Physics with a 100 TeV pp collider

TH Wednesday Seminar
CERN, May 28 2014

Michelangelo L. Mangano
CERN, PH-TH

Dec 2011

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arXiv:1112.2518v1 [hep-ex]

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

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[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, submissions to Crakow Strategy Group Open Symposium

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)

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

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

LEP3 – Higgs factory in the LHC tunnel

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

Febr 2014

Design study for Future Circular Colliders

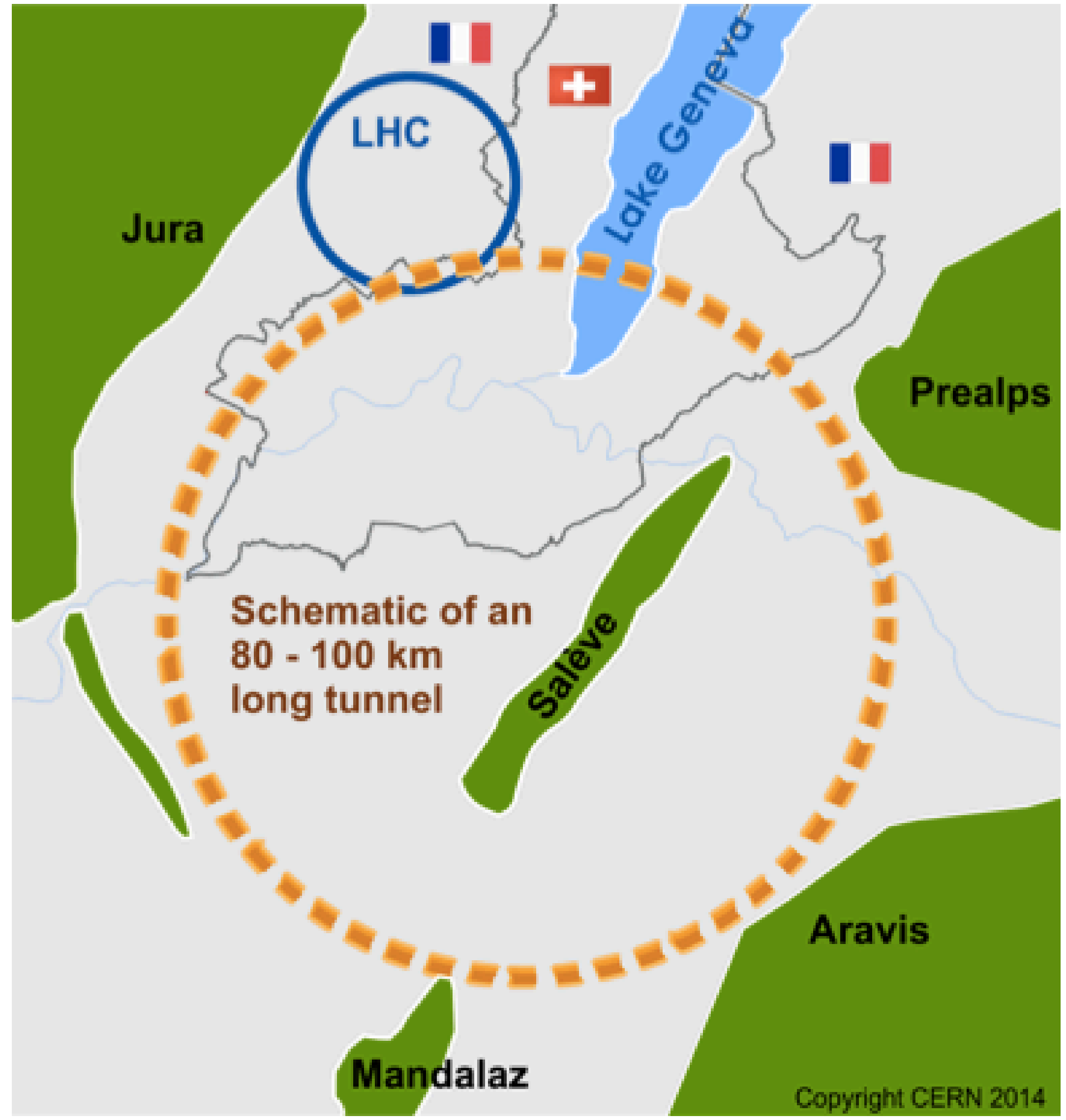
https://espace2013.cern.ch/fcc/

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



M.Benedikt

UNIVERSITÉ DE GENÈVE FCC

Future Circular Colliders Study Kickoff Meeting

12-15 February 2014
University of Geneva, Geneva
Europe/Zurich timezone

Search

Webcast: Please note that this event will be available live via the Webcast Service.

Future Circular Collider Kickoff Meeting

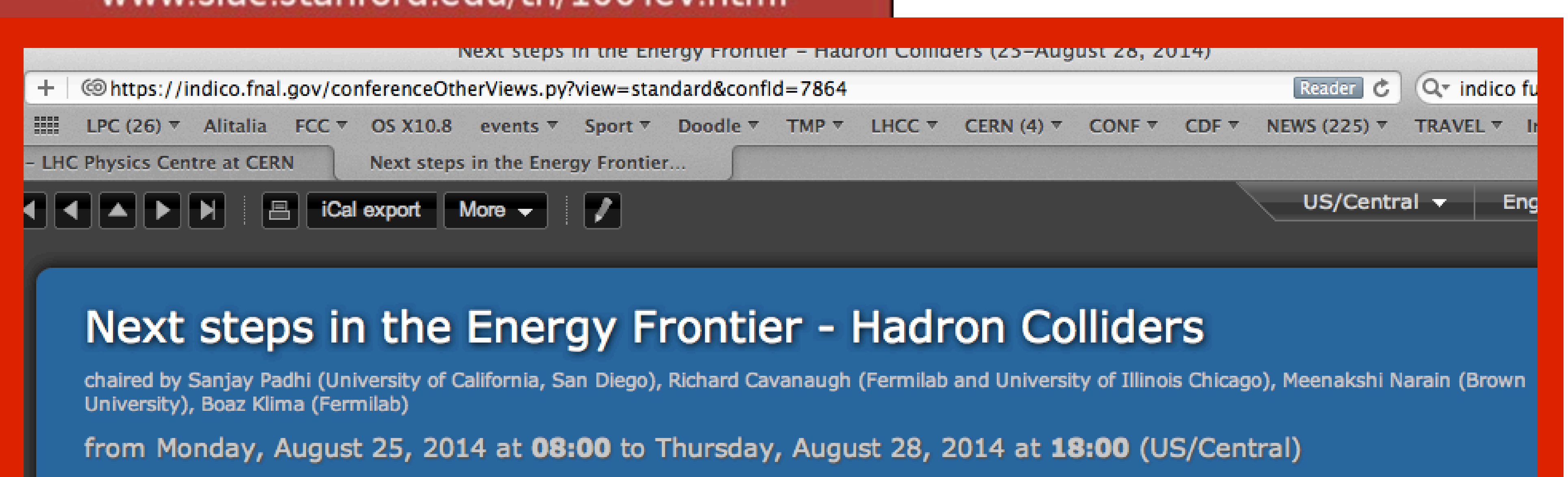
Machines and infrastructure conceptual designs	Technologies R&D activities Planning	Physics experiments detectors	
Infrastructure	High-field magnets	Hadron physics experiments interface, integration	MLM F.Gianotti A.Ball
Hadron collider conceptual design	Superconducting RF systems	$e^+ e^-$ coll. physics experiments interface, integration	J. Ellis P. Janot A. Blondel
Hadron injectors	Cryogenics	e^- - p physics and integration aspects	M. Klein
Lepton collider conceptual design	Specific technologies		
Safety, operation, energy management environmental aspects	Planning		

Target: conceptual design report (CDR) ready for the next Strategy Group assessment (~2018)

- **Goal of this effort:** Conceptual design report (CDR) and first cost estimate ready for the next Strategy Group assessment (~2018)
- **Likely next step:** Commission a full technical design report (TDR), ready for the following Strategy Group assessment (~2024)
- **Plausible next step at 2024 Strategy Review:** Review TDR and updated cost estimate, in view of LHC14@300fb^{-1} results and more. Recommend CERN Council to approve, abort, or postpone.

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

Parallel activities in the world



The landscape at the TeV scale

What's hiding behind/beyond the TeV scale ?

A few crucial questions specific to the TeV scale demand an answer and require exploration:

- **Hierarchy problem/Naturalness**
  - where is everybody else beyond the Higgs ?
- **EW dynamics above the symmetry breaking scale**
  - weakly interacting? strongly interacting ? other interactions, players ?
- **Dark matter**
  - is TeV-scale dynamics (WIMPs) at the origin of Dark Matter ?
- **Cosmological EW phase transition**
  - is it responsible for baryogenesis ?

Remarks

- Despite the relevance of these questions, and the conviction that they will find an answer, there is no guarantee that such answer will come soon.
- There is no absolute no-lose theorem in sight, pointing with absolute certainty to a given experimental facility
- The planning of future facilities may need to be driven by the exploratory spirit that characterized the golden age of particle physics.
- But the directions are clear:
    - higher energy (push the search for “everyone else”)
    - higher-precision studies (of Higgs sector, of EW interactions)

pp at 100 TeV opens three windows:

➥ Access to new particles in the few→30 TeV mass range, beyond LHC reach

➥ Immense/much-increased rates for phenomena in the sub-TeV mass range ⇒

increased precision w.r.t. LHC and possibly ILC

➥ Access to very rare processes in the sub-TeV mass range ⇒

search for stealth phenomena, invisible at the LHC

Each of these windows requires dedicated physics studies, and poses different challenges to the detector design:

- High-mass exploration:
  - reach estimates
  - scaled-up LHC detectors: contain multi-10 TeV jets (deeper calorimetry), measure multi-TeV muons (higher B-fields, larger radii)
- Higher rates for TeV-scale processes, precision physics:
  - vastly increased trigger bands, HLT intelligence and processing power, read-out and storage technology and strategies
  - calorimeter granularity, ability to reconstruct and tag the nature of "jet objects"
  - improved theoretical control and systematics
- Rare and stealthy processes:
  - trigger sophistication, lower thresholds, low-pT reconstruction
  - pileup mitigation
  - hermetic coverage, including tracking
  - greater control of SM backgrounds, data-driven and theory-driven

- **Bottom line:**
  - keep a VERY open mind for detector design, envisage different detectors optimized to deal with high-mass and with (sub)-TeV physics

Physics topics list

FHC.1.1 Exploration of EW Symmetry Breaking (EWSB)

FHC.1.1.1 High-mass WW scattering, high mass HH production

FHC.1.1.2 Rare Higgs production/decays and precision studies of Higgs properties

FHC.1.1.3 Additional BSM Higgs bosons: discovery reach and precision physics programme

FHC.1.1.4 New handles on the study of non-SM EWSB dynamics (e.g. dynamical EWSB and composite H, etc)

FHC.1.2 Exploration of BSM phenomena

FHC.1.2.1 discovery reach for various scenarios (SUSY, new gauge interactions, new quark and leptons, compositeness, etc.)

FHC.1.2.2 Theoretical implications of discovery/non-discovery of various BSM scenarios, e.g. address questions such as:

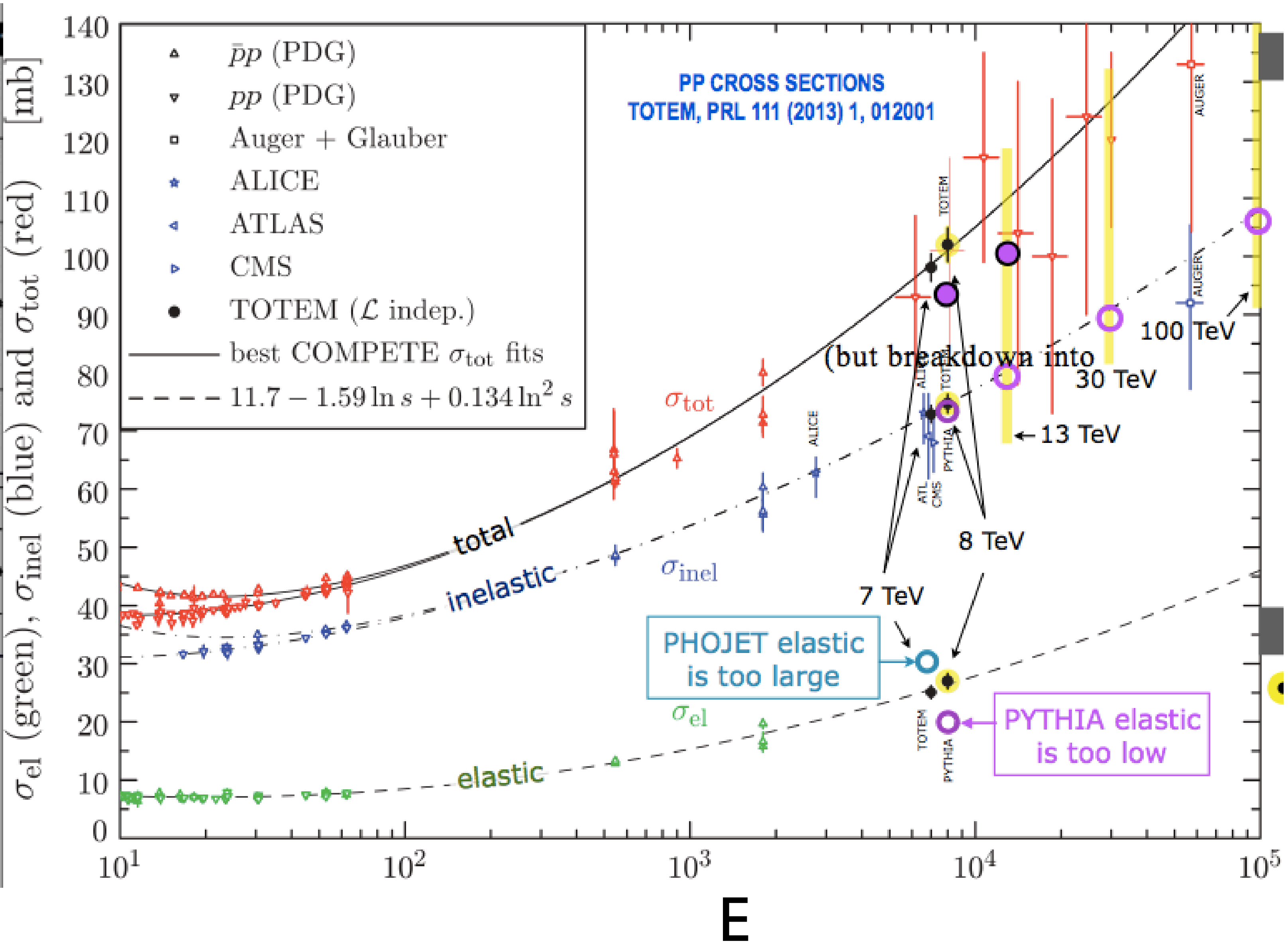
- FHC.1.2.2.1 what remains of Supersymmetry if nothing is seen at the scales accessible at 100 TeV?
- FHC.1.2.2.2 which new opportunities open up at 100 TeV for the detection and study of dark matter?
- FHC.1.2.2.3 which new BSM frameworks, which are totally outside of the HL-LHC reach, become accessible/worth-discussing at 100 TeV ?

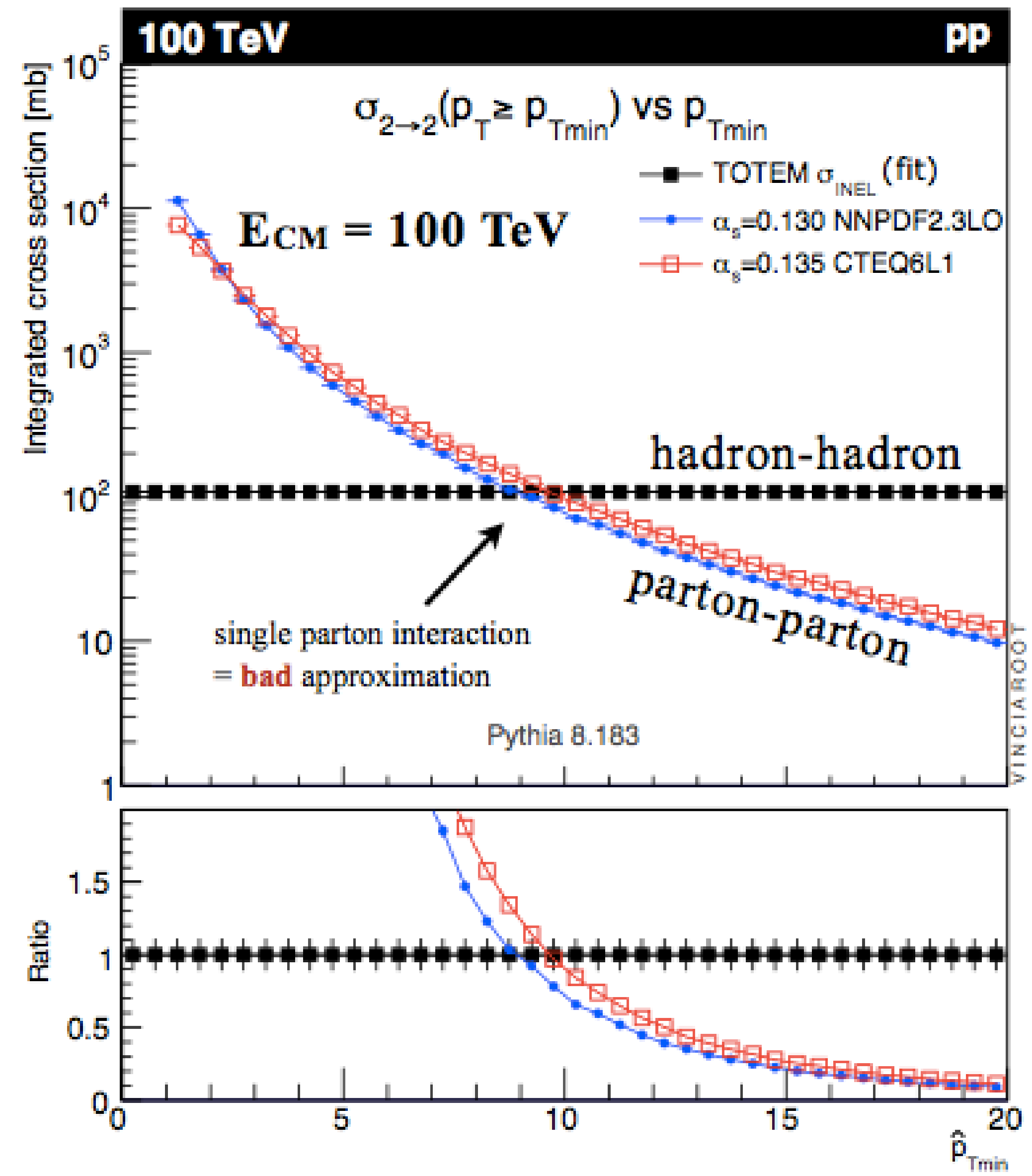
FHC.1.3 Continued exploration of SM particles
FHC.1.3.1 Physics of the top quark (rare decays, FCNC, anomalous couplings, ...)
FHC.1.3.2 Physics of the bottom quark (rare decays, CPV, ...)
FHC.1.3.2 Physics of the tau lepton (e.g. tau -> 3 mu, tau -> mu gamma and other LFV decays)
FHC.1.3.2 W/Z physics
FHC.1.3.3 QCD dynamics

FHC.1.4 Opportunities other than pp physics:
FHC.1.4.1 Heavy Ion Collisions
FHC.1.4.2 Fixed target experiments:
FHC.1.4.2.1 "Intensity frontier": kaon physics, mu2e conversions, beam dump experiments and searches for heavy photons, heavy neutrals, and other exotica...
FHC.1.4.2.2 Heavy Ion beams for fixed-target experiments

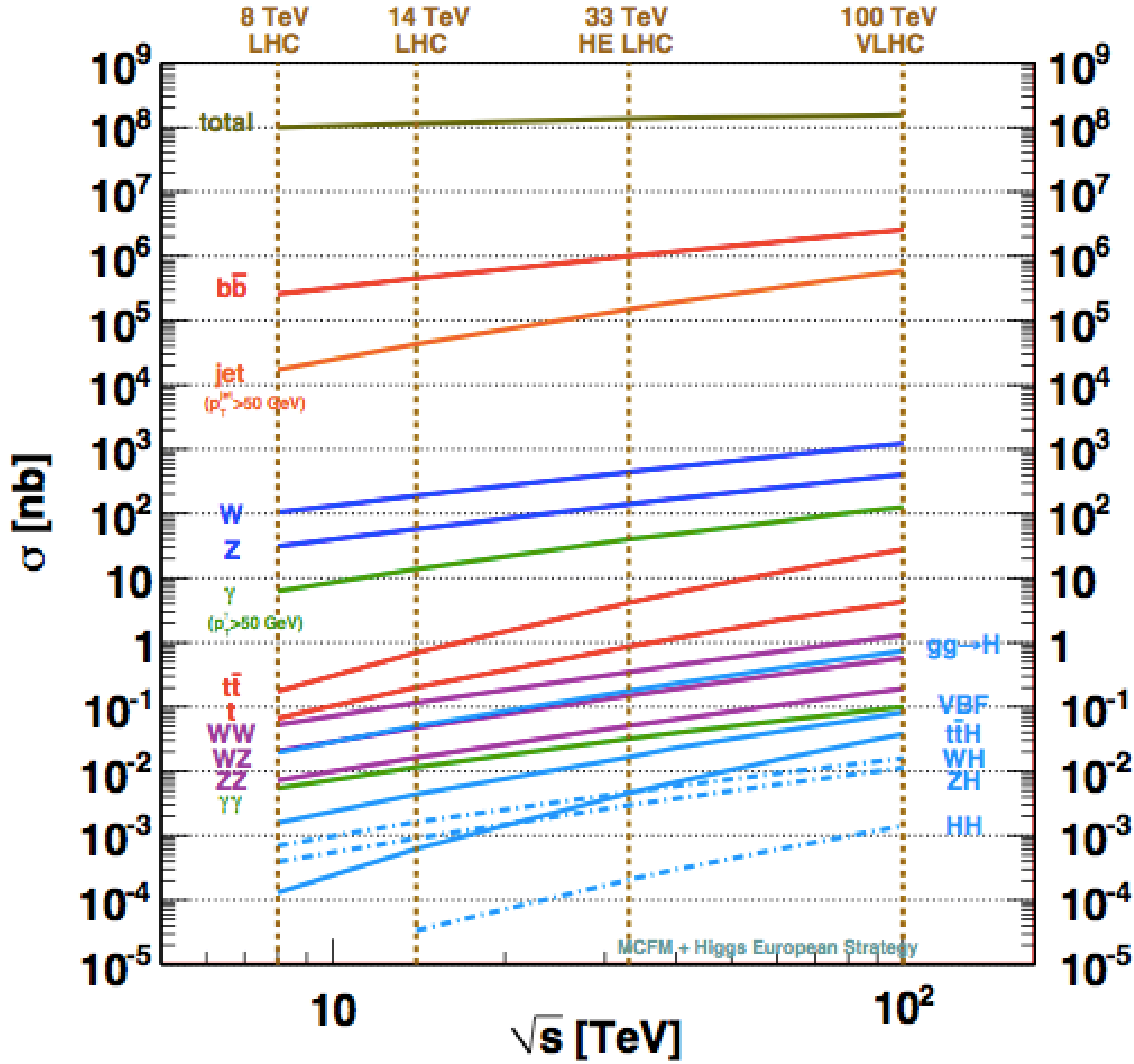
FHC.1.5 Theoretical tools for the study of 100 TeV collisions
FHC.1.5.1 PDFs
FHC.1.5.2 MC generators
FHC.1.5.3 N^nLO calculations
FHC.1.5.4 EW corrections

Global aspects of 100 TeV pp collisions



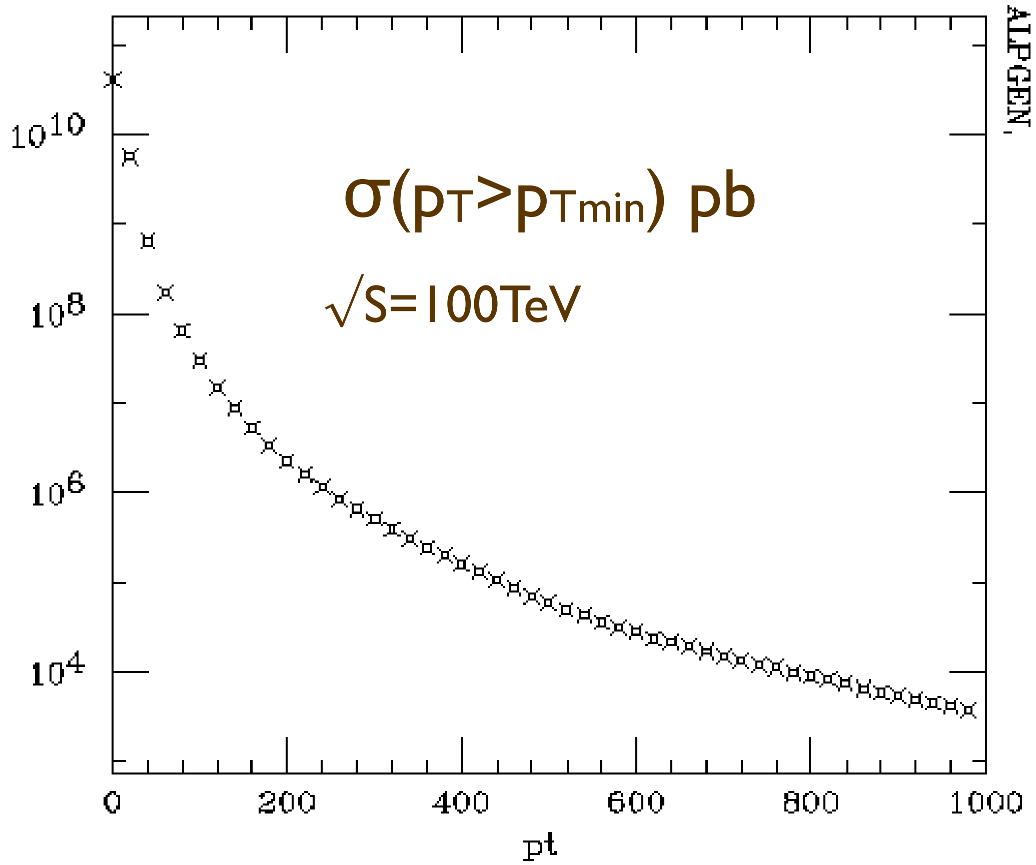


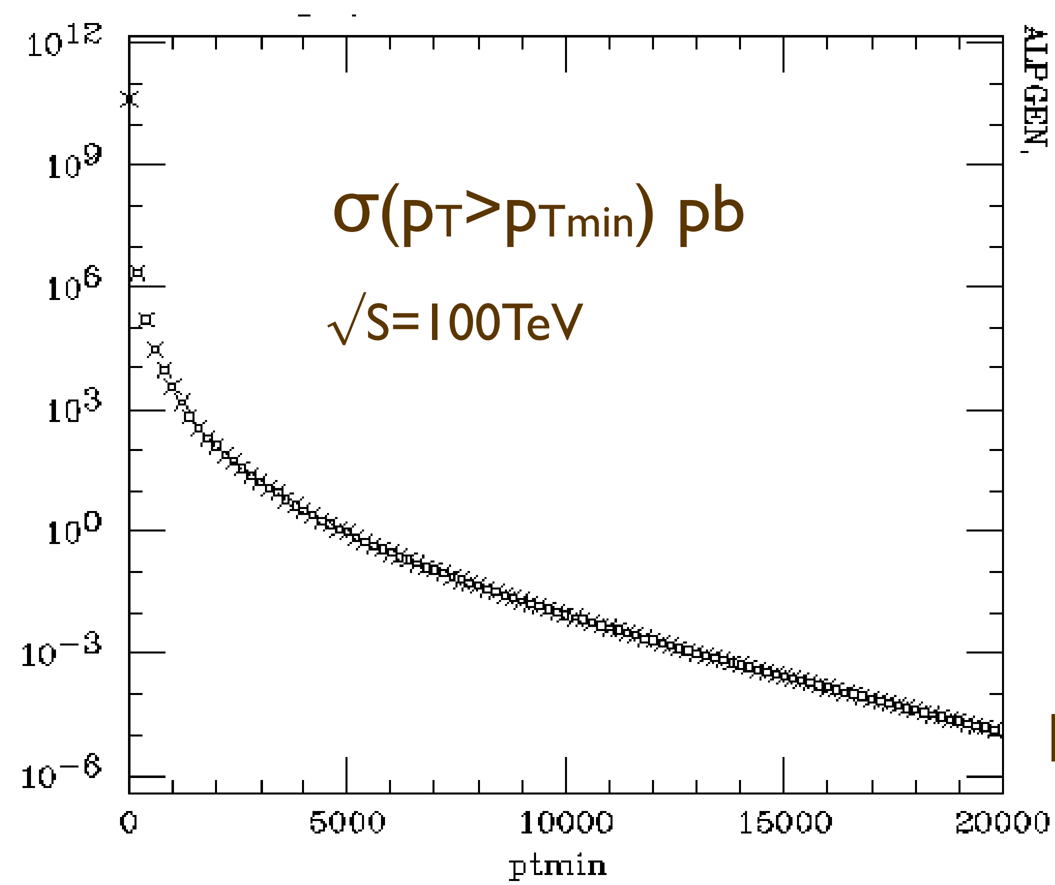
P.Skands



- See e.g. Report of the Snowmass 2013 energy frontier QCD working group, http://arxiv.org/abs/1310.5189v1

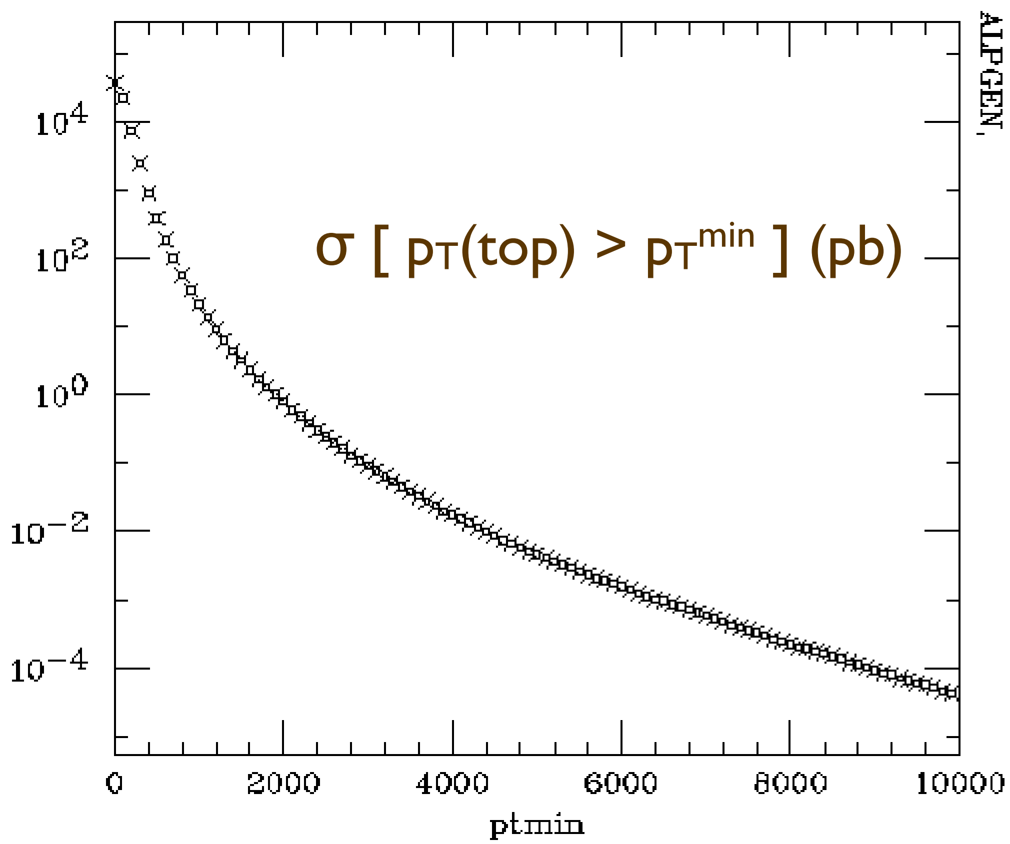
Inclusive jets

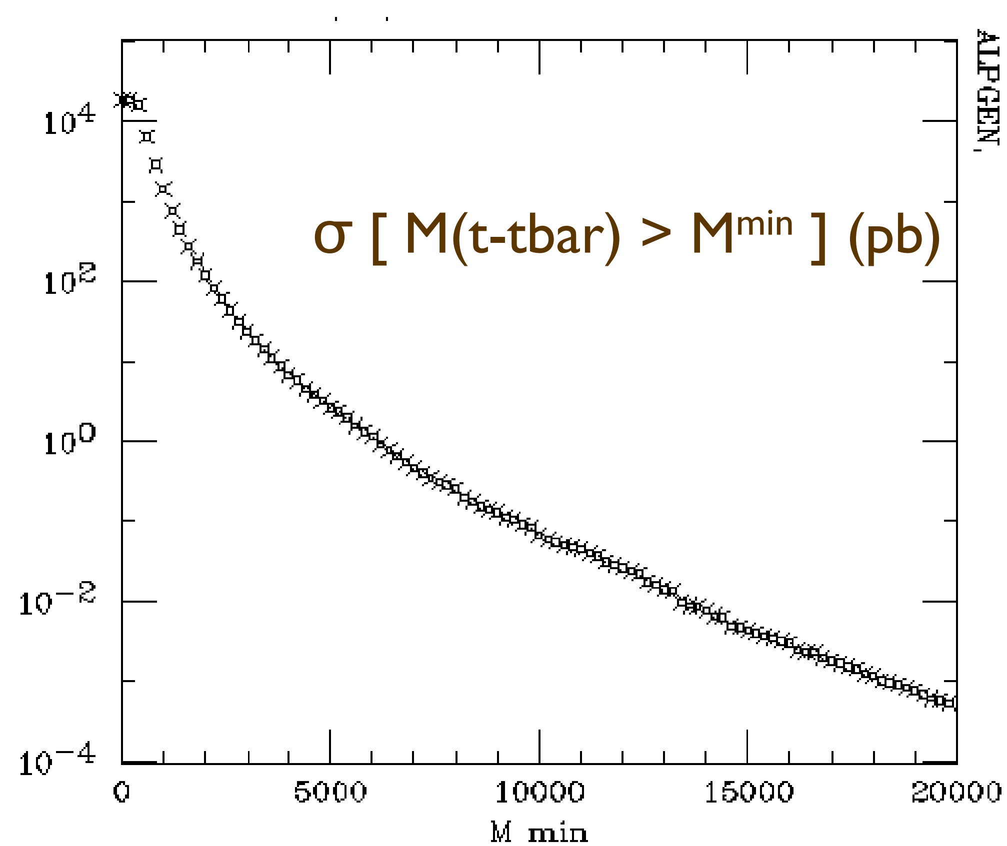




1 event/100fb^{-1}

Inclusive t-tbar production

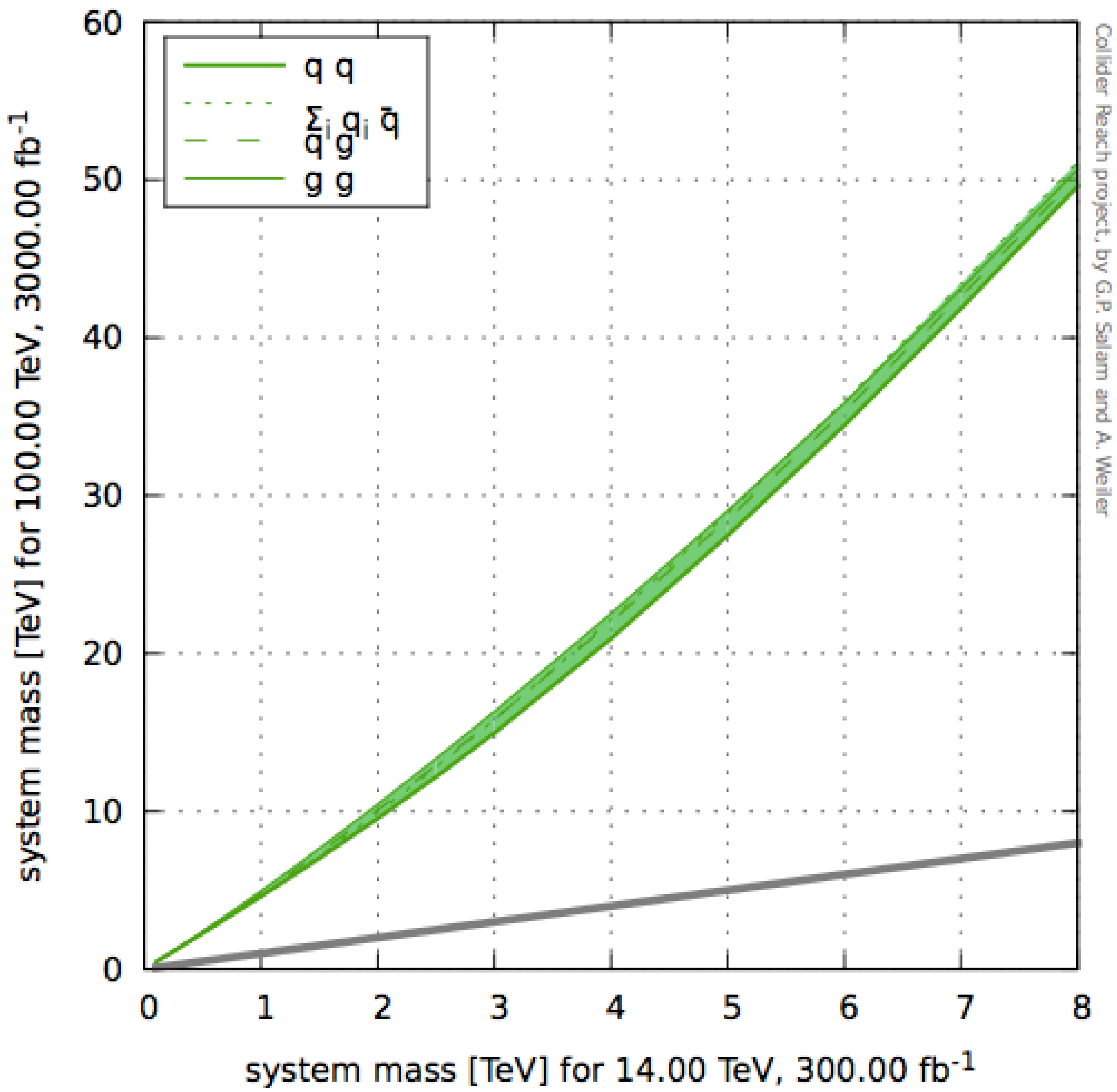




Projecting the discovery reach

http://cern.ch/collider-reach, Salam, & Weiler

$$14\ \text{TeV}_{300\ fb^{-1}} \rightarrow 100\ \text{TeV}_{3\ ab^{-1}}$$



The PDF choice was CT10nlo.LHgrid

Original mass	gg	qg	allqq	qqbar
100.	469.	465.	462.	457.
125.	585.	579.	575.	568.
150.	702.	693.	687.	679.
200.	937.	923.	912.	902.
300.	1414.	1386.	1365.	1350.
500.	2394.	2332.	2279.	2261.
700.	3401.	3300.	3206.	3194.
1000.	4956.	4793.	4619.	4640.
1250.	6287.	6072.	5818.	5892.
1500.	7647.	7382.	7038.	7187.
2000.	10444.	10090.	9552.	9905.
2500.	13337.	12908.	12185.	12781.
3000.	16319.	15833.	14954.	15795.
4000.	22531.	21986.	20933.	22162.
5000.	29050.	28508.	27467.	28894.
6000.	35863.	35366.	34451.	35960.
7000.	43079.	42620.	41854.	43411.
8000.	50671.	50230.	49590.	51132.

Rule of thumb: at fixed Luminosity, discovery reach scales like 2/3 E_{beam}
=> x 5 from 14 to 100 TeV

Without a guarantee that any particular new phenomenon will manifest itself, the exploration of the discovery potential must be accompanied by a more focused understanding of what are the qualitative changes made possible by the access to the 100 TeV region. Address obvious questions such as:

- if we haven't seen something by 14 TeV, why should it show up by 100 TeV?
- what are the origins and the motivations of mass scales in the range beyond the LHC, but within the reach of 100 TeV?
- what are the new rare processes that become interesting to explore with the increased statistics possible at 100 TeV?
- are there BSM scenarios for which one can formulate “sort of” no-lose theorems at 100 TeV ?
- For phenomena that could already be probed at the LHC, which new observables and states that may open up for exploration at 100 TeV?
- How do these interplay with other probes that could be available 30 years from now (e.g. from the cosmos, from an e+e– collider, etc)?
- ...

Few examples of ongoing studies, ideas, possible tasks, etc.

Higgs

Higgs physics

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

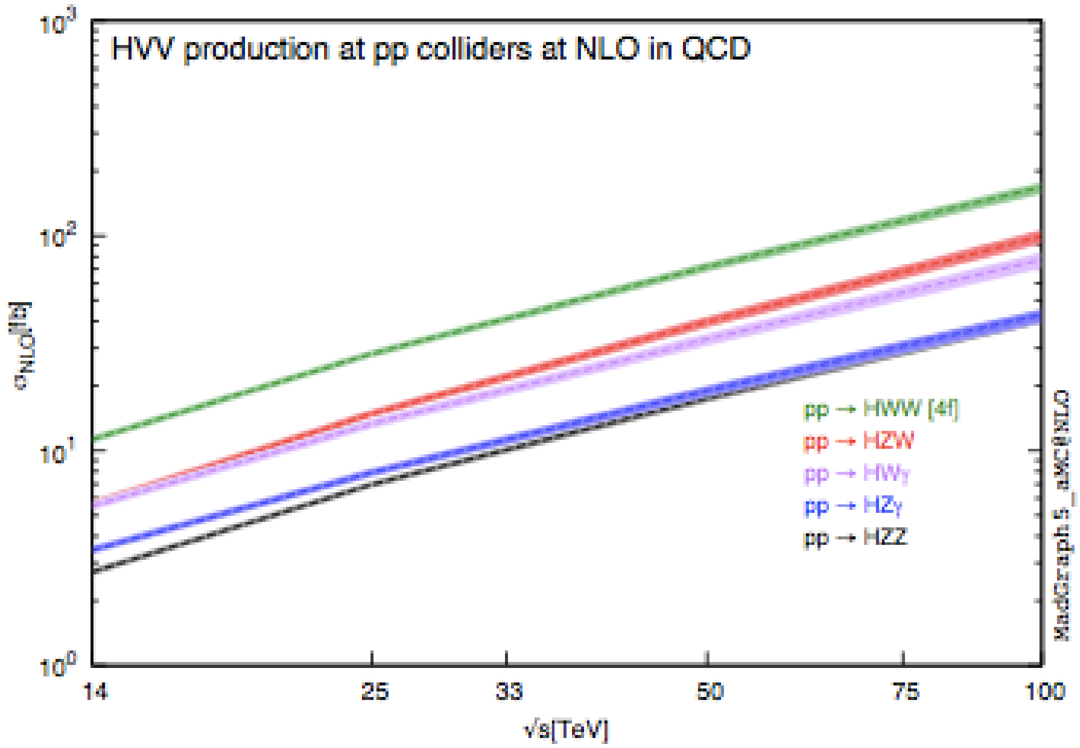
In several cases, the gains in terms of "useful" rate are much bigger.
E.g. when we are interested in the large-invariant mass behaviour of the final states:
$\sigma(ttH, p_T^{top} > 500\text{ GeV}) \Rightarrow R(100) = 250$

Task: explore new opportunities for measurements, to reduce systematics with independent/complementary kinematics, backgrounds, etc.etc.

Examples: how much can we reduce jet veto systematics by "measuring" jet rates/vetoes in "clean" channels like $H \to ZZ^* / \gamma\gamma$?

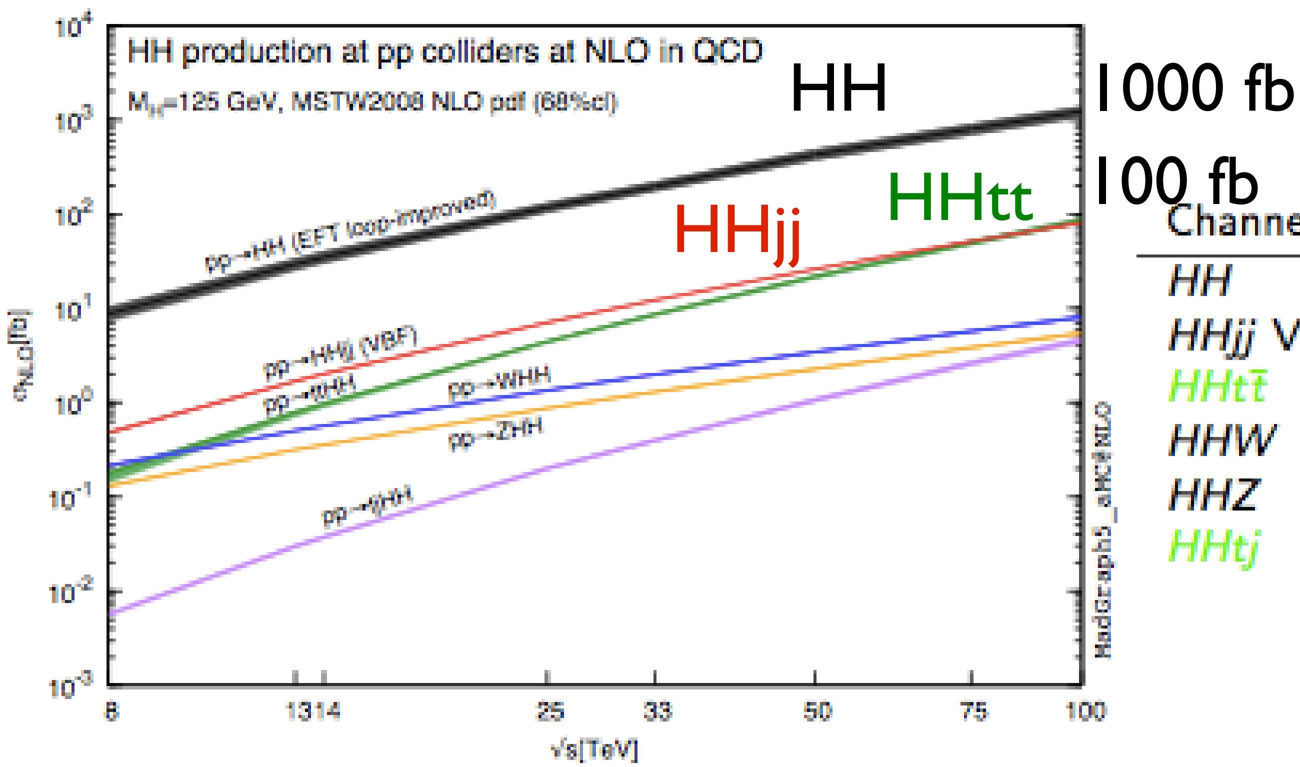
Rare H production modes

Higgs-diboson associated production



Channel	$\frac{\sigma_{100}}{\sigma_{14}}$	$\frac{\sigma_{100}}{\sigma_{8}}$
HWW	20	35
HZW	20	45
$HW\gamma$	15	35
$HZ\gamma$	10	30
HZZ	15	40

Higgs-pair associated production



Channel	$\frac{\sigma_{100}}{\sigma_{14}}$	$\frac{\sigma_{100}}{\sigma_{8}}$
HH	35	150
$HHjj$ VBF	45	180
$HHt\bar{t}$	100	600
HHW	15	40
HHZ	15	40
$HHtj$	130	800

Which opportunities for new measurements and probes of Higgs properties are made possible by these new channels ?

P.Torrielli, MadGraph5-aMC@NLO

Example: Top Yukawa coupling to sub-% precision ?

At 14 TeV $\sigma(ttH)$ = 0.6113 pb $[\,^{+5.9\%}_{-9.3}\,]_{\text{Scale}} \pm$ 8.9% $_{\text{PDF}+\alpha S}$

Higgs XS WG, arXiv:1101.0593 and twiki page

At 100 TeV $\sigma(ttH)$ = 37.9 pb ~ 60 x σ(14 TeV)

$L(fb^{-1})$	Exp.	$\kappa_g \cdot \kappa_Z/\ \kappa_H$	κ_γ/κ_Z	κ_W/κ_Z	κ_b/κ_Z	κ_τ/κ_Z	κ_Z/κ_g	κ_t/κ_g	κ_μ/κ_Z	$\kappa_{Z\gamma}/\kappa_Z$
300	ATLAS	[3,6]	[5,11]	[4,5]	N/a	[11,13]	[11,12]	[17,18]	[20,22]	[78,78]
	CMS	[4,6]	[5,8]	[4,7]	[8,11]	[6,9]	[6,9]	[13,14]	[22,23]	[40,42]
3000	ATLAS	[2,5]	[2,7]	[2,3]	N/a	[7,10]	[5,6]	[6,7]	[6,9]	[29,30]
	CMS	[2,5]	[2,5]	[2,3]	[3,5]	[2,4]	[3,5]	[6,8]	[7,8]	[12,12]

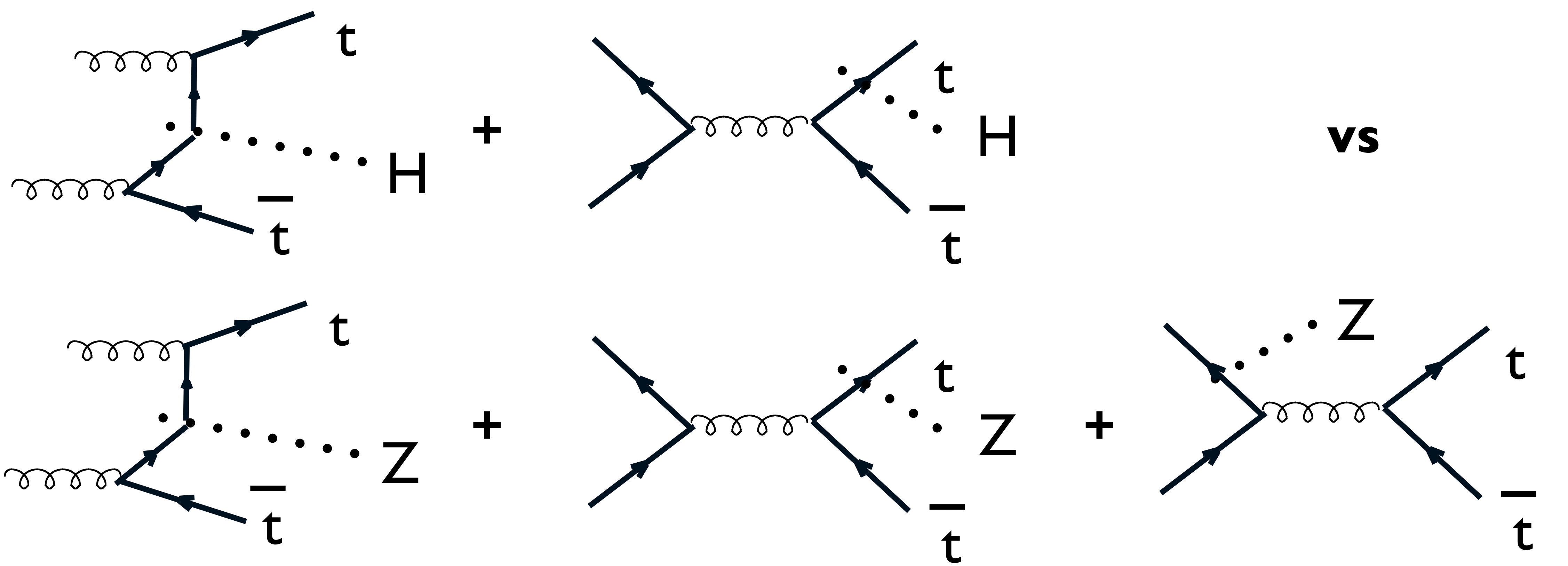
Table 1. Estimated precision on the measurements of ratios of Higgs boson couplings. These values are obtained at $\sqrt{s}$ = 14 TeV using an integrated dataset of 300 fb^{-1} at LHC, and 3000 fb^{-1} at HL-LHC. Numbers in brackets are % uncertainties on couplings for [no theory uncertainty, current theory uncertainty] in the case of ATLAS and for [Scenario2, Scenario1] in the case of CMS.

Note: assume no invisible Higgs decay contributing to the Higgs width

CMS Scenario 2: same systematics as 2012 (TH and EXP)
CMS Scenario 1: half the TH syst, and scale with 1/sqrt(L) the EXP syst

ATLAS Scenario 2: same TH systematics as 2012, EXP syst driven by stats scaled accordingly
ATLAS Scenario 1: same as 2, but TH syst →0

$pp \to tt\,H$ vs $pp \to tt\,Z$



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:

data from R.Frederix

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

	$\delta\sigma(ttH)$	$\delta\sigma(ttZ)$	**$\sigma(ttH)/\sigma(ttZ)$**	**$\delta[\sigma(ttH)/\sigma(ttZ)]$**
14 TeV	± 9.8%	± 12.3%	**0.608**	**±2.6%**
100 TeV	± 9.6%	± 10.8%	**0.589**	**±1.2%**

PDF dependence (CTEQ6.6. only)

data from R.Frederix

	$\delta\sigma(ttH)$	$\delta\sigma(ttZ)$	**$\delta[\sigma(ttH)/\sigma(ttZ)]$**
14 TeV	± 4.8%	± 5.3%	**±0.75%**
100 TeV	± 2.7%	± 2.3%	**±0.48%**

NB Uncertainty bands for x symmetrized around $(x_{min}+x_{max})/2$

Additional Higgs bosons

⇒ commonly present in most SM extensions. E.g. at least 2 H doublets is mandatory in SUSY

⇒ implications for flavour, CPV, EW baryogenesis, ...

Difficult scenarios for searches at LHC:

- suppressed couplings to W/Z
- large masses

Problems addressed at 100 TeV thanks to higher rates, higher M reach

E.g. 2HDM in SUSY

$m_h, m_H, m_A, m_{H^\pm}$ $\tan\beta \equiv \langle\Phi_2\rangle / \langle\Phi_1\rangle$

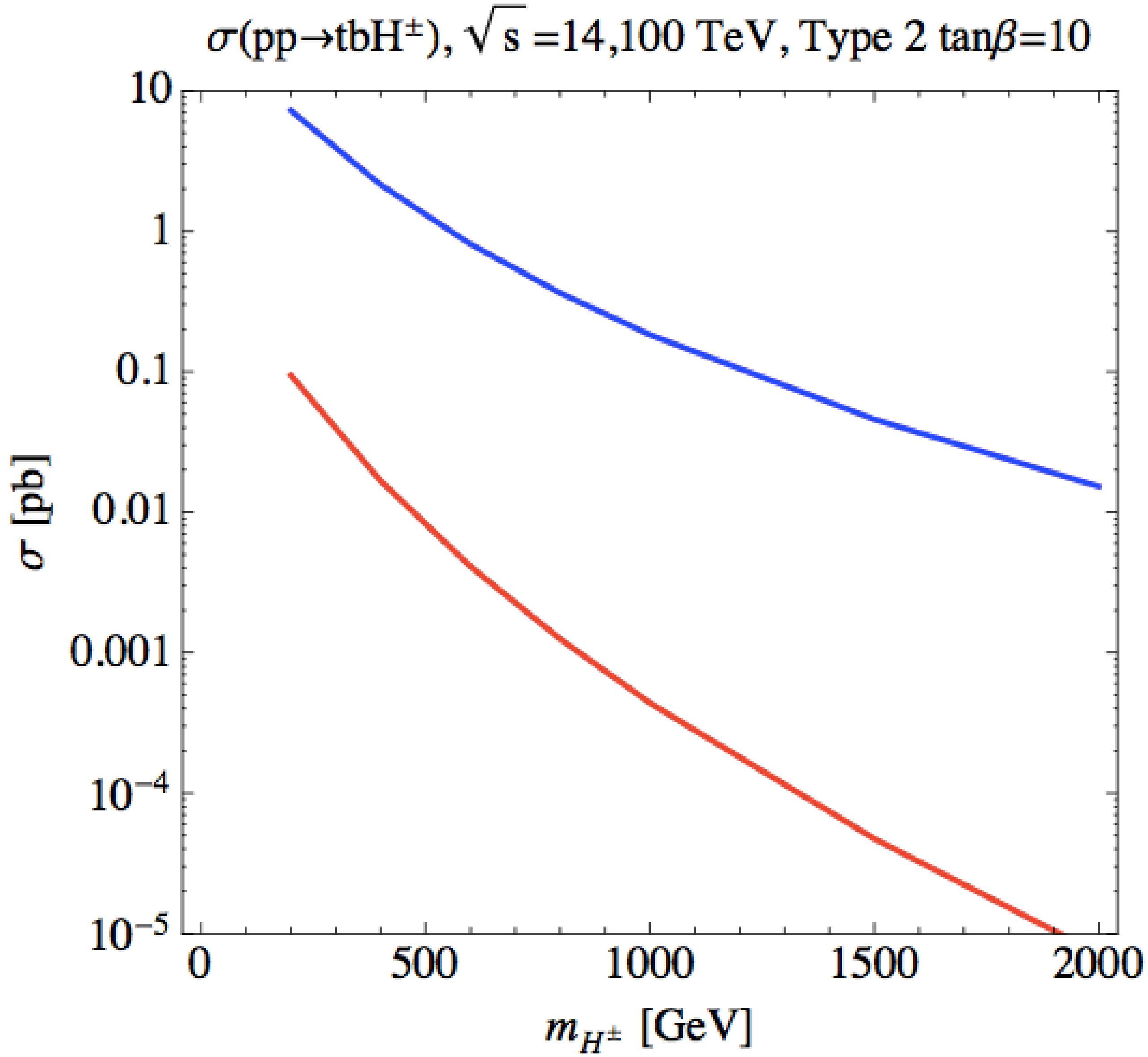
Fine tuning and naturalness: (N.Craig, BSM@100 Wshop)

$$\Delta \approx \sin^2(2\beta)\frac{m_H^2}{m_h^2}$$

$$\Delta(\tan\beta = 50) \leq 1 \rightarrow m_H \lesssim 3.1\ \text{TeV}$$

Extra H can be heavy, well above LHC reach, but cannot be arbitrarily heavy

Example: associated $H^{\pm}$ t b production



(N.Craig, BSM@100 Wshop)

Generic features of very heavy H production/decay

Decoupling from W/Z ⇒

- "narrow", since $\Gamma \propto m_H$ (cfr $\Gamma \propto m_H^3$ when decaying to W/Z)
- H/A → hh, tt dominate (boosted regime)

Interesting questions

⇒ will there be no-lose scenarios ? E.g. for

- o MSSM 2HDM
- o 2HDM EW baryogenesis
- o ...

⇒ how will, in these scenarios, naturalness constraints from the stop/gluino sectors compare to those from the Higgs sector?

Studies of such questions and of discovery reach just starting.

EW interactions at high energy

Exploration of EW interactions at high energy via Multi-gauge boson production

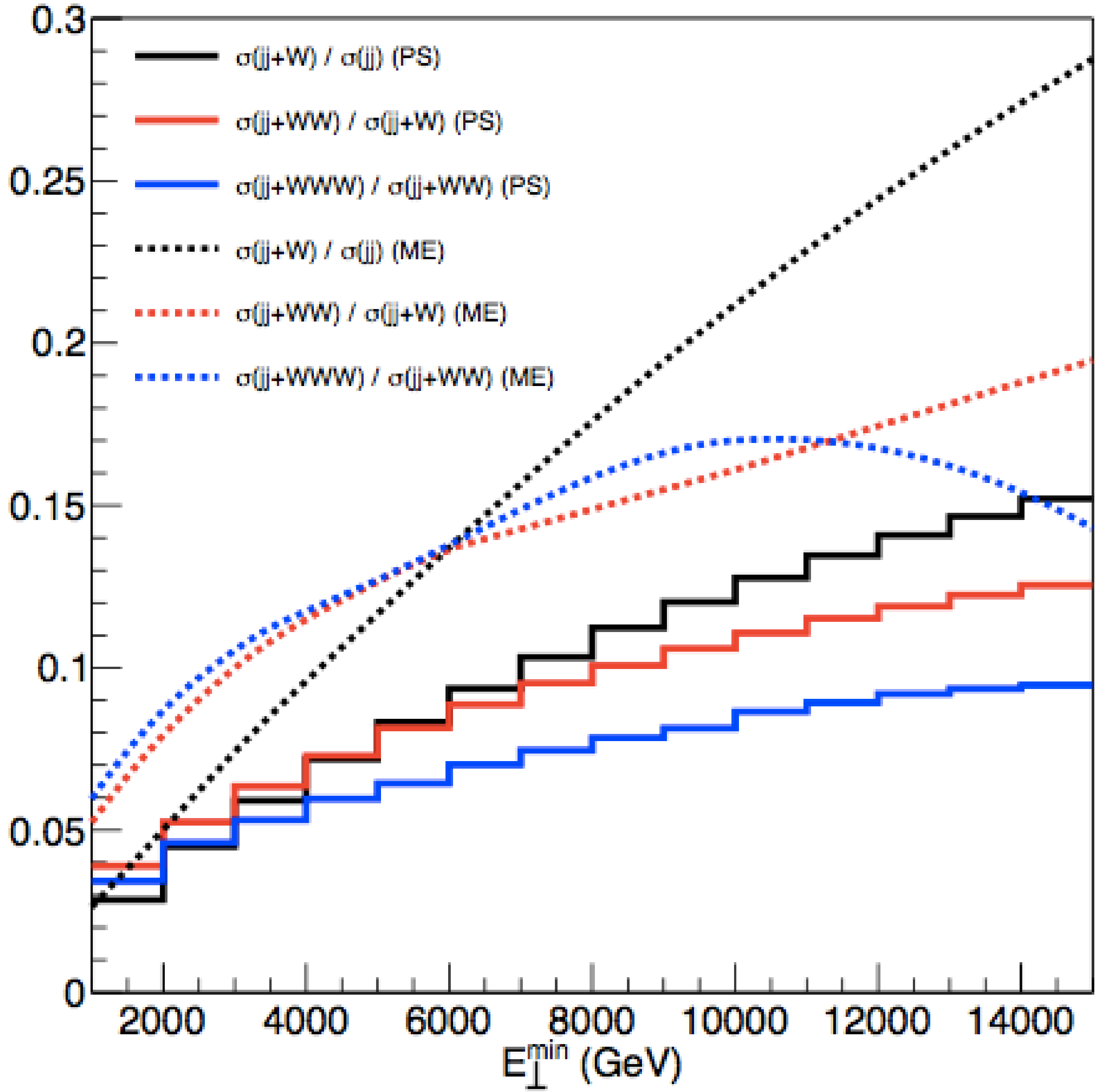
At 100 TeV:

WW	**σ=770 pb**	(no BR included)
WWW	**σ=2 pb**	
WWZ	**σ=1.6 pb**	
WWWW	**σ=15 fb**	
WWWZ	**σ=20 fb**	
....		

Tasks:

o determine experimental accept/eff's: how high can we go in multiplicity?
o what can we learn on EW interactions at high energy from these studies?
o which variables/correlations to consider?
o can we use dijet decays at high pt(W) ?

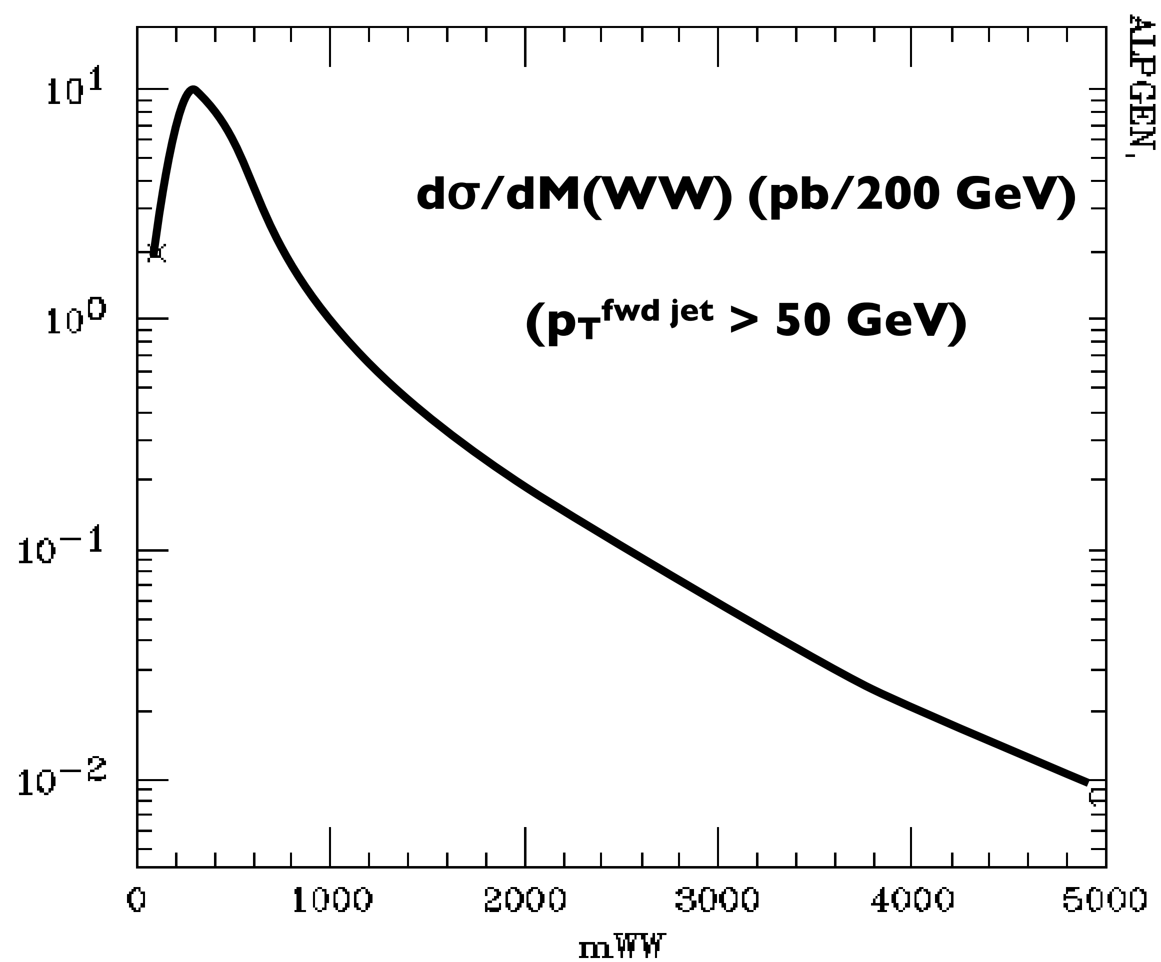
~ 10% probability of W emission from high-energy quark jets



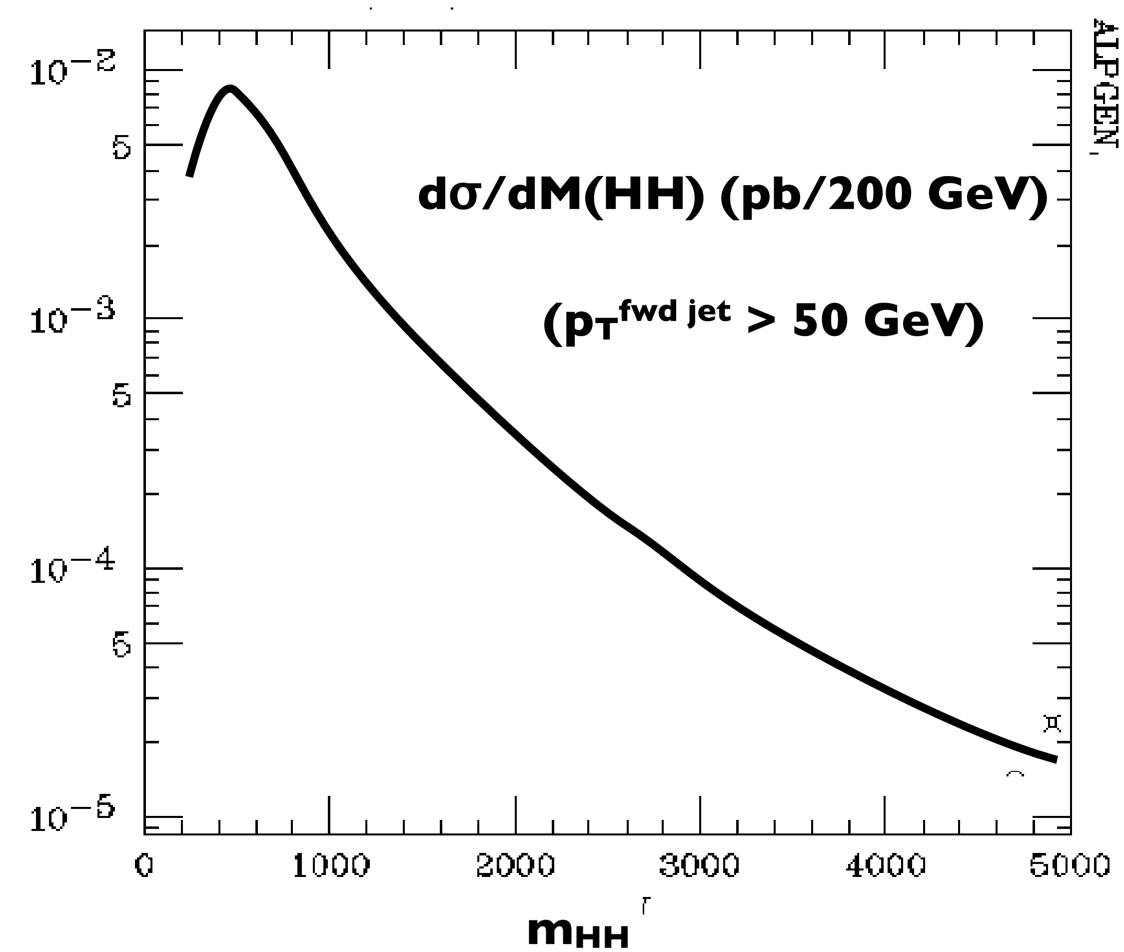
Christiansen

EWSB probes: high mass WW/HH in VBF

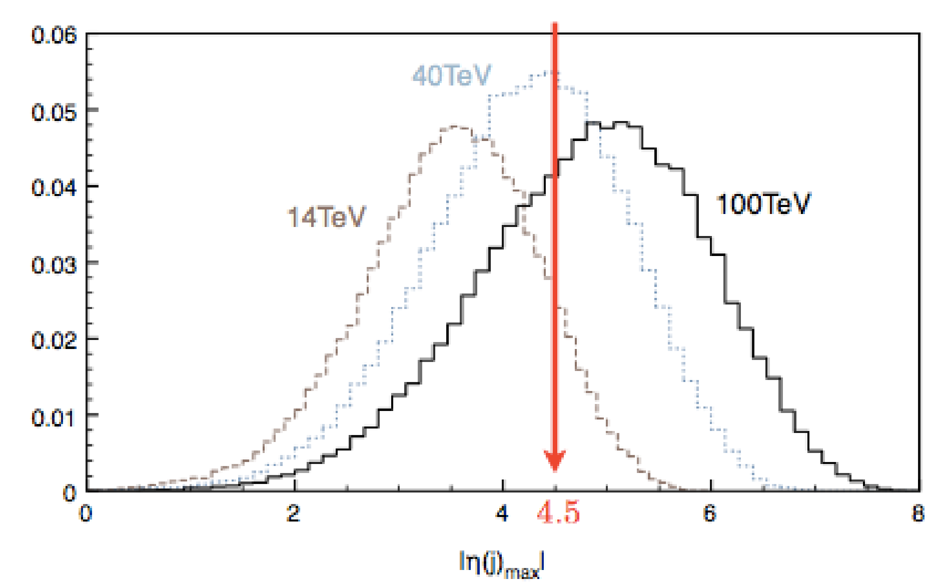
SM rates at 100 TeV



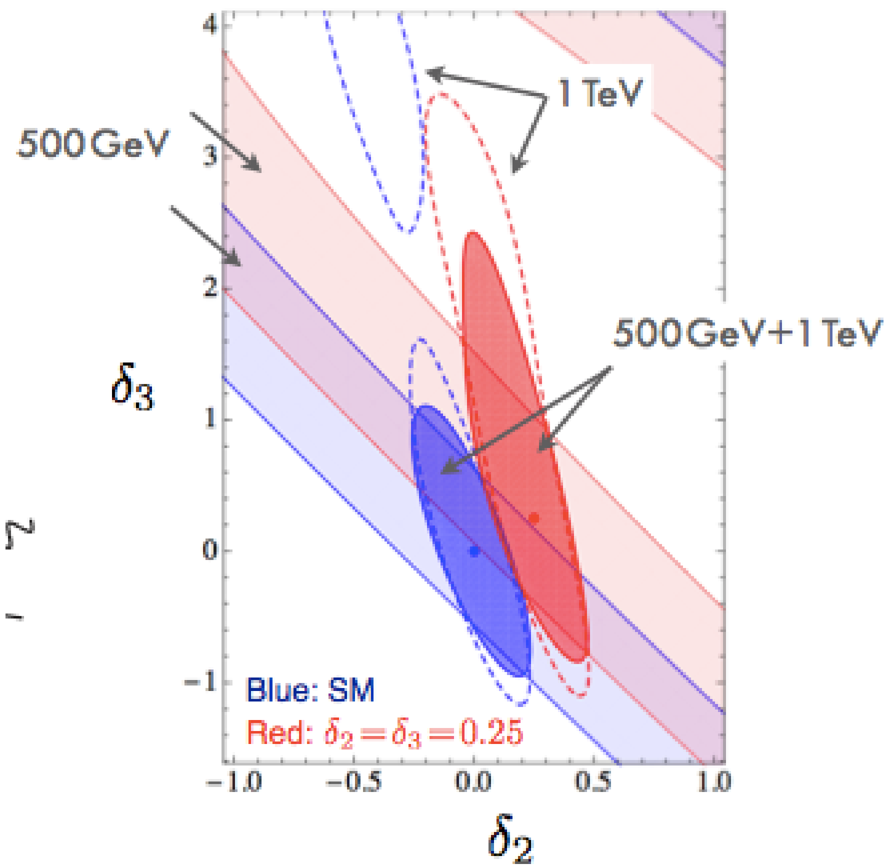
100 fb with M(WW) > ~3 TeV



1 fb with M(HH) > ~2 TeV



ILC



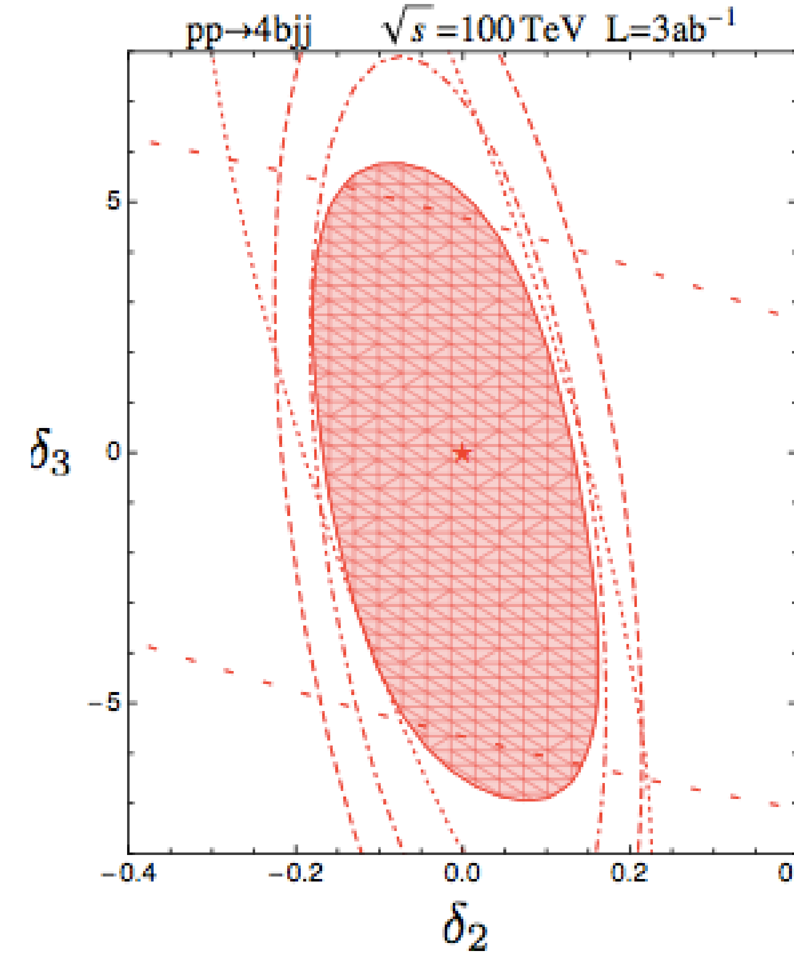
CLIC 3 TeV

Results with 1ab^{-1}

5% precision on δ_2 ($f \sim 1.1\,\mathrm{TeV}$)

30% precision on δ_3

pp 100 TeV



Contino, O. Bondu, A. Massironi and J. Rojo

Grojean, Pappadopulo, Rattazzi, Thamm JHEP 1402 (2014) 006

WIMP DM search

Can a 100 TeV collider detect or rule out WIMP scenarios for DM ?

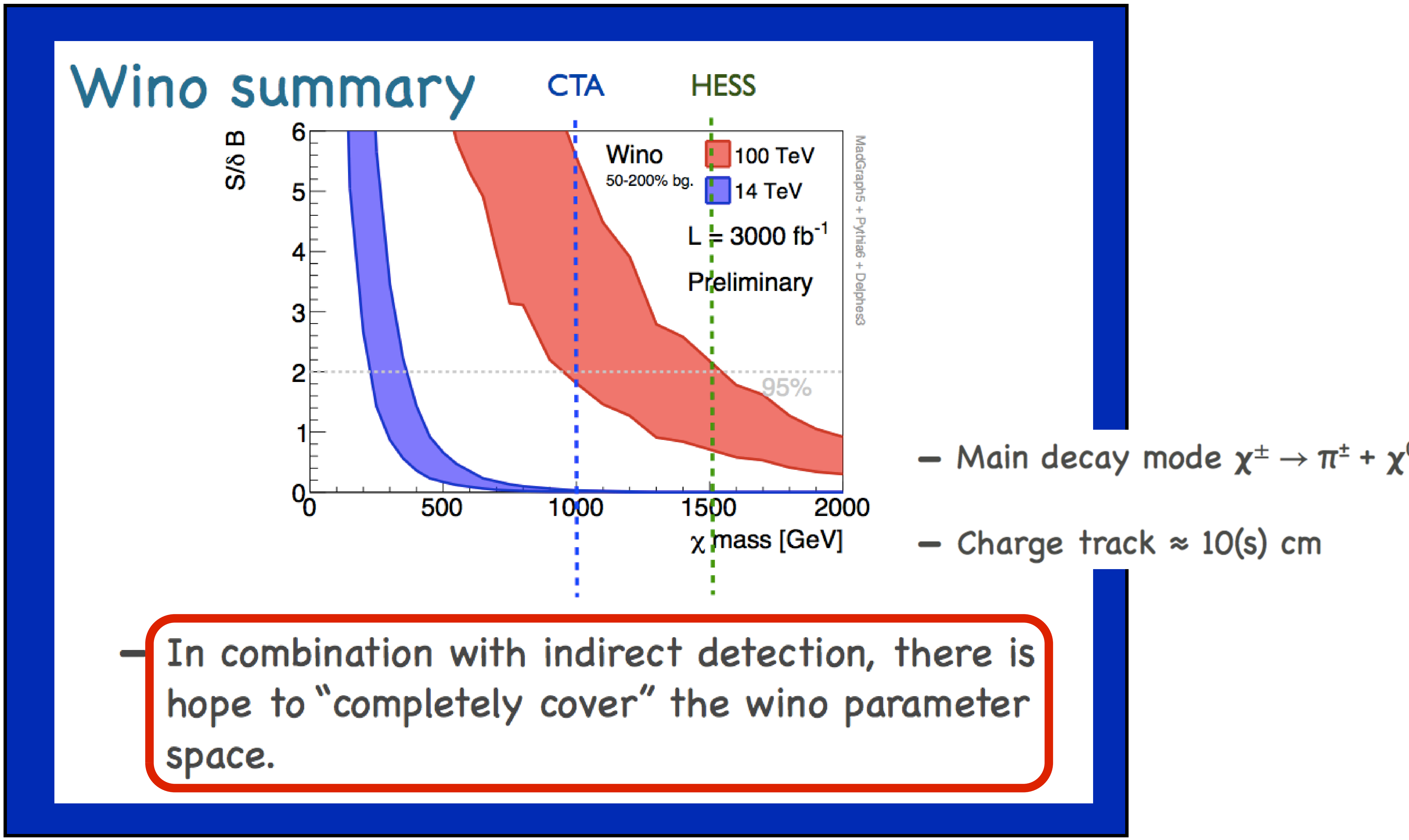
DM overclosure upper limits:
$M_{WIMP} < 1.8$ TeV $(g^2/0.3)$ ⇒

wino: m≲3 TeV

higgsino: m≲1.1 TeV

In anomaly-mediated SUSY or split SUSY ⇒

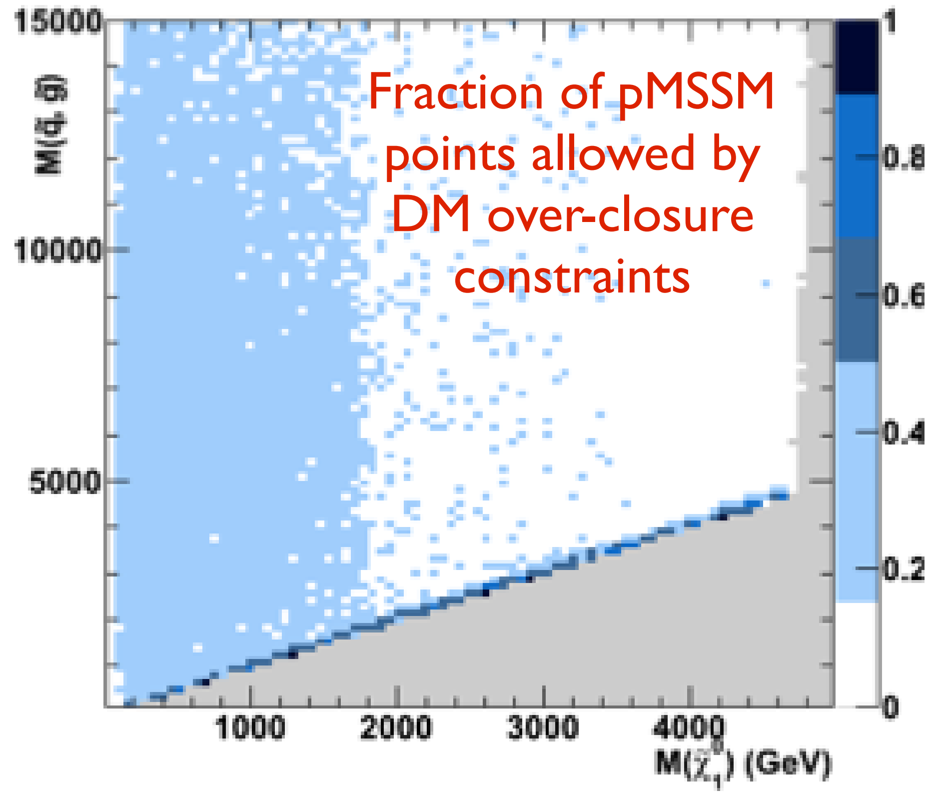
m_{gluino} ≲ 10 TeV



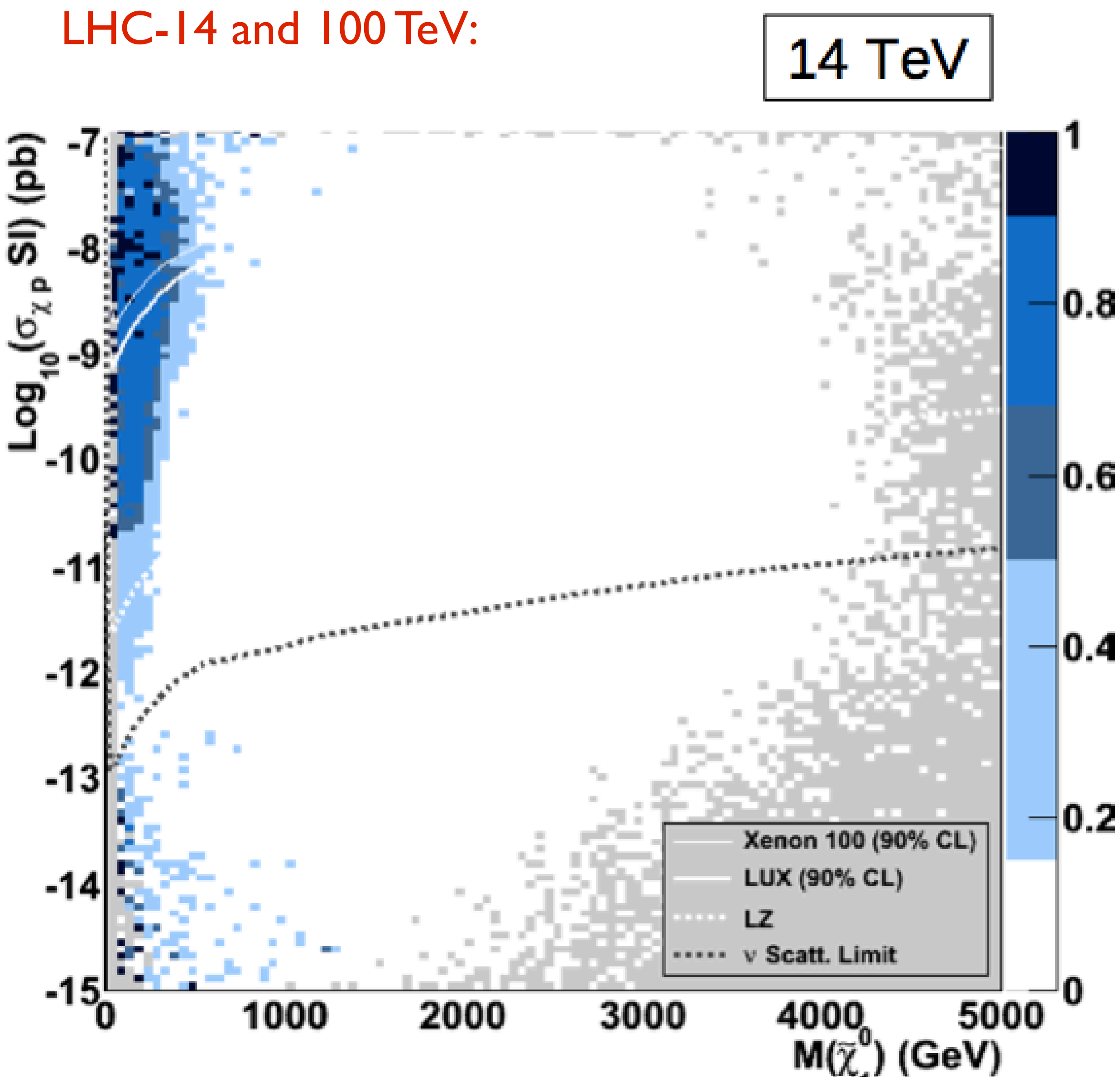
L.T.Wang, (see also P.Schwaller and T.Cohen) BSM@100 TeV Workshop

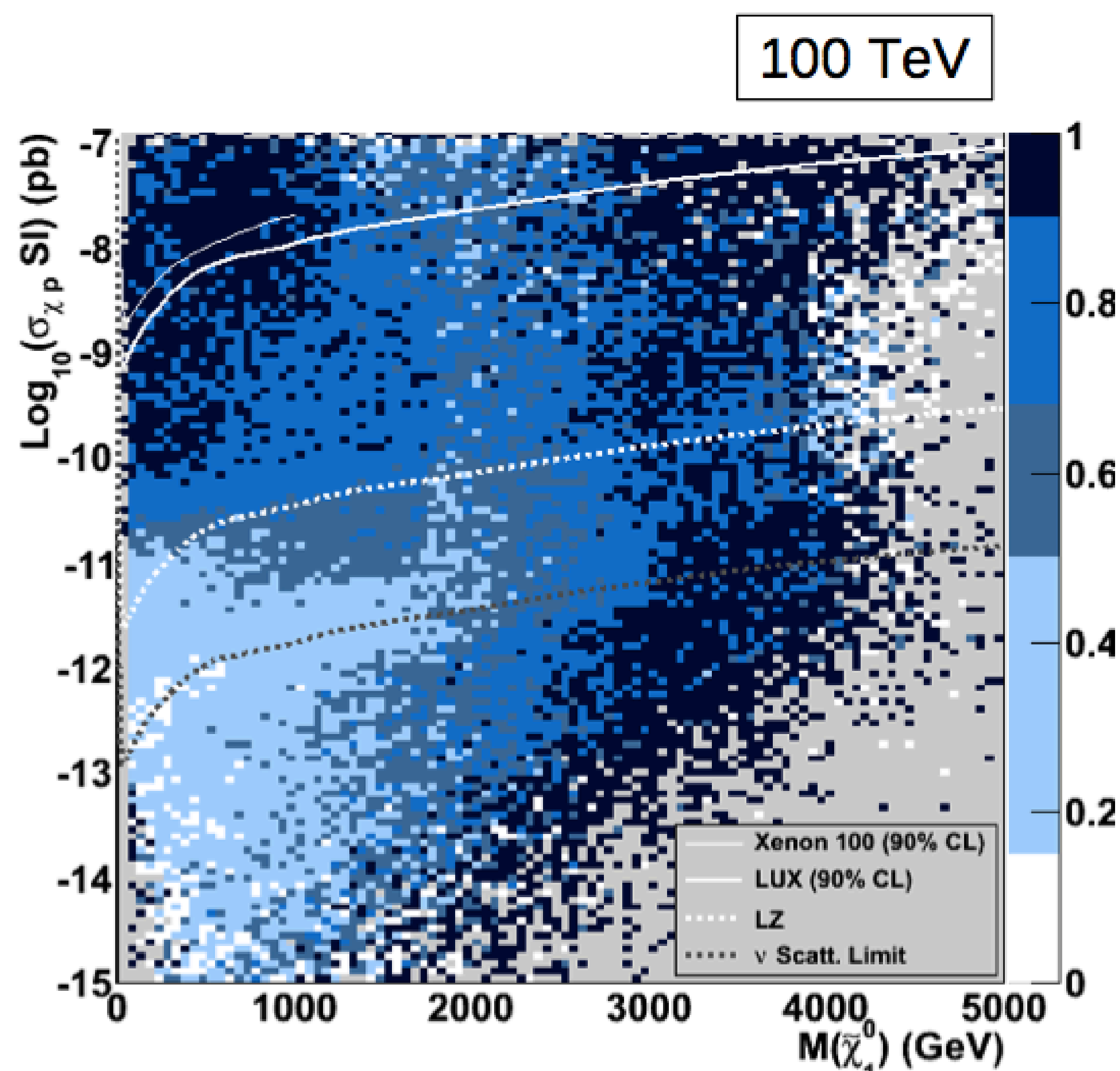
Coverage of pMSSM parameter space using DM constraints and direct searches at 14 and 100 TeV

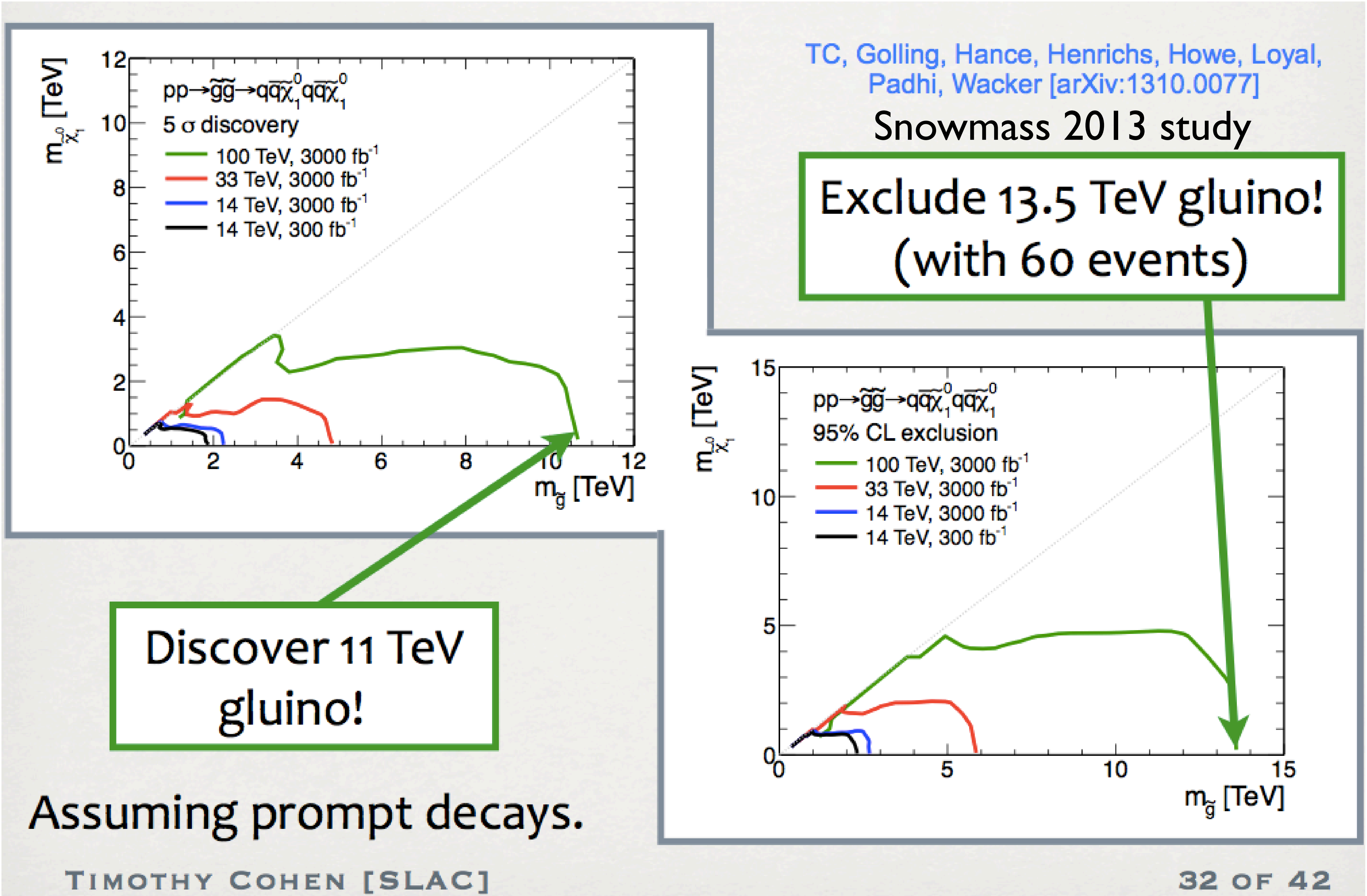
Arbey, **Battaglia**, Mahmoudi



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







T.Cohen, BSM@100 TeV Workshop,
http://indico.cern.ch/event/284800/

Production and study of SM particles and processes

Improving knowledge of SM interactions contributes to improving sensitivity to BSM searches

The continued exploration of the properties of SM interactions, both in the EW and QCD sector, remains a goal of any future facility, and provides benchmarks for the performance and optimization of the experiments

Example: FCC-ee

J.Ellis

Quantity	Physics	Present precision		TLEP Stat errors	Possible TLEP Syst. Errors	TLEP key	Challenge
M_z (keV)	Input	91187500 ±2100	Z Line shape scan	5 keV	<100 keV	E_cal	QED corrections
Γ_z (keV)	$\Delta\rho$ (T) (no $\Delta\alpha$!)	2495200 ±2300	Z Line shape scan	8 keV	<100 keV	E_cal	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.0001	<0.001	Statistics	QED corrections
N_ν	PMNS Unitarity sterile ν's	2.984 ±0.008	Z Peak	0.00008	<0.004		Bhabha scat.
N_ν	PMNS Unitarity sterile ν's	2.92 ±0.05	(γ+Z_inv) (γ+Z→ ℓℓ)	0.001 (161 GeV)	<0.001	Statistics	
R_b	δ_b	0.21629 ±0.00066	Z Peak	0.000003	<0.000060	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta\rho$, ε_3, $\Delta\alpha$ (T, S)	0.1514 ±0.0022	Z peak, polarized	0.000015	<0.000015	4 bunch scheme, > 2exp	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	<0.5 MeV	E_cal & Statistics	QED corections
m_{top} MeV/c2	Input	173200 ± 900	Threshold scan	10 MeV	<10MeV	E_cal & Statistics	Theory interpretation 40 MeV?

http://CERN.CH/tlep

TLEP/FCC-ee Physics Report: http://arxiv.org/abs/arXiv:1308.6176

Example: FCC-eh

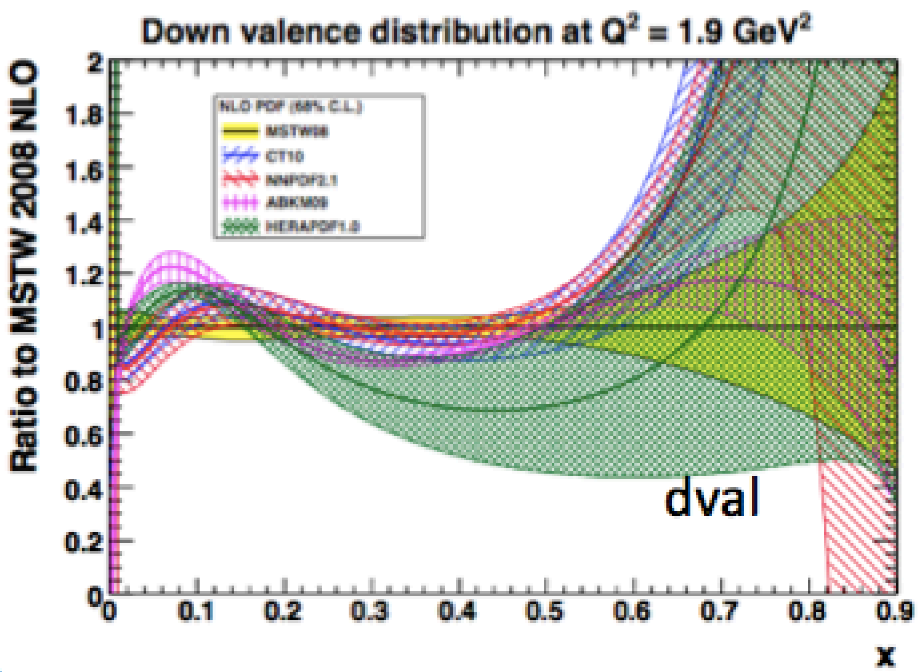
M.Klein

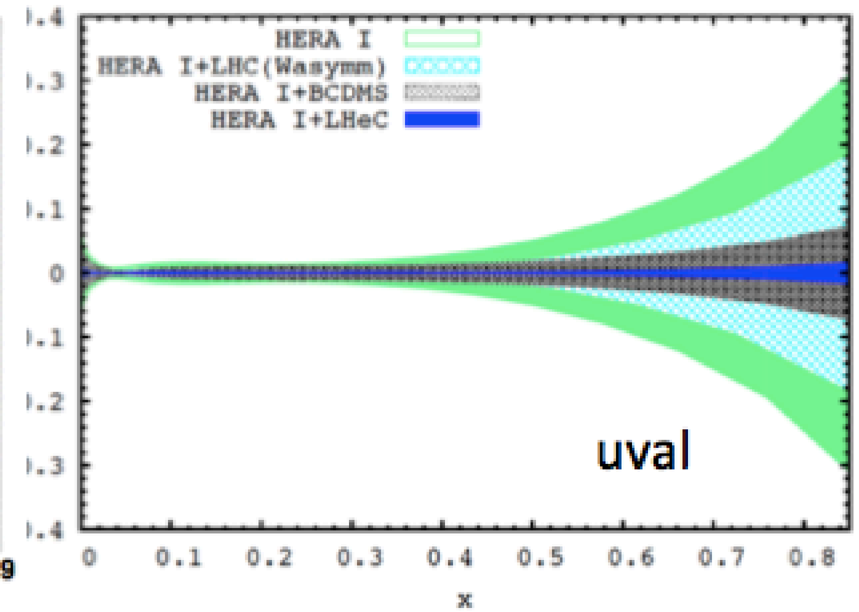
Valence quark distributions

Now... ...Then

Current knowledge is limited at high x:

- Lumi barrier
- challenging systematic
- nuclear effects
- Effects of higher twists

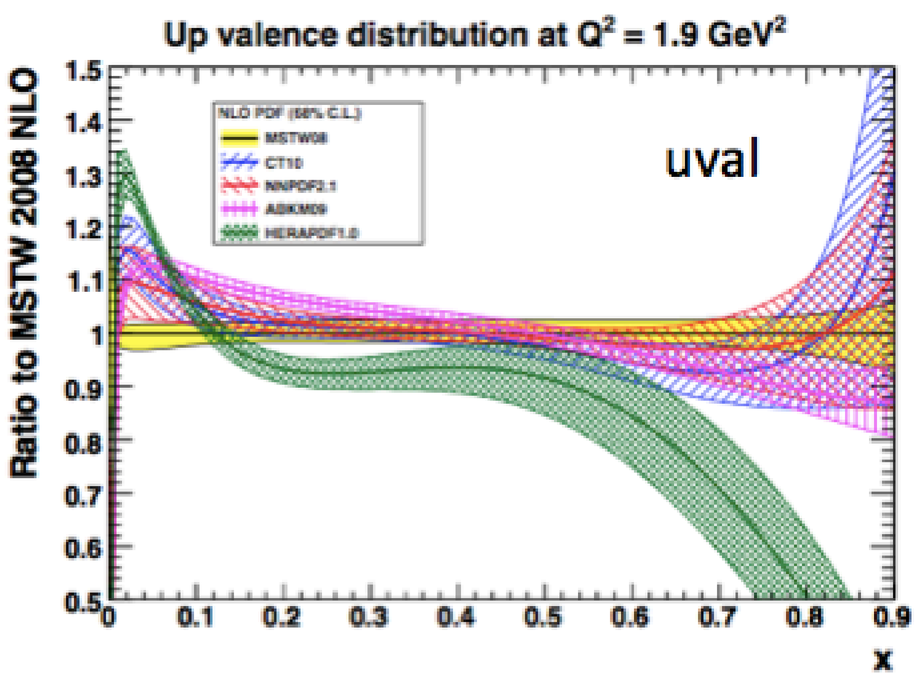


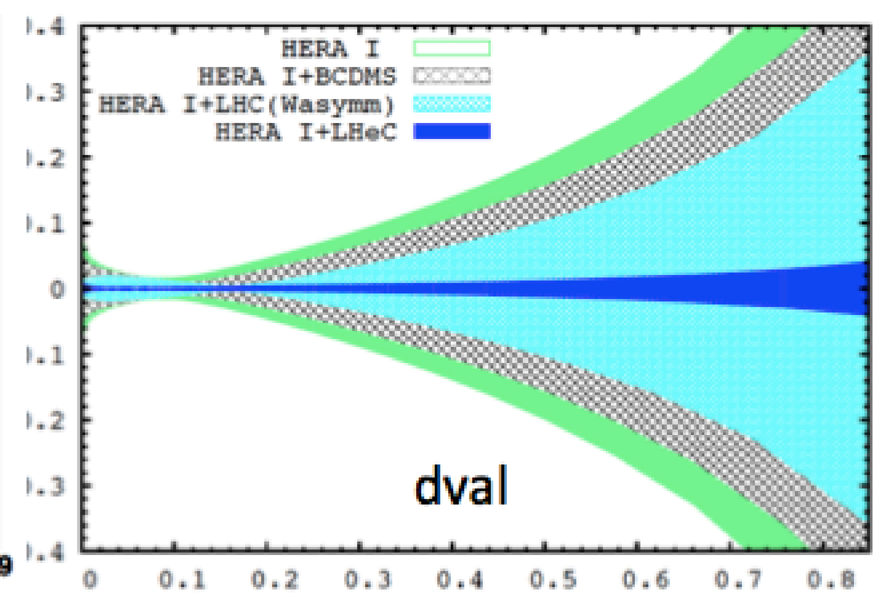


LHeC could improve the knowledge of the valence at high x to a precision of:

- 2% (uval) x=0.8
- 4% (dval) x=0.8

Important for d/u limit clarification





http://CERN.CH/lhec

LHeC Physics Report: http://arxiv.org/abs/arXiv:1206.2913

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

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

⇒ precision measurements

⇒ rare decays, FCNC probes

($H\to e\mu$, $t\to cV$ ($V=Z,g,\gamma$), $t\to cH$, ...)

⇒ CP violation

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

=> 10^{12} W bosons from top decays

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

=> 10^{11} $t \to W \to$ taus ⇒ rare decays $\tau\to 3\mu$, $\mu\gamma$, CPV

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

⇒ rare decays $D\to\mu^+\mu^-$, ..., CPV

The possibility of detectors dedicated to final states in the 0.1 - 1 TeV region deserves very serious thinking:

focus on Higgs, DM and weakly interacting new particles, top, W

W decays

Melia

- W mass ??
- SM rare decays -- Examples:

$W^\pm \to \pi^\pm \gamma$ — $BR_{SM} \sim 10^{-9}$, CDF $\leq 6.4 \times 10^{-5}$

$W^\pm \to D_s^\pm \gamma$ — $BR_{SM} \sim 10^{-9}$, CDF $\leq 1.2 \times 10^{-2}$

What is the theoretical interest in measuring these rates? What else ?

- SM inclusive decays -- Examples:

$R = BR_{had} / BR_{lept}$: what do we learn ? Achievable precision for CKM, α_S , ... ?

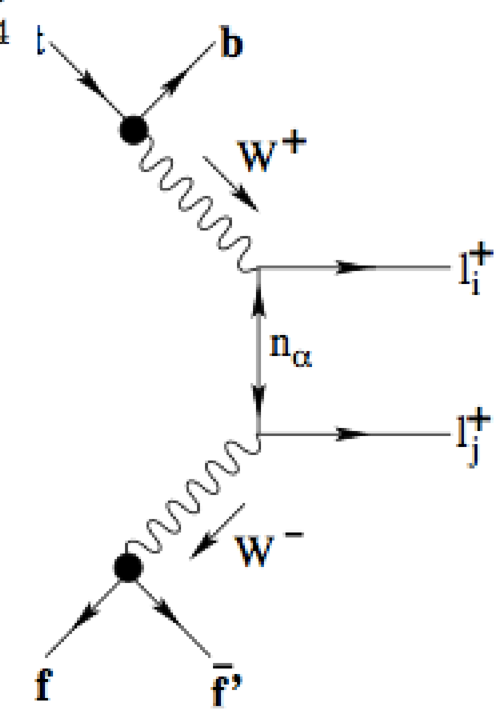
- BSM decays -- Are there interesting channels to consider?

-- Example

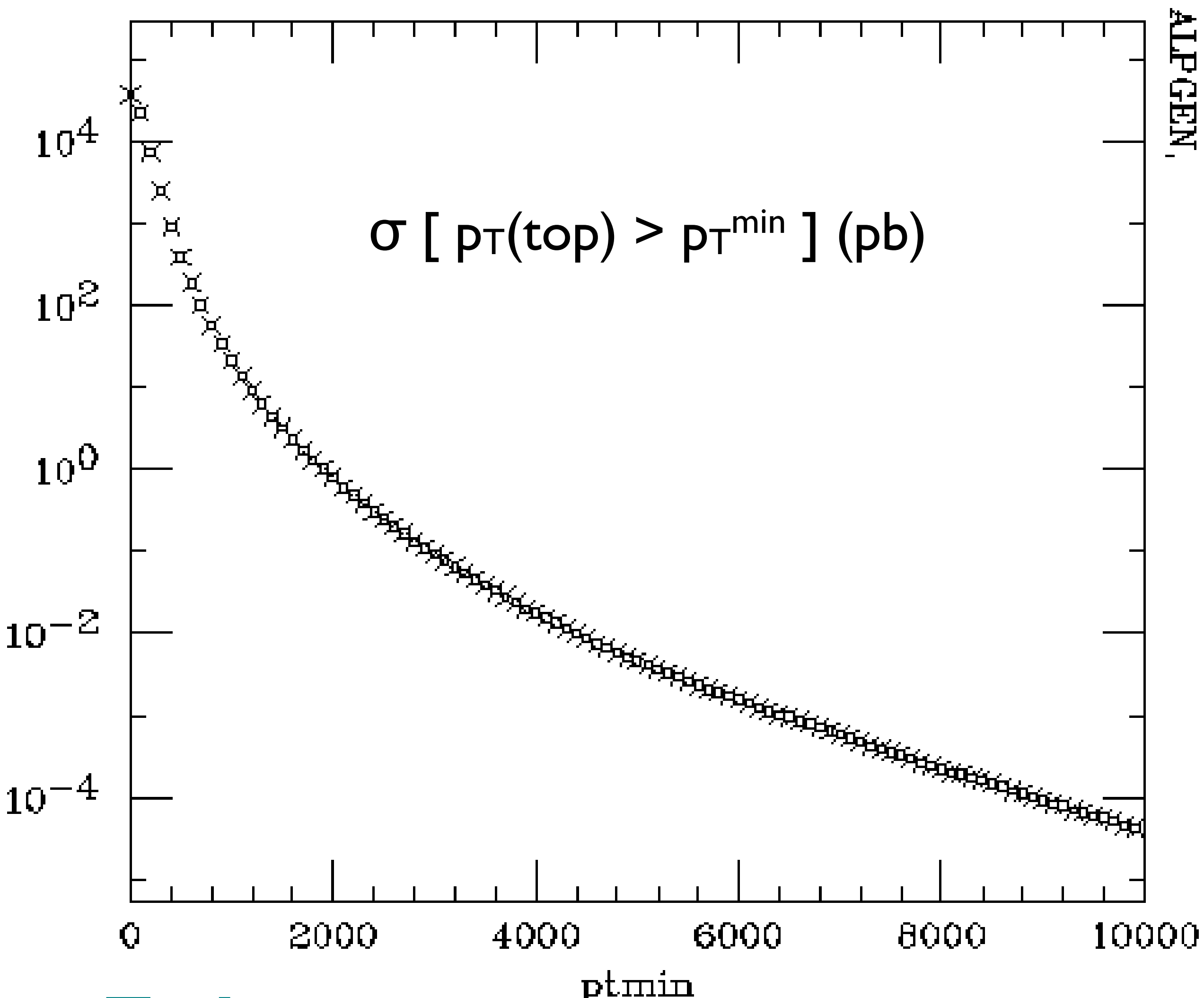
BNL-HET-06/9
OITS-784

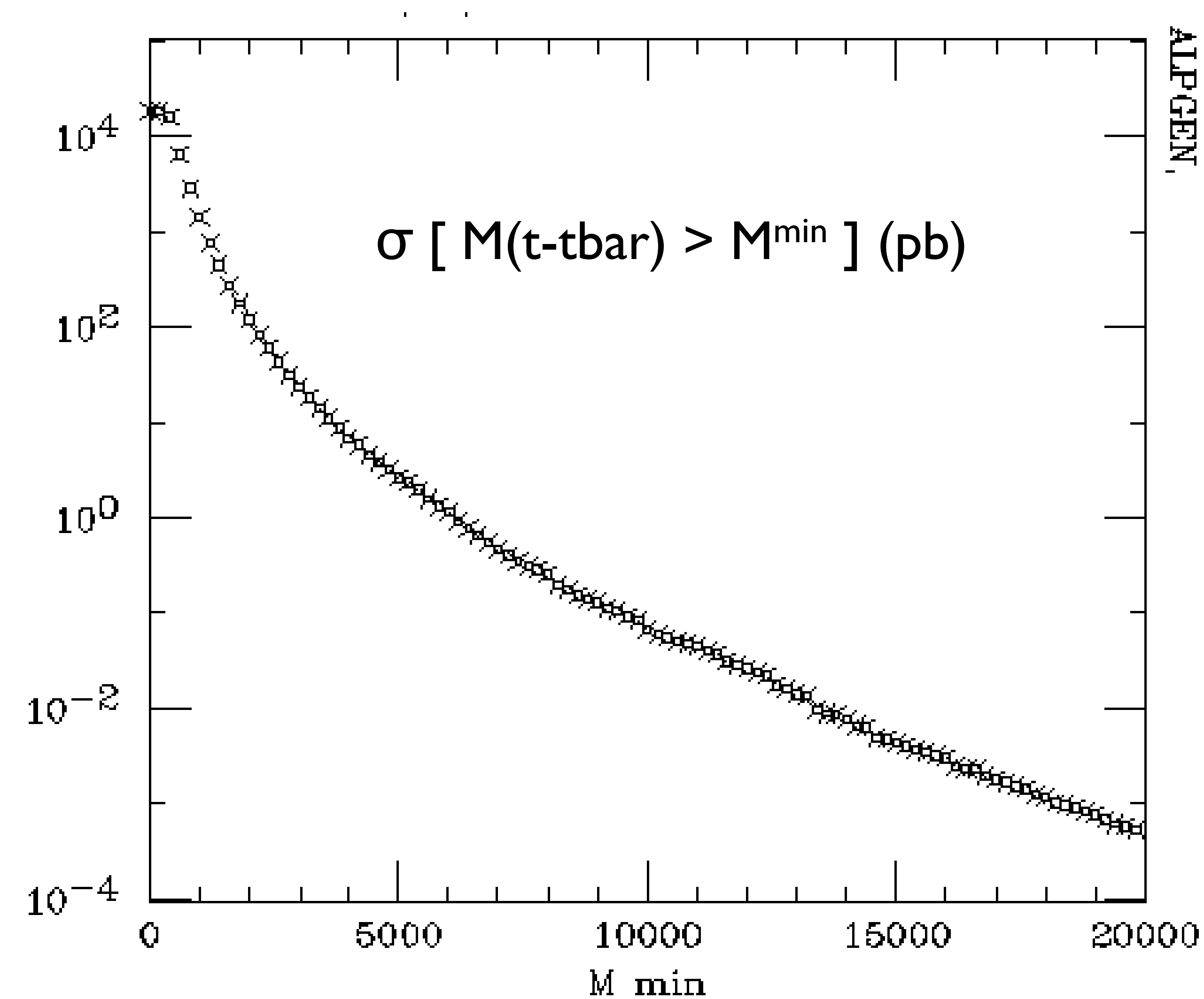
Majorana neutrinos and lepton-number-violating signals in top-quark and W-boson rare decays

Shaouly Bar-Shalom[a,*] Nilendra G. Deshpande[b,†] Gad Eilam[a,‡] Jing Jiang[b,§] and Amarjit Soni[c,¶]



Inclusive t-tbar production: distributions





Tasks:

o explore tagging of multi-TeV tops

o study mass resolution for resonance searches, define search potential (σ_{BSM} vs M_{BSM})

o explore opportunities for top coupling studies at large Q

Example: what can we learn from
10^4 pp → W* → top+ bottom with M(tb) > 7 TeV ?

Probing top couplings

JA Aguilar-Saavedra

Wtb $-\frac{g}{\sqrt{2}}\bar{b}_L \frac{i\sigma^{\mu\nu}q_\nu}{M_W} g_R \, t_R W_\mu^-$

Ztt $-\frac{g}{2c_W}\bar{t} \frac{i\sigma^{\mu\nu}q_\nu}{M_Z} d_V^Z \, t Z_\mu$

$\sqrt{2} C_{uW}^{33} \frac{v^2}{\Lambda^2}$

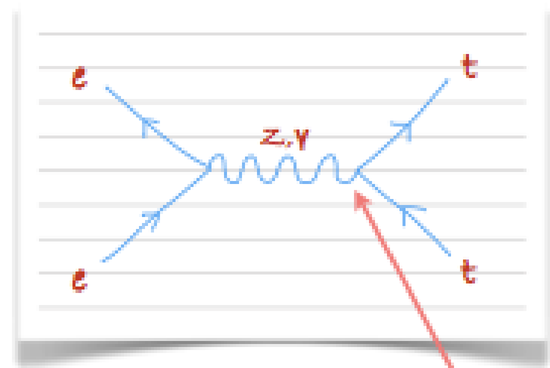
$\sqrt{2}c_W \, \mathrm{Re}\, C_{uW}^{33} \frac{v^2}{\Lambda^2} + \text{other}$

$\frac{\sqrt{2}}{e} s_W \, \mathrm{Re}\, C_{uW}^{33} \frac{v m_t}{\Lambda^2} + \text{other}$

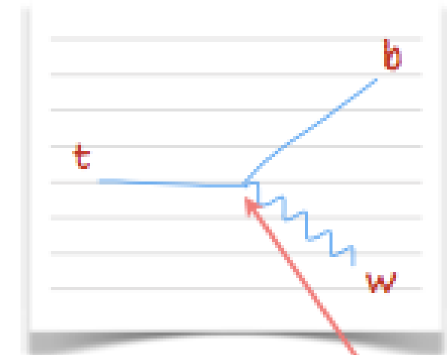
γtt $-e\bar{t} \frac{i\sigma^{\mu\nu}q_\nu}{m_t} d_V^\gamma \, t A_\mu$

Weak moments: the contenders

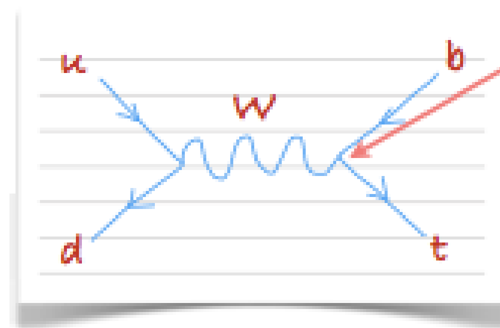
the old favorite: $t\bar{t}$ at ILC



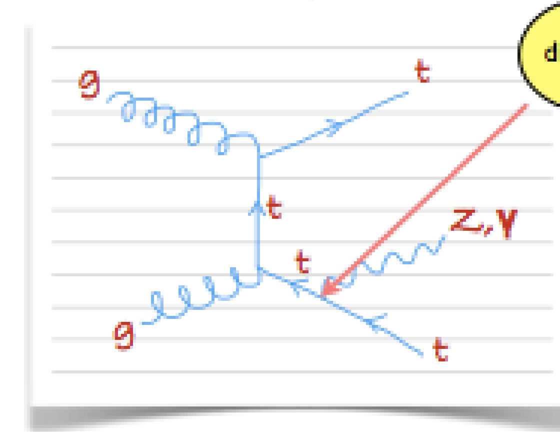
the newcomer: $t\bar{t}$ at TLEP



the underdog: $t\bar{b}$ at FHC



the other: $t\bar{t}Z/\gamma$ at FHC



top dipole int here

top dipole int here

Projected sensitivity reach:

ILC	$\mathrm{Re}\, C_{uW}^{33}/\Lambda^2 \in [-0.128, 0.140]\ \mathrm{TeV}^{-2}$	95% CL	$\Lambda > 2.7\sqrt{\mathrm{Re}\, C}\ \mathrm{TeV}$
FCC-ee	$\mathrm{Re}\, C_{uW}^{33}/\Lambda^2 \in [-0.083, 0.083]\ \mathrm{TeV}^{-2}$	95% CL	$\Lambda > 3.5\sqrt{\mathrm{Re}\, C}\ \mathrm{TeV}$
FCC-hh	$\mathrm{Re}\, C_{uW}^{33}/\Lambda^2 \in [-0.043, 0.046]\ \mathrm{TeV}^{-2}$	95% CL	$\Lambda > 4.7\sqrt{C}\ \mathrm{TeV}$

Top decays and interactions

Rare decays: $t \to W Z b$, ...
FCNC probes: $t \to cV$ ($V=Z,g,\gamma$), $t \to cH$
CP violation: spin/momentum correlations of decay products, ...

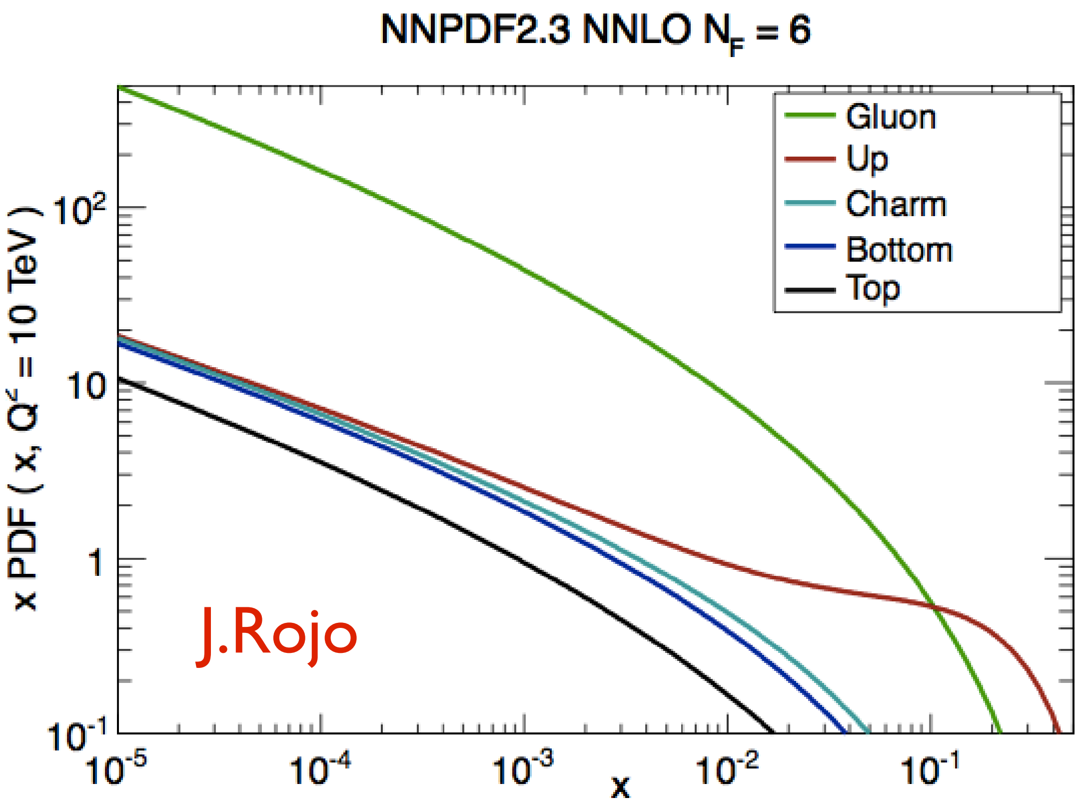
BSM@100:
Zupan (FCNC top int's)
Kamenik (CPV top int's)

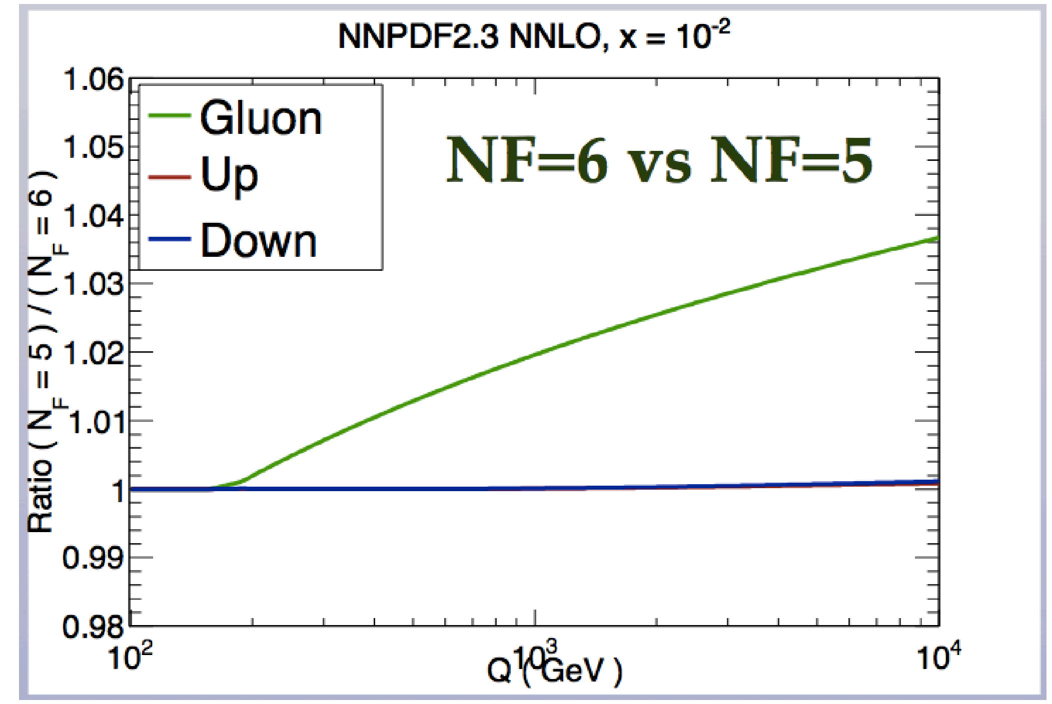
Top as a tool for BSM searches

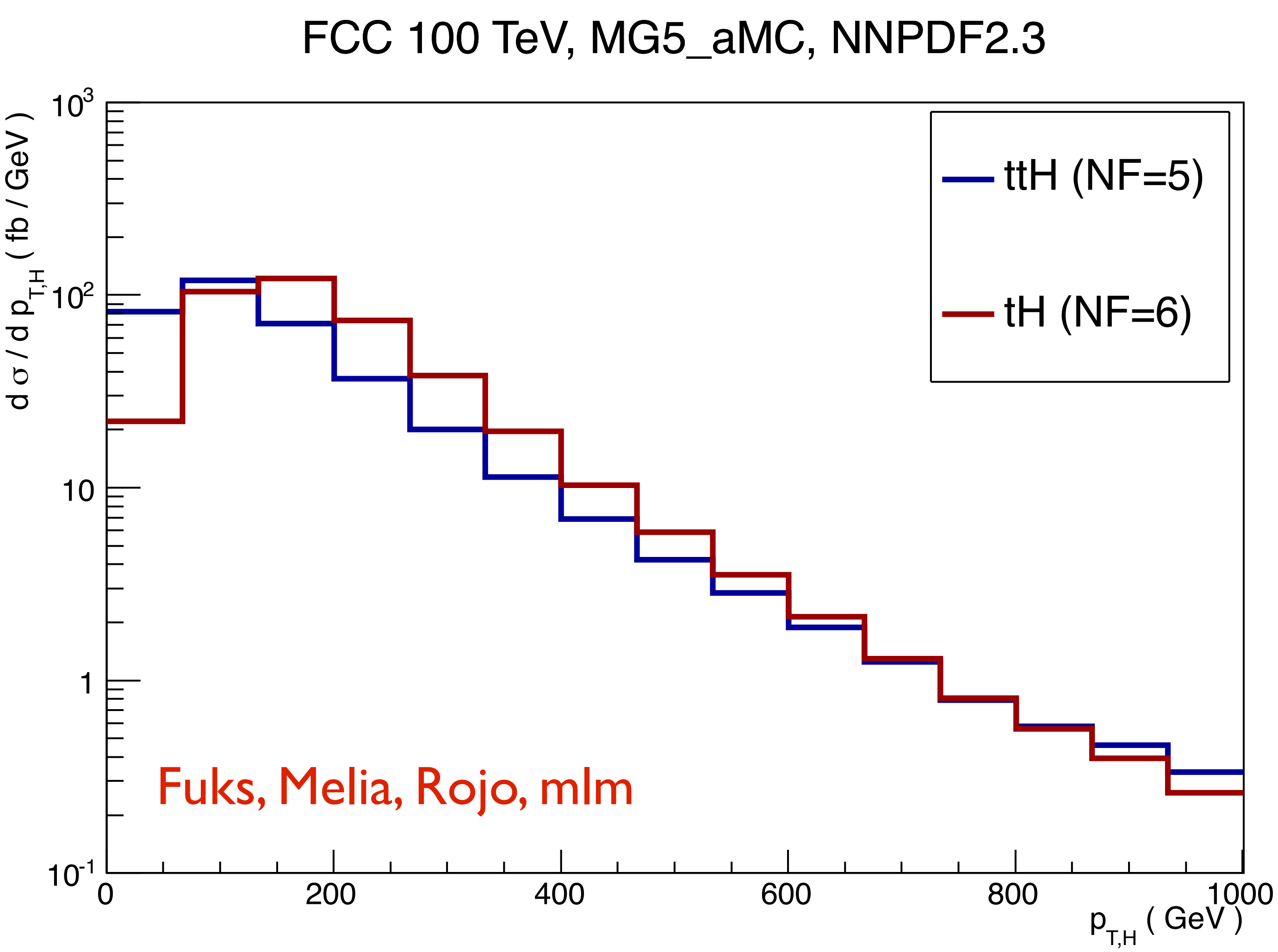
Tasks:

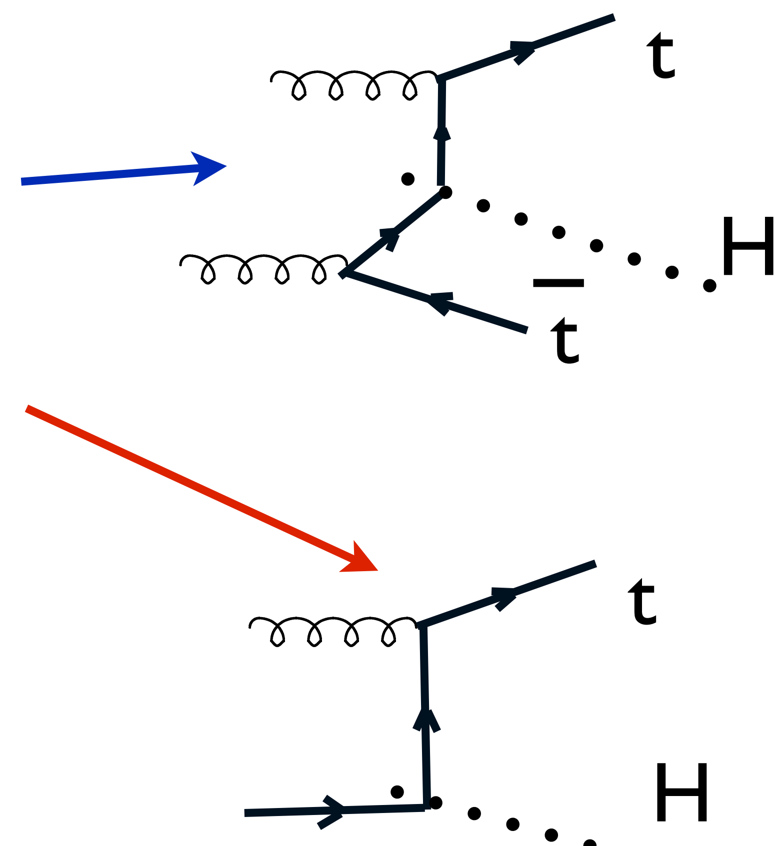
o quantitative exploration of measurement potential (statistics, systematics, dedicated detector/trigger requirements)

Top PDFs


NNPDF2.3 NNLO N_F = 6
Gluon
Up
Charm
Bottom
Top
x PDF (x, Q² = 10 TeV)
x
J.Rojo


NNPDF2.3 NNLO, x = 10⁻²
Gluon
Up
Down
NF=6 vs NF=5
Ratio (N_F = 5) / (N_F = 6)
Q (GeV)


FCC 100 TeV, MG5_aMC, NNPDF2.3
ttH (NF=5)
tH (NF=6)
d σ / d p_T,H (fb / GeV)
p_T,H (GeV)
Fuks, Melia, Rojo, mlm


t
H
t̄
t
H

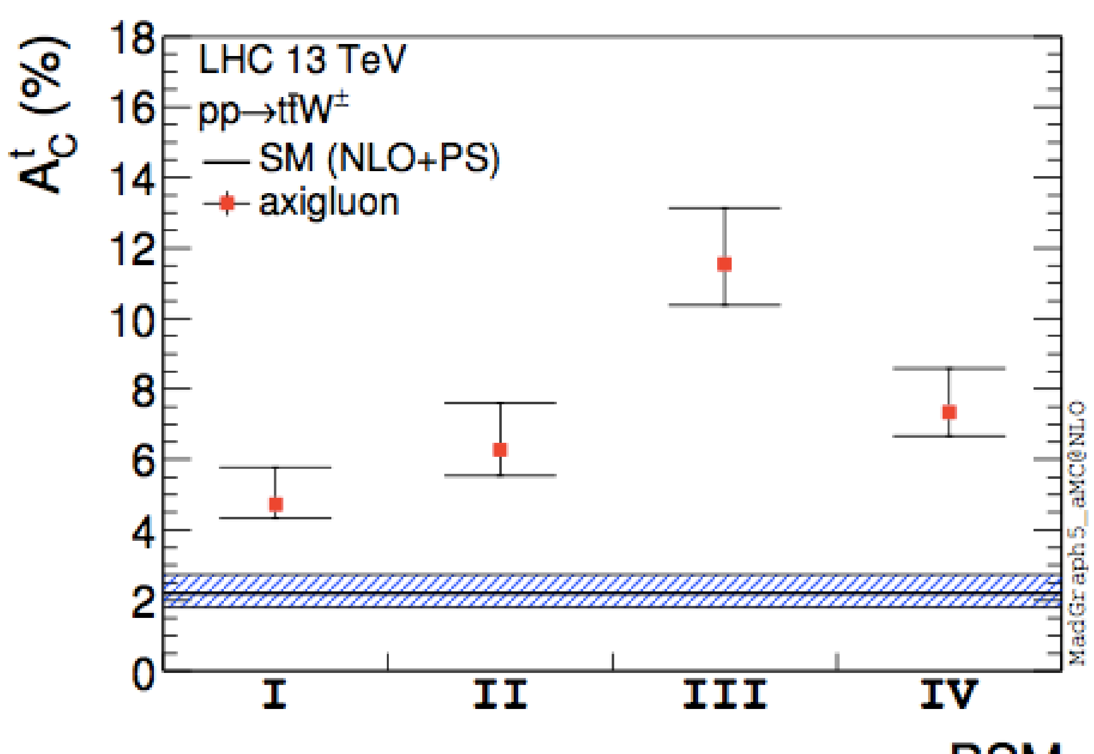
Top "polarimetry" with ttW, and Tevatron's A_{FB}

I. Tsinikos

gg→W ttbar is clearly forbidden ⇒ presence of W singles out (polarized) q-qbar initial state

		8 TeV	13 TeV	14 TeV	33 TeV	100 TeV
$t\bar{t}$	σ(pb)	$198^{+15\%+2\%}_{-14\%-3\%}$	$661^{+15\%+2\%}_{-13\%-3\%}$	$786^{+14\%+2\%}_{-13\%-3\%}$	$4640^{+12\%+1\%}_{-11\%-2\%}$	$30700^{+13\%+1\%}_{-13\%-2\%}$
	$A^t_C(\%)$	$0.72^{+0.14}_{-0.09}$	$0.45^{+0.09}_{-0.06}$	$0.36^{+0.01}_{-0.02}$	$0.11^{+0.07}_{-0.04}$	$0.07^{+0.02}_{-0.04}$
$t\bar{t}W^\pm$	σ(fb)	$210^{+11\%+2\%}_{-11\%-2\%}$	$587^{+13\%+2\%}_{-12\%-1\%}$	$678^{+14\%+2\%}_{-12\%-1\%}$	$3220^{+17\%+1\%}_{-13\%-1\%}$	$19000^{+20\%+1\%}_{-17\%-1\%}$
	$A^t_C(\%)$	$2.37^{+0.56}_{-0.38}$	$2.24^{+0.43}_{-0.32}$	$2.23^{+0.43}_{-0.33}$	$1.95^{+0.14}_{-0.14}$	$1.85^{+0.03}_{-0.07}$
	$A^b_C(\%)$	$8.50^{+0.15}_{-0.10}$	$7.54^{+0.02}_{-0.04}$	$7.50^{+0.01}_{-0.03}$	$5.37^{+0.22}_{-0.30}$	$3.36^{+0.15}_{-0.19}$
	$A^e_C(\%)$	$-14.83^{-0.65}_{+0.95}$	$-13.16^{-0.81}_{+1.12}$	$-12.84^{-0.81}_{+1.11}$	$-9.21^{-0.87}_{+1.05}$	$-4.94^{-0.63}_{+0.72}$

Impact of axigluon models compatible with Tevatron A_{FB}



Expected statistical sensitivity

- 14 TeV ($\mathcal{L} = 3000\ \text{fb}^{-1}$):

  $\delta_{\text{rel}} A^t_C = 14\%, \delta_{\text{rel}} A^b_C = 4\%, \delta_{\text{rel}} A^e_C = 2\%$
- 100 TeV ($\mathcal{L} = 3000\ \text{fb}^{-1}$):

  $\delta_{\text{rel}} A^t_C = 3\%, \delta_{\text{rel}} A^b_C = 2\%, \delta_{\text{rel}} A^e_C = 1\%$

* Off-shell W/Z production above 10 TeV DY mass. E.g.

- measure the running of EW couplings, sensitive to new weakly-interacting particles, possibly hidden from direct discovery (⇒ Rudermann at BSM@100 TeV wshop, Galloway at SLAC)

- 10^4 pp → W^* → top+ bottom with M(tb) > 7 TeV

* QCD jets up to 25-30 TeV ⇒ running of α_S , ...

* SM violation of B+L via EW anomaly (not viable below 30 TeV) (⇒ Khoze and Ringwald at BSM@100 TeV wshop)

* Growth of heavy flavour densities inside proton (c, b and ultimately top) ⇒new opportunities for studies within and beyond the SM (⇒ Perez at BSM@100 TeV wshop)

* ....

Plenty of room for new ideas

Other topics

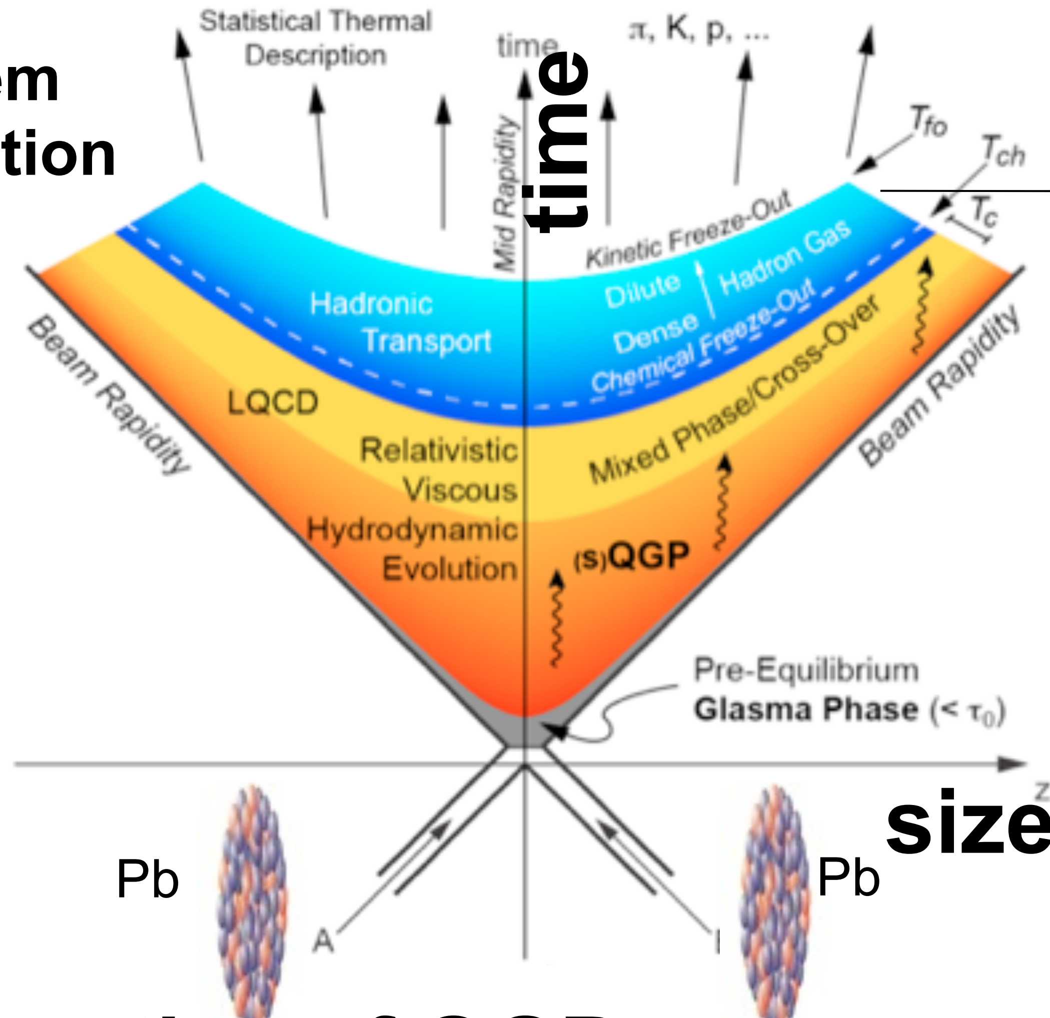
- The FCC will redefine the scope and role of CERN as a laboratory. The scale of the project may require not just international participation, beyond the CERN member states, but also engagement of other science communities (low-energy nuclear physics, light sources, medical sciences, applied accelerator 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.

Ions at the FCC

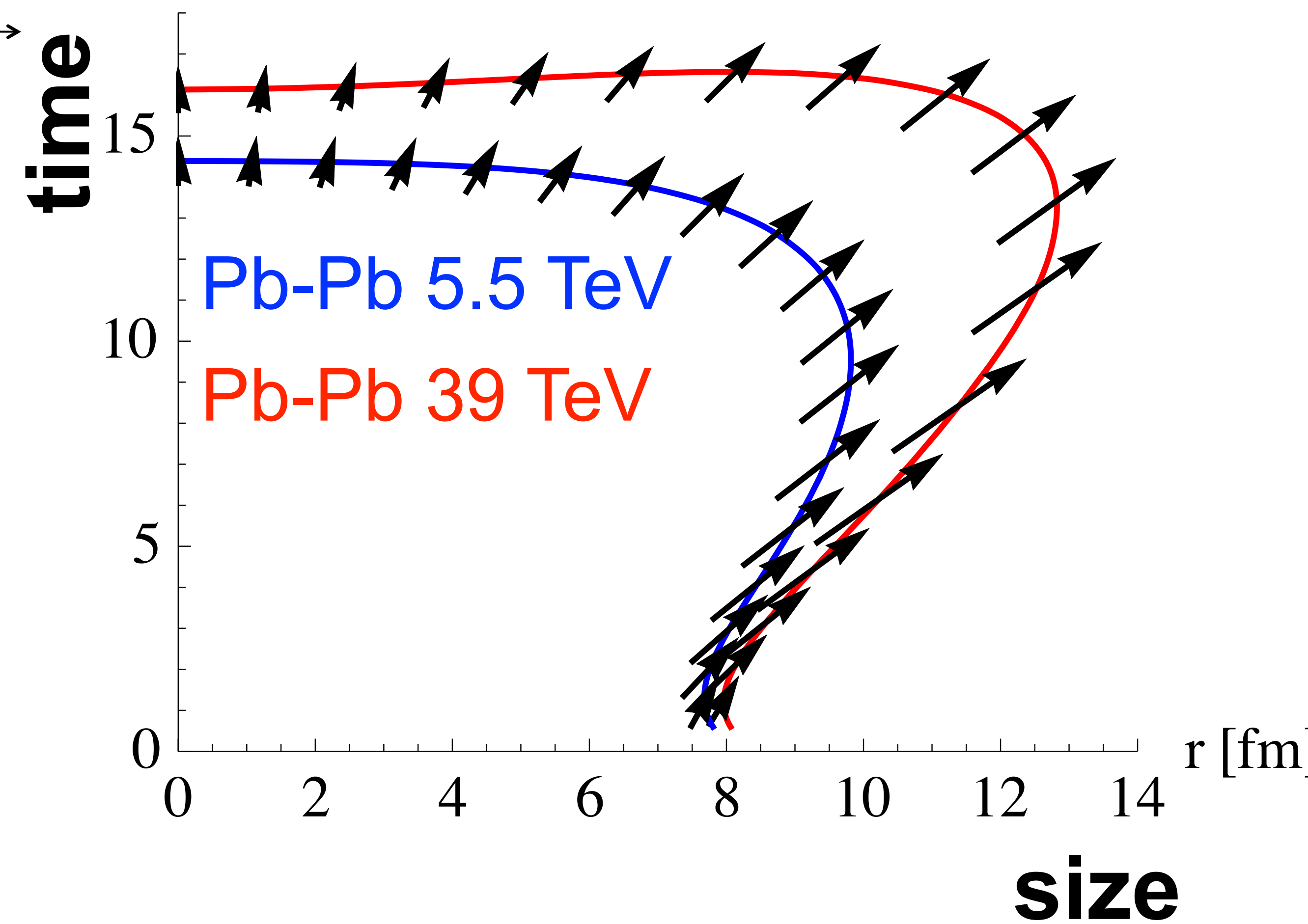
- A discussion group on "Ions at the FCC" started: coordinated by A. Dainese, S. Masciocchi, U. Wiedemann
  - sub-group of "FHC Physics, Experiments, Detectors"
- Three meetings up to now, Dec 16-17, Jan 29, April 10
  - https://indico.cern.ch/conferenceDisplay.py?confId=288576
  - https://indico.cern.ch/conferenceDisplay.py?confId=290413
  - http://indico.cern.ch/event/309010/
- Participation from CERN accelerator team, theory, ALICE, ATLAS, CMS
- Goal: explore opportunities with heavy ions at the FCC
  - Saturation (contacts: N. Armesto, M. van Leeuwen)
  - Soft physics (contact: U. Wiedemann)
  - Hard probes (contacts: A. Dainese, C. Roland, C. Salgado)
  - UPC (contact: D. d'Enterria)

Quark-Gluon Plasma studies at FCC

System evolution



Hydrodynamic freeze-out curves
(S. Flörchinger)



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?

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

So far:
- 7 preparatory mtgs of the pp WG
- Mtg on EM calorimeters
- Task force on "Software platform for FCC studies (hh/ee/eh)"
- "BSM opportunities at 100 TeV" Workshop:
  http://indico.cern.ch/event/284800/

This week: **100 TeV physics workshop**, May 26-28
http://indico.cern.ch/event/304759/

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

Table 1: FHC baseline parameters compared to LHC and HL-LHC parameters.

	LHC (Design)	HL-LHC	HE-LHC	FHC
Main parameters and geometrical aspects				
c.m. Energy [TeV]	14		33	100
Circumference C [km]	26.7		26.7	100 (83)
Dipole field [T]	8.33		20	16 (20)
Arc filling factor	0.79		0.79	0.79
Straight sections	8		8	12
Average straight section length [m]	528		528	1400
Number of IPs				2 + 2
Injection energy [TeV]	0.45		> 1.0	3.3 (**TBC**)
Physics performance and beam parameters				
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	5.0	5.0	5.0
Optimum run time [h]	15.2	10.2	5.8	12.1 (10.7)
Optimum average integrated lumi / day [fb^{-1}]	0.47	2.8	1.4	2.2 (2.1)
Assumed turnaround time [h]				5
Overall operation cycle [h]				17.4 (16.3)
Peak no. of inelastic events / crossing at - 25 ns spacing - 5 ns spacing	27	135 (lev.)	147	171 34
Total / inelastic cross section [mbarn]	111 / 85		129 / 93	153 / 108
Luminous region RMS length [cm]				5.7 (5.3)
Beam lifetime due to burn off [h]	45	15.4	5.7	19.1 (15.9)

https://indico.cern.ch/event/298180/contribution/0/material/0/0.pdf

	LHC (Design)	HL-LHC	HE-LHC	FHC
Beam parameters				
Number of bunches at - 25 ns - 5 ns	2808		2808	10600 (8900) 53000 (44500)
Bunch population $N_b[10^{11}]$ - 25 ns - 5 ns	1.15	2.2	2808	1.0 0.2
Nominal transverse normalized emittance [µm] - 25 ns - 5 ns	3.75	2.5	1.38	2.2 0.44
Number of IPs contributing to ΔQ	3	2	2	2
Maximum total b-b tune shift ΔQ	0.01	0.015	0.01	0.01
Beam current [A]	0.584	1.12	0.478	0.5
RMS bunch length [cm]	7.55		7.55	8 (7.55)
IP beta function [m]	0.55	0.15 (min)	0.35	1.1
RMS IP spot size [µm] - 25 ns - 5 ns	16.7	7.1 (min)	5.2	6.8 3
Full crossing angle [µrad] - 25 ns - 5 ns	285	590	185	74 **TBD**
Other beam and machine parameters				
Stored beam energy [GJ]	0.392	0.694	0.701	8.4 (7.0)
SR power per ring [MW]	0.0036	0.0073	0.0962	2.4 (2.9)
Arc SR heat load [W/m/aperture]	0.17	0.33	4.35	28.4 (44.3)
Energy loss per turn [MeV]	0.0067		0.201	4.6 (5.86)

Final Remarks

- **Our field has other open puzzles, associated e.g. to**
  - **neutrinos**
  - **flavour**
  - **axion**
  - **inflation**
  - **accelerated cosmological expansion**
  - **...**
- **These puzzles hint at scales that are typically much larger than O(TeV), even as large as the GUT scale**
- **The complete understanding of TeV-scale physics is necessary to put in perspective and properly interpret the information about those high scales that may come from indirect probes (neutrinos, $\mu \to e\gamma$, p-decay, coupling unification, ...)**
- **A 100 TeV pp collider provides both the immense discovery potential and the rich programme of measurements that are needed to fully and conclusively explore the TeV scale**

Proposed physics topics to be used in the study of synergy/complementarity among experiments at FCC-hh/ee/eh

List-v1.1 (John, Christophe, Alain)14-05-2014

-- Higgs physics:
- precision studies
- higher-dimensional operators, composite Higgs
- rare and exotic decays
- multiple Higgs production
- extra Higgs bosons

-- Interface with cosmology:
- dark matter
- baryogenesis
- right-handed/(almost) sterile neutrinos

-- New physics related to EWSB:
- WW scattering
- supersymmetry
- extra dimensions
- composite models

-- Rare flavour-changing processes:
- Rare H decays
- Rare Z decays
- lepton-flavour violation

-- Extensions of the SM:
- extra vector-like fermions
- SU(2)Rmodels
- leptoquarks

-- QCD:
- Perturbation theory
- Modelling final states