IAS programme on The Future of High Energy Physics

Status of the FCC study

M.L. Mangano
CERN PH-TH

Many FCC-specific aspects already touched on in previous talks

- Accelerator challenges ☞ *V. Shiltsev and R.Talman*
- Detector challenges ☞ *Kotwal, Pontecorvo, Murray,*
- Physics landscape ☞ *C.Quigg*
  - Precision measurements, Higgs studies ☞ *Tenchini, Qian, Yao, Liu*
  - BSM ☞ *Wang, Jung, Shu*

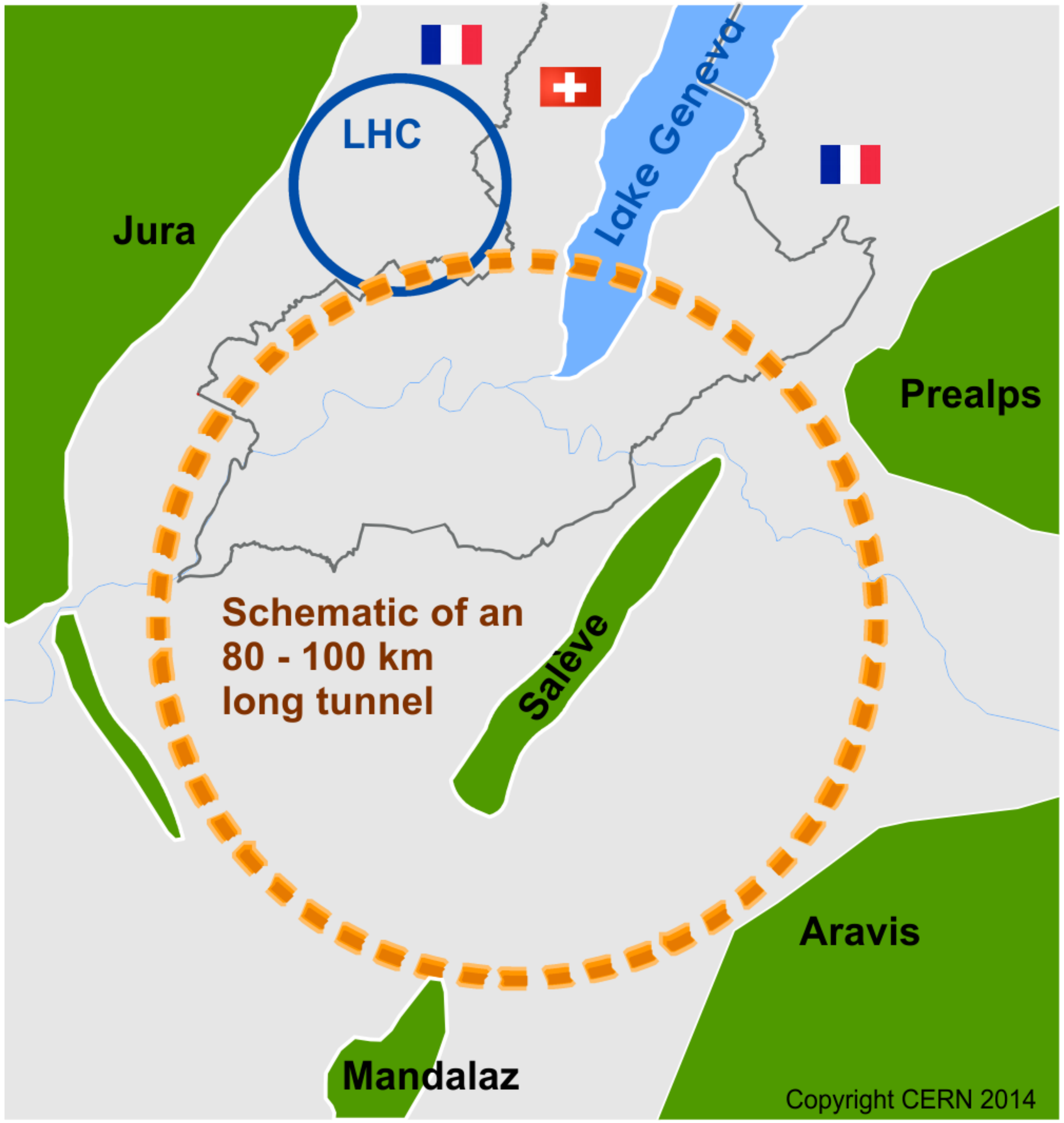
... and indirectly in other talks focused on CepC/SppC

I shall limit myself to fill in some gaps, report on organizational aspects of the physics studies, and provide a personal perspective on few issues emerged during the discussions at this meeting

Future Circular Collider study: scope

Forming an international collaboration to study:

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



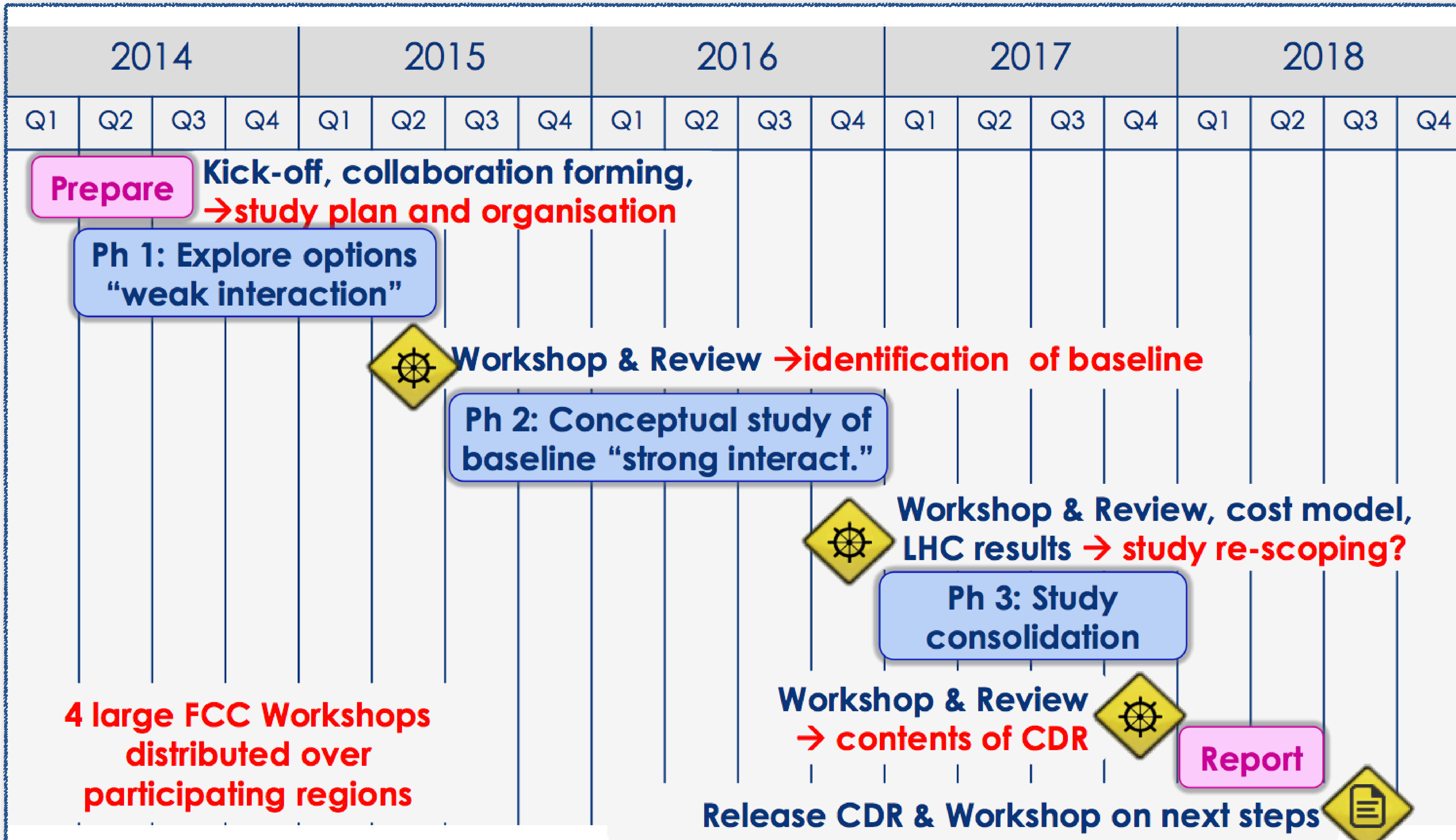
- **80-100 km infrastructure** in Geneva area
- ***e⁺e⁻* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**

FCC-hh	FCC-ee	FCC-eh
pp @100 TeV	e^+e^- @ $\sqrt{S}$ = 91, 160, 240, 350 GeV	$e^{\pm}$(50-175 GeV)-p(50 TeV)

Study structure

Machines and infrastructure conceptual designs	Technologies R&D activities Planning	Physics experiments detectors
Infrastructure	High-field magnets	Hadron physics experiments interface, integration
Hadron collider conceptual design	Superconducting RF systems	$e^+ e^-$ coll. physics experiments interface, integration
Hadron injectors	Cryogenics	e^- - p physics and integration aspects
Lepton collider conceptual design	Specific technologies	
Safety, operation, energy management environmental aspects	Planning	

The 5-year international FCC design study



First progress to be reported at the

FCC Week 2015, Washington DC, March 23-27 2015

- **Goal of this 5-year phase:** **Conceptual design report (CDR) and first cost estimate ready for the next Strategy Group assessment (~2018)**

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⇨ **we have ~10 years to articulate the physics case, focusing on the physics discussion and on the study of LHC results**

Physics and Experiments at the FCC

FCC-PHYSics-COordination-group

FCC-ee
Alain Blondel
John Ellis
Christophe Grojean
Patrick Janot

FCC-hh
Austin Ball
Fabiola Gianotti
Michelangelo Mangano

FCC-he
Max Klein
Monica d'Onofrio

Aims of the FCC «Physics and Experiments» design study:

-- to establish the physics capabilities of the FCC machines (- ee, hh, he)
and the complementarity and coverage of the **complex.**

-- scope the discovery sensitivities to a number of (new) physics scenarios by
-- direct observation of new particles
-- precision measurements of Higgs, Electroweak, Flavour etc observables
-- search for rare or forbidden phenomena

-- understand the experimental environment

-- establish the sensitivity of the physics performance of detectors to basic properties
and identify which ones:
-- are within reach of existing technologies and R&D
-- would most benefit from a new, dedicated, detector R&D program

-- define suitable layouts and requirements for infrastructure , study staging scenarios

-- identify which issues would require new theoretical calculations or
additional external or internal experimental input

FCC-ee physics activities documented on:

- http://indico.cern.ch/category/5259/
- http://cern.ch/tlep

To join the study group:
http://tlep.web.cern.ch/contribute-to-the-design-study

Forthcoming events:

FCC-ee Physics Workshop, Pisa SNS, 3-5 Febr 2015

http://agenda.infn.it/conferenceDisplay.py?ovw=True&confId=8830

JHEP
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Accepted: December 25, 2013
Published: January 29, 2014

First look at the physics case of TLEP

The TLEP Design Study Working Group

M. Bicer,[a] H. Duran Yildiz,[b] I. Yildiz,[c] G. Coignet,[d] M. Delmastro,[d] T. Alexopoulos,[e] C. Grojean,[f] S. Antusch,[g] T. Sen,[h] H.-J. He,[i] K. Potamianos,[j] S. Haug,[k] A. Moreno,[l] A. Heister,[m] V. Sanz,[n] G. Gomez-Ceballos,[o] M. Klute,[o] M. Zanetti,[o] L.-T. Wang,[p] M. Dam,[q] C. Boehm,[r] N. Glover,[r] F. Krauss,[r] A. Lenz,[r] M. Syphers,[s] C. Leonidopoulos,[t] V. Ciulli,[u] P. Lenzi,[u] G. Sguazzoni,[u] M. Antonelli,[v] M. Boscolo,[v] U. Dosselli,[v] O. Frasciello,[v] C. Milardi,[v] G. Venanzoni,[v] M. Zobov,[v] J. van der Bij,[w] M. de Gruttola,[x] D.-W. Kim,[y] M. Bachtis,[z] A. Butterworth,[z] C. Bernet,[z] C. Botta,[z] F. Carminati,[z] A. David,[z] L. Deniau,[z] D. d'Enterria,[z] G. Ganis,[z] B. Goddard,[z] G. Giudice,[z] P. Janot,[z] J. M. Jowett,[z] C. Lourenço,[z] L. Malgeri,[z] E. Meschi,[z] F. Moortgat,[z] P. Musella,[z] J. A. Osborne,[z] L. Perrozzi,[z] M. Pierini,[z] L. Rinolfi,[z] A. de Roeck,[z] J. Rojo,[z] G. Roy,[z] A. Sciabà,[z] A. Valassi,[z] C.S. Waaijer,[z] J. Wenninger,[z] H. Woehri,[z] F. Zimmermann,[z] A. Blondel,[aa] M. Koratzinos,[aa] P. Mermod,[aa] Y. Onel,[ab] R. Talman,[ac] E. Castaneda Miranda,[ad] E. Bulyak,[ae] D. Porsuk,[af] D. Kovalskyi,[ag] S. Padhi,[ag] P. Faccioli,[ah] J. R. Ellis,[ai] M. Campanelli,[aj] Y. Bai,[ak] M. Chamizo,[al] R.B. Appleby,[am] H. Owen,[am] H. Maury Cuna,[an] C. Gracios,[ao] G. A. Munoz-Hernandez,[ao] L. Trentadue,[ap] E. Torrente-Lujan,[aq] S. Wang,[ar] D. Bertsche,[as] A. Gramolin,[at] V. Telnov,[at] M. Kado,[au] P. Petroff,[au] P. Azzi,[av] O. Nicrosini,[aw] F. Piccinini,[aw] G. Montagna,[ax] F. Kapusta,[ay] S. Laplace,[ay] W. da Silva,[ay] N. Gizani,[az] N. Craig,[ba] T. Han,[bb] C. Luci,[bc] B. Mele,[bc] L. Silvestrini,[bc] M. Ciuchini,[bd] R. Cakir,[be] R. Aleksan,[bf] F. Couderc,[bf] S. Ganjour,[bf] E. Lançon,[bf] E. Locci,[bf] P. Schwemling,[bf] M. Spiro,[bf] C. Tanguy,[bf] J. Zinn-Justin,[bf] S. Moretti,[bg] M. Kikuchi,[bh] H. Koiso,[bh] K. Ohmi,[bh] K. Oide,[bh] G. Pauletta,[bi] R. Ruiz de Austri,[bj] M. Gouzevitch[bk] and S. Chattopadhyay[bl]

JHEP01(2014)164

FCC-ee experiments

Experimental Studies: A. Blondel, P. Janot

- Discovery through precision measurements, rare, or invisible processes.

Electroweak Physics at the Z pole
R. Tenchini
F. Piccinini

Di-boson Physics m_W measurement
R. Tenchini

H(126) Properties
M. Klute
K. Peters

Top Quark Physics
P. Azzi

QCD and $\gamma\gamma$ Physics
D. d'Enterria
P. Skands

Flavour Physics
S. Monteil
J. Kamenic

New Physics
M. Pierini
C. Rogan

- Develop the necessary tools

Understand the experimental conditions

Offline Software
B. Hegner
C. Bernet
common across FCC

Online Software
C. Leonidopoulos

Experimental Environment
N. Bacchetta

- Set constraints (specifications) on possible detector designs to match statistical precision

Detector Designs
A. Cattai
G. Rolandi

Synergy with linear collider detectors:
ILD proposed as benchmark, SID (CERN group)
both require L^* modifications!
Several detectors possible:
lots of space for new ideas!

NB Conveners have mission for one year to assemble group and find co-conveners

FCC-ee Phenomenology Studies

Phenomenology Studies: J. Ellis, C. Grojean

- Match theory predictions to FCC-ee experimental precisions

QCD and $\gamma\gamma$ Physics
(Joint exp/th)
P. Skands

Precision EW calculations
S. Heinemeyer

Flavour Physics
(Joint exp/th)
Jernej Kamenik

- How to discover new physics in precision measurements, in rare decays (Z, W, t, H, b, c, τ, …) in rare or invisible processes (Right Handed neutrinos etc..)

:

Model Building and New Physics
Andreas Weiler

Synergy with
FCC-hh physics
Linear collider physics,
LEP physics
HF physics

- Set up the framework for global fits and understand the complementarity with other colliders (LHC, FCC-hh, in particular)

Global Analysis, Combination, Complementarity
John Ellis

Physics and Organisation of the FCC-he Study

Higgs - Uta Klein, Masahiro Khuze – **selfcoupling, 2nd and 3rd generation, CP**

PDFs – Voica Radescu, Frank Olness – **new evolution, full unfolding, high x**

BSM – Monica D'Onofrio, Georges Azuelos – **SUSY, Leptoquarks, CI, substructure**

Top – Olaf Behnke, Christian Schwanenberger – **6FVS, top PDF, anomalous coupling**

Low x - Paul Newman, Anna Stasto – **Gluon saturation, breakdown of DGLAP**

Heavy Ions – Nestor Armesto with low x – **Nuclear Structure, QGP**

Detector – Peter Kostka, Alessandro Polini - **Design and Simulation, IR**

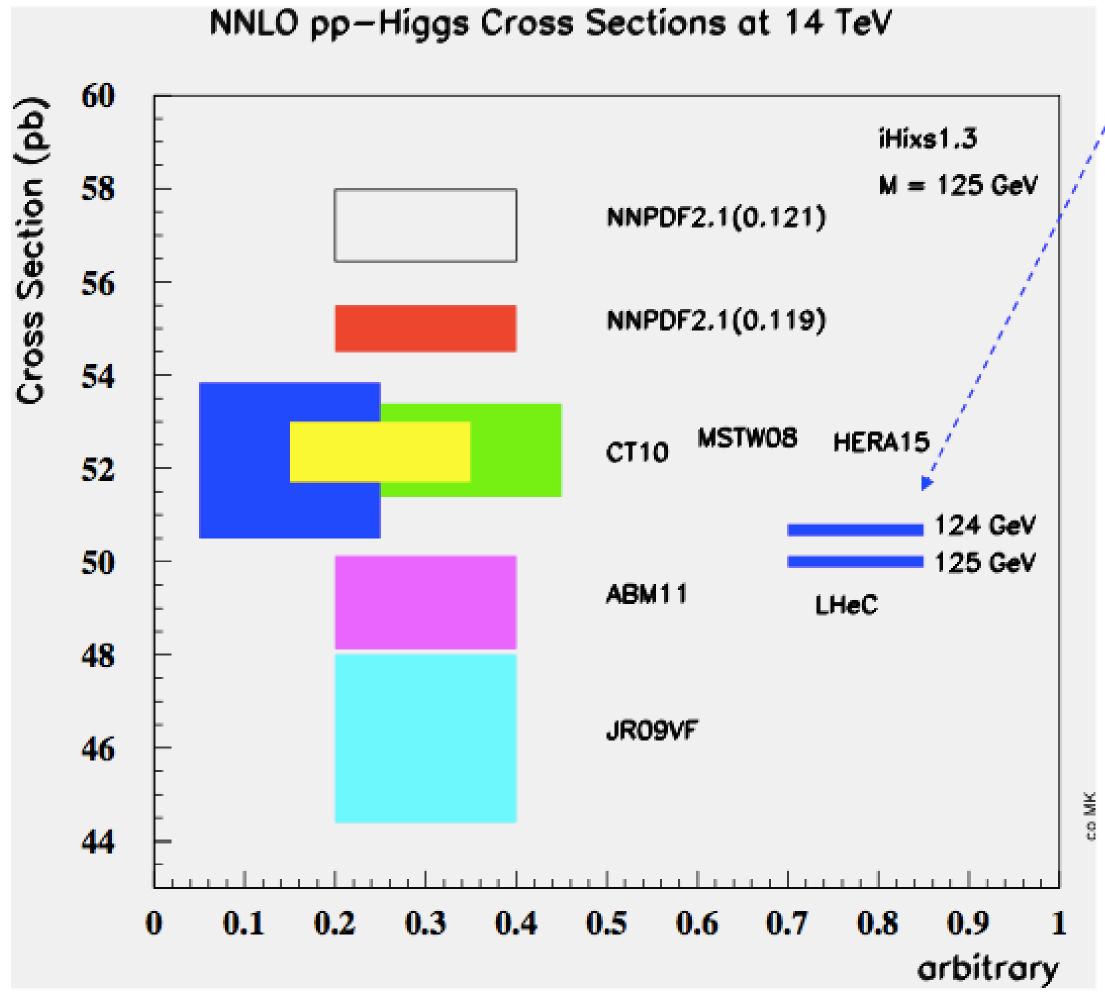
Software – Paul Laycock and Peter Kostka – **Simulation of ep/eA Detector**

In close collaboration with eh coordination group and machine physicists

Forthcoming Workshop:
CERN and Chavannes 24---27. June 2015 (TH, acc, exp)

Precision PDFs for Higgs at the LHC

The benefits for the pp physics programme of ep data at LHC and beyond



O.Brüning and M.K. arXiv:1305.2090, MPLA 2013

LHeC:

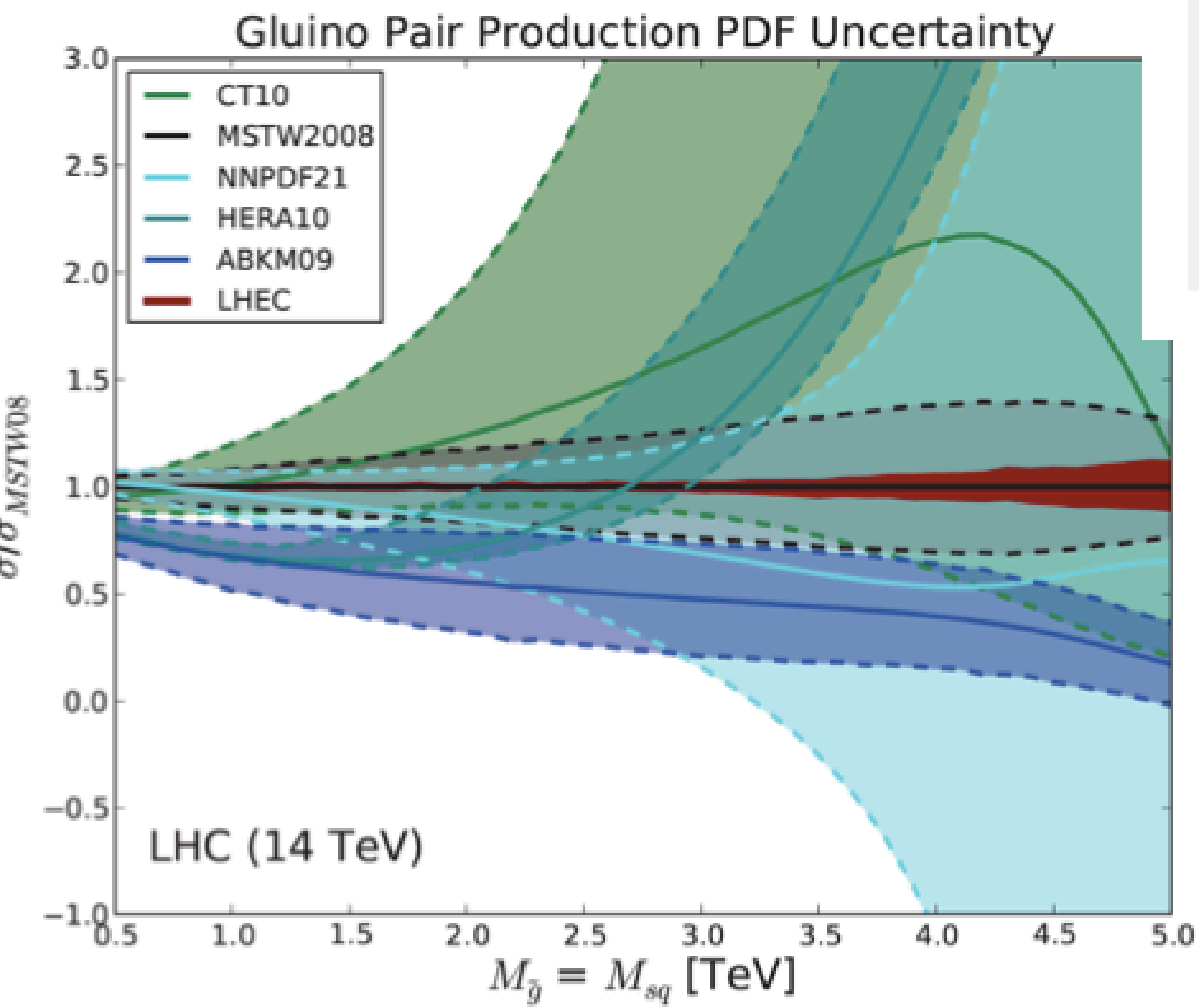
Exp uncertainty of predicted H cross section is 0.25% (sys+sta), using LHeC only.

Leads to H mass sensitivity.

Strong coupling underlying parameter (0.005 → 10%). LHeC: 0.0002 !

Needs N^{3}LO

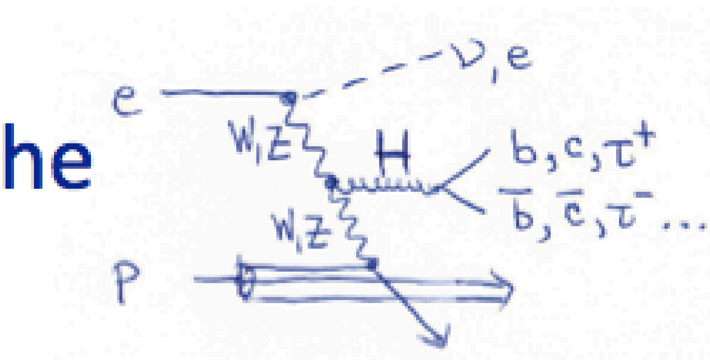
HQ treatment important ...



LHeC Note 2012-005
arXiv:1211.5102

LHeC PDFset on LHAPDF
V.Radescu, MK

Higgs Physics in DIS at the LHeC and FCC-he



Higgs in e^-p		CC - LHeC	NC - LHeC	CC - FHeC
Polarisation		-0.8	-0.8	-0.8
Luminosity [ab^{-1}]		1	1	5
Cross Section [fb]		196	25	850
Decay	BrFraction	N^H_{CC}	N^H_{NC}	N^H_{CC}
$H \to b\bar{b}$	0.577	113 100	13 900	2 450 000
$H \to c\bar{c}$	0.029	5 700	700	123 000
$H \to \tau^+\tau^-$	0.063	12 350	1 600	270 000
$H \to \mu\mu$	0.00022	50	5	1 000
$H \to 4l$	0.00013	30	3	550
$H \to 2l2\nu$	0.0106	2 080	250	45 000
$H \to gg$	0.086	16 850	2 050	365 000
$H \to WW$	0.215	42 100	5 150	915 000
$H \to ZZ$	0.0264	5 200	600	110 000
$H \to \gamma\gamma$	0.00228	450	60	10 000
$H \to Z\gamma$	0.00154	300	40	6 500

Cross section at FCC-he 1pb ep→ vHX

Luminosity O(10^{34}) is crucial for H → HH [0.5 fb] and rare H decays

Event rates for 1ab^{-1}. Note the LHeC WW-H cross section is as large as the Z*→ ZH cross section at the ILC or FCC- or CEPC, but it is much larger at the FCC-he

ep colliders 11.2014 Max Klein	CEPC	MEIC	eRHIC	HERA 92-07	CepC	LHeC	SepC	FCC-he
$\sqrt{s}$/GeV	**13**	**35**	**122**	**319**	**1000**	**1300**	**3375**	**3464**
$L/10^{33}$ $cm^{-2}s^{-1}$	0.4	5.6	1.5	0.04	4.8	16	8.9	10
E_e/GeV	3	5	15.9	27.6	120	60	80	60
E_p/GeV	15	60	250	920	2100	7000	35600	50000
f /MHz	500	750	9.4	10.4	20	40	40	40
$N_{e/p}10^{10}$	3.7/0.54	2.5/0.42	3.3/3	3/7	1.3/16.7	0.4/22	3.3/5	0.5/10
$\varepsilon_{e/p}$ /µm	.03/.15	54/.35	32/.27	4.6/.09y	250/1	20/2.5	7.4/2.4	10/2
$\beta^*_{e/p}$/cm	10/2	10/2	5/5	28/18 y	4.2/10	10/5	9.3/75	9/40
comment	Lanzhou	full acc.	"Day1"	HERA II	Booster	ERL (H)	$E_e = M_W$	ERL (HH)
source	X.Chen July 14	McKoewn POETIC14	Litvinenko S.Brook 14	B.Holzer at CERN 2008	Y.Peng Oct. 2014	Frank Z. LHeC 2014	Y.Peng Oct. 2014	Frank Z. IPAC 2014

FCC-hh physics activities documented on:

- o http://indico.cern.ch/categoryDisplay.py?categId=5258
- o https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

Mailing lists (see e.g. header of any of the mtgs in the Indico category above) => register to be kept uptodate

PLAN: prepare a report documenting the physics opportunities at 100 TeV, on the time scale of end-2015, ideally in cooperation with efforts in other regions

Forthcoming event at CERN:

Higgs and BSM at 100 TeV Workshop (March 11-13 2015)

https://indico.cern.ch/event/352868/

Status of physics/detector studies for the 100 TeV pp collider documented on

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

Twiki for 100 TeV pp collider studies (Future Circular Collider FCC-hh)

This twiki is intended to provide a common area to collect and share information related to FCC-hh studies.

Detector studies (Under construction):

- DetectorGeneral
- InnerDetector (to be done)
- CalorimetrySystem (to be done)
- MuonsSystem (to be done)
- MagneticSystem (to be done)

Physics studies:

- Tools (to come soon)
- Standard Model (to come soon)
- HiggsEWSymmetry
- BSM

Some useful related links:

- Agenda for the FCC-hh meetings: indico agenda

Dark Matter studies for FCC-hh

TH Convener: Pedro Schwaller, CERN

Ongoing studies

- Almost degenerate Higgsinos (Mahbubani, Schwaller, Zurita) Show Details
- Alternative signals with photons to discover neutralinos in compressed spectra (Delgado) Show Details
- Examining a monojet signal (Schwaller) Show Details
- Jet+MET and dijet+MET signatures of the Higgs portal (Mc Cullough, N.Craig, T.Lou, and A.Thalapillil) Show Details
- DM benchmarks (Doglioni, Boveia) Show Details

Other Literature

- Searches at 100 TeV
    - *Neutralino Dark Matter at 14 and 100 TeV*, M. Low and L.-T. Wang, arxiv:1404.0682
    - *The Relic Neutralino Surface at a 100 TeV collider*, J. Bramante et al, arxiv:1412.4789
    - *Wino-like Minimal Dark Matter and future colliders*, M.Cirelli, F.Sala, M.Taoso, arXiv:1407.7058
    - *Hunting electroweakinos at future hadron colliders and direct detection experiments*, G. Grilli di Cortona, arXiv:1412.5952
- Higgs portals, Unitarity constraints
    - *Perturbative Unitarity Constraints on Gauge Portals*, S.El Hedri et al, arXiv:1412.5660
    - *Perturbative Unitarity Constraints on Charged/Colored Portals*, M.Cahill-Rowley et al, arXiv:1501.03153
    - *The Higgs Portal Above Threshold*, N.Craig et al, arXiv:1412.0258

Other aspects

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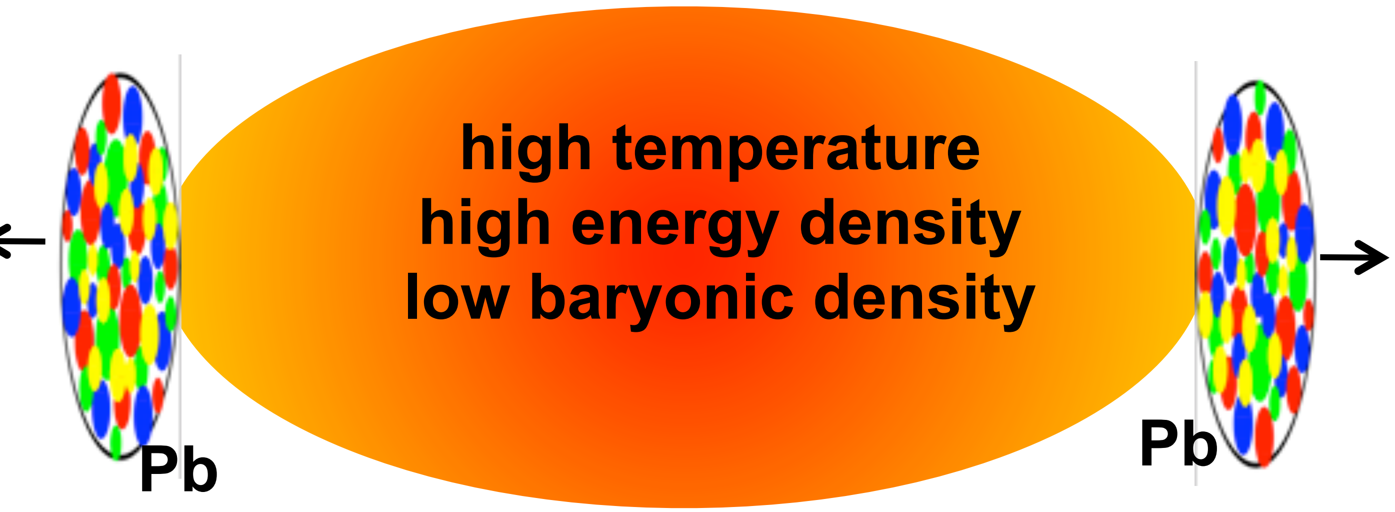
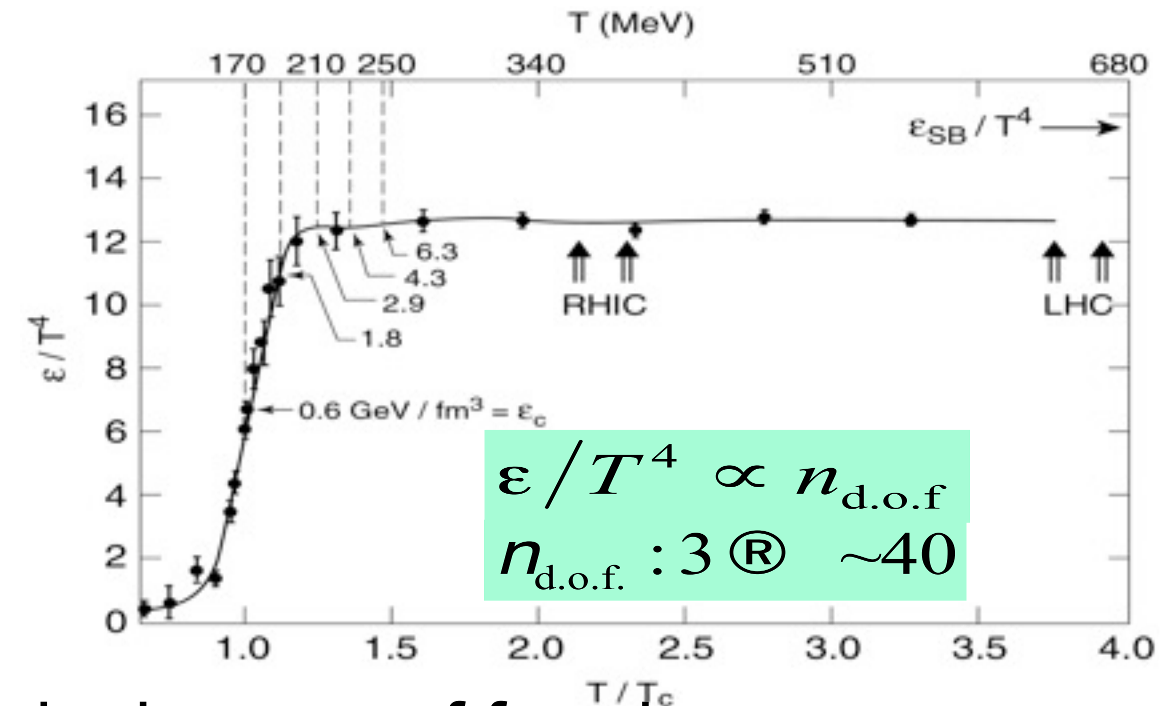
- The FCC will redefine the scope and role of the HEP laboratory that will host it, w.r.t. scope and role of previous HEP labs.
- For CERN, the scale of the project may require not just international participation, beyond the CERN member states, but also engagement of other science communities (low-energy nuclear physics, light sources, medical sciences, applied accelerator physics, advanced technology, ...)
- While the above has not entered our radars as yet, the least we can envisage today is maintaining at the FCC a rich and diverse HEP programme, fully exploiting the injector chain (fixed target experiments) and the beam options (heavy ions). The FCC study is mandated to explore these opportunities as well, and assess their impact on the whole project.

High-density QCD in the final state: the Quark Gluon Plasma



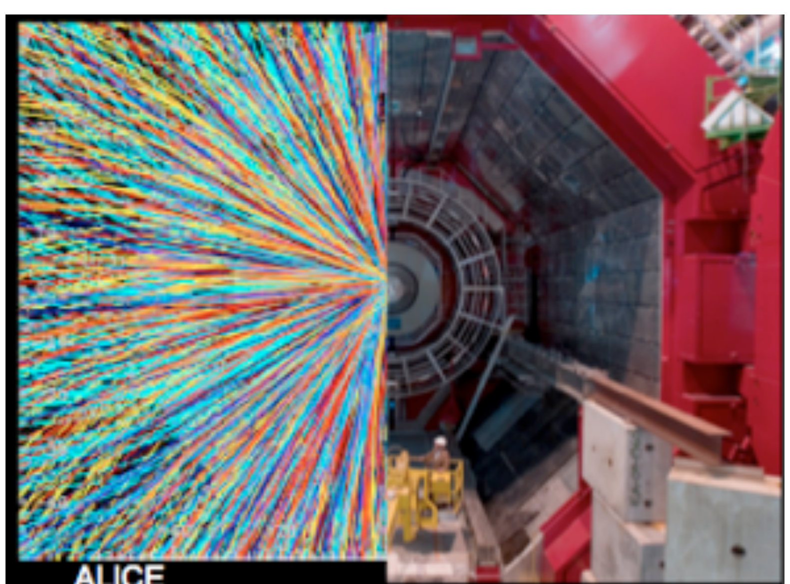


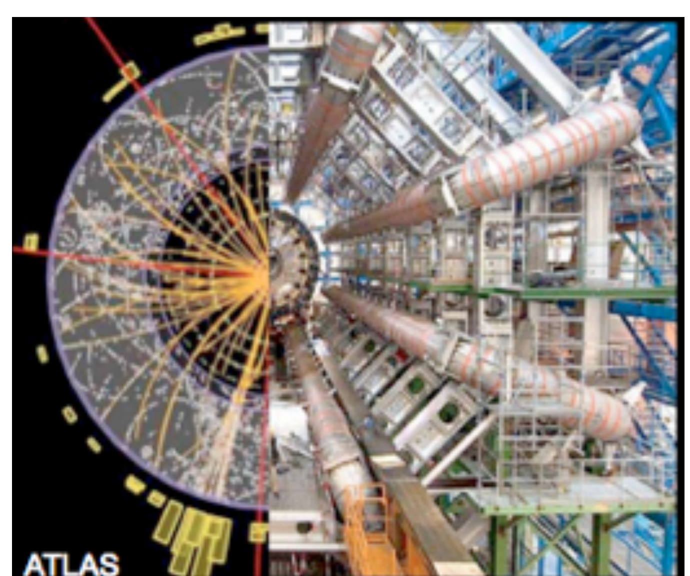
- Lattice QCD predicts phase transition at T_c~170 MeV

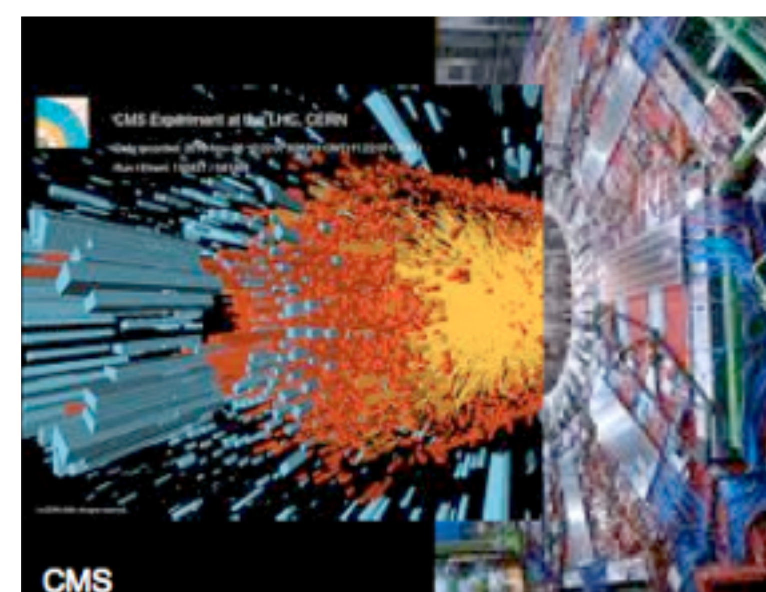
  → **Quark-Gluon Plasma**

- Confinement is removed

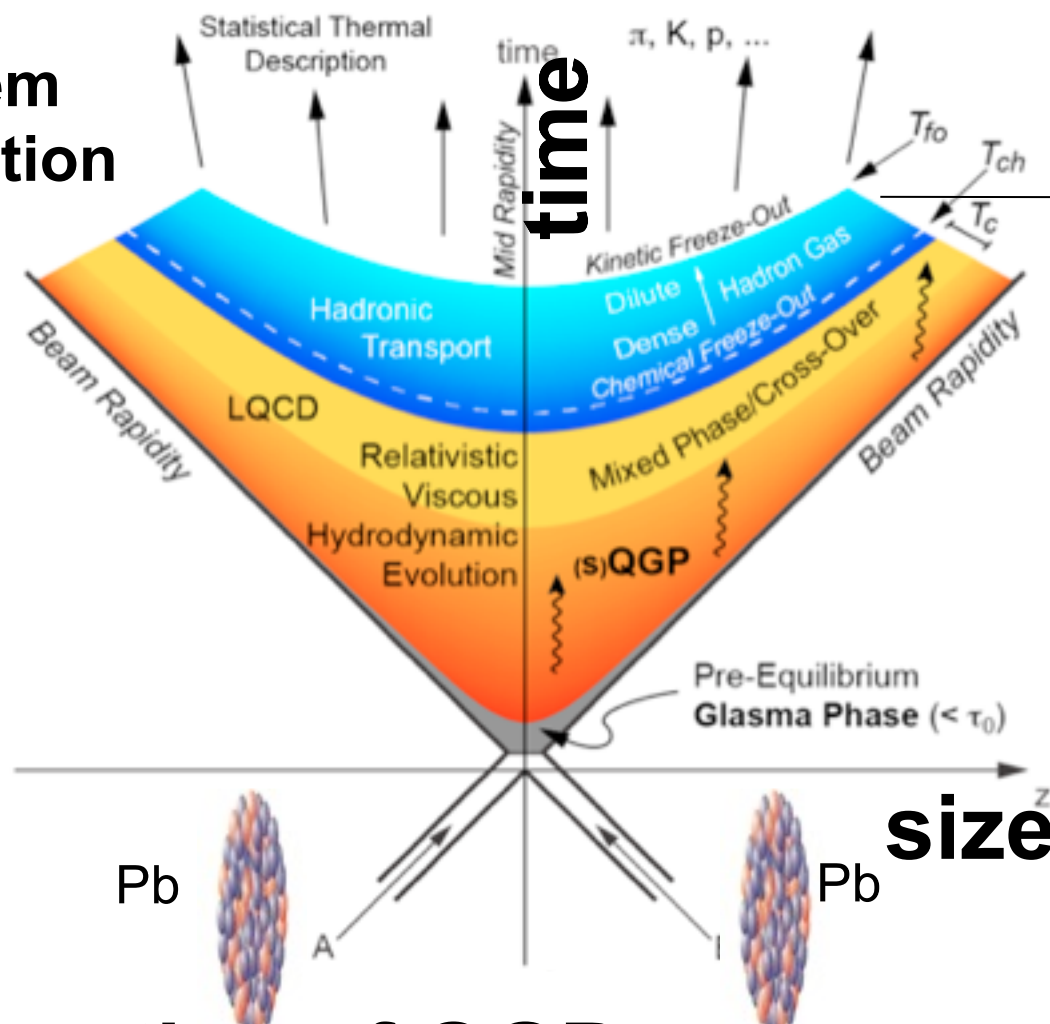
- Partonic degrees of freedom
- Unique opportunity to study in the laboratory spatially-extended multi-particle QCD system

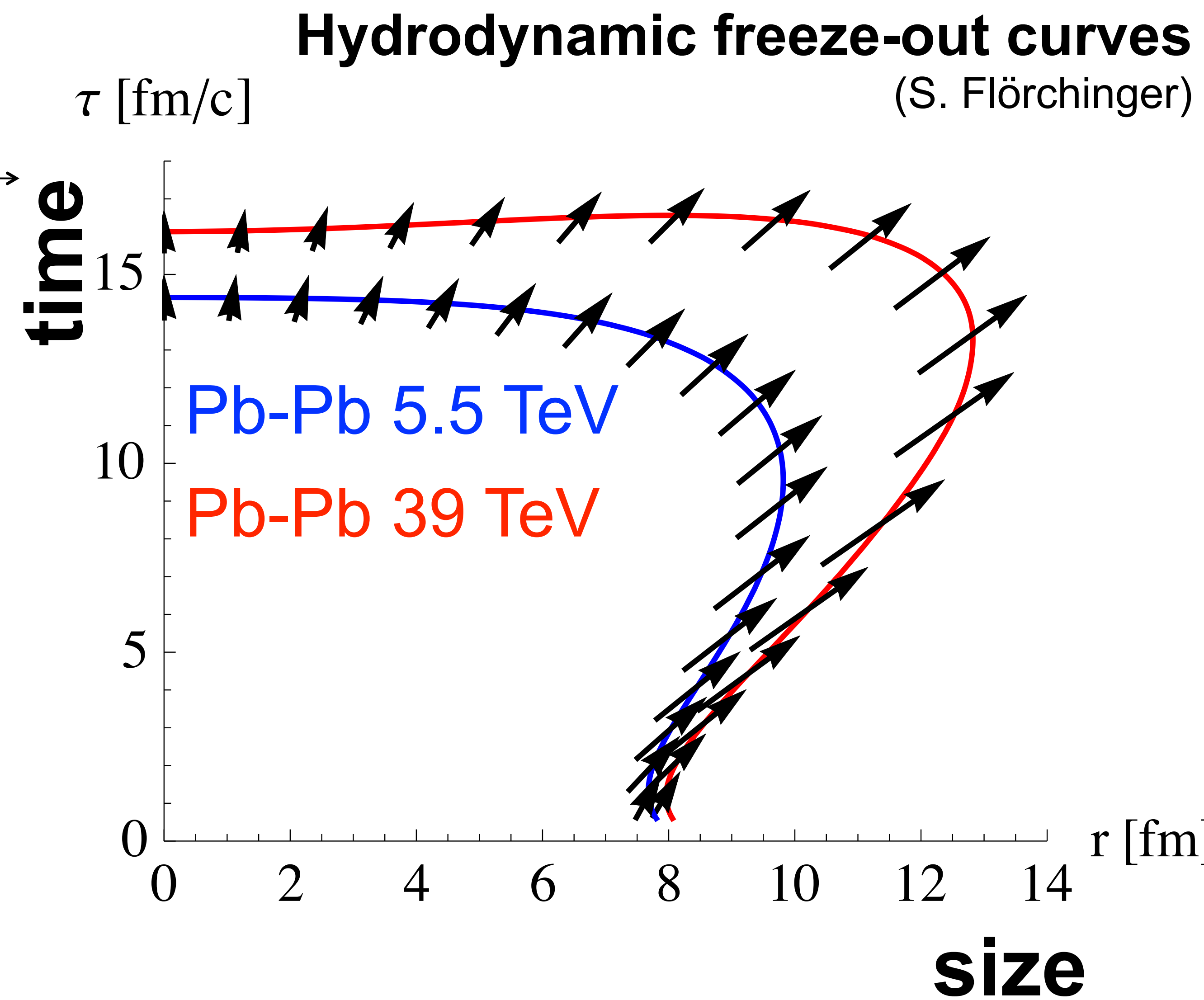






Quark-Gluon Plasma studies at FCC





Properties of QGP:

- QGP volume increases strongly
- QGP lifetime increases
- Collective phenomena enhanced (better tests of QGP transport)
- Initial temperature higher
- Equilibration times reduced

Quark-Gluon Plasma studies at FCC

Questions to be addressed in future studies include:

Higher Temp.

- Larger **number of degrees of freedom** in QGP at FCC energy? → g+u+d+s**+charm** ?
- Changes in the **quarkonium spectra**? does **Υ(1S) melt** at FCC?

Higher energy

- How do studies of **collective flow** profit from **higher multiplicity and stronger expansion**? More stringent **constraints on transport properties** such as shear viscosity or other properties not accessible at the LHC
- **Hard probes** are sensitive to medium properties. At FCC, **longer in-medium path length and new, rarer probes** become accessible. How can both features be exploited?

Ongoing discussions on the possible use of the injector complex

WG conveners: B. Goddard (acc), F. Teubert (exp), G. Isidori (TH)
http://indico.cern.ch/category/6070/

- Test beams needs and requirements (esp multi-TeV)
- Proton EDM experimental measurement (Y.Semertzidis)
- Polarized protons in the FCC
- High-L collisions inside the high-E booster (e.g. to continue LHCb-like expts focused on rare decays like $\tau \to 3\mu$)
- Continued programme of rare K decays
- Crystals for beam extraction

Remarks on some points emerged from the discussions ....

from R.Talman's talk:

- "Luminosity" is a Dependent Variable, Not an Input Parameter

- "Ground Up" Rather Than "Constrained Parameter" Design

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- In particular, the current FCC beam parameters were developed starting from the obvious target of at least reproducing the HL-LHC luminosity.
- This gives a meaningful benchmark to start the exercise of parameter-setting and optimization, an exercise that will take place in the years leading to the CDR.
- *... all of this (including the site ....) can evolve as the analysis progresses ...*

Alignment | Shaft Tools

Choose alignment option

93km quasi-circular ▼

Tunnel depth at centre: 299mASL

Gradient Parameters

Azimuth (°): -15

Slope Angle x-x(%): .5

Slope Angle y-y(%): 0

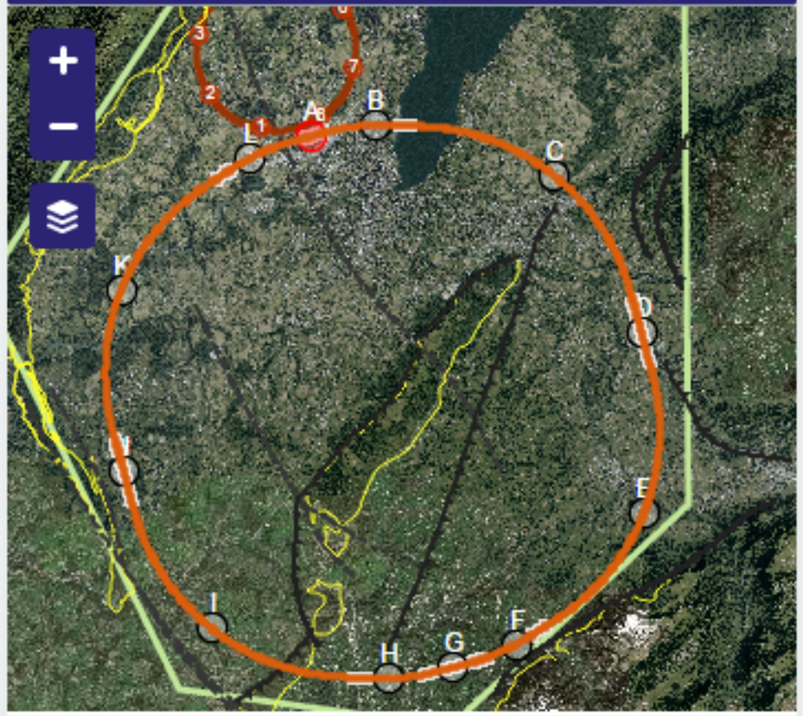
CALCULATE

Alignment centre

X: 2499812 Y: 1106889

LHC Intersection	CP 1	CP 2
Angle		
Depth	589m	589m

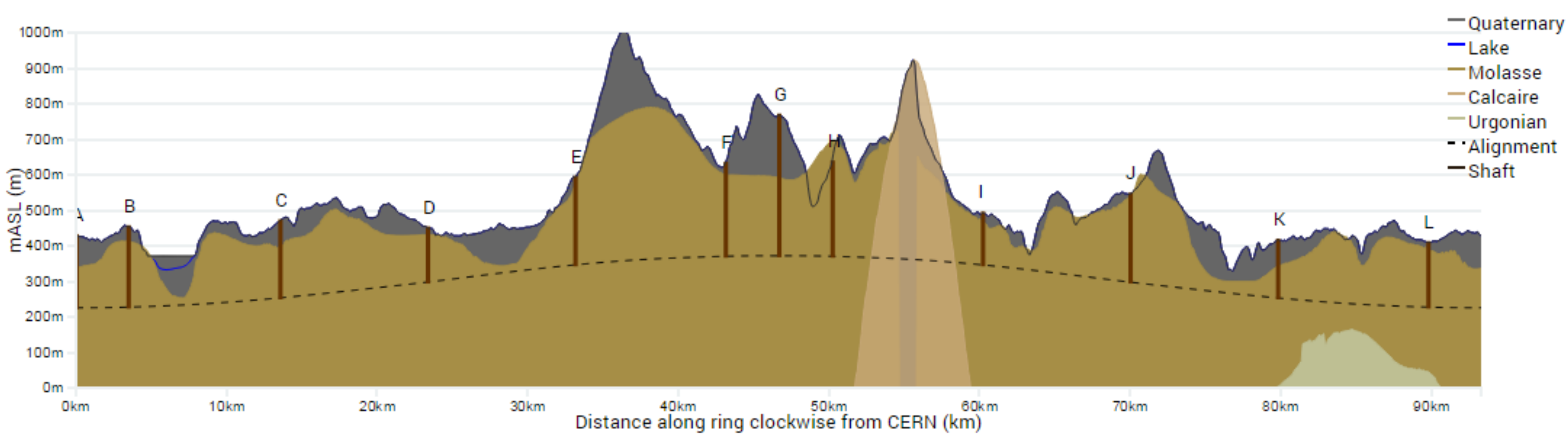
Alignment Location



Geology Intersected by Shafts | Shaft Depths

	Shaft Depth (m)				Geology (m)			
Point	Actual	Min	Mean	Max	Quaternary	Molasse	Urgonian	Calcaire
A	203	200	204	212	93	111	0	0
B	227	219	226	231	41	185	0	0
C	218	208	217	225	75	143	0	0
D	153	150	154	158	19	134	0	0
E	247	233	249	261	24	223	0	0
F	262	251	269	304	32	230	0	0
G	396	392	393	396	177	220	0	0
H	266	231	274	322	0	325	0	0
I	146	141	144	149	26	120	0	0
J	248	247	251	258	6	242	0	0
K	163	153	159	164	76	87	0	0
L	182	182	184	187	17	165	0	0
Total	2711	2607	2724	2867	585	2185	0	0

Alignment Profile



Geology Intersected by Tunnel

FCC performance determining parameters

- **Baseline parameters:**
  - Beam optics scaled from LHC, accounting for Nb3Sn ➔ beta=1.1m
  - Conservative beam-beam tune shift limit ➔ 0.01 (2 experiments)
  - Beam (bunch) parameters similar to present LHC beam ➔3.5 times more bunches
  - Baseline beam current 0.5 A, total synchrotron radiation 2 x 2.5 MW.
  - Turn-around time 5 hours assumed (pre-injectors well understood)

- Synchrotron radiation loss and heat extraction from cold mass is major design issue and performance determining factor.
  - Dissipated power proportional to total beam current.
  - Limit set to 2 x 2.5 MW beam power for dimensioning of magnet and cooling systems (present assumptions 100 MW refrigerator power)
    - This fixes the total beam current ➔ machine protection, dumps,…
    - Difficult to upgrade later since the complete magnet, vacuum and cryogenic systems need to be dimensioned accordingly!
  - Luminosity 5E34/cm^2/s, 250 fb-1/year (~125 days effective operation)

FCC performance upgrade

- Parameters that might be improved with operational experience:
  - Optics improvements to reduce beta ➔ **beta from 1.1 m to 0.3 m**
  - Increased beam-beam tune shift limit and corresponding increase in beam brightness via synchrotron radiation damping ➔ **0.01 to 0.03.**
  - Installation of crab cavities to compensate for crossing angle
  - Turnaround time reduced to 4 hours.

- **Effective improvement factor wrt baseline is 4 – 5**
  - **Luminosity 2.5E35/cm^2/s (peak), ~1000 fb-1/year**
  - **(~125 days eff. operation)**

- Further improvement might be achieved via significant improvement on the turn-around time
  - Potential to gain factor 2 in integrated luminosity by decreasing from 4 hours to 1 hour
  - Maybe only achievable with new injector ➔ major cost and effort

Summary

- Phase 1: baseline luminosity 5E34/cm^2/s (peak)
  - Integral ~250 fb-1/year (with operation model 125 days/year)
  - 10 years phase 1 operation
  - **Total accumulated lumi in phase 1: 2500 fb-1.**

- Phase 2: upgrade luminosity 2.5E35/cm^2/s (peak)
  - Integral ~1000 fb-1/year (with operation model 125 days/year)
  - 15 years phase 2 operation
  - **Total accumulated lumi in phase 1: 15000 fb-1.**

- **Total accumulated luminosity over 25 years 17500 fb-1 (w/o new injector)** *from the discussion on Luminosity, Friday afternoon:*

- how ambitious should be the luminosity goals ?

- what's the minimum acceptable luminosity ?

from the discussion on Luminosity, Friday afternoon:
- how ambitious should be the luminosity goals ?
- what's the minimum acceptable luminosity ?

Physics considerations on luminosity goals

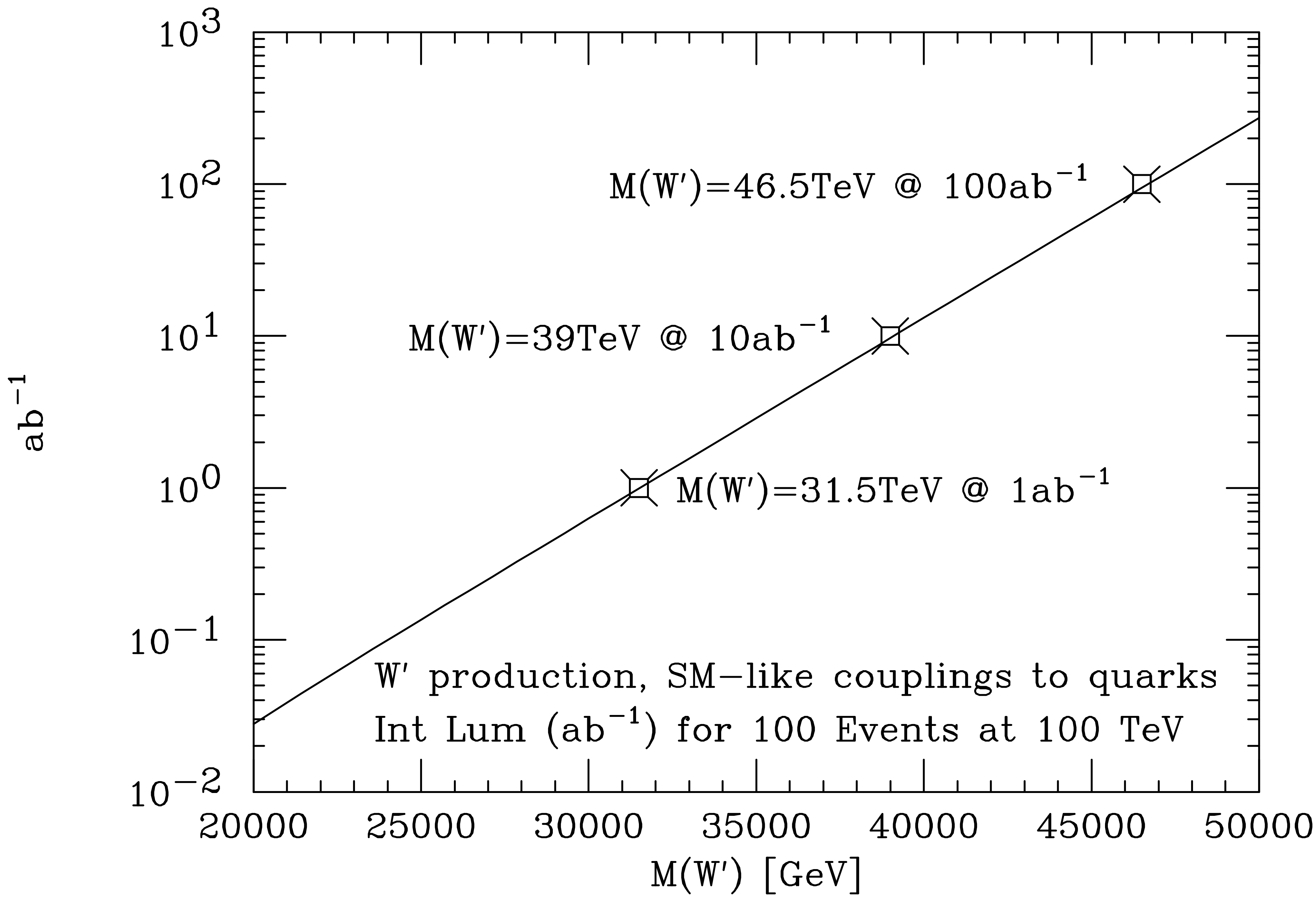
Luminosity must guarantee:

- Extension of the discovery reach at the high mass end
- Extension of the discovery reach for rare processes at masses well below the kinematical edge
- Higher statistics for studies of new particles to be discovered at the LHC
- Higher statistics for studies of the Higgs

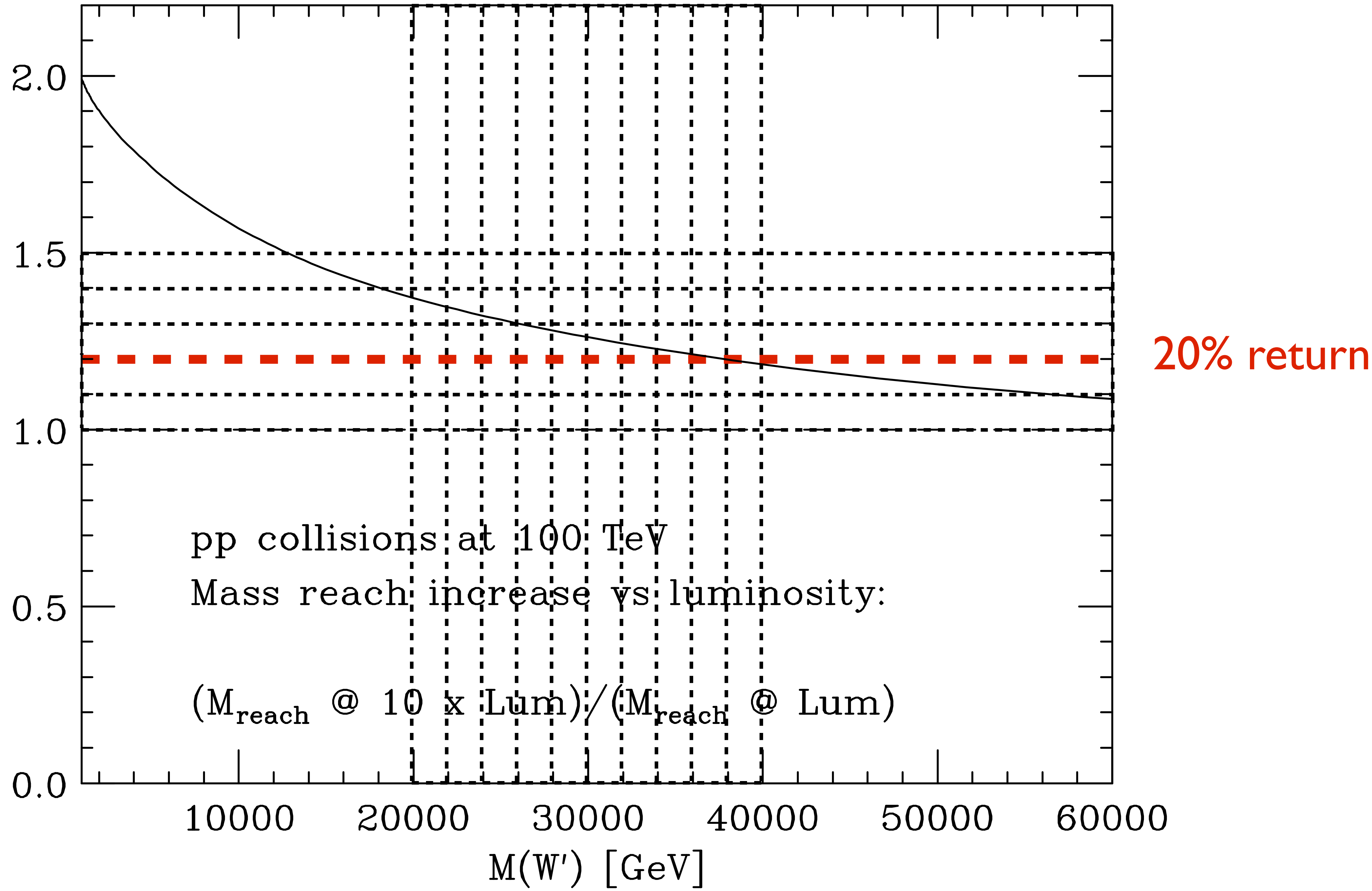
Extension of the discovery reach at high mass

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

- One could argue that the 10 x increase in lum is not justified if the increase in sensitivity is below a level of O(20%).
- Beyond this level, extra lum is not justified by the desire to push the mass reach

See e.g. the history of Tevatron achievements: after 1 fb^{-1}, limited progress at the high-mass end, but plenty of results at "low" mass (W, top and b physics, Higgs sensitivity, ...)

Example from HL-LHC studies: $Z' \to e^+e^-$

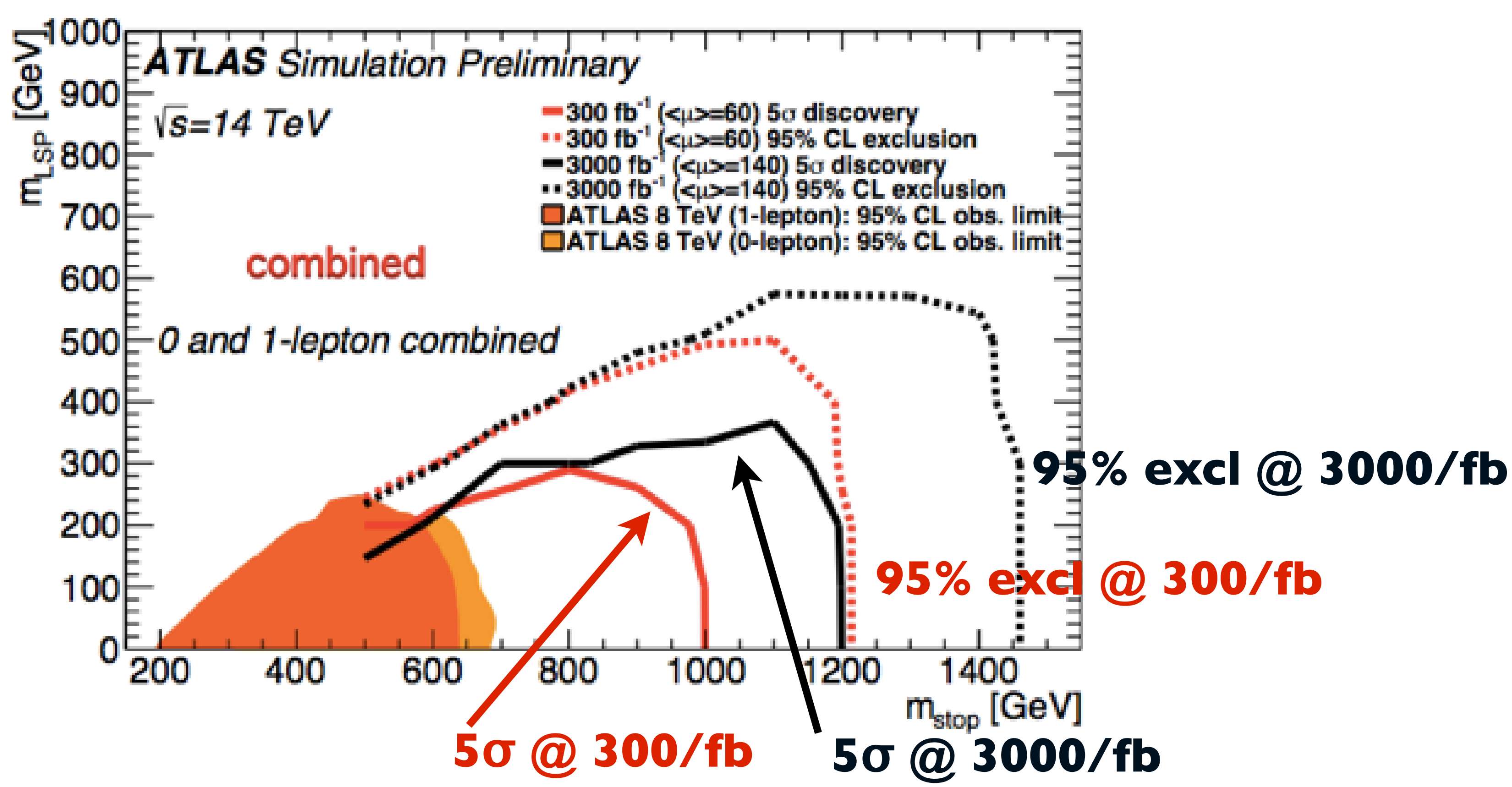
ATLAS/CMS HL docs	300/fb	3000/fb
95% excl (ATLAS)	**6.5 TeV**	7.8 TeV
5σ (CMS)	5.1 TeV	**6.2 TeV**

- *$\Delta M/M \sim 20\% \Rightarrow$ the LHC reaches the threshold of saturation of the mass reach already at 300fb^{-1} . Notice that 95% exclusion at 300 makes unlikely the 5σ discovery at 3000. In fact the main justification for the HL-LHC is the higher-statistics study of the Higgs, not the extension of the mass reach*
- *In this case, **the scaling $L \propto E_{beam}^2$ gives L(100) ~ 15ab^{-1}***

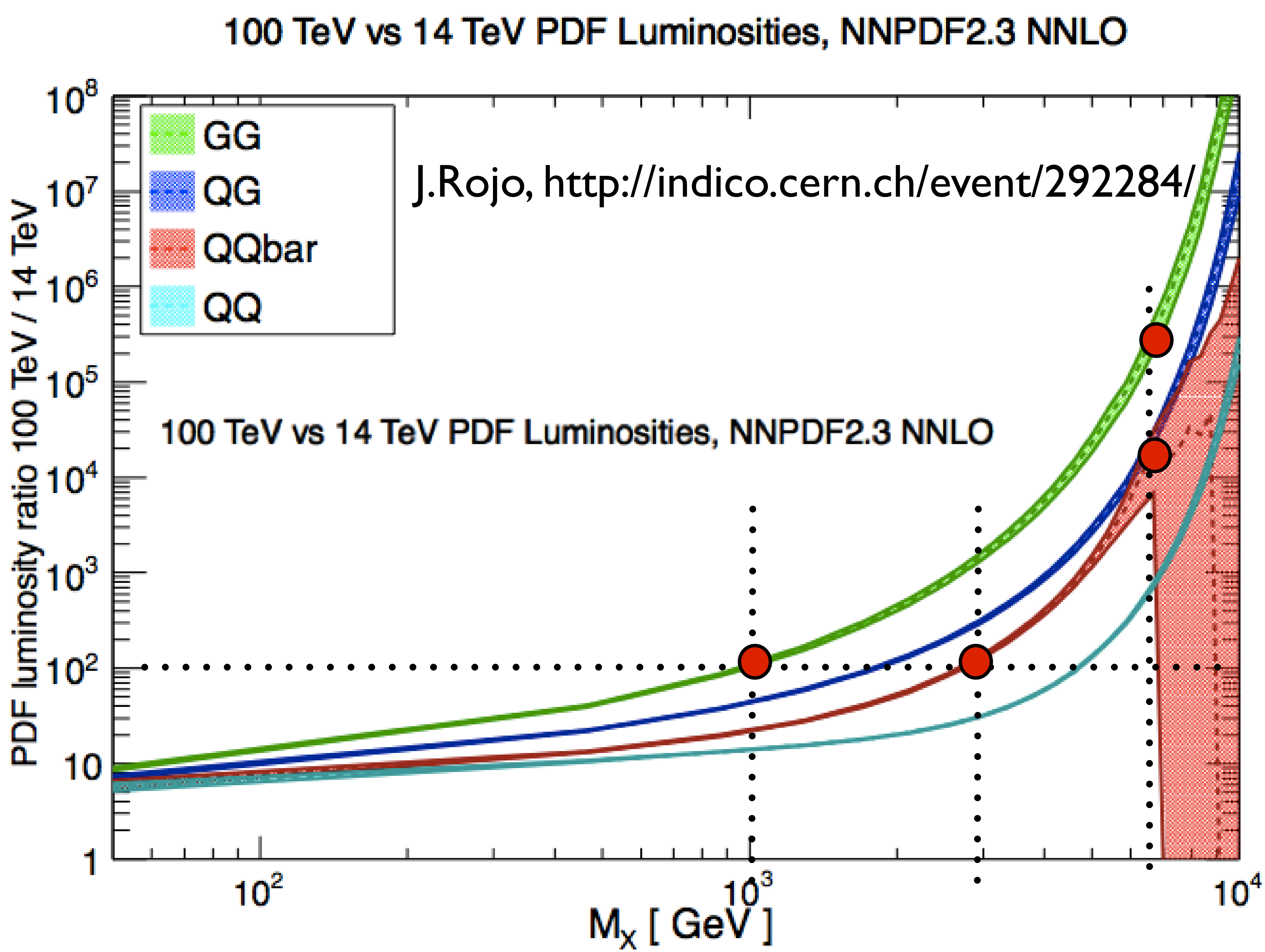
Extension of the discovery reach at low mass

- The extension power of higher lum can be important at lower masses, e.g. for processes with very suppressed rates, or difficult to separate from the bg.
- In this case, though, one might benefit more from improved detection efficiency than from pure luminosity.
- **The luminosity discussion is extremely process dependent (bg's, detector performance, pileup issues, etc)**

HL-LHC example: Direct stop searches (ATLAS Snowmass doc)



Higher statistics for studies of particles discovered at the LHC



At the edge of the HL-LHC discovery reach, namely $m_X \sim 6.5$ TeV :

$$\sigma(100\ \mathrm{TeV}) / \sigma(14\ \mathrm{TeV}) \sim \begin{cases} 10^4 \text{ for q-qbar} \to X \\ 10^5 \text{ for } gg \to X \end{cases}$$

This means:

- If **X** is discovered at the HL-LHC, it can be confirmed at 100 TeV with $10^{-(4\div5)}$ of the HL-LHC luminosity, i.e. O(30-300 pb^{-1})
  - => L < 5×10^{31} in the 1st year
- A luminosity of O(0.1 – 1 fb^{-1}) allows in principle the discovery of particles beyond the HL-LHC reach
  - => L < 2×10^{32} in the 1st year
- A luminosity of the order of the HL-LHC luminosity allows to improve by orders of magnitude the precision of the measurements of particle **X** discovered at the mass-end of the LHC reach

Higher statistics for Higgs studies

NLO rates

R(E) = σ(E TeV)/σ(14 TeV)

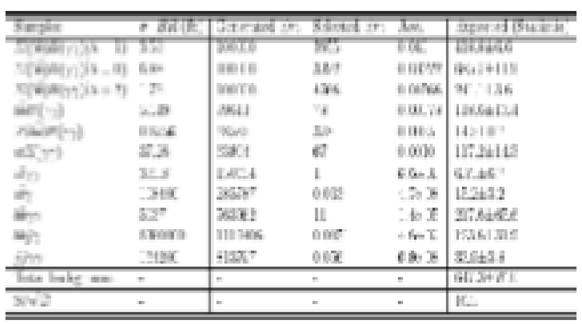
	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

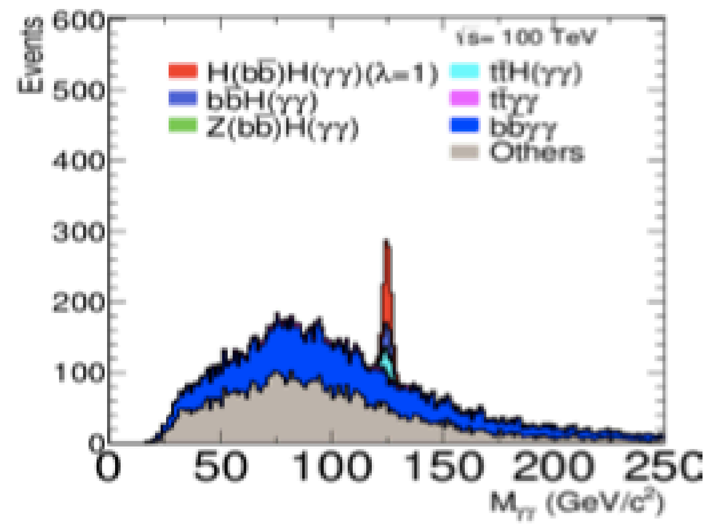
- Gains in the range 10-50, however ....
- => needs detailed studies, considering also the prospects to study rare decays, selfcouplings,etc.etc.

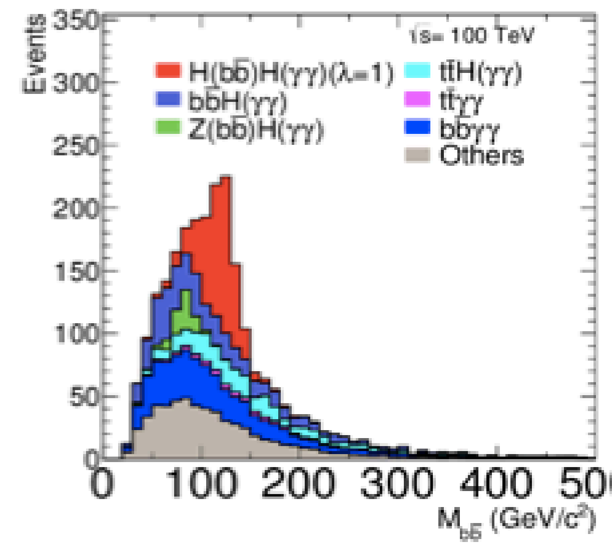
Example: Weiming's talk on measurement of H selfcoupling at 100 TeV

Updating HH→bbγγ at Tev100

- Using Delphes 3.1.14 and the results depends on detector performace assumed.
- Including jjγγ, bbjγ, ttγ, ttγγ with ATLAS fγ=0.0093e(-Et/27.5) for HL-LHC
- Tighten mγγ window from 10 GeV used for snowmass to 6 GeV.







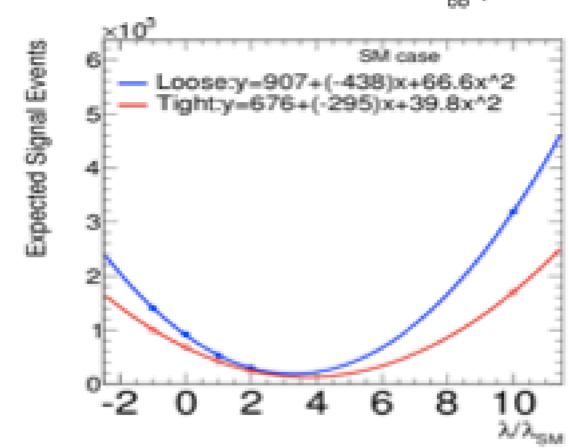
•Significance = 16.5 with 3 ab-1.

•H coupling dλ/λ=15% with dσ/dλ=-0.51

•ArXiv:1412.7154 reported 40% using ATLAS photon ID eff.

•To achieve 5% precision, we need to combine with other channels or get more integrated luminosity (~30 ab-1).

•Also start to probe Higgs coupling in VBF, ttHH channels.



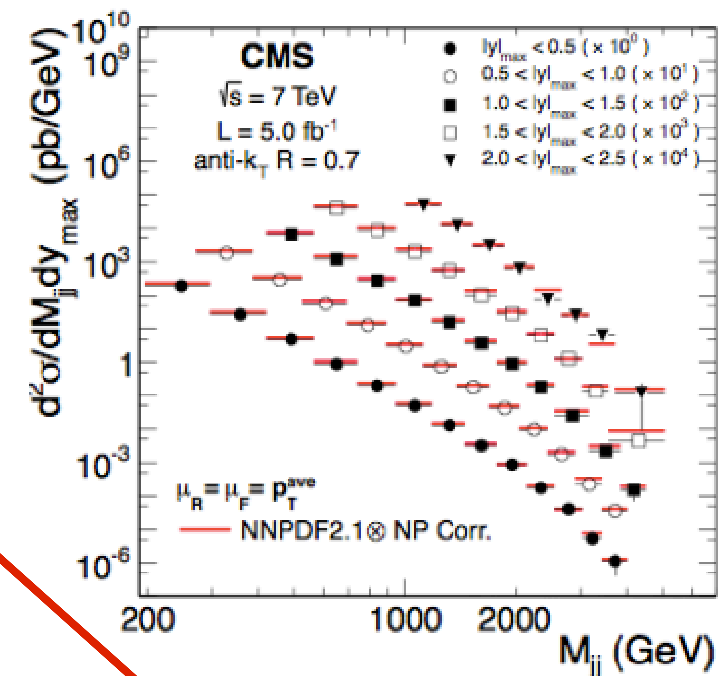
3

Charlie's view:

FCC Is a Discovery Machine

- Unknown new physics cannot provide unambiguous guidance.
- Well understood SM process that is relatively insensitive to simulation and/or analysis details as metric.
- Sufficient precision for comparison with SM at $M_{jj} \sim 0.5\sqrt{s}$ in 2 years

➔ $\mathcal{L} \sim 10^{36}$ cm^{-2} sec^{-1}



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Luminosity Requirements

10^{36} cm^{-2} sec^{-1} or bust!

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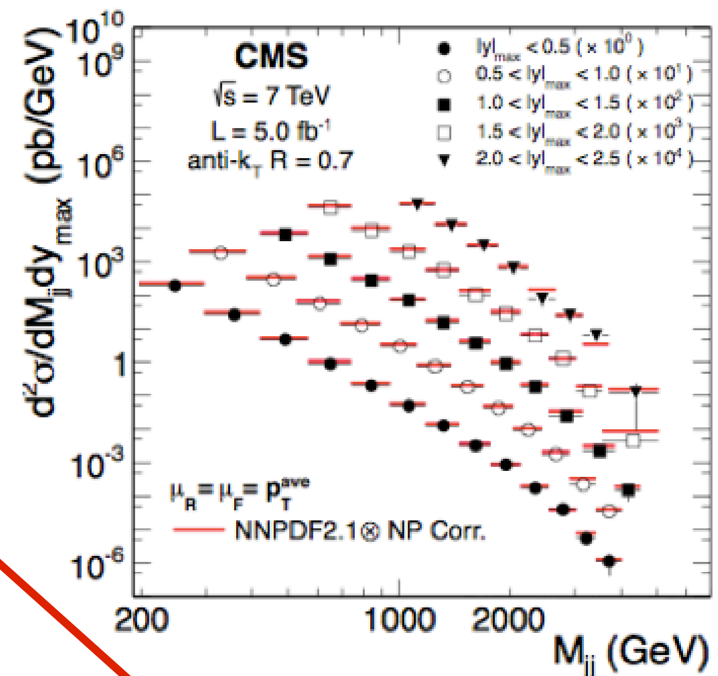

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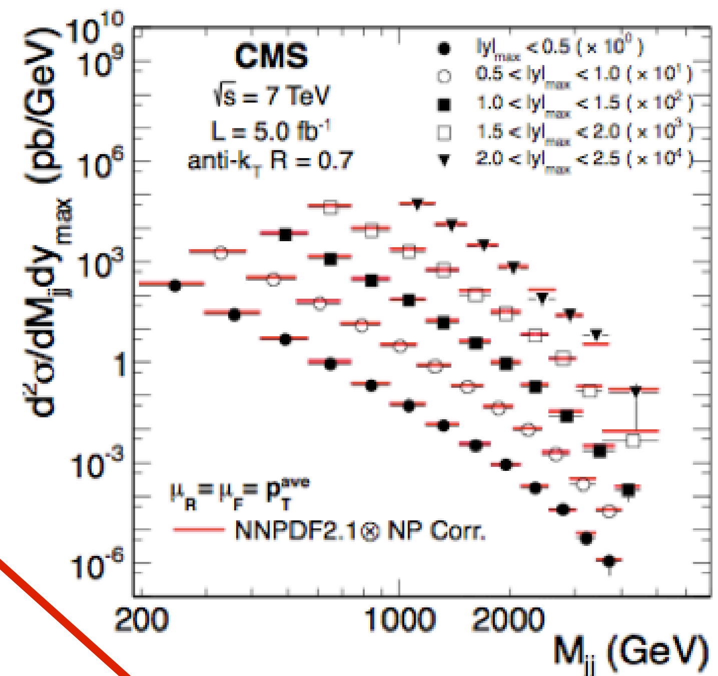

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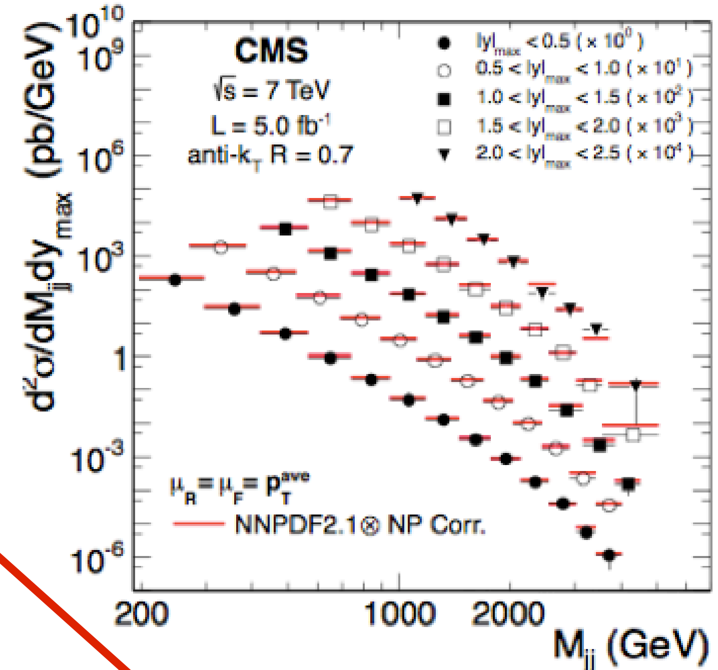

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... so even Charlie must agree that 5x10^{34} is enough !!

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- **More aggressive** luminosity goals may be required by specific measurements, but do not seem justified by generic arguments. Further work on ad hoc scenarios (particularly at low mass, elusive signatures, etc) is nevertheless desirable.

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- The goal of O(10-20 ab^{-1}) seems justified by the current perspective on
  - extension of the mass reach
  - high-statistics studies of possible new physics to be discovered at (HL)-LHC
  - high-statistics studies of the Higgs
- **More aggressive** luminosity goals may be required by specific measurements, but do not seem justified by generic arguments. Further work on ad hoc scenarios (particularly at low mass, elusive signatures, etc) is nevertheless desirable.
- For a large class of after-LHC scenarios, **less aggressive** lumi goals are also fully acceptable as optimal compromise between physics return and technical/experimental challenges