



Phenomenology: summary of parallel session discussions related to FCC-hh

FCC Design Study kickoff meeting,
Univ. of Geneva, Febr 12-15 2014

Michelangelo L. Mangano
CERN, PH-TH

14:00 Perspectives at the Energy Frontier



Presenter(s): Chris QUIGG (*Fermi National Accelerator Lab. (US)*)

Room: Basement - MS 050

Location: University of Geneva - UNI MAIL

14:30 Status and plans for the Heavy Ion physics studies

Presenter(s): Andrea DAINESSE (*INFN - Padova (IT)*)

Room: Basement - MS 050

Location: University of Geneva - UNI MAIL

15:00 QCD at the FCC: opportunities and challenges

Presenter(s): Giulia ZANDERIGHI

Room: Basement - MS 050

Location: University of Geneva - UNI MAIL

16:00 Status and plans for the physics studies of TLEP

Presenter(s): Jonathan R. ELLIS (*CERN*)

Room: Basement - MS 050

Location: University of Geneva - UNI MAIL

16:30 Summary of the BSM@100 TeV wshop, status and plans for the physics studies of FHC

Presenter(s): Michelangelo MANGANO (*CERN*)

Room: Basement - MS 050

Location: University of Geneva - UNI MAIL

17:00 Status and prospects of precise Higgs and BSM calculations for the FCC

Presenter(s): Michael SPIRA (*Paul Scherrer Institut (CH)*)

Room: Basement - MS 050

Location: University of Geneva - UNI MAIL

17:30 Prospects for Higgs and BSM studies in ep collisions at the FCC

Presenter(s): Uta KLEIN (*University of Liverpool (GB)*)

Room: Basement - MS 050

Location: University of Geneva - UNI MAIL

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to label XX contribution
to the session

FHC.1.1 Exploration of EW Symmetry Breaking (EWSB)

FHC.1.1.1 High-mass WW scattering, high mass HHH production **MLM, FHC2**

FHC.1.1.2 Rare Higgs production/decays and precision studies of Higgs properties
Gray FHC5, Curtin, BSM@100

FHC.1.1.3 Additional BSM Higgs bosons: discovery reach and precision physics programme
Craig, BSM@100

FHC.1.1.4 New handles on the study of non-SM EWSB dynamics (e.g. dynamical EWSB and composite H, etc) **Rattazzi, BSM@100**

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.) **Doglioni (q*, Mjj) FHC4, Hooberman (EWinos)/Clement (DY)/Mermod (monopoles) Fuks (polarization) FHC5, Battaglia BSM@100**

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? **Cote FHC1/3, Wang, Schwaller, BSM@100**
- FHC.1.2.2.3 which new BSM frameworks, possibly totally outside of the HL-LHC reach, become accessible/worth-discussing at 100 TeV ? **Cohen, Khoze, Ringwald, ..., BSM@100**

Quigg @ //

The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

Thought experiment: *identify a tipping point*

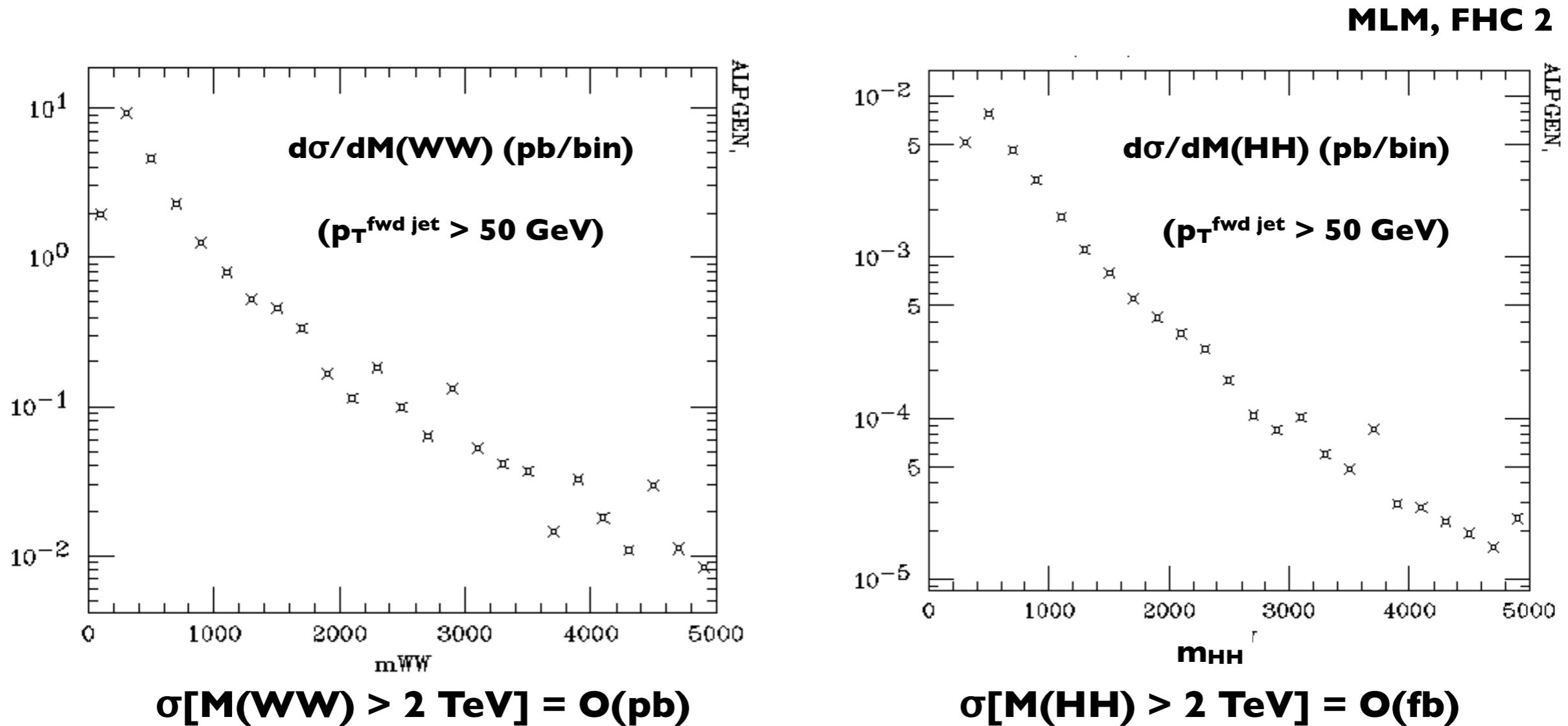
W^+W^- , ZZ , HH , HZ satisfy s-wave unitarity,

provided $M_H \leq (8\pi\sqrt{2}/3G_F)^{1/2} \approx 1 \text{ TeV}$

- If bound is respected, perturbation theory is “everywhere” reliable
- If not, weak interactions among W^\pm , Z , H become strong on 1-TeV scale

New phenomena are to be found around 1 TeV

EWSB probes: high mass WW/HH in VBF



Tasks:

- o study the mass reach for SM production
- o test impact of BSM effects
- o compare to reach of precise $\text{BR}(H)$, VBF, $\lambda_{H\bar{H}H}$ measurements (TLEP, CLIC)
- o compare to reach for direct manifestation of BSM particles
- o

Multi-gauge boson production (no BR included)

WW	$\sigma=770 \text{ pb}$
WWW	$\sigma=2 \text{ pb}$
WWZ	$\sigma=1.6 \text{ pb}$
WWWW	$\sigma=15 \text{ fb}$
WWWZ	$\sigma=20 \text{ fb}$
....	

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 $\text{pt}(W)$?

$\sqrt{s} = 1.3 \text{ TeV}$ $\sqrt{s} = 3.5 \text{ TeV}$ **H production**

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_{CC}^H	N_{NC}^H	N_{CC}^H
$H \rightarrow b\bar{b}$	0.577	113 100	13 900	2 450 000
$H \rightarrow c\bar{c}$	0.029	5 700	700	123 000
$H \rightarrow \tau^+\tau^-$	0.063	12 350	1 600	270 000
$H \rightarrow \mu\mu$	0.00022	50	5	1 000
$H \rightarrow 4l$	0.00013	30	3	550
$H \rightarrow 2l2\nu$	0.0106	2 080	250	45 000
$H \rightarrow gg$	0.086	16 850	2 050	365 000
$H \rightarrow WW$	0.215	42 100	5 150	915 000
$H \rightarrow ZZ$	0.0264	5 200	600	110 000
$H \rightarrow \gamma\gamma$	0.00228	450	60	10 000
$H \rightarrow Z\gamma$	0.00154	300	40	6 500

Uta Klein, Higgs@FCC-he

FFC-he, $H \rightarrow HH$ cross section $\sim 0.4 \text{ fb}$

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HH production

Fiducial cross-sections for CC $e^- p$ DIS : $HH \rightarrow 4b$ (branching ratios included) and unpolarised electron beam



Processes	E_e (GeV)	$\sigma(\text{fb})$	$\sigma_{eff}(\text{fb})$
$e^- p \rightarrow \nu_e h h j, h \rightarrow b\bar{b}$	60	0.04	0.01
	120	0.10	0.024
	150	0.14	0.034

 $p_{T,j,b} > 20 \text{ GeV}$ $\cancel{E}_T > 25 \text{ GeV}$ $|\eta_j| < 5, \Delta R = 0.4$

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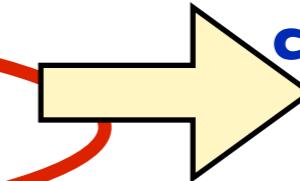
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covered in my Thursday plenary talk

FHC: physics topics list



FHC.1.3 Continued exploration of SM particles

FHC.1.3.1 Physics of the top quark (rare decays, FCNC, anomalous couplings, ...)

Kamenik, Zupan, BSM@100

~~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 **Ruderman, BSM@100**

FHC.1.3.3 QCD dynamics

FHC.1.4 Opportunities other than pp physics:

FHC.1.4.1 Heavy Ion Collisions **HI WG**

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... **Jacobsson, FHC5**

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 **Rojo, FHC4**

FHC.1.5.2 MC generators

FHC.1.5.3 NⁿLO calculations

FHC.1.5.4 EW corrections

10^{10} Higgs bosons => $10^4 \times$ today **Curtin (exotic H decays) BSM@100**

10^{12} top quarks => $5 \cdot 10^4 \times$ today

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

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

=> 10^{11} t → W → τ $\Rightarrow \tau \rightarrow 3\mu, \tau \rightarrow \mu\gamma, CPV, \dots$

=> few $\times 10^{11}$ t → W → charm hadrons $\Rightarrow D$ mixing, CPV, D → $\mu^+\mu^-$, ...

Tasks:

o countless list ! plus

o examine the possibility of detectors dedicated to final states in the 0.1 - 1 TeV region, with focus on Higgs, DM and weakly interacting new particles, top, W

W decays

MLM @ //



- o W mass ??

- o SM rare decays -- Examples:

$$W^\pm \rightarrow \pi^\pm \gamma$$

$BR_{SM} \sim 10^{-9}$, CDF $\leq 6.4 \times 10^{-5}$

$$W^\pm \rightarrow D_s^\pm \gamma$$

$BR_{SM} \sim 10^{-9}$, CDF $\leq 1.2 \times 10^{-2}$

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

- o SM inclusive decays -- Examples:

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

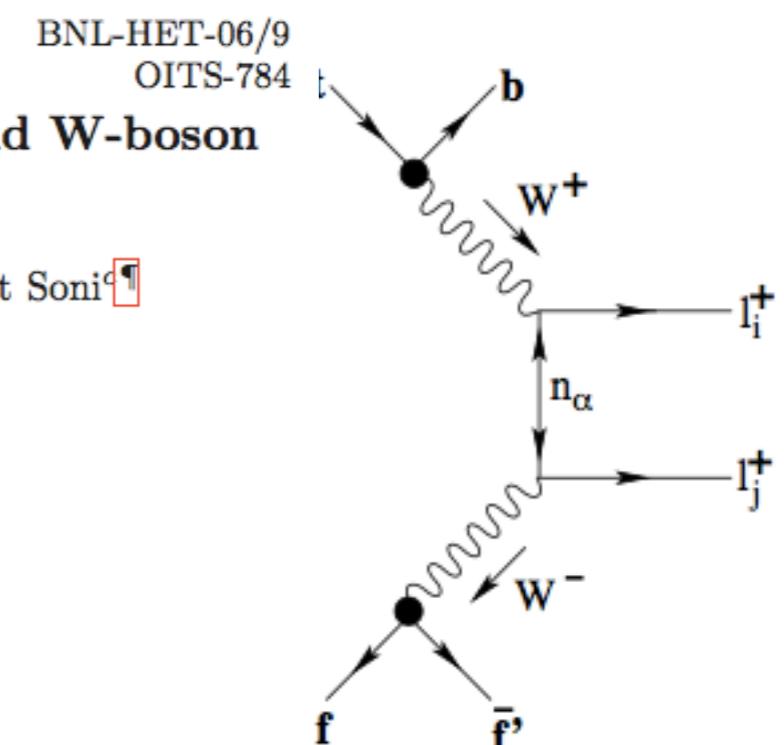
- o BSM decays -- Are there interesting channels to consider?

-- Example

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,¶}

^aPhysics Department, Technion - Israel Institute of Technology, Haifa 32000, Israel



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FHC.1.4.2.1 "Intensity frontier": kaon physics, mu₂e conversions, beam dump experiments and searches for heavy photons, heavy neutrals, and other exotica... **Jacobsson, FHC5**

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Conclusions

FCC provides lots of possibilities for new QCD studies, but more thoughts/work is required!

Some things relatively easy, some are just really new ground

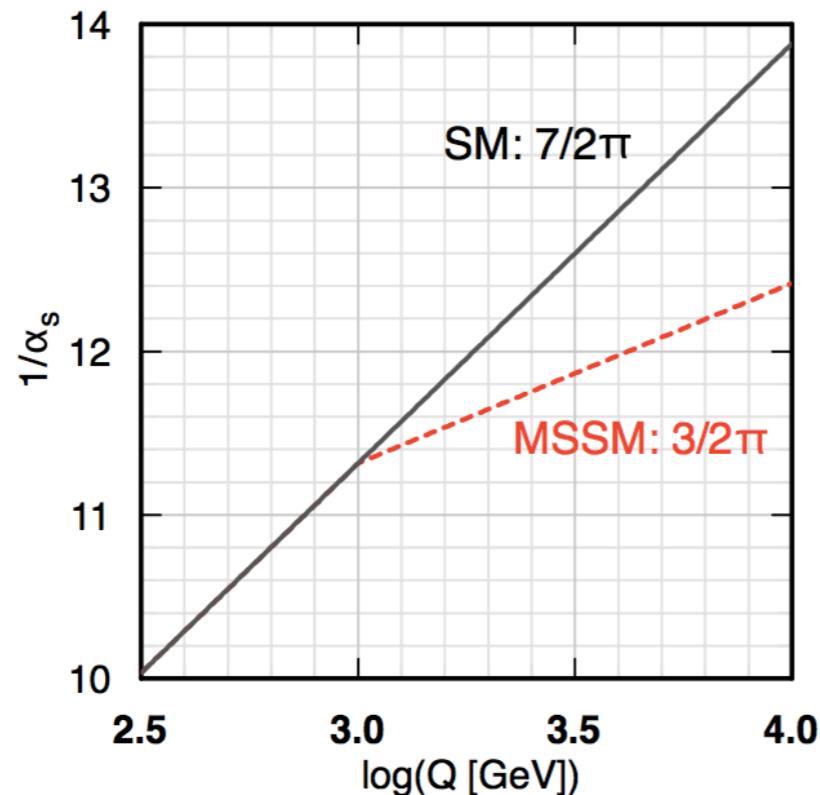
- treatment of interplay of QCD and EW corrections
- generic inclusion of EW Sudakov logarithms
- inclusion of top PDF
- implementation of mixed QCD-EW PDF evolution
- impact of double parton scattering
- better understanding of small x
- in general resummations more important (larger phase space increases ratio of scales)
- will scale variation still do a decent job for uncertainties?
will we come up with something as generic, but better?

Quigg @ //

QCD could be complete, up to M_{Planck}
... but that doesn't prove it must be
Prepare for surprises!

How might QCD Crack?

(Breakdown of factorization)
Free quarks / unconfined color
New kinds of colored matter
Quark compositeness
Larger color symmetry containing QCD



α_s at 100 TeV pp-collider

Zanderighi @ //

How about measuring α_s from Z+1jet? Could also measure the running nicely over a very large range of p_t values ...

Deviation from QCD running could provide indirect evidence for New Physics

If not Z+1jet, what observable/process would be best...? e.g. ratio of Z+1jet/ZZ ?

Certainly worth exploring the potential of a 100 TeV hadron collider also in this direction

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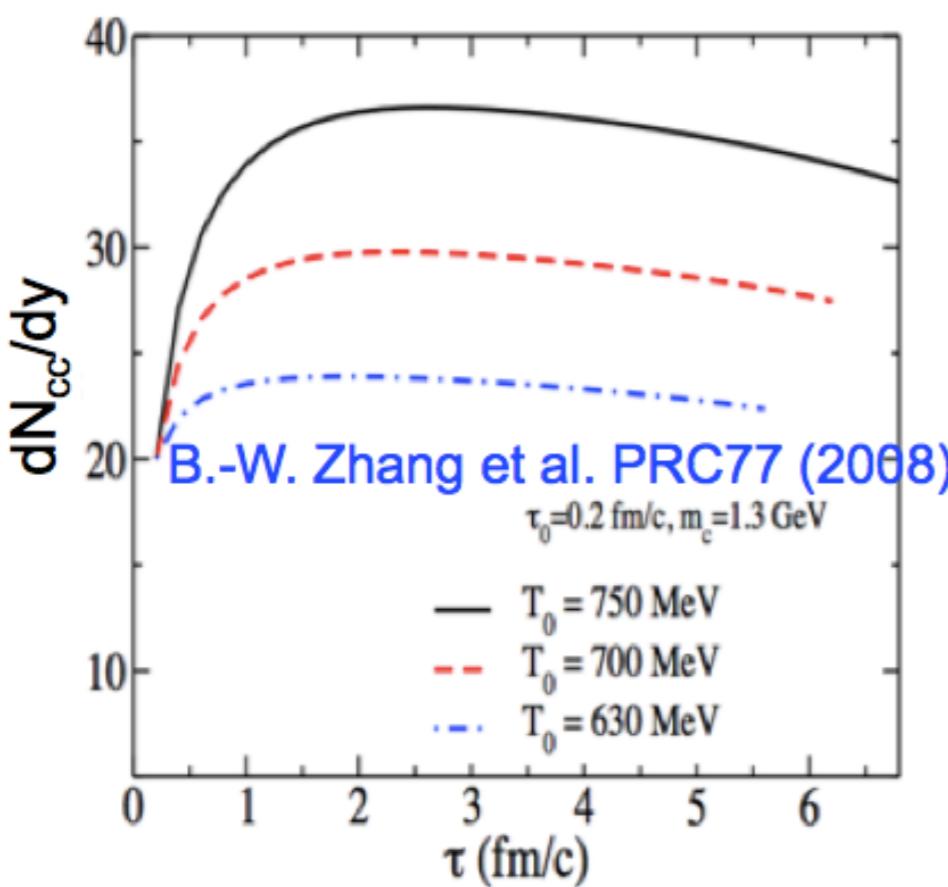
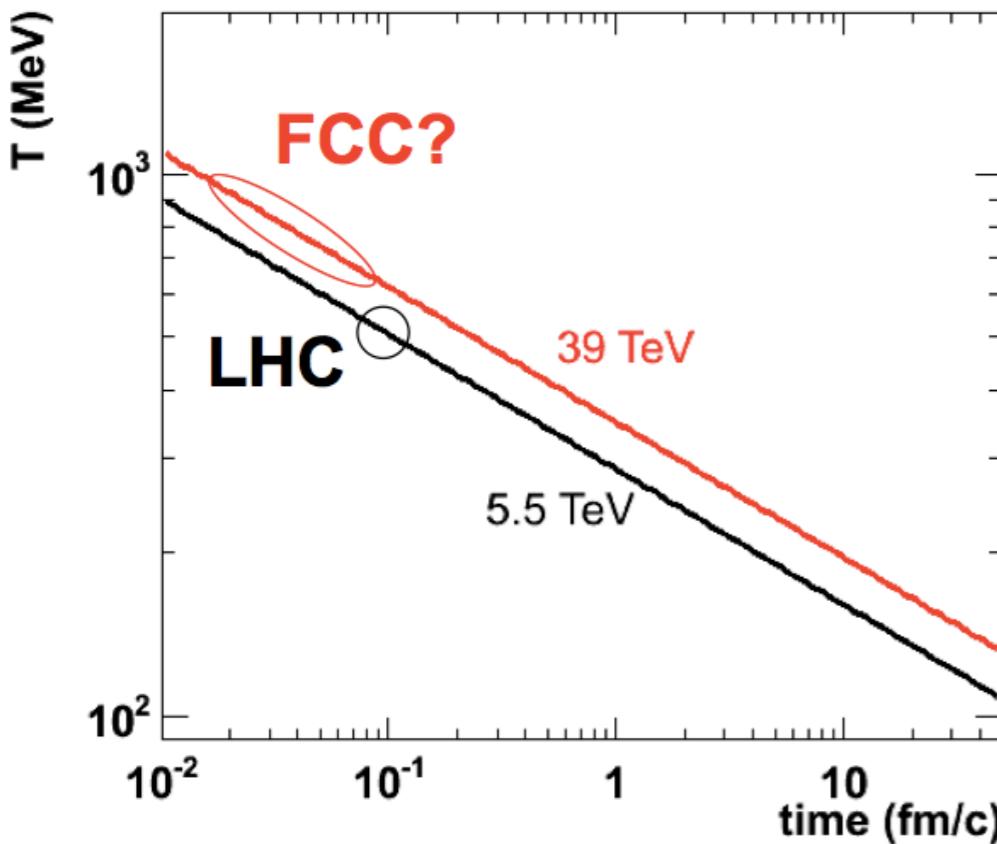
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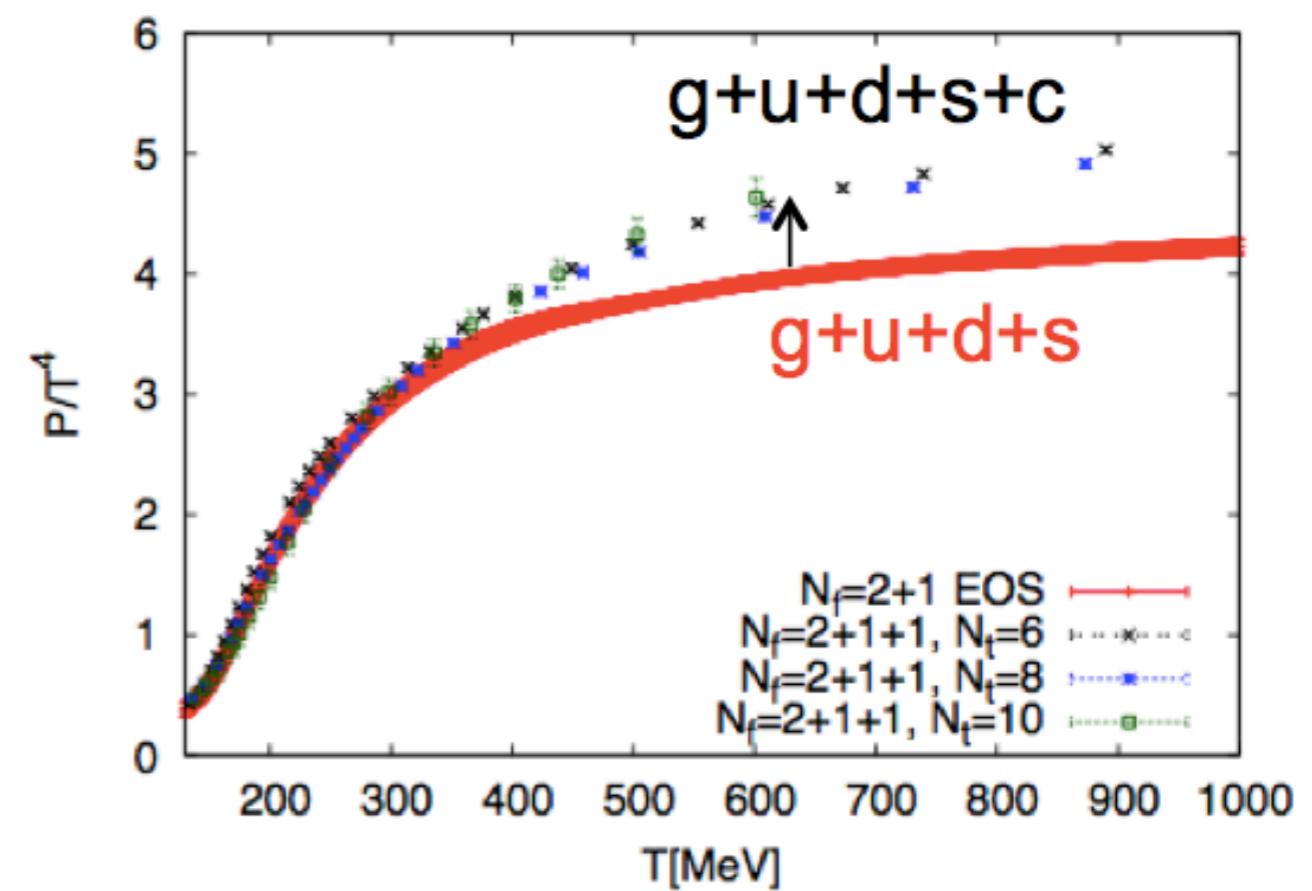
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$T \sim \text{GeV} \Rightarrow$

- ~thermal charm production
- change in QGP eqn of state

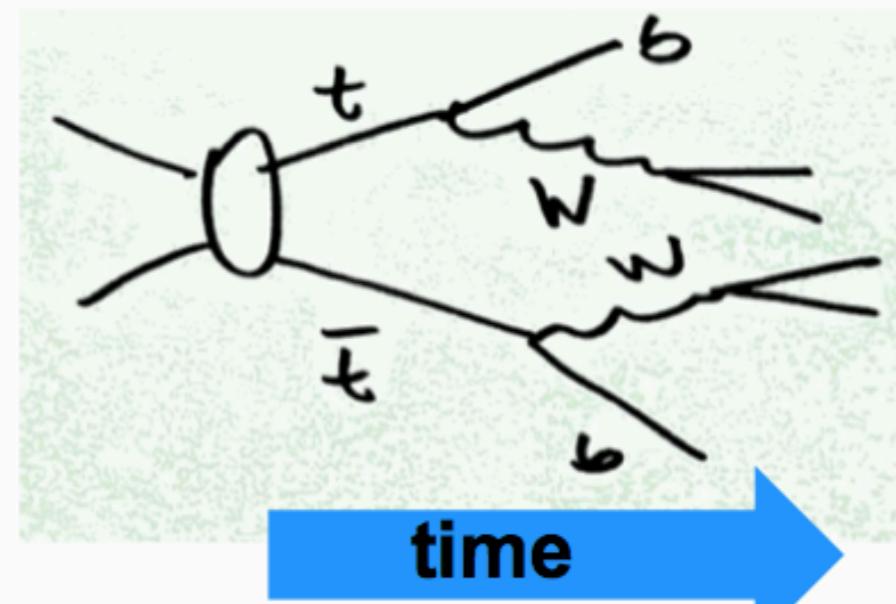


An interesting physics case: boosted color singlets in the medium



First estimation of the timescales
for boosted objects in the medium

$$t\bar{t} \rightarrow b\bar{b} + \ell + 2 \text{jets} + E_T$$



time

	Pt=1 TeV	Pt=500 GeV
ttbar produced	0 fm/c	0 fm/c
top \rightarrow W+b	1 fm/c	0.5 fm/c
W decay	1.6 fm/c	0.8 fm/c
qqbar in singlet	2.3 fm/c	1.3 fm/c

→ Interaction with the medium starts

A tool to probe timescale of medium evolution?

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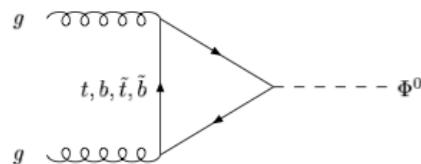
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- most QCD and elw. corrections known → $\Delta \lesssim 10 - 15\% @ HC$
→ $\Delta \lesssim 1 - 5\% @ e^+e^-$
- important to develop NLO event generators [\leftarrow backgrounds]

(i) $gg \rightarrow h/H$



- NLO QCD corrections: $\sim 10 \dots 100\%$

- NNLO calculated for $m_t \gg M_\phi \Rightarrow$ further increase by 20–30%
[mass effects small]

Marzani, Ball, Del Duca, Forte, Vicini
Harlander, Ozeren
Pak, Rogal, Steinhauser

- NNNLO estimated for $m_t \gg M_\phi$
scale dependence: $\Delta \lesssim 10 - 15\%$

⇒ scale stabilization

Catani, de Florian, Grazzini, Nason
Moch, Vogt
Ravindran
Ball, Bonvini, Forte, Marzani, Ridolfi

- NNLL soft gluon resummation: 10 – 15%
Georgi, ...
Gamberini, ...
S., Djouadi, Graudenz, Zerwas
Dawson, Kauffman
- elw. corrections: $\sim 5\%$
- QCD corrections to squark loops: 10–100%
Harlander, Kilgore
Anastasiou, Melnikov
Ravindran, Smith, van Neerven
- genuine SUSY–QCD corrections: 10–100%
[$\leftarrow \Delta_b @ \text{large } \tan\beta$]
Harlander, Steinhauser, Hofmann
Degrassi, Slavich
Anastasiou, Beerli, Daleo
Mühlleitner, Rzezak, S.
- SUSY-elw. corrections unknown
- impl. of $gg \rightarrow \phi$ in POWHEG including mass effects @ NLO
Bagnaschi, Degrassi, Slavich, Vicini

- MSSM: large SUSY–QCD corrections to $\phi^0 \rightarrow b\bar{b}$

$$\propto \frac{\alpha_s}{\pi} \frac{m_{\tilde{g}} \mu \tan\beta}{M_{SUSY}^2} \sim \Delta_b$$

Plans for pheno@FCC-hh



- Continue informal mtgs, with a 1/few-weeks schedule
- Looking for WG conveners (TH+exp)
- Form WG's on topics indicated in previous slide. Engage/collect material from whoever is working on 100 TeV topics
- Organize 2/3-day workshops, with a ~6-month frequency, to bring all WGs together
- 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