The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2326-2

School on Strongly Coupled Physics Beyond the Standard Model

16 - 24 January 2012

Introduction to Collider Physics (SLIDES)

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Introduction to Collider Physics

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01/16-01/18, 2012

Cornell University
Laboratory for Elementary-Particle Physics

Parton Distribution Functions (PDFs)

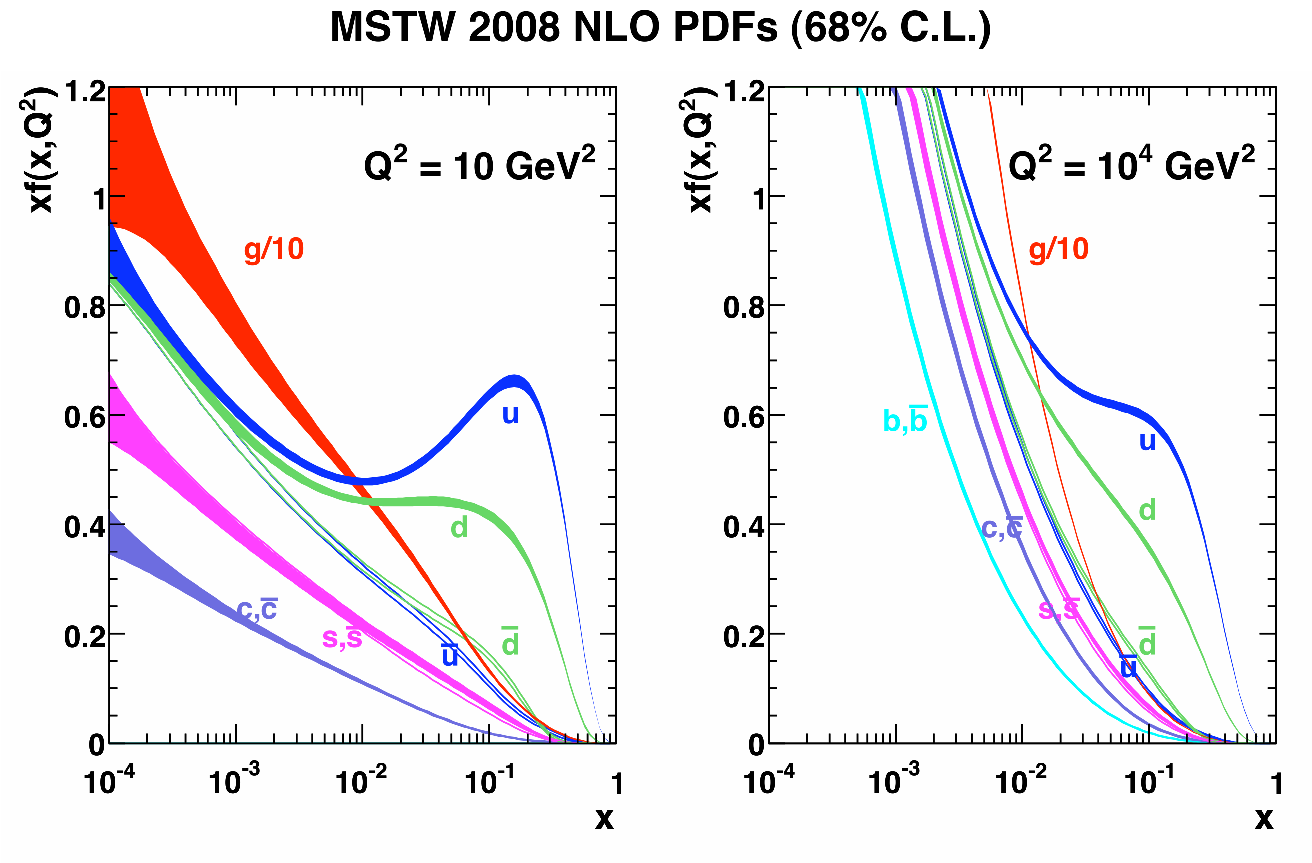


Figure 1: MSTW 2008 NLO PDFs at $Q^2 = 10$ GeV^2 and $Q^2 = 10^4$ GeV^2.

Martin, Stirling, Thorne, Watt, 0901.0002

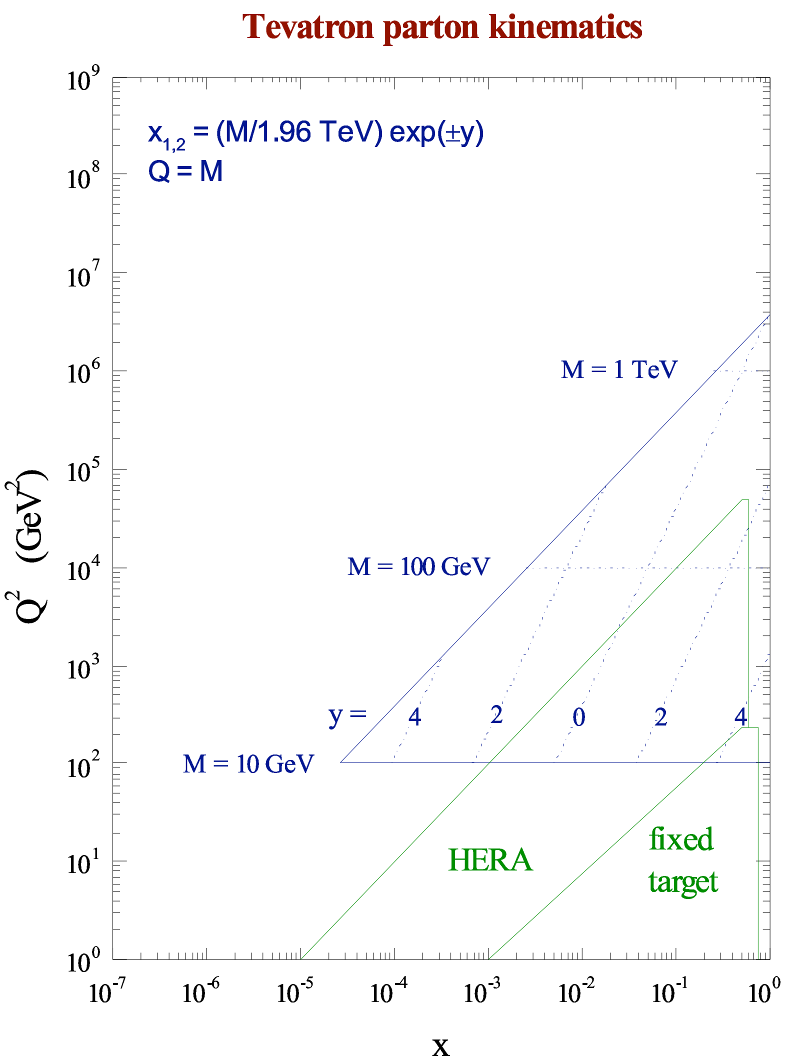
$$
\begin{aligned}
xu_v(x,Q_0^2) &= A_u\, x^{\eta_1}(1-x)^{\eta_2}(1+\epsilon_u\sqrt{x}+\gamma_u\, x),\\
xd_v(x,Q_0^2) &= A_d\, x^{\eta_3}(1-x)^{\eta_4}(1+\epsilon_d\sqrt{x}+\gamma_d\, x),\\
xS(x,Q_0^2) &= A_S\, x^{\delta_S}(1-x)^{\eta_S}(1+\epsilon_S\sqrt{x}+\gamma_S\, x),\\
x\Delta(x,Q_0^2) &= A_\Delta\, x^{\eta_\Delta}(1-x)^{\eta_S+2}(1+\gamma_\Delta\, x+\delta_\Delta\, x^2),\\
xg(x,Q_0^2) &= A_g\, x^{\delta_g}(1-x)^{\eta_g}(1+\epsilon_g\sqrt{x}+\gamma_g\, x)+A_{g'}\, x^{\delta_{g'}}(1-x)^{\eta_{g'}},\\
x(s+\bar{s})(x,Q_0^2) &= A_+\, x^{\delta_S}\,(1-x)^{\eta_+}(1+\epsilon_S\sqrt{x}+\gamma_S\, x),\\
x(s-\bar{s})(x,Q_0^2) &= A_-\, x^{\delta_-}(1-x)^{\eta_-}(1-x/x_0),
\end{aligned}
$$

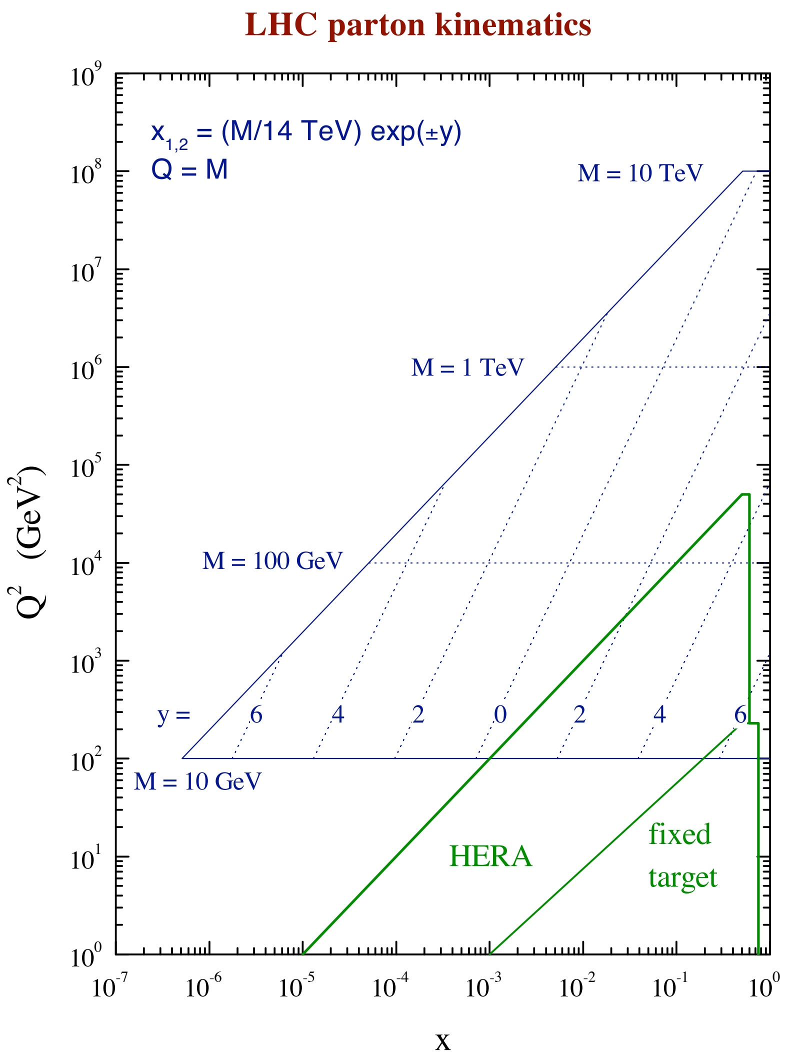
Process	Subprocess	Partons	x range
$\ell^\pm\{p,n\}\to\ell^\pm X$	$\gamma^* q\to q$	$q,\bar{q},g$	$x\gtrsim 0.01$
$\ell^\pm n/p\to\ell^\pm X$	$\gamma^* d/u\to d/u$	d/u	$x\gtrsim 0.01$
$pp\to\mu^+\mu^- X$	$u\bar{u},d\bar{d}\to\gamma^*$	$\bar{q}$	$0.015\lesssim x\lesssim 0.35$
$pn/pp\to\mu^+\mu^- X$	$(u\bar{d})/(u\bar{u})\to\gamma^*$	$\bar{d}/\bar{u}$	$0.015\lesssim x\lesssim 0.35$
$\nu(\bar{\nu})\,N\to\mu^-(\mu^+)\,X$	$W^* q\to q'$	$q,\bar{q}$	$0.01\lesssim x\lesssim 0.5$
$\nu\,N\to\mu^-\mu^+ X$	$W^* s\to c$	s	$0.01\lesssim x\lesssim 0.2$
$\bar{\nu}\,N\to\mu^+\mu^- X$	$W^*\bar{s}\to\bar{c}$	$\bar{s}$	$0.01\lesssim x\lesssim 0.2$
$e^\pm p\to e^\pm X$	$\gamma^* q\to q$	$g,q,\bar{q}$	$0.0001\lesssim x\lesssim 0.1$
$e^+ p\to\bar{\nu}\,X$	$W^+\{d,s\}\to\{u,c\}$	d,s	$x\gtrsim 0.01$
$e^\pm p\to e^\pm c\bar{c}\,X$	$\gamma^* c\to c,\ \gamma^* g\to c\bar{c}$	$c,\ g$	$0.0001\lesssim x\lesssim 0.01$
$e^\pm p\to \text{jet}+X$	$\gamma^* g\to q\bar{q}$	g	$0.01\lesssim x\lesssim 0.1$
$p\bar{p}\to\text{jet}+X$	$gg,qg,qq\to 2j$	g,q	$0.01\lesssim x\lesssim 0.5$
$p\bar{p}\to(W^\pm\to\ell^\pm\nu)\,X$	$ud\to W,\bar{u}\bar{d}\to W$	$u,d,\bar{u},\bar{d}$	$x\gtrsim 0.05$
$p\bar{p}\to(Z\to\ell^+\ell^-)\,X$	$uu,dd\to Z$	d	$x\gtrsim 0.05$

Parameter	LO	NLO	NNLO
$\alpha_S(Q_0^2)$	0.68183	0.49128	0.45077
$\alpha_S(M_Z^2)$	0.13939	0.12018	0.11707
A_u	1.4335	0.25871	0.22250
η_1	$0.45232^{+0.022}_{-0.018}$	$0.29065^{+0.019}_{-0.013}$	$0.27871^{+0.018}_{-0.014}$
η_2	$3.0409^{+0.079}_{-0.067}$	$3.2432^{+0.062}_{-0.039}$	$3.3627^{+0.061}_{-0.044}$
ϵ_u	$-2.3737^{+0.54}_{-0.48}$	$4.0603^{+1.6}_{-2.3}$	$4.4343^{+2.4}_{-2.7}$
γ_u	8.9924	30.687	38.599
A_d	5.0903	12.288	17.938
η_3	$0.71978^{+0.057}_{-0.082}$	$0.96809^{+0.11}_{-0.11}$	$1.0839^{+0.12}_{-0.11}$
$\eta_4-\eta_2$	$2.0835^{+0.32}_{-0.45}$	$2.7003^{+0.50}_{-0.52}$	$2.7865^{+0.50}_{-0.44}$
ϵ_d	$-4.3654^{+0.28}_{-0.22}$	$-3.8911^{+0.31}_{-0.29}$	$-3.6387^{+0.27}_{-0.28}$
γ_d	7.4730	6.0542	5.2577
A_S	$0.59964^{+0.036}_{-0.030}$	$0.31620^{+0.030}_{-0.021}$	$0.64942^{+0.047}_{-0.041}$
δ_S	-0.16276	-0.21515	-0.11912
η_S	$8.8801^{+0.33}_{-0.33}$	$9.2726^{+0.23}_{-0.33}$	$9.4189^{+0.25}_{-0.33}$
ϵ_S	$-2.9012^{+0.33}_{-0.37}$	$-2.6022^{+0.71}_{-0.96}$	$-2.6287^{+0.49}_{-0.51}$
γ_S	16.865	30.785	18.065
$\int_0^1 dx\ \Delta(x,Q_0^2)$	$0.091031^{+0.012}_{-0.009}$	$0.087673^{+0.013}_{-0.011}$	$0.078167^{+0.012}_{-0.0091}$
A_Δ	8.9413	8.1084	16.244
η_Δ	$1.8760^{+0.24}_{-0.30}$	$1.8691^{+0.23}_{-0.32}$	$2.0741^{+0.18}_{-0.35}$
γ_Δ	$8.4703^{+2.0}_{-0.3}$	$13.609^{+1.1}_{-0.6}$	$6.7640^{+0.77}_{-0.41}$
δ_Δ	-36.507	-59.289	-36.090
A_g	0.0012216	1.0805	3.4055
δ_g	$-0.83657^{+0.15}_{-0.14}$	$-0.42848^{+0.066}_{-0.057}$	$-0.12178^{+0.23}_{-0.16}$
η_g	$2.3882^{+0.51}_{-0.50}$	$3.0225^{+0.43}_{-0.36}$	$2.9278^{+0.68}_{-0.41}$
ϵ_g	-38.997^{+36}_{-35}	-2.2922	-2.3210
γ_g	1445.5^{+880}_{-750}	3.4894	1.9233
$A_{g'}$	—	-1.1168	-1.6189
$\delta_{g'}$	—	$-0.42776^{+0.053}_{-0.047}$	$-0.23999^{+0.14}_{-0.10}$
$\eta_{g'}$	—	$32.869^{+6.5}_{-5.9}$	$24.792^{+6.5}_{-5.2}$
A_+	$0.10302^{+0.029}_{-0.017}$	$0.047915^{+0.0095}_{-0.0076}$	$0.10455^{+0.019}_{-0.016}$
η_+	$13.242^{+2.9}_{-1.4}$	$9.7466^{+1.0}_{-0.8}$	$9.8689^{+1.0}_{-0.6}$
A_-	$-0.011523^{+0.009}_{-0.018}$	$-0.011629^{+0.009}_{-0.023}$	$-0.0093692^{+0.006}_{-0.024}$
η_-	10.285^{+16}_{-6}	11.261^{+22}_{-6}	9.5783^{+26}_{-5}
x_0	0.017414	0.016050	0.018556
r_1	-0.39484	-0.57631	-0.80834
r_2	-1.0719	0.81878	1.2669
r_3	-0.28973	-0.083208	0.15098

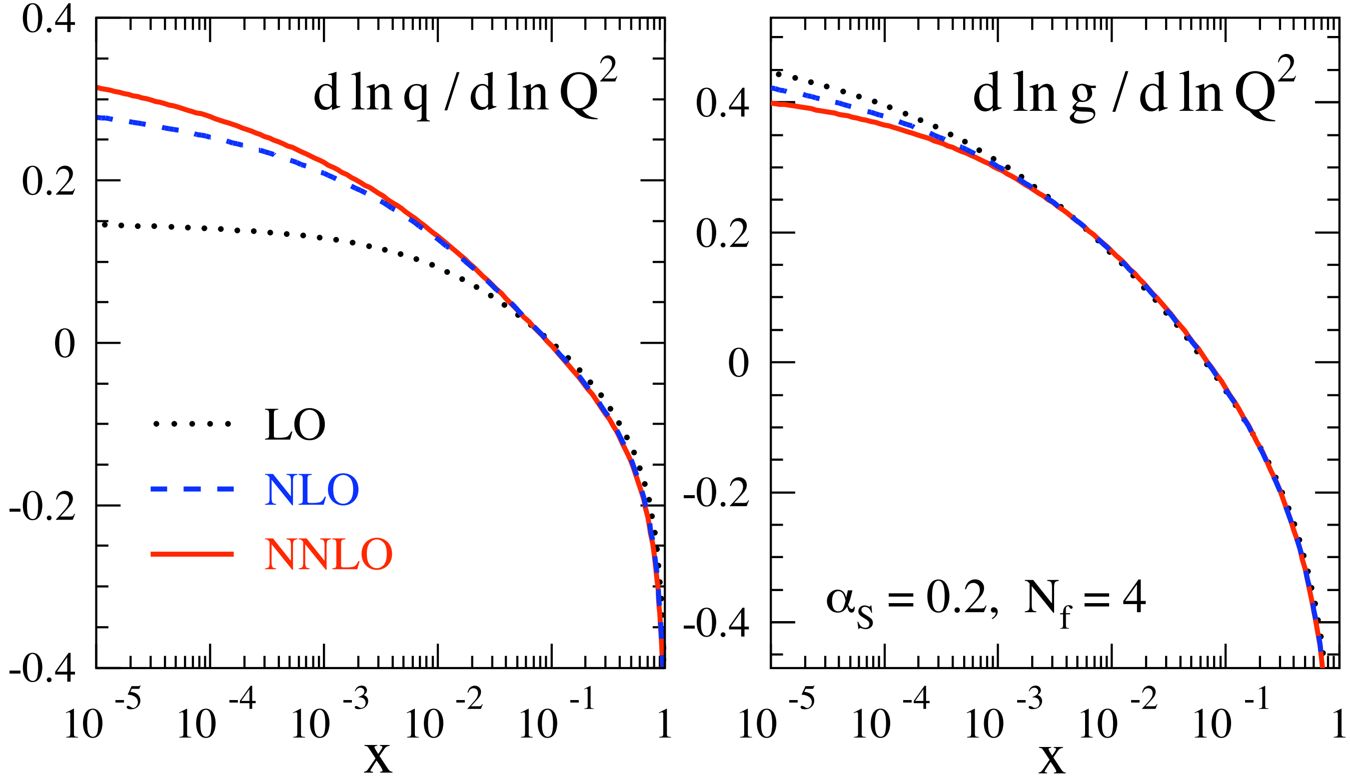
MSTW, 0901.0002

Parton kinematics



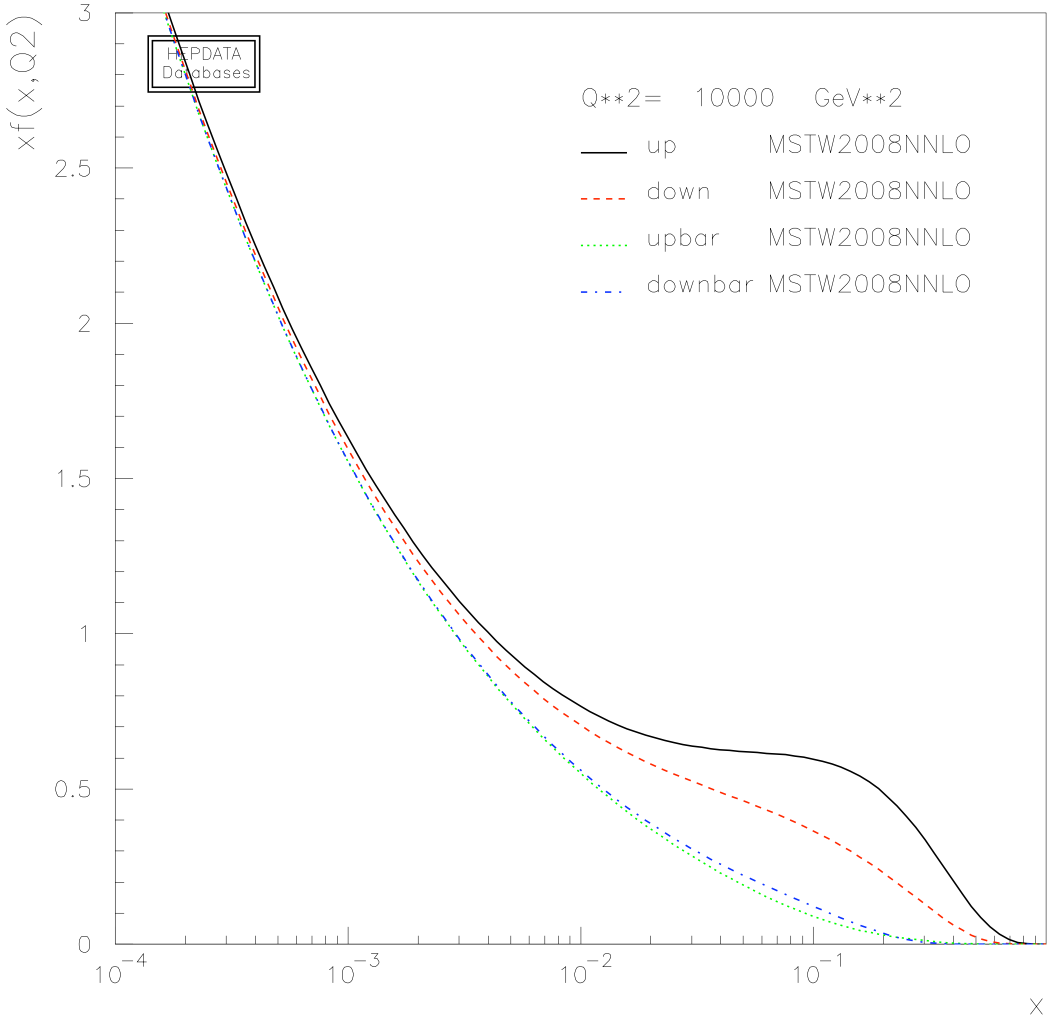


S.-O. Moch, KITP talk, 2008

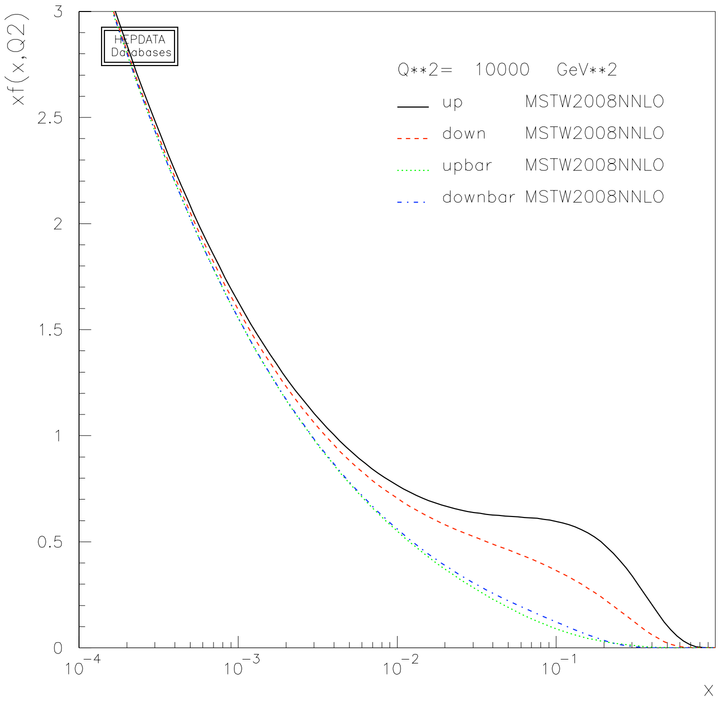


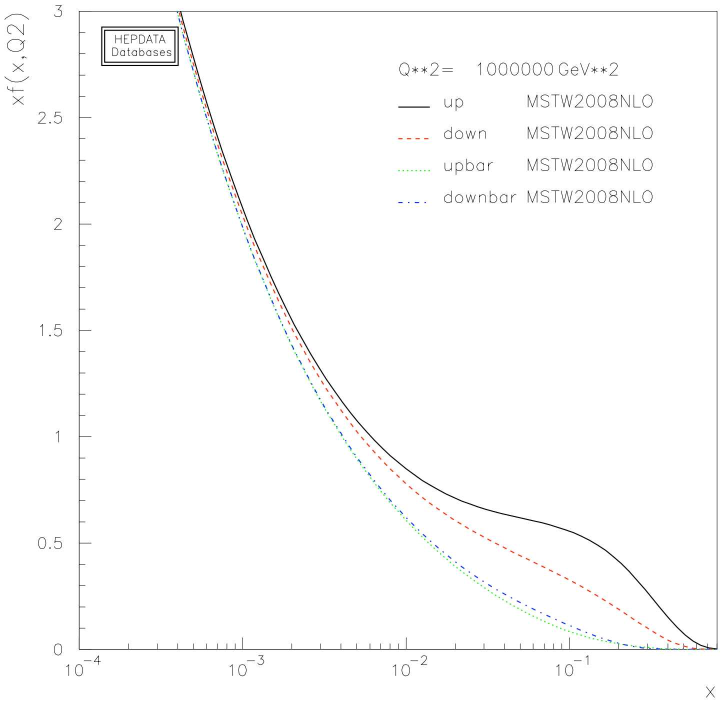
DGLAP evolution: at higher Q2, parton densities shift towards low x

Plot: S.-O. Moch, KITP talk, 2008



http://durpdg.dur.ac.uk/cgi-bin/hepdata/pdfplot2

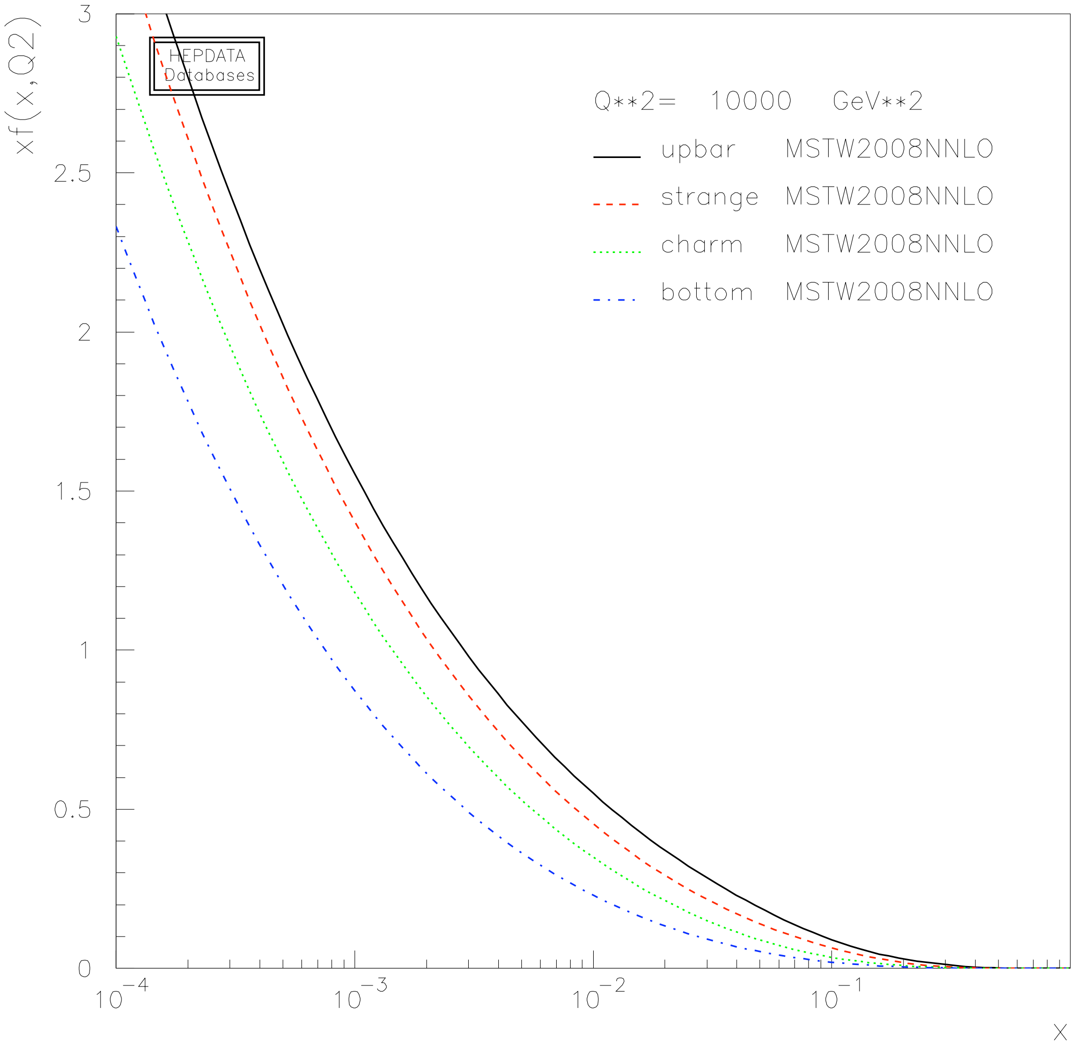




Q=100 GeV

Q=1000 GeV

http://durpdg.dur.ac.uk/cgi-bin/hepdata/pdfplot2



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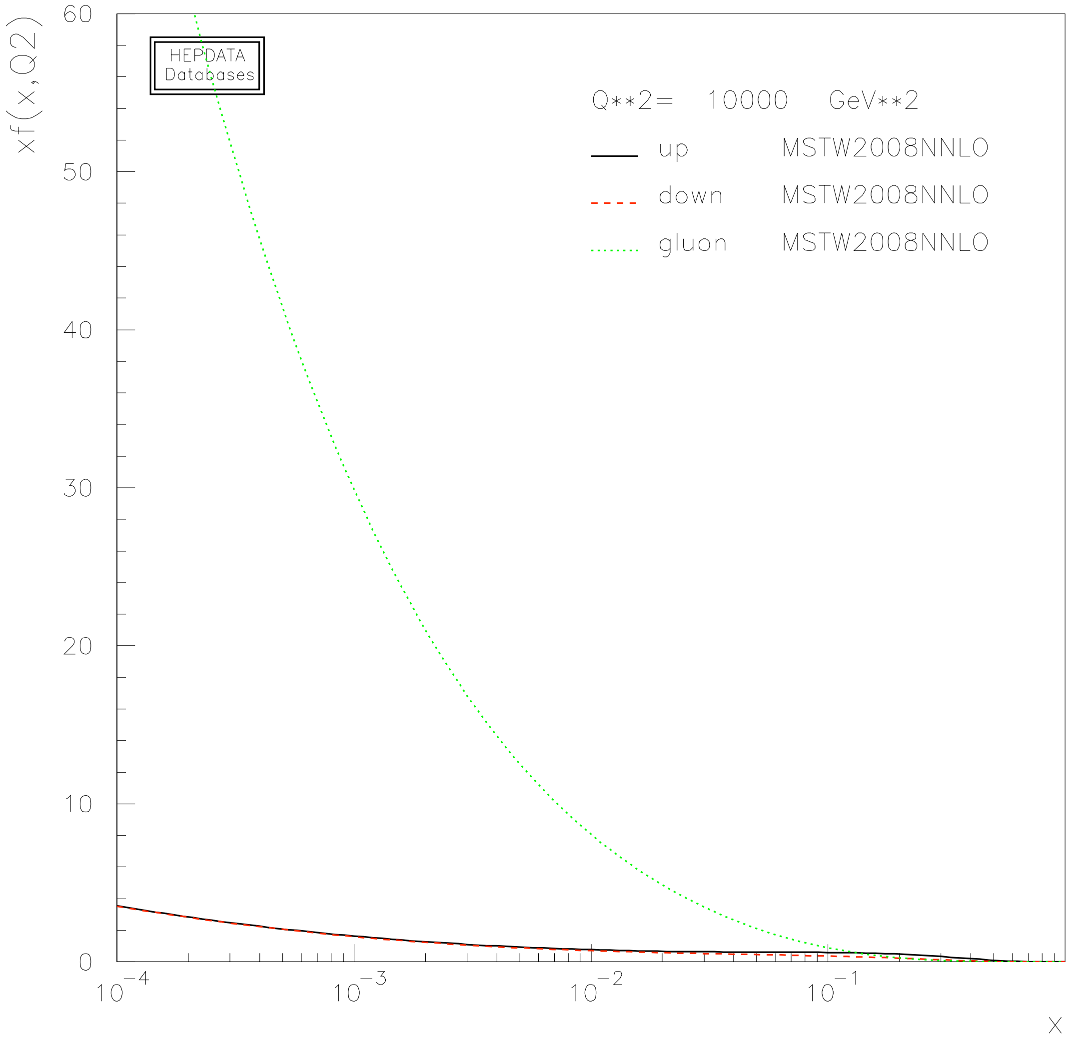

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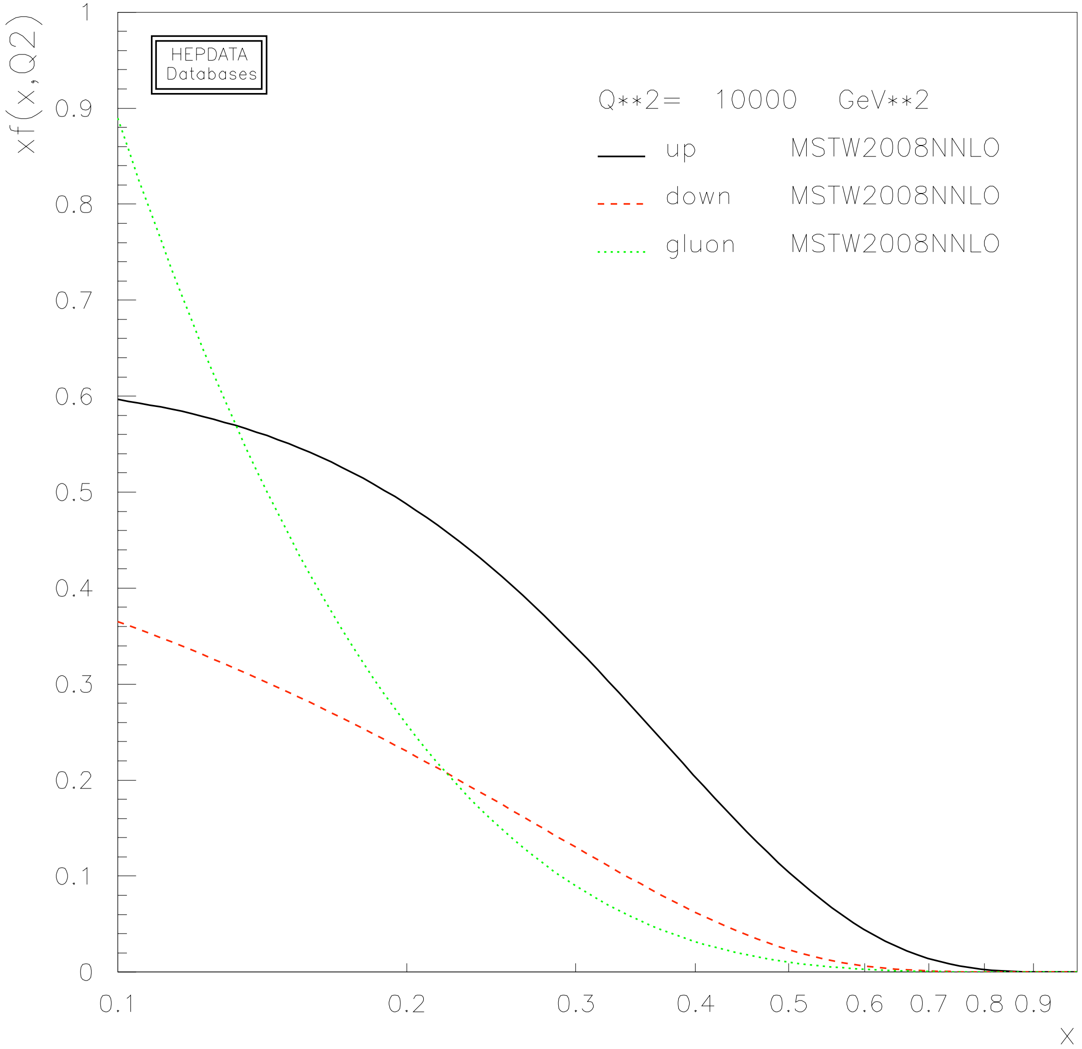

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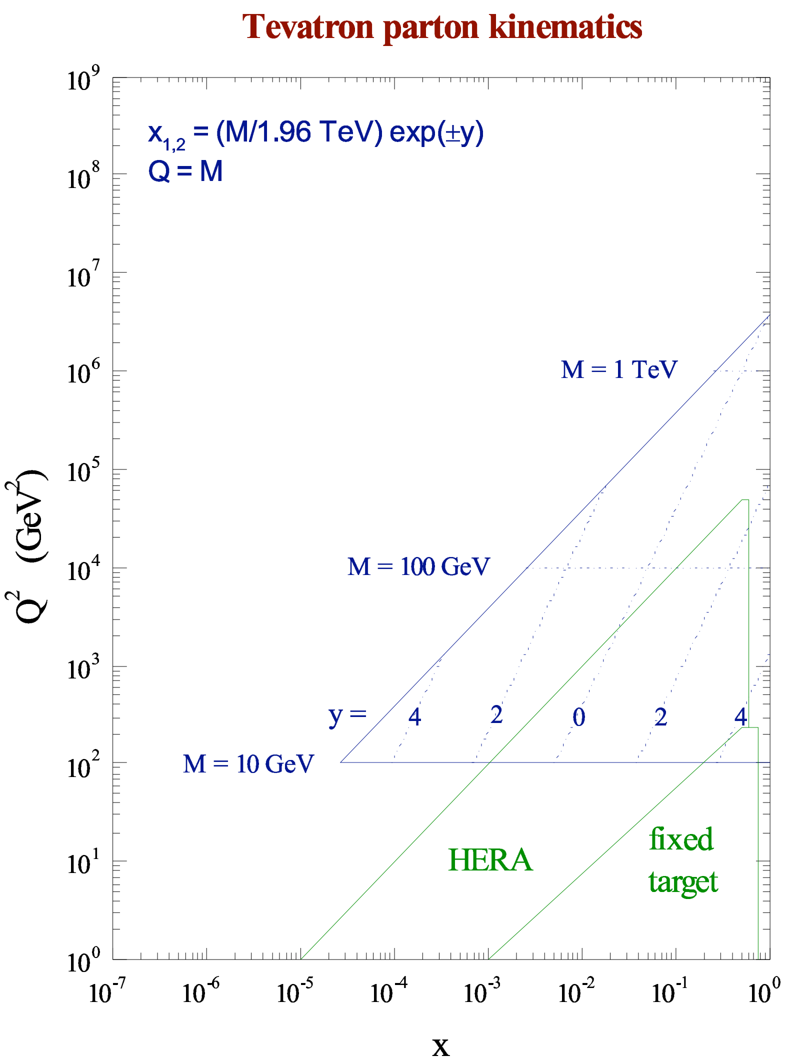
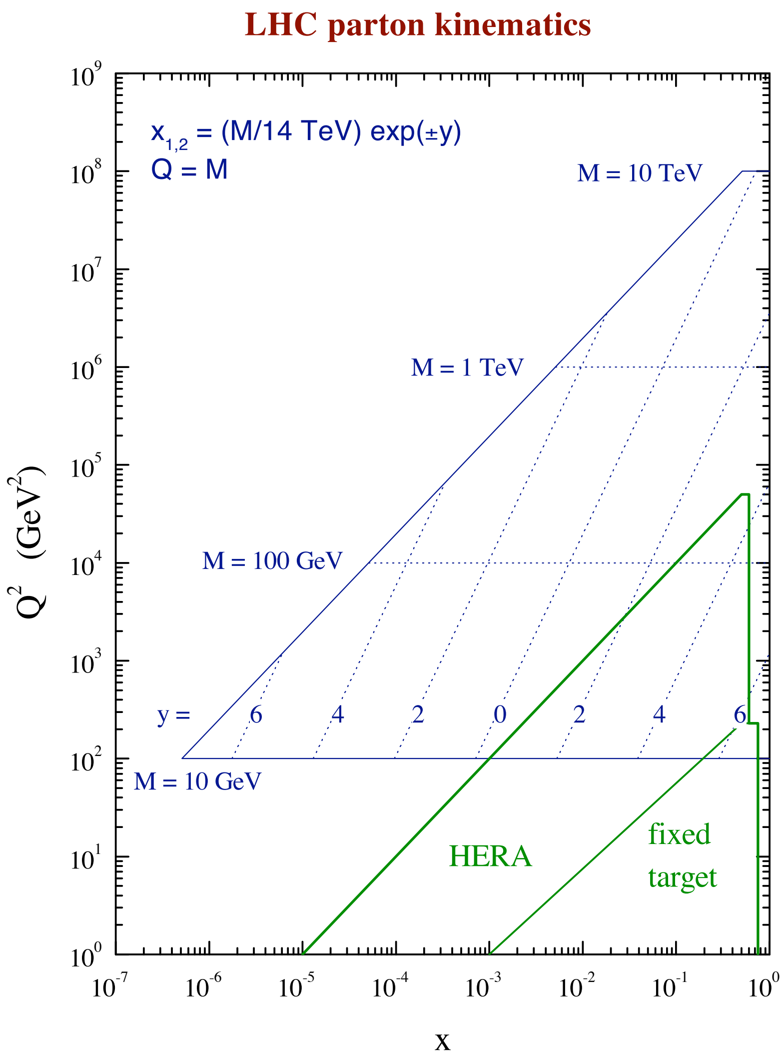
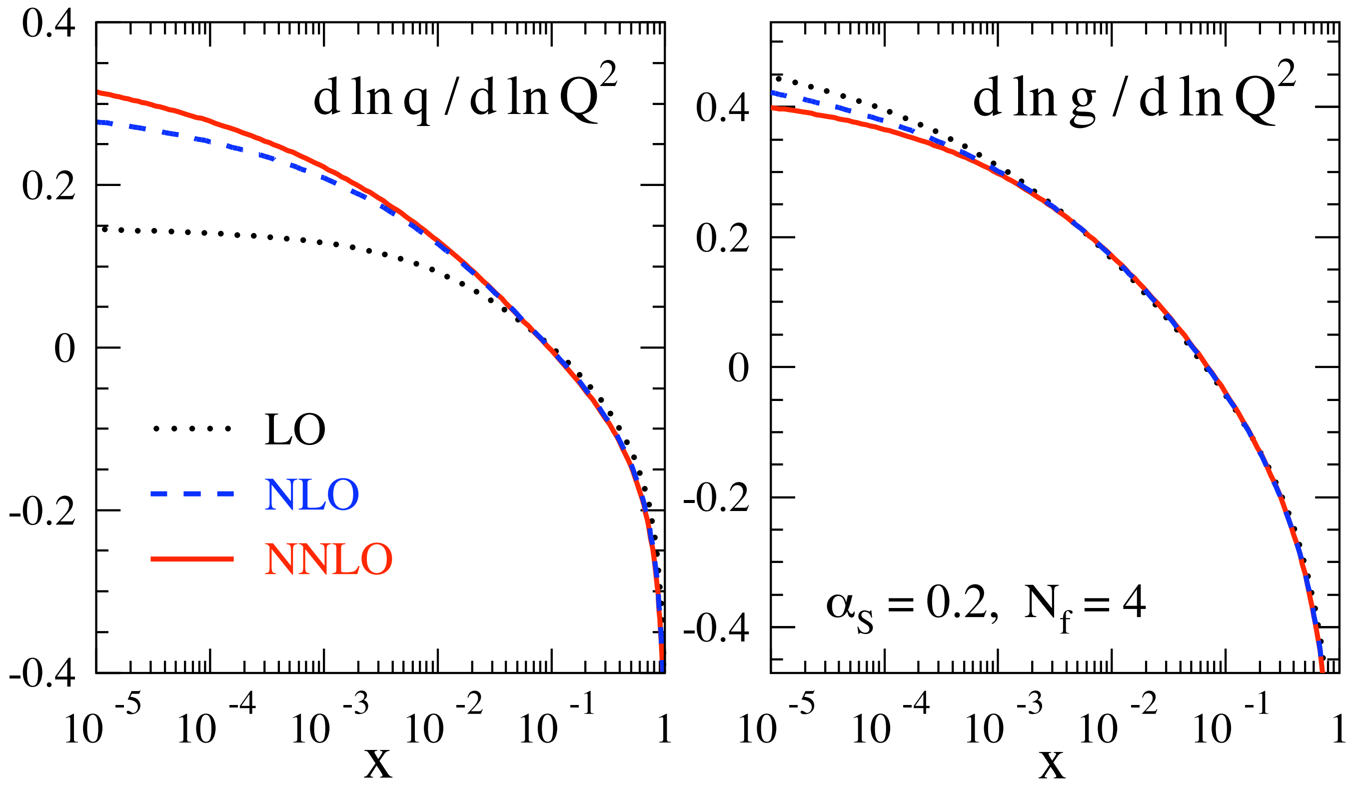
Electroweak Boson Production

Parton kinematics





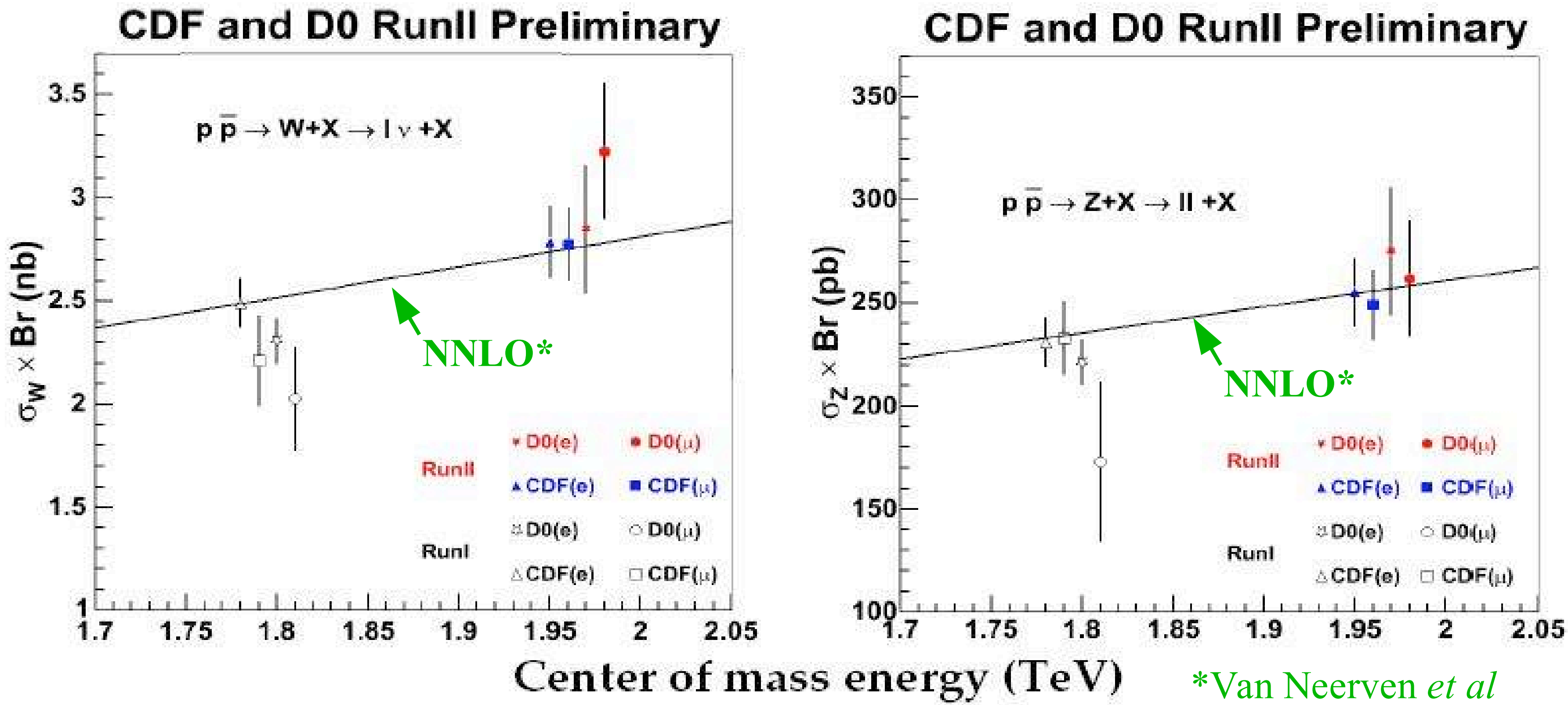
S.-O. Moch, KITP talk, 2008



DGLAP evolution: at higher Q2, parton densities shift towards low x

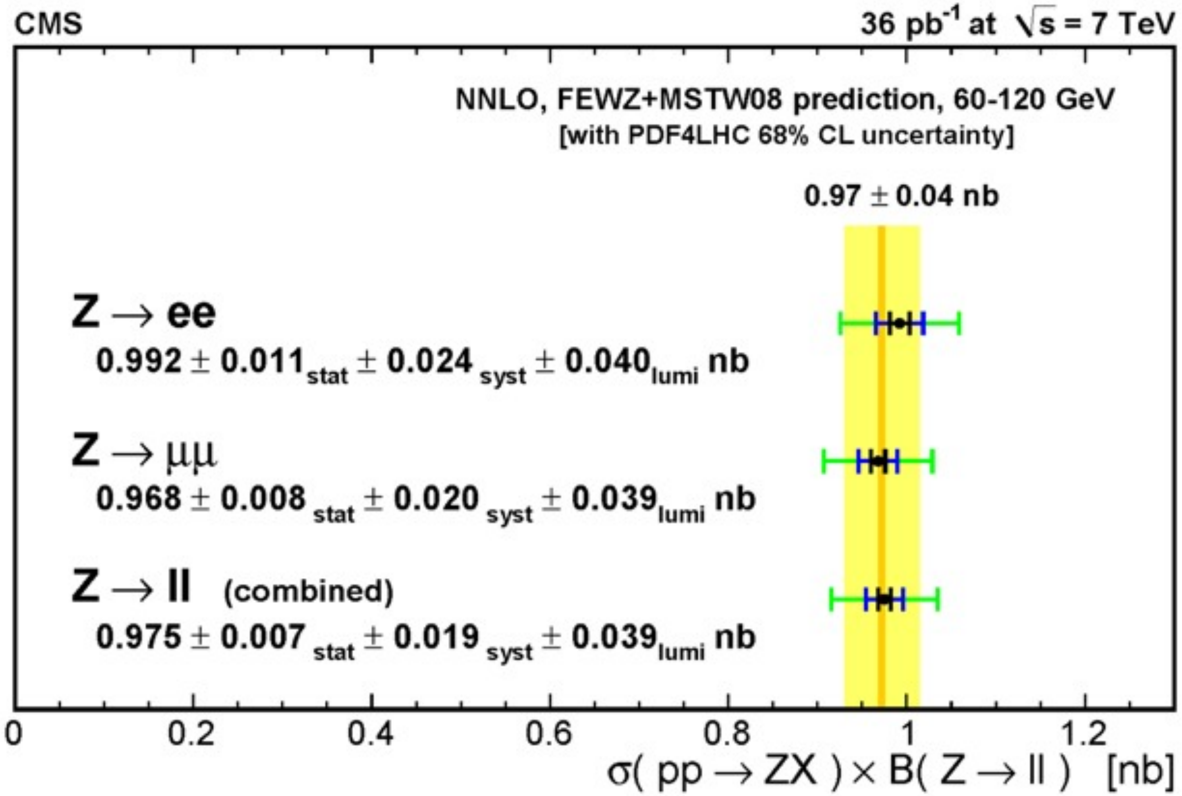
Plot: S.-O. Moch, KITP talk, 2008

Inclusive Cross Sections



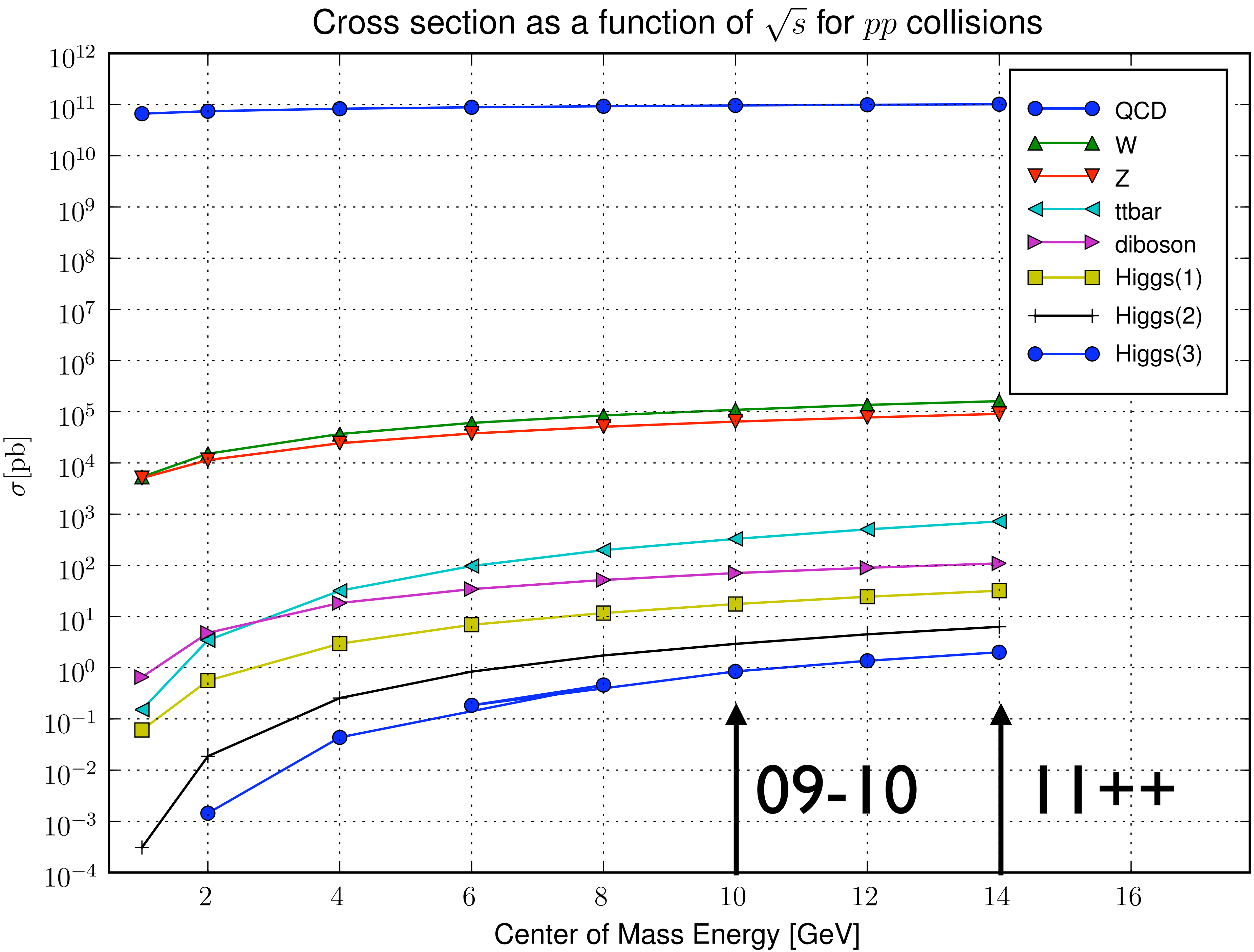
*Van Neerven *et al*
(nucl phys. B359, 343, 1991)

Hesketh, Moriond 2004

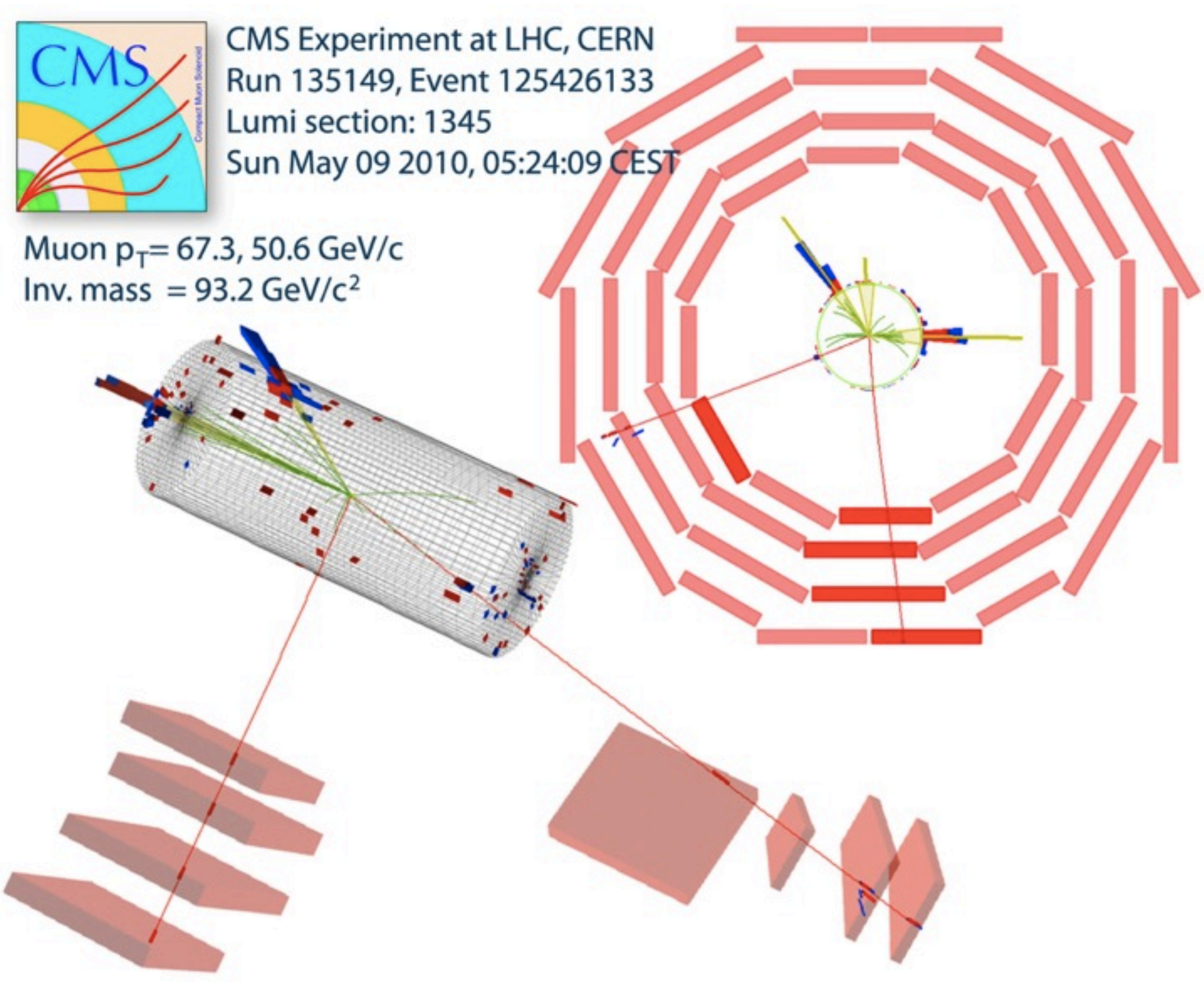


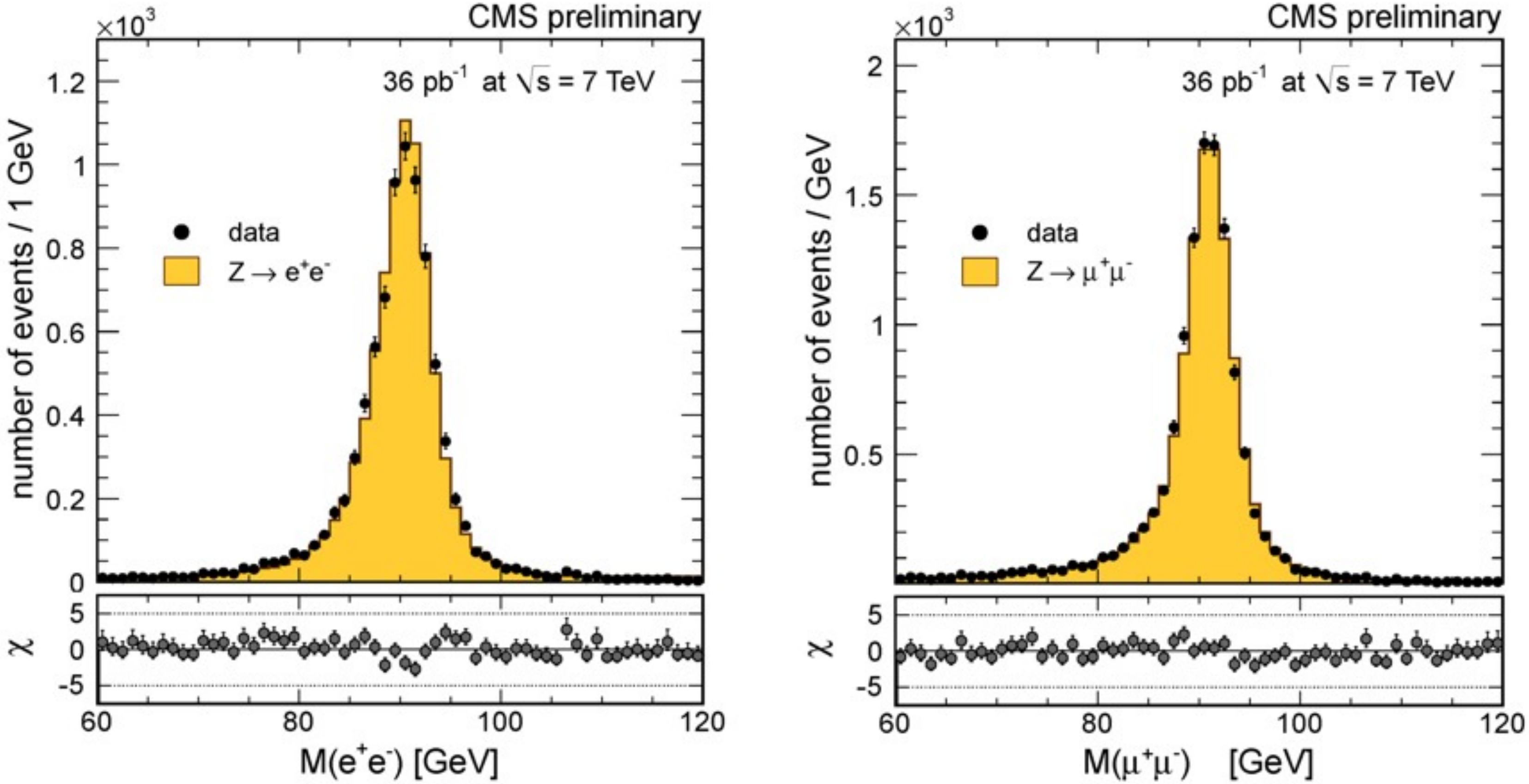
CMS-EWK-10-005, arXiv:1107.4789

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

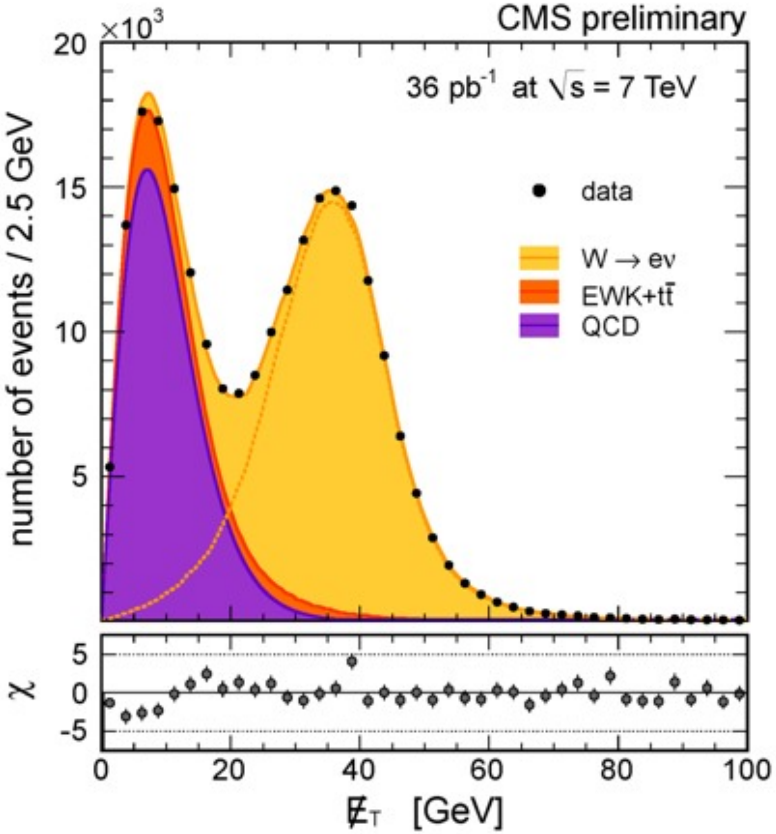


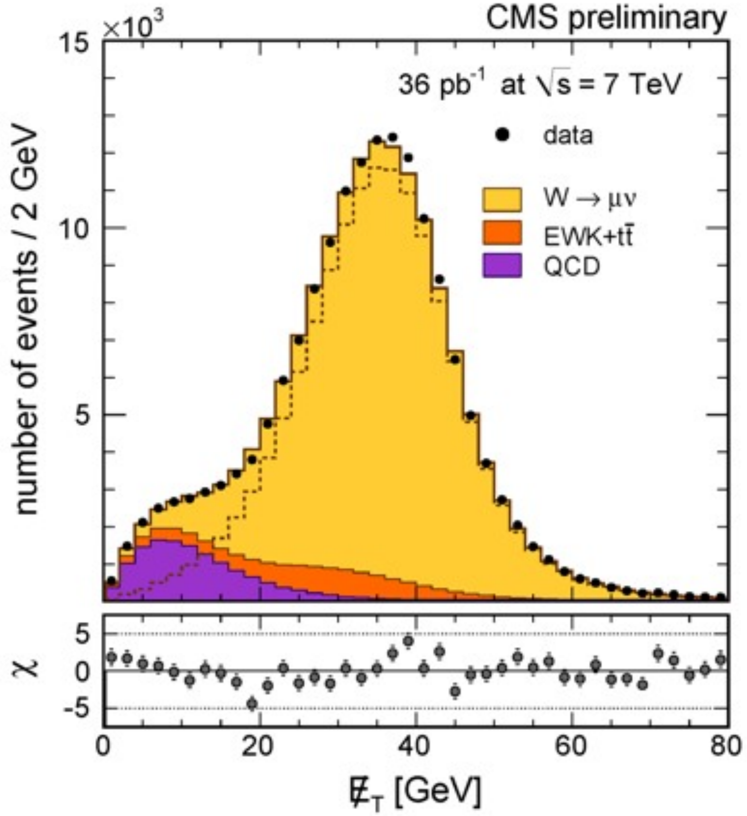
Cross section as a function of $\sqrt{s}$ for pp collisions
σ[pb]
Center of Mass Energy [GeV]
QCD
W
Z
ttbar
diboson
Higgs(1)
Higgs(2)
Higgs(3)
09-10
11++


CMS
CMS Experiment at LHC, CERN
Run 135149, Event 125426133
Lumi section: 1345
Sun May 09 2010, 05:24:09 CEST
Muon p_T= 67.3, 50.6 GeV/c
Inv. mass = 93.2 GeV/c^2

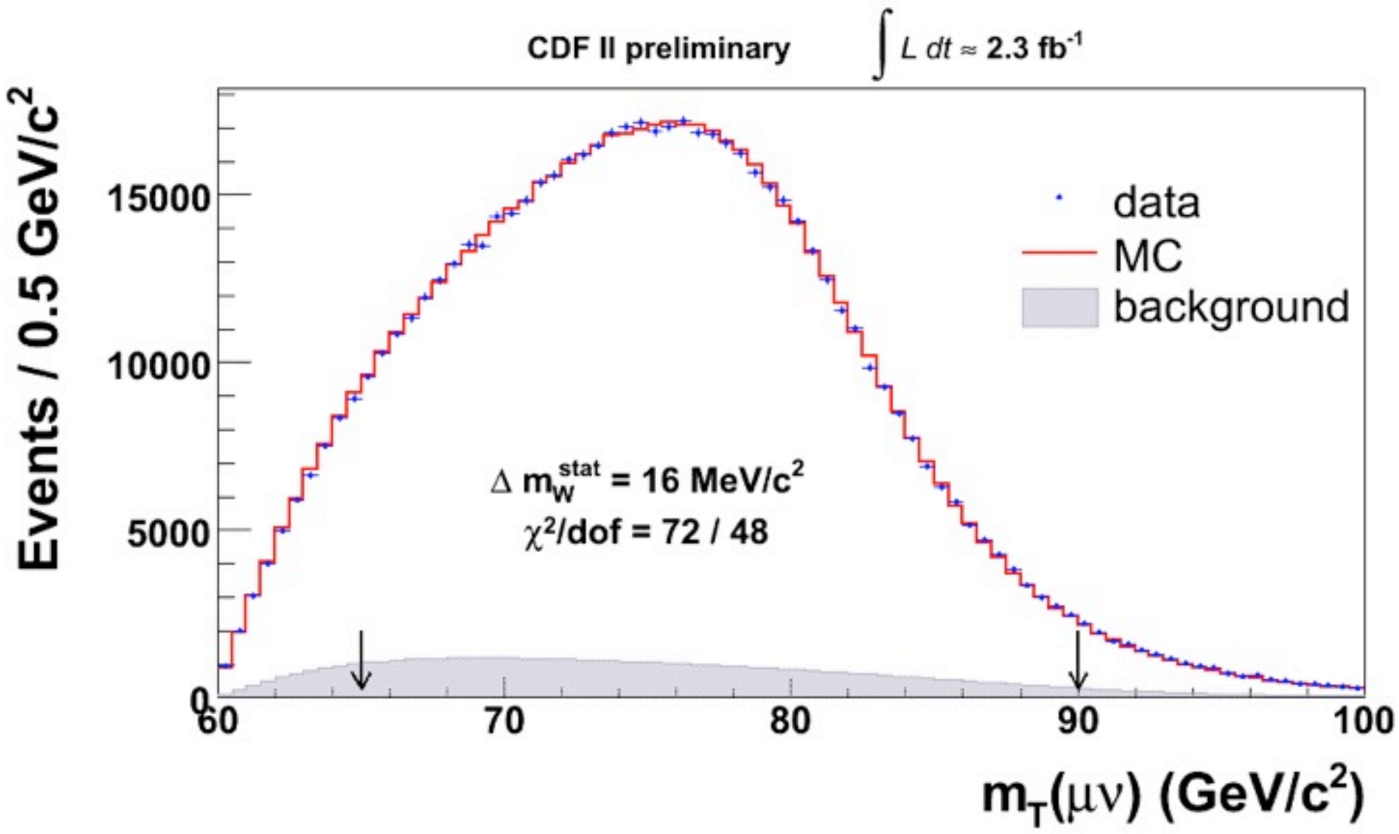


CMS-EWK-10-005, arXiv:1107.4789





CMS-EWK-10-005, arXiv:1107.4789



http://www-cdf.fnal.gov/physics/ewk/2008/wmass/

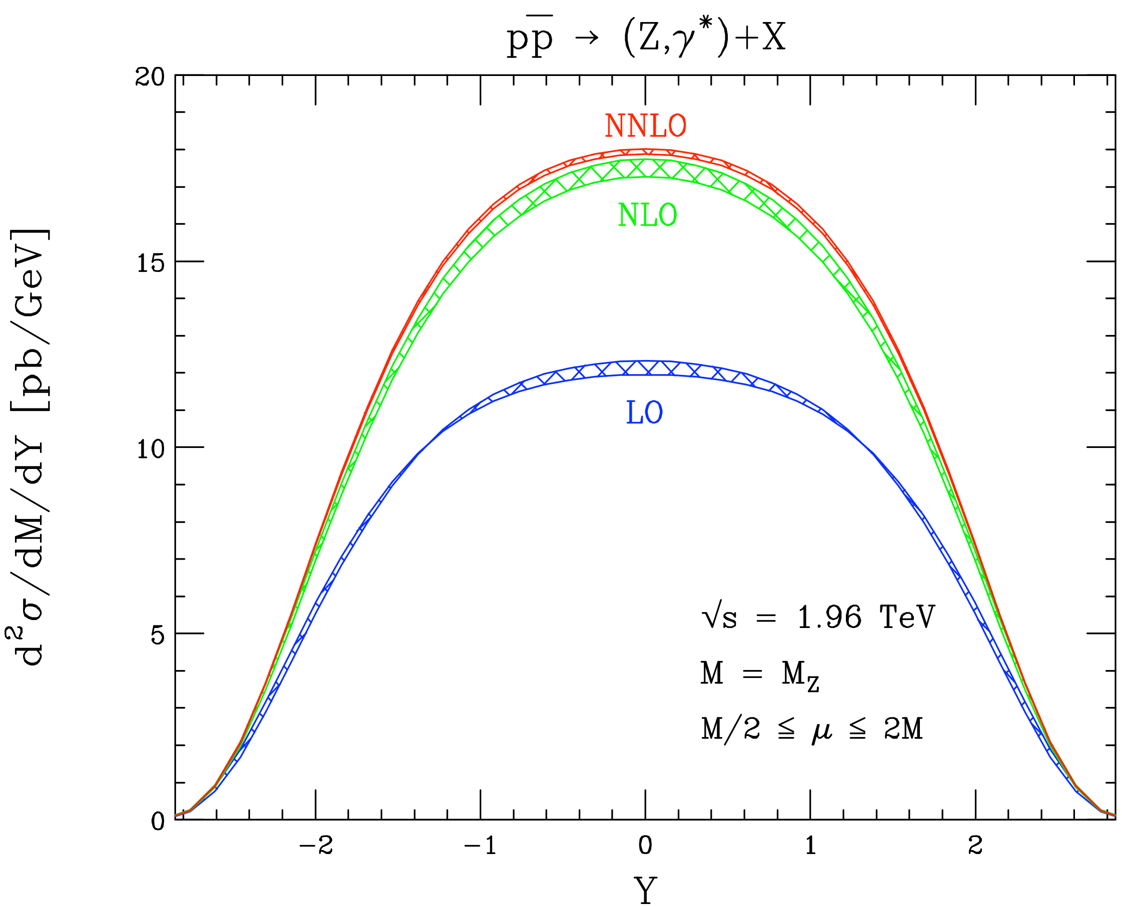


Figure 5: The CMS rapidity distribution of an on-shell Z boson at Run II of the Tevatron. The LO, NLO, and NNLO results have been included. The bands indicate the variation of the renormalization and factorization scales in the range $M_Z/2 \leq \mu \leq 2M_Z$.

Anastasiou, Dixon, Melnikov, Petriello, hep-ph/0312266

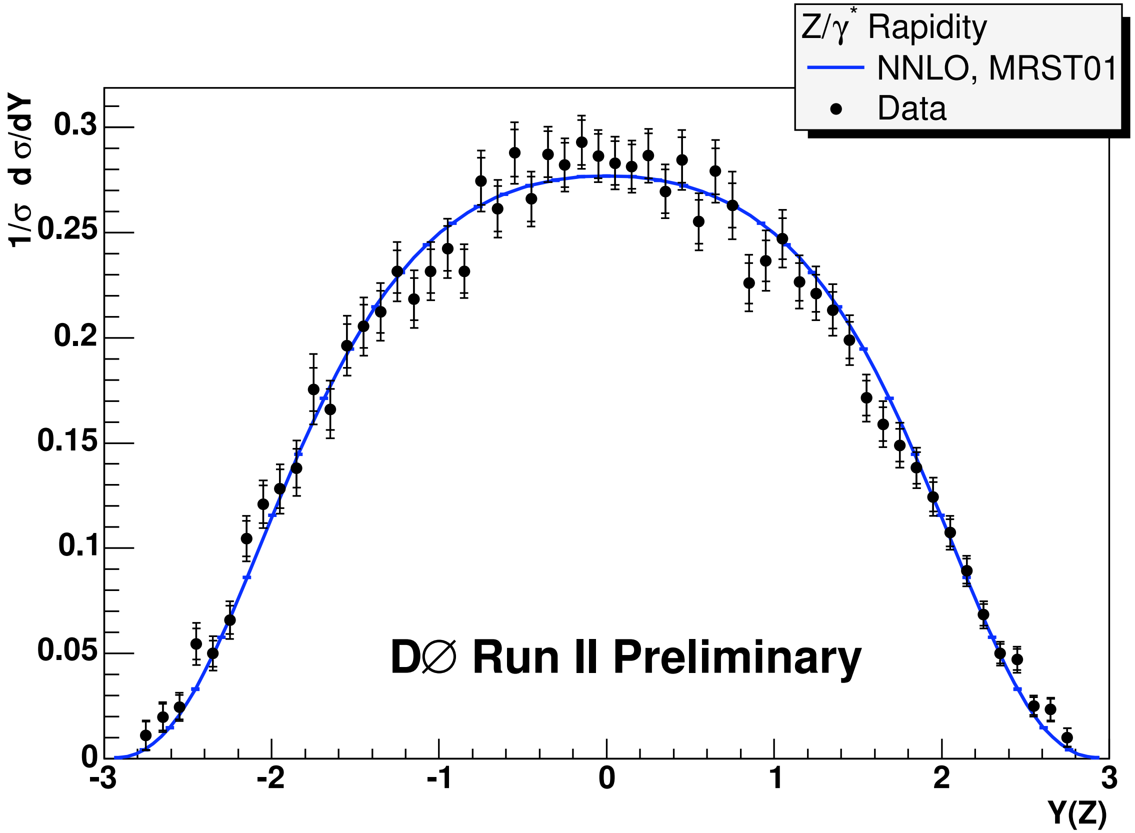
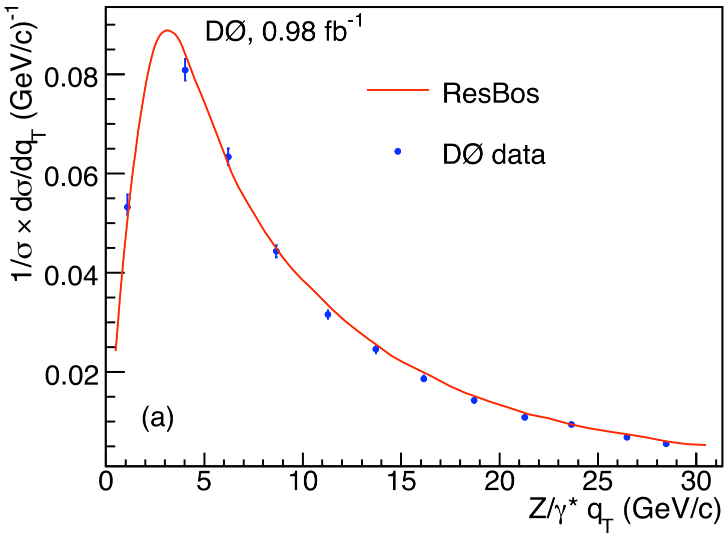


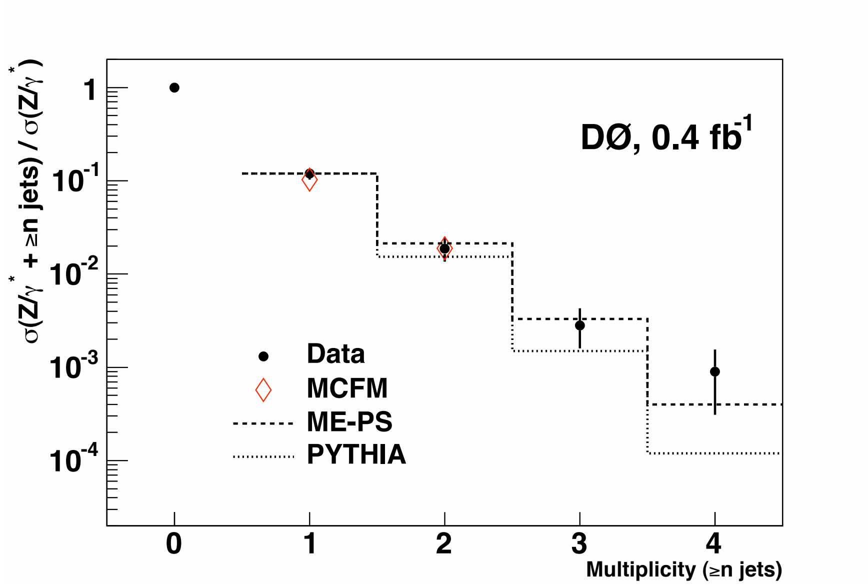
FIG. 5: Analysis result. The outer error bars show the total error, combining statistical and systematic errors, while the inner error bars indicate the statistical error alone. The solid line shows the NNLO prediction based on the MRST 2001 PDFs.

D0, Winter 2005 Conferences

Soft/Collinear Jets

Z+Jets at the Tevatron





(Jet pT > 20 GeV required)

D0, PRL 100, 102002 (2008)

D0, PLB 658, 112 (2008)

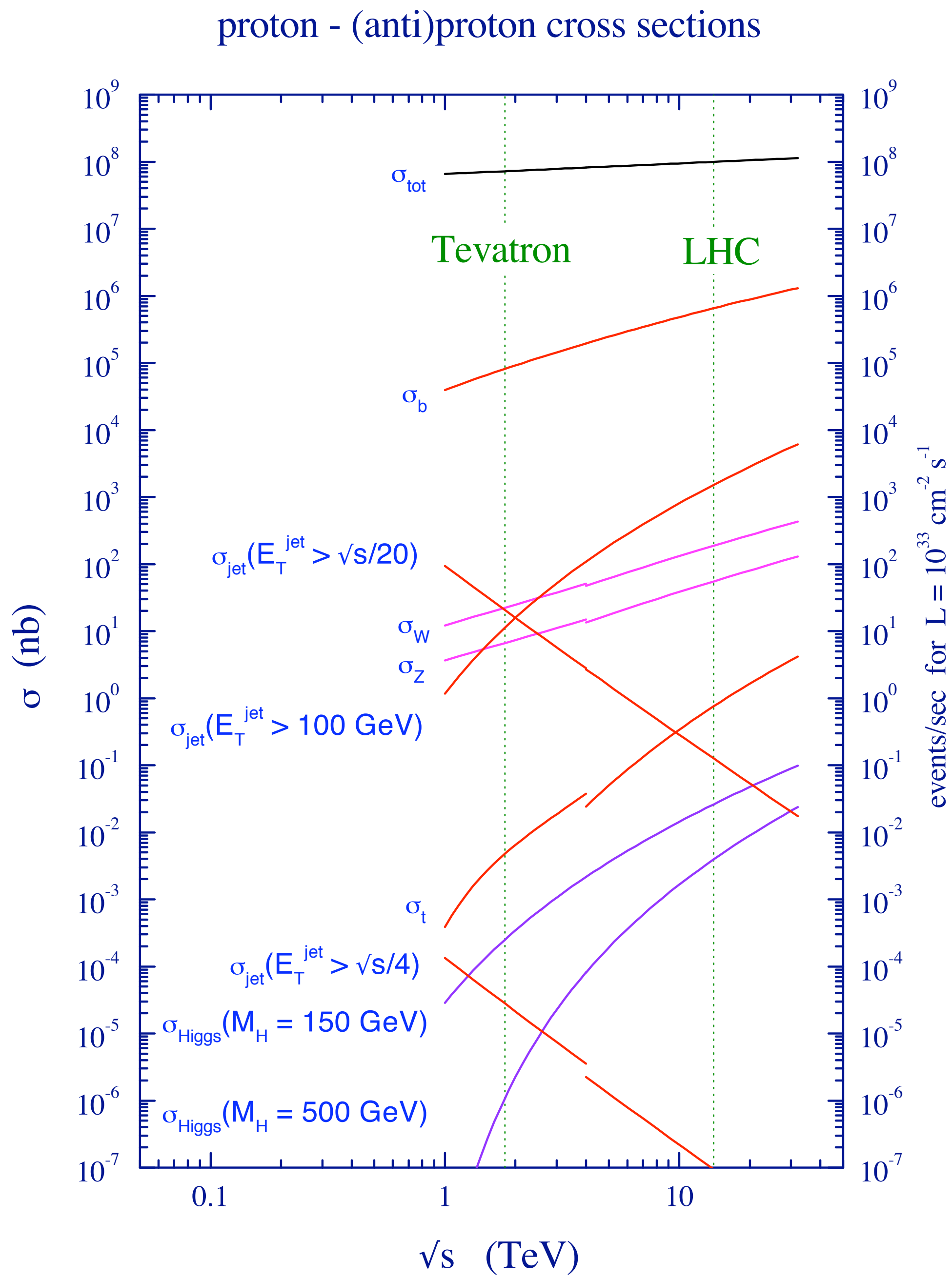
New Physics Searches

Planning a New Physics Search - 1

- I have a theory predicting new particle(s) X. What do I do?
- Identify couplings of X (no need to get all 2's right yet!)
- Identify X production processes, roughly order by strength
  - Minimize # of particles (eps. massive) in final state
  - Remember QCD > Electroweak
- Derive Feynman rules needed for the strongest signal process (this time, get your 2's right!)
- Compute signal cross section, and expected # of events in your exp. (need luminosity values)
- If # of events < 10, give up.

Planning a New Physics Search - 2

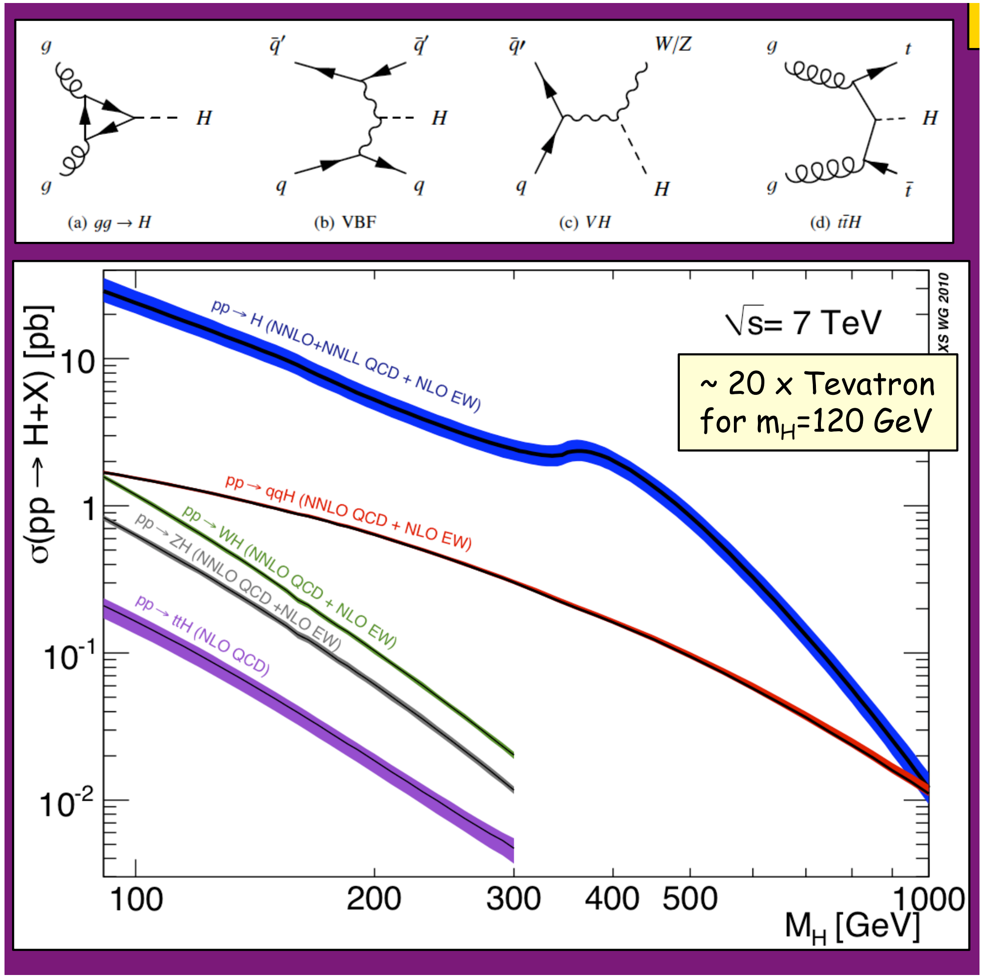
- Is X stable and charged under EM or QCD? (Yes - special case, see later. No - continue.)
- Is X stable and uncharged under EM/QCD? X is MET. Check that there are observable "tag" particles in your signal event. (Can use jets/gammas).
- If X unstable: Enumerate X decay channels and compute their branching ratios. Include cascade decays. List possible final states in terms of "detector objects": SM leptons, jets, missing pT ("MET").
- For each final state, list all SM processes that can produce it.
- For each final state, compute signal and SM rates (sigma*Br), imposing loose acceptance cuts if necessary (e.g. min jet pT)


proton - (anti)proton cross sections
Tevatron
LHC
σ_tot
σ_b
σ_jet(E_T^jet > √s/20)
σ_W
σ_Z
σ_jet(E_T^jet > 100 GeV)
σ_t
σ_jet(E_T^jet > √s/4)
σ_Higgs(M_H = 150 GeV)
σ_Higgs(M_H = 500 GeV)
σ (nb)
events/sec for L = 10^33 cm^-2 s^-1
√s (TeV)
0.1
1
10

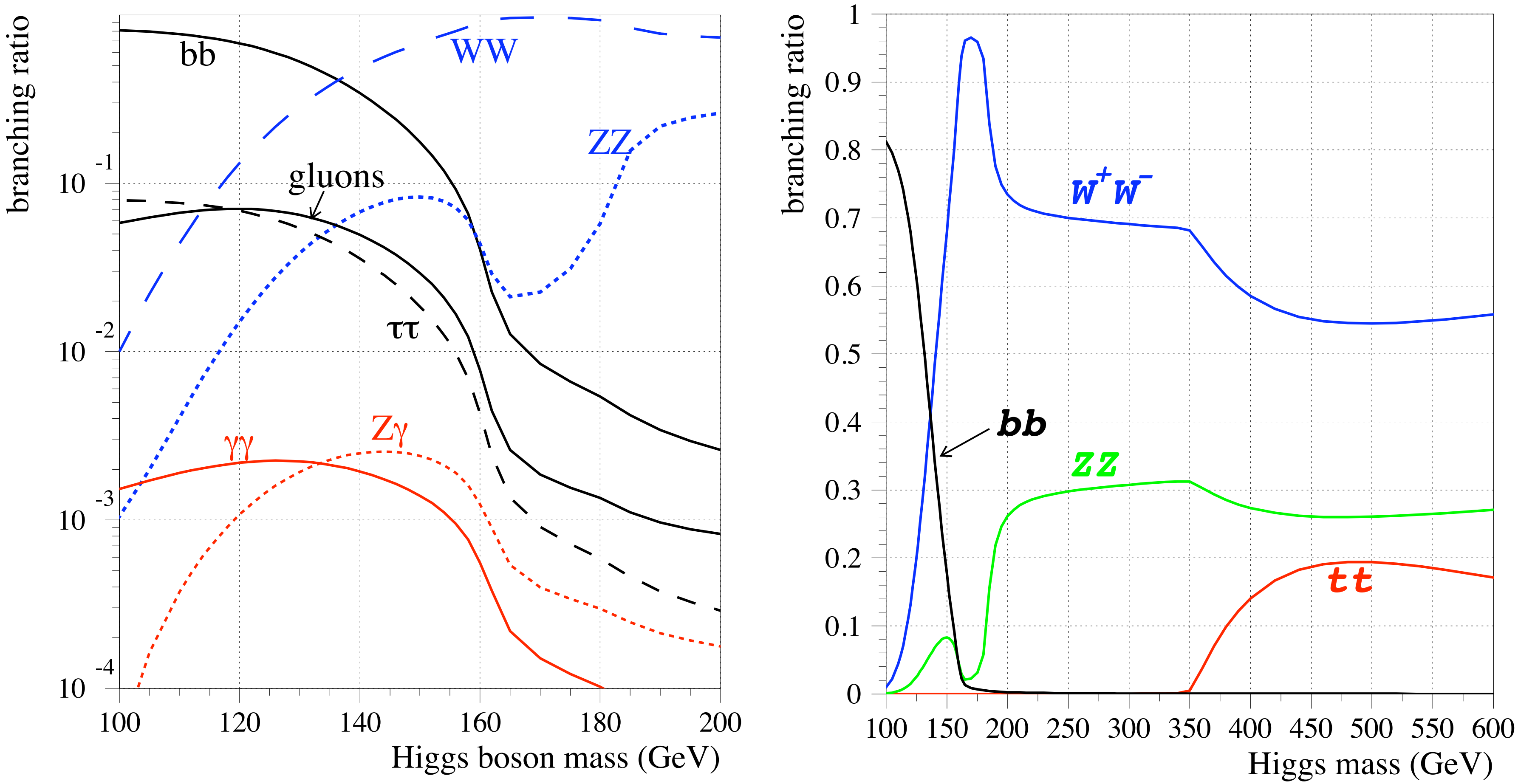
Planning a New Physics Search - 3

- 3 conditions for success
  - Events: $N_{\rm sig} = \sigma_{\rm sig} \times L_{\rm int} \times {\rm Br} \times {\rm Eff} \geq$ a few $\qquad \propto L_{\rm int}$
  - Statistics: $N_{\rm sig}/\sqrt{N_{\rm SM}} \geq$ a few $\qquad \propto L_{\rm int}^{1/2}$
  - Systematics: $N_{\rm sig}/N_{\rm SM} \geq ({\rm a\ few}) \times \sigma_{\rm sys}$ $\qquad \propto L_{\rm int}^{0}$
- $\sigma_{\rm sys}$ includes uncalculated higher-order corrections, pdf errors, and ideally some estimate of detector systematics (talk to your exp colleagues!)
- If the 3 conditions are NOT met, impose selection cuts: exploit differences in kinematic distributions between signal and SM events
- Iterate until the 3 conditions are met
- BINGO!

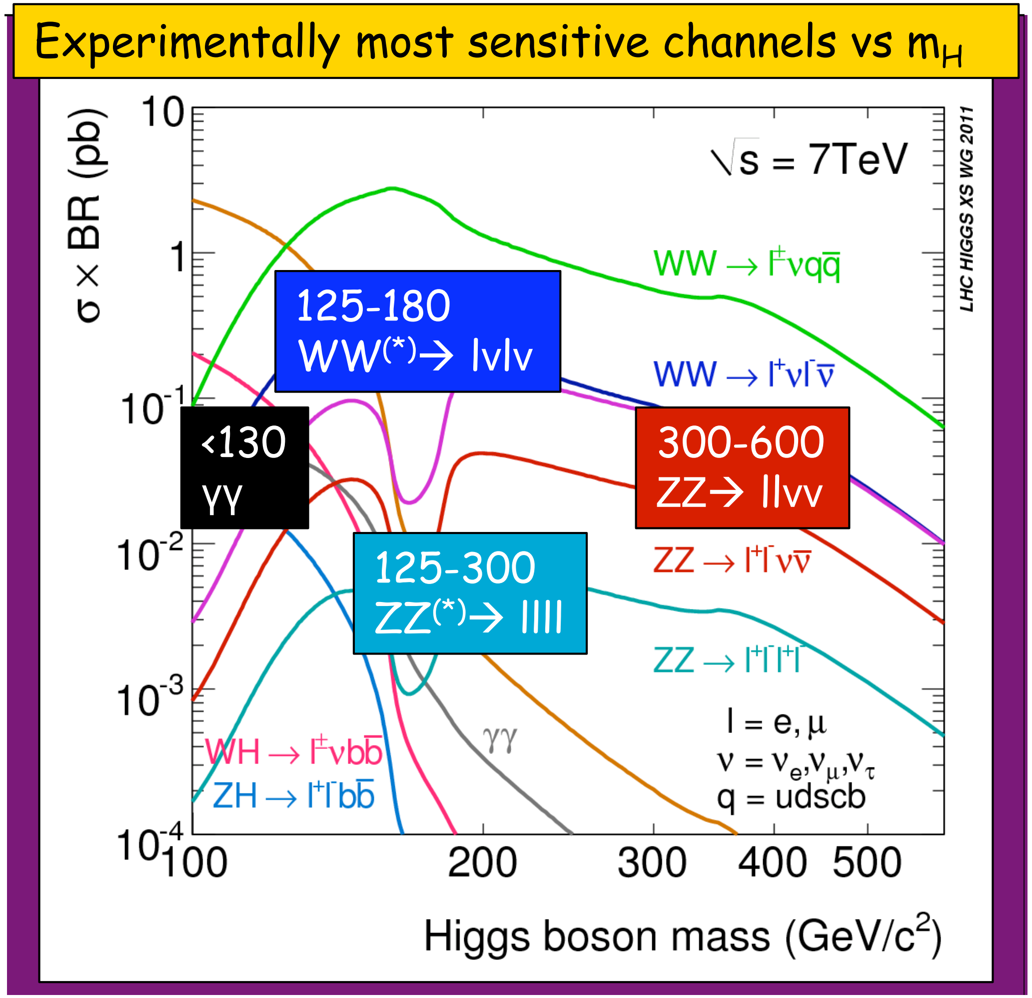
Example: Higgs Search



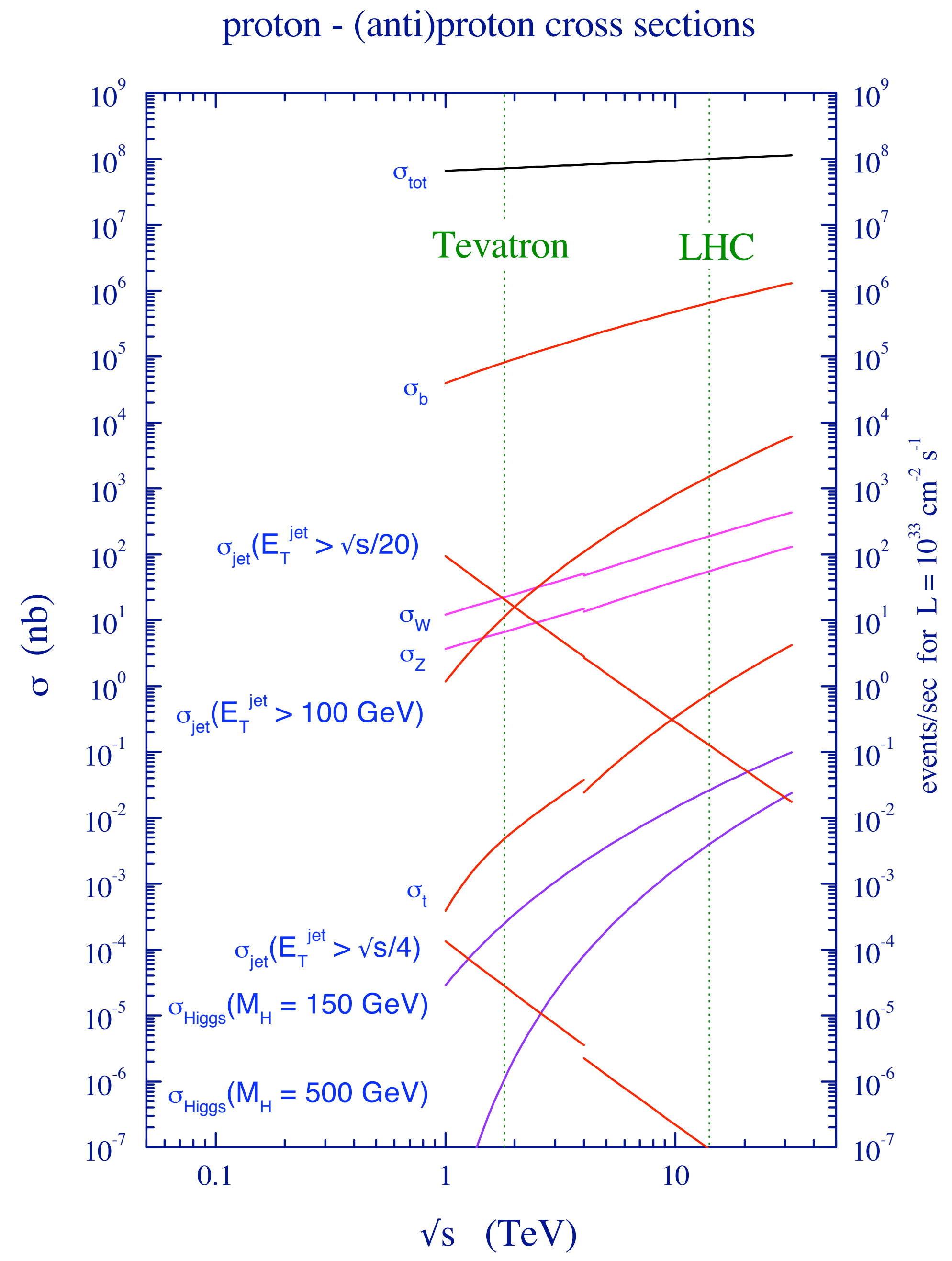
Higgs production cross section - LHC



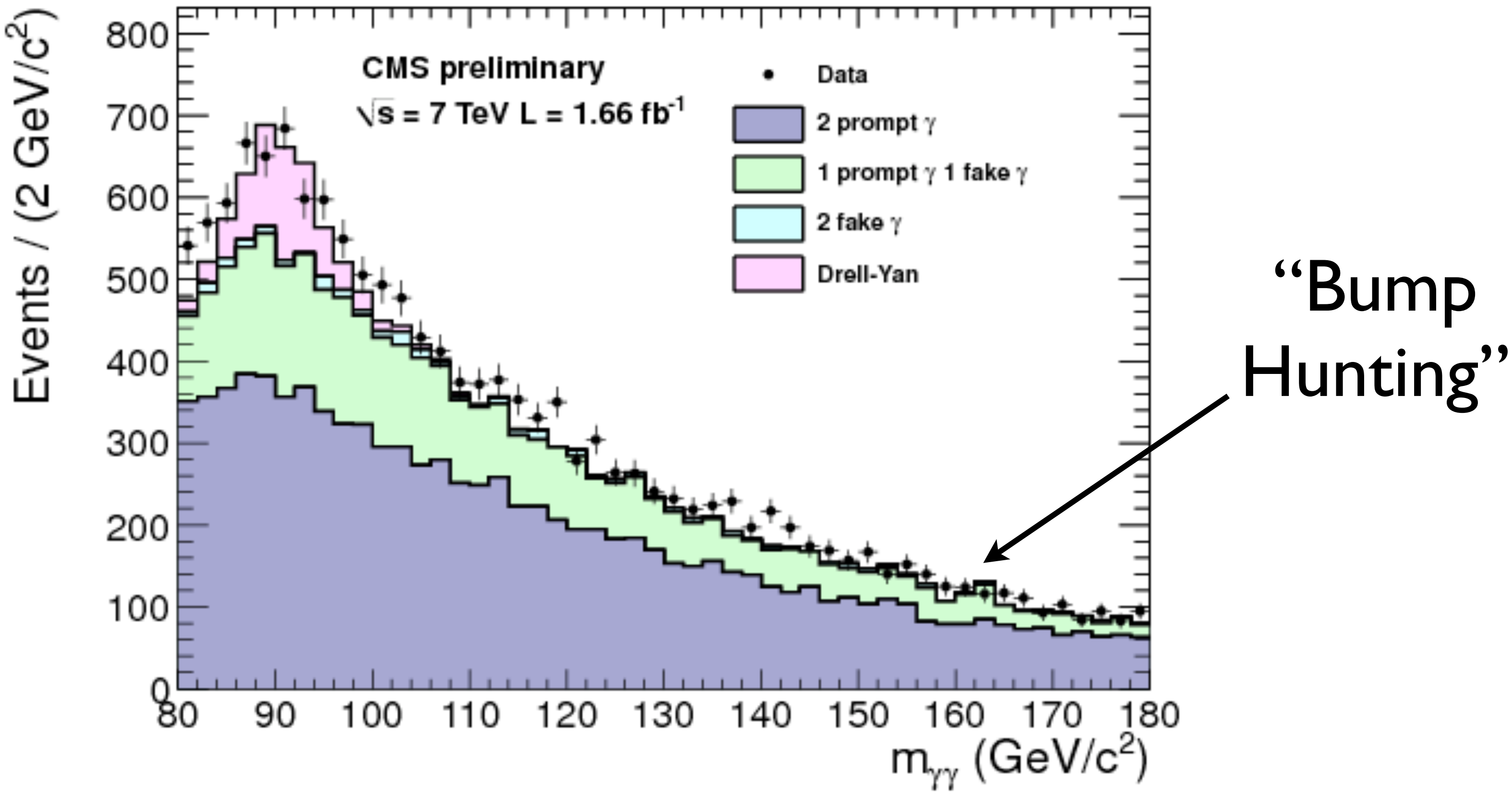
http://diablo.phys.northwestern.edu/pc/brs.html



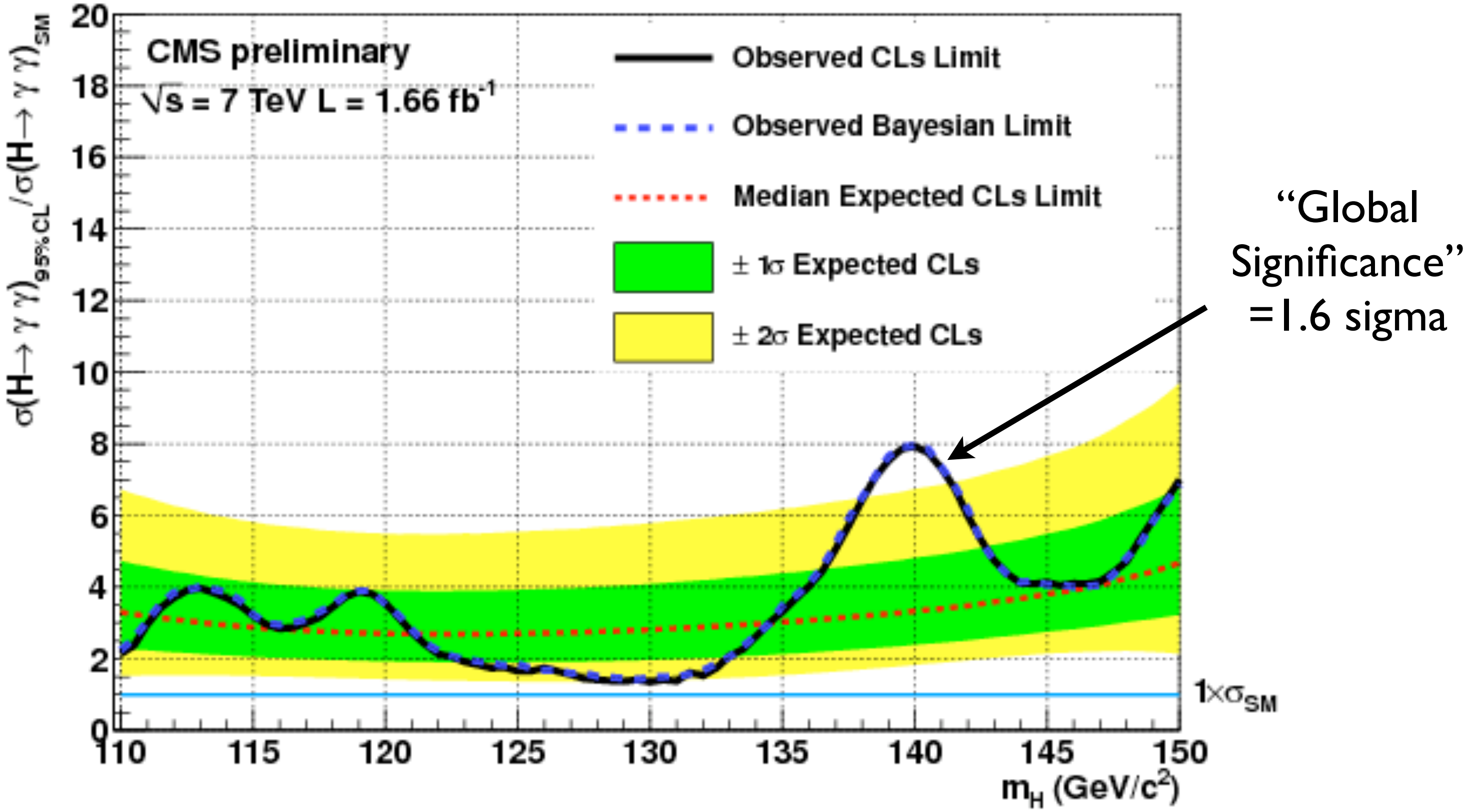
Experimentally most sensitive channels vs m_H
σ × BR (pb)
10
1
10^-1
10^-2
10^-3
10^-4
100
200
300
400
500
Higgs boson mass (GeV/c^2)
√s = 7TeV
LHC HIGGS XS WG 2011
WW → l±νqq̄
WW → l+νl-ν̄
ZZ → l+l-νν̄
ZZ → l+l-l+l-
WH → l±νbb̄
ZH → l+l-bb̄
γγ
l = e, μ
ν = νe,νμ,ντ
q = udscb
125-180
WW(*)→ lνlν
<130
γγ
300-600
ZZ→ llνν
125-300
ZZ(*)→ llll


proton - (anti)proton cross sections
σ (nb)
events/sec for L = 10^33 cm^-2 s^-1
√s (TeV)
Tevatron
LHC
σtot
σb
σjet(ET jet > √s/20)
σW
σZ
σjet(ET jet > 100 GeV)
σt
σjet(ET jet > √s/4)
σHiggs(MH = 150 GeV)
σHiggs(MH = 500 GeV)
0.1
1
10

H > 2 photons Search

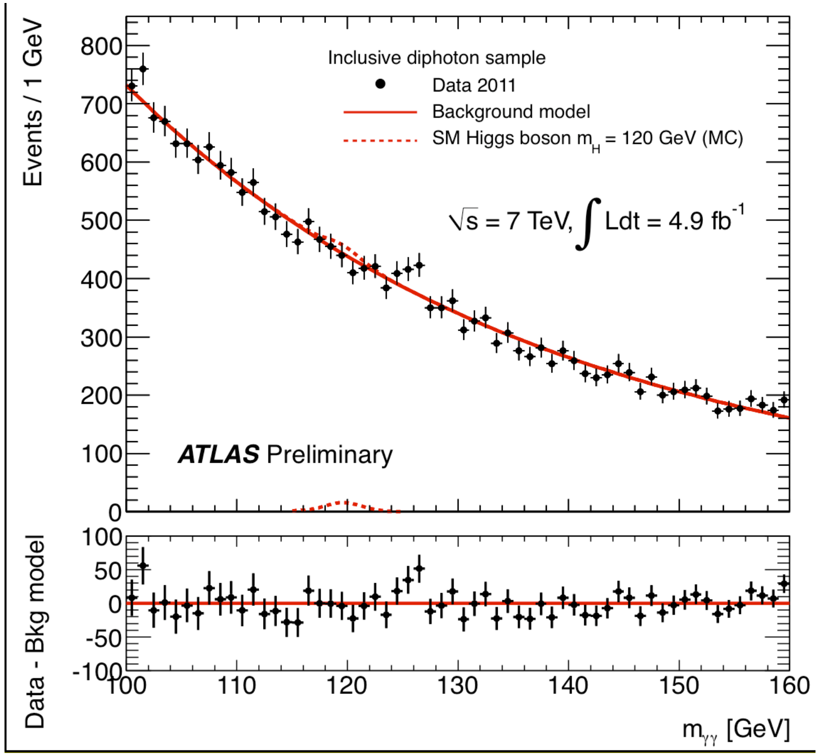


CMS, HIG-11-021



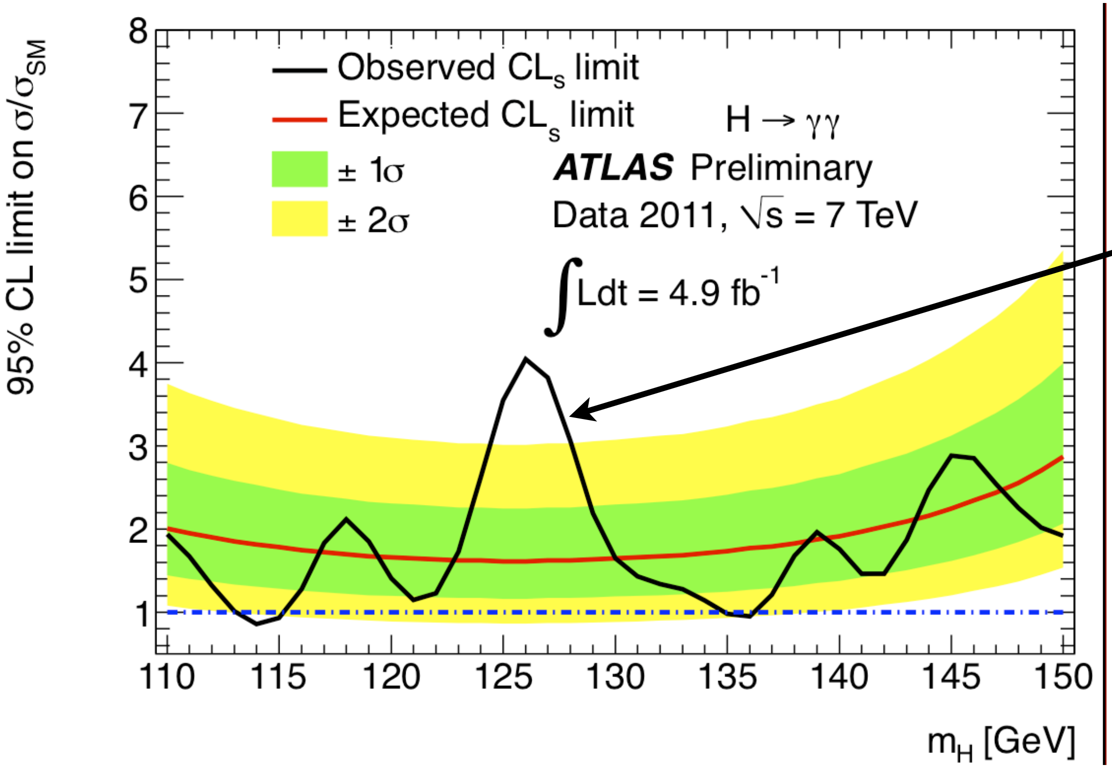
CMS, HIG-11-021

H > 2 photons Search



ATLAS, Dec 13 2011 CERN talk

H > 2 photons Search



"Global Significance" =1.5 sigma

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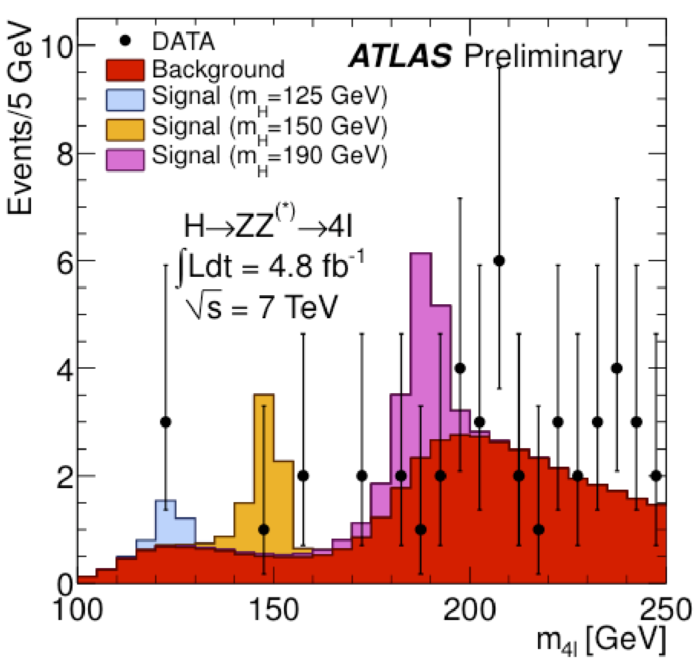
H > ZZ* -> 4 leptons Search



In the region m_H < 141 GeV (not already excluded at 95% C.L.) 3 events are observed: two 2e2μ events (m=123.6 GeV, m=124.3 GeV) and one 4μ event (m=124.6 GeV)

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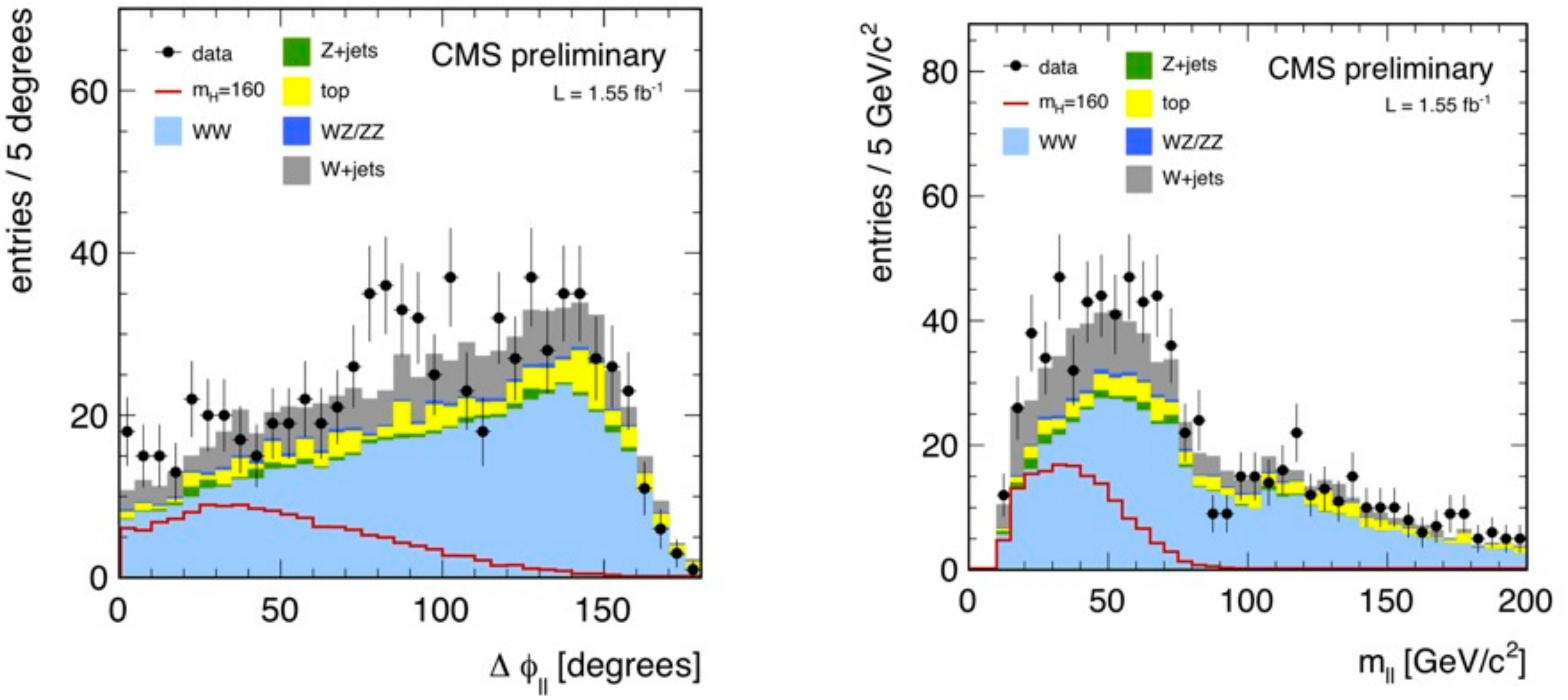
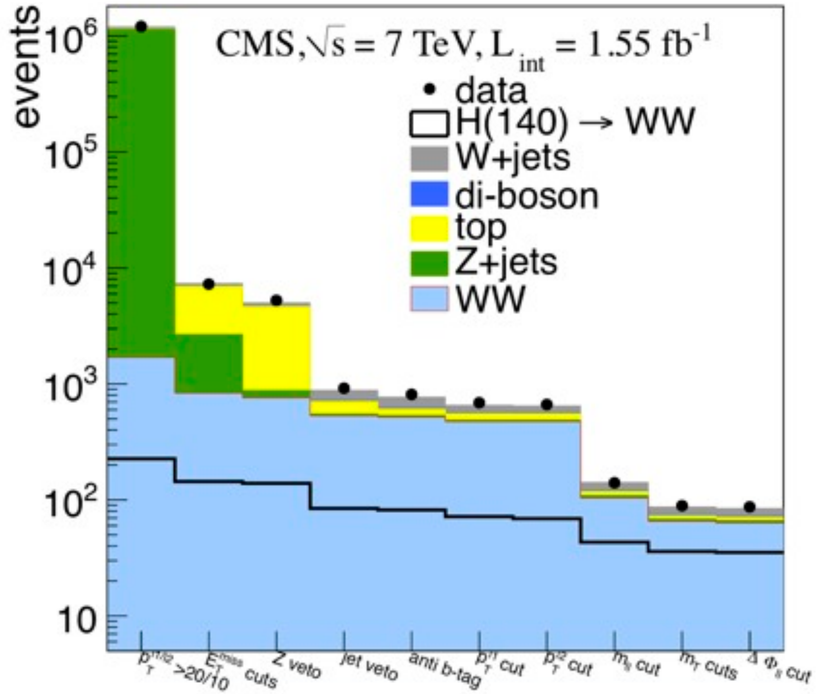
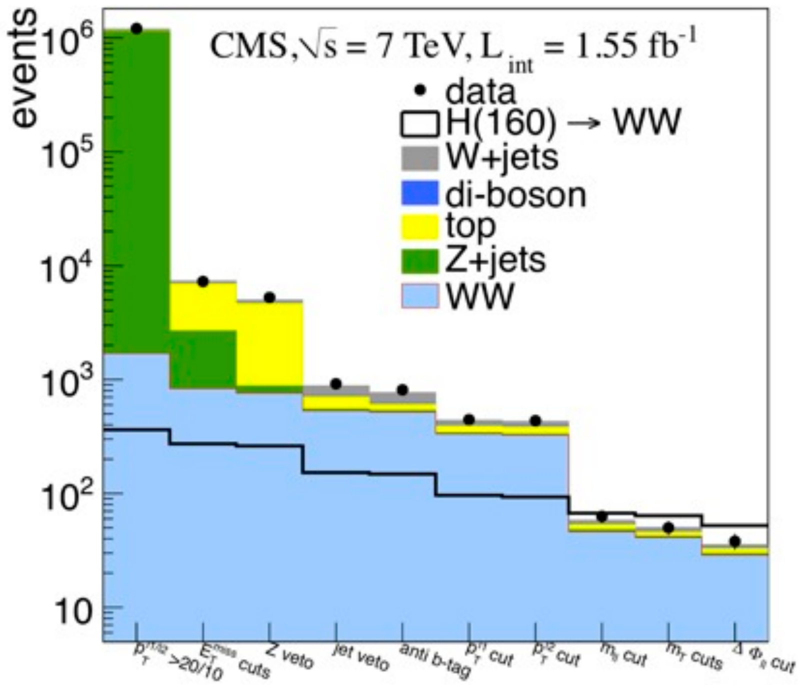
H > WW* > 2l+2nu Search



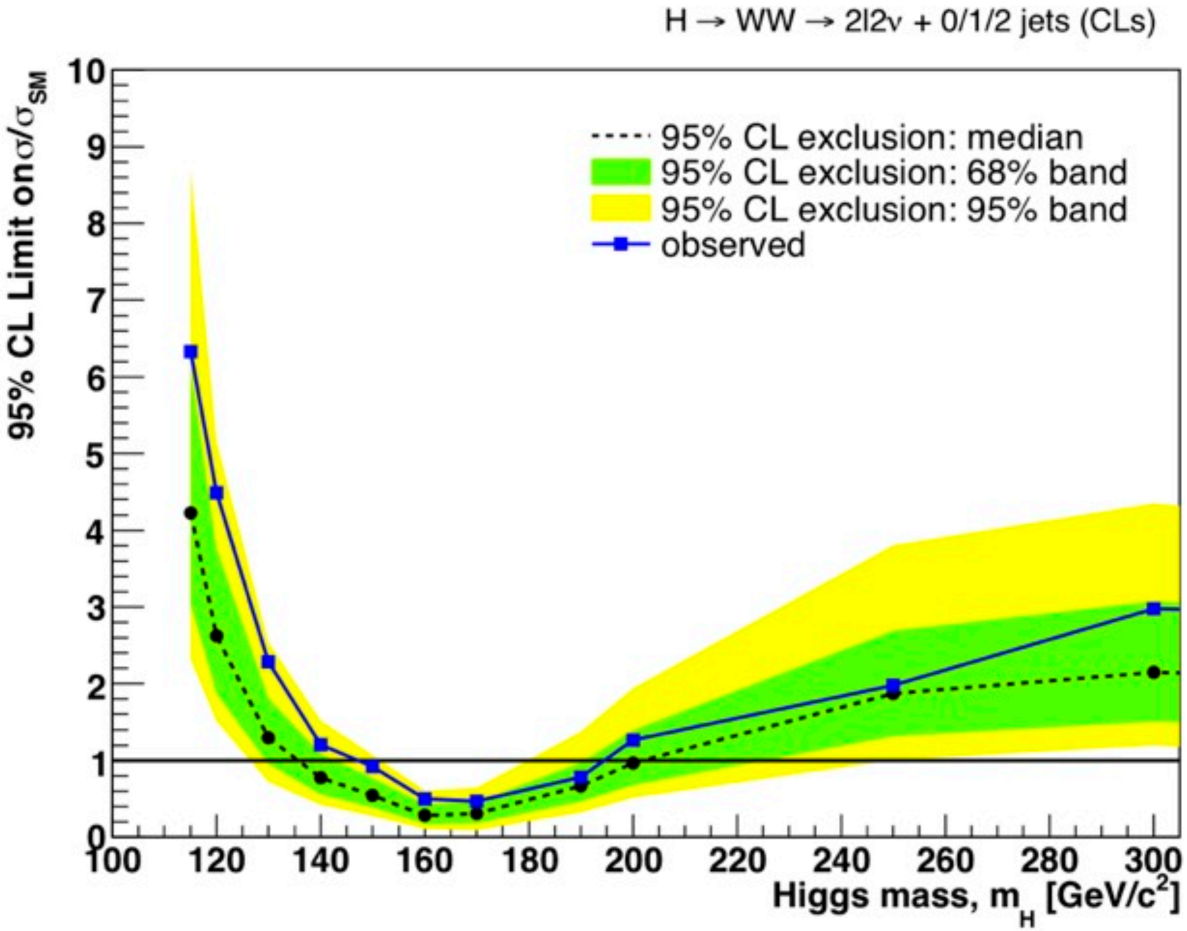
CMS, HIG-11-014

“Cut Flow Evolution Charts”





CMS, HIG-11-014

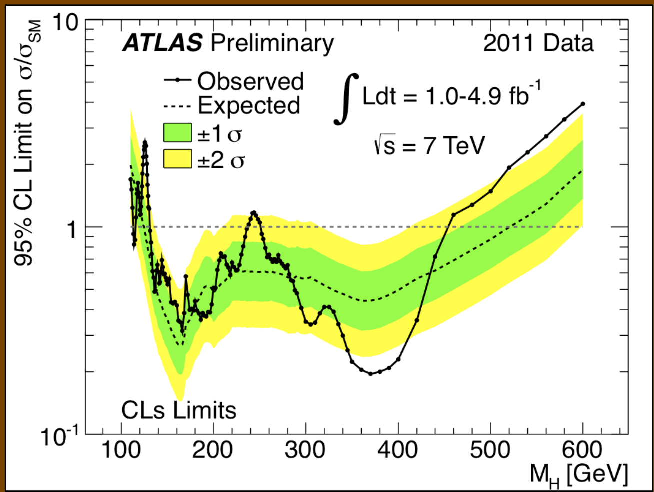


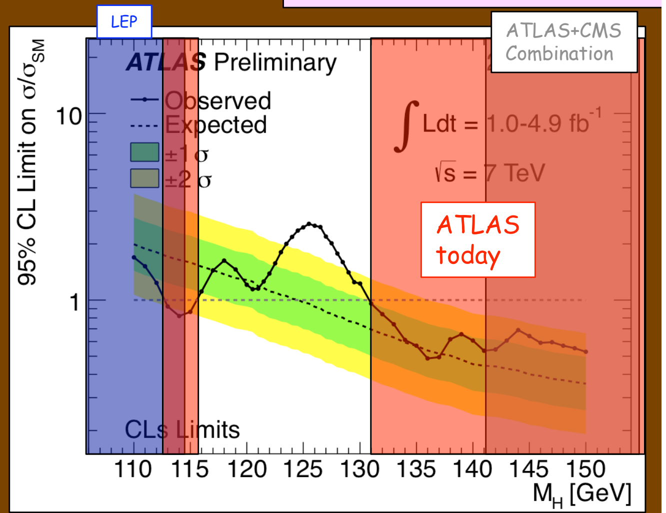
CMS, HIG-11-014

Combining All Channels

Putting all channels together → combined constraints

H→γγ, H→ ττ
H→ WW$^{(*)}$→ lνlν
H→ ZZ$^{(*)}$ → 4l, H→ ZZ → llνν
H→ ZZ → llqq, H→ WW→lνqq
W/ZH→ lbb+X not included





Excluded at 95% CL	$112.7 < m_H < 115.5$ GeV $131 < m_H < 453$ GeV, except 237-251 GeV
Expected if no signal	124.6-520 GeV

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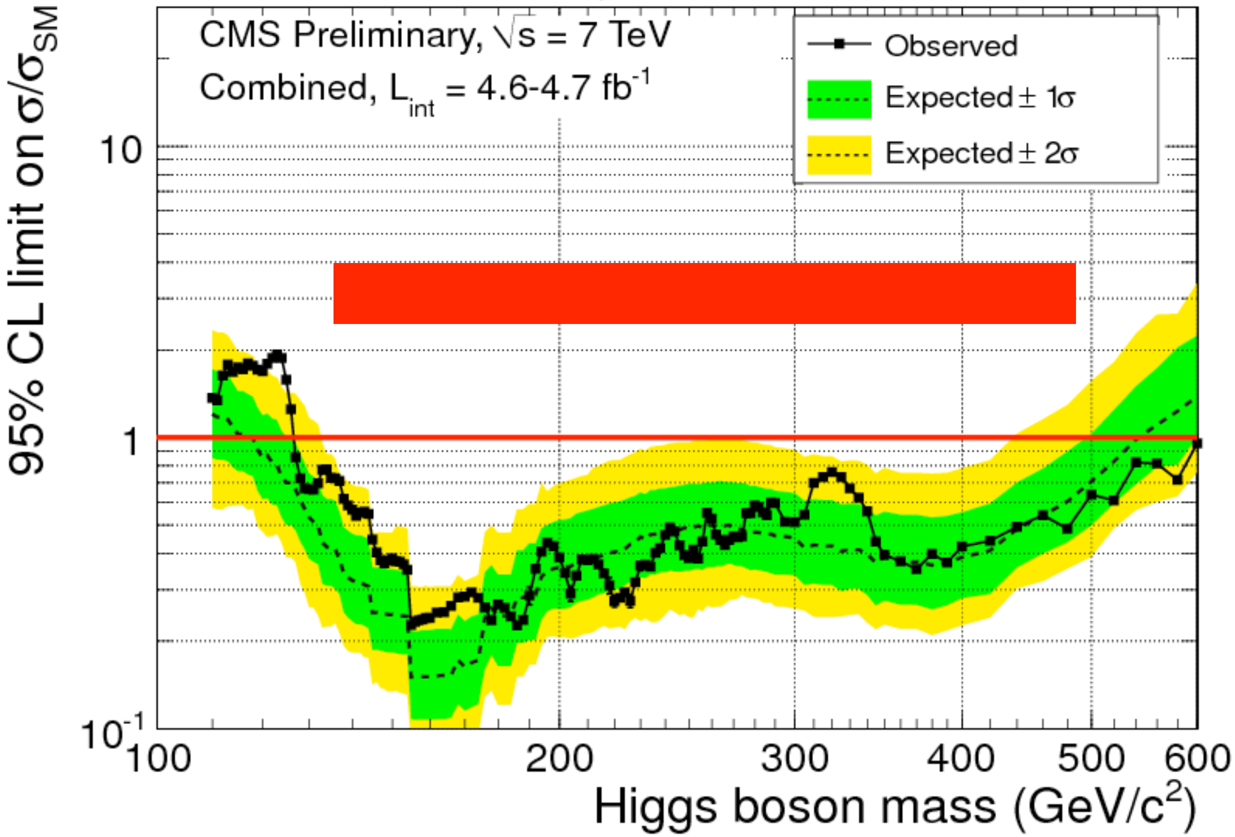
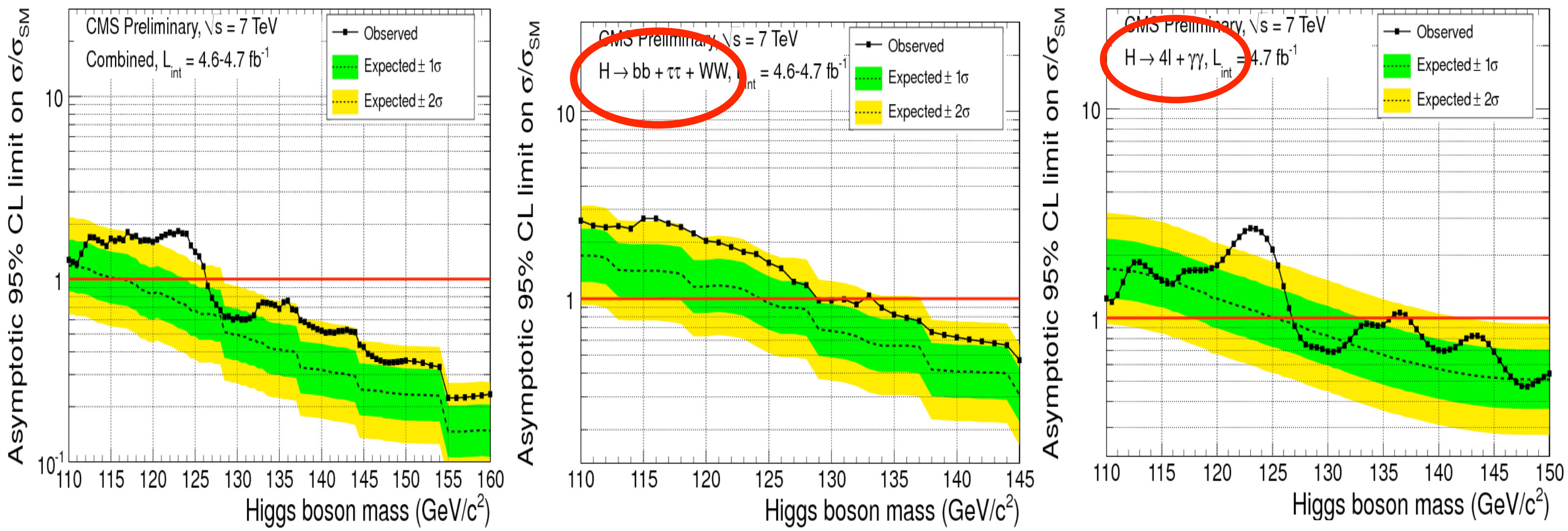
Combining All Channels

Limits on σ/σ_{sm} (CLs method)



Zoom in the low mass region



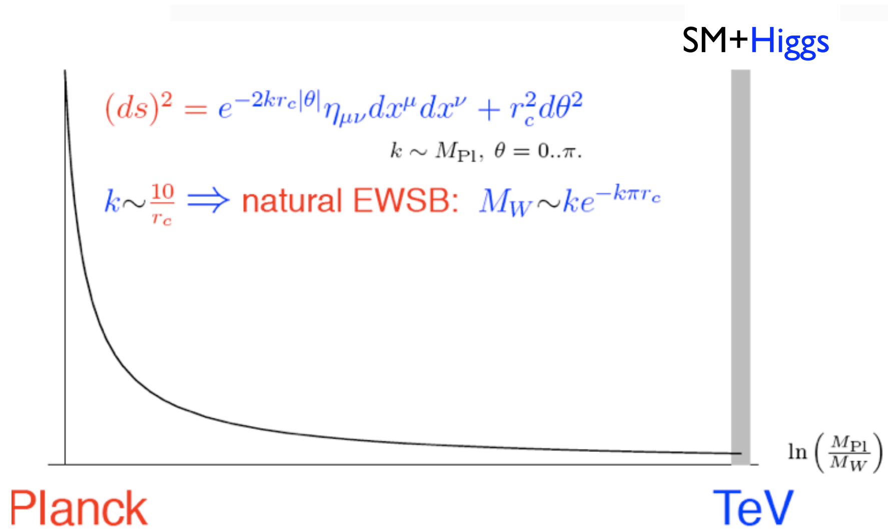
We cannot exclude the presence of the SM Higgs boson below 127GeV because of a modest excess of events in the region between 115 and 127GeV.

The excess at low mass is produced by a broad excess driven by the low resolution channels (H2TT, H2WW, H2BB, center), modulated by the localized excesses seen by the high resolution channels (H2GG and H2ZZ, right).

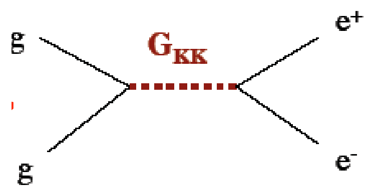
Examples of BSM Signatures Relevant for This School

Warped (RS) Extra Dimension

- Original model had the SM on the TeV brane, solves the hierarchy problem

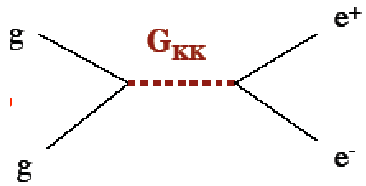


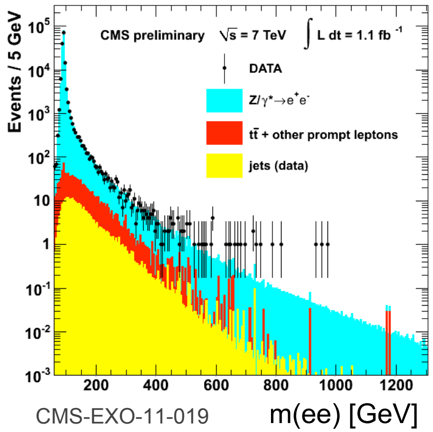
- New states: KK gravitons at the TeV scale

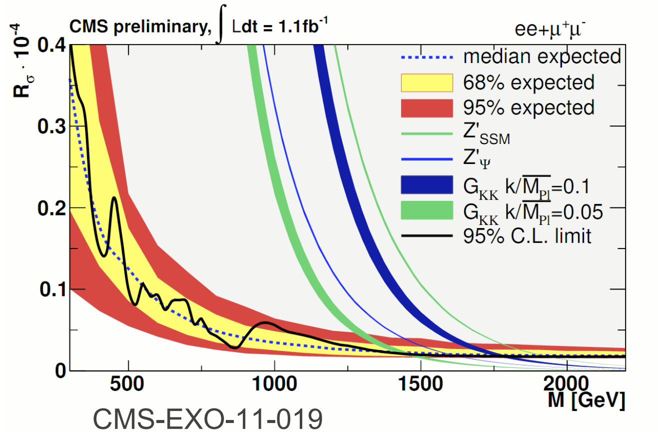


- Couplings: $\mathcal{L} \sim \frac{1}{(\mathrm{TeV})^2} T_{\mu\nu} G^{\mu\nu}_{\mathrm{KK}}$

RS: LHC Searches







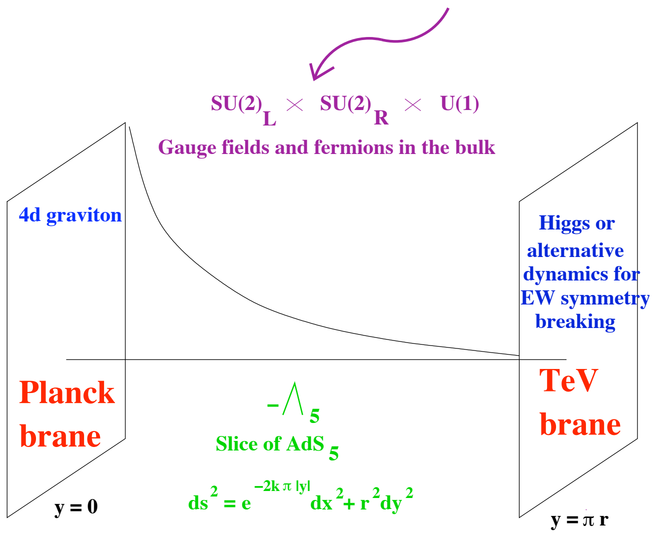
RS graviton (k/M_{Pl} = 0.1):

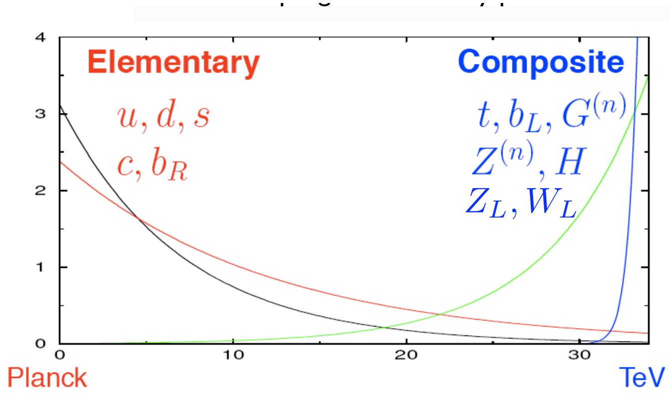
m(G) > 1.8 TeV at 95% C.L.

[a similar bound is obtained from 2-photon resonance search]

RS with Bulk Matter

- It was subsequently realized that models with SM gauge fields and fermions in the "bulk" are more interesting:





- natural solution to fermion mass hierarchy problem

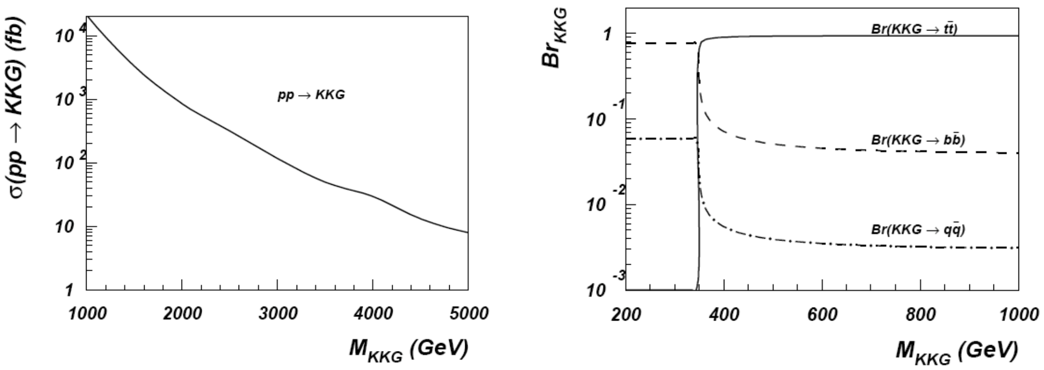
- natural suppression of flavor-changing neutral currents

- possibility of gauge coupling unification, as in the MSSM

figure credits: G. Perez, G. Servant

RS with Bulk Matter: Pheno

- Good: all SM states now have KK modes!
- Bad: the KKs do not couple to light quarks and leptons much...
- Worse: PEW constraints force KK masses > 3 TeV or so
- KK gluon is probably the easiest target at the LHC



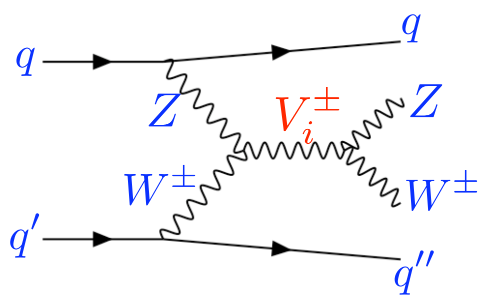
Agashe et. al., hep-ph/0612015; Lillie et.al., hep-ph/0701166

Final state: A pair of highly-boosted tops ("top jets"?)

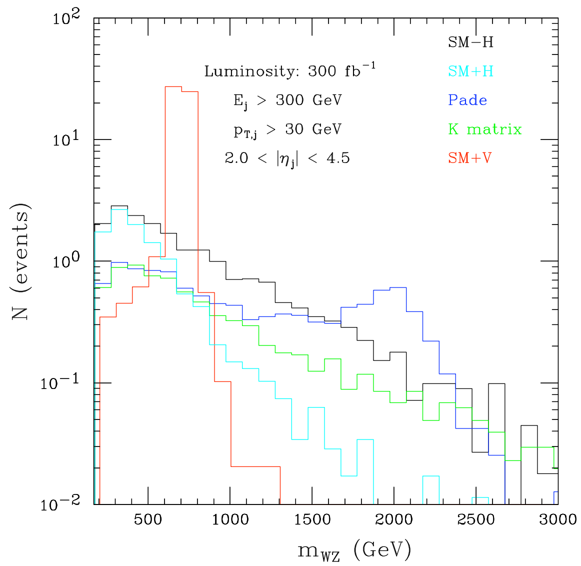
See Gilad Perez's lectures next week!

Higgsless Phenomenology

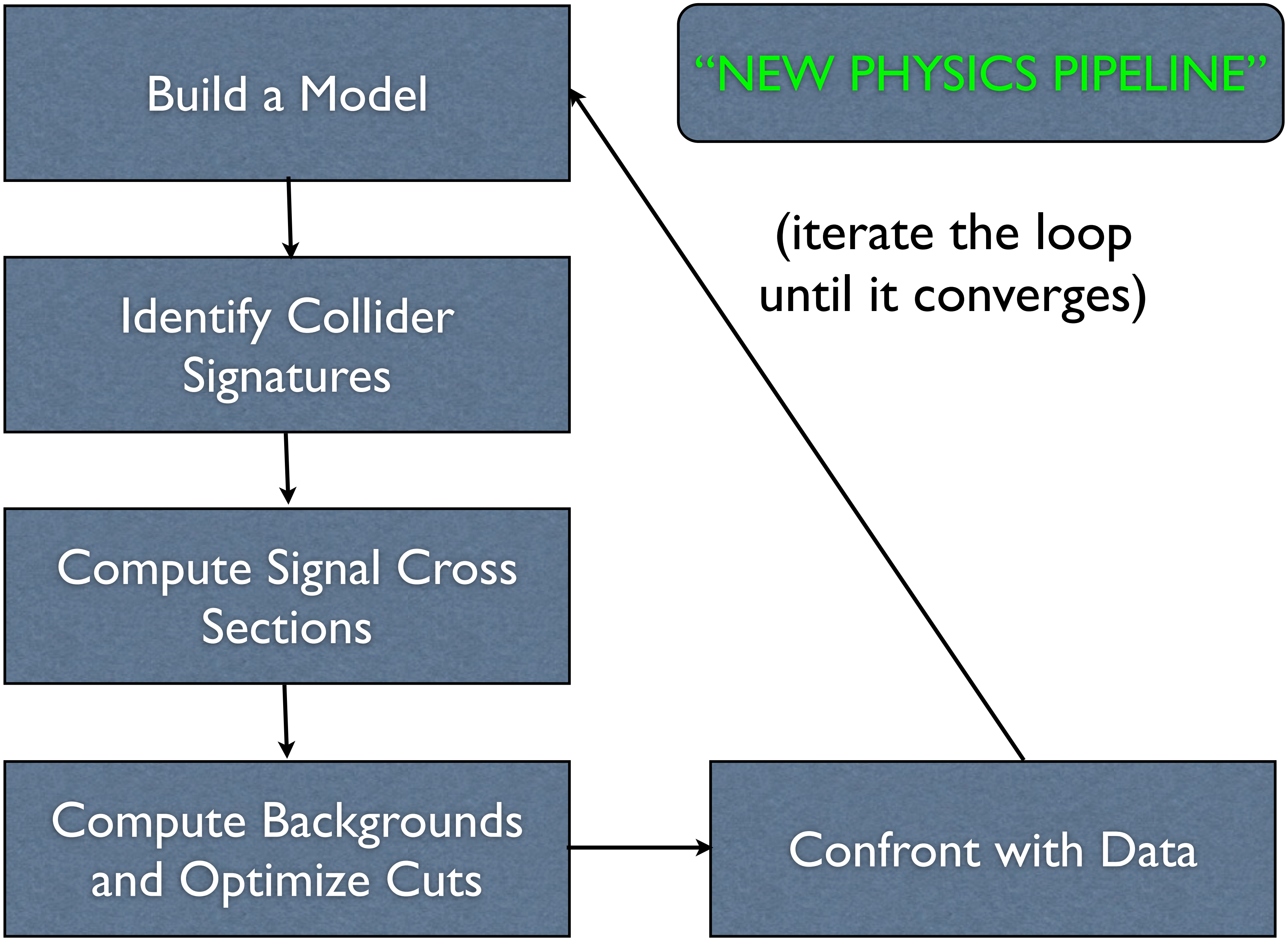
- Best place to search for all higgsless models is W/Z scattering
- Unitarity must be restored, typically resonances appear
- 5D Higgsless model predicts narrow, light (sub-TeV) resonances



[Birkedal, Matchev, MP, hep-ph/0412278]



Gold-Plated Channel: 2j+3l+Et_miss


Build a Model
"NEW PHYSICS PIPELINE"
Identify Collider Signatures
(iterate the loop until it converges)
Compute Signal Cross Sections
Compute Backgrounds and Optimize Cuts
Confront with Data

Monte Carlo Tools for BSM

- Monte Carlo predictions from models are essential for theory/experiment connection
- Old model: MC developers implement models in general-purpose generators, users use these tools (slow!)
- New model (over the last ~3-4 years):
  - users implement models in parton-level matrix element generators (e.g. Madgraph), output Les Houches Accord-compatible files
  - LHA files are passed on to the rest of the simulation chain (same as SM, except if long-lived BSM states)

- 2 Evening tutorials on MadGraph, Pythia, Herwig
- All grad students (and others) are welcome!
- Registration is free