Fermilab, 13 August '08

The Standard Model confronts the LHC

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Lecture 1

- Status of the SM EW theory
- The Higgs problem

Lecture 2

- Status of QCD
- Top quark

Lecture 3

- Problems of the SM
- Motivation for new physics at the TeV scale
- Avenues for new physics

QCD

LHC is a hadron collider

QCD is of fundamental importance for the design and the interpretation of experiments

Also, ALICE is dedicated to the study of heavy ion collisions to understand the QCD phase diagram at high temperatures and densities

QCD stands as a very solid building block of the SM

The unbroken gauge symmetry of the SM is $SU(3)xU(1)_Q$

QCDxQED

For many years the field theory of reference was QED, now QCD is a more complex and intriguing framework

Steady progress in techniques to extract precise predictions (higher order perturbative, resummation, event simulation, non perturbative, ...)

Comparison with experiment is excellent

QCD is a "simple" theory

$$L = -\frac{1}{4}\sum_{A=1}^{8} F^{A\mu\nu}F^{A}_{\mu\nu} + \sum_{j=1}^{n_f} \bar{q}_j(i\hat{D} - m_j)q_j$$

but with an extremely rich dynamical content:

- Asymptotic freedom
- Confinement
- Complex hadron spectrum (light and heavy quarks)
- Spontaneous breaking of (approx.) chiral symm.
- Phase transitions

  [Deconfinement (q-g plasma), chiral symmetry restauration,……]
- Highly non trivial vacuum topology

  [Instantons, $U(1)_A$ symm. breaking, strong CP violation (?)]
- • •

Strong CP violation: possible new physics ?

The axial anomaly breaks the singlet axial current

$$\partial_\mu j_5{}^\mu = \frac{\alpha_s}{4\pi} Tr(F_{\alpha\beta}\tilde{F}^{\alpha\beta}) \qquad \tilde{F}^{\alpha\beta} = \frac{1}{2}\varepsilon^{\alpha\beta\gamma\delta}F_{\gamma\delta}$$

The rhs is a 4-divergence

So if such a term is added to the lagrangian normally
it would not affect the eq.ns of motion

$$\Delta L = \theta \frac{\alpha_s}{4\pi} Tr(F_{\alpha\beta}\tilde{F}^{\alpha\beta})$$

But in QCD it has an effect given the topology of the vacuum in non abelian gauge theories which is far from trivial:

$\theta = \theta_{\text{instantons}} +$ Arg Det m   m quark mass matrix θ should apriori be o(1). But it would contribute to the neutron electric dipole moment:

$$d_n(e \cdot cm) \simeq 3 \cdot 10^{-16}\theta$$

From experiment: $|\theta| \leq 10^{-10}$

The "strong CP problem" consists in finding an explanation:

- Non rinormalisation theorem in SUSY
- An ad hoc symmetry (Peccei-Quinn) spont. broken --> axion
- Something not understood on vacuum topology?

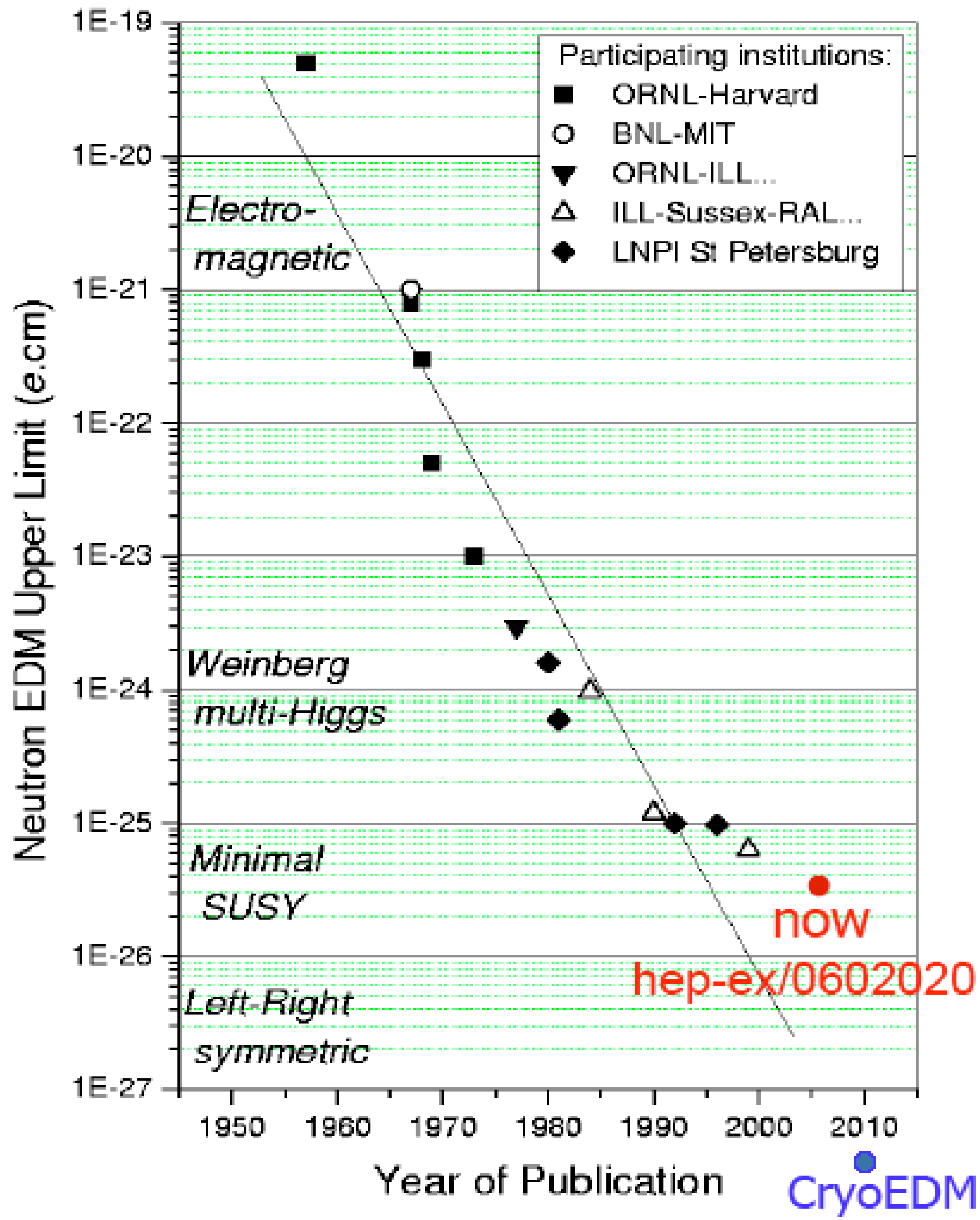
••••••

CPV in FC channels is dominated by CKM

What in flavour conserv. channels?

New limit on nEDM from Grenoble

$|d_n| < 3\ 10^{-26}$ e cm (90%cl)



How do we get predictions from QCD?

- Non perturbative methods

•Lattice simulations (great continuous progress)

•Effective lagrangians

* Chiral lagrangians
* Heavy quark effective theories
* SCET
* NRQCD
* AdS/CFT correspondence ••••••

•QCD sum rules

•Potential models (quarkonium)

- Perturbative approach

Based on asymptotic freedom.

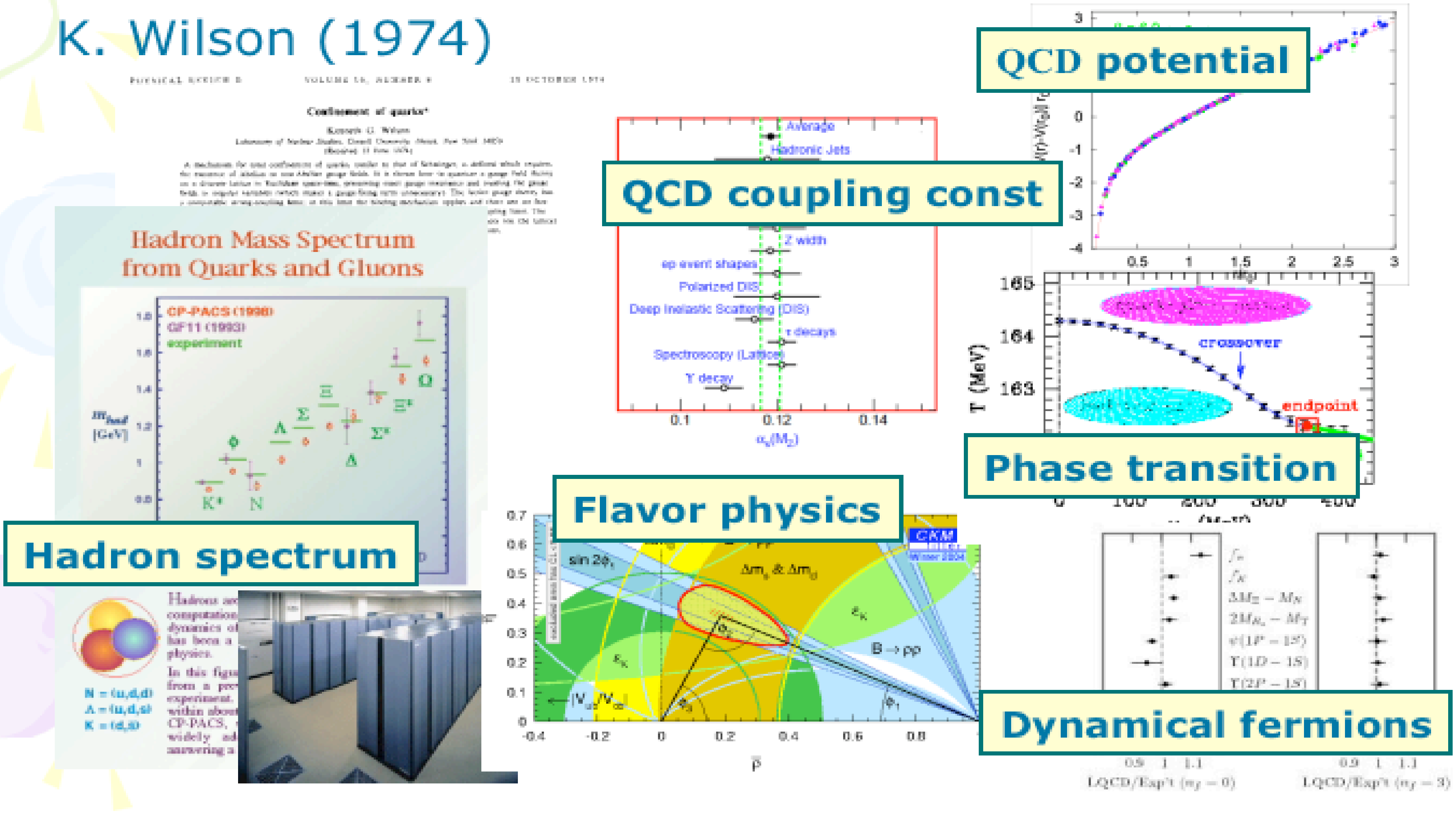
It still remains the main quantitative connection to experiment.

The main tool for non perturbative QCD in continuous progress

Hashimoto, ICHEP'04

30 years of lattice QCD

K. Wilson (1974)



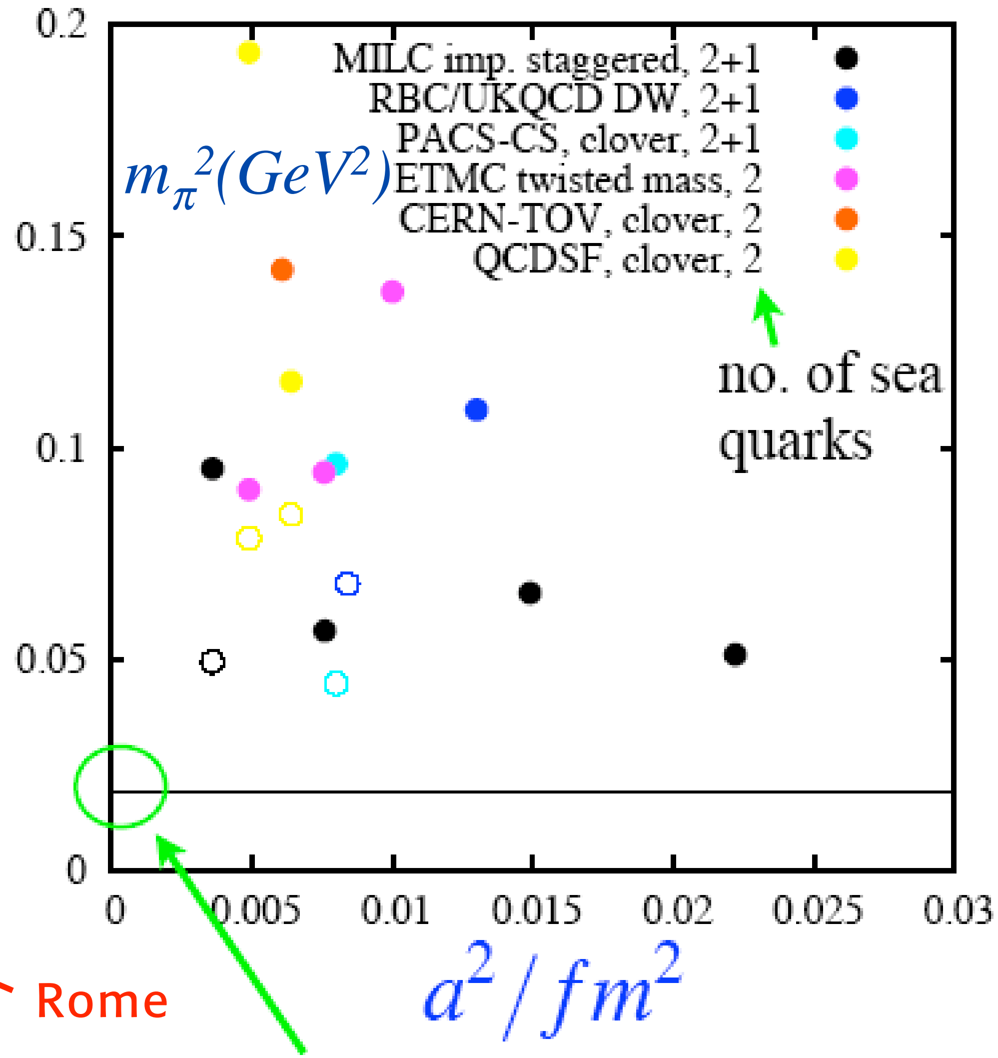
Lattice calculations have shown great progress

Unquenched fermions
Chiral logs control
Simulation techniques
Many-teraflop computers

Davies LP'07

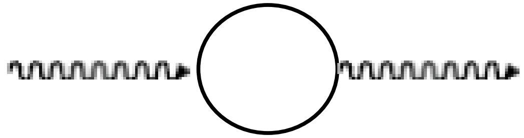
	speed	chiral symm.	collab.
imp.stagg. (asqtad)	fast	OK	MILC/ HPQCD/ FNAL
domain wall	slow	good	RBC/ UKQCD
clover	fast	bad	PACS-CS QCDSF CERN-TOV
twisted mass	fast	OK	ETMC

Rome



Quenched vs unquenched

Dynamical fermions:



quark loops allowed

Computing the fermion determinant is very hard

$$\int d\psi \, d\bar{\psi} \exp \int d^4x \, \bar{\psi}(\widehat{D} + m)\psi = Det(\widehat{D} + m)$$

quenched: replace with 1
unquenched: compute it

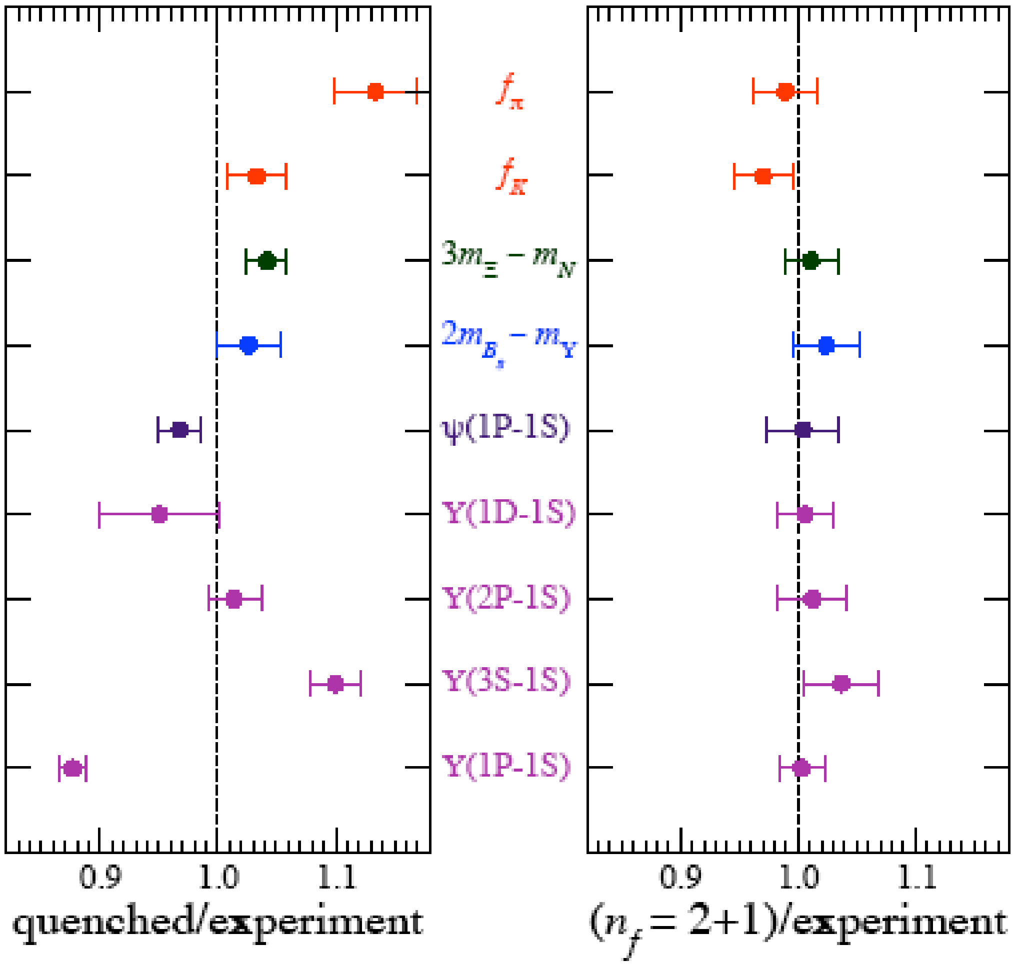
How hard depends on the method: several approaches with pro's and con's

The quenched approximation (QA) is being abandoned: what was rough agreement in QA is now precise with unquenching

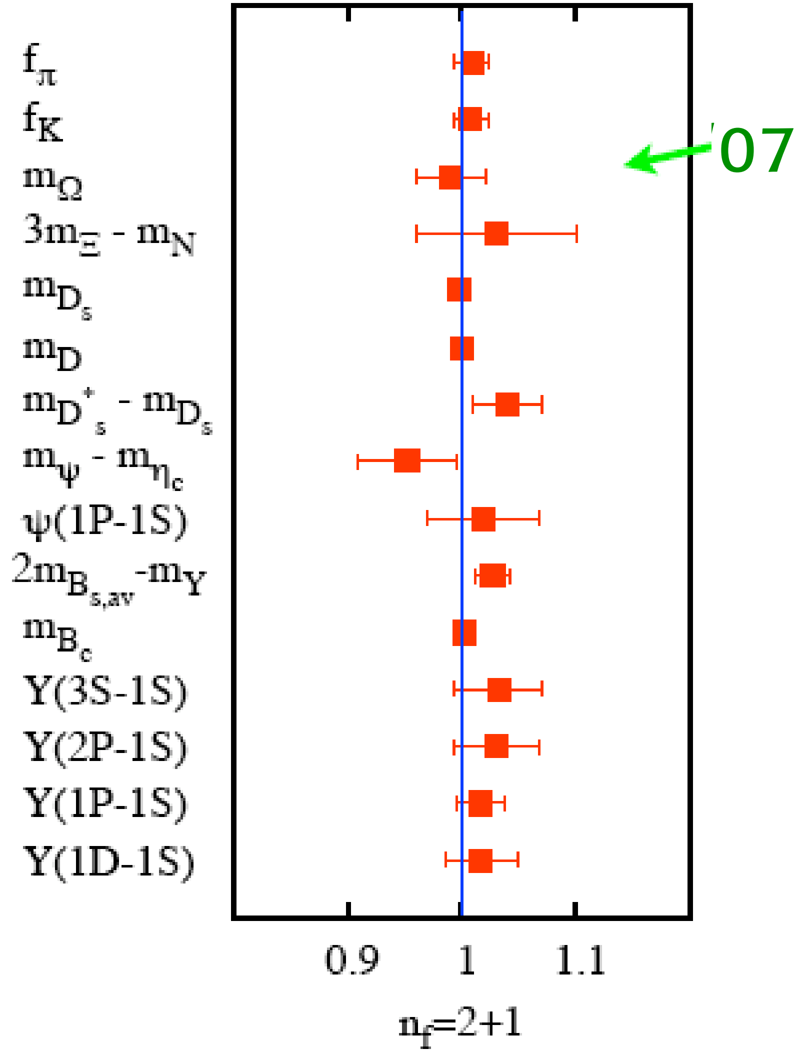
old

quenched

unquenched

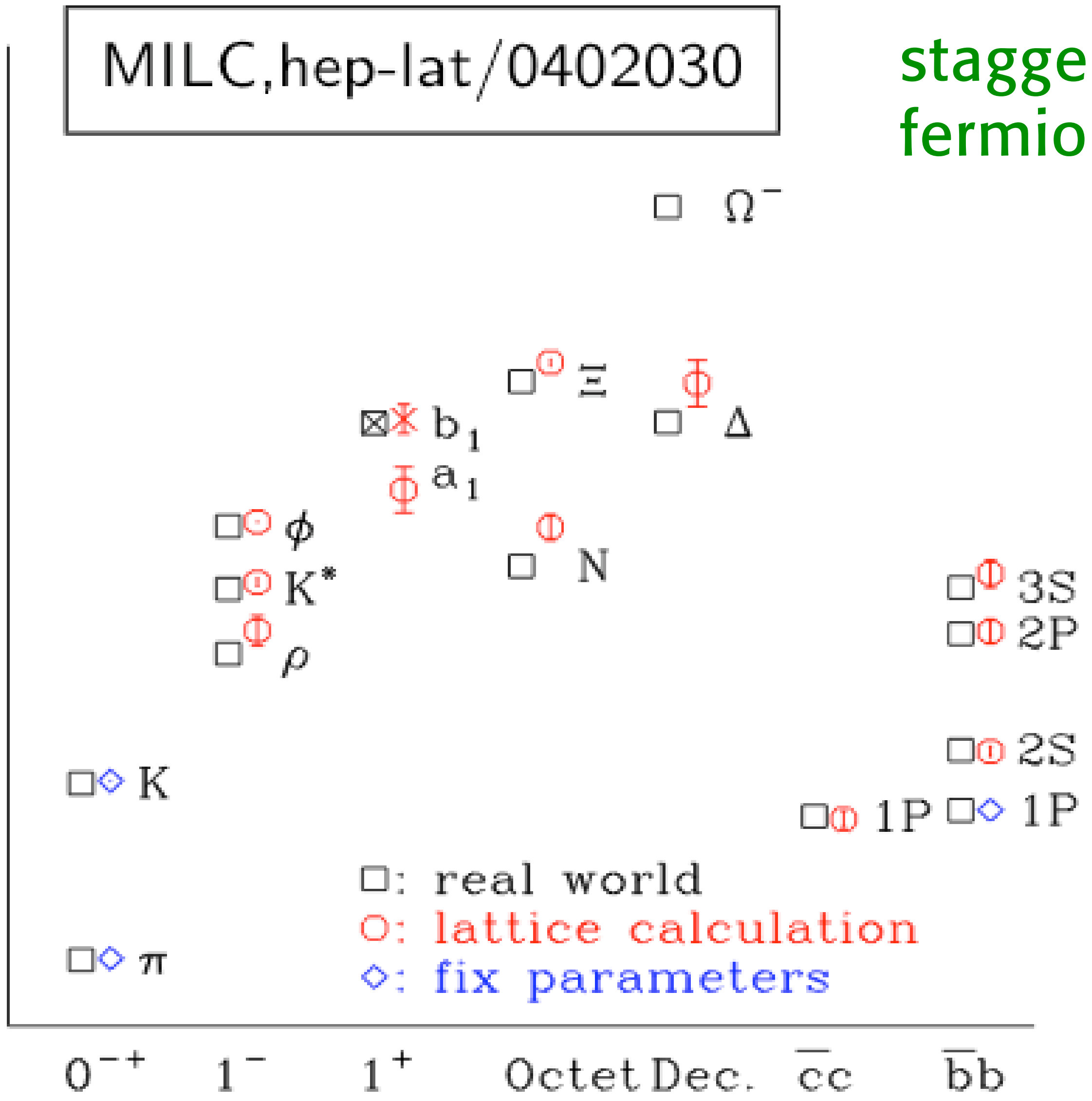


new



Unquenched lattice simulations reproduce spectrum well

Ukawa



staggered fermions

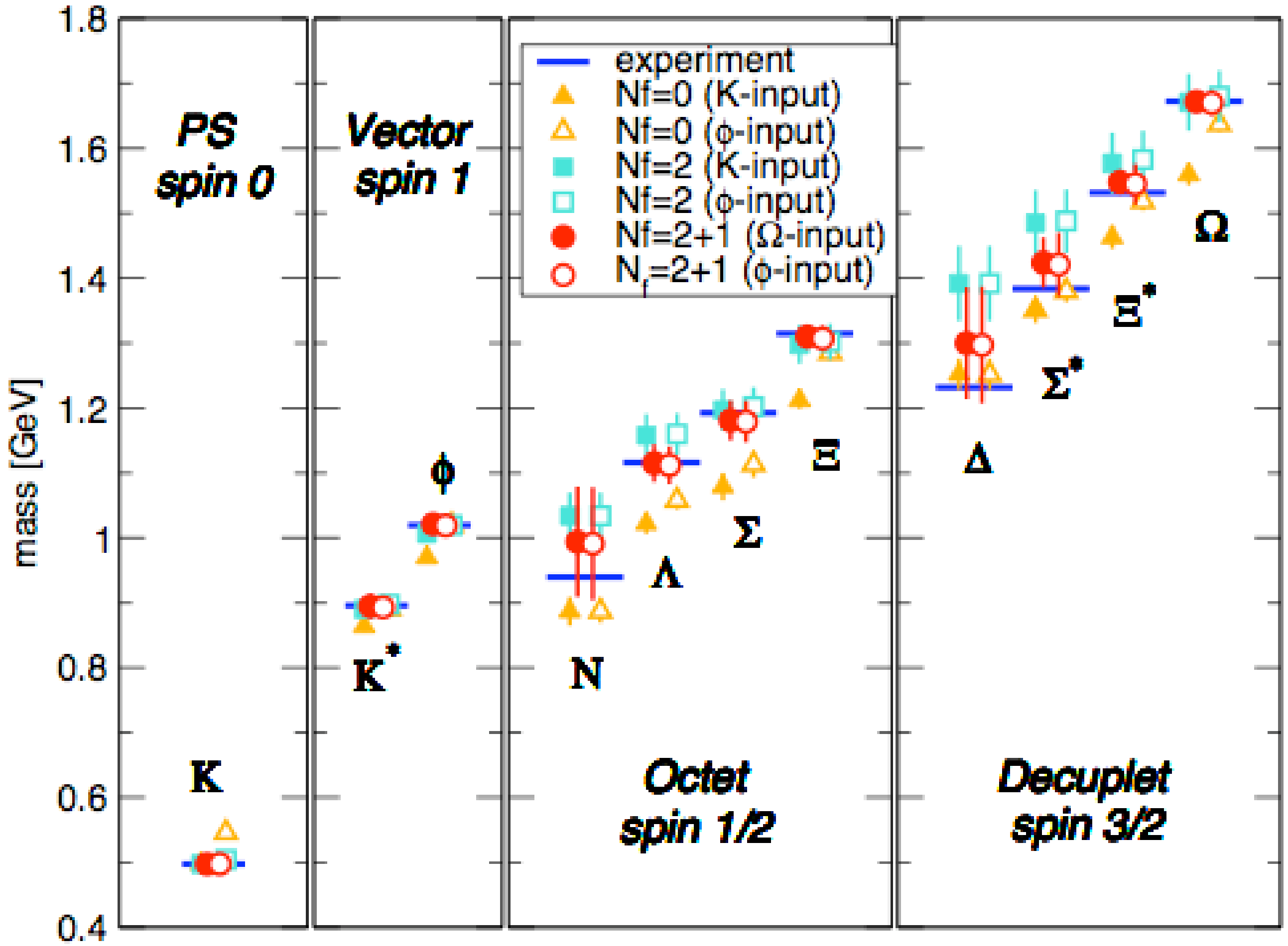
Note:
p/ρ ~ 1.2
not 1.5
as from
3q/2q

Unquenched lattice simulations reproduce spectrum well

Kuromashi'07

Wilson N_f=2+1

Here the focus is on strange particles



Kronfeld

Chiral extrapolation

- Lattice simulation is limited in a heavier quark mass region $m_q \sim (0.5\text{-}1) m_s$.

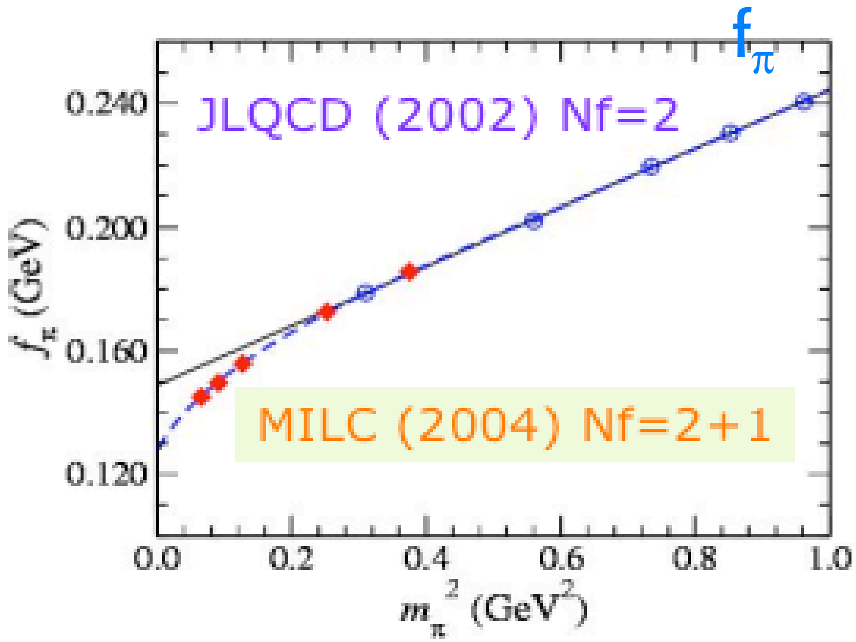
ChPT predicts the chiral log near the chiral limit.

$c \log(m_q/1\text{GeV})$

with a fixed coefficient.

Staggered simulation can push the quark mass much lower.

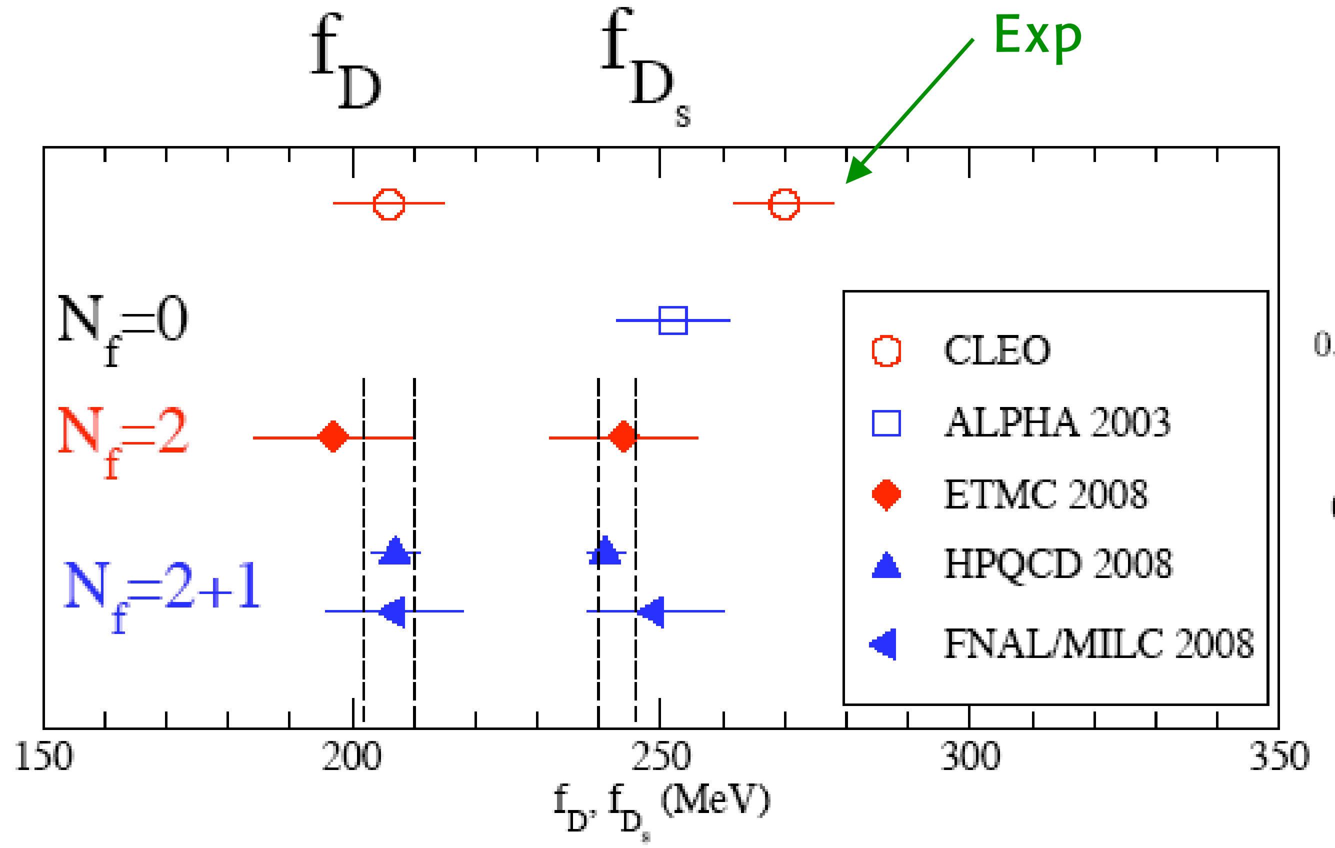
$$\langle 0|\partial^\mu A_\mu|\pi\rangle = f_\pi m_\pi^2$$

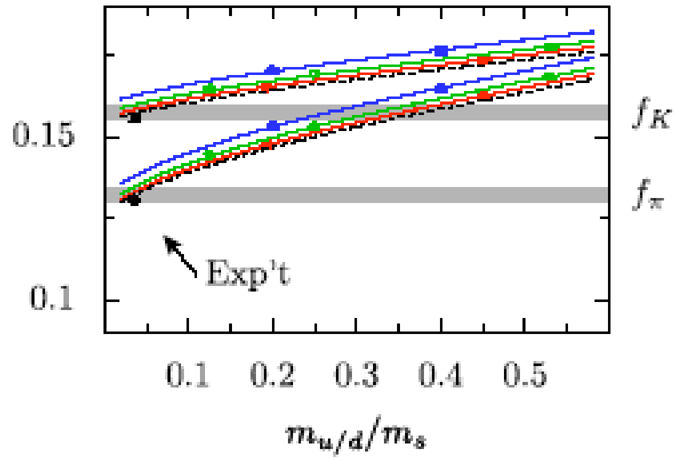


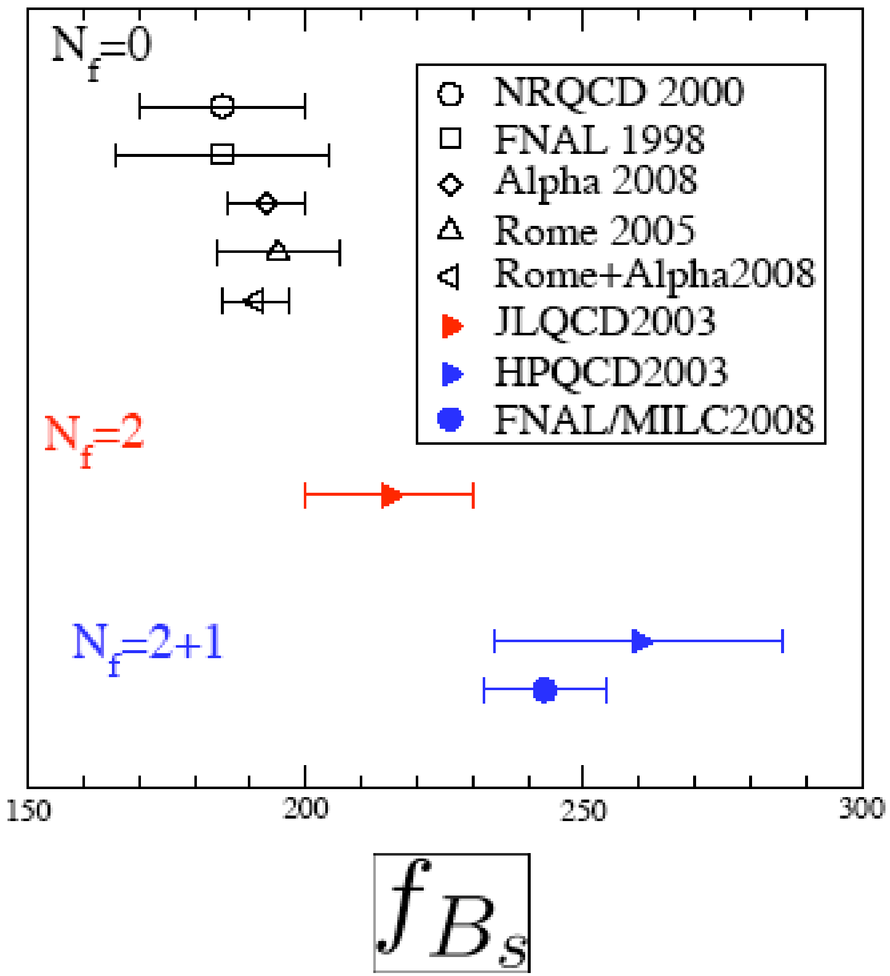
Pseudoscalar constants

Onogi, ICHEP'08

A problem with f_{Ds}? Or the theoretical error is underestimated?







	n_f	$\frac{f_{B_s}}{f_{B_d}}$
HPQCD	2+1	1.20(3)
FNAL/MILC	2+1	1.25(4)

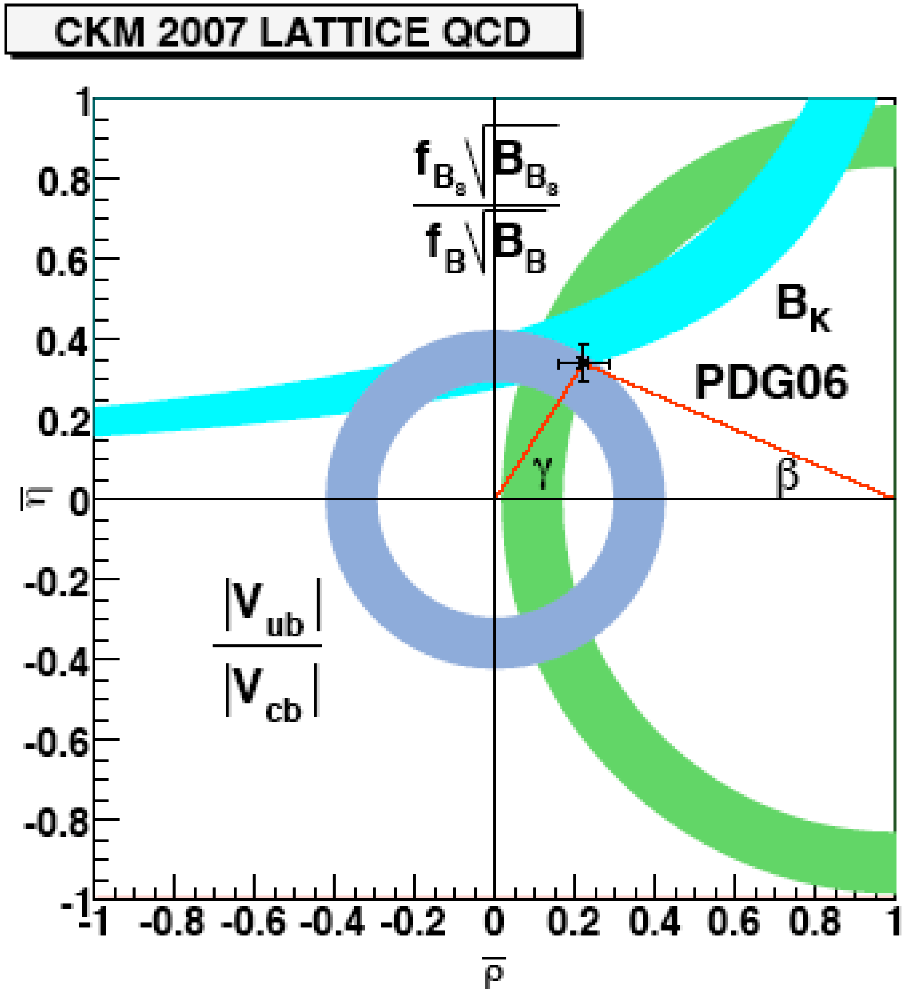
Here there is an increase going from n_f=0 to unquenched (not in f_{Ds})

Lattice is playing an increasingly important role in flavour physics

Davies LP'07

Lattice inputs
(2+1 sea quarks):

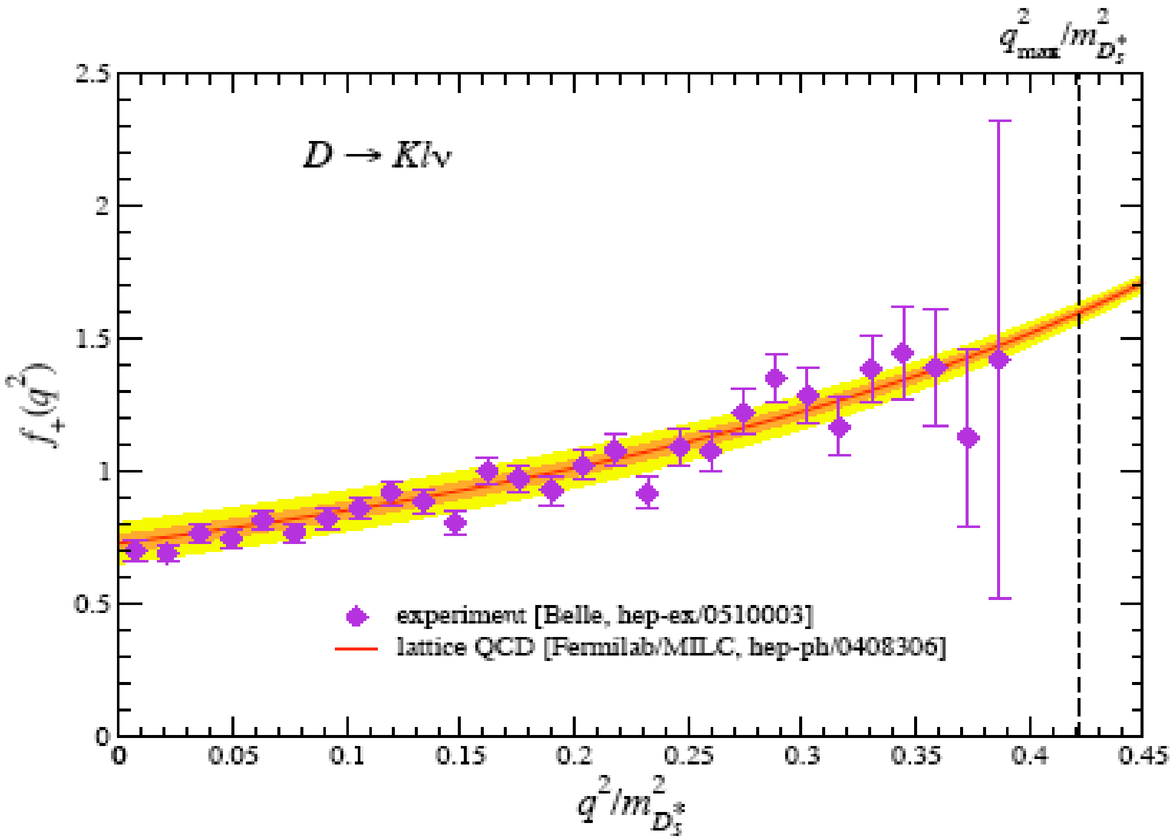
B_K
$f_K/f_\pi \;, f_+(K \to \pi l \nu)$
$F(B \to D^* l \nu)$
$f_+(B \to \pi l \nu)$
$$\frac{f_{B_s}\sqrt{B_{B_s}}}{f_B\sqrt{B_B}}$$



$D \to \{K, \pi\} l\nu$

Mackenzie, FPCP'06

A prediction: shape of the $D \to K\, l\nu$ form factor.



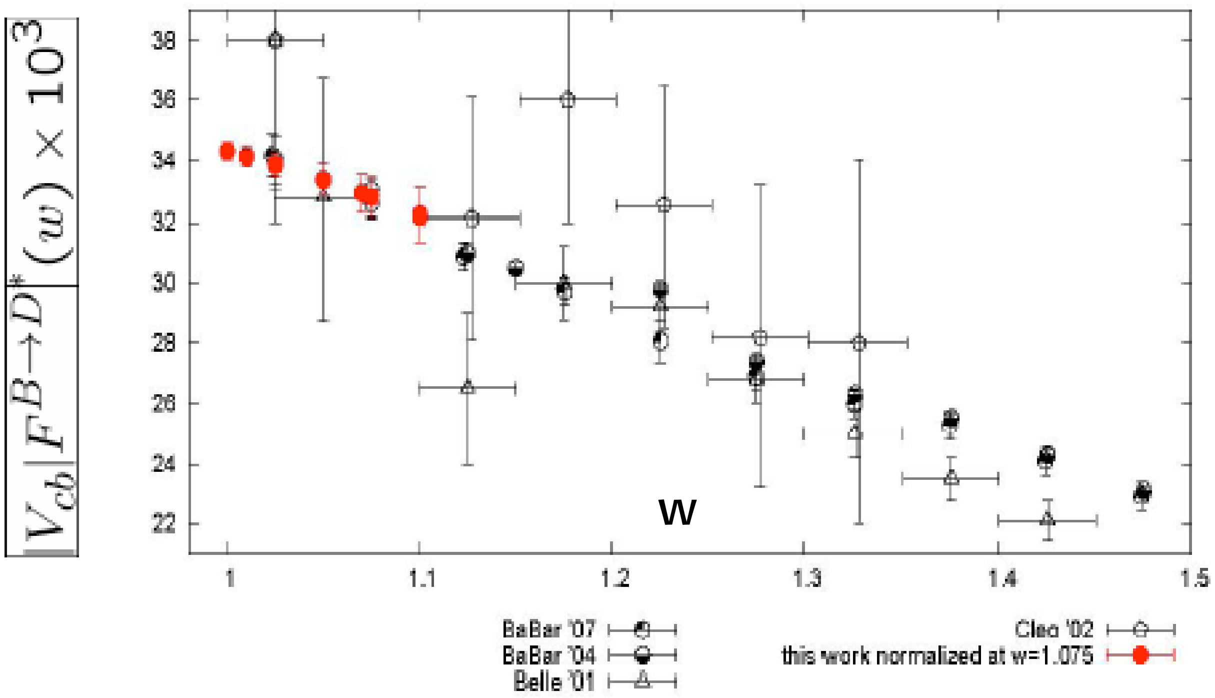
CLEO-c is threatening to drastically improve. → More stringent tests.

B->D*lν

de Divitiis, Petronzio, Tantalo '07

n_f=0 (quenched)

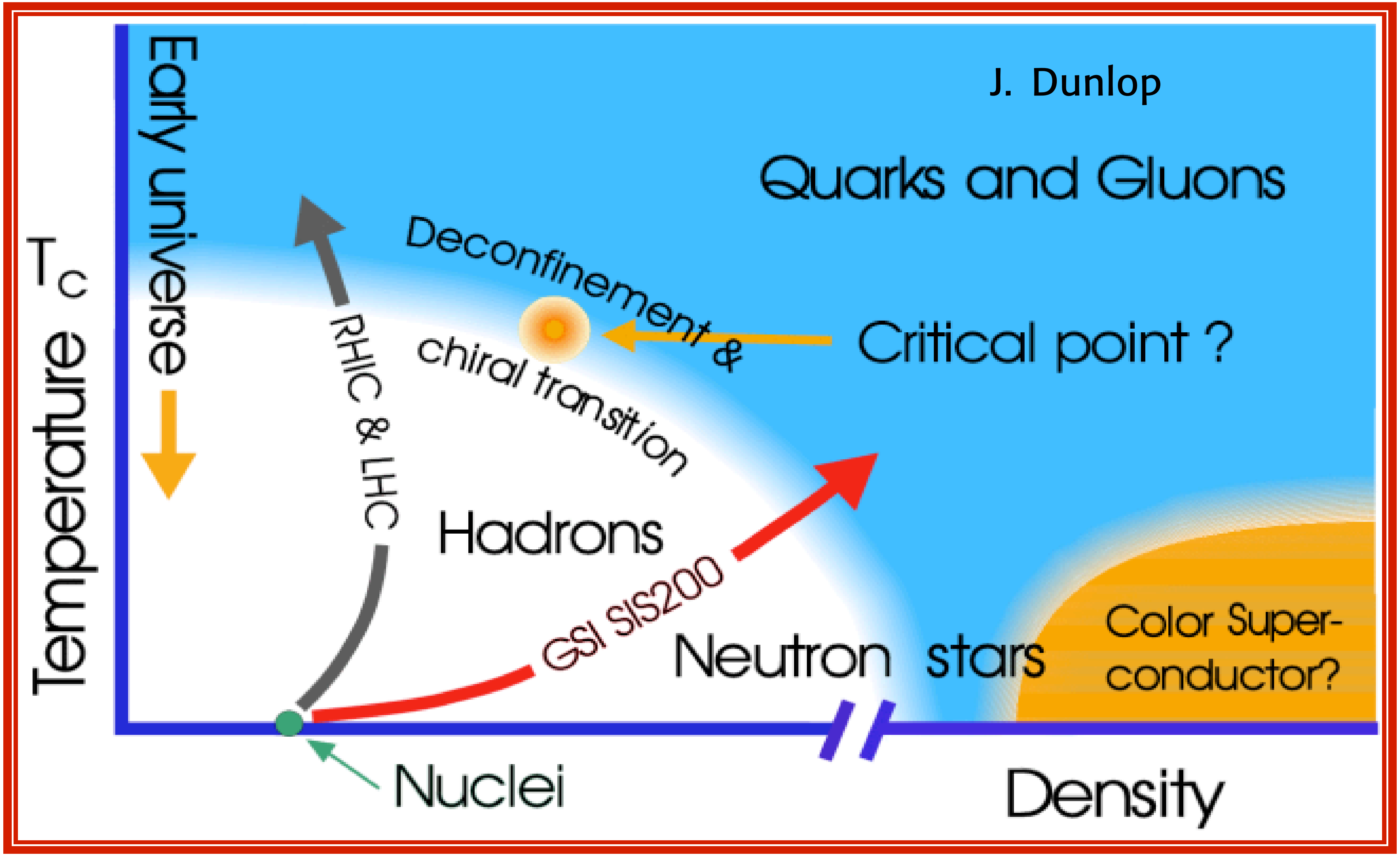
w dependence: lattice vs experiment



ICHEP08

The QCD phase diagram

Studied on the lattice and probed by colliding heavy ions at SPS, RHIC, LHC



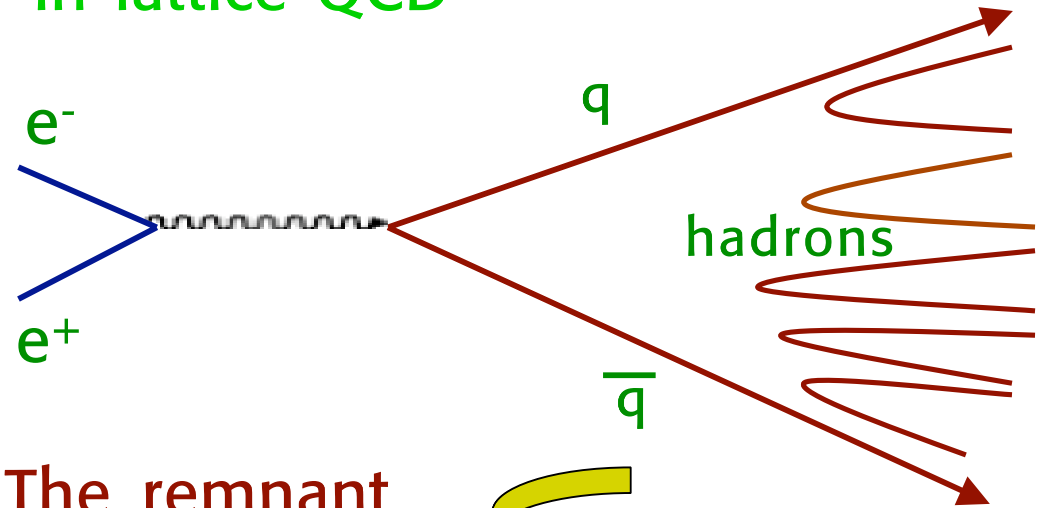
Confinement: no free coloured particles

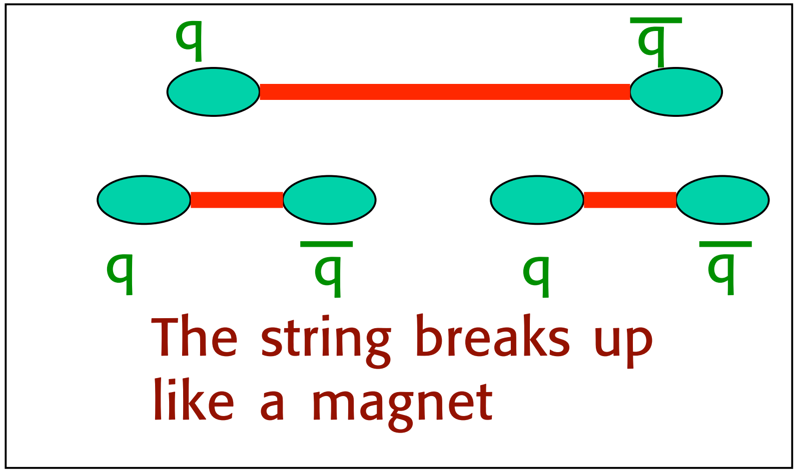
q-$\bar{q}$ potential:

$$V(r) \approx C_F\left[\frac{\alpha_s(r)}{r} + \dots + \sigma r\right]$$

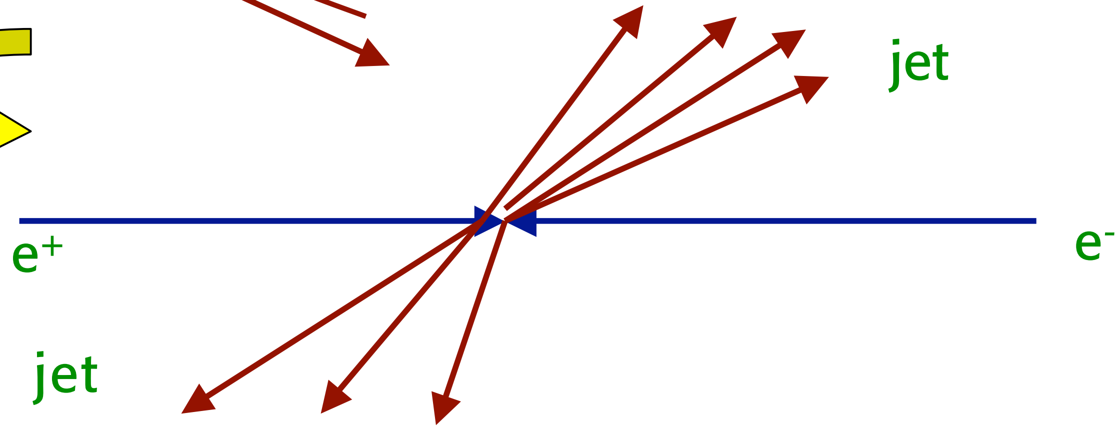
short long dist.

Has been studied in lattice QCD





The remnant of q is a jet of colourless hadrons

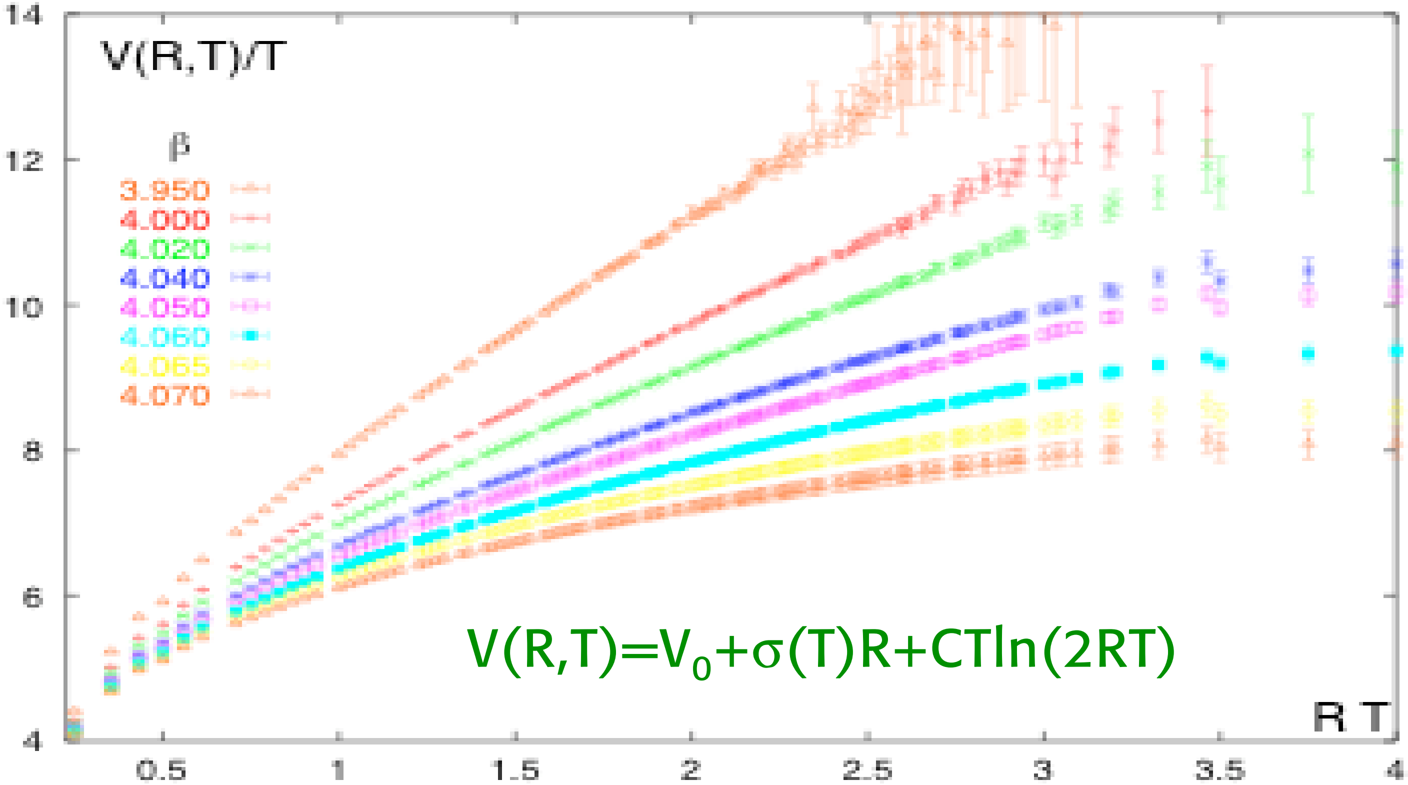


Confinement on the lattice

Potential between static quarks on the lattice

Kaczmarek, Karsch, Laermann, Lutgemeier '00

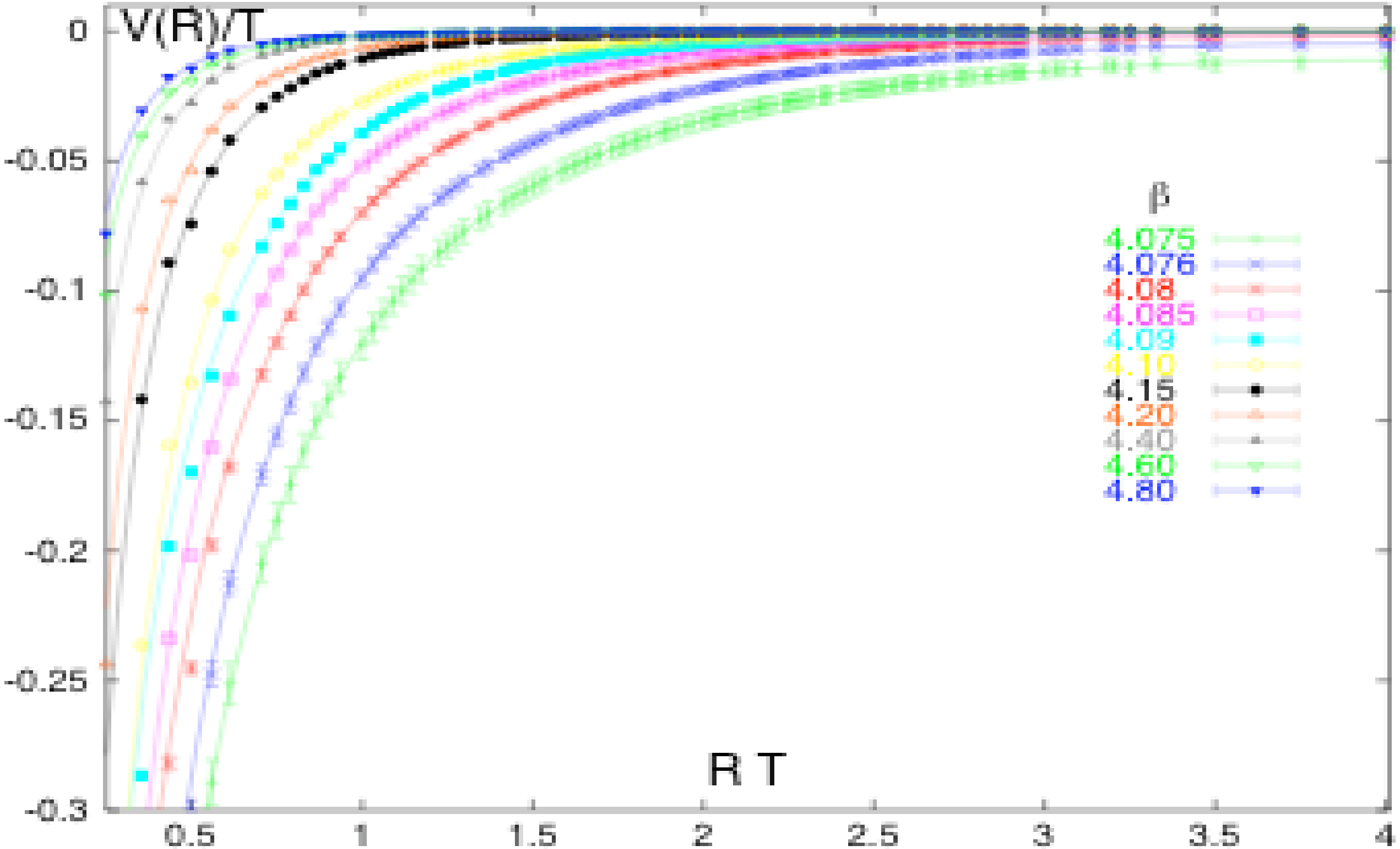
quenched approx.



Potential in units of kT (k=1) as function of R in units 1/T, for different β=1/T

The linearly rising term slope vanishes at T_C

At $T > T_C$ the slope at large R remains zero

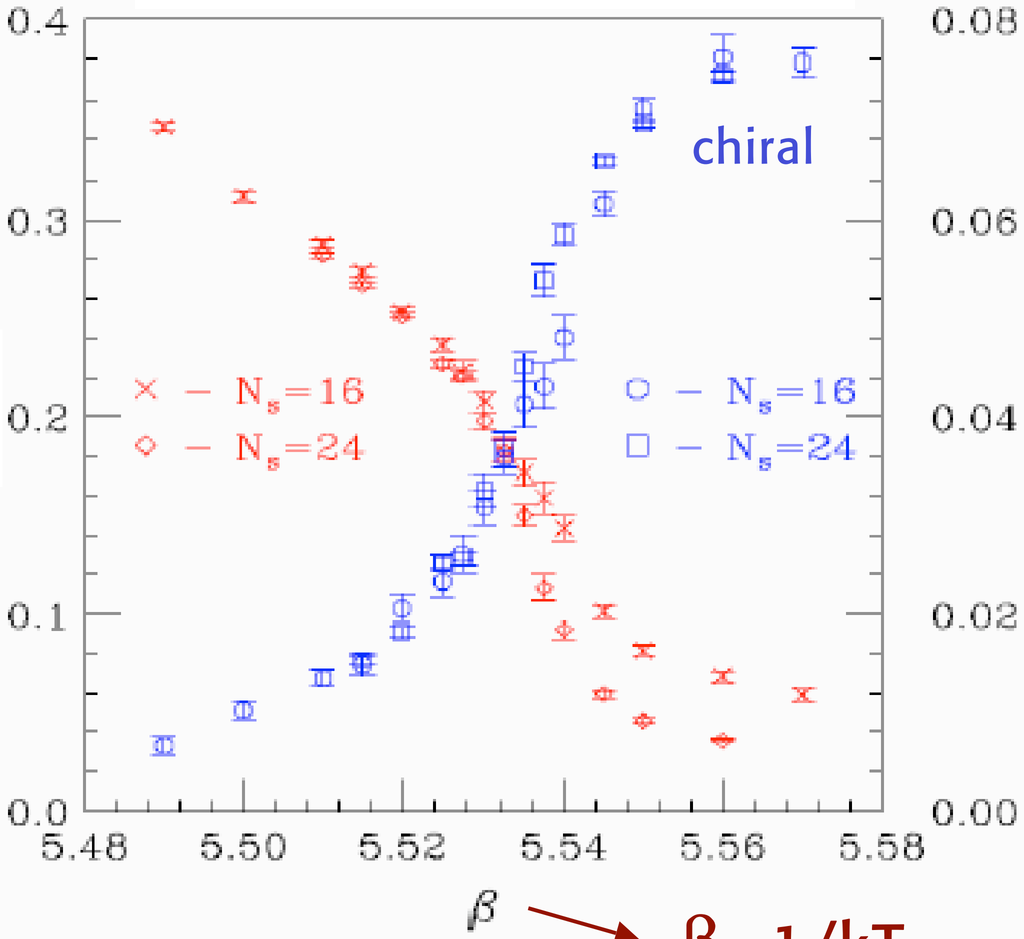


T_C depends on the number of quark flavours

Lattice QCD predicts a rapid transition, with correlated deconfinement and chiral restauration

$\langle \bar{q} q \rangle$

chiral



$$\langle L \rangle = \left\langle \mathrm{tr}\,\exp(i \int_0^{1/T} A_4 \, d\tau) \right\rangle$$

$$\sim \exp(-F_Q / T)$$

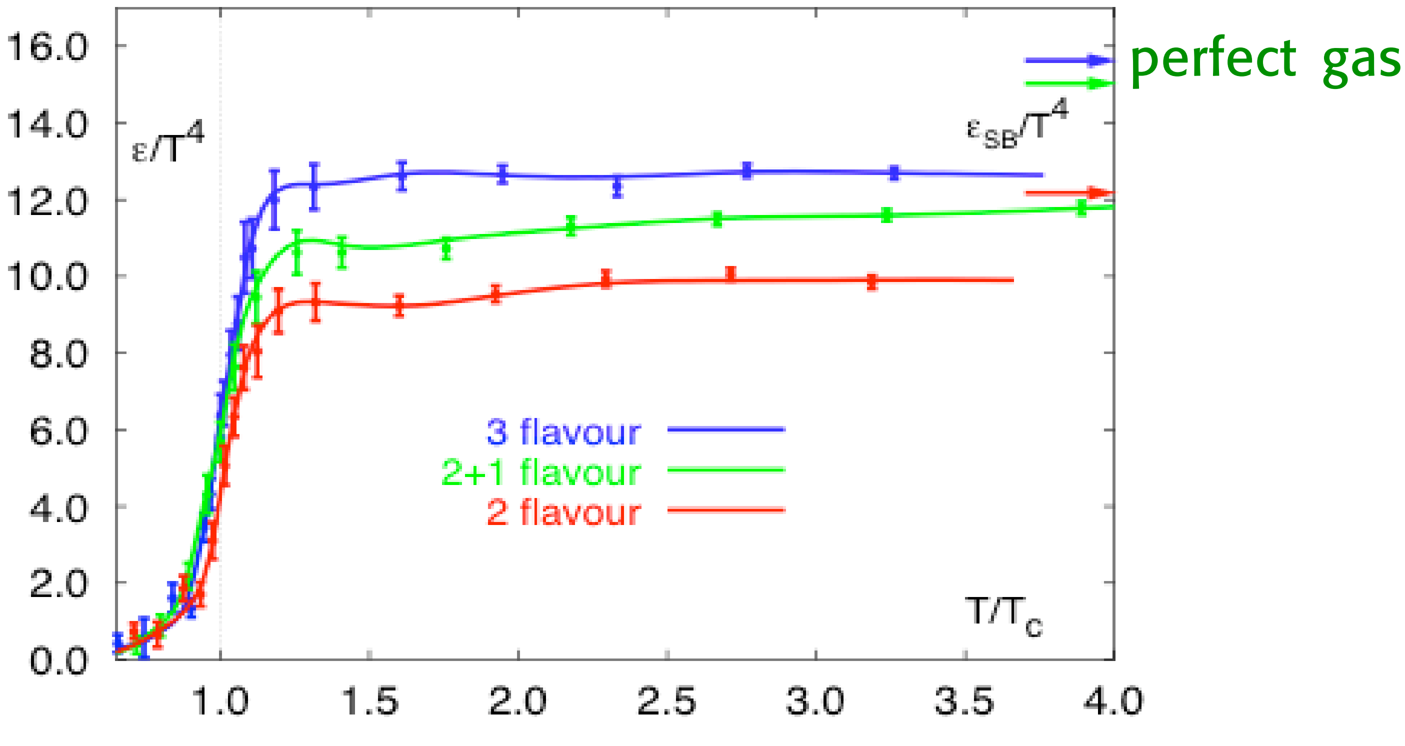
confinement

N_f=2, χQCD

Kogut and Sinclair, hep-lat/0408003

$\beta = 1/kT$

- **energy density increases sharply by the latent heat of deconfinement**



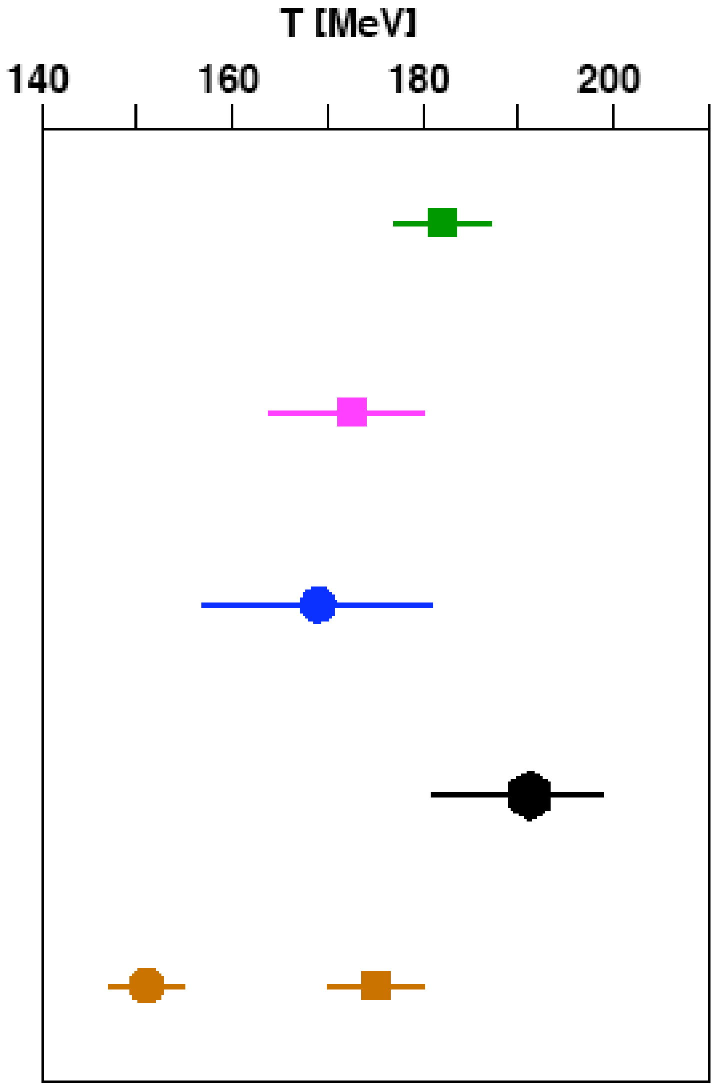
For $N_f = 2, 2+1$:

$T_c \simeq \ 175 \text{ MeV}$

$\epsilon(T_c) \simeq 0.5 - 1.0 \text{ GeV/fm}^3$

Summary of recent results on T_c

use T=0 scale: r0=0.469fm   Karsch LAT'07



Nf=2:

V.G. Bornyakov et al, POS Lat2005, 157 (2006)
(improved Wilson, Nt=8, 10; input: r0=0.5 fm)
(added Nt=12, Lattice'07)   (rescaled to r0)

Y. Maezawa et al., hep–lat/0702005 (QM'2006)
(improved Wilson, Nt=4, 6; input: m–rho)
(no cont. exp. yet)

Nf=2=1:

C. Bernard et al., Phys.Rev. D71, 034504 (2005)
(improved staggered (asqtad), Nt=4,6,8, input r1)
(rescaled to r0)

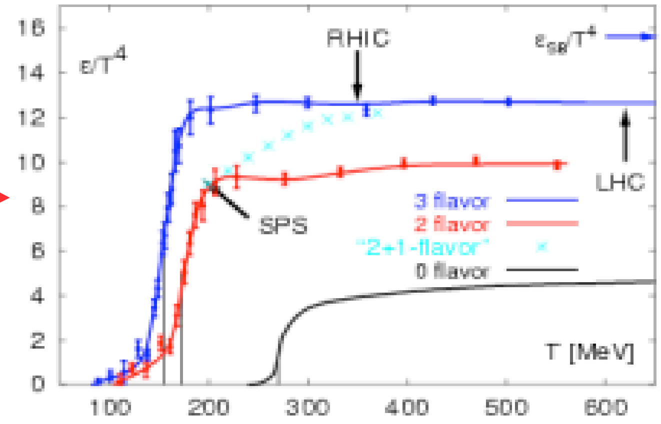
M. Cheng et al., Phys.Rev D74, 054507 (2006)
(improved staggered (p4), Nt=4,6; input r0)

Y. Aoki et al., Phys. Lett. B643, 46 (2006)
(staggered (stout), Nt=4,6,8,10; input fK)
(converted to r0)

● chiral   ■ deconfinement   ⬢ chiral+deconfinement

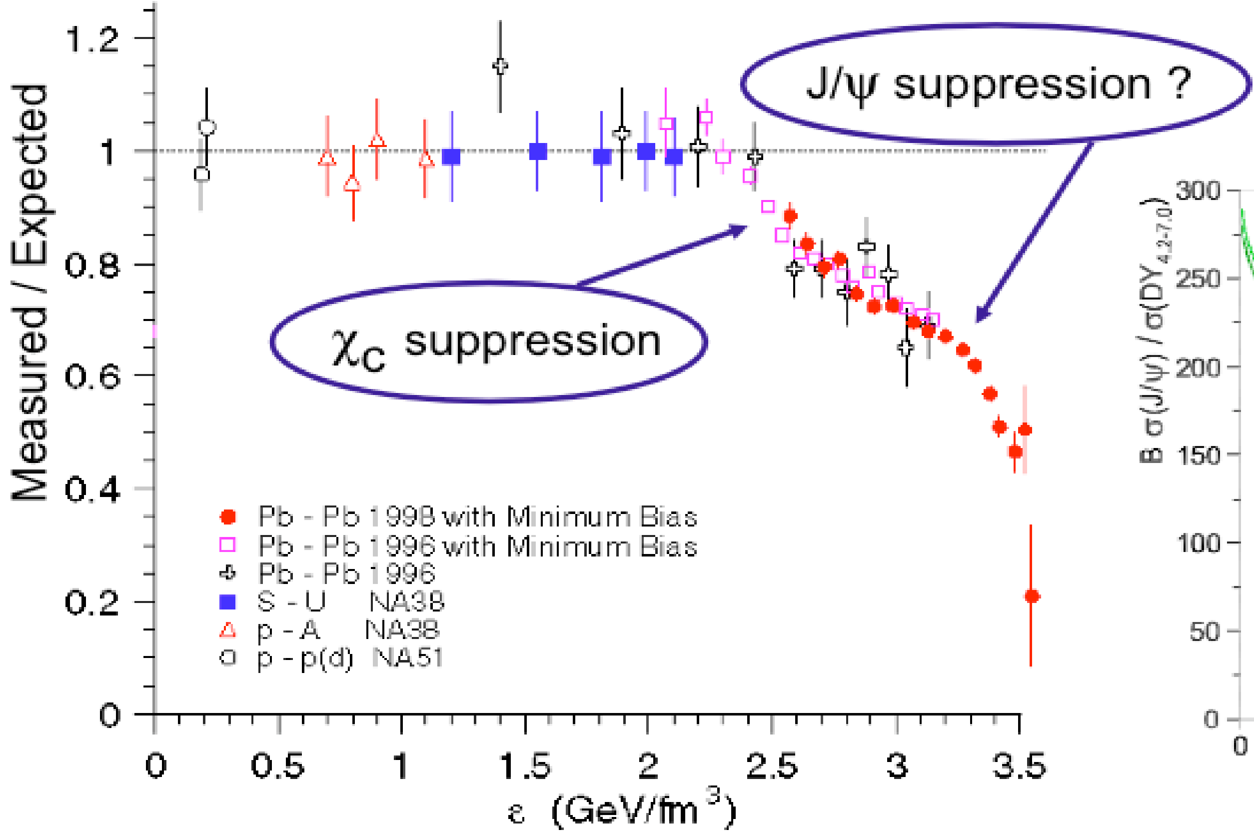
Experimental signals? CERN

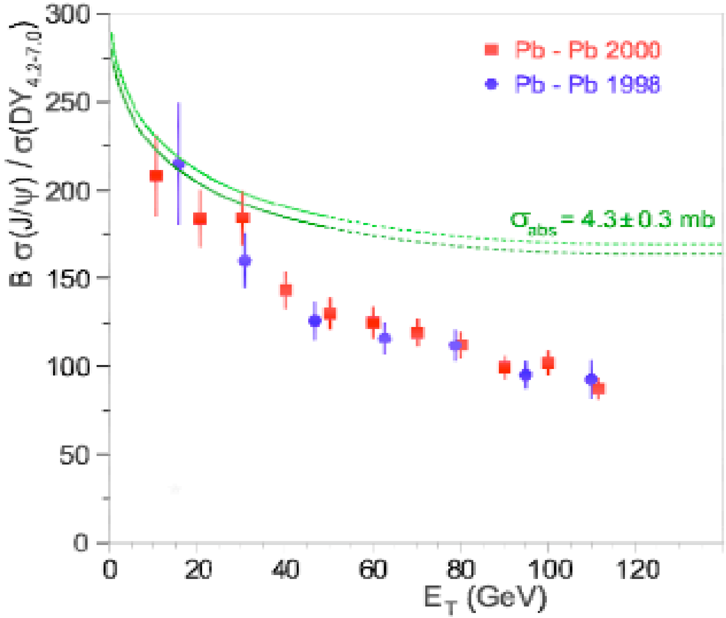
Apparently the SPS was well positioned to probe the transition region



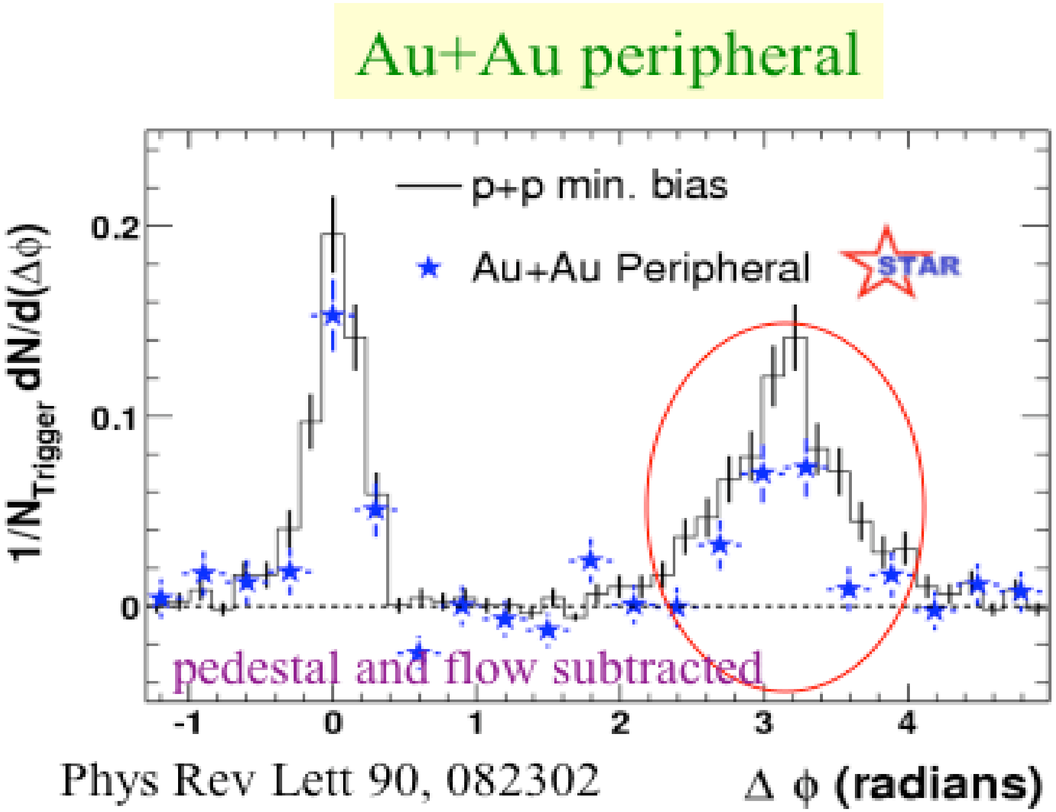
J/ψ suppression from p-A to Pb-Pb collisio

- The J/ψ production is suppressed in Pb-Pb collisions with respect to the yields extrapolated from proton-nucleus data → evidence for a deconfined QCD phase

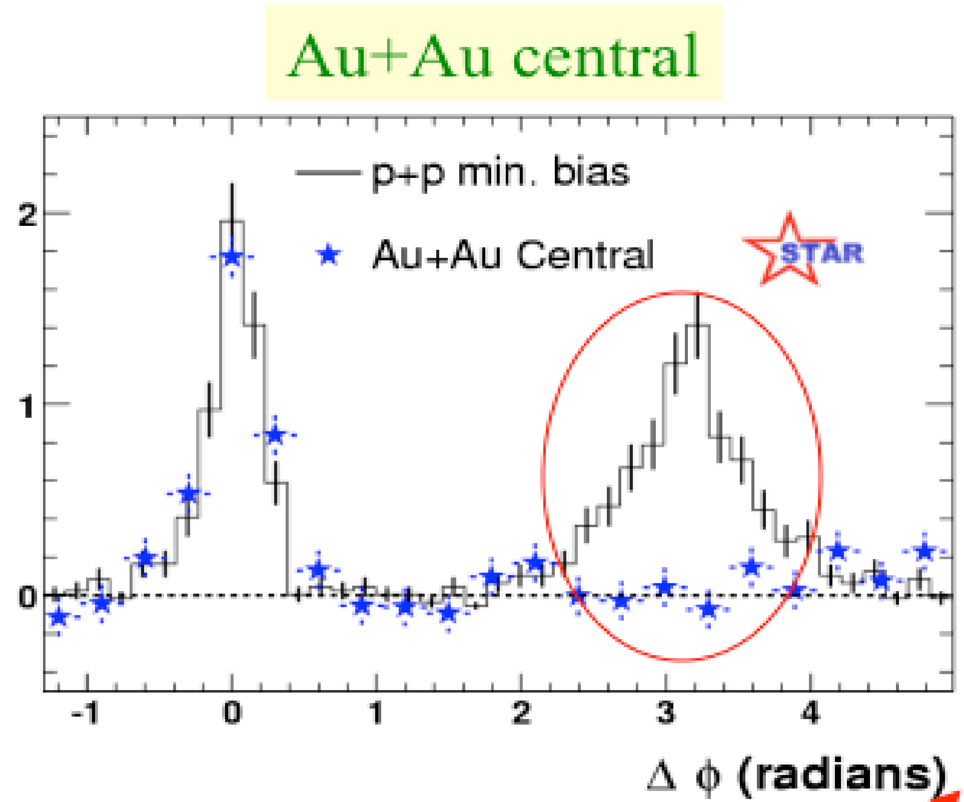




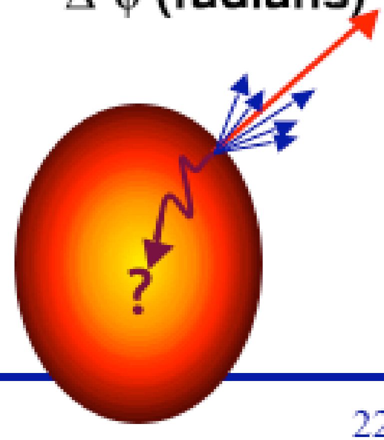
Azimuthal distributions in Au+Au



Phys Rev Lett 90, 082302



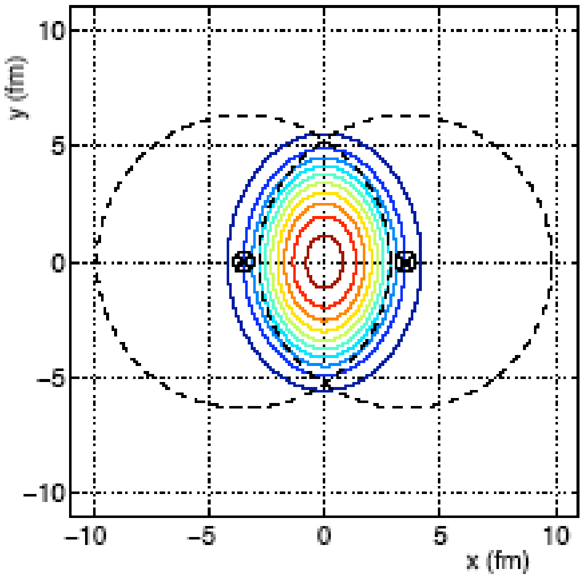
Near-side: peripheral and central Au+Au similar to p+p

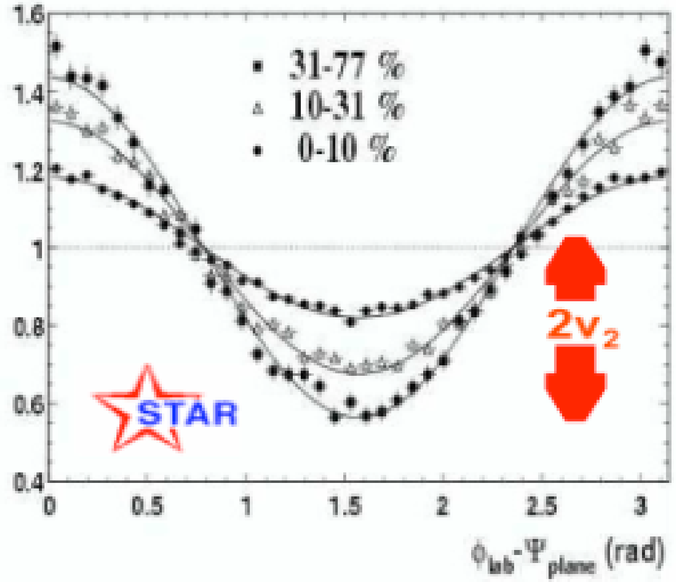


Strong suppression of back-to-back correlations in central Au+Au

Elliptic flow: a tool to study the primeval final state

Jacobs, Wang

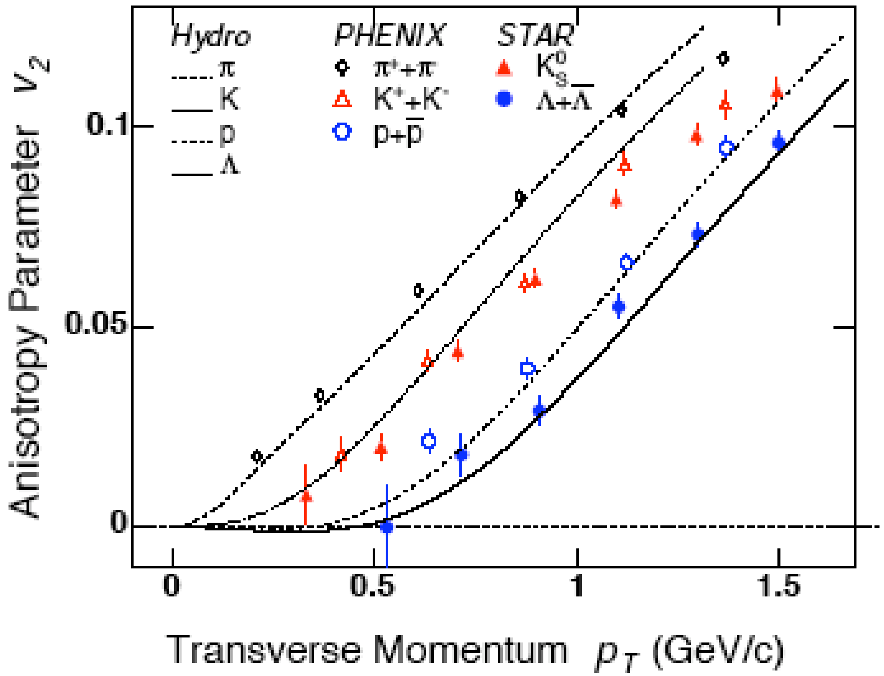




$$\frac{dN}{d\phi} \sim \left(1 + 2v_2 \cos\left[2\left(\phi - \phi_0\right)\right] + \ldots\ldots\right)$$

dominant anisotropy parameter

Hydrodynamic calculations are based on a phase made up of coloured partons (the plasma appears as a liquid with small viscosity)



AdS/CFT correspondence "predicts" $\eta/s=1/4\pi$

η/s = shear viscosity/entropy density

N=4 SUSY Yang-Mills in 4-dim is related to a string theory in $AdS_5 x S_5$ (4+1 large dimensions + 5 extra compactified 5 dim)

Maldacena '97,'99

At large T also N=4 SUSY YM has a plasma

$gN_C=\lambda$

For such gauge theories that have a plasma and are dual to string theories in higher dimensions, one has (strong coupling, large N_C):

$\eta/s=1/4\pi$

Rajagopal, ICHEP'08

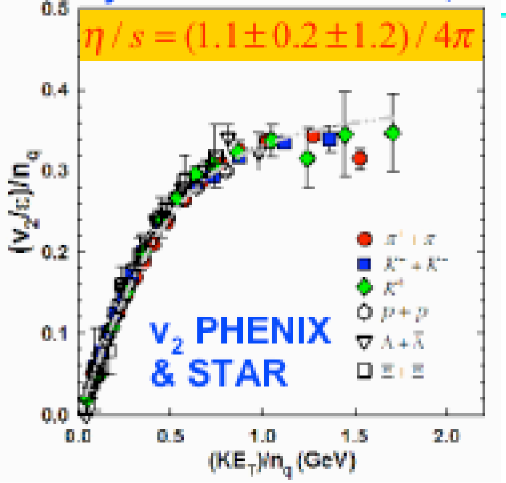
$\varepsilon/T^4=3/4(\varepsilon/T^4)_{\text{weak coupling}}$

This suggests a form of universality that could extend to also include QCD (??)

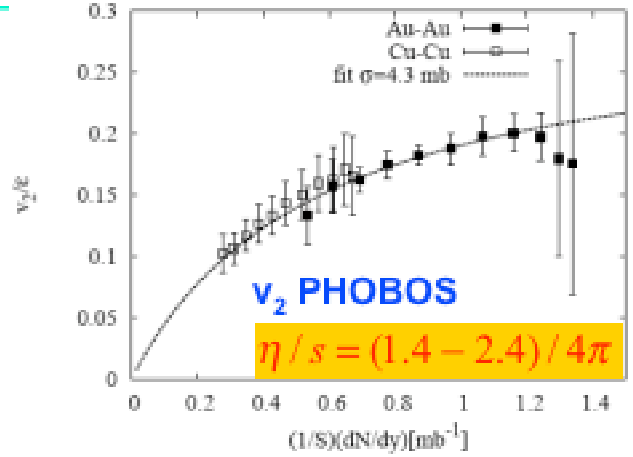
Pert. QCD: $\eta/s=1$, for water $\eta/s\sim 10$, $\eta/s>1/4\pi$ conjectured for all substance

Jacak, ICHEP'08

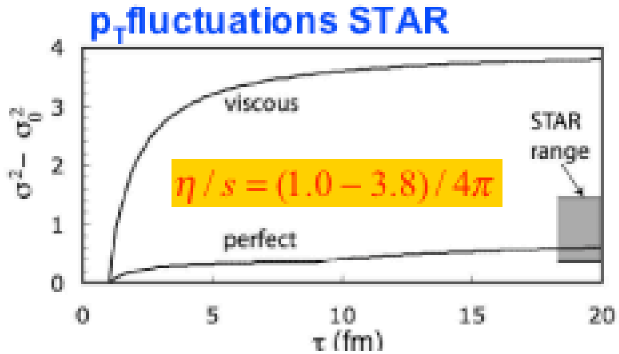
R. Lacey et al.: PRL 98:092301, 2007



H.-J. Drescher et al.: arXiv:0704.3553



S. Gavin and M. Abdel-Aziz: PRL 97:162302, 2006

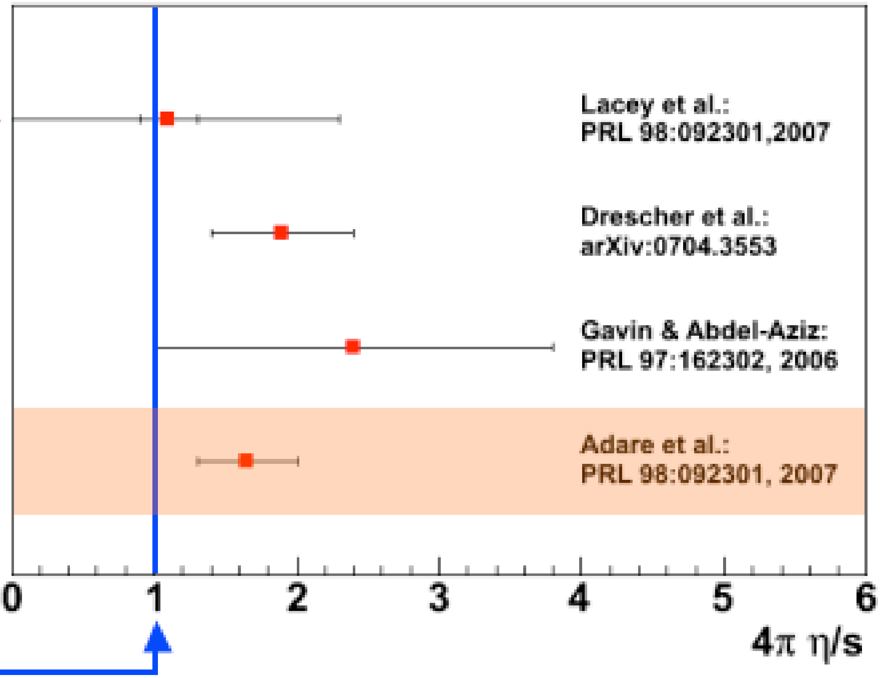


- estimates of η/s based on flow and fluctuation data

  indicate small value as well

  close to conjectured limit

  significantly below η/s of helium (4πη/s ~ 9)



conjectured quantum limit

Viscosity, elliptic flow, inclusive spectra, partonic energy loss in medium, strangeness enhancement,
J/ψ suppression

....

are all suggestive of early production of a coloured partonic medium with high energy density ($\varepsilon \sim 5$-10 GeV/fm^3) and temperature ($T \sim 170$-180 MeV) then expanding as a near ideal fluid

Viscosity, elliptic flow, inclusive spectra, partonic energy loss in medium, strangeness enhancement,
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....
are all suggestive of early production of a coloured partonic medium with high energy density ($\varepsilon \sim 5\text{-}10$ GeV/fm^3) and temperature ($T \sim 170\text{-}180$ MeV) then expanding as a near ideal fluid

but only suggestive!

Perturbative QCD: A time of very difficult computations

Since α_s is not too small, $\alpha_s(m_Z^2) \sim 0.12$, the need of high order perturbative calculations, resummation of logs at all orders .... is particularly acute

Ingenious new computational techniques and software have been developed and many calculations have been realized that only a decade ago appeared as impossible.
Some examples follow:

Splitting functions

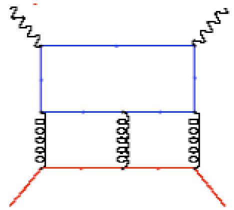
In 2004 the calculation of the NNLO splitting functions has been totally completed $\alpha_s P \sim \alpha_s P_1 + \alpha_s^2 P_2 + \alpha_s^3 P_3 + \ldots\ldots$

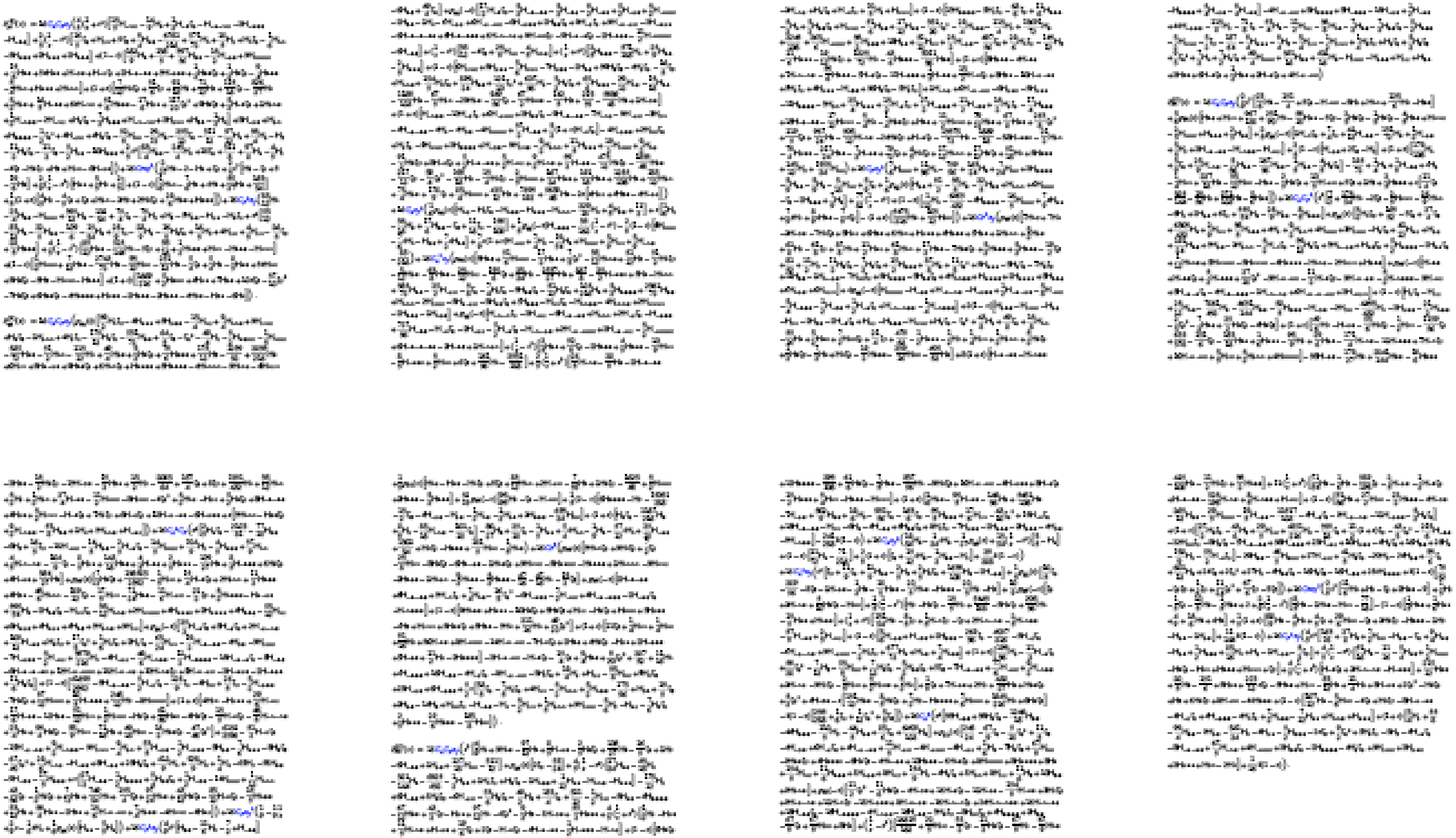
Moch, Vermaseren, Vogt '04

⊕ A really monumental, fully analytic, computation

NNLO singlet splitting functions

9607 3-loop diagrams





3rd order coeff. functions also computed Moch, Vermaseren, Vogt'05

Singlet splitting function at small x

Resum $(\alpha_s \log 1/x)^n$

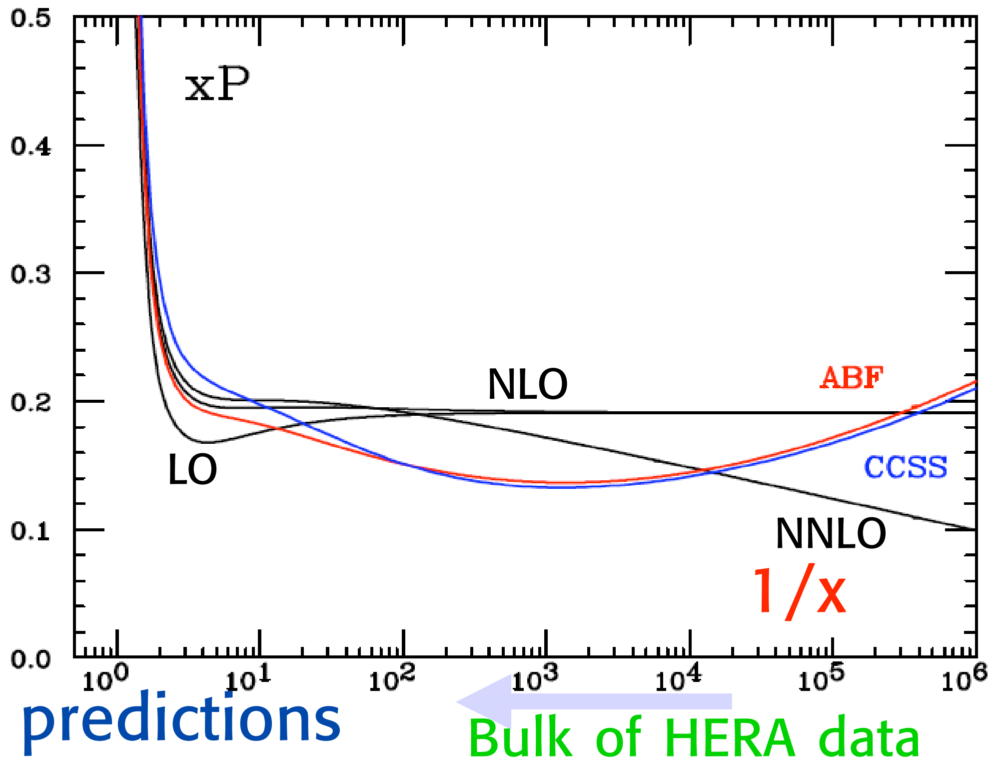
The problem of correctly including BFKL at small x has been solved

Ciafaloni, Colferai, Salam, Stasto '07 (CCSS)
Altarelli, Ball, Forte '07 (ABF)

Momentum cons.+ symmetry + running coupling effect

→ soft simple pole in anom. dim

- BFKL sharp rise tamed
- resummed result close to NLO in HERA region
- new expansion stable



Makes the ground solid for LHC predictions (eg b production)

$$x_1 x_2 s = (2m_b)^2 \Rightarrow \bar{x} = \sqrt{x_1 x_2} \sim \frac{2m_b}{\sqrt{s}} \sim 0.7 \cdot 10^{-3}$$

Inclusive hadronic Z and τ decay at $o(\alpha_s^4)$ (NNNLO!!)

Baikov, Chetyrkin, Kuhn '08

~20.000 diagrams

τ decay complete, Z decay only non singlet $\Sigma_f Q_f^2$ terms

(singlet terms $(\Sigma_f Q_f)^2$ small at $o(\alpha_s^3)$)

$$R(Q^2)=3\,\Sigma_f Q_f^2\,[1+a_s+1.4097a_s^2-12.76709a_s^3-80.0075a_s^4+\ldots]$$

$n_f=5$, $a_s=\alpha_s(Q^2)/\pi$

Can be used to improve α_s from τ and from Z

$\alpha_s(m_Z^2)=$ 0.1185---> 0.1190±0.0026

$\alpha_s(m_\tau^2)=$ 0.3455---> 0.332±0.016 or $\alpha_s(m_Z^2)=$ 0.1202±0.0019

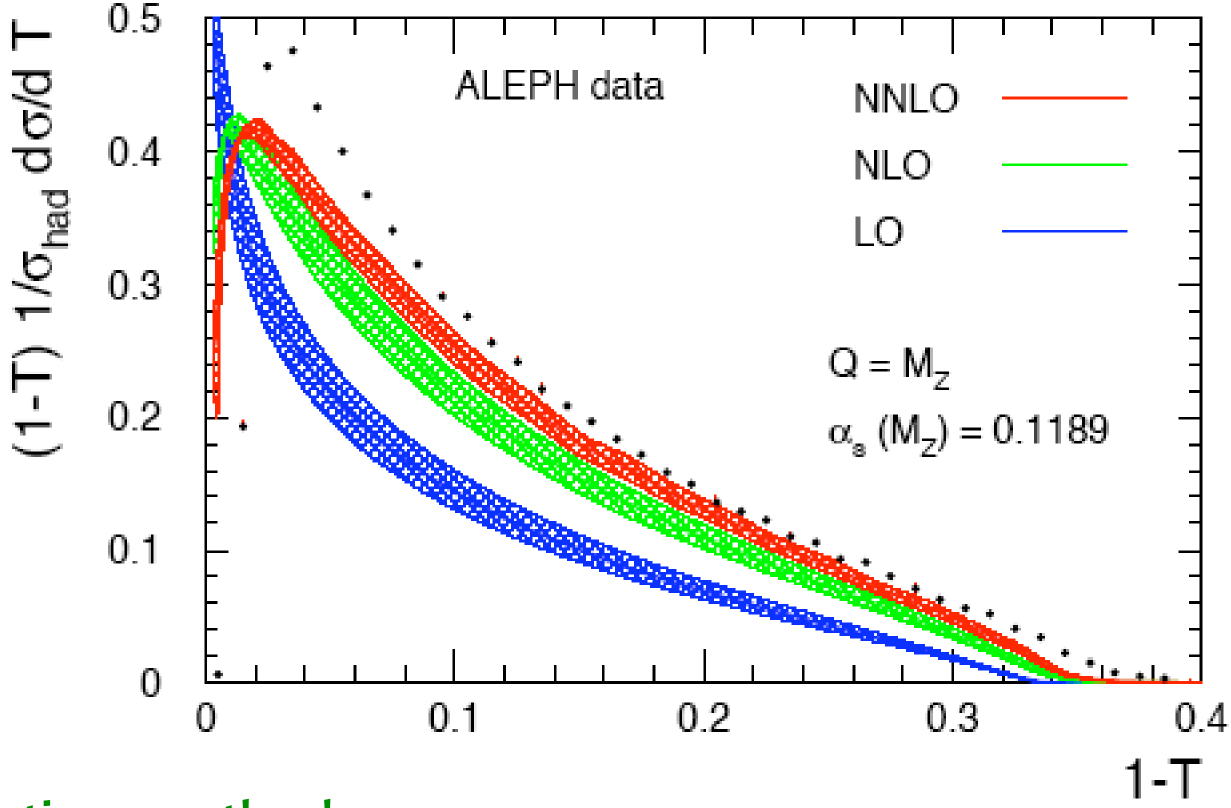
As a result, the two come closer!

Hadronic event shapes at NNLO in e^+e^- annihilation

Gehrmann-De Ridder, Gehrmann, Heinrich '07

Warning: Weinzierl '08
a bug found

LO	$\gamma^* \to q\bar{q}g$	tree level
NLO	$\gamma^* \to q\bar{q}g$	one loop
	$\gamma^* \to q\bar{q}gg$	tree level
	$\gamma^* \to q\bar{q}q\bar{q}$	tree level
NNLO	$\gamma^* \to q\bar{q}g$	two loop
	$\gamma^* \to q\bar{q}gg$	one loop
	$\gamma^* \to q\bar{q}q\bar{q}$	one loop
	$\gamma^* \to q\bar{q}q\bar{q}g$	tree level
	$\gamma^* \to q\bar{q}ggg$	tree level

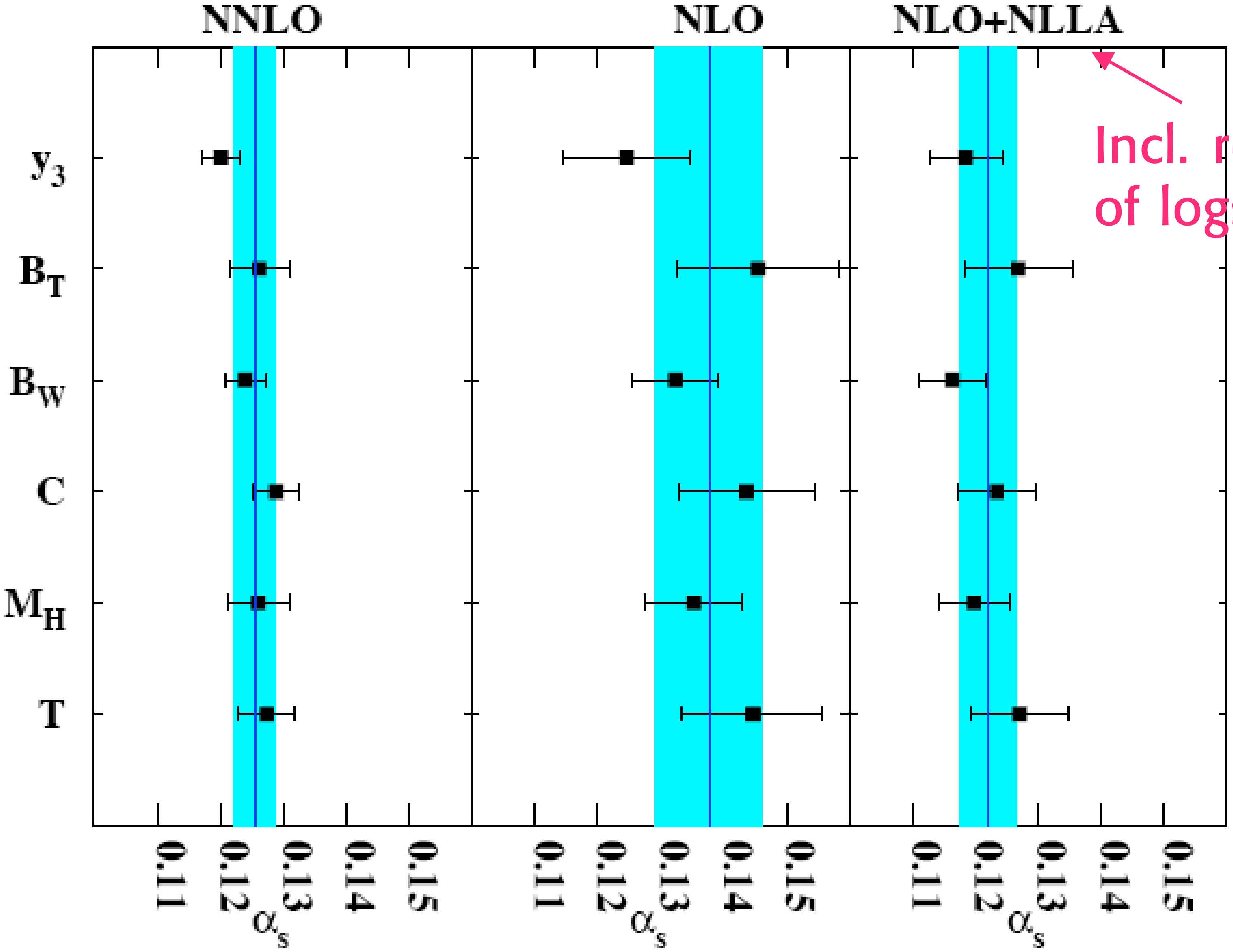


Based on the antenna subtraction method

Kosower; Campbell, Cullen, Glover

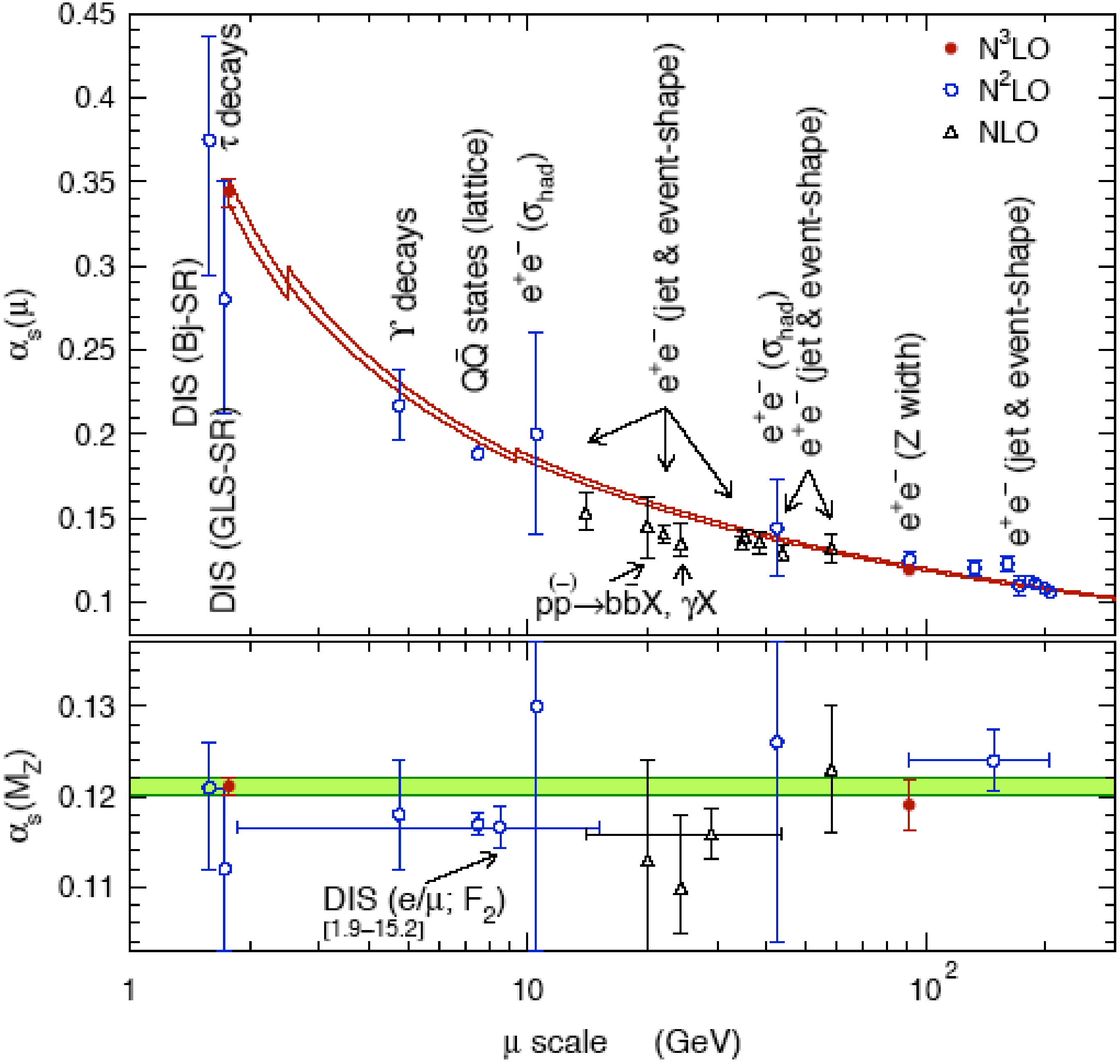
Application to α_s: $\alpha_s(m_Z^2)$= 0.1240±0.0034

Dissertori, Gehrmann-De Ridder, Gehrmann, Heinrich, Stenzel '07



Incl. resumm. of logs

Measurements of α_s offer a striking confirmation of QCD



Davier et al '08

B-->$X_s\gamma$ at NNLO: a great achievement by many theorists

A main constraint on new physics models

- Inclusive rate at NNLO almost exactly completed

Misiak et al '06

$$\mathcal{B}(\bar{B} \to X_s\gamma)_{E_\gamma > 1.6\,\mathrm{GeV}} = \mathcal{B}(\bar{B} \to X_c e\bar{\nu})^{\mathrm{exp}} \left[\frac{\Gamma(b \to s\gamma)}{\Gamma(b \to ce\bar{\nu})}\right]_{\mathrm{LO\,EW}} f\left(\frac{\alpha_s(M_W)}{\alpha_s(m_b)}\right) \times$$

$$\times \left\{1 + \underbrace{\mathcal{O}(\alpha_s)}_{\substack{\mathrm{NLO} \\ \sim 25\%}} + \underbrace{\mathcal{O}(\alpha_s^2)}_{\substack{\mathrm{NNLO} \\ \sim 7\%}} + \underbrace{\mathcal{O}(\alpha_{\mathrm{em}})}_{\sim 4\%} + \underbrace{\mathcal{O}\left(\frac{\Lambda^2}{m_b^2}\right)}_{\sim 1\%} + \underbrace{\mathcal{O}\left(\frac{\Lambda^2}{m_c^2}\right)}_{\sim 3\%} + \underbrace{\mathcal{O}\left(\frac{\alpha_s\Lambda}{m_b}\right)}_{<\sim 5\%}\right\}$$

- Effect of photon cut at NNLO evaluated

$\Gamma(E_\gamma > E_0) = \Gamma(B\text{-->}X_s\gamma)F(E_0)$ Becher, Neubert '06

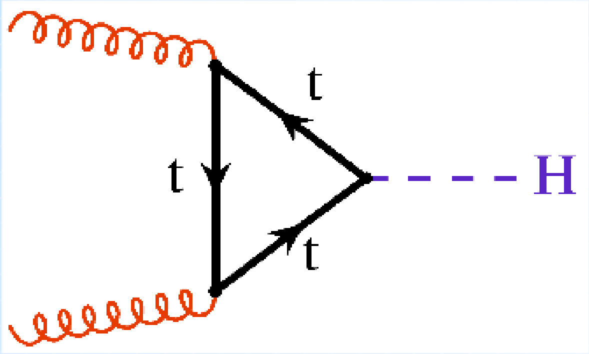
$B[B\text{-->}X_s\gamma, E_0 = 1.6\ \mathrm{GeV}](10^{-4}) = 3.15 \pm 0.23$ (pert. th)

$= 2.98 \pm 0.26$ ($F(E_0)$ non pert. OPE)

EXP: 3.55 ± 0.26 $\sim 1.5\,\sigma$

Higgs production via g+g -> H

Very important for the LHC



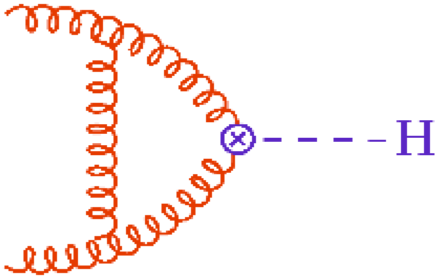
Effective lagrangian (m_t -> infinity)

$$\mathcal{L} = C_1 H G^{\mu\nu} G_{\mu\nu}$$

C_1 known to α_s^4

Chetyrkin, Kniehl, Steinhauser'97

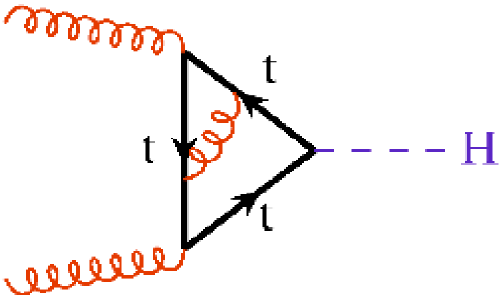
NLO corr.s computed with effective lagrangian

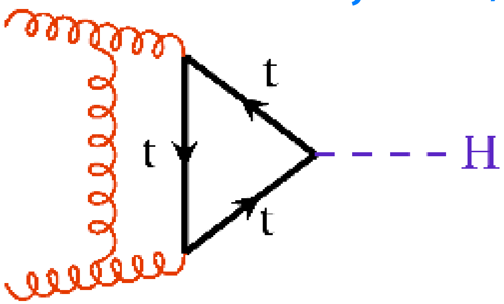


Dawson
Djouadi, Spira, Graudenz, Zerwas

AND the full theory

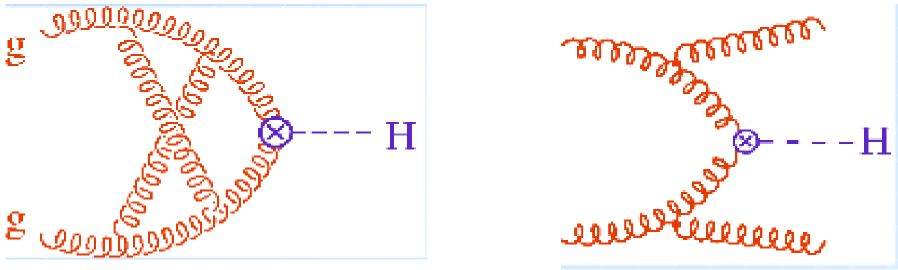
Djouadi, Spira, Graudenz, Zerwas





They agree very well

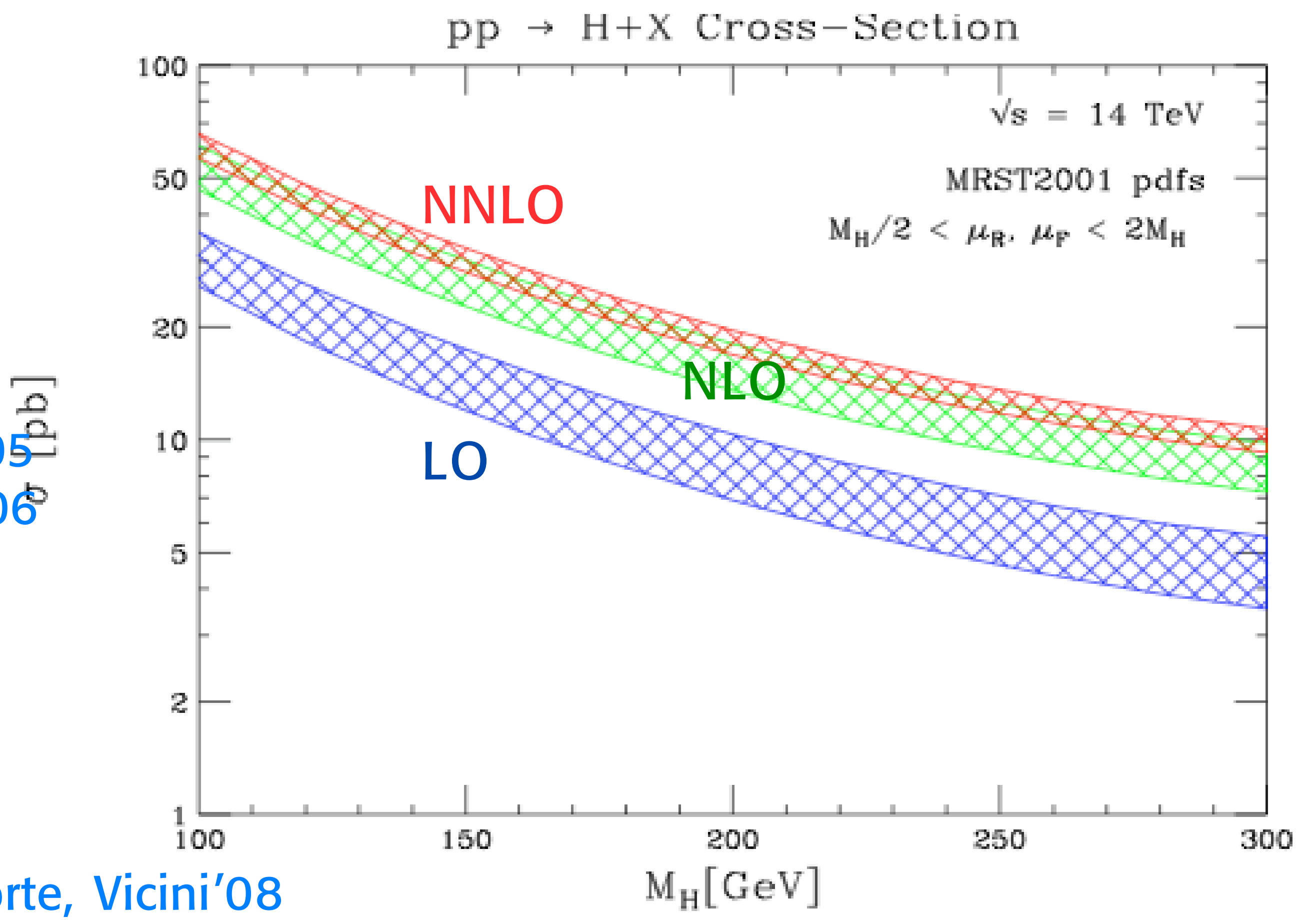
More recently the NNLO calculation was completed (analytic)



Catani, de Florian, Grazzini ’01.
Harlander, Kilgore ’01, ‘02
Anastasiou, Melnikov’02
Ravindran, Smith, van Neerven ’03

Also NLO y and p_T distributions have been computed

De Florian, Grazzini, Kunszt ‘99
Glosser, Schmidt’02
Anastasiou, Melnikov, Petriello’05
Ravindran, Smith, van Neerven’06



Recent progress:
Resummation of large partonic-energy logs

DeMarzani, Ball, Del Duca, Forte, Vicini’08

Higgs p_T distribution: $[\log(p_T/m_H)]^n$ resummed

Bozzi, Catani, De Florian, Grazzini'03-'08

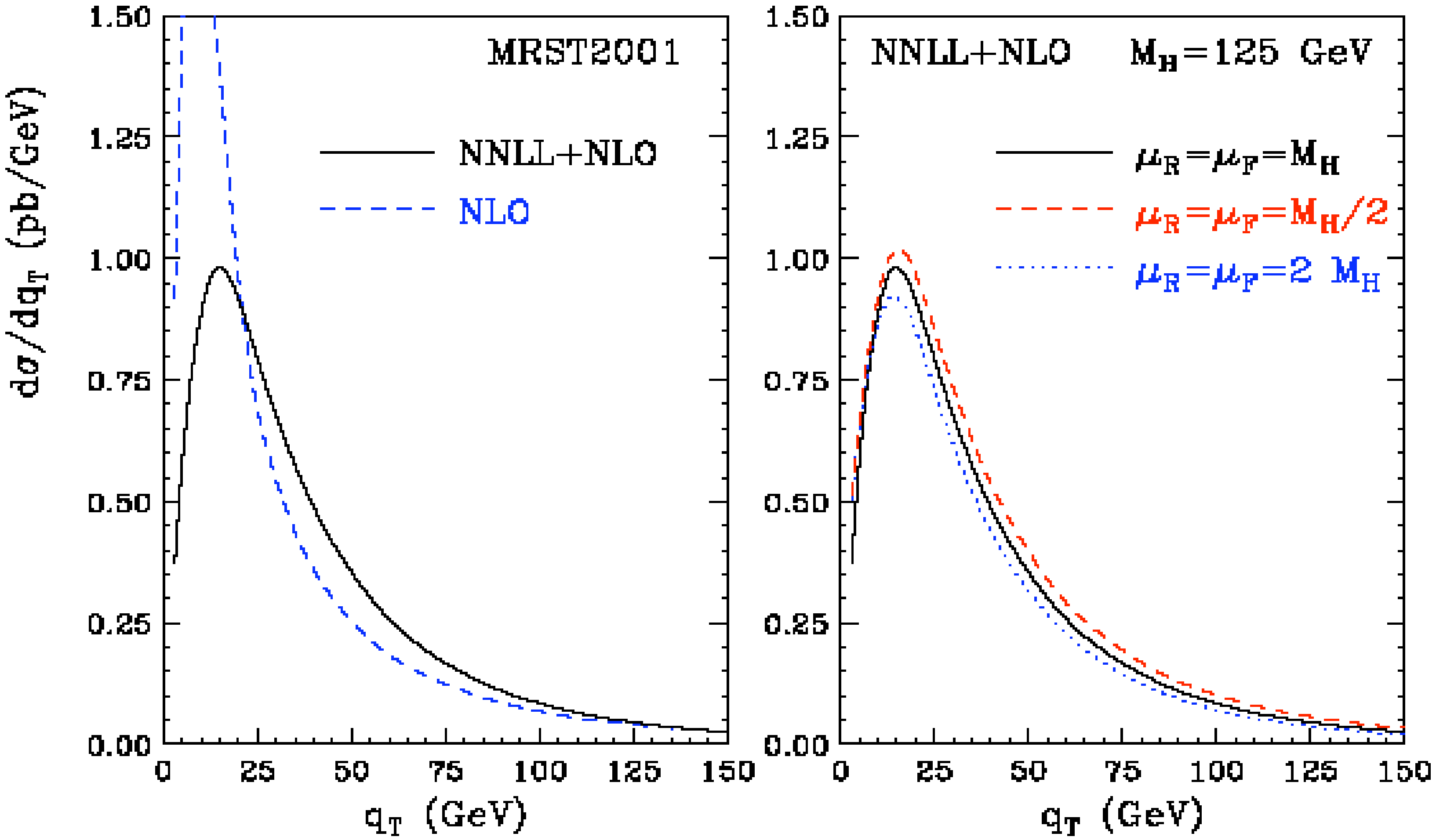
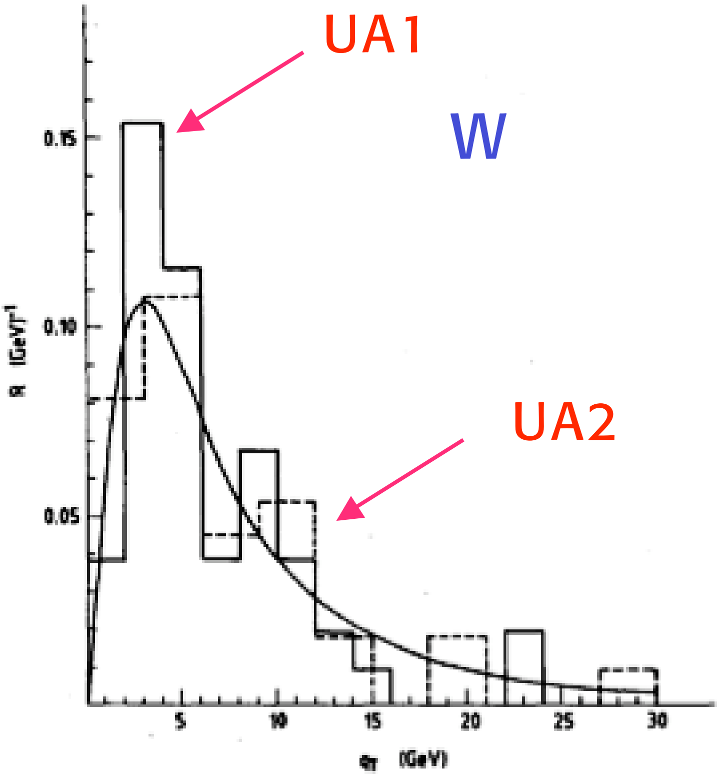


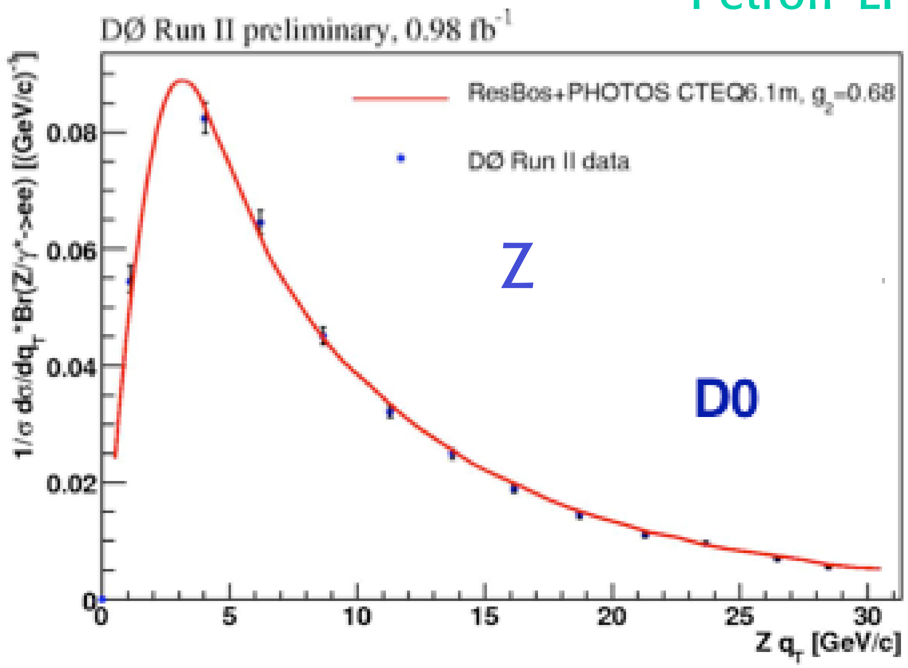
Figure 7. Resummed pQCD prediction for the Higgs transverse momentum distribution at the LHC, from Bozzi *et al.*[25]

~25 years ago I started at CERN by computing the W and Z p_T distribution in QCD



GA, K.Ellis, M. Greco, G.Martinelli '84

Petroff LP'07



In agreement with perturbative QCD augmented by Collins-Soper-Sterman (CSS) resummation at low q_T

J. Collins, D. Soper, G. Sterman, Nucl. Phys. B250 (1985) 199.

ResBos describes data well up to ~ 30 GeV

F. Landry, R. Bock, P.Nadolsky, C.P. Yuan
Phys. Rev. D 67, 073016 (2003)

NNLO describes better above 30 GeV

K. Melnikov and F. Petriello Phys. Rev. D74 114017 (2006)

Yesterday the W&Z
today the Higgs!

QCD event simulation

A big boost in the preparation to LHC experiments

General algorithms for computer NLO calculations
eg the dipole formalism — Catani, Seymour,..

Matching matrix elements and parton showers
e.g. MC@NLO — Frixione, Nason, Webber
POWHEG (both based on HERWIG) — Nason; Frixione, Nason, Oleari; Frixione, Nason, Ridolfi

Perturbative (+ resumm.s)

$$d\sigma = A\alpha_S^N [\, 1 + (c_{1,1}L + c_{1,0})\alpha_S + (c_{2,2}L^2 + c_{2,1}L + +c_{2,0})\alpha_S^2 + \ldots\,]$$

L= large log eg $L=\log(p_T/m)$

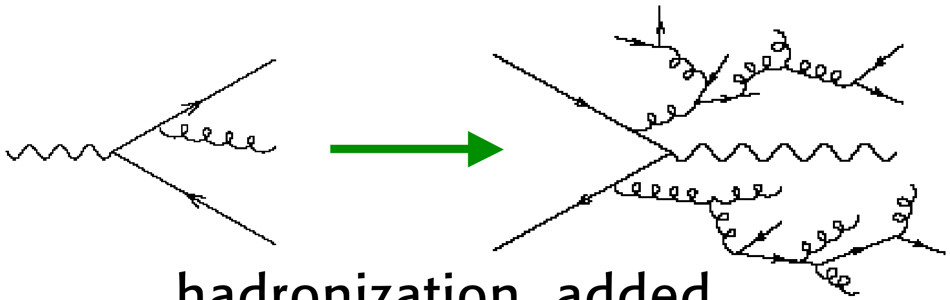
Complementary virtues:
the hard skeleton plus
the shower development
and hadronization

Parton showers

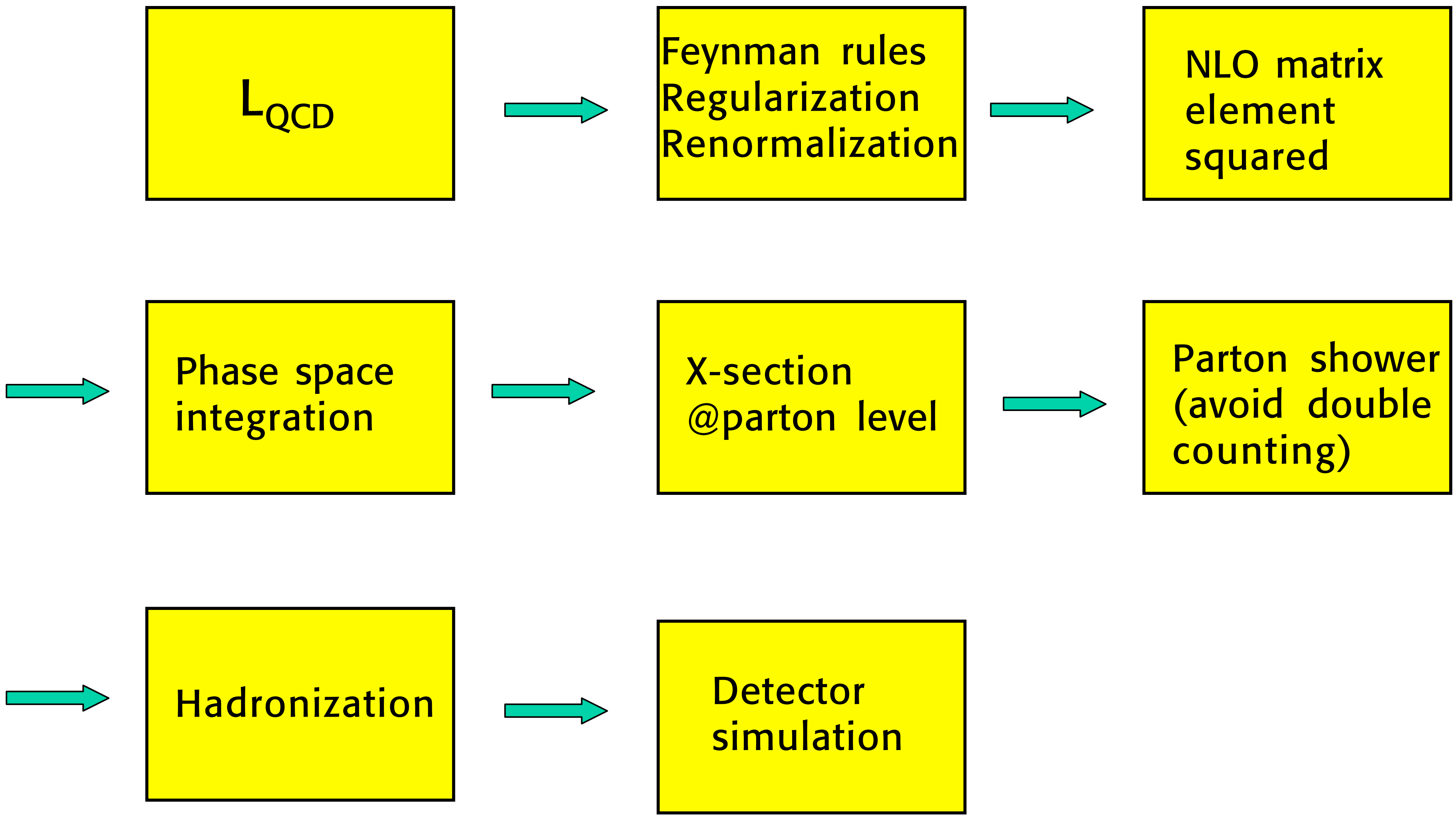
collinear emissions factorize

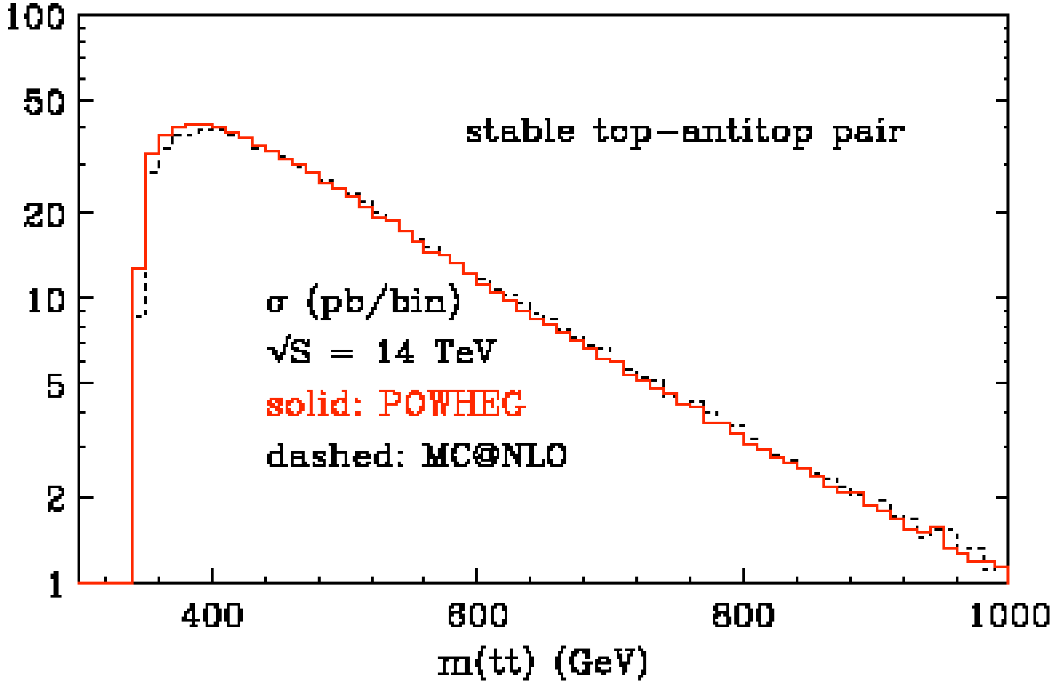
$$d\sigma_{q\bar{q}g} = d\sigma_{q\bar{q}} \times \frac{\alpha_S}{2\pi}\frac{dt}{t}P_{qq}(z)dz\frac{d\varphi}{2\pi}$$

$$t = (p_q + p_g)^2 \longrightarrow 0$$



hadronization added


L_{QCD}
Feynman rules
Regularization
Renormalization
NLO matrix element squared
Phase space integration
X-section @parton level
Parton shower (avoid double counting)
Hadronization
Detector simulation



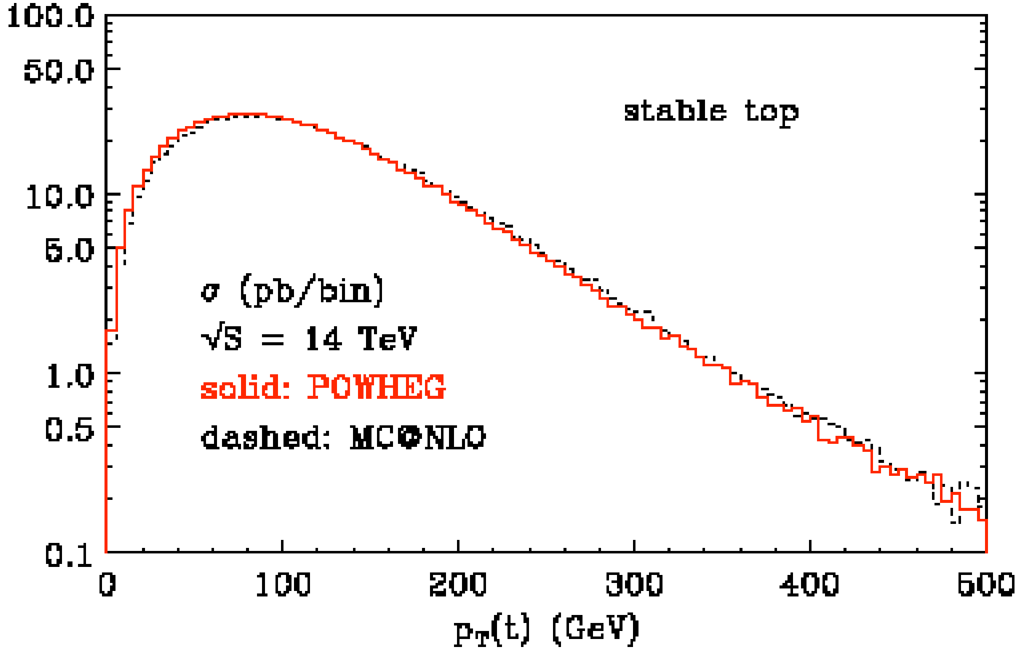
Good agreement
POWHEG vs MC@NLO

POsitive Weight Hadroproduction
Event Generator

Frixione, Nason, Ridolfi ’07

LHC applications ready:

- W, Z production
- WW, WZ, ZZ
- Higgs
- Heavy quarks
- Single top



In summary:

QCD is solid and well supported by experiment but it takes a lot of work and ingenuity to extract its predictions

Top physics

The top quark is very special: it is the only normal fermion

$m_t = 172.6 \pm 1.4$ GeV ~ v (the Higgs vev)

$h_t \sim 1$ (the top Yukawa coupling)

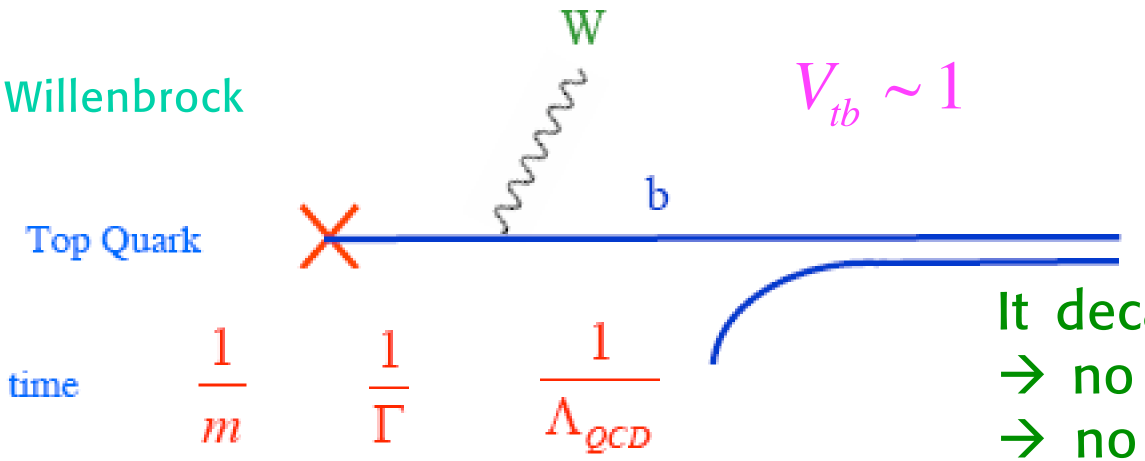
$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right]$$

$\Gamma \sim 1.3$ GeV $> \Lambda_{QCD}$ $\qquad$ $\tau \sim 0.5\ 10^{-24}$ s

$o(\alpha_s^2)$ also known

$$\Gamma_t = \Gamma_t^B (1 - 0.81\alpha_s - 1.81\alpha_s^2)$$

Chetyrkin et al '99



It decays before hadronization
→ no top hadrons,
→ no top-onium

Rare top decays are really rare (V_{tb}~1)!

Unitarity: $$|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$$

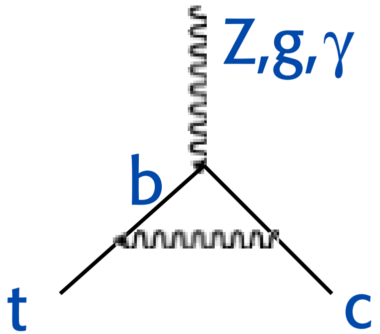
o(λ_c^6) ($A\,\lambda_c^2$)^2

unless there is a 4th generation

$$B(t \to Ws) \sim |V_{ts}|^2 \sim (4.1 \cdot 10^{-2})^2 \sim 1.7 \cdot 10^{-3}$$

$$B(t \to Wd) \sim |V_{td}|^2 \sim (8.5 \cdot 10^{-3})^2 \sim 7 \cdot 10^{-5}$$

FCNC decays: $t \to Zc \quad t \to gc \quad t \to \gamma c$



GIM suppressed $A \sim g_{Z,g,\gamma} V_{tb} V_{cb}^{*} G_F m_W^{2} \dfrac{m_b^{2}}{m_W^{2}}$

$$B(t \to Z, g, \gamma + c) \sim 5 \cdot 10^{-11} - 10^{-13}$$

Top rare decays in the SM far below the LHC sensitivity

Table 24: Branching ratios for the main SM top decay channels.

channel	$BR_{\rm SM}$	channel	$BR_{\rm SM}$
bW	1	sW	$1.6 \cdot 10^{-3}$
dW	$\sim 10^{-4}$	bWg	$0.3\ (E_g > 10$ GeV)
$bW\gamma$	$3.5 \cdot 10^{-3}\ (E_\gamma > 10$ GeV)	bWZ	$2 \cdot 10^{-6}$
cW^+W^-	$\sim 10^{-13}$	bW^+H	$< 10^{-7}$
qg	$5 \cdot 10^{-11}$	$q\gamma$	$5 \cdot 10^{-13}$
qZ	$1.3 \cdot 10^{-13}$	cH	$< 10^{-13}$

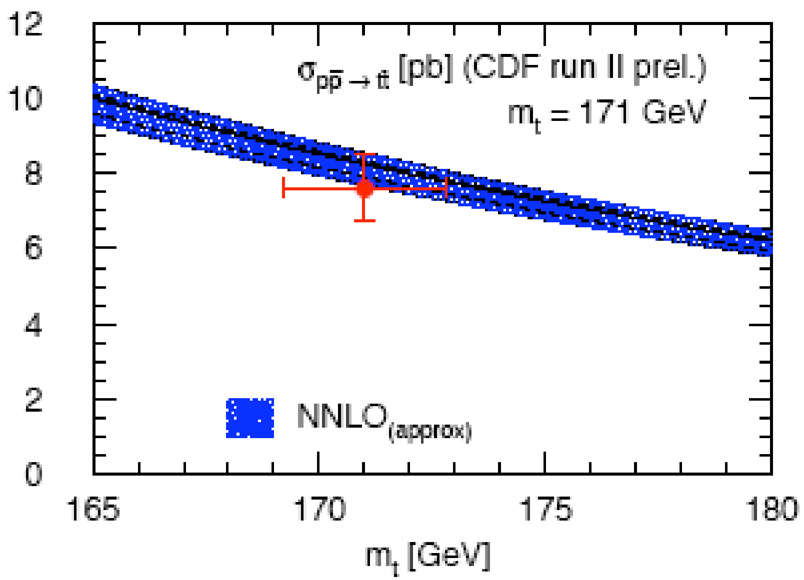
← Altarelli, Conti, Lubicz '01 (for bWZ)

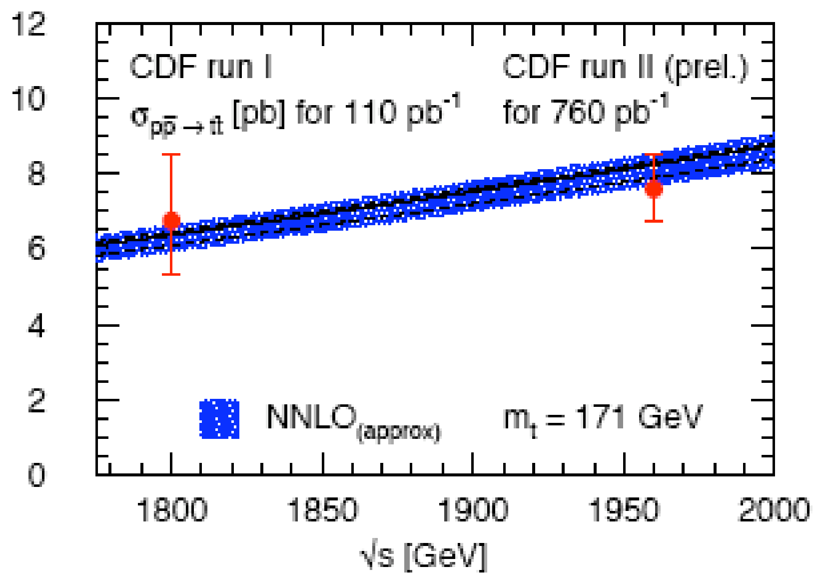
} Eilam, Hewlett, Soni '91; Mele, Petrarca, Soddu'98 (for $q\gamma$, cH)

Total top production cross-section at hadron colliders
(another QCD difficult calculation!)

$\sigma_{t\bar{t}}$

- NLO complete Nason, Dawson, Ellis '88; W. Beenakker et al '89
- Partial results at NNLO Moch, Uwer '08
- Threshold resummation of soft gluons at NNLO
  Kidonakis, Sterman '97; Cacciari et al '08, Kidonakis, R. Vogt '08



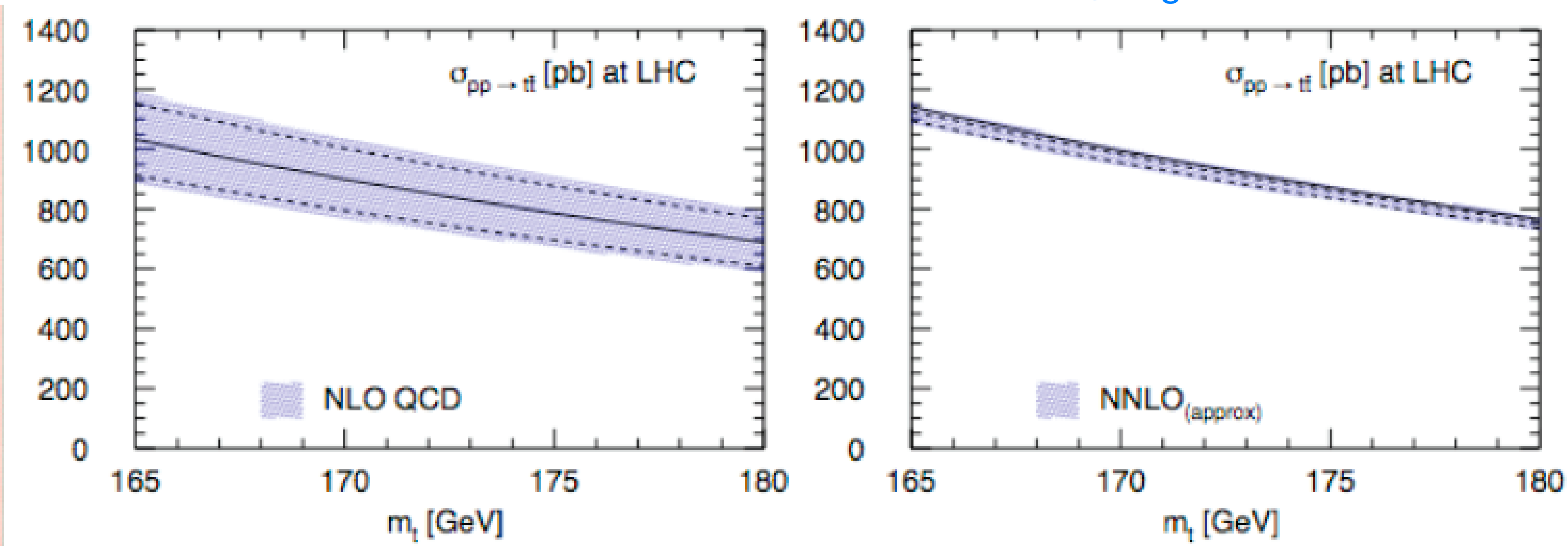


Moch,Uwer, arXiv:0804.1476

The future: complete NNLO

$\sigma_{t\bar{t}}$ at the LHC

Moch, Vogt '08



CTEQ6.5 $\sigma = 908\ ^{+82(9.0\%)}_{-85(9.3\%)}\ \text{(scales)}\ ^{+30(3.3\%)}_{-29(3.2\%)}\ \text{(PDFs) pb}$

Mangano'08

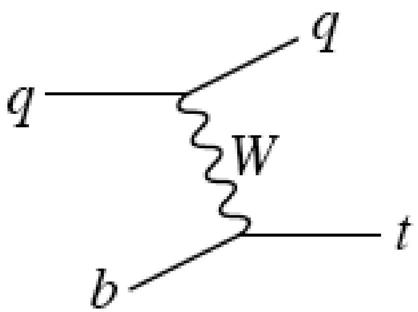
MRSTW-06 $\sigma = 961\ ^{+89(9.2\%)}_{-91(9.4\%)}\ \text{(scales)}\ ^{+11(1.1\%)}_{-12(1.2\%)}\ \text{(PDFs) pb}$

MRST−CTEQ = 53 ± 33 pb

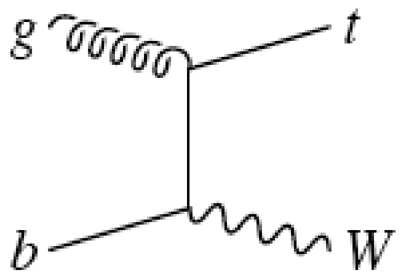
pdf uncert's underestimated?

Single top production

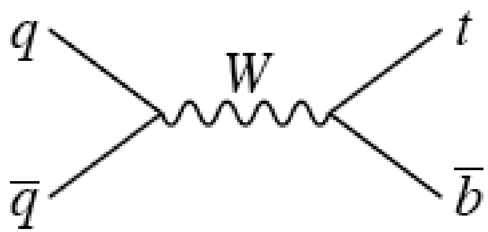
Smith, Willenbrock; Bordes, van Eijk; Stelzer et al; Harris et al; Sullivan; Mrenna, Yuan; Campbell et al; Cao, Yuan; Kidonakis



t-channel



Wt mode



s-channel

b-quark in the initial state

Wackeroth

Predictions for σ_t (with $m_t = 171.4$ GeV, MRST2004nnlo, and scale, PDF, δm_t uncertainties):

NLO + soft resummation

σ_t(NLO+NNNLO th.corr. at NLL)[pb]	Tevatron	LHC
t-channel	1.15 ± 0.07	150 ± 6
s-channel	0.54 ± 0.04	7.8 ± 0.7
tW mode	0.13 ± 0.03	44 ± 5
$t\bar{t}$ (KV,NNLO approx.,172 GeV)	7.8 ± 0.4	$968 + 80 - 52$

Kidonakis, PRD74 (2006), PRD75 (2007)

Complete 1-loop EW corr'ns also known

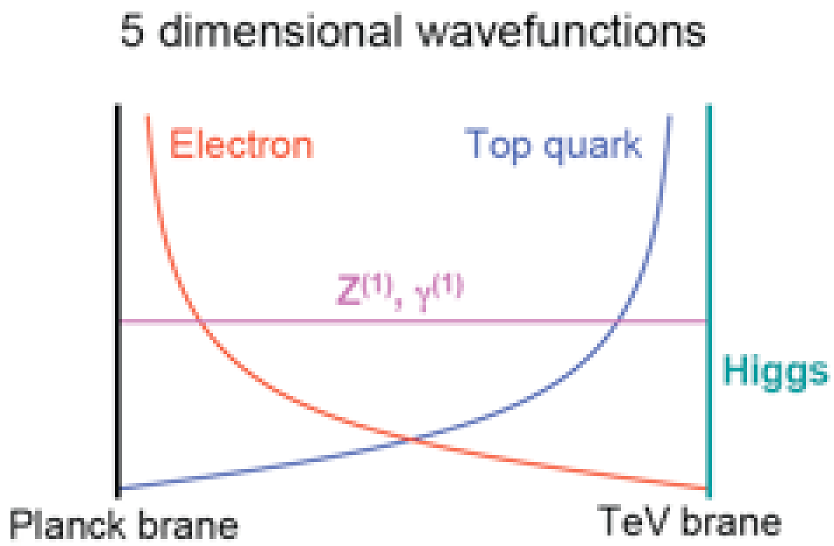
Beccaria et al

More interesting

Due to its large mass the top is strongly coupled to the Higgs:

→ possible relation with EW symmetry breaking

- In an extra dim model make the top close to the TeV brane where the Higgs is located far from the Planck brane



- Try to replace the Higgs with a top condensate

Bardeen, Hill, Lindner '90

$$L \sim \frac{1}{M^2}(\bar{t}_L t_R)(\bar{t}_L t_R) \longrightarrow \langle \bar{t}_L t_R \rangle \sim \Lambda_t^{\,3} \longrightarrow m_t \sim m_W \sim \frac{\Lambda_t^{\,3}}{M^2}$$

Too drastic. Evolved into top color, tumbling top condensate...

S.P. Martin '92

Hill '91

Higgs compositeness: a modern approach

A low energy theory from truncation of some UV completion

Contino,Kramer, Son, Sundrum'06
Giudice, Grojean, Pomarol, Rattazzi'07
[see also BESS: Casalbuoni at al, '87]

$L=L_{elem}+L_{comp}+L_{mixing}$

$$\mathcal{L}_{elementary} = -\frac{1}{4}F_{\mu\nu}^2 + \bar{\psi}_L i \not{D} \psi_L + \bar{\tilde{\psi}}_R i \not{D} \tilde{\psi}_R$$

SM minus the Higgs sector

$$\mathcal{L}_{composite} = -\frac{1}{4}\rho_{\mu\nu}^2 + \frac{M_*^2}{2}\rho_\mu^2 + |D_\mu H|^2 - V(H) + \bar{\chi}(i\not{D} - m)\chi + \bar{\tilde{\chi}}(i\not{D} - \tilde{m})\tilde{\chi} - \bar{\chi}\left(Y_{*u}\tilde{H}\tilde{\chi}^u + Y_{*d}H\tilde{\chi}^d\right) + \text{h.c.}$$

H are pseudo Goldstone bosons of larger broken gauge group, eg $SU(3)xSU(2)_L\ xSU(2)_R xU(1)$
(ρ_μ corresponding massive vector bosons)

$$\mathcal{L}_{mixing} = -M_*^2\,\frac{g_{el}}{g_*}A_\mu\rho_\mu^* + \frac{M_*^2}{2}\left(\frac{g_{el}}{g_*}A_\mu\right)^2 + (\bar{\psi}_L\Delta\chi_R + \bar{\tilde{\psi}}_R\tilde{\Delta}\tilde{\chi}_L + \text{h.c.})$$

$g_{el} \ll g^*$
$M_* \sim$ TeV

		$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_X$
ρ_μ		Gauge Fields			
$(\tilde{H}, H)$		$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	0
χ	Q	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{1}$	$\frac{1}{6} \cdot \sqrt{\frac{3}{2}}$
	L	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$(-\frac{1}{2}) \cdot \sqrt{\frac{3}{2}}$
$\tilde{\chi}$	$\tilde{U}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\frac{2}{3} \cdot \sqrt{\frac{3}{2}}$
	$\tilde{D}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$(-\frac{1}{3}) \cdot \sqrt{\frac{3}{2}}$
	$\tilde{N}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0
	$\tilde{E}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$(-1) \cdot \sqrt{\frac{3}{2}}$

The vector boson mass terms make a total gien by:

$$\frac{M_*^2}{2}\left(\rho_\mu - \frac{g_{el}}{g_*}A_\mu\right)^2$$

The SM gauge bosons (orthogonal combinations)

$$\frac{g_*}{\sqrt{g_{el}^2+g_*^2}}A_\mu + \frac{g_{el}}{\sqrt{g_{el}^2+g_*^2}}\rho_\mu^*$$

remain massless before EW symmetry breaking.

The SM couplings are $$g = \frac{g_{el}\, g_*}{\sqrt{g_{el}^2+g_*^2}} \simeq g_{el}$$

Mixing generates mass eigenstates:

light: $|SM_n\rangle = \cos\varphi_n|\text{elementary}_n\rangle + \sin\varphi_n|\text{composite}_n\rangle$

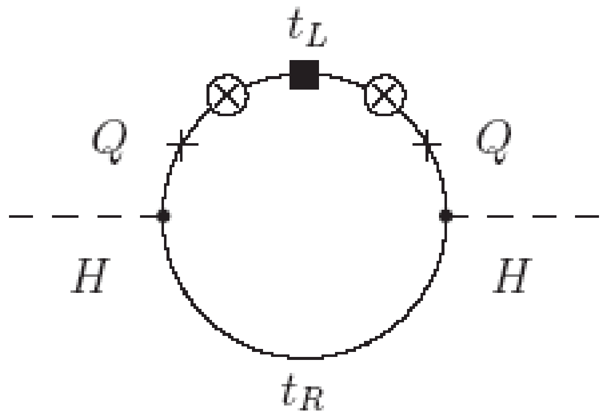
heavy: $|\text{heavy}_n\rangle = -\sin\varphi_n|\text{elementary}_n\rangle + \cos\varphi_n|\text{composite}_n\rangle$

But the Higgs is totally composite: $\sin\theta_H=0$
Possibly also t_R could be totally composite
(t_L which sits in a doublet with b_L cannot be composite)

New physics in the composite sector is well hidden because light particles have small mixing angles

The hierarchy problem: the Higgs is light because only acquires mass thru interactions with the elementary sector from their composite components

$$\delta m^2_{h|mixing} \propto M_*^2 \times \text{mixing angles}$$



The top loop occurs with the mediation of the composites, so that the diagram has no quadratic divergence

A pragmatic effective description that can be applied to diverse underlying theories