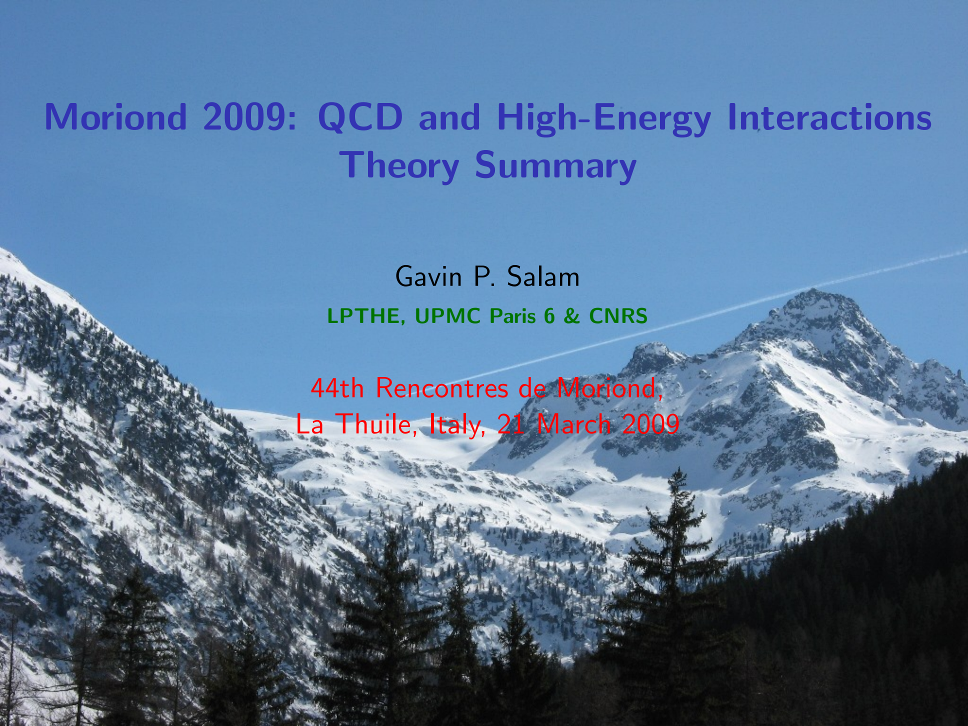
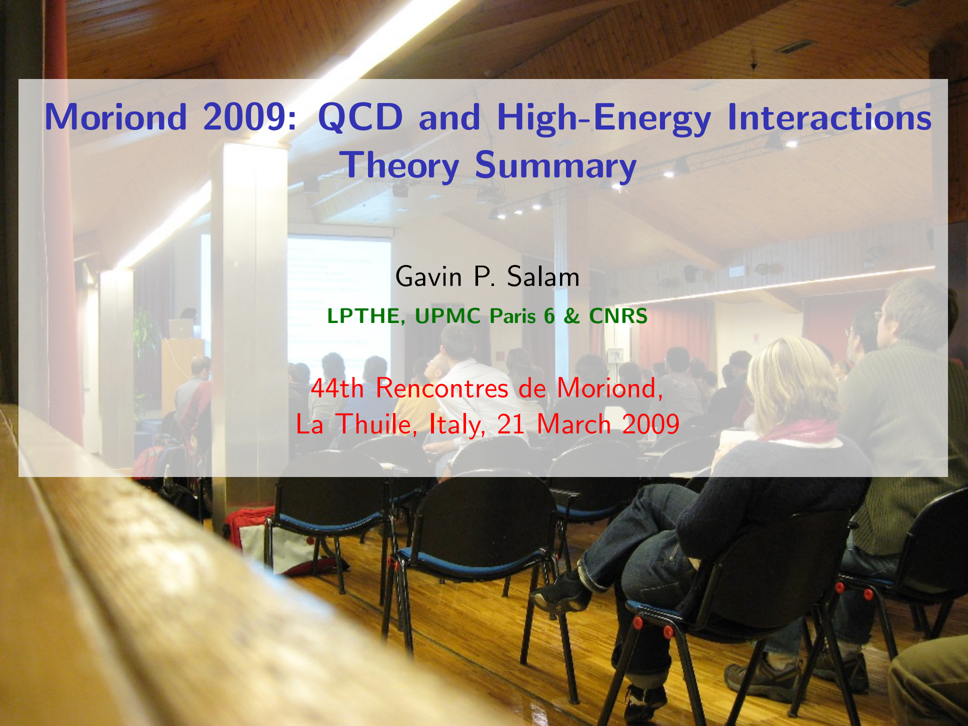
Moriond 2009: QCD and High-Energy Interactions
Theory Summary

Gavin P. Salam

LPTHE, UPMC Paris 6 & CNRS

44th Rencontres de Moriond,
La Thuile, Italy, 21 March 2009





Moriond 2009: QCD and High-Energy Interactions
Theory Summary

Gavin P. Salam

LPTHE, UPMC Paris 6 & CNRS

44th Rencontres de Moriond,
La Thuile, Italy, 21 March 2009

Statistics:

- 102 talks planned
- 32 theory talks planned (10 in morning, 22 in afternoon)
- 30 theory talks given

Statistics:

- 102 talks planned
- 32 theory talks planned (10 in morning, 22 in afternoon)
- 30 theory talks given

From schedule: **at 95% confidence level we can rule out** the hypothesis that theorists were equally likely to be assigned morning or afternoon slots.

Because organisers believe theorists sleep later?

The topics were varied

Non-Perturbative QCD & Lattice

Perturbative Methods in QCD

Data – Theory Interface

Beyond the Standard Model

Heavy-Ion Physics

To help put together this talk I've taken a few liberties:

I've chopped, merged, or even recoloured some slides

If your plot/slide looks a little bizarre. . .

To help put together this talk I've taken a few liberties:

I've chopped, merged, or even recoloured some slides

If your plot/slide looks a little bizarre. . .

[And if I've completely misunderstood your talk,
let me know before I do the proceedings!]

Non (or barely) perturbative QCD

Because it's what we're made of

Because it's relevant to extracting CKM & new-physics constraints from weak hadronic decays.

Because it's far from fully explored.

Most powerful tool is **lattice QCD**

2× mass spectrum (BMW, PACS-CS)
2× decays (MILC, RBC/UKQCD)
1× heavy-ions (HotQCD)
1× BSM (Brower)
+ present in many exptl. talks

Major issues:

- **control of all systematics**
- **handling of light quarks (u,d)**

Systematics in lattice calculations

Van de Water

- Lattice calculations typically quote the following sources of error:
  - (1) Monte carlo statistics & fitting
  - (2) Tuning lattice spacing, a, and quark masses
  - (3) Matching lattice gauge theory to continuum QCD
    - (Sometimes split up into relativistic errors, discretization errors, perturbation theory, ...)
  - (4) Chiral extrapolation to physical up, down quark masses
  - (5) Extrapolation to continuum
    - (Often combined with chiral extrapolation)
- In order to verify understanding and control of systematic uncertainties in lattice calculations, **COMPARE RESULTS FOR KNOWN QUANTITIES WITH EXPERIMENT**
- Two such examples are the pion decay constant and the $D \to K \ell \nu$ form factor . . .

Systematics in lattice calculations

- Lattice calculations typically quote the following sources of error:

  (1) Monte carlo statistics & fitting

  (2) Tuning lattice spacing, a, and quark masses

  (3) Matching lattice gauge theory to continuum QCD

  - (Sometimes split up into relativistic errors, discretization errors, perturbation theory, ...)

  (4) Chiral extrapolation to physical up, down quark masses

Van de Water

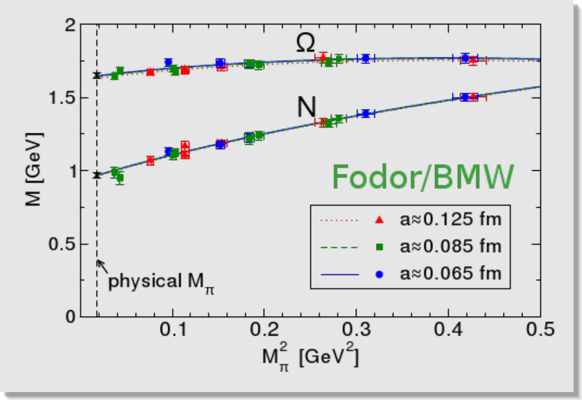
Also, issue of different kinds of light-quarks:

- Staggered — theoretically questioned (but works where testable)
- Wilson — theoretically OK, harder computationally
- Domain-wall — cleanest chiral limit, hardest computationally

[NB: need light quarks to get sensible m_π]

N(939) mass [Wilson fermions]

Issue of systematics

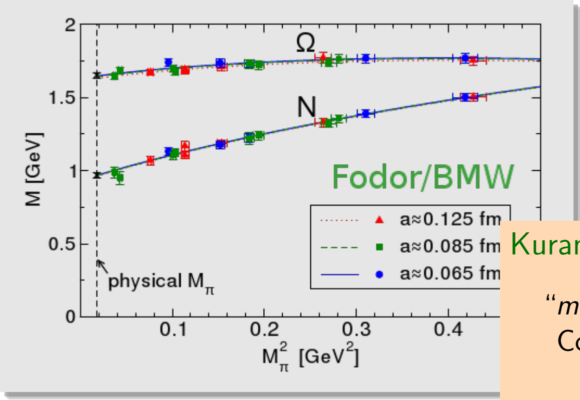


Need to control

- $M_\pi \longrightarrow$ true value
- lattice spacing $a \longrightarrow 0$

N(939) mass [Wilson fermions]

Issue of systematics



Need to control

- $M_\pi \to$ true value
- lattice spacing $a \to 0$

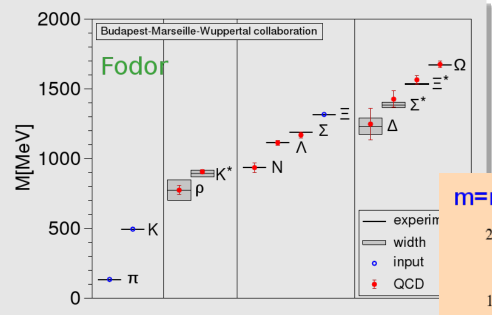
Kuramashi/PACS-CS:

"$m_{ud} = 0$ is a singular point; Convergence radius is m_{ud} ($m_\pi^2 < 0.036$ GeV^2)"

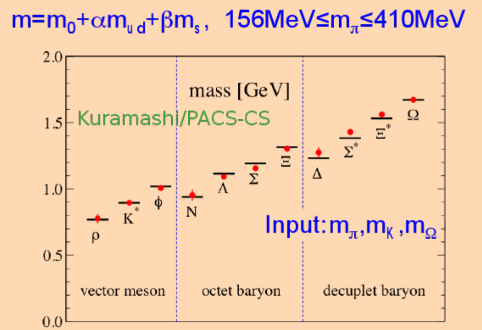
Believe results once you have multiple lattice spacings below this. $\to$ **need more CPU time**

N(939) mass [Wilson fermions]

Results



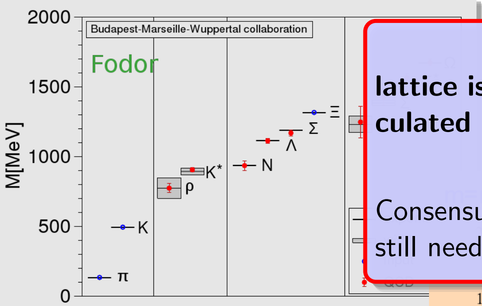
[stated **complete**]



[stated **not yet complete**]

N(939) mass [Wilson fermions]

Results

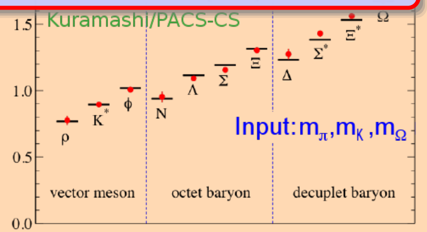


[stated **complete**]

After 35 years' work,
lattice is clearly close to having calculated proton mass!

$\sim$ 95% of our mass!

Consensus on control of all systematics still needs a few months more?



[stated **not yet complete**]

The other few % (m_u, m_d)?

Calculating things we don't know

$N_F = 2$ EM Spectrum

- QED+QCD calculation is carried out for $N_F = 2$ DWF.
- Using $m^2_{\pi^\pm}, m^2_{K^\pm}, m^2_{K^0}$ value from experiment, quark masses are estimated.
- Nonperturbatively determined Z factor $1/Z_m = Z_S = 0.62(4)$

Izubuchi / RBC-UKQCD

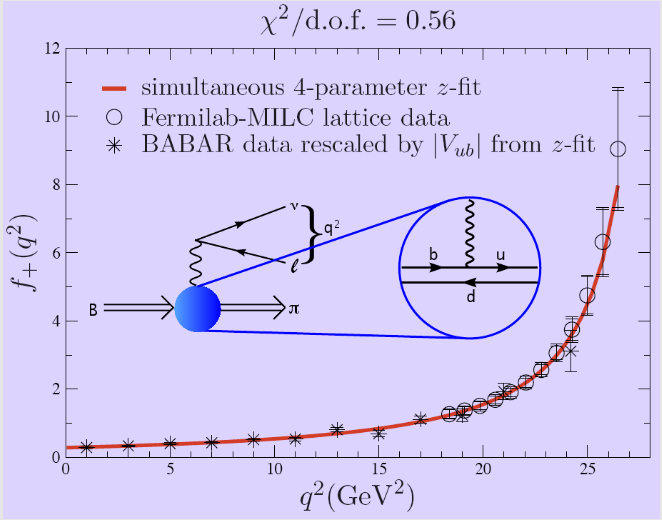
$$
\begin{aligned}
m_u^{\overline{MS}}(2\,GeV) &= 3.02(27)(19) \text{ MeV},\\
m_d^{\overline{MS}}(2\,GeV) &= 5.49(20)(34) \text{ MeV},\\
m_{ud}^{\overline{MS}}(2\,GeV) &= 4.25(23)(26) \text{ MeV},\\
m_s^{\overline{MS}}(2GeV) &= 119.5(56)(74) \text{ MeV},\\
m_u/m_d &= 0.550(31),\\
m_s/m_{ud} &= 28.10(38).
\end{aligned}
$$

Uses domain-wall fermions (more "expensive"):
$n_f = 2 + 1$ results in progress.

V_{ub} from $B \to \pi \ell \nu$ & lattice [staggered]

Comparison with other determinations

Moriond QCD 2009 Van de Water



-8%

6%

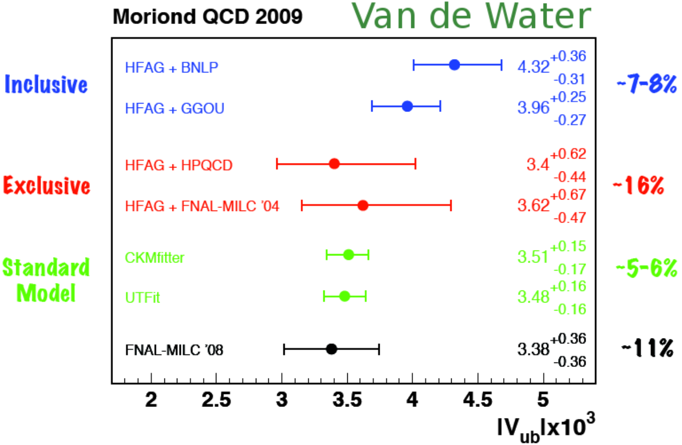
-6%

1%

inations

V_{ub} from $B \to \pi \ell \nu$ & lattice [staggered]

Comparison with other determinations

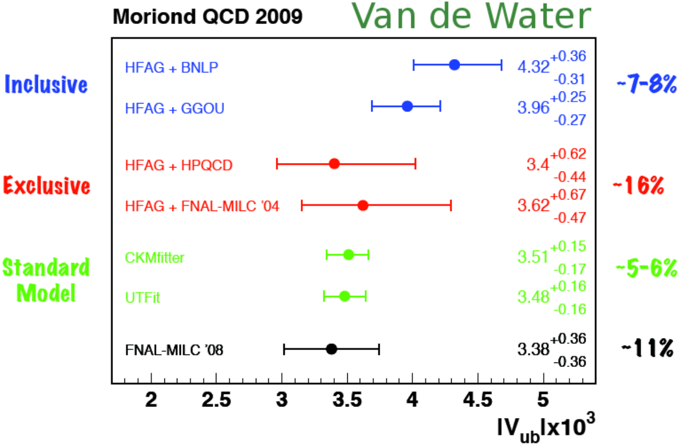


- New exclusive $|V_{ub}|$ approximately **1-2 - σ lower than inclusive determinations**
- Consistent with preferred values from unitarity triangle analyses

V_{ub} from $B \to \pi \ell \nu$ & lattice [staggered]

Comparison with other determinations

Van de Water



- New ex
- Consist

- ▶ Lattice agrees better with SM than inclusive methods
- ▶ And good description of q^2 shape is powerful cross-check

counters "questionnability" of staggered fermions

η_b : new $b\bar{b}$ state just above Υ (HFS)

- QCD NLL approximation: Penin

$$E^{\rm th}_{\rm hfs} = 39 \pm 11\,({\rm th})\,^{+9}_{-8}\,(\delta\alpha_s)\ {\rm MeV}$$

- HPQCD and UKQCD collaborations (NRQCD)

Phys.Rev. D72, 094507 (2005)

$$E^{\rm lat}_{\rm hfs} = 61 \pm 14\ {\rm MeV} \qquad -\frac{21}{4}\frac{\alpha_s}{\pi}\ln(am_b)E_{\rm hfs} \approx -20\ {\rm MeV}$$

- TWQCD collaboration (QCD)

Phys.Lett. B651, 171 (2007)

$$E^{\rm lat}_{\rm hfs} = 70 \pm 10\ {\rm MeV} \qquad m_b = 4.65(5)\ {\rm GeV}$$

is suspicious,

- Experiment:

$$E^{\rm exp}_{\rm hfs} = 71.4 \pm 2.7\,({\rm syst})\,^{+2.3}_{-3.1}\,({\rm stat})\ {\rm MeV}$$

η_b : new $b\bar{b}$ state just above Υ (HFS)

- QCD NLL approximation: Penin

$$E^{\text{th}}_{\text{hfs}} = 39 \pm 11\,(\text{th})\,^{+9}_{-8}\,(\delta\alpha_s)\ \text{MeV}$$

- HPQCD and UKQCD collaborations (NRQCD)

Phys.Rev. D72, 094507 (2005)

$$E^{\text{lat}}_{\text{hfs}} = 61 \pm 14\ \text{MeV} \qquad -\frac{21}{4}\frac{\alpha_s}{\pi}\ln(am_b)E_{\text{hfs}} \approx -20\ \text{MeV}$$

- TWQCD collaboration (QCD)

Phys.Lett. B651, 171 (2007)

$$E^{\text{lat}}_{\text{hfs}} = 70 \pm 10\ \text{Me}$$ $m_b = 4.65(5)$ GeV

- Experiment:

$$E^{\text{exp}}_{\text{hfs}} = 71.4 \pm 2.7$$

Challenging mix of large and small scales

- "Obvious" conclusion: NLL wrong?
- But not so obviously the case
- η_c works fine. Luck or physics?

Exotics: much left to understand

expt | ref | params | modes | signal | comments

interest \ robustness	★	★★	★★★	★★★★
★★★★	$Y(4350)$?	$Z_1(4051)$ tetraquark hadrocharmonium artefact	$Z(4430)$ tetraquark D^*D_1 molecule threshold effect artefact	$X(3872)$ DD^* molecule threshold effect tetraquark
★★★	$X(4160)$?	$Y(4260)$ hybrid (ccg) threshold effect	$Y(4660)$ radial hybrid (ccg) 5S vector $f_0\ \psi'$ molecule	Swanson
★★	$Y(4140)$ tetraquark artefact	$Y(3940)$ χ'_{cJ}	$X(3940)$ χ'_{cJ}	
★	$Y(4008)$?	$Z(3940)$ χ'_{c2} sets scale for 2P states (inverted?)	h_c tests long range spin dynamics	η'_c tests $O(1/m^2)$ dynamics

Perturbative QCD predictions

Because pQCD happens at HERA, Tevatron & LHC

Because backgrounds and signals for new physics often involve pQCD component

And because field theory has yet to yield all its secrets

NLO calculations

Traditional methods:

Vector-Boson Fusion

$t\bar{t}$ + jet

New Methods:

W + 3 jets

W + 3 jets

NLO: wishes & difficulties

- Missing many needed NLO computations — Campbell

An experimenter's wishlist

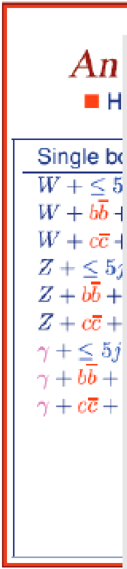
- Hadron collider cross-sections one would like to know at NLO

Run II Monte Carlo Workshop, April 2001

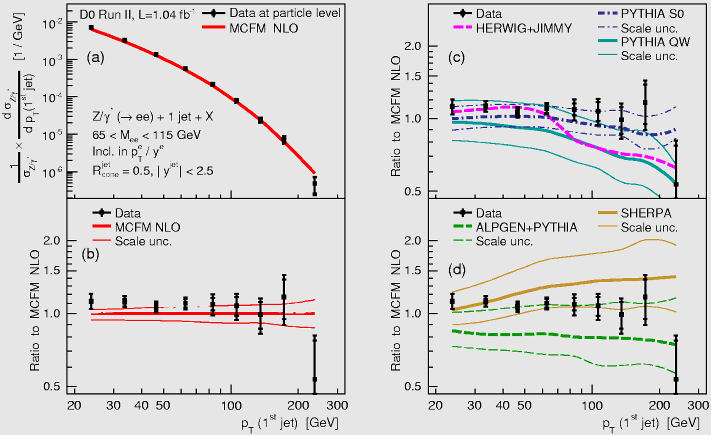
Single boson	Diboson	Triboson	Heavy flavour
$W + \leq 5j$	$WW + \leq 5j$	$WWW + \leq 3j$	$t\bar{t} + \leq 3j$
$W + b\bar{b} + \leq 3j$	$WW + b\bar{b} + \leq 3j$	$WWW + b\bar{b} + \leq 3j$	$t\bar{t} + \gamma + \leq 2j$
$W + c\bar{c} + \leq 3j$	$WW + c\bar{c} + \leq 3j$	$WWW + \gamma\gamma + \leq 3j$	$t\bar{t}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

NLO: wishes & difficulties

- Missing many needed NLO computations   Campbell



Z + jet (p_t of jet)   Nilsen



Only NLO gets normalisation & shape reliably correct

NLO: wishes & difficulties

- Missing many needed NLO computations — Campbell

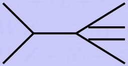
An experimenter's wishlist

- Hadron collider cross-sections one would like to know at NLO

Run II Monte Carlo Workshop, April 2001

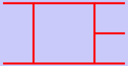
Single boson	Diboson	Triboson	Heavy flavour
$W+\leq 5j$	$WW+\leq 5j$	$WWW+\leq 3j$	$t\bar{t}+\leq 3j$
$W+b\bar{b}+\leq 3j$	$WW+b\bar{b}+\leq 3j$	$WWW+b\bar{b}+\leq 3j$	$t\bar{t}+\gamma+\leq 2j$
$W+c\bar{c}+\leq 3j$	$WW+c\bar{c}+\leq 3j$	$WWW+\gamma\gamma+\leq 3j$	$t\bar{t}+W+\leq 2j$
$Z+\leq 5j$	$ZZ+\leq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

2 -> 3 @ NLO ~



2 -> 4 @ Tree

+



2 -> 3 @ 1−loop

Bottleneck

+

Tricks to cancel divergences

(dipole subtraction)

NLO: wishes & difficulties

- Missing many needed NLO computations Campbell

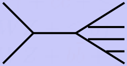
An experimenter's wishlist

- Hadron collider cross-sections one would like to know at NLO

Run II Monte Carlo Workshop, April 2001

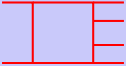
Single boson	Diboson	Triboson	Heavy flavour
$W+\leq 5j$	$WW+\leq 5j$	$WWW+\leq 3j$	$t\bar{t}+\leq 3j$
$W+b\bar{b}+\leq 3j$	$WW+b\bar{b}+\leq 3j$	$WWW+b\bar{b}+\leq 3j$	$t\bar{t}+\gamma+\leq 2j$
$W+c\bar{c}+\leq 3j$	$WW+c\bar{c}+\leq 3j$	$WWW+\gamma\gamma+\leq 3j$	$t\bar{t}+W+\leq 2j$
$Z+\leq 5j$	$ZZ+\leq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

2 -> 4 @ NLO ~



2 -> 5 @ Tree

+



2 -> 4 @ 1−loop

+ **Tricks to cancel divergences**

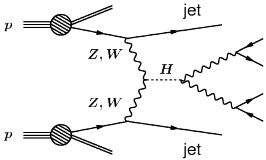
(dipole subtraction)

Impossible so far!

Vector-boson fusion @ NLO

summary

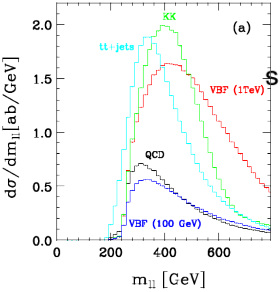
Jaeger



✦ explicit calculations revealed that VBF reactions are perturbatively well-behaved

(moderate NLO QCD and EW corrections, negligible higher order and interference effects)

✦ backgrounds are well under control



signatures of new physics in the gauge boson sector should be observable at the LHC

↓

VBF crucial for understanding mechanism of electroweak symmetry breaking

$t\bar{t}$ + jet @ NLO

One of the last $2 \rightarrow 3$ "Les Houches" processes

Weinzierl

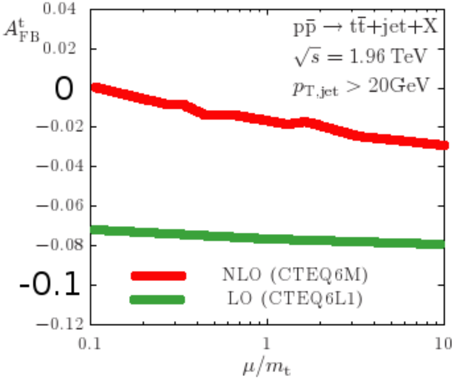
Significant complexity:

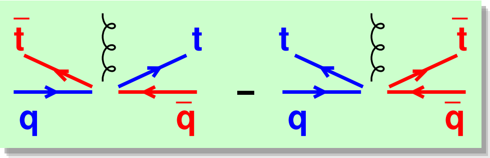
- 450 loop diagrams
- Mass scale m_t

$t\bar{t}$ + jet @ NLO

One of the last 2 → 3 "Les Houches" processes

Weinzierl





Significant complexity:

- 450 loop diagrams
- Mass scale m_t

Forwards-backwards asymmetry (non-zero only with jets)

- Strongly diluted by NLO
- Calls for *physical explanation*

New methods

Traditional methods grow **factorially** in complexity with increasing number of legs.

(e.g. $2 \to 3 \equiv$ 5-legs had 450 loop diags).

New methods do away with Feynman diagrams.
Instead use hidden secrets of field theory for **loops**
(initiated by Bern, Dixon & Kosower, over 15 years ago)

BlackHat $\leftrightarrow$ **Maitre**

Rocket $\leftrightarrow$ **Melnikov**

Loop ingredients

Melnikov

- Important steps include
  - The idea introduced by Bern,Dixon,Kosower
  - Cuts w.r.t. loop momentum give (box) coefficients directly (Cachazo, Britto, Feng)
  - Ossola-Pittau-Papadopoulos (OPP) tensor integral reduction technique
  - The OPP procedure meshes well with unitarity (Ellis, Kunszt, Giele)
  - D-dimensional unitarity (Giele, Kunszt, K.M.)

Loop ingredients

- Important steps include **Melnikov**
  - The idea introduced by Bern,Dixon,Kosower
  - Cuts w.r.t. loop momentum give (box) coefficients directly (Cachazo, Britto, Feng)
  - Ossola-Pittau-Papadopoulos (OPP) tensor integral reduction technique
  - The OPP procedure meshes well with unitarity (Ellis, Kunszt, Giele)
  - D-dimensional unitarity (Giele, Kunszt, K.M.)

Basic idea: instead of doing loop integrals,

Sew together tree-amplitudes at (specially-chosen) fixed internal momenta

Loop ingredients

Blackhat/Maitre

- Uses new progress in the use of unitarity techniques, spinor formalism, complex momenta [Ossola,Papadopoulos,Pittau;Forde;Badger]
  - Cut containing part: 4 Dim, using Forde's method
  - Rational part: 1- loop recursion (reuse of lower point results) [Berger,Bern,Dixon,Forde,Kosower]
- Advantages of unitarity vs Feynman diagrams
  - Work with simpler on-shell objects → numerically more stable
  - Unitarity method scales better with increasing number external legs

Power of the methods

Melnikov

- Currently, Rocket can compute the following one-loop amplitudes
  - N-gluon scattering amplitudes
  - two quark (massless and massive)+ N-gluon scattering amplitudes
  - W boson + two quarks + N-gluons
  - W boson + four quarks + 1 gluon
  - tt+Ngluons, ttqq+N gluons (Schulze)

Power of the methods

- Currently, Rocket can compute the following one-loop amplitudes

Melnikov

  - N-gluon scattering amplitudes
  - two quark (massless and massive)+ N-gluon scattering amplitudes
  - W boson + two quarks + N-gluons
  - W boson + four quarks + 1 gluon
  - tt+Ngluons, ttqq+N gluons (Schulze)

Note appearance of **"*N* gluons"**

This changes the nature of the (1-loop) game

Note also: extra quarks are harder. . .

What seems realistic with these methods?

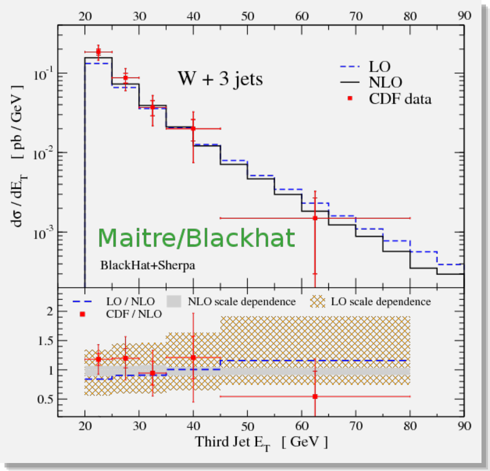
- $2 \rightarrow 4$ and $2 \rightarrow 5$ processes — Any more seems too slow?
- In large-N_c limit for now
- One bottleneck is combination with real radiation
  Blackhat $\leftrightarrow$ Sherpa, Rocket $\leftrightarrow$ MCFM

What have they achieved so far?

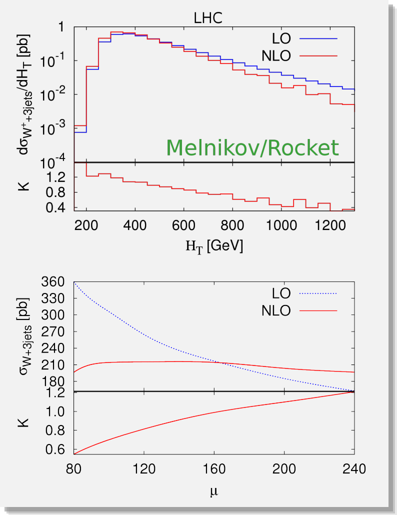
- Blackhat: $pp \rightarrow W + 3$-jets, at large N_c, all subprocesses except fermion loops — good to a few %
- Rocket: $pp \rightarrow W + 3$-jets, at large N_c, just $Wqqggg$ subprocess, w/o fermion loop — good to 20–30%

NLO W+3-jet Results

All channels, leading N_c

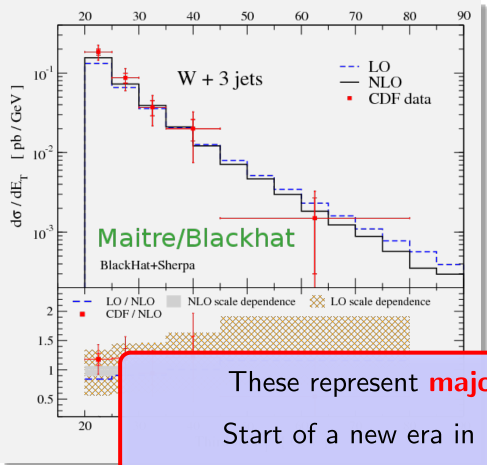


Wqqggg channels, leading N_c

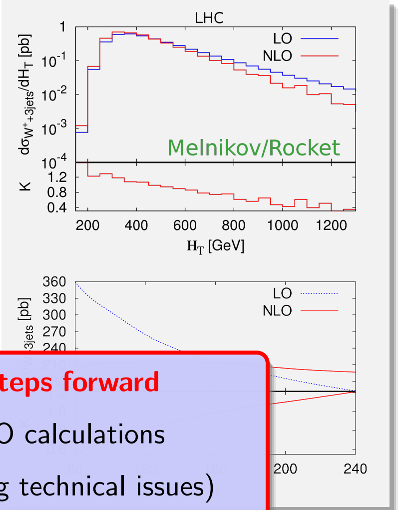


NLO W+3-jet Results

All channels, leading N_c



Wqqggg channels, leading N_c



These represent **major steps forward**

Start of a new era in NLO calculations

(expect progress on remaining technical issues)

NLO is not our only way of predicting

- NLO + parton shower — White, MC@NLO
- p_T resummation of logarithmic enhancements — Ferrera
- Tree-level, & large-multiplicity approximations — Andersen
  Unintegrated parton distributions / forward jets — Hautmann
- NNLO — Ferrera: exclusive $p\bar{p} \to Z$ @ NNLO
  Heslop: N=4 SUSY multi-leg two-loop
- Barely perturbative physics of *pp* and *pA* collisions — Pierog

NLO is not our only way of predicting

- NLO + parton shower — White, MC@NLO

  Wt production

  Issue is that NLO to $pp \to Wt$ includes $pp \to Wt\bar{b}$

  This interferes with non-resonant $t\bar{t}$.

  Non-trivial problem, and important addition to MC@NLO

- p_T resummation of logarithmic enhancements — Ferrera
- Tree-level, & large-multiplicity approximations — Andersen
  Unintegrated parton distributions / forward jets — Hautmann
- NNLO — Ferrera: exclusive $p\bar{p} \to Z$ @ NNLO
  Heslop: N=4 SUSY multi-leg two-loop
- Barely perturbative physics of pp and pA collisions — Pierog

NLO is not our only way of predicting

- NLO + parton shower — White, MC@NLO
- p_T resummation of logarithmic enhancements — Ferrera

Z/γ^* p_t distribution

p_t resummation is important ingredient for Higgs @ LHC ($H \to \gamma\gamma$)

Validation with Z is key for validation. Intermediate results (NLL+LO) shown as step to accurate NNLL+NLO prediction.

- Tree-level, & large-multiplicity approximations — Andersen
  Unintegrated parton distributions / forward jets — Hautmann
- NNLO — Ferrera: exclusive $p\bar{p} \to Z$ @ NNLO
  Heslop: N=4 SUSY multi-leg two-loop
- Barely perturbative physics of pp and pA collisions — Pierog

NLO is not our only way of predicting

- NLO + parton shower — White, MC@NLO
- p_T resummation of logarithmic enhancements — Ferrera
- **Tree-level, & large-multiplicity approximations** — **Andersen**
  Unintegrated parton distributions / forward jets — **Hautmann**
- NNLO — Ferrera: exclusive $p\bar{p} \to Z$ @ NNLO
  Heslop: N=4 SUSY multi-leg two-loop
- Barely perturbative physics of pp and pA collisions — Pierog

NLO is not our only way of predicting

- NLO + parton shower — White, MC@NLO
- p_T resummation of logarithmic enhancements — Ferrera
- Tree-level, & large-multiplicity approximations — Andersen
  Unintegrated parton distributions / forward jets — Hautmann
- NNLO — Ferrera: exclusive $p\bar{p} \rightarrow Z$ @ NNLO
  Heslop: N=4 SUSY multi-leg two-loop
- Barely perturbative physics of pp and pA collisions — Pierog

NLO is not our only way of predicting

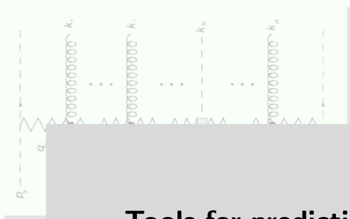
- NLO + parton shower — White, MC@NLO
- p_T resummation of logarithmic enhancements — Ferrera
- Tree-level, & large-multiplicity approximations — Andersen
  Unintegrated parton distributions / forward jets — Hautmann
- NNLO — Ferrera: exclusive $p\bar{p} \to Z$ @ NNLO
  Heslop: N=4 SUSY multi-leg two-loop
- Barely perturbative physics of *pp* and *pA* collisions — Pierog

EPOS Monte Carlo for min-bias physics

Multiple binary parton-parton interactions, with energy-sharing, remnants, screening & shadowing.

For particle physics & cosmic-ray air showers

Multi-jet predictions (H + jets)



Andersen: Alternative to

Madgraph — Alpgen — Sherpa — HELAC-Helas

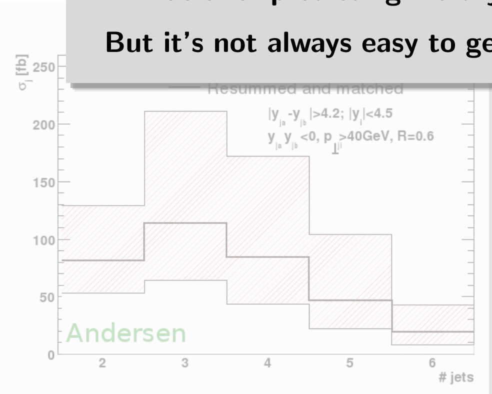
can't

jet-

Premise:

Tools for predicting multi-jet final states exist.

But it's not always easy to get the answer you need.

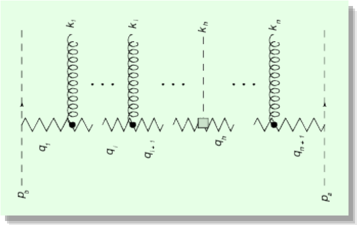


Uses Fadin-Kuraev-Lipatov approx. (large rapidities)

Compares well to exact tree-level

Applied to Hjj (admixes with $WW \to H$).

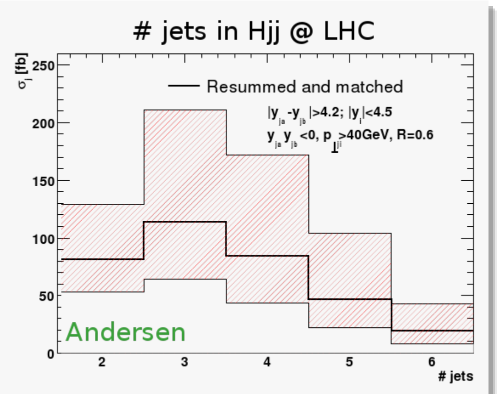
Multi-jet predictions (H + jets)



Andersen: Alternative to

Madgraph — Alpgen —
Sherpa — HELAC-Helas

multi-jet predictions.



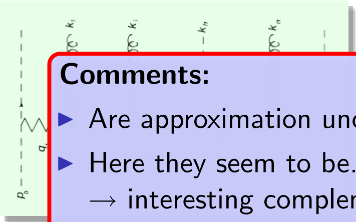
On grounds that they can't easily reach very high jet-multiplicities (with H).

Uses Fadin-Kuraev-Lipatov approx. (large rapidities)

Compares well to exact tree-level

Applied to Hjj (admixes with $WW \to H$).

Multi-jet predictions (H + jets)



Andersen: Alternative to

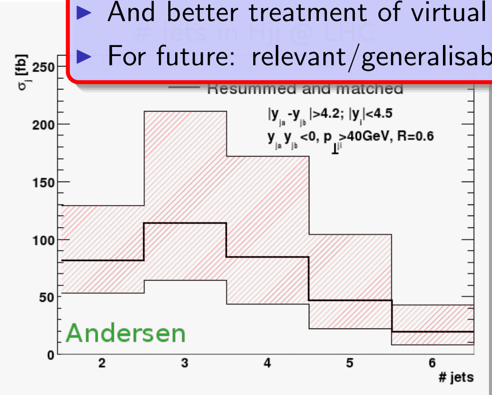
Madgraph — Alpgen —
Sherpa — HELAC … has

multi-jet predictions.

On grounds that they can't easily reach very high jet-multiplicities (with H).

Comments:

- Are approximation uncertainties smaller than intrinsic LO tree?
- Here they seem to be.
  → interesting complement to "fixed-order" methods.
- And better treatment of virtual corrections?
- For future: relevant/generalisable to other processes?

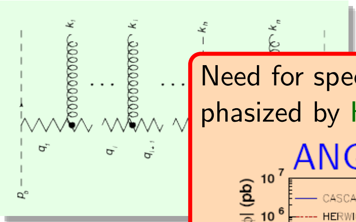


Uses Fadin-Kuraev-Lipatov approx. (large rapidities)

Compares well to exact tree-level

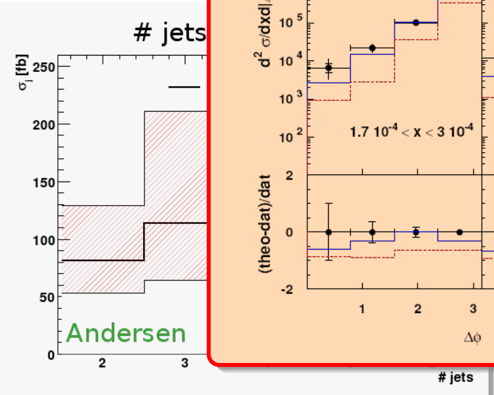
Applied to Hjj (admixes with $WW \to H$).

Multi-jet predictions (H + jets)

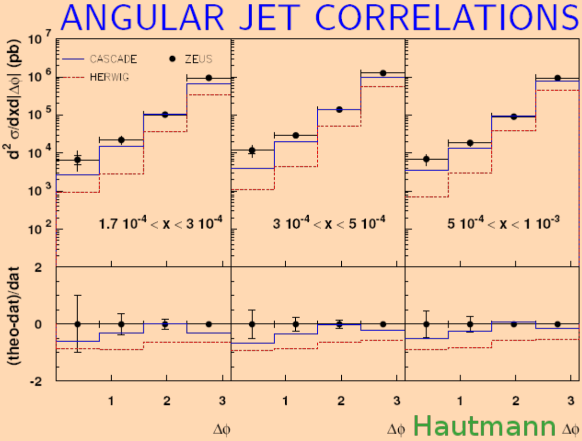


Andersen: Alternative to

n't
et-
ap-
to
el
ith



Need for special care / BFKL-type effects also emphasized by Hautmann:



Push to higher accuracy

Heslop (N=4 SUSY, MHV)

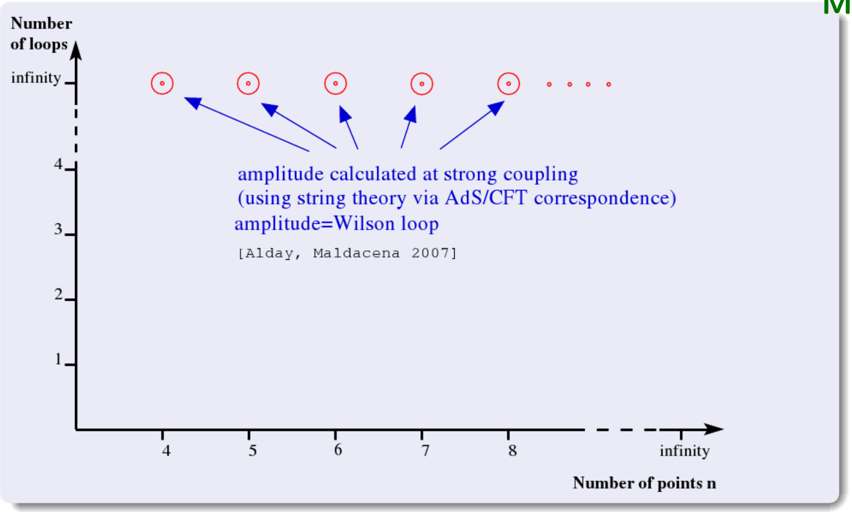
Can 2-loop (NNLO ingredient) diagrams be calculated easily? And multiloop?

Heslop discussed remarkable patterns found in supersymmetric "Maximal-Helicity-Violating" (MHV) amplitudes: relation to simpler "Wilson Loops"

Push to higher accuracy

Evidence so far...

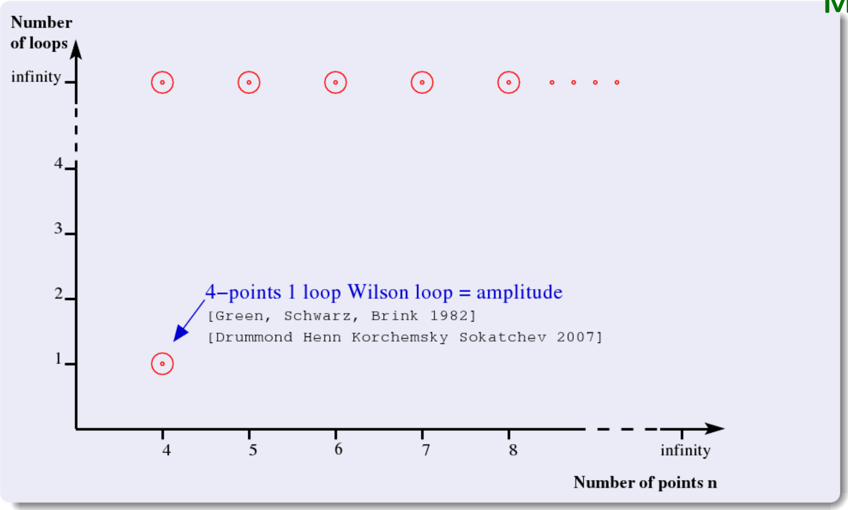
Heslop (N=4 SUSY, MHV)



Push to higher accuracy

Evidence so far...

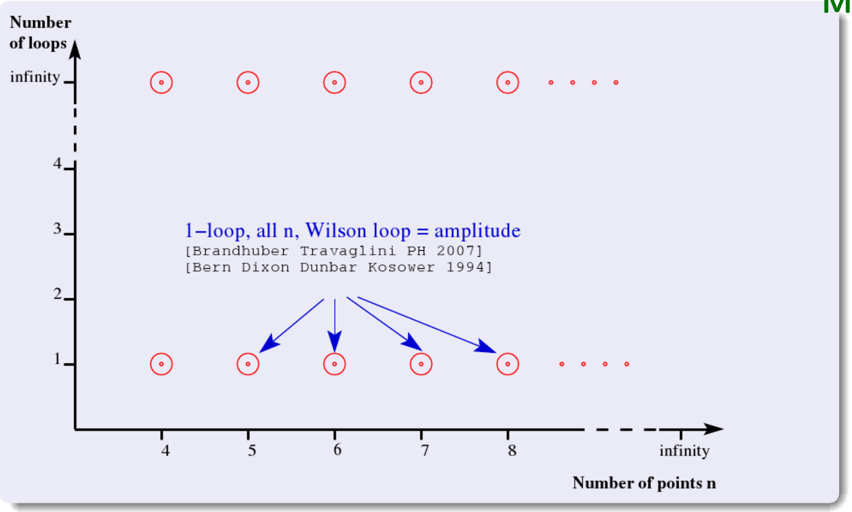
Heslop (N=4 SUSY, MHV)



Push to higher accuracy

Evidence so far...

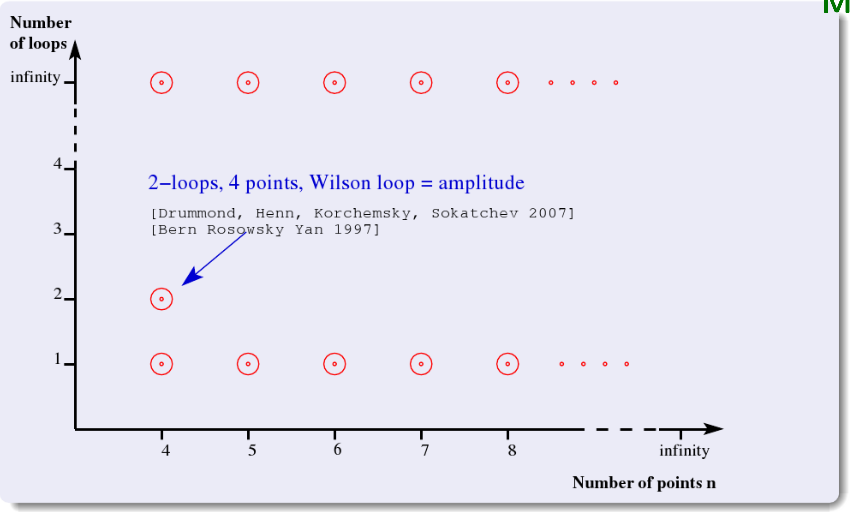
Heslop (N=4 SUSY, MHV)



Push to higher accuracy

Evidence so far...

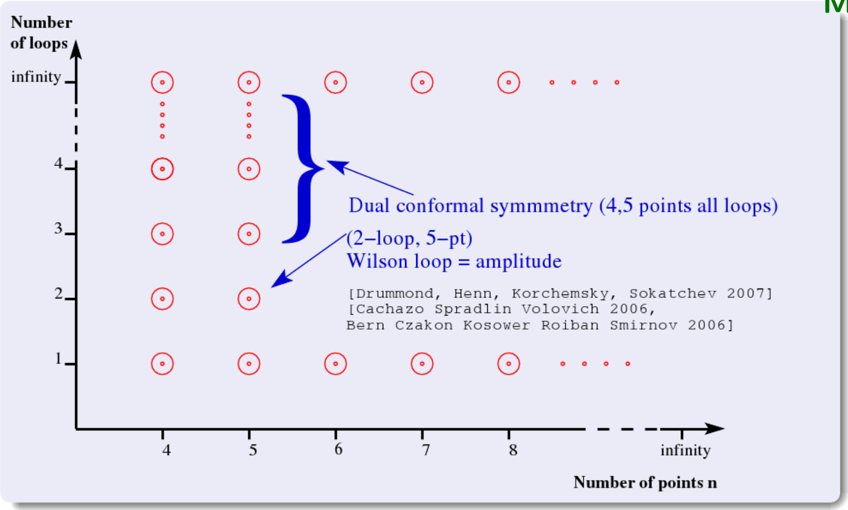
Heslop (N=4 SUSY, MHV)



Push to higher accuracy

Evidence so far...

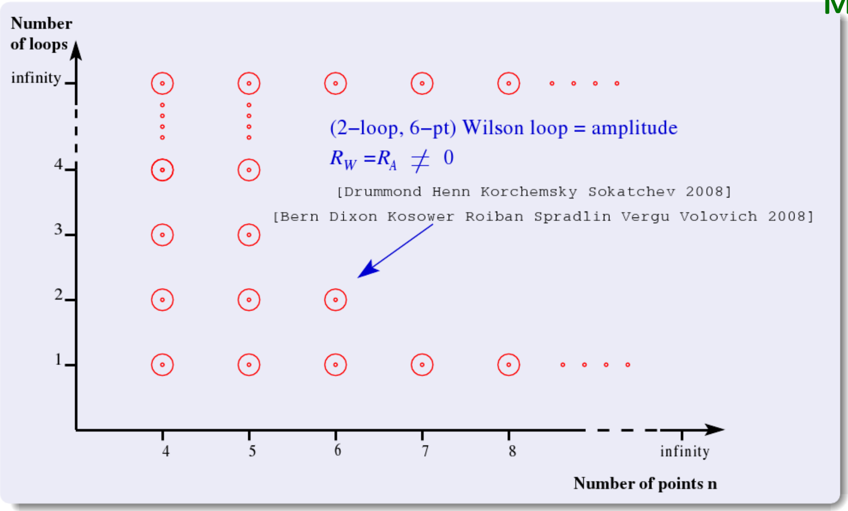
Heslop (N=4 SUSY, MHV)



Push to higher accuracy

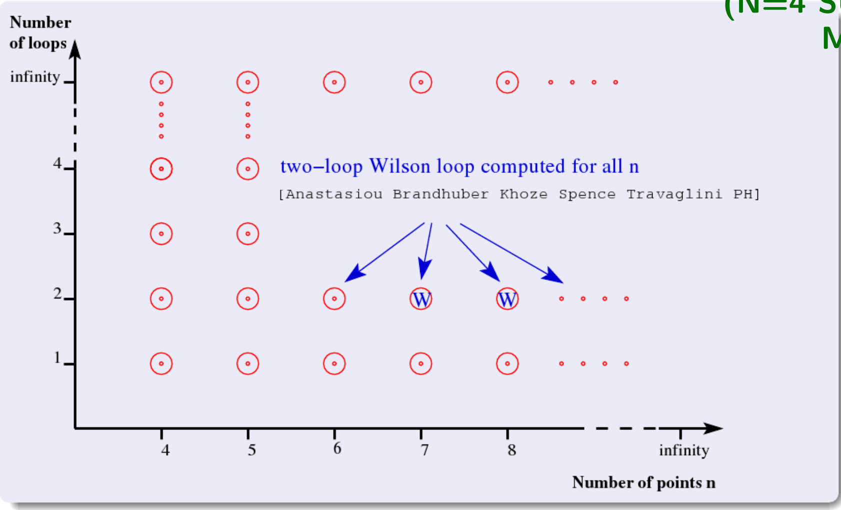
Evidence so far...

Heslop (N=4 SUSY, MHV)



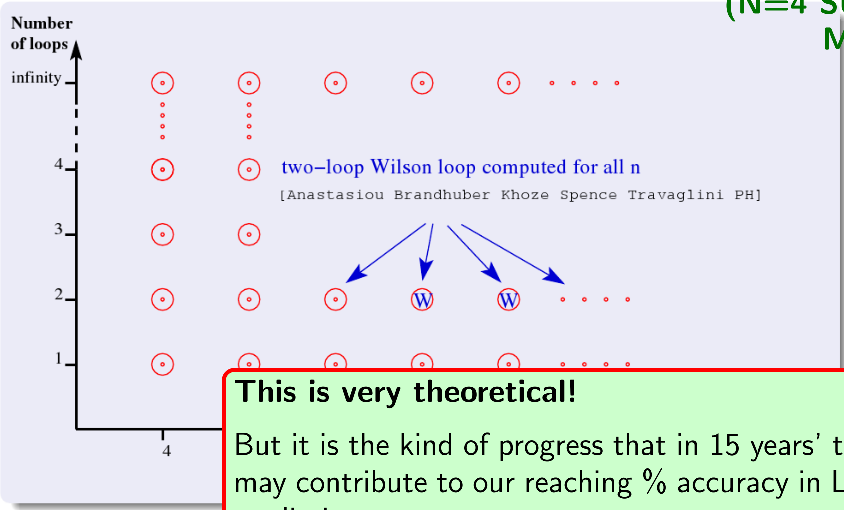
Push to higher accuracy

Heslop (N=4 SUSY, MHV)



Push to higher accuracy

Heslop (N=4 SUSY, MHV)



This is very theoretical!

But it is the kind of progress that in 15 years' time may contribute to our reaching % accuracy in LHC predictions.

(Collider) Data $\longleftrightarrow$ Theory

Because interface is crucial to getting best out of both

Topics were quite varied:

EW fits

Higgs Bounds

PDF fits

Improved LHC $VH, H \to b\bar{b}$ search

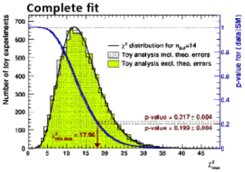
Gfitter: a new program as alternative to Zfitter

- Validated against Zfitter

Goodness of fit:

- o standard fit: $\chi^2_{min}/n_{dof} = 16.4/13$
- o complete fit: $\chi^2_{min}/n_{dof} = 18.0/14$

➤ p-value evaluated using toy-MC



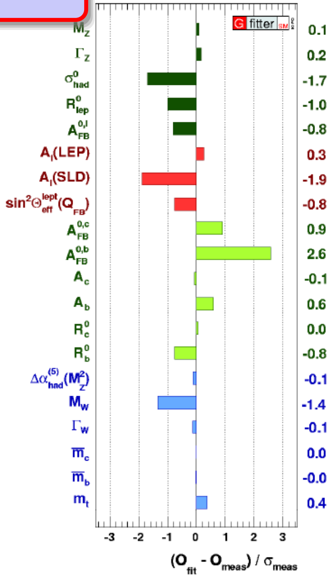
➤ Probability for wrongly rejecting SM: (21.7±0.4)%

- o No indication of new physics

➤ Pull values of complete fit:

- o largest χ^2_{min} contribution from A_{FB} of b-quark 2.6σ
- o Small contributions from M_Z, $\Delta\alpha^{had}(M_Z)$, m_c, m_b indicate that their input accuracies exceed fit requirements

➤ Complete fit results in backup slides

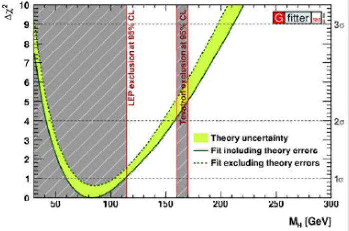


Gfitter: a new program as alternative to Zfitter

- Validated against Zfitter

Higgs mass result:

- M_H from standard fit:
  - Fit input for M_W is our preliminary average!
  - Central value ±1σ: $M_H = 82.8^{+30}_{-23}\,\text{GeV}$
  - 2σ and 3σ interval: [41, 158] and [28, 211] GeV
  - (Previously: $M_H = 80^{+30}_{-23}\,\text{GeV}$)



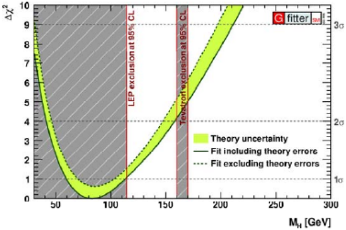
- Shift of mean and intervals up by about 3GeV

Gfitter: a new program as alternative to Zfitter

- Validated against Zfitter

Higgs mass result:

- M_H from standard fit:
  - Fit input for M_W is our preliminary average!
  - Central value ±1σ: $M_H = 82.8^{+30}_{-23}\ \mathrm{GeV}$
  - 2σ and 3σ interval: [41, 158] and [28, 211] GeV
  - (Previously: $M_H = 80^{+30}_{-23}\ \mathrm{GeV}$)



- Shift of mean and intervals up by about 3GeV

Tevatron's fit:

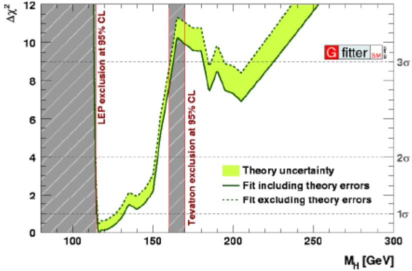
Kehoe: $m_H = 90^{+36}_{-27}\mathrm{GeV}$

Robert Kehoe (SMU) - Tevatron Top Mass Measurements

Gfitter: a new program as alternative to Zfitter

- Validated against Zfitter

Higgs mass result with LEP and Tevatron exclusions:



$\Delta\chi^2$ as a function of M_H for the *complete fit (including the latest results from the direct Higgs searches).*

$$M_H = 116^{+15.6}_{-1.3}\ \text{GeV}$$

Tevatron's fit:

Kehoe: $m_H = 90^{+36}_{-27}\,\text{GeV}$

Robert Kehoe (SMU) - Tevatron Top Mass Measurements

HiggsBounds:

Incorporate results of all experimental searches into single package, for testing new models, new SM X-sections.

…ded in *HiggsBounds*

K. Williams

1. $e^+e^- \to (h_k)Z \to (b\bar{b})Z$
2. $e^+e^- \to (h_k)Z \to (\tau^+\tau^-)Z$
3. $e^+e^- \to (h_k \to h_i h_i)Z \to (b\bar{b}b\bar{b})Z$
4. $e^+e^- \to (h_k \to h_i h_i)Z \to (\tau^+\tau^-\tau^+\tau^-)Z$
5. $e^+e^- \to (h_k \to h_i h_i)Z \to (b\bar{b})(\tau^+\tau^-)Z$

and Higgs pair production

1. $e^+e^- \to (h_k h_i) \to (b\bar{b}b\bar{b})$
2. $e^+e^- \to (h_k h_i) \to (\tau^+\tau^-\tau^+\tau^-)$
3. $e^+e^- \to (h_k \to h_i h_i)h_i \to (b\bar{b}b\bar{b})b\bar{b}$
4. $e^+e^- \to (h_k \to h_i h_i)h_i \to (\tau^+\tau^-\tau^+\tau^-)\tau^+\tau^-$
5. $e^+e^- \to (h_k \to b\bar{b})(h_i \to \tau^+\tau^-)$
6. $e^+e^- \to (h_k \to \tau^+\tau^-)(h_i \to b\bar{b})$

Tevatron search topologies

- $p\bar{p} \to WH \to l\nu b\bar{b}$
- $p\bar{p} \to WH \to W^+W^-W^\pm$
- $p\bar{p} \to ZH \to l^+l^- b\bar{b}$
- $p\bar{p} \to ZH \to \nu\bar{\nu}b\bar{b}$
- $p\bar{p} \to WH/ZH \to b\bar{b} + E_T^{miss.}$ (SM)
- $p\bar{p} \to H \to W^+W^- \to l^+l'^-\nu\nu$
- $p\bar{p} \to bH, H \to b\bar{b}$
- $p\bar{p} \to H \to \tau^+\tau^-$

- $p\bar{p} \to H/HW/HZ/H$ via VBF, $H \to \tau^+\tau^-$ (SM)
- $p\bar{p} \to H/HW/HZ/H$ via VBF, $H \to \gamma\gamma$
- combined Higgs production and decay (SM) (+ hadronic remainders)

HiggsBounds:

Incorporate results of all experimental searches into single package, for testing new models, new SM X-sections.

...ded in *HiggsBounds*

K. Williams

1. $e^+e^- \to (h_k)Z \to (b\bar{b})Z$
2. $e^+e^- \to (h_k)Z \to (\tau^+\tau^-)Z$
3. $e^+e^- \to (h_k \to h_i h_i)Z \to (b\bar{b}b\bar{b})Z$
4. $e^+e^- \to (h_k \to h_i h_i)Z \to (\tau^+\tau^-\tau^+\tau^-)Z$
5. $e^+e^- \to (h_k \to h_i h_i)Z \to (b\bar{b})(\tau^+\tau^-)Z$

and Higgs pair production

1. $e^+e^- \to (h_k h_i) \to (b\bar{b}b\bar{b})$
2. $e^+e^- \to (h_k h_i) \to (\tau^+\tau^-\tau^+\tau^-)$
3. $e^+e^- \to (h_k \to h_i h_i)h_i \to (b\bar{b}b\bar{b})b\bar{b}$
4. $e^+e^- \to ($
5. $e^+e^- \to ($
6. $e^+e^- \to ($

Tevatron search topologies

- $p\bar{p} \to WH \to l\nu b\bar{b}$
- $p\bar{p} \to WH \to W^+W^-W^\pm$
- $p\bar{p} \to ZH \to l^+l^- b\bar{b}$
- $p\bar{p} \to ZH \to \nu\bar{\nu}b\bar{b}$
- $p\bar{p} \to WH/ZH \to b\bar{b} + E_T^{miss.}$ (SM)
- $p\bar{p} \to H \to W^+W^- \to l^+l'^-\nu\nu$
- $p\bar{p} \to bH, H \to b\bar{b}$
- $p\bar{p} \to H \to \tau^+\tau^-$

(SM)

(+ hadronic remainders)

An impressive and valuable collation of information!

Greatly facilitates task of exploring new models.

And allows easy inclusion of latest theory developments.

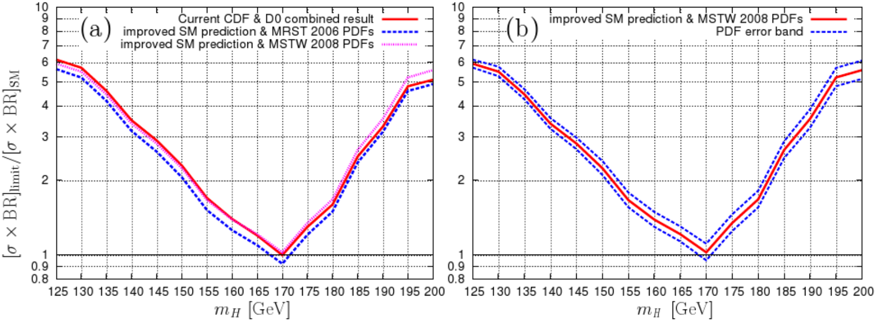
Example 1: Effect of new SM gluon fusion cross sections

New results for $p\bar{p} \to gg \to H$, which include

- mixed QCD-electroweak corrections.
- more recent PDFs and K-factors

(see C.Anastasiou, R.Boughezal, R.Petriello 2009 and refs. therein)

Using *HiggsBounds* to see the effect on the Tevatron exclusions:



In the legend, 'current' means before Thursday!

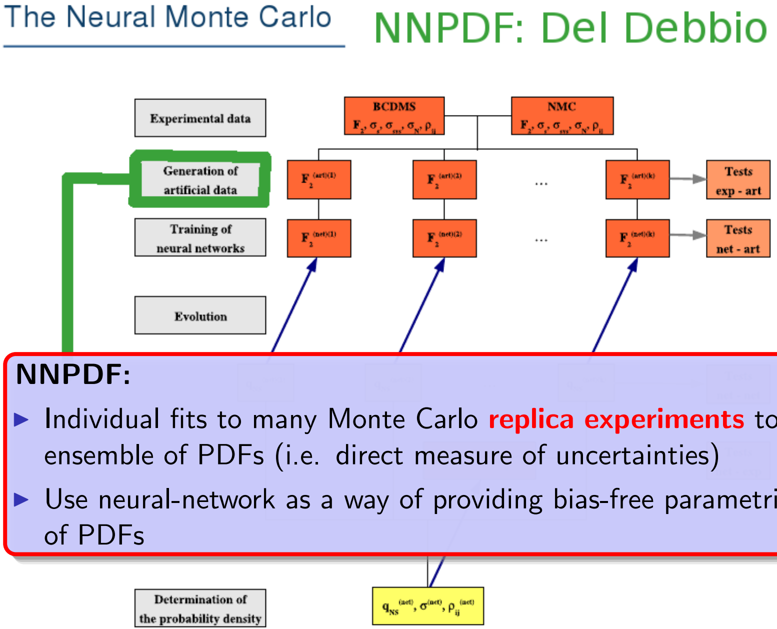
PDFs

PDFs (and their uncertainties) are crucial input
to nearly all Tevatron & LHC studies

Issues in traditional PDF fits (CTEQ/MSTW):

- Estimation of uncertainties, done by (arbitrary?) $\delta\chi^2 \sim 50$
- Parametrisation bias

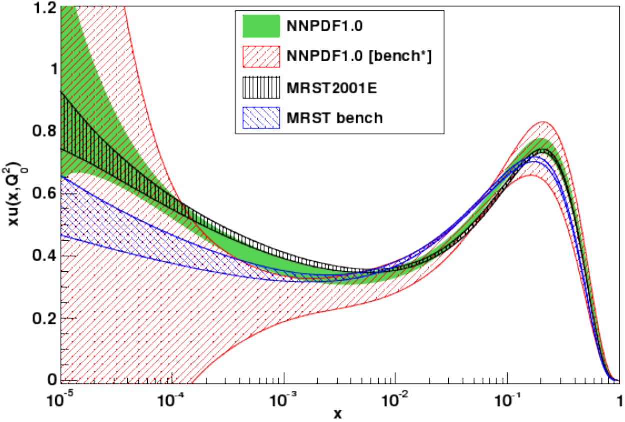
NNPDF: Del Debbio



NNPDF:

- Individual fits to many Monte Carlo **replica experiments** to get ensemble of PDFs (i.e. direct measure of uncertainties)
- Use neural-network as a way of providing bias-free parametrisations of PDFs

NNPDF results



up quark PDF

in normal fits & "benchmark" comparison fits (reduced data-set)

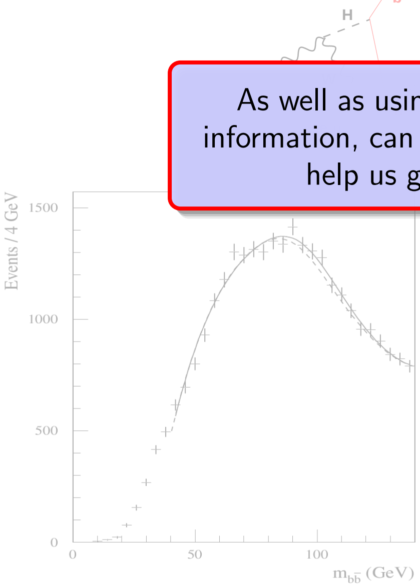
(NNPDF, unlike MRST bench: errors increase with reduced data)

NNPDF status:

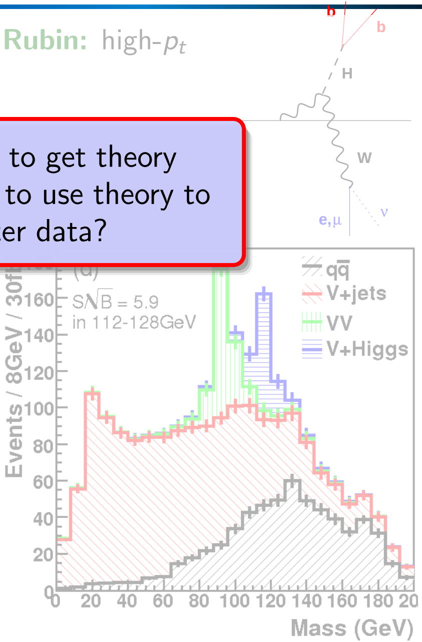
- Still needs inclusion of heavy-quark effects & $p\bar{p}$ data
- Once this is done, it will be a serious (superior?) competitor to CTEQ & MSTW.

$pp \longrightarrow VH$, Higgs$\longrightarrow b\bar{b}$ @ LHC

ATLAS TDR: all p_t



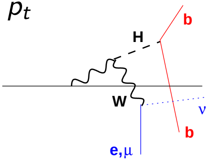
Rubin: high-p_t

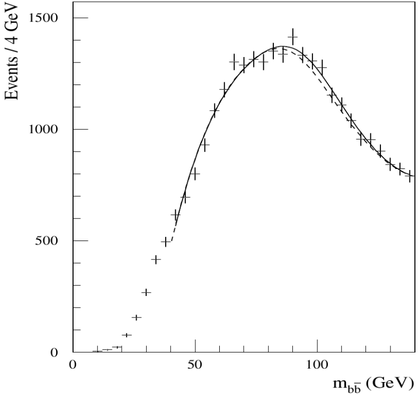


As well as using data to get theory information, can we try to use theory to help us get better data?

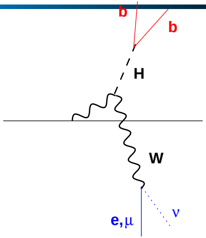
$pp \to VH$, Higgs$\to b\bar{b}$ @ LHC

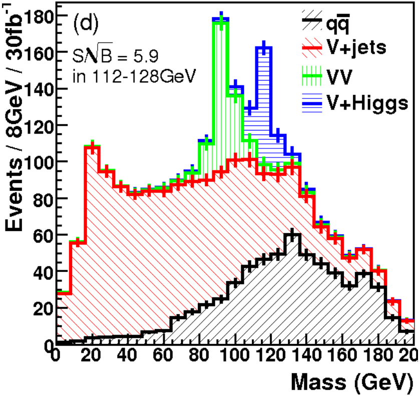
ATLAS TDR: all p_t





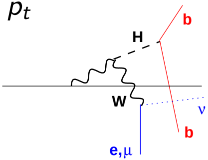
Rubin: high-p_t



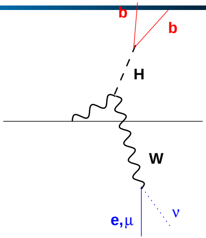


$pp \longrightarrow VH$, Higgs$\longrightarrow b\bar{b}$ @ LHC

ATLAS TDR: all p_t



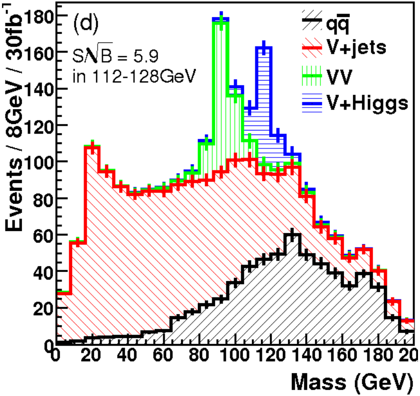
Rubin: high-p_t



- Selection of high-p_t subset of Higgs bosons
- Theory-inspired jet substructure techniques

Make it possible to recover clearer & more Higgs significant signal?

These ideas may well be useful elsewhere too. . .



Theory ↔ data

LHC $WH, H \to b\bar{b}$ example looks a lot like many currently searches.

huge backgrounds
similar signal and background distribution

Currently: near-universal reliance on **neural networks** to improve S/B

NNs are very non-transparent

Theory ↔ data

LHC $WH, H \to b\bar{b}$ example looks a lot like many currently searches.

huge backgrounds
similar signal and background distribution

Currently: near-universal reliance on **neural networks** to improve S/B

NNs are very non-transparent

A suggestion for a rule of thumb:

If NN improves signal by (say) 20%: then also show cut-based analysis — it'll be a lot more convincing.

If NN improves signal by (say) $\times 2$: then figure out a "plain" analysis that takes advantage of the corresponding physics.

New Phenomena:

Theories we don't yet know: Beyond Standard Model (BSM)

A theory we do know (QCD), with yet-to-be discovered exotic behaviour? In Heavy-Ion Collisions.

BSM

BSM

Issues

- SUSY: how do we break it? Lalak
- Strongly-interacting models: how do we say anything about them? Brower
- Other simple models? Kanemura

BSM

Issues

- SUSY: how do we break it? Lalak
- Strongly-interacting models: how do we say anything about them? Brower
- Other simple models? Kanemura

> Tramsmission of supersymmetry breakdown may easily be a mixture of many schemes - the gauge-gravity system a good example
>
> Lalak

BSM

Issues

- SUSY: how do we break it? Lalak
- Strongly-interacting models: how do we say anything about them? Brower
- Other simple models? Kanemura

Lattice for BSM: Brower

One of the most economical ideas for explaining electroweak scale:

The Higgs is composite (a bit like a pion).

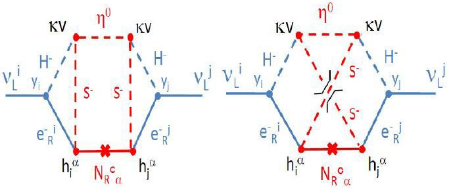
Its mass is generated by non-perturbative dynamics of a new QCD-like theory "technicolour".

Technicolour is generally considered to be excluded (calculations assume it behaves similarly to QCD).

But suppose technicolour is only marginally similar to QCD? Will it still be excluded? Only way to tell is by lattice calculations.

[it's not irrelevant that we start, finally, to have full control of systematics in QCD lattice calculations]

TeV origin for ν-mass, DM, baryon asym



Neutrino mass from loop effects

$$m^{\nu}_{ij} \sim C_{ij} \left(\frac{1}{16\pi^2}\right)^3 \frac{(\mathrm{vev})^2}{1\ \mathrm{TeV}}$$

$C_{ij} \sim y_i y_j$ (SM Yukawa couplings)

Predictions in Higgs physics and DM physics

- Invisible decay of SM-like h
- Direct search of DM
- Light H^+ scenario
- Type-X Yukawa coupling (Leptonic Higgs)
- Non-decoupling property of S^+

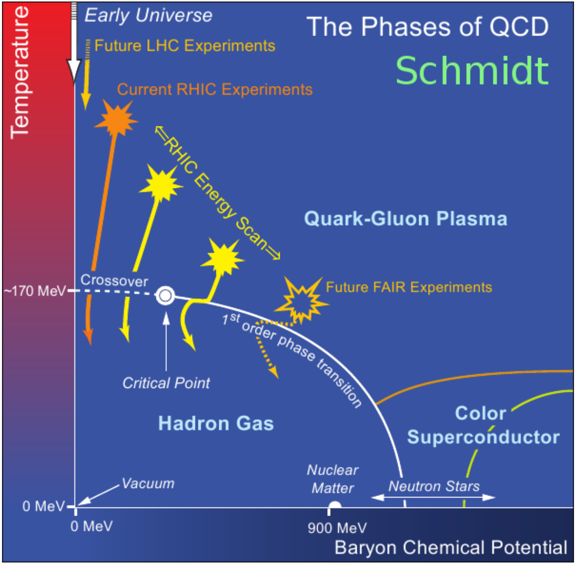
Testable at experiments

Distinguishable from SM, MSSM, Type-II 2HDM, etc
by the experiment at LHC, ILC etc

Kanemura

Heavy-Ion Collisions

they produce a hot dense "medium" (quark-gluon plasma)



HIC Questions

Can we understand the "medium"?

Can we model/calculate the medium in detail?
Greiner, Schmidt [Kerbikov]

Can we learn something about it with probes that traverse it?
Ferreiro, Salgado, Zakharov

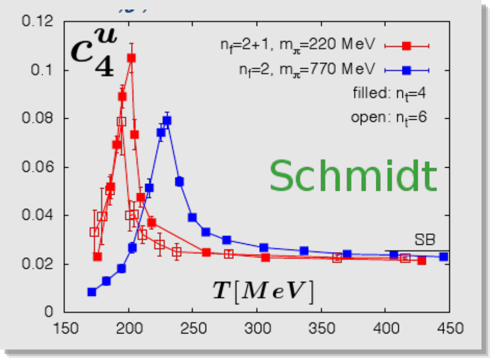
Might the medium surprise us?
Warringa

Lattice Equation of State

- start from Taylor expansion of the pressure,

$$\frac{p}{T^4} = \frac{1}{VT^3} \ln Z(V,T,\mu_u,\mu_d,\mu_s) = \sum_{i,j,k} c_{i,j,k}^{u,d,s} \left(\frac{\mu_u}{T}\right)^i \left(\frac{\mu_d}{T}\right)^j \left(\frac{\mu_s}{T}\right)^k$$

- calculate expansion coefficients for fixed temperature



This (with other plots), provides a "lattice" hint for the existence of a critical point.

Microscopic description of plasma

BAMPS: Boltzmann Approach of MultiParton Scatterings

Z. Xu and C. Greiner, PRC 71, 064901 (2005); 76, 024911 (2007)

A transport algorithm solving the Boltzmann-Equations for on-shell partons with pQCD interactions

$$p^{\mu}\partial_{\mu}f(x,p) = C_{gg\to gg}(x,p) + C_{gg\leftrightarrow ggg}(x,p)$$

Greiner

↑ (Z)MPC, VNI/BMS, AMPT

↑ new development ggg → gg, radiative „corrections“

Elastic scatterings are ineffective in thermalization !

Inelastic interactions are needed !

Microscopic description of plasma

BAMPS: Boltzmann Approach of MultiParton Scatterings

Z. Xu and C. Greiner, PRC 71, 064901 (2005); 76, 024911 (2007)

A transport algorithm solving the Boltzmann-Equations for on-shell partons with pQCD interactions

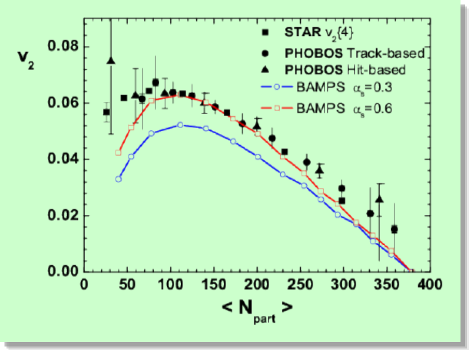
$$p^{\mu}\partial_{\mu}f(x,p) = C_{gg\to gg}(x,p) + C_{gg\leftrightarrow ggg}(x,p)$$

Greiner

(Z)MPC, VNI/BMS, AMPT

Elastic scatterings are ineffective

Inelastic interactions are needed



Microscopic description of plasma

BAMPS: Boltzmann Approach of MultiParton Scatterings

Z. Xu and C. Greiner, PRC 71, 064901 (2005); 76, 024911 (2007)

A transport algorithm solving the Boltzmann-Equations for on-shell partons with pQCD interactions

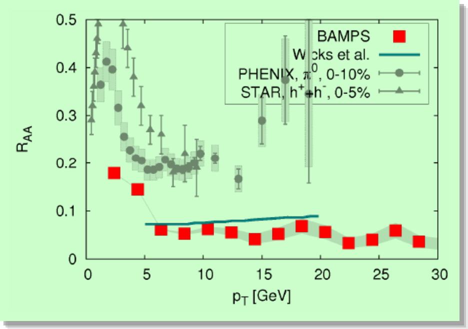
$$p^{\mu}\partial_{\mu}f(x,p) = C_{gg\to gg}(x,p) + C_{gg\leftrightarrow ggg}(x,p)$$

Greiner

(Z)MPC, VNI/BMS, AMPT

Elastic scatterings are ineffective

Inelastic interactions are needed



Microscopic description of plasma

BAMPS: Boltzmann Approach of MultiParton Scatterings

Z. Xu and C. Greiner, PRC 71, 064901 (2005); 76, 024911 (2007)

A transport algorithm solving the Boltzmann-Equations for on-shell partons with pQCD interactions

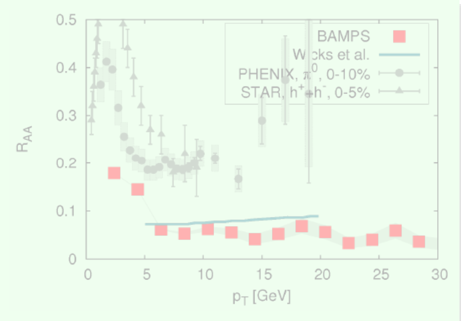
$$p^\mu \partial_\mu f(x,p) = C_{gg\to gg}(x,p) + C_{gg\leftrightarrow ggg}(x,p)$$

Greiner

A microscopic description can provide much insight.

Getting everything to work is non-trivial?

Is it question of “details” or something more fundamental?



Probes of the medium

Longstanding probe is J/ψ (which “melts” in hot medium)

Recent years, much work on **hard partons traversing medium**.
Their **energy loss** gives handle on medium properties.

Probes of the medium

Longstanding probe is J/ψ (which "melts" in hot medium)

J/ψ is tricky: first understand it in cold nuclear matter

- We have studied the influence of J/ψ kinematics on shadowing effect:

  within 2 schemes: intrinsic (2→ 1) and extrinsic (2→2) p_T
  for different shadowings: EKS98, EPS08, nDGg
  using s-channel cut model as the production model for p+p in 2→ 2

  in the framework of a Glauber MC code

Ferreiro

Recent years, much work on **hard partons traversing medium**.
Their **energy loss** gives handle on medium properties.

Probes of the medium

Longstanding probe is J/ψ (which “melts” in hot medium)

Recent years, much work on **hard partons traversing medium**. Their **energy loss** gives handle on medium properties.

Paradigm: radiative and collisional energy loss

- What about synchrotron loss? Zakharov
- Detailed Monte Carlo for radiation energy loss Salgado

Energy loss due to synchrotron radiation Zakharov

Without magnetic field jet quenching is dominated by the induced gluon emission due to multiple scattering on thermal partons. The collisional energy loss gives small effect $\Delta E_{col}/\Delta E_{rad} \sim 0.2 - 03$, and $\Delta E_{col}/E \sim 0.03 - 0.05$ at $E \lesssim 40$ GeV

Can the synchrotron radiation modify strongly the jet quenching?

$$\frac{\epsilon_{mag}}{\epsilon_{thermal}} \sim \alpha_s \left(\frac{gH}{m_D^2}\right)^2$$

This ratio is ~ 0.3 if $gH \sim m_D^2$. Such a value of magnetic field is requred by the scenario with turbulent viscosity [Asakawa, Bass, Müller (2007)] for explaining small η/s.
$gH \sim m_D^2$ gives $\Delta E/E \sim 0.1 - 0.2$ at $E \sim 10 - 20$ GeV for $L \sim 2 - 4$ fm.
The finite-size effects become important if $L_c \sim L$. We have $L_c \sim 1 - 2$ fm. The finite-size effects may suppress the energy loss by a factor ~ 0.5.
The finite coherence length of the turbulent magnetic field, L_m, suppresses the radiation as well. For the unstable magnetic field modes the wave vector $k^2 \lesssim \xi m_D^2$ [Asakawa, Bass, Müller (2007)], we have $L_m/L_c \gtrsim 1$. The turbulent suppression should not be strong, and as a plausible estimate one can take the turbulent suppression factor ~ 0.5.
With these suppression factors we have

$$\Delta E_{synch} \sim \Delta E_{coll}$$

Energy loss due to synchrotron radiation Zakharov

Without magnetic field jet quenching is dominated by the induced gluon emission due to multiple scattering on thermal partons. The collisional energy loss gives small effect $\Delta E_{col}/\Delta E_{rad} \sim 0.2 - 03$, and $\Delta E_{col}/E \sim 0.03 - 0.05$ at $E \lesssim 40$ GeV

Can the synchrotron radiation modify strongly the jet quenching?

Bottom line:

Reasonable assumptions about chromomagnetic field $\rightarrow$

$$\Delta E_{\text{synchrotron}} \sim \Delta E_{\text{collisional}} \sim \frac{1}{4} \Delta E_{\text{radiative}}$$

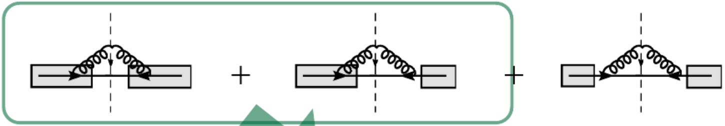
Bass, Müller (2007)], we have $L_m/L_c \gtrsim 1$. The turbulent suppression should not be strong, and as a plausible estimate one can take the turbulent suppression factor ~ 0.5. With these suppression factors we have

$$\Delta E_{synch} \sim \Delta E_{coll}$$

Radiative (medium-modified) energy loss

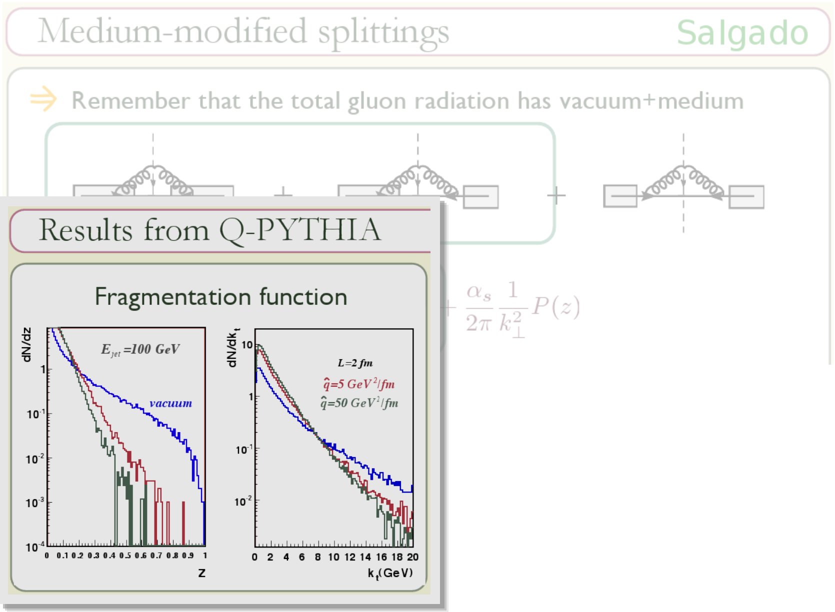
Medium-modified splittings — Salgado

⇒ Remember that the total gluon radiation has vacuum+medium

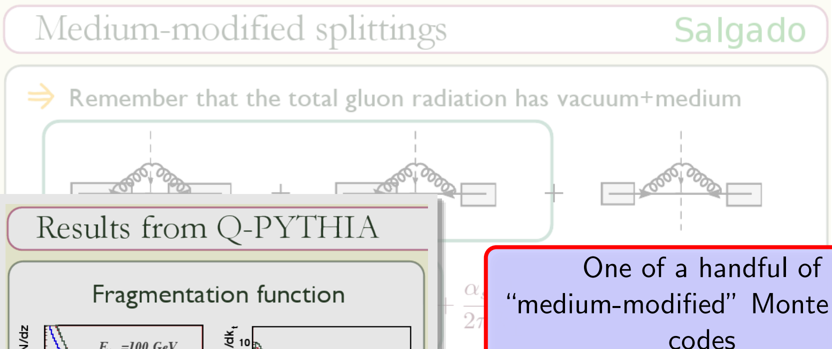


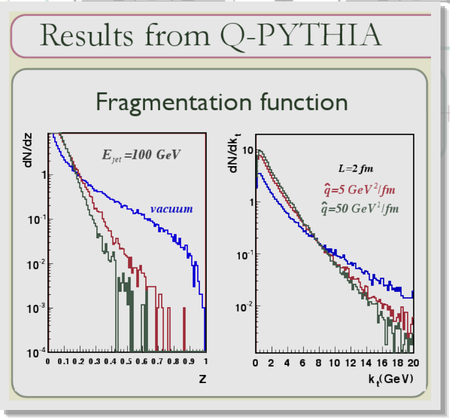
$$\frac{dI}{dzdk_\perp^2} = \frac{dI^{\rm med}}{dzdk_\perp^2} + \frac{\alpha_s}{2\pi}\frac{1}{k_\perp^2}P(z)$$

Radiative (medium-modified) energy loss



Radiative (medium-modified) energy loss



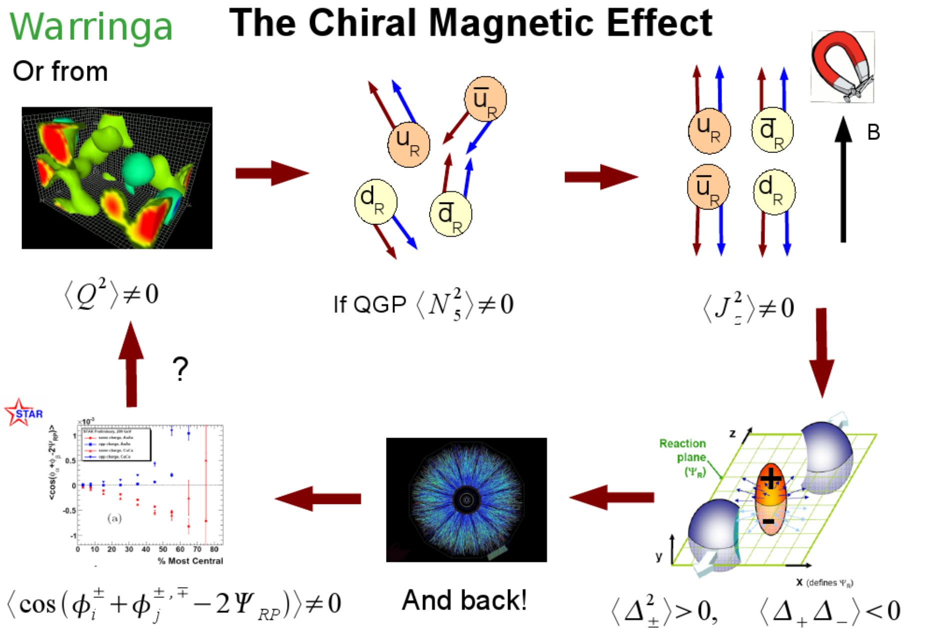


One of a handful of "medium-modified" Monte Carlo codes

Essential in testing ideas for exclusive studies in HI collisions, e.g. jet studies.

And for relating results to medium properties.

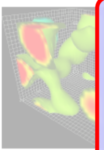
Last of the theory talks: QCD in a twist



Last of the theory talks: QCD in a twist

Warringa **The Chiral Magnetic Effect**

Or from

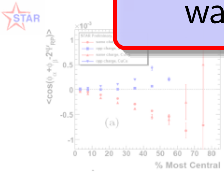


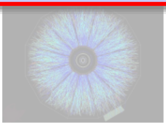
B

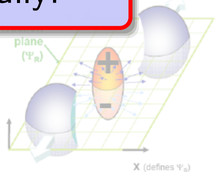
$\langle Q^2 \rangle$

People have been discussing topological effects in SU(N) theories for a **l o n g** time.

Assuming this stands up to scrutiny, it's a major achievement to have finally found a way of seeing them experimentally!







$\langle \cos(\phi_i^{\pm} + \phi_j^{\pm,\mp} - 2\Psi_{RP}) \rangle \neq 0$ And back! $\langle \Delta_{\pm}^2 \rangle > 0, \quad \langle \Delta_+ \Delta_- \rangle < 0$


And as the closing talk of the workshop,
a final thank you to the organisers!