Channels, Chases, & Challenges – New Physics at the LHC

Jürgen Reuter

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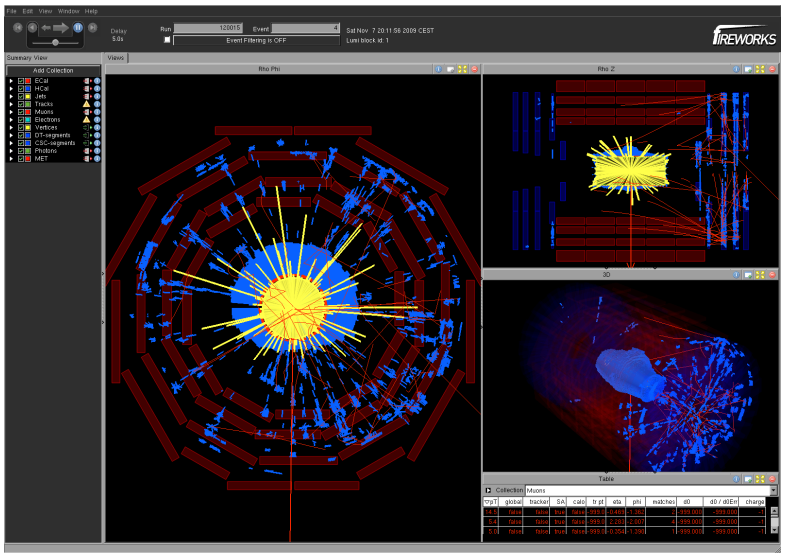
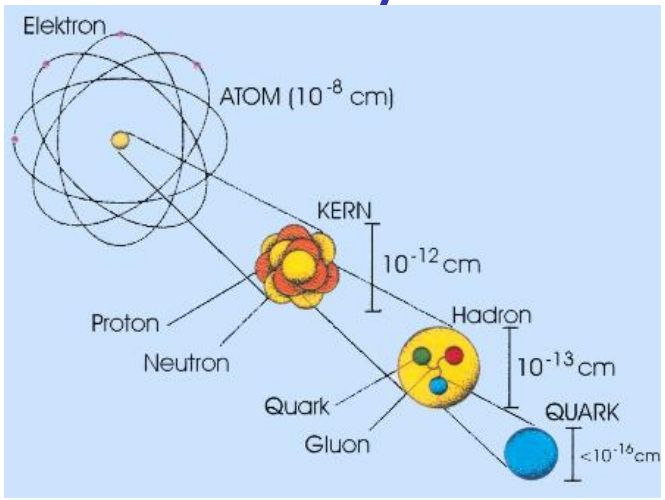


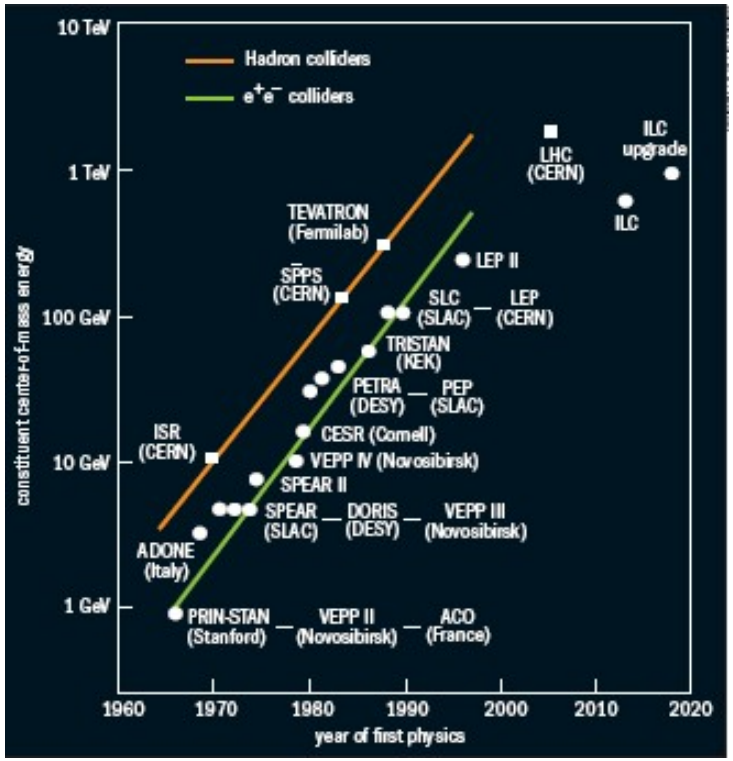
Talk, University of Glasgow, 07. January 2010

Particle Physics - "The High Energy Frontier"

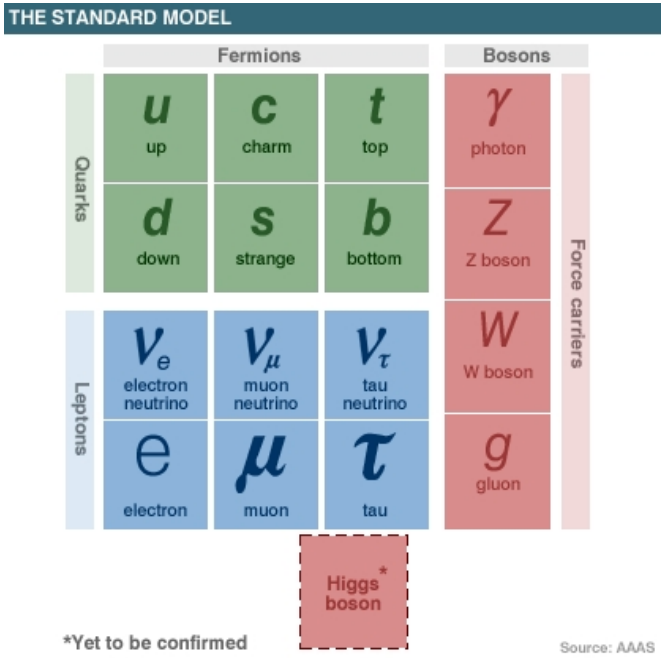


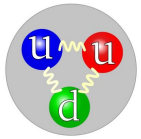
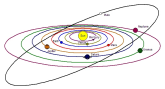
System	Size	Energy
Molecules	10^{-8} m	$\sim 10^{-1}$ eV
Atoms	10^{-10} m	$\sim$ eV . . . . . keV
Nuclei	10^{-14} m	~ 10 MeV
Nucleons	10^{-15} m	$\lesssim 1$ GeV

Resolving power: $\Delta x \sim (\Delta E)^{-1} \Rightarrow$
High energy colliders



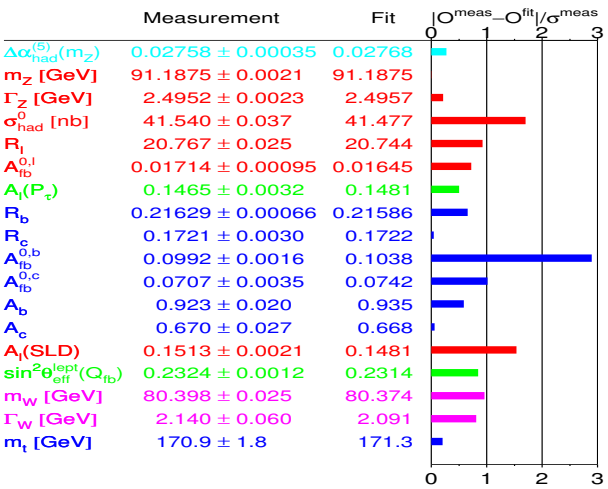
The Standard Model of Particle Physics – Successes



Interaction	Strength	Range	Property
strong	1	$\sim 10^{-15}$ m	
electromagnetic	10^{-2}	∞	
weak	10^{-12}	$\lesssim 10^{-17}$ m	
gravitation	10^{-39}	∞	

- Interactions: relativistic quantum field theories
- weak interactions: radioactive decays Fermi, 1934
- electroweak unification Glashow, Salam, Weinberg, 1967-1969
- strong interactions: asymptotic freedom Gross, Politzer, Wilczek, 1973
- Discovery of the gluon DESY 1979 W, Z CERN, 1983
- Experimental confirmation: better than 1%

The Standard Model of Particle Physics – Doubts



– describes microcosm (too well?)

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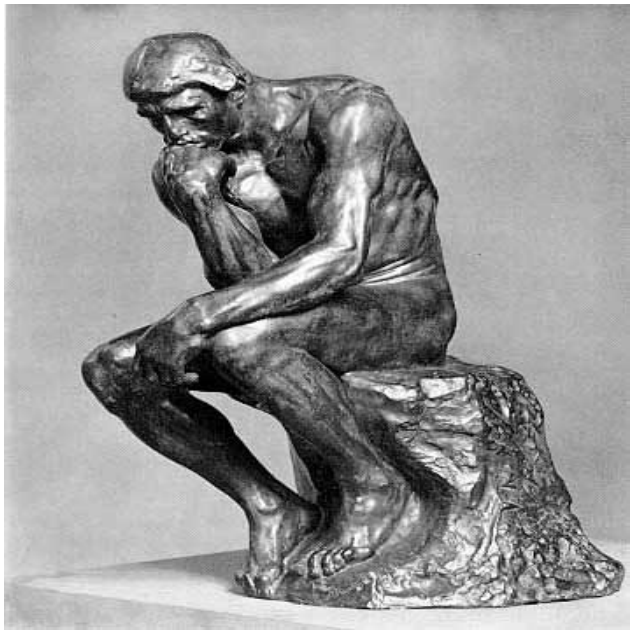
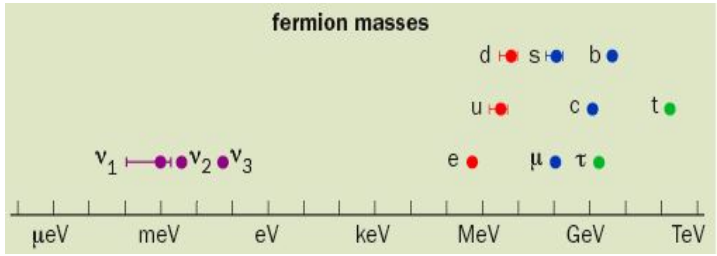
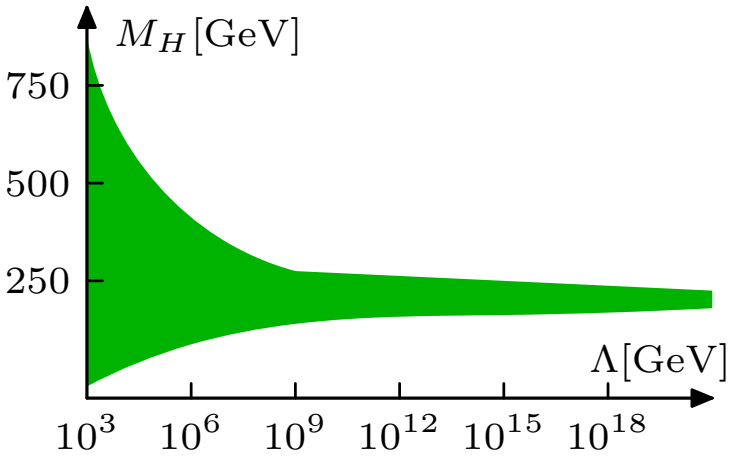


- describes microcosm (too well?)
- 28 free parameters



- Form of the Higgs potential ?



Hierarchy problem

chiral symmetry: $\delta m_f \propto v \ln(\Lambda^2/v^2)$

no symmetry protects Higgs from quantum corrections

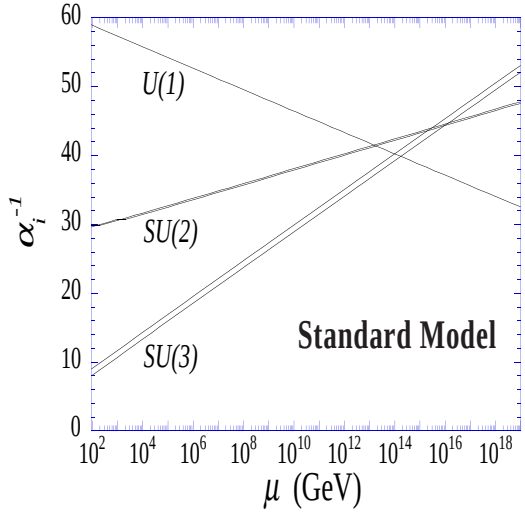
$$\delta M_H^2 \propto \Lambda^2 \sim M_{\text{Planck}}^2 = (10^{19})^2\ \text{GeV}^2$$

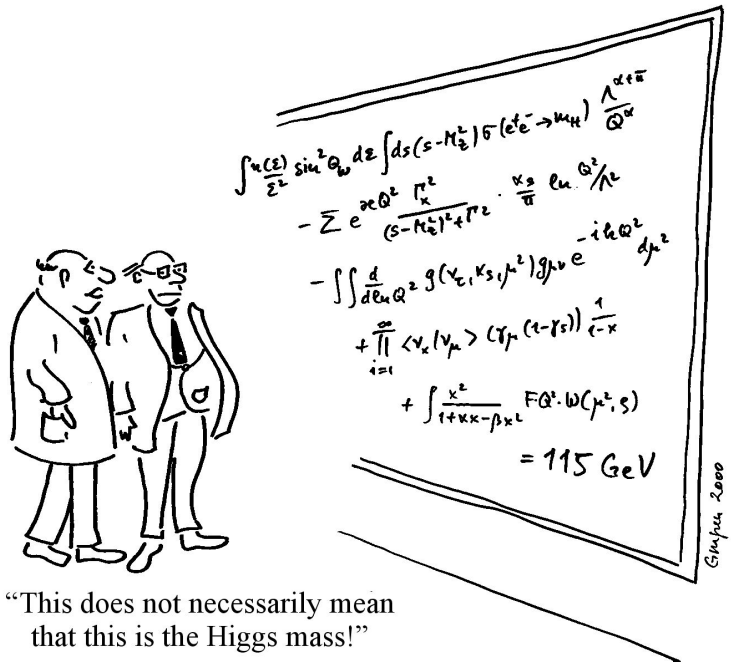
20000 GeV^2 = (10000000000000000000000000000020000 –

10000000000000000000000000000000000) GeV^2

Open Questions

- Unification of all forces (?)
- Baryon asymmetry $\Delta N_B - \Delta N_{\bar{B}} \sim 10^{-9}$ missing CP violation
- Flavour: three generations
- Tiny neutrino masses: $m_\nu \sim \frac{v^2}{M}$
- Dark matter:
  - stable
  - weakly interacting
  - $m_{DM} \sim 100\,\text{GeV}$
- Quantum theory of gravity
- Cosmic inflation
- Cosmological constant





"This does not necessarily mean that this is the Higgs mass!"


bosonicTC
TC-TC
composite Higgs
hypercolor
supercolor
techni-GIM
extended TC
pseudo NGB
NOT YET THOUGHT OF
NOT YET THOUGHT OF
6th gen
5th gen
4th gen
vector-like family
S,T,U
lepto quark
sterile ν
heavy Majorana ν
fractionally charged
milli-charged
mono-pole
effective SUSY
SUSY
NMSSM
nMSSM
MSSM +RPV
ununified SM
axigluon
Z'ψ
Z'I
Z'SM
Z'χ
Z'η
W_R
X Y
NOT YET THOUGHT OF
shadow matter
mirror symmetry
triplet Higgs
doubly charged Higgs
Type I
Type II
general 2HDSM
spontaneous CP
superweak
milli-weak
Weinberg's 3HD
Majoron
axion
familon
NGB
saxion
axino
worm-hole
Extra dim
quintessence
k-essence
composite W,Z
contact int.
strings
heterotic
matrix
M
IIB
IIA
F
I
N=2
N=4
N=8

Ideas for New Physics since 1970

(1) **New building blocks, sub structure**

- Technicolor/Topcolor: Higgs bound state of strongly interacting particles

(2) **Symmetry for the elimination of quantum corrections**

- Supersymmetry: Spin-statistics $\Rightarrow$ bosonic and fermionic corrections cancel each other
- Little-Higgs models: Global symmetries $\Rightarrow$ corrections from particles of like statistics cancel each other

(3) **Nontrivial space-time structure eliminates hierarchy**

- Additional space dimensions: Gravitation appears only weak
- Noncommutative space-time: Space-time coarse-grained

(4) **Ignoring the hierarchy**

- Anthropic Principle: Parameters are the way they are, because we observe them

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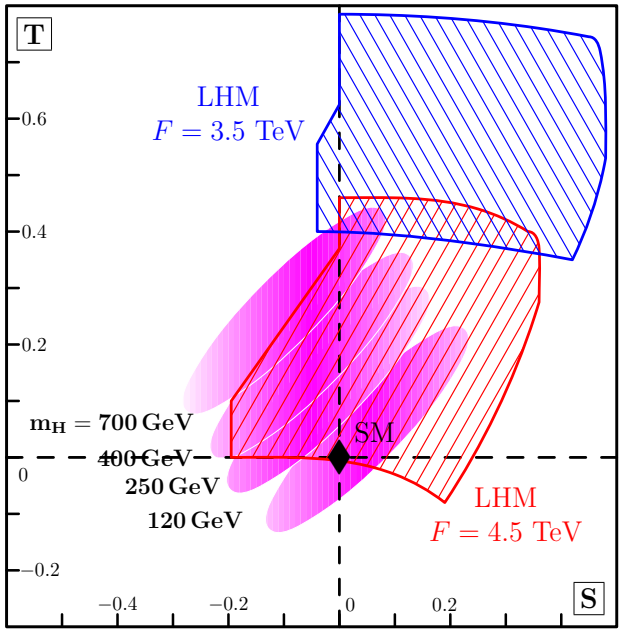
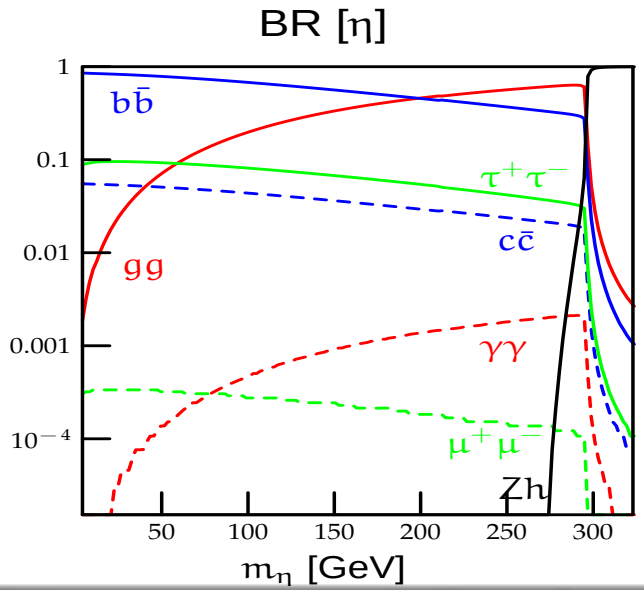
Little Higgs Models

Kilian/JR **PRD 70** (2004), 015004; Kilian/Rainwater/JR **PRD 71** (2005), 015008; **PRD 74** (2006), 095003; Butenuth/JR

- "Little Big Higgs": Higgs boson heavy $(300 - 500\,\text{GeV})$
- Extensive low-energy constraints
- Tiny neutrino masses in LHM
- General search strategy at the LHC
- Proposal of methods to distinguish model classes





- Prediction of new scalar particles: Pseudoaxions
- Light electroweak singlets
- Good discovery prospects at LHC
- Model building aspects: T parity and dark matter in generalized models

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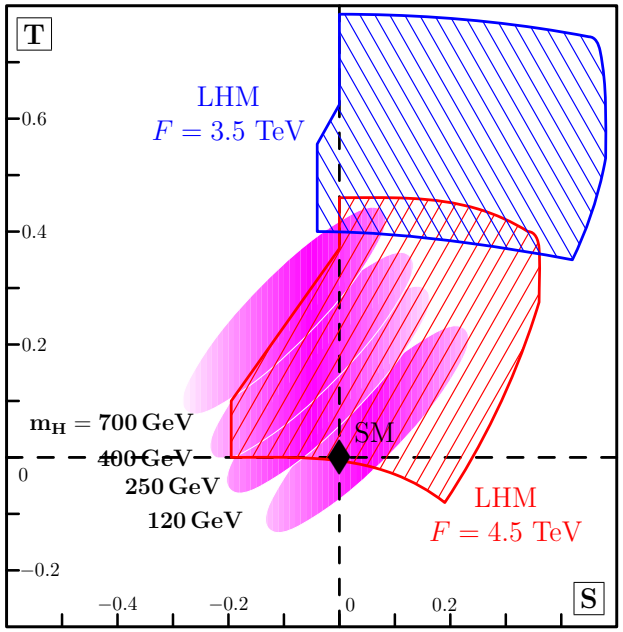

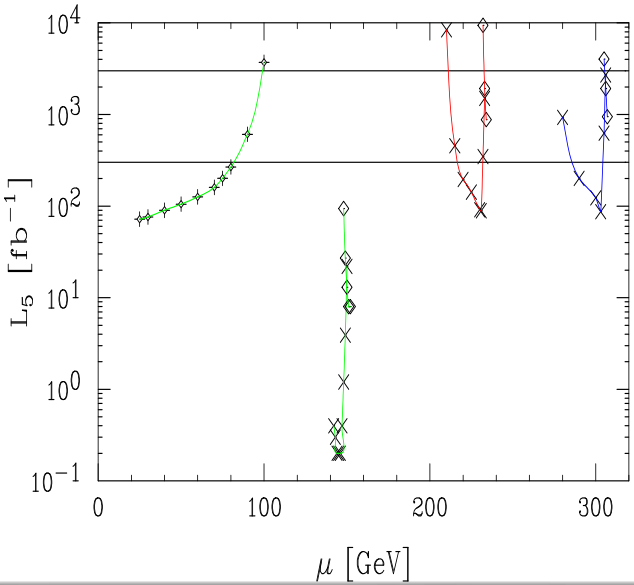

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Desperately
Seeking
SUSY

E_6 SUSY Grand Unification

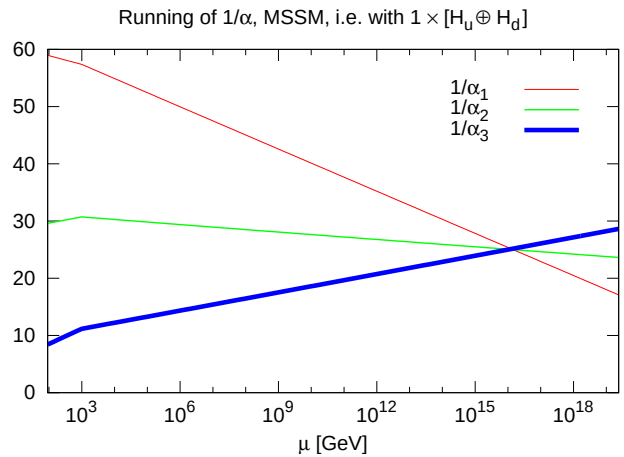
JR/Kilian, PLB 642 (2006), 81

Supersymmetry: consistent extrapolation to high scales

$\Rightarrow$ two Higgs doublets H^u, H^d

$\Rightarrow$ TeV-scale SM-superpartners

Bottom-Up Approach: just MSSM



- Unifies Higgs and matter fields
- Ansatz: all new particles in the spectrum at TeV scale

$$Q_L = (\mathbf{3},\mathbf{2})_{\frac{1}{6},Q'_Q} \qquad L_L = (\mathbf{1},\mathbf{2})_{-\frac{1}{2},Q'_L}$$

$$u^c = (\bar{\mathbf{3}},\mathbf{1})_{-\frac{2}{3},Q'_u} \qquad \nu^c = (\mathbf{1},\mathbf{1})_{0,Q'_\nu=0}$$

$$d^c = (\bar{\mathbf{3}},\mathbf{1})_{\frac{1}{3},Q'_d} \qquad e^c = (\mathbf{1},\mathbf{1})_{1,Q'_e}$$

$$H^u = (\mathbf{1},\mathbf{2})_{\frac{1}{2},Q'_{H^u}}$$

$$H^d = (\mathbf{1},\mathbf{2})_{-\frac{1}{2},Q'_{H^d}}$$

$$S = (\mathbf{1},\mathbf{1})_{0,Q'_S \neq 0}$$

$$D = (\mathbf{3},\mathbf{1})_{-\frac{1}{3},\ Q'_D}$$

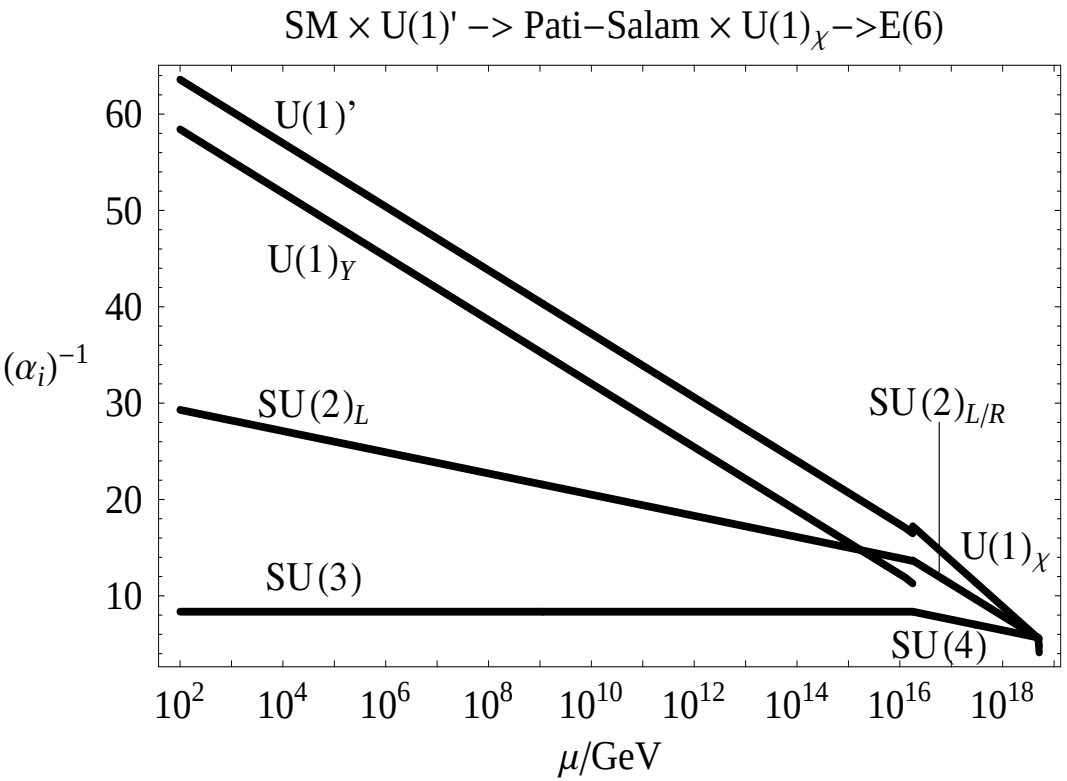
$$D^c = (\bar{\mathbf{3}},\mathbf{1})_{\frac{1}{3},-Q'_D}$$

Intermediate Pati-Salam symmetry

JR/Kilian 2006, King et al. 2008

- Additional particles spoil simple unification
- Gauge couling unification below Λ_{Planck} due to intermediate

$$SU(4) \times SU(2)_L \times SU(2)_R[\times U(1)_\chi]$$ Pati-Salam symmetry at $\sim 10^{16}$GeV



- $SU(2)_R$ and $SU(2)_L$: identical particle content $\Rightarrow$ running
- Crossing of $SU(4)$ and $SU(2)_{L/R}$ couplings determines E_6 breaking scale
- Lepton number: 4^{th} color
- $T^{15}_{SU(4)} \propto \frac{B-L}{2}$
- $Y = \frac{B-L}{2} + T^3_R$
- Integrating out ν^c (see-saw)

$\Rightarrow$ appropriate breaking

Model building aspects

JR/Kilian, PLB 642 (2006); Braam/Knochel/JR, 2010

- Embed $E_6 \subset E_6 \otimes SU(3) \subset E_8$
- $A_4 \subset SO(3) \subset SU(3)$ flavour symmetry $\Rightarrow$ protects the proton
  Proton decay only by E_6 gauge bosons: $\tau(p) \gtrsim 10^{40}$ yrs Mallot/JR, 2010
- Mirror matter Kaluza-Klein tower breaks E_8
  Possible embedding in $N = 2$ supersymmetry
- E_6 breaking from an orbifold fixed-point construction
- E_6 superpotential vanishes exactly
- Pati-Salam breaking by adjoint $\mathbf{78}$ rep. of E_6
- Both electroweak and $U(1)_\chi$ symmetry radiatively broken
- Cocktail of dark matter candidates!

Investigation Of The Parameter Space

Braam/JR, 2010

- # free parameters $\sim \mathcal{O}(100)$, additional assumptions:
  - Unified soft breaking parameters - Flavour structur
  $\Rightarrow$ Limitation on 14 free parameters
- Constraints:
  (1) Experimental lower bounds on masses of new particles
  (2) Running parameters perturbative up to Λ_{E_6}
  (3) Scalar (non-Higgs) mass terms have to remain positive
  ($\Leftrightarrow$ No unwanted symmetry breaking)

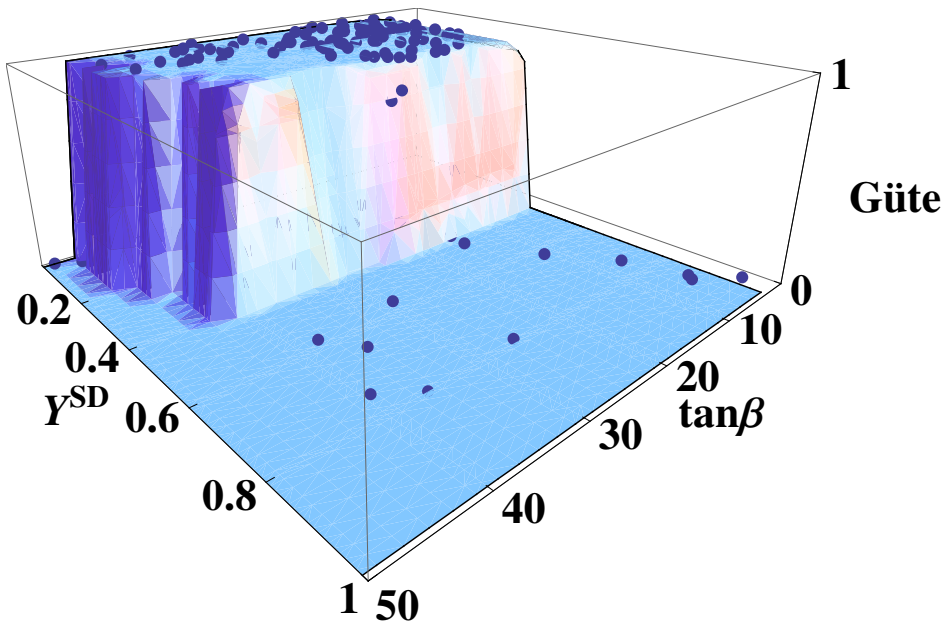
- 14-dim parameter space

$\Rightarrow$ grid scanning $\longrightarrow 10^{28}$ points

- Investigation per point (RGE, Higgs potential minimization, calculation of masses) ~ 5 s

Sol: Monte-Carlo Markov-Chain through parameter space

$\Rightarrow$ Effective search for sensible parameter tupels



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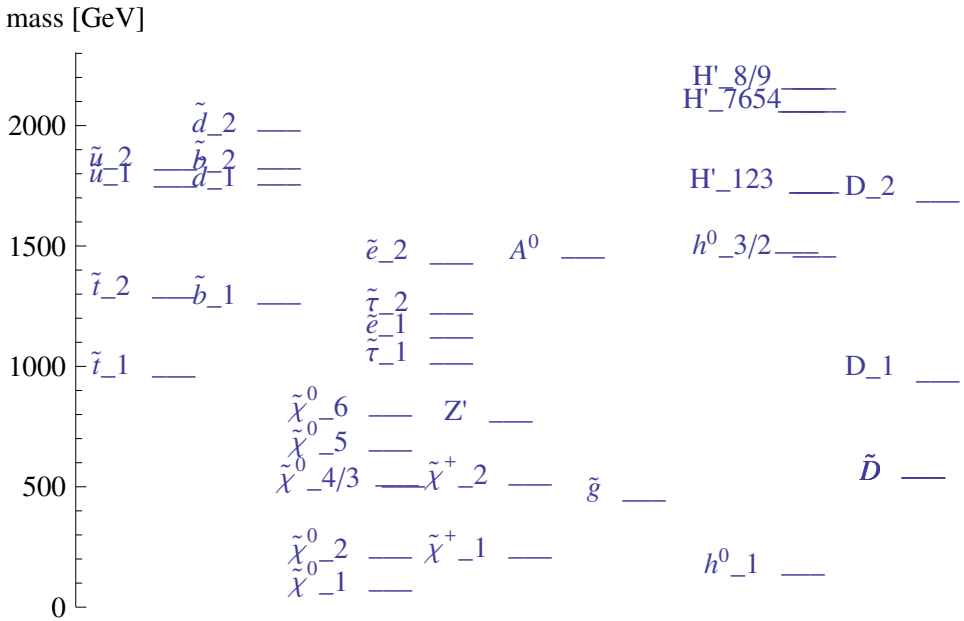
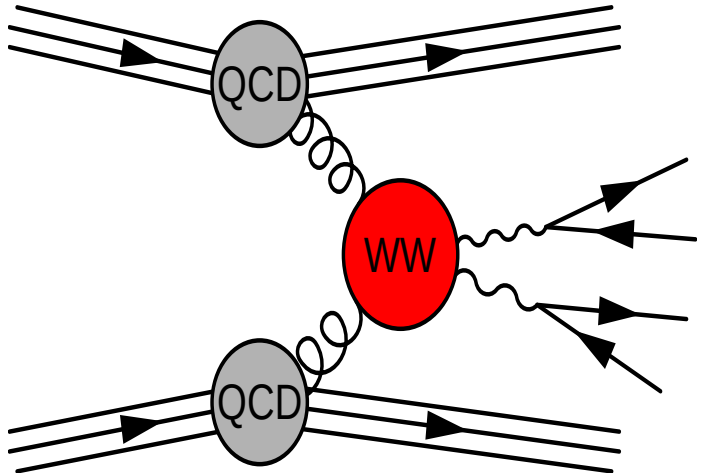
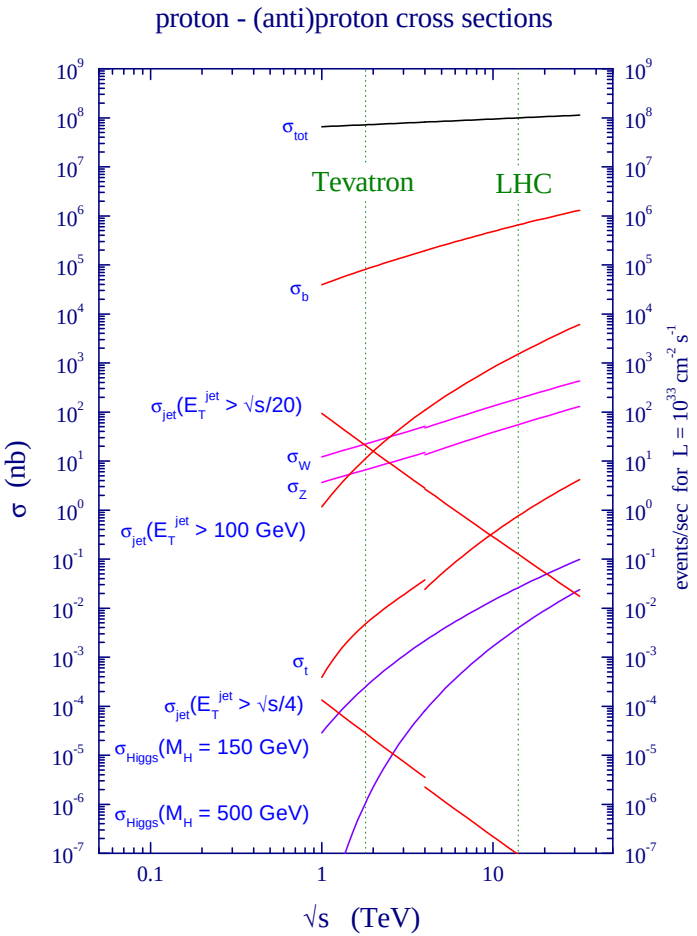


The challenge of the LHC

Partonic subprocesses: qq, qg, gg

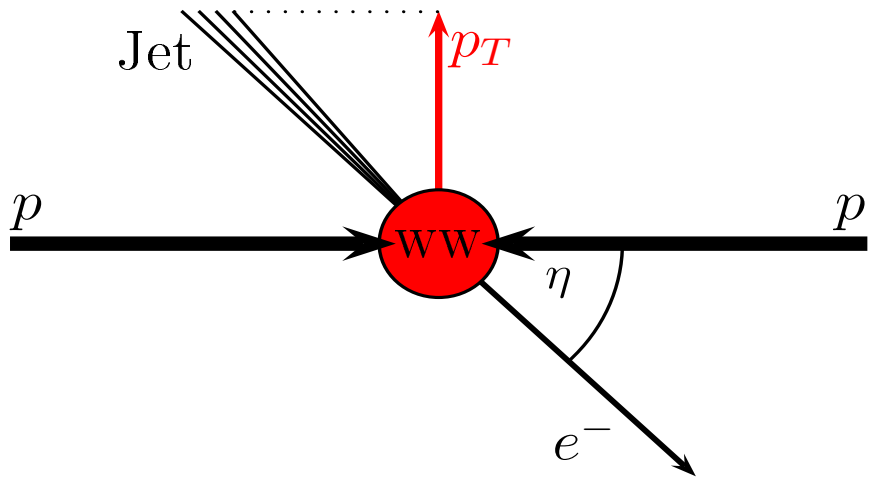
No fixed partonic energy





$R = \sigma\mathcal{L}$ $\mathcal{L} = 10^{34}\,\text{cm}^{-1}\text{s}^{-1}$

High rates for t, W/Z, H, $\Rightarrow$ **huge backgrounds**



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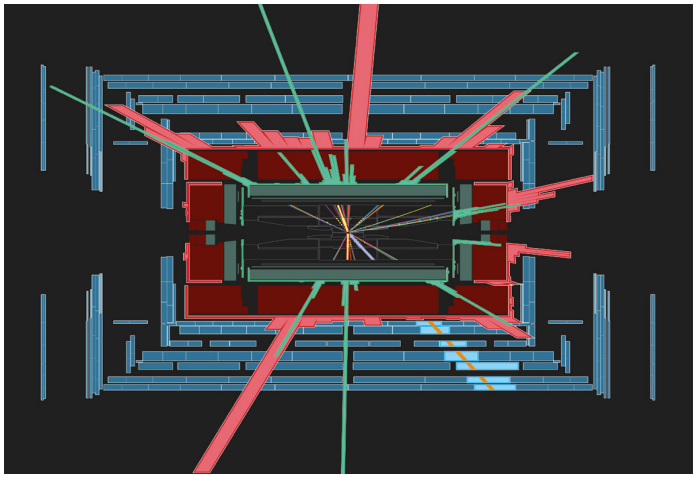

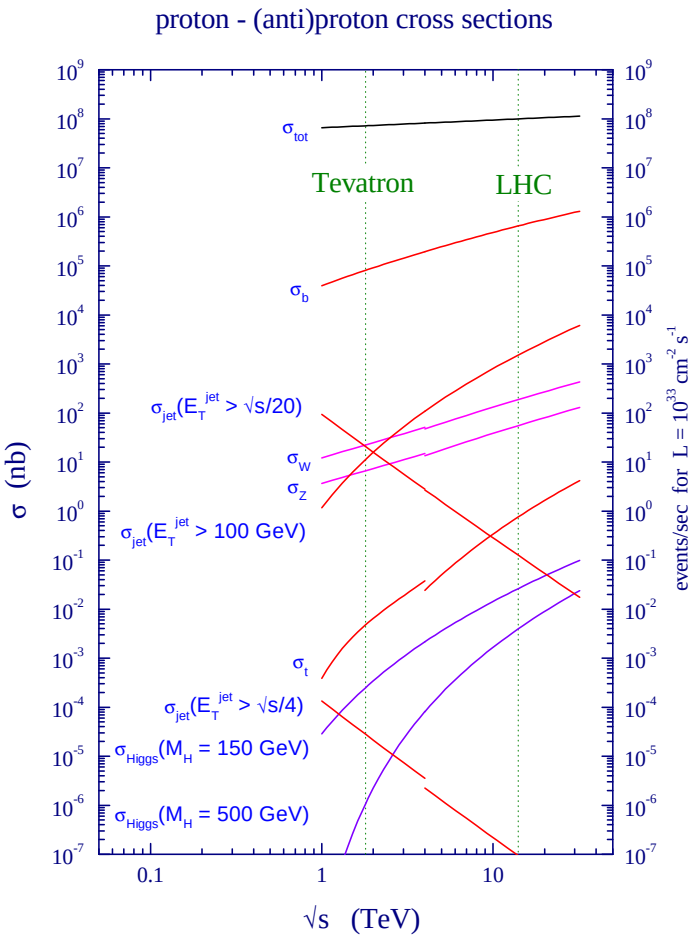

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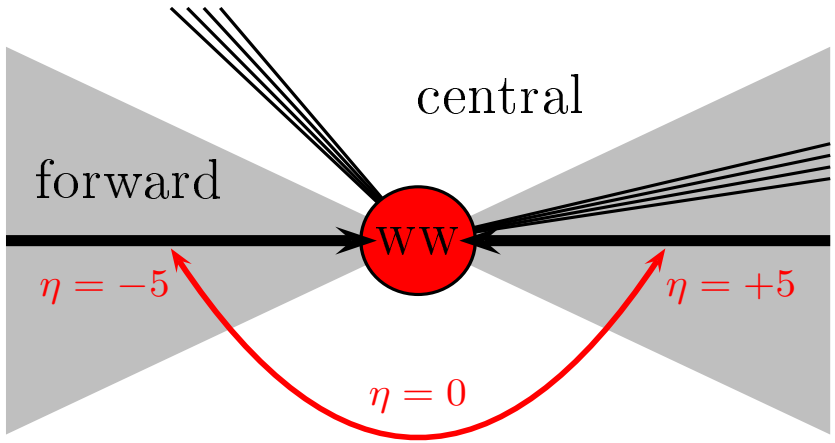
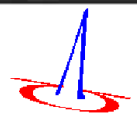


WHIZARD

Kilian/Ohl/JR + PhDs, hep-ph/0102195, 0708.4233

- Acronym: **W**, **HI**ggs, **Z**, **A**nd **R**espective **D**ecays (deprecated)
- Fast Multi-Channel Monte-Carlo integration
- Very efficient phase space and event generation
- Optimized matrix elements
- Current version: 2.0.0β `http://projects.hepforge.org/whizard` and `http://whizard.event-generator.org`
- parton shower ($p_\perp$ ordered) and analytic (v2.0)
- no hadronization
- underlying event: preliminary version for v2.1
- Arbitrary processes: a generator generator (O'Mega)
- BSM: cf. next page
- 2.0 features: ME/PS matching, cascades, new versatile user interface and syntax, WHIZARD as a shared library

WHIZARD – Overview over BSM Models



Very high level of Complexity:

- $e^+e^- \to t\bar{t}H \to b\bar{b}b\bar{b}jj\ell\nu$ (110,000 diagrams)
- $e^+e^- \to ZHH \to ZWWWW \to bb + 8j$ (12,000,000 diagrams)
- $pp \to \ell\ell + nj, n = 0, 1, 2, 3, 4, \ldots$ (2,100,000 diagrams with 4 jets + flavors)
- $pp \to \tilde{\chi}_1^0\tilde{\chi}_1^0 bbbb$ (32,000 diagrams, 22 color flows, $\sim 10,000$ PS channels)
- $pp \to VVjj \to jj\ell\ell\nu\nu$ incl. anomalous TGC/QGC
- Test case $gg \to 9g$ (224,000,000 diagrams)

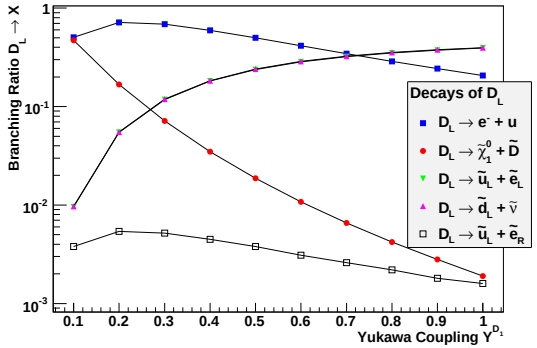
MODEL TYPE	with CKM matrix	trivial CKM
QED with e, μ, τ, γ	–	`QED`
QCD with d, u, s, c, b, t, g	–	`QCD`
Standard Model	`SM_CKM`	`SM`
SM with anomalous couplings	`SM_ac_CKM`	`SM_ac`
SM with K matrix	—	`SM_KM`
MSSM	`MSSM_CKM`	`MSSM`
MSSM with gravitinos	—	`MSSM_Grav`
NMSSM	—	`NMSSM`
extended SUSY models	—	`PSSSM`
Littlest Higgs	—	`Littlest`
Littlest Higgs with ungauged $U(1)$	—	`Littlest_Eta`
Littlest Higgs with T parity	—	`Littlest_Tpar`
Simplest Little Higgs (anomaly-free)	—	`Simplest`
Simplest Little Higgs (universal)	—	`Simplest_univ`
UED	—	`UED`
SUSY Xdim. (inoff.)	—	`SED`
Noncommutative SM (inoff.)	—	`NCSM`
SM with Z'	—	`Zprime`
SM with gravitino and photino	—	`GravTest`
Augmentable SM template	—	`Template`

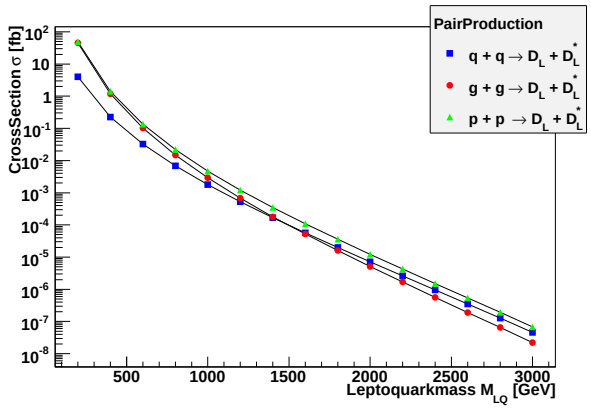
easy to implement new models

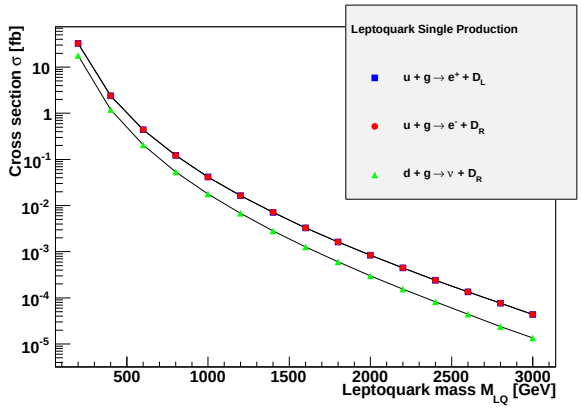
Predictions from E_6 GUTs for LHC

Braam/JR/Wiesler, 0909.3081

- Simulations for the E_6 model with `WHIZARD`
- Implementation of leptoquark/leptoquarkino + Higgs/weak ino sector
- First analyses: BRs, cross sections for scalar leptoquarks, S/B
- In progress: leptoquarkino pheno







Cuts		Background	$m_D = 0.6$ TeV		$m_D = 0.8$ TeV		$m_D = 1.0$ TeV	
p_T	$M_{\ell\ell}$	N_{BG}	N_1	$S_1/\sqrt{B}$	N_2	$S_2/\sqrt{B}$	N_3	$S_3/\sqrt{B}$
50	10	413274	64553	**93**	14823	**23**	4819	**7**
100	150	3272	40749	**194**	10891	**92**	3767	**45**
200	150	198	12986	**113**	5678	**74**	2405	**47**

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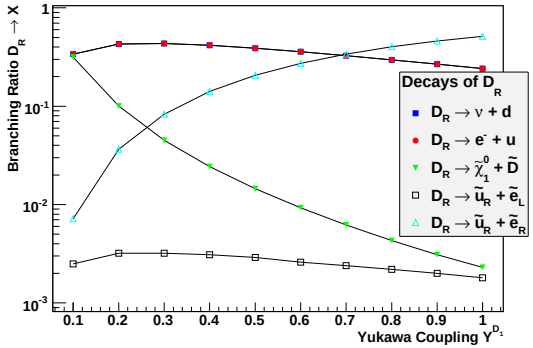
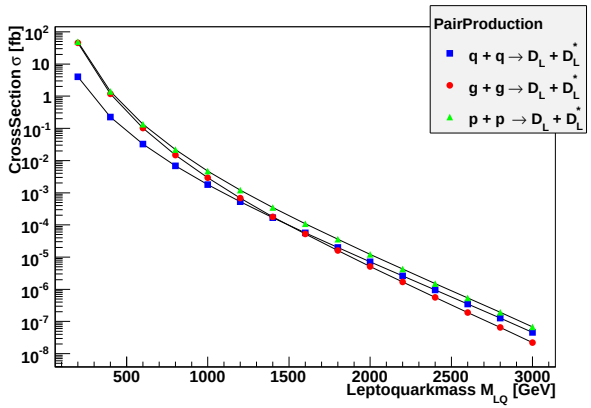
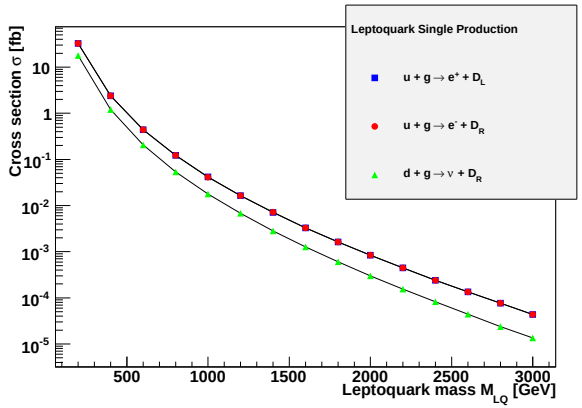
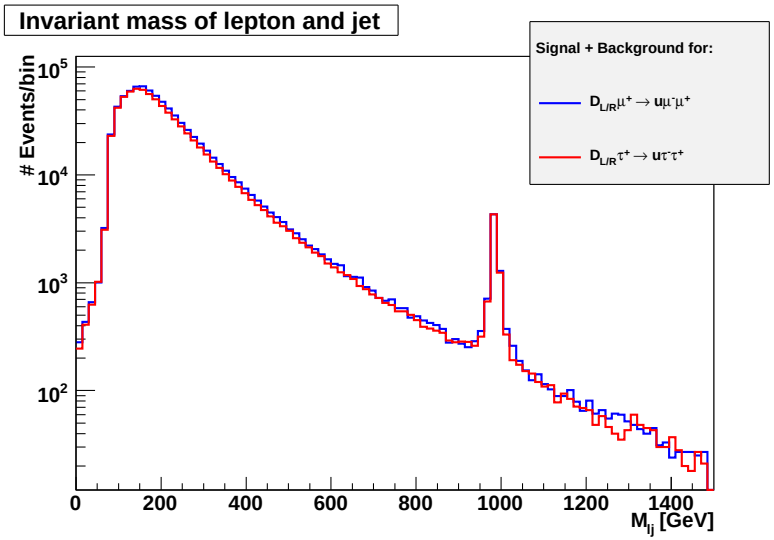


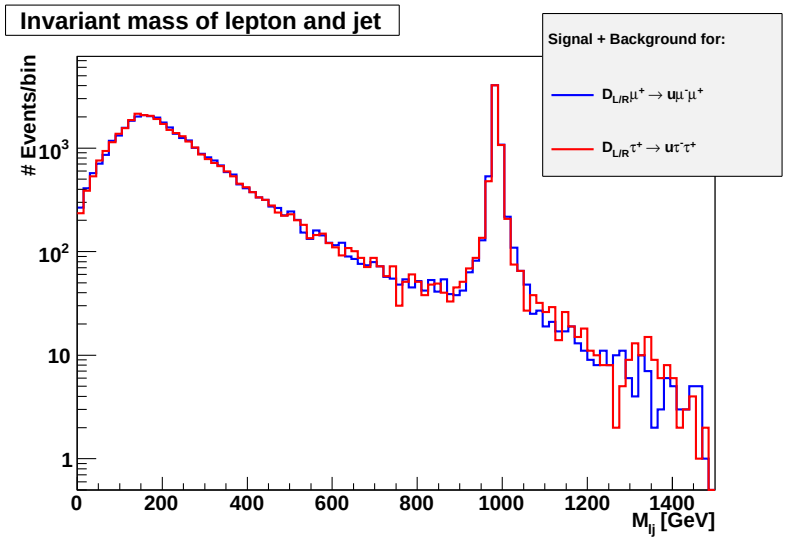


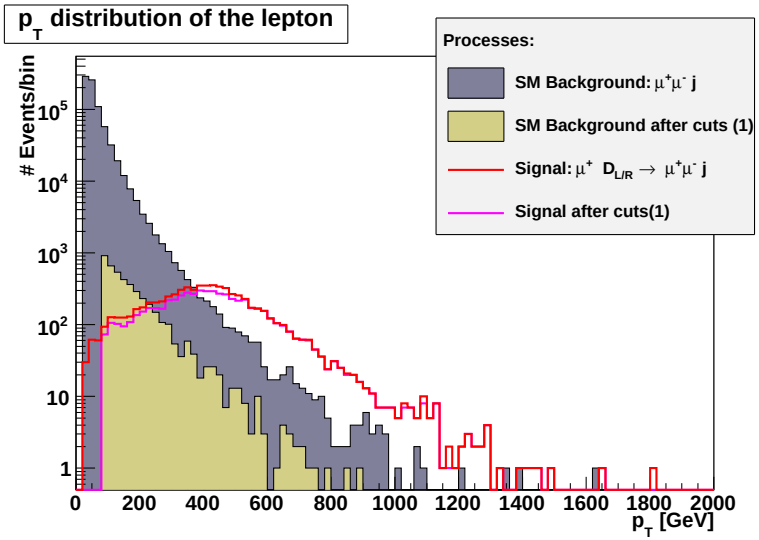


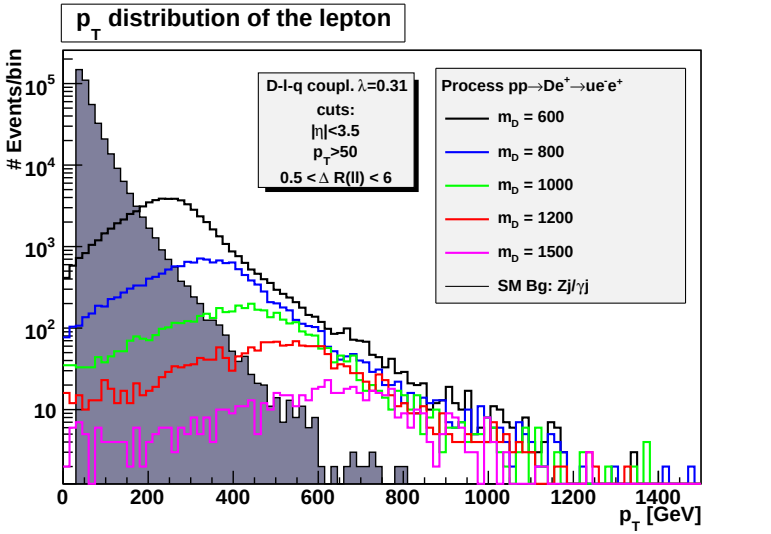
Cuts		Background	$m_D = 0.6$ TeV		$m_D = 0.8$ TeV		$m_D = 1.0$ TeV	
p_T	$M_{\ell\ell}$	N_{BG}	N_1	$S_1/\sqrt{B}$	N_2	$S_2/\sqrt{B}$	N_3	$S_3/\sqrt{B}$
50	10	413274	64553	**93**	14823	**23**	4819	**7**
100	150	3272	40749	**194**	10891	**92**	3767	**45**
200	150	198	12986	**113**	5678	**74**	2405	**47**

Braam/JR/Wiesler, 0909.3081









Resonances in VV scattering

Alboteanu/Kilian/JR, 0806.4145

Model-independent description for LHC, respect weak isospin ($\rho \approx 0$):

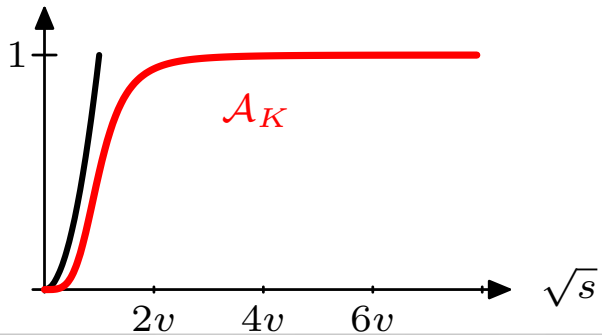
	$J=0$	$J=1$	$J=2$
$I=0$	σ^0 (Higgs ?)	ω^0 (γ'/Z' ?)	a^0 (Graviton ?)
$I=1$	$\pi^\pm, \pi^0$ (2HDM ?)	$\rho^\pm, \rho^0$ (W'/Z' ?)	$t^\pm, t^0$
$I=2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$f^{\pm\pm}, f^\pm, f^0$

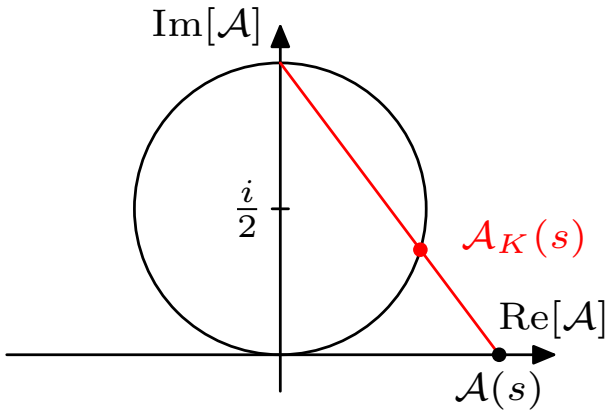
LHC access limited: 1. resonance correct, guarantee unitarity

K-Matrix unitarization

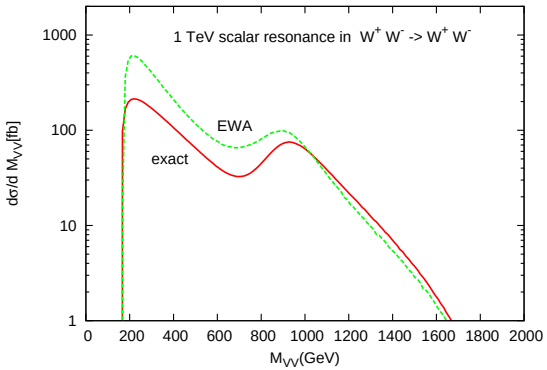
$$\mathcal{A}_K(s) = \mathcal{A}(s)/(1 - i\mathcal{A}(s))$$

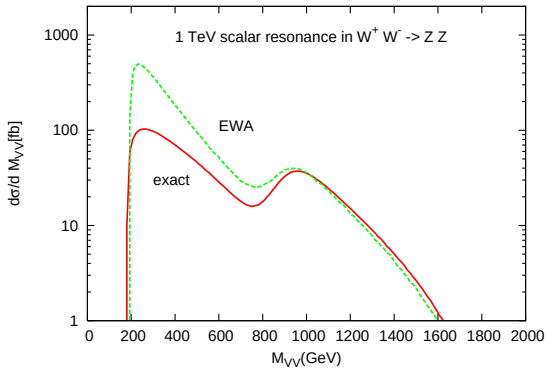
- Low-energy theorem (LET): $\frac{s}{v^2}$
- K-matrix ampl.: $|\mathcal{A}(s)|^2 \overset{s\to\infty}{\to} 1$
- Poles $\pm iv$: M_0, Γ large

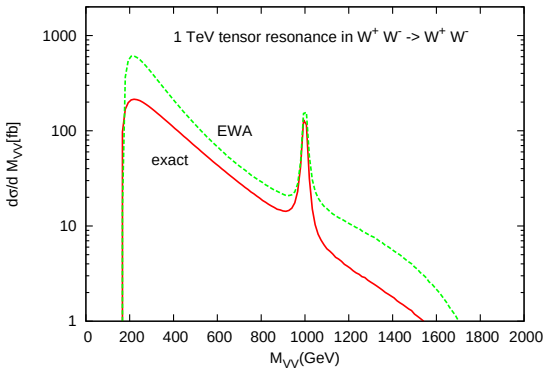


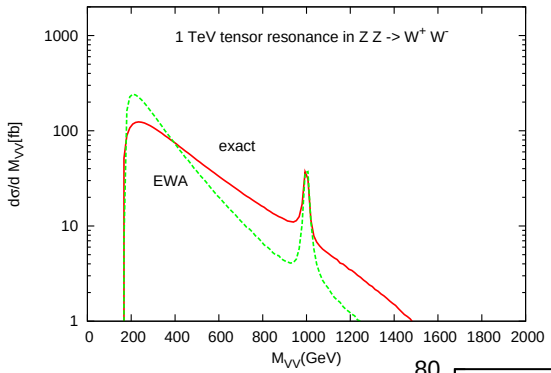


- Unitarization in each spin-isospin eigen-channel
- breaks crossing invariance
- Explicit “time arrow” in WHIZARD



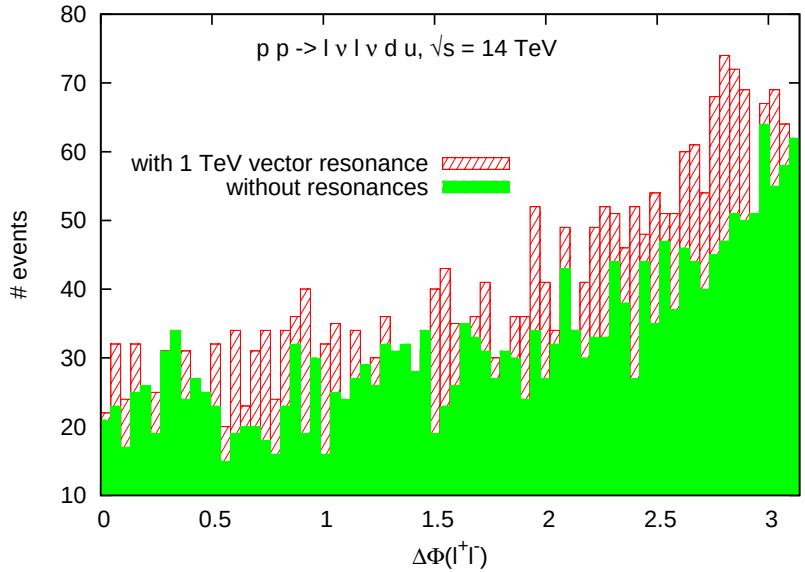






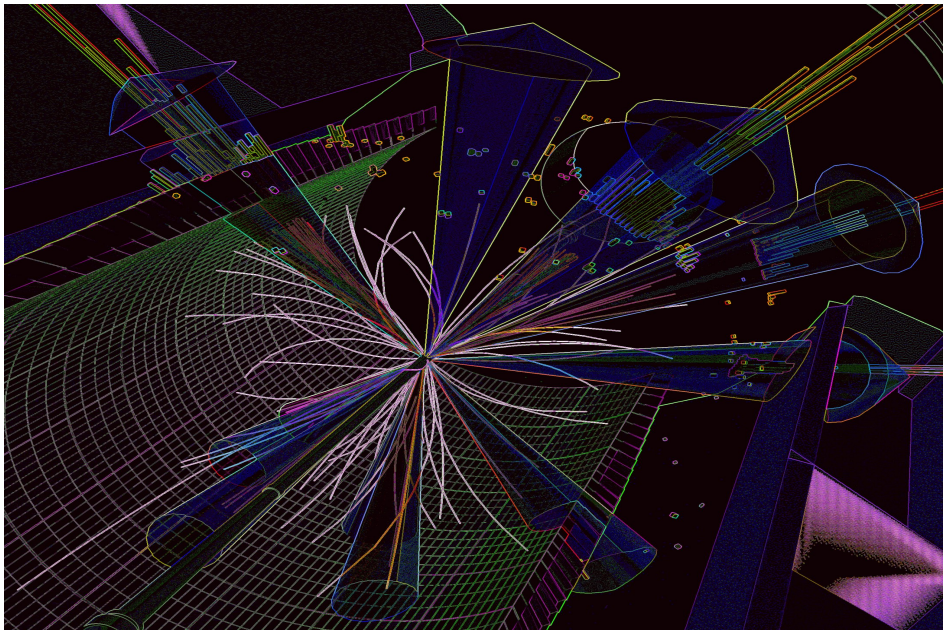
- Effective W approx. vs. WHIZARD full matrix elements
- Shapes/normalization of distributions heavily affected
- EWA: Sideband subtraction completely screwed up!

- Example: 850 GeV vector resonance
- coupling $g_\rho = 1$
- Discriminator: angular correlations
- Ongoing ATLAS study



Outlook

- LHC: new era of physics is beginning
- New particles, new symmetries, new interactions
- A lot to do: Model building and phenomenology
  Joint effort of theorists and experimentalists!
- Interesting times ahead!



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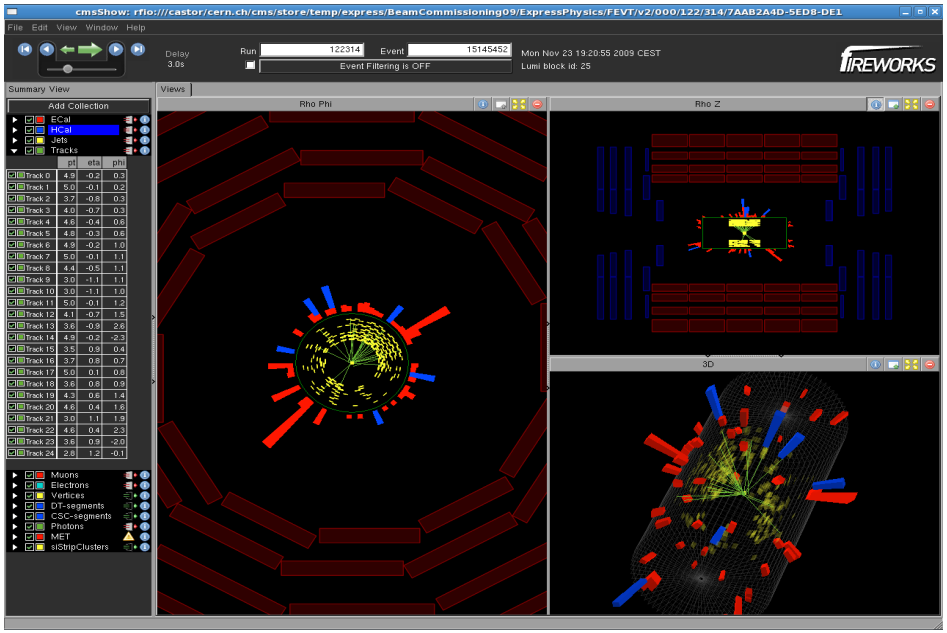

"Though this be madness, yet there is method in 't.". - (Hamlet, Act II, Scene II).