FCC - protons: physics opportunities

UK HEP Forum 2014
"Future Colliders"

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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?**
- **...**

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- **Hierarchy problem**
  - "natural" solution, at the TeV scale?

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

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Readiness to address both scenarios relies on:

(1) extended energy/mass reach
(2) precision
(3) sensitivity (to elusive signatures)

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

search for stealth phenomena, invisible at the LHC

- The current work on the physics of FCC-hh is focused on exploring the potential of this collider to address these 3 targets (precision, mass reach, sensitivity)
- The ongoing studies should not be viewed as “physics cases”. The goal is assessing the potential and the opportunities.
- The “physics case” will emerge at the end, when confronting the potential against the explicit circumstances arising from the future 10 years of LHC running, DM searches, Belle2, etc., and in view of the overall synergy/complementarity with the other components of the project (*ee* and *eh*)

Current goals of the study

- Extrapolate to higher energy the LHC potential for bread and butter searches:
  - define discovery mass reach for Z', gluinos, new quarks, compositeness, etc.etc.etc.
- Identify new analysis opportunities, unique to the FCC:
  - use of immense statistics (precision, rare phenomena)
  - use of extreme kinematical configurations (improved S/B, increased sensitivity to high scales)
  - innovative observables or probes (sensitivity to elusive final states)
- Identify possible no-lose scenarios for specific and compelling BSM frameworks, for which the FCC can provide conclusive yes/no answers

Contents

- Examples of new measurement ideas
- Luminosity needs
- Detector envelope drivers

Precision: Higgs properties

Following tables from Snowmass Higgs WG report,
http://arxiv.org/abs/1310.8361

Table 1-20. *Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$, and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume (e^-,e^+) polarizations of (−0.8, 0.3) at 250 and 500 GeV and (−0.8, 0.2) at 1000 GeV, plus a 0.5% theory uncertainty. CLIC numbers assume polarizations of (−0.8, 0) for energies above 1 TeV. TLEP numbers assume unpolarized beams.*

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 − 7%	2 − 5%	8.3%	4.4%	3.8%	2.3%	−/5.5/<5.5%	1.45%
κ_g	6 − 8%	3 − 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 − 6%	2 − 5%	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	4 − 6%	2 − 4%	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 − 8%	2 − 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	10 − 13%	4 − 7%	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	14 − 15%	7 − 10%	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%
κ_μ	20%	7%	90%		16%	10%	– / 11 / 6%	6%
$\kappa_{Z\gamma}$	40%	10%					tbd	

Table 1-24. *Expected per-experiment precision on the triple-Higgs boson coupling. ILC numbers include $bbbb$ and $bbWW^*$ final states and assume (e^-, e^+) polarizations of (−0.8, 0.3) at 500 GeV and (−0.8, 0.2) at 1000 GeV. ILC500-up is the luminosity upgrade at 500 GeV, not including any 1000 GeV running. ILC1000-up is the luminosity upgrade with a total of 1600 fb^{-1} at 500 GeV and 2500 fb^{-1} at 1000 GeV. CLIC numbers include only the $bbbb$ final state and assume 80% electron beam polarization. HE-LHC and VLHC numbers are from fast simulation [102] and include only the $bb\gamma\gamma$ final state. ‡ILC luminosity upgrade assumes an extended running period on top of the low luminosity program and cannot be directly compared to CLIC numbers without accounting for the additional running period.*

	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	500	1600‡	500+1000	1600+2500‡	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

- There is no question that the absolute precision achievable at e+e– colliders is, on average, superior to that attainable by a hadron machine

- But notice that couplings like HWW and HZZ are already strongly constrained by EWPT, and deviations from their SM values, if any, are bound to be small. Couplings involved in rare decays, like $H \to \mu\mu$, $H \to Z\gamma$, and HHH coupling, are much less constrained, and give a hadron collider great sensitivity to possible BSM signals.

- The potential for Higgs precision studies at future hadron and lepton colliders are therefore largely complementary and synergetic. (see e.g. m_Z vs m_W)

- Furthermore, hadron collider experiments have many handles, which are only starting to be discovered and exploited, and whose ultimate precision potential is far from having been fully appreciated.

- ***Example***:

  - *Higgs total width measurement from rate at large Higgs off-shell mass w.r.t. peak .....*

Higgs physics

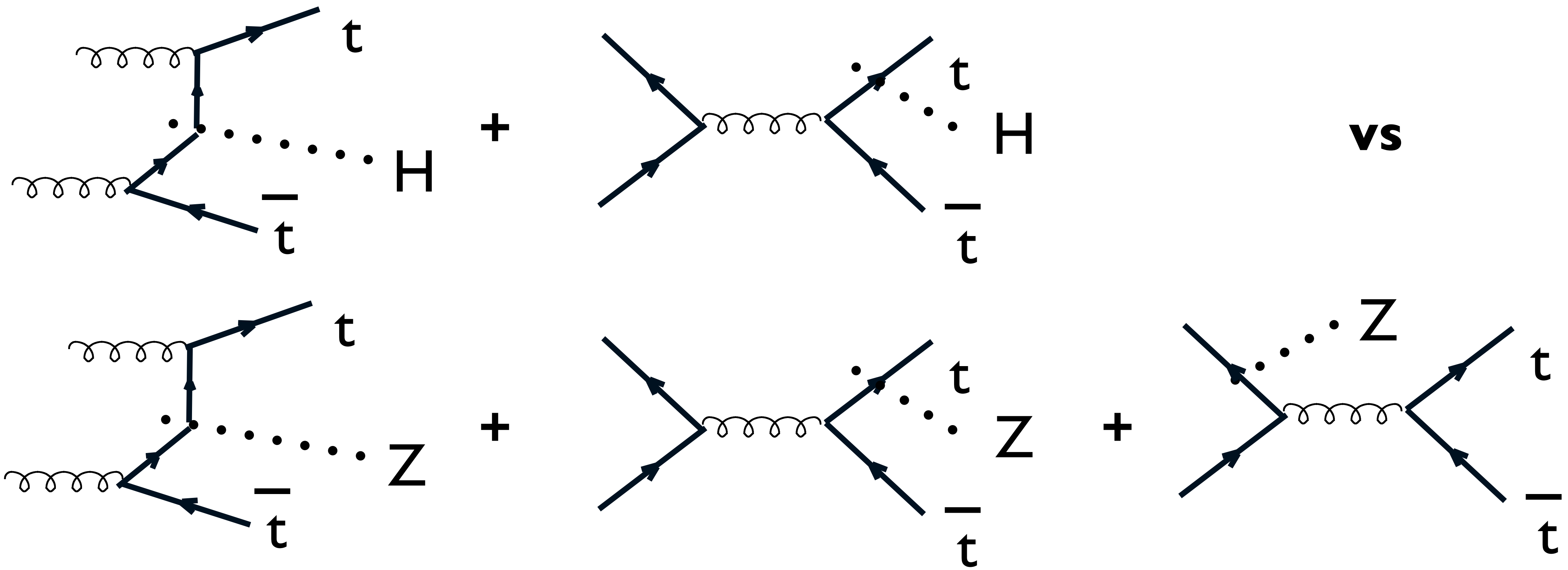
NLO rates $\mathbf{R(E)} = \sigma(E\ \mathrm{TeV})/\sigma(14\ \mathrm{TeV})$

	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:
$\sigma(ttH, p_T^{top} > 500\ \mathrm{GeV}) \Rightarrow R(100) = 250$

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

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] μ_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)

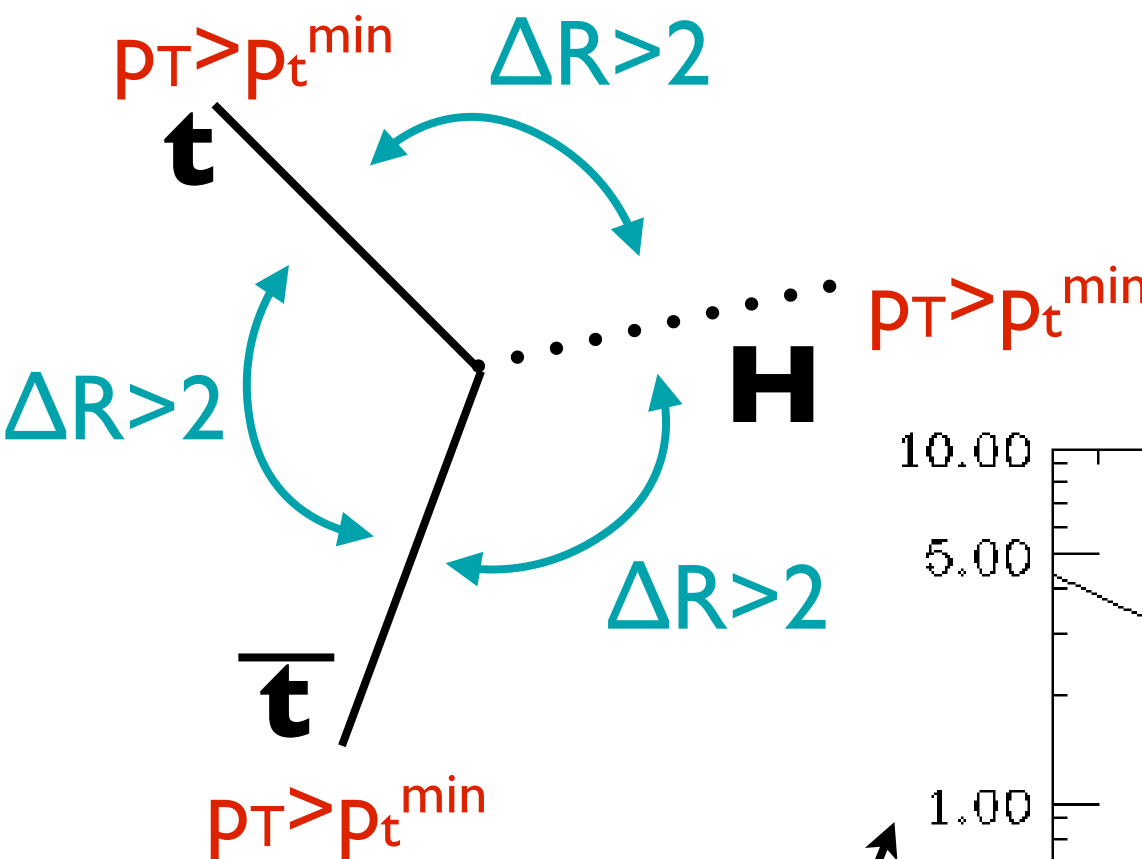
	δσ(ttH)	δσ(ttZ)	**δ[σ(ttH)/σ(ttZ)]**
14 TeV	± 4.8%	± 5.3%	**±0.75%**
100 TeV	± 2.7%	± 2.3%	**±0.48%**

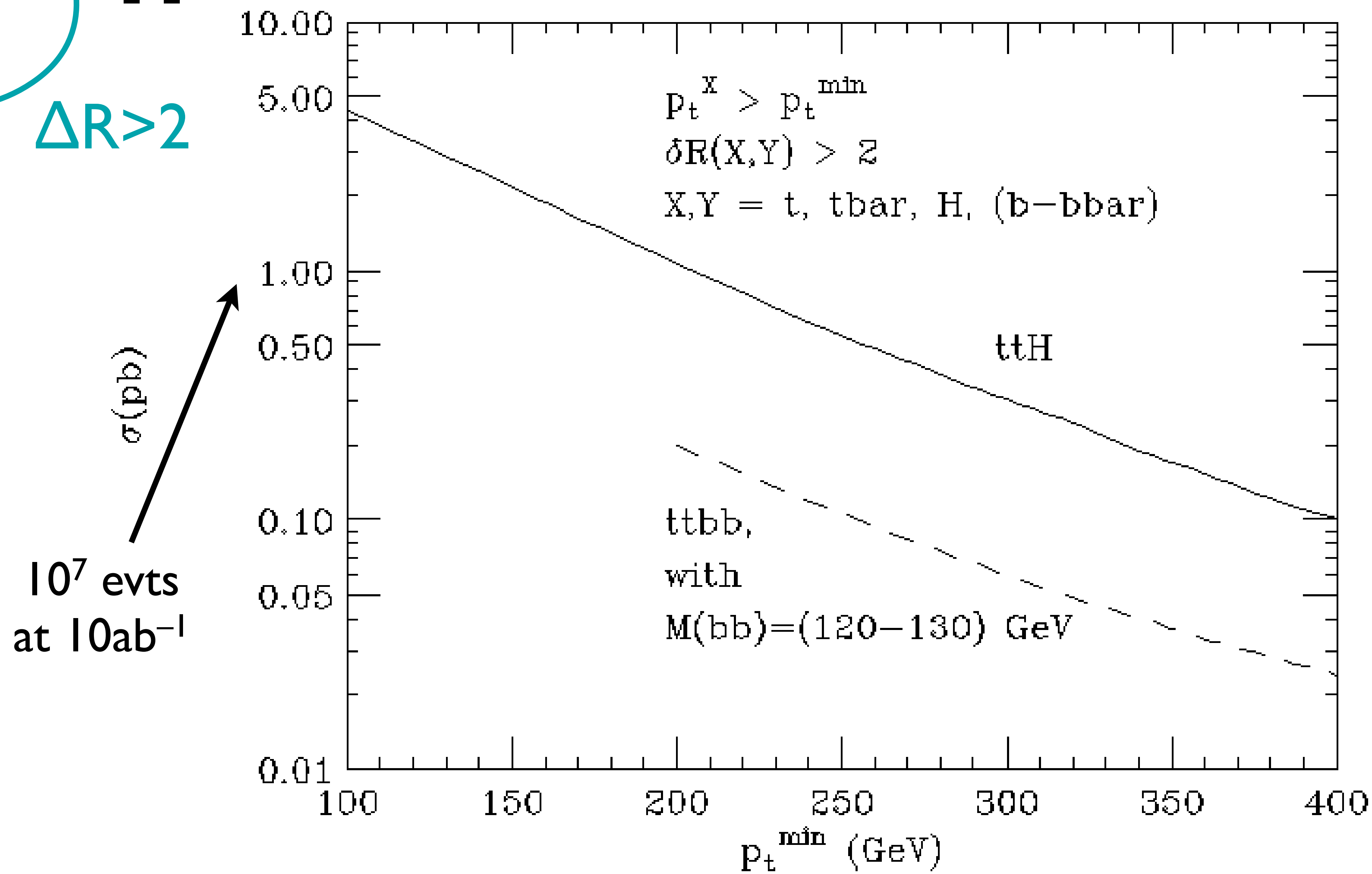
** The uncertainty reduction survives after applying kinematical cuts to the final states*

** Both scale and PDF uncertainties will be reduced further, well before FCC!*

Example, ttH at large pt

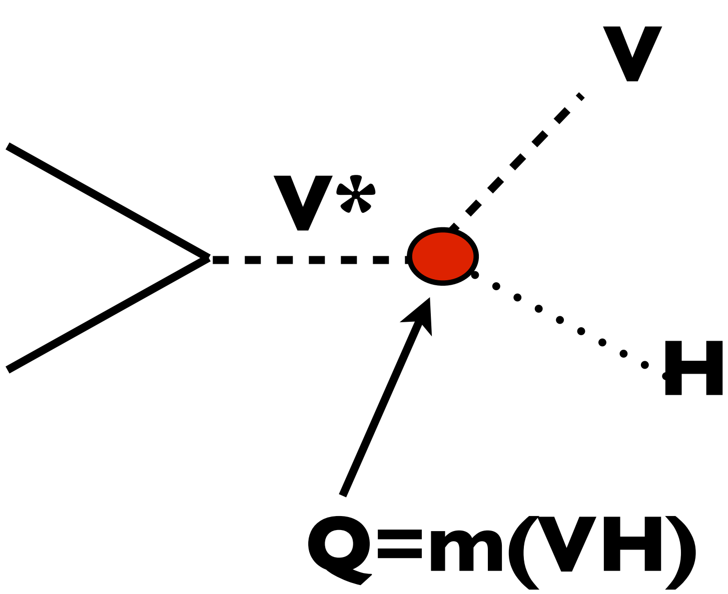
- S/B > 1
- 10 M evts at $10ab^{-1}$ w. ptmin=200 GeV, before further cuts

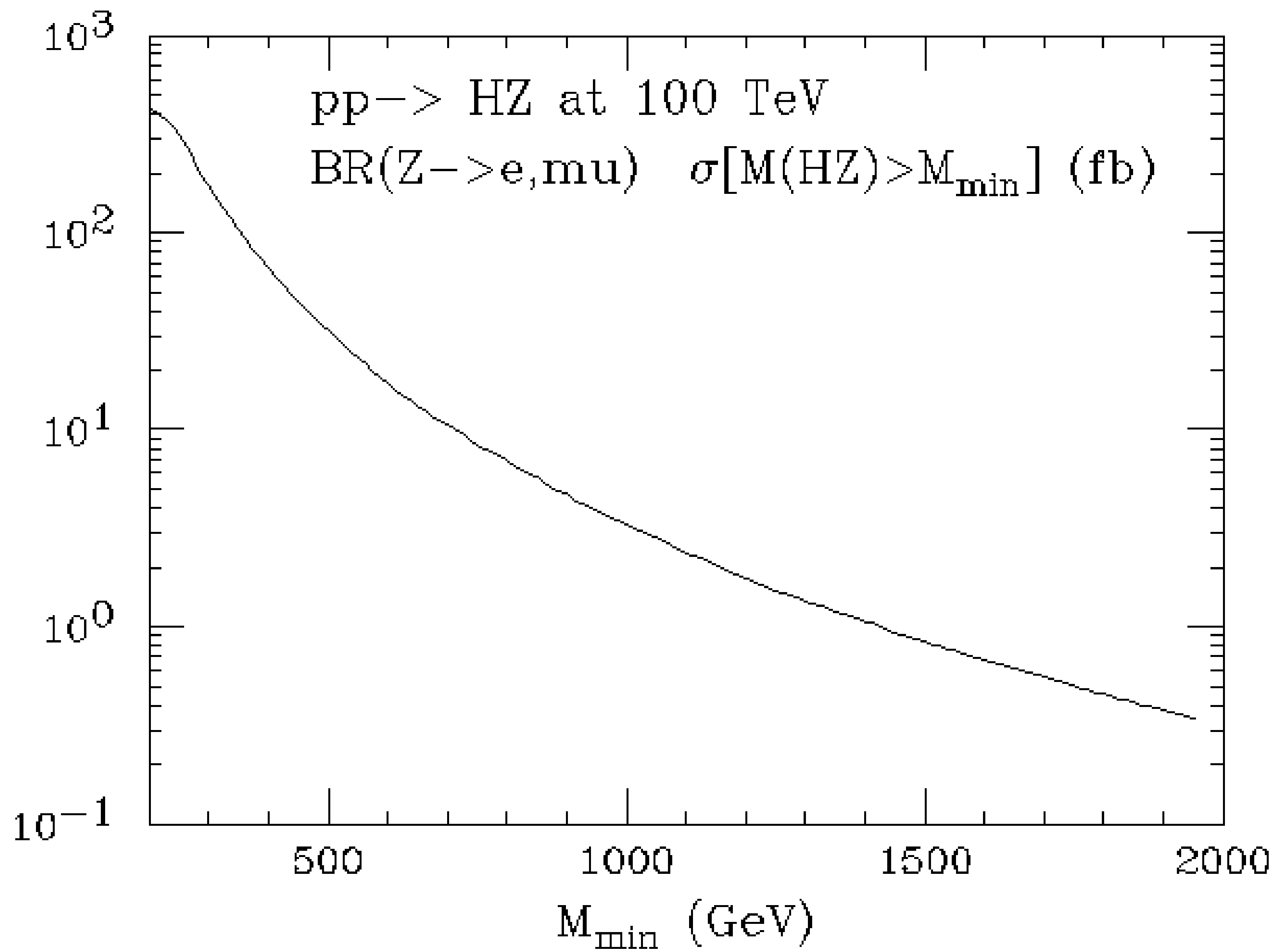




Example, ZH at large mass

- Sensitivity to anomalous VVH couplings complementary to what given by high-precision B(H→VV) measurements
- Optimal use of boosted object tagging, to access both hadronic and leptonic W/Z decays, H→bb, etc,





More in general ...

- Statistics allows to bring the precision in the measurement of BR ratios to sub-% level (e.g. B($\to\gamma\gamma$)/B($H\to ZZ^*$). Relying on the sub-% measurement of benchmark BR's from FCC-ee, FCC-hh can export this precision to other channels it has access to.

- Experimental feasibility, and theoretical implications, of these measurements are under study

- Several of these new ideas can be already explored at HL-LHC

Higgs: beyond precision physics

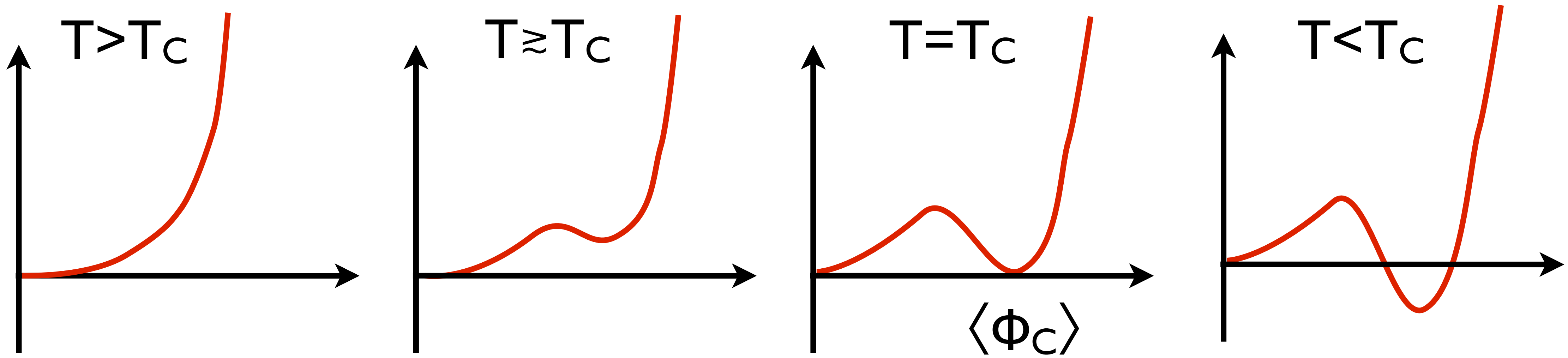
The Higgs boson is directly connected to several key questions:

- What's the real origin of the Higgs potential, which breaks EW symmetry?
  - underlying strong dynamics? composite Higgs?
  - RG evolution from GUT scales?
  - Are there partners of the Higgs (e.g. $H^{\pm}$, A^0, $H^{\pm\pm}$, ... , EW-singlets, ...)

- The hierarchy problem: what protects the smallness of m_H / $m_{Plank,GUT,...}$?

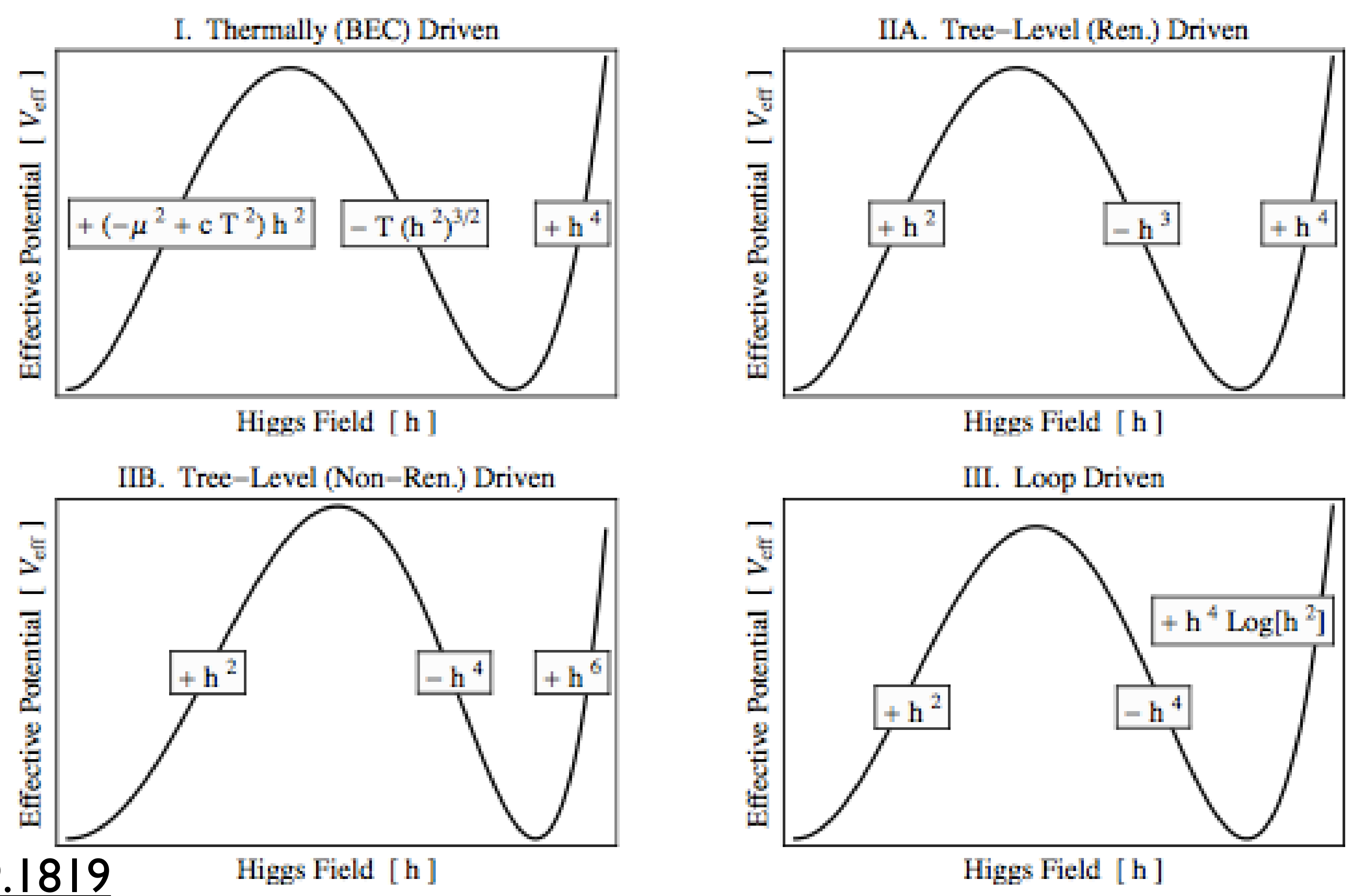
- Is there a relation between Higgs, EWSB and Dark Matter?

- What happens at the EW phase transition (PT) during the Big Bang?
  - what's the order of the phase transition?
  - are the conditions realized to allow EW baryogenesis?
  - does the PT wash out possible pre-existing baryon asymmetry?
  - is there a relation between baryogenesis and DM?



Strong 1st order phase transition $\Rightarrow \langle \Phi_C \rangle > T_C$

In the SM this requires $m_H \lesssim 80$ GeV $\Rightarrow$ new physics, coupling to the Higgs and effective at scales O(TeV), must modify the Higgs potential to make this possible



Chung et al,
http://arxiv.org/abs/1209.1819

Understanding the role of the EWPT in the evolution or generation of the baryon asymmetry of the Universe is a key target for future accelerators

- Experimental probes:
  - study of triple-Higgs couplings (... and quadruple, etc)
  - search for components of an extended Higgs sector (e.g. 2HDM, extra singlets, ...)
  - search for new sources of CP violation, orginating from (or affecting) Higgs interactions

$\Rightarrow$ all under study

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  - can WIMPS, detectable in direct and indirect (DM annihilation) experiments, be discovered at future colliders?

<u>DM overclosure upper limits:</u>

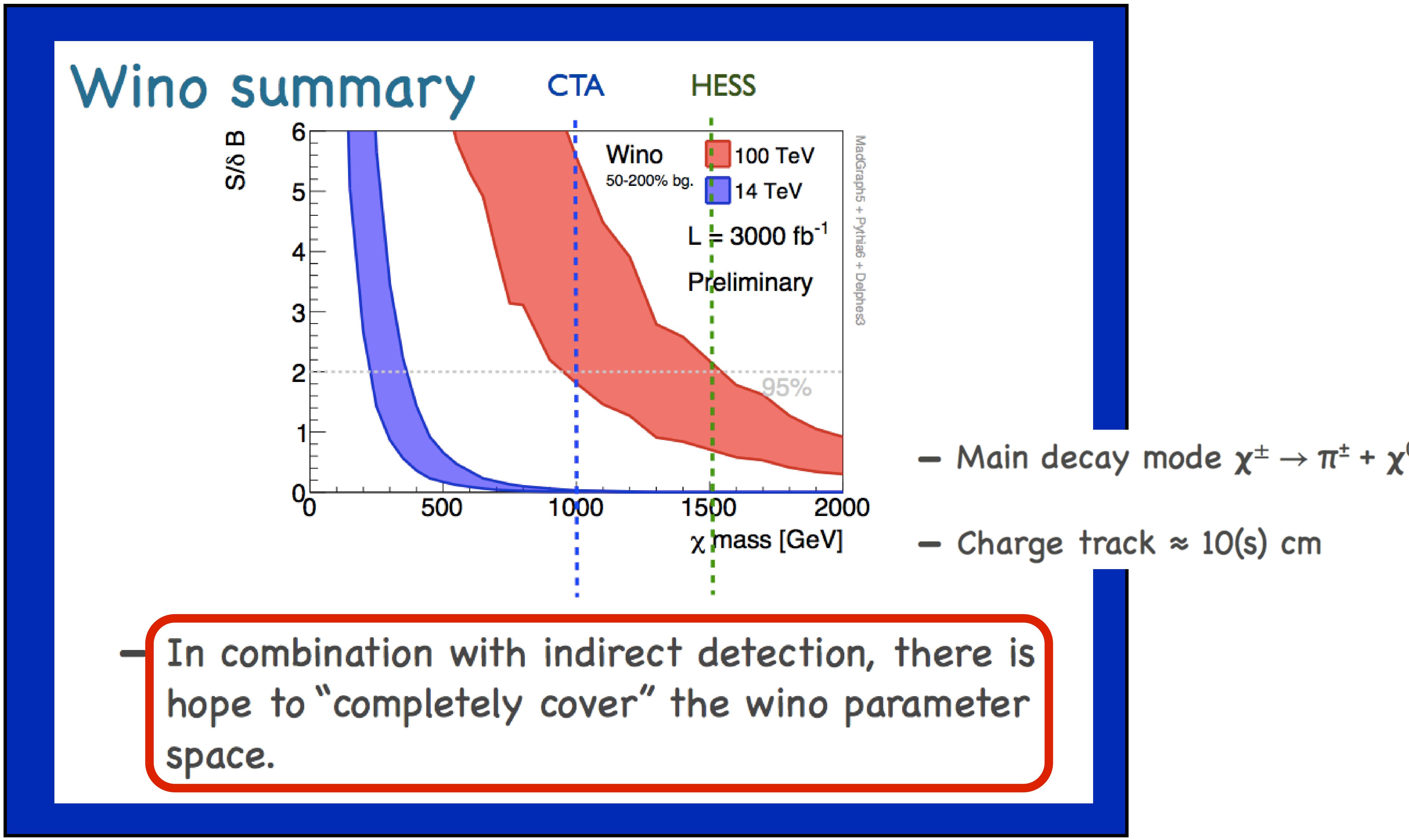
$M_{WIMP} < 1.8$ TeV $(g^2/0.3)$ $\Rightarrow$

wino: m≲3 TeV

higgsino: m≲1.1 TeV

In anomaly-mediated SUSY or split SUSY $\Rightarrow$

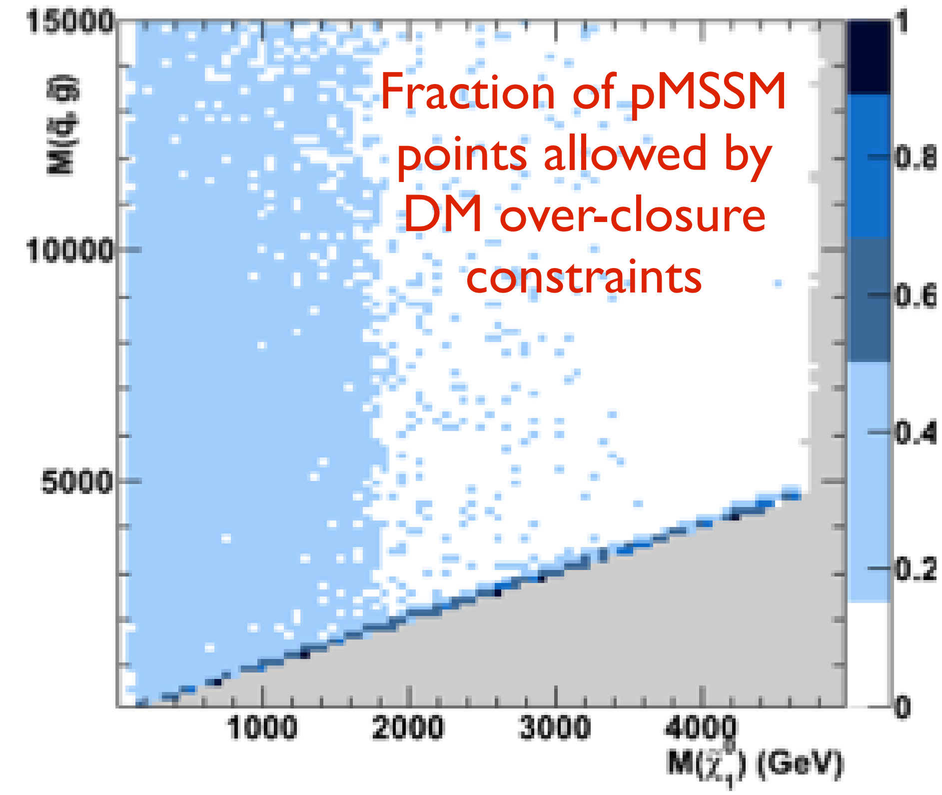
$\mathbf{m_{gluino}} \lesssim$ **10 TeV**



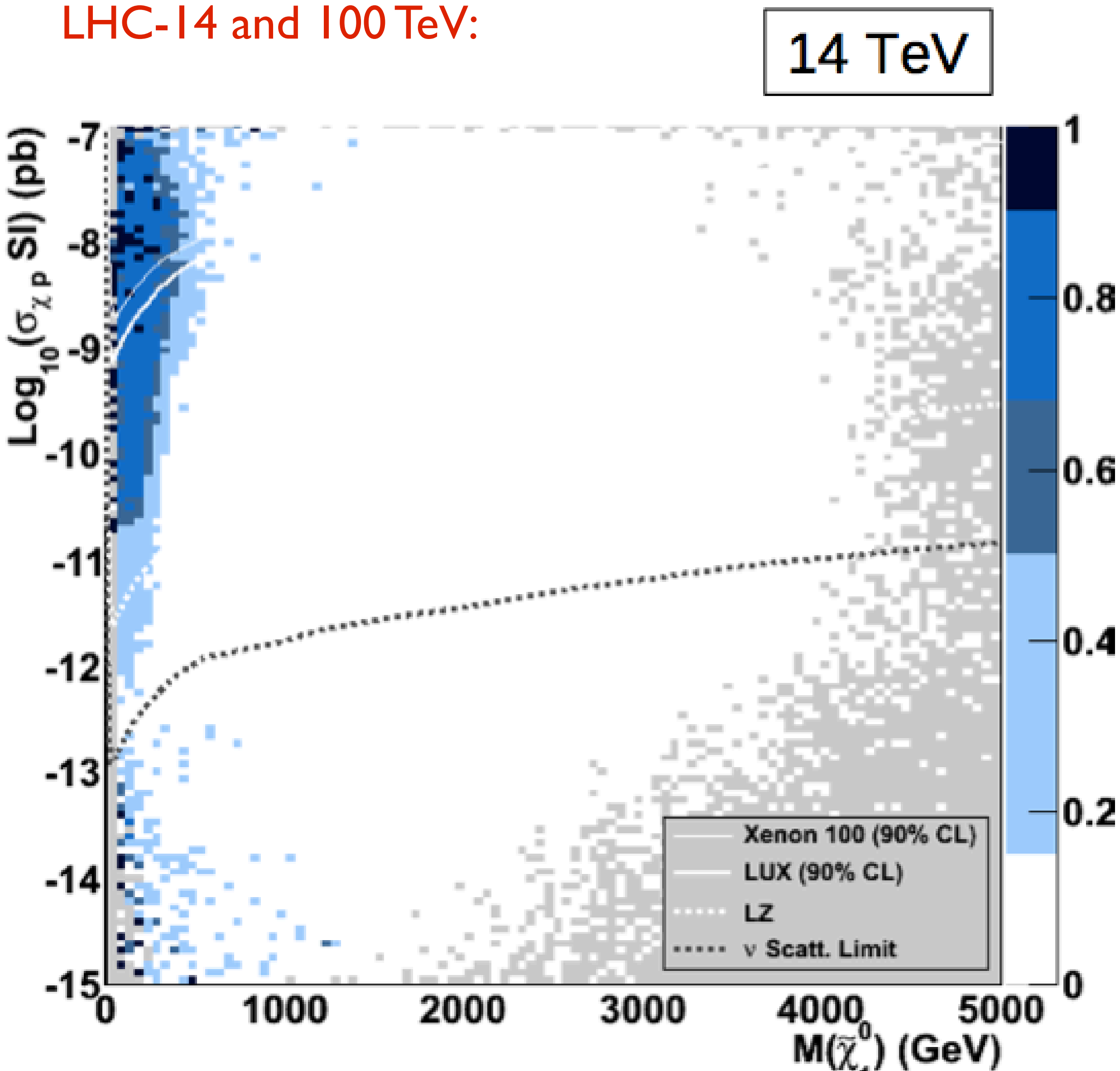
L.T.Wang, (see also P.Schwaller and T.Cohen) BSM@100 TeV Workshop

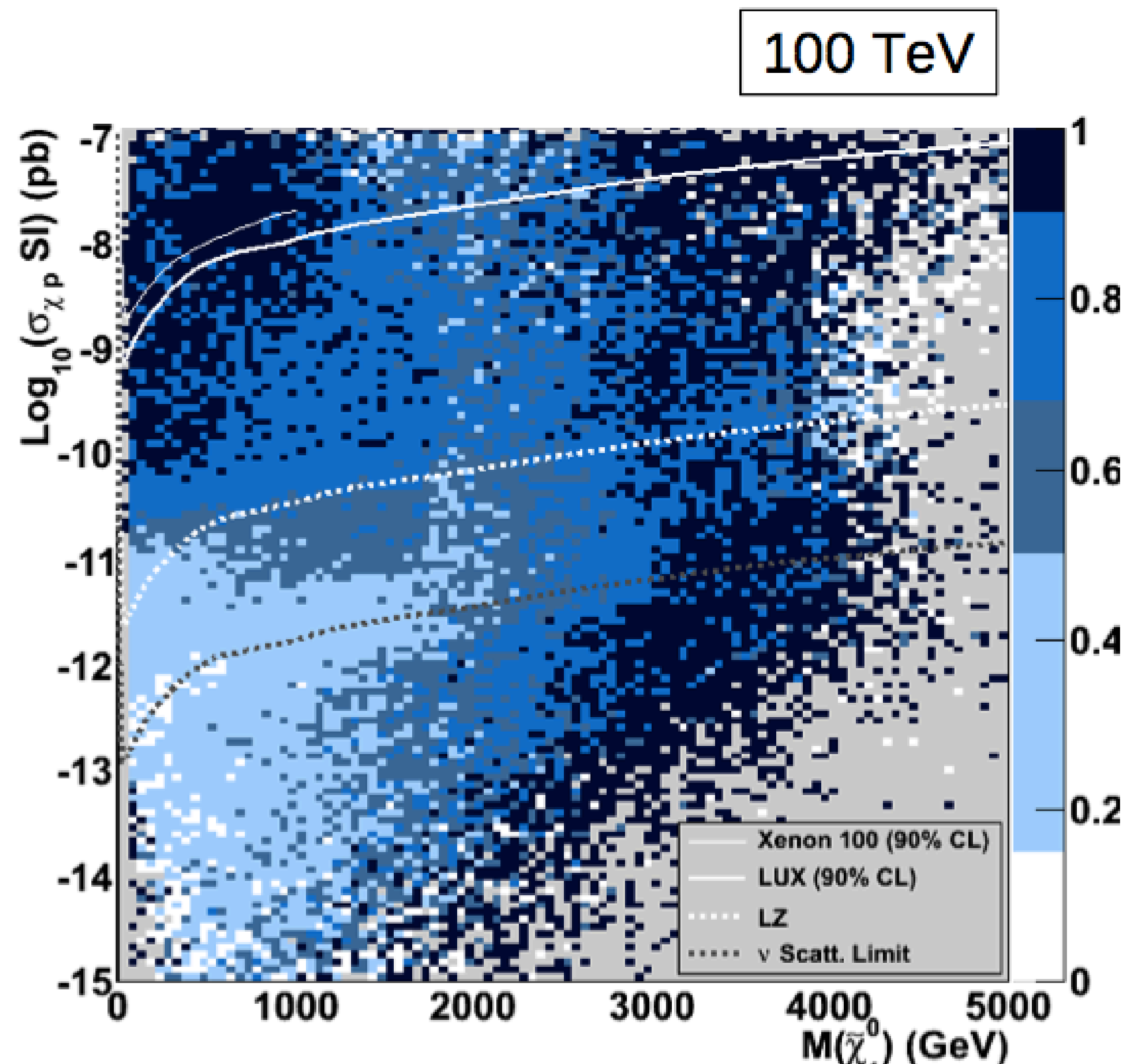
Coverage of pMSSM parameter space using DM constraints and direct searches at 14 and 100 TeV

Arbey, **Battaglia**, Mahmoudi



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





Exploration of the high mass scale

- *indirect sensitivity (i.e. departures from SM behaviour via virtual effects)*

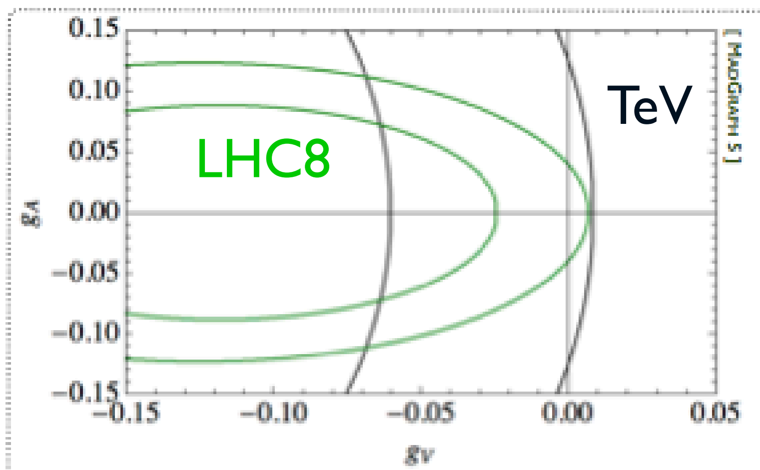
- *direct sensitivity: search for production of new particles*

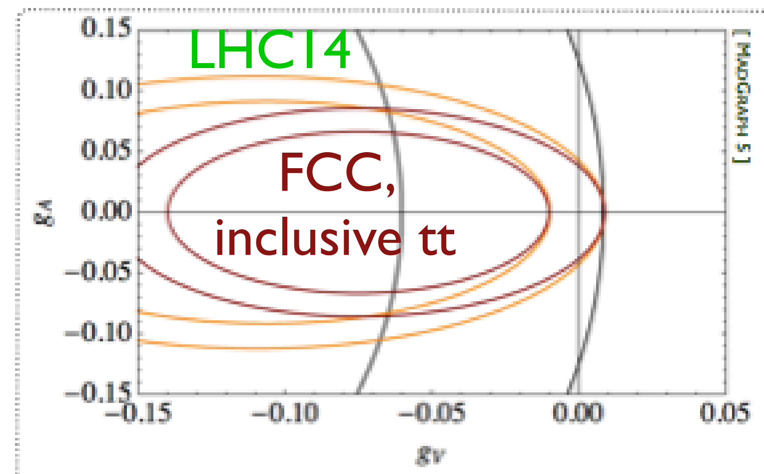
Example, tt at large mass

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)

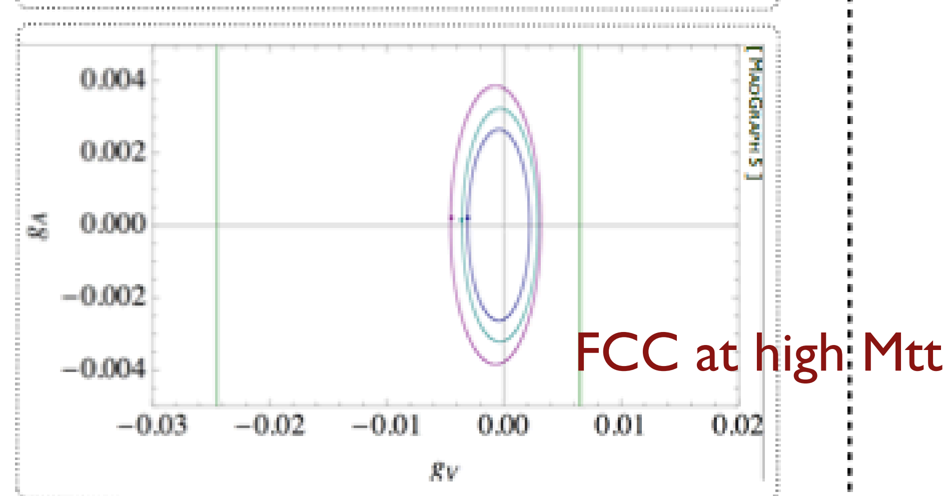
Applications: top dipole moments

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



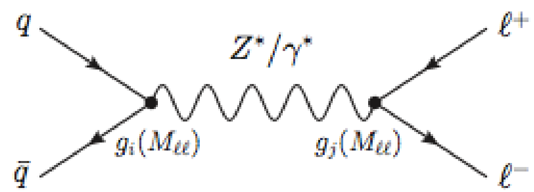


- Top pair-production total cross sections
  - ➢ constraints on g_A and g_V
- Existing data: Tevatron; LHC-8
- Predictions: LHC-14; FCC-100
  - ★ Major improvement not foreseen…
  - ★ LHC: assuming 5% syst. + stat. for 100 fb^{-1}
  - ★ FCC: assuming 5% syst. + stat. for 1 ab^{-1}
- Using instead highly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

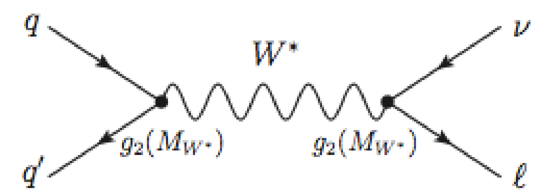


Running Electroweak Couplings as a Probe of New Physics

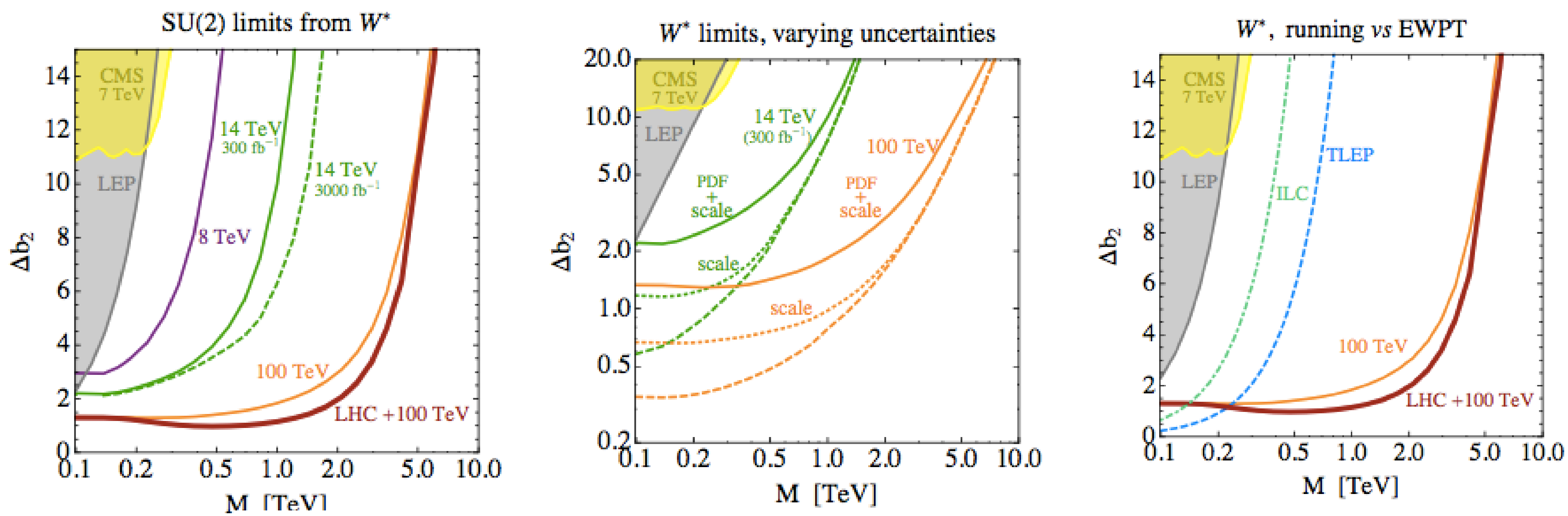
D.Alves, J. Galloway, J.Ruderman, J.Walsh *arXiv:1410.6810*

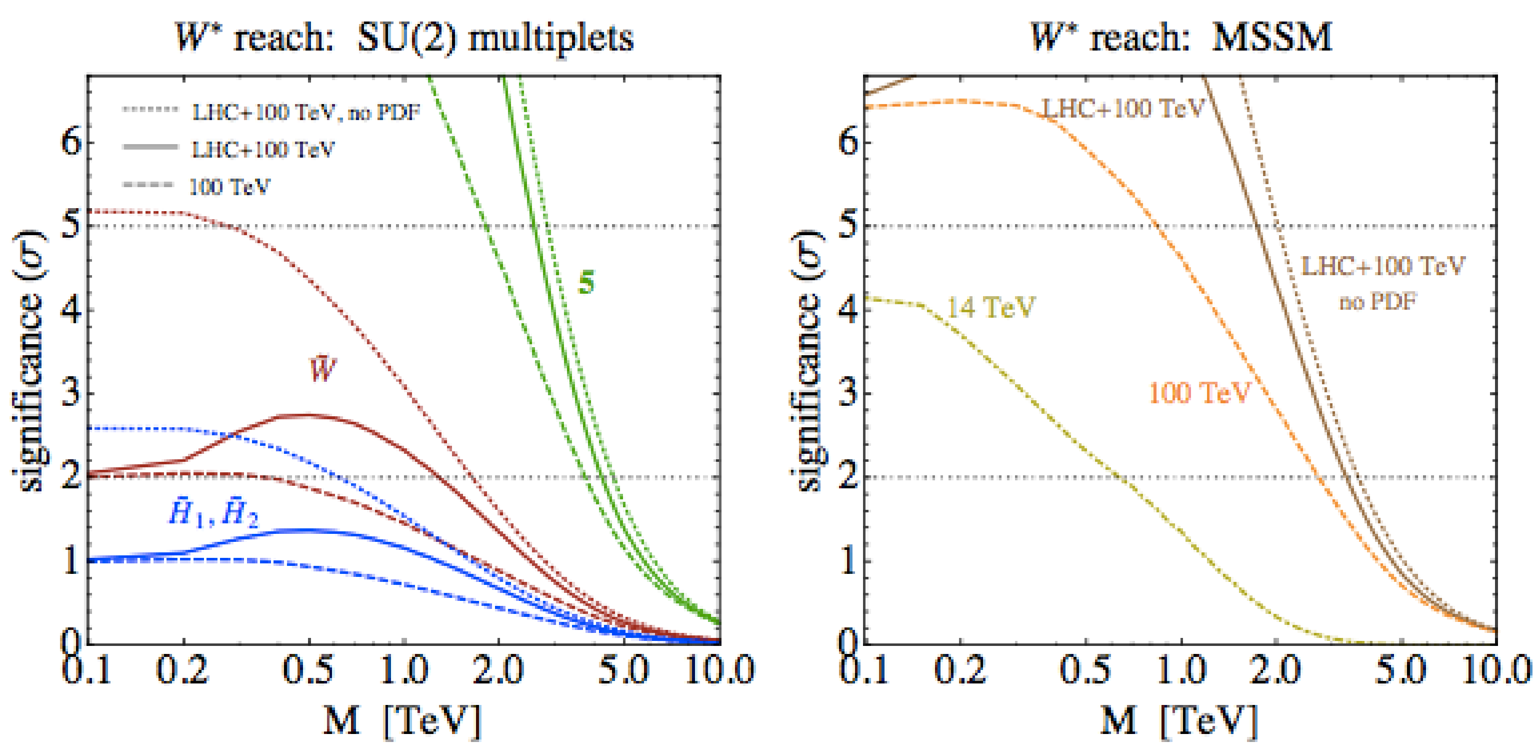


$$\frac{d\sigma}{dm_{ll}} \Rightarrow \alpha_{1,2}(q)$$



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

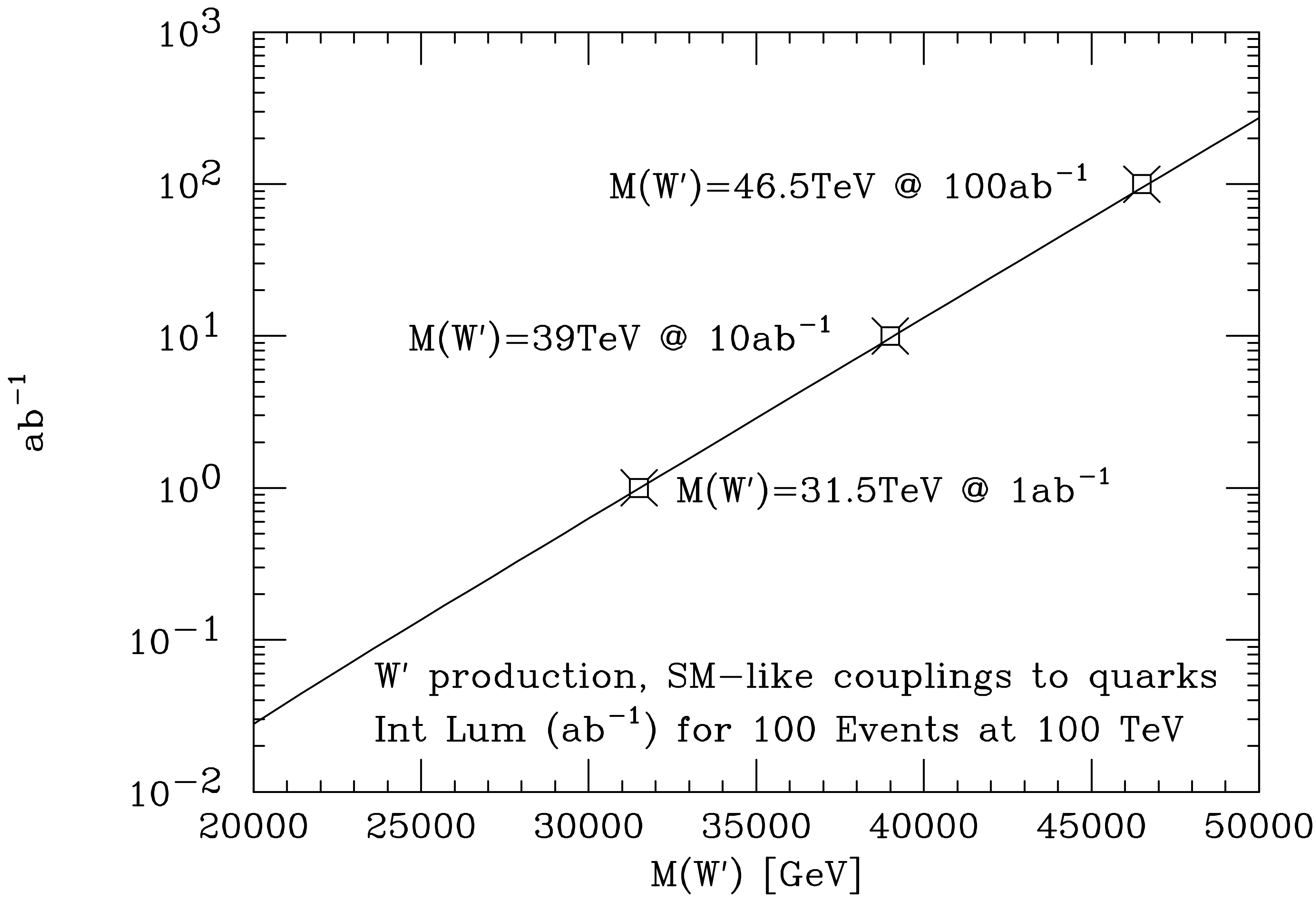




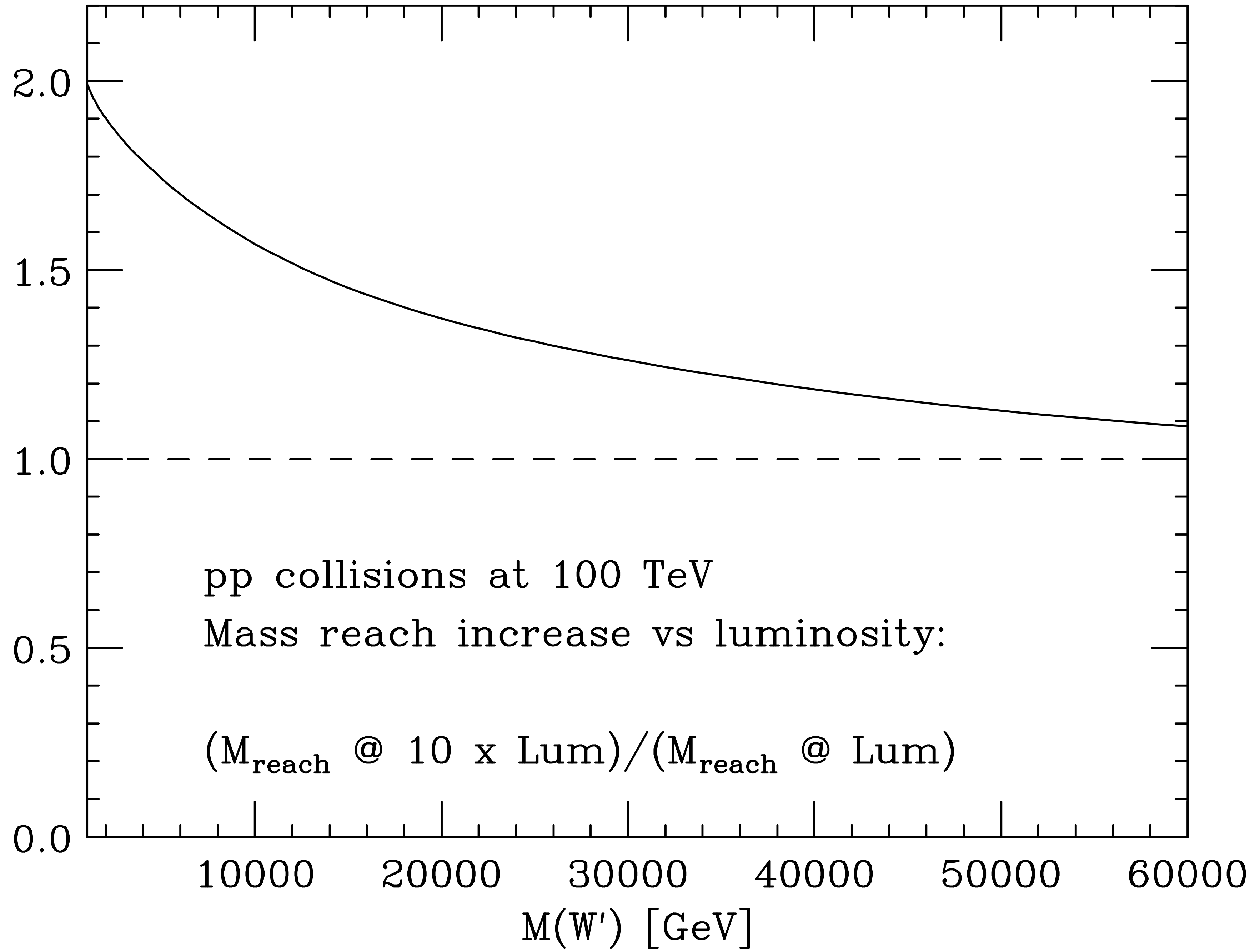
Luminosity vs Energy at a hadron collider

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



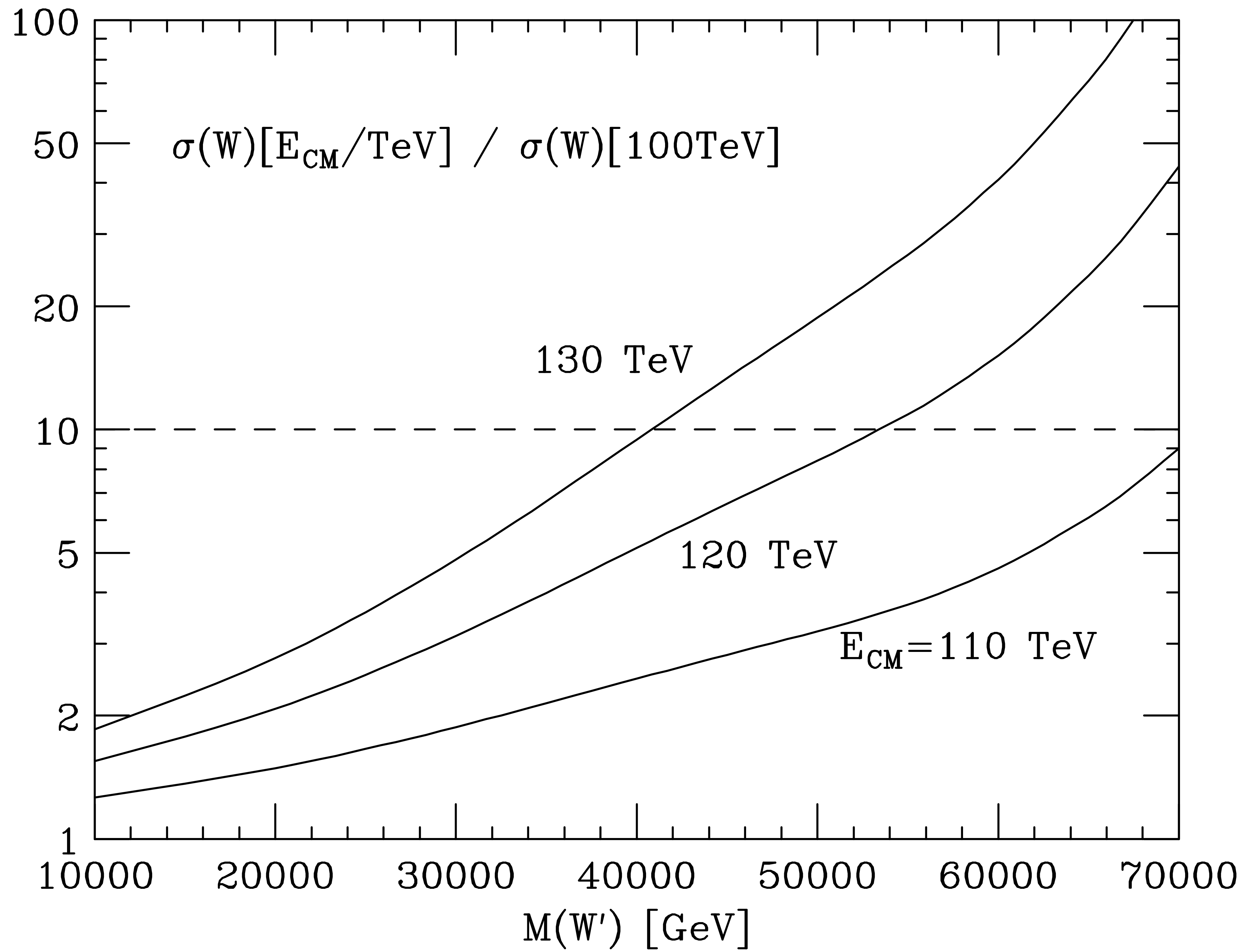
At L=O(ab^{-1}), Lum x 10 ⇒ ~ M + 7 TeV



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

See 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, ...)

Luminosity vs CM Energy



.... *bottom line:*

- Physicists will be happy to take as much Lum as the accelerator can deliver!

- But Lum beyond some saturation point (e.g. L such that 10xL gives ΔM_{reach} <0.2 M_{reach}) is not automatically justified by the extension of the exploration at the high end, rather by the need of higher stat for more accurate/ sensitive studies at lower masses. ⇒ implications for the detector optimization?

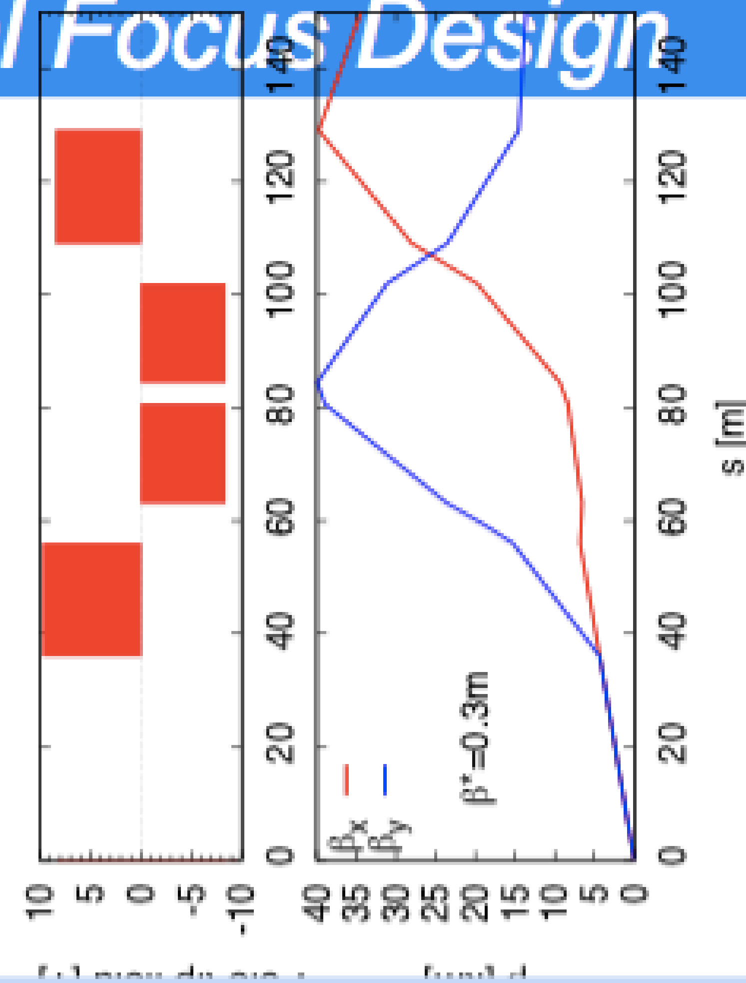
- Lum comes at a cost, in money, physics performance, and in the efficiency and safety of operations.
  - high current/power →safety risk
  - small emittance/β^* →short Lum lifetime, short L^* →.....

- Optimization is a must !

Some important choices in the design of the detectors and accelerator require "urgent" input from physics considerations

Interaction Region and Final Focus Design

R. Tomas



Two design being investigated:

- L* = 46m / 38m (how much is needed?)
- β* = 0.8m / 0.3m (goal <1.1m)

It is easier to obtain small beta-functions with shorter L*

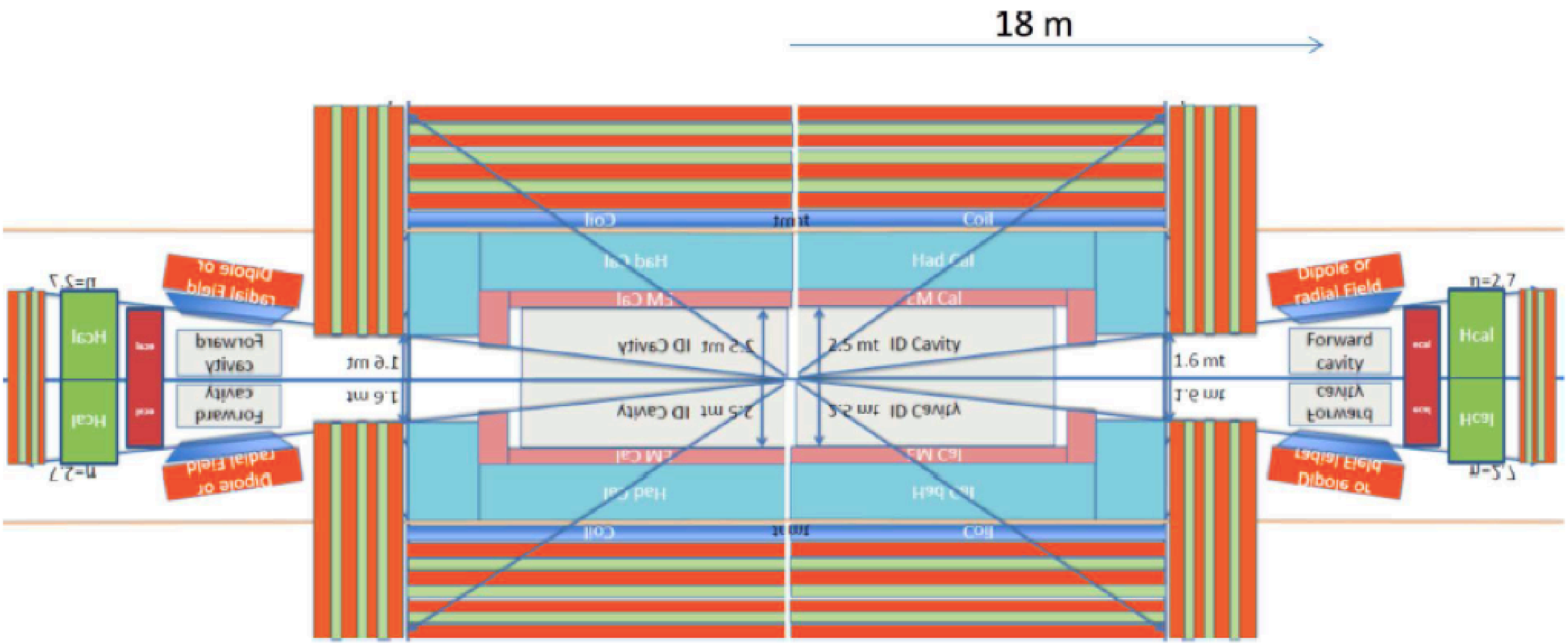
Will have a tendency to reduce L*

Need to understand detector requirements as soon as possible

Many issues need to be addressed

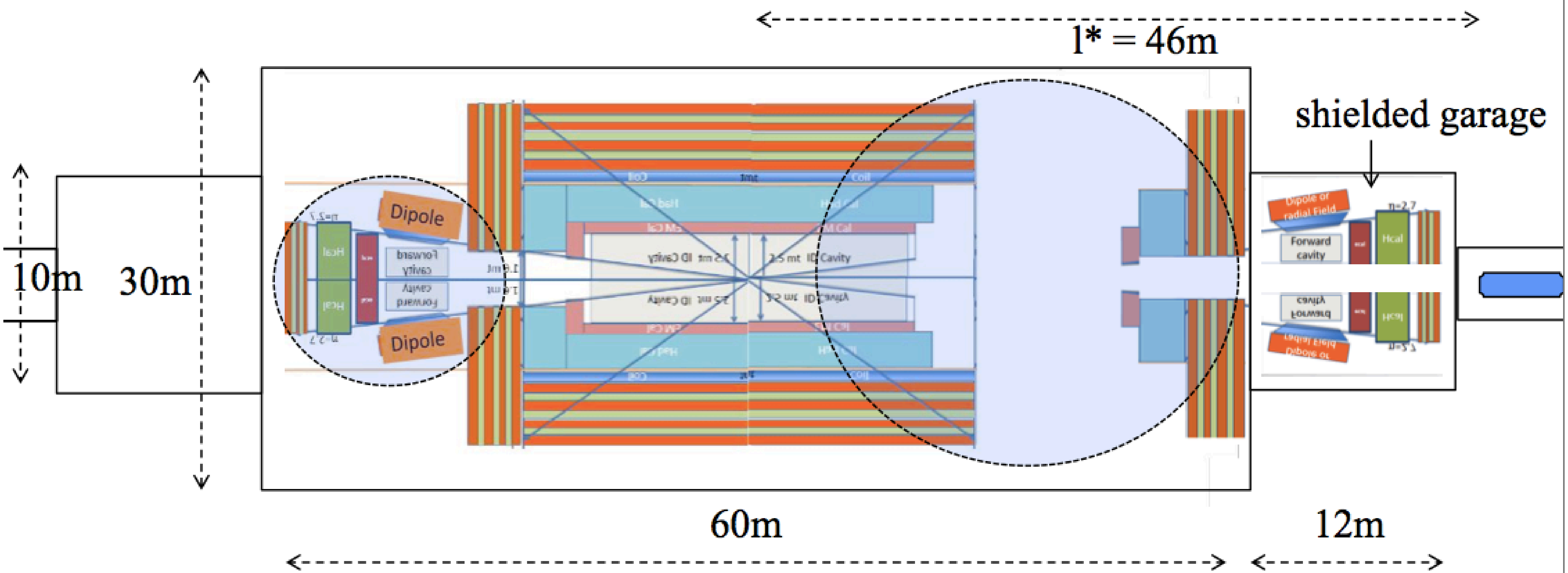
- Magnet performance
- Radiation effects
- Space constraints from experiments
- Beam-beam effects and mitigation
- …

L* = 46-38m seems consistent with scale of proposed detector layouts, e.g.



however ....

Maintenance scenarios look difficult



B.Palmer, FNAL wshop "Future hadron colliders":

2) LUMINOSITY

$$\mathcal{L} \propto \frac{\gamma\, I}{\beta^*}\Delta\nu \qquad I \propto (f\ N_p) \qquad \Delta\nu \propto \left(\frac{N_p}{\epsilon_\perp}\right)$$

where f = bunch frequency, N_p = protons per bunch, $\epsilon_\perp$ = normalized rms transverse emittance, β^* = IP Courant-Snyder function, $\Delta\ \nu$ = beam-beam tune shift, and I = beam current

Fundamental cross sections fall with $1/\gamma^2$, so lumiosity should rise as γ^2. Going from LHC at 14 TeV to 100 TeV we need:

$$\boxed{\mathcal{L}_{100} \geq 1\ 10^{34} \times \left(\frac{100}{14}\right)^2 = 5\ 10^{35} \quad (\mathrm{cm}^{-2}\mathrm{s}^{-1})}$$

With fixed I and $\Delta\nu$ this requires

$$\boxed{\beta^*_{LHC} = 55(\mathrm{cm}) \quad \rightarrow \quad \beta^*_{this} \approx 5.5(\mathrm{cm})}$$

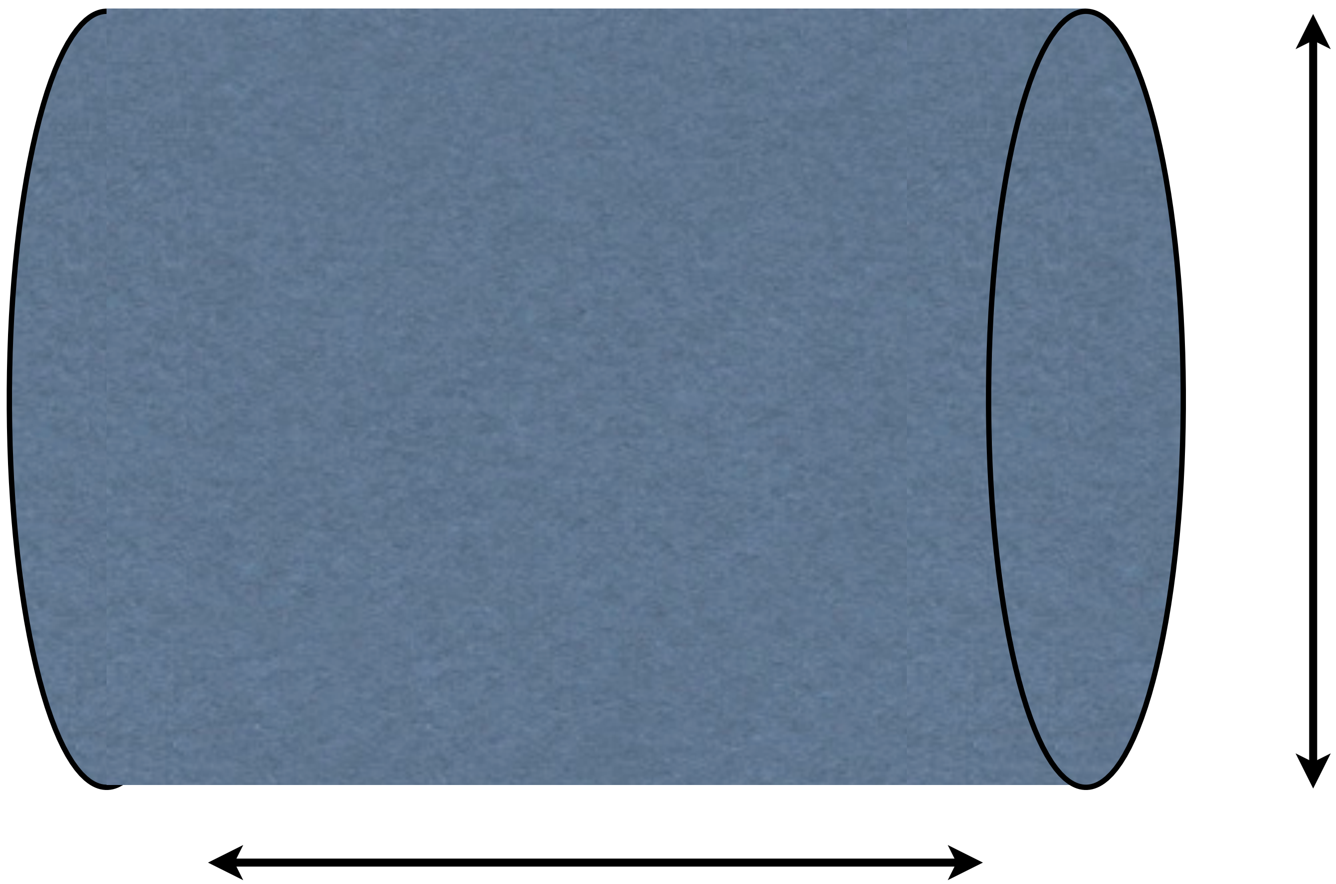
(c.f. β^*=5 (mm) in 3 a TeV muon collider lattice[8].)

cfr: L = 46 (38) m needed for β* = 80 (30) cm*

Forward acceptance clashes against machine needs for high luminosity

Since rate ∝ (acceptance × luminosity), there is room for optimization ...

Key physics drivers of the detector envelope



- muon pt resolution (BL^2)
- jet containment (cal depth, L)
- broadening of collimated jets (BL^2)
  - jet substructure
  - b-tagging

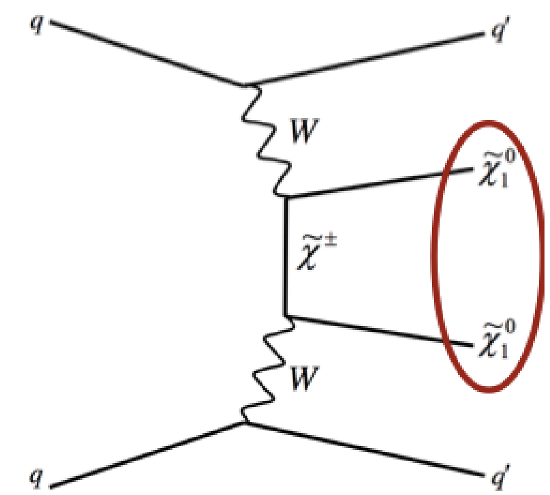
- eta acceptance:
  - lepton, gamma acceptance (Higgs, W/Z, ...)
  - jets (VBF)
  - missing E_T

It is urgent to provide clear and justified recommendations to those designing the accelerator and the detectors

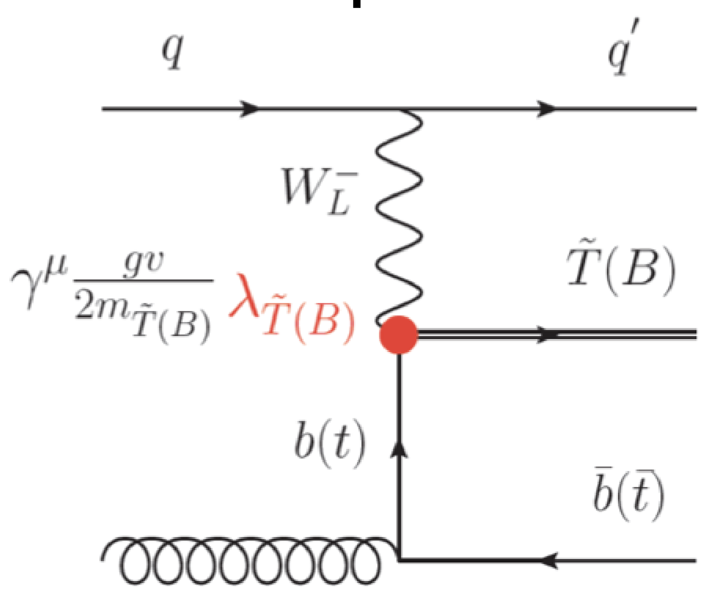
Drivers for forward-jet acceptance

<u>Vector boson fusion and scattering:</u>

- WW → H
- WW → WW
- WW → HH
- WW → ew-inos/DM candidates/etc



<u>s-channel resonances in Wq fusion:</u>



<u>Missing-ET resolution</u>

Heather Gray, FCC-hh mtg Febr 6 http://indico.cern.ch/event/297201/

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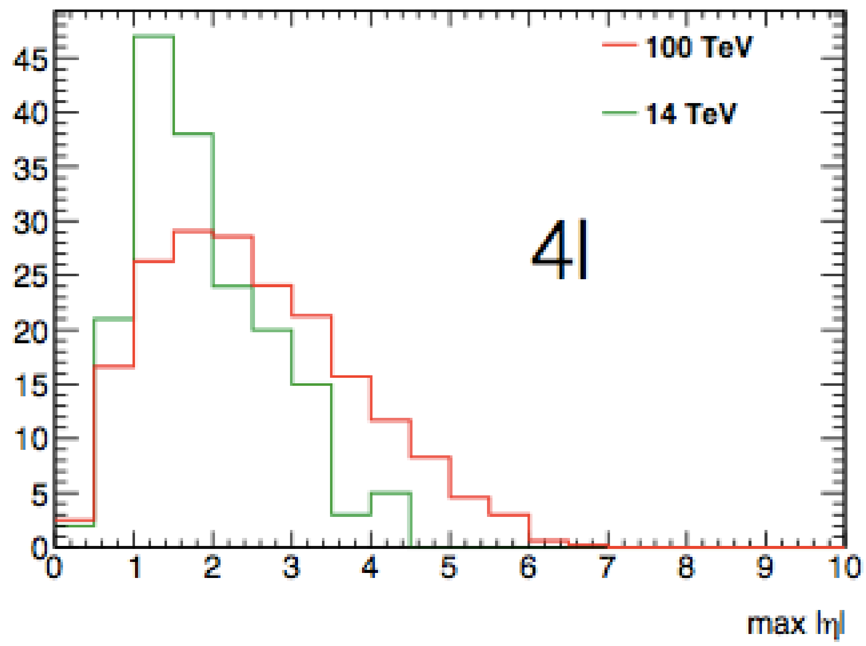
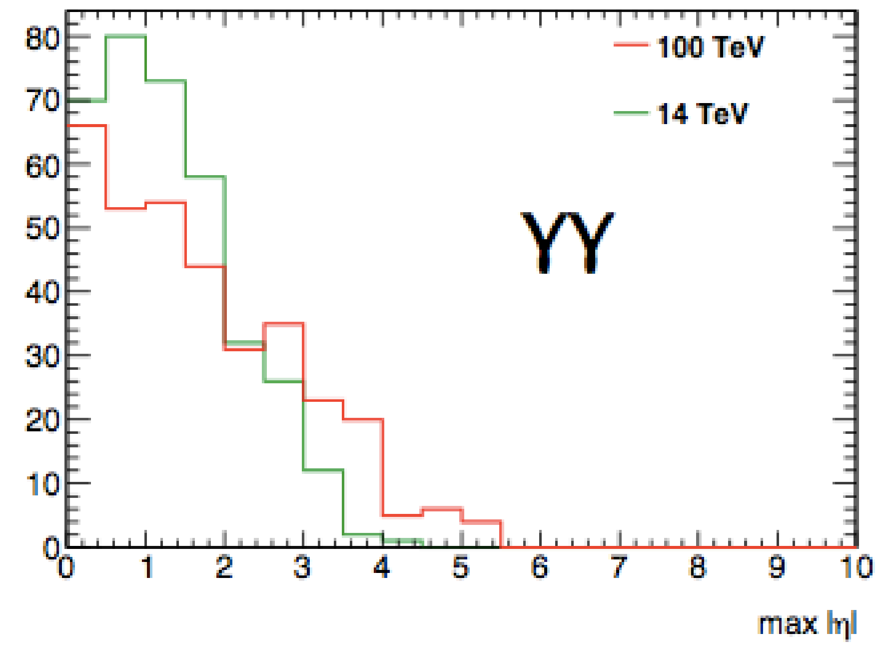
ggF Production at 14 and 100 TeV



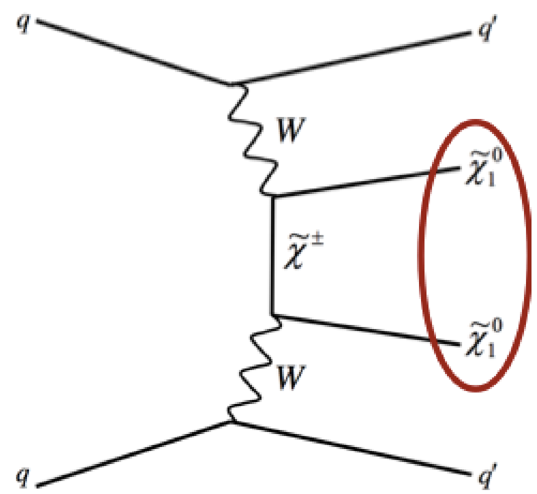


		$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 4$	$\lvert\eta\rvert < 5$
ll	100 TeV	0.66	0.92	0.98
	14 TeV	0.87	1	1
YY	100 TeV	0.83	0.97	1
	14 TeV	0.96	1	1

Significant acceptance loss with $|\eta| < 2.5$

Can the cost of covering $\eta>2.5$ be used to regain the acceptance loss in cheaper ways, e.g. lowering p_T trigger thresholds ?

pp→X X jet jet, with X=slepton, stop, sbottom, gauginos



Comp. Spectra Via VBF at 100 TeV

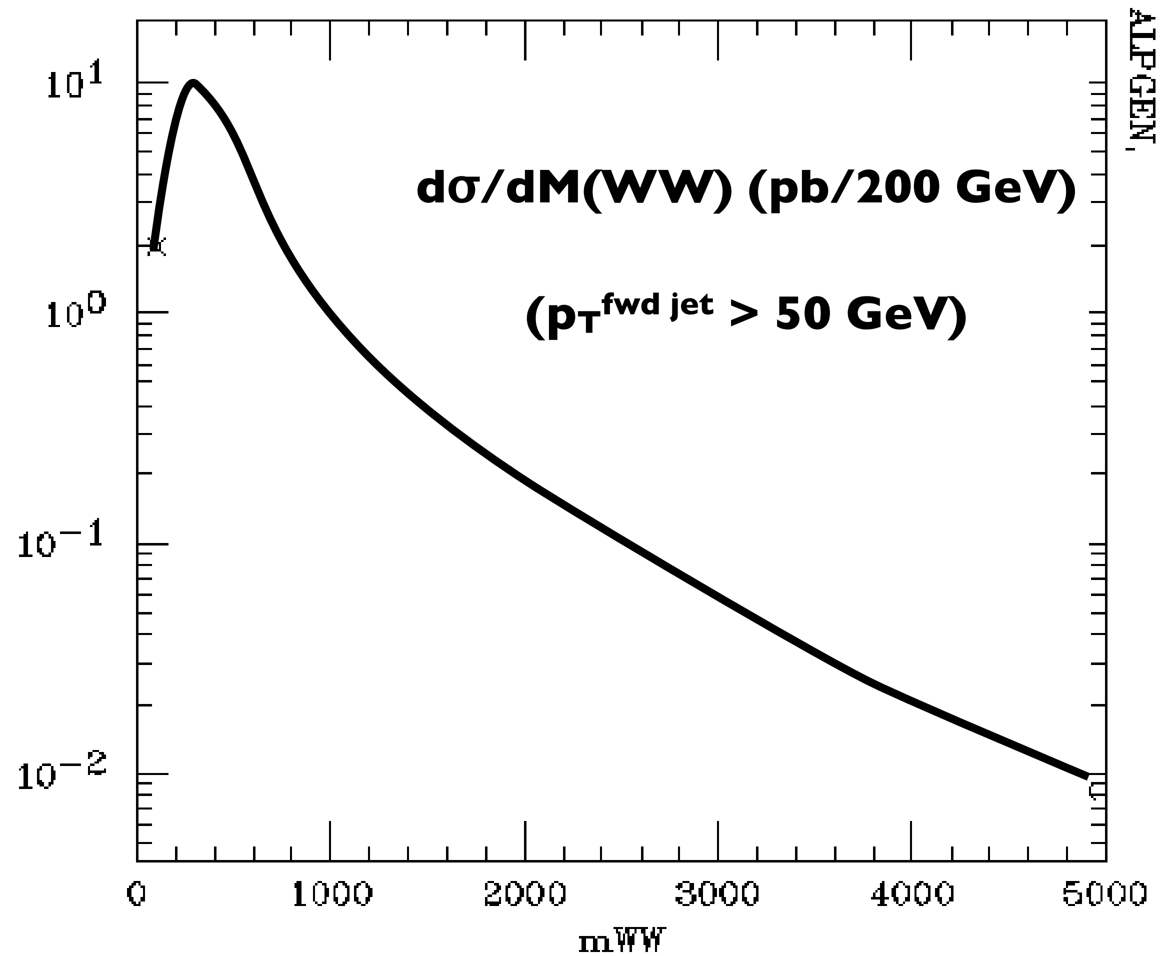
We consider 5 spectra with small mass gaps:

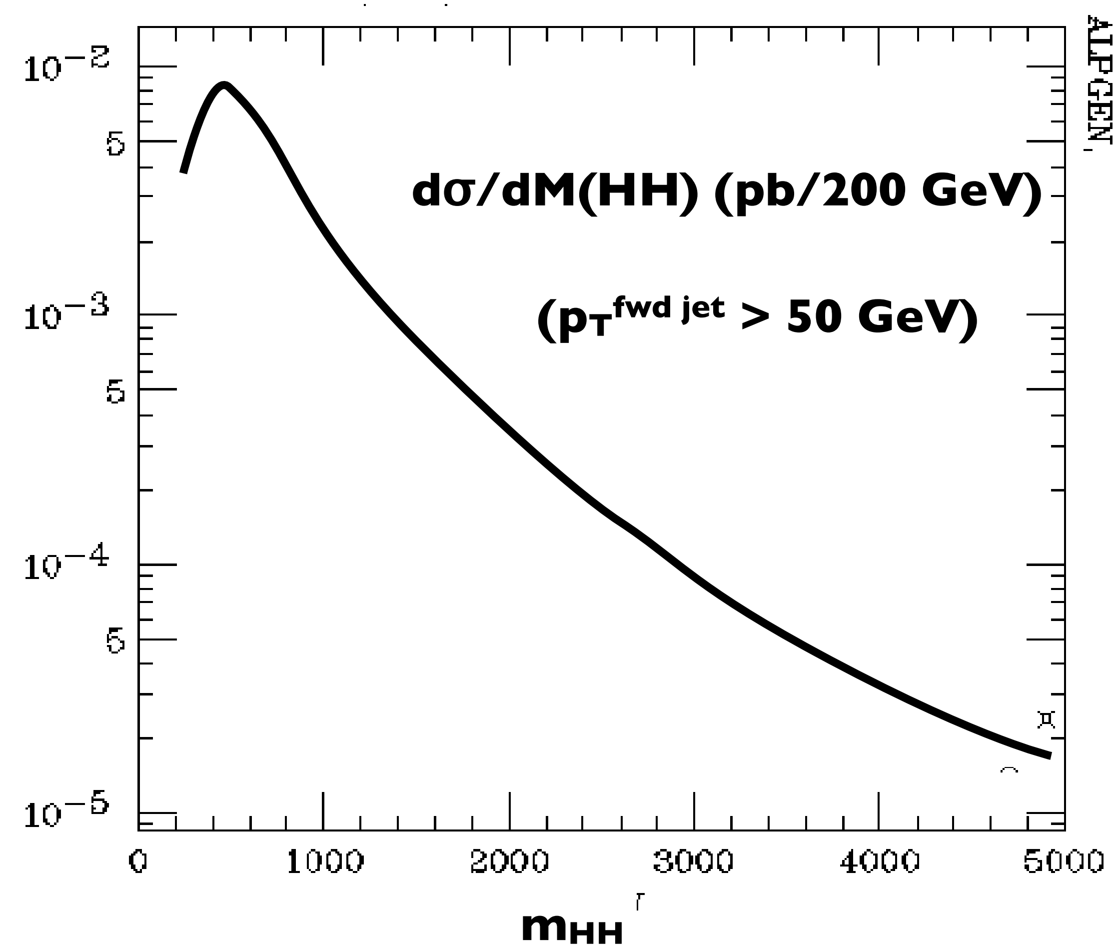
1. $\tilde{e}_1, \tilde{\mu}_1$: 329, $\tilde{\nu}$: 319, $\tilde{\chi}_i^0$: 206,290,332,671, $\tilde{\chi}_i^\pm$: 208,337
2. $\tilde{e}_1, \tilde{\mu}_1$: 231, $\tilde{\nu}$: 218, $\tilde{\chi}_i^0$: 185,237,299,356, $\tilde{\chi}_i^\pm$: 229,354
3. $\tilde{\mu}_1, \tilde{e}_1$: 489, $\tilde{\nu}$: 483, $\tilde{\chi}_i^0$: 88,500,818,829, $\tilde{\chi}_i^\pm$: 500,829
4. $\tilde{\mu}_1, \tilde{e}_1$: 205, $\tilde{\nu}$: 190, $\tilde{\chi}_i^0$: 188,216,1019,1021, $\tilde{\chi}_i^\pm$: 216,1022
5. $\tilde{\mu}_1, \tilde{e}_1$: 496, $\tilde{\nu}$: 491, $\tilde{\chi}_i^0$: 481,501,1019,1027, $\tilde{\chi}_i^\pm$: 501,1026

⇒ very light central systems !

EWSB probes: high mass WW/HH in VBF

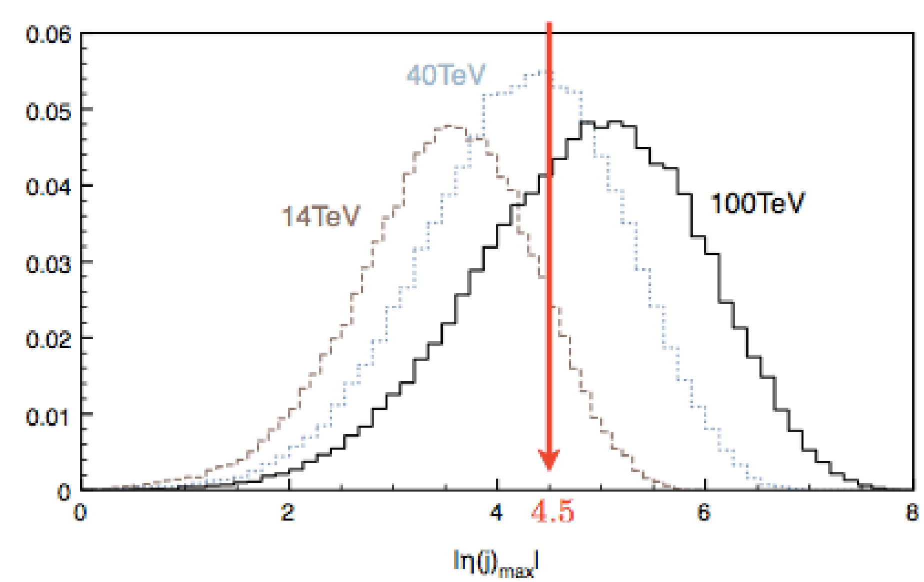
SM rates at 100 TeV





100 fb with M(WW) > ~3 TeV

1 fb with M(HH) > ~2 TeV



- There is a lot of work to be done still to properly define the scope, potential and requirements of physics with forward jets.
- What's the impact of MET requirements (both for high mass and low mass scenarios)?
- Impact of VBF studies on Higgs couplings (including H selfcouplings) must be compared with direct search for resonances
- Is VBF physics best done in a "multi-TeV" detector, or in a more compact dedicated "TeV-scale detector ?

Muons

Design Criteria

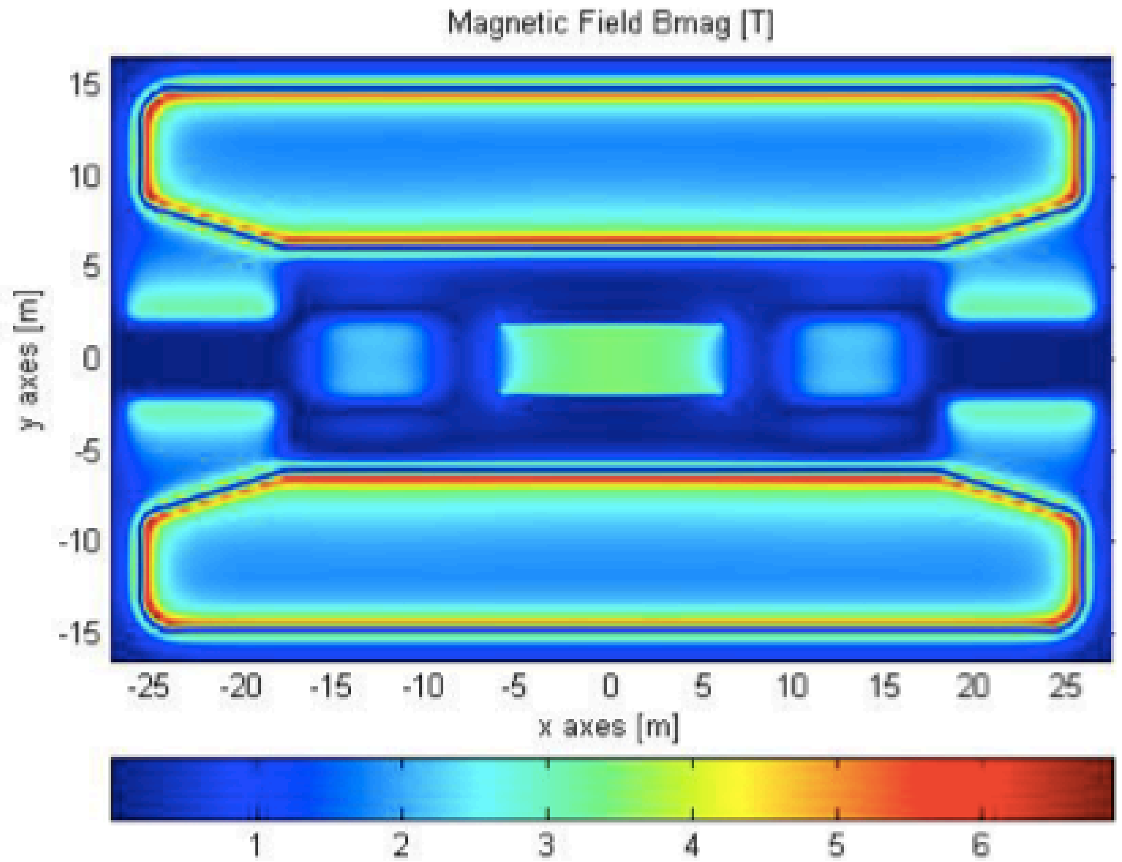
- LHC @ $\sqrt{s}$ = 14 TeV or SSC @ $\sqrt{s}$ = 40 TeV
  - $|\eta|$ range < 2.7
  - Momentum Resolution $\sigma(pT)/pT \sim 10\%$ @ pT = 1 TeV
  - Beam Cross Tagging $\tau \ll 25$ ns
  - Trigger 1 MU pT > 20 GeV/c, 2 MU pT > 10 GeV/c, 3 MU pT > 6 GeV/c
  - Highest detector hit rate ~ 15 kHz/cm^2

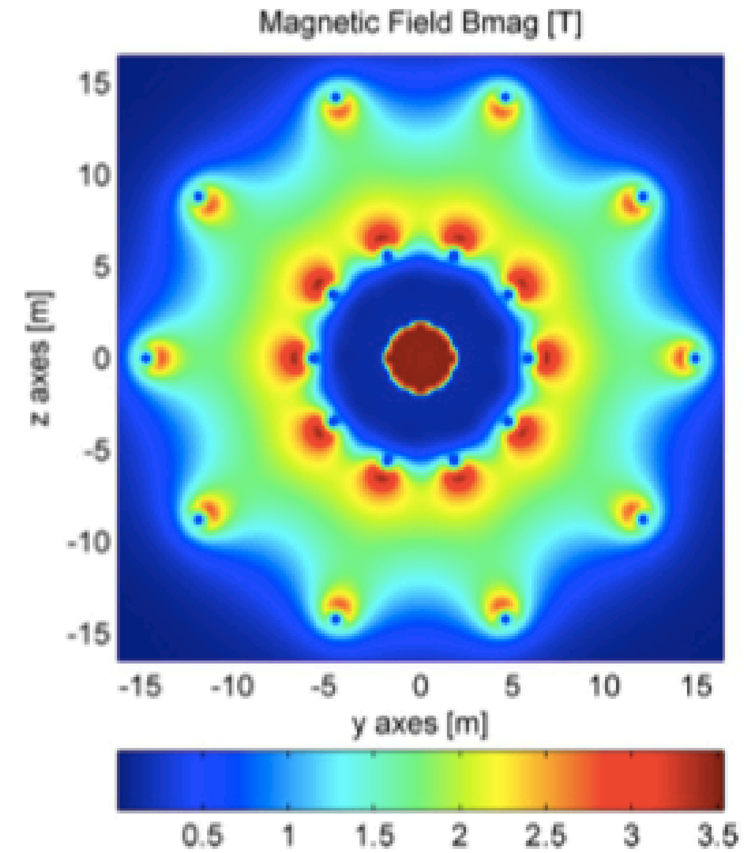
- Scaling factors for same chamber resolution
  - $\sqrt{s}$ ratio ~ 7 for LHC or 2.5 for SSC required increase in BL^2
  - $|y_{max}|$ ratio ~ $\ln[(\sqrt{s}=100)/M_p]/[(\sqrt{s}=14)/M_p] \sim 11.5/9.5 \sim 1.2$

- FCC @ $\sqrt{s}$ = 100 TeV
  - $|\eta|$ range < $2.7 \times y_{max}(100)/y_{max}(14) \sim 3.2 \Rightarrow \theta > 4.7^\circ$
  - Momentum resolution $\sigma(pT)/pT \sim 10\%$ @ pT = 7 TeV/c
  - Beam Cross Tagging $\tau \ll 25$ ns
  - Trigger 1 MU pT > 20 GeV/c, 2 MU pT > 10 GeV/c, 3 MU etc.
    - With BL^2 ~ 7X or 2.5X could raise threshold to higher value but threshold will be determined by bkg. suppression, trigger bandwidth & physics
  - Highest detector hit rate ~ 30 kHz/cm^2

$$B\,L^2\ (\mathrm{FCC}) = 100/14\ B\,L^2\ (\mathrm{LHC}) = 7\ B\,L^2\ (\mathrm{LHC})$$

2. Option 3: Toroids + Solenoid + Dipoles



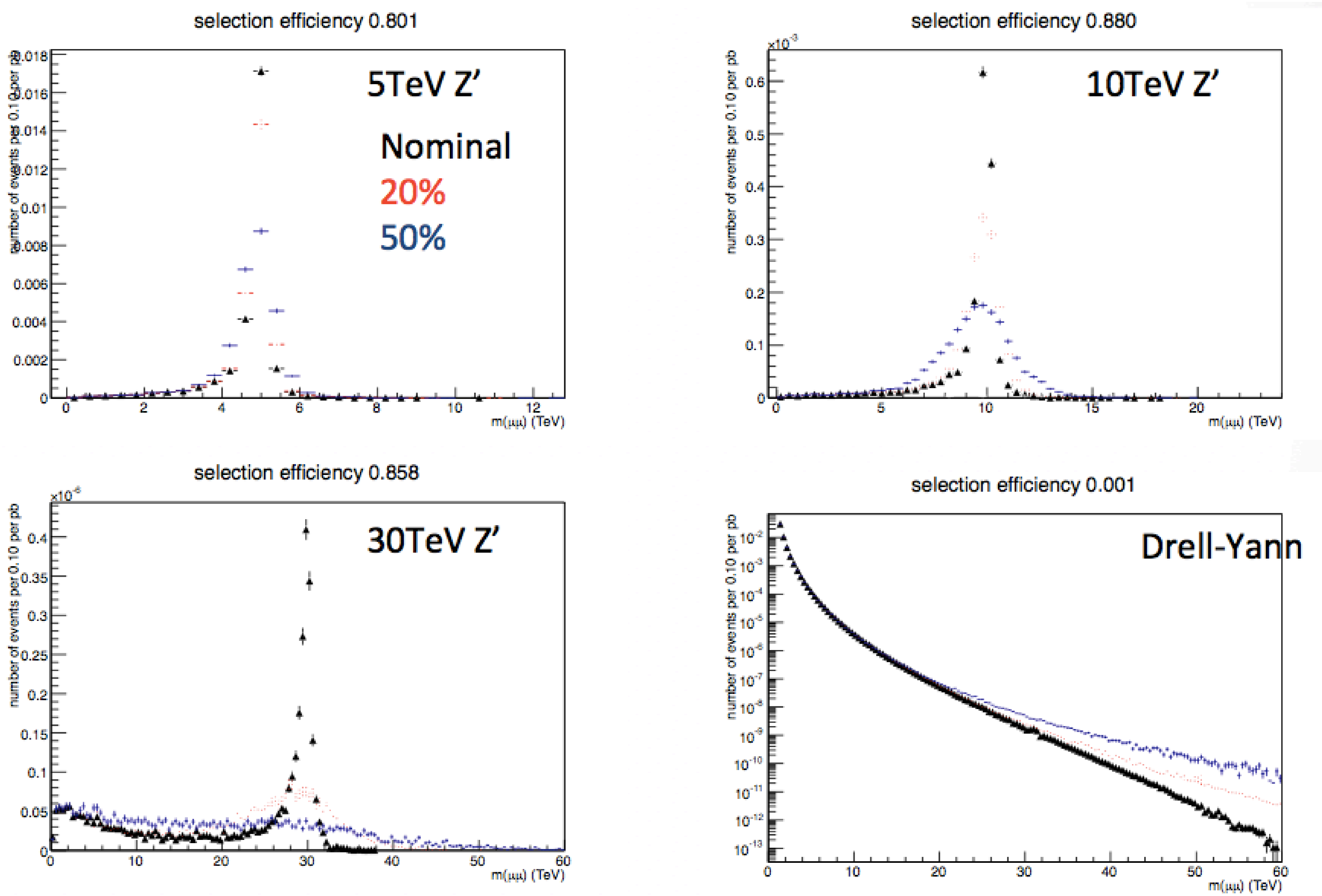


- 3.5 T in central solenoid, 2 T - 10 Tm in dipoles and ≈1.7 T in toroid.
- 55 GJ stored energy (for 16 Tm; 130 Tm^2)!
- 0.6 GJ in Solenoid , 0.9 GJ in 2 Dipoles, 2x2.1 GJ in the two End Cap Toroids, and 47.5 GJ in the Barrel Toroid.

Herman ten Kate
Alexey Dudarev, Leonardo Gerritse, Jeroen van Nugteren,
FCC Workshop @ CERN, 27 May 2014

Clement Helsens, FCC mtgs and updates

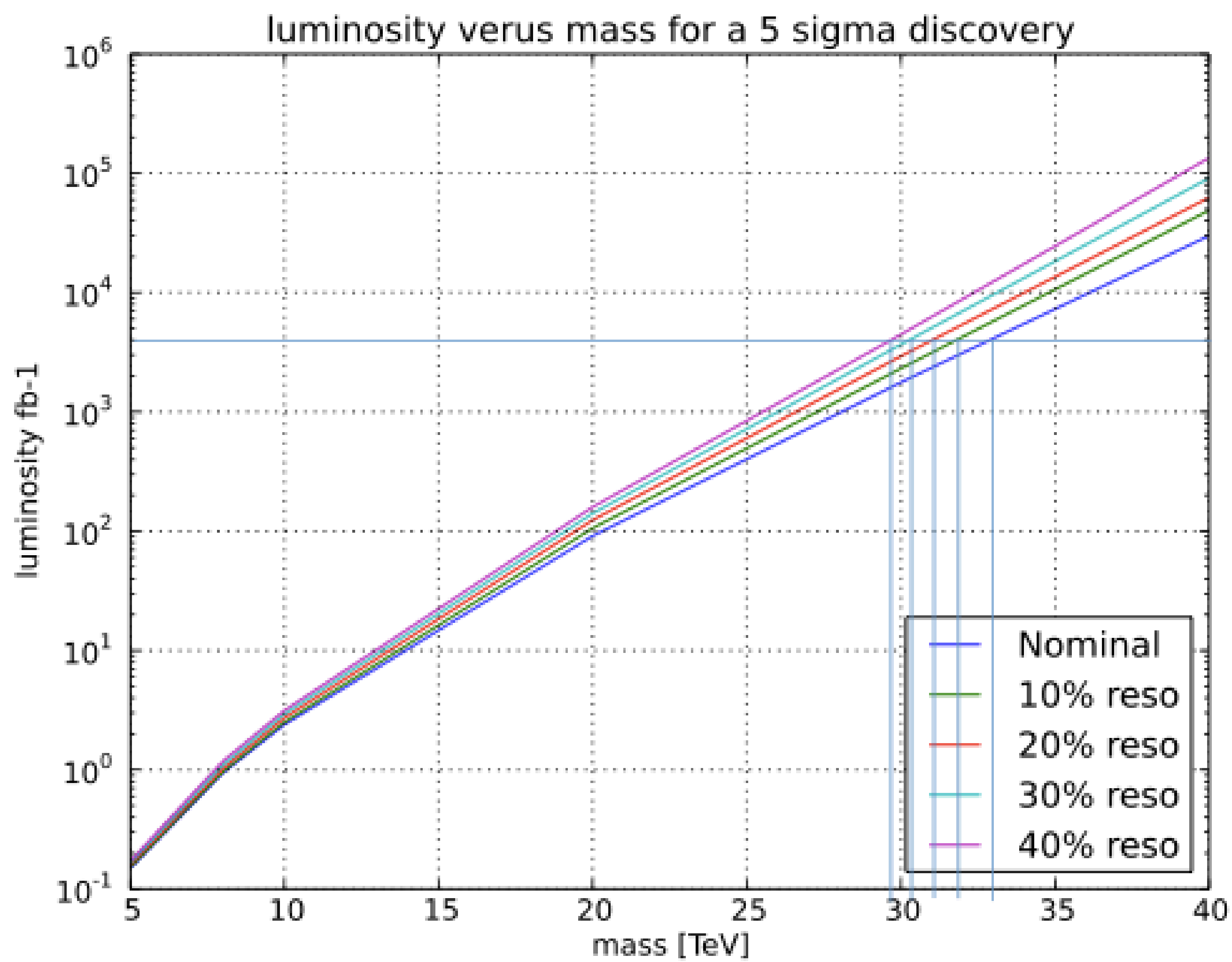
impact of different assumptions on muon momentum resolution at 10 TeV
(nominal: natural Z’ width, 3% in this case)



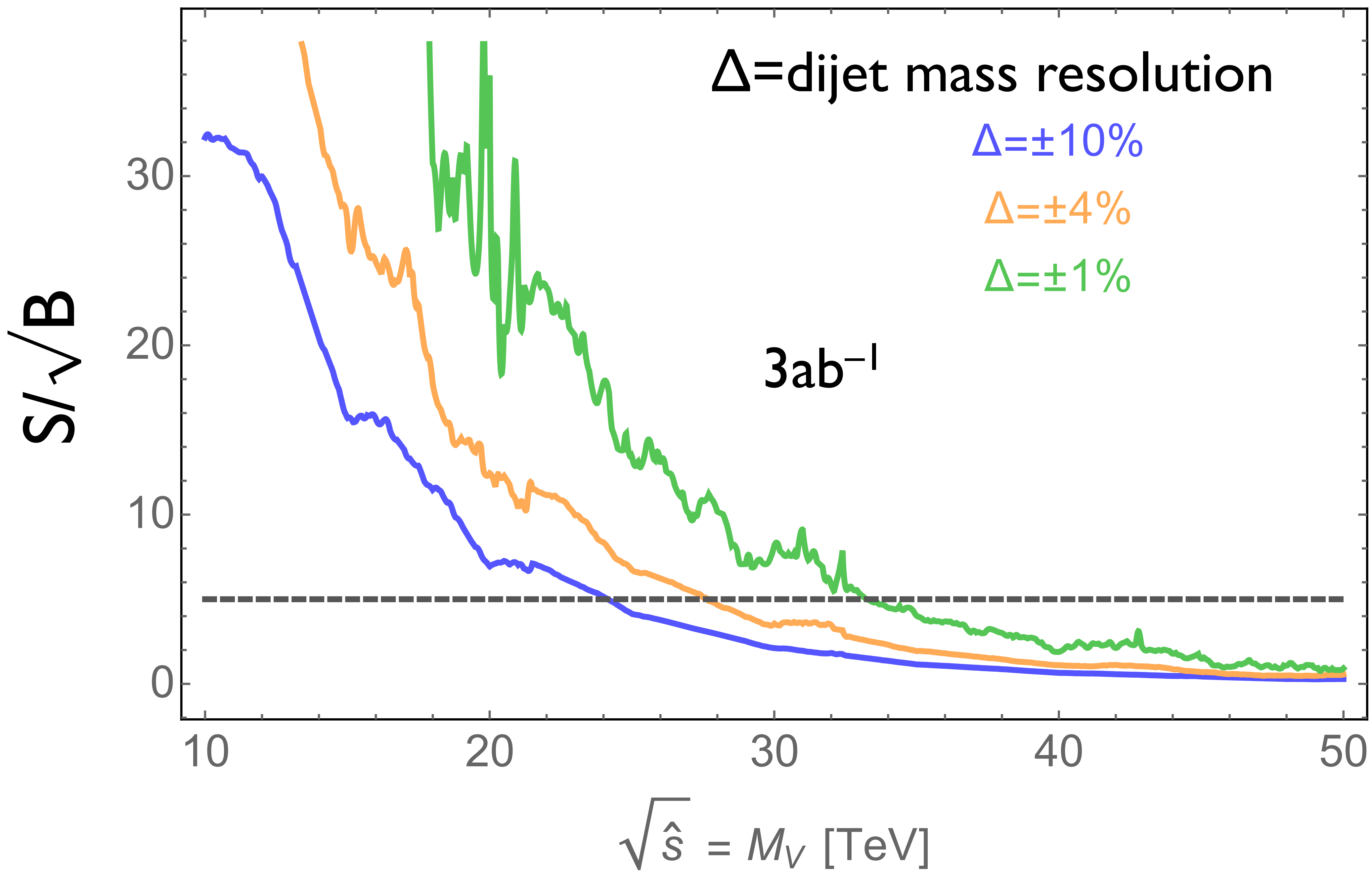
Sensitivity

Luminosity (fb^{-1}) to discover at 5sigma

	5TeV	8TeV	10TeV	20TeV	30TeV	40TeV
Nominal	0.15	0.93	2.39	91.2	1770	29983
10%	0.15	0.96	2.51	106.1	2312	48914
20%	0.16	1.02	2.72	123.9	2932	62653
30%	0.16	1.09	2.93	140.9	3674	91116
40%	0.17	1.18	3.14	159.4	4462	134534



Compare with discovery reach in dijet channel



Remarks

- At these masses, dijets may provide comparable discovery reach for Z', provided energy resolution in the 4-5% range ⇒ can far can we push jet performance at the highest E_T ?
- Observation reach in dimuon not terribly compromised by resolution going from 10 to 30-40% at 10 TeV ⇒ BL^2 increase by 2-3 may be sufficient
  - in ~absence of DY bg, studies of angular distributions, couplings, etc are not affected by worse δp_T
- More compelling physics cases may be invoked to request $7 \times BL^2$:
  - spreading out dense jets, b-tagging, etc.
- Are there different, stringent performance requirements for muons, leading to different constraints on teh detector design?
  - E.g. mass resolution and trigger efficiency for $H \rightarrow \mu\mu$?

Other issues

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- 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.

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

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 events at CERN:

Higgs and EWSB WG, workplan discussion (November 24)
https://indico.cern.ch/event/348468/

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

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

General FCC Workshop, Washington DC, March 23-27 2015

FCC-hh parameters

FCC-ACC-SPC-0001

3. Parameter Overview

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

	LHC (Design)	HL-LHC	HE-LHC	FCC-hh
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
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 σ_{proton} [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)
Beam parameters				
Number of bunches *n* at - 25 ns - 5 ns	2808		2808	10600 (8900) 53000 (44500)
Bunch population $N[10^{11}]$ - 25 ns - 5 ns	1.15	2.2	1	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 n/a
Other beam and machine parameters				
Stored energy per beam [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)
Critical photon energy [keV]	0.044		0.575	4.3 (5.5)
Longitudinal emittance damping time [h]	12.9		1.0	0.54 (0.32)
Horizontal emittance damping time [h]	25.8		2.0	1.08 (0.64)
Initial longitudinal IBS ε rise time [h]* - 25 ns - 5 ns	57	23.3	40	1132 (396) 226 (303)
Initial horizontal IBS ε rise time [h]* - 25 ns - 5 ns	103	10.4	20	943 (157) 189 (29)
Dipole coil aperture [mm]	56		40	40
Beam half aperture [cm]	~2		1.3	1.3
Mechanical aperture clearance at any energy at any element				>12

*The growth times are only indicative. They have been calculated for a specific RF configuration and need to be estimated again once the RF system is defined.