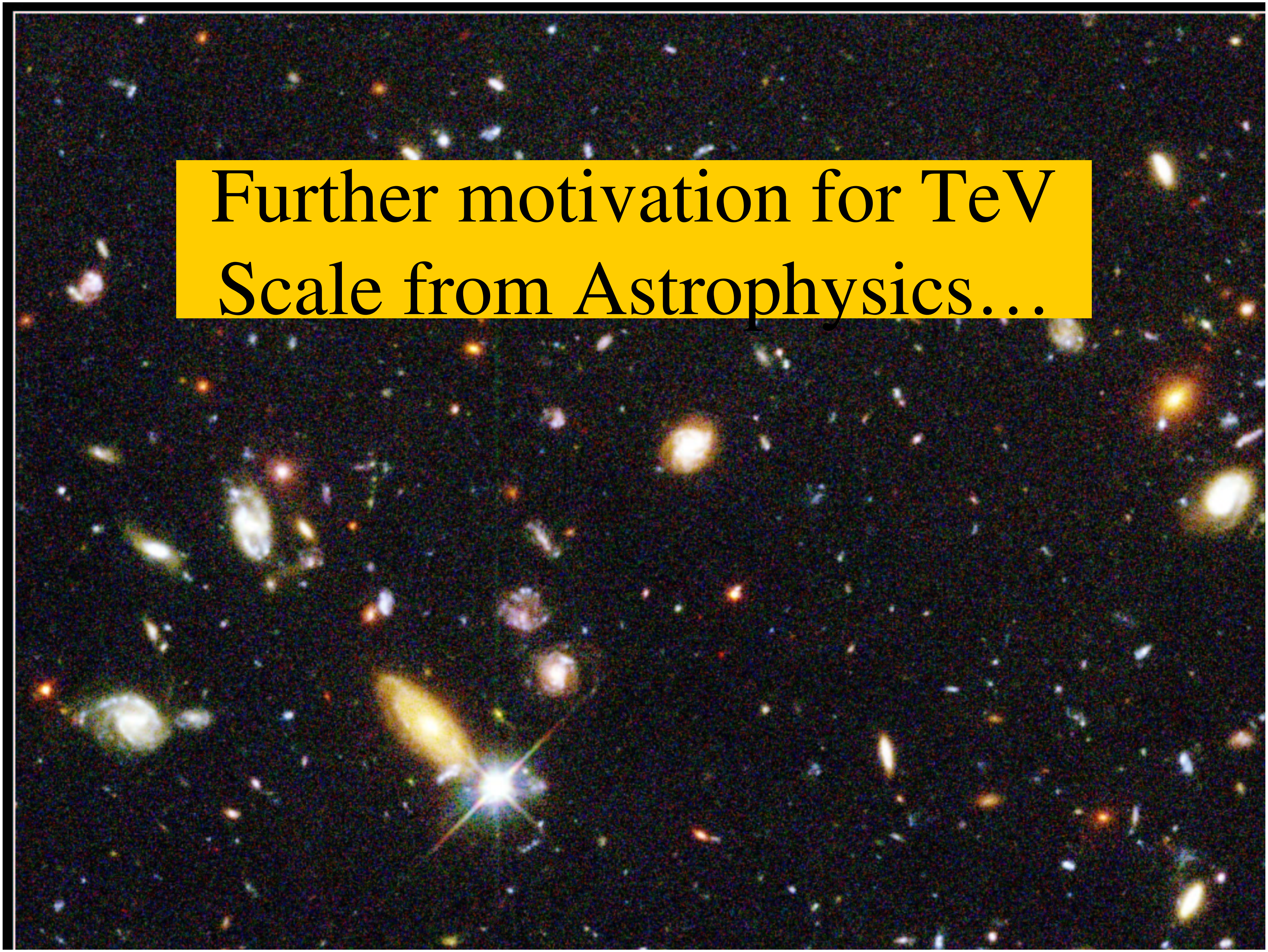
- 23% of universe is cold dark matter:

$$\Omega_{CDM}h^2=.1126^{+.0161}_{-.0181}$$

- WMAP (and others): Cosmology is a precision science $\longrightarrow$ Implications for particle physics!

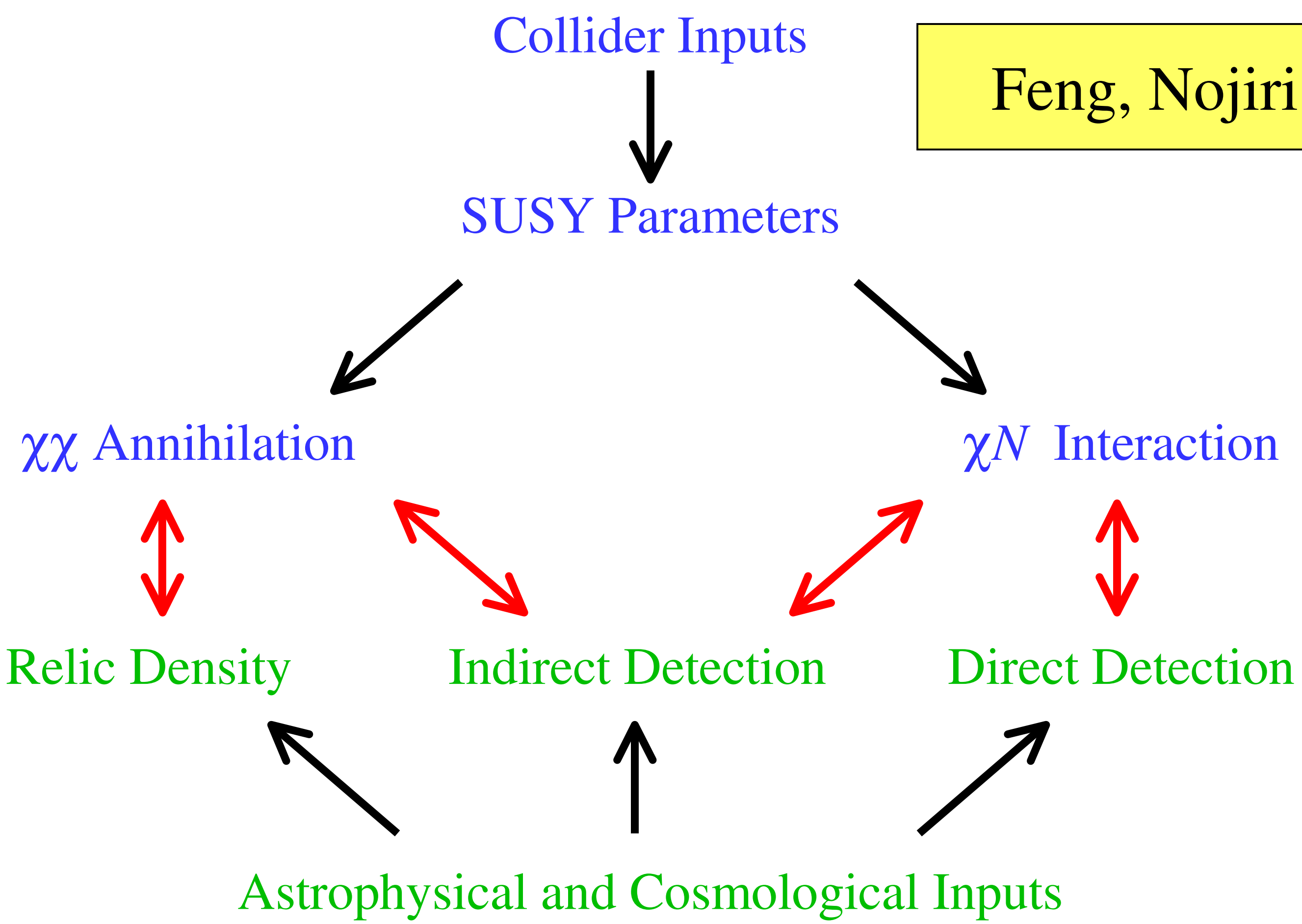


Further motivation for TeV Scale from Astrophysics…



Connection between particle/cosmology

Feng, Nojiri

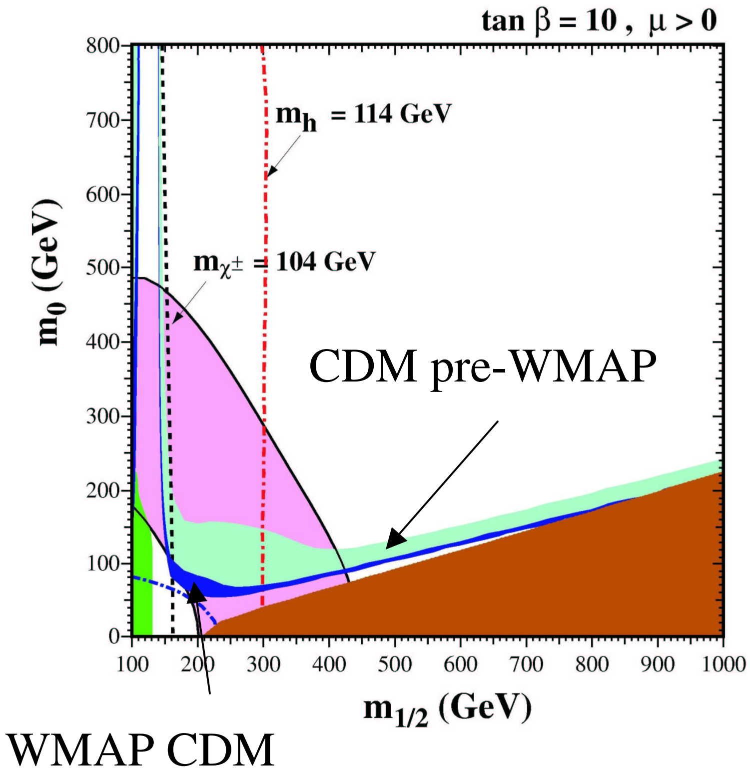


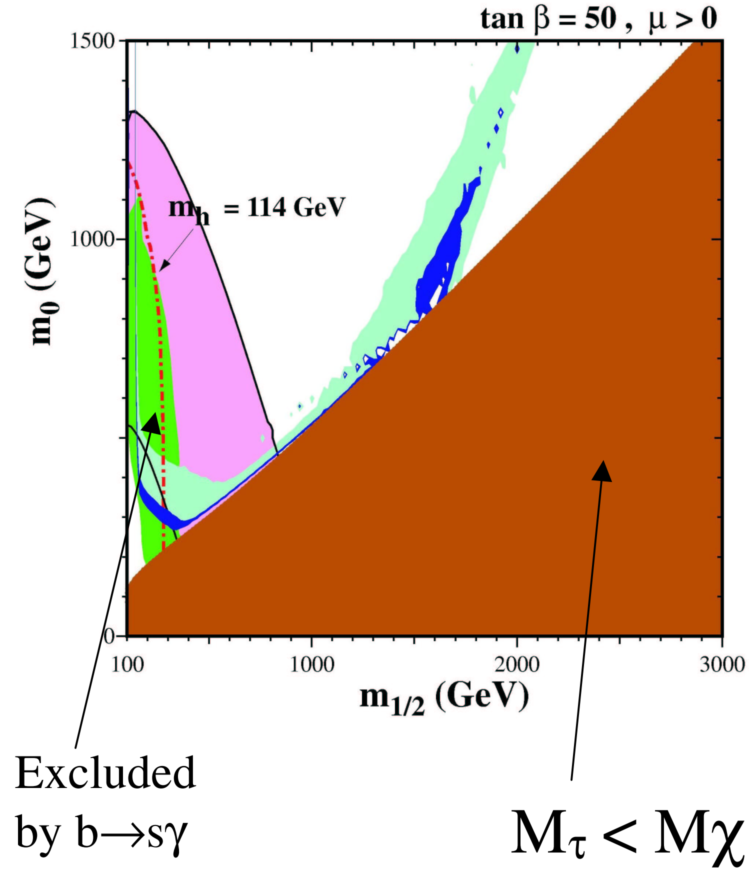
Cold dark matter points to TeV Scale

- SUSY models have natural dark matter candidate
- LSP is neutral and weakly interacting
  - Assuming R parity
- On general grounds, LSP contributes correct relic density if mass is 300 GeV-1 TeV
- WMAP results imply M_χ <500 GeV for tan β < 40 in mSugra type models
- SUSY particles within reach of LHC and LC

Ellis, Olive, Santoso, & Spanos, hep-ph/0303043

mSugra limits from CDM



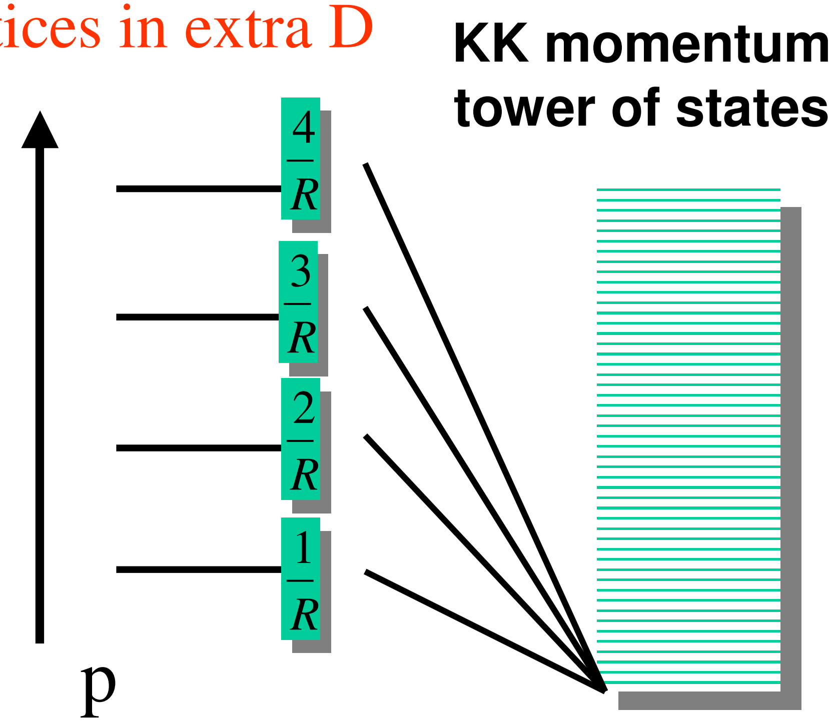


Ellis, Olive, Santoso, Spanos, hep-ph/0303043

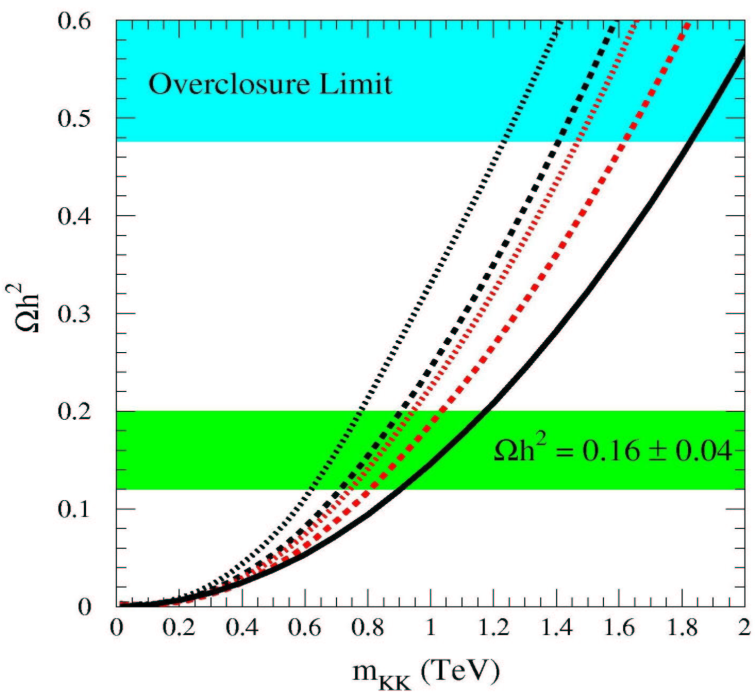
Extra dimension models have natural dark matter candidate

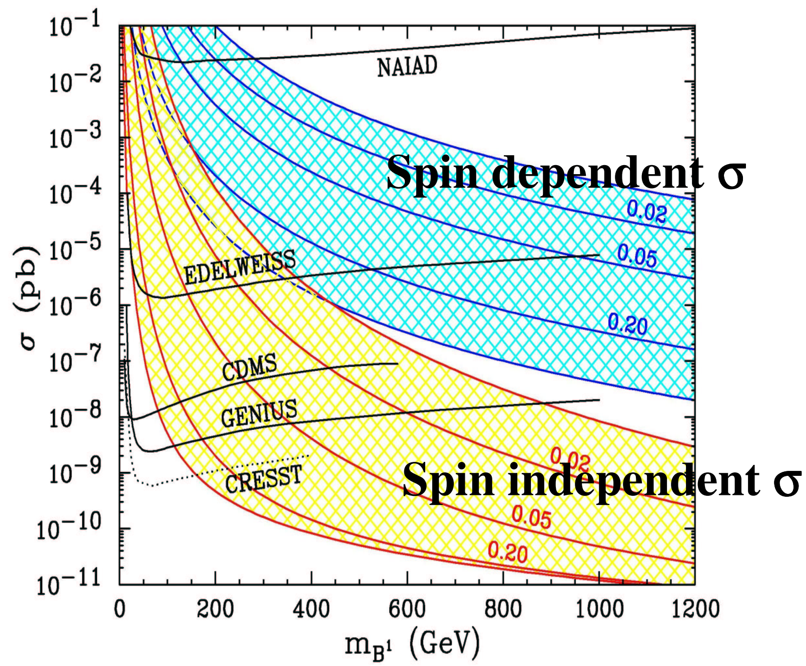
- Extra dimensions give tower of new Kaluza-Klein states
- Universal extra dimensions: all SM fields propagate in extra dimensions [Appelquist, Cheng, Dobrescu, hep-ph/0012100]
- Momentum conservation at vertices in extra D gives conserved KK number
- Lightest particle stable, can be neutral

KK WIMP



KK Wimps have TeV Scale





KK Wimps not Majorana→

efficient s-channel annihilation

Correct relic density with higher

mass than LSP

Servant & Tait, hep-ph/0206071

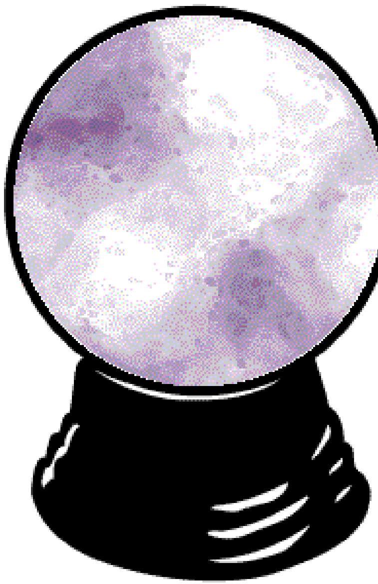
Constructive interference of different contributions

→Lower bound on σ

Cheng, Feng, Matchev, hep-ph/0207125

Outlook

- Physics at TeV scale will be rich!
  - *Lots of new ideas*
  - *Connection with astrophysics*
- LHC/LC will probe TeV scale
  - *Tremendous progress in our understanding*
- Surprises await us!



Crystal Ball