Higgs, Supersymmetry, and CP Violation

JAE SIK LEE

National Center for Theoretical Sciences, Hsinchu, TAIWAN

♠ *Contents*

♠ The $1^{\rm st}$ part: Introduction to

Higgs, Supersymmetry, CP Violation and the LHC

... Please don't be too picky

♠ The $2^{\rm nd}$ part: My works on manifestations of

CP Violation through the Supersymmetric Higgs sector

at the LHC and other low-energy experiments

... Please don't feel too sleepy

THE 1st PART

♠ *Higgs* (1/5)

- Why Particles Physics?

  ... to find answers to the Eternal Questions of

"What is the world made of?"

and

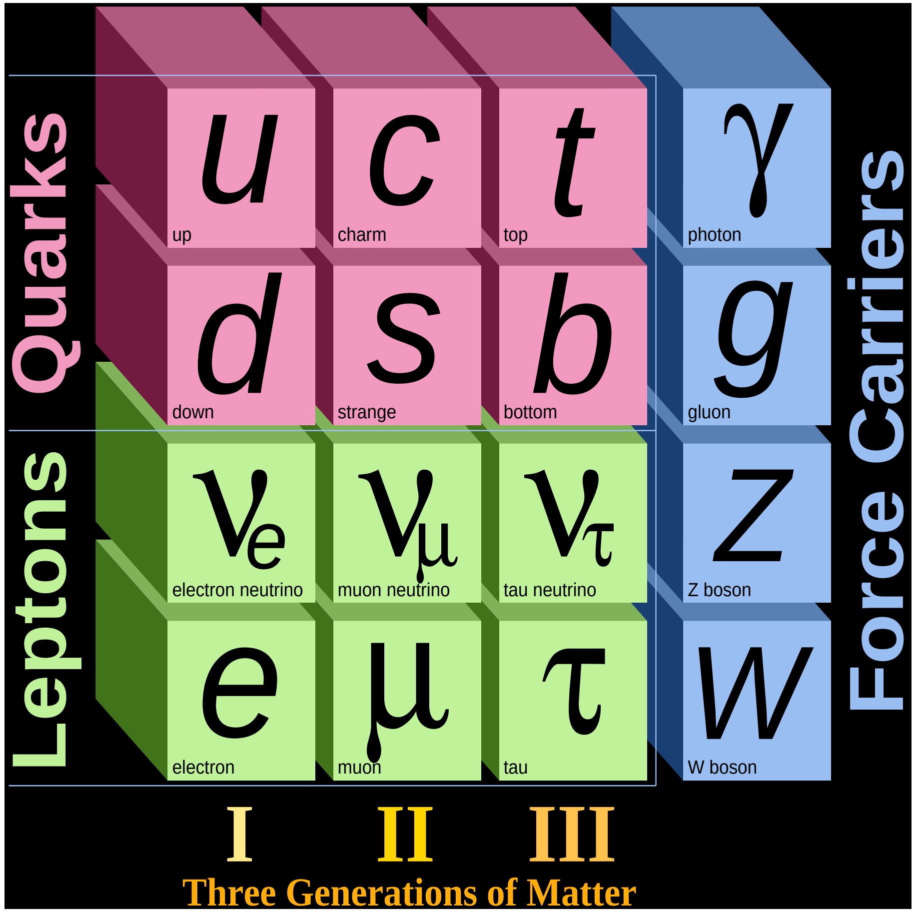
"What holds it together?"

The Particle Adventure

the fundamentals of matter and force

http://particleadventure.org/particleadventure/

- Answers to the Questions in 2011: Standard Model



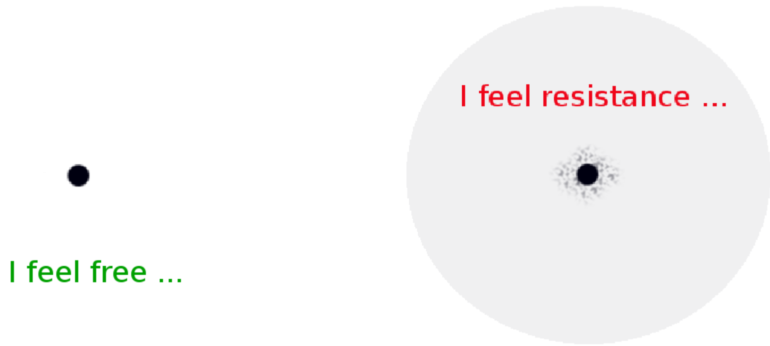
They are all Massive except γ and g

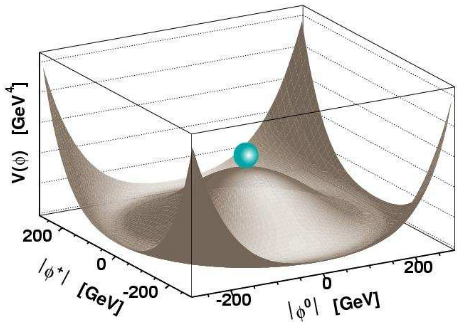
The *BIG* question is :

How do they become massive?

♠ *Higgs* $(3/5)$

- Spontaneous breaking of Electroweak symmetry Y. Nambu, PRL**4**(1960)380 *Nobel Prize 2008*
  We are NOT living in "True Void" $\Rightarrow$ The "Vacuum" is filled with Nonvanishing Field Strength of a scalar field called a Higgs boson : $\boxed{\langle H\rangle_0 \neq 0}$



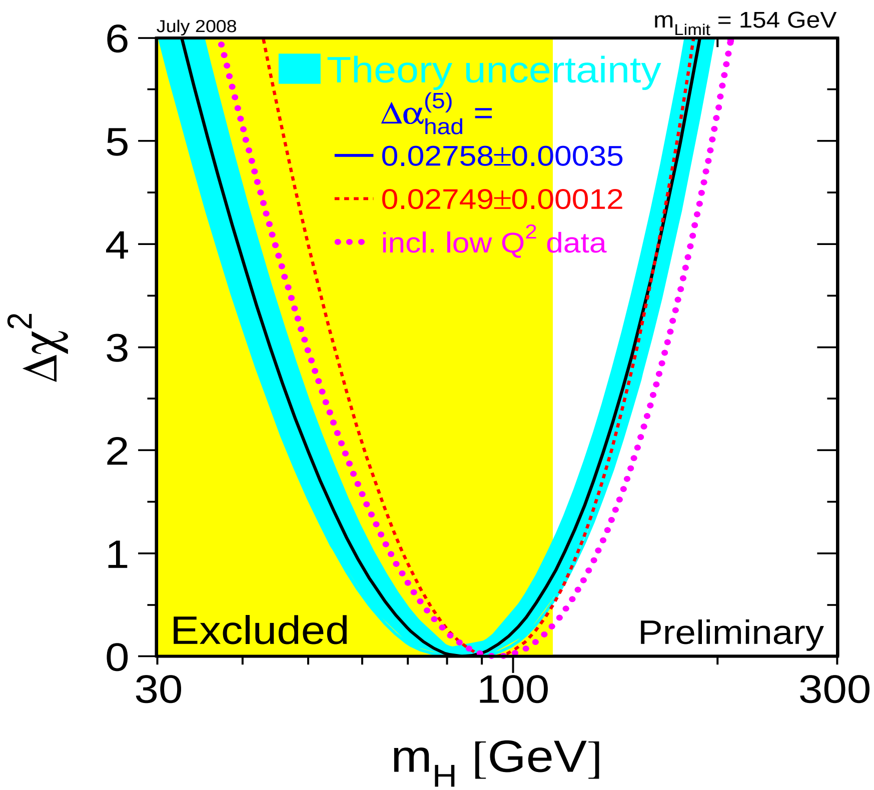


Yukawa interactions $\Rightarrow m_l$ and m_q

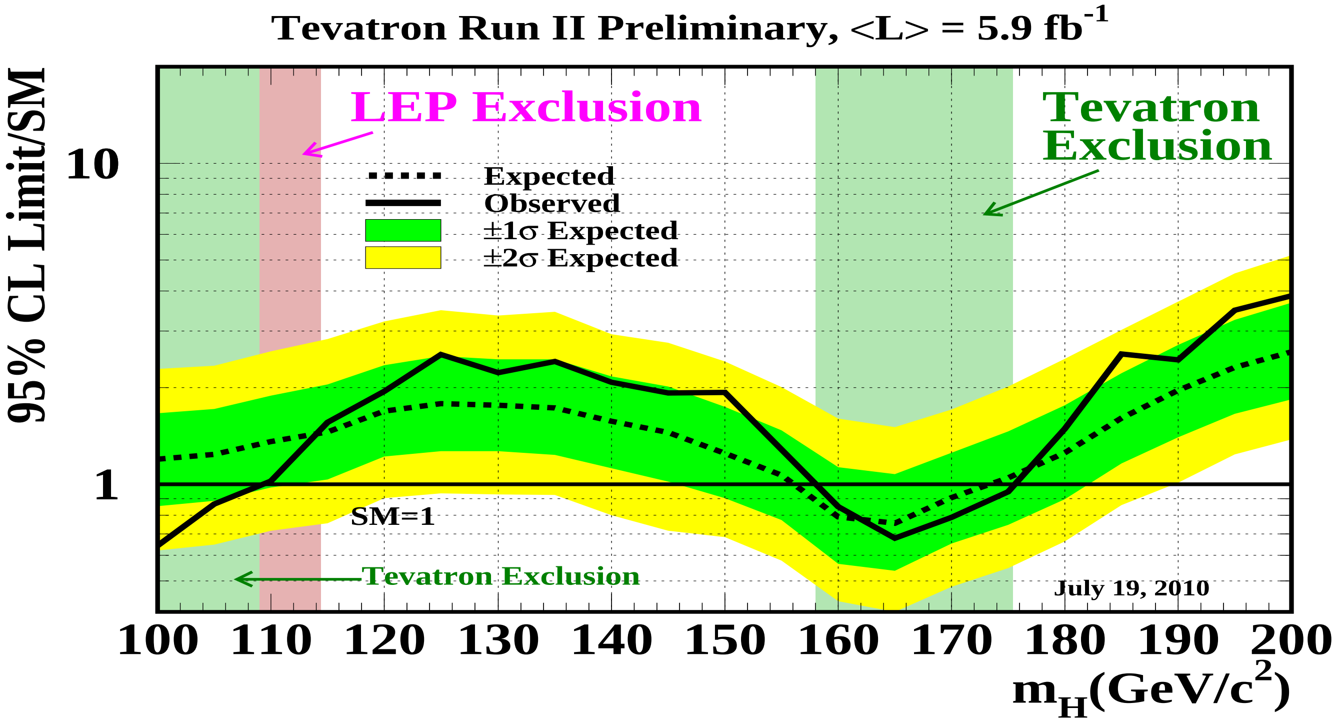
Gauge interactions $\Rightarrow M_W$ and M_Z

$*$ Something else may be needed for m_ν

- Status of the SM Higgs:
  - LEP bound: $M_H^{\rm SM} \geq 114.4$ GeV (95 % C.L.) ADLO, arXiv:hep-ex/0306033
  - Electroweak precision data: $M_H^{\rm SM} \lesssim 185$ GeV (95 % C.L.) direct-search limit included ACDDLOS, arXiv:0811.4682[hep-ex]

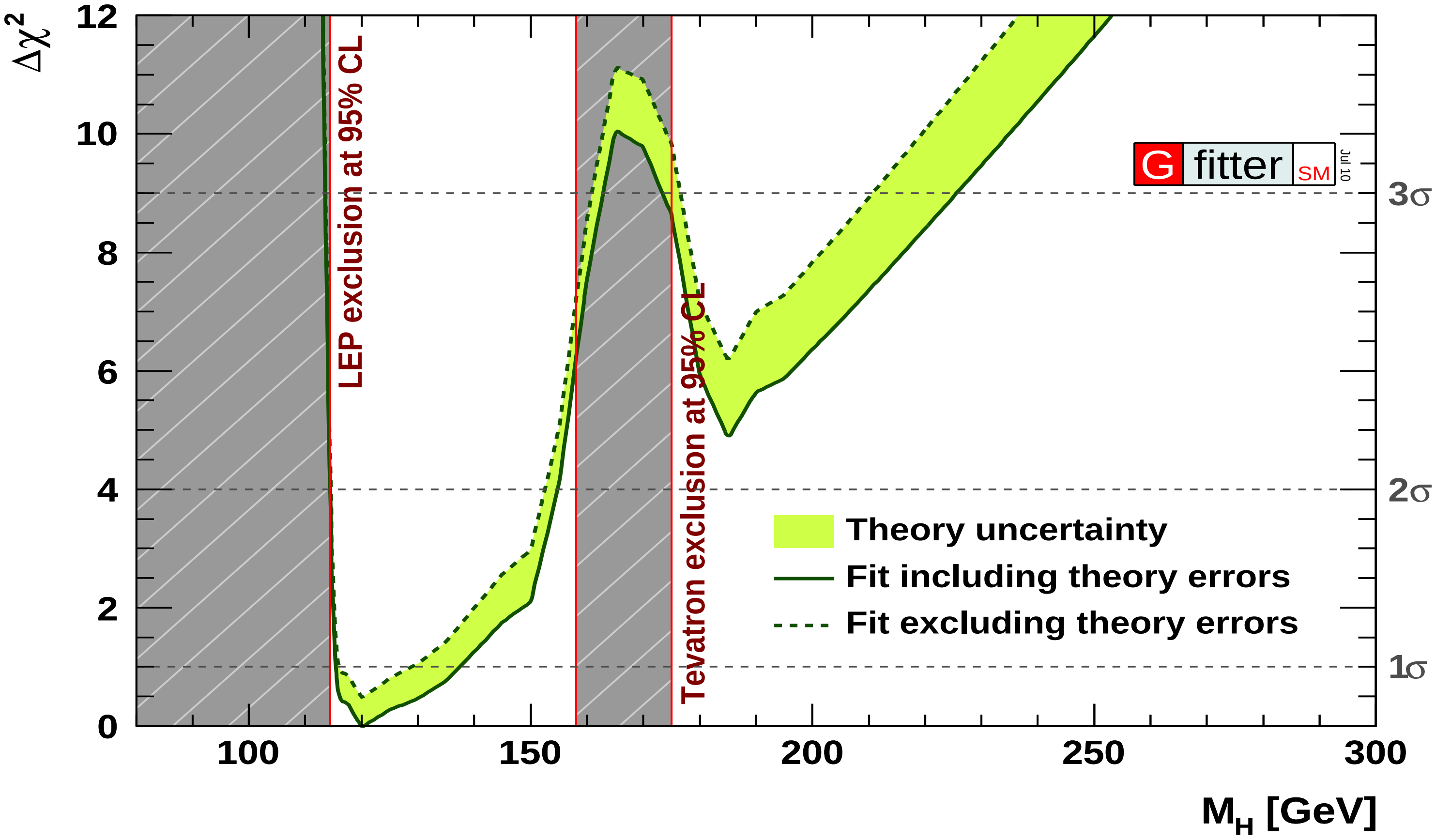


- Status of the SM Higgs: ... *continued*
  - Tevatron exclusion: 158 GeV $\lesssim M_H^{\rm SM} \lesssim$ 175 GeV (95 % C.L.) CDF/D0, arXiv:1007.4587[hep-ex]



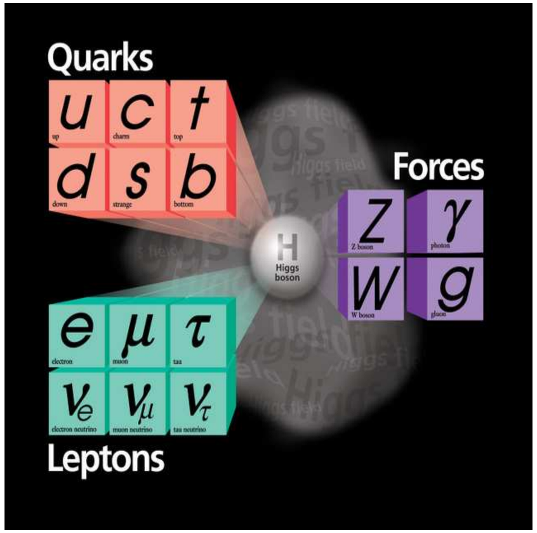
♠ *Higgs:* $(4''/5)$

- Status of the SM Higgs: *combining all...* Gfitter, arXiv:0811.0009



We anticipate the SM Higgs boson lighter than ∼ 200 GeV

Higgs = the God particle ? Leon Lederman, *The God Particle: If the Universe Is the Answer, What Is the Question?*



- *elusive ...*
- *controlling behind indirectly...*

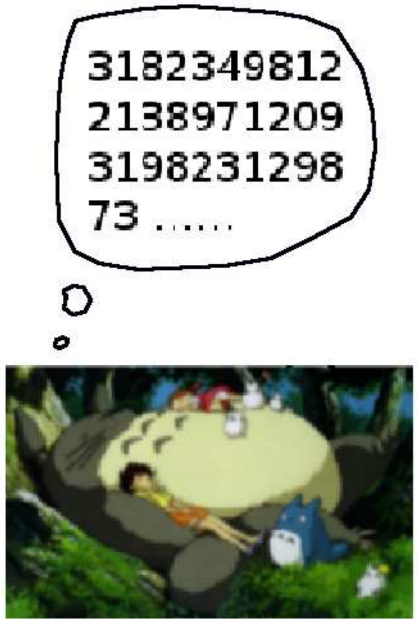
and ...

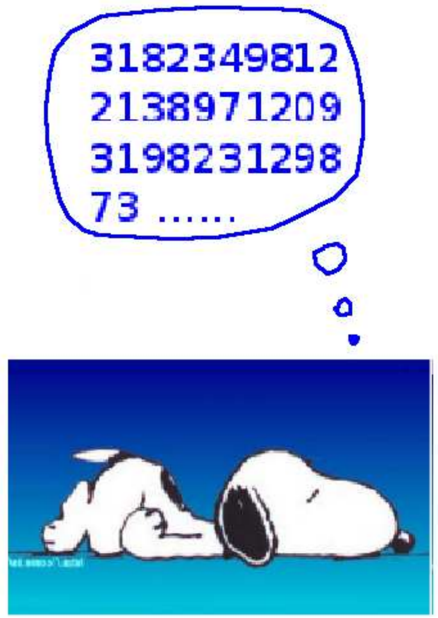
causing conceptual problems ...

♠ *Supersymmetry* (1/4)

- The Naturalness Problem

$$M_H^2 \sim {m_0}^2 - \frac{\Lambda^2}{16\pi^2} \quad \text{with} \quad \Lambda \sim 10^{19}\ \text{GeV} \quad \text{and} \quad M_H \sim 10^2\ \text{GeV}$$





$\mathcal{P} \ll$ a thunderbolt $\otimes$ a lottery ticket

Isn't it *natural* to assume
there is *something* ?

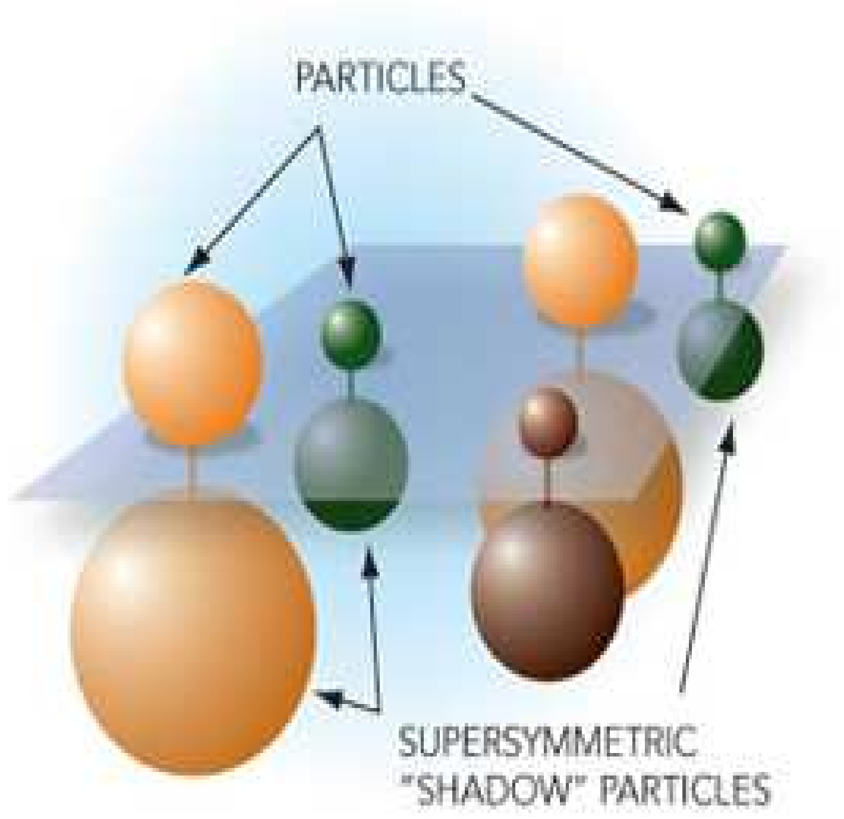
♠ *Supersymmetry* (2/4)

- Introducing Supersymmetry

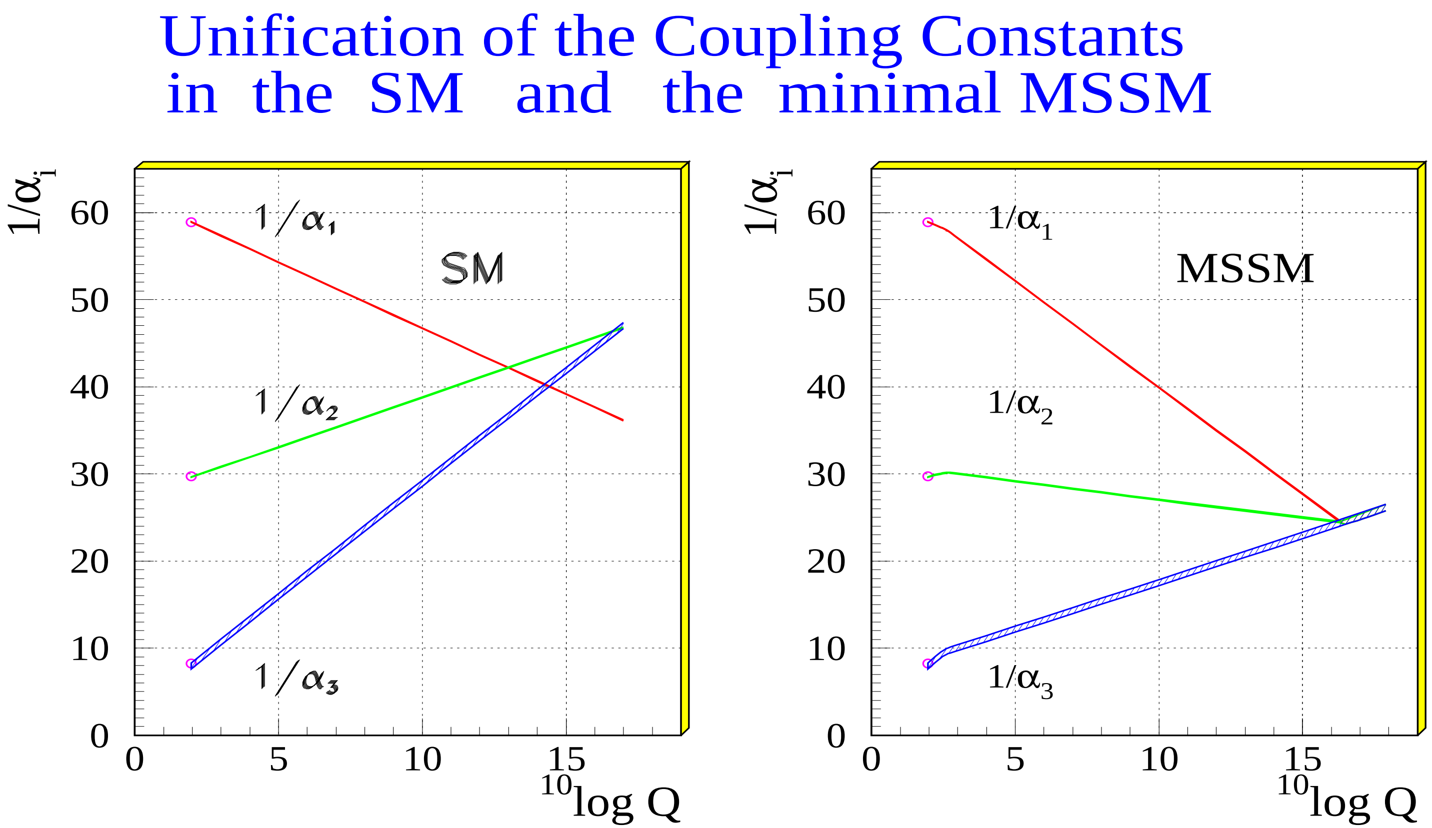
$$\delta M_H^2 \sim -\not{\Lambda}^2 \;\; (\text{Particles}) + \not{\Lambda}^2 \;\; (\text{"S"Particles}) + \underline{M_{\rm SUSY}^2} \, \log(\Lambda^2/M_{\rm SUSY}^2)$$

$M_{\rm SUSY} \sim \mathcal{O}(1)$ TeV

Great Discoveries at the LHC !

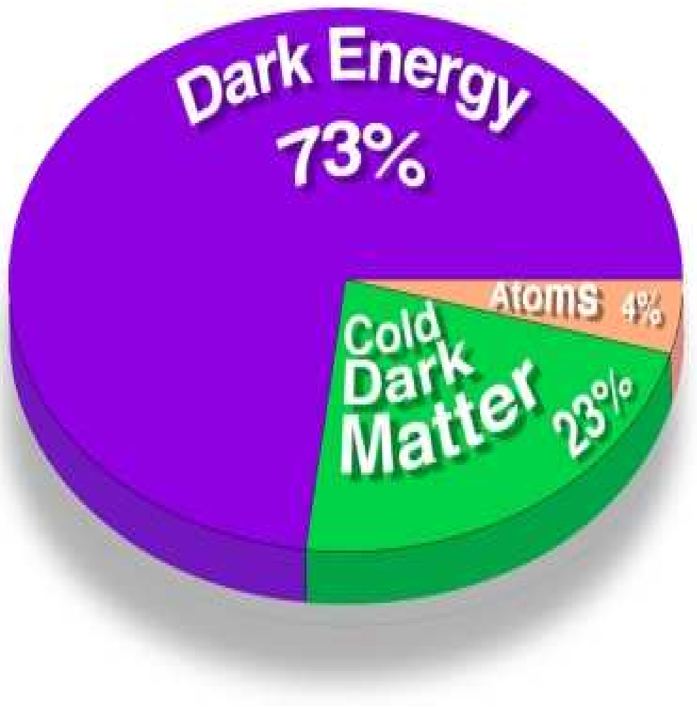


- <u>Support for the existence of "S" Particles (I)</u>



♠ *Supersymmetry* (4/4)

- <u>Support for the existence of "S" Particles (II)</u>



Source: Robert Kirshner
Source: NASA/WMAP Science Team

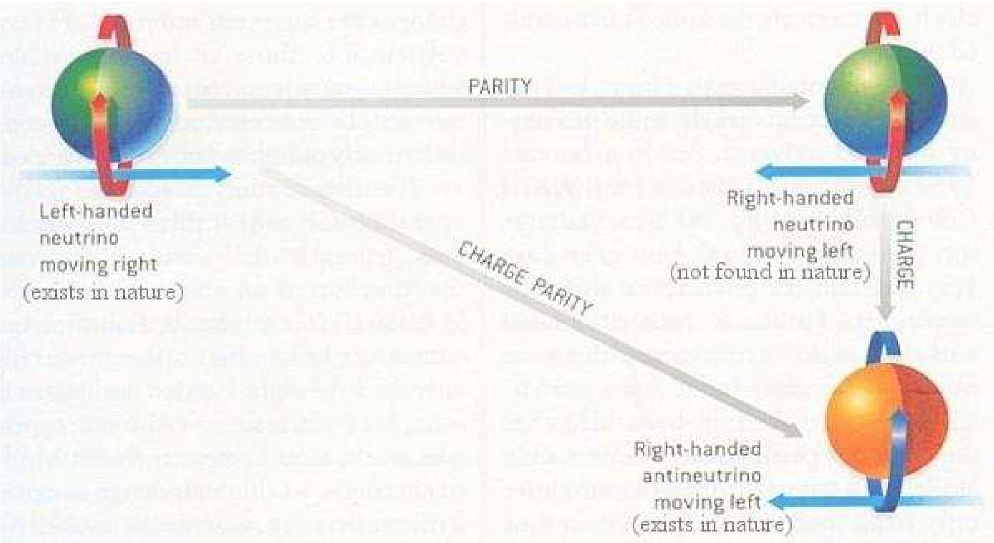
C. L. Bennett *et al.*, "First Year WMAP Observations: Preliminary Maps and Basic Results," Astrophys. J. Suppl. **148** (2003) 1 [arXiv:astro-ph/0302207];
M. Tegmark *et al.* [SDSS Collaboration], "Cosmological parameters from SDSS and WMAP," Phys. Rev. D **69** (2004) 103501 [arXiv:astro-ph/0310723];
P. Gondolo [arXiv:hep-ph/0501134]

$$
\begin{aligned}
\Omega_\Lambda &= 0.72 \pm 0.08 \\
\Omega_m &= 0.27 \pm 0.016 \\
&= \begin{cases} \Omega_b = 0.0448 \pm 0.0018 \\ \Omega_{\mathrm{CDM}} = 0.226 \pm 0.0016 \end{cases}
\end{aligned}
$$

CDM = Lightest Supersymmetric Particle ?

♠ *CP violation* (1/4)

- <u>What is CP Violation?</u>:



http://universe-review.ca

If *Nature* treated

Left-handed particle moving right and

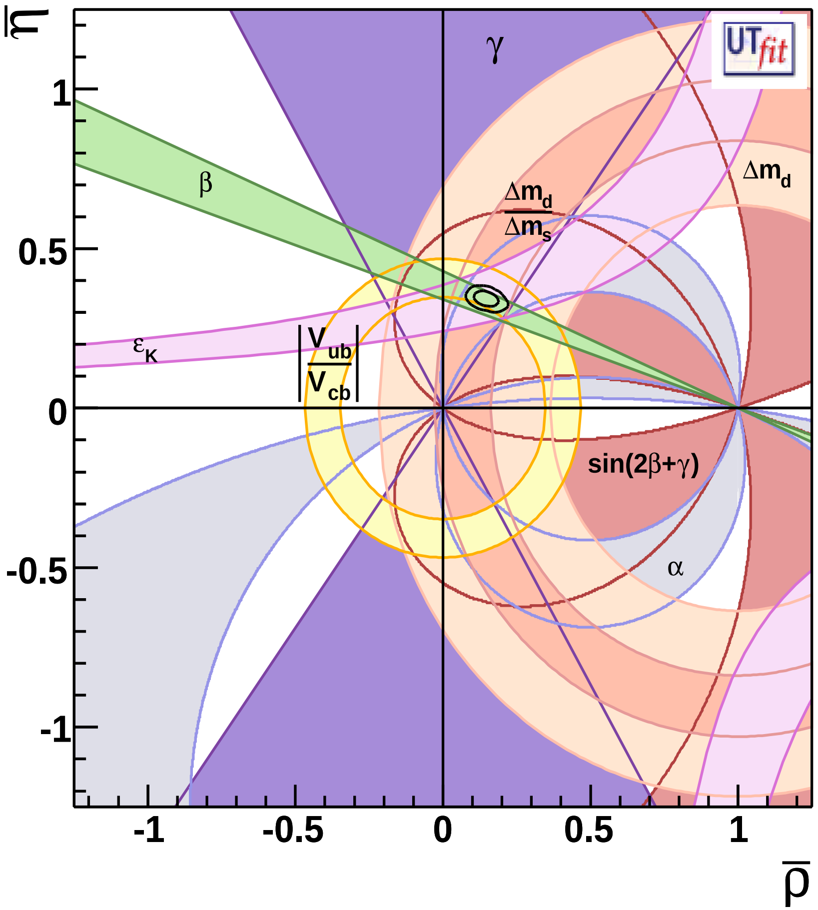
Right-handed antiparticle moving left

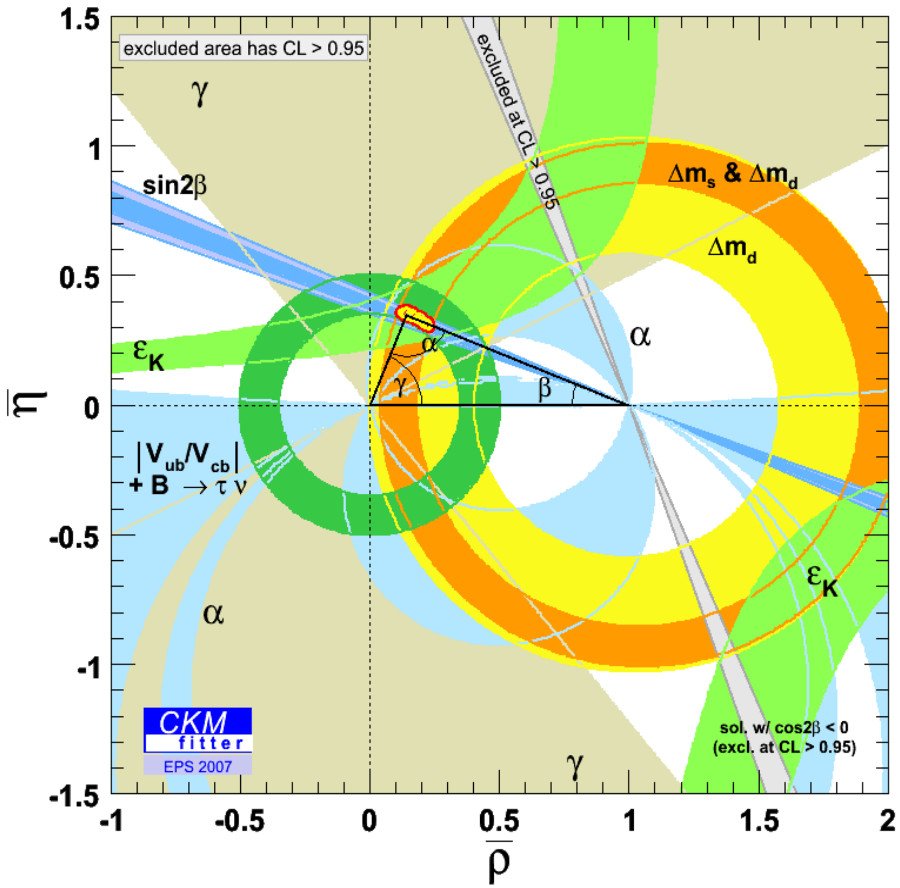
differently, we are saying

CP is violated

♠ *CP violation* (2/4)

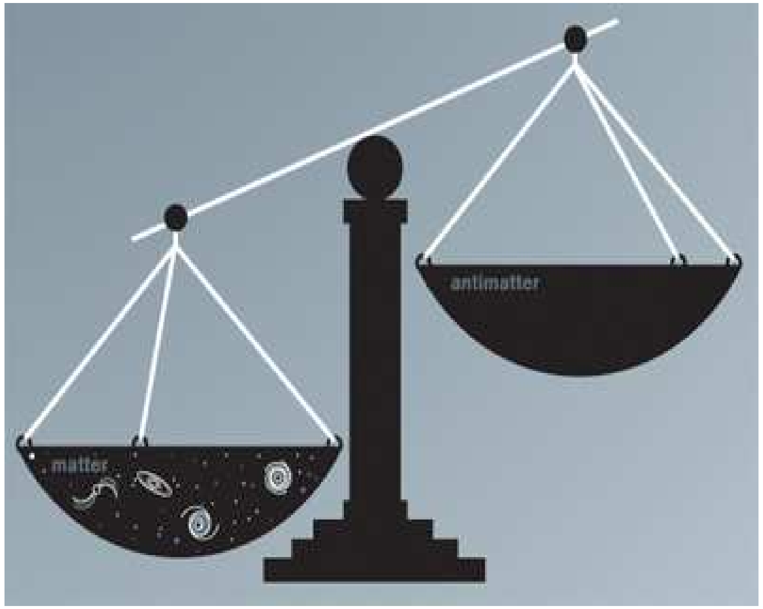
- Why CP Violation?: ⇒ There IS CP Violation! M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49** (1973) 652 *Nobel Prize 2008*





♠ *CP violation* (3/4)

- Then, who ordered "more" CP violation beyond the SM CKM phase? A. D. Sakharov, JETP Letters **5**(1967)24



CP violation in the SM is too weak to explain the matter dominance of the Universe J. Cline, arXiv:hep-ph/0609145

The matter-dominated Universe did!

♠ CP violation (4/4)

- Even the minimal SUSY model contains many possible sources of CP violation:

  – Gaugino mass terms: $3 \oplus 3 = 6$

$$-\mathcal{L}_{\rm soft} \supset \frac{1}{2}(M_3\,\widetilde{g}\widetilde{g} + M_2\,\widetilde{W}\widetilde{W} + M_1\,\widetilde{B}\widetilde{B} + {\rm h.c.})$$

  – Trilinear $\mathbf{a}$ terms $\mathbf{a}_{\mathbf{f}ij} \equiv \mathbf{h}_{\mathbf{f}ij} \cdot \mathbf{A}_{\mathbf{f}ij}$: $3 \times (3 \oplus 6 \oplus 9) = 54$

$$-\mathcal{L}_{\rm soft} \supset (\widetilde{u}_R^*\,\mathbf{a_u}\,\widetilde{Q}H_2 - \widetilde{d}_R^*\,\mathbf{a_d}\,\widetilde{Q}H_1 - \widetilde{e}_R^*\,\mathbf{a_e}\,\widetilde{L}H_1 + {\rm h.c.})$$

  – Sfermion mass terms: $5 \times (3 \oplus 3 \oplus 3) = 45$

$$-\mathcal{L}_{\rm soft} \supset \widetilde{Q}^\dagger\,\mathbf{M}^2_{\widetilde{\mathbf{Q}}}\,\widetilde{Q} + \widetilde{L}^\dagger\,\mathbf{M}^2_{\widetilde{\mathbf{L}}}\,\widetilde{L} + \widetilde{u}_R^*\,\mathbf{M}^2_{\widetilde{\mathbf{u}}}\,\widetilde{u}_R + \widetilde{d}_R^*\,\mathbf{M}^2_{\widetilde{\mathbf{d}}}\,\widetilde{d}_R + \widetilde{e}_R^*\,\mathbf{M}^2_{\widetilde{\mathbf{e}}}\,\widetilde{e}_R$$

1 KM phase (SM) $\Longrightarrow$ 1 + 45 (Minimal SUSY Model)

♠ *LHC* (1/6)

- LHC = the Large Hadron Collider

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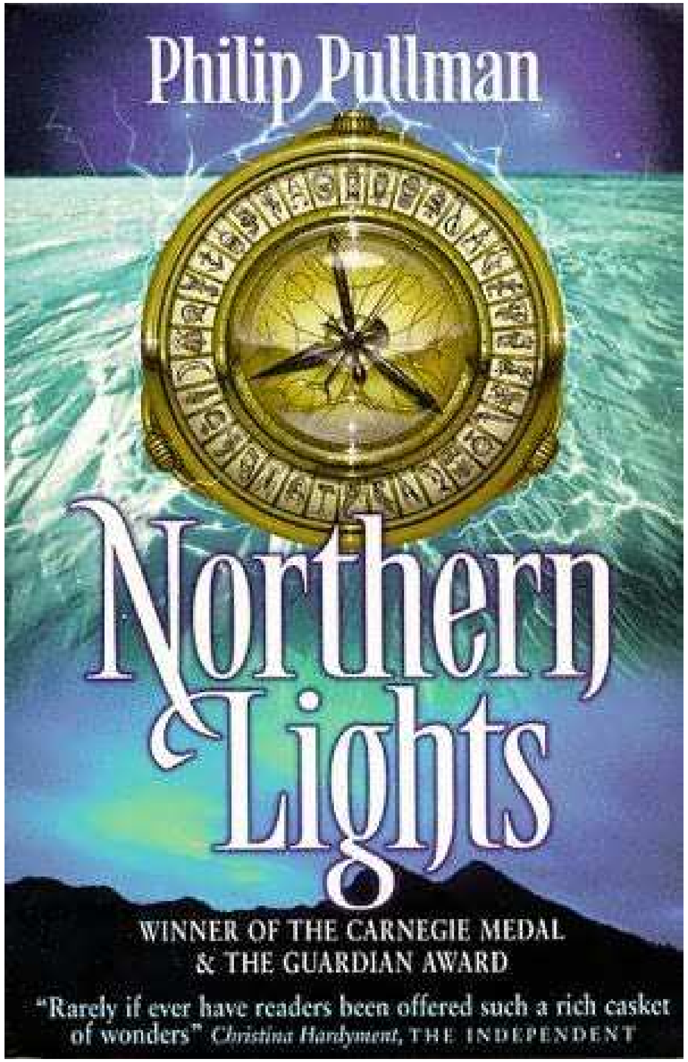


"Human beings can't see anything without wanting to destroy it, Lyra, *That's* original sin. And I'm going to destroy it."

... Lord Asriel

HIS DARK MATERIALS trilogy #1

♠ *LHC* (2/6)

- Two protons collide with a kinetic energy of 14 TeV 1 GeV $\simeq$ a proton mass

- then the two protons are $destroyed$ to disappear and we will see something ...

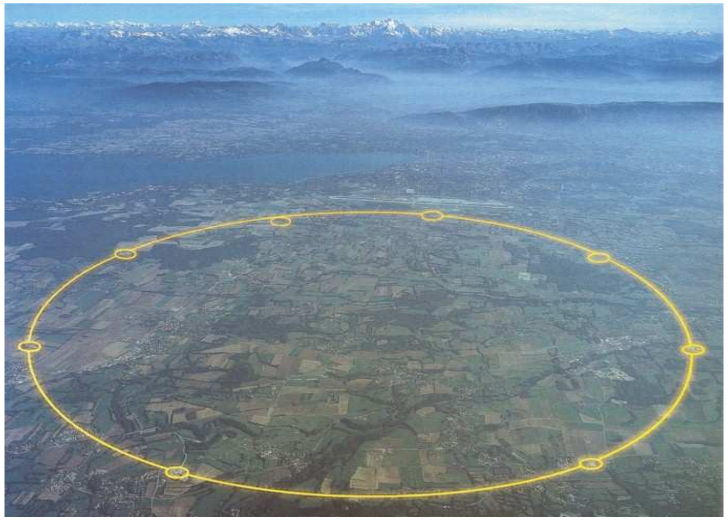
♠ *LHC* (3/6)

- Past and present ...

  1989 : R&D starts
  1997 : Construction starts
  2003 : Underground installation starts
  2008 : Installation completed

  11 Sep 2008 : First beam circulated
  20 Sep 2008 : Magnet failures ...

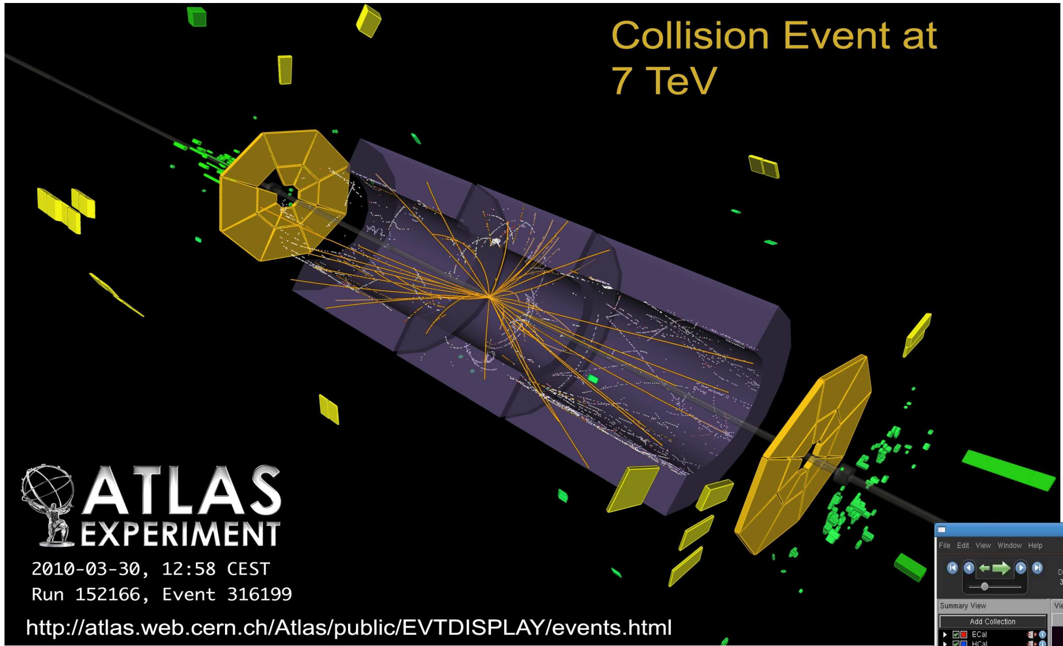
  23 Nov 2009 : First collisions at $\sqrt{s} = 900$ GeV
  8 Dec 2009 : First collisions at $\sqrt{s} = 2.36$ TeV
  30 Mar 2010 : First collisions at $\sqrt{s} = 7$ TeV

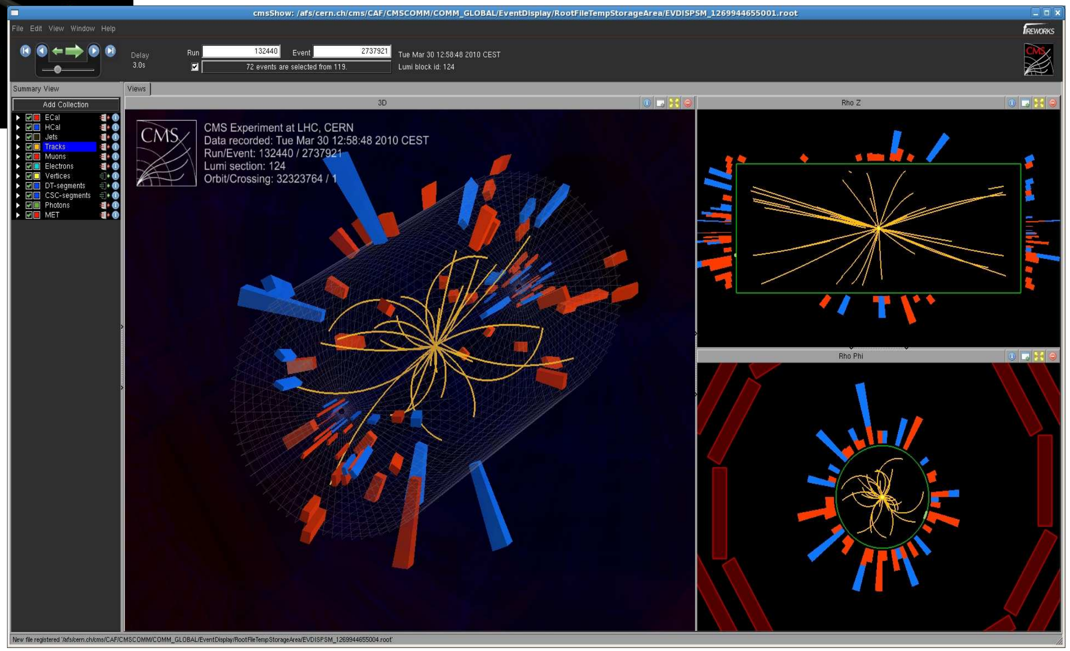


LHC.JPG

From Junichi Kanzaki's talk @ KEKPH2010

♠ LHC $(3'/6)$


Collision Event at
7 TeV
ATLAS
EXPERIMENT
2010-03-30, 12:58 CEST
Run 152166, Event 316199
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html


CMS Experiment at LHC, CERN
Data recorded: Tue Mar 30 12:58:48 2010 CEST
Run/Event: 132440 / 2737921
Lumi section: 124
Orbit/Crossing: 32323764 / 1
CMS

♠ *LHC* (4/6)

- ... and near/far future of the LHC

2010 ∼ 2011 : 7 TeV (3.5+3.5 TeV) runs until 1 fb^{-1} ***LHC 1/2***

⇒ For SUSY searches with 35 pb^{-1}, see next page

2012 ∼ 2012 : Shutdown for repairing to achieve 7 (6.5) TeV/beam collisions

2013 ∼ 2014 : Go to 7 (6.5) + 7 (6.5) TeV runs to get ~ 10 fb^{-1} ***LHC***

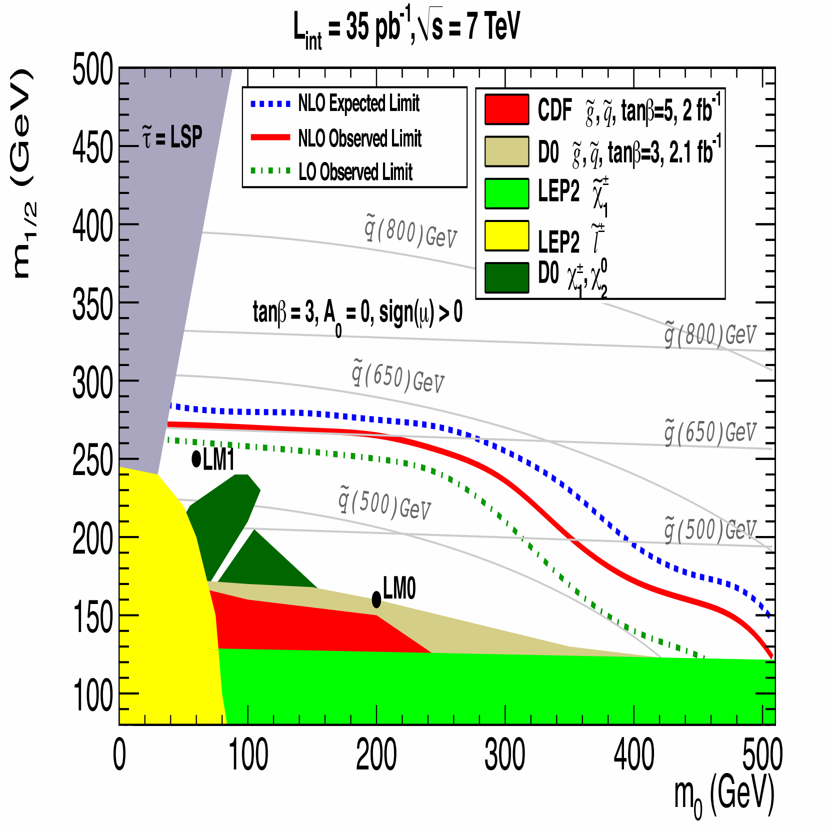
2015 ∼ 202? : accumulate 3000 fb^{-1} with $250 \sim 300$ fb^{-1} per year

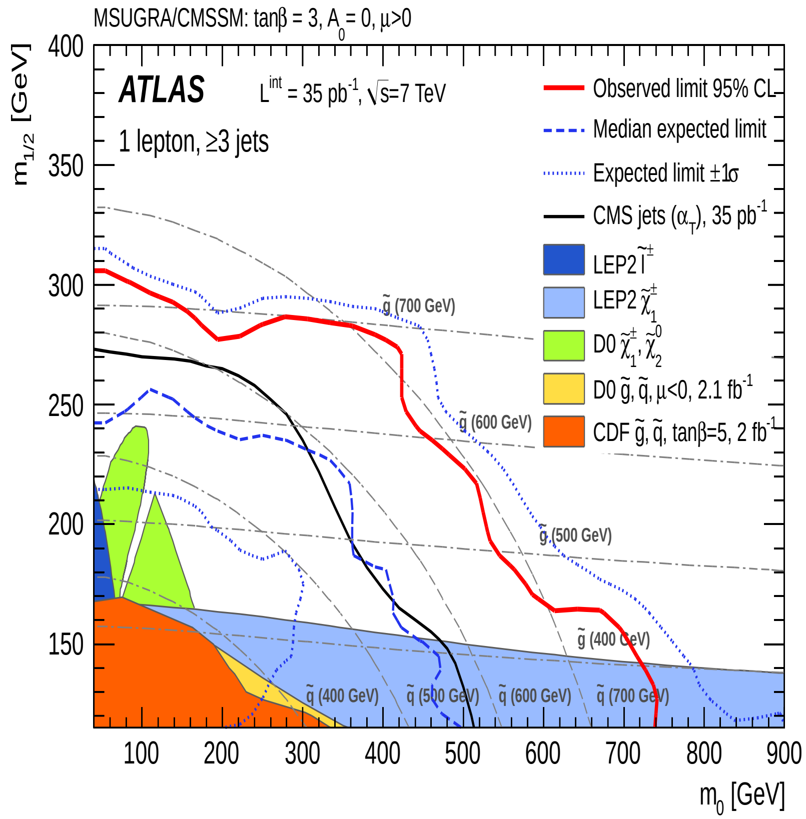
again, from Junichi Kanzaki's talk @ KEKPH2010, or
LHC Performance Workshop - Chamonix 2010 (Jan)

♠ *Initial SUSY searches with 35 pb^{-1} at the LHC*

- CMS (jets + missing E_T; left) and ATLAS (lepton + jets + missing E_T; right)

CMS, PLB698(2011)196,2011, arXiv:1101.1628 [hep-ex] and ATLAS, arXiv:1102.2357 [hep-ex]





ATLAS, more stringent ...

♠ *LHC* (4′/6)

- ... and near/far future of the LHC

2010 ∼ 2011 : 7 TeV (3.5+3.5 TeV) runs until 1 fb^{-1} ***LHC 1/2***

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again, from Junichi Kanzaki's talk @ KEKPH2010, or

LHC Performance Workshop - Chamonix 2010 (Jan)

♠ *LHC* $(5/6)$

- ... and near/far future of the LHC: *... continued*

3000 fb^{-1} $\approx$ 2,400,000,000 $t\bar{t}$ pairs : Top factory

$\approx$ 100,000,000 130 GeV SM Higgs bosons

$\approx$ 3,000,000 $\mathcal{O}(1)$ TeV gluinos + squarks

$\approx$ 300,000 $\mathcal{O}(1)$ TeV charginos + neutralinos

♠ *LHC* (6/6)

- ... and near/far future of the L

3000 fb^{-1} ≈ 2,400,000,000 $t\bar{t}$

≈ 100,000,000 130

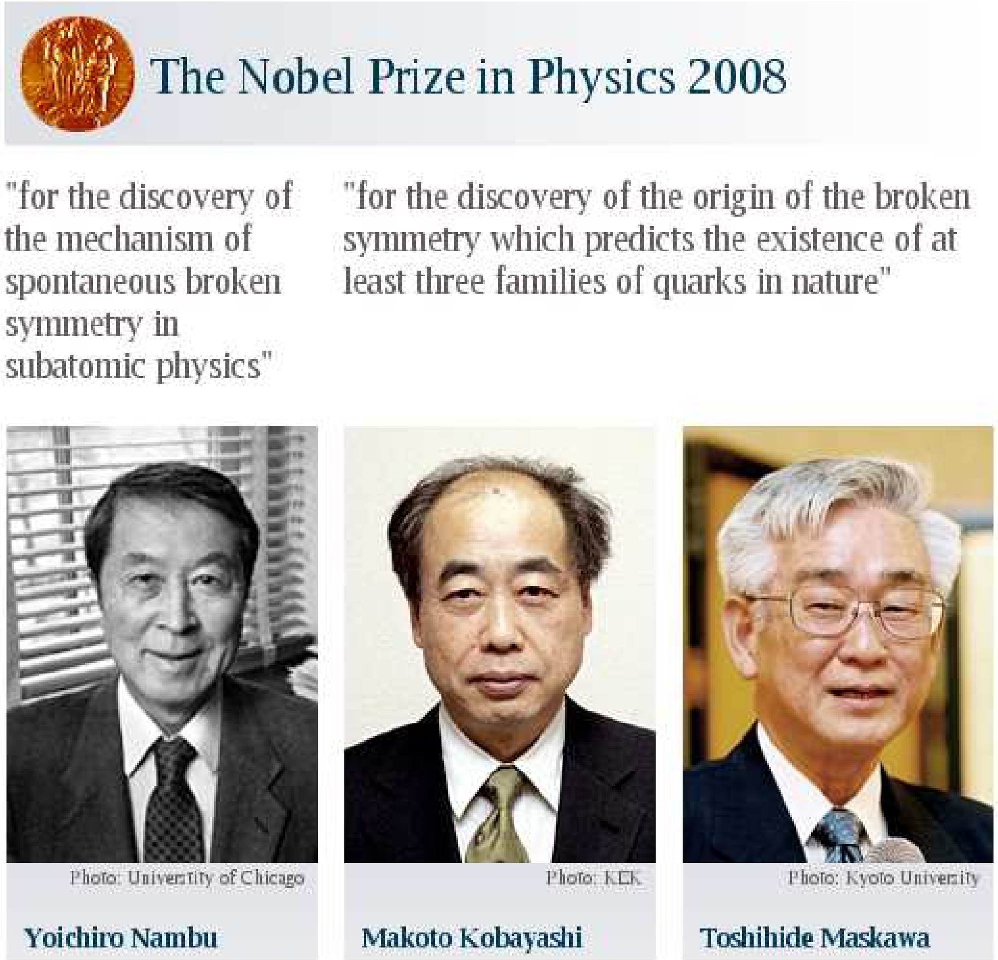
≈ 3,000,000 $\mathcal{O}(1)$ T

≈ 300,000 $\mathcal{O}(1)$ Te

THE 2nd PART

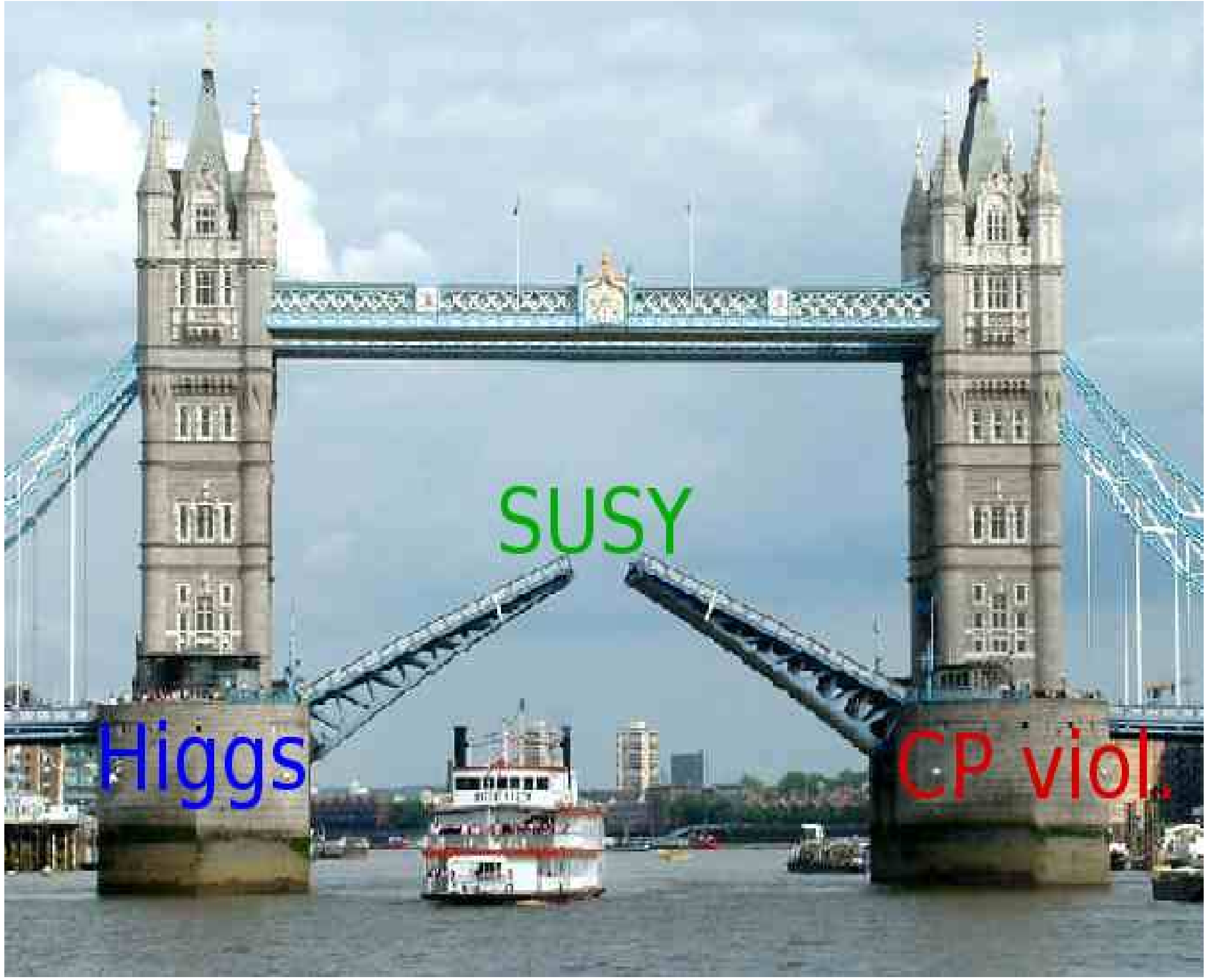
♠ *Preliminary* (1/4)

- The Nobel Prize in Physics 2008: *"Passion for symmetry"* *(broken?)*



♠ *Preliminary* (2/4)

- My works aim at ...:



♠ *Preliminary* (3/4)

- Introducing SUSY $\Longrightarrow$ Introducing lots of additional CP phases ! :

$$1 \text{ KM phase (SM)} \Longrightarrow 1 + 45 \text{ (Minimal SUSY Model)}$$

My Question:

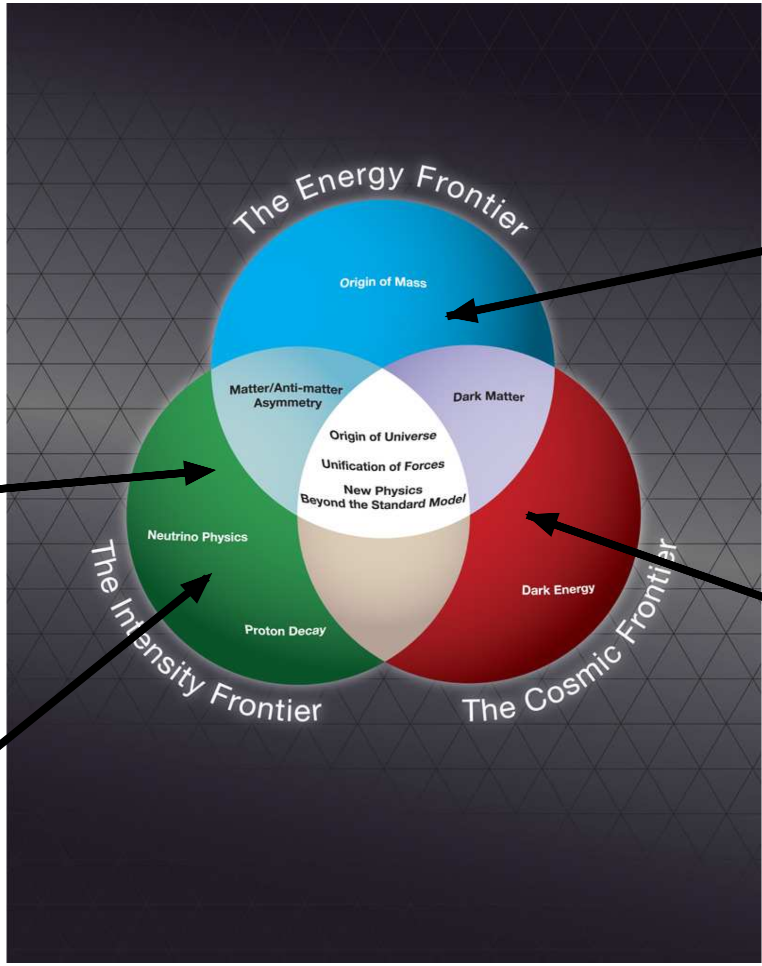
How does the SUSY CP violation manifest itself through the Higgs sector ?

more specifically,

Where to find it? and Why through Higgs sector?

♠ Preliminary (4/4)

- Where to find it?



http://www.er.doe.gov/hep/vision/index.shtml

Colliders : LHC

$\left\{ \begin{array}{l} SM\ Higgs \\ MSSM\ Higgs \\ CPV\ Signatures \end{array} \right.$

B-meson Obsrvables

$\left\{ \begin{array}{l} \Delta M_{B_{d,s}}\,,\, B_s \to \mu^+\mu^-\,, \\ B \to \tau\nu\,,\, B \to X_s\gamma\,, \\ \cdots \end{array} \right.$

Dark Matter

$\{\ \chi\chi \to \gamma\,,\bar{p}\,, etc$

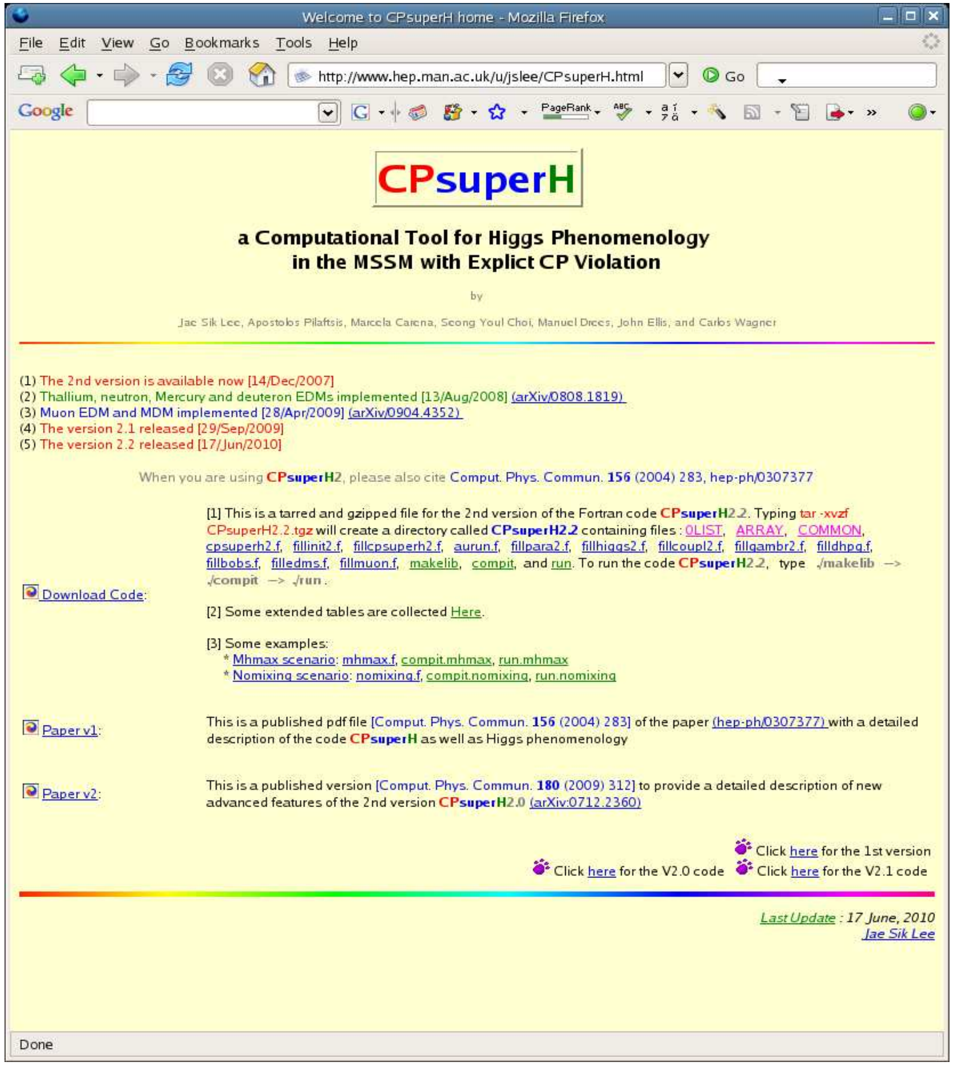
Electric Dipole Moments

♠ *Preliminary* $(4'/4)$

- Why through Higgs sector?
  - `Experimental Side:` LHC
    - Higgs boson will be searched most intensively
    - Higgs boson will be studied most extensively
  - `Theoretical Side:` Quantum sensitivity
    - Large quantum correction
    - Resonant enhancement

♠ CPsuperH

- Tool: CPsuperH : △ RG-improved effective potential approach



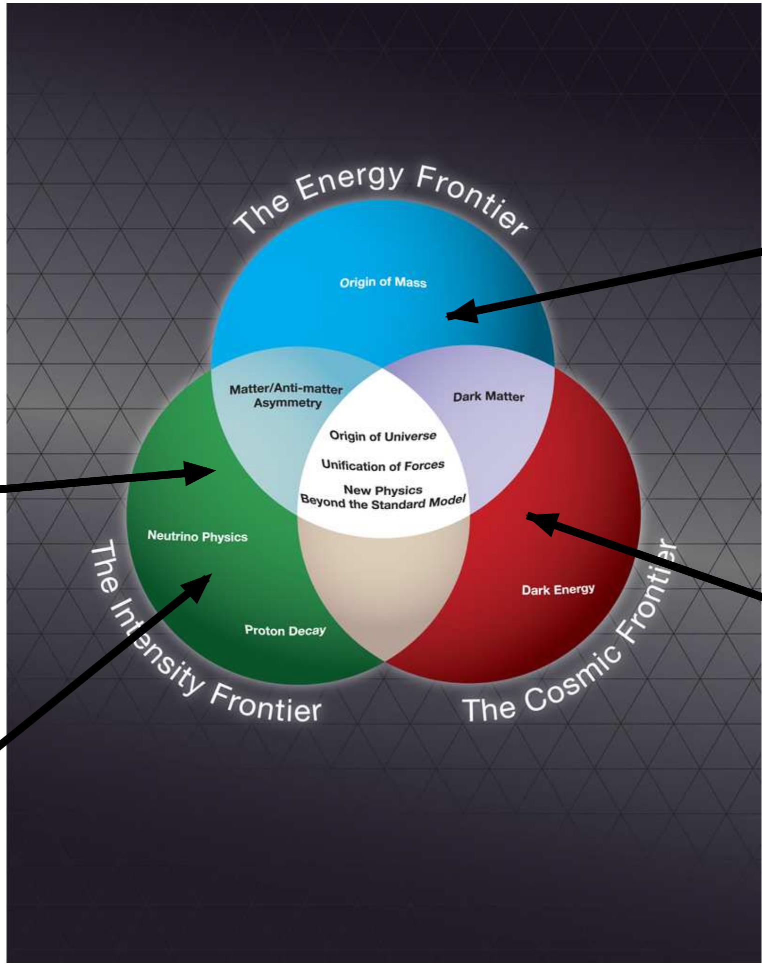
– For *experimentalists* as well as phenomenologists who are exploring the MSSM Higgs sector both in *CP-conserving* and CP-violating cases V. M. Abazov *et al.* [D0 Collaboration], "Search for neutral supersymmetric Higgs bosons in multijet events at s**(1/2) = 1.96-TeV," Phys. Rev. Lett. **95** (2005) 151801 [arXiv:hep-ex/0504018];

A. Abulencia *et al.* [CDF Collaboration], "Search for charged Higgs bosons from top quark decays in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96-TeV," Phys. Rev. Lett. **96** (2006) 042003 [arXiv:hep-ex/0510065].

– *Consistent* computational tool for both Energy- and Intensity-Frontier experiments including several B observables and EDMs

♠ *Where to find it ?*

II-A Colliders



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Colliders : LHC

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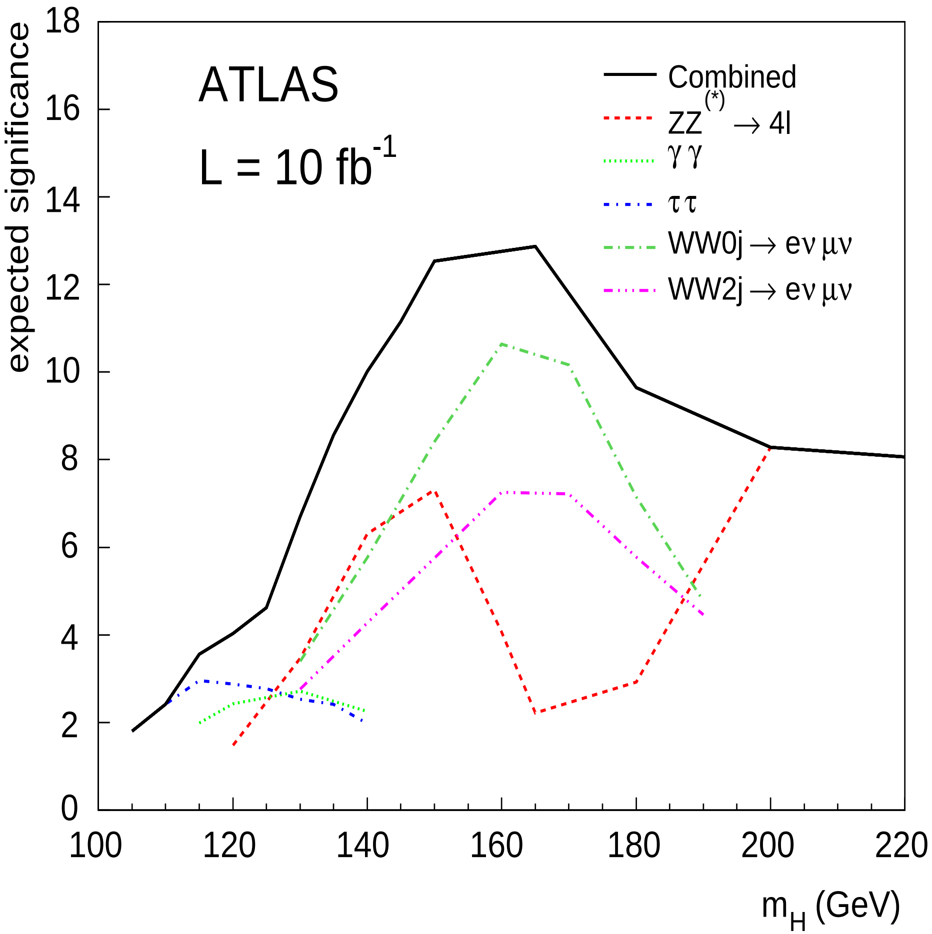
Dark Matter

$\{\ \chi\chi \to \gamma\,,\bar{p}\,, etc$

Electric Dipole Moments

♠ *SM Higgs* $(1/2)$

- LHC Discovery Significance of the SM Higgs ATLAS TDR, arXiv:0901.0512[hep-ex]



- $H \rightarrow \tau\tau$
- $H \rightarrow \gamma\gamma$

▷ $H \rightarrow WW^* \rightarrow l\nu l\nu$ (GF)

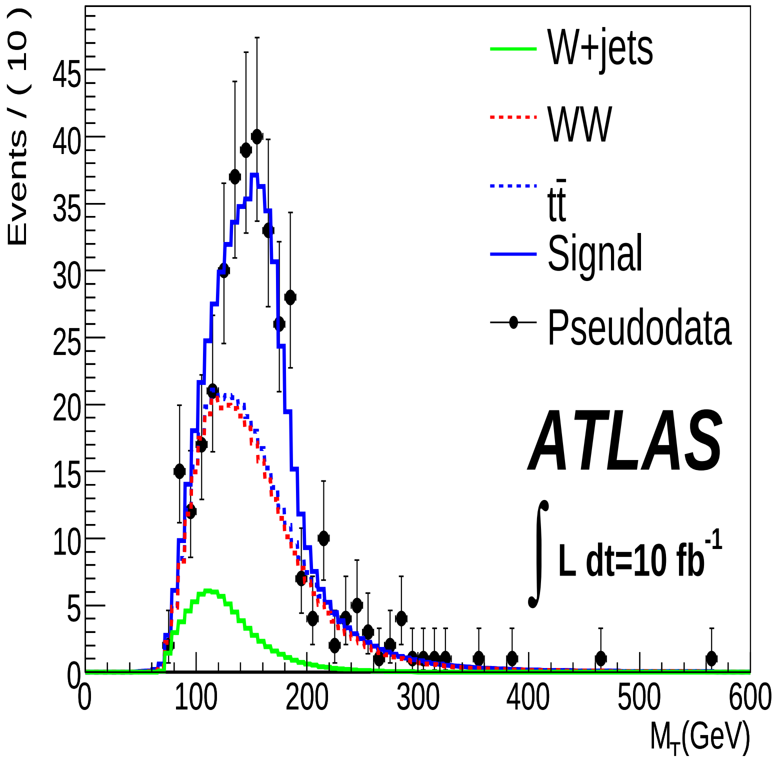
▷ $H \rightarrow WW^* \rightarrow l\nu l\nu$ (VBF)

□ $H \rightarrow ZZ^{(*)} \rightarrow 4\,l$

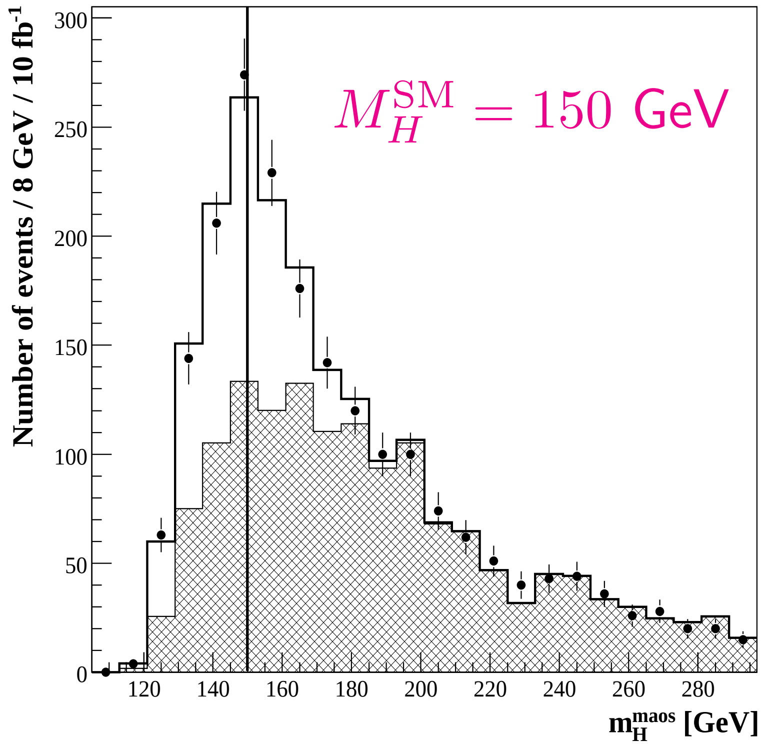
The WW channel plays a dominant role for 130 GeV $\lesssim M_H \lesssim 190$ *GeV !*

♠ *SM Higgs* (2/2)

- The 2 missing neutrinos: Transverse mass vs. MAOS Higgs mass



End point



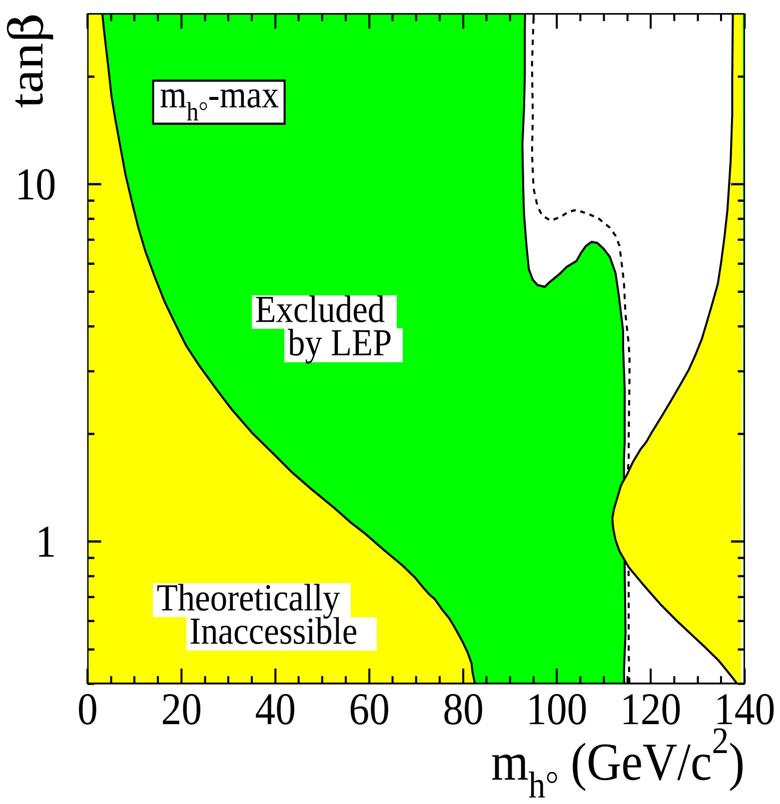
Mass peak

K. Choi, S. Choi, JSL, C.B. Park, PRD**80** (2009) 073010;

K. Choi, JSL, C.B. Park, arXiv:1008.2690 [hep-ph], to appear in PRD

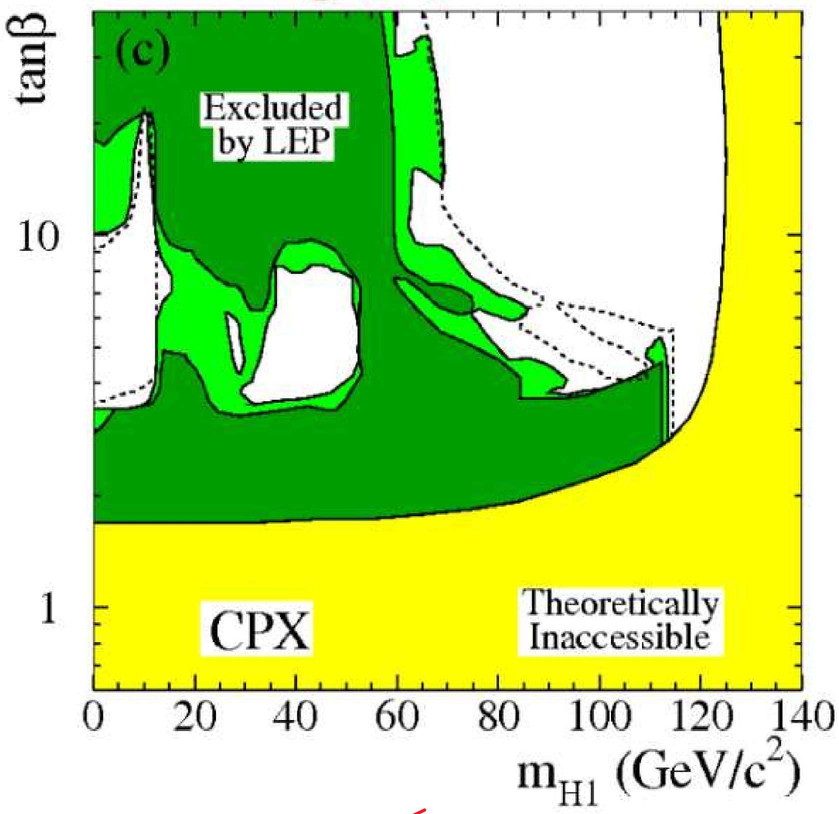
- LEP Limits on the MSSM Higgs: A. Djouadi, hep-ph/0503173 and references there in: P. Bechtle, CPNSH Report, CERN-2006-009, hep-ph/0608079; ADLO, hep-ex/0602042, Combined results with FeynHiggs

CP Conserving



$M_{H_1} \gtrsim$ 90 GeV ?

arg(A)=90

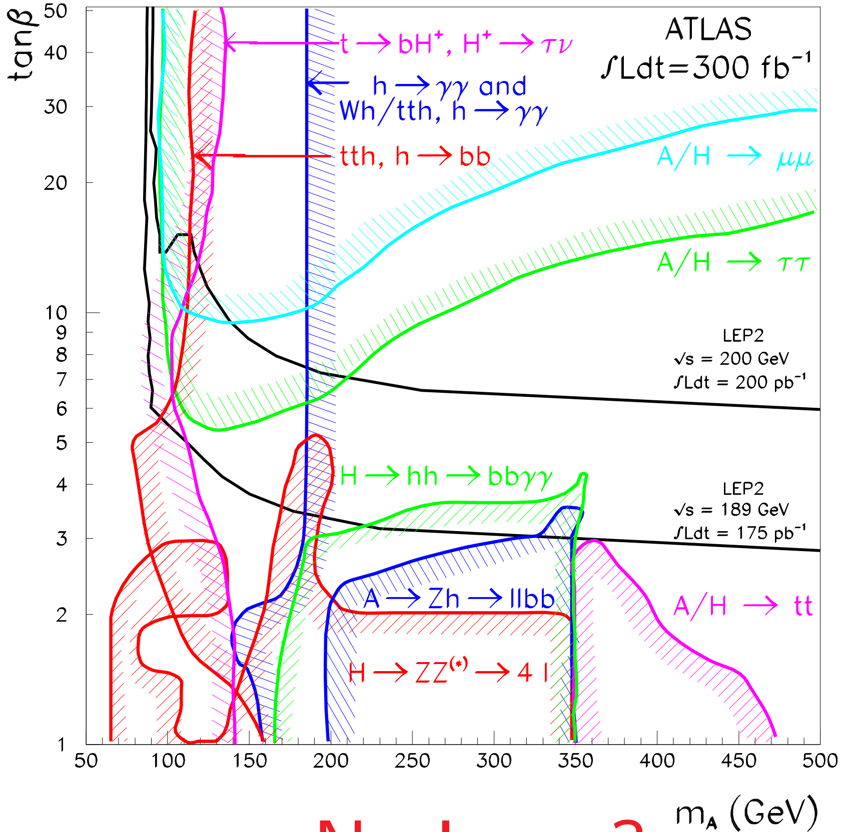


$M_{H_1} \lesssim$ 10 GeV !

♠ MSSM Higgs (2/2)

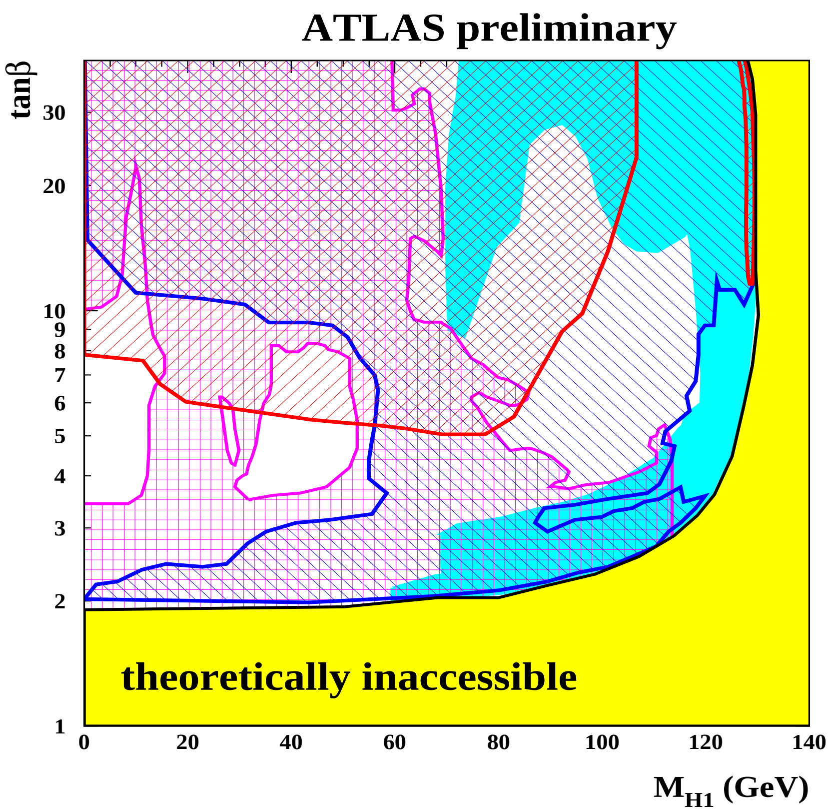
- LHC Discovery of the MSSM Higgs: ATLAS TDR(1999); M. Schumacher, CPNSH Report, CERN-2006-009, hep-ph/0608079

CP Conserving



No Lose ?

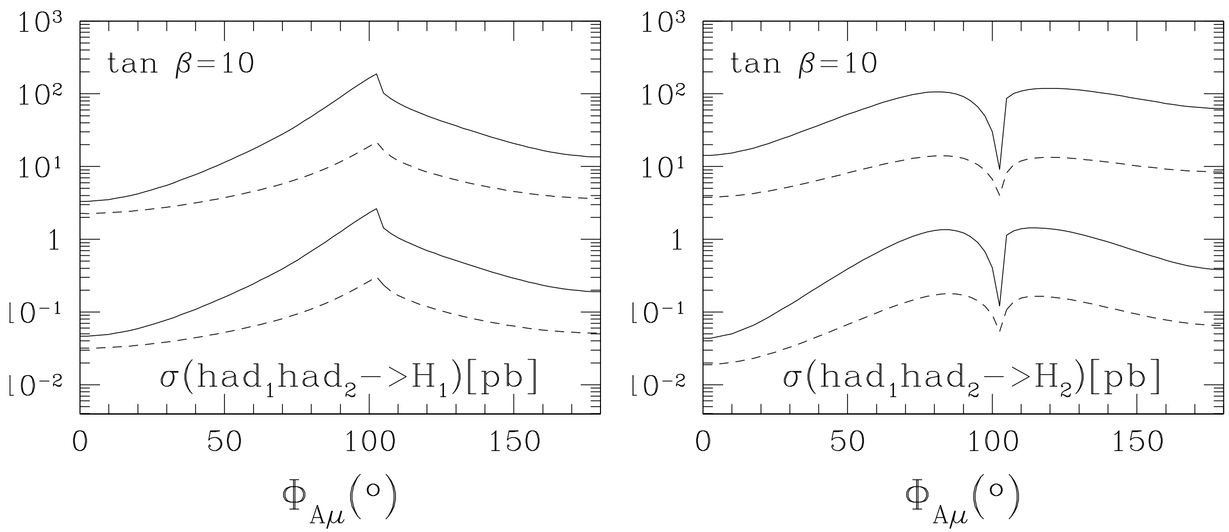
CP Violating



No Higgs !

♠ b-quark Fusion (1/2)

- Strong dependence of Higgs-boson production via b-quark fusion on CP phases: CPX Scenario with $\Phi_3 = 0^\circ$ or $\Phi_3 = 180^\circ$ and $M_{H_1} = 115$ GeV. F. Borzumati and JSL, PLB595(2004)347 and PLB641(2006)486



$*$ Solid: $\Phi_3 = 180^\circ$ and Dashed: $\Phi_3 = 0^\circ$

$*$ Around $\Phi_{A\mu} = 100^\circ$, $M_{H_2} - M_{H_1} \simeq 3$ GeV $\Longrightarrow$ Distinguishable ?

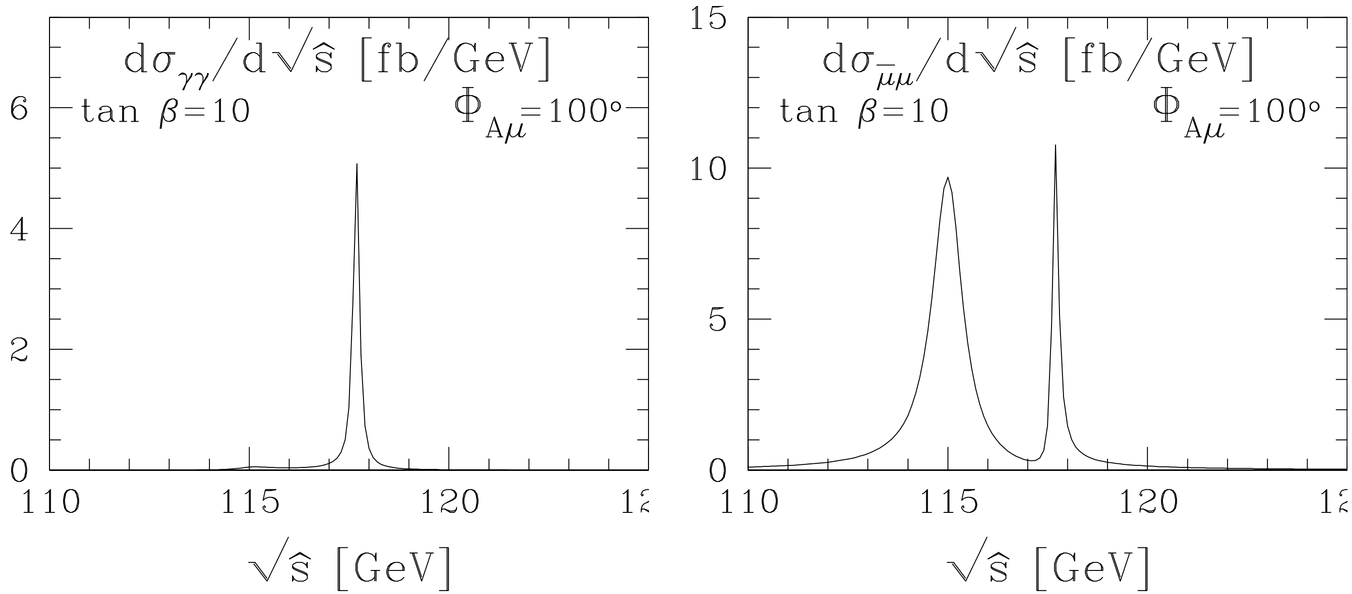
♠ *b-quark Fusion* (2/2)

- Invariant mass distribution when Higgs bosons decay into two γ's and/or $\mu^+\mu^-$

At the LHC, the experimental resolution $\delta M_{\gamma\gamma} \sim 1$ GeV and $\delta M_{\mu\mu} \sim 3$ GeV

ATLAS TDR, Vol 2, CERN-LHCC-99-15, ATLAS-TDR-15 (1999); CMS Physics TDR, Volume II, CERN-LHCC-2006-021, 25 June 2006

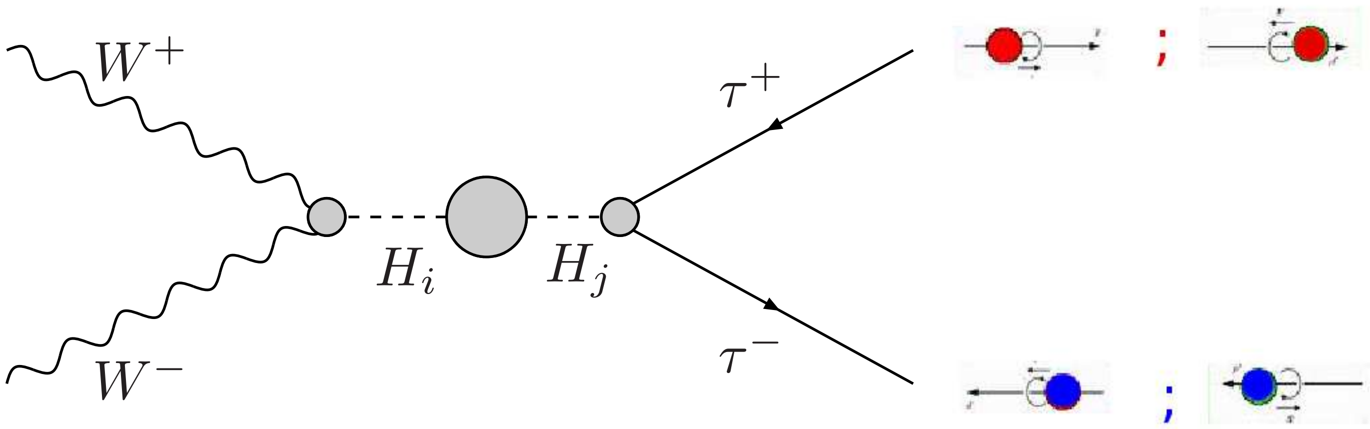
$H_{1,2} \to \gamma\gamma$ $\qquad$ $H_{1,2} \to \mu^+\mu^-$



One peak $\qquad$ *Two peaks*

♠ *CP Asymmetries* (1/3)

- CP asymmetry in Higgs decays in the tau leptons : J. Ellis, JSL and A. Pilaftsis, D71(2005)075007



σ_{RR} σ_{LL}

$$\mathcal{A}_{\rm CP} = \frac{\sigma_{RR} - \sigma_{LL}}{\sigma_{RR} + \sigma_{LL}} \quad \text{with} \quad \begin{cases} \sigma_{RR} \equiv \sigma(pp \to H \to \tau_R^+ \tau_R^- X) \\ \sigma_{LL} \equiv \sigma(pp \to H \to \tau_L^+ \tau_L^- X) \end{cases}$$

♠ *CP Asymmetries* (2/3)

- Resonant transitions between Higgs bosons enhance the asymmetry!:

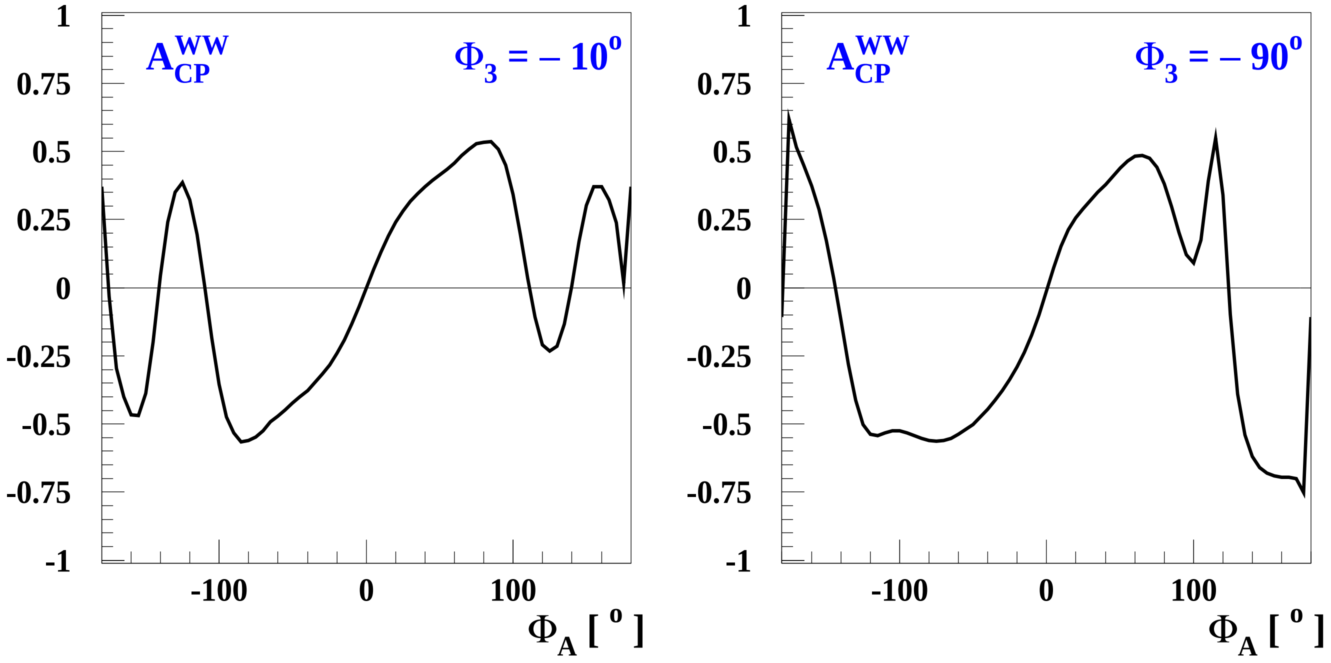
when $\Delta M_H \simeq \Gamma_H$

The neutral Higgs bosons should not be treated separately !

J. Ellis, JSL and A. Pilaftsis, D70(2004)075010

♠ *CP Asymmetries* (3/3)

- Integrated CP asymmetry $\mathcal{A}_{\rm CP}^{WW}$ with $\sigma_{\rm tot}^{WW} > 0.2$ pb:

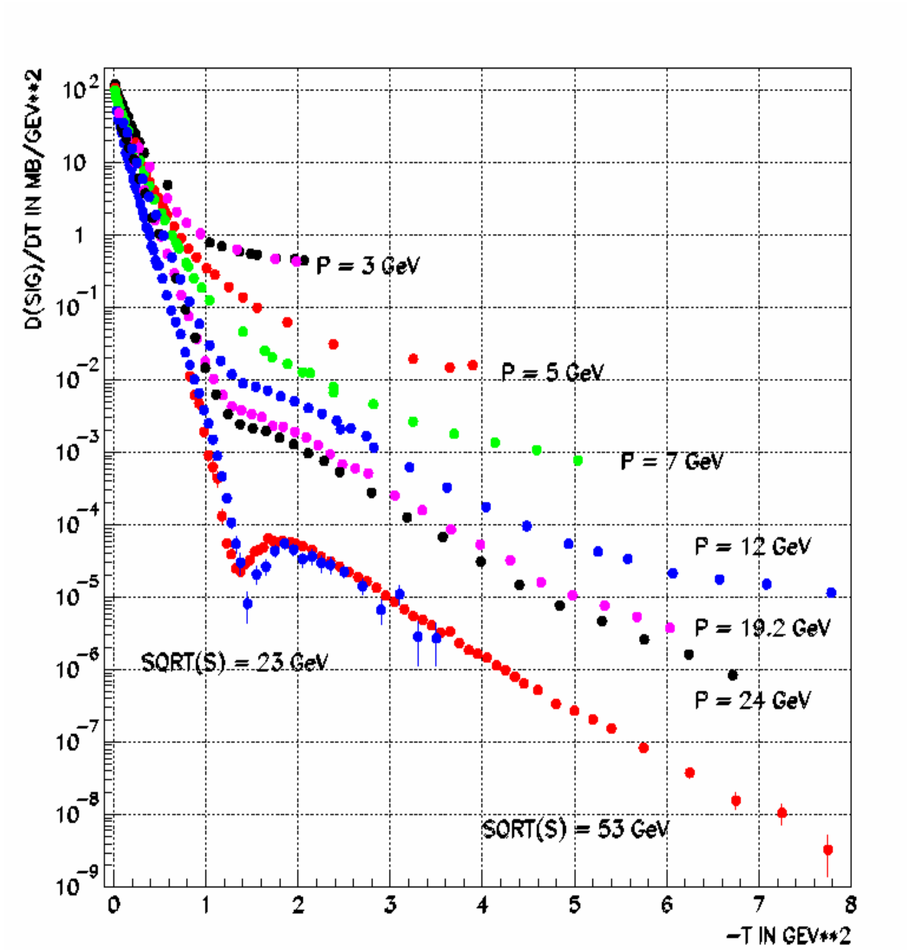


CP asymmetry is large over the whole ranges of CP phases !

♠ *Diffraction* (1/3)

- <u>Diffraction</u> is a process with a t-channel exchange leading to a Large Rapidity Gap

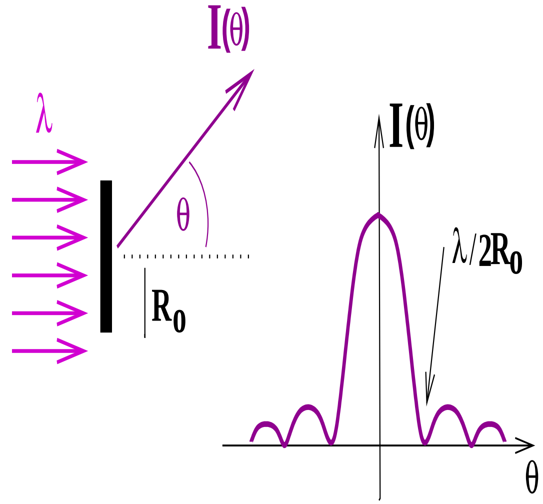
M. Arneodo, M. Diehl, hep-ph/0511047



The differential cross section

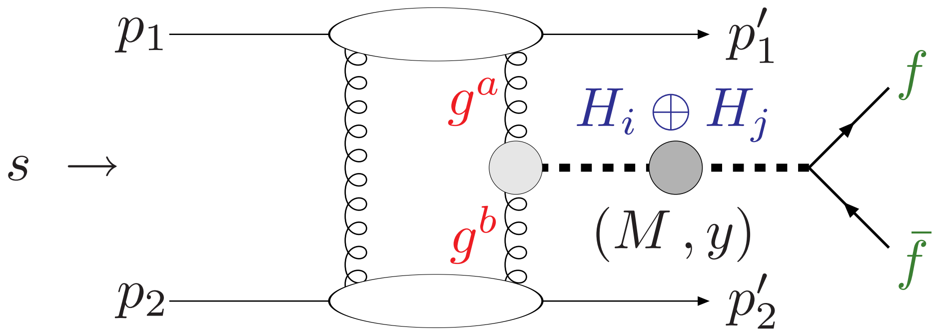
$$\left.\frac{d\sigma\,(pp \rightarrow pp)}{d\,t}\right|_{\text{elastic}}$$

has a resemblance to the diffraction pattern in optics:



♠ *Diffraction* (2/3)

- Exclusive double diffractive process



† $M^2 = s - 2\sqrt{s}(E_1' + E_2') + (p_1' + p_2')^2$
$\Rightarrow \delta M \sim 1$ GeV !

† Clean environment due to the large rapidity gap

Outgoing protons remain intact & scatter through small angles with $p_\perp \ll 1$ GeV

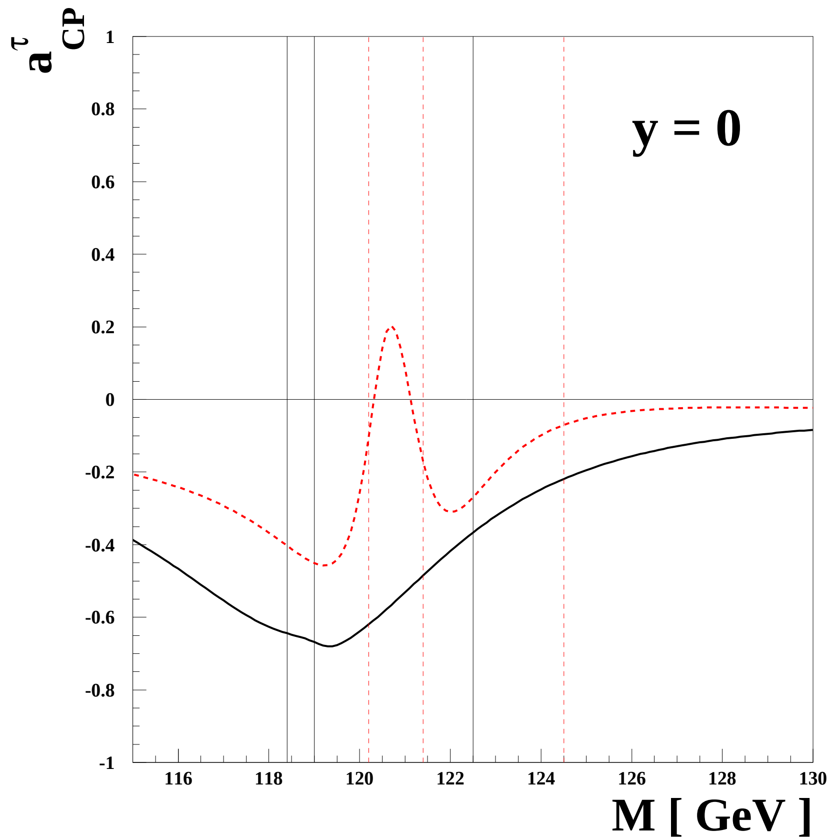
J. Ellis, JSL and A. Pilaftsis, D71(2005)075007

$*$ Need TOTEM/ATLASFP detectors

A. De Roeck, *et al.*, EPJC**25** (2002) 391; M. Boonekamp, *et al.*, PLB**598** (2004) 243; K. A. Assamagan *et al.* hep-ph/0406152; B. E. Cox, hep-ph/0409144, hep-ph/0501064; B.E. Cox*, J.R. Forshaw, JSL, J.W. Monk* and A. Pilaftsis, PRD**68** (2003) 075004; V.A. Khoze, A.D. Martin and M.G. Ryskin, EPJC**34** (2004) 327

♠ *Diffraction* (3/3)

- $\underline{pp \to pH_i p\,;\, H_i \to \tau^+\tau^-}$ $(\Phi_A\,,\Phi_3) = (90^\circ\,,-90^\circ)$ $(\Phi_A\,,\Phi_3) = (90^\circ\,,-10^\circ)$

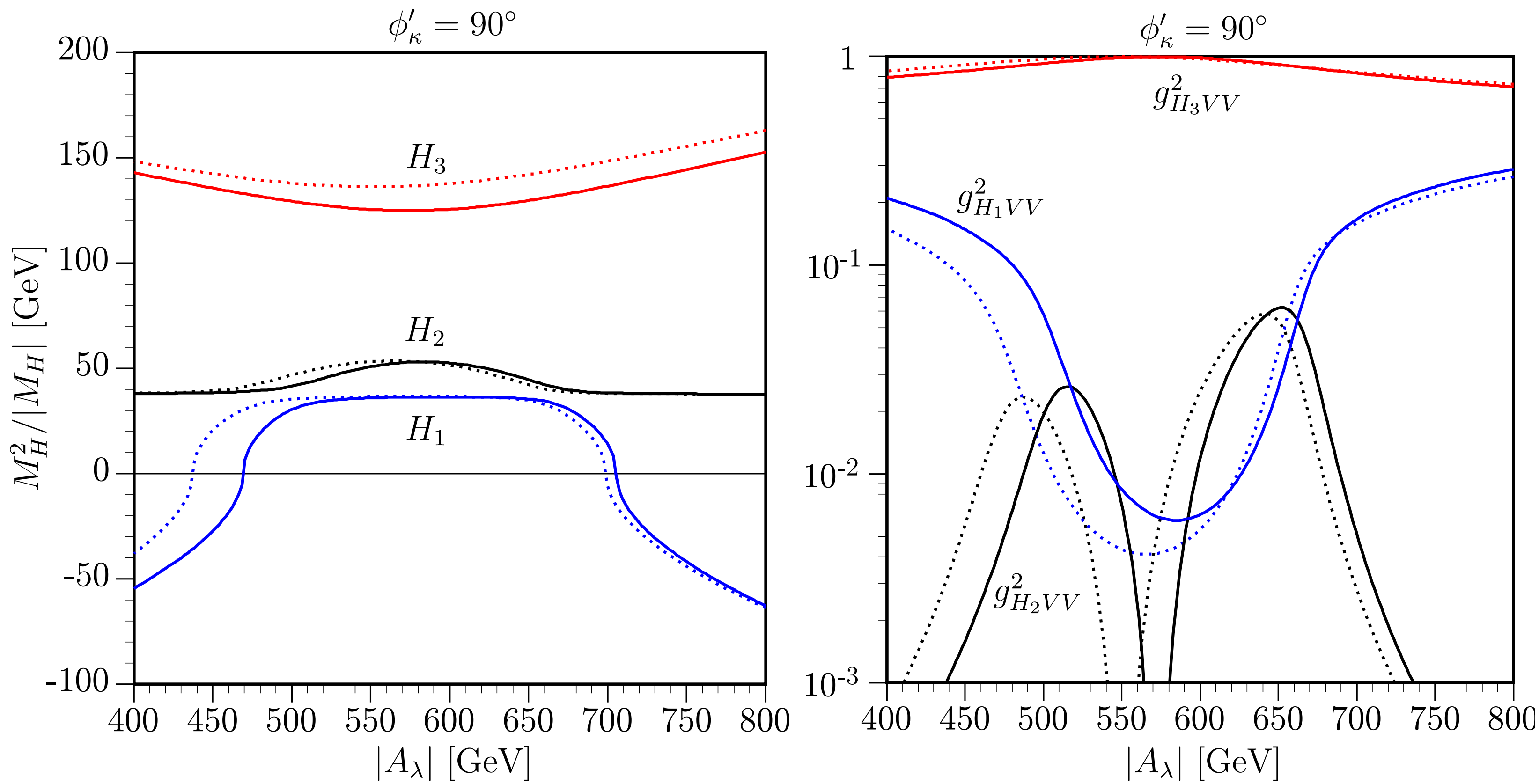


Invariant mass distribution can be studied !

- The μ problem J. E. Kim and H. P. Nilles, Phys. Lett. B **138**, 150 (1984)

$$\mu H_1 H_2 \longrightarrow S H_1 H_2$$

More Higgs bosons and more CP violation !



K. Cheung, T. J. Hou, JSL and E. Senaha, PRD82(2010)075007

♠ *Beyond the Minimal SUSY Model* (2/2)

- We are working on ...
  - Constraints from EDMs on the new CP violation
  - ElectroWeak Phase Transitions
  - New CP-phase driven baryogenesis
  - B- and K-meson observables
  - Collider signatures of the light Higgs bosons
  - Higgs Inflation(?)
  - etc

♠ Summary (LHC)

- Phases of the LHC :

I (2013 ∼ 2014) : $LHC\ with\ \mathcal{L} \sim\ 10\ fb^{-1}$

SM Higgs Discovery,
Non-SM-like Higgs decays and productions, Multiple Higgs peaks

II (2015 ∼ 2016) : $LHC\ with\ \mathcal{L} \sim 300\ fb^{-1}$

$\mathrm{I} \oplus$ Strongly-coupled Higgs, CP asymmetries, Final-state spin-spin correlations

III (2017 ∼ 202?) : $LHC\ with\ \mathcal{L} \gg 300\ fb^{-1}$

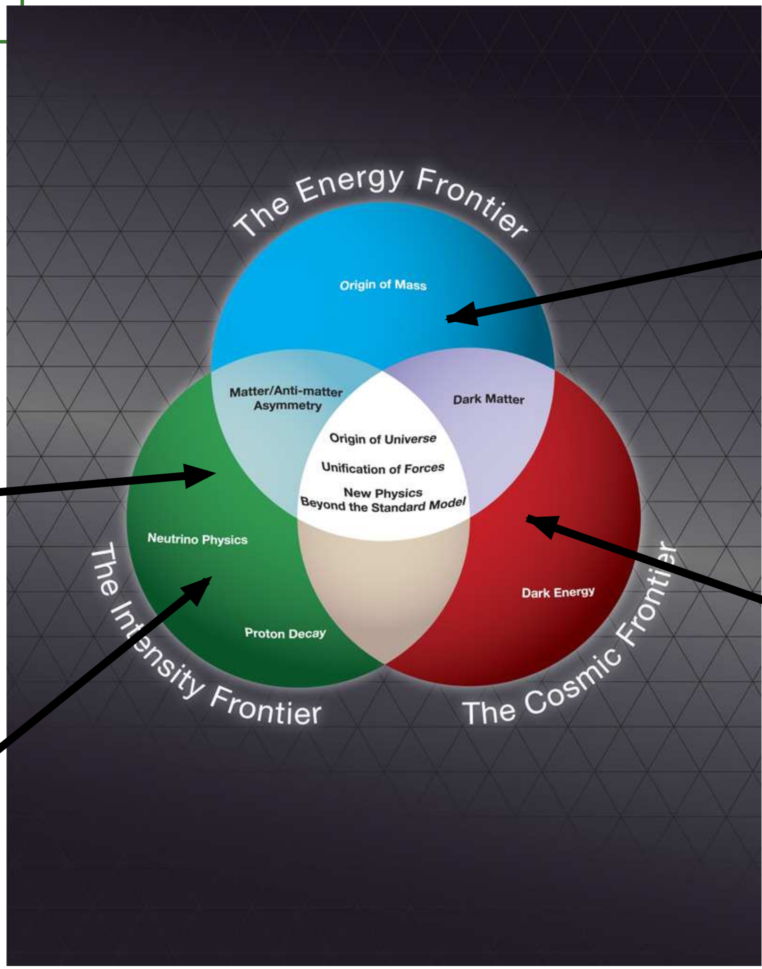
$\mathrm{I} \oplus \mathrm{II} \oplus$ Exotic Higgs productions

♠ *Conclusions and Future Prospects*

- Spontaneous breaking of the electroweak symmetry *may* be responsible for the masses of SM particles
- Supersymmetry *may* stabilize the Higgs-boson masses against the Quantum corrections
- The additional CP phases in the models extended by Supersymmetry *may* explain the matter dominance of the Universe
- The Supersymmetric CP phases *may* manifest themselves through the Higgs sector in Energy-, Intensity-, and Cosmic-Frontier experiments
- The LHC is to give definite answers to these *may*'s

♠ *Where to find it ?*

II-B B-meson Observables



http://www.er.doe.gov/hep/vision/index.shtml

Colliders

$\left\{ \begin{array}{l} LEP\ Holes \\ LHC\ Signatures \end{array} \right.$

B-meson Obsrvables

$\left\{ \begin{array}{l} \Delta M_{B_{d,s}}, B_s \to \mu^+\mu^-, \\ B \to \tau\nu, B \to X_s\gamma, \\ \ldots \end{array} \right.$

Dark Matter

$\{ \ \chi\chi \to \gamma, \bar{p}, etc$

Electric Dipole Moments

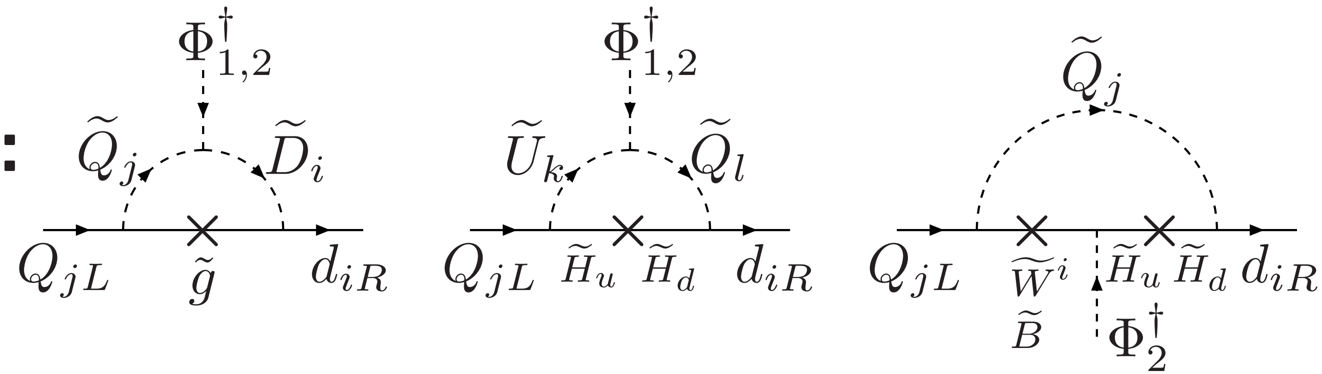
♠ B *Observables* (1/4)

- Higgs-mediated B-meson mixing and rare decays: LHCb and SuperB J. Ellis, JSL and A. Pilaftsis, PRD76(2007)115011

$$\left(-\mathcal{L}^{d}_{\rm eff}\right)^{H} \;=\; \frac{g}{2M_W}\,\bar{d}\,\widehat{M}_d\,\mathbf{g}^{L}_{H_i\bar{d}d}\,P_L\,d\,H_i + {\rm h.c.}$$

$$\mathbf{g}^{L}_{H_i\bar{d}d} \;\propto\; V^{\dagger}_{\rm CKM}\,[\mathbf{1} + \tan\beta\,\Delta_d]^{-1}\,V_{\rm CKM}$$

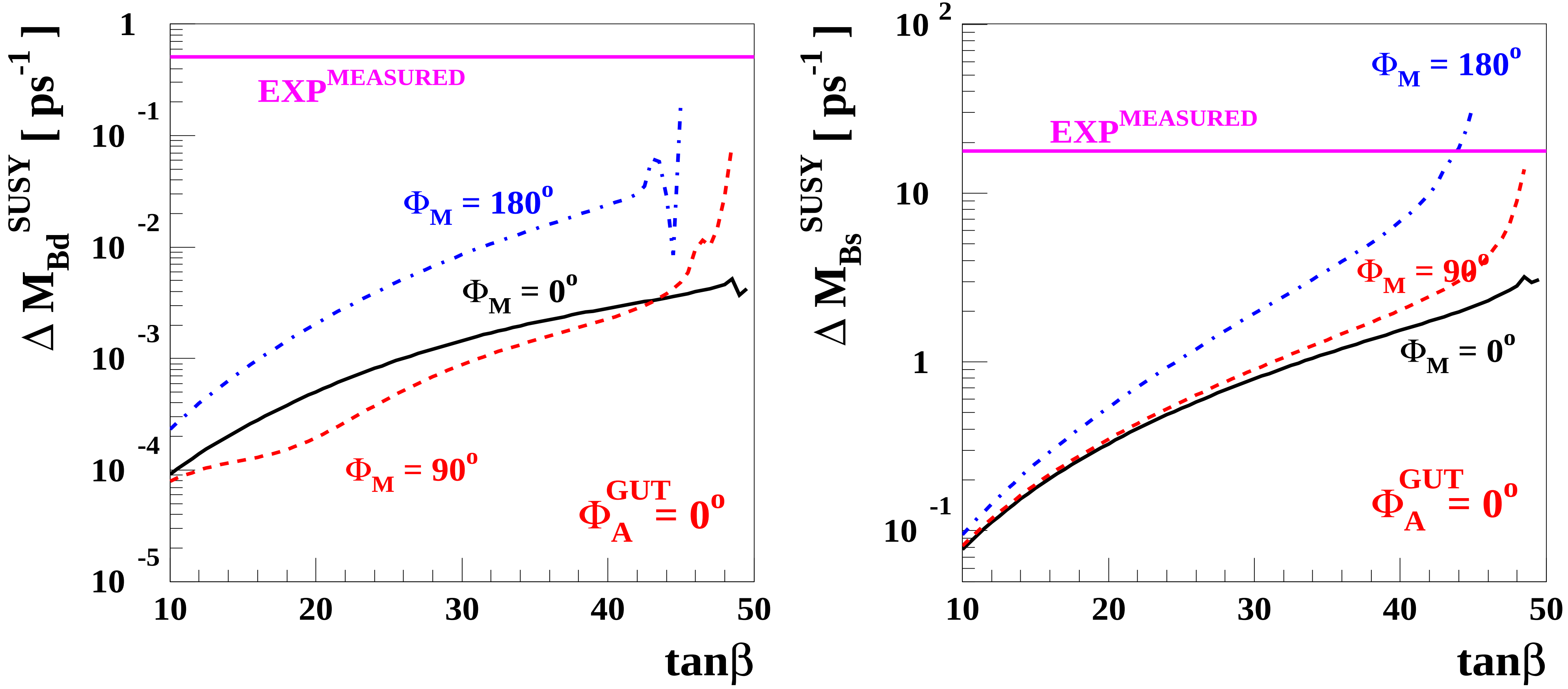
$\Delta_d[\Phi_{\rm CP}]$:



Non-universal Quantum interactions inducing the mixing and rare decays !

♠ B *Observables* (2/4)

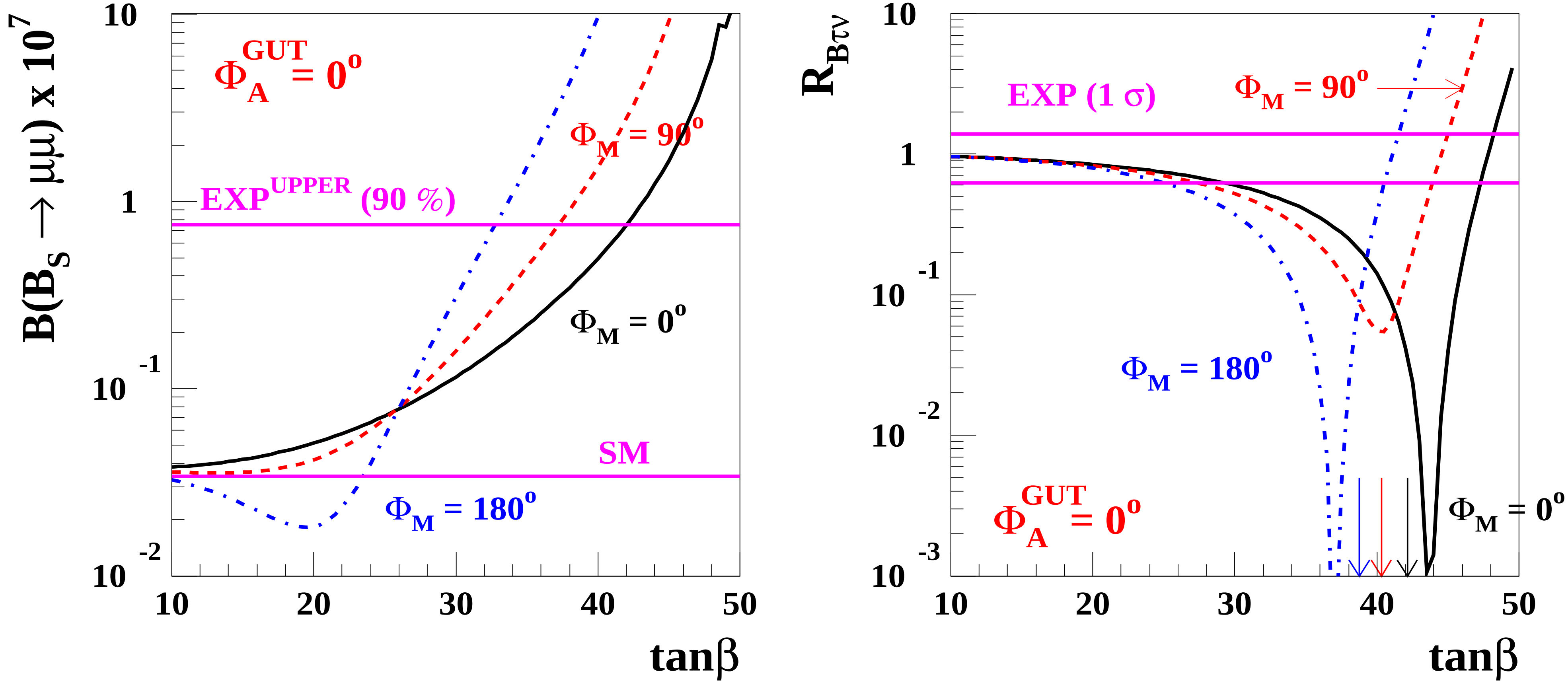
- $\Delta M_{B_d}^{\rm SUSY}$ and $\Delta M_{B_s}^{\rm SUSY}$ as functions of $\tan\beta(M_{\rm SUSY})$ for three values of $\Phi_M \equiv \Phi_1 = \Phi_2 = \Phi_3$ SPS1a-like scenario $\widetilde{M}_{L,E} = 200$ GeV and $\Phi_A^{\rm GUT} = 0°$



Strong CP phase dependence

♠ *B Observables* (3/4)

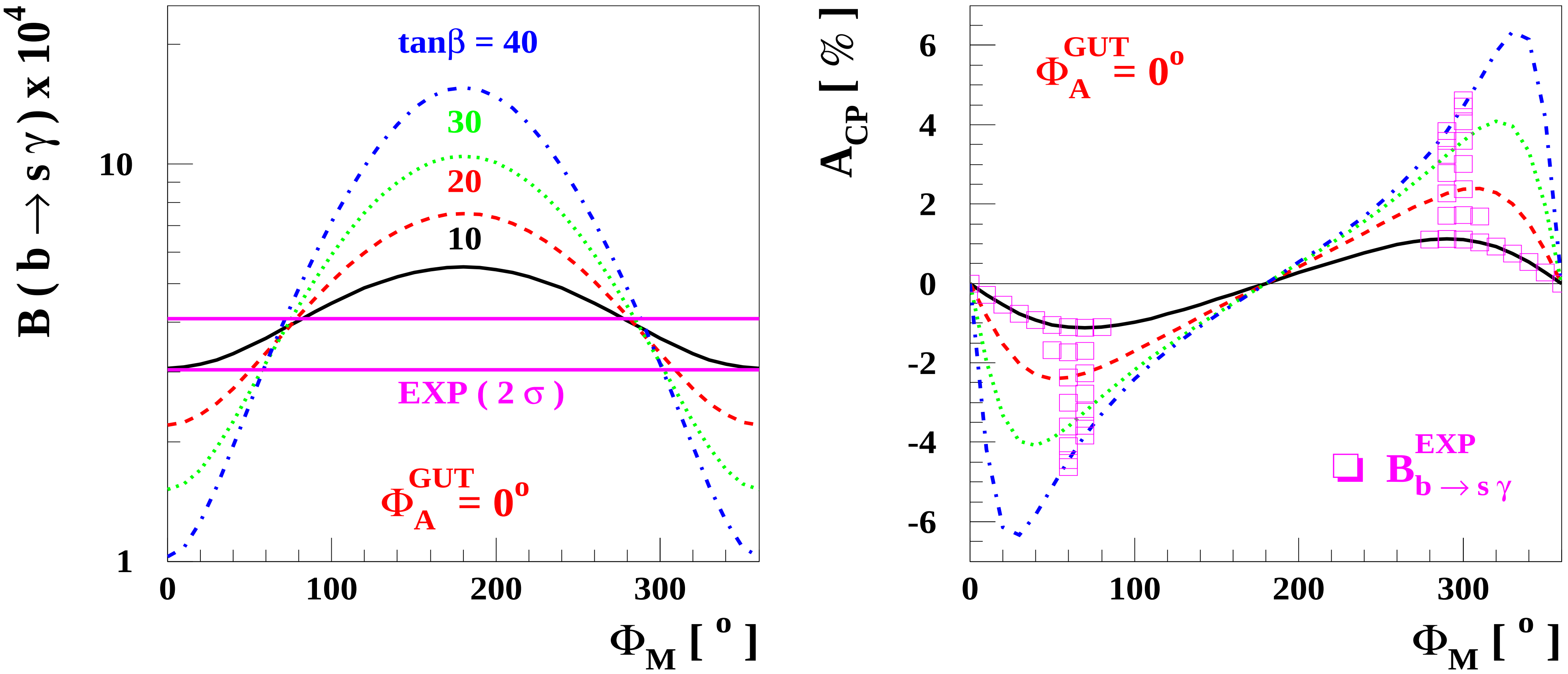
- $B(\bar{B}^0_s \to \mu^+\mu^-)$ and the ratio $R_{B\tau\nu}$ as functions of $\tan\beta(M_{\rm SUSY})$ for three values of $\Phi_M \equiv \Phi_1 = \Phi_2 = \Phi_3$ SPS1a-like scenario $\widetilde{M}_{L,E} = 200$ GeV and $\Phi_A^{\rm GUT} = 0^\circ$



Strong CP phase dependence

♠ B *Observables* (4/4)

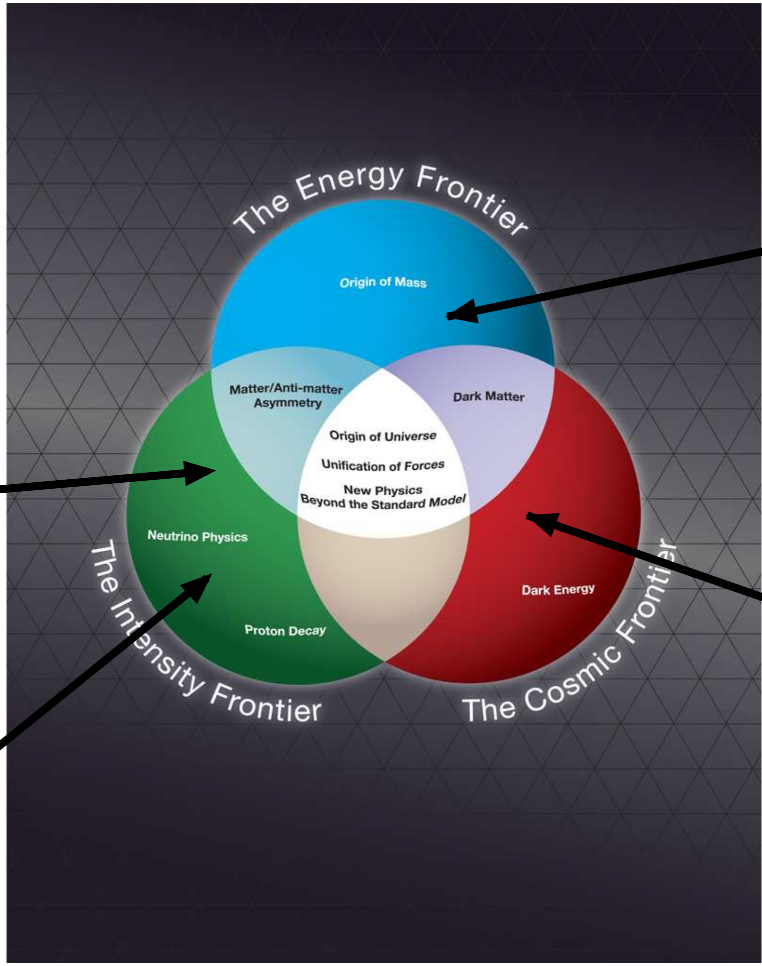
- $B(B \to X_s\gamma)$ and $\mathcal{A}_{\rm CP}^{\rm dir}(B \to X_s\gamma)$ as functions of Φ_M for four values of $\tan\beta(M_{\rm SUSY}) = 10\,,20\,,30\,,40$ SPS1a-like scenario $\widetilde{M}_{L,E} = 200$ GeV and $\Phi_A^{\rm GUT} = 0^\circ$



Strong CP phase dependence

♠ *Where to find it ?*

II-C EDMs



http://www.er.doe.gov/hep/vision/index.shtml

Colliders

$\left\{ \begin{array}{l} LEP\ Holes \\ LHC\ Signatures \end{array} \right.$

B-meson Obsrvables

$\left\{ \begin{array}{l} \Delta M_{B_{d,s}}\,,\, B_s \to \mu^+\mu^-\,, \\ B \to \tau\nu\,,\, B \to X_s\gamma\,, \\ \ldots \end{array} \right.$

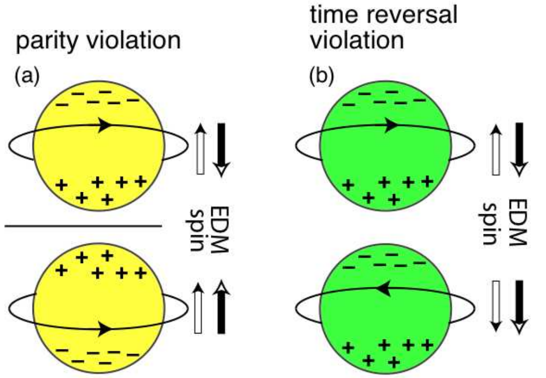
Dark Matter

$\{\ \chi\chi \to \gamma\,,\, \bar{p}\,,\, etc$

Electric Dipole Moments

♠ *EDMs* $(1/4)$

- Electric Dipole Moments (EDMs): T violation $\Rightarrow$ CP violation (under CPT)



$$\mathcal{H}^{\mathrm{EDM}} = -d\ \mathbf{E}\cdot\hat{\mathbf{s}}$$

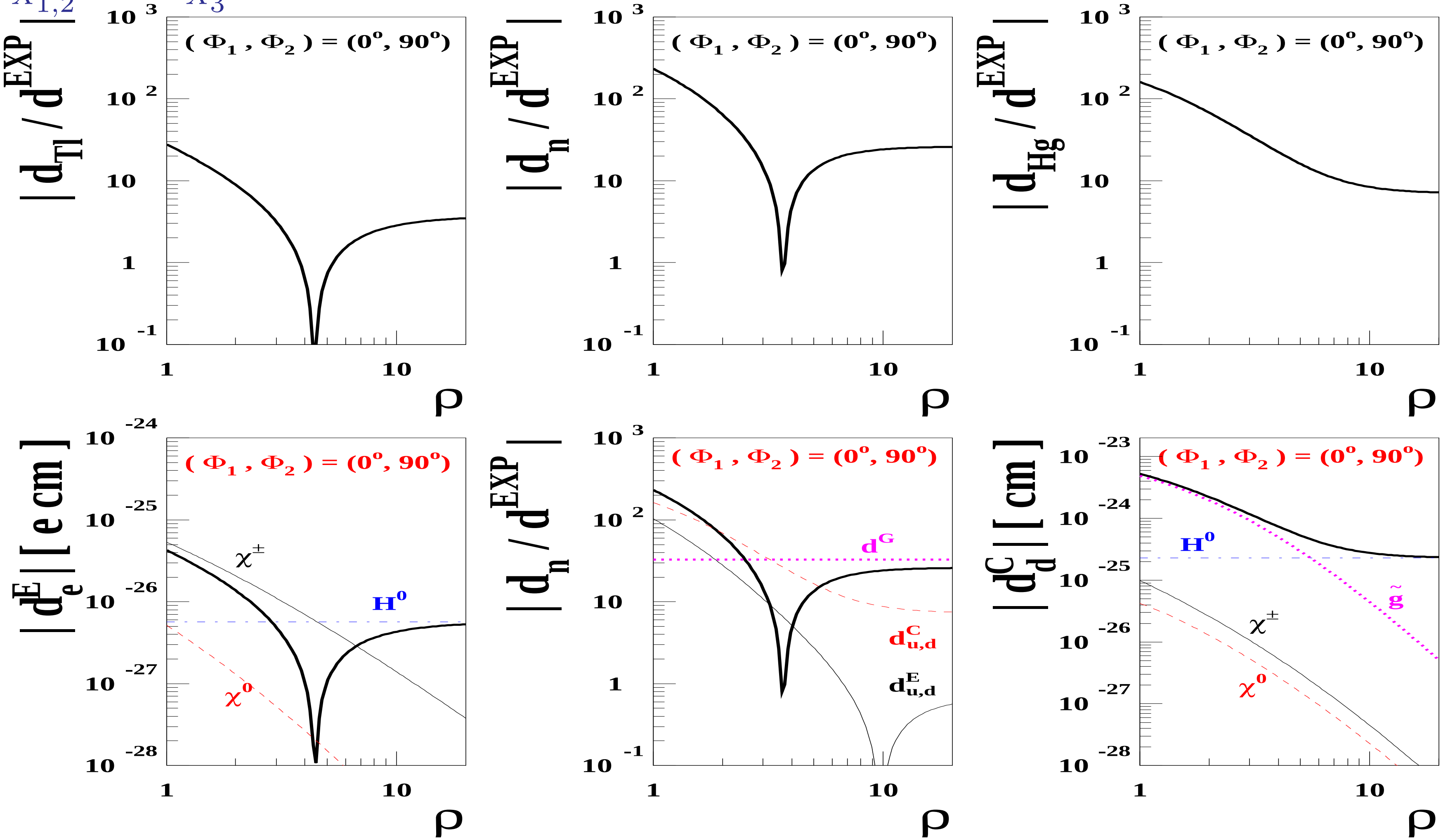
$$|d_{\mathrm{Tl}}| < 9\times 10^{-25}\ \mathrm{e\,cm}\,,\quad |d_{\mathrm{Hg}}| < 3.1\times 10^{-29}\ \mathrm{e\,cm}\,,\quad |d_{\mathrm{n}}| < 3\times 10^{-26}\ \mathrm{e\,cm}$$

B. C. Regan, E. D. Commins, C. J. Schmidt and D. DeMille, PRL**88** (2002) 071805; W. C. Griffith, M. D. Swallows, T. H. Loftus, M. V. Romalis, B. R. Heckel and E. N. Fortson, PRL**102** (2009) 101601; C. A. Baker *et al.*, PRL**97** (2006) 131801

– No large CP phases? -No! But, one needs to introduce some hierarchy between first two and third generations and/or some moderate tuning among parameters

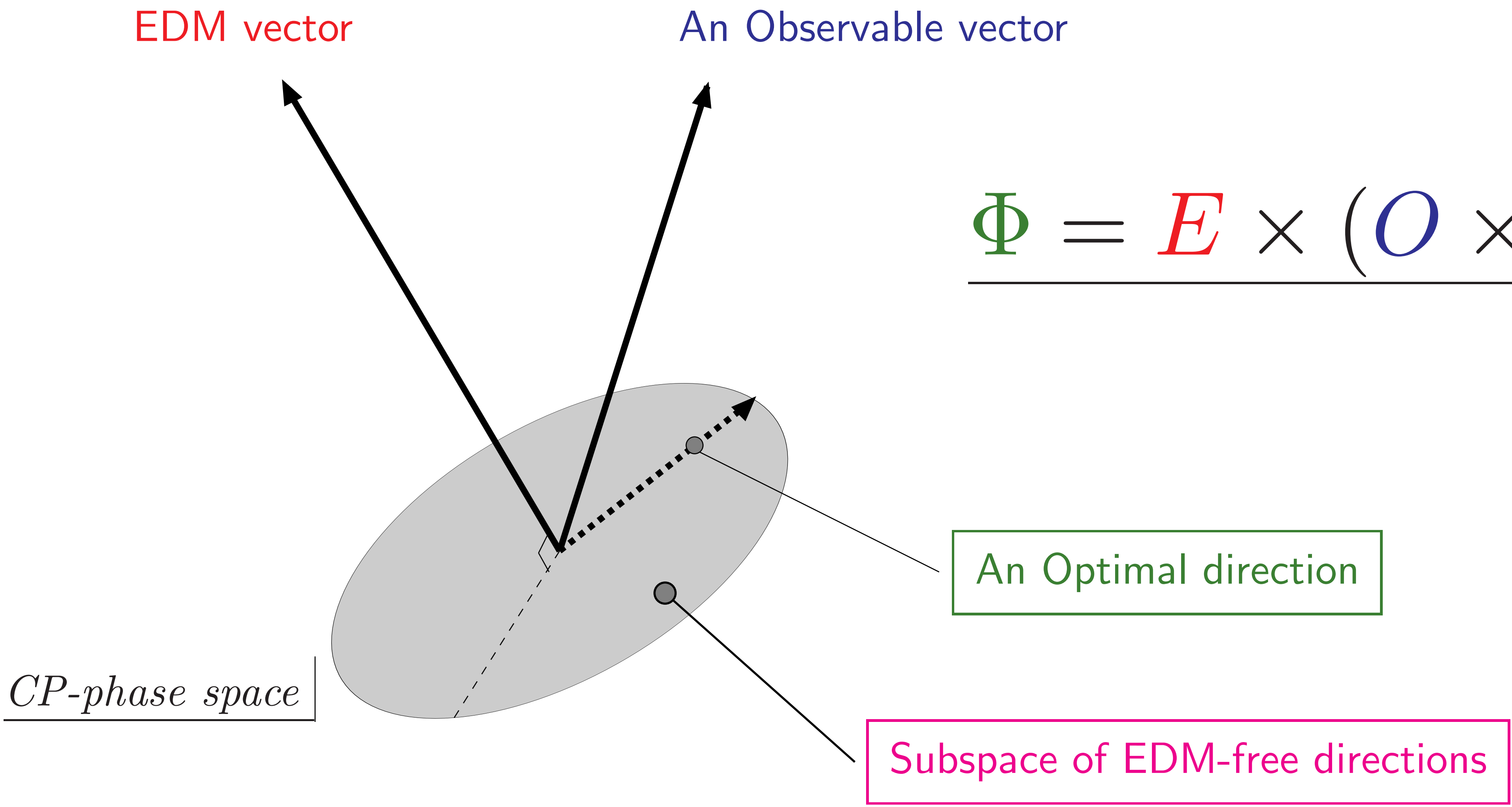
♠ *EDMs* $(2/4)$

- <u>EDM constraints and *cancellation*</u>: CPX Scenario with $\Phi_{A_{t,b}} = \Phi_3 = 90^\circ$, $\Phi_{A_{u,d,c,s}} = 0^\circ$ $\tan\beta = 5$, $M_{H^\pm} = 300$ GeV, $|M_2| = 2|M_1| = 100$ GeV, and $M_{\rm SUSY} = 0.5$ TeV The hierarchy factor ρ: $M_{\tilde{X}_{1,2}} = \rho\, M_{\tilde{X}_3}$ with $X = Q = U = D = L = E$ J. Ellis, JSL and A. Pilaftsis, JHEP08(2008)049



♠ *EDMs* $(3/4)$

- Analytic determination of the cancellation regions: EDM-free directions and Optimal direction J. Ellis, JSL and A. Pilaftsis, JHEP10(2010)049



$$\Phi = E \times (O \times E)$$

♠ *EDMs* (4/4)

- Optimal direction : the higher-dimensional generalization with N CP phases and n EDM constraints

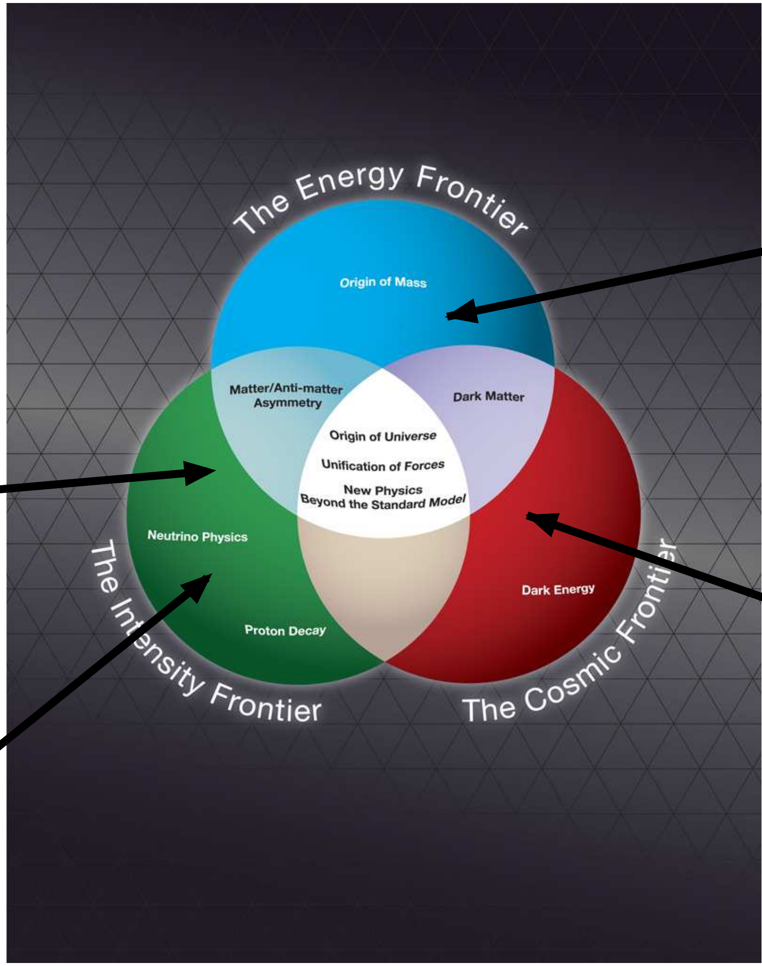
$$\Phi_\alpha = \epsilon_{\alpha\beta_1\cdots\beta_n\gamma_1\cdots\gamma_{N-n-1}} E^{(1)}_{\beta_1} \cdots E^{(n)}_{\beta_n} B_{\gamma_1\cdots\gamma_{N-n-1}}$$

where (N-n-1)-dimensional B form is

$$B_{\gamma_1\cdots\gamma_{N-n-1}} = \epsilon_{\gamma_1\cdots\gamma_{N-n-1}\sigma\beta_1\cdots\beta_n} O_\sigma E^{(1)}_{\beta_1} \cdots E^{(n)}_{\beta_n}$$

♠ *Where to find it ?*

II-D Dark Matter



http://www.er.doe.gov/hep/vision/index.shtml

Colliders

$\left\{ \begin{array}{l} LEP\ Holes \\ LHC\ Signatures \end{array} \right.$

B-meson Obsrvables

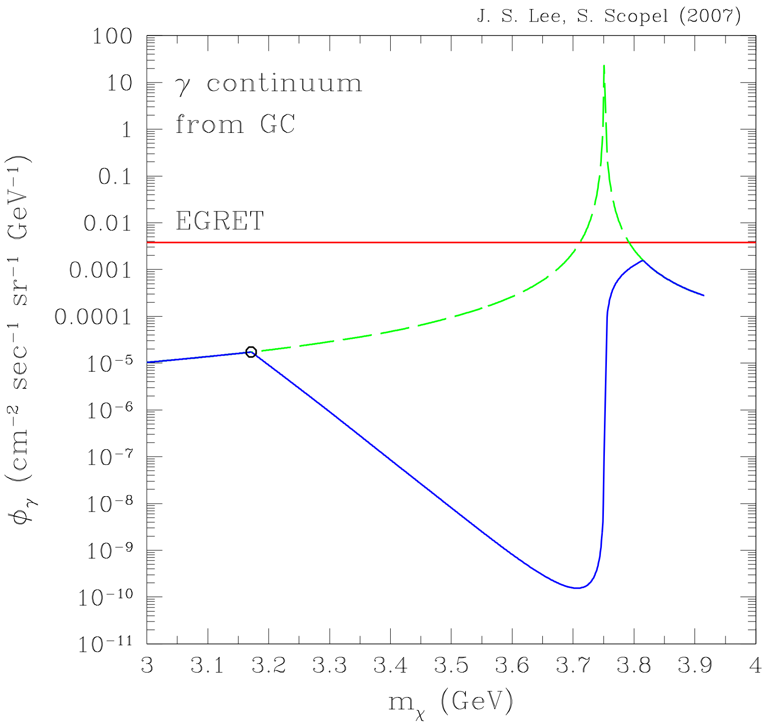
$\left\{ \begin{array}{l} \Delta M_{B_{d,s}}\,,\, B_s \to \mu^+\mu^-\,, \\ B \to \tau\nu\,,\, B \to X_s\gamma\,, \\ \ldots \end{array} \right.$

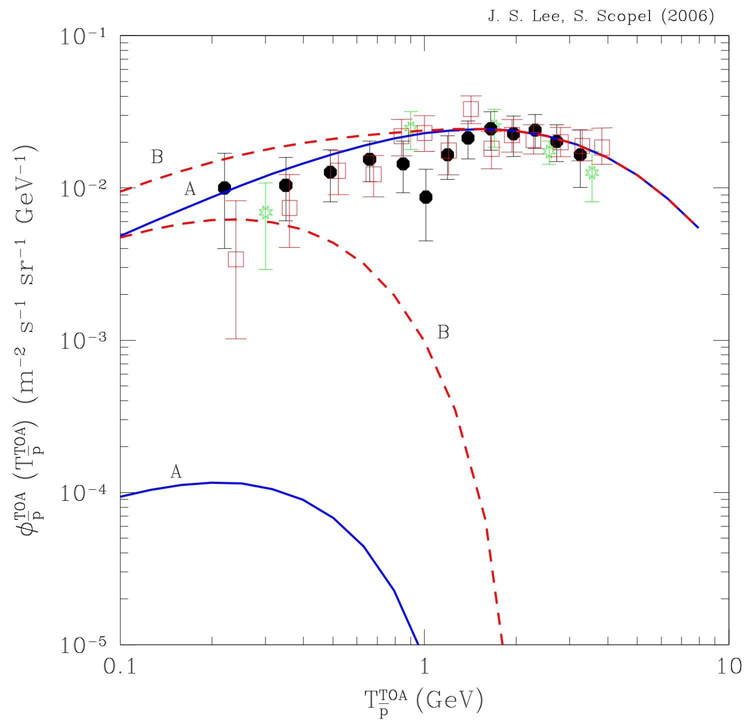
Dark Matter

$\{\ \chi\chi \to \gamma\,,\bar{p}\,, etc$

Electric Dipole Moments

- LEP Holes ⇒ Very light 7.5 GeV Higgs signals through the inclusive process $\chi\chi \to H \to \gamma\,,\bar{p}$ JSL and S. Scopel, Phys. Rev. D **75** (2007) 075001 [arXiv:hep-ph/0701221]





♠ MAÔS *momenta of the missing neutrinos* (1/2)

- MAÔS = M_{T2}-Assisted On-shell Scheme:

$$H \to W(p+k)\,W(q+l) \to l(p)\;\nu(k)\;\;l'(q)\;\nu'(l)$$

$$(M_H^2)^{\text{MAÔS}} = (p + k^{\text{MAÔS}} + q + l^{\text{MAÔS}})^2$$

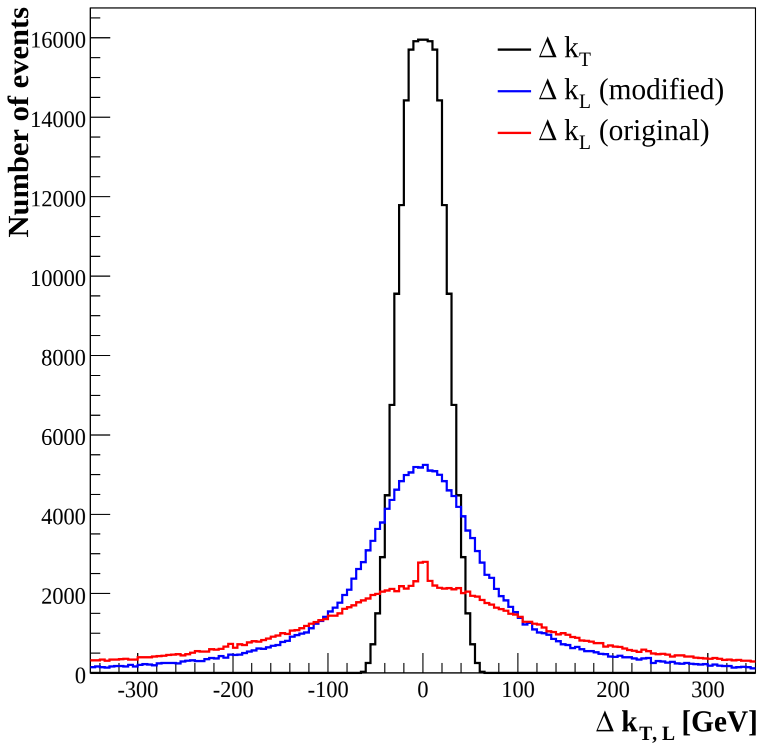
$$\mathbf{k}_T^{\text{MAÔS}} = -\mathbf{q}_T \quad \text{and} \quad \mathbf{l}_T^{\text{MAÔS}} = -\mathbf{p}_T$$

$$k_L^{\text{MAÔS}} = \frac{|\mathbf{k}_T^{\text{MAÔS}}|}{|\mathbf{p}_T|} p_L, \quad l_L^{\text{MAÔS}} = \frac{|\mathbf{l}_T^{\text{MAÔS}}|}{|\mathbf{q}_T|} q_L$$

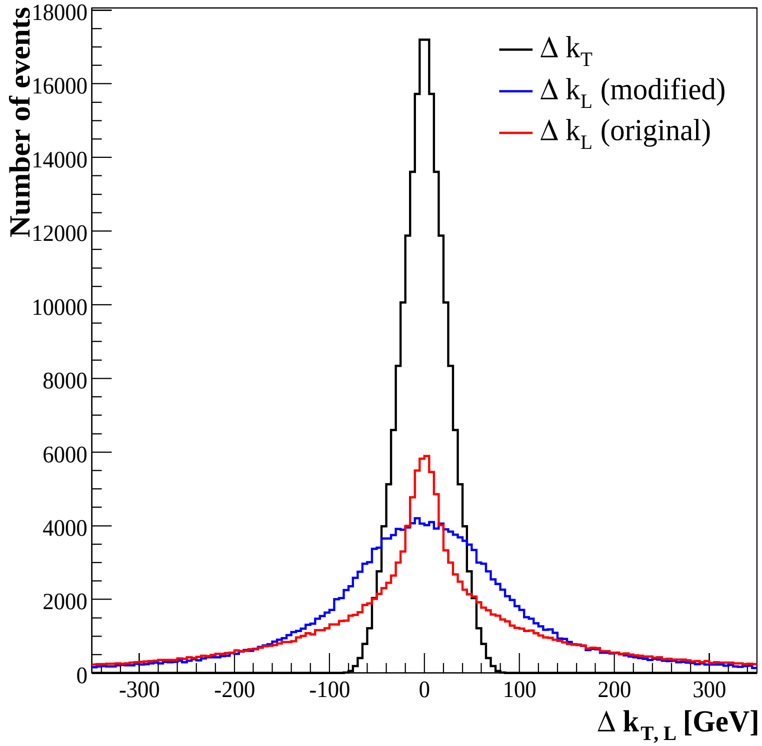
♠ MAÔS *momenta of the missing neutrinos* (2/2)

- Is the modified MAÔS scheme working well?:

$M_H = 140$ GeV

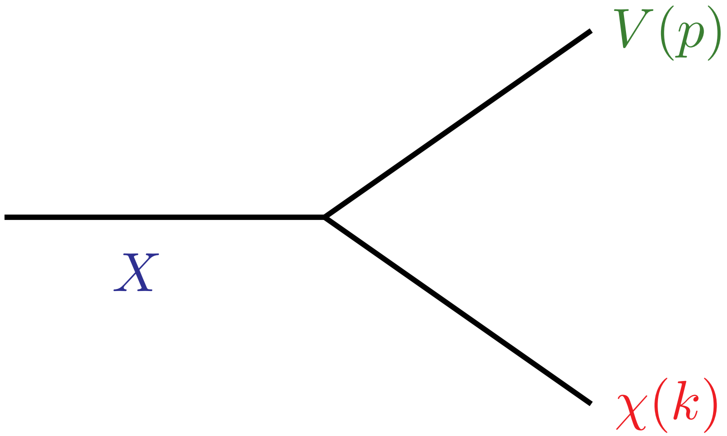


$M_H = 180$ GeV



♠ M_{T2}: 1/2

- Transverse Mass M_T :



$$p^\mu = \left(\sqrt{m_V{}^2 + |\mathbf{p}_T|^2 + p_L^2}\,, \mathbf{p}_T\,, p_L\right)$$

$$k^\mu = \left(\sqrt{m_\chi{}^2 + |\mathbf{k}_T|^2 + k_L^2}\,, \mathbf{k}_T\,, k_L\right)$$

$$\mathbf{k}_T = \not{\mathbf{p}}_T \; (\textit{fully determined})$$

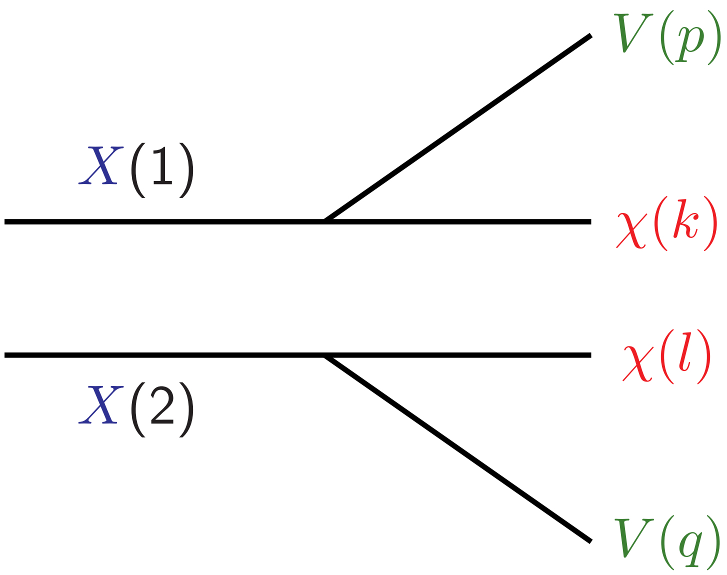
$$M_X{}^2 = m_V{}^2 + m_\chi{}^2 + 2\left(\sqrt{m_V{}^2 + |\mathbf{p}_T|^2 + p_L^2}\sqrt{m_\chi{}^2 + |\mathbf{k}_T|^2 + k_L^2} - \mathbf{p}_T \cdot \mathbf{k}_T - p_L k_L\right)$$

$$M_T{}^2 = m_V{}^2 + m_\chi{}^2 + 2\left(\sqrt{m_V{}^2 + |\mathbf{p}_T|^2}\;\sqrt{m_\chi{}^2 + |\mathbf{k}_T|^2} - \mathbf{p}_T \cdot \mathbf{k}_T\right)$$

$$M_T \leq M_X$$

♠ M_{T2}: 2/2

- ... then M_{T2} ?: Generalization of M_T when there are 2 missing particles



$$\mathbf{k}_T + \mathbf{l}_T = \not{\mathbf{p}}_T$$

Only determined are ...

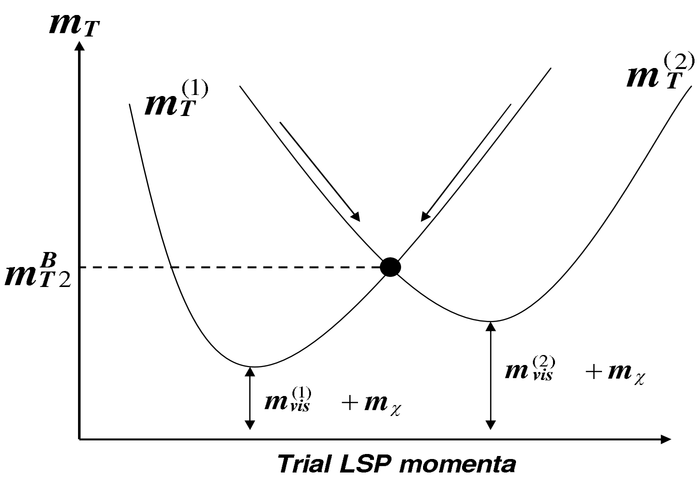
the 2 among the 4 unknown degrees of freedom !

... but we know:

$$\max\{M_T^{(1)}, M_T^{(2)}\}(\mathbf{k}_T^{\rm true}, \mathbf{l}_T^{\rm true}) \leq M_X$$

♠ M_{T2}: $2'/2$

- ... then M_{T2} ?: Generalization of M_T when there are 2 missing particles



$$\mathbf{k}_T + \mathbf{l}_T = \not{\mathbf{p}}_T$$

Only determined are ...

the 2 among the 4 unknown degrees of freedom !

... but we know:

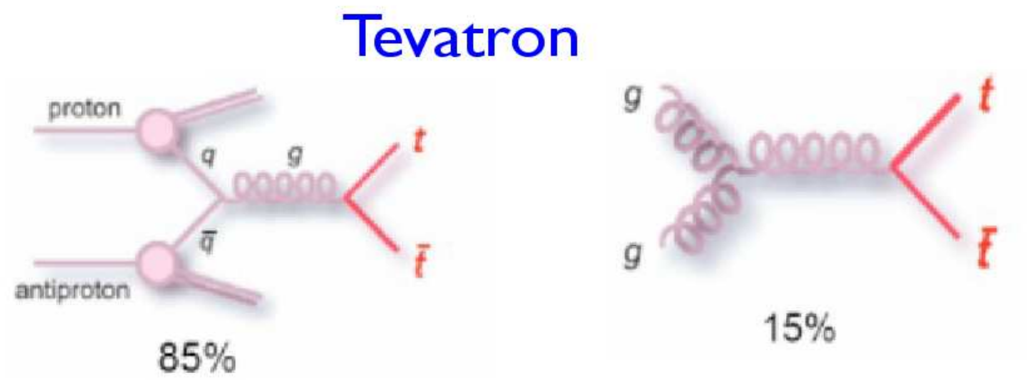
$$\max\{M_T^{(1)}, M_T^{(2)}\}(\mathbf{k}_T^{\rm true}, \mathbf{l}_T^{\rm true}) \le M_X$$

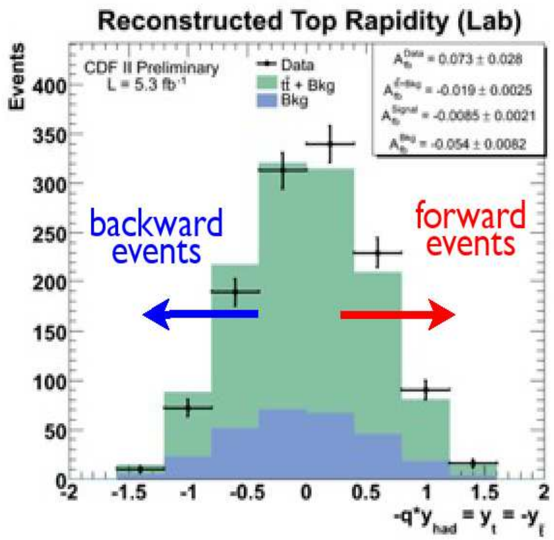
$$\max\{M_T^{(1)}, M_T^{(2)}\}(\mathbf{k}_T^{\rm min}, \mathbf{l}_T^{\rm min}) \le \max\{M_T^{(1)}, M_T^{(2)}\}(\mathbf{k}_T^{\rm true}, \mathbf{l}_T^{\rm true}) \le M_X$$

$$M_{T2} \equiv \min_{\mathbf{k}_T + \mathbf{l}_T = \not{\mathbf{p}}_T}\left[\max\left\{M_T^{(1)}, M_T^{(2)}\right\}\right] \le M_X$$

♠ $A_{\rm FB}$ *at the Tevatron:* 1/2

- $q\bar{q} \to t\bar{t}$ and $A_{\rm FB}$ at the Tevatron Shabamina(Blois2010)





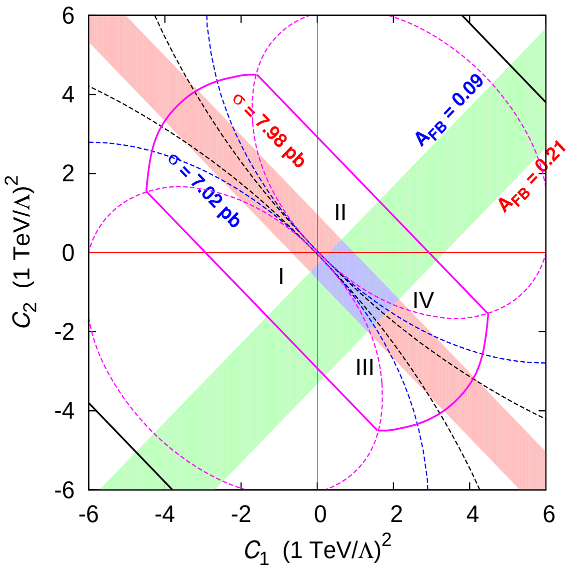
A_{fb} (raw) = 0.073 ± 0.028

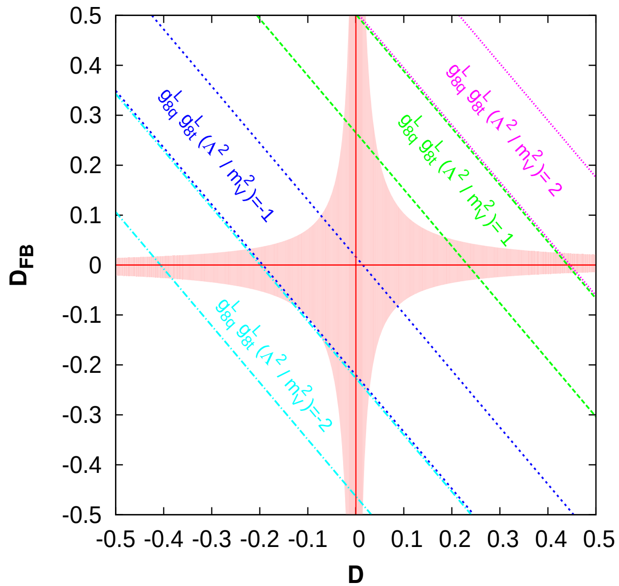
$$A_{\rm FB} \equiv \frac{N_t(\cos\theta \geq 0) - N_{\bar{t}}(\cos\theta \geq 0)}{N_t(\cos\theta \geq 0) + N_{\bar{t}}(\cos\theta \geq 0)} = (0.15 \pm 0.05 \pm 0.024)$$

Pertinent $\sim 2\sigma$ deviation !

- Effective Lagrangian approach to explain the anomaly D.-W. Jung, P. Ko, JSL, S.-h. Nam, PLB691(2010)238; D.-W. Jung, P. Ko, JSL, arXiv:1012.0102 [hep-ph]

$$\mathcal{L}_6 = \frac{g_s^2}{\Lambda^2} C_{8q}^{AB} \, (\bar{q}_A T^a \gamma_\mu q_A)(\bar{t}_B T^a \gamma^\mu t_B)$$





$$C_1 \equiv C_{8q}^{RR} + C_{8q}^{LL}\,, \quad C_2 \equiv C_{8q}^{LR} + C_{8q}^{RL}\,, \quad D\,, D_{\rm FB} \propto (C_{8q}^{RR} - C_{8q}^{LL}) \pm (C_{8q}^{LR} - C_{8q}^{RL})$$

♠ *Backup*

- CPX Scenario: Recall CPV mixing $\propto \Im\mathrm{m}(A_f\mu)/M_{\rm SUSY}^2$

$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\rm SUSY}$$
$$|\mu| = 4\,M_{\rm SUSY}\,, \quad |A_{t,b,\tau}| = 2\,M_{\rm SUSY}$$
$$|M_3| = 1 \;\; \mathrm{TeV}$$

Varying parameters are :

$$\tan\beta\,, \quad M_{H^\pm}^{\rm pole}\,, \quad M_{\rm SUSY}$$
$$(\Phi_\mu)\,, \quad \Phi_{A_t}\,, \quad \Phi_{A_b}\,, \quad \Phi_{A_\tau}\,, \quad \Phi_3$$

* M_1 and M_2

* For simplicity, common Φ_A

♠ Backup

- Large $\tan\beta$ and $M_{H^\pm}^{\rm pole} \sim 150$ GeV $\Rightarrow$ Trimixing scenario J. Ellis, JSL and A. Pilaftsis, PRD70(2004)075010, PRD71(2005)075007, PRD72(2005)095006, and NPB718(2005)247

$$\tan\beta = 50, \quad M_{H^\pm}^{\rm pole} = 155 \ \ {\rm GeV},$$
$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = M_{\tilde{L}_3} = M_{\tilde{E}_3} = 0.5 \ \ {\rm TeV},$$
$$|\mu| = 0.5 \ \ {\rm TeV}, \quad |A_{t,b,\tau}| = 1 \ \ {\rm TeV}, \quad |M_{1,2}| = 0.3 \ \ {\rm TeV}, |M_3| = 1 \ \ {\rm TeV},$$
$$\Phi_\mu = 0^\circ, \quad \Phi_{1,2} = 0^\circ \,.$$

For $\Phi_{A_t,A_b,A_\tau} = 90^\circ$ and $\Phi_3 = -90^\circ$, we have (in GeV)

$$M_{H_1} = 117.6, \quad M_{H_2} = 118.7, \quad M_{H_3} = 122.6,$$
$$\Gamma_{H_1} = 1.48, \quad \Gamma_{H_2} = 8.12, \quad \Gamma_{H_3} = 8.21.$$

All Higgs bosons are nearly degenerate with $\Gamma_i \gtrsim \Delta M_H$!

- SPS1a-like scenario
  - At M_Z: Three gauge couplings $\alpha_1(M_Z)$, $\alpha_2(M_Z)$, and $\alpha_3(M_Z)$
  - At $m_t^{\rm pole}$: Quark and Lepton masses $m_{q,l}(m_t^{\rm pole})$ and $V_{\rm CKM}(m_t^{\rm pole})$
  - At $M_{\rm SUSY}$: $\tan\beta(M_{\rm SUSY})$
  - At $M_{\rm MFV} = M_{\rm GUT}$: 19 MCPMFV Parameters

$$|M_{1,2,3}|\,{\rm e}^{i\,\Phi_{1,2,3}}\,, \quad |A_{u,d,e}|\,{\rm e}^{i\,\Phi_{A_{u,d,e}}}\,, \quad \widetilde{M}^2_{Q,U,D,L,E}\,, \quad M^2_{H_{u,d}}$$

Specifically, we have taken the parameter set:

$$|M_{1,2,3}| = 250 \;\; {\rm GeV}$$

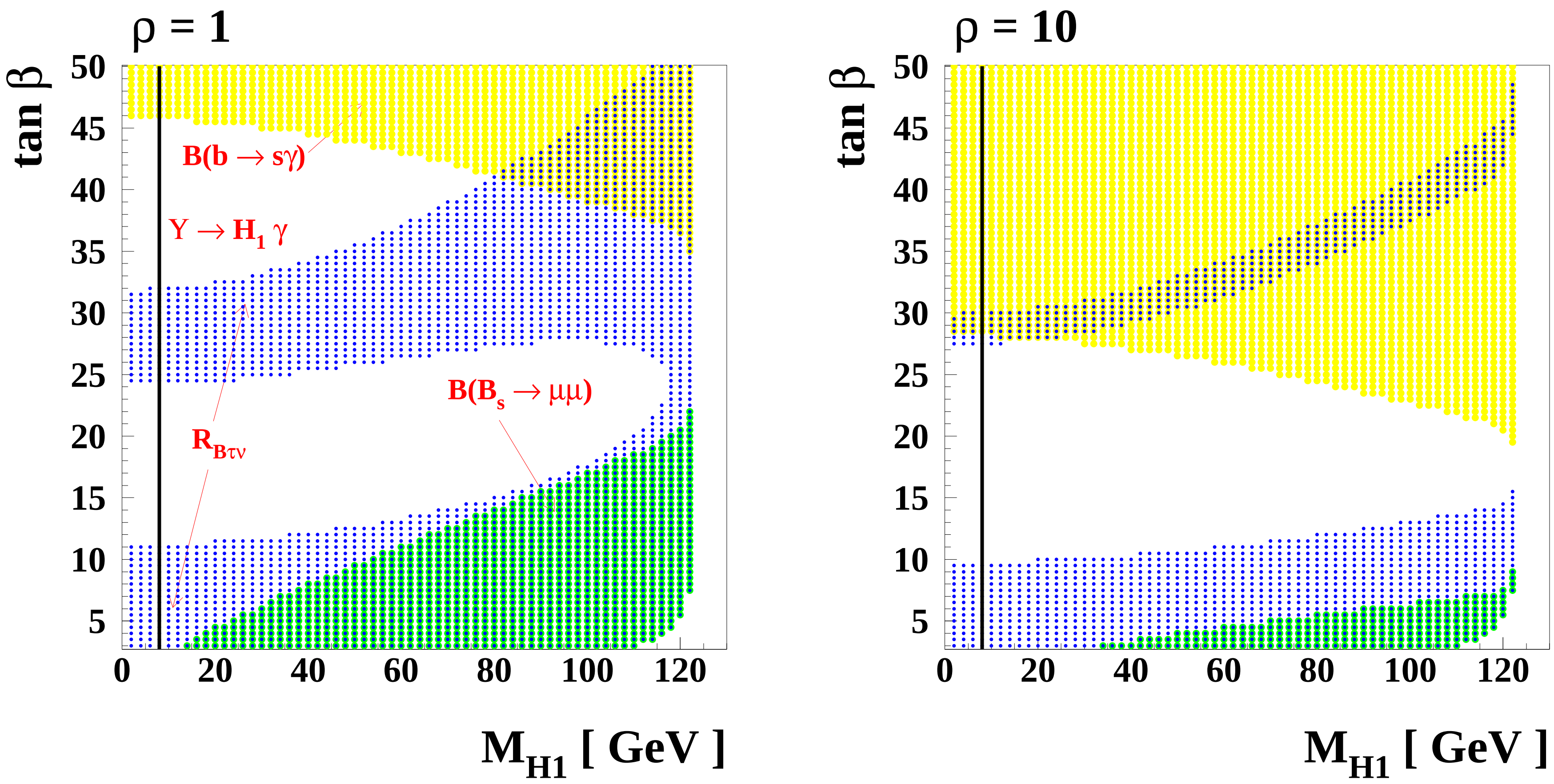
$$M^2_{H_u}=M^2_{H_d}=\widetilde{M}^2_Q=\widetilde{M}^2_U=\widetilde{M}^2_D=\widetilde{M}^2_L=\widetilde{M}^2_E = (100 \;\; {\rm GeV})^2$$

$$|A_u| = |A_d| = |A_e| = 100 \;\; {\rm GeV}$$

This parameter set is equivalent to SPS1a when $\Phi_{A_{u,d,e}} = 180^\circ$ and $\Phi_{1,2,3} = 0^\circ$ if $M_{\rm SUSY} = m_t^{\rm pole}$ and $\tan\beta = 10$

♠ *Backup*

- The B-meson observables strike against CPX!: $B(B_s \to \mu^+\mu^-)$ (95 %), $B(B \to X_s\gamma)$ (2 σ), $R_{B\tau\nu}$ (1 σ), $\Upsilon(1S) \to H_1\gamma$ CPX scenario with $\Phi_A = \Phi_3 = 90^\circ$ and $M_{\rm SUSY} = 0.5$ TeV JSL, M. Carena, J. Ellis, A. Pilaftsis, C.E.M. Wagner, arXiv:0712.2360; JSL and S. Scopel, PRD75(2007)075001



The CPX scenario excluded ? ... flavour-mixing terms