Karlsruhe Institute of Technology

# Introductory remarks

**Kirill Melnikov**

**TTP KIT**

QCD@West Lake School
Institute for Modern Physics, Zhejiang University, Hangzhou, China
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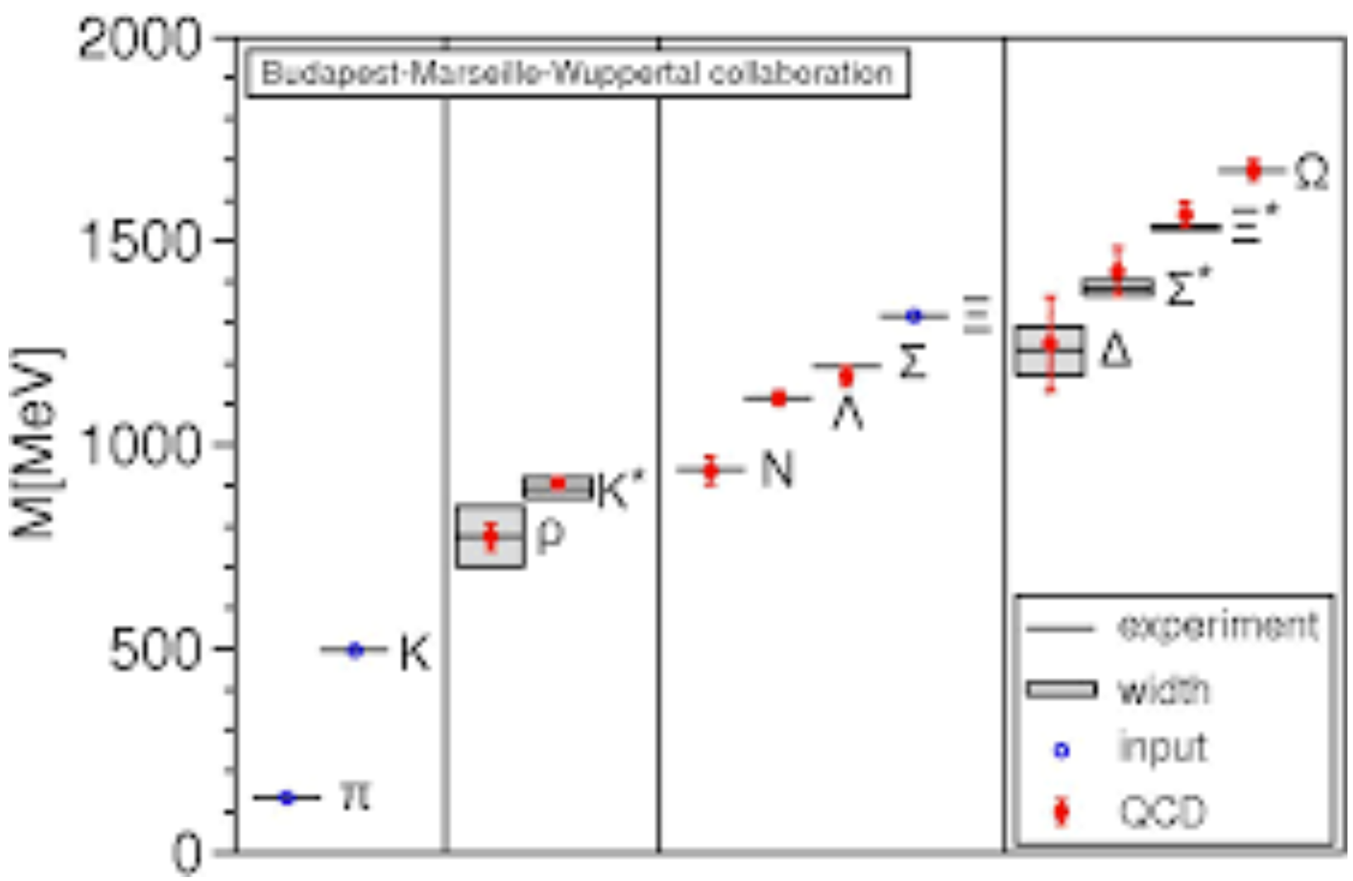
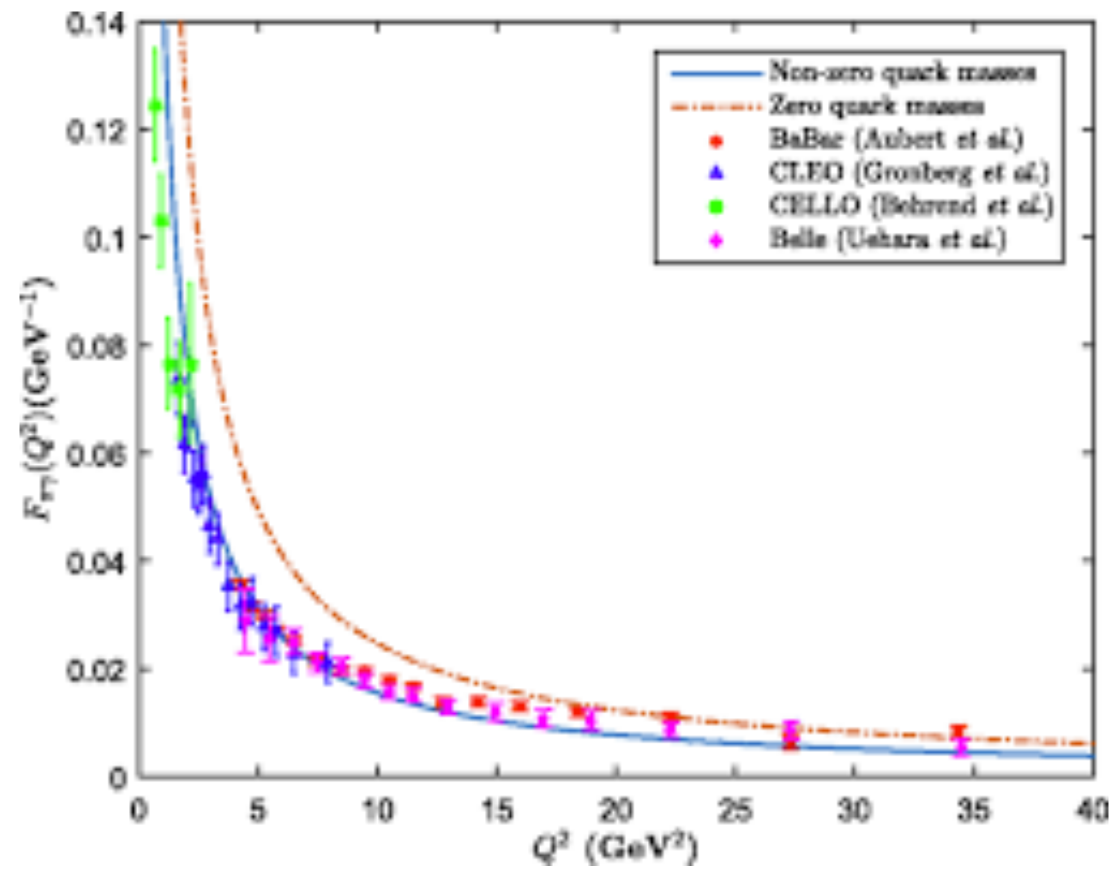
# QCD is multi-facet

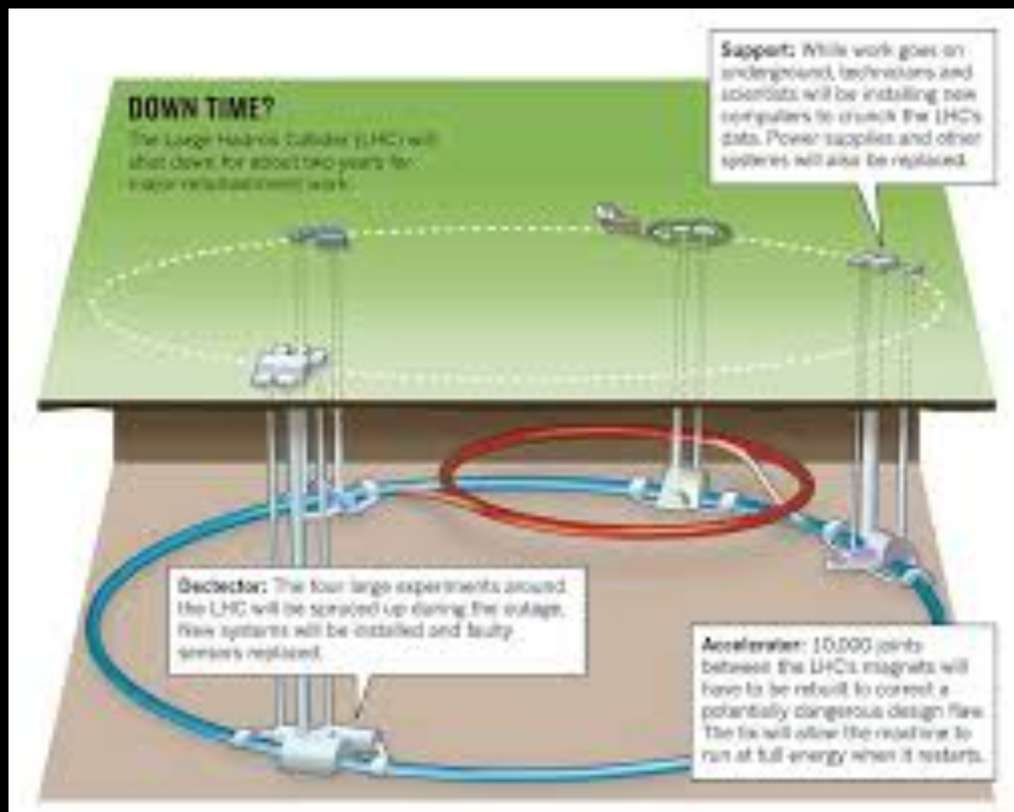
This school is about QCD - the theory of strong interactions. Strong interactions are interactions between hadrons; they determine hadron properties, such as masses, magnetic moments, lifetimes, form factors etc.

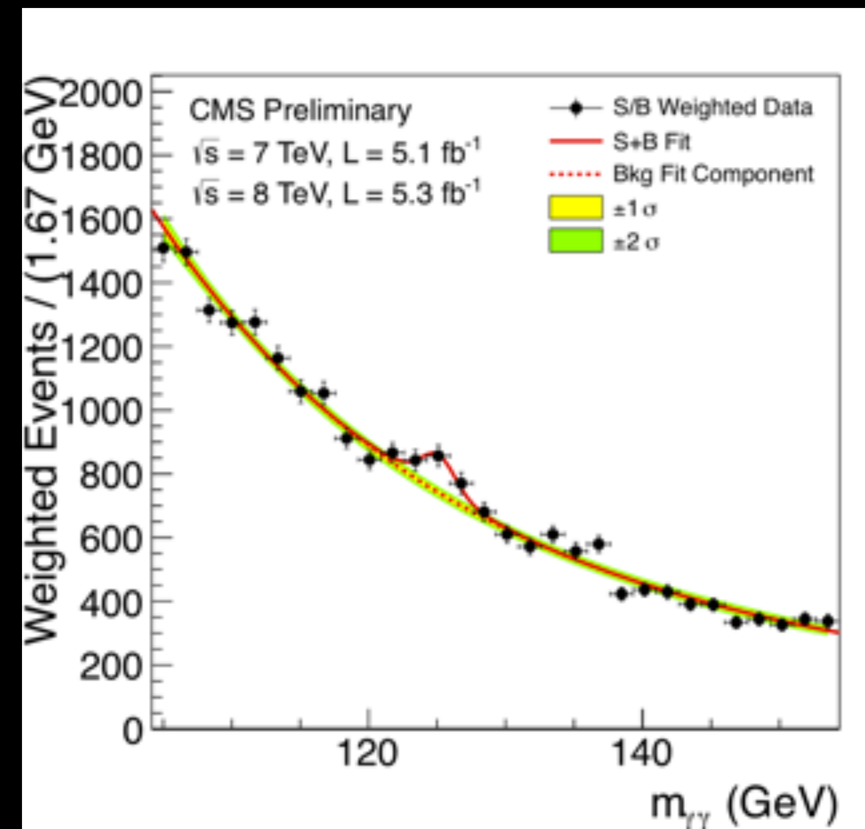
Since our focus will be the LHC physics, we will mostly talk about QCD in the context of quarks and gluons.

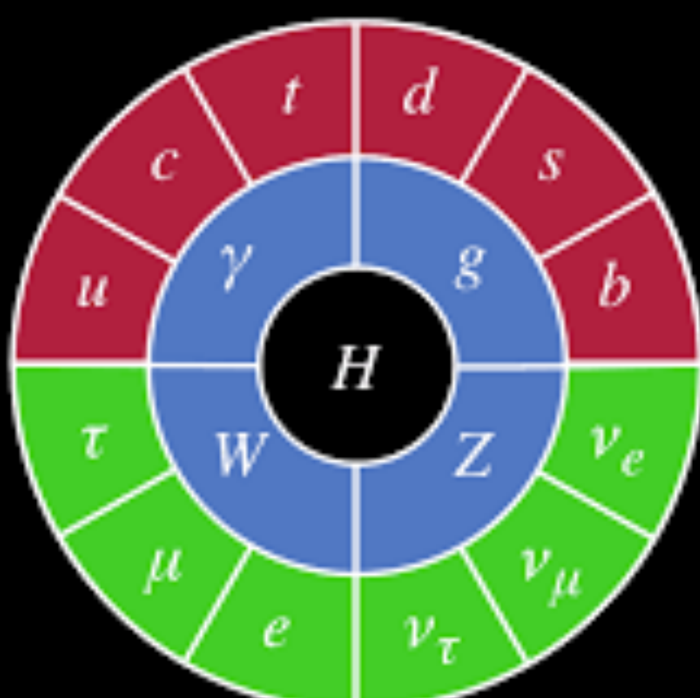


# What is the physics beyond the Standard Model?

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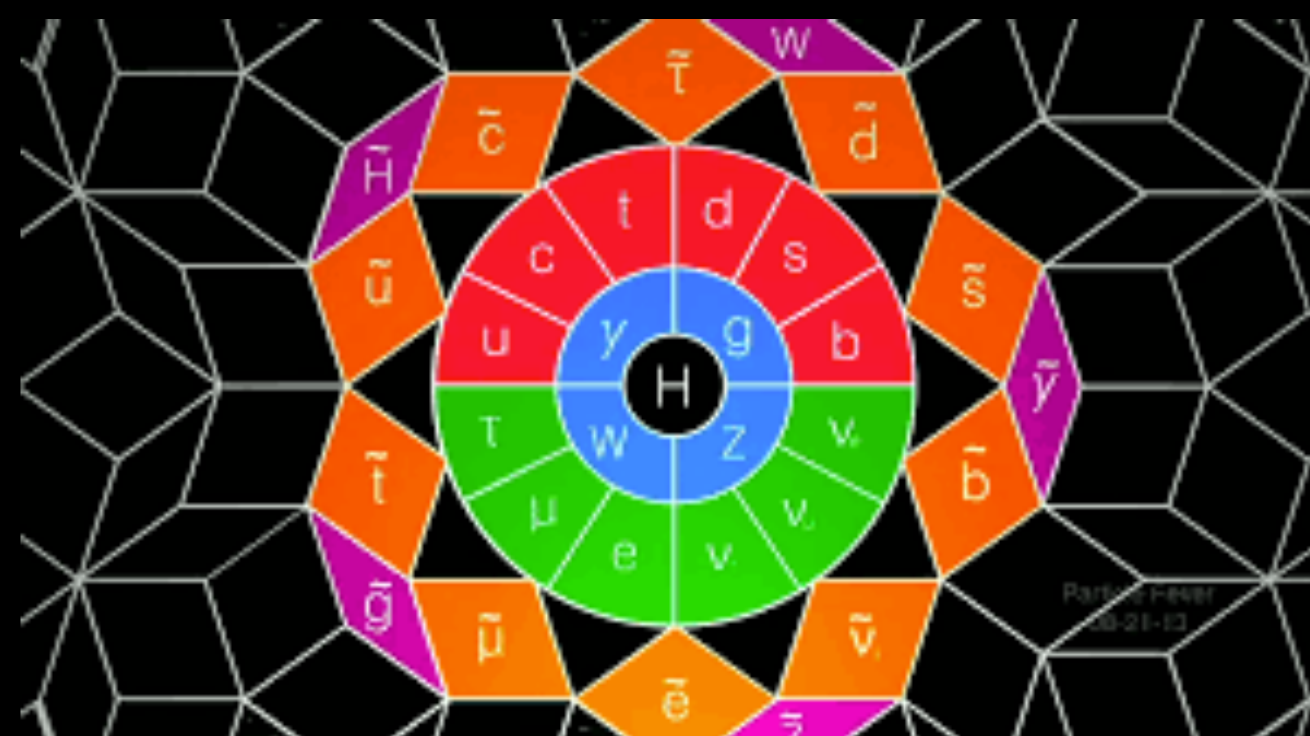
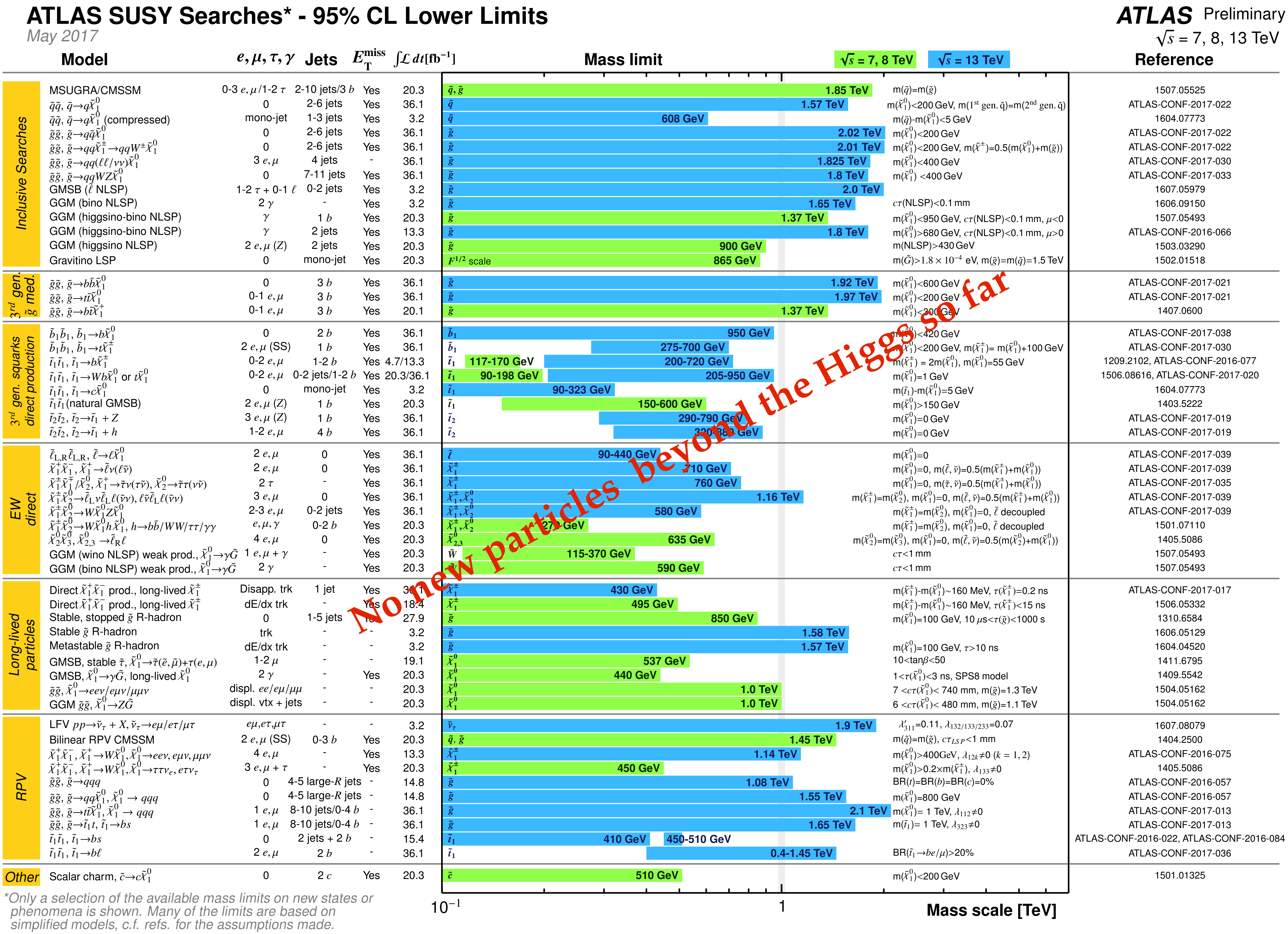



ATLAS SUSY Searches* - 95% CL Lower Limits
May 2017
ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV
Model | $e, \mu, \tau, \gamma$ | Jets | $E_T^{miss}$ | $\int \mathcal{L}\, dt[fb^{-1}]$ | Mass limit | Reference
$\sqrt{s}$ = 7, 8 TeV
$\sqrt{s}$ = 13 TeV
Inclusive Searches
MSUGRA/CMSSM | 0-3 $e,\mu$/1-2 $\tau$ | 2-10 jets/3 $b$ | Yes | 20.3 | $\tilde{q},\tilde{g}$ 1.85 TeV | m($\tilde{q}$)=m($\tilde{g}$) | 1507.05525
$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 36.1 | $\tilde{q}$ 1.57 TeV | m($\tilde{\chi}_1^0$)<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$) | ATLAS-CONF-2017-022
$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed) | mono-jet | 1-3 jets | Yes | 3.2 | $\tilde{q}$ 608 GeV | m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<5 GeV | 1604.07773
$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 36.1 | $\tilde{g}$ 2.02 TeV | m($\tilde{\chi}_1^0$)<200 GeV | ATLAS-CONF-2017-022
$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 36.1 | $\tilde{g}$ 2.01 TeV | m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$)) | ATLAS-CONF-2017-022
$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$ | 3 $e,\mu$ | 4 jets | - | 36.1 | $\tilde{g}$ 1.825 TeV | m($\tilde{\chi}_1^0$)<400 GeV | ATLAS-CONF-2017-030
$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$ | 0 | 7-11 jets | Yes | 36.1 | $\tilde{g}$ 1.8 TeV | m($\tilde{\chi}_1^0$) <400 GeV | ATLAS-CONF-2017-033
GMSB ($\tilde{\ell}$ NLSP) | 1-2 $\tau$ + 0-1 $\ell$ | 0-2 jets | Yes | 3.2 | $\tilde{g}$ 2.0 TeV | | 1607.05979
GGM (bino NLSP) | 2 $\gamma$ | - | Yes | 3.2 | $\tilde{g}$ 1.65 TeV | $c\tau$(NLSP)<0.1 mm | 1606.09150
GGM (higgsino-bino NLSP) | $\gamma$ | 1 $b$ | Yes | 20.3 | $\tilde{g}$ 1.37 TeV | m($\tilde{\chi}_1^0$)<950 GeV, $c\tau$(NLSP)<0.1 mm, $\mu$<0 | 1507.05493
GGM (higgsino-bino NLSP) | $\gamma$ | 2 jets | Yes | 13.3 | $\tilde{g}$ 1.8 TeV | m($\tilde{\chi}_1^0$)>680 GeV, $c\tau$(NLSP)<0.1 mm, $\mu$>0 | ATLAS-CONF-2016-066
GGM (higgsino NLSP) | 2 $e,\mu$ ($Z$) | 2 jets | Yes | 20.3 | $\tilde{g}$ 900 GeV | m(NLSP)>430 GeV | 1503.03290
Gravitino LSP | 0 | mono-jet | Yes | 20.3 | $F^{1/2}$ scale 865 GeV | m($\tilde{G}$)>1.8 × $10^{-4}$ eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV | 1502.01518
3rd gen. $\tilde{g}$ med.
$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$ | 0 | 3 $b$ | Yes | 36.1 | $\tilde{g}$ 1.92 TeV | m($\tilde{\chi}_1^0$)<600 GeV | ATLAS-CONF-2017-021
$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0-1 $e,\mu$ | 3 $b$ | Yes | 36.1 | $\tilde{g}$ 1.97 TeV | m($\tilde{\chi}_1^0$)<200 GeV | ATLAS-CONF-2017-021
$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$ | 0-1 $e,\mu$ | 3 $b$ | Yes | 20.1 | $\tilde{g}$ 1.37 TeV | m($\tilde{\chi}_1^0$)<300 GeV | 1407.0600
3rd gen. squarks direct production
$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$ | 0 | 2 $b$ | Yes | 36.1 | $\tilde{b}_1$ 950 GeV | m($\tilde{\chi}_1^0$)<420 GeV | ATLAS-CONF-2017-038
$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$ | 2 $e,\mu$ (SS) | 1 $b$ | Yes | 36.1 | $\tilde{b}_1$ 275-700 GeV | m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^\pm$)= m($\tilde{\chi}_1^0$)+100 GeV | ATLAS-CONF-2017-030
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^\pm$ | 0-2 $e,\mu$ | 1-2 $b$ | Yes | 4.7/13.3 | $\tilde{t}_1$ 117-170 GeV, 200-720 GeV | m($\tilde{\chi}_1^\pm$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV | 1209.2102, ATLAS-CONF-2016-077
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$ | 0-2 $e,\mu$ | 0-2 jets/1-2 $b$ | Yes | 20.3/36.1 | $\tilde{t}_1$ 90-198 GeV, 205-950 GeV | m($\tilde{\chi}_1^0$)=1 GeV | 1506.08616, ATLAS-CONF-2017-020
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ | 0 | mono-jet | Yes | 3.2 | $\tilde{t}_1$ 90-323 GeV | m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)=5 GeV | 1604.07773
$\tilde{t}_1\tilde{t}_1$ (natural GMSB) | 2 $e,\mu$ ($Z$) | 1 $b$ | Yes | 20.3 | $\tilde{t}_1$ 150-600 GeV | m($\tilde{\chi}_1^0$)>150 GeV | 1403.5222
$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$ | 3 $e,\mu$ ($Z$) | 1 $b$ | Yes | 36.1 | $\tilde{t}_2$ 290-790 GeV | m($\tilde{\chi}_1^0$)=0 GeV | ATLAS-CONF-2017-019
$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$ | 1-2 $e,\mu$ | 4 $b$ | Yes | 36.1 | $\tilde{t}_2$ 320-880 GeV | m($\tilde{\chi}_1^0$)=0 GeV | ATLAS-CONF-2017-019
EW direct
$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$ | 2 $e,\mu$ | 0 | Yes | 36.1 | $\tilde{\ell}$ 90-440 GeV | m($\tilde{\chi}_1^0$)=0 | ATLAS-CONF-2017-039
$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$ | 2 $e,\mu$ | 0 | Yes | 36.1 | $\tilde{\chi}_1^\pm$ 710 GeV | m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$)) | ATLAS-CONF-2017-039
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$ | 2 $\tau$ | - | Yes | 36.1 | $\tilde{\chi}_1^\pm$ 760 GeV | m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$)) | ATLAS-CONF-2017-035
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$ | 3 $e,\mu$ | 0 | Yes | 36.1 | $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 1.16 TeV | m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$)) | ATLAS-CONF-2017-039
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$ | 2-3 $e,\mu$ | 0-2 jets | Yes | 36.1 | $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 580 GeV | m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled | ATLAS-CONF-2017-039
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$ | $e,\mu,\gamma$ | 0-2 $b$ | Yes | 20.3 | $\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 270 GeV | m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled | 1501.07110
$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$ | 4 $e,\mu$ | 0 | Yes | 20.3 | $\tilde{\chi}_{2,3}^0$ 635 GeV | m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$)) | 1405.5086
GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$ | 1 $e,\mu+\gamma$ | - | Yes | 20.3 | $\tilde{W}$ 115-370 GeV | $c\tau$<1 mm | 1507.05493
GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$ | 2 $\gamma$ | - | Yes | 20.3 | $\tilde{W}$ 590 GeV | $c\tau$<1 mm | 1507.05493
Long-lived particles
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ | Disapp. trk | 1 jet | Yes | 36.1 | $\tilde{\chi}_1^\pm$ 430 GeV | m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)~160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns | ATLAS-CONF-2017-017
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ | dE/dx trk | - | Yes | 18.4 | $\tilde{\chi}_1^\pm$ 495 GeV | m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)~160 MeV, $\tau(\tilde{\chi}_1^\pm)$<15 ns | 1506.05332
Stable, stopped $\tilde{g}$ R-hadron | 0 | 1-5 jets | Yes | 27.9 | $\tilde{g}$ 850 GeV | m($\tilde{\chi}_1^0$)=100 GeV, 10 $\mu$s<$\tau(\tilde{g})$<1000 s | 1310.6584
Stable $\tilde{g}$ R-hadron | trk | - | - | 3.2 | $\tilde{g}$ 1.58 TeV | | 1606.05129
Metastable $\tilde{g}$ R-hadron | dE/dx trk | - | - | 3.2 | $\tilde{g}$ 1.57 TeV | m($\tilde{\chi}_1^0$)=100 GeV, $\tau$>10 ns | 1604.04520
GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$ | 1-2 $\mu$ | - | - | 19.1 | $\tilde{\chi}_1^0$ 537 GeV | 10<tan$\beta$<50 | 1411.6795
GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$ | 2 $\gamma$ | - | Yes | 20.3 | $\tilde{\chi}_1^0$ 440 GeV | 1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model | 1409.5542
$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to eev/e\mu v/\mu\mu v$ | displ. $ee/e\mu/\mu\mu$ | - | - | 20.3 | $\tilde{\chi}_1^0$ 1.0 TeV | 7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, m($\tilde{g}$)=1.3 TeV | 1504.05162
GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to Z\tilde{G}$ | displ. vtx + jets | - | - | 20.3 | $\tilde{\chi}_1^0$ 1.0 TeV | 6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, m($\tilde{g}$)=1.1 TeV | 1504.05162
RPV
LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$ | $e\mu,e\tau,\mu\tau$ | - | - | 3.2 | $\tilde{\nu}_\tau$ 1.9 TeV | $\lambda'_{311}$=0.11, $\lambda_{132/133/233}$=0.07 | 1607.08079
Bilinear RPV CMSSM | 2 $e,\mu$ (SS) | 0-3 $b$ | Yes | 20.3 | $\tilde{q},\tilde{g}$ 1.45 TeV | m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm | 1404.2500
$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to eev, e\mu v, \mu\mu v$ | 4 $e,\mu$ | - | Yes | 13.3 | $\tilde{\chi}_1^\pm$ 1.14 TeV | m($\tilde{\chi}_1^0$)>400GeV, $\lambda_{12k}\neq0$ ($k$ = 1, 2) | ATLAS-CONF-2016-075
$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$ | 3 $e,\mu+\tau$ | - | Yes | 20.3 | $\tilde{\chi}_1^\pm$ 450 GeV | m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^\pm$), $\lambda_{133}\neq0$ | 1405.5086
$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$ | 0 | 4-5 large-$R$ jets | - | 14.8 | $\tilde{g}$ 1.08 TeV | BR($t$)=BR($b$)=BR($c$)=0% | ATLAS-CONF-2016-057
$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$ | 0 | 4-5 large-$R$ jets | - | 14.8 | $\tilde{g}$ 1.55 TeV | m($\tilde{\chi}_1^0$)=800 GeV | ATLAS-CONF-2016-057
$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$ | 1 $e,\mu$ | 8-10 jets/0-4 $b$ | - | 36.1 | $\tilde{g}$ 2.1 TeV | m($\tilde{\chi}_1^0$)= 1 TeV, $\lambda_{112}\neq0$ | ATLAS-CONF-2017-013
$\tilde{g}\tilde{g}$, $\tilde{g}\to\bar{t}_1 t$, $\tilde{t}_1\to bs$ | 1 $e,\mu$ | 8-10 jets/0-4 $b$ | - | 36.1 | $\tilde{g}$ 1.65 TeV | m($\tilde{t}_1$)= 1 TeV, $\lambda_{323}\neq0$ | ATLAS-CONF-2017-013
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$ | 0 | 2 jets + 2 $b$ | - | 15.4 | $\tilde{t}_1$ 410 GeV, 450-510 GeV | | ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$ | 2 $e,\mu$ | 2 $b$ | - | 36.1 | $\tilde{t}_1$ 0.4-1.45 TeV | BR($\tilde{t}_1\to be/\mu$)>20% | ATLAS-CONF-2017-036
Other
Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$ | 0 | 2 $c$ | Yes | 20.3 | $\tilde{c}$ 510 GeV | m($\tilde{\chi}_1^0$)<200 GeV | 1501.01325
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.
$10^{-1}$
1
Mass scale [TeV]
No new particles beyond the Higgs so far

# ATLAS SUSY Searches* - 95% CL Lower Limits

May 2017

**ATLAS** Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV

Mass limit: $\sqrt{s}$ = 7, 8 TeV / $\sqrt{s}$ = 13 TeV

| | Model | $e,\mu,\tau,\gamma$ | Jets | $E_T^{miss}$ | $\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$ | Mass limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| Inclusive Searches | MSUGRA/CMSSM | 0-3 $e,\mu$/1-2 $\tau$ | 2-10 jets/3 $b$ | Yes | 20.3 | $\tilde{q},\tilde{g}$ 1.85 TeV | $m(\tilde{q})$=$m(\tilde{g})$ | 1507.05525 |
| | $\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 36.1 | $\tilde{q}$ 1.57 TeV | $m(\tilde{\chi}_1^0)$<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$) | ATLAS-CONF-2017-022 |
| | $\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed) | mono-jet | 1-3 jets | Yes | 3.2 | $\tilde{q}$ 608 GeV | $m(\tilde{q})$-$m(\tilde{\chi}_1^0)$<5 GeV | 1604.07773 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 36.1 | $\tilde{g}$ 2.02 TeV | $m(\tilde{\chi}_1^0)$<200 GeV | ATLAS-CONF-2017-022 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 36.1 | $\tilde{g}$ 2.01 TeV | $m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$) | ATLAS-CONF-2017-022 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$ | 3 $e,\mu$ | 4 jets | - | 36.1 | $\tilde{g}$ 1.825 TeV | $m(\tilde{\chi}_1^0)$<400 GeV | ATLAS-CONF-2017-030 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$ | 0 | 7-11 jets | Yes | 36.1 | $\tilde{g}$ 1.8 TeV | $m(\tilde{\chi}_1^0)$ <400 GeV | ATLAS-CONF-2017-033 |
| | GMSB ($\tilde{\ell}$ NLSP) | 1-2 $\tau$ + 0-1 $\ell$ | 0-2 jets | Yes | 3.2 | $\tilde{g}$ 2.0 TeV | | 1607.05979 |
| | GGM (bino NLSP) | 2 $\gamma$ | - | Yes | 3.2 | $\tilde{g}$ 1.65 TeV | $c\tau$(NLSP)<0.1 mm | 1606.09150 |
| | GGM (higgsino-bino NLSP) | $\gamma$ | 1 $b$ | Yes | 20.3 | $\tilde{g}$ 1.37 TeV | $m(\tilde{\chi}_1^0)$<950 GeV, $c\tau$(NLSP)<0.1 mm, $\mu$<0 | 1507.05493 |
| | GGM (higgsino-bino NLSP) | $\gamma$ | 2 jets | Yes | 13.3 | $\tilde{g}$ 1.8 TeV | $m(\tilde{\chi}_1^0)$>680 GeV, $c\tau$(NLSP)<0.1 mm, $\mu$>0 | ATLAS-CONF-2016-066 |
| | GGM (higgsino NLSP) | 2 $e,\mu$ ($Z$) | 2 jets | Yes | 20.3 | $\tilde{g}$ 900 GeV | m(NLSP)>430 GeV | 1503.03290 |
| | Gravitino LSP | 0 | mono-jet | Yes | 20.3 | $F^{1/2}$ scale 865 GeV | $m(\tilde{G})$>1.8 × $10^{-4}$ eV, $m(\tilde{g})$=$m(\tilde{q})$=1.5 TeV | 1502.01518 |
| 3rd gen. $\tilde{g}$ med. | $\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$ | 0 | 3 $b$ | Yes | 36.1 | $\tilde{g}$ 1.92 TeV | $m(\tilde{\chi}_1^0)$<600 GeV | ATLAS-CONF-2017-021 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0-1 $e,\mu$ | 3 $b$ | Yes | 36.1 | $\tilde{g}$ 1.97 TeV | $m(\tilde{\chi}_1^0)$<200 GeV | ATLAS-CONF-2017-021 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$ | 0-1 $e,\mu$ | 3 $b$ | Yes | 20.1 | $\tilde{g}$ 1.37 TeV | $m(\tilde{\chi}_1^0)$<300 GeV | 1407.0600 |
| 3rd gen. squarks direct production | $\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$ | 0 | 2 $b$ | Yes | 36.1 | $\tilde{b}_1$ 950 GeV | $m(\tilde{\chi}_1^0)$<420 GeV | ATLAS-CONF-2017-038 |
| | $\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$ | 2 $e,\mu$ (SS) | 1 $b$ | Yes | 36.1 | $\tilde{b}_1$ 275-700 GeV | $m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^{\pm})$= $m(\tilde{\chi}_1^0)$+100 GeV | ATLAS-CONF-2017-030 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$ | 0-2 $e,\mu$ | 1-2 $b$ | Yes | 4.7/13.3 | $\tilde{t}_1$ 117-170 GeV, 200-720 GeV | $m(\tilde{\chi}_1^{\pm})$ = 2$m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV | 1209.2102, ATLAS-CONF-2016-077 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$ | 0-2 $e,\mu$ | 0-2 jets/1-2 $b$ | Yes | 20.3/36.1 | $\tilde{t}_1$ 90-198 GeV, 205-950 GeV | $m(\tilde{\chi}_1^0)$=1 GeV | 1506.08616, ATLAS-CONF-2017-020 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ | 0 | mono-jet | Yes | 3.2 | $\tilde{t}_1$ 90-323 GeV | $m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$=5 GeV | 1604.07773 |
| | $\tilde{t}_1\tilde{t}_1$(natural GMSB) | 2 $e,\mu$ ($Z$) | 1 $b$ | Yes | 20.3 | $\tilde{t}_1$ 150-600 GeV | $m(\tilde{\chi}_1^0)$>150 GeV | 1403.5222 |
| | $\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$ | 3 $e,\mu$ ($Z$) | 1 $b$ | Yes | 36.1 | $\tilde{t}_2$ 290-790 GeV | $m(\tilde{\chi}_1^0)$=0 GeV | ATLAS-CONF-2017-019 |
| | $\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$ | 1-2 $e,\mu$ | 4 $b$ | Yes | 36.1 | $\tilde{t}_2$ 320-880 GeV | $m(\tilde{\chi}_1^0)$=0 GeV | ATLAS-CONF-2017-019 |
| EW direct | $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$ | 2 $e,\mu$ | 0 | Yes | 36.1 | $\tilde{\ell}$ 90-440 GeV | $m(\tilde{\chi}_1^0)$=0 | ATLAS-CONF-2017-039 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$ | 2 $e,\mu$ | 0 | Yes | 36.1 | $\tilde{\chi}_1^{\pm}$ 710 GeV | $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$) | ATLAS-CONF-2017-039 |
| | $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$ | 2 $\tau$ | - | Yes | 36.1 | $\tilde{\chi}_1^{\pm}$ 760 GeV | $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$) | ATLAS-CONF-2017-035 |
| | $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$ | 3 $e,\mu$ | 0 | Yes | 36.1 | $\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 1.16 TeV | $m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$) | ATLAS-CONF-2017-039 |
| | $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$ | 2-3 $e,\mu$ | 0-2 jets | Yes | 36.1 | $\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 580 GeV | $m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled | ATLAS-CONF-2017-039 |
| | $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$ | $e,\mu,\gamma$ | 0-2 $b$ | Yes | 20.3 | $\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 270 GeV | $m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled | 1501.07110 |
| | $\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$ | 4 $e,\mu$ | 0 | Yes | 20.3 | $\tilde{\chi}_{2,3}^0$ 635 GeV | $m(\tilde{\chi}_2^0)$=$m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_2^0)$+$m(\tilde{\chi}_1^0)$) | 1405.5086 |
| | GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$ | 1 $e,\mu$ + $\gamma$ | - | Yes | 20.3 | $\tilde{W}$ 115-370 GeV | $c\tau$<1 mm | 1507.05493 |
| | GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$ | 2 $\gamma$ | - | Yes | 20.3 | $\tilde{W}$ 590 GeV | $c\tau$<1 mm | 1507.05493 |
| Long-lived particles | Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$ | Disapp. trk | 1 jet | Yes | 36.1 | $\tilde{\chi}_1^{\pm}$ 430 GeV | $m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns | ATLAS-CONF-2017-017 |
| | Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$ | dE/dx trk | - | Yes | 18.4 | $\tilde{\chi}_1^{\pm}$ 495 GeV | $m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$<15 ns | 1506.05332 |
| | Stable, stopped $\tilde{g}$ R-hadron | 0 | 1-5 jets | Yes | 27.9 | $\tilde{g}$ 850 GeV | $m(\tilde{\chi}_1^0)$=100 GeV, 10 $\mu$s<$\tau(\tilde{g})$<1000 s | 1310.6584 |
| | Stable $\tilde{g}$ R-hadron | trk | - | - | 3.2 | $\tilde{g}$ 1.58 TeV | | 1606.05129 |
| | Metastable $\tilde{g}$ R-hadron | dE/dx trk | - | - | 3.2 | $\tilde{g}$ 1.57 TeV | $m(\tilde{\chi}_1^0)$=100 GeV, $\tau$>10 ns | 1604.04520 |
| | GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$ | 1-2 $\mu$ | - | - | 19.1 | $\tilde{\chi}_1^0$ 537 GeV | 10<tan$\beta$<50 | 1411.6795 |
| | GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$ | 2 $\gamma$ | - | Yes | 20.3 | $\tilde{\chi}_1^0$ 440 GeV | 1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model | 1409.5542 |
| | $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$ | displ. $ee/e\mu/\mu\mu$ | - | - | 20.3 | $\tilde{\chi}_1^0$ 1.0 TeV | 7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV | 1504.05162 |
| | GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to Z\tilde{G}$ | displ. vtx + jets | - | - | 20.3 | $\tilde{\chi}_1^0$ 1.0 TeV | 6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV | 1504.05162 |
| RPV | LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$ | $e\mu$,$e\tau$,$\mu\tau$ | - | - | 3.2 | $\tilde{\nu}_\tau$ 1.9 TeV | $\lambda'_{311}$=0.11, $\lambda_{132/133/233}$=0.07 | 1607.08079 |
| | Bilinear RPV CMSSM | 2 $e,\mu$ (SS) | 0-3 $b$ | Yes | 20.3 | $\tilde{q},\tilde{g}$ 1.45 TeV | $m(\tilde{q})$=$m(\tilde{g})$, $c\tau_{LSP}$<1 mm | 1404.2500 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$ | 4 $e,\mu$ | - | Yes | 13.3 | $\tilde{\chi}_1^{\pm}$ 1.14 TeV | $m(\tilde{\chi}_1^0)$>400GeV, $\lambda_{12k}\neq0$ ($k$ = 1, 2) | ATLAS-CONF-2016-075 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$ | 3 $e,\mu$ + $\tau$ | - | Yes | 20.3 | $\tilde{\chi}_1^{\pm}$ 450 GeV | $m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$ | 1405.5086 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$ | 0 | 4-5 large-$R$ jets | - | 14.8 | $\tilde{g}$ 1.08 TeV | BR($t$)=BR($b$)=BR($c$)=0% | ATLAS-CONF-2016-057 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$ | 0 | 4-5 large-$R$ jets | - | 14.8 | $\tilde{g}$ 1.55 TeV | $m(\tilde{\chi}_1^0)$=800 GeV | ATLAS-CONF-2016-057 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$ | 1 $e,\mu$ | 8-10 jets/0-4 $b$ | - | 36.1 | $\tilde{g}$ 2.1 TeV | $m(\tilde{\chi}_1^0)$= 1 TeV, $\lambda_{112}\neq0$ | ATLAS-CONF-2017-013 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$ | 1 $e,\mu$ | 8-10 jets/0-4 $b$ | - | 36.1 | $\tilde{g}$ 1.65 TeV | $m(\tilde{t}_1)$= 1 TeV, $\lambda_{323}\neq0$ | ATLAS-CONF-2017-013 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$ | 0 | 2 jets + 2 $b$ | - | 15.4 | $\tilde{t}_1$ 410 GeV, 450-510 GeV | | ATLAS-CONF-2016-022, ATLAS-CONF-2016-084 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$ | 2 $e,\mu$ | 2 $b$ | - | 36.1 | $\tilde{t}_1$ 0.4-1.45 TeV | BR($\tilde{t}_1\to be/\mu$)>20% | ATLAS-CONF-2017-036 |
| Other | Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$ | 0 | 2 $c$ | Yes | 20.3 | $\tilde{c}$ 510 GeV | $m(\tilde{\chi}_1^0)$<200 GeV | 1501.01325 |

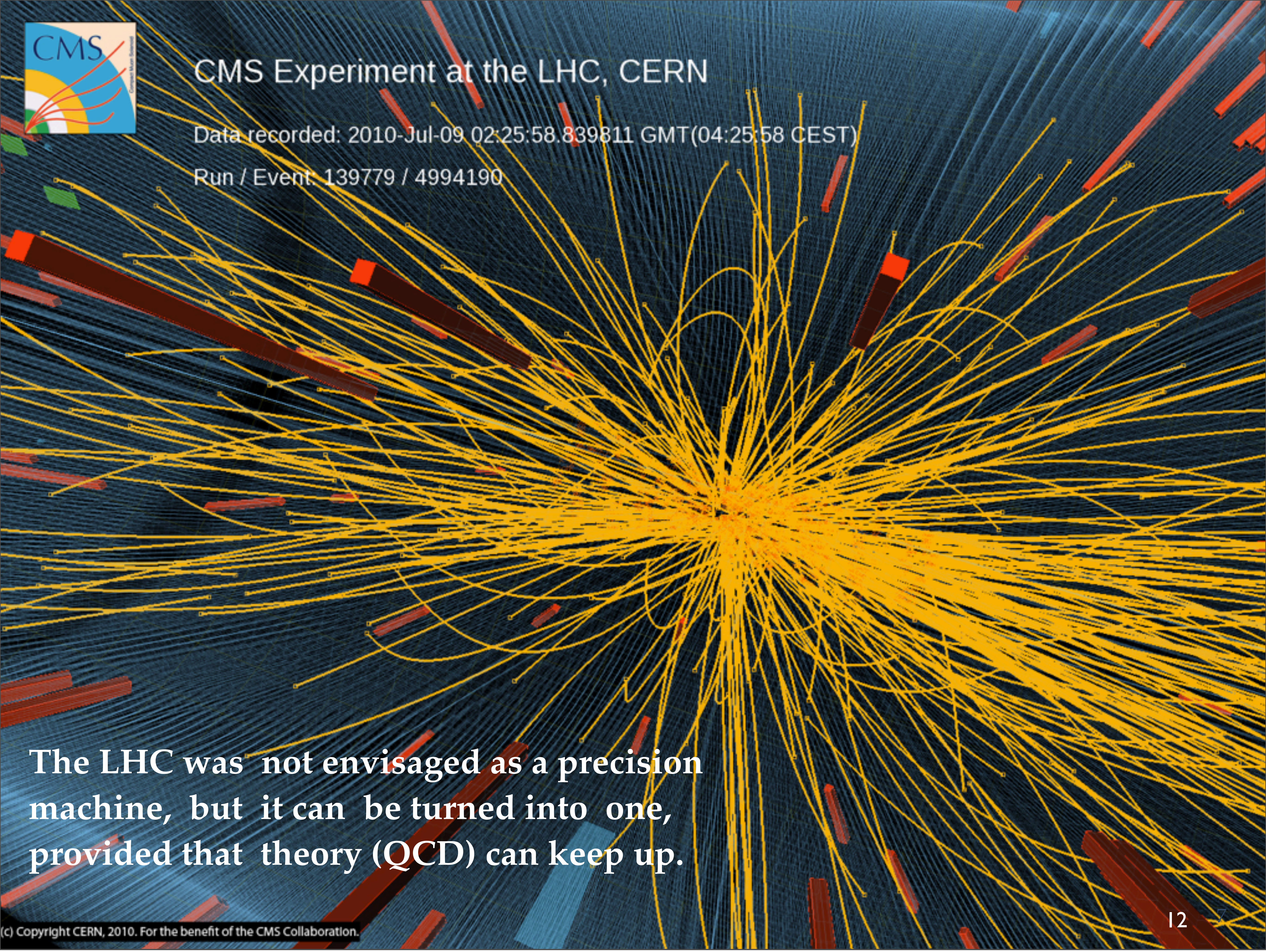
Mass scale [TeV] (axis: $10^{-1}$, 1)

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

**In the midst of every crisis lies an opportunity**

These results suggest a paradigm change:

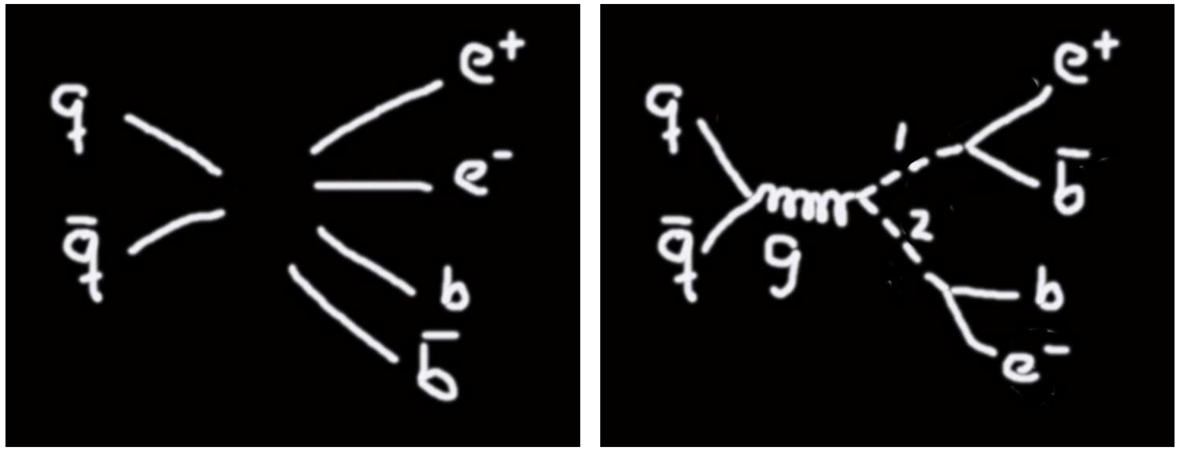
indirect searches for new particles and interactions at hadron colliders will feature more and more prominently in the exploration of physics beyond the Standard Model.

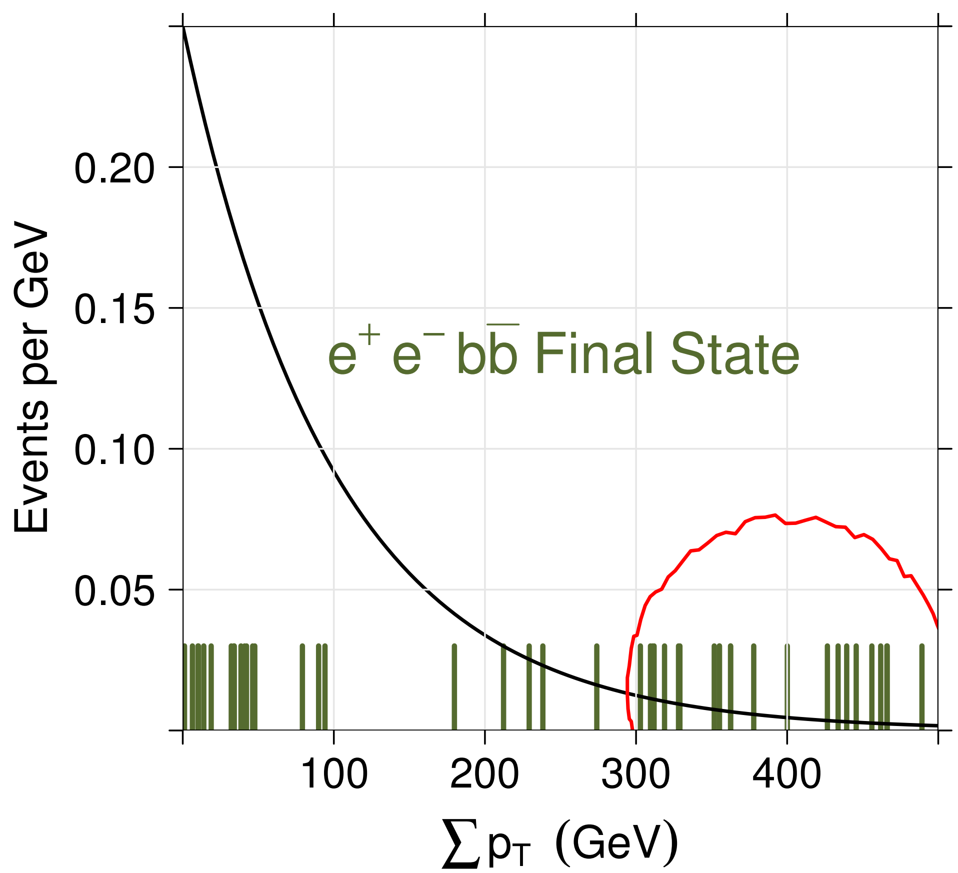



The LHC was not envisaged as a precision machine, but it can be turned into one, provided that theory (QCD) can keep up.

# The new paradigm of discovery

## BARD: Interpreting New Frontier Energy Collider Physics





Bruce Knuteson*
*MIT*

Stephen Mrenna†
*FNAL*



In contemporary high energy physics experiments, it is not uncommon to observe discrepancies between data and Standard Model predictions. Most of these discrepancies have been explained away over time. To convincingly demonstrate that an observed effect is evidence of physics beyond the Standard Model, it is necessary to prove it is (1) not a likely statistical fluctuation, (2) not introduced by an imperfect understanding of the experimental apparatus, (3) not due to an inadequacy of the implementation of the Standard Model prediction, and (4) interpretable in terms of a sensible underlying theory. Those who object to (4) as being necessary fail to appreciate that most hypothesis development in science occurs before, rather than after, publication. This last criterion is essential, and will likely point the way to other discrepancies that must exist if the interpretation is correct.


Main idea behind this paper was to search systematically for a correlated set of deviations from the SM predictions and a possibility to explain them with a single NP hypothesis. With null search results from the LHC, this idea becomes extremely timely...

# The original wishlist

Knuteson then came up with the ``next-to-leading order (NLO) wishlist'' (circa 2004) , i.e. the list of processes whose reliable description he thought was instrumental for making his idea a reality. The appearance of the wishlist started a concerted effort by theorists to improve ways and means to perform NLO computations -- the beginning of the NLO revolution.

Note that we have ticked off one cross section from the first list

*An experimenter's wishlist*

Run II Monte Carlo Workshop

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

# Precision physics at the LHC?

Systematic precision studies at hadron colliders, aimed at discovering New Physics through indirect effects, have never been attempted before.

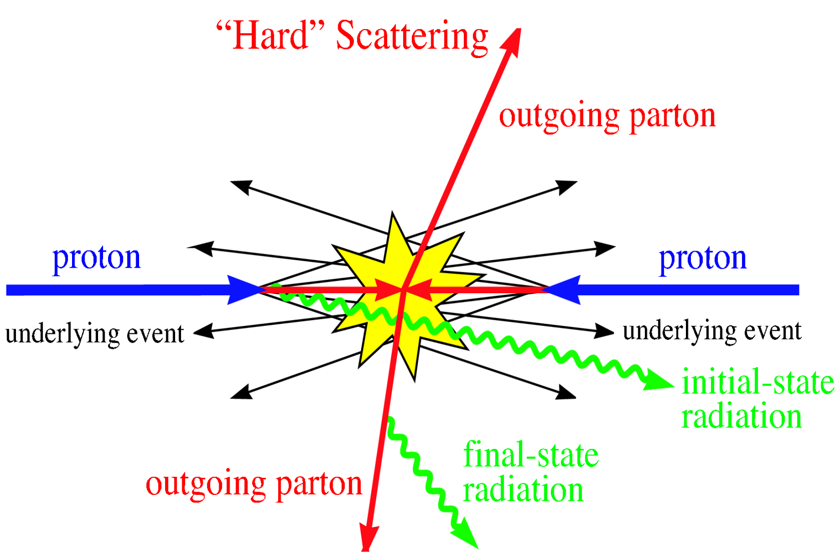
Indeed, hadrons are composite particles kept together by a poorly understood strong force. If we can't understand (compute) properties of one proton, can we confidently describe what happens when two protons collide?

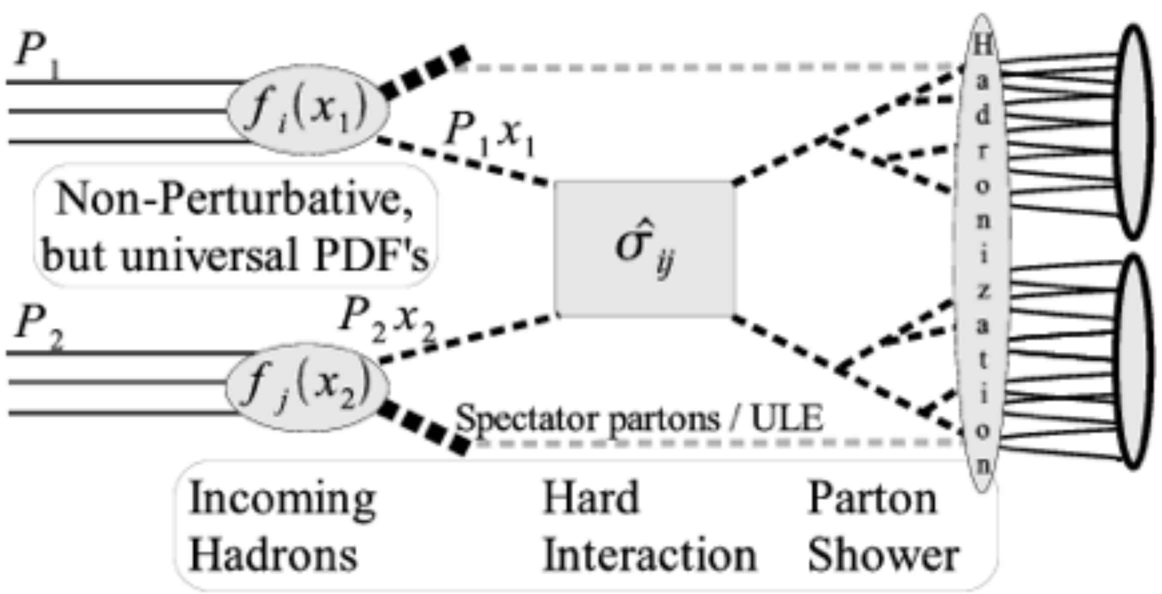
We believe that, to some extent, this can be done and that outcomes of certain (hard) hadron collisions can be understood starting directly from the SM Lagrangian.

Sufficiently inclusive hard hadron processes can be described by the collinear factorization formula.

**Collins, Soper, Sterman**

$$d\sigma = \int dx_1 dx_2 f_i(x_1) f_j(x_2) d\sigma_{ij}(x_1, x_2) F_J (1 + \mathcal{O}(\Lambda_{QCD}^n / Q^n)) \qquad n \geq 1$$



# LHC: the world of quarks and gluons

Hard scattering processes at the LHC can be understood in terms of quarks and gluons; very limited knowledge about protons is needed. Physics of quarks and gluons is governed by a non-abelian SU(3) gauge-field theory -- the QCD.

1) The Lagrangian

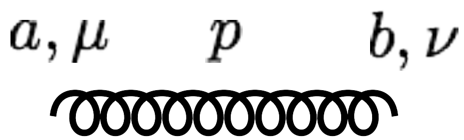
$$\mathcal{L}_{\rm QCD} = \sum \bar{q}_j \left( i\hat{D} - m_j \right) q_j - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu}$$

$$D_\mu = \partial_\mu - i g_s T^a A^a_\mu, \quad G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + i g_s f^{abc} A^b_\mu A^c_\nu. \qquad [T^a, T^b] = i f_{abc} T^c$$

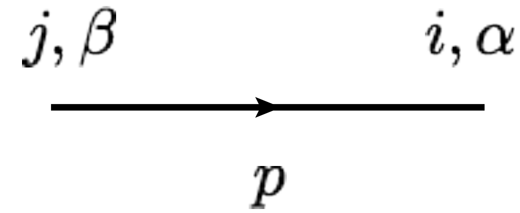
2) Degrees of freedom: quarks (up, down, strange, charm, bottom, top) and gluons (also ghosts, see later).

3) SU(3) group --> interaction charges (color) --> each quark can appear in one of the three color states and a gluon in one of eight.

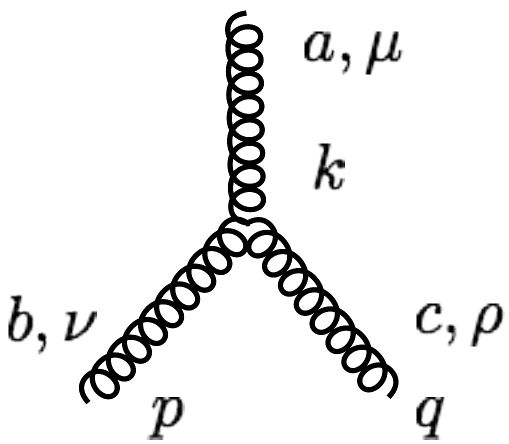
# QCD Feynman rules



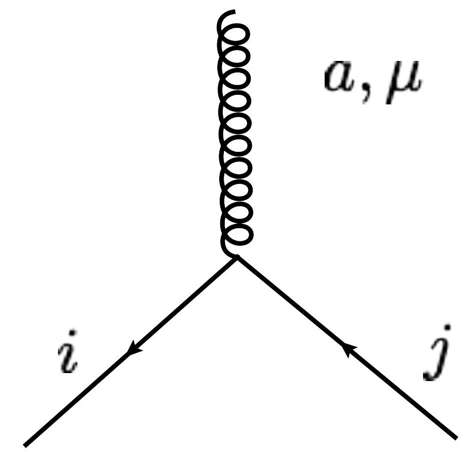

$$= \frac{-i\delta^{ab}}{p^2}\left(-g_{\mu\nu} + \xi\frac{p_\mu p_\nu}{p^2}\right)$$



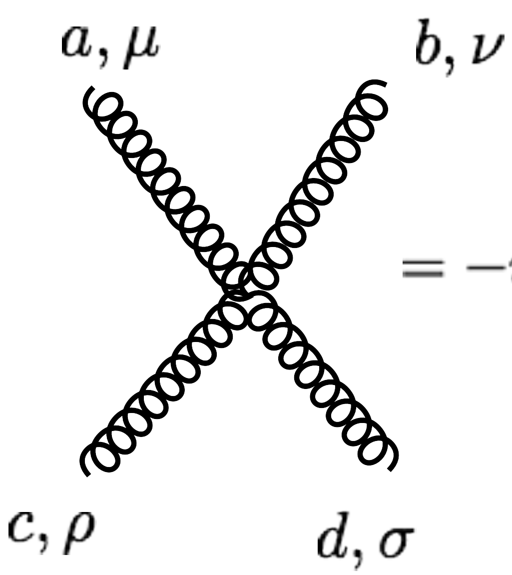

$$= \left(\frac{i}{\hat{p}}\right)_{\alpha\beta}\delta^{ij}$$



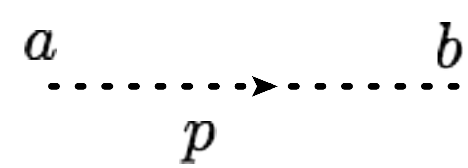

$$\begin{aligned} = g_s f^{abc}( \quad & g^{\mu\nu}(k-p)^\rho \\ & + g^{\nu\rho}(p-q)^\mu \\ & + g^{\rho\mu}(q-k)^\nu) \end{aligned}$$



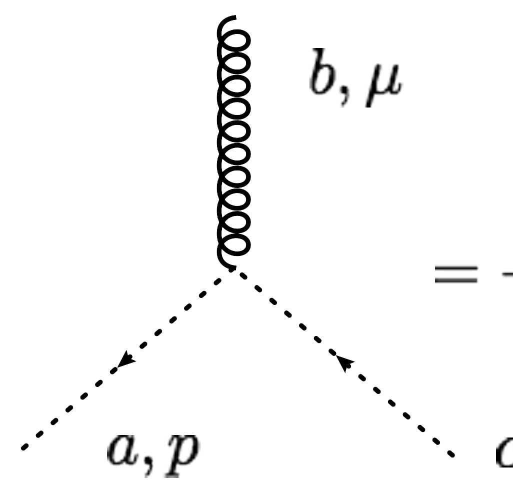

$$= i g_s \gamma^\mu T^a_{ij}$$




$$\begin{aligned} = -i g_s^2 \Big[ & f^{abe} f^{cde}(g^{\mu\rho} g^{\nu\sigma} - g^{\mu\sigma} g^{\nu\rho}) \\ & + f^{ace} f^{bed}(g^{\mu\nu} g^{\rho\sigma} - g^{\mu\sigma} g^{\nu\rho}) \\ & + f^{ade} f^{bce}(g^{\mu\nu} g^{\rho\sigma} - g^{\mu\rho} g^{\nu\sigma}) \Big] \end{aligned}$$



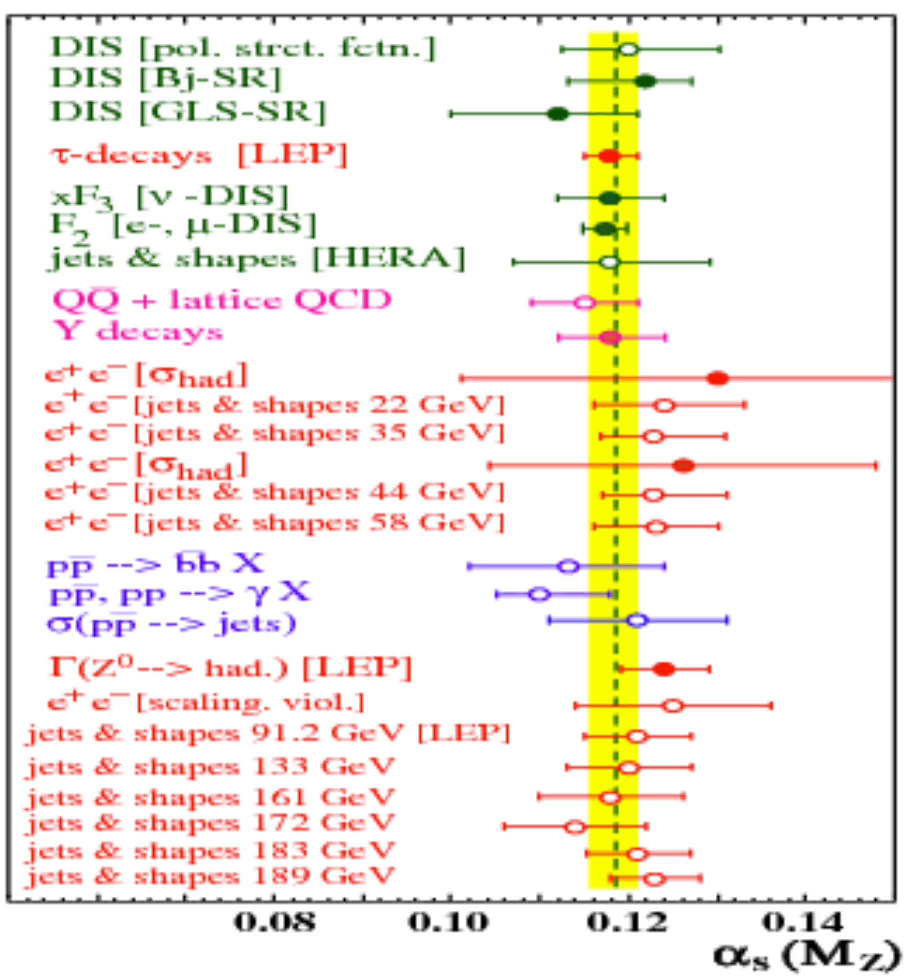

$$= \frac{i\delta^{ab}}{p^2}$$

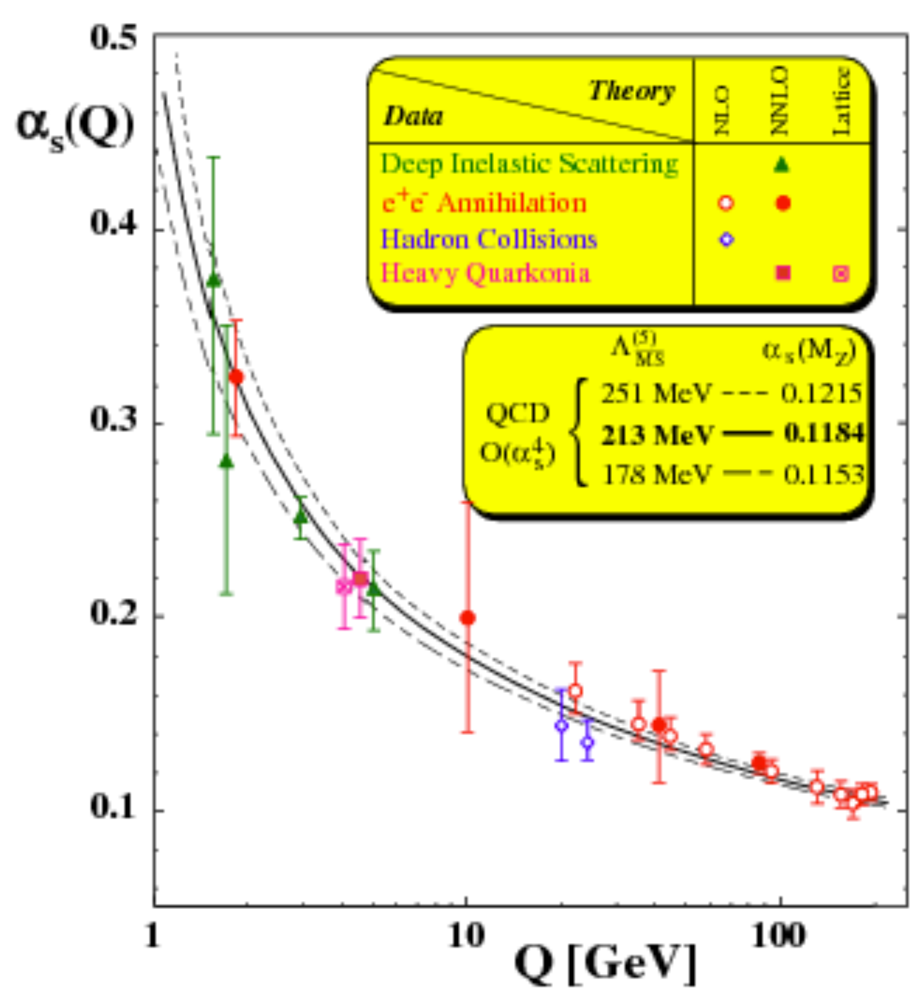



$$= -g_s f^{abc} p^\mu$$

# The running coupling constant

The effective coupling constant in QCD changes in such a way that it decreases at large momenta transfers (short distances). This phenomenon, known as the asymptotic freedom, enables us to describe perturbatively hard scattering processes at the LHC.



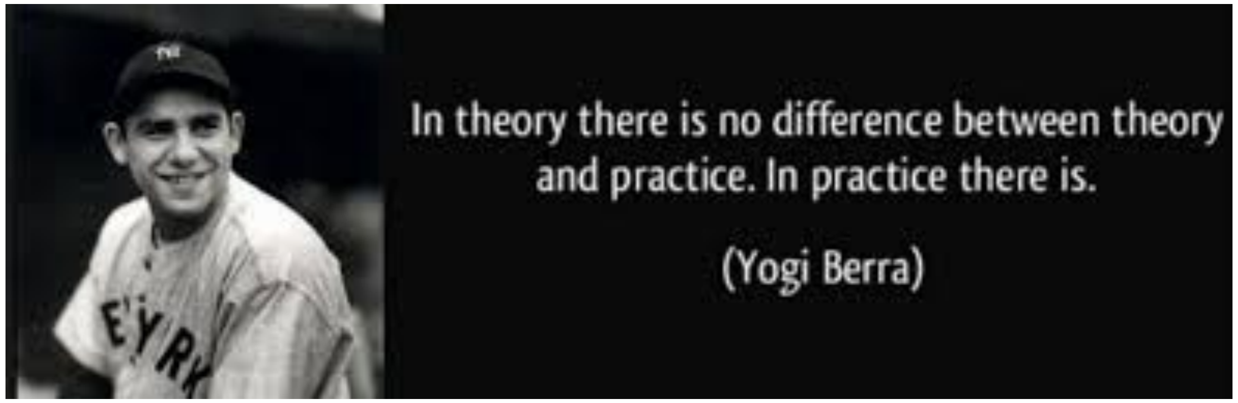

$$\alpha_s(\mu) = \frac{1}{\beta_0 \log \frac{\mu^2}{\Lambda^2}},$$

$$\beta_0 = \frac{33 - 2n_f}{12\pi} \sim 0.5|_{n_f=5}$$

$$\Lambda \approx 300 \text{ MeV}$$

# Perturbation theory for cross sections

Starting from the QCD Feynman rules -- and fixing initial and final states for which we would like to know the scattering amplitudes and the order in perturbation theory, we can put together Feynman diagrams and calculate them using standard rules of perturbative QFTs.




Sounds simple but not quite:

- need to deal with (very) large number of diagrams and integrals (algebraic complexity);

**Badger**

- need to be able to compute complicated loop integrals (analytic complexity);

**Tancredi**

- need to understand complex interplay between final states with different multiplicities, to arrive at predictions that are insensitive to long-distance (non-perturbative) effects.

**Röntsch**

# Cross sections and observables

In addition, quite often we have to go beyond fixed order perturbation theory:

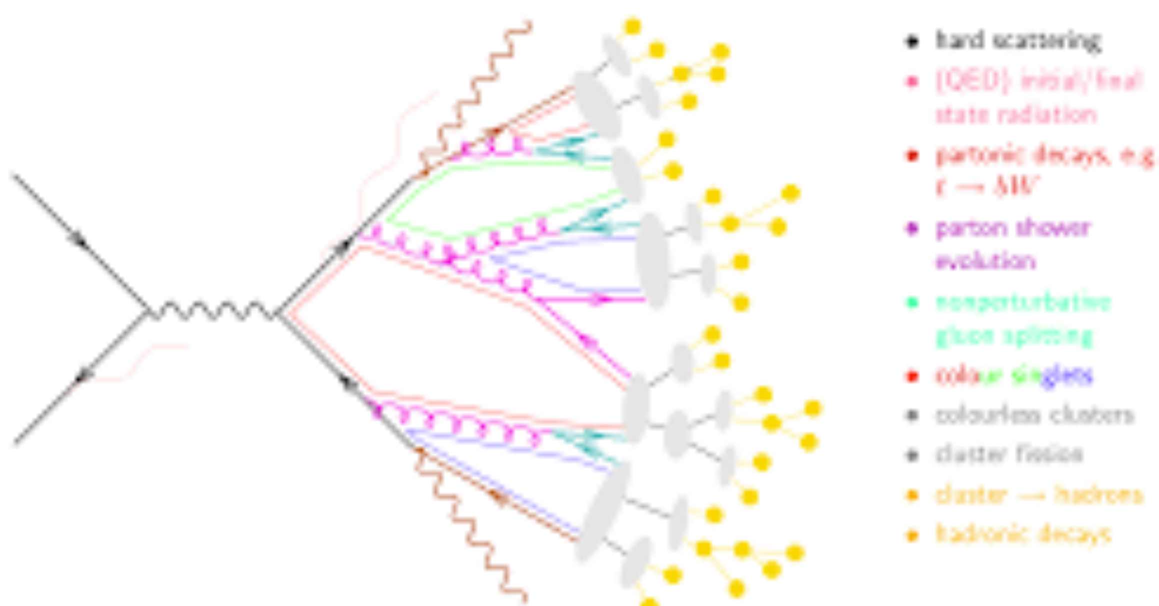
- phase-space regions where fixed order perturbation theory fails but long-distance effects are still suppressed;

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp} = \sum_k^\infty \alpha_s^k \ln^{2k} \frac{p_\perp}{m} c_k$$

**Monni**

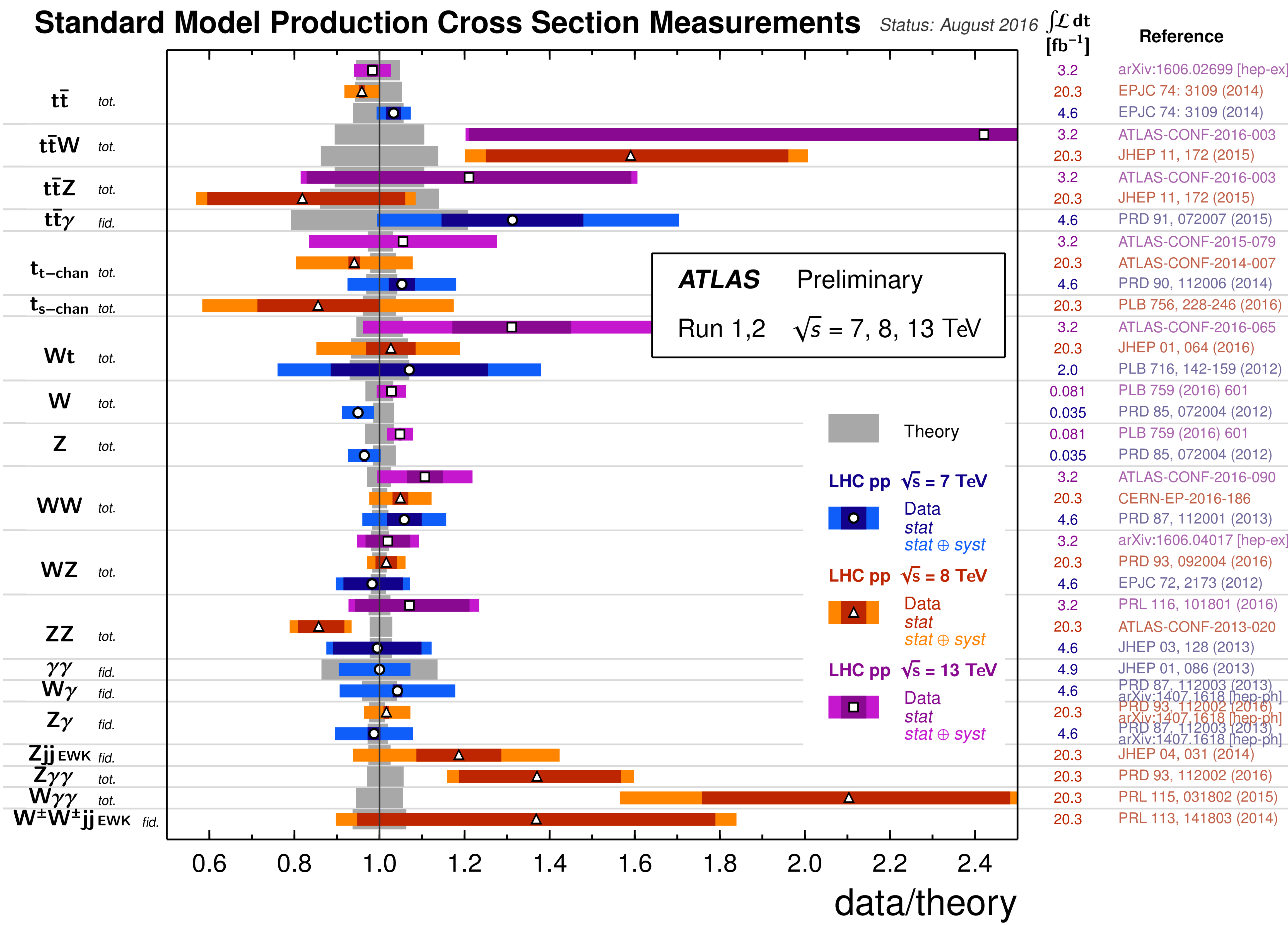
- hadrons, not quarks and gluons hit LHC detectors; need to model the transition to connect theoretical computations with experimental measurements.

**Hoeche**



## What has been studied and how well?

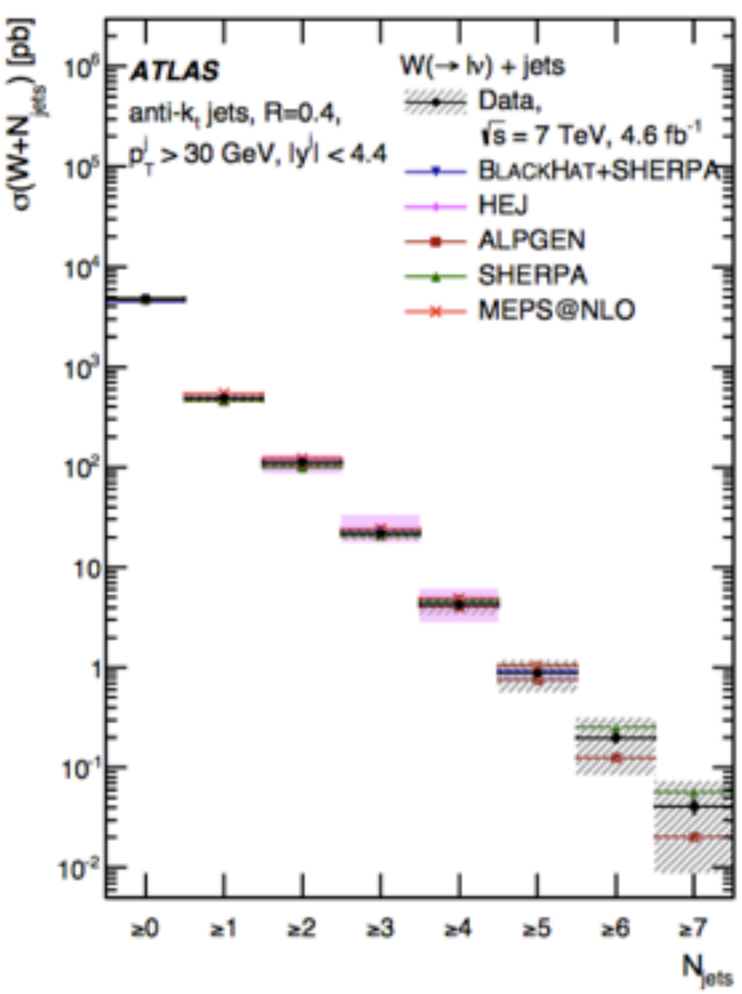
# What has been studied and how well?

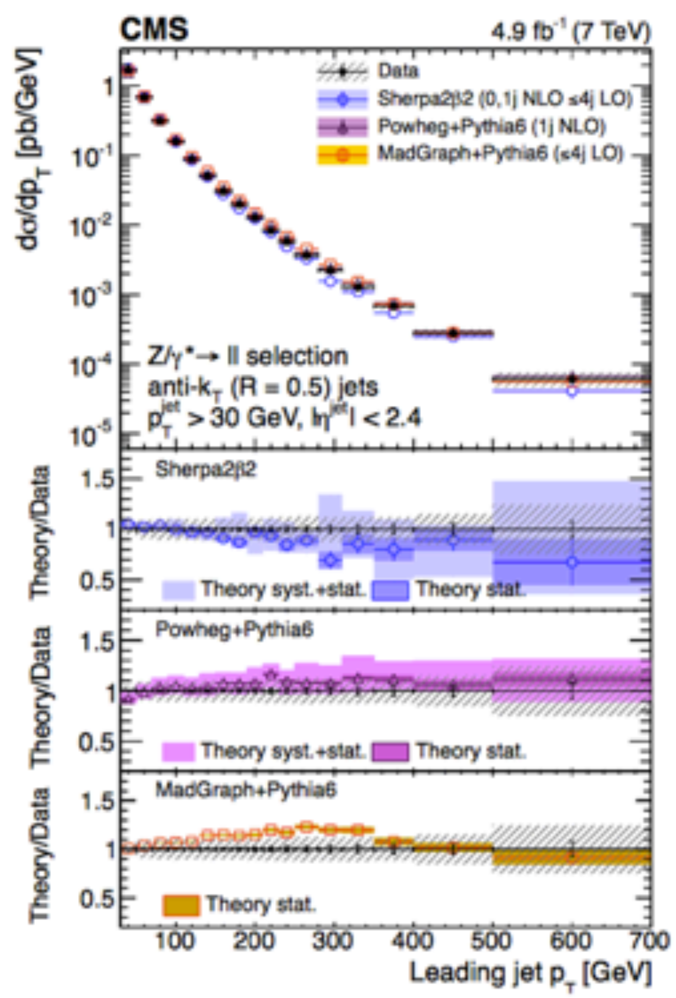


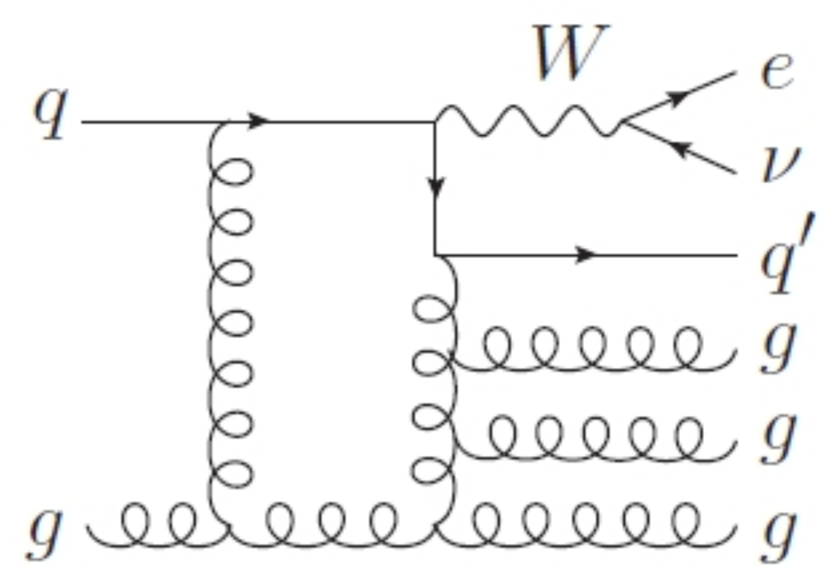
# What has been studied and how well?

Vector boson production in association with jets (up to seven !) .   Need to describe kinematic properties of jets; sufficient statistics to be sensitive to O(1-10) percent accuracy.

Physics: PDFs;  backgrounds to BSM searches with complex signatures.




Gigantic number of tree-level and one-loop diagrams needed to compute cross-sections and kinematic  distributions. Very  hard if traditional methods are  used -- modern unitary-based methods for one-loop computations.

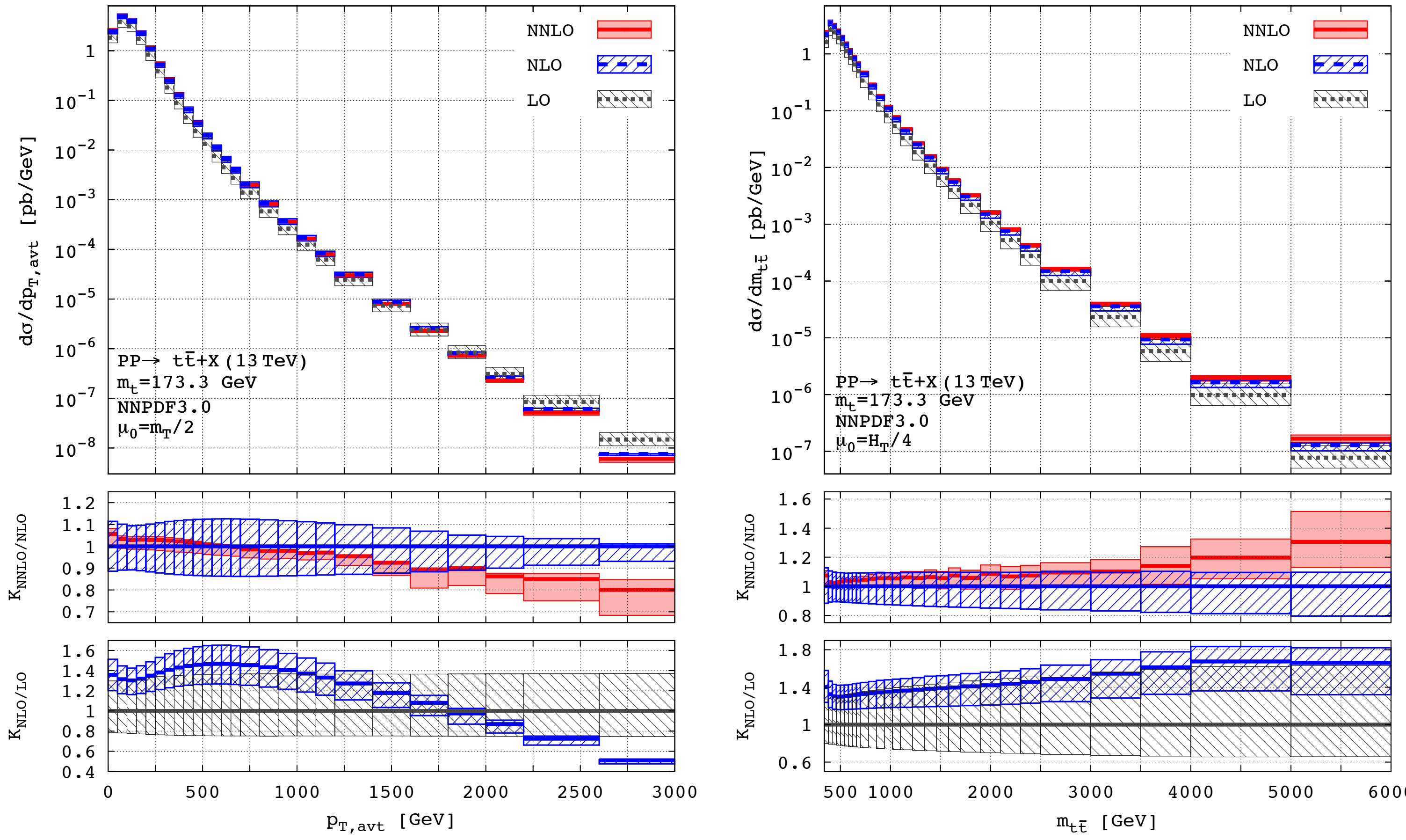
# What has been studied and how well?

Top quark pair production cross section is currently measured to about 3 percent -- need NNLO QCD accuracy.

Physics: backgrounds to top-like BSM physics, gluon PDF, top quark mass.

- fully-differential NNLO-QCD predictions for $t\bar{t}$ production

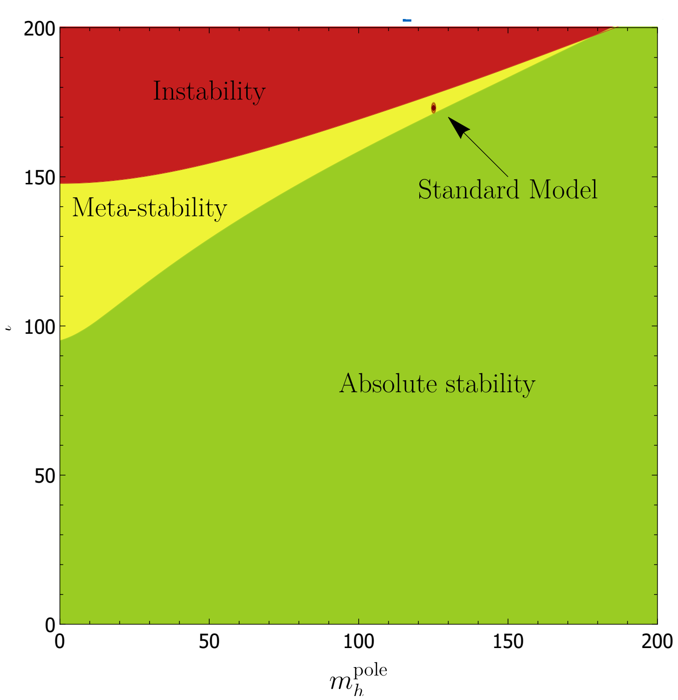
[Czakon,Heymes,Mitov '16]

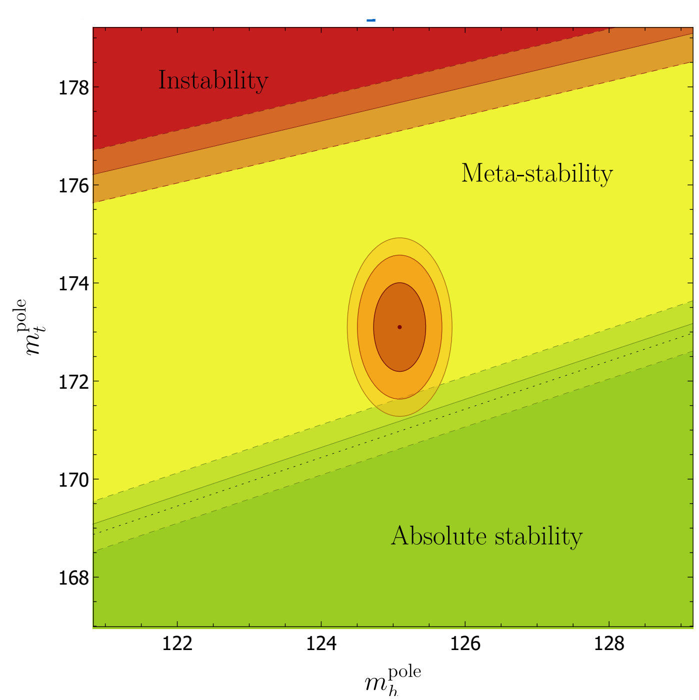


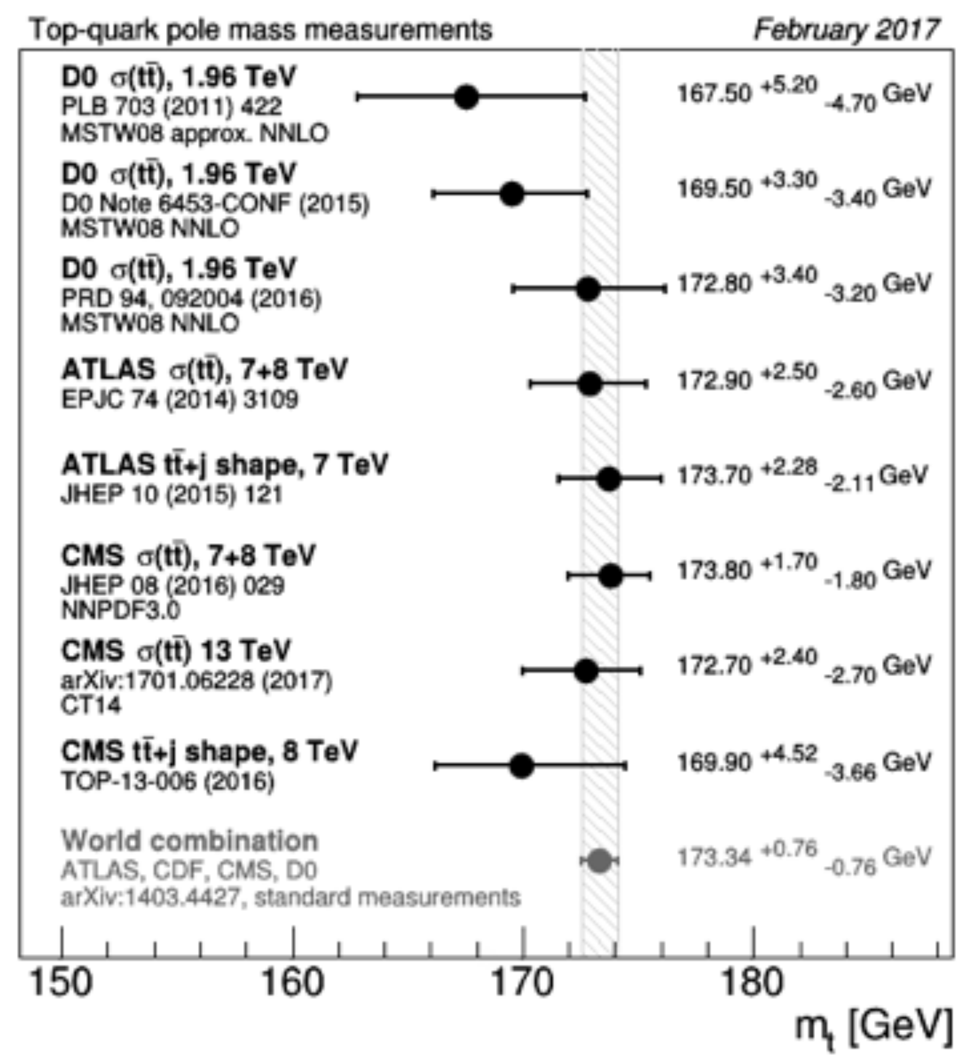

Very complex loop diagrams with massive particles inside -- we still do not know how to compute them analytically. Complicated subtraction scheme to put together final states with different multiplicities.

# What has been studied and how well?

Top quark mass may shine brightly, as it hold keys to the fate of our Universe,  but it has a past.. a dark  connection to the underworld of non-perturbative QCD.




$$\tau_{\mathrm{SM}} = \left(\frac{\Gamma}{V}\right)^{-1/4} = 10^{139^{+102}_{-51}} \text{ years}$$

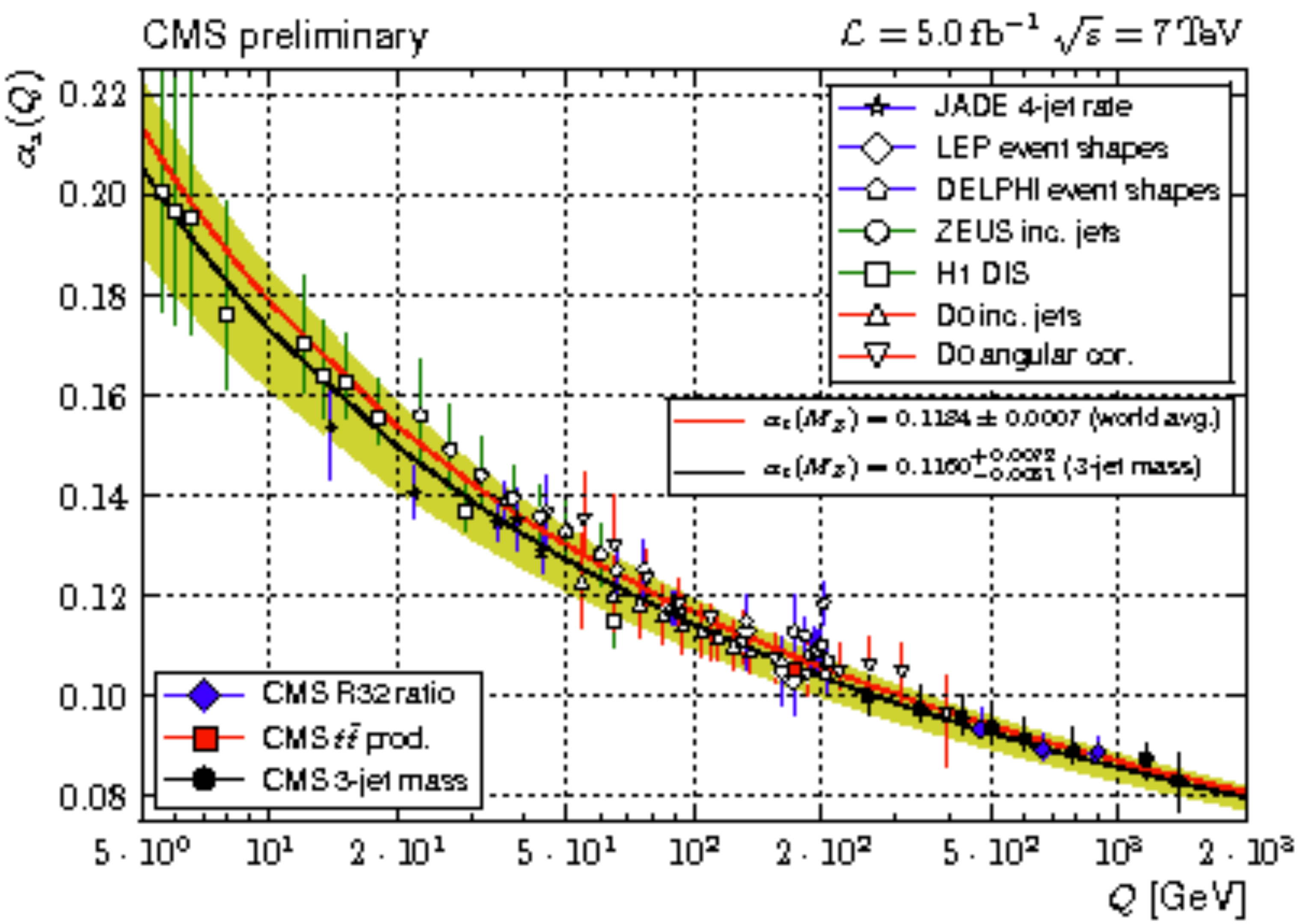
Uncertainty equal parts $m_t$, $\alpha_s$, threshold corrections

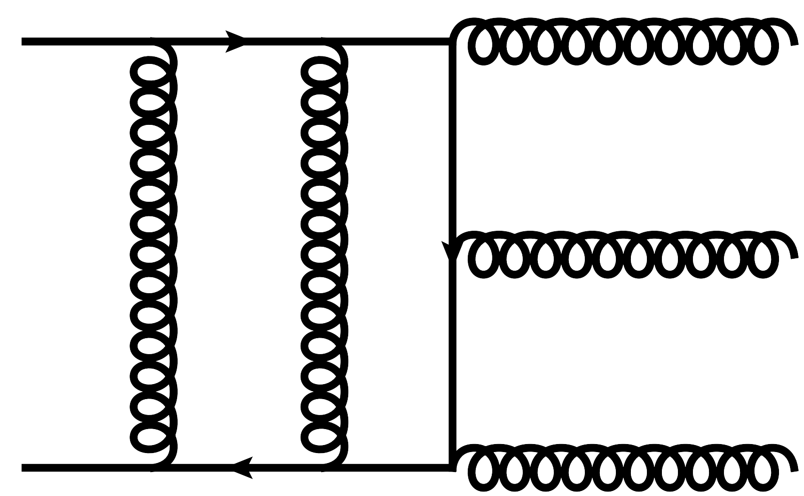
The most precise measurements of the top quark pole mass rely on parton shower event generators, to correlate kinematics of complex final states with the value of the top quark mass and to estimate non-perturbative effects.

**Where do we go from here ?**

# The strong coupling constant

Measurement of the strong coupling constant at the shortest distances. Statistically unlimited. Need NNLO QCD corrections to three jet production at the LHC.

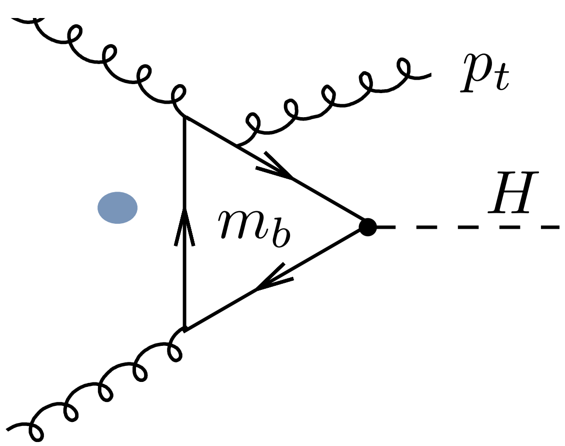


Very complicated loop integrals; enormous amount of algebra. Will the current attempts to compute the 3-jet rate lead to new groundbreaking methods for multi-loop computations?

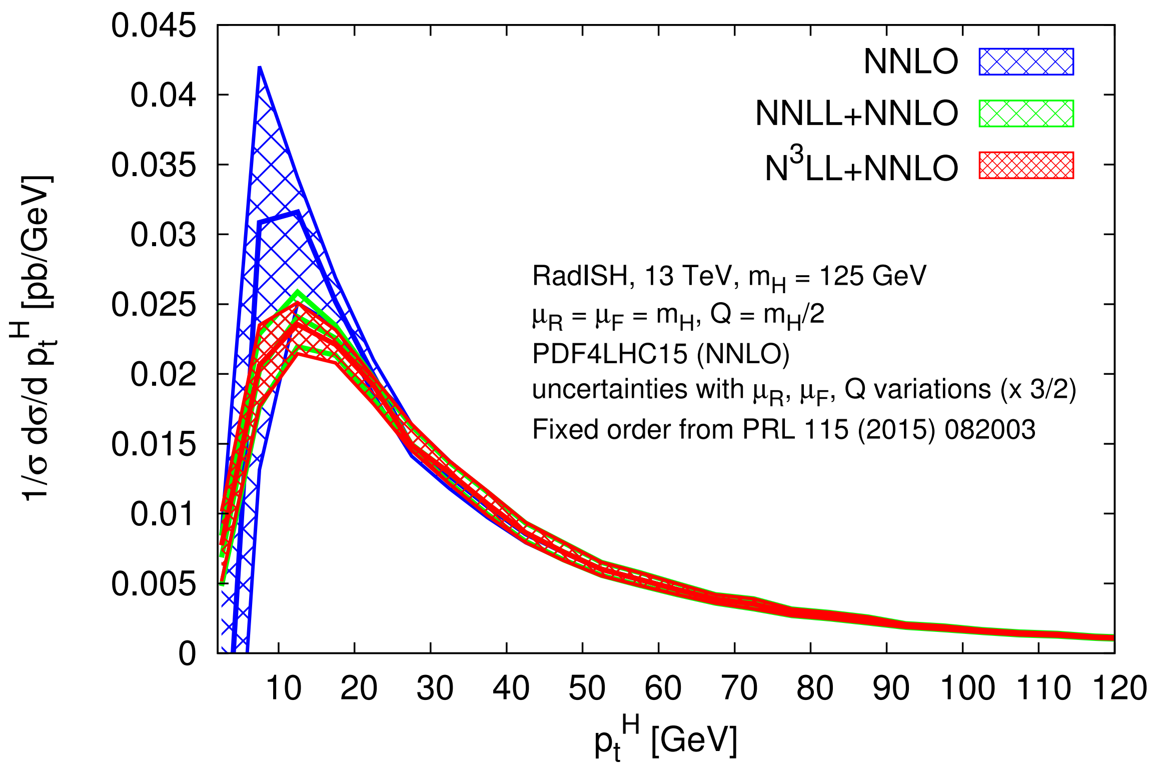
# Light quark Yukawa couplings

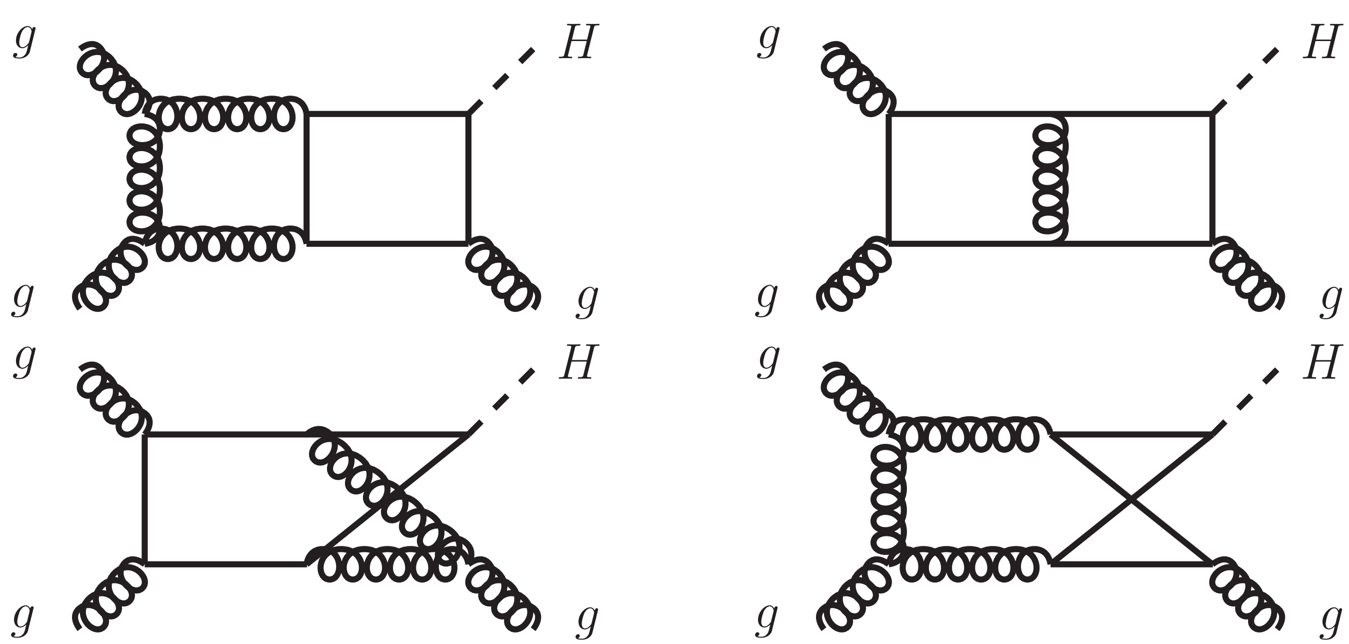
Higgs transverse momentum distribution can be used to study Yukawa couplings of light quarks (b,c). Unconventional logarithms that depend on the light quark masses. Re-summation of these logarithms is not understood. Impacts precision of the transverse momentum distribution.




$$m_b/p_\perp \ll 1$$

$$\alpha_s \ln^2 \frac{p_\perp}{m_b} \gg 1$$

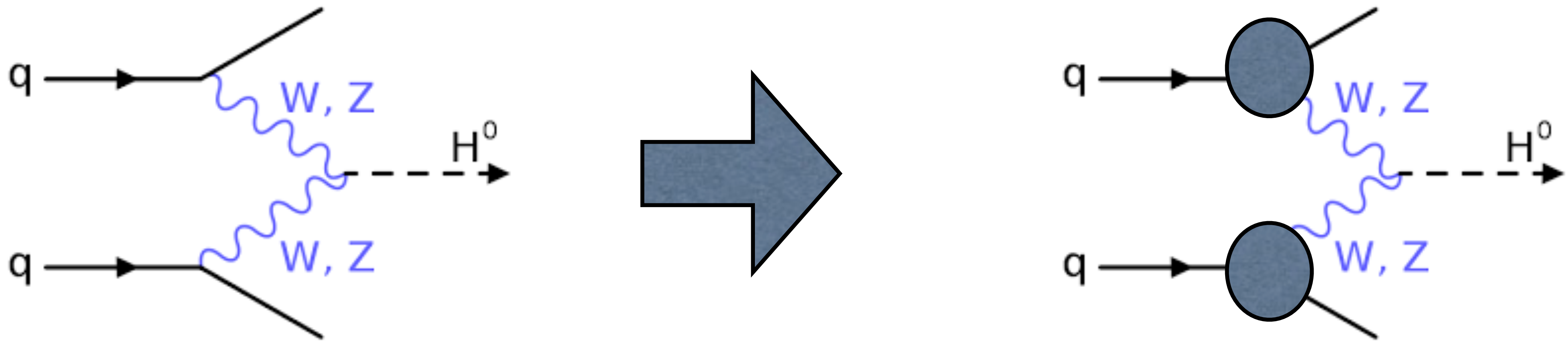


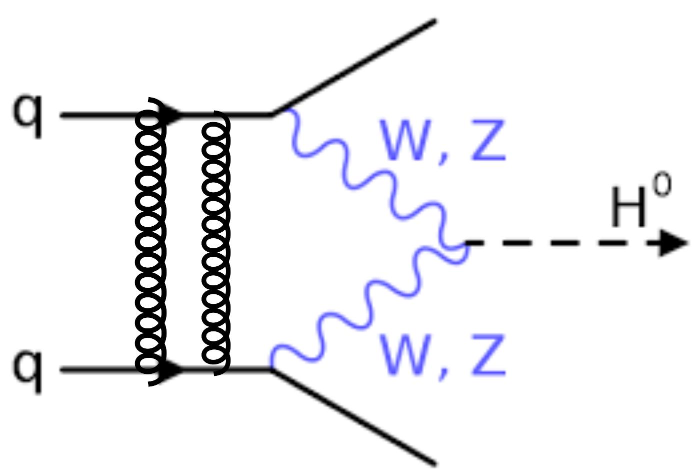




**Bizon, Monni, Re, Rottoli, Torrielli**

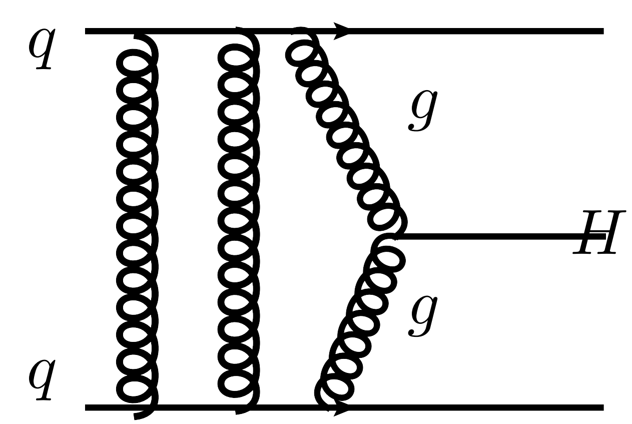
# Higgs gauge coupling

Weak boson fusion gives access to Higgs coupling to vector boson -- same coupling that breaks the electroweak symmetry? Very precise predictions are available -- in the factorization approximation. Time to go beyond it. Computing H+2jets at NNLO for weak boson fusion kinematics will help further to improve the precision of the coupling extraction.




Beyond the factorization approximation




Background at NNLO

# What will we need from pQCD

For this research program to succeed, it will be important:

- to understand better the role of non-perturbative effects in collider QCD and their impact on observables;

- to make parton showers a systematically-improvable approximation;

- to understand re-summations for more exclusive quantities;

- to learn how to get around the exponential growth in algebraic complexity in multi-loop multi-parton computations ;

- to find robust ways to compute Feynman integrals that do not rely on simplifications allowed by special cases (multi-mass cases etc.);

- to design physically-transparent and efficient subtraction schemes at NNLO. Connect them to resummations and parton showers.

# Conclusions

Quantum Chromodynamics is both a very broad and very deep subject; during this week we will talk about just a few topics that are relevant for how QCD is used to describe hard hadron collisions.

We will cover just a small fraction of what is out there to be learned -- just a tip of an iceberg. Nevertheless, we all hope that these lectures will help you in your scientific endeavors. Enjoy !