Seminarium Fizyki Wysokich Energii

23.10.2009

Teoria cząstek elementranych 2009-nowe metody

Maria Krawczyk
IFT

Teoria cząstek elementarnych ~Model Standardowy

Nowe metody

Standard Model Theory for Colliders Physics

B. Anastasiou (EPS 2009)
Assault on the NLO Wishlist: pp $\rightarrow$ ttbb

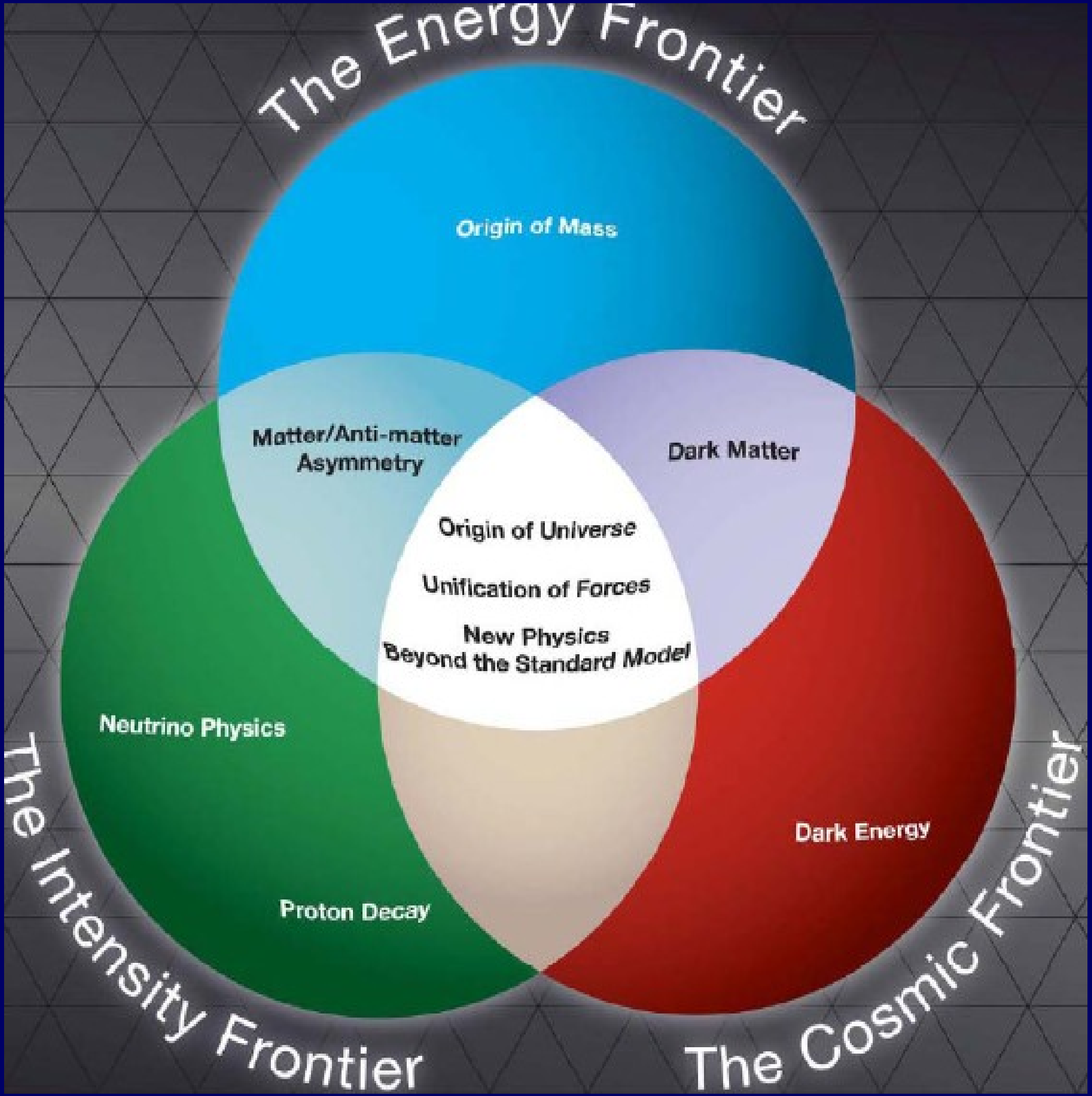
M. Worek (Ustroń 2009)

Nonperturbative Field Theory

R.Janik (EPS 2009)

Evolution of the Universe to the present Inert phase (EPS2009..)

Teoria cząstek elementarnych



THE THEORY OF MATTER and STANDARD MODEL(S)

F. Wilczek, LEPFest, Nov.2000 (hep-ph/0101187)

Theory of Matter = $SU(2)_{I\ weak} \times U(1)_{Y\ weak} \times SU(3)_{color}$

Theory of Matter refers to the core concepts:

- quantum field theory
- gauge symmetry
- spontaneous symmetry breaking
- asymptotic freedom
- the assignments of the lightest quarks and leptons

Standard Models: Choose the number of Higgs (scalar) doublets
SM=1HDM, 2HDM (MSSM), 3HDM ...
Note, that the lightest scalar is often SM-like

NonStandard Models are based on more radical assumptions.

Brout-Englert-Higgs mechanism

Spontaneous breaking of EW symmetry

$SU(2) \times U(1) \rightarrow U(1)_{QED}$

Standard Model

Doublet of SU(2): $\Phi = (\varphi^+, v+H+i\zeta)^T$

Masses for $W^{+/-}$, Z (tree $\rho = 1$), no mass for the photon

Fermion masses via Yukawa interaction

Higgs particle H_{SM} - spin 0, neutral, CP even

couplings to WW/ZZ, Yukawa couplings to fermions

mass $\leftrightarrow$ selfinteraction unknown

Standard Model Theory for collider physics

Babis Anastasiou
ETH Zurich

A theory revolution

- Deeper understanding of the structure of gauge theories
- Sharp theoretical predictions for collider experiments
- A new technical revolution and a pace of progress to be very proud of

Highlights

- Revolutionary new methods for one-loop calculations and a promise for precise multi-particle production cross-sections at the Tevatron and the LHC
- Impressive progress on NNLO methods which has lead to precision phenomenology for LEP, HERA, Tevatron and the LHC

One-loop amplitudes

final states with many particles at the LHC

JET ALGORITHMS

Jet physics at LEP, strong coupling

NNLO theory

DIS at HERA

PDFs for the Tevatron and the LHC

Drell-Yan and Higgs @ Tevatron/LHC

tops and di-bosons

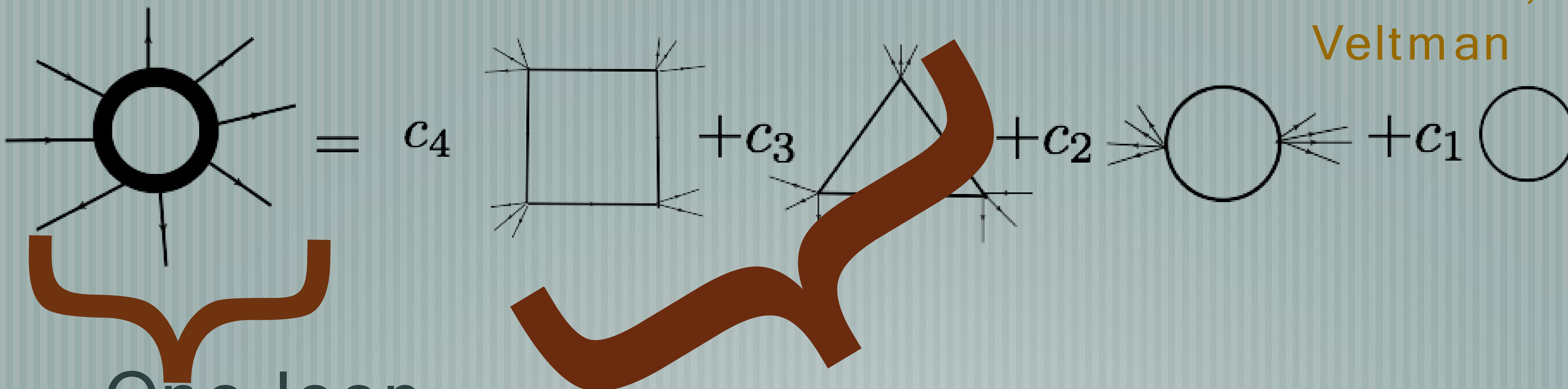
One-loop amplitudes from trees... and masters!!! and masters! and masters!

Trees in Gauge theory

Loop Master Integrals in scalar field theory

Master Integrals

Passarino, Veltman *1980s*



One-loop amplitude in Gauge theory

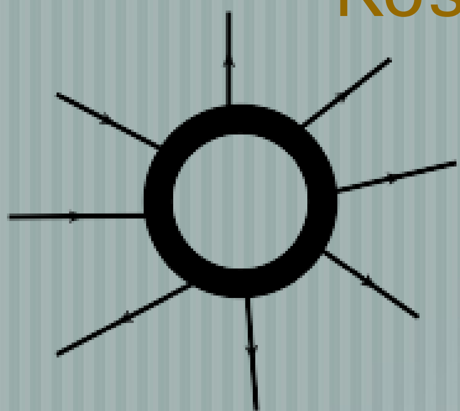
Integrals in scalar field theory

Known method(s) to compute c_i coefficients had a (# Legs)! computational cost

Unitarity

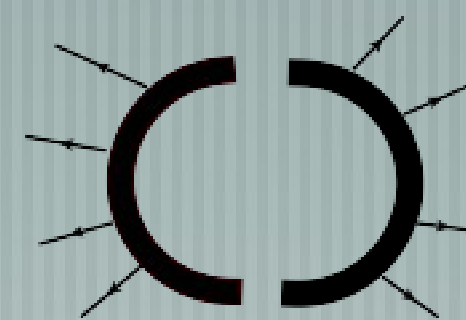
Bern, Dixon, Dunbar, Kosower

1990s



$$\approx \int \frac{d^d k}{k^2 (k+p)^2}$$

$Tree \times Tree$



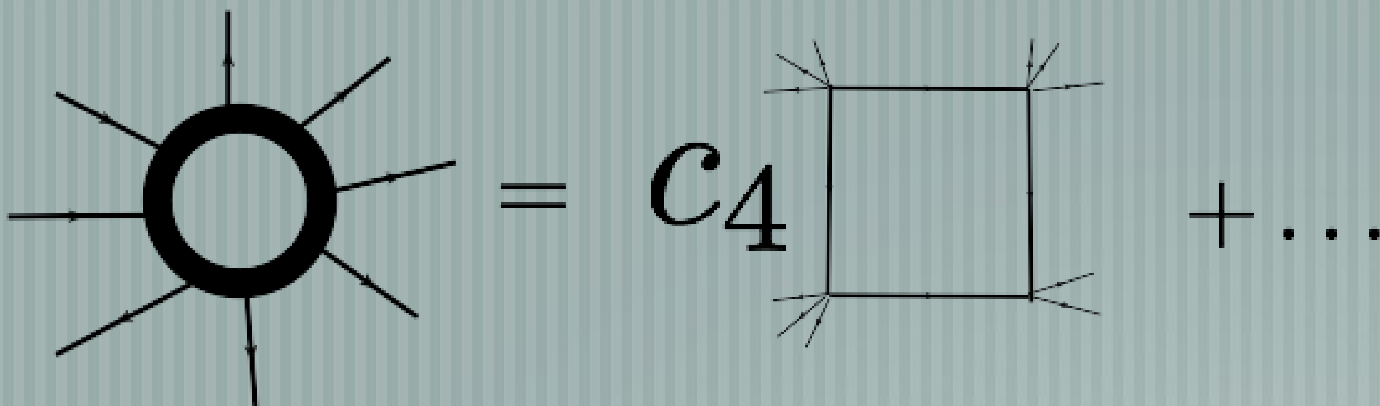
- Trees as input for the integrand
- Manifest gauge invariance
- Simplifications by using "natural" spinor variables

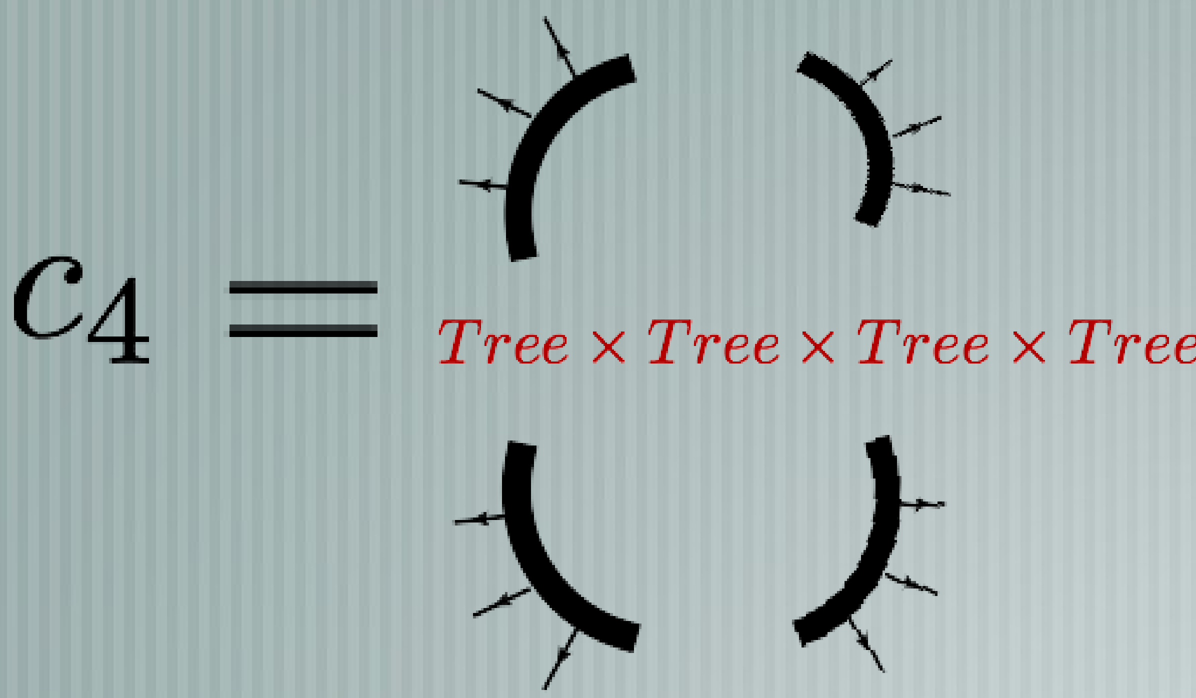
- Mismatch between Trees in four dimensions and loop integration in D-dimensions
- Introduction of four dimensional helicity regularization scheme
- Clever theory input (collinear factorization) to recover the full one-loop amplitude

Trees were an essential ingredient. No explicit connection of master integral coefficients to tree amplitudes.

Coefficient of box master !

Britto, Cachazo, Feng *2004*



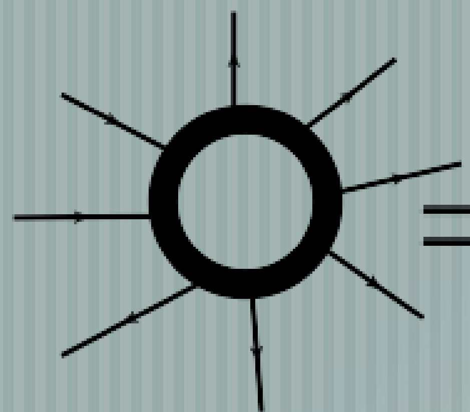


- Simple product of four tree amplitudes

ONE-LOOP INTEGRAND

Ossola, Papadopoulos, Pittau *2006*

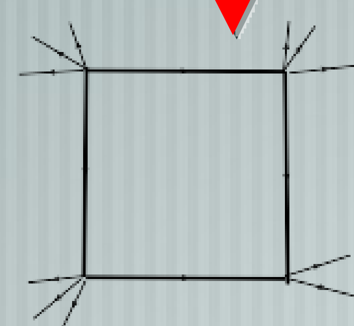
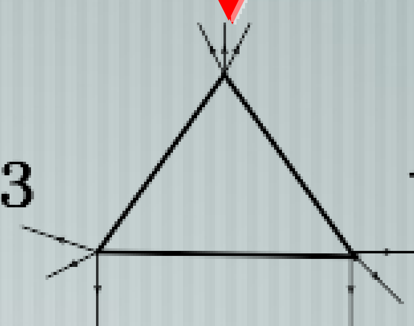
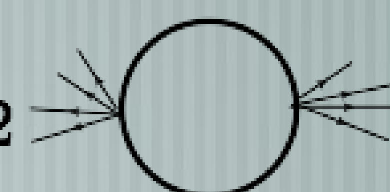
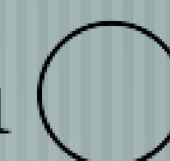
(building on del Aguila, Pittau, 2004)



$$= \int \frac{d^d k}{(2\pi)^d} \Big[c_4\, f_4(\vec{k}) + c_3\, f_3(\vec{k}) + c_2\, f_2(\vec{k}) + c_1\, f_1(\vec{k})$$

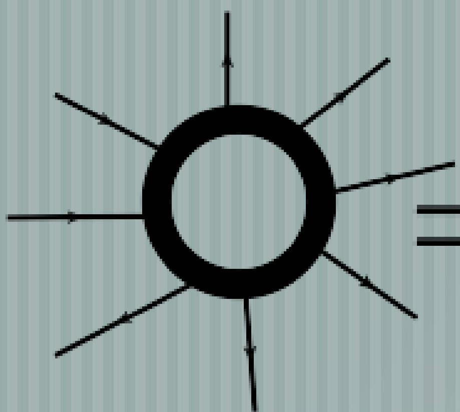
$$+ \tilde{c}_4\, \tilde{f}_4(\vec{k}) + \tilde{c}_3\, \tilde{f}_3(\vec{k}) + \tilde{c}_2\, \tilde{f}_2(\vec{k}) + \tilde{c}_1\, \tilde{f}_1(\vec{k}) \Big]$$

After Integration:

$= c_4$  $+c_3$  $+c_2$  $+c_1$ 

ONE-LOOP INTEGRAND

Ossola, Papadopoulos, Pittau *2006*



$$= \int \frac{d^d k}{(2\pi)^d} \Big[c_4\, f_4(\vec{k}) + c_3\, f_3(\vec{k}) + c_2\, f_2(\vec{k}) + c_1\, f_1(\vec{k})$$

$$+ \tilde{c}_4\, \tilde{f}_4(\vec{k}) + \tilde{c}_3\, \tilde{f}_3(\vec{k}) + \tilde{c}_2\, \tilde{f}_2(\vec{k}) + \tilde{c}_1\, \tilde{f}_1(\vec{k}) \Big]$$

$\tilde{f}_i(\vec{k}), f_i(\vec{k})$: Known rational functions of the loop momentum

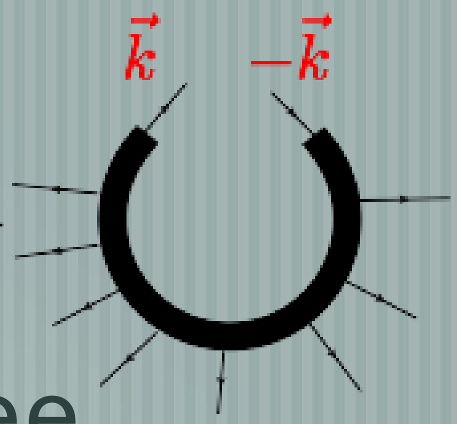
$\tilde{c}_i, c_i$: coefficients can be determined algebraically computing the integrand at a sufficient number of values for $\vec{k}$

ONE-LOOP INTEGRAND

Ossola, Papadopoulos, Pittau *2006*

$$\int \frac{d^d k}{(2\pi)^d} \Big[c_4\, f_4(\vec{k}) + c_3\, f_3(\vec{k}) + c_2\, f_2(\vec{k}) + c_1\, f_1(\vec{k})$$

$$+ \tilde{c}_4\, \tilde{f}_4(\vec{k}) + \tilde{c}_3\, \tilde{f}_3(\vec{k}) + \tilde{c}_2\, \tilde{f}_2(\vec{k}) + \tilde{c}_1\, \tilde{f}_1(\vec{k}) \Big] = \int \frac{d^d k}{(2\pi)^d}$$



- ☑ Integrand is "easy", essentially a tree amplitude

  Evaluate integrand at loop momenta values such as loop particles are set ON SHELL

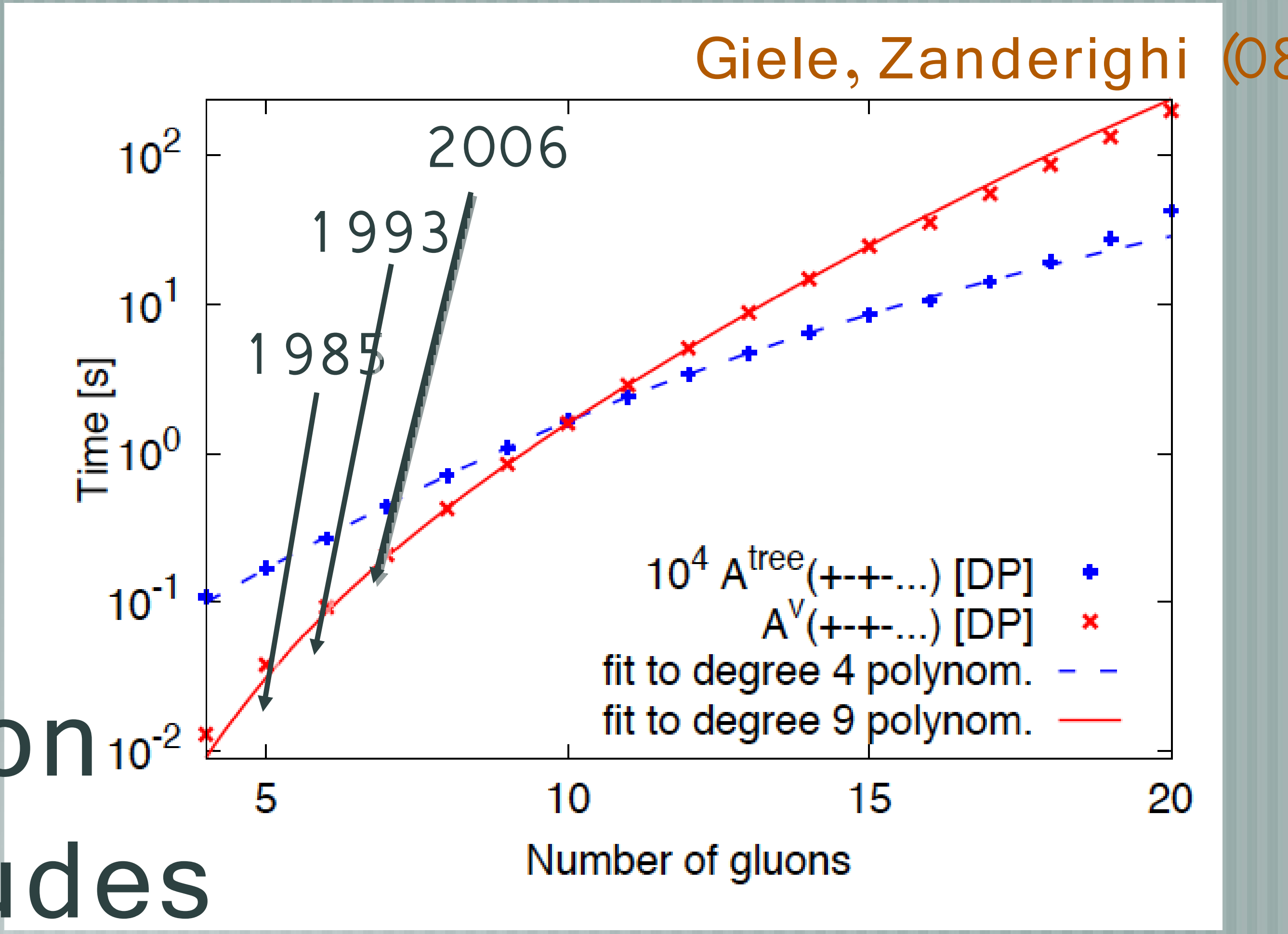
- ☑ ON-SHELL: determines coefficients successively

Conflict of dimensions

- Loop Integrations in D dimensions, Tree amplitudes in four dimensions. Mismatch, i.e. missing terms from amplitude evaluation. Requires a second calculation.
  - Specialized tree-like recursions in D=4 for the missing terms
    Berger, Bern, Dixon, Forde, Kosower 2006
  - Elegant/general solution: Amplitude in a general dimension from results in D=5 and D=6. Ellis, Giele, Kunszt, Melnikov 2008
  - Specialized Feynman rules for missing terms: Draggiotis, Garzelli, Papadopoulos, Pittau 2009

Breathtaking developments

- One-loop amplitudes with 22 gluons Giele, Zanderighi (08); Lazopoulos (08); Giele,Winter (09)



- numerical evaluation of all 2 to 4 amplitudes in the Les-Houches 2007 wish-list

van Hameren, Papadopoulos, Pittau (09)

$$q\bar{q}, gg \to t\bar{t}b\bar{b}, b\bar{b}b\bar{b}, W^+W^-b\bar{b}, t\bar{t}gg$$

$$q\bar{q}' \to Wggg, Zggg$$

W+3 jets: NLO cross-section

Large Nc approximation

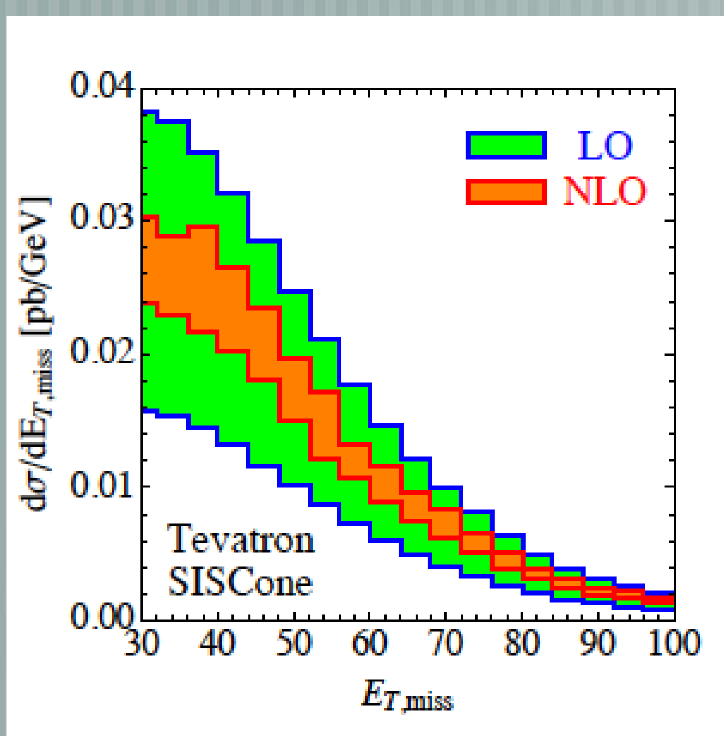
Ellis,Giele,Kunszt,Melnikov,Zanderighi;

Berger,Bern,Dixon,Cordero,Forde, Gleisberg,Ita,Kosower,Maitre

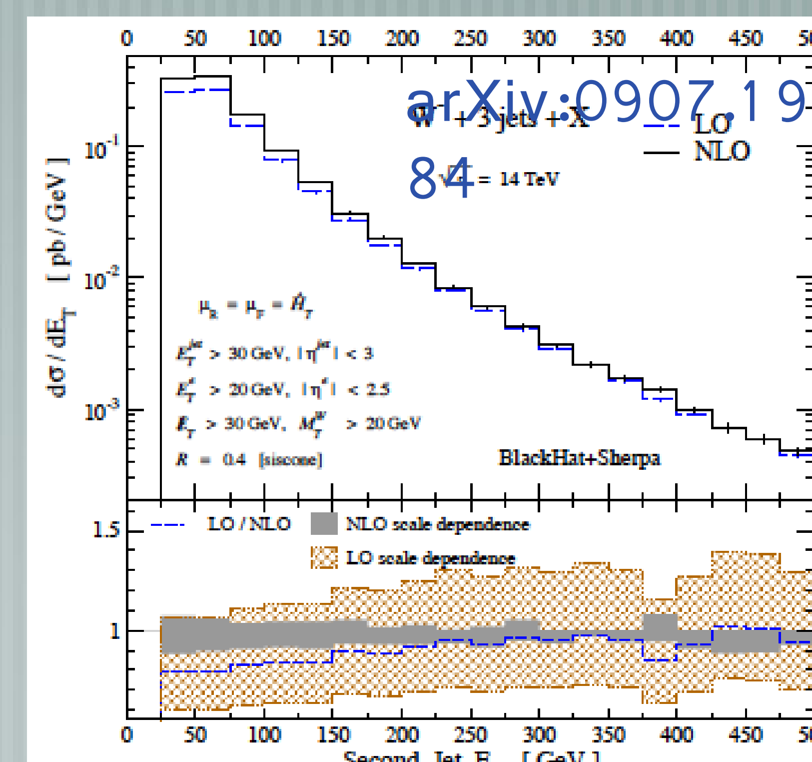
arXiv:0906.1445

NEW: complete NLO

Berger,Bern,Dixon,Cordero, Forde,Gleisberg,Ita,Kosowe Maitre (arXiv:0907.1984)



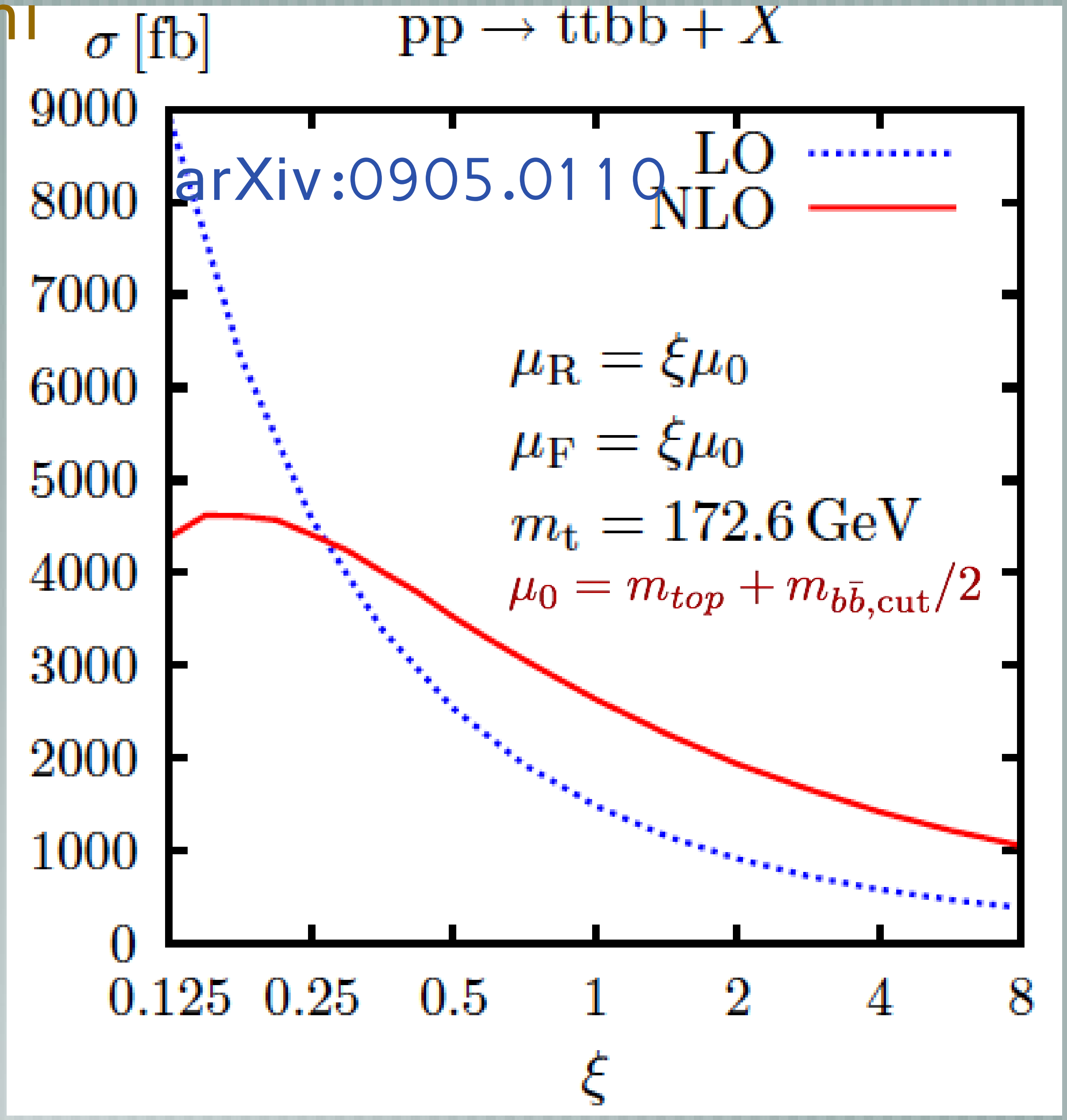
Start of a new era, with precise theoretical predictions for multi-particle production at the LHC



$pp \longrightarrow t\bar{t}b\bar{b}$:NLO cross-section

Brendenstein,Denner,Dittmaier,Pozzorini

- First full NLO calculation for a 2 to 4 process at a hadron collider
- Important Higgs boson background
- With Feynman diagrams
- intelligent, mostly numerical reduction, to master integrals
- exploits infrared regulators other than the dimension



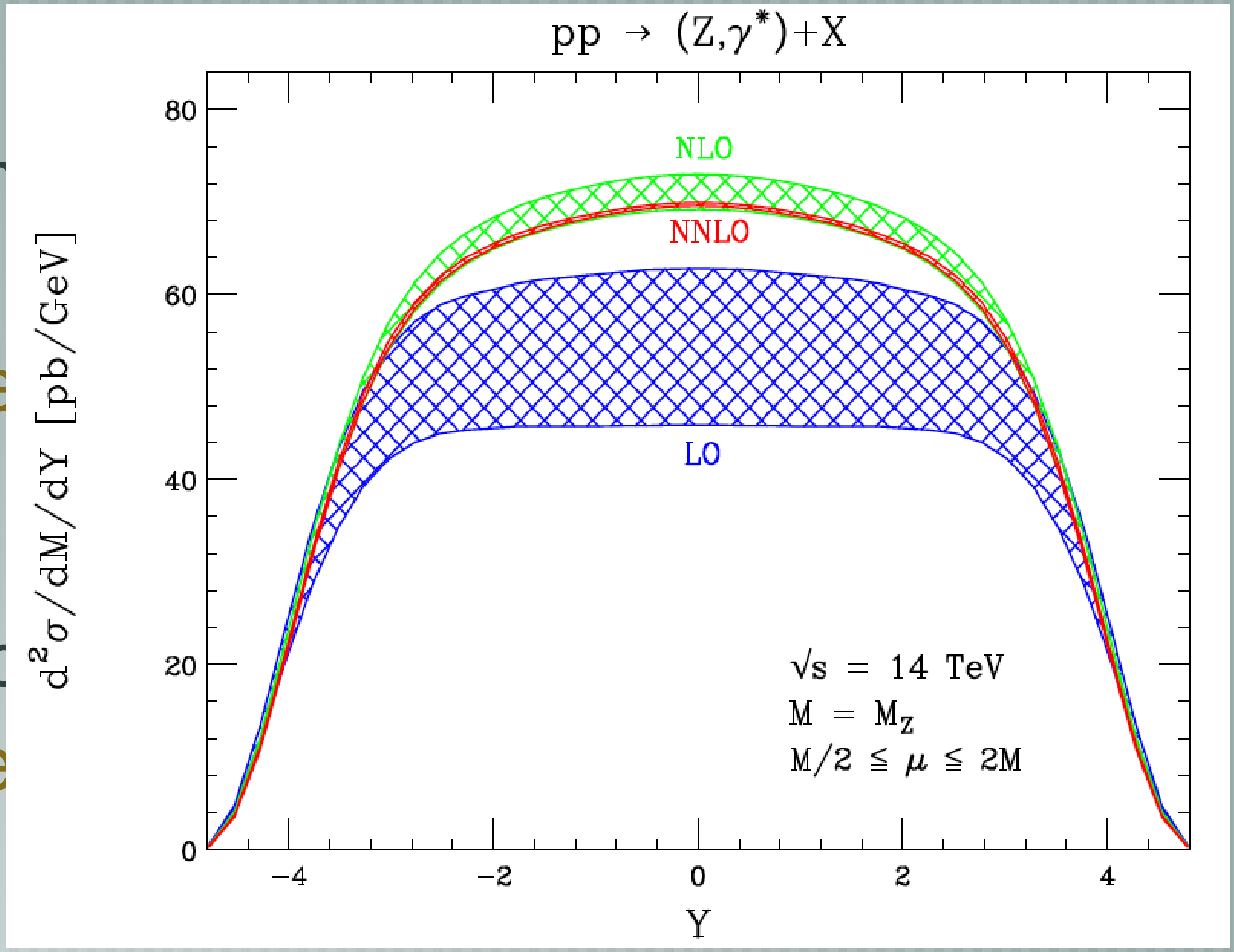
very large NLO corrections

NLO calculations @ LHC

- What can we hope for?
- We cannot do better than tree calculations..., i.e. processes with 7 or 8 particles in the final state.
- All 2 to 4 processes with both Feynman diagrammatic and unitarity methods
- 2 to 5 and perhaps 2 to 6 processes with unitarity methods

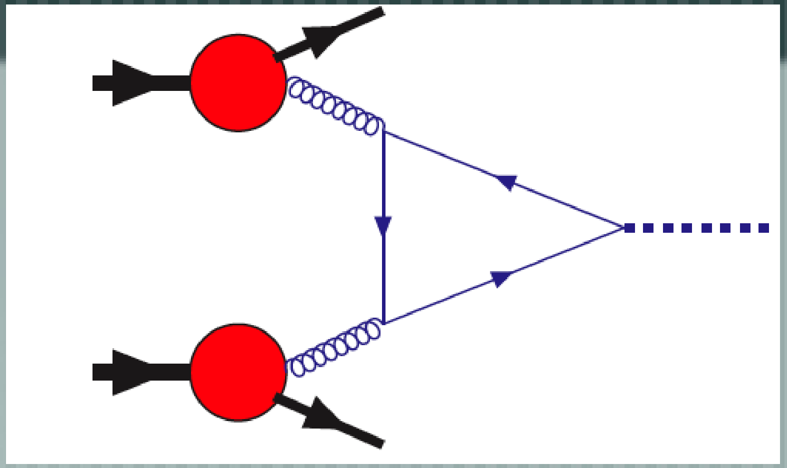
Drell-Yan theory

- NNLO total cross-section
  Hamberg, van Neerven 1990; Harlander, Kilgore 2002
- NNLO rapidity distribution
  CA,Dixon,Menikov,Petrieo 2004
- Fully differential NNLO
  Melnikov,Petriello 2006;Catani, Cieri,Ferrera,Grazzini2009

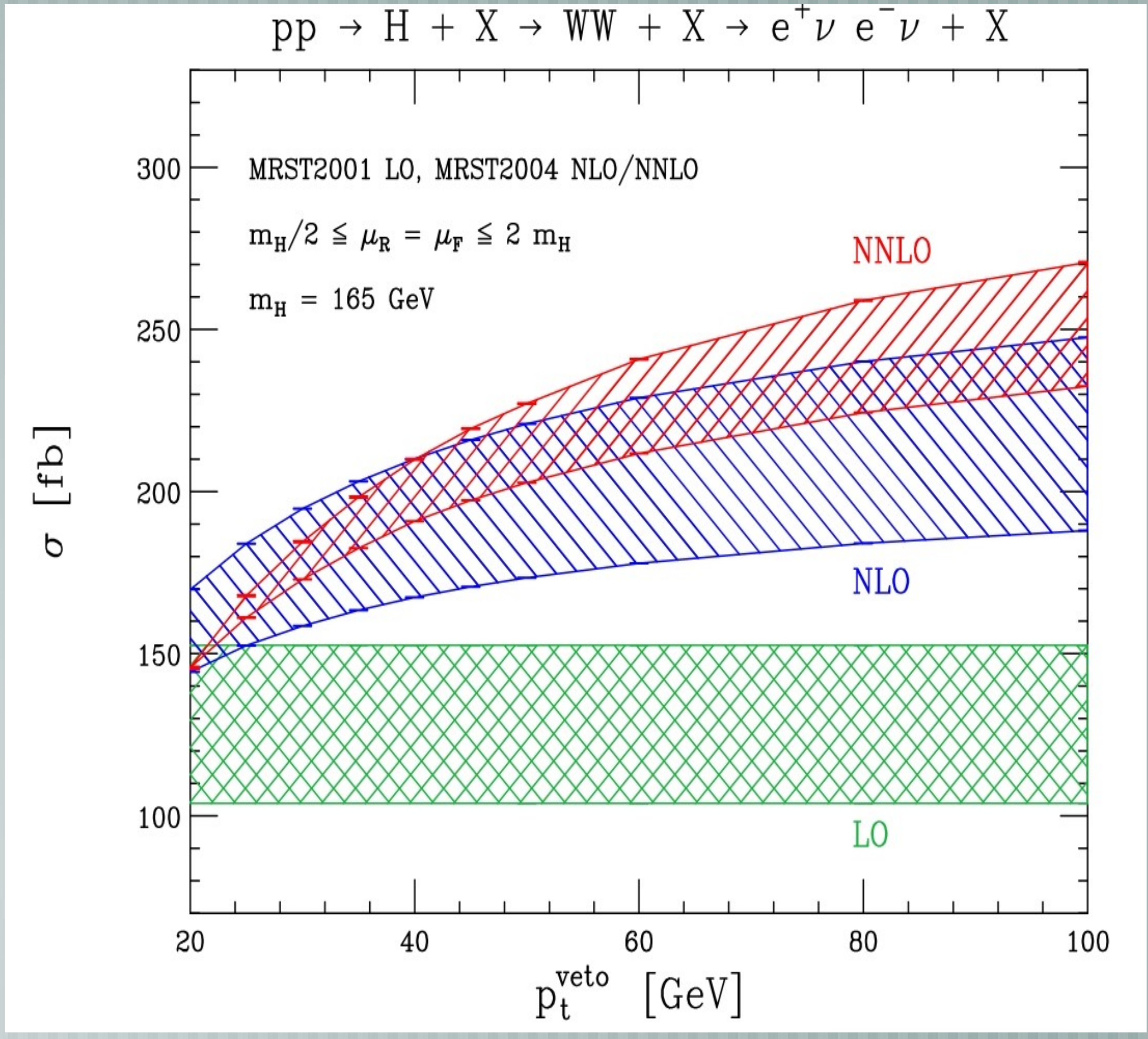


NEXT(?): W-mass measurement requires mixed QCDxQED corrections

Higgs via gluon fusion



- Total [Harlander,Kilgore 02; CA,Melnikov 02; Ravindran, Smith 03] and fully differential cross-sections through NNLO [CA,Melnikov,Petriello 04; CA,Dissertori, Stockli 07; Catani,Grazzini 07]
- Very large perturbative corrections, which are sensitive to selection cuts



Outlook

- Our abilities in simulating precisely collider processes have grown tremendously.
- New computational methods at NLO are extremely powerful. A classic work which will be part of future field theory books. Advanced N..NLO understanding (Super Yang-Mills theory lessons?)?
- Ready to take on the big challenge of finding new physics convincingly in hadron collider data

M. Worek

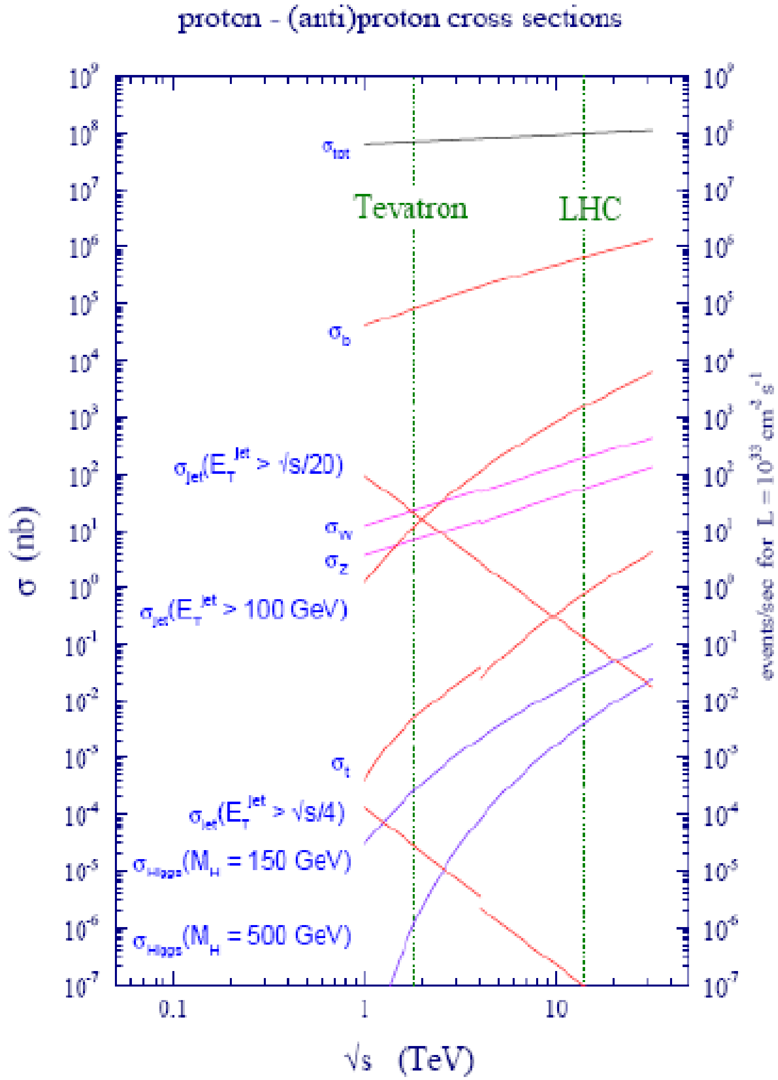
Assault on the NLO Wishlist: pp → ttbb

Importance of multi-leg processes at the LHC

- Huge W, Z and top-quark production rates plus multiple jet emission
- Multi-particle signatures with leptons, jets and missing energy
- Backgrounds to Higgs boson(s) and new physics

Benefits of higher order calculations

- Less sensitivity to unphysical input scales
  ⇨ LO up to a factor of 2, NLO 10%-20%
- First predictive normalisation of observables
- Improved shape of distributions
- Improve description of jets
- Cross sections under control

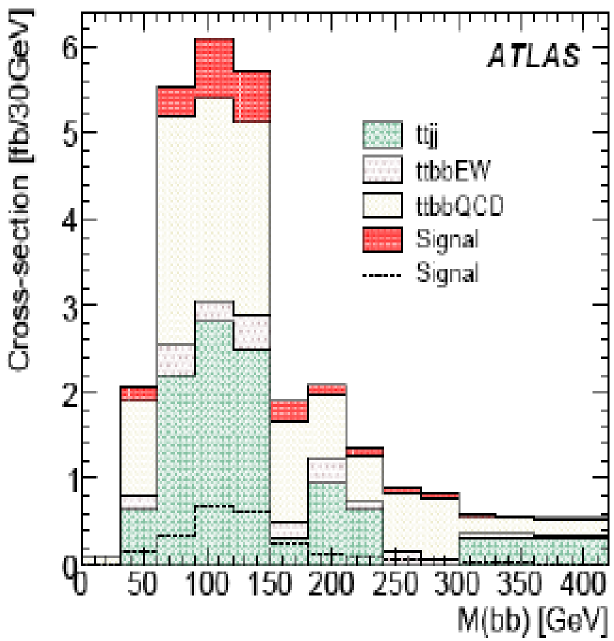


Doświadczenie

- Very important background to **ttH** production where the Higgs boson decays into a bb pair

$$m_H \leqslant 135\ GeV$$

- Early studies of ttH production at ATLAS and CMS suggested discovery potential
- Analyses with more realistic backgrounds show that the signal significanceis jeopardized if the background from **ttbb** and **tt + jets** final states is not controlled very well
- **ttjj** ⇨ 'reducibe' background, b-tagging
- **ttbb** ⇨ 'irreducibe' background
- **Problem:** misassociation of b-tagged jets to the orginal partons



- Reconstructed mass distribution
- All samples, contributions stacked
- Signal contribution also shown separately at the bottom.

Teoria : NLO dla 2 → 4 procesów

current technical frontier..

- NLO QCD corrections to ttH — W. Beenakker, S. Dittmaier, M. Krämer, B. Plümper, M. Spira, P.M. Zerwas (2001) TeVatron & LHC
  L. Reina, S. Dawson (2001) TeVatron
  S. Dawson, L.H. Orr, L. Reina, D. Wackeroth (2003) LHC
- NLO QCD corrections to ttbb — A. Bredenstein, A. Denner, S. Dittmaier, S. Pozzorini (2008)
  A. Bredenstein, A. Denner, S. Dittmaier, S. Pozzorini (2009)
- Confirm published results
- Demonstrate the power of system based on HELAC-PHEGAS, HELAC-1LOOP, CUTTOOLS and HELAC-DIPOLES in realistic computation with 6 external legs and massive partons

NLO Wishlist

Single boson	Diboson	Triboson	Heavy flavor
$W + \leq 5j$	$WW + \leq 5j$	$WWW + \leq 3j$	$t\bar{t} + \leq 3j$
$W + b\bar{b} + \leq 3j$	$WW + b\bar{b} + \leq 3j$	$WWW + b\bar{b} + \leq 3j$	$t\bar{t} + \gamma + \leq 2j$
$W + c\bar{c} + \leq 3j$	$WW + c\bar{c} + \leq 3j$	$WWW + \gamma\gamma + \leq 3j$	$t\bar{t} + W + \leq 2j$
$Z + \leq 5j$	$ZZ + \leq 5j$	$Z\gamma\gamma + \leq 3j$	$t\bar{t} + Z + \leq 2j$
$Z + b\bar{b} + \leq 3j$	$ZZ + b\bar{b} + \leq 3j$	$WZZ + \leq 3j$	$t\bar{t} + H + \leq 2j$
$Z + c\bar{c} + \leq 3j$	$ZZ + c\bar{c} + \leq 3j$	$ZZZ + \leq 3j$	$t\bar{b} + \leq 2j$
$\gamma + \leq 5j$	$\gamma\gamma + \leq 5j$		$b\bar{b} + \leq 3j$
$\gamma + b\bar{b} + \leq 3j$	$\gamma\gamma + b\bar{b} + \leq 3j$		$b\bar{b}\,t\bar{t}$
$\gamma + c\bar{c} + \leq 3j$	$\gamma\gamma + c\bar{c} + \leq 3j$		
	$WZ + \leq 5j$		
	$WZ + b\bar{b} + \leq 3j$		
	$WZ + c\bar{c} + \leq 3j$		
	$W\gamma + \leq 3j$		
	$Z\gamma + \leq 3j$		

- Cross section at NLO precision

$$\sigma = \sigma^{LO} + \sigma^{NLO}$$

- LO cross section (exclusive cross section in Born approximation integrated over available phase space of m final state particles)

$$\sigma^{LO} = \int_m d^{(4)}\sigma^B \qquad d^{(4)}\sigma^B = d^{(4)}\Phi^{(m)}|M_m|^2 F_J^{(m)}$$

- NLO part consists of two contributions:
  - ⇨ emissions of additional parton (real corrections)
  - ⇨ virtual (one loop) corrections to Born matrix element
  - ⇨ collinear subtraction term (higher order corrections residing in PDF)

$$\sigma^{NLO} = \int_m d^{(d)}\sigma^{NLO} = \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(d)}\sigma^V + \int_m d^{(d)}\sigma^C$$

- Integrals IR divergent separately but sum finite ⇨ KLN mass factorization theorem
- How to get individual contributions finite ?

Procedura odjęcia

- Construct a subtraction term for real emission
  - encodes all IR divergences, can be analitically integrated over in d dimensions

$$\sigma^{NLO} = \int_{m+1} d^{(d)}\sigma^{R} - \int_{m+1} d^{(d)}\sigma^{A} + \int_{m+1} d^{(d)}\sigma^{A} + \int_{m} d^{(d)}\sigma^{V} + \int_{m} d^{(d)}\sigma^{C}$$

$$\rightarrow \boxed{\int_{m+1} \left[d^{(4)}\sigma^{R} - d^{(4)}\sigma^{A}\right]} + \boxed{\int_{m} \left[d^{(d)}\sigma^{V} + \int_{1} d^{(d)}\sigma^{A} + d^{(d)}\sigma^{C}\right]}$$

Finite, integrated over in 4 dimensions

Integral of extra particle in d dimensions

Remaining m-particle part in 4 dimensions

Massless: S. Catani, M.H. Seymour, Nucl. Phys. B485, 291 (1997)

Massive: S. Catani, S. Dittmaier, M.H. Seymour, Z. Trocsanyi, Nucl. Phys. B627, 189 (2002)

Polarized: M. Czakon, C. G. Papadopoulos, M. Worek, JHEP 0908 (2009) 085

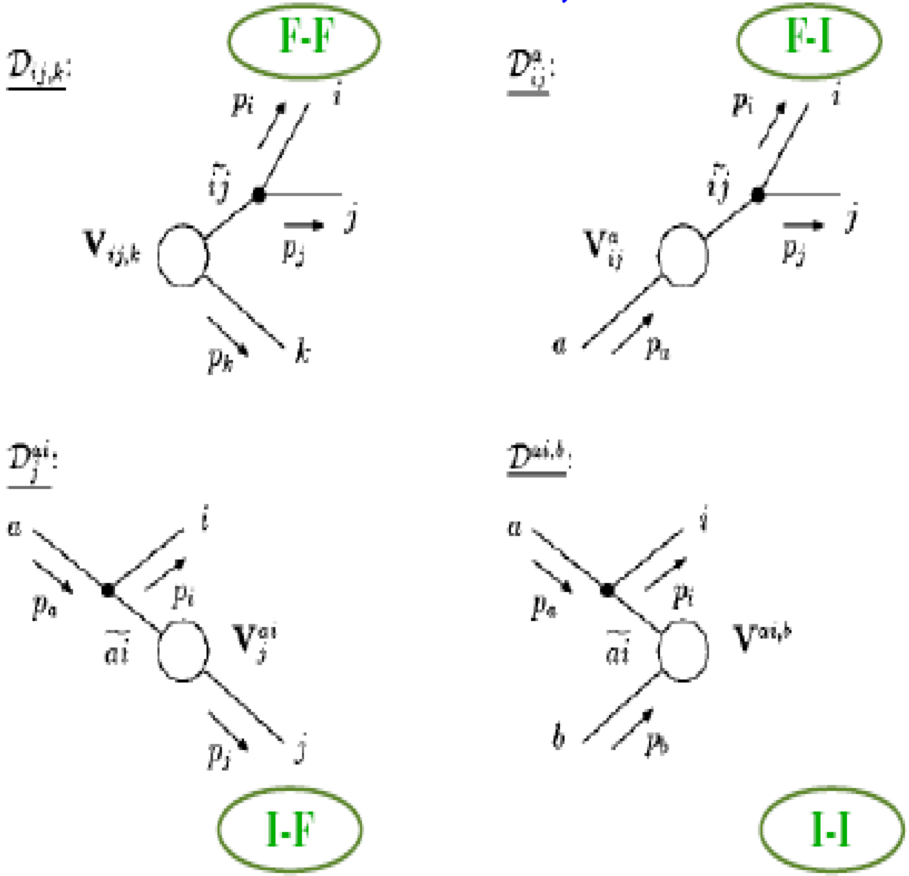
Granica miękkiej i kolinearnej emisji w QCD - uniwersalna

- Full subtraction term for any matrix element given by sum of all possible dipoles

$$\int d\Phi \sum \left(|M_{m+1}|^2 - \mathcal{D} \right)$$

$$\mathcal{D} = \sum_{\{i,j\}} \sum_{k \neq i,j} \mathcal{D}_{ij,k} + \sum_{\{i,j\}} \sum_{a} \mathcal{D}_{ij}^{a} + \sum_{a,i} \sum_{j \neq i} \mathcal{D}_{j}^{ai} + \sum_{a,i} \sum_{b \neq a} \mathcal{D}^{ai,b}$$

F-final, I-initial



- Dipole functions generate the limit where one of partons becomes soft or both partons become collinear to each other
- Splitting parton – emitter
- Spectator can be initial and final state particle

http://helac-phegas.web.cern.ch/helac-phegas/

Helac-dipoles

- Complete and publicly available automatic implementation of CS dipole subtraction
  - phase space integration of subtracted real radiation and integrated dipoles in both massless and massive cases
- Extended for arbitrary polarizations
  - Monte Carlo over polarization states of external particles implemented
- Phase space restriction on the dipole phase space implemented
  - α_{max} introduced, cuts off dipole function for phase space regions away from singularity
- PHEGAS used for phase space generation with multi-channel optimization
  - phase space denisity of channel given by product of Feynman diagrams denominators

Poprawki wirtualne

- One-loop n particle amplitude

$$A = \sum_{I \in \{1,2,\ldots,n\}} \int \frac{\mu^{4-d} d^d \bar{q}}{(2\pi)^d} \frac{\bar{N}_I(\bar{q})}{\prod_{i \in I} \bar{D}_i(\bar{q})} \qquad \bar{D}_i(\bar{q}) = (\bar{q} + p_i)^2 - m_i^2, \quad i = 1,2,\ldots,n$$

$$A = \sum_i d_i \, Box_i + \sum_i c_i \, Triangle_i + \sum_i b_i \, Bubble_i + \sum_i a_i \, Tadpole_i + R$$

- Amplitude can be expressed in basis of known integrals such 4-, 3-, 2-, 1-point scalar integrals

- In order to calculate one loop amplitude three main building blocks are needed:

  - Evaluation of numerator function N(q) - **HELAC-1LOOP**
  - Determination of coefficients via reduction method - **OPP, CUTTOOLS**
  - Evaluation of scalar functions - **ONELOOP**

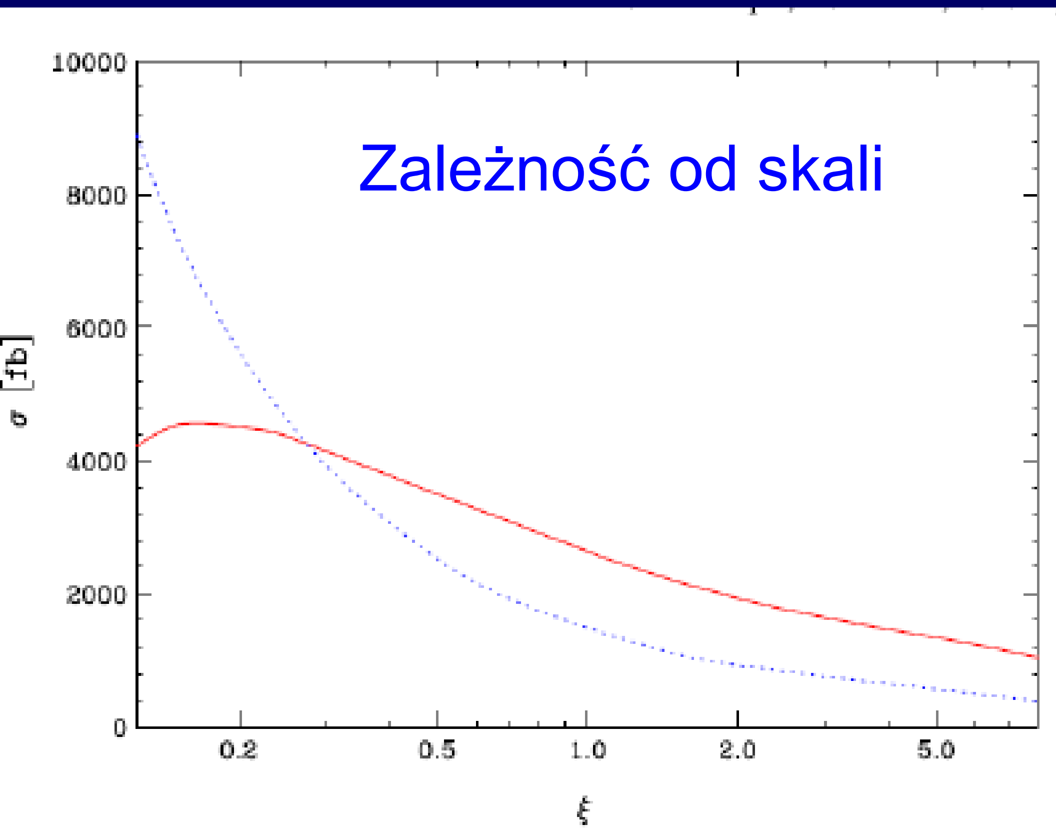
LHC

$$\sigma^{\mathrm{LO}}_{t\bar{t}b\bar{b}}(\mathrm{LHC}, m_t = 176.2\ \mathrm{GeV}, \mathrm{CTEQ6L1}) = 1489.2\ {}^{+1036.8\ (70\%)}_{-\ \ 565.8\ (38\%)}\ \mathrm{fb}$$

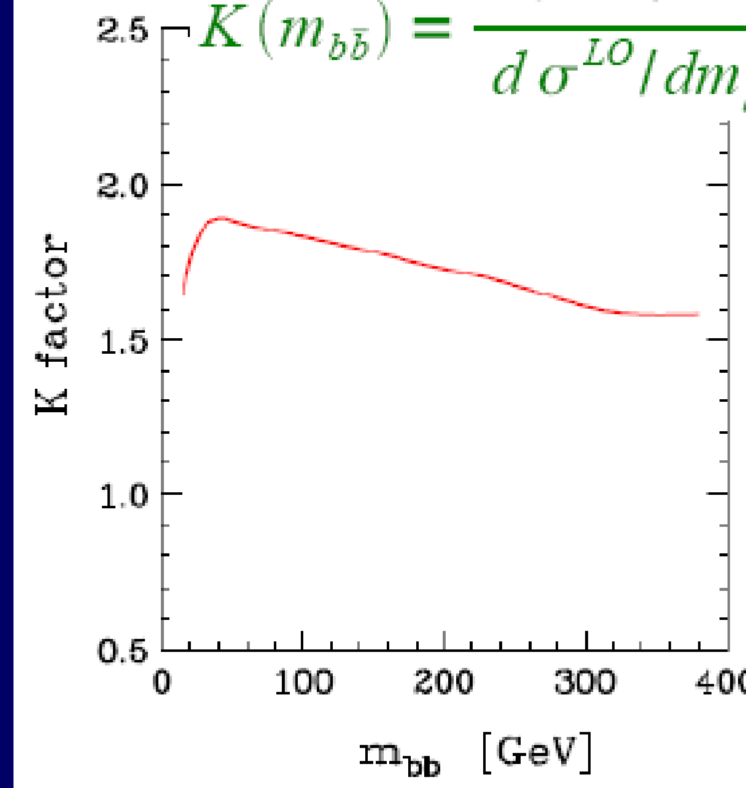
$$\sigma^{\mathrm{NLO}}_{t\bar{t}b\bar{b}}(\mathrm{LHC}, m_t = 176.2\ \mathrm{GeV}, \mathrm{CTEQ6M}) = 2636\ {}^{+862\ (33\%)}_{-703\ (27\%)}\ \mathrm{fb}\ .$$

G. Bevilacqua, M. Czakon, C.G. Papadopoulos, R. Pittau, M. Worek arXiv:0907.4723 [hep-ph]

LHC for $\mu_R = \mu_F = \xi \cdot m_t$ at LO & NLO



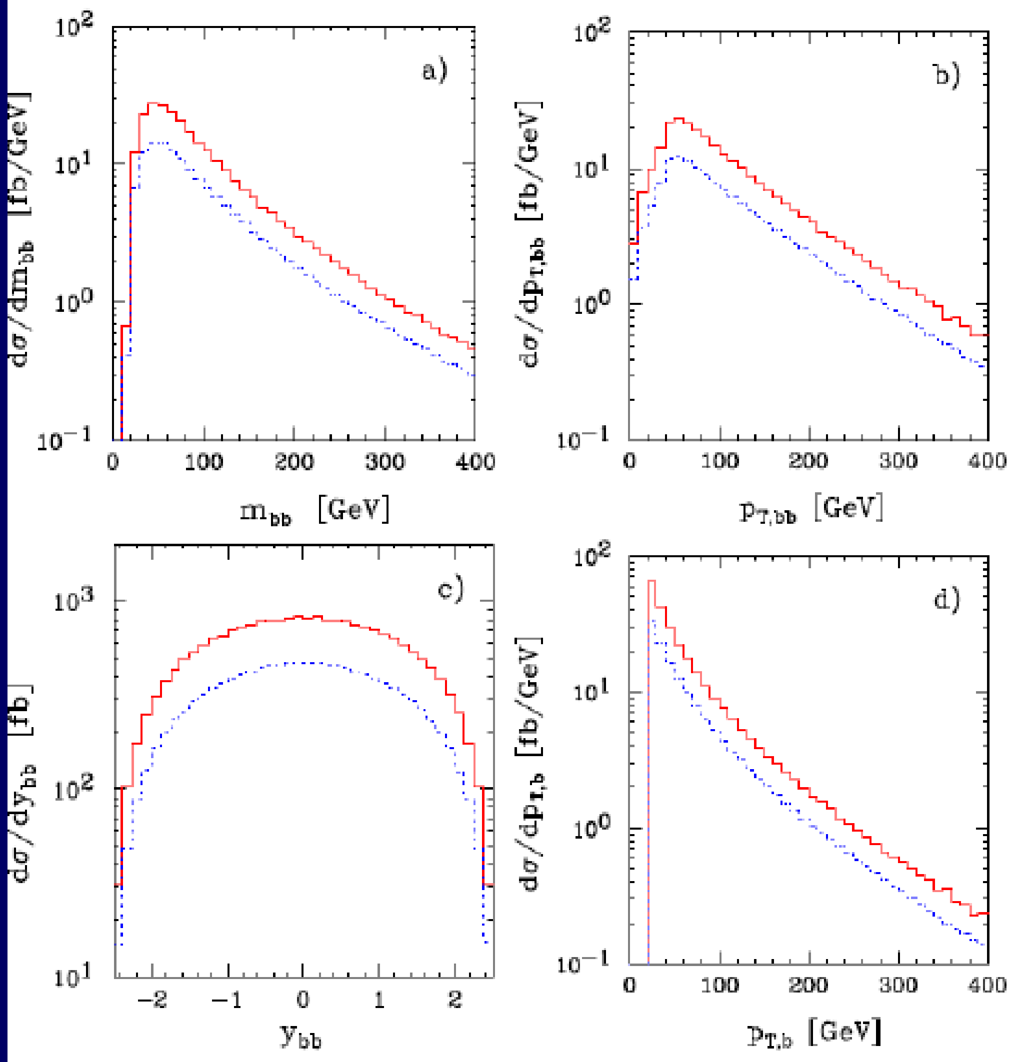
$$K(m_{b\bar{b}}) = \frac{d\sigma^{NLO}/dm_{b\bar{b}}}{d\sigma^{LO}/dm_{b\bar{b}}}$$



Wyniki – różniczkowe przekroje czynne

G. Bevilacqua, M. Czakon, C.G. Papadopoulos, R. Pittau, M. Worek arXiv:0907.4723 [hep-ph]

NEW !



- Differential cross sections at the LHC for $pp \rightarrow ttbb + X$

- Invariant mass distribution of bb pair
- Transverse momentum of bb pair
- Rapidity distribution of bb pair
- Transverse momentum of b quark

- LO $\rightarrow$ blue dashed line
- NLO $\rightarrow$ red solid line

- All distributions for $\alpha_{max} = 0.01$
- Large corrections, relatively constant, contrary to case of quark initial states

Janik
Niepert. teoria pola

> Two-dimensional integrable QFT's become relevant for four-dimensional physics due to the AdS/CFT correspondence

Co chcielibyśmy zrozumieć?

- <u>QCD</u>

  - trudna, biegnąca stała sprzężenia,
- mieszanka efektów pert. i niepert.
- <u>Metody tradycyjne</u>

  - obliczenia na siatkach
- - modele próżni QCD
- - modele efektywne (nie z fund. Teorii)
- *Są inne prostsze teorie z cechowaniem i inne metody*

AdS/CFT correspondence

$\mathcal{N} = 4$ Super Yang-Mills theory	$\equiv$	Superstrings on $AdS_5 \times S^5$
strong coupling nonperturbative physics very difficult		(semi-)classical strings or supergravity 'easy'
weak coupling 'easy'		highly quantum regime very difficult

New ways of looking at nonperturbative gauge theory physics...

Intricate links with General Relativity...

Dlaczego tak interesujące?

- Fascinating as it relates two *completely different* theoretical constructions: 4D gauge theory and string theory in 10D
- Use $\mathcal{N} = 4$ SYM as a theoretical laboratory for studying nonperturbative gauge theory physics
- In this theory one can perform quite rigorous computations at strong coupling
- The natural language of the AdS/CFT correspondence appropriate to strongly coupled $\mathcal{N} = 4$ SYM is quite new w.r.t. conventional gauge theory methods
- Try to build some new physical intuitions within this new language

$\mathcal{N} = 4$ SYM may be the 'harmonic oscillator' of four dimensional gauge theories

D. Gross

Ku ścisłemu rozwiązaniu dla każdego sprzężenia

Local operators in gauge theory $\longleftrightarrow$ String states in $AdS_5 \times S^5$

Operator dimension

$$\langle O(x)O(y)\rangle = \frac{const}{|x-y|^{2\Delta}}$$

$\longleftrightarrow$ Energy of the corresponding string state

One has to find the energy levels of an *integrable* two-dimensional QFT...

- We extended the string computation to give the result up to 5 loops (no gauge theoretical computation so far) [Bajnok,Hegedus,RJ,Łukowski]

$$\begin{aligned}\Delta &= 4+12\,g^2-48\,g^4+336\,g^6+96(-26+6\,\zeta(3)-15\,\zeta(5))\,g^8\\ &\quad -96(-158-72\,\zeta(3)+54\,\zeta(3)^2+90\,\zeta(5)-315\,\zeta(7))\,g^{10}\end{aligned}$$

- This could be extended to twist two operators at 4 loops [Bajnok,RJ,Łukowski]
- Nontrivial relations with BFKL and NLO BFKL equations...

Nowe metody – sektor Higgsa

Ginzburg, Ivanov, 2009
Kanishev, MK, Sokołowska

2HDM:

Różne stany próżni → spektrum cząstek Higgsa

→ ciemna materia

Dziś – Inert Model (cząstka Higgsa h,

4 skalary (H,A,H+,H-)

najlżejsza np. H – ciemna)

zgodny z danymi

Pytanie: co było wcześniej?

Stany próżni we Wczesnym Wszechświecie

Przejścia fazowe?

Brout-Englert-Higgs mechanism

Spontaneous breaking of EW symmetry

$SU(2) \times U(1) \rightarrow ?$

Two Higgs Doublet Models

Two doublets of SU(2) ($Y=1$, $\rho=1$) - Φ_1 , Φ_2

Masses for $W^{+/-}$, Z , no mass for photon?

Fermion masses via Yukawa interaction –

various models: Model I, II, III, IV,X,Y,...

5 scalars: H+ and H- and neutrals:

- CP conservation: CP-even h, H & CP-odd A
- CP violation: h_1,h_2,h_3 with undefinite CP parity*

Sum rules (relative couplings to SM χ)

2HDM Potential

Lee'73, Haber, Gunion, Glashow, Weinberg, Paschos, Despande, Ma, Wudka, Branco, Rebelo, Lavoura, Ferreira, Barroso, Santos, Bottela, Silva, Diaz-Cruz, Grimus, Ecker, Ivanov, Ginzburg, Krawczyk, Osland, Nishi, Nachtmann, Akeroyd, Kanemura, Kalinowski, Grządkowski ,Hollik, Rosiek..

$$V = \lambda_1(\Phi_1^\dagger\Phi_1)^2+\lambda_2(\Phi_2^\dagger\Phi_2)^2+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)$$

$$+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)+ [\lambda_5(\Phi_1^\dagger\Phi_2)^2+h.c]$$

$$+ [(\lambda_6(\Phi_1^\dagger\Phi_1)+\lambda_7(\Phi_2^\dagger\Phi_2))(\Phi_1^\dagger\Phi_2)+h.c]$$

$$-m^2_{11}(\Phi_1^\dagger\Phi_1)-m^2_{22}(\Phi_2^\dagger\Phi_2)-[m^2_{12}(\Phi_1^\dagger\Phi_2)+h.c.]$$

Z_2 symmetry transformation: $\Phi_1 \to \Phi_1 \quad \Phi_2 \to -\Phi_2$

Hard Z_2 symmetry violation: λ_6, λ_7 terms

Soft Z_2 symmetry violation: m^2_{12} term (Re $m^2_{12}=\mu^2$)

Explicit Z_2 symmetry in V: $\lambda_6, \lambda_7, m^2_{12}=0$

Possible vacuum states (for real V, Z_2)

A. Barroso, P.M. Ferreira, R. Santos, J.P. Silva, hep-ph/0507329,

The most general vacuum state

$$\langle\phi_1\rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}v_1 \end{pmatrix}, \quad \langle\phi_2\rangle = \begin{pmatrix} u \\ \frac{1}{\sqrt{2}}v_2 e^{i\xi} \end{pmatrix}$$

v_1, v_2, u , ξ - real, ≥ 0

$v^2 = v_1^2 + v_2^2 + u^2 = (246\ \text{GeV})^2$

Inert	I	$u = v_2 = 0$
Normal (CP conserving)	N	$u = \xi = 0$
Charge Breaking	Ch	$u \neq 0 \quad v_2 = 0$
[Vacuum	B	$u = v_1 = 0$]
~~CP violating~~	~~CP~~	~~$u = 0\ \xi \neq 0$~~

Various vacua on (λ_4 , λ_5) plane (Z_2 sym V)

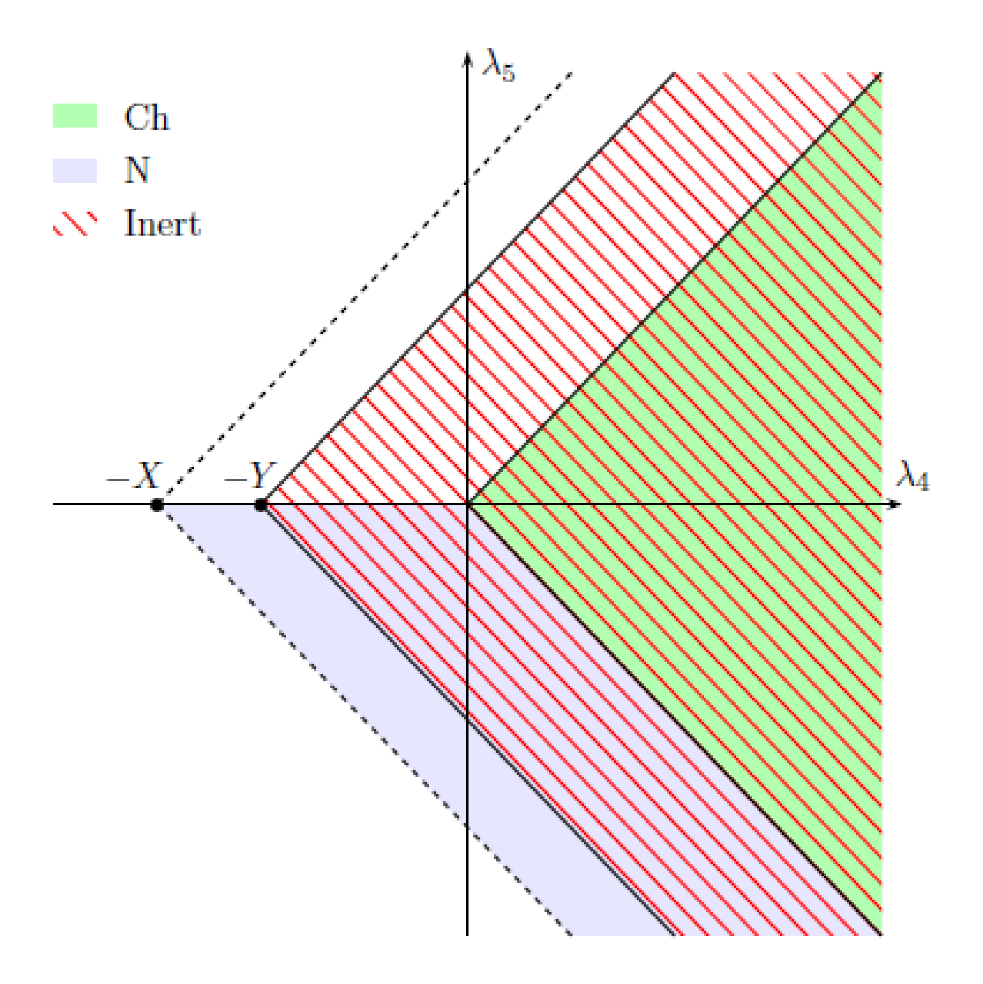
Positivity constrains on V:

$X = \sqrt{\lambda_1 \lambda_2} + \lambda_3 > 0$

$\lambda_4 \pm \lambda_5 > -X$

Inert (or B)

$Y = M_{H+}^2 \, 2/v^2$



Charge Breaking Ch

Normal

Note the overlap of the Inert with N and Ch !

Inert or Dark 2HDM

Ma'78
Barbieri'06

Z_2 symmetry under $\Phi_1 \to \Phi_1 \quad \Phi_2 \to - \Phi_2$

both <u>in L and in vacuum</u> → Inert Model

Today

$\langle \Phi_1^T \rangle = (0,v) \qquad \langle \Phi_2^T \rangle = (0,0)$

→ Φ_1 as in SM, with Higgs boson h (SM-like)

→ Φ_2 - <u>no vev</u>, with 4 scalars (no Higgs bosons!)

no interaction with fermions (inert doublet)

Conservation of the Z_2 symmetry; only Φ_2 has odd Z_2-parity

→ The lightest scalar – a candidate for dark matter

(Φ_2 dark doublet with dark scalars) .

Testing Inert Model

To consider

properties of SM-like h (light and heavy)

properties of dark scalars

(produced only in pairs!)

DM candidate

Colliders signal/constraints

Barbieri et al '2006 for heavy h

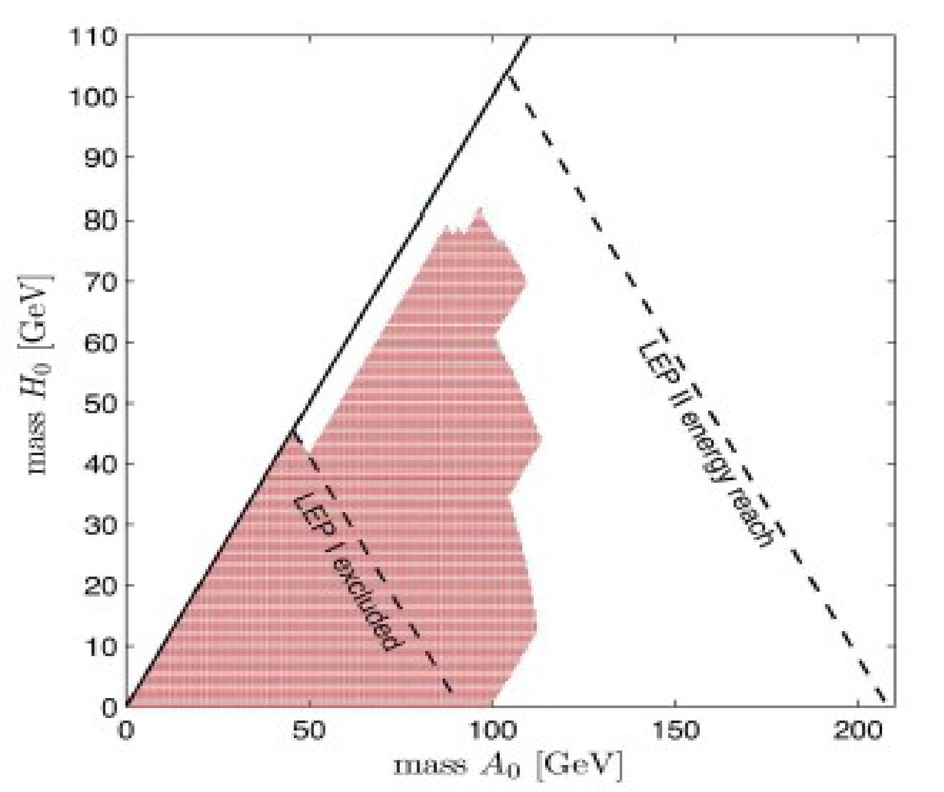
Cao, Ma, Rajasekaren' 2007 for a light h

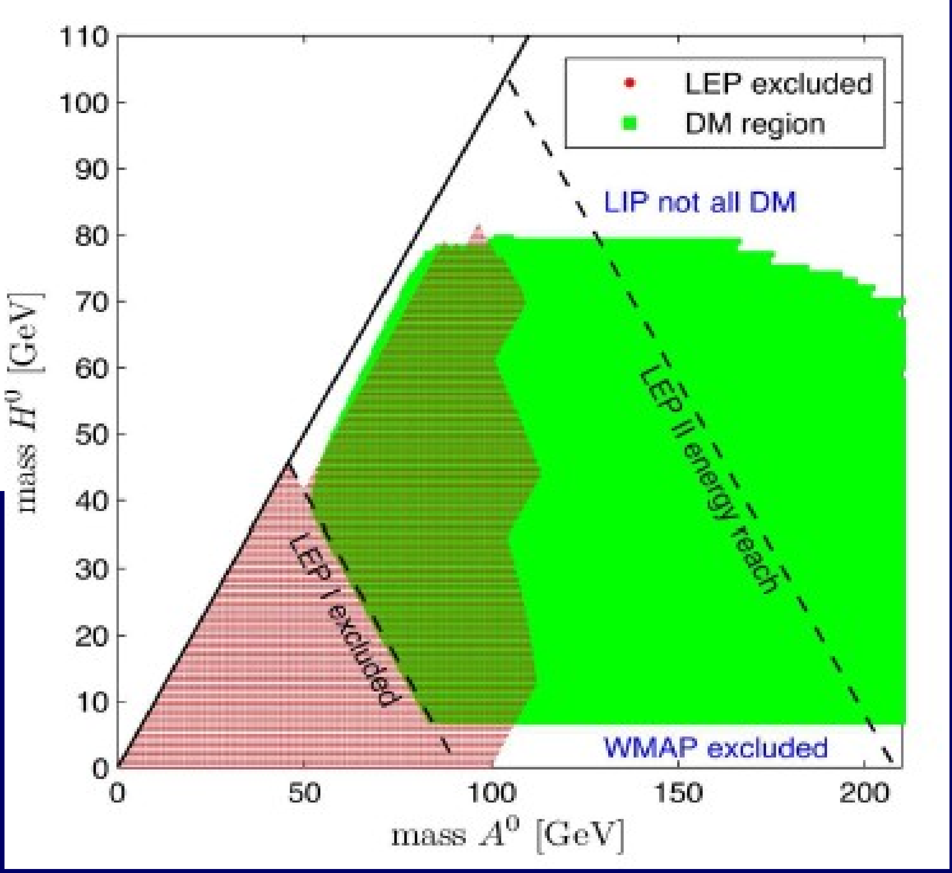
LEP II: $M_H + M_A > M_Z$, $\Delta(A, H) = 5 - 30$ GeV for $M_h = 105 - 110$ GeV

EW precision data: $(M_{H+} - M_A)(M_{H+} - M_H) = M^2, M = 120^{+20}_{-30}$ GeV

Dark 2HDM: LEP II exclusion

Lundstrom et al 0810.3924





LEP II + WIMP

M_h = 200 GeV

$M_A - M_H > 8$ GeV

Inert Model: constraints LEP+DM → LHC

E. Dolle, S. Su, 0906.1609 [hep-ph]

LEP (exclusion and EW precision data)

+ relic density using MicroOMEGA/CalCHEP

$\delta_1 = m_{H\pm} - m_S$ $\delta_2 = m_A - m_S$

Viable region for relic density

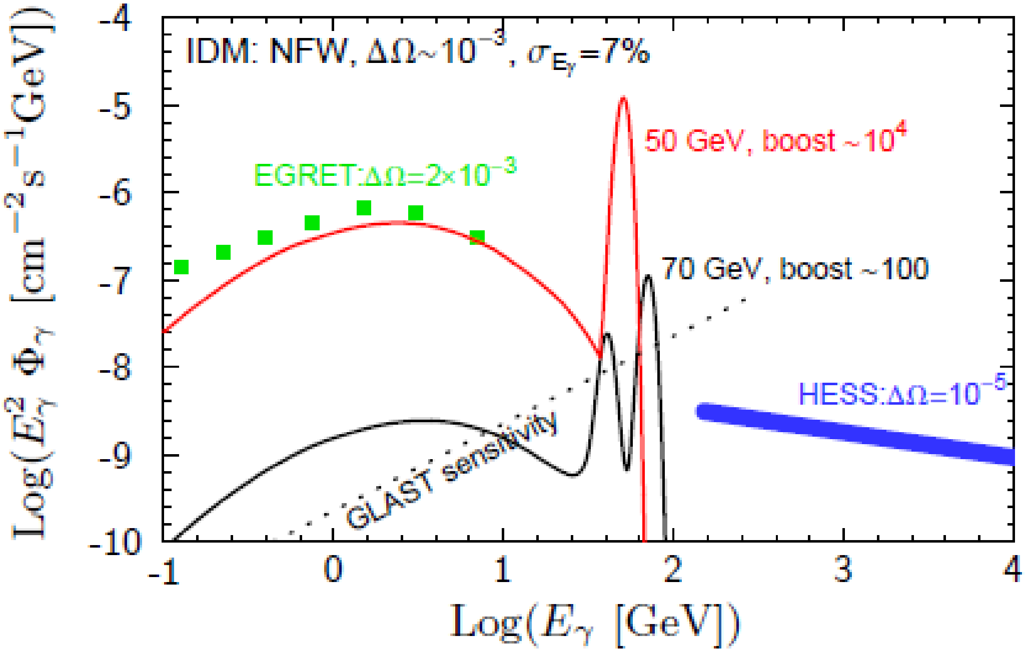
S=H

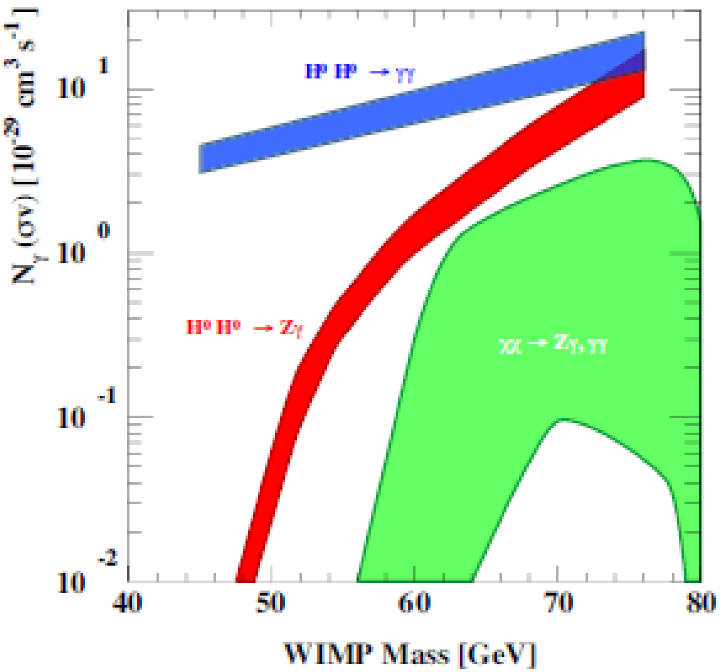
	DM	SM h	m_S	δ_1, δ_2	λ_L
(I)	low m_S	low m_h	30 – 60 GeV	50 - 90 GeV	-0.2 to 0
(II)			60 – 80 GeV	at least one is large	-0.2 to 0.2
(III)		high m_h	50 – 75 GeV	large δ_1 $\delta_2 < 8$ GeV	-1 to 3
(IV)			~ 75 GeV	large δ_1, δ_2	-1 to 3
(V)	high m_S	low m_h	500 – 1000 GeV	small δ_1, δ_2	-0.2 to 0.3

09

Significant Gamma Lines from Inert Doublet Model

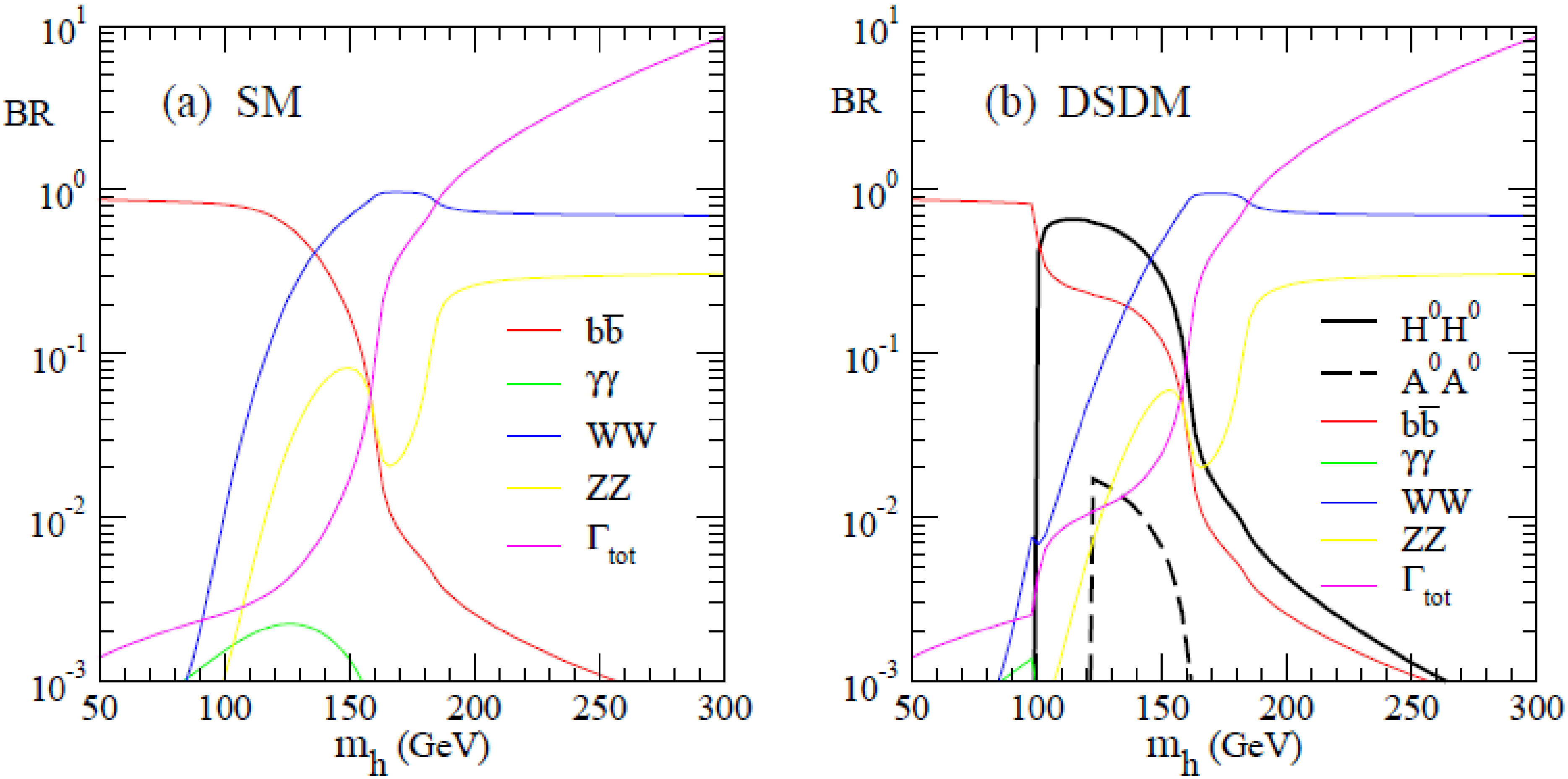
Gustafsson,Lundstrom,Bergstrom,Edsjo' 2007 studied direct annihilation of HH into $\gamma\gamma$ and $Z\gamma$ for M_H between 40-80 GeV (loop process, energy below WW threshold).





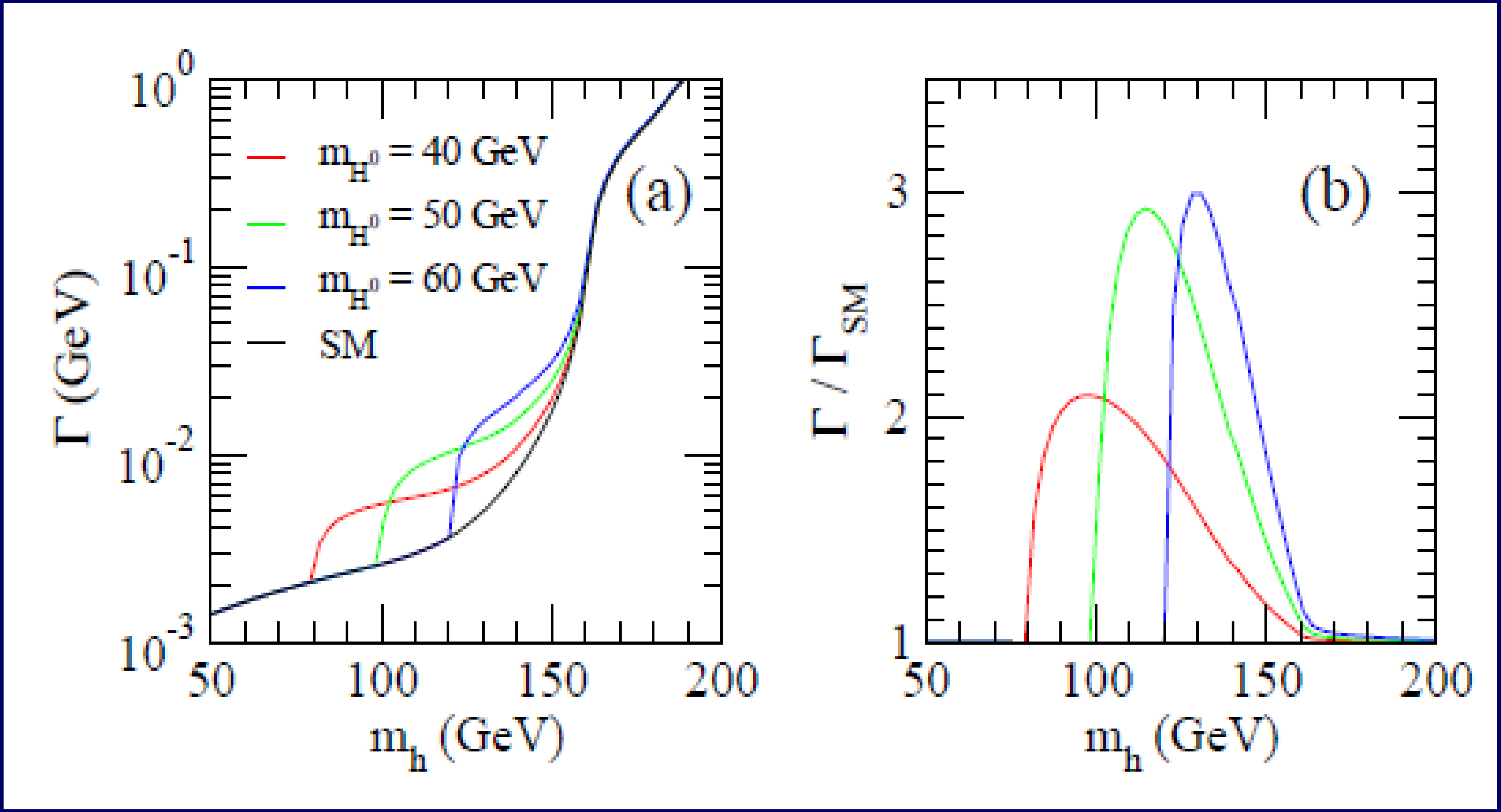
Dark 2HDM – additional decays for h

Ma' 2007



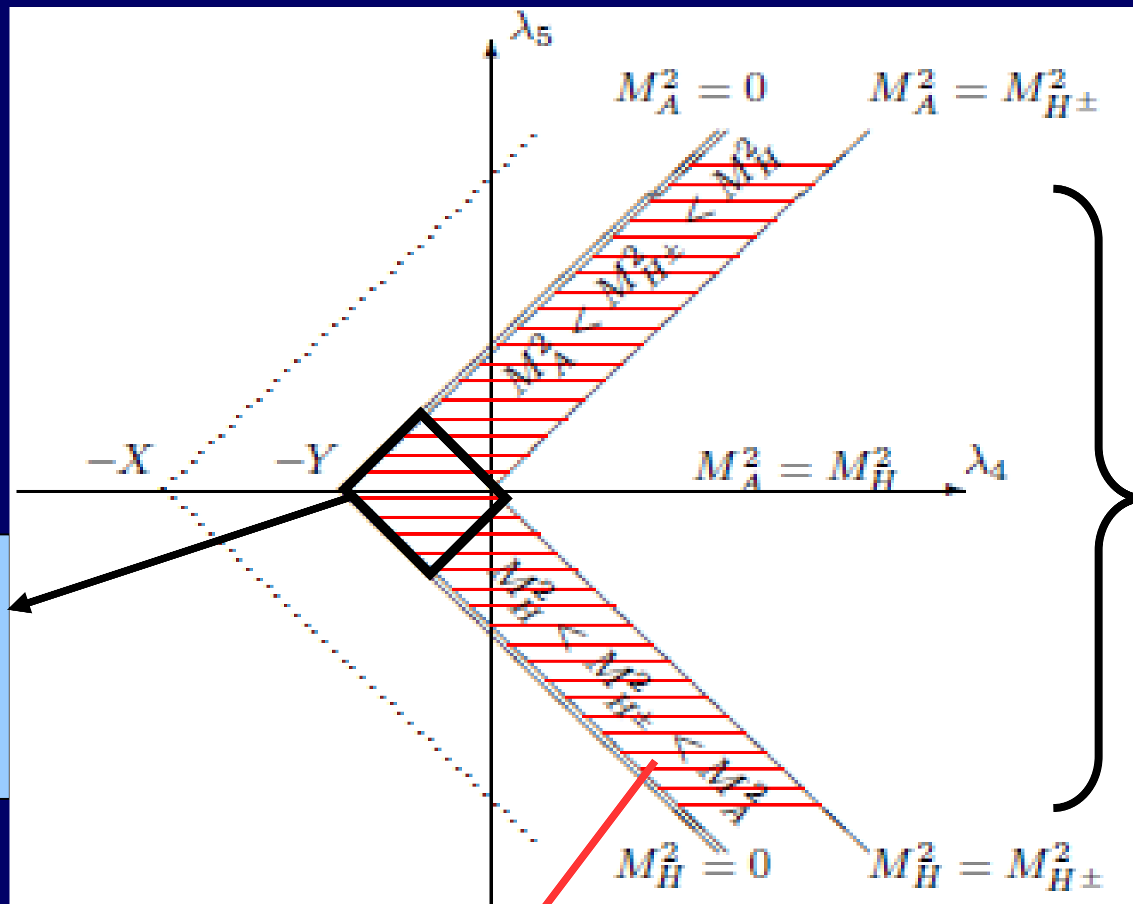
For $M_H = 50$ GeV, $\Delta(A,H)$=10 GeV, M_{H+}=170 GeV, m_{22}=20 GeV

Dark 2HDM – total width of h



Intert Model – dark scalar masses

using X (positivity) and $Y = M_{H+}^2\, 2/v^2$



here H+ is the heaviest

here H+ is the lightest

here H is the dark matter candidate ($\lambda_5 < 0$)

Evolution of the Universe – different vacua in the past ?

We consider 2HDM with an explicit Z_2 symmetry assuming that today the Inert Model is realized.

Useful parametrization with k and δ

$$\lambda_2/\lambda_1 = k^4, \quad m_{11}^2 = m^2(1-\delta), \quad m_{22}^2 = k^2 m^2(1+\delta)$$

$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5, \quad \tilde{\lambda}_{345} = \lambda_3 + \lambda_4 - \lambda_5.$$

$$\Lambda_{345\pm} = \sqrt{\lambda_1\lambda_2} \pm \lambda_{345}, \quad \tilde{\Lambda}_{345\pm} = \sqrt{\lambda_1\lambda_2} \pm \tilde{\lambda}_{345}, \quad \Lambda_{3\pm} = \sqrt{\lambda_1\lambda_2} \pm \lambda_3.$$

Yukawa interaction – Model I →

all fermions couple only to Φ_1

Possible vacua:

Ch — u≠0

$$v_1^2 = \frac{m^2k^2}{2}\left(\frac{1}{\Lambda_{3+}} - \frac{\delta}{\lambda_{3-}}\right), \quad v_2 = 0, \quad u^2 = \frac{m^2}{2}\left(\frac{1}{\Lambda_{3+}} + \frac{\delta}{\lambda_{3-}}\right)$$

$$\mathcal{E}_{ch} = -\frac{m^4k^2}{8}\left(\frac{1}{\Lambda_{3+}} + \frac{\delta^2}{\Lambda_{3-}}\right)$$

Inert, B, N — u=0

Inert:

$$v_2 = 0, \; v^2 = v_1^2 = \frac{m^2(1-\delta)}{\lambda_1}, \quad \mathcal{E}_A = -\frac{m^4(1-\delta)^2}{8\lambda_1}$$

B:

$$v_1 = 0, \; v^2 = v_2^2 = \frac{m^2(1+\delta)}{k^2\lambda_1}, \quad \mathcal{E}_B = -\frac{m^4(1+\delta)^2}{8\lambda_1}$$

N:

$$v_1^2 = \frac{m^2k^2}{2}\left(\frac{1}{\Lambda_{345+}} - \frac{\delta}{\Lambda_{345-}}\right), \quad v_2^2 = \frac{m^2}{2}\left(\frac{1}{\Lambda_{345+}} + \frac{\delta}{\Lambda_{345-}}\right),$$

$$\mathcal{E}_C = -\frac{k^2m^4}{4}\left(\frac{1}{\Lambda_{345+}} + \frac{\delta^2}{\Lambda_{345-}}\right)$$

Depending on value of δ →

a true vacuum (with the minimal energy)

Depending on δ → a true vacuum

$$\mathcal{E}_I - \mathcal{E}_N = \frac{m^4}{8}\frac{(\Lambda_{345-} + \delta\Lambda_{345+})^2}{\lambda_1 \Lambda_{345-}\Lambda_{345+}}, \quad \mathcal{E}_I - \mathcal{E}_{Ch} = \frac{m^4}{8}\frac{(\Lambda_{3-} + \delta\Lambda_{3+})^2}{\lambda_1 \Lambda_{3-}\Lambda_{3+}}$$

$$\mathcal{E}_N - \mathcal{E}_{Ch} = \frac{k^2 m^2}{4}\lambda_{45}\left[\frac{1}{\Lambda_{3+}\Lambda_{345+}} - \frac{\delta^2}{\Lambda_{3-}\Lambda_{345-}}\right], \quad \mathcal{E}_I - \mathcal{E}_B = \frac{m^4\delta}{2\lambda_1}.$$

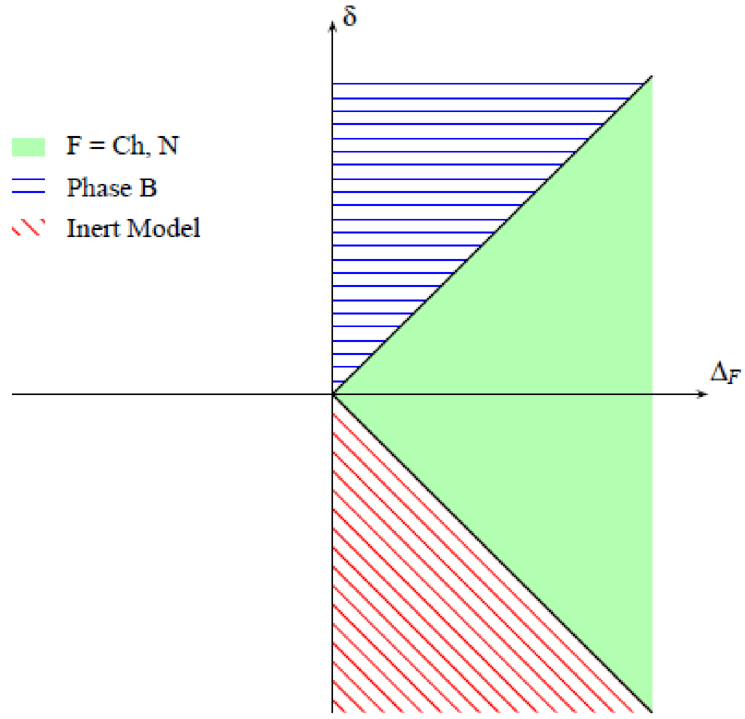
For Ch

$$\Delta_{Ch} = \Lambda_{3-}/\Lambda_{3+} > 0$$

For N

$$\Delta_N = \Lambda_{345-}/\Lambda_{345+} > 0$$

So, if δ change with time?



Phase transitions from the EW symmetric phase

[redacted] $\Lambda_{3-} > 0,\ \lambda_4 + \lambda_5 > 0$ $\delta(T_{Ch\pm}) = \pm\Delta_{Ch}$

Two second order phase transitions:

$EW \xrightarrow{II} \text{Phase B} \xrightarrow{II} \text{Charged phase} \xrightarrow{II} \text{Inert phase}$

[redacted] $\Lambda_{345-} > 0,\ \lambda_4 + \lambda_5 < 0$ $\delta(T_{N\pm}) = \pm\Delta_N$

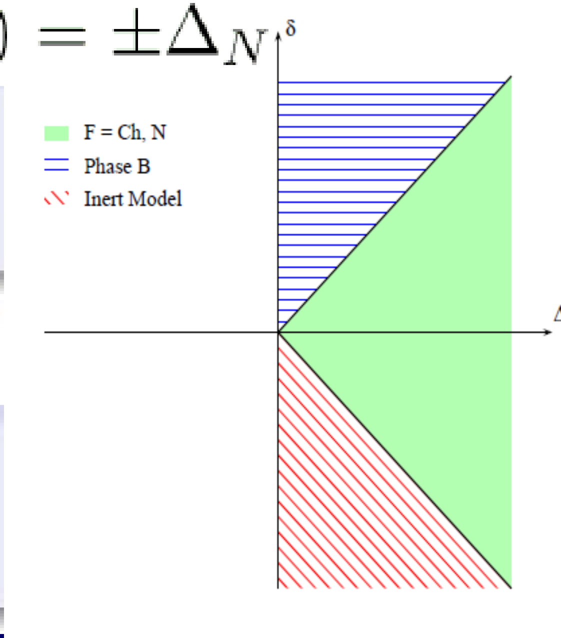
Two second order phase transitions:

$EW \xrightarrow{II} \text{Phase B} \xrightarrow{II} \text{Phase N} \xrightarrow{II} \text{Inert phase}$

[redacted]

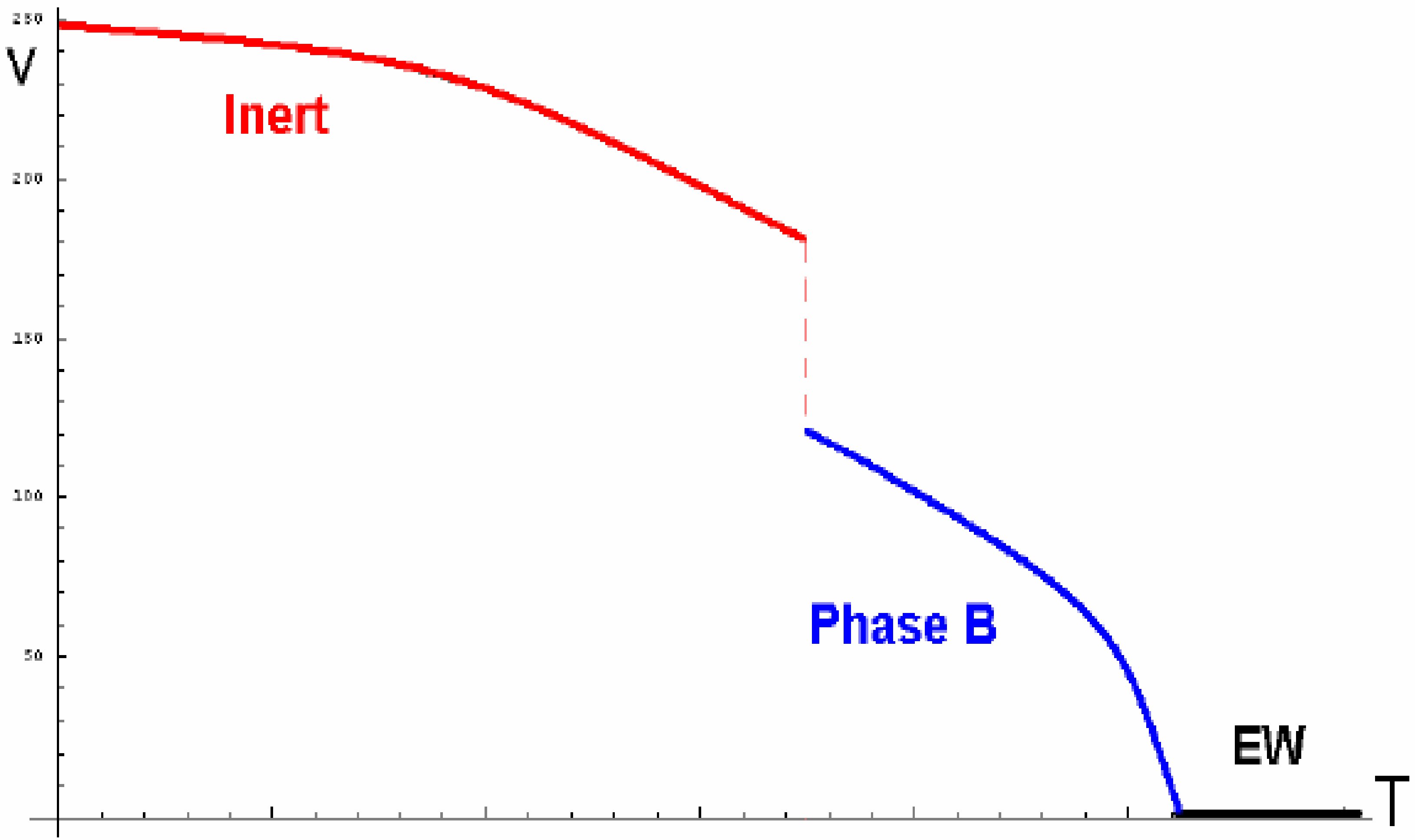
First order phase transition:

$EW \xrightarrow{II} \text{Phase B} \xrightarrow{I} \text{Inert phase}$



to the present INERT phase

EW – B – I: an example



Conclusions

- Rich content of 2HDMs
- Intert Model in agreement with present data – soon tests at FERMI and LHC
- What was in the Past?

  - EW $\xrightarrow{II}$ Phase B $\xrightarrow{I}$ Inert phase
  - EW $\xrightarrow{II}$ Phase B $\xrightarrow{II}$ Phase N $\xrightarrow{II}$ Inert phase
  - EW $\xrightarrow{II}$ Phase B $\xrightarrow{II}$ Charged phase $\xrightarrow{II}$ Inert phase
  - EW $\xrightarrow{II}$ Inert phase

- Various scenarios
- Can we find clear signals ?

excluded if DM neutral !

B-Inert is the 1st order phase transition –discontinuities

It is possible not to have DM at high temperature

Teoria cząstek elementarnych