StandarD model Physics

The double-simplex

QuickTime™ and a
Animation decompressor
are needed to see this picture.

[Quigg,04]

at the LHC

Fabio Maltoni

OUTLINE

	Examples
Motivations	
SM Physics we know but we need to know better	QCD, $\sigma(W,Z), m_W, m_t$
SM Physics we know is there but not seen yet	Single-top, Rare dec Vector Boson scatte
SM Physics we do not know if it is there or not!	Higgs
Outlook	

Effective Lagrangian

$$\mathcal{L}_{eff} = -\frac{1}{4}G^{A\mu\nu}G^{A}_{\mu\nu} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}W^{A\mu\nu}W^{A}_{\mu\nu}$$

Gaug

$$+i\bar{Q}^i_L \not{D} Q^i_L + i\bar{u}^i_R \not{D} u^i_R + i\bar{d}^i_R \not{D} d^i_R + i\bar{L}^i_L \not{D} L^i_L + i\bar{e}^i_R \not{D} e^i_R$$

Matt

$$+M_W^2 W^{+\mu} W^-_\mu + \frac{1}{2}\frac{M_W^2}{\cos^2\theta_W} Z^\mu Z_\mu$$

Mass

$$-m_u^{ij}\bar{u}^i_L u^j_R -$$

*Non linearly realized. Unitary gauge.

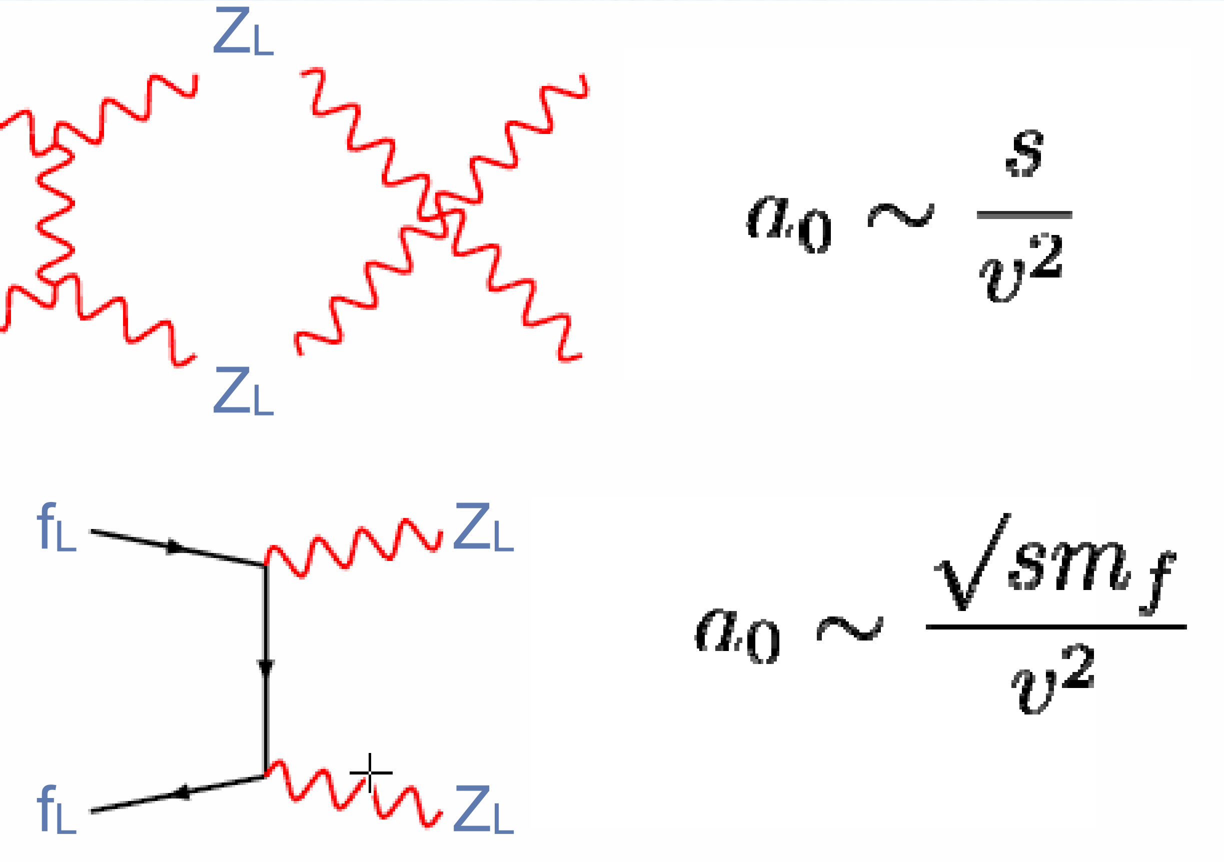
** Except for neutrino's masses and dark matt

Perfectly defined gauge-invariant* Lagrangian!

It describes all** we know!

effective Lagrangian

[Chanowitz, Gallard.1985]
[Appelquist, Chanowitz,19



Inelastic tree-level amplitu
for longitudinal W and Z
fermions violate unitarity a
scale:

$$\Lambda_{EWSB} = \sqrt{8\pi} v$$

Our effective descrip
contains information on whe
is going to fail.

Only case we know of wh
unknown physics has to app
below 1 TeV.

SM lagrangian

SU(3) SU(2)$_L$ U(1)$_Y$

$$\mathcal{L}_{SM} = -\frac{1}{4}G^{A\mu\nu}G^{A}_{\mu\nu} - \frac{1}{4}W^{A\mu\nu}W^{A}_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu}$$ Gauge

$$+i\bar{Q}^i_L \not{D} Q^i_L + i\bar{u}^i_R \not{D} u^i_R + i\bar{d}^i_R \not{D} d^i_R + i\bar{L}^i_L \not{D} L^i_L + i\bar{e}^i_R \not{D} e^i_R$$ Matter

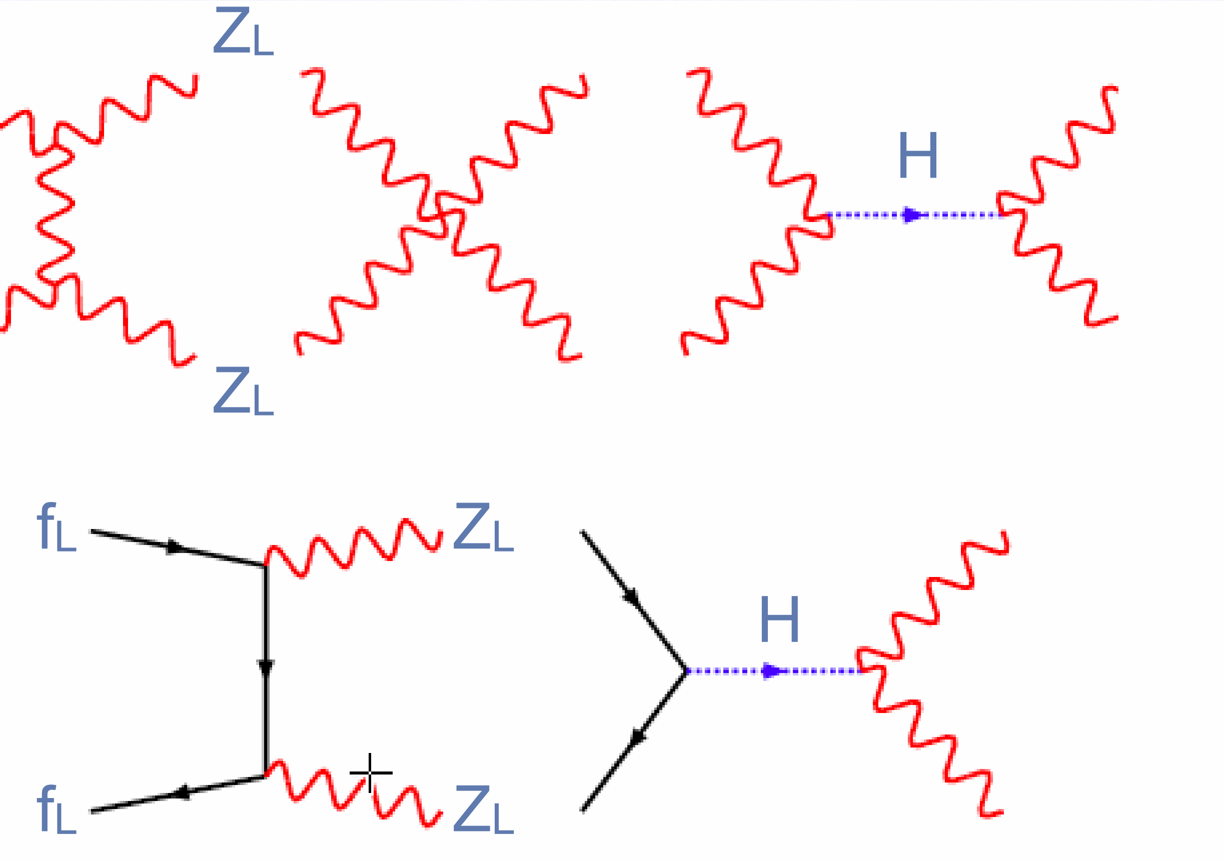
$$-\Gamma^{ij}_u \bar{Q}^i_L \epsilon \phi^* u^j_R - \Gamma^{ij}_d \bar{Q}^i_L \phi d^j_R - \Gamma^{ij}_e \bar{L}^i_L \phi e^j_R + h.c.$$ Yukawa

$$+(D^\mu\phi)^\dagger(D^\mu\phi) + \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2$$ Higgs

Spontaneous symmetry breaking $\Rightarrow \phi = \frac{H + v}{\sqrt{2}}$

SM is unitary

[Chanowitz, Gallard.1985]
[Appelquist, Chanowitz,19



$$a_0 \sim \frac{s}{v^2} - \frac{s}{v^2} \sim \frac{m_H^2}{v^2}$$

$$a_0 \sim \frac{\sqrt{s} m_f}{v^2} - \frac{\sqrt{s} m_f}{v^2} \sim$$

SM is a linear gauge theory valid up to arbitrary scales, with m_H<1 TeV.

Our strategy in a nutshell

$$\mathcal{L}_{SM} = -\frac{1}{4}G^{A\mu\nu}G^{A}_{\mu\nu} - \frac{1}{4}W^{A\mu\nu}W^{A}_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} \qquad \text{Gauge}$$

$$+i\bar{Q}^i_L \not{D} Q^i_L + i\bar{u}^i_R \not{D} u^i_R + i\bar{d}^i_R \not{D} d^i_R + i\bar{L}^i_L \not{D} L^i_L + i\bar{e}^i_R \not{D} e^i_R \qquad \text{Matter}$$

$$-\Gamma^{ij}_u \bar{Q}^i_L \epsilon \phi^* u^j_R - \Gamma^{ij}_d \bar{Q}^i_L \phi d^j_R - \Gamma^{ij}_e \bar{L}^i_L \phi e^j_R + h.c. \qquad \text{Yukawa}$$

$$+(D^\mu \phi)^\dagger (D^\mu \phi) + \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2 \qquad \text{Higgs}$$

Perform precision measurements to estab
direct evidence for Higgs and BSM physics.

Use the heaviest particles (W,Z, top) as direct
obes of the EWSB sector and BSM physics.

OUTLINE

Motivations

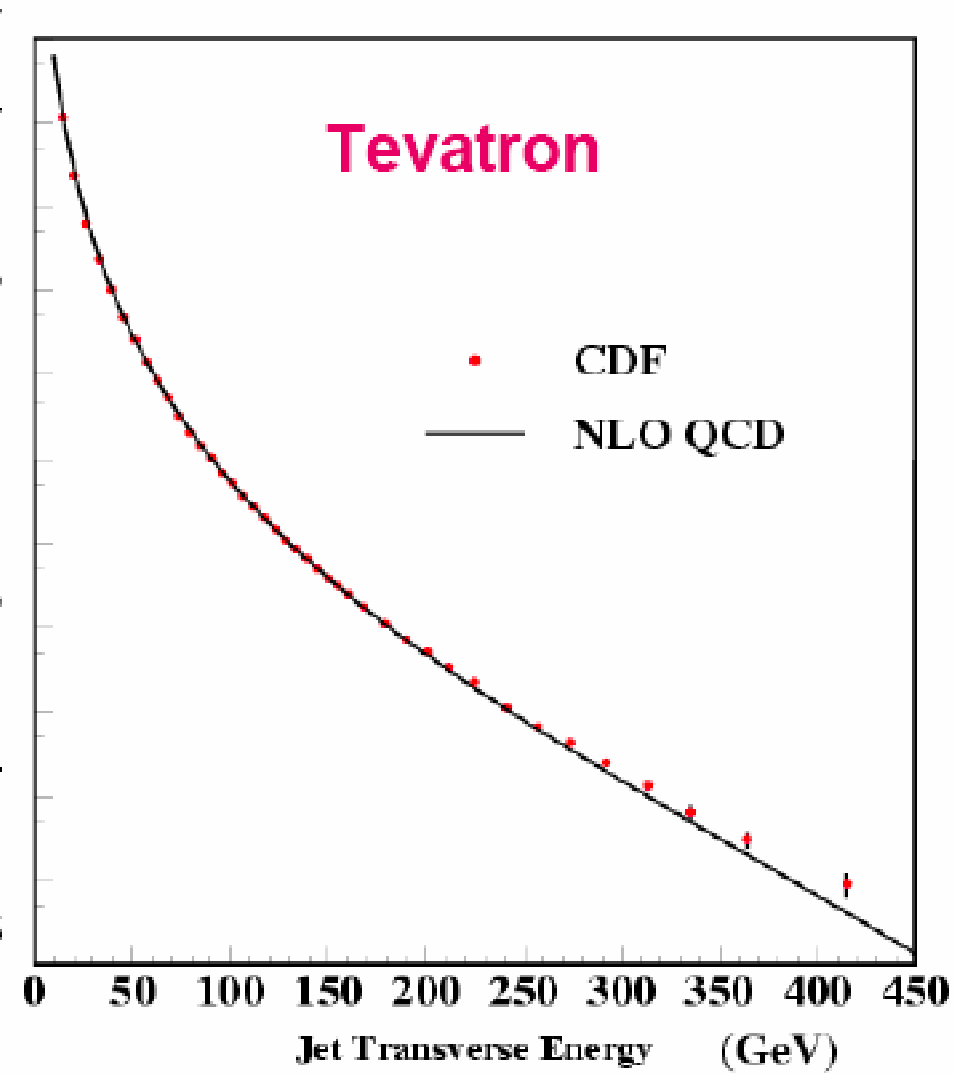
SM Physics we know but we need to know better

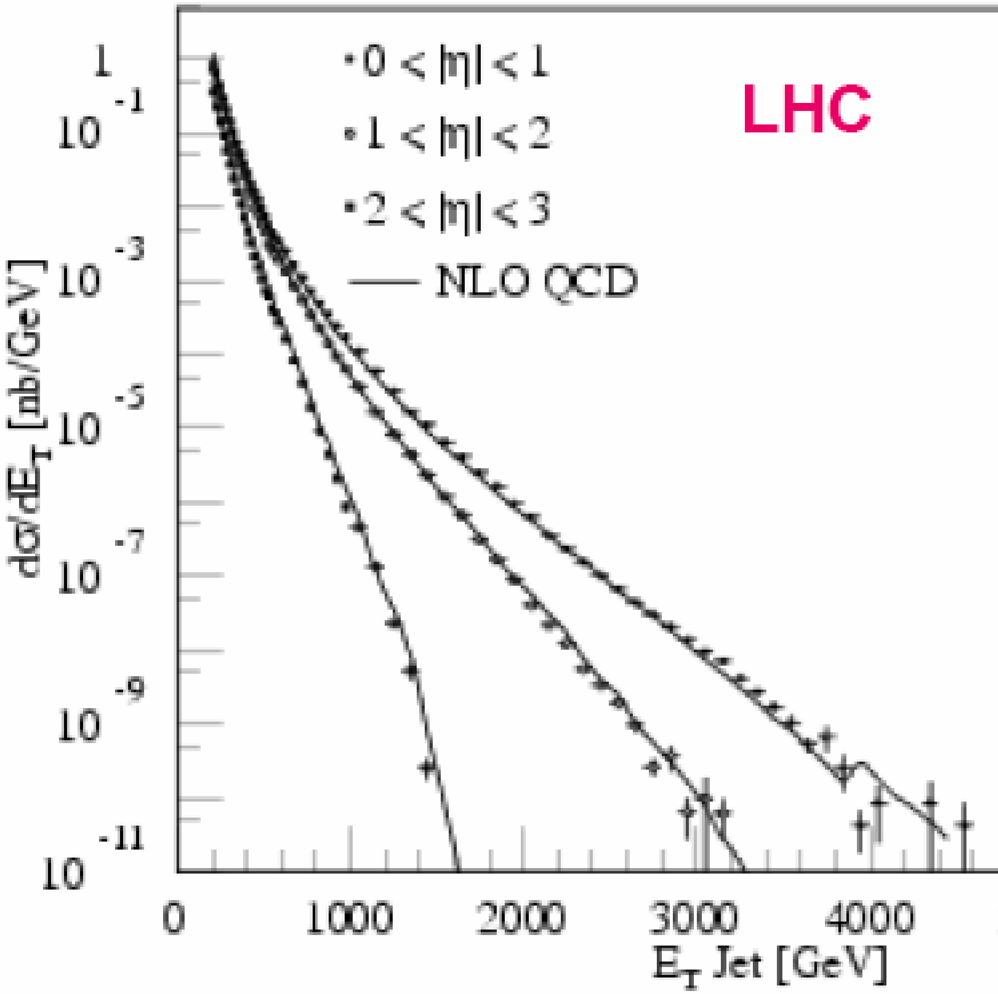
QCD, $\sigma(W,Z)$, m_W, m_t

SM Physics we know is there but not seen yet

SM Physics we do not know if it is there or not!

Outlook





ressive agreement over 9 orders nagnitude! At high E_T statistically ted. Theoretical uncertaintes

Enormous rates (10^3 events/s v E_T>100 GeV).

How to calibrate jet energy scale?

increased by order of magnitudes wrt
on.

s with vectors bosons, tops and heavy and
s with rates >1 Hz.

physics down order of magnitudes.

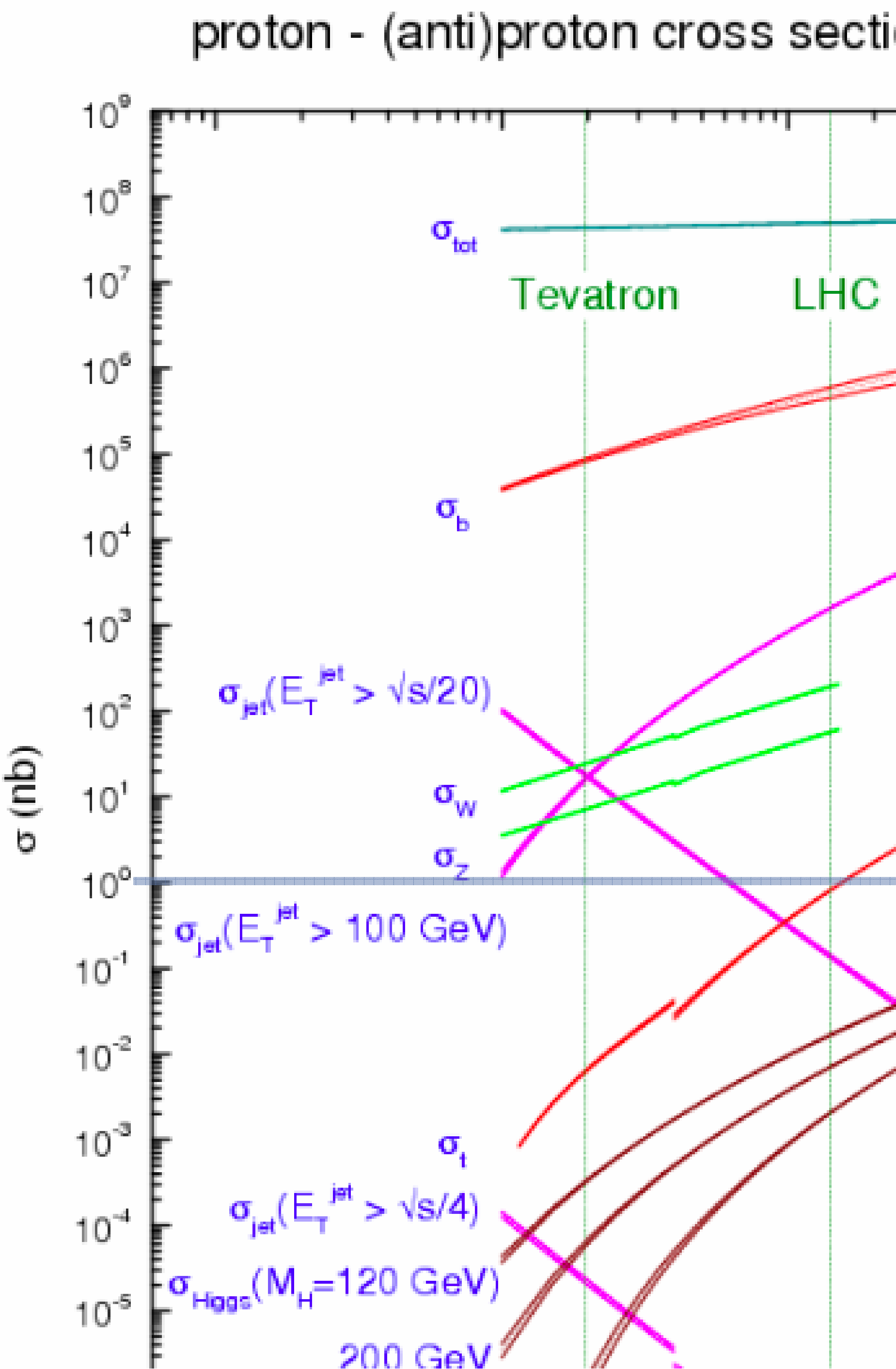
to understand QCD backgrounds well!

factorization theorem for short-distance
ve processes:

$$= \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab \to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

gredients necessary:

on Distribution functions (from exp).



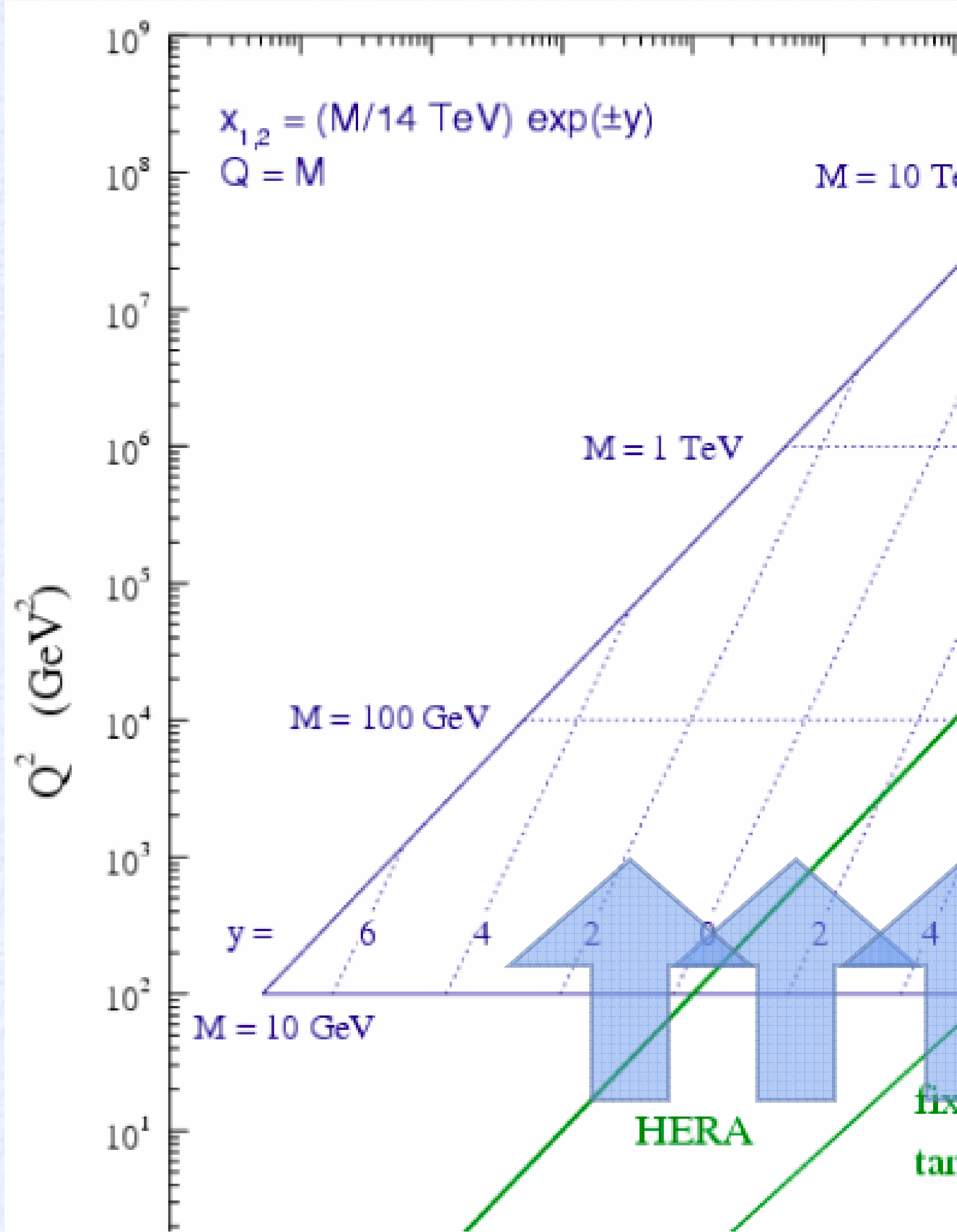
measured at HERA and fixed-target ments. x dependence from data. endence from DGLAP evolution.

tly:

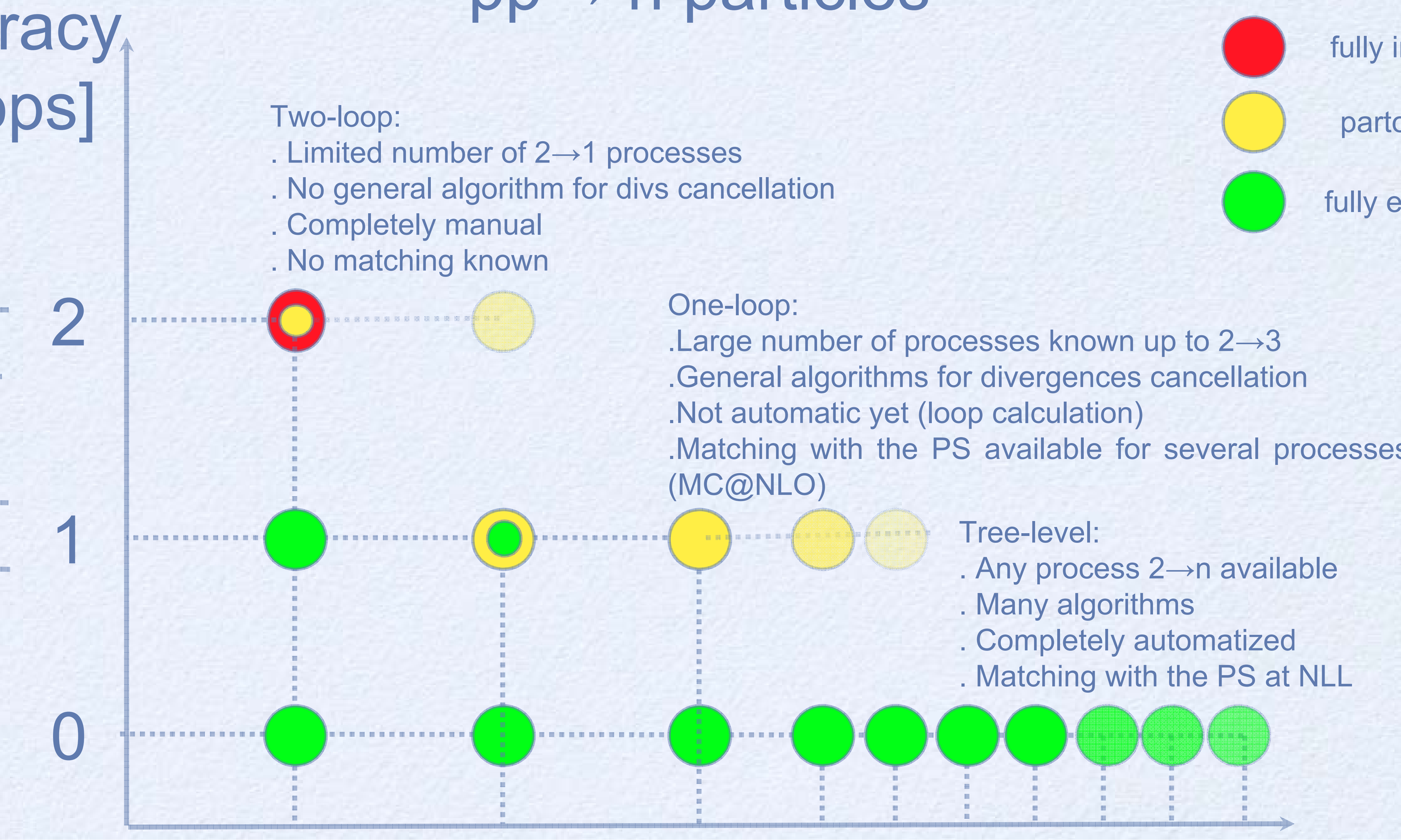
calculation of the 3-loop splitting kernels ardest calculation in QCD") ermaseren,Vogt. 2004]

er with short distance NNLO calculation ts of NNLO PDF sets. [MRST and Alekhin,

with errors: Various "traditional ds",[CTEQ and MRST, 2003]. Also new ches, the functional space [Giele, Keller,



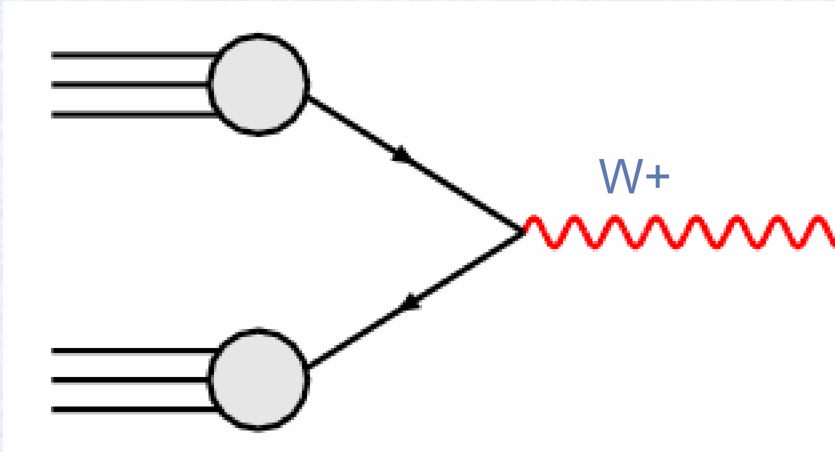
pp→ n particles



W cross section

$$\sigma^{th}(W) = \sum_{ab} \mathcal{P}_{ab} \otimes \hat{\sigma}_{ab}(W)$$

$$\sigma^{exp}(W) = \frac{1}{BR(W \to \ell\nu)} \frac{1}{\int \mathcal{L}dt} \frac{N^{sig}}{A_W}$$



asuring σ(W), one needs to estimate the acceptance A_W eory and the luminosity from an independent source. A clusive description of the final state is needed.

y is accurate enough, one can use σ(W) to:

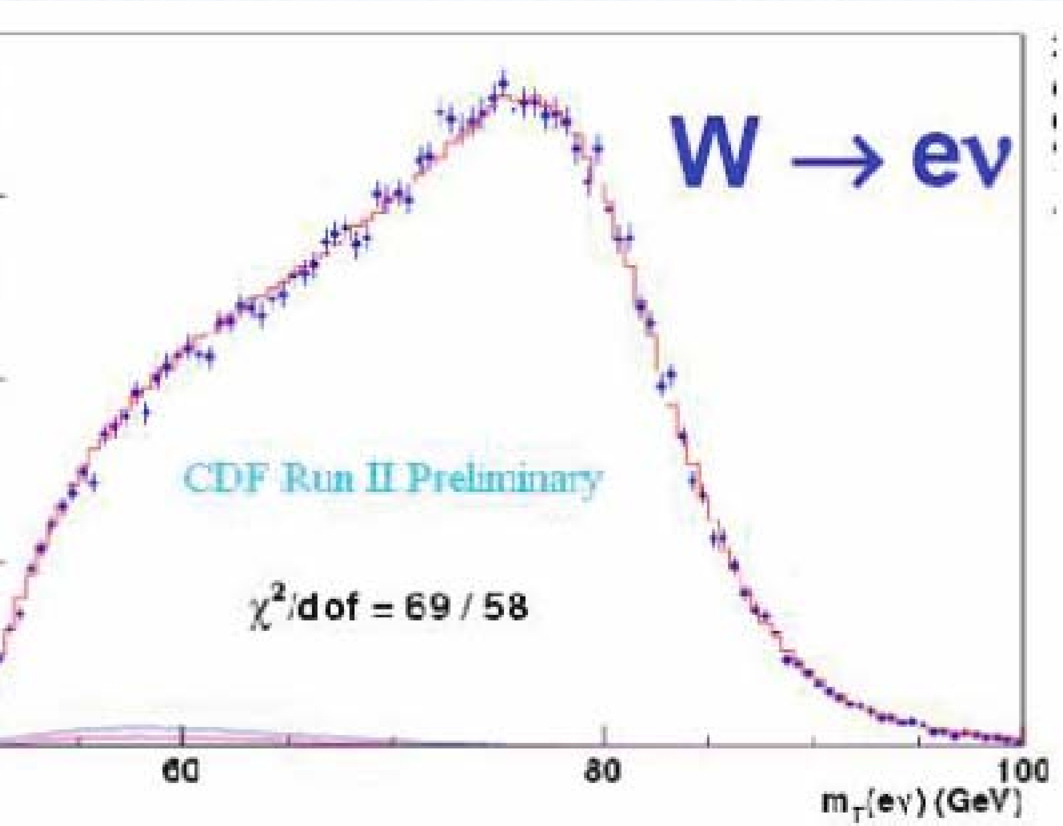
ectly measure Γ_W
R= σ(W) BR(W→lν)/σ(Z) BR(Z→ll))
act direct information on the PDF
sure the collider luminosity
act parton-parton luminosity (=luminosity+PDF)

Theory Status:

Best QCD predictions at present:
> Fully exclusive (PS interfaced)
at NLO+NLL[Frixione, Webber,
> Partly exclusive prediction at N
[Anastasiou, Dixon, Melnikov, P
> Resummed pt distribution at NL
[Balazs, Qiu, Yuan, 1995]
> 1-loop EW corrections
[Baur, Wackeroth. 200

Spin correlations are important!
[Frixione, Mangano, 2004]
Exclusive NNLO calculation WIT

W mass

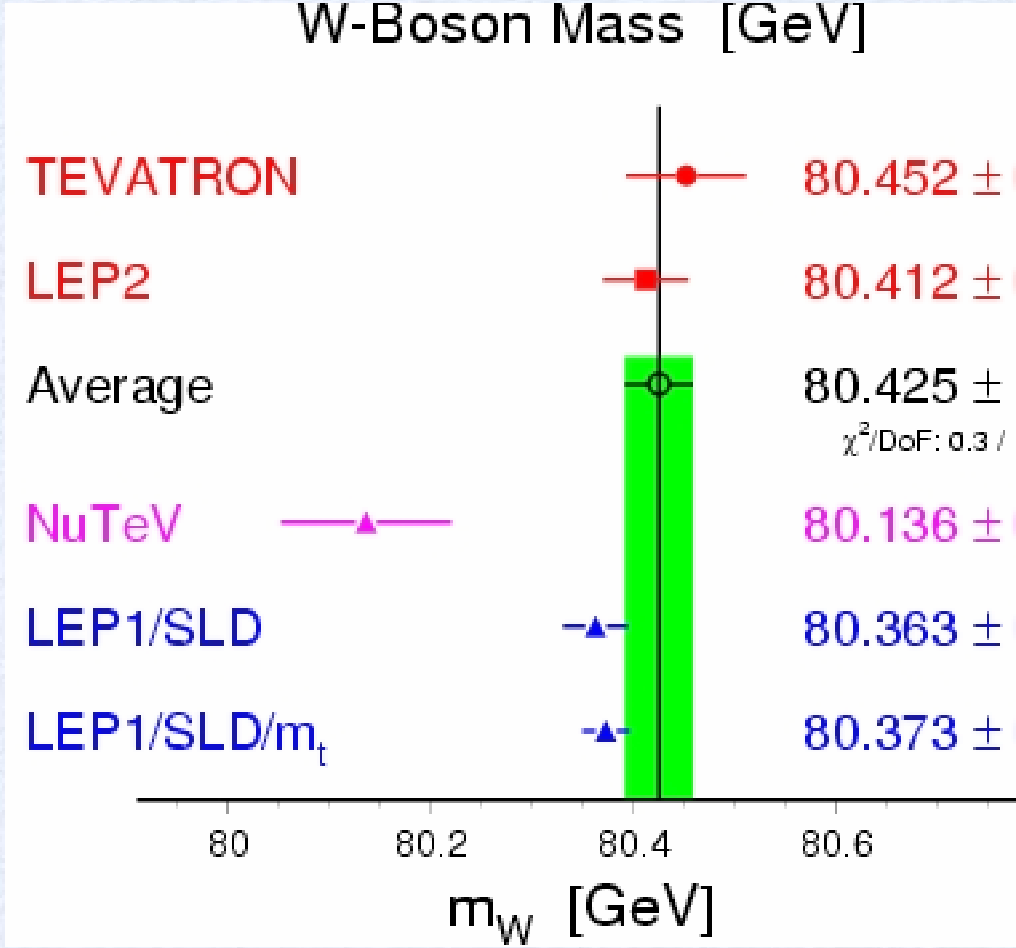


n II expectation:

prove on LEP2 result: δm_W=40 MeV 2fb^{-1} per lepton channel per periment.

C expectation:

$_W$=15 MeV from transverse mass

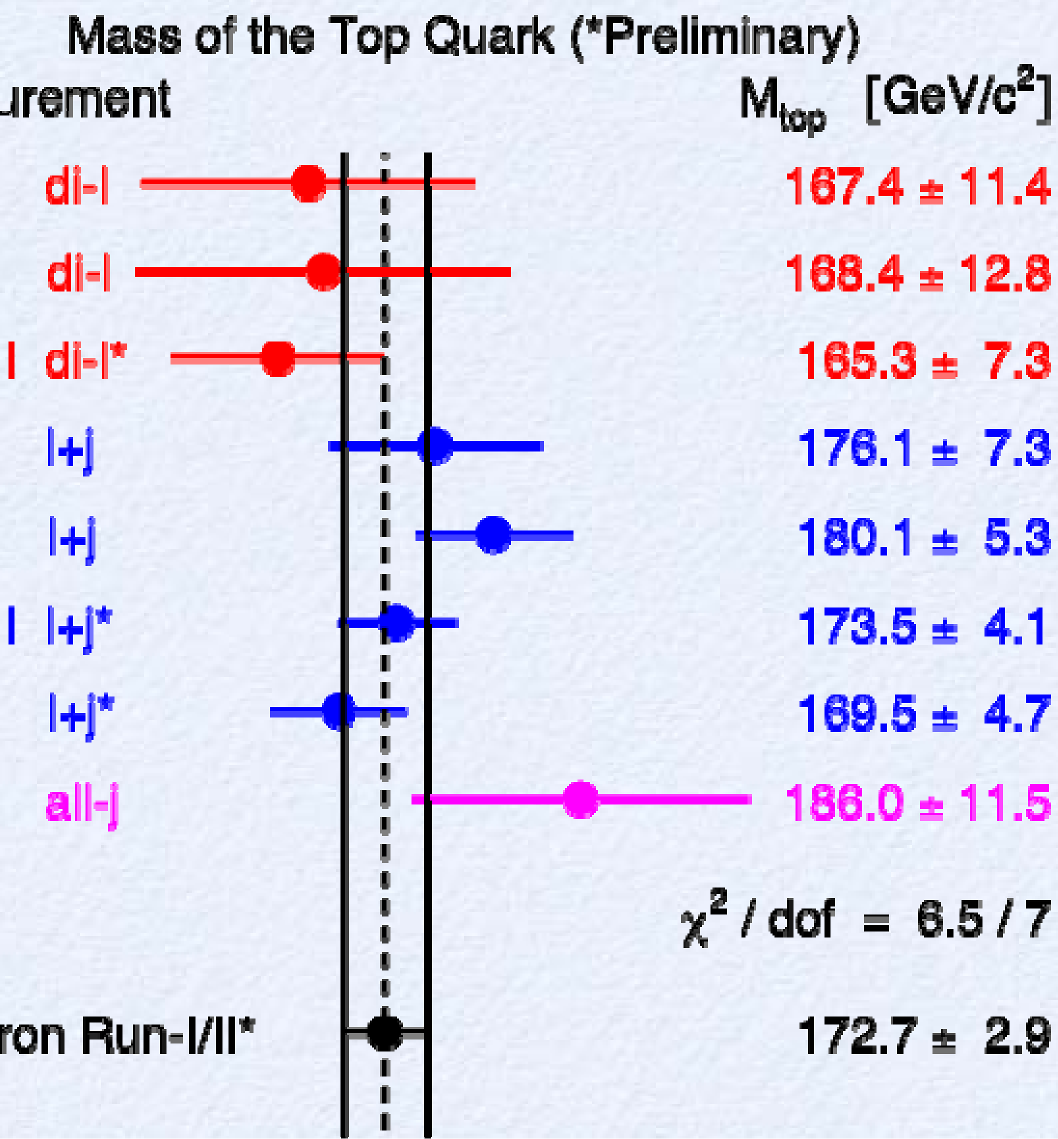


Need:

$$\delta m_W \sim 7 \times 10^{-3}\ \delta m_t$$

In the SM, it is the only quark with a “natural mass”:

$m_{top} = y_t v/\sqrt{2} \approx 174$ GeV $\Rightarrow y_t \approx 1$



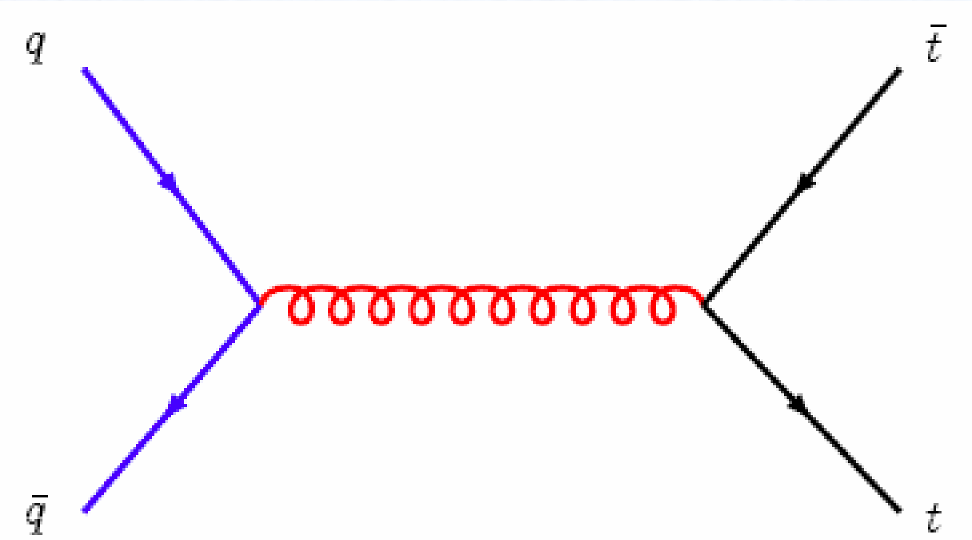
Many methods. Two important ones

I. Template mass: global kinematica
based on likelihood of matching the
masses of the different objects in th
chain.

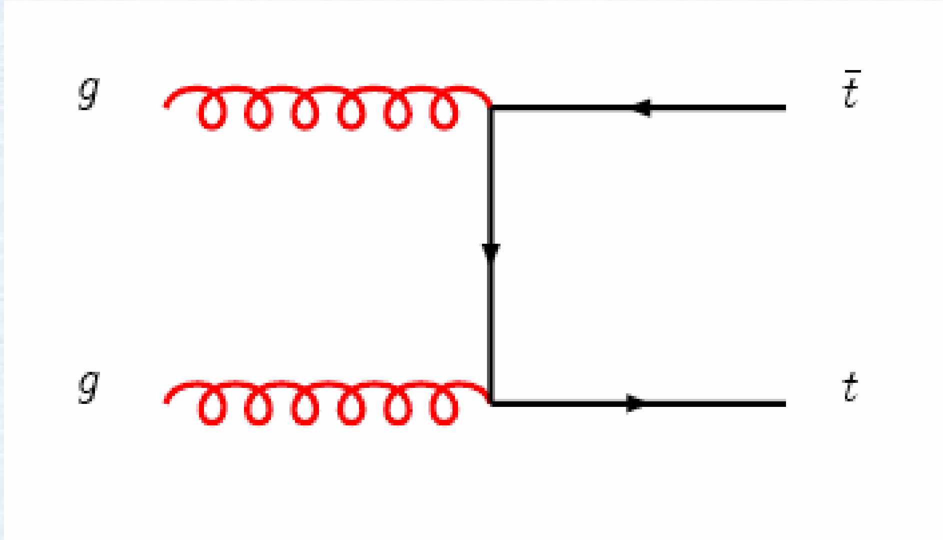
II. Matrix element (also called DLM)
“maximal” use of the information co
the ME (both signal and backgroun
build a likelihood of an event has a
top mass.

Both methods suffer from jet ES an
ISR/FSR uncertainties.

Tevatron



LHC



85% of the total cross section

10 tt pairs per day

% of the time there is extra radiation that pt(tt)>15 GeV.

are produced closed to threshold, in a $_1$[8] state. Same spin directions. 100% rrelated in the off-diagonal basis.

orry because of the backgrounds:

90% of the total cross section

1 tt pair per second

Almost 70% of the time there is radiation so that pt(tt)>30 GeV.

tt can be easily produced away threshold. On threshold they ar state, with opposite spin directio 100% correlation.

OUTLINE

Motivations

SM Physics we know but we need to know better

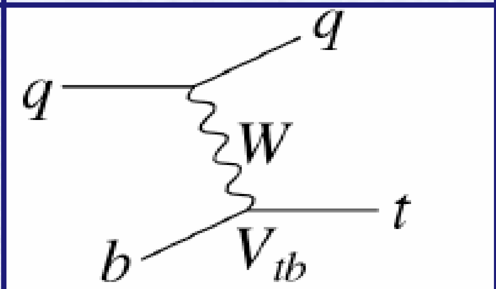
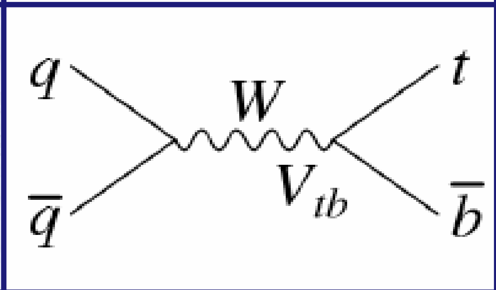
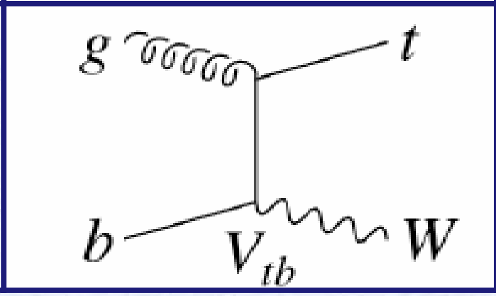
SM Physics we know is there but not seen yet

Single-top

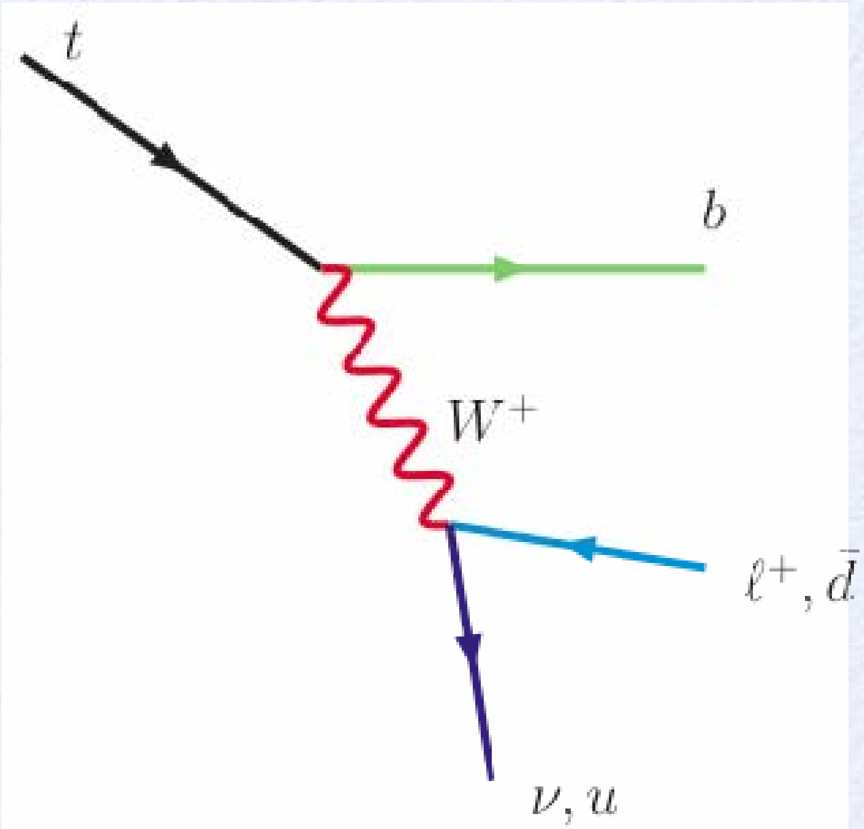
SM Physics we do not know if it is there or not!

Outlook

Single top

Process	Diagram	Accuracy	CTEQ6M, mt=178 GeV,th er σ (pb) TeV II	 LHC
channel		NLO [Stelzer, Sullivan, Willenbrock. 1997]	1.85	239
-channel		(N)NLO [Smith, Willenbrock.1996 Chetyrkin,Steinhauser. 2001]	0.82	9.8
tW		NLO [Campbell, Tramontano. '05]	0.129	64

signals available in MCFM (Campbell, Ellis) and t- and s-channel soon in MC@NL
ixione, Webber). Most of the backgrounds are also known at NLO. However, analys



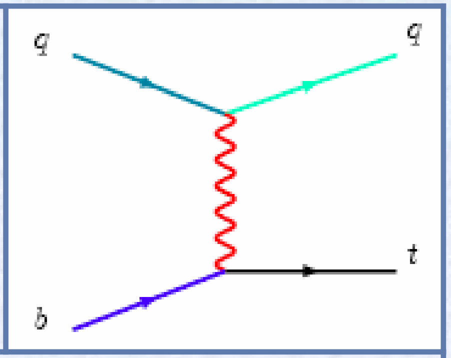
Top can decay into a real W $\Rightarrow$
$\Gamma \approx G_F m_t^3 |V_{tb}|^2 >> \Lambda_{QCD} \Rightarrow$
Very short life. Top is the only quar
does not feel non perturbative QCD
effects! No top-hadrons, no top-
spectroscopy but a ``clean" quark.

In an experiment one is sensitive no
to the total width but to the branchin
ratio:

$$R = \frac{\Gamma(t \to Wb)}{\Gamma(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 +}$$

CDF has performed such a measurem
R=0.94 does only tell us that $V_{tb} >> V_{td}$

t channel



SM info

st rate, dominant at the LHC, where 62%
8% anti-top.

$Vtb|^2$.
rd jet in final state, top central,
times one extra forward bottom. FB
metric at the Tevatron. Main background
s+jet (and tt at the LHC).

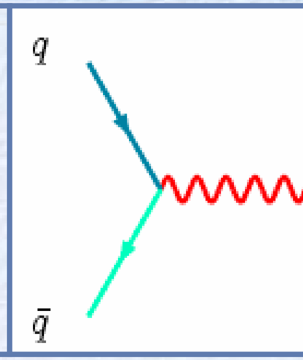
polarized along spectator jet (most of
nes) in the 2→2 configuration.

BSM window

tive to new production modes,

Tait
and

s channel



SM info

Smallest at the LHC, where 63% top, 37%
anti-top.

$\sigma \propto |Vtb|^2$. Very well known. DY mig
used for normalization.

Central high-pt b-jet. Main backgrounds
and W+Q's+jets.

Top is polarized along beam axis a
Tevatron.

BSM window

Sensitive to vector (extra Z) and scalar (t

OUTLINE

Motivations

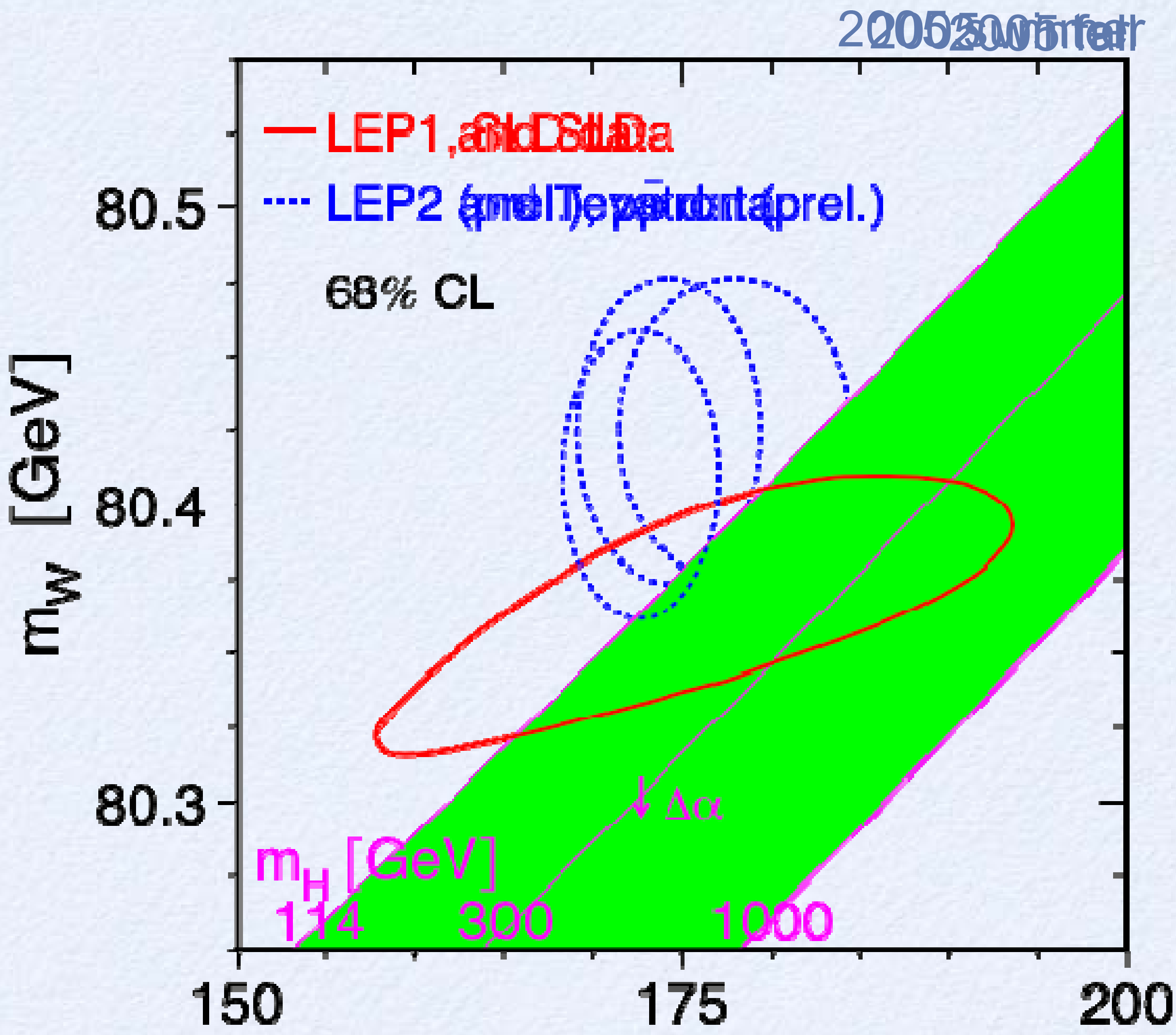
SM Physics we know but we need to know better

SM Physics we know is there but not seen yet

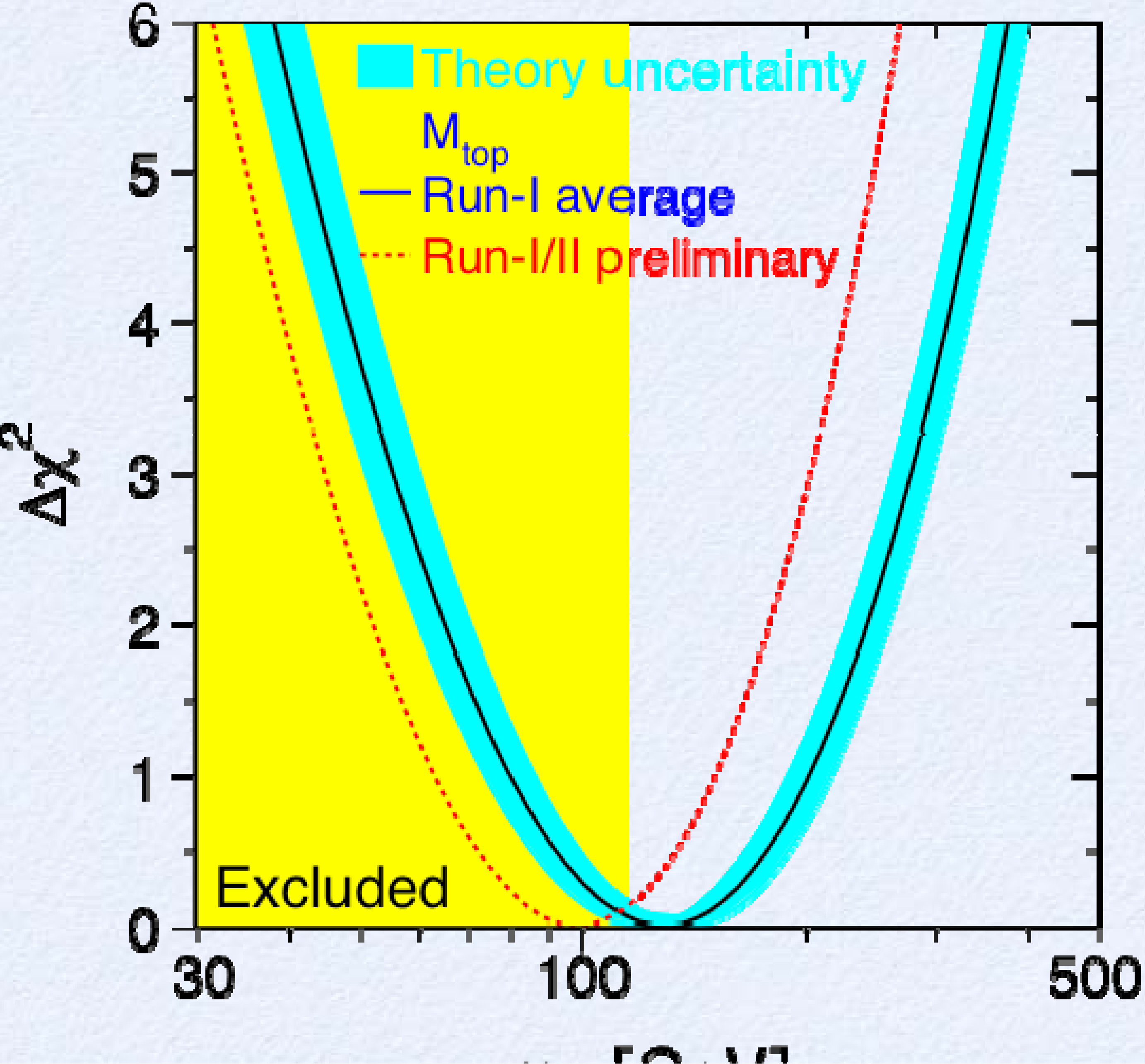
SM Physics we do not know if it is there or not!

Higgs

Outlook



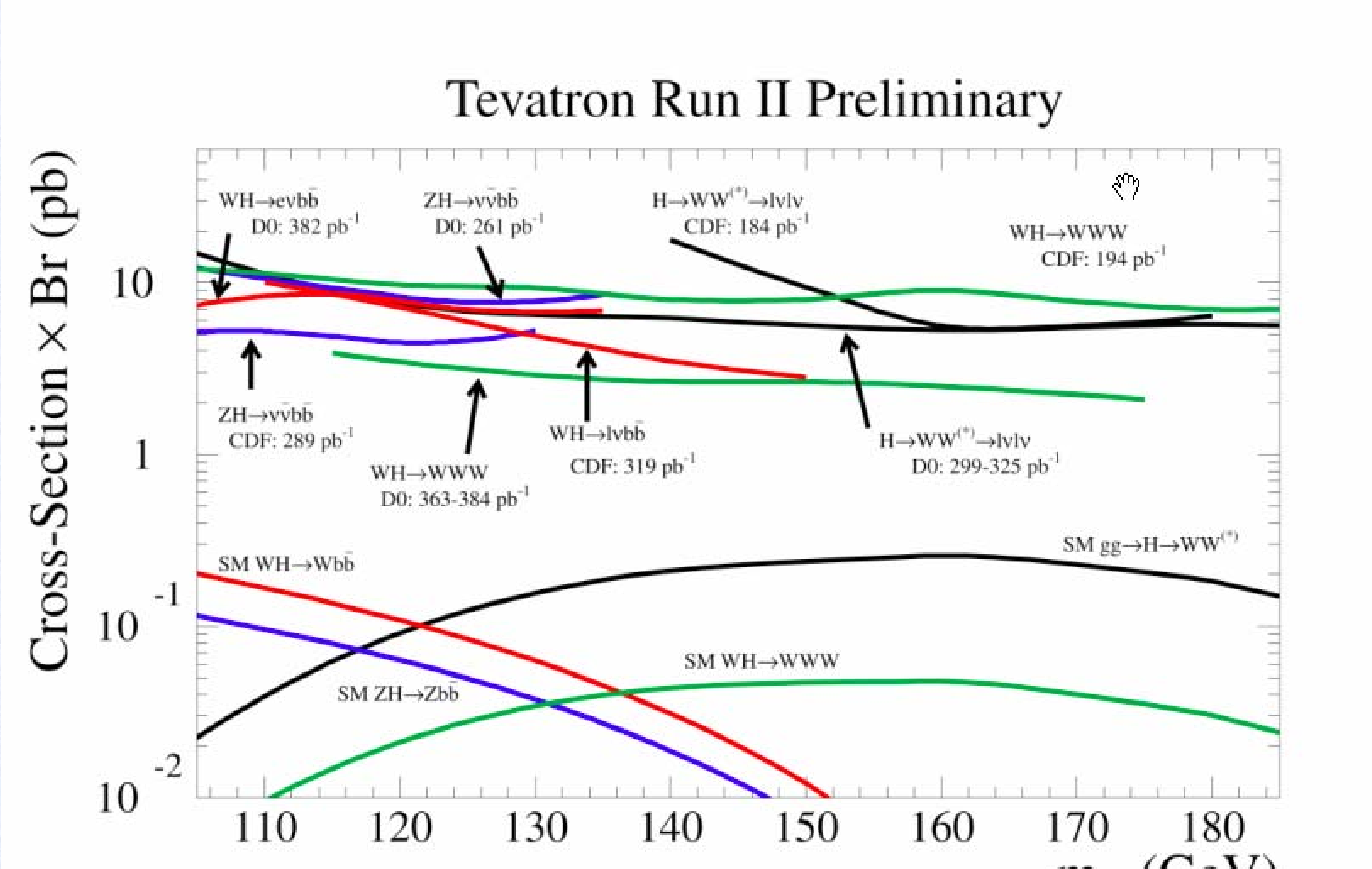
LEP1,
LEP2
(prel.)
68% CL
80.5
80.4
80.3
mW [GeV]
mH [GeV]
114
300
1000
Δα
150
175
200



m_H>114 GeV from L

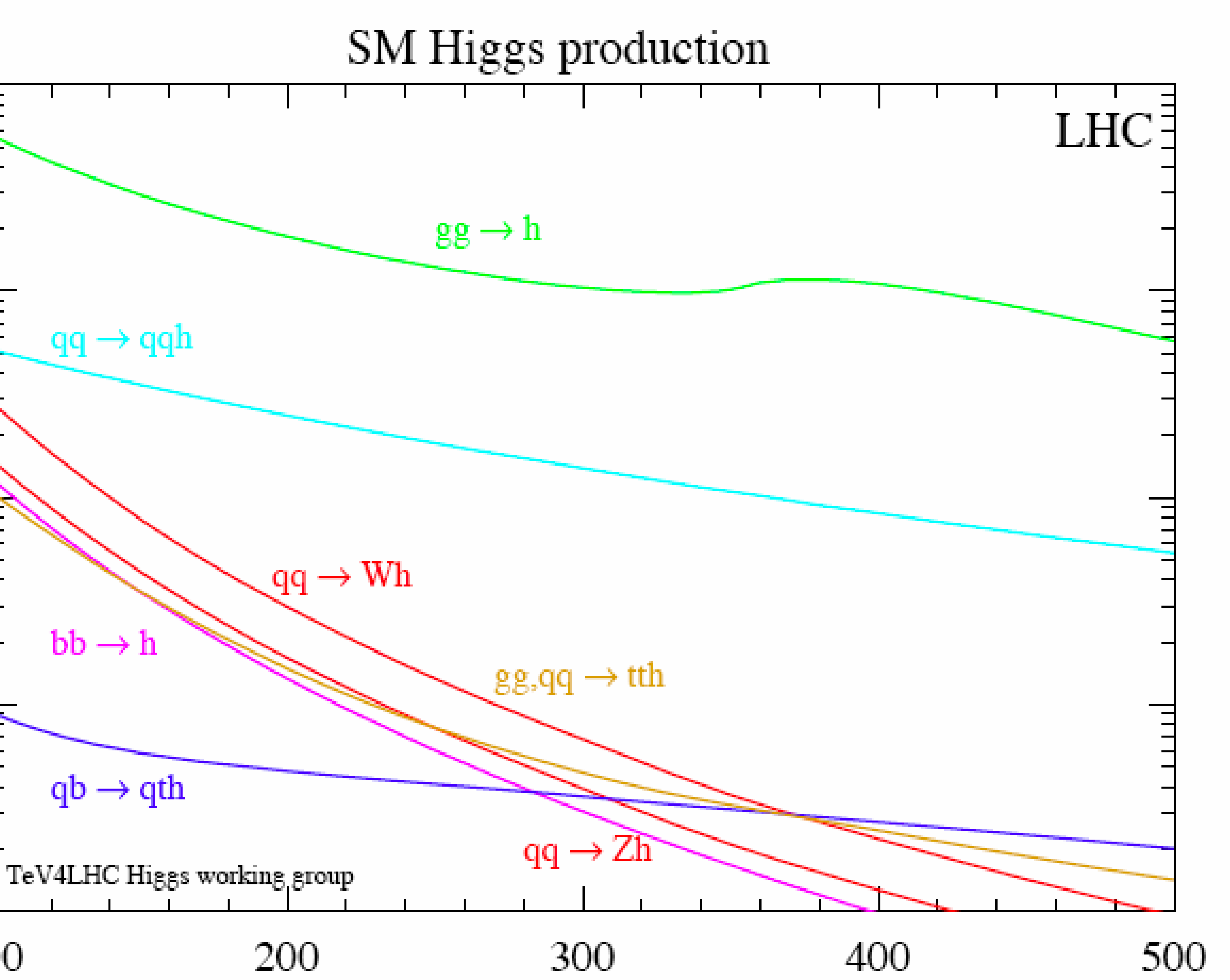
m_H<208 GeV @ 95

STAND



Tevatron Run II Preliminary
Cross-Section × Br (pb)
WH→evbb̄
D0: 382 pb⁻¹
ZH→νν̄bb̄
D0: 261 pb⁻¹
H→WW(*)→lνlν
CDF: 184 pb⁻¹
WH→WWW
CDF: 194 pb⁻¹
ZH→νν̄bb̄
CDF: 289 pb⁻¹
WH→WWW
D0: 363-384 pb⁻¹
WH→lνbb̄
CDF: 319 pb⁻¹
H→WW(*)→lνlν
D0: 299-325 pb⁻¹
SM gg→H→WW(*)
SM WH→Wbb̄
SM WH→WWW
SM ZH→Zbb̄
10
1
10⁻¹
10⁻²
110
120
130
140
150
160
170
180

LHC

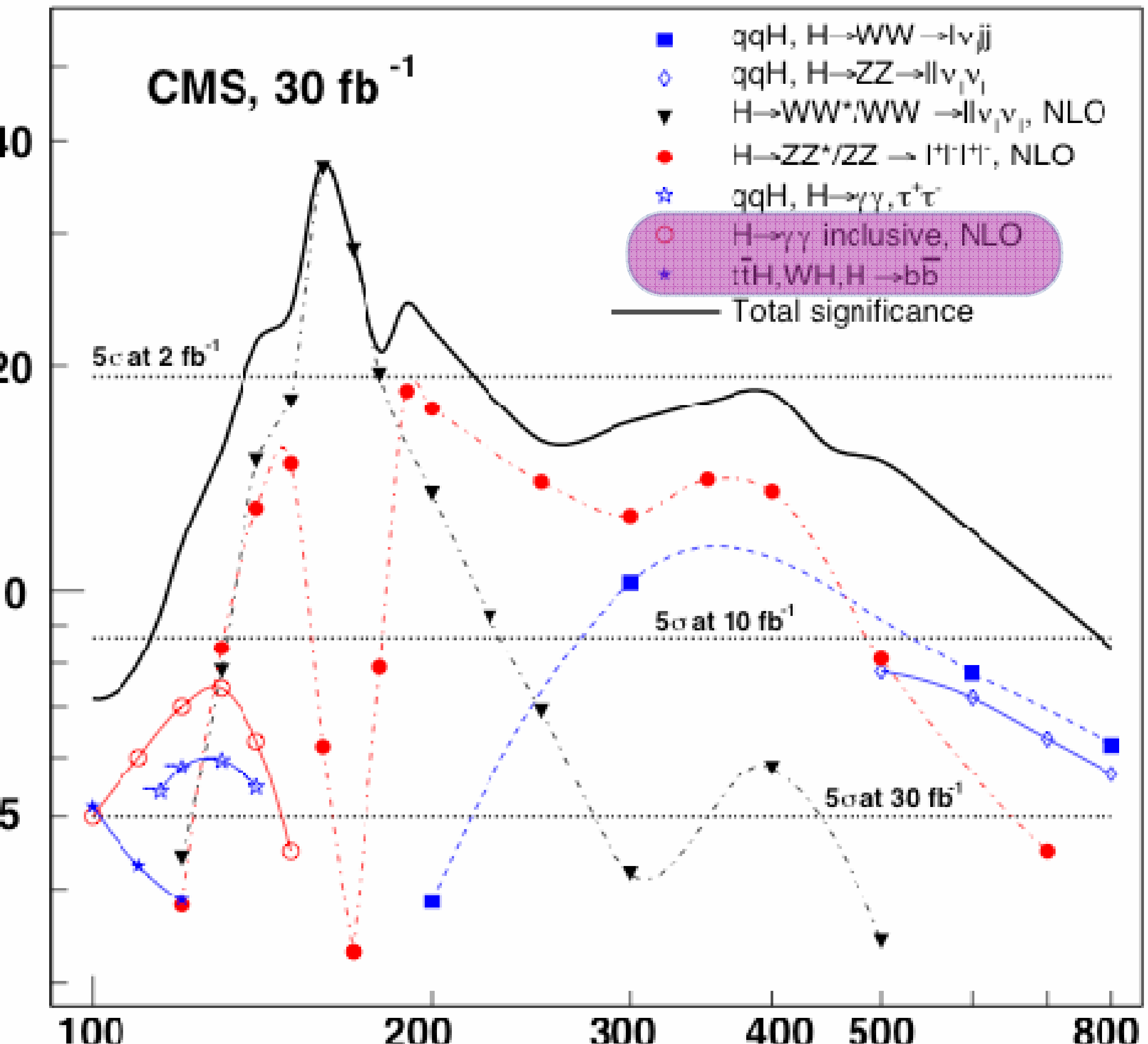


All relevant signals known at NLO in QCD.

Various channels/decay are complementary: Inclusive/associated pro with rare/common decay r

Very different strategies ar systematics.

LHC



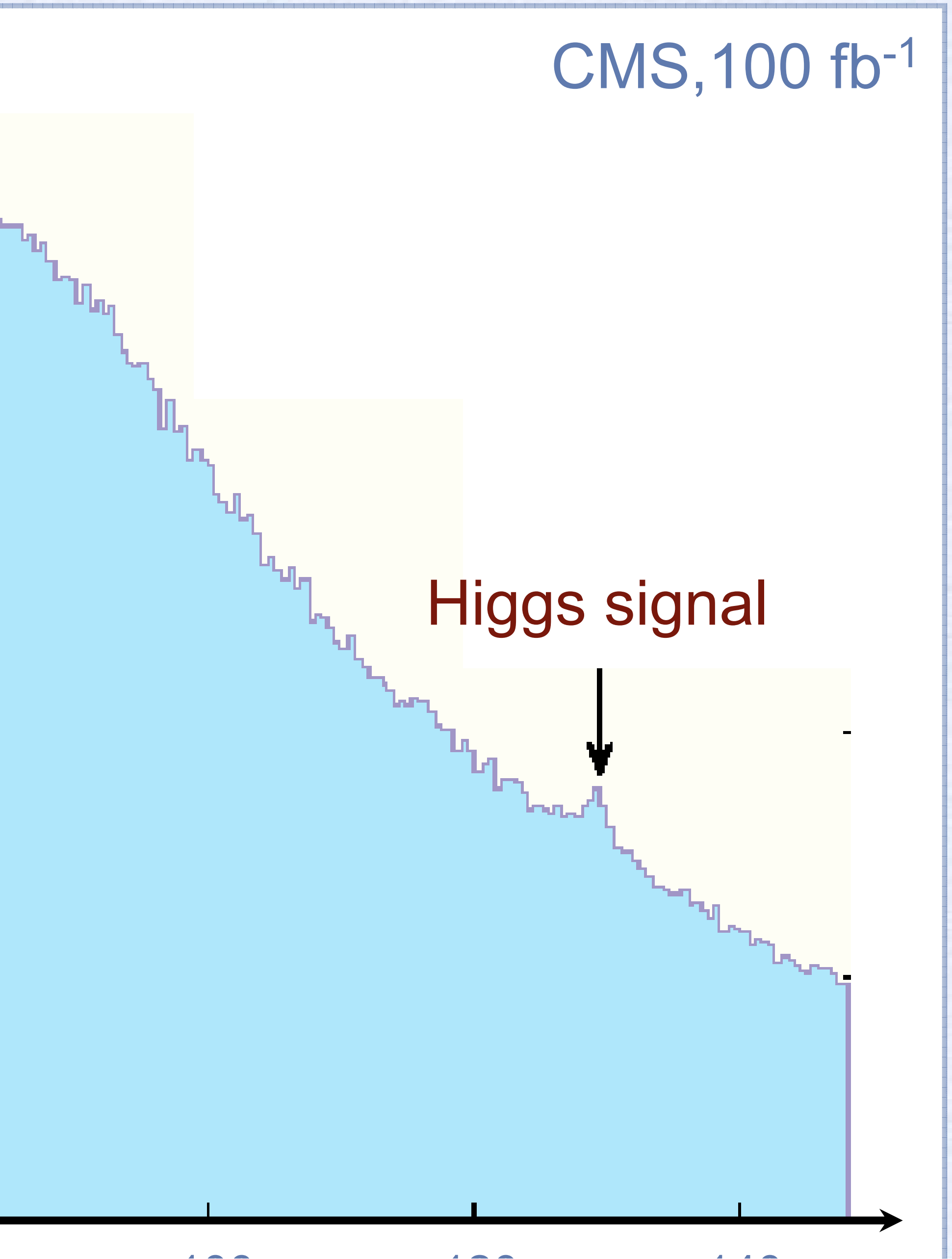
All relevant signals known at NLO in QCD.

Various channels/decay are complementary: Inclusive/associated pro with rare/common decay m

Very different strategies ar systematics.

Two Examples for light Hig

1. gg→H→γγ
2. gg→ttH→ttbb

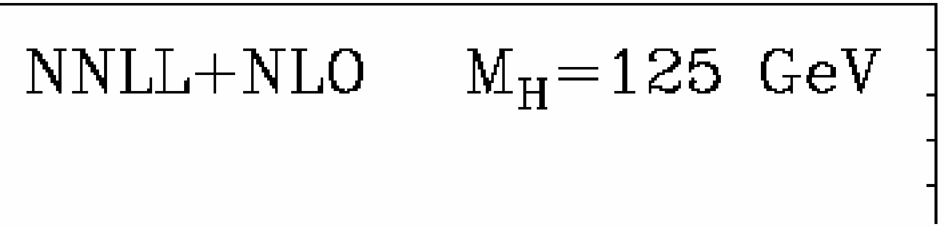


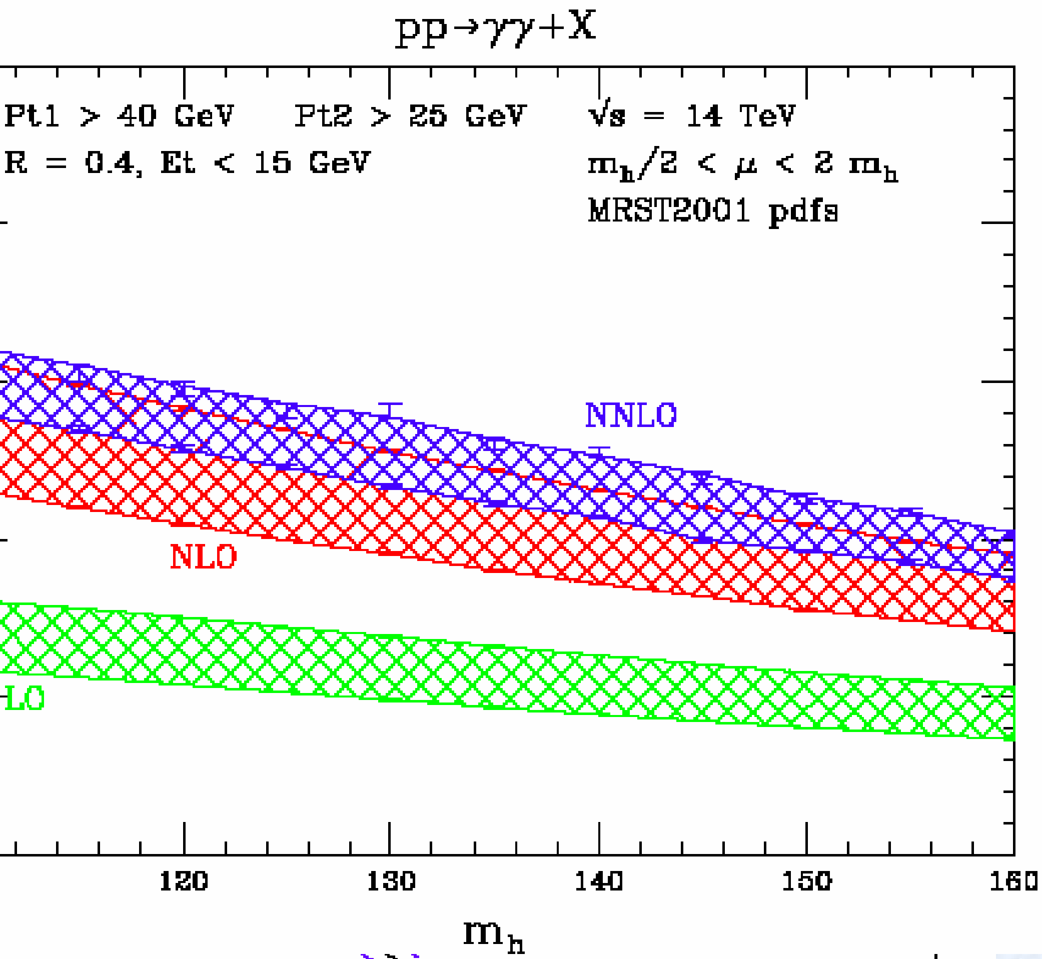
Huge background from QCD.

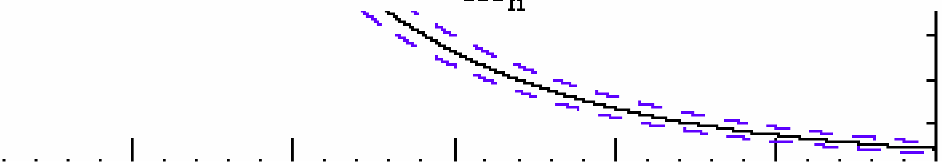
qq→γγ known at NLO (DIPHOX) including fragmentation contributions
[Binoth, Guillet, Pilon, Werlen. 2000]

gg→γγ direct known at NLO (two-loop)
[Bern, Dixon, Schmidt. 2002]

On the other hand this is an example of a di that does not need an accurate the prediction for the background. Data model suffice.







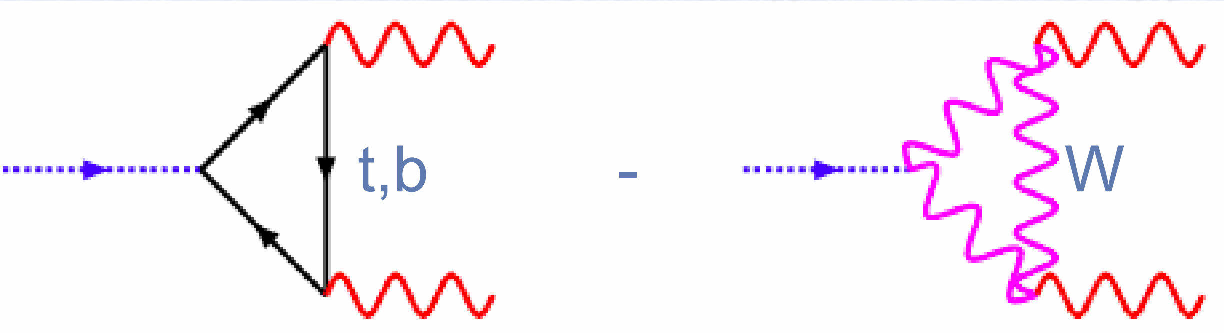
Dominant production mechanism at hadron colliders.
The story of the most accurate prediction in QCD:

QCD corrections:
[Daswon.1991] [Djouadi, Graudenz, Spira, Zerwas. 199
[Kramer, Laenen, Spira.1998] [Catani, De Florian, Graz
[Harlander, Kilgore.2001,2002] [Anastasiou, Melnikov.2
[Ravindran,Smith, Van Neerven. 2003]
[Catani, De Florian, Grazzini, Nason.2003]

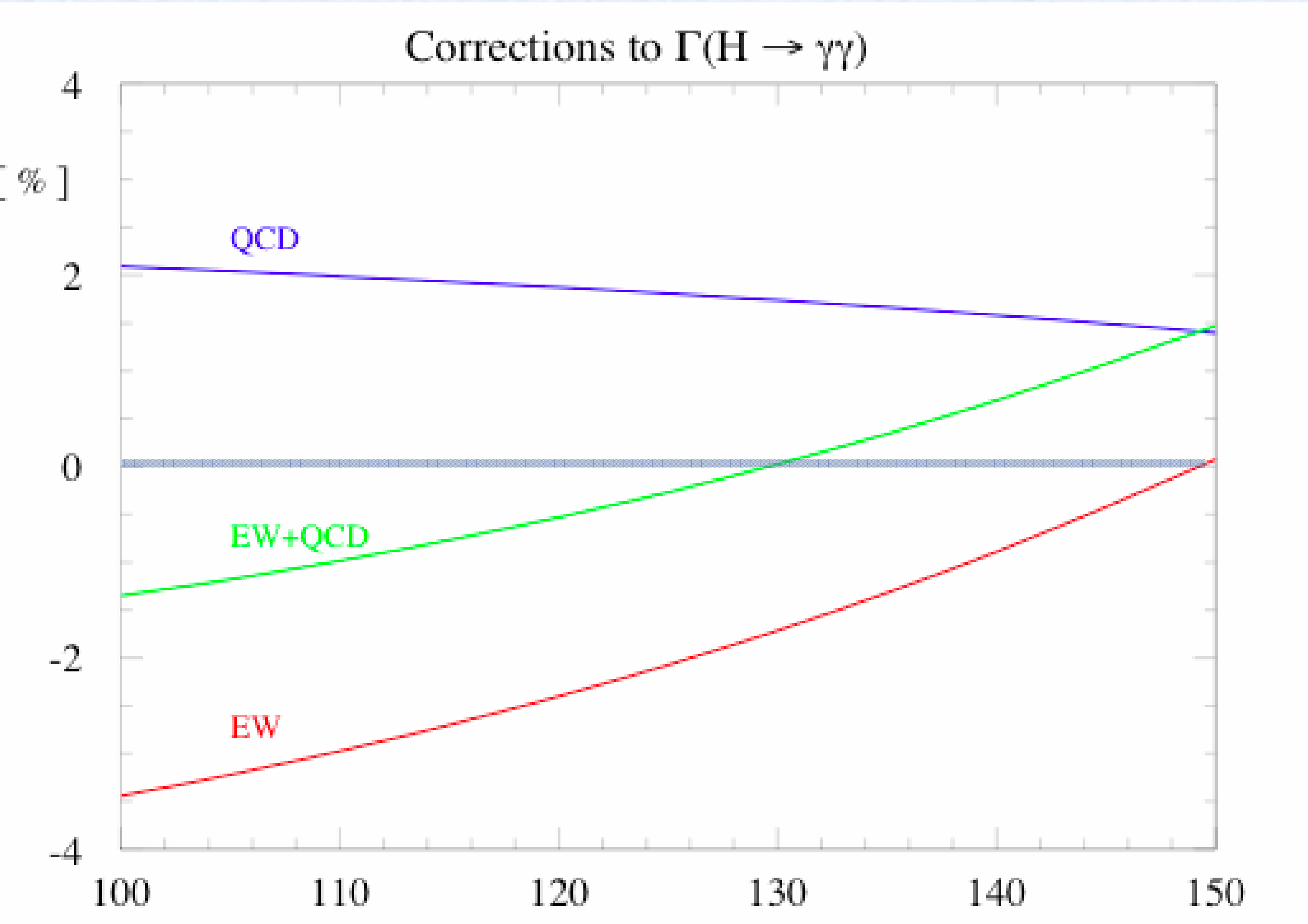
Two-loop EW corrections:
[Djouadi, Gambino, Kniehl. 1998]
[Aglietti, Bonciani, Degrassi, Vicini. 2004]
[Degrassi, FM. 2004]

PDF evolution at NNLO (“Guinness of QCD”):
[Moch, Vogt, Vermaseren, 2004]

Best QCD predictions at present:
> Fully exclusive (PS interfaced) predictio
at NLO+NLL[Frixione, Webber, 2003]
> Fully exclusive prediction at NNLO (first
[Anastasiou, Melnikov, Petriello. 2004]



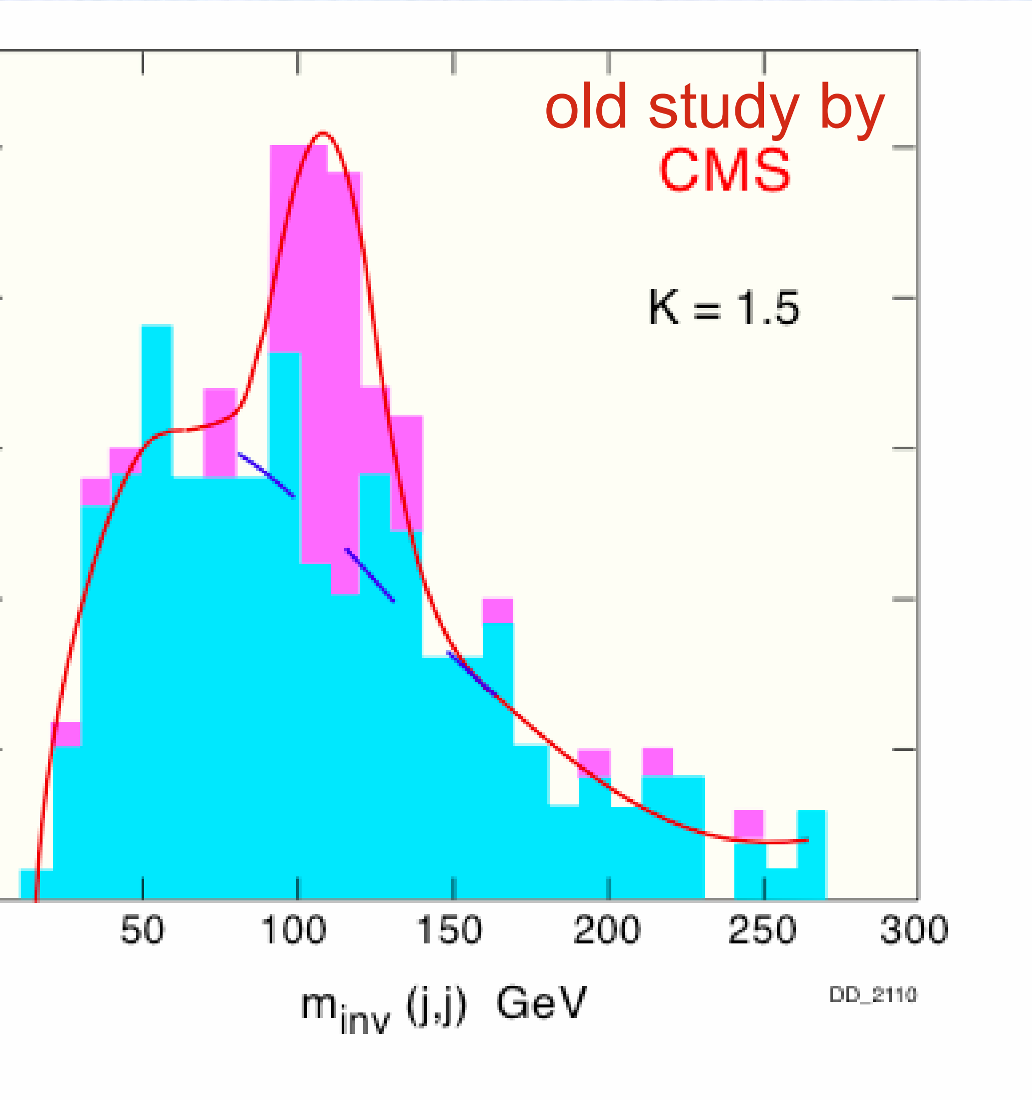
QCD corrections:
[Djouadi, Spira, van der Bij, Z
[Daswon, Kaufmann. 1993]
[Fleischer, Tarasov^2 . 2004]



Two-loop EW corrections:
[Djouadi, Gambino, Kniehl. 1
[Aglietti, Bonciani, Degrassi,
[Degrassi, FM. 2005]

Very small correction
Overall, gg→H→γγ is
of the most
accurate predictions
in hadron collisions!

ttH production



Signal cross section of ~1 pb, known at NLO. K-factor of order 1.
[Beenakker,Dittmaier,Kramer,Plumper,Spira,Z
2002] [Dawson,Jackson,Orr,Reina,Wackeroth

Typical signature 4b+2j+l+mEt: very difficult!

Key issues:
1. Combinatorics
2. b-tagging
3. Invariant mass resolution
4. Background modeling: ttbb,ttjj are known
LO⇒normalization very uncertain.

Extremely good knowledge of the c
necessary.

Higgs couplings

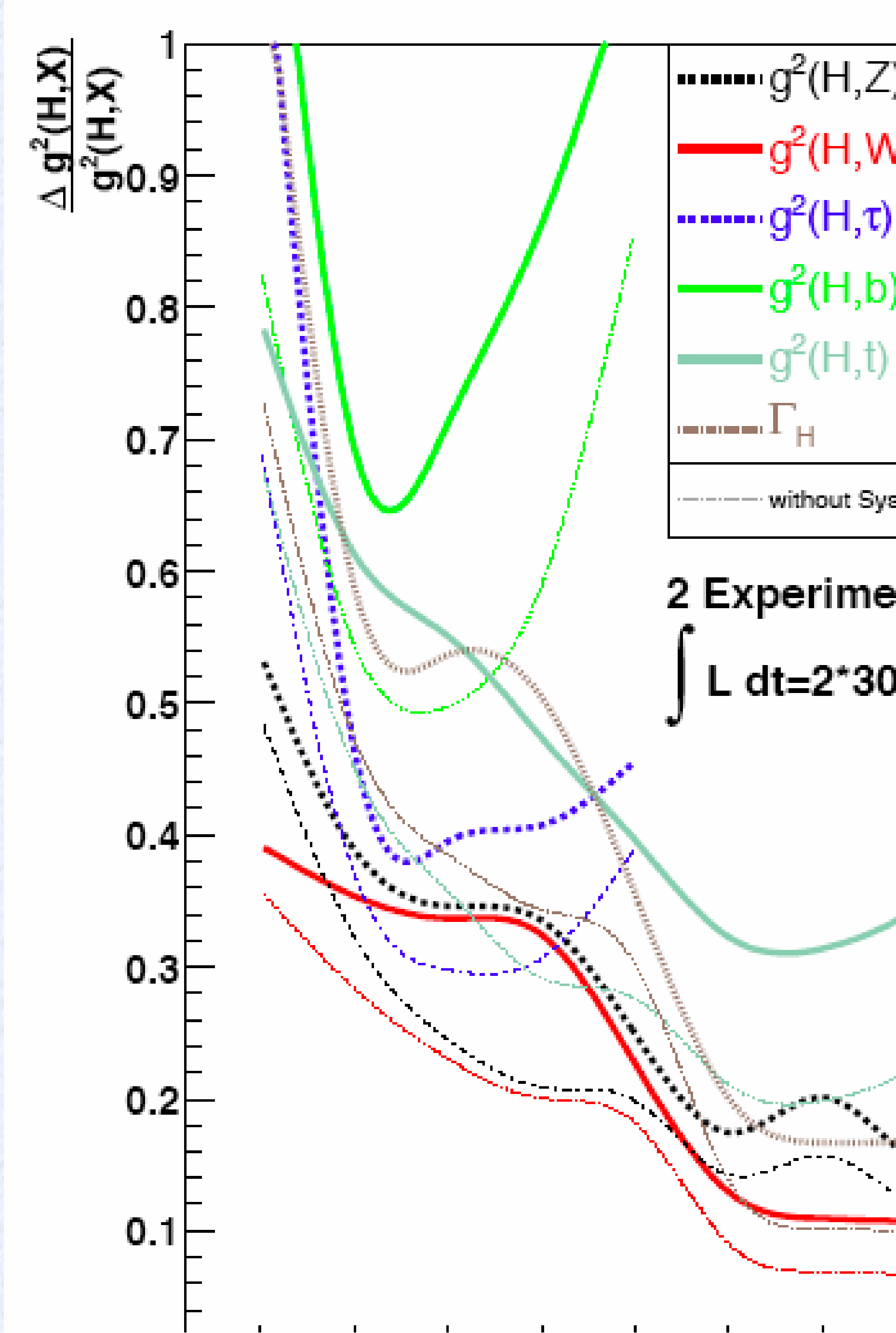
a "Higgs" has been found, its SM nature can
ed by measuring its couplings to fermions,
bosons as well as the Higgs self-coupling.

fit on all the relevant channels for each mass
gg→H; qq→Hqq; qq→ZH,WH;gg→ttH):

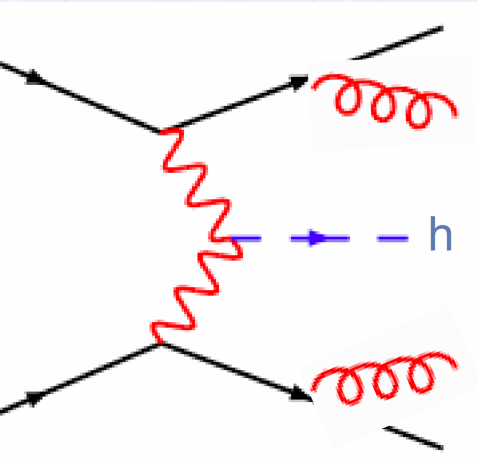
$$) \times BR(H \to xx) = \frac{\sigma_p^{SM}(H)}{\Gamma_p^{SM}} \times \frac{\Gamma_p \Gamma_x}{\Gamma}$$

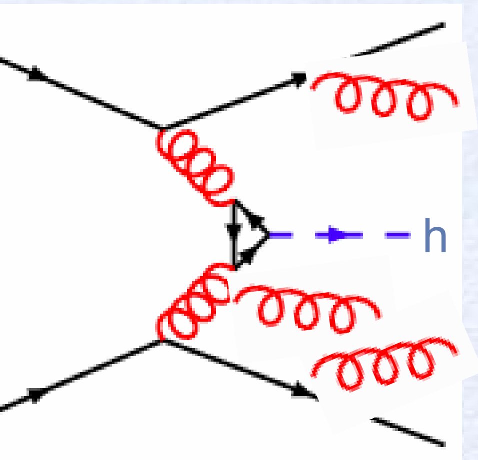
cy of the couplings of 10-30% can be
ed.

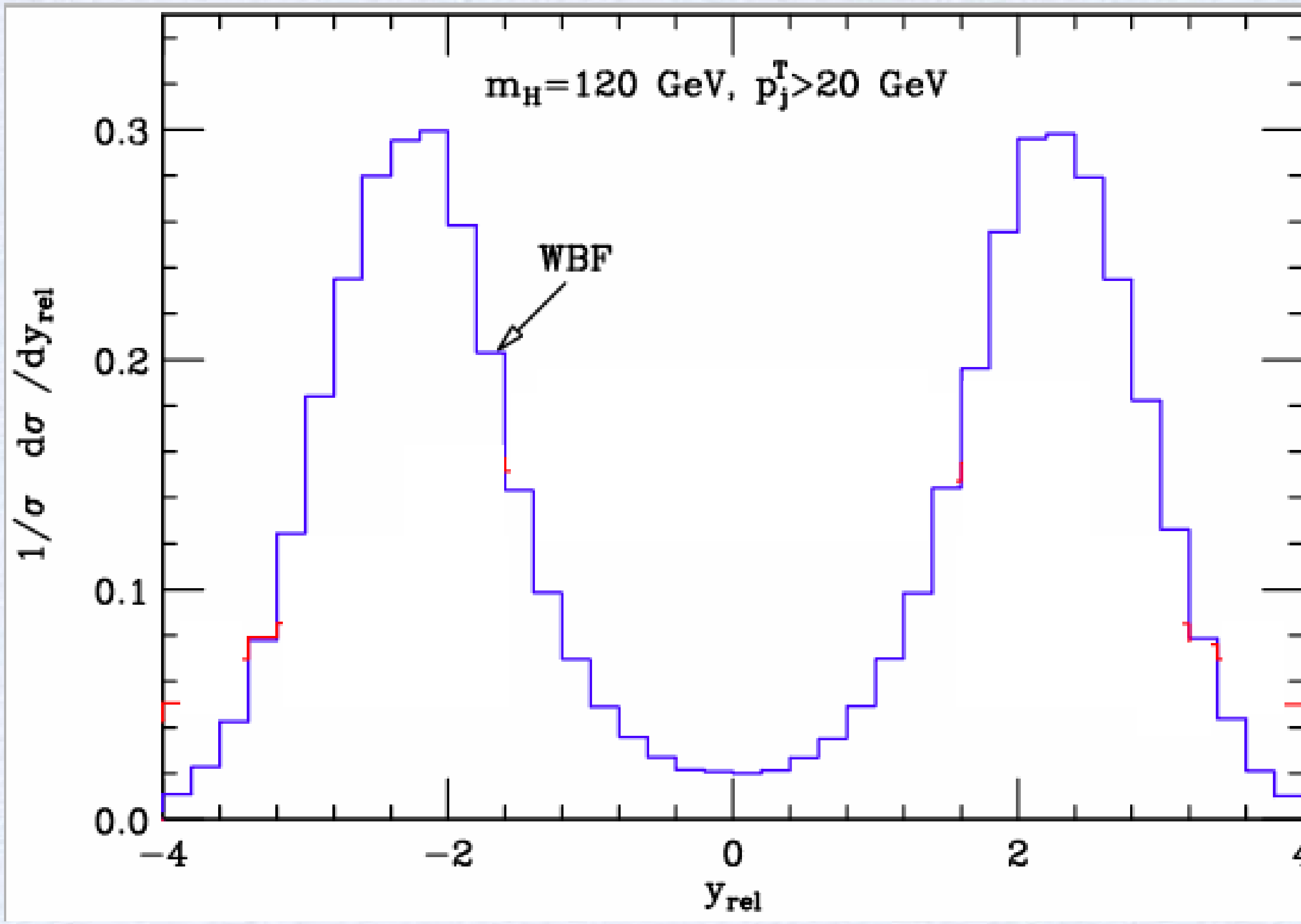
t systematic uncertainty from gg→H
d at NNLO [Anastasiou, Melnikov, Petriello. 2005]



ctor boson fusion will play a crucial role in studying the Higgs properties, in man
ay channels (ZZ,WW,ττ,ϒϒ). Typical signature is two forward jets and a "rapidi
o". Central jet veto will be essential to select not only signal from background, b
o VBF from QCD production.

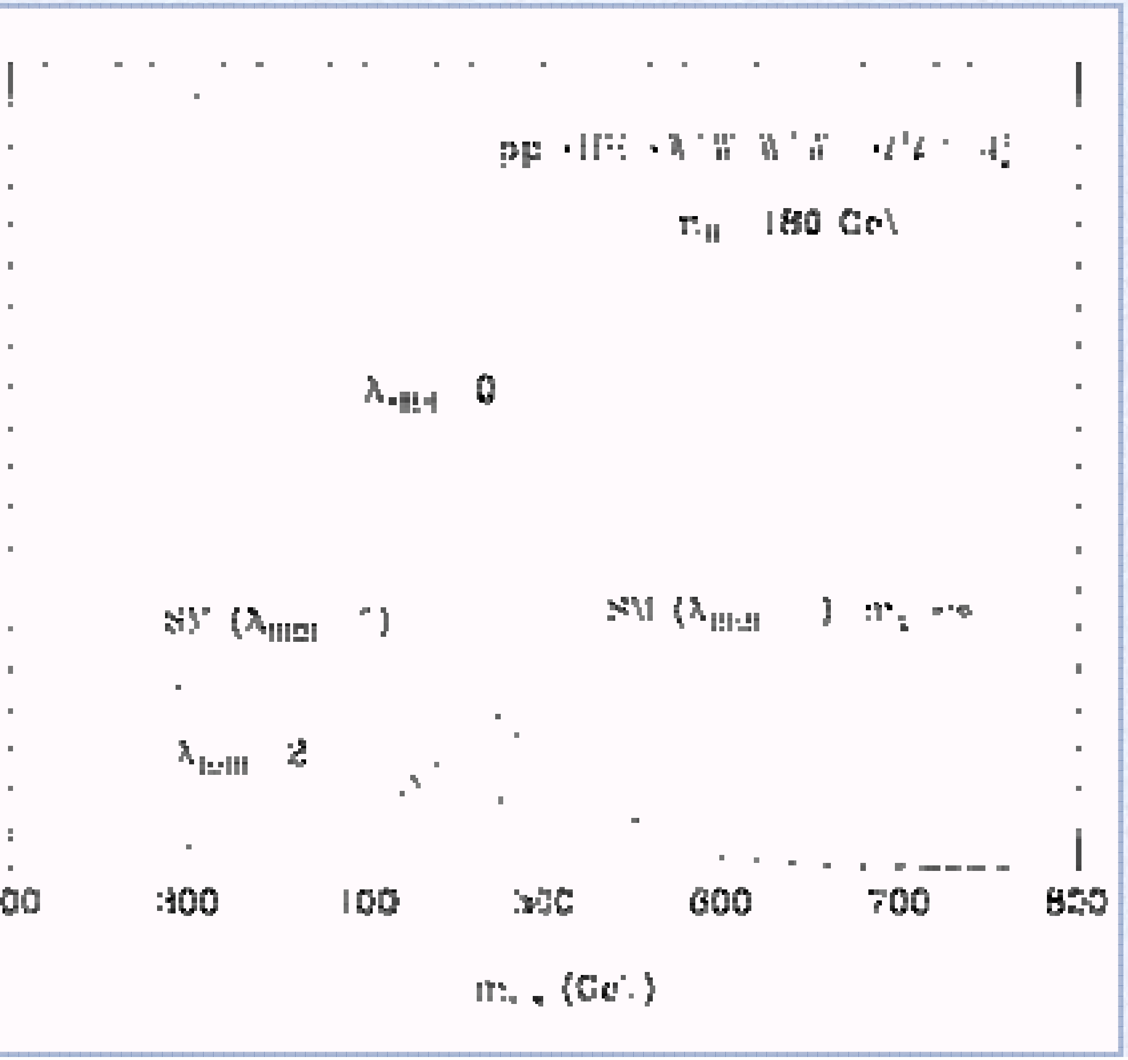






Higgs self couplings

$$\mathcal{L}_H = \frac{1}{2}(\partial^\mu H)^2 - \lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$



Higgs potential completely determined by knowledge of the Higgs mass.

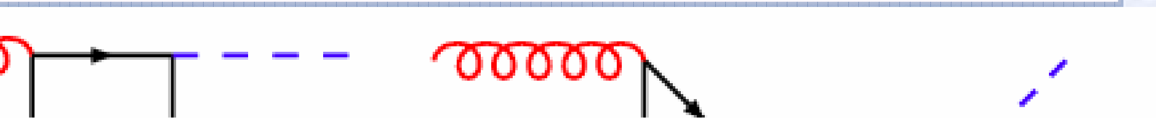
gg→HH, two diagrams with negative interf

Large top mass limit not a good approxima

NLO corrections known only in the large top limit...

0<lambda<3 @ 95% with 300 fb^{-1} with 160<m_H <200

For smaller Higgs masses<140, HH→γγbb



Quartic couplings need HHH production a
cannot be determined at the LHC

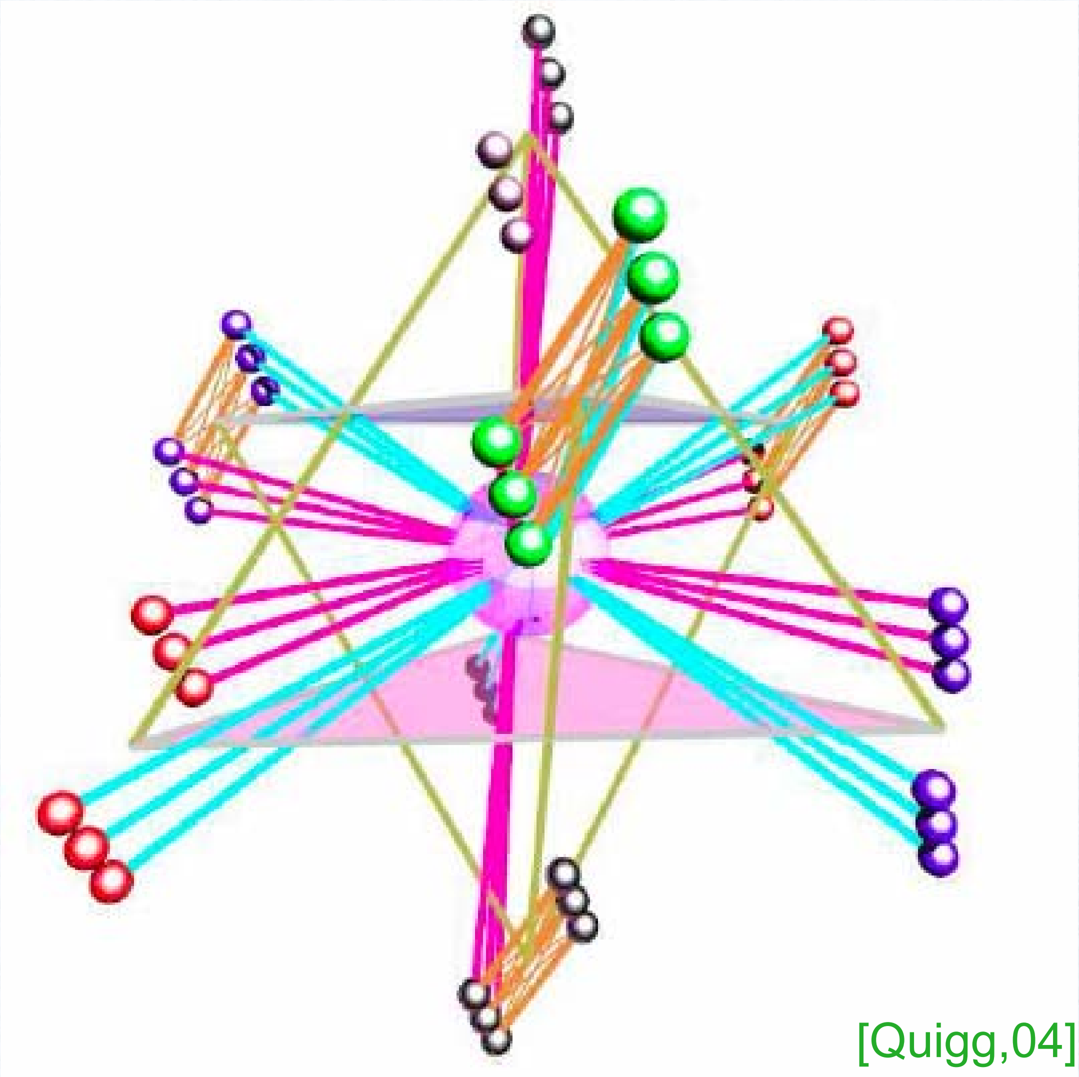
Outlook

LHC will uncover the mechanism of EWSB and possibly new phys
at the TeV scale.

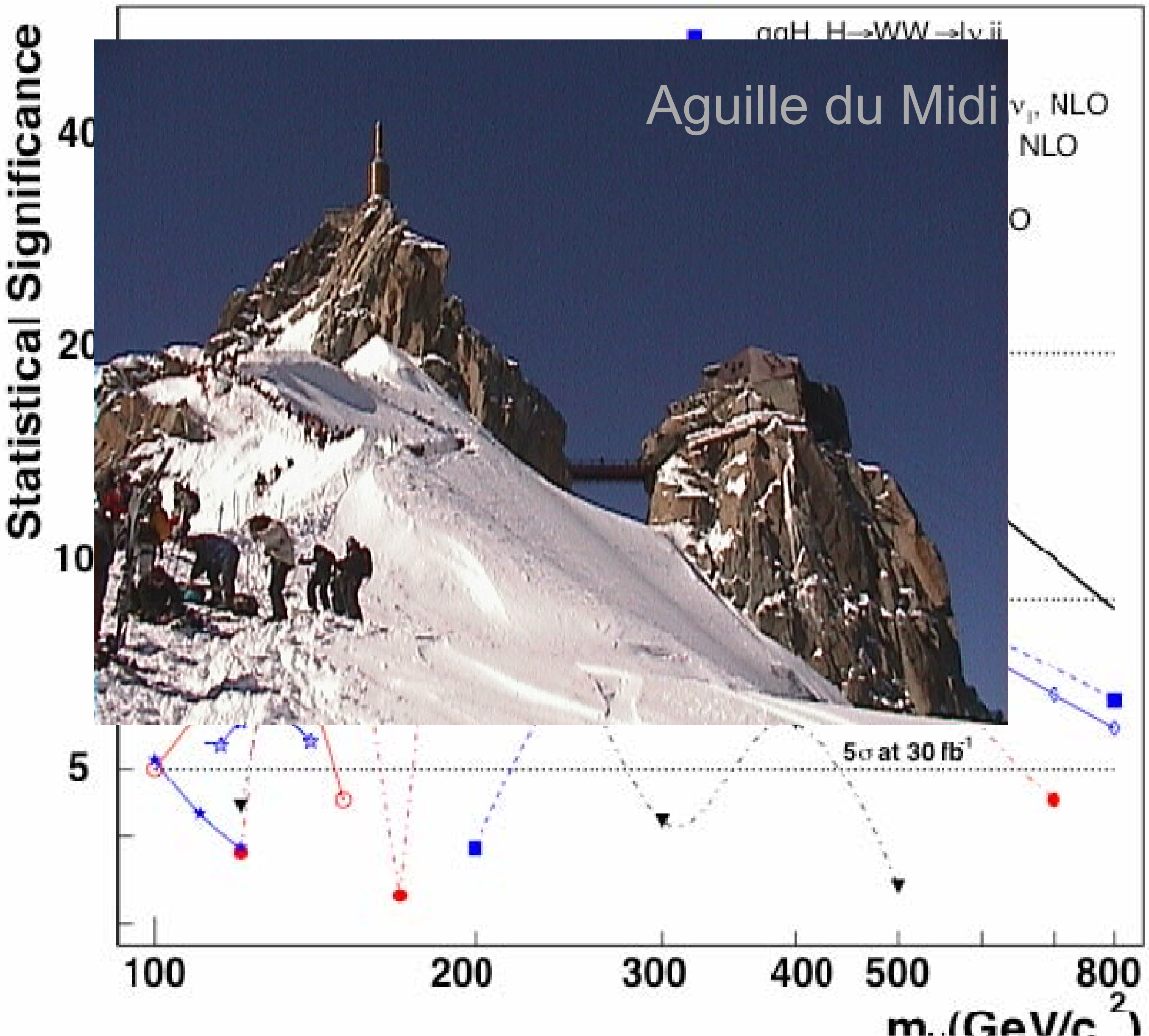
Most probably discoveries will rely not only on our understanding o
the detectors but also on our detailed knowledge of SM processes

Many developments and on-going efforts:

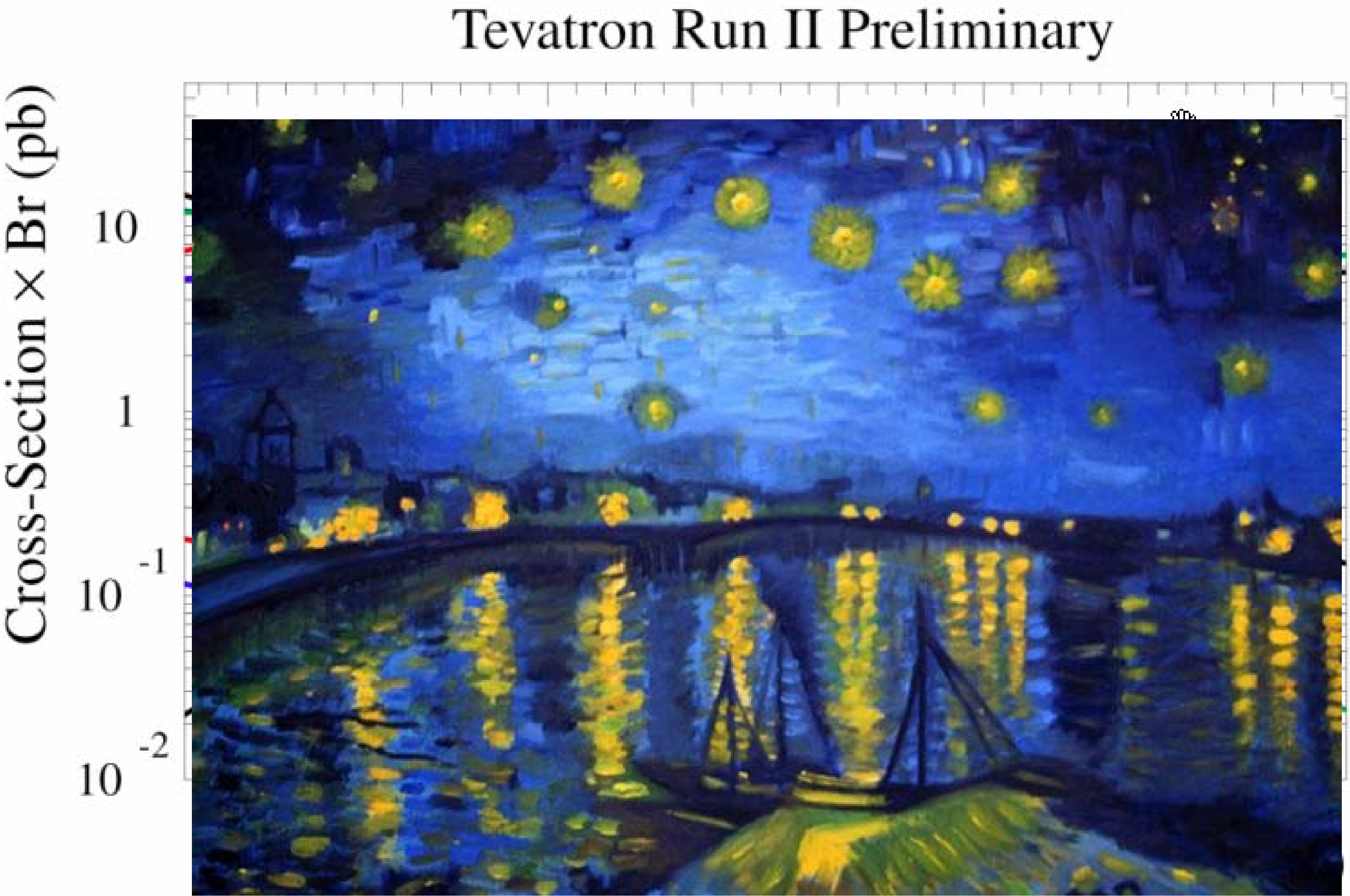
- Predictions for signals (and backgrounds) available at an unprecedented level of accuracy $\Rightarrow$ precision physics possible;
- New analysis strategies developed;
- More data and models to be challenged with.



[Quigg,04]


Aguille du Midi
Statistical Significance
40
20
10
5
5σ at 30 fb-1
100
200
300
400
500
800


$\frac{\Delta g^2(H,X)}{g^2(H,X)}$


Tevatron Run II Preliminary
Cross-Section × Br (pb)
10
1
10 -1
10 -2