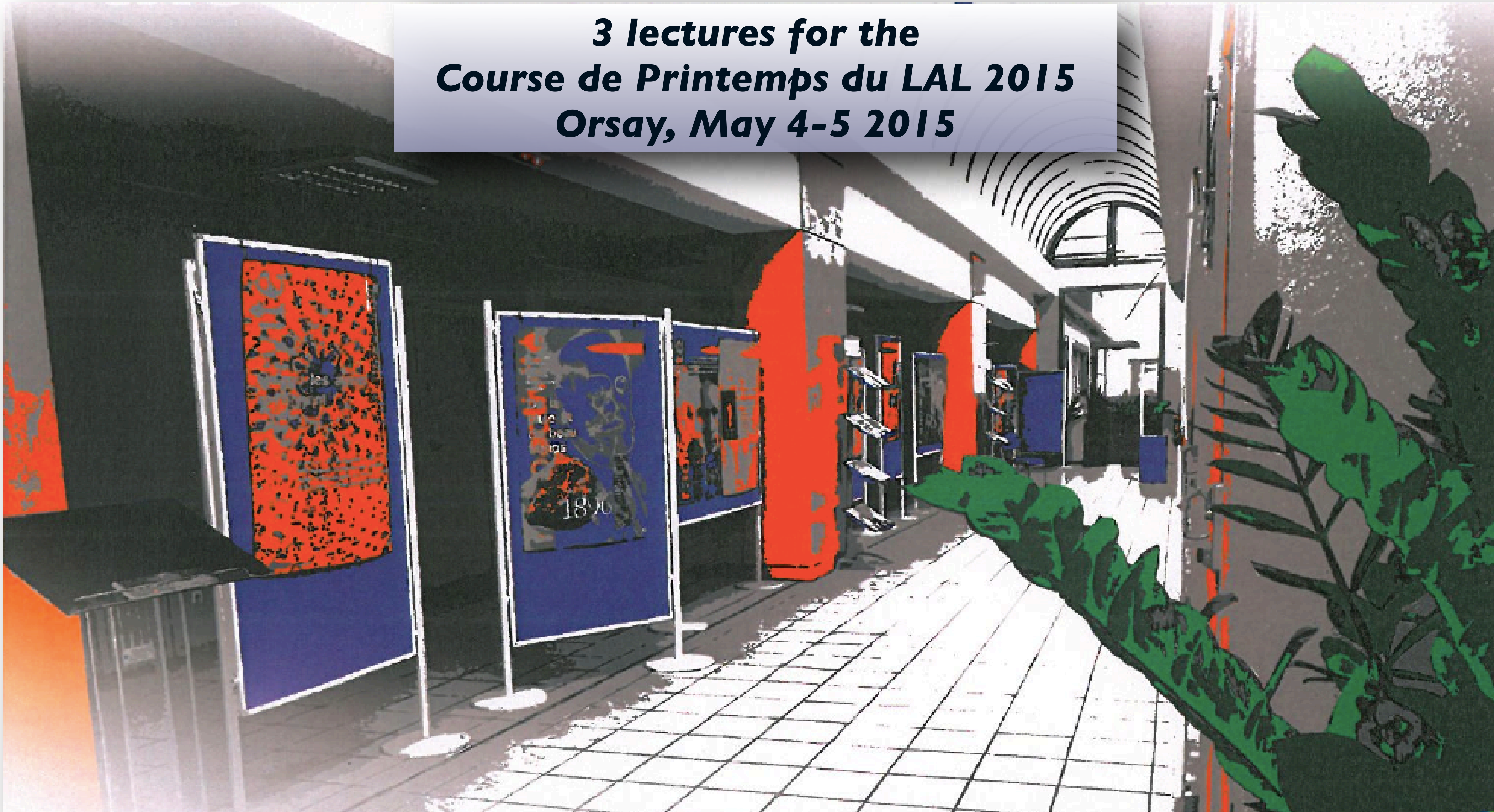
SM and BSM physics after the Higgs discovery

3 lectures for the
Course de Printemps du LAL 2015
Orsay, May 4-5 2015



Lecture 3

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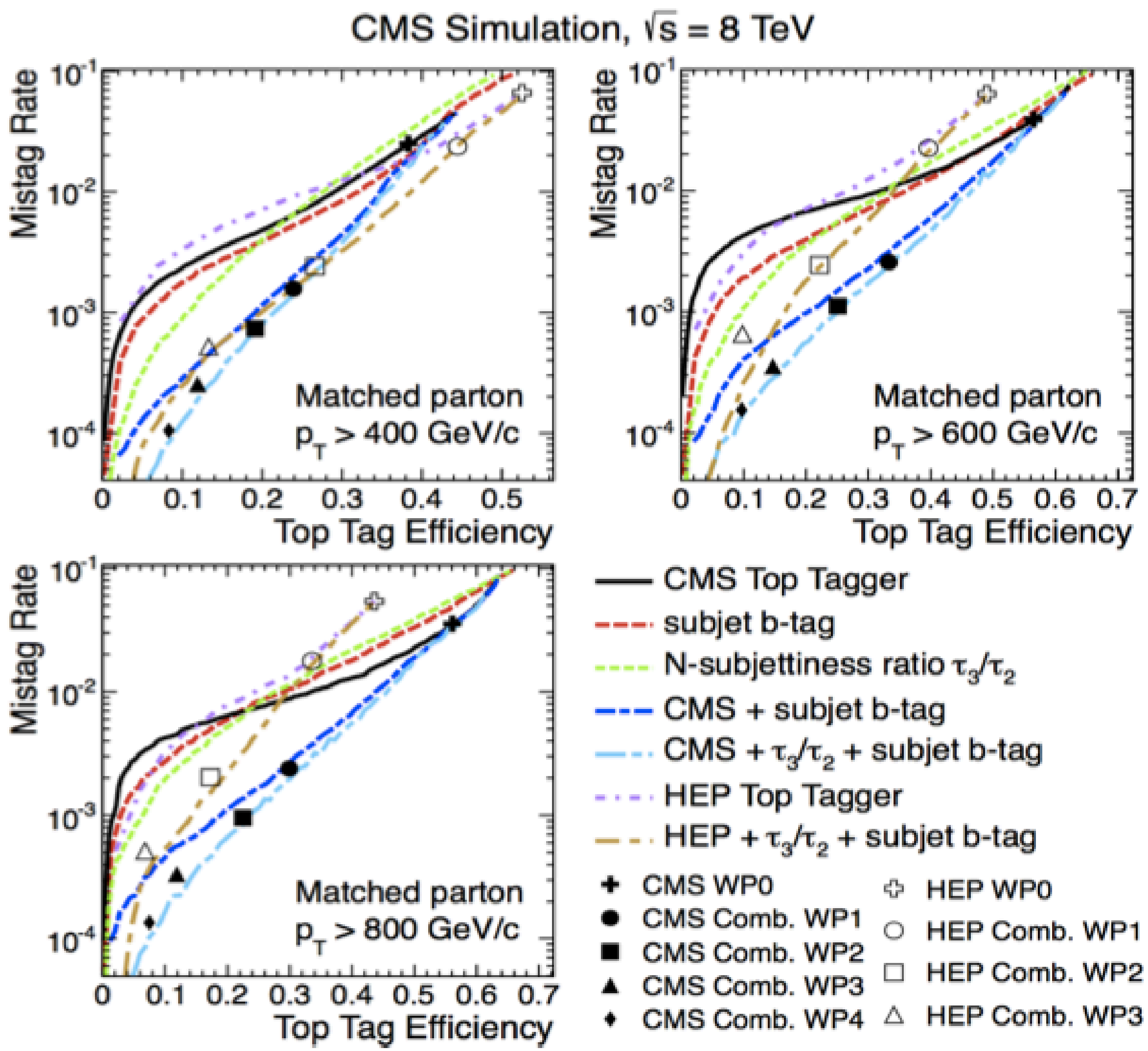
Few slides to address François' question on top tagging .....

CMS Top Tagger



CMS-JME-13-007

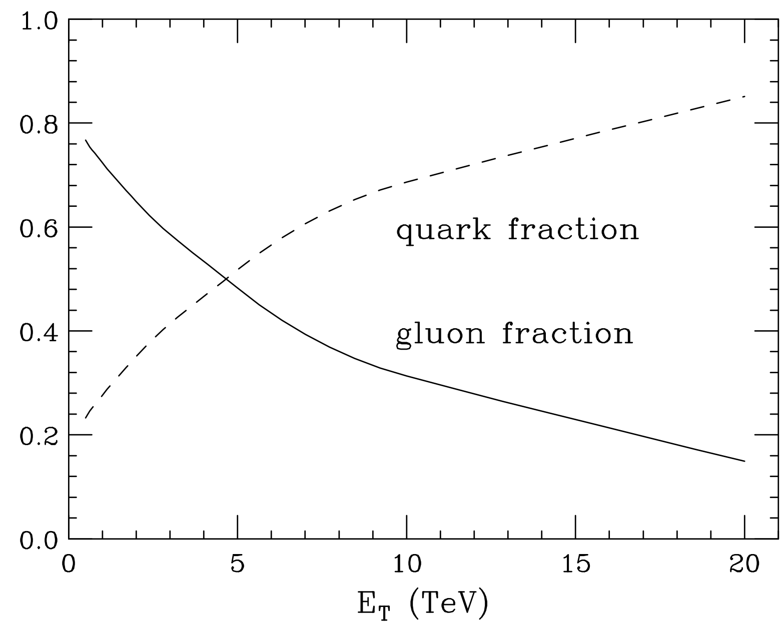
Jets at high E_T

Consider some features of jet structure at high E_T. Compare jets from:

- top quark (hadronic) decay
- bottom quark
- inclusive jets
- W hadronic decay

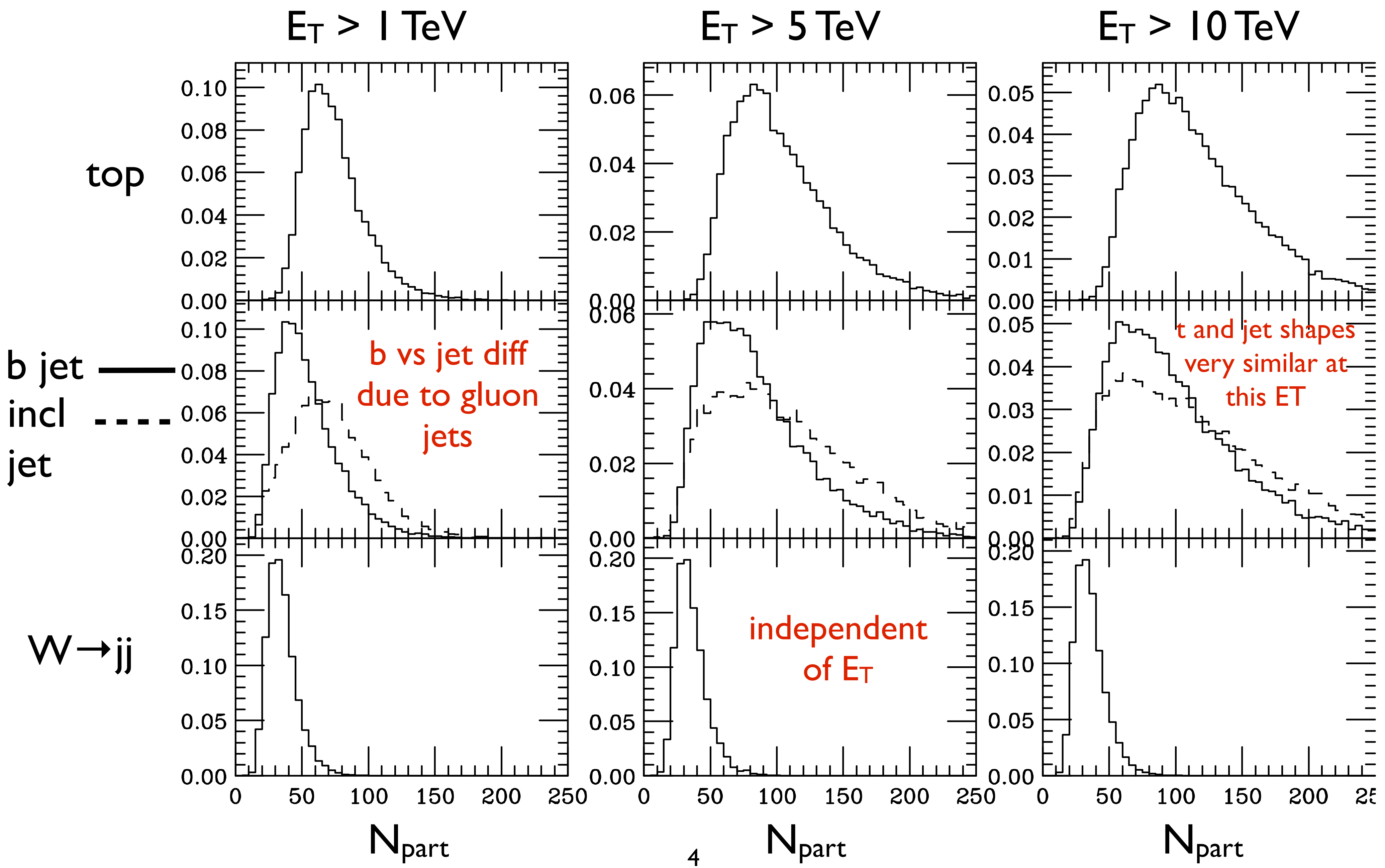
Jets are defined by anti-k_T . Use R=1 to define jet, then look inside at smaller R.
No soft UE, no pileup.
Generation: Alpgen + Herwig

NB: Inclusive jets here means jets from the QCD background. Thus they include a mixture of light quark and gluon jets, which varies vs E_T

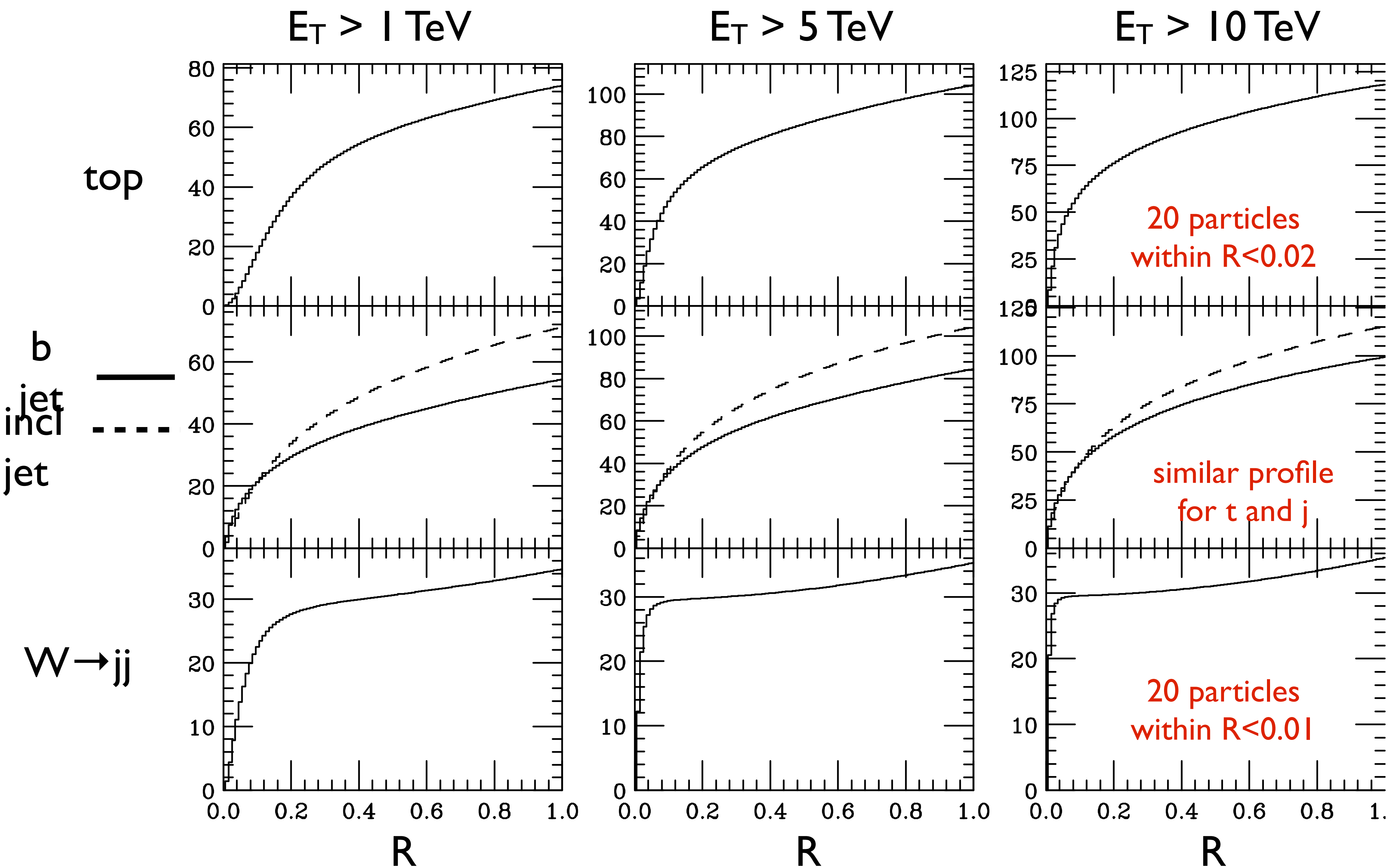


Particle multiplicity distribution: $1/\sigma \, d\sigma/dN_{part}$

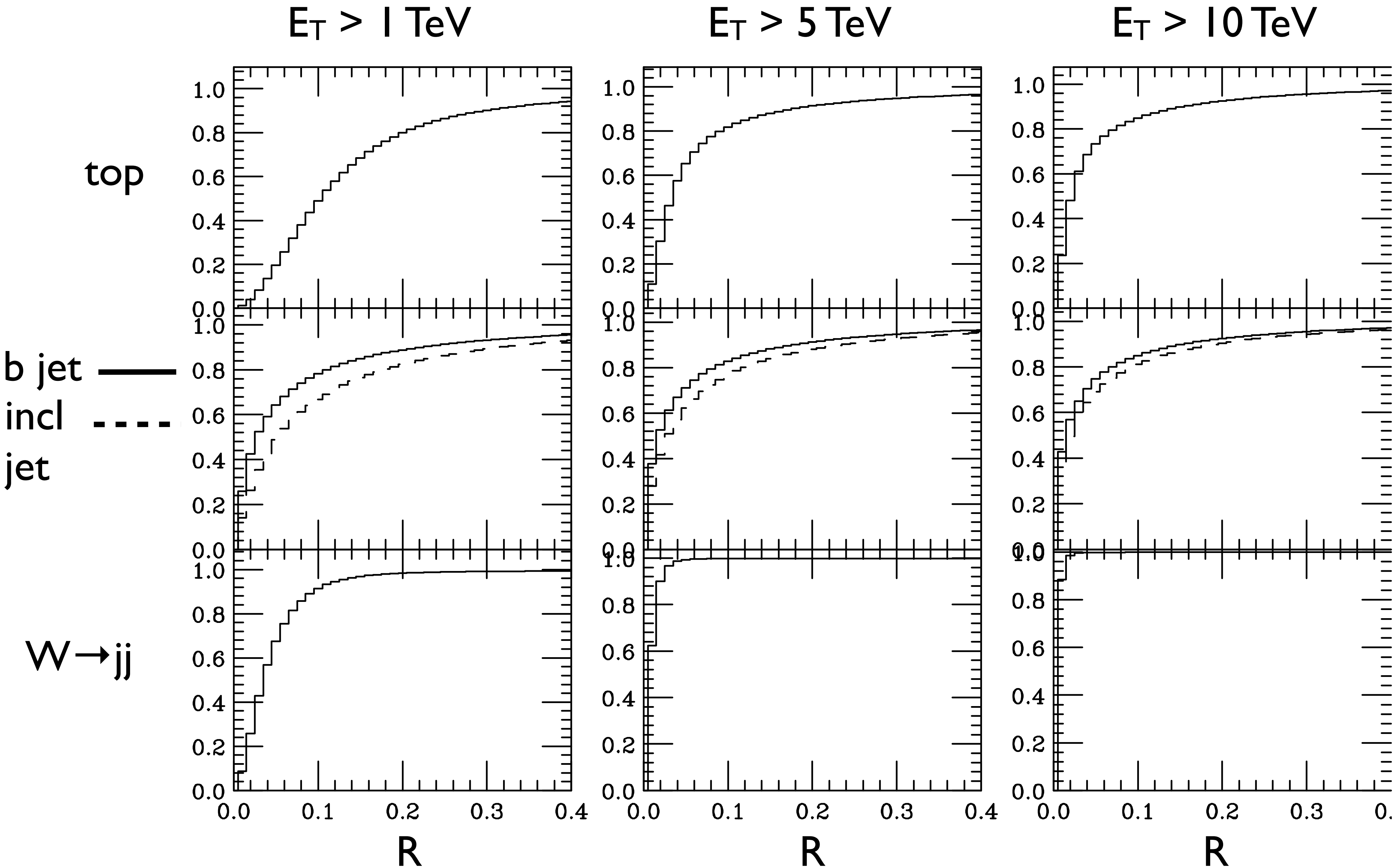
(particle: everything except neutrinos, neutral and charged, with stable π^0)



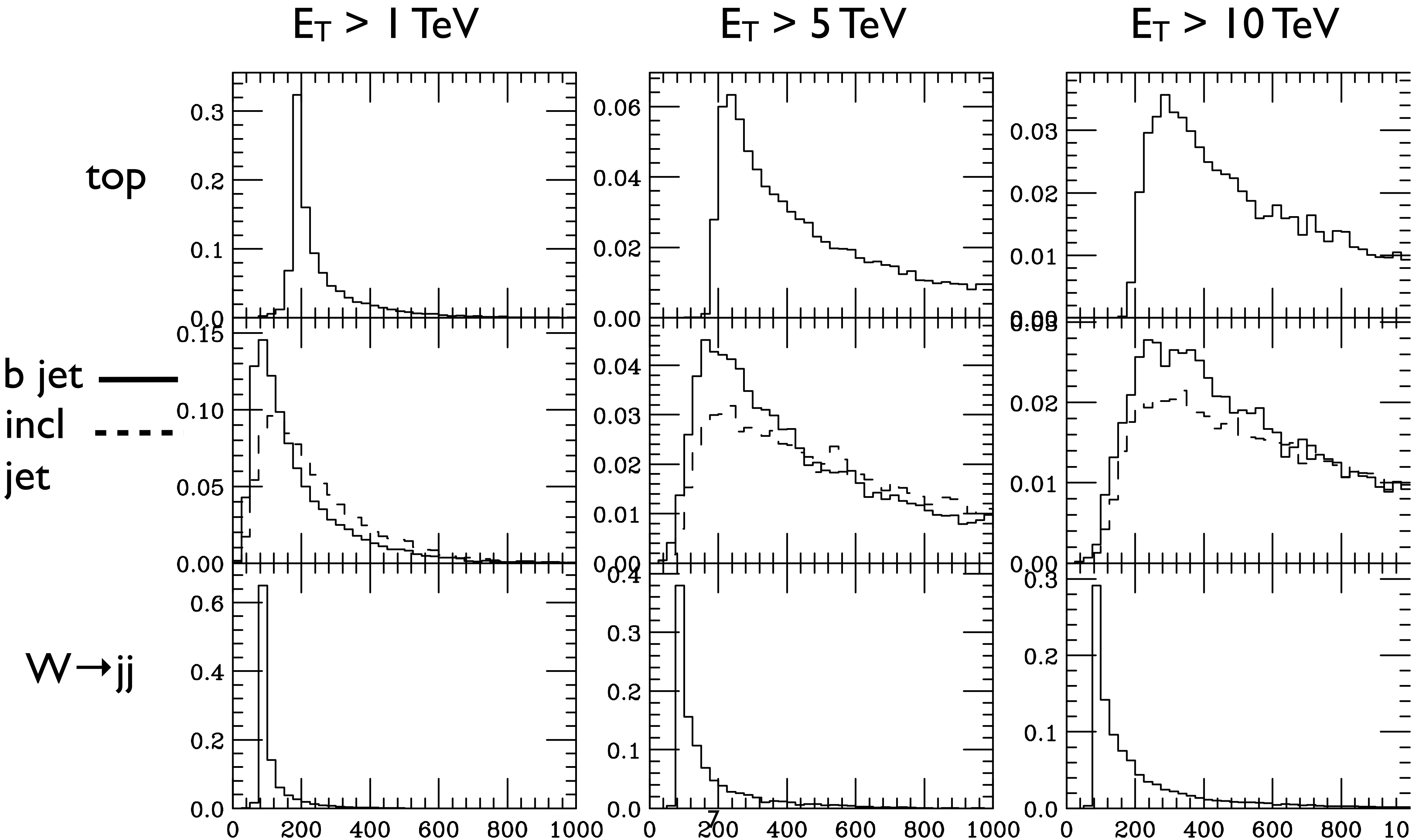
Average particle multiplicity shape: N_{part} (r<R)



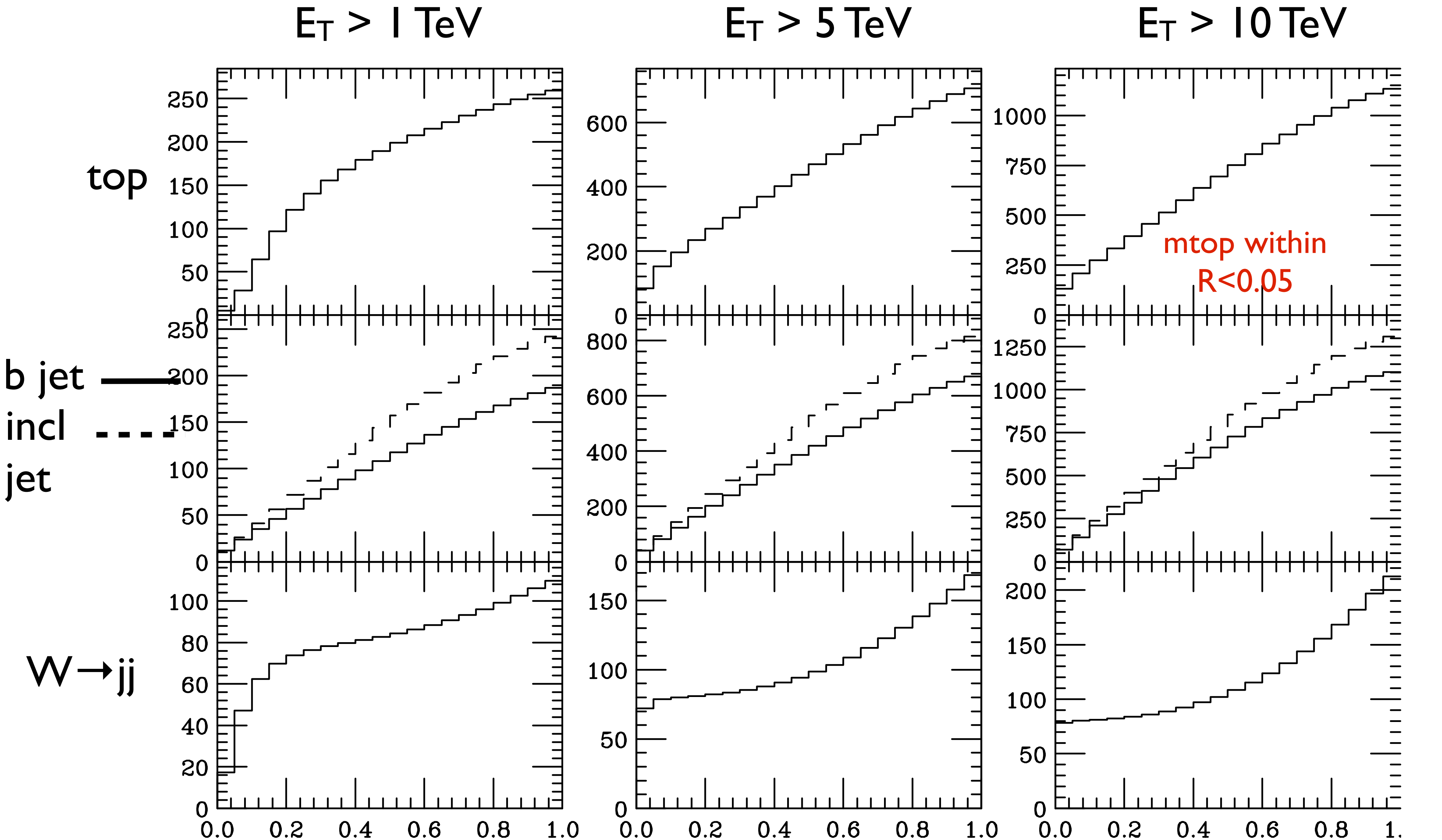
Energy shape: E(r<R) / E(r<1)



Jet mass distribution: $1/\sigma \; d\sigma/dM_{jet}$



Average jet mass: M(particles with r<R)



Tracking down hyper-boosted top quarks, Larkowski et al, arXiv:1503.03347

	Process	Cross section at pp, $\sqrt{s} = 100$ TeV		
		$p_T > 1$ TeV (pb)	$p_T > 5$ TeV (fb)	$p_T > 10$ TeV (ab)
Standard Model Signals	$pp \to t\bar{t}$	12	2.8	24
Standard Model Signals	$pp \to t\bar{t}j$	52	14	94
Standard Model Signals	$pp \to tj$	0.67	0.46	0.76
Standard Model Signals	$pp \to t\bar{t}V$	0.40	0.30	3.7
Standard Model Signals	$pp \to t\bar{t}H$	0.19	7.4e-02	0.65
Standard Model Signals	$pp \to t\bar{t}t\bar{t}$	0.17	8.5e-02	0.51
Standard Model Bkgds	$pp \to jj$	3500	1000	11000
Standard Model Bkgds	$pp \to jjV$	110	130	2200
BSM	$pp \to Z' \to t\bar{t}$ ($m_{Z'} = 3$ TeV)	4.6	-	-
BSM	$pp \to Z' \to t\bar{t}$ ($m_{Z'} = 15$ TeV)	7.1e-03	4.7	-
BSM	$pp \to Z' \to t\bar{t}$ ($m_{Z'} = 30$ TeV)	7.1 e-05	6.5e-02	48
BSM	$pp \to \tilde{t}\bar{\tilde{t}} \to t\bar{t} + \not{E}_T$ ($m_{\tilde{t}} = 1$ TeV)	0.49	7.8e-03	-
BSM	$pp \to \tilde{t}\bar{\tilde{t}} \to t\bar{t} + \not{E}_T$ ($m_{\tilde{t}} = 5$ TeV)	7.5e-04	0.063	-
BSM	$pp \to \tilde{t}\bar{\tilde{t}} \to t\bar{t} + \not{E}_T$ ($m_{\tilde{t}} = 10$ TeV)	4.4e-06	0.27e-03	0.024
BSM	$pp \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t} + \not{E}_T$ ($m_{\tilde{g}} = 2$ TeV)	2.5	0.94	-
BSM	$pp \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t} + \not{E}_T$ ($m_{\tilde{g}} = 5$ TeV)	2.7e-02	1.5	11
BSM	$pp \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t} + \not{E}_T$ ($m_{\tilde{g}} = 10$ TeV)	1.9e-04	0.12	4.5

Tracking down hyper-boosted top quarks, Larkowski et al, arXiv:1503.03347

bg efficiency, per jet

20% Top Efficiency

	p_T cut	[2.5, 5] TeV	[5, 7.5] TeV	[7.5, 10] TeV	[10, 15] TeV	[15, 20] TeV
gluons	CMS	2%	3%	4%	5%	6%
	FCC	1%	2%	2%	3%	4%
quarks	CMS	1%	2%	3%	5%	7%
	FCC	0.5%	1%	1.5%	2%	4%

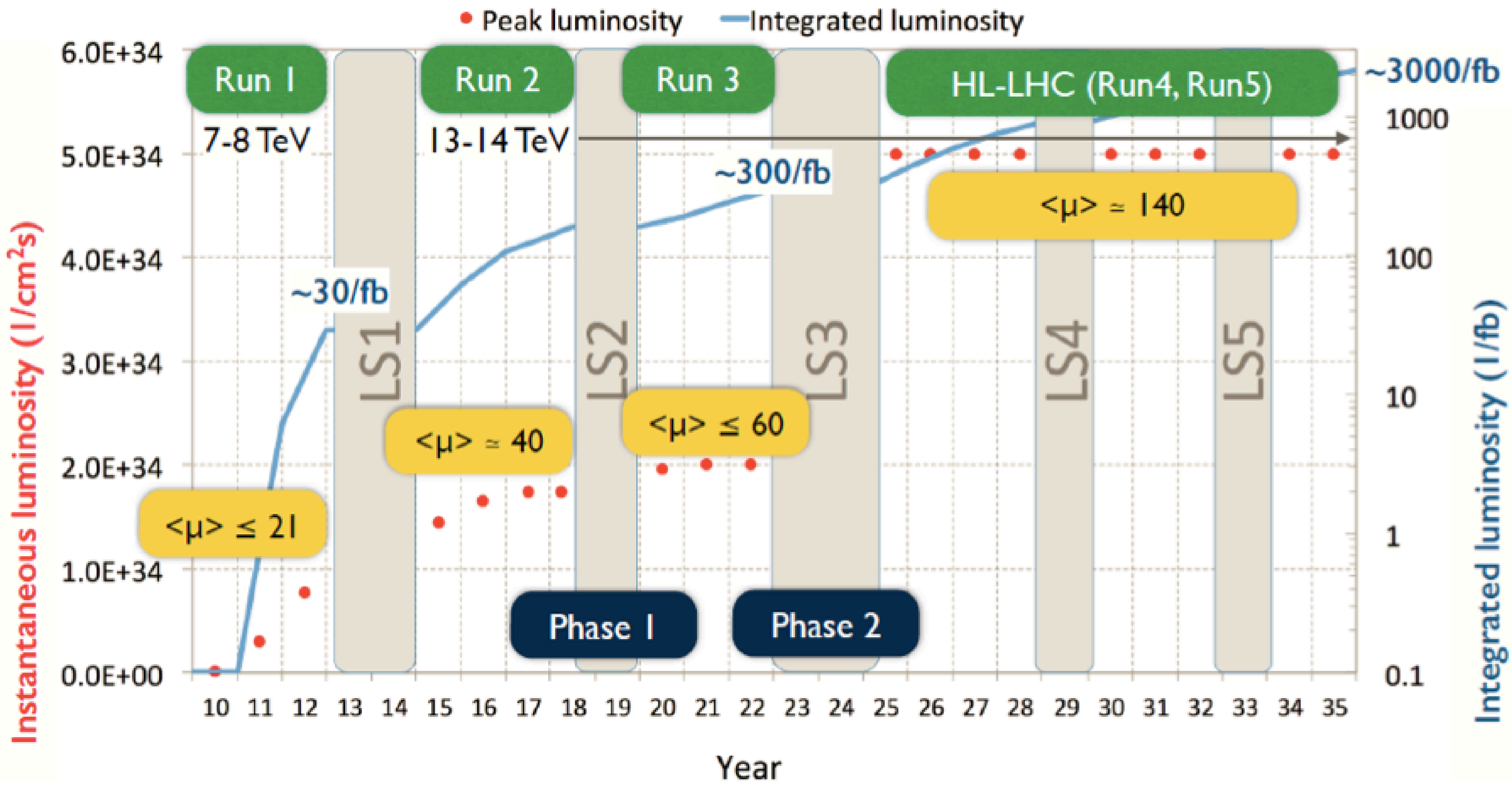
	CMS	FCC
B_z (T)	3.8	6.0
Length (m)	6	12
Radius (m)	1.3	2.6
ϵ_0	0.90	0.95
R^*	0.002	0.001
$\sigma(p_T)/p_T$	$0.2 \cdot p_T$ (TeV/c)	$0.02 \cdot p_T$ (TeV/c)
$\sigma(\eta, \phi)$	0.002	0.001

Table 2: Tracking-related parameters for the CMS and FCC setup in Delphes.

	CMS	FCC
$\sigma(E)/E$ (ECAL)	$7\%/\sqrt{E} \oplus 0.7\%$	$3\%/\sqrt{E} \oplus 0.3\%$
$\sigma(E)/E$ (HCAL)	$150\%/\sqrt{E} \oplus 5\%$	$50\%/\sqrt{E} \oplus 1\%$
$\eta \times \phi$ cell size (ECAL)	(0.02×0.02)	(0.01×0.01)
$\eta \times \phi$ cell size (HCAL)	(0.1×0.1)	(0.05×0.05)

Table 3: Calorimeter parameters for the CMS and FCC setup in Delphes.

The future LHC programme



HL-LHC physics reach and performance documented at

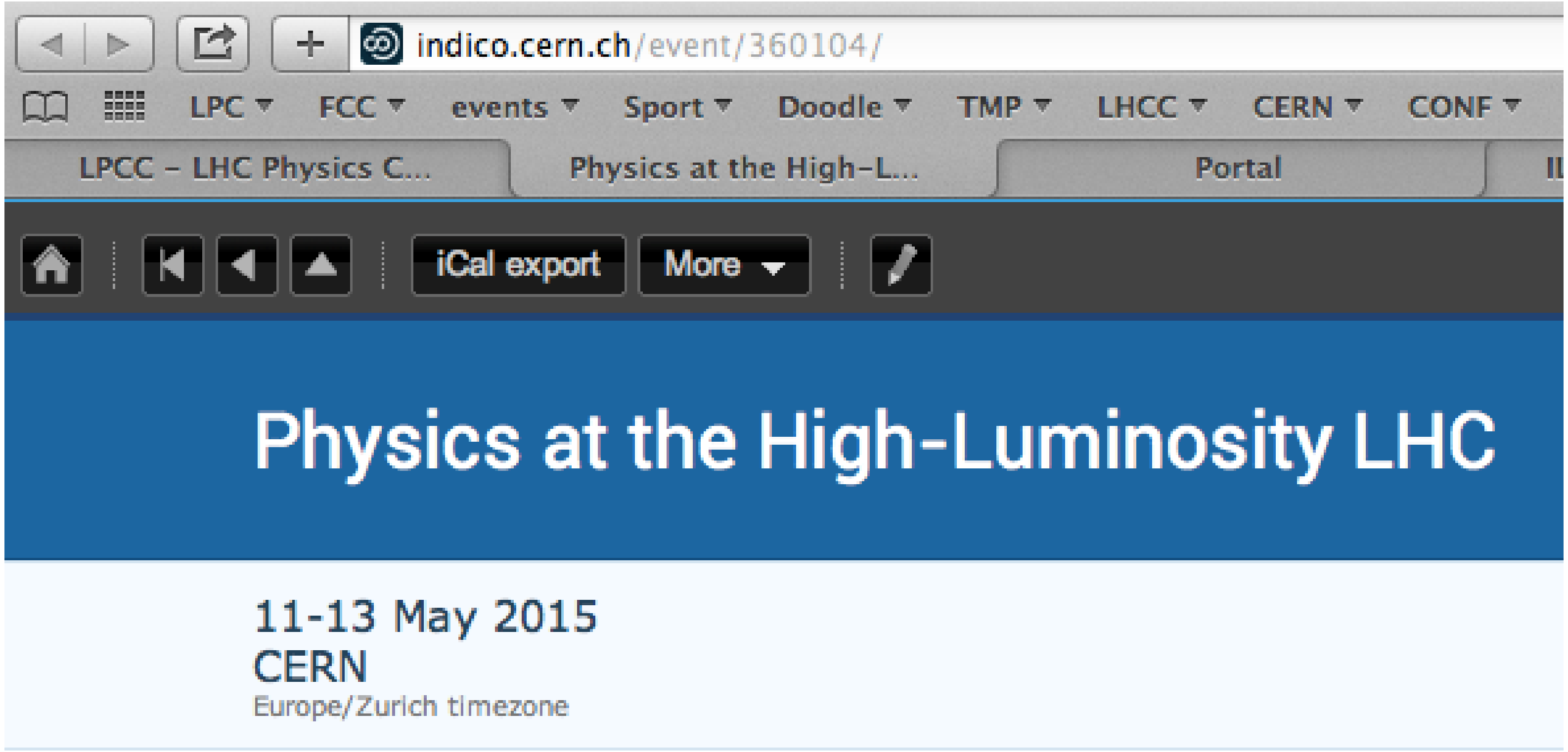
ATLAS

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies

CMS

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

HL-LHC physics Workshop next week at CERN:



Key Higgs targets for the LHC

- Improve the precision of current BR and coupling measurements, with a O(%) target
- H couplings to top and to Higgs
  - These are the input ingredients to the "vacuum-stability" analysis
- Complete detection of H couplings to EW gauge bosons: $H \to Z\gamma$
- H couplings to 2nd generation
  - start from $H \to \mu\mu$
  - ideas to probe Hcc via exclusive $H \to J/\psi\ \gamma$
- Search for flavour violating Higgs couplings
- Search for additional, BSM, Higgs states (as in e.g. 2HDM)

Summary by A.Apyan at
ECFA HL-LHC workshop

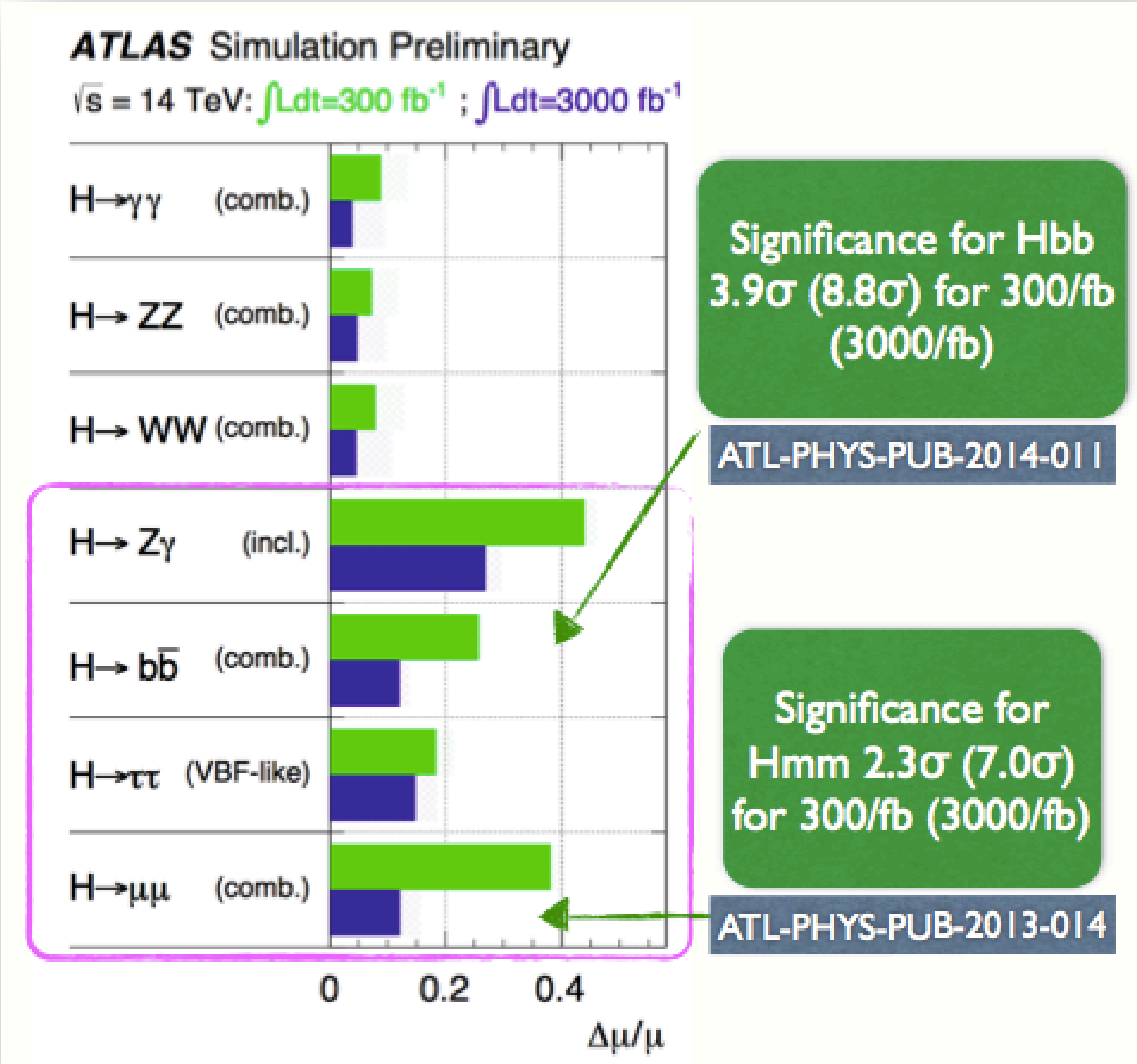
	Higgs bosons at $\sqrt{s}$=14TeV
HL-LHC, 3000fb^{-1}	170M
VBF (all decays)	13M
ttH (all decays)	1.8M
H->Zγ	230k
H->μμ	37k
HH (all)	121k

Coupling fit, assuming no BSM decays

		κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300fb^{-1}	ATLAS	[9,9]	[9,9]	[8,8]	[11,14]	[22,23]	[20,22]	[13,14]	[24,24]	[21,21]
300fb^{-1}	CMS	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000fb^{-1}	ATLAS	[4,5]	[4,5]	[4,4]	[5,9]	[10,12]	[8,11]	[9,10]	[14,14]	[7,8]
3000fb^{-1}	CMS	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

- ATLAS: [no theory uncert., full theory uncert.]
- CMS: [δ_{TH} scaled by 1/2, δ_{exp} scaled by $1/\sqrt{L}$, Syst as run 1]

Higgs decays



5-10% precision in best cases

$H \rightarrow \mu\mu$: first proof of H coupling to 2nd generation fermions

On theory uncertainties

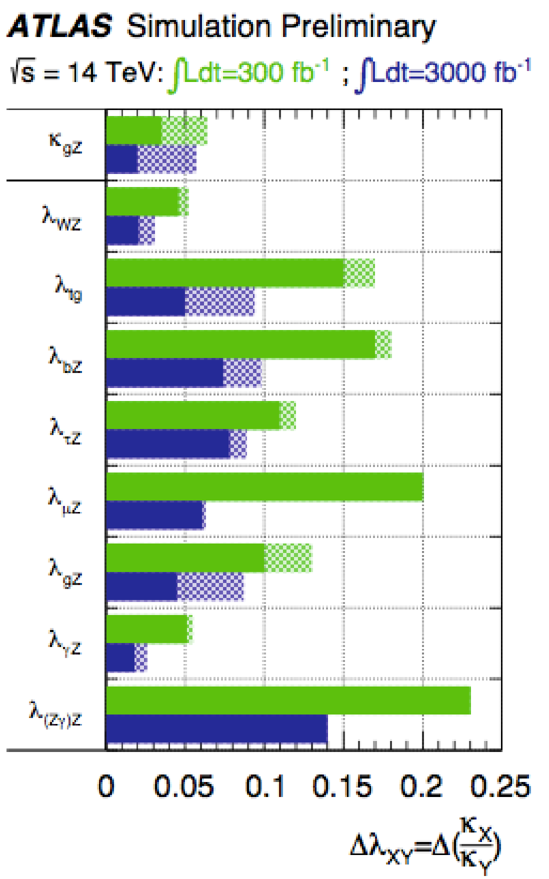


Figure 3: Relative uncertainty expected for the determination of coupling scale factor ratios λXY in a generic fit without assumptions, assuming a SM Higgs boson with a mass of 125 GeV and with 300 fb^{-1} or 3000 fb^{-1} of 14 TeV LHC data. The hashed areas indicate the increase of the estimated error due to current theory systematic uncertainties.

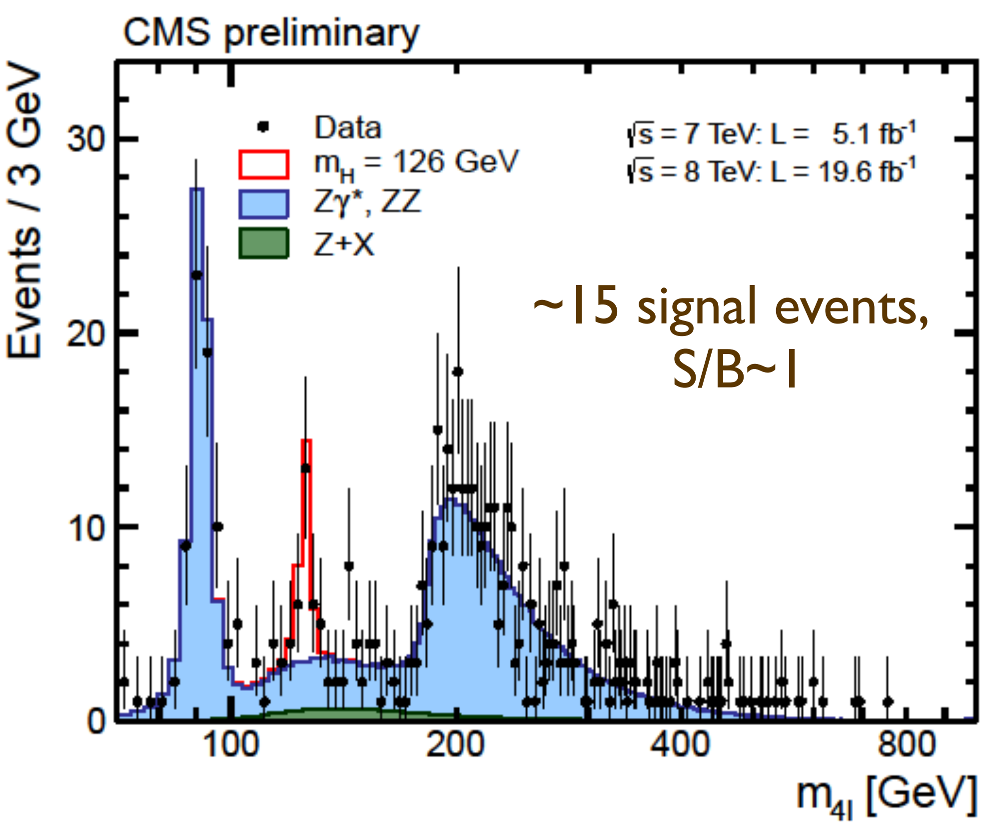
Scenario	Status 2014	Deduced size of uncertainty to increase total uncertainty by $\lesssim$10% for 300 fb^{-1}			by $\lesssim$10% for 3000 fb^{-1}				
Theory uncertainty (%)	[10–12]	κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$									
PDF	8	2	-	-	1.3	-	-	-	-
incl. QCD scale (MHOU)	7	2	-	-	1.1	-	-	-	-
p_T shape and 0j $\to$ 1j mig.	10–20	-	3.5–7	-	-	1.5–3	-	-	-
1j $\to$ 2j mig.	13–28	-	-	6.5–14	-	3.3–7	-	-	-
1j $\to$ VBF 2j mig.	18–58	-	-	-	-	-	6–19	-	-
VBF 2j $\to$ VBF 3j mig.	12–38	-	-	-	-	-	-	6–19	-
VBF									
PDF	3.3	-	-	-	-	-	2.8	-	-
$t\bar{t}H$									
PDF	9	-	-	-	-	-	-	-	3
incl. QCD scale (MHOU)	8	-	-	-	-	-	-	-	2

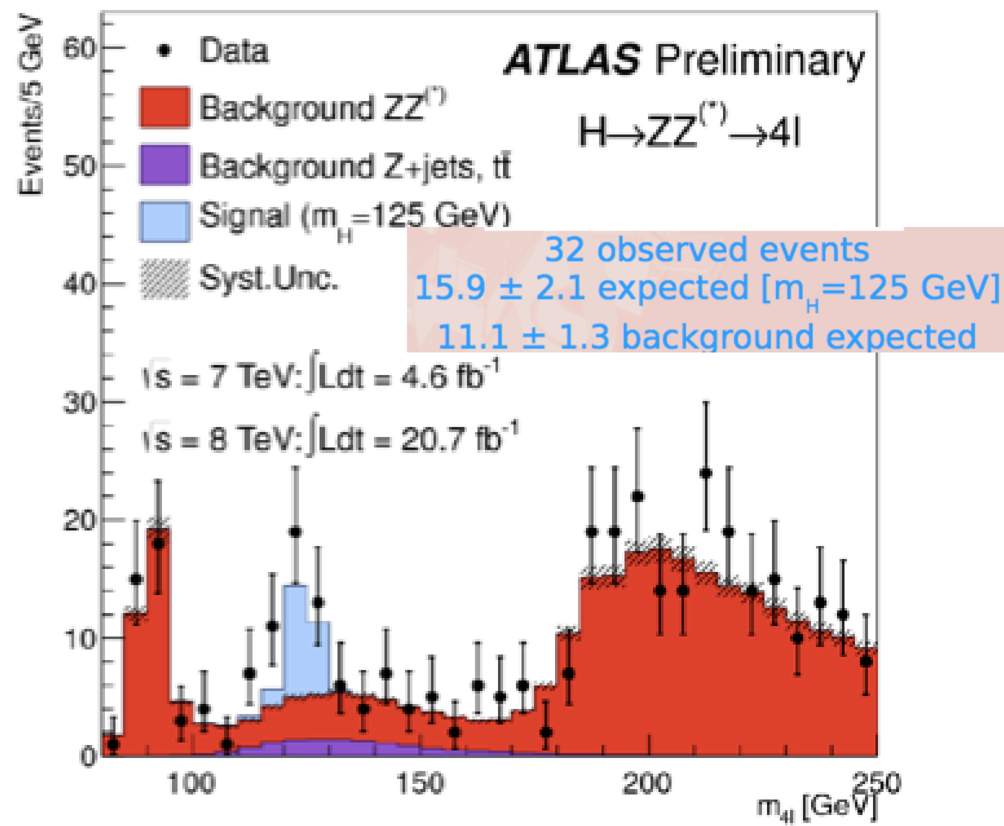
Table 6: Estimation of the deduced size of theory uncertainties, in percent (%), for different Higgs coupling measurements in the generic Model 15 from Table 5, requiring that each source of theory systematic uncertainty affects the measurement by less than 30% of the total experimental uncertainty and hence increase the total uncertainty by less than 10%. A dash "-" indicates that the theory uncertainty from existing calculations [10–12] is already sufficiently small to fulfill the condition above for some measurements. The same applies to theory uncertainties not mentioned in the table for any measurement. The impact of the jet-bin and p_T related uncertainties in $gg \to H$ depends on analysis selections and hence no single number can be quoted. Therefore the range of uncertainty values used in the different analysis is shown.

dominated by modeling

ATL-PHYS-PUB-2014-016

Modeling (e.g. jet veto efficiencies, pt spectra, ..) will be improved by comparison of TH calculations and data, using "clean" Higgs observables ....

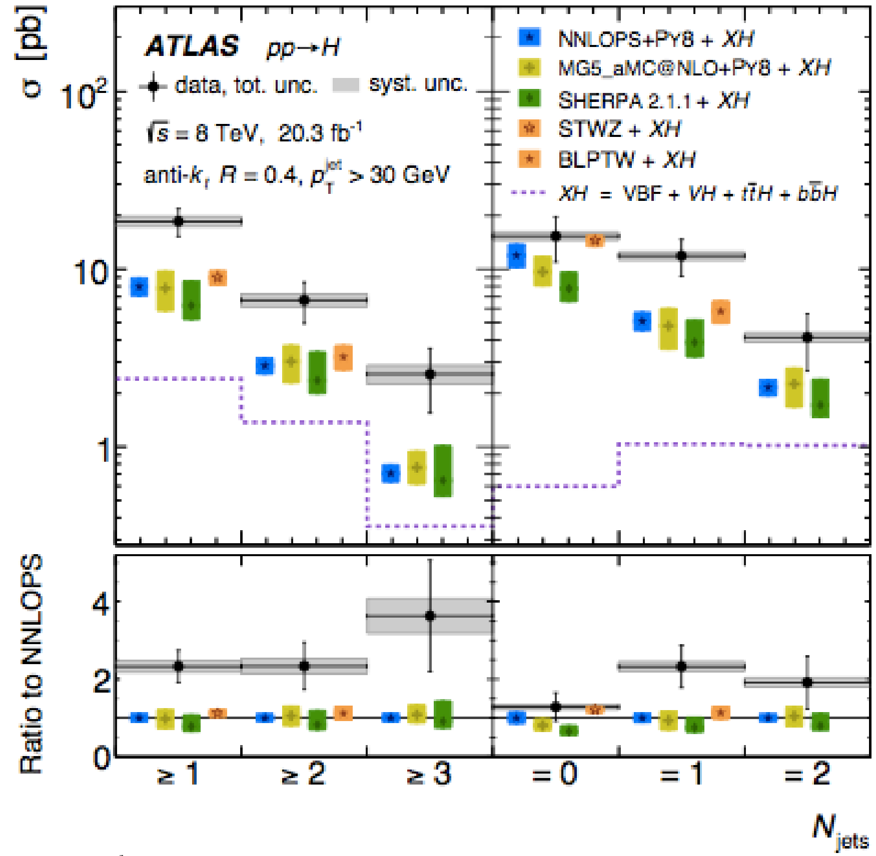


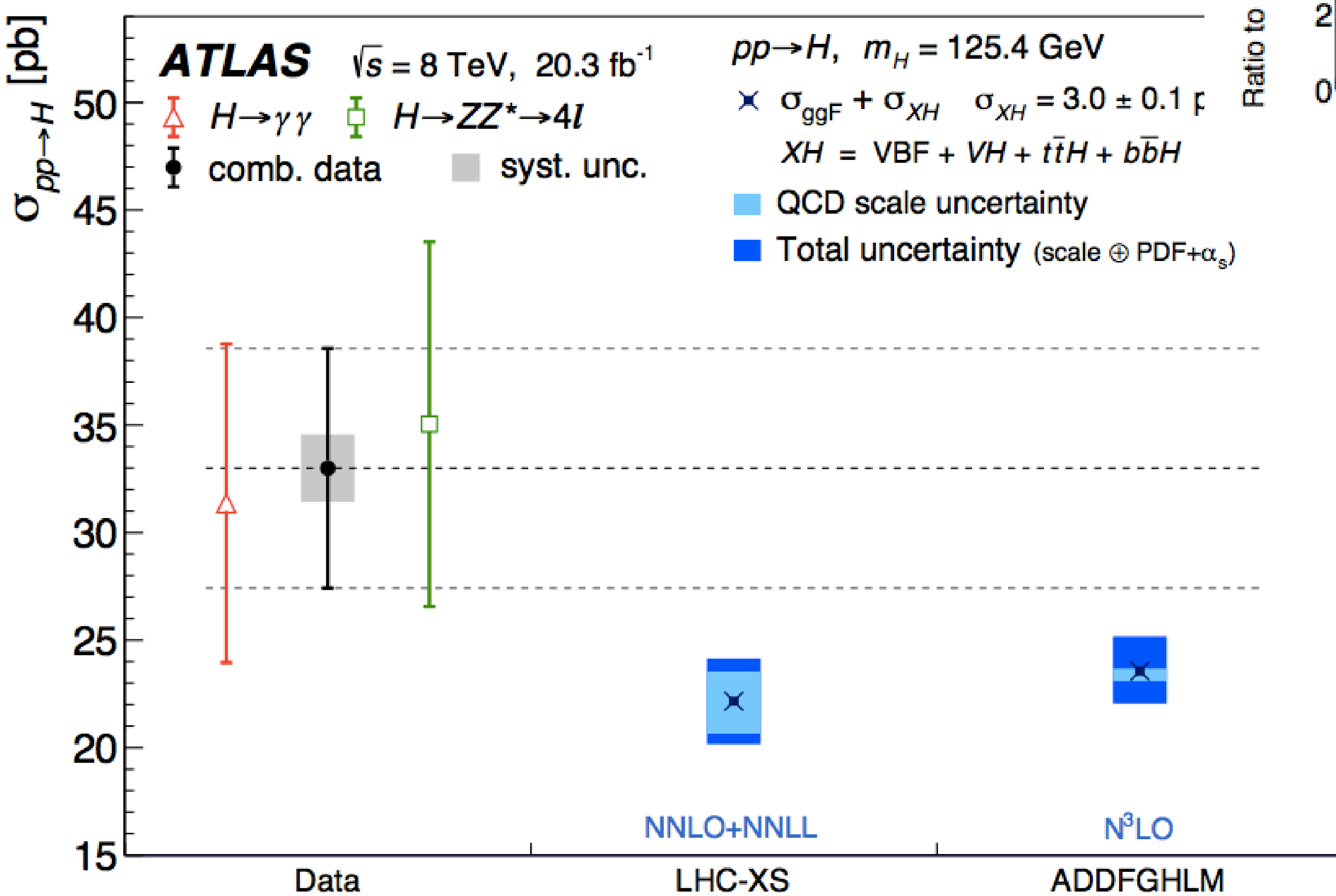


There is already enough to start plotting pt(H), N_{jet} distribution in H production, etc.

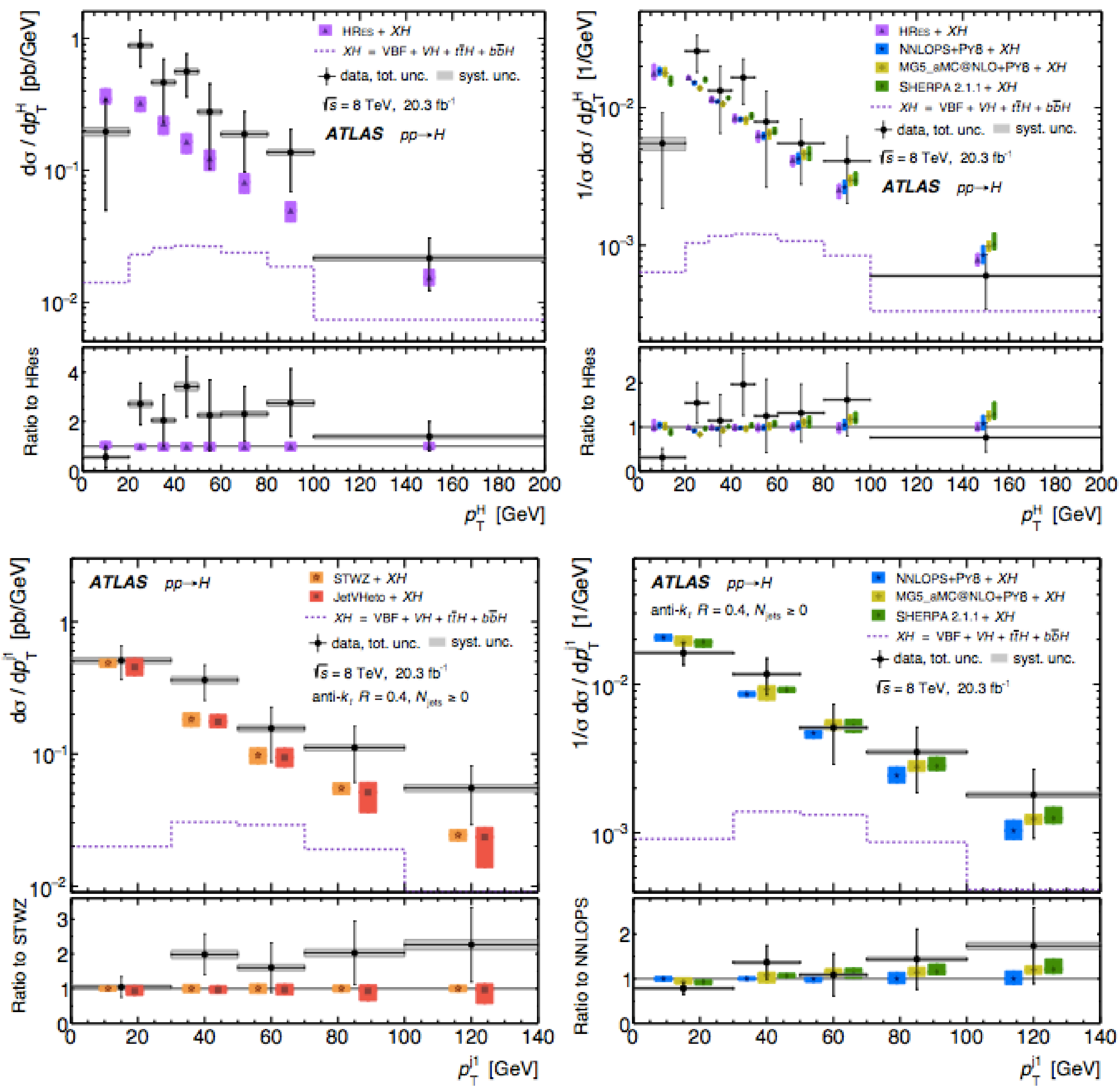
Total and Differential Higgs Cross Sections from H → γγ and H →ZZ* →4l

ATLAS, arXiv:1504.05833





NB Most of the TH vs data discrepancy comes from final states with ≥ 1 jet, which in other analyses (WW*) are left out ....


HRes + XH
XH = VBF + VH + ttH + bbH
data, tot. unc.
syst. unc.
√s = 8 TeV, 20.3 fb⁻¹
ATLAS pp→H
dσ / dp_T^H [pb/GeV]
Ratio to HRes
p_T^H [GeV]
NNLOPS+PY8 + XH
MG5_aMC@NLO+PY8 + XH
SHERPA 2.1.1 + XH
1/σ dσ / dp_T^H [1/GeV]
STWZ + XH
JetVHeto + XH
anti-k_t R = 0.4, N_jets ≥ 0
dσ / dp_T^j1 [pb/GeV]
Ratio to STWZ
p_T^j1 [GeV]
1/σ dσ / dp_T^j1 [1/GeV]
Ratio to NNLOPS

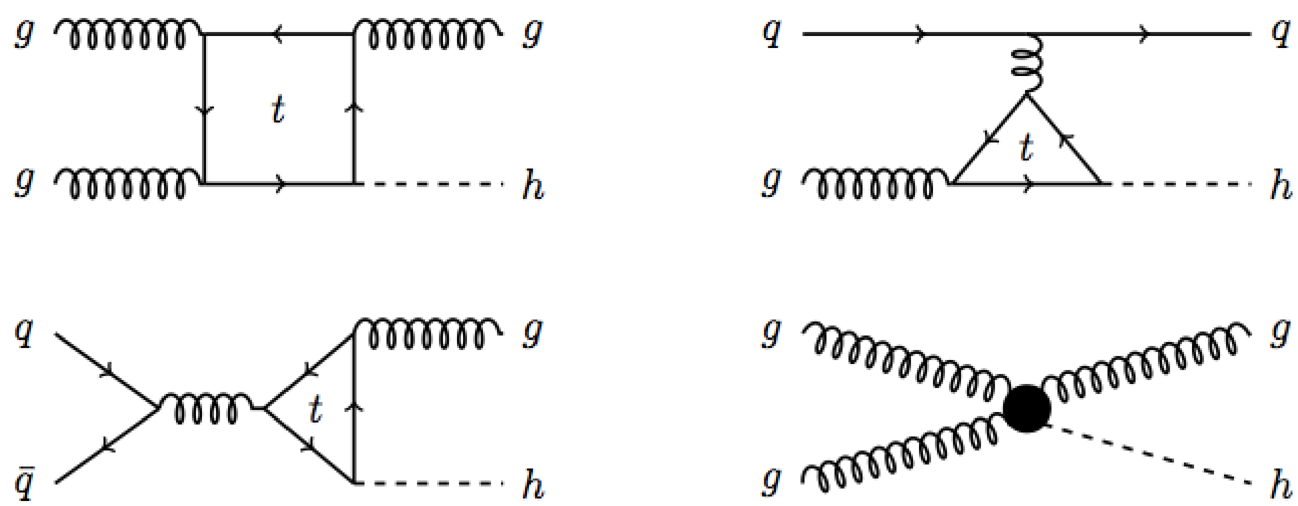
Using H+jet to resolve the virtual loop in the ggH coupling

Azatov and Paul, arXiv:1309.5273   Grojean, Salvioni, Schlaffer, Weiler, arXiv:1312.3317

$$-\kappa_t \frac{m_t}{v} \bar{t}th + \kappa_g \frac{\alpha_s}{12\pi} \frac{h}{v} G^a_{\mu\nu} G^{\mu\nu\, a} \quad \Rightarrow \quad \frac{\sigma_{\rm incl}(\kappa_t, \kappa_g)}{\sigma^{\rm SM}_{\rm incl}} \simeq (\kappa_t + \kappa_g)^2$$

$\Rightarrow$ impossible to resolve from inclusive rate origin of possible deviations, and possibility of cancellations

In H+jet production instead:



$$\Rightarrow \quad \frac{\sigma_{p_T^{\rm min}}(\kappa_t, \kappa_g)}{\sigma^{\rm SM}_{p_T^{\rm min}}} = (\kappa_t + \kappa_g)^2 + \delta\, \kappa_t\, \kappa_g + \epsilon\, \kappa_g^2$$

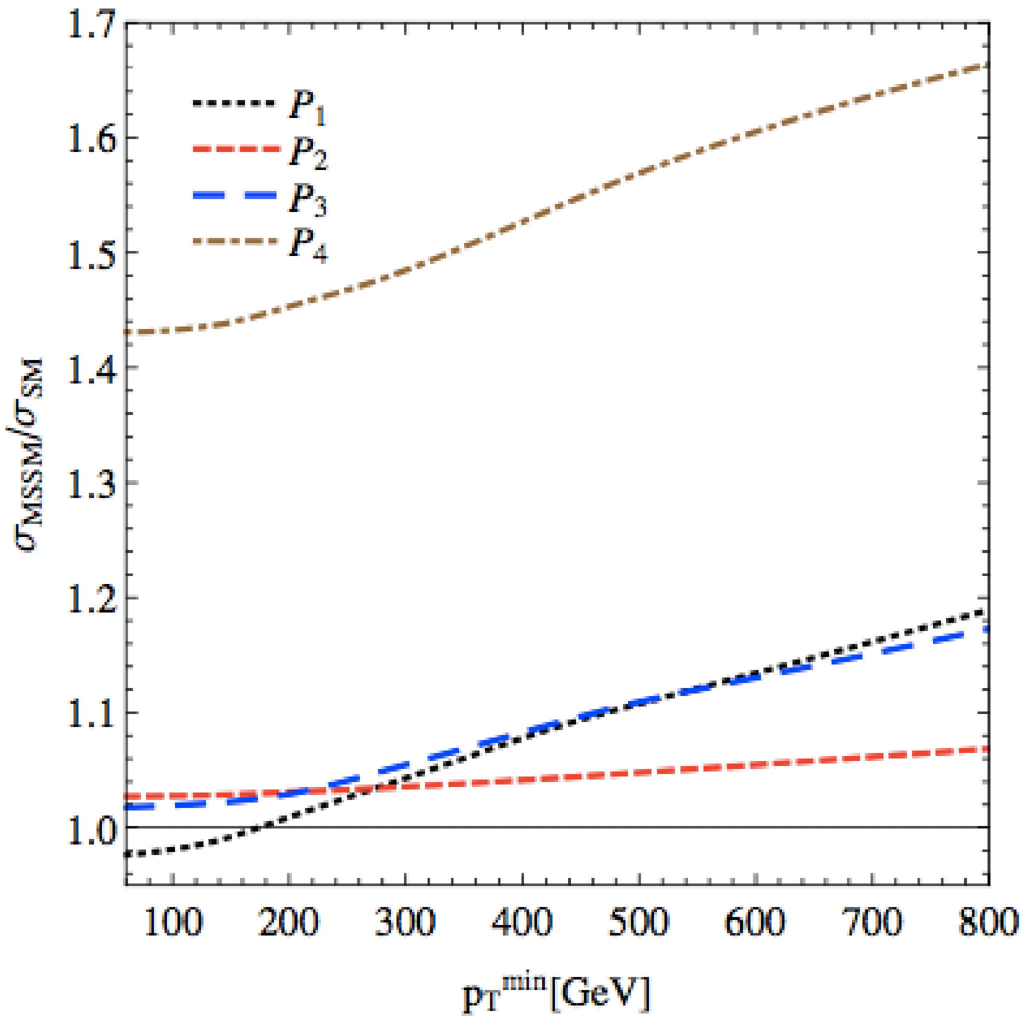
$\delta(p_T)$ and $\varepsilon(p_T)$ with different p_T shapes

Examples of stealth stop effects on H pt spectrum

Point	$m_{\tilde{t}_1}$ [GeV]	$m_{\tilde{t}_2}$ [GeV]	A_t [GeV]	Δ_t
P_1	171	440	490	0.0026
P_2	192	1224	1220	0.013
P_3	226	484	532	0.015
P_4	226	484	0	0.18

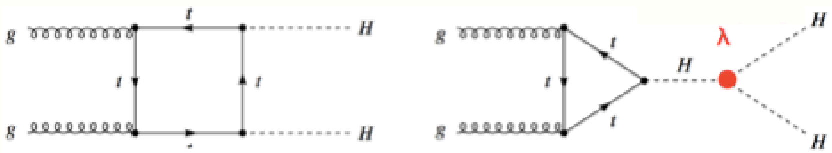
$$\frac{\Gamma(gg \to h)}{\Gamma(gg \to h)_{\rm SM}} = (1 + \Delta_t)^2$$

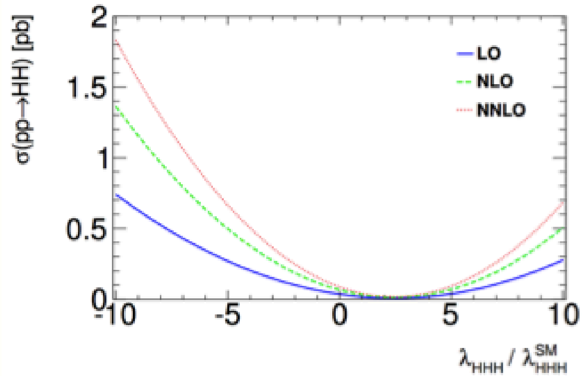
No impact on inclusive gg→H rate

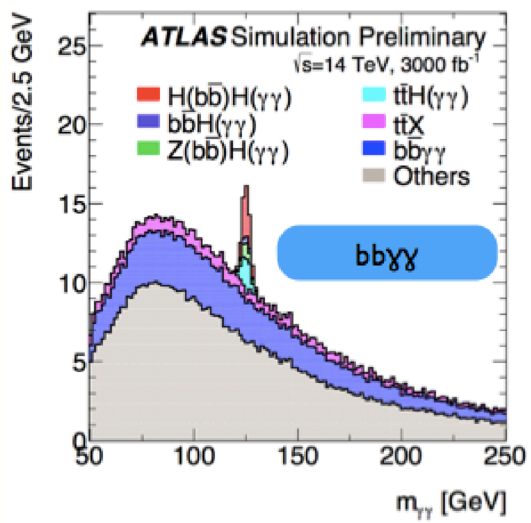


Higgs selfcoupling: HH→bbγγ

- Measurement of the Higgs pair production to probe the trilinear coupling and thus the Higgs potential
- Negative interference between the box and s-channel leading to suppression of event yield



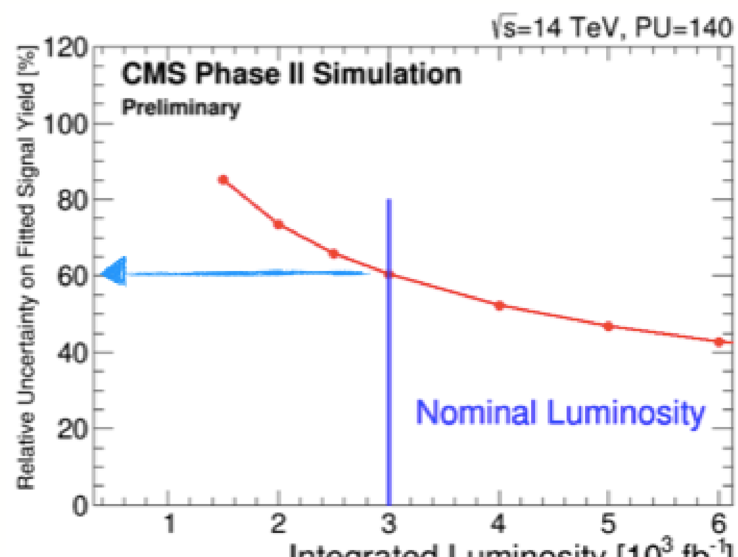




ATL-PHYS-PUB-2014-019

process	Expected events in 3000 fb^{-1}
SM HH→bbγγ	8.4± 0.1
bbγγ	9.7 ± 1.5
ccγγ, bbγj, bbjj, jjγγ	24.1 ± 2.2
top background	3.4 ± 2.2
ttH(γγ)	6.1 ± 0.5
Z(bb)H(γγ)	2.7 ± 0.1
bbH(γγ)	1.2 ± 0.1
Total background	47.1 ± 3.5
S/√B (barrel+endcap)	1.2
S/√B (split barrel and endcap)	1.3

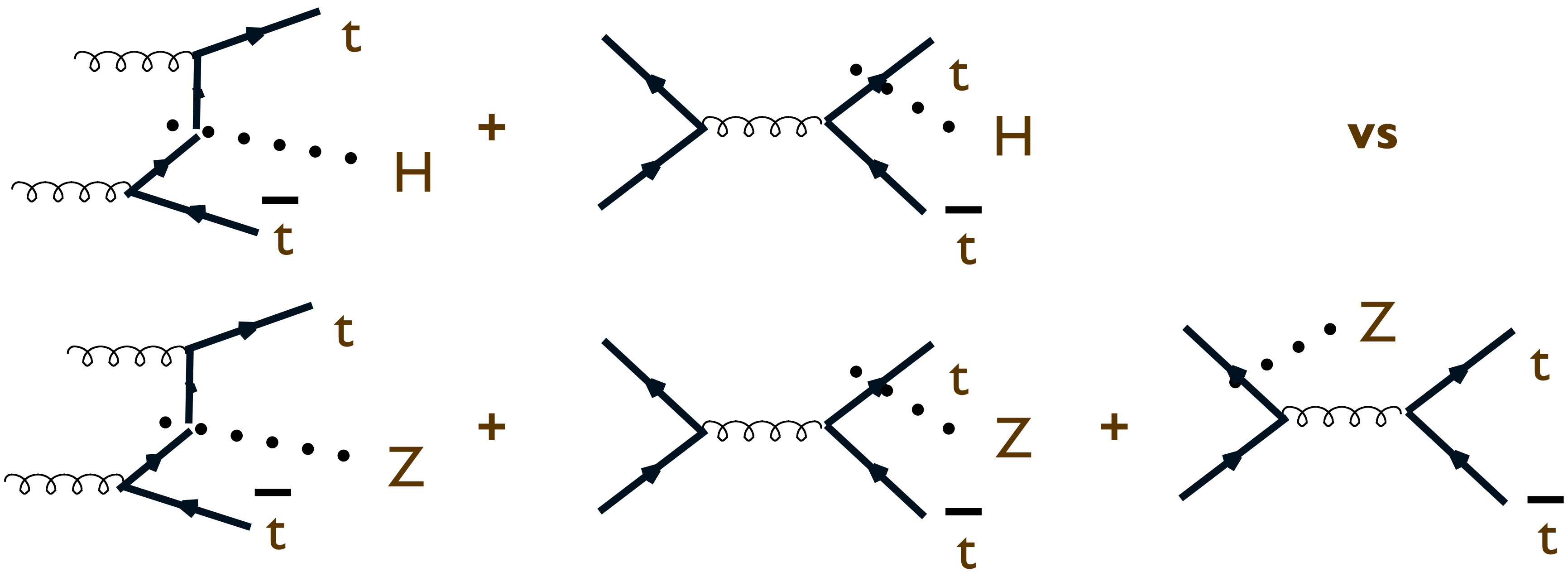
Physics Performance for 2nd ECFA workshop



60% precision on signal yield (if SM coupling)

High statistics may also allow new observables to be used ....

Example, y_{top} from $pp \to tt\ H / pp \to tt\ Z$



To the extent that the qqbar → tt Z/H contributions are subdominant:

- Identical production dynamics:

o correlated QCD corrections, correlated scale dependence
o correlated α_s systematics

- $m_Z \sim m_H \Rightarrow$ almost identical kinematic boundaries:

o correlated PDF systematics
o correlated m_{top} systematics

For a given y_{top}, we expect $\sigma(ttH)/\sigma(ttZ)$ to be predicted with great precision

NLO scale dependence:

Scan μ_R and μ_F independently, at $\mu_{R,F} = [0.5, 1, 2]\ \mu_0$, with $\mu_0 = m_H+2m_t$

	δσ(ttH)	δσ(ttZ)	**σ(ttH)/σ(ttZ)**	**δ[σ(ttH)/σ(ttZ)]**
14 TeV	± 9.8%	± 12.3%	**0.608**	**±2.6%**
100 TeV	± 9.6%	± 10.8%	**0.589**	**±1.2%**

PDF dependence (CTEQ6.6 -- similar for others)

	δσ(ttH)	δσ(ttZ)	**δ[σ(ttH)/σ(ttZ)]**
14 TeV	± 4.8%	± 5.3%	**±0.75%**
100 TeV	± 2.7%	± 2.3%	**±0.48%**

HL-LHC projection: $\delta\mu/\mu_{ATLAS}$ (tt[H→γγ]) ~ 15% => $\delta y_t/y_t$ ~ 8%

** The uncertainty reduction survives after applying kinematical cuts to the final states*

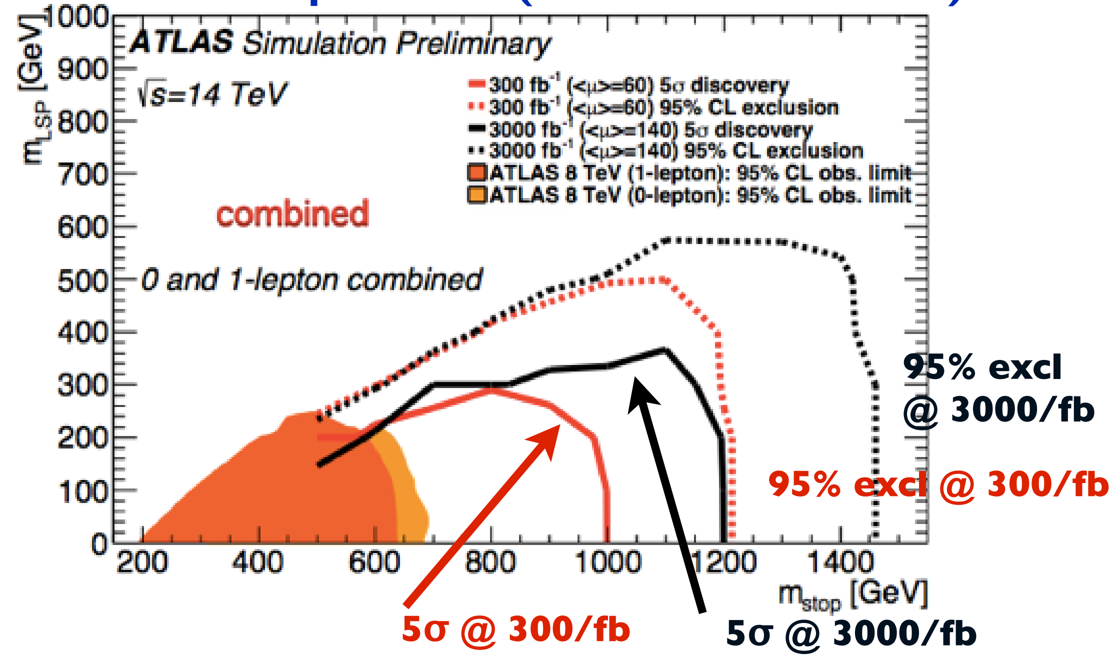
** Both scale and PDF uncertainties will be reduced further in the next few years*

LHC vs HL-LHC: extension of the discovery reach at high M

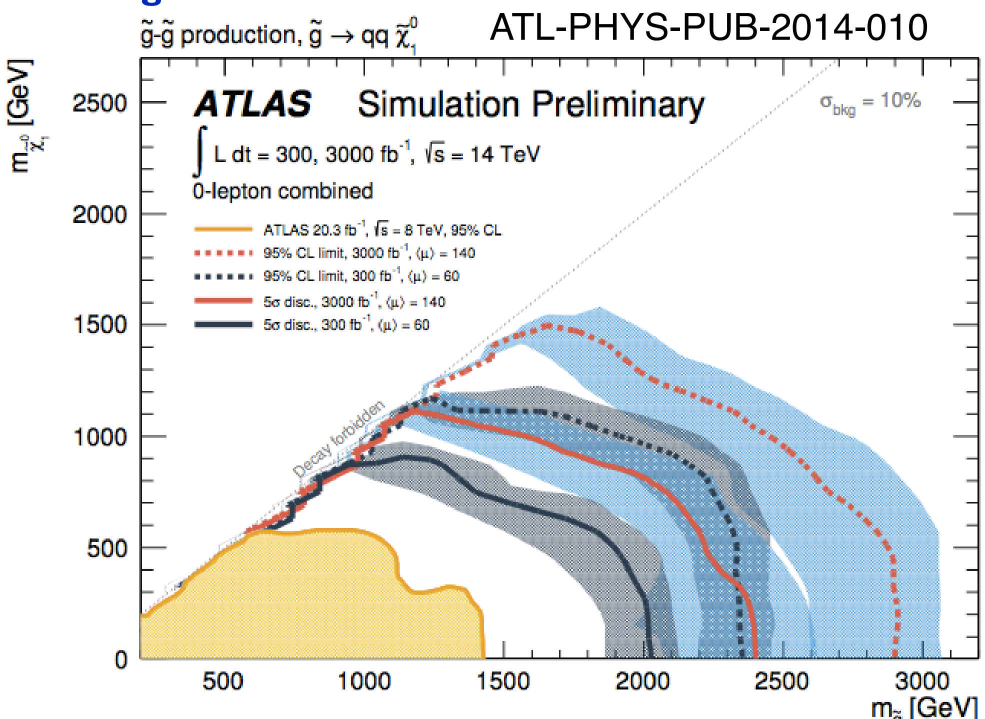
Z' → e^+e^-

ATLAS/CMS HL docs	300/fb	3000/fb
95% excl (ATLAS)	**6.5 TeV**	7.8 TeV
5σ (CMS)	5.1 TeV	**6.2 TeV**

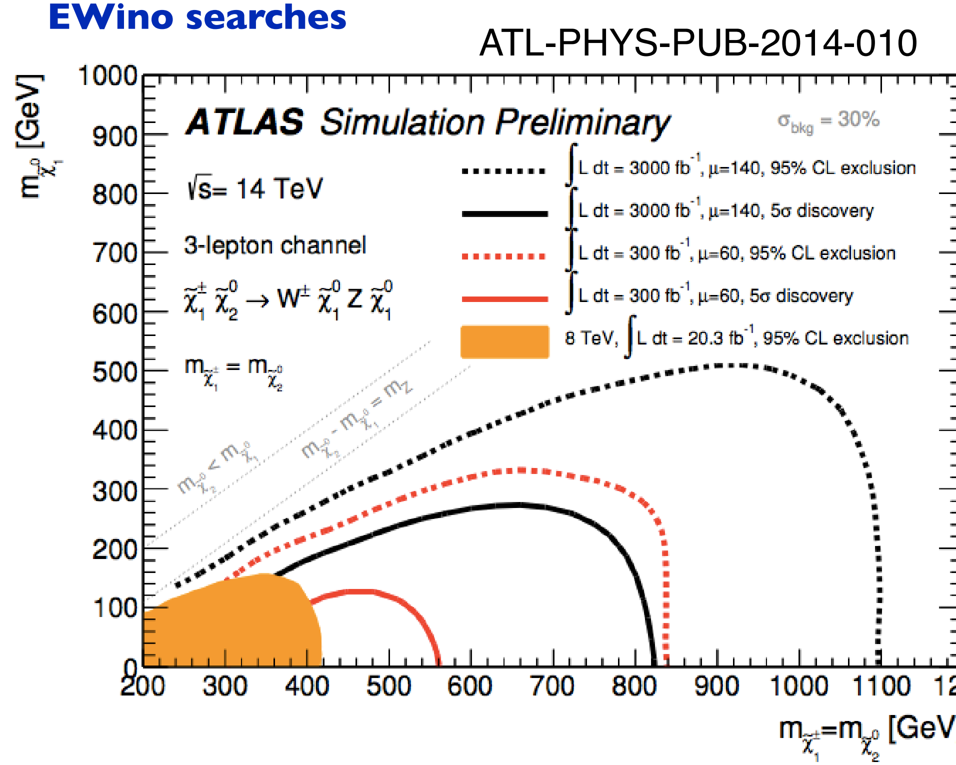
Direct stop searches (ATLAS Snowmass doc)



Direct gluino searches



EWino searches



Message:

- What's been excluded at Lum will not be discovered at 10 x Lum

  ➡ The extension of the discovery reach at high mass is not the key deliverable of HL-LHC

- The gain will come from higher precision, and the skillful use of experience and detector/trigger upgrades to boost sensitivity to rare/elusive processes, beyond the 10x Lumi increase

  ➡ see Tevatron experience:

  - m_W, m_{top}, B_S oscillations ...
  - and with just a bit more of L: $B_S \to \mu^+\mu^-$ and Higgs ....

- *If anything, one could argue that what's needed is $10ab^{-1}$, not $3ab^{-1}$ ....*

Beyond the LHC:
Future Circular Colliders

Dec 2011 ***Latest LHC data corner the Higgs boson to within a small mass window in the 115-130 GeV range***

CERN-OPEN-2011-047
20 January 2012
Version 2.9
arXiv:1112.2518v1 [hep-ex]

A High Luminosity e^+e^- Collider in the LHC tunnel to study the Higgs Boson

Alain Blondel[1], Frank Zimmermann[2]
[1]DPNC, University of Geneva, Switzerland; [2]CERN, Geneva, Switzerland

Abstract: We consider the possibility of a 120x120 GeV e+e- ring collider in the LHC tunnel. A luminosity of 10^{34}/cm^2/s can be obtained with a luminosity life time of a few minutes. A high operation efficiency would require two machines: a low emittance collider storage ring and a separate accelerator injecting electrons and positrons into the storage ring to top up the beams every few minutes. A design inspired from the high luminosity b-factory design and from the LHeC design report is presented. Statistics of about 2x10^4 HZ events per year per experiment can be collected for a Standard Higgs Boson mass of 115-130 GeV.

Summer 2012.

Higgs discovery => submissions to European Strategy Group Symposium

From the upgrade of the accelerator infrastructure in the LHC tunnel .....

LEP3 – Higgs factory in the LHC tunnel

Prepared by Frank Zimmermann, CERN, 9 April 2012; revised on 3 August 2012

CERN-ATS-2012-237

High Energy LHC
Document prepared for the European HEP strategy update

Oliver Brüning, Brennan Goddard, Michelangelo Mangano*, Steve Myers, Lucio Rossi, Ezio Todesco and Frank Zimmerman

CERN, Accelerator & Technology Sector
* CERN, Physics Department

..... to the development of more ambitious goals

EDMS Nr: 1233485
Group reference: CERN/GS-SE 27 July 2012

PRE-FEASIBILITY STUDY FOR AN 80KM TUNNEL PROJECT AT CERN

John Osborne (CERN), Caroline Waaijer (CERN), ARUP, GADZ

LEP3 and TLEP:

High luminosity e^+e^- circular colliders for precise Higgs and other measurements

Alain Blondel (University of Geneva), **John Ellis** (King's College London), **Patrick Janot** (CERN), **Mike Koratzinos** (University of Geneva), **Marco Zanetti** (MIT), **Frank Zimmermann** (CERN)

Fall 2012
The idea caught up …

Accelerators for a Higgs Factory: Linear vs. Circular (HF2012)

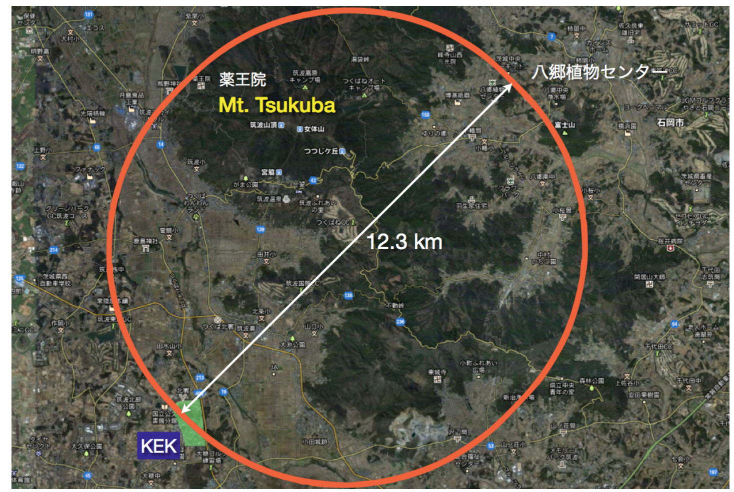
chaired by Weiren Chou (Fermilab)

from Wednesday, November 14, 2012 at **08:00** to Friday, November 16, 2012 at **17:00** (US/Central)
at **Fermilab (One West, Wilson Hall)**
Batavia, IL 60510 USA

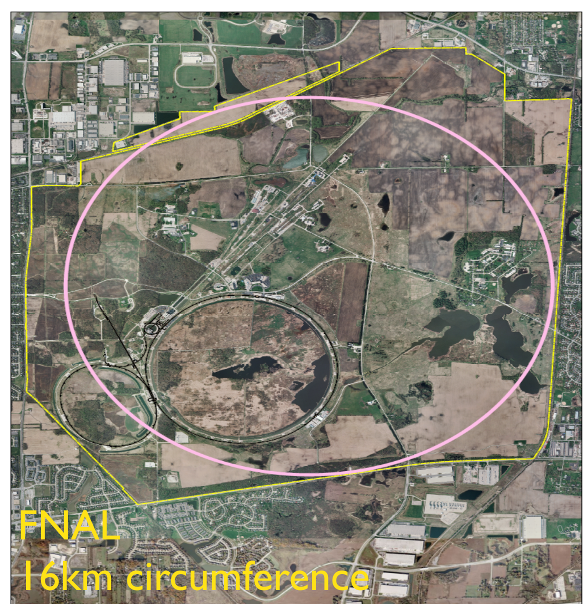
Circular e+e- Higgs Factories
Convener: Dr. Daniel Schulte (CERN)

09:00 **LEP3 and TLEP** *25'*
Speaker: Dr. Frank Zimmermann (CERN)
Material: Slides

09:40 **SuperTristan** *15'*
Speaker: Dr. Katsunobu Oide (KEK)
Material: Slides

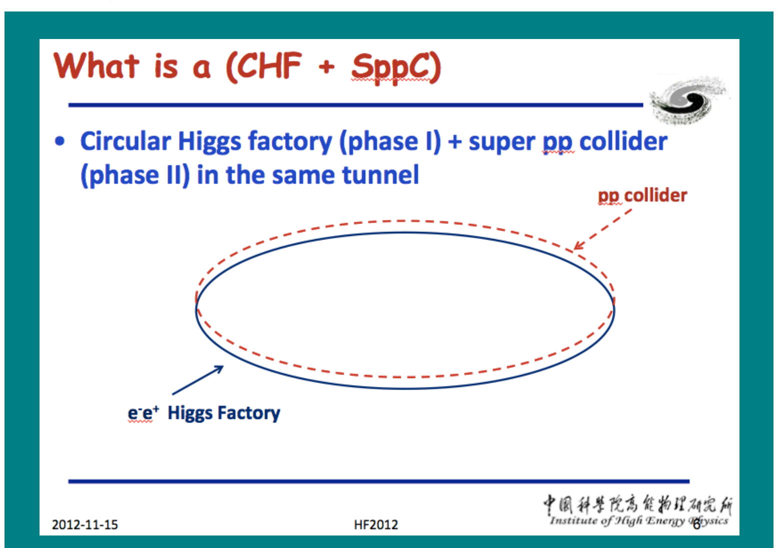


10:05 **Fermilab Site Filler** *15'*
Speaker: Dr. Tanaji Sen (Fermilab)
Material: Slides



10:30 **Coffee Break** *30'*

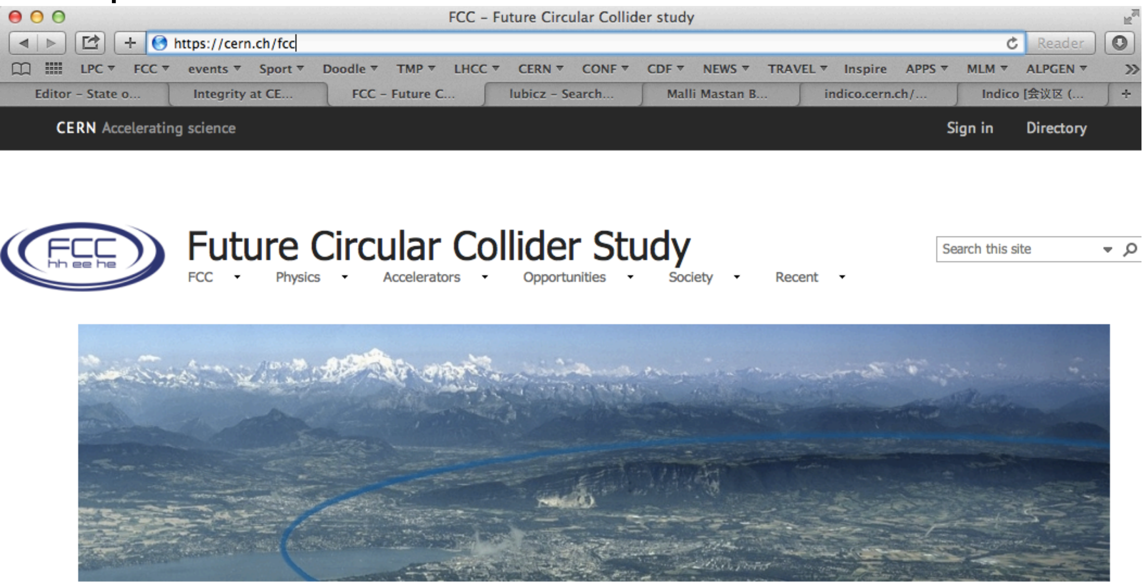
11:00 **IHEP Higgs Factory** *15'*
Speaker: Dr. Qing QIN (IHEP)
Material: Slides



Final report:
http://www-bd.fnal.gov/icfabd/HF2012.pdf

… and two efforts are formalized and develop into studies towards Conceptual Design Reports

http://cern.ch/fcc



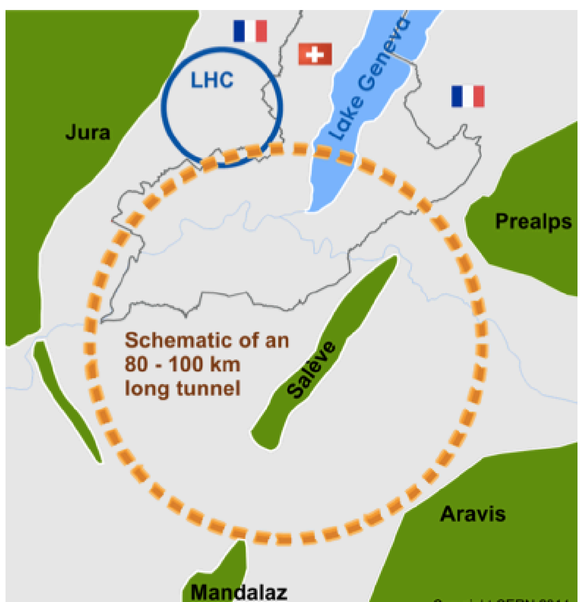
http://cepc.ihep.ac.cn

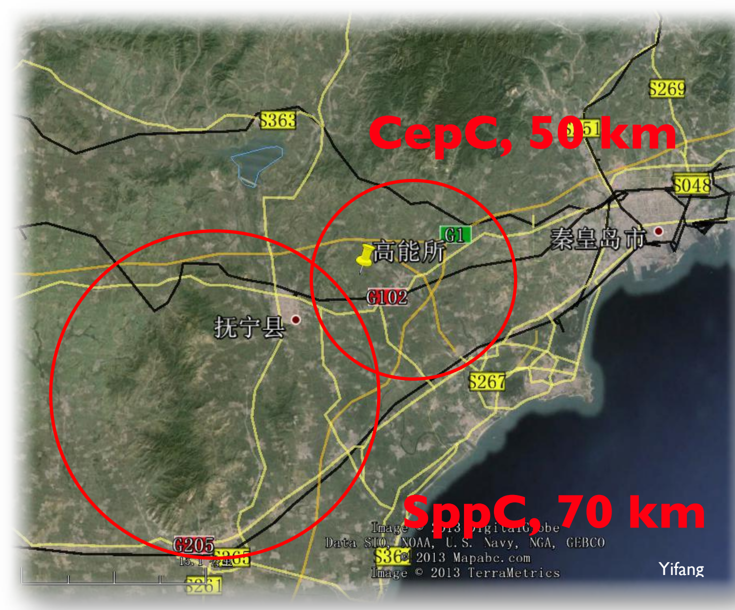
Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)** → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- ***e⁺e⁻* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area






Future Circular Collider Study Kickoff Meeting (12-15 February 2014)
indico.cern.ch/event/282344/
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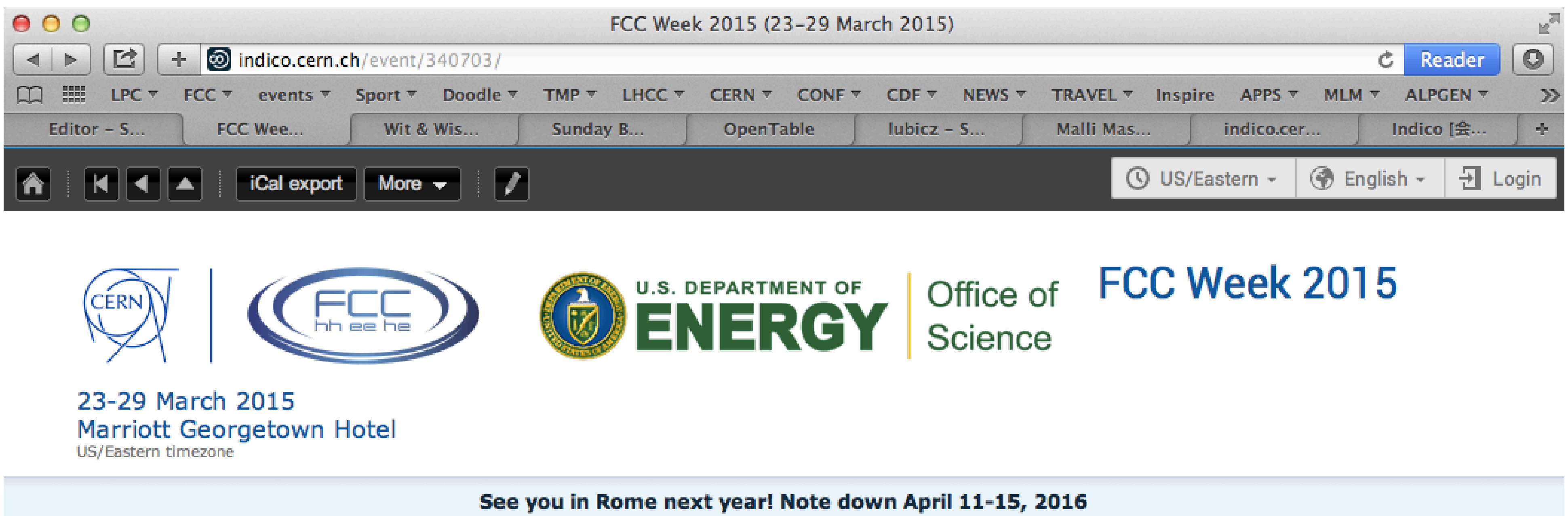
Search
There is a live webcast for this event.
Future Circular Collider Study Kickoff Meeting


FCC Week 2015 (23-29 March 2015)
indico.cern.ch/event/340703/
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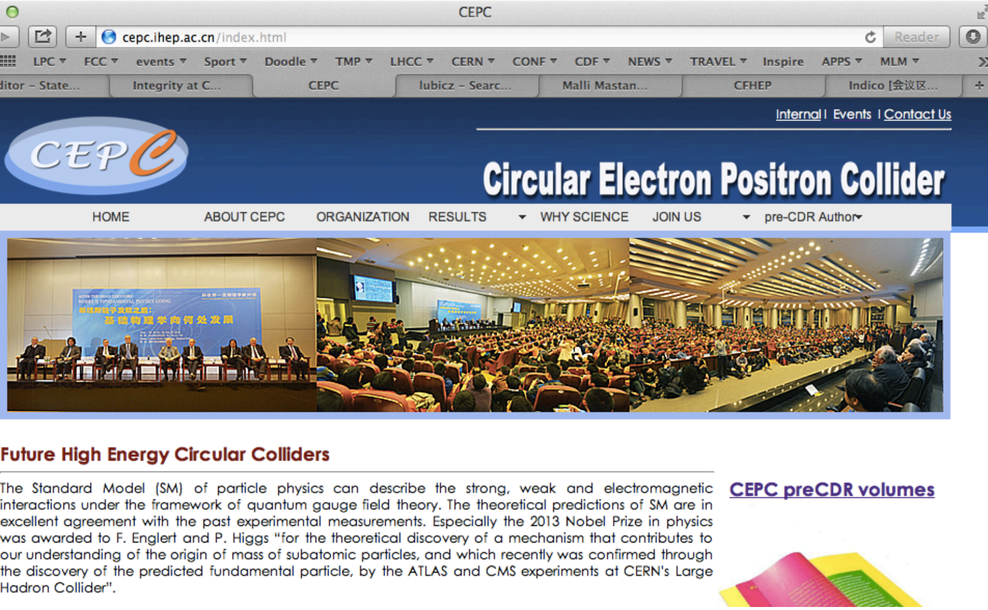
Office of Science
FCC Week 2015
23-29 March 2015
Marriott Georgetown Hotel
US/Eastern timezone
See you in Rome next year! Note down April 11-15, 2016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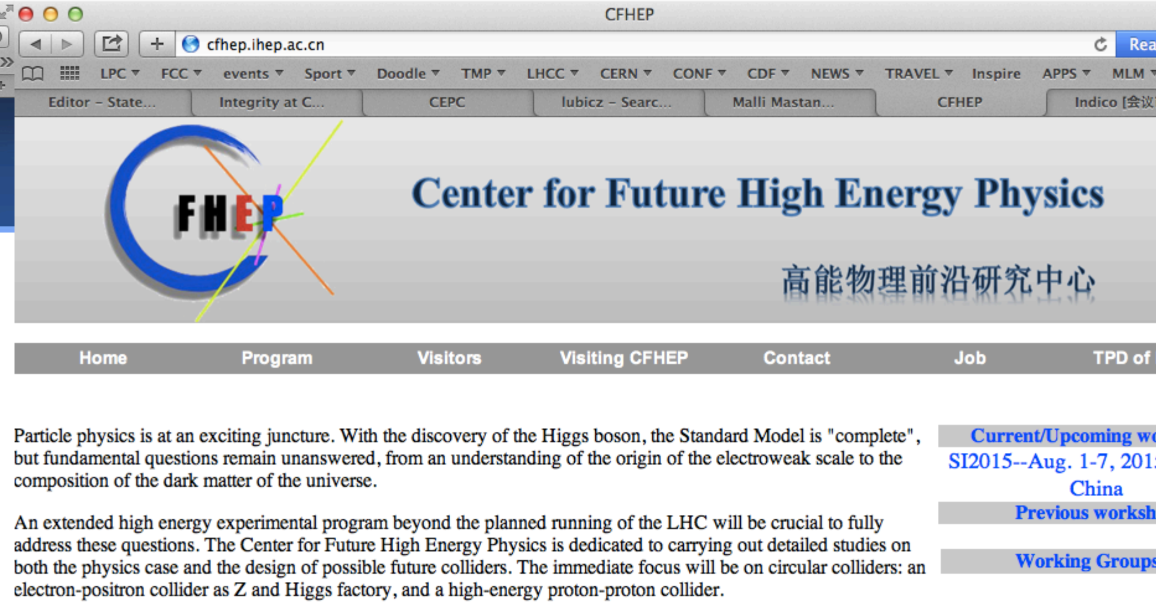
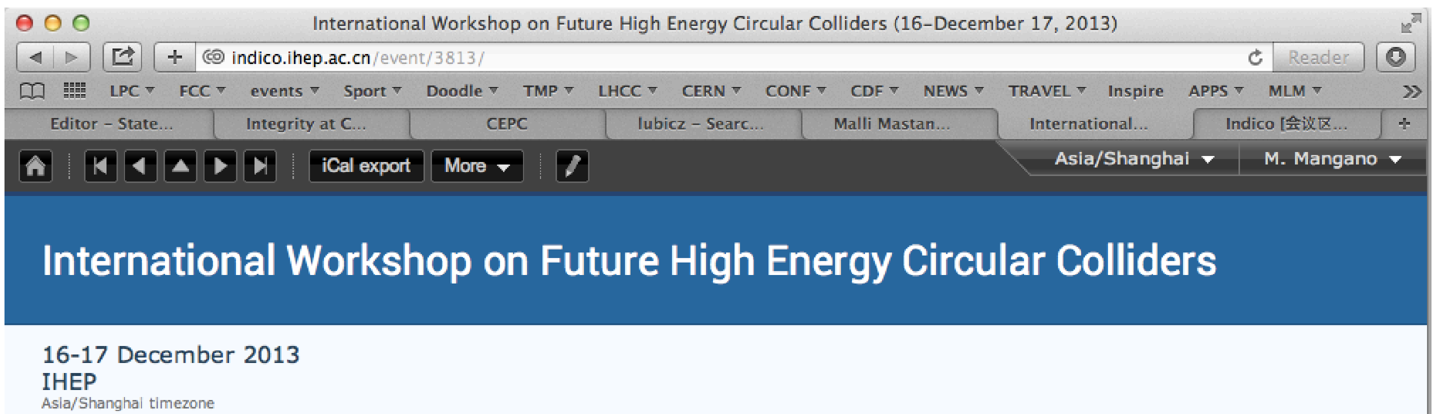
Circular Electron Positron Collider
HOME ABOUT CEPC ORGANIZATION RESULTS WHY SCIENCE JOIN US pre-CDR Author
Future High Energy Circular Colliders
The Standard Model (SM) of particle physics can describe the strong, weak and electromagnetic interactions under the framework of quantum gauge field theory. The theoretical predictions of SM are in excellent agreement with the past experimental measurements. Especially the 2013 Nobel Prize in physics was awarded to F. Englert and P. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".
CEPC preCDR volumes


CFHEP
cfhep.ihep.ac.cn
FHEP
Center for Future High Energy Physics
高能物理前沿研究中心
Home Program Visitors Visiting CFHEP Contact Job TPD of
Particle physics is at an exciting juncture. With the discovery of the Higgs boson, the Standard Model is "complete", but fundamental questions remain unanswered, from an understanding of the origin of the electroweak scale to the composition of the dark matter of the universe.
An extended high energy experimental program beyond the planned running of the LHC will be crucial to fully address these questions. The Center for Future High Energy Physics is dedicated to carrying out detailed studies on both the physics case and the design of possible future colliders. The immediate focus will be on circular colliders: an electron-positron collider as Z and Higgs factory, and a high-energy proton-proton collider.
Current/Upcoming w
SI2015--Aug. 1-7, 201
China
Previous worksh
Working Group


International Workshop on Future High Energy Circular Colliders (16–December 17, 2013)
indico.ihep.ac.cn/event/3813/
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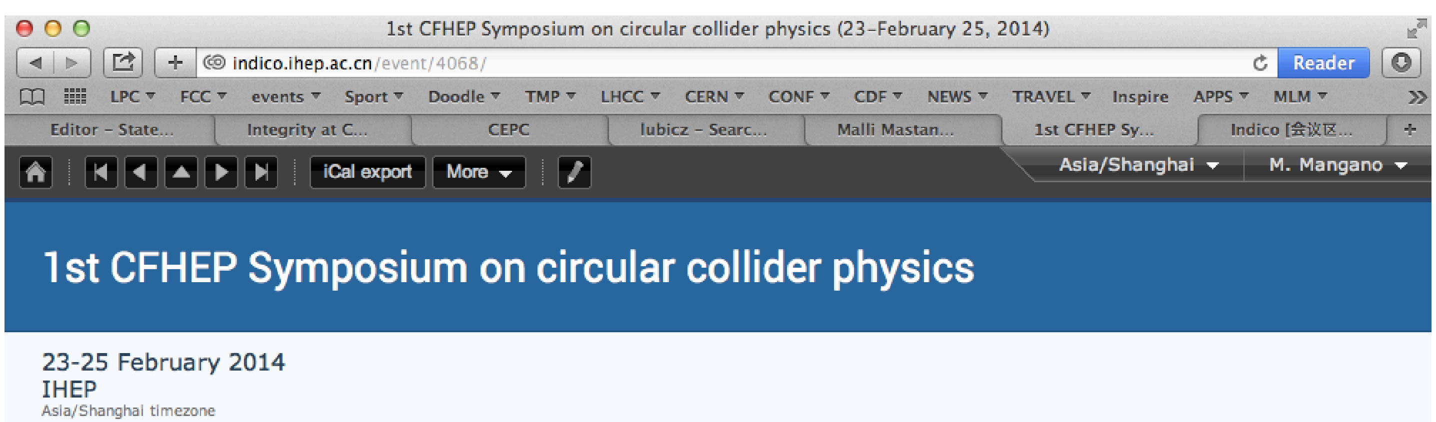
Asia/Shanghai
M. Mangano
International Workshop on Future High Energy Circular Colliders
16-17 December 2013
IHEP
Asia/Shanghai timezone


1st CFHEP Symposium on circular collider physics (23–February 25, 2014)
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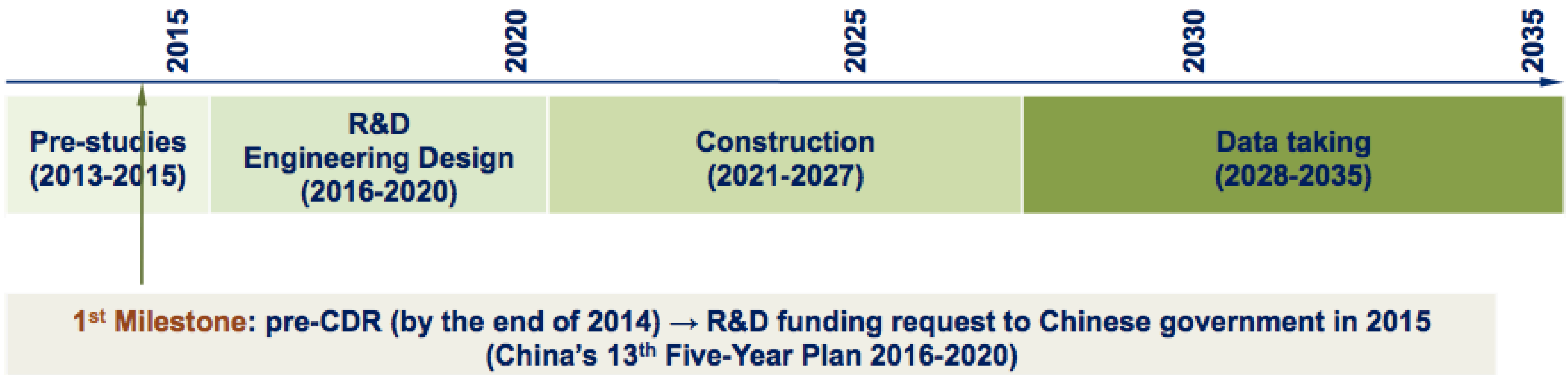
1st CFHEP Symposium on circular collider physics
23-25 February 2014
IHEP
Asia/Shanghai timezone

Project Timeline

CEPC



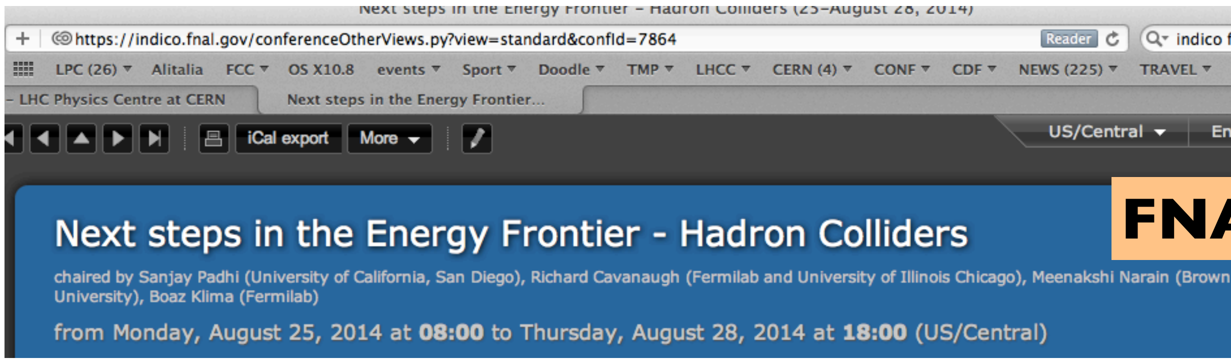
SppC

Preliminary Conceptual Design Reports from:
http://cepc.ihep.ac.cn/preCDR/volume.html
- Vol 2: Accelerator (ready)
- Vol 1: Physics and detectors (any day soon ....)

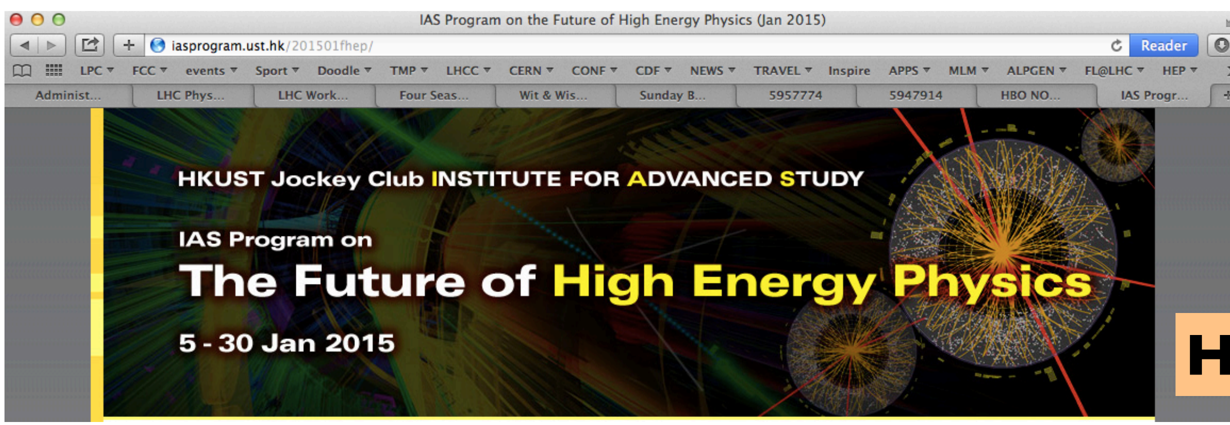
Physics workshops spontaneously organized all over the world document better than anything else the physics results, and the interest of the community ....

SLAC

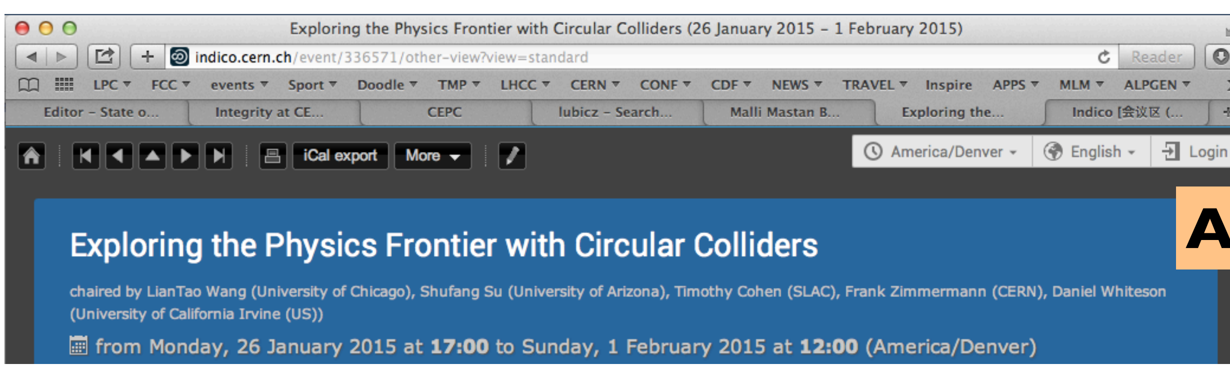
FNAL



Hong Kong



Aspen



The big questions

- **What's the origin of Dark matter / energy ?**
- **What's the origin of matter/antimatter asymmetry in the universe?**
- **What's the origin of neutrino masses?**
- **What's the origin of EW symmetry breaking?**
- **What's the solution to the hierarchy problem?**
- **...**

Remark:

there is no experiment/facility, proposed or conceivable, in the lab or in space, accelerator or non-accelerator driven, which will guarantee an answer to any of the questions above

$\Rightarrow$

- target broad and well justified scenarios
- consider the potential of given facilities to provide conclusive answers to relevant (*and answerable!*) questions
  - can we identify forms of *no-lose theorems ?*
- weigh the value of knowledge that will be acquired, no matter what, by a given facility (*the value of "measurements"*)

Most of the "big questions" touch directly on weak scale physics.

There are relevant, well defined questions, whose answer can be found exploring the TeV scale, and which can help guide the evaluation of the future colliders. E.g.

- **Dark matter**
  - is TeV-scale dynamics (e.g. WIMPs) at the origin of Dark Matter ?
- **Baryogenesis**
  - did it arise at the cosmological EW phase transition ?
- **EW Symmetry Breaking**
  - what's the underlying dynamics? weakly interacting? strongly interacting ? other interactions, players at the weak scale besides the SM Higgs ?
- **Hierarchy problem**
  - "natural" solution, at the TeV scale?

Key issue in addressing these questions, after LHC8
(and, hopefully not, but possibly after LHC14)

Why don't we see the new physics ?

- **Is the mass scale beyond the LHC reach ?**

- **Is the mass scale within LHC's reach, but final states are elusive to the direct search ?**

These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

Readiness to address both scenarios is the best hedge for the field:

- *precision*
- *sensitivity (to elusive signatures)*
- *extended energy/mass reach*

Key goals of a future circular collider complex

- Thorough **measurements** of the Higgs boson and its dynamics
- Significant extension, via direct and indirect probes, of the **search** for physics phenomena beyond the SM

Fulfilling these goals will also require dedicated attention to crucial ingredients, such as

- *the progress of theoretical calculations for precision physics*
- *the experimental data needed to improve the knowledge of fundamental inputs such as SM parameters, PDFs and to assess/reduce theoretical systematics*
  - *relevance of running* e^+e^- *at Z pole and tt threshold*
  - *relevance of ep programme*

- Maximal exploitation of the facility, e.g.
  - *physics with heavy ion collisions*
  - *physics with the injector complex*

Reference literature

NB: click on underlined documents to access relevant URLs

- **FCC-ee**: "First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164
- **FCC-eh**: no document as yet, see however
  - "A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector", J.Phys. G39 (2012) 075001
- **FCC-hh**: no document as yet (in progress, expected by end of 2015)
- **CEPC/SPPC**: Physics and Detectors pre-CDR completed, to be posted soon on
  - http://cepc.ihep.ac.cn/preCDR/volume.html

See also:

- Physics Briefing Book to the European Strategy Group (ESG 2013)
- Planning the Future of U.S. Particle Physics (Snowmass 2013): Chapter 3: Energy Frontier, arXiv:1401.6081

Higgs couplings programme

- Precise measurement of main Higgs couplings:
  - W,Z bosons, 3rd generation fermions (⇒probe existence of BSM effective couplings, e.g. due to non-elementary nature of H, determine CP properties, etc.)
- Couplings to 2nd and 1st generation (⇒universality of Higgs mass-generation mechanism)
- Higgs selfcouplings (⇒probe Higgs potential, to test possible underlying structure of Higgs, deviations from "mexican hat", etc)
- Couplings to non-SM objects (e.g. invisible decays)
- non-SM couplings (e.g. forbidden decays)

Projections

g_{HXY}	FCC-ee
ZZ	0.16%
WW	0.85%
γ γ	1.7%
Zγ	
tt	
bb	0.88%
τ τ	0.94%
cc	1.0%
ss	
μμ	6.4%
uu,dd	
ee	
HH	
BR_{exo}	0.48%

model indep. fit of 240 GeV data

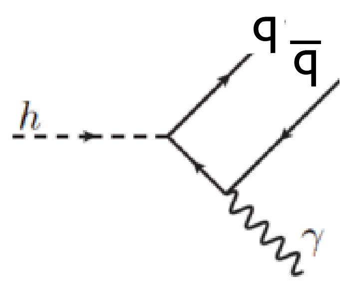
$H \to J/\Psi\, \gamma$ → y_c

$H \to \phi\, \gamma$ → y_s

50 evts

$H \to \rho\, \gamma$

$H \to \omega\, \gamma$ → y_u, y_d



$e^+e^- \to H$

L = 10 ab^{-1}

$\kappa_e < 2.2$ at 3σ

Projections

g_{HXY}	FCC-ee
ZZ	0.16%
WW	0.85%
γ γ	1.7%
Zγ	
tt	
bb	0.88%
τ τ	0.94%
cc	1.0%
ss	H→Vγ, in progr.
μμ	6.4%
uu,dd	H→Vγ, in progr.
ee	e^+e^-→H, in progr.
HH	
BR_{exo}	0.48%

model indep. fit of 240 GeV data

Projections

	σ	N / 10ab^{-1}
gg→H	740 pb	7.4 G
VBF	82 pb	0.8 G
WH	16 pb	160 M
ZH	11 pb	110 M
ttH	38 pb	380 M
gg→HH	1.4 pb	14 M

g_{HXY}	FCC-ee	FCC-hh	
ZZ	0.16%		
WW	0.85%		
γ γ	1.7%		
Zγ		1% ?	→ extrapolation from HL-LHC estimates
tt		1% ?	→ from ttH/ttZ
bb	0.88%		
τ τ	0.94%		
cc	1.0%		
ss	H→Vγ, in progr.		
μμ	6.4%	2% ?	→ extrapolation from HL-LHC estimates
uu,dd	H→Vγ, in progr.		
ee	e^+e^-→H, in progr.		
HH		5% ?	→ from HH → bb γγ
BR_{exo}	0.48%	< 10^{-6} ?	→ for specific channels, like H→eμ, ...

FCC-hh ambitious but possible targets?

Higgs selfcouplings: pp→HH

- gg→HH (most promising?) , qq→HHqq (via VBF)
- Reference benchmark process: HH→bb γγ
- Goal: 5% (or better) precision for SM selfcoupling

$HH \to b\bar{b}\gamma\gamma$	Barr,Dolan,Englert,Lima, Spannowsky JHEP 1502 (2015) 016	Contino, Azatov, Panico, Son arXiv:1502.00539	He, Ren, Yao (follow-up of Snowmass study)
FCC$_{@100\text{TeV}}$ 3/ab	30~40%	30%	15%
FCC$_{@100\text{TeV}}$ 30/ab	10%	10%	5%
$S/\sqrt{B}$	8.4	15.2	16.5
Details	✓ λ_{HHH} modification only ✓ $c \to b$ & $j \to \gamma$ included ✓ Background systematics ○ $b\bar{b}\gamma\gamma$ not matched ✓ $m_{\gamma\gamma} = 125 \pm 1$ GeV	✓ Full EFT approach ○ No $c \to b$ & $j \to \gamma$ ✓ Marginalized ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 5$ GeV ✓ Jet /W_{had} veto	✓ λ_{HHH} modification only ✓ $c \to b$ & $j \to \gamma$ included ○ No marginalization ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 3$ GeV

Work in progress to compare studies, harmonize performance assumptions, optimize, etc
⇒ ideal benchmarking framework

M.Son, HH summary at FCC week

ttH/ttZ

- Potential % theory precision for ttH coupling
- Goal: % level exptl precision $\Rightarrow$ > 10 K events

ttH (pb)	ttZ (pb)	ttH/ttZ
33.9 $[^{+7.06\%}_{-8.29\%}]$Scale $[^{+0.941\%}_{-1.26\%}]$PDF	57.9 $[^{+8.93\%}_{-9.46\%}]$Scale $[^{+0.901\%}_{-1.20\%}]$PDF	0.585 $[^{+1.29\%}_{-2.02\%}]$Scale $[^{+0.0526\%}_{-0.0758\%}]$PDF

- reference benchmark procs: H→bb and H→γγ
- establish requirements to cancel exptl syst's in ratios ttH/ttZ

tt + (H→γγ): b tagging, lept eff/acc, γ eff, $m_{\gamma\gamma}$, ...

$$
\begin{aligned}
p_{T,j} &> 25 \text{ GeV}, |\eta_j| < 2.5, \\
p_{T,b} &> 25 \text{ GeV}, |\eta_b| < 2.5, \\
p_{T,\gamma} &> 25 \text{ GeV}, |\eta_\gamma| < 2.5, \\
120 \text{ GeV} &< m_{\gamma\gamma} < 130 \text{ GeV}, \\
p_{T,\ell^\pm/\tau^\pm} &> 20 \text{ GeV}, |\eta_{\ell^\pm/\tau^\pm}| < 2.5, \\
E_{T,\text{miss}} &> 20 \text{ GeV}, \\
\Delta R_{jj} > 0.4, \Delta R_{bj} &> 0.4, \Delta R_{bb} > 0.4.
\end{aligned}
$$

In 30ab^{-1}

~**100K** (semi-)leptonic ttH signal events

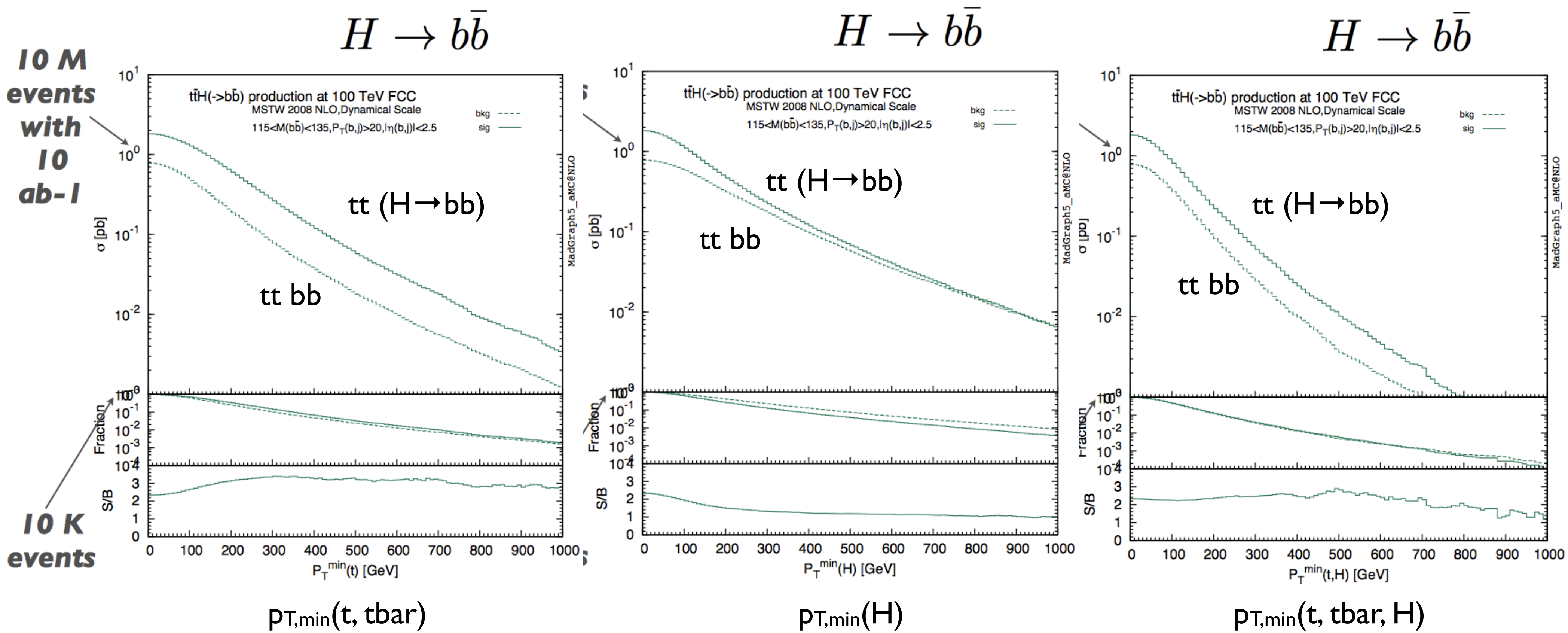
~**12K** irreducible bg (ttγγ)

(H-S Shao, preliminary, H&BSM@100 TeV wshop)

ttH/ttZ

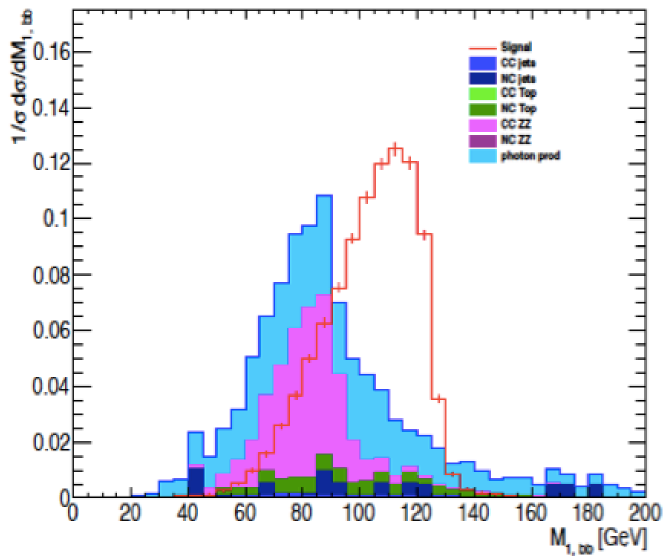
tt + (H→bb): b tagging in boosted configurations, lept eff/acc, m_{bb}, ...

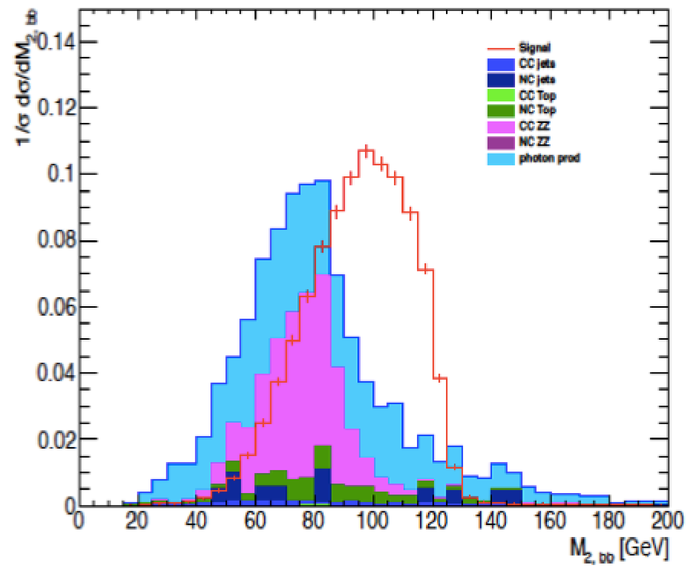
115<M($b\bar{b}$)<135,P_T(b,j)>20,|η(b,j)|<2.5

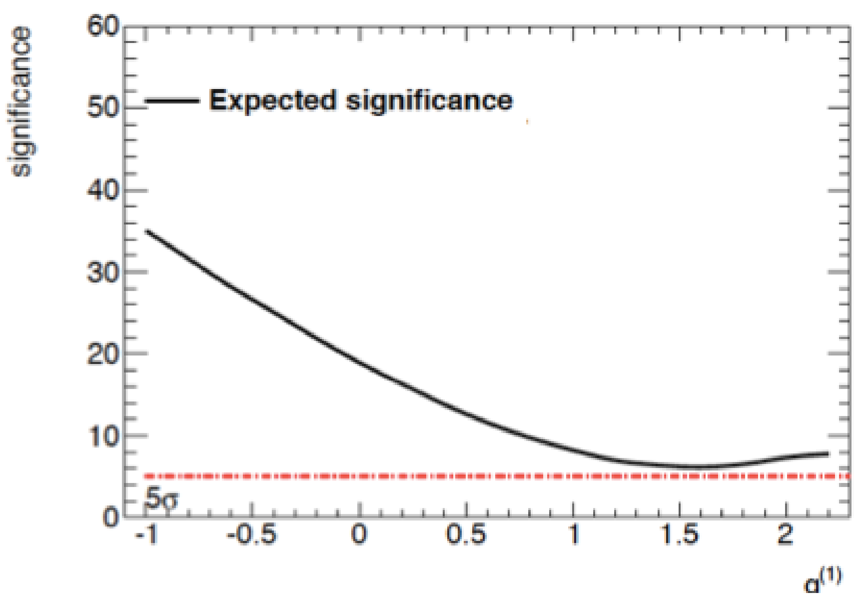


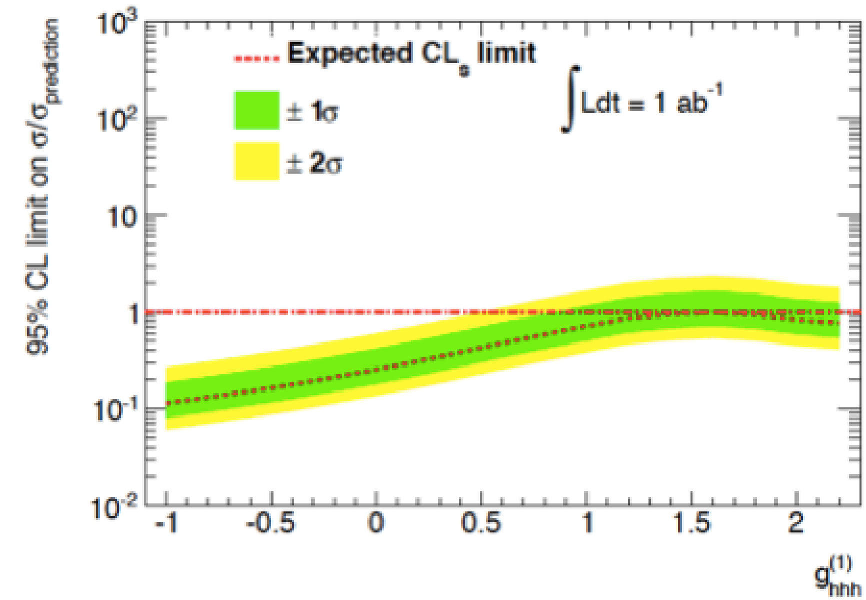
(H-S Shao, preliminary, H&BSM@100 TeV wshop)

HH→4b reconstruction in FCC-eh



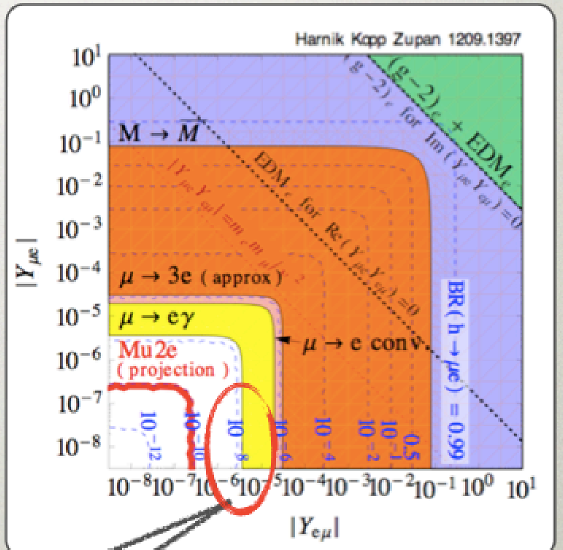






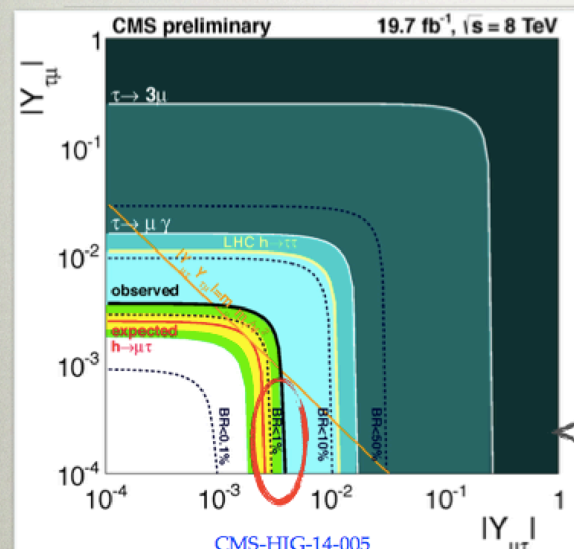
$h \to \mu e$

- indirect bounds better than LHC
- $h \to \mu e$ very clean channel



- what can one do with 10^9 Higgses @100TeV?

$h \to \tau\mu$



- right now: 2j channel statistics limited, 0j+1j not
- how about with ~10^9 h? **LHC8 ⇒ 100 TeV 3 ab^{-1}**
- assume same scaling for signal and bckg
  - $Br \sim 10^{-2} \Rightarrow Br \sim 10^{-4}$
  - $\Lambda \sim 0.2$ TeV $\Rightarrow \Lambda \sim 2$TeV
- if bckg free
  - $Br \sim 10^{-2} \Rightarrow Br \sim 10^{-6}$
  - $\Lambda \sim 0.2$ TeV $\Rightarrow \Lambda \sim 20$TeV ($Y_{\mu\tau} Y_{\tau\mu} = m_\mu m_\tau / \Lambda^2$)

FCC week, Mar 26 2015, Washington DC

BSM Higgs Sectors

D.Curtin @ FCC week

Big Picture Motivations

- Naturalness
  - SUSY
  - pGB
  - uncolored?
- Electroweak Phase Transition
  - Baryogenesis?
- Higgs Portal
  - Dark Matter?
  - *Generic BSM*

IR Models

- SM+S (mixed/unmixed)
- SM+fermions
- 2HDM
- 2HDM+S
- SILH
- ....

UV Completions & Rest of Theory

Observables at Current + Future Colliders

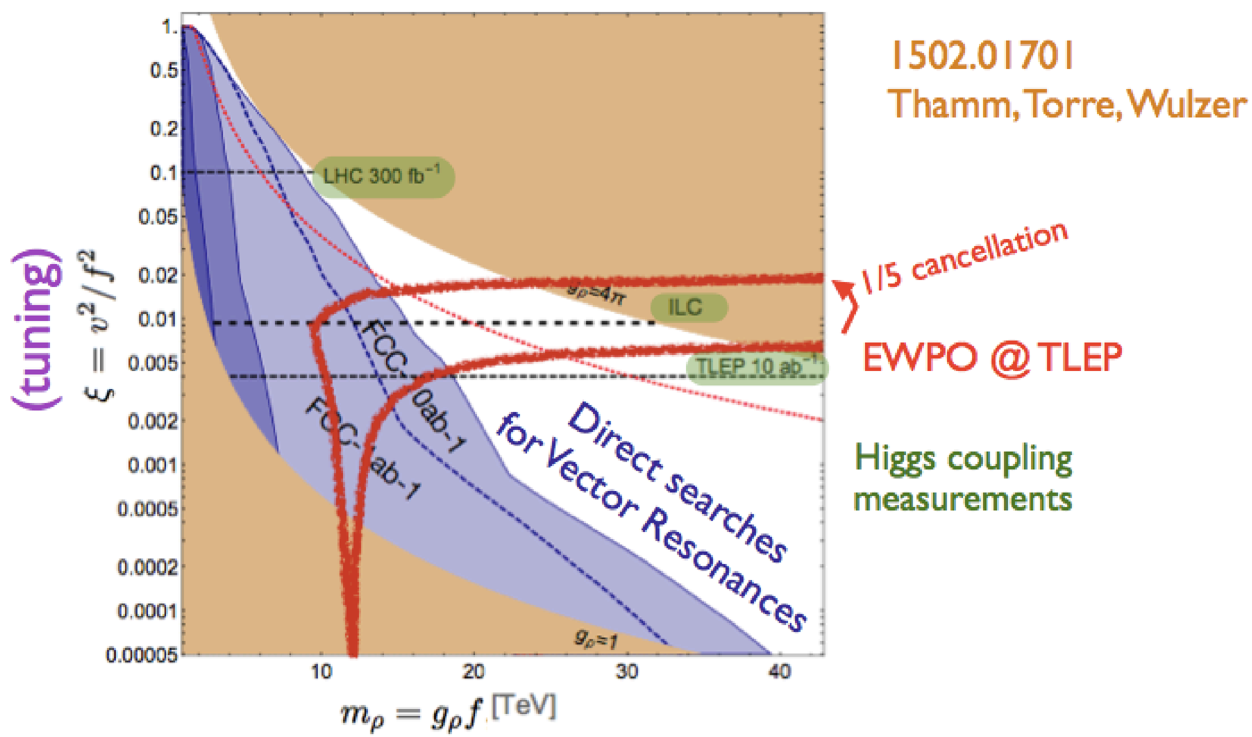
- producing extra higgs states (incl. superpartners)
- Exotic Higgs Decays
- Electroweak Precision Observables
- Higgs coupling measurements
- Higgs portal direct production of new states
- Higgs self coupling measurements
- Zh cross section measurements

Composite Higgs Models

D.Curtin @ FCC week

Want Lepton colliders to probe Higgs coupling deviations & EWPO

Want 100 TeV to produce vector resonances of strongly coupled sector (as well as top partners)



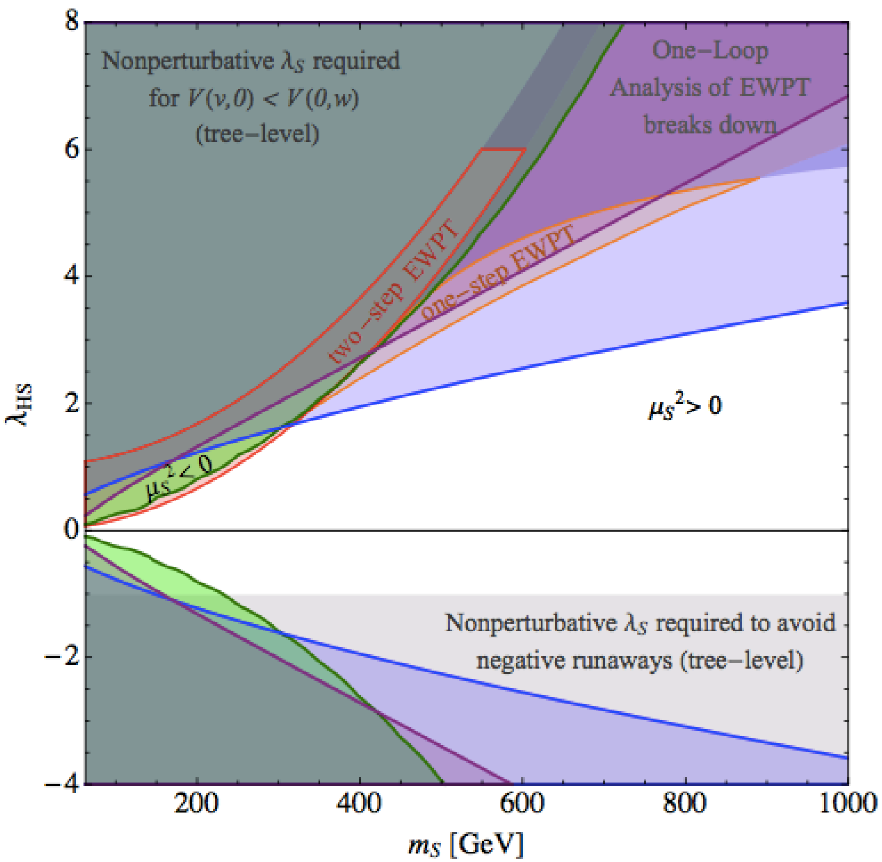
Interplay of EW precision tests (Tera-Z@FCC-ee), Higgs BR measurements (H@FCC-ee) and direct resonance searches (10-30 TeV, @ FCC-hh)

Minimal stealthy model for a strong EWPT

$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4$$

D.Curtin @ FCC week

Unmixed SM+S. No exotic higgs decays, no higgs-singlet mixing, no EWPO, ...



Two regions with strong EWPT

Only Higgs Portal signatures:

- $h^* \to SS$ direct production
- Higgs cubic coupling
- $\sigma(Zh)$ deviation (> 0.6% @ TLEP)

100 TeV collider could cover *entire* parameter space.

TLEP (super ILC) can cover *some* of parameter space.

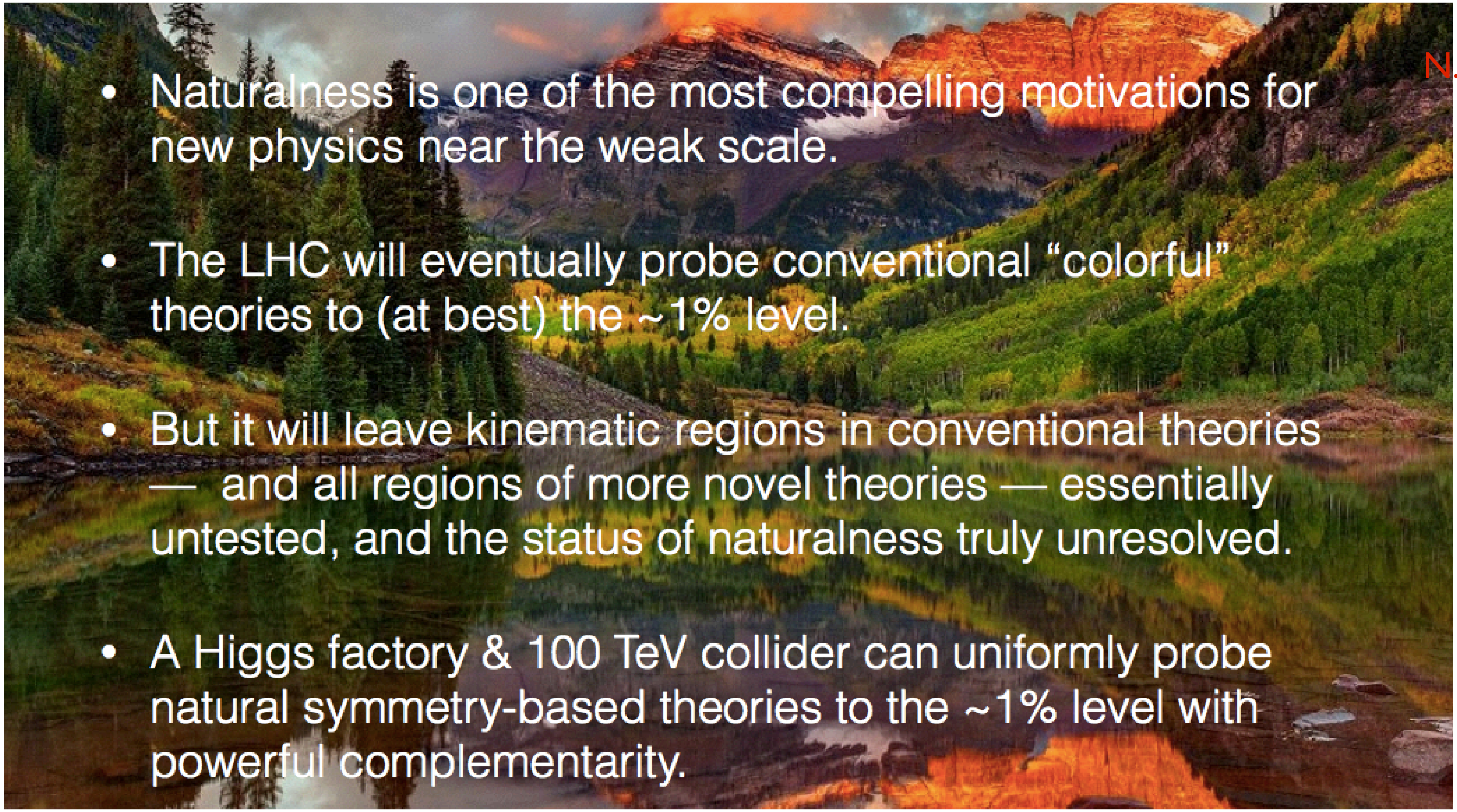
Potential complimentarily!

1409.0005 DC, Patrick Meade, Tien-Tien Yu

⇒ Appearance of first "**no-lose**" arguments for classes of compelling scenarios of new physics

Scenarios for new physics

- Guidelines for the future
  - Search for all that's searchable!
  - Don't necessarily try to tie together under a single interpretation all TH issues and exptl puzzles ....
  - .... but still make reference to established conceptual frameworks as guiding principles to steer the exploration!



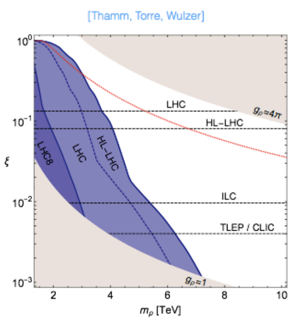
N.Craig @ FCC week

Colorful naturalness

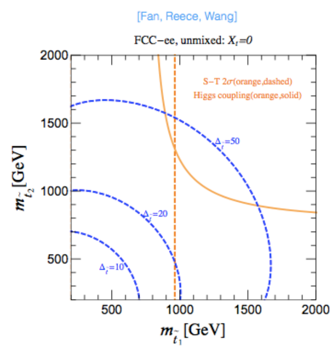
Probing at a Higgs factory:

Look for **O**(loop*v/m) [SUSY] or **O**(v/f) [global] Higgs coupling deviations; precision electroweak corrections.

[Thamm, Torre, Wulzer]



[Fan, Reece, Wang]



Where we'll be @ Higgs factory:
Sensitive to kinematic holes at LHC.

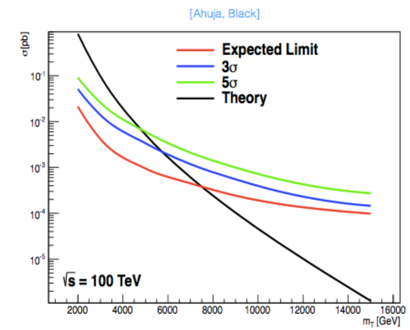
~1-2% level

Colorful naturalness

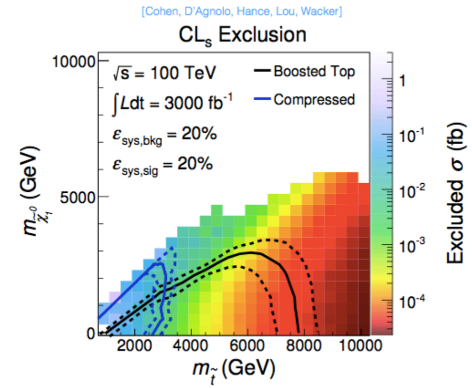
Probing at 100 TeV:

Look for the light partner states

[Ahuja, Black]

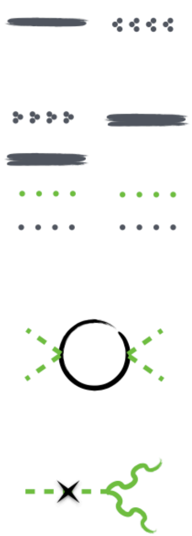


[Cohen, D'Agnolo, Hance, Lou, Wacker]



Where we'll be @ 100 TeV: "generically"

~.05% level

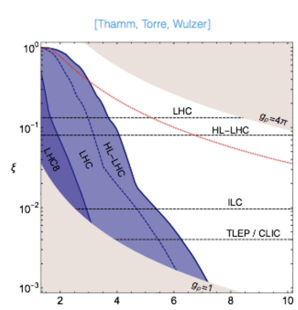


Neutral naturalness

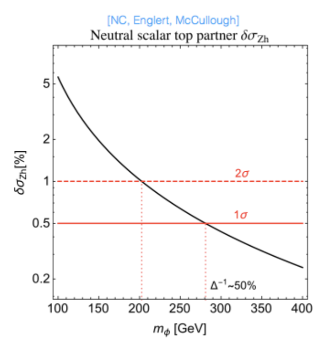
Probing at a Higgs factory:

Look for **O**(loop*v/m) oblique [SUSY] or **O**(v/f) [global] Higgs coupling deviations.

[Thamm, Torre, Wulzer]



[NC, Englert, McCullough]



Where we'll be @ Higgs factory:

~1% level (global)
~50% level (SUSY)

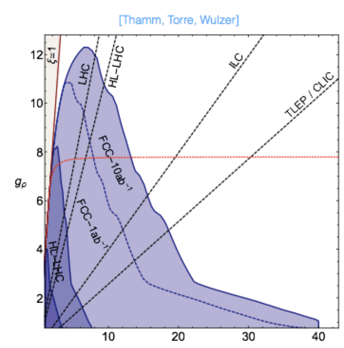
Even if the light natural states are neutral, there are heavier states with SM charges

Neutral naturalness

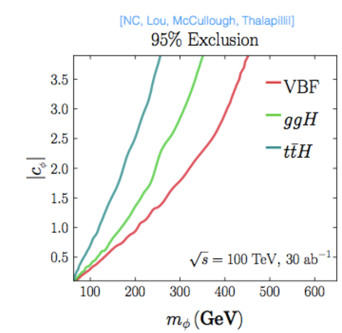
Probing at 100 TeV

Look for the UV completion, or probe light states via the Higgs portal.

[Thamm, Torre, Wulzer]



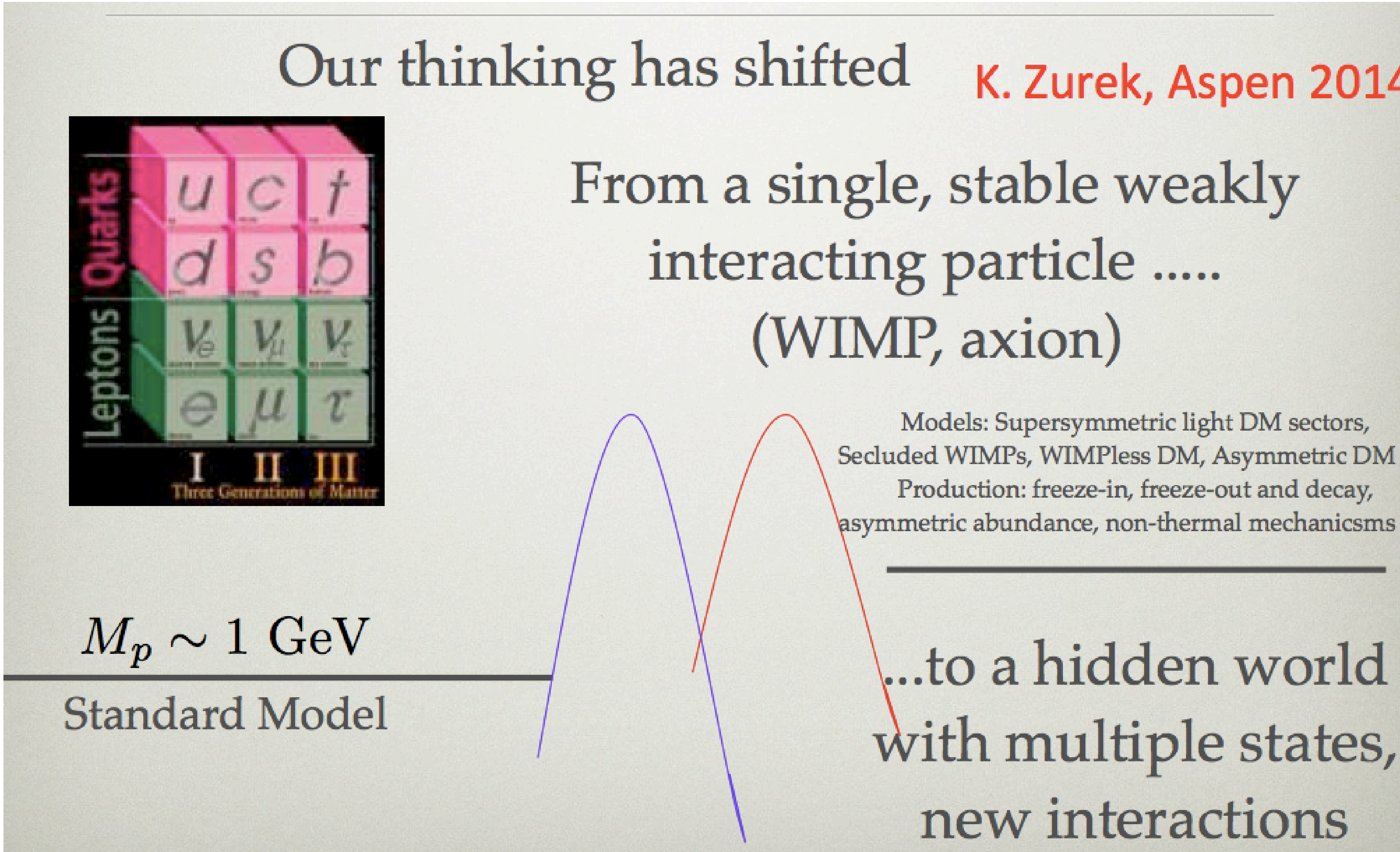
[NC, Lou, McCullough, Thalapillil]



Where we'll be @ 100 TeV:

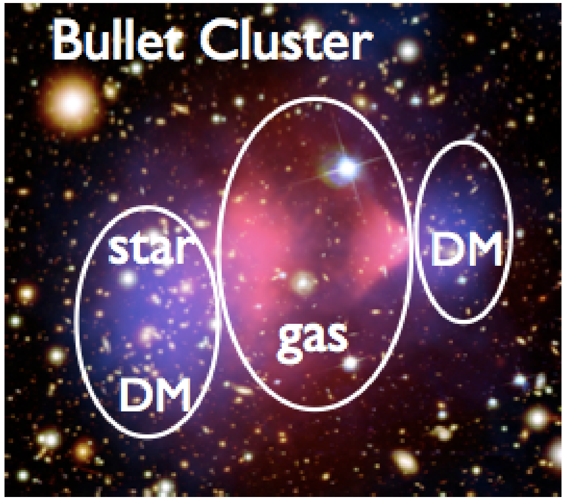
~1% level

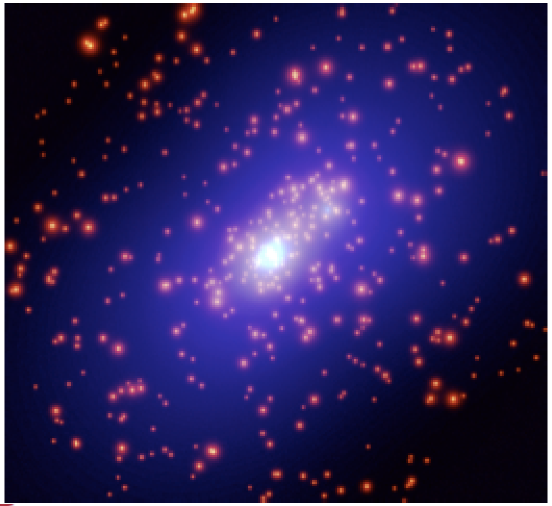
Dark Matter



ASPEN 2014: https://indico.cern.ch/event/276476/

Evidence building up for self-interacting DM





- A really large scattering cross section!

a nuclear-scale cross section

$\sigma \sim 1\,\mathrm{cm}^2\,(m_X/\mathrm{g}) \sim 2\times10^{-24}\,\mathrm{cm}^2\,(m_X/\mathrm{GeV})$

For a WIMP: $\sigma \sim 10^{-38}\,\mathrm{cm}^2\,(m_X/100\,\mathrm{GeV})$

SIDM indicates a new mass scale

Hai-Bo Yu, ASPEN 2014:
https://indico.cern.ch/event/276476/

More in general, interest is growing in scenarios for EWSB with rich sectors of states only coupled to the SM particles via <u>weakly interacting</u> "portals"

DM overclosure upper limits:

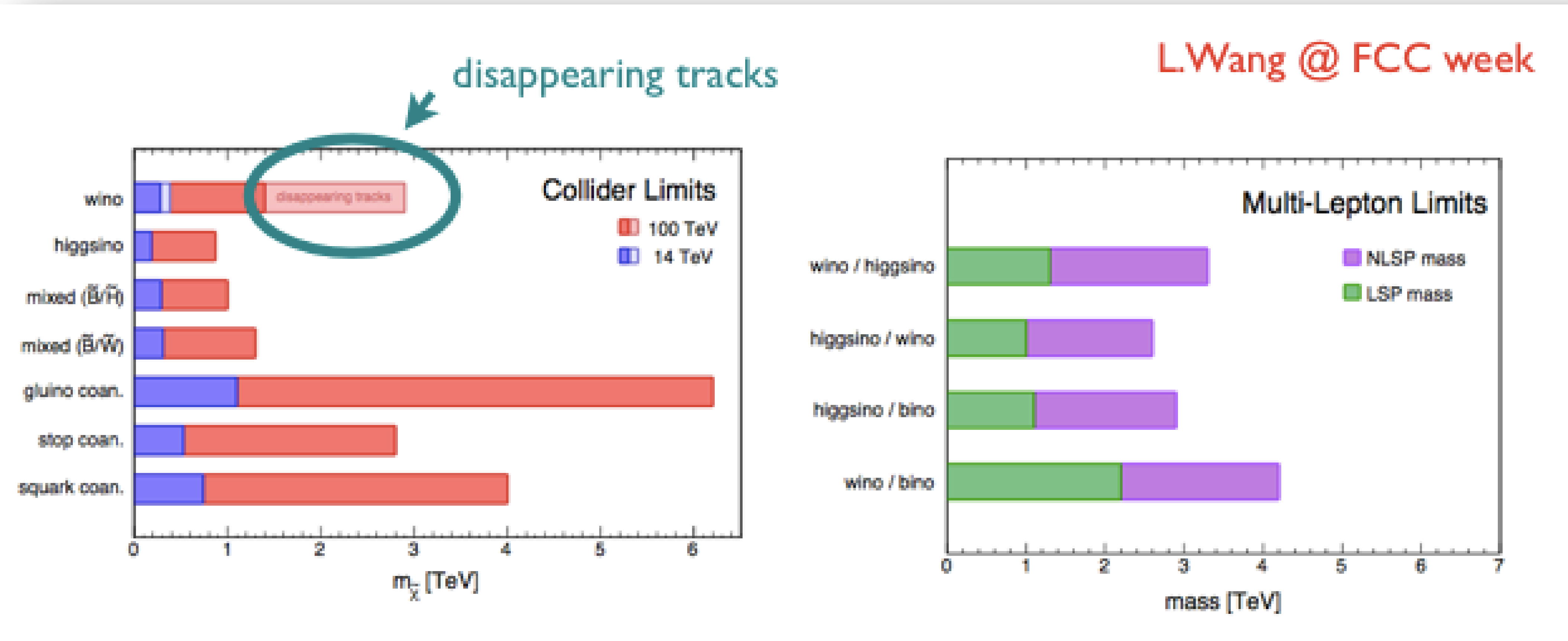
$M_{WIMP} < 1.8\,\text{TeV}\,(g^2/0.3) \Rightarrow$

wino: m≲3 TeV

higgsino: m≲1.1 TeV

In anomaly-mediated SUSY or split SUSY ⇒

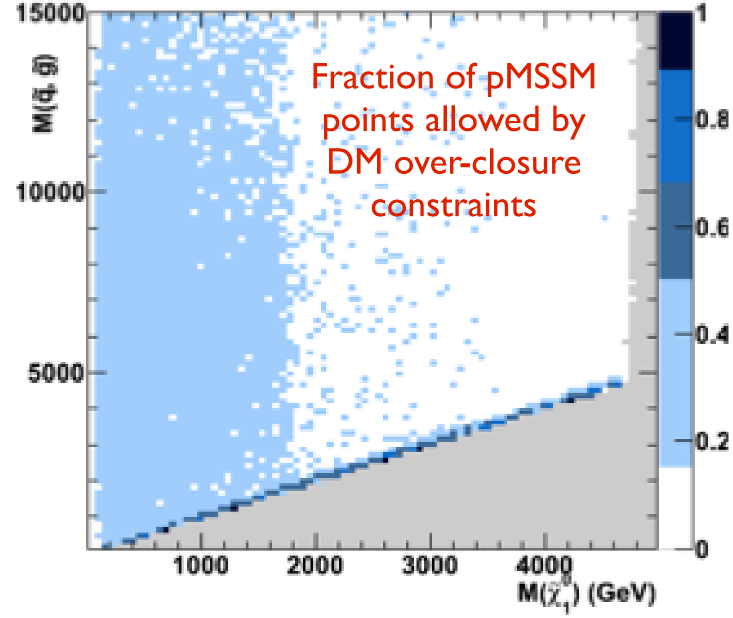
$m_{gluino} \lesssim$ 10 TeV



Towards no-lose arguments for Dark Matter scenarios .....

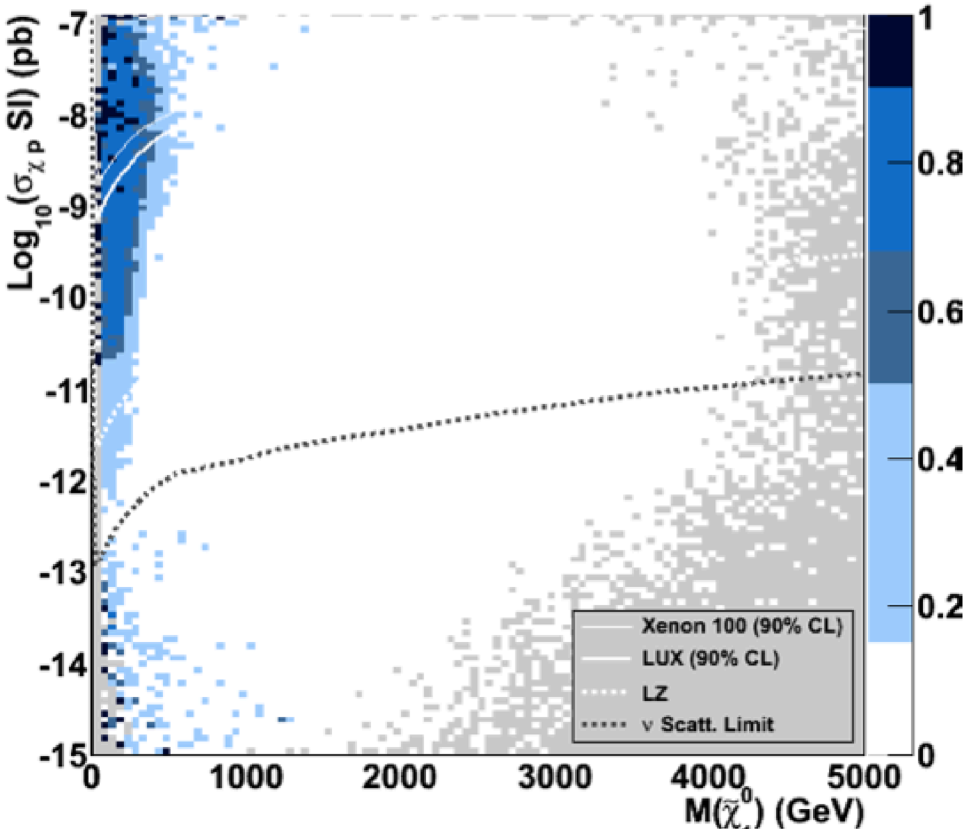
Coverage of pMSSM parameter space using DM constraints and direct searches at 14 and 100 TeV

Arbey, **Battaglia**, Mahmoudi

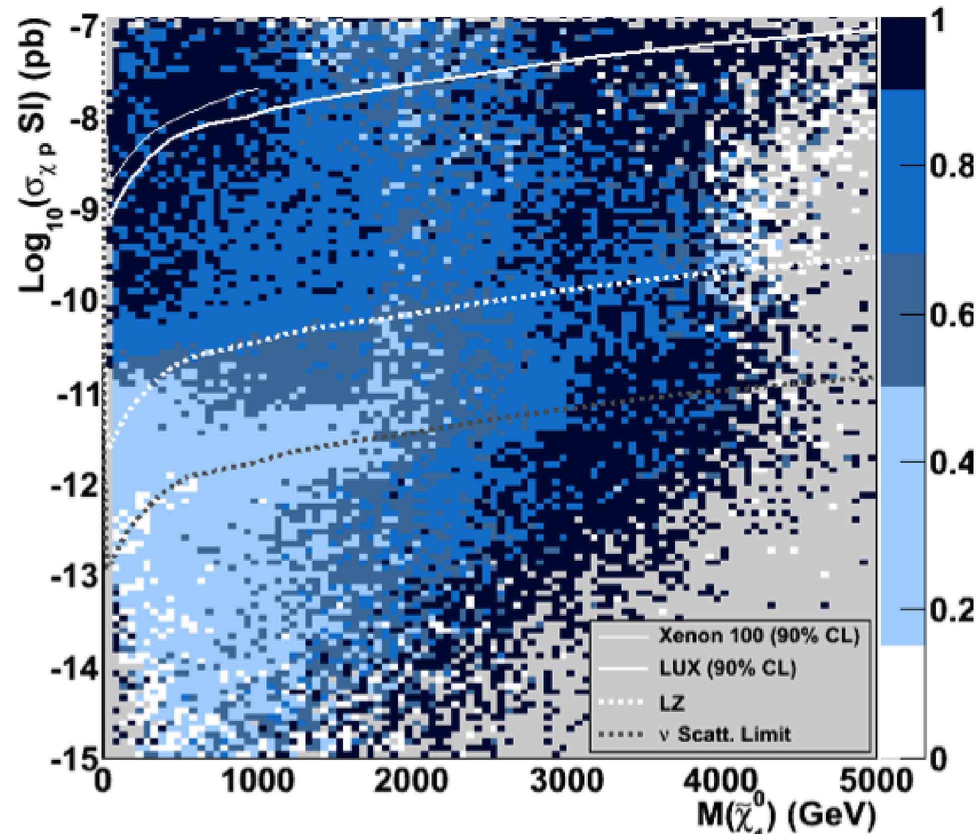


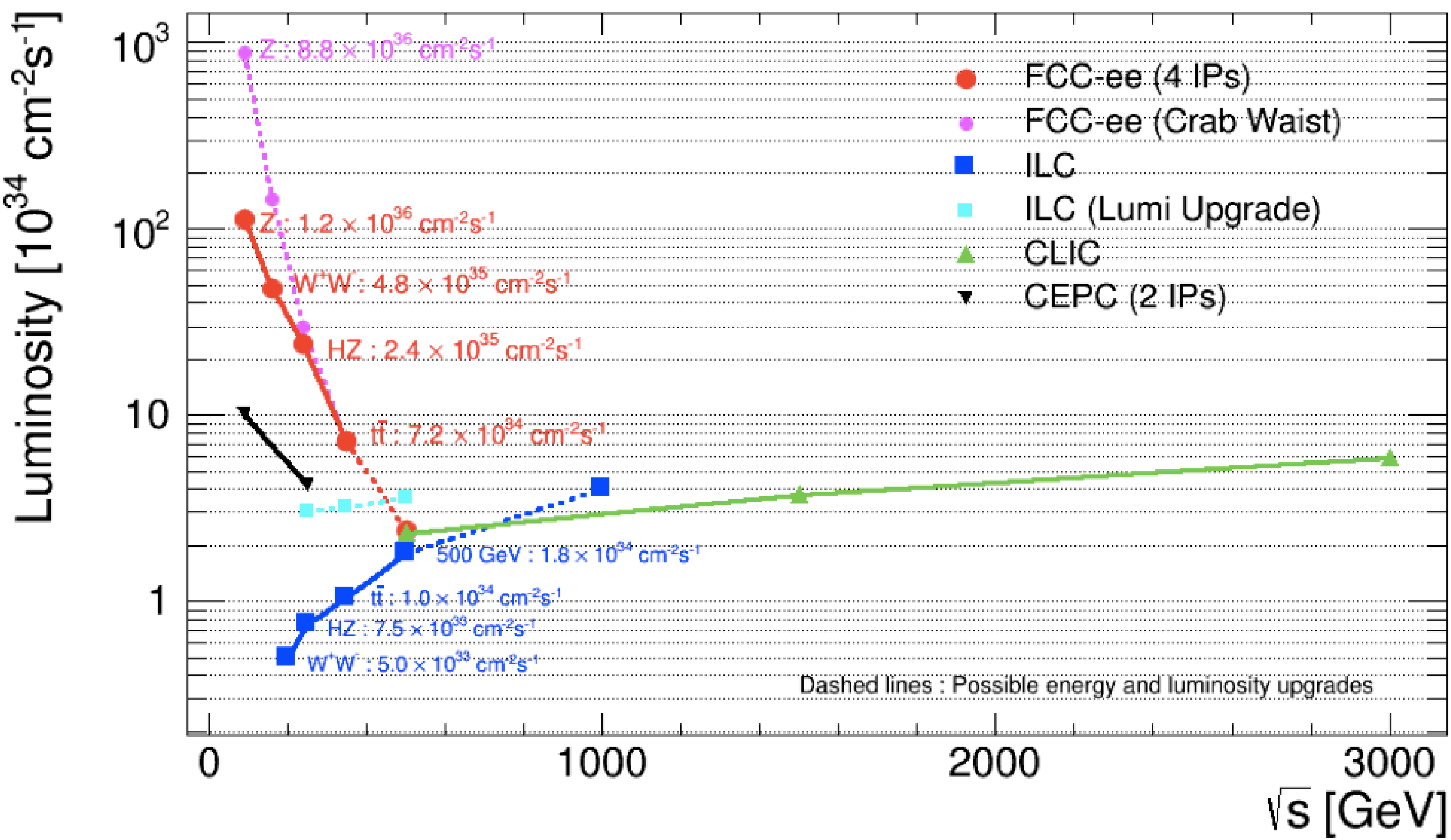
Fraction of pMSSM points that can be excluded at LHC-14 and 100 TeV:

14 TeV



100 TeV





Luminosity [10^34 cm^-2 s^-1]
√s [GeV]
Z : 8.8 × 10^36 cm^-2 s^-1
Z : 1.2 × 10^36 cm^-2 s^-1
W+W- : 4.8 × 10^35 cm^-2 s^-1
HZ : 2.4 × 10^35 cm^-2 s^-1
tt̄ : 7.2 × 10^34 cm^-2 s^-1
500 GeV : 1.8 × 10^34 cm^-2 s^-1
tt̄ : 1.0 × 10^34 cm^-2 s^-1
HZ : 7.5 × 10^33 cm^-2 s^-1
W+W- : 5.0 × 10^33 cm^-2 s^-1
FCC-ee (4 IPs)
FCC-ee (Crab Waist)
ILC
ILC (Lumi Upgrade)
CLIC
CEPC (2 IPs)
Dashed lines : Possible energy and luminosity upgrades

From the global programme, 1–2 orders of magnitude more precise measurements of EW parameters

X	Physics	Present precision		TLEP stat Syst Precision	TLEP key	Challenge
M_Z MeV/c2	Input	91187.5 ±2.1	Z Line shape scan	0.005 MeV <±0.1 MeV	E_cal	QED corrections
Γ_Z MeV/c2	$\Delta\rho$ (T) (no $\Delta\alpha$!)	2495.2 ±2.3	Z Line shape scan	0.008 MeV <±0.1 MeV	E_cal	QED corrections
R_l	α_s , δ_b	20.767 ± 0.025	Z Peak	0.0001 ± 0.002 - 0.0002	Statistics	QED corrections
N_ν	Unitarity of PMNS, sterile ν's	2.984 ±0.008	Z Peak Z+γ(105/161)	0.00008 ±0.004 0.0004-0.001	->lumi meast Statistics	QED corrections to Bhabha scat.
R_b	δ_b	0.21629 ±0.00066	Z Peak	0.000003 ±0.000020 - 60	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta\rho$, ε_3 ,$\Delta\alpha$ (T, S)	0.1514 ±0.0022	Z peak, polarized	±0.000015	4 bunch scheme	Design experiment
M_W MeV/c2	$\Delta\rho$, ε_3 , ε_2, $\Delta\alpha$ (T, S, U)	80385 ± 15	Threshold (161 GeV)	0.3 MeV <1 MeV	E_cal & Statistics	QED corections
m_{top} MeV/c2	Input	173200 ± 900	Threshold scan	10 MeV	E_cal & Statistics	Theory limit at 100 MeV?

$10\ ab^{-1}$ at 100 TeV imply:

10^{10} Higgs bosons => 10^4 x today

10^{12} top quarks => 5 10^4 x today

=>10^{12} W bosons from top decays => *probe rare W decays ?*

=>10^{12} b hadrons from top decays (particle/antiparticle tagged)

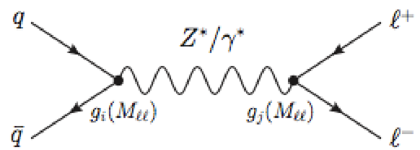
=>10^{11} $t \to W \to$ taus => *can solve the $B(W \to \tau\nu)$ puzzle ?*

=> few x10^{11} $t \to W \to$ charm hadrons

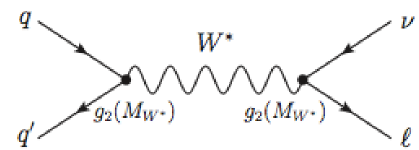
=> plenty of new studies and opportunities for measurements become available ..... few examples

Running Electroweak Couplings as a Probe of New Physics

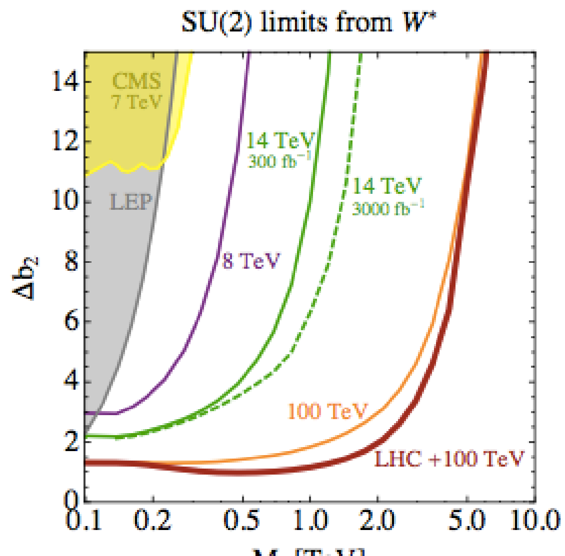
D.Alves, J. Galloway, J.Ruderman, J.Walsh *arXiv:1410.6810*

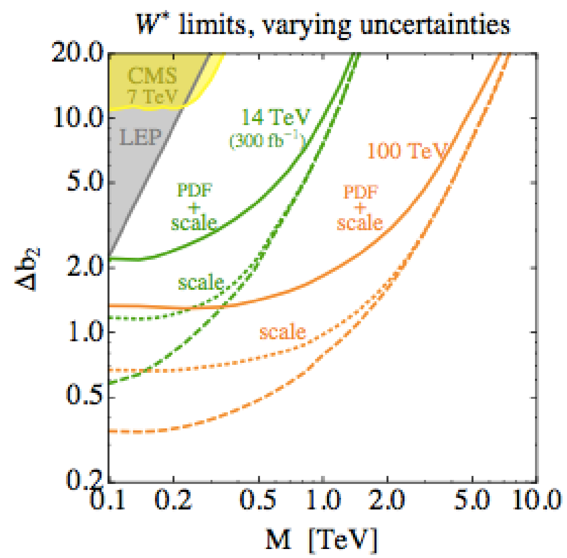


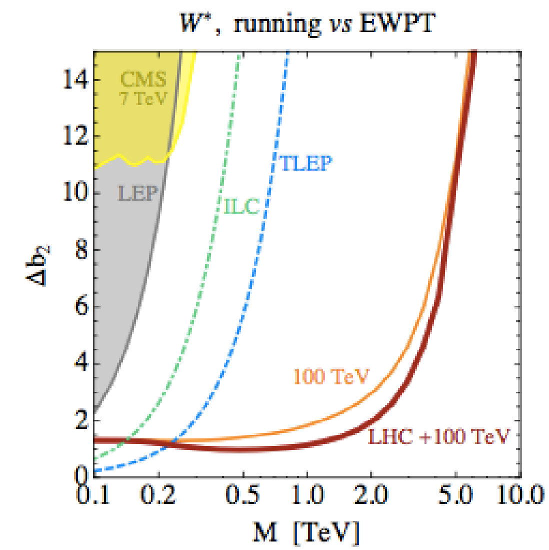
$$\frac{d\sigma}{dm_{ll}} \Rightarrow \alpha_{1,2}(q)$$

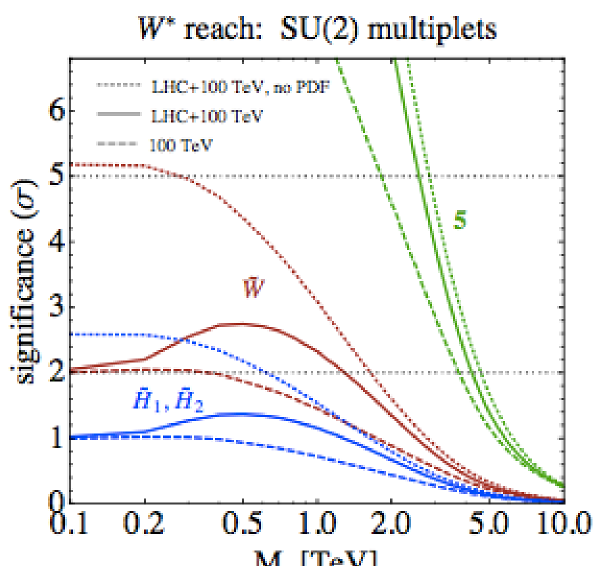


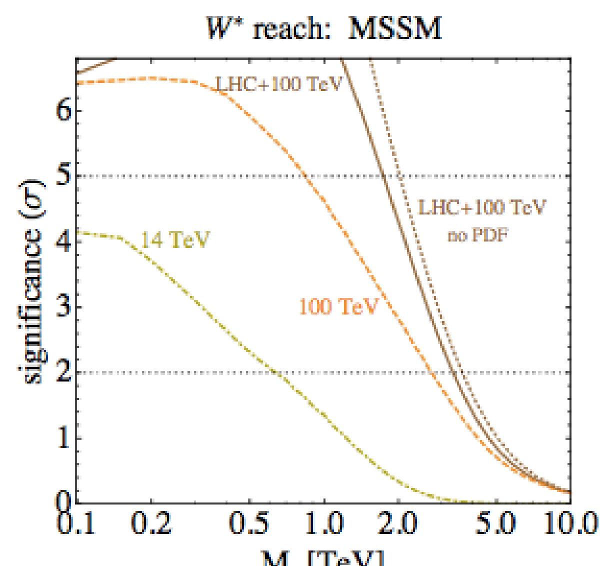
$$\frac{d\sigma}{dM_T} \Rightarrow \alpha_2(q)$$









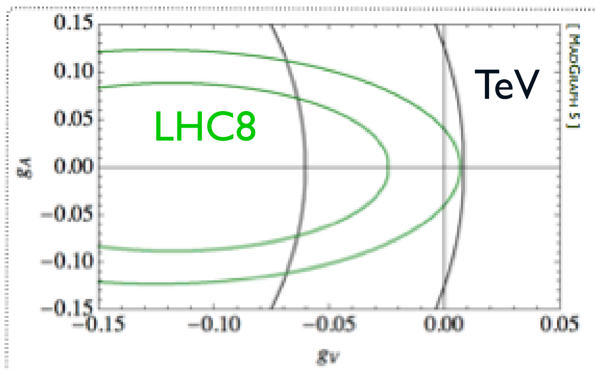


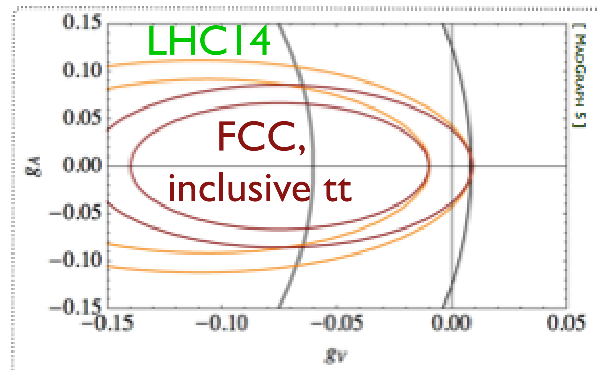
Example, tt at large mass

σ_{LO} [pb]	No M_{tt} cut	M_{tt} > 1 TeV	M_{tt} > 2 TeV	M_{tt} > 3TeV	M_{tt} > 5 TeV
LHC-14	560 pb	14.5 pb	0.31 pb	0.017 pb	9.93 10^{-5} pb
FCC-100	19700 pb (x35)	1510 pb (x100)	135.9 pb (x440)	27.2 pb (x1600)	2.86 pb (x30000)

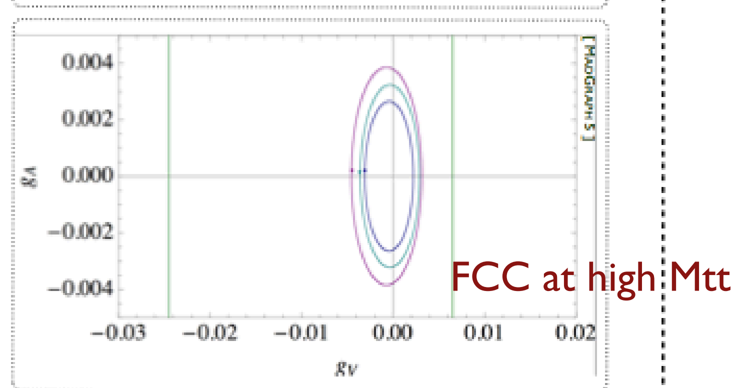
Applications: top dipole moments

✦ Top chromomagnetic and chromoelectric moments $\mathcal{L} = \frac{ig_s}{m_t}\bar{t}\sigma^{\mu\nu}\left[g_V + ig_A\gamma_5\right]T_a t G^a_{\mu\nu}$





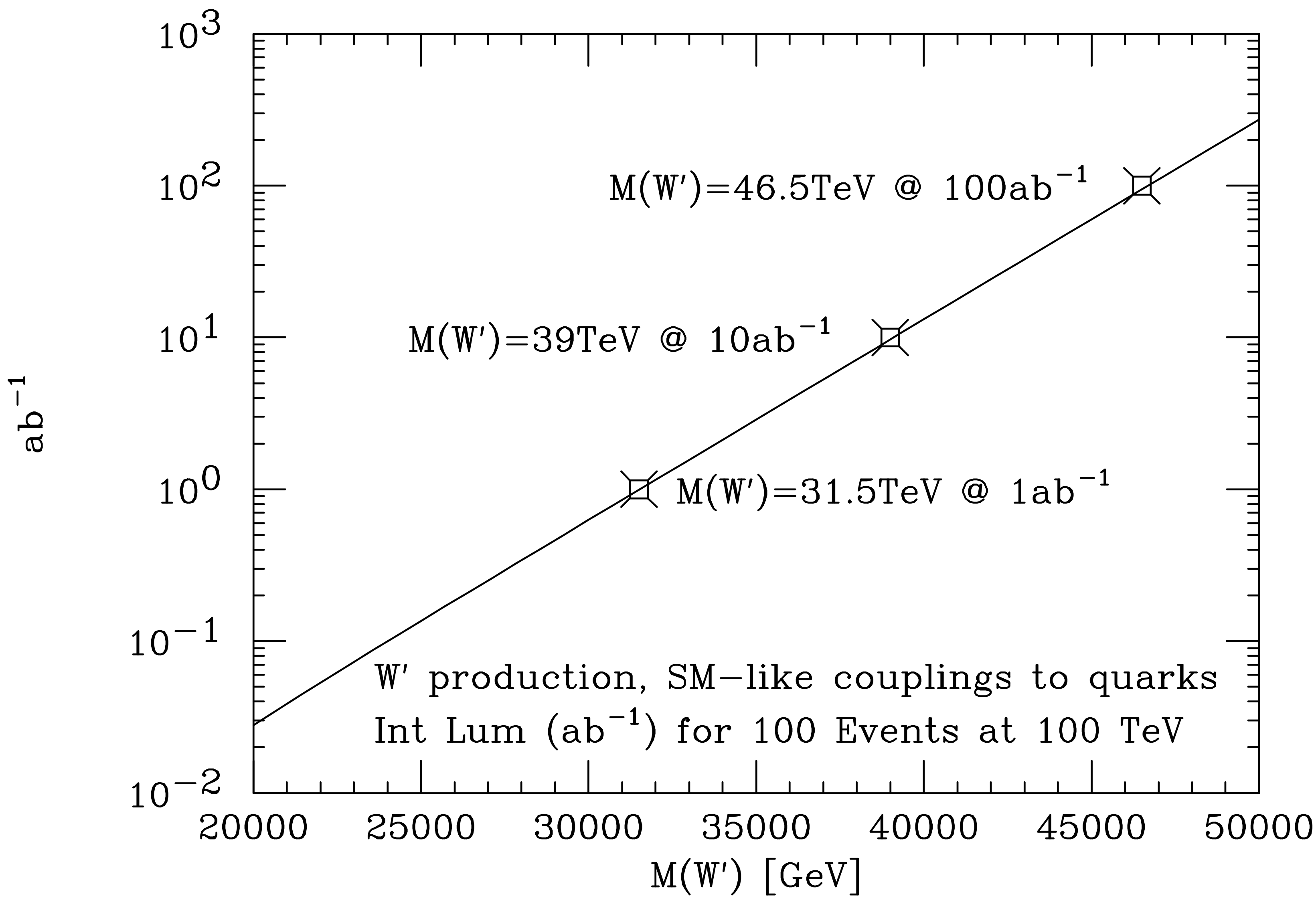
- Top pair-production total cross sections
  - ➢ constraints on g_A and g_V
- Existing data: Tevatron; LHC-8
- Predictions: LHC-14; FCC-100
  - ★ Major improvement not foreseen…
  - ★ LHC: assuming 5% syst. + stat. for 100 fb^{-1}
  - ★ FCC: assuming 5% syst. + stat. for 1 ab^{-1}
- Using instead highly massive top pairs
  - ★ M_{jj} > 6 TeV or 10 TeV or 15 TeV



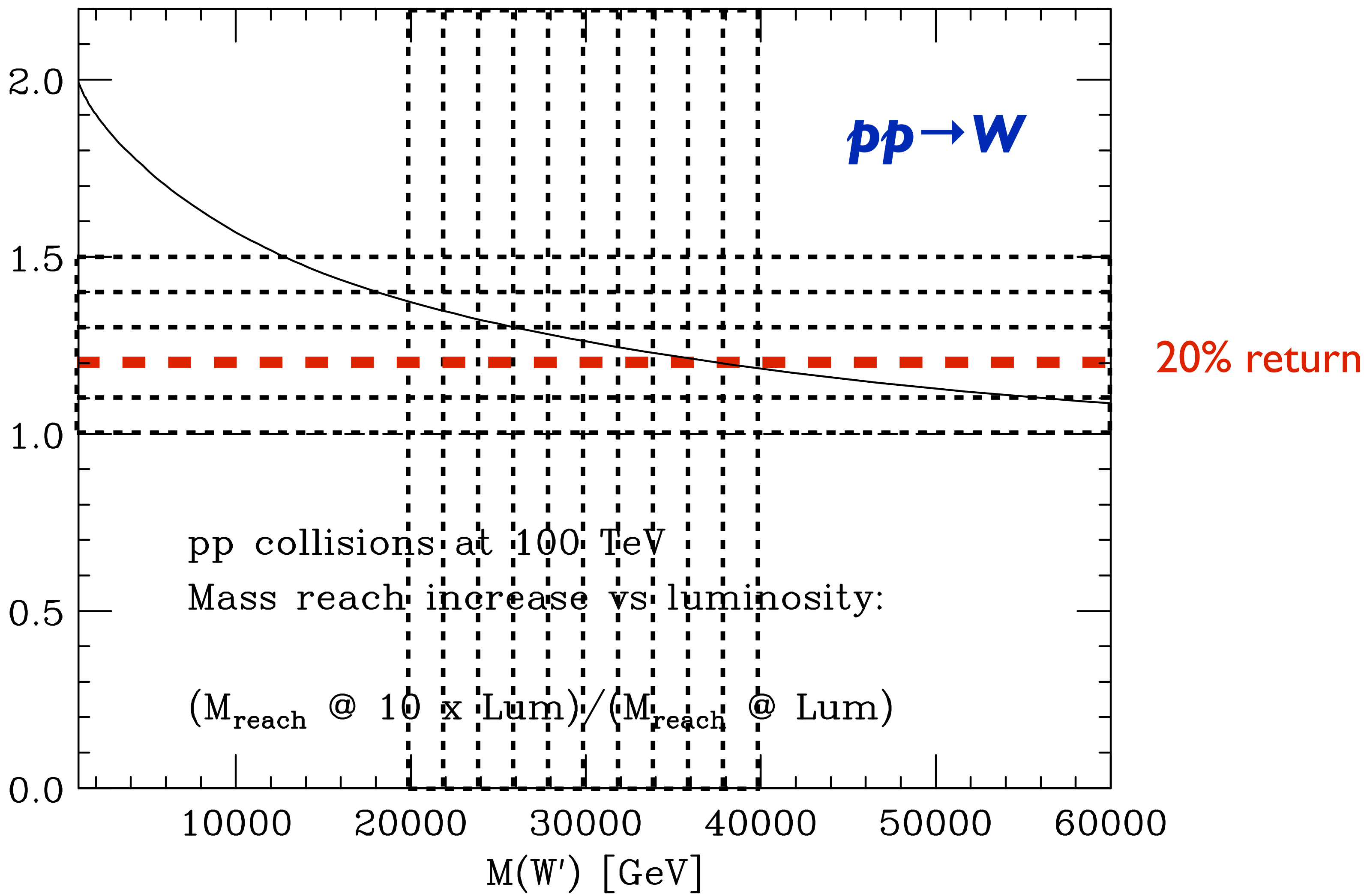
Extension of the discovery reach at high mass

Example: discovery reach of **W' with SM-like couplings**

NB For SM-like Z', $\sigma_{Z'}$ BR_{lept} ~ 0.1 x $\sigma_{W'}$ BR_{lept} , ⇒ rescale lum by ~ 10



At L=O(ab^{-1}), Lum x 10 ⇒ ~ M + 7 TeV



Lum x 10 ⇒ relative gain much larger at low mass than at high mass

See Hinchliffe et al, arXiv:1504.06108, for a more detailed discussion of luminosity goals for the 100 TeV collider

Physics with heavy ions

- **Conveners**: Dainese, Masciocchi (exp), Armesto, Salgado, Wiedemann (TH)
- **Mailing list:** *fcc-ions@cern.ch*
- **Twiki page**:
  - *https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HeavyIons*

Topics discussed so far (4 workshops, see Indico agendas for details)

- Charm at chemical equilibrium?
- Probes of gluon saturation at small x
- Nuclear PDFs
- Flows
- Hard probes, from jets to top quark production
- Ultraperipheral collisions
- ...

Physics with injectors

- **Conveners**: Goddard (accelerator), Isidori (theory), Teubert (experiments)
- **Mailing list**: *fcc-experiments-physin@cern.ch*

Topics discussed so far (4 mtgs, see Indico agendas for details)

- Physics prospects with polarized protons, and implications for the injector complex
- Low-energy proton ring for proton electric dipole moment measurement
- Collisions in the high-energy booster for high-rate studies of LFV τ decays
- Rare K decays
- Crystal beam extraction
- Test beam requirements for future detectors