Physics and phenomenology,

parallel session summary and perspective

M.L.Mangano, CERN PH-TH

Target: highlight synergy and complementarity of the ee, eh and hh physics programmes

Conveners: MLM, J.Ellis, C.Grojean, N.Arkani Hamed, J.Lykken, S.Su, R.Sundrum

Discovery via precision EW/Higgs/flavour physics (chair J.Ellis)

EW Precision measurements summary *30'*
Speaker: Roberto Tenchini (Universita di Pisa & INFN)
Material: Slides

Summary of potential for Higgs precision measurements *30'*
Speaker: Markus Klute (MIT)
Material: Slides

BSM discovery in flavor physics and rare decays *20'*
Speaker: Jure Zupan (Cincinnati Univ.)
Material: Slides

EWSB probes of BSM (chair D.Denisov)

Sensitivity to new physics of precision Higgs and EW observables *30'*
Speaker: Jiji Fan (Syracuse Univ.)
Material: Slides

H selfcouplings, vector-boson scattering at high mass, high-energy probes of EWSB
Speaker: Minho Son (EPFL)
Material: Slides

BSM Higgs sectors *30'*
Speaker: David Curtin (Maryland Univ.)
Material: Slides

(In)direct probes of the high-mass frontier (chair R.Sundrum)

Naturalness at the 100 TeV scale *30'*
Speaker: Nathaniel Craig (UCSB)
Material: Slides

Direct BSM exploration at the high-mass frontier *30'*
Speaker: Maurizio Pierini (California Institute of Technology (US))
Material: Slides

Precision measurements of alphas, PDF, role of PDF in high-mass BSM studies
Speaker: Voica Ana Maria Radescu (Heidelberg Univ.)
Material: Slides

Dark matter at FCC (chair J.Lykken)

Dark matter at FCC: theoretical framework *30'*
Speaker: Lian Tao Wang (Chicago Univ.)
Material: Slides

Dark matter searches at FCC *30'*
Speaker: Philip Coleman Harris (CERN)
Material: Slides

Key goals of the FCC

- Complete exploration of the Higgs boson and its dynamics

- Significant extension, via direct and indirect probes, of the search for physics phenomena beyond the SM

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

- *the progress of theoretical calculations for precision physics*
- *the experimental data needed to improve the knowledge of fundamental inputs such as SM parameters, PDFs and to assess/reduce theoretical systematics*

Higgs couplings programme

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

H couplings

M.Klute, M.Son, J.Zupan (and M.Klein in eh session)

	Model-independent fit		
Coupling	TLEP-240	TLEP	
g_{HZZ}	0.16%	**0.15%**	(0.18%)
g_{HWW}	0.85%	**0.19%**	(0.23%)
g_{Hbb}	0.88%	**0.42%**	(0.52%)
g_{Hcc}	1.0%	**0.71%**	(0.87%)
g_{Hgg}	1.1%	**0.80%**	(0.98%)
$g_{H\tau\tau}$	0.94%	**0.54%**	(0.66%)
$g_{H\mu\mu}$	6.4%	**6.2%**	(7.6%)
$g_{H\gamma\gamma}$	1.7%	**1.5%**	(1.8%)
BR_{exo}	0.48%	**0.45%**	(0.55%)

- At FCC-hh:
  - Hμμ coupling: 2% precision (extrapol from HL-LHC stats)

$e^+e^- \to H$ | **L = 10 ab^{-1}** **κ_e < 2.2 at 3σ**

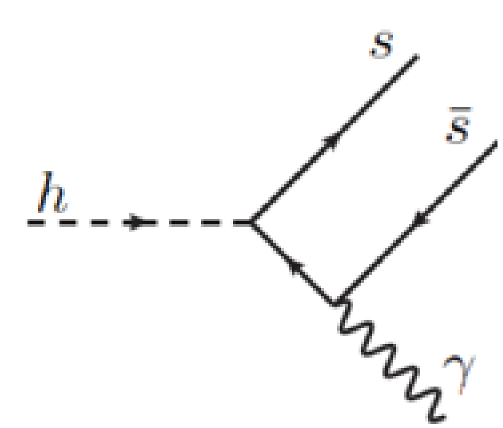
$H \to J/\Psi\,\gamma$ → y_c

$H \to \phi\,\gamma$ → y_s

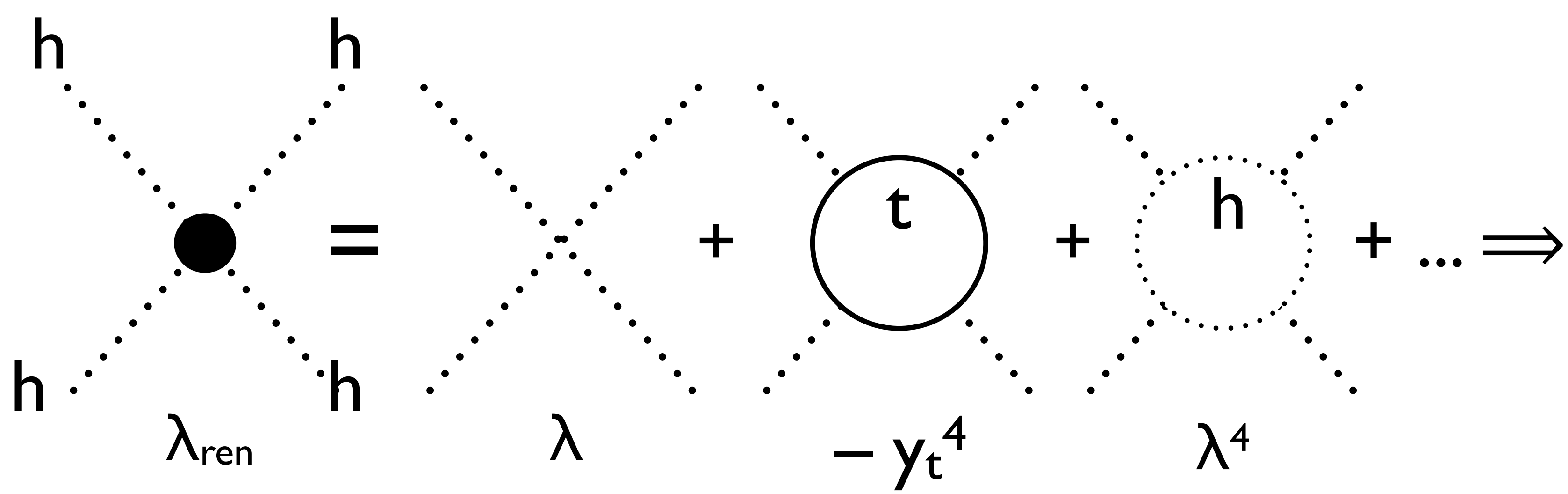
50 evts

$H \to \rho\,\gamma$

$H \to \omega\,\gamma$ → y_u, y_d

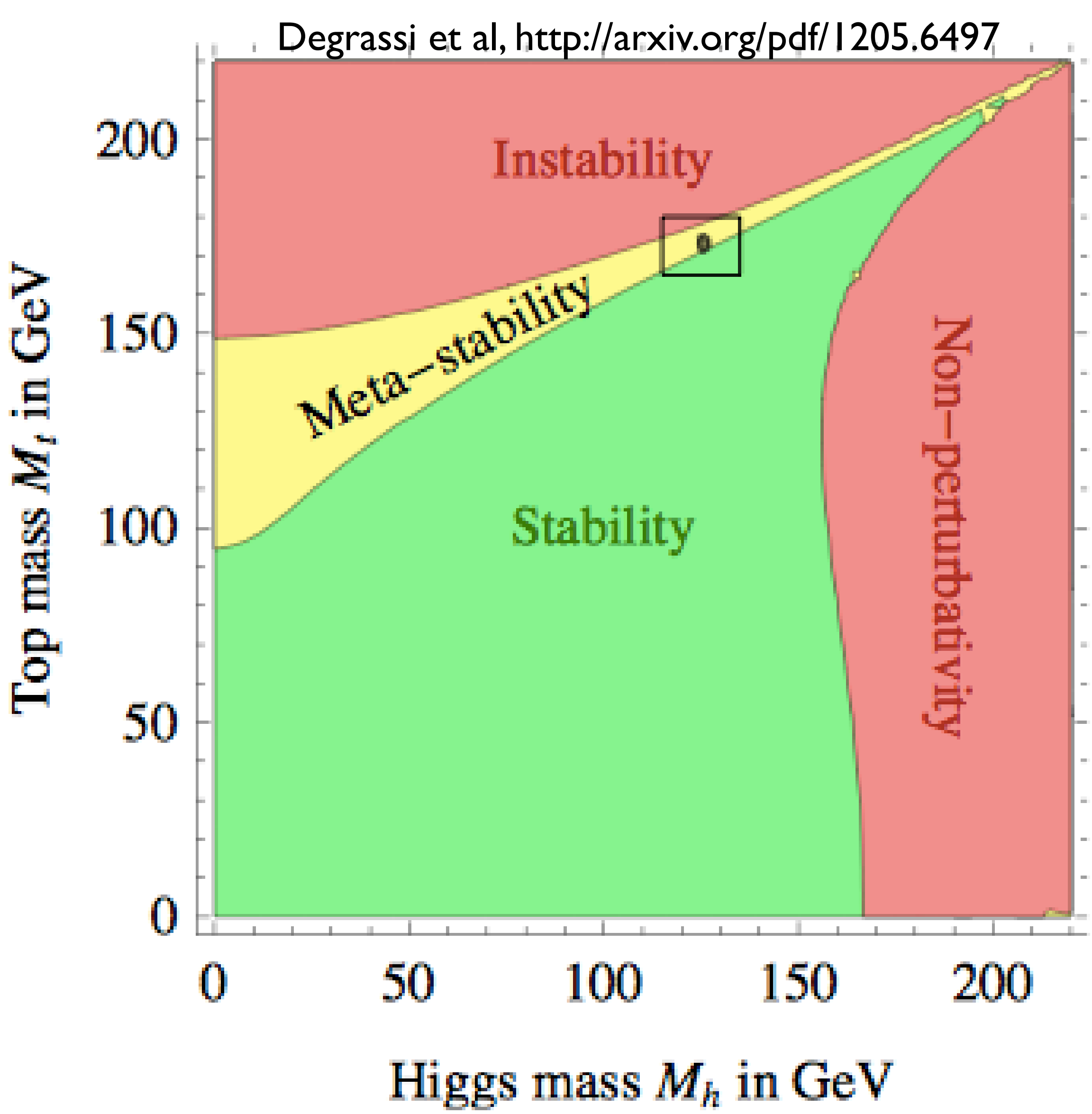


(meta)Stability of the Higgs potential



$$\frac{d\lambda}{d\log\mu} \propto \lambda^4 - y_t^4$$

$$\propto a\, m_H^4 - b\, m_t^4$$



Higgs selfcoupling and coupling to the top are the key inputs to assess the stability of the Higgs potential

@FCC-hh:

- ttH coupling:
  - 1% theoretical precision on y_{top} , from measurement of σ(ttH)/σ(ttZ) and using BR info from FCC-ee

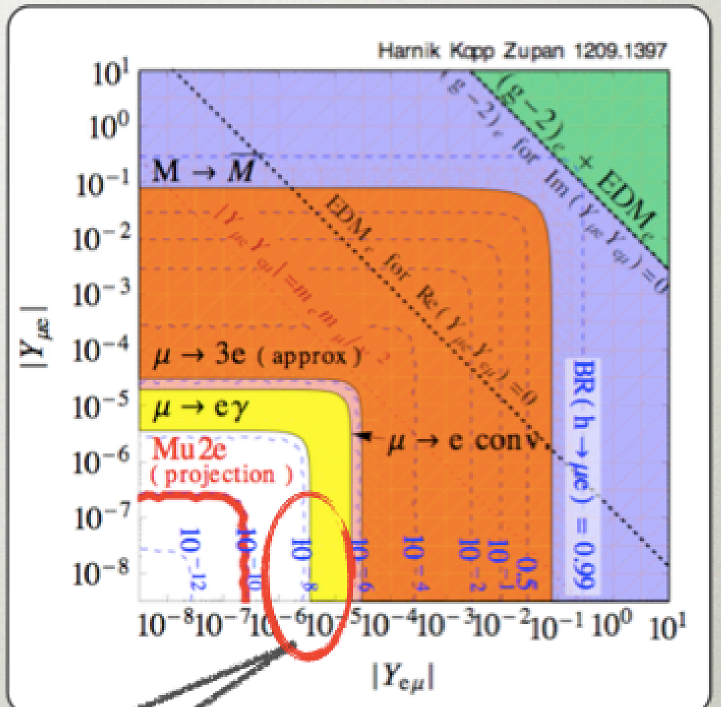
- H selfcoupling:

M.Son

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

$h \to \mu e$

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

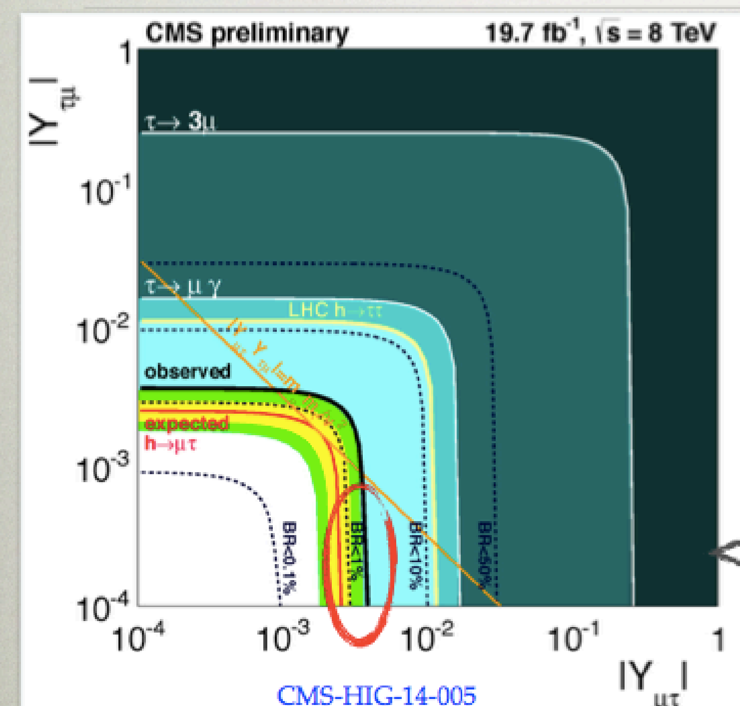


- what can one do with 10^9 Higgses @100TeV?

FCC week, Mar 26 2015, Washington DC

J.Zupan

$h \to \tau\mu$



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

J. Zupan BSM discovery… 11 FCC week, Mar 26 2015, Washington DC

BSM Higgs Sectors

D.Curtin

Big Picture Motivations

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

IR Models

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

UV Completions & Rest of Theory

Observables at Current + Future Colliders

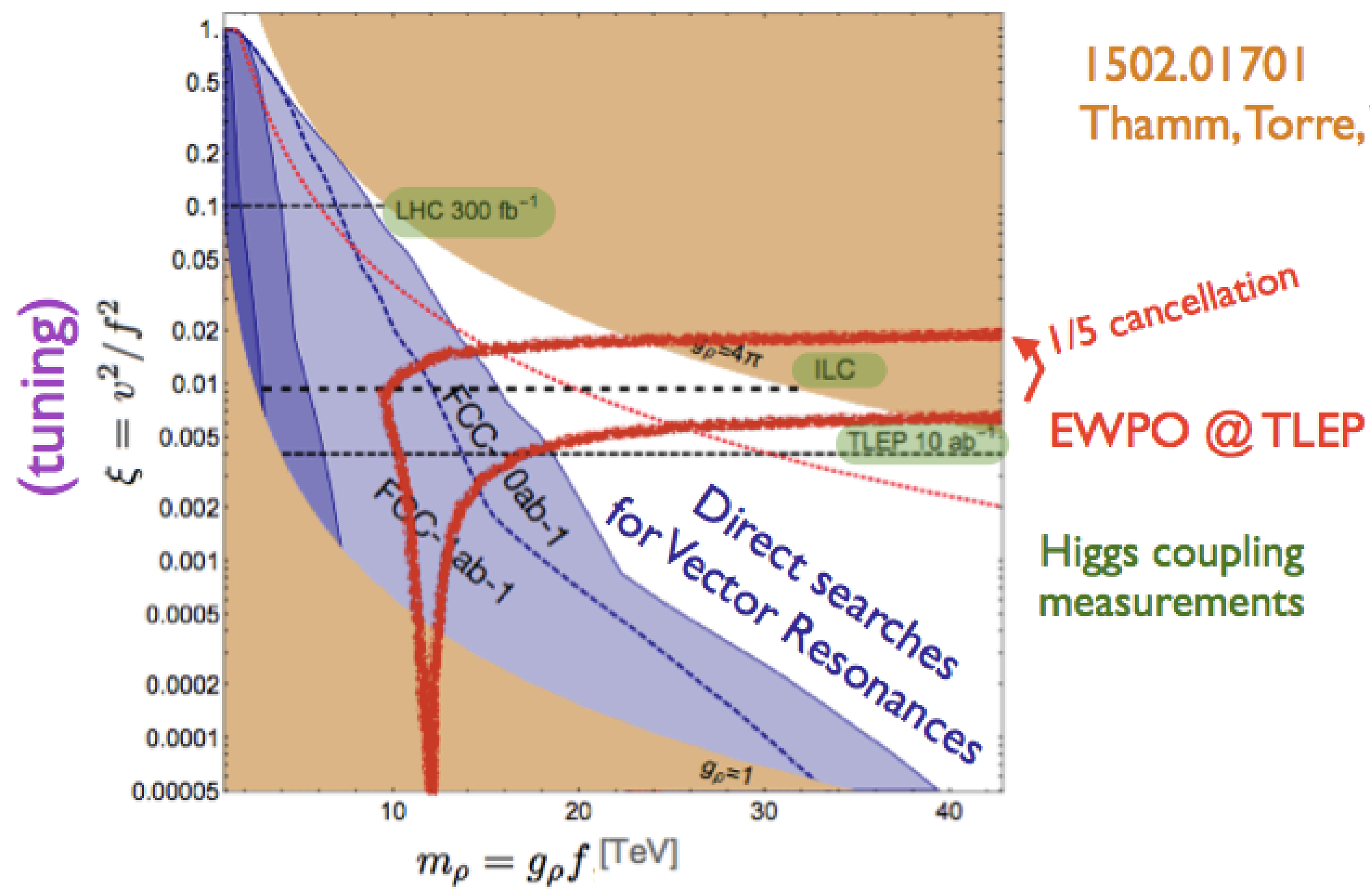
- producing extra higgs states (incl. superpartners)
- Exotic Higgs Decays
- Electroweak Precision Observables
- Higgs coupling measurements
- Higgs portal direct production of new states
- Higgs self coupling measurements
- Zh cross section measurements

Composite Higgs Models

D.Curtin

Want Lepton colliders to probe Higgs coupling deviations & EWPO

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



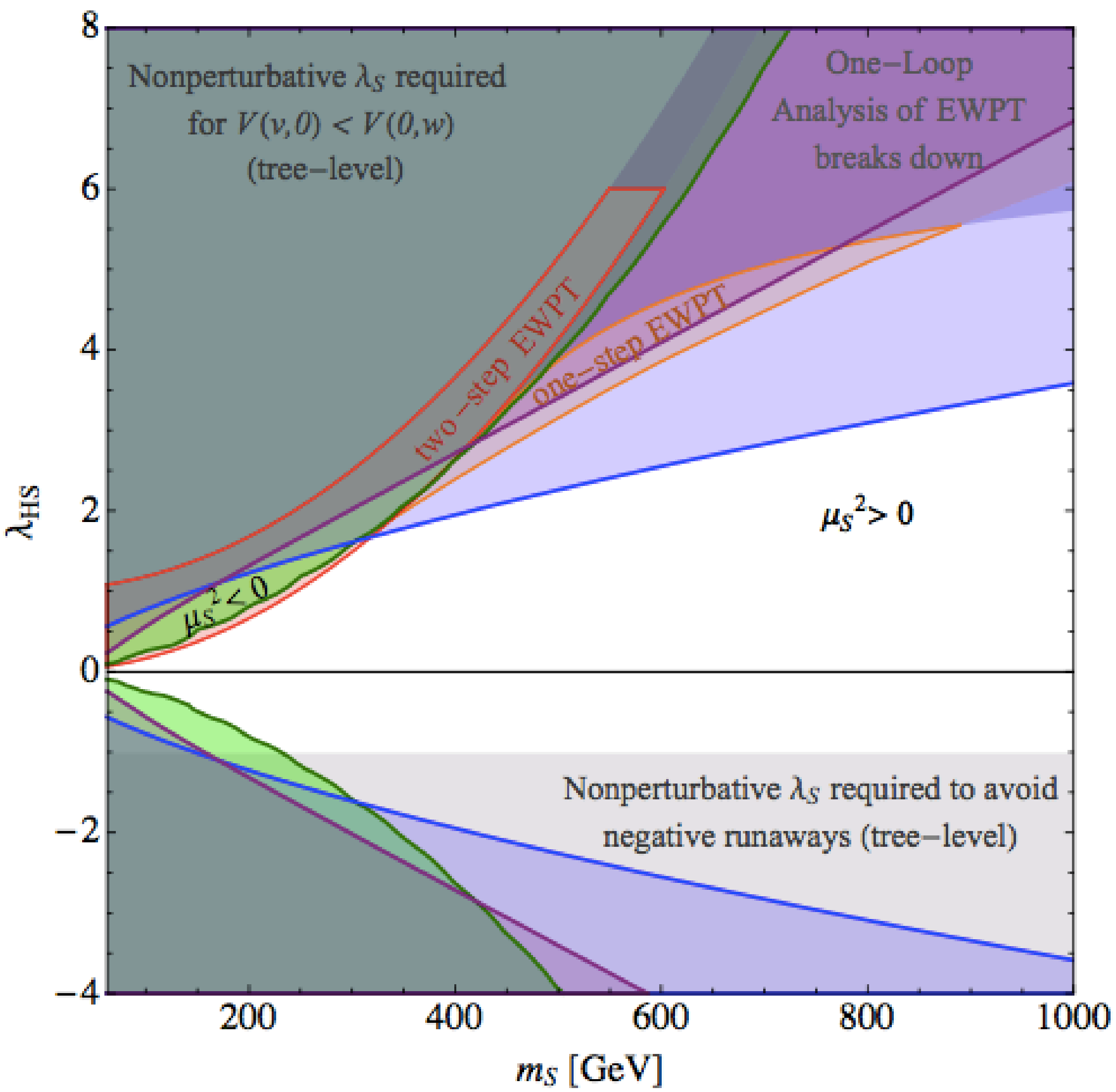
Interplay of EW precision tests (Tera-Z@FCC-ee), Higgs BR measurements (H@FCC-ee) and direct resonance searches (10-30 TeV, @ FCC-hh)

Minimal stealthy model for a strong EWPT

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

D.Curtin

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



Two regions with strong EWPT

Only Higgs Portal signatures:

h*→SS direct production

Higgs cubic coupling

σ(Zh) deviation (> 0.6% @ TLEP)

100 TeV collider could cover *entire* parameter space.

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

Potential complimentarily!

1409.0005 DC, Patrick Meade, Tien-Tien Yu

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

D.Curtin

- Both lepton and 100 TeV pp colliders are vital for this effort!

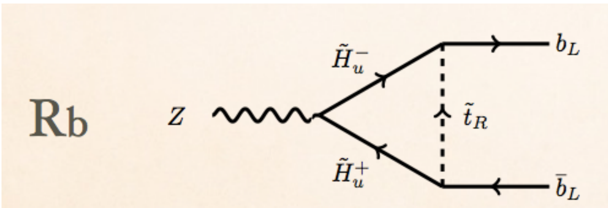
Observables at Current + Future Colliders	100 TeV	ILC/TLEP
• producing extra higgs states (incl. superpartners)	✓	
• Exotic Higgs Decays	✓	✓
• Electroweak Precision Observables		✓
• Higgs coupling measurements	(✓)	✓
• Higgs portal direct production of new states	✓	
• Higgs self coupling measurements	✓	(✓)
• Zh cross section measurements		✓

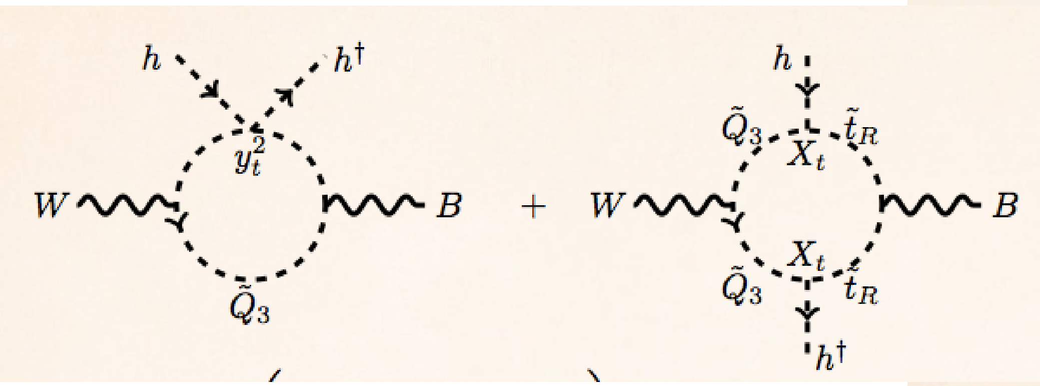
EW precision physics

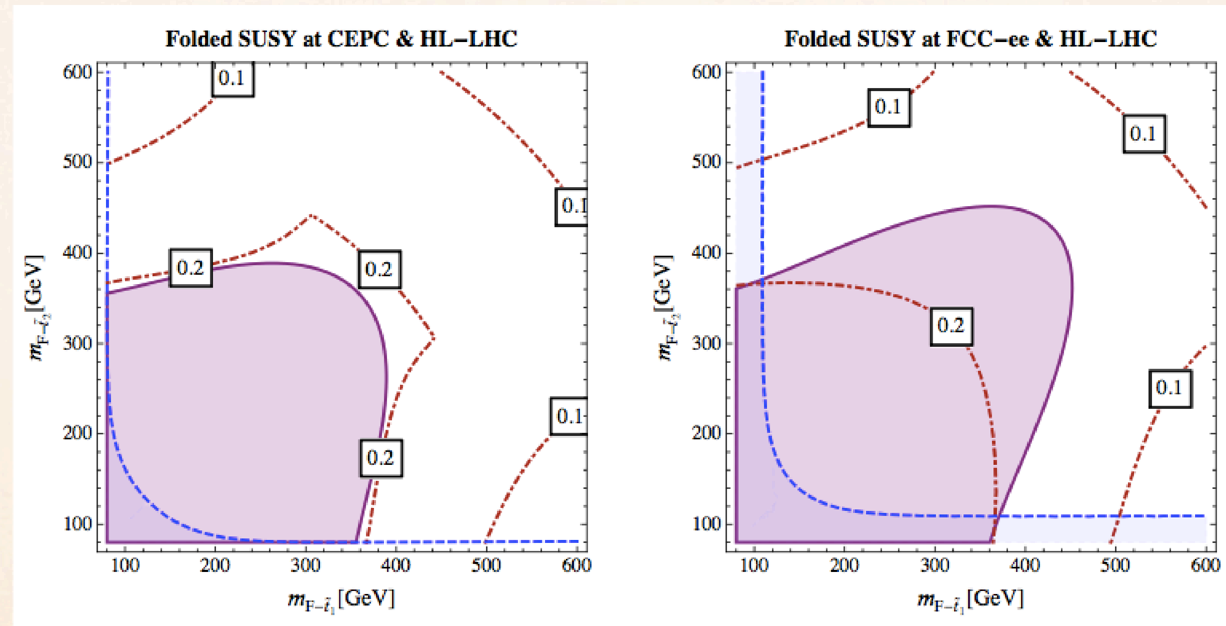
R.Tenchini, JJ.Fan

- Needed to push forward the programme of indirect probes of BSM phenomena

In certain hidden natural SUSY scenarios with non-colored stops such as folded SUSY (Burdman, Chacko, Goh, Harnik 2006), Higgs-photon coupling have some sensitivity and EWPT could be the most sensitive probe in region away from a blind spot.







sensitivity to possible scale of Higgs compositness

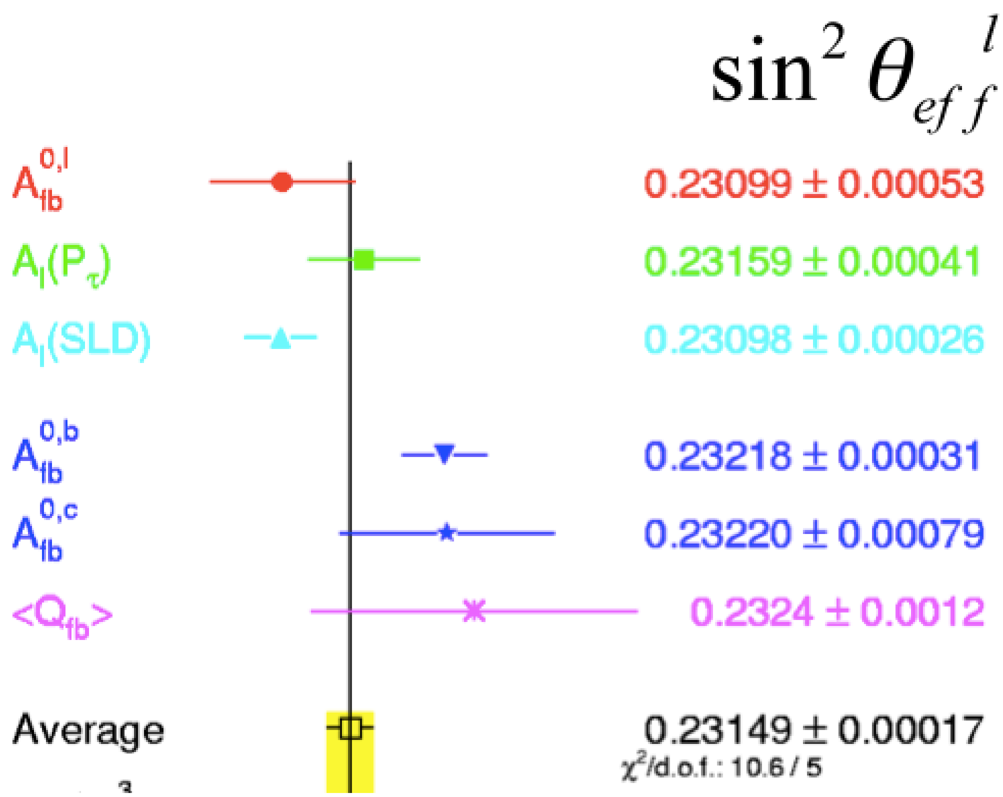
Experiment	κ_Z (68%)	f (GeV)
HL-LHC	3%	1.0 TeV
ILC500	0.3%	3.1 TeV
ILC500-up	0.2%	3.9 TeV
CEPC	0.2%	3.9 TeV
TLEP	0.1%	5.5 TeV

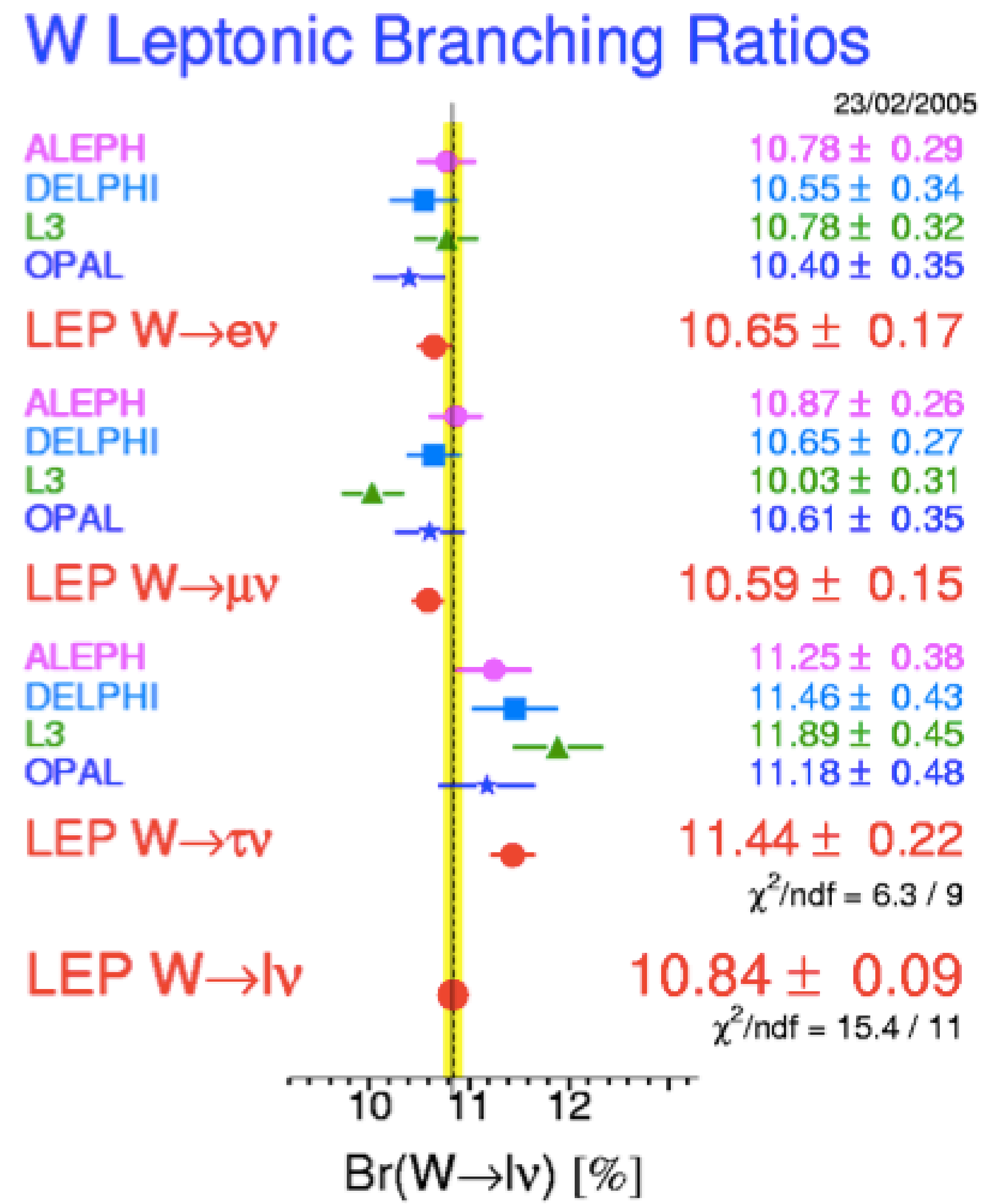
Experiment	S (68%)	f (GeV)
ILC	0.012	1.1 TeV
CEPC (opt.)	0.02	880 GeV
CEPC (imp.)	0.014	1.0 TeV
TLEP-Z	0.013	1.1 TeV
TLEP-t	0.009	1.3 TeV

EW precision physics

R.Tenchini, JJ.Fan

- Needed to clarify outstanding issues left open by LEP/SLC!!





- **LEP final combination statistically dominated**

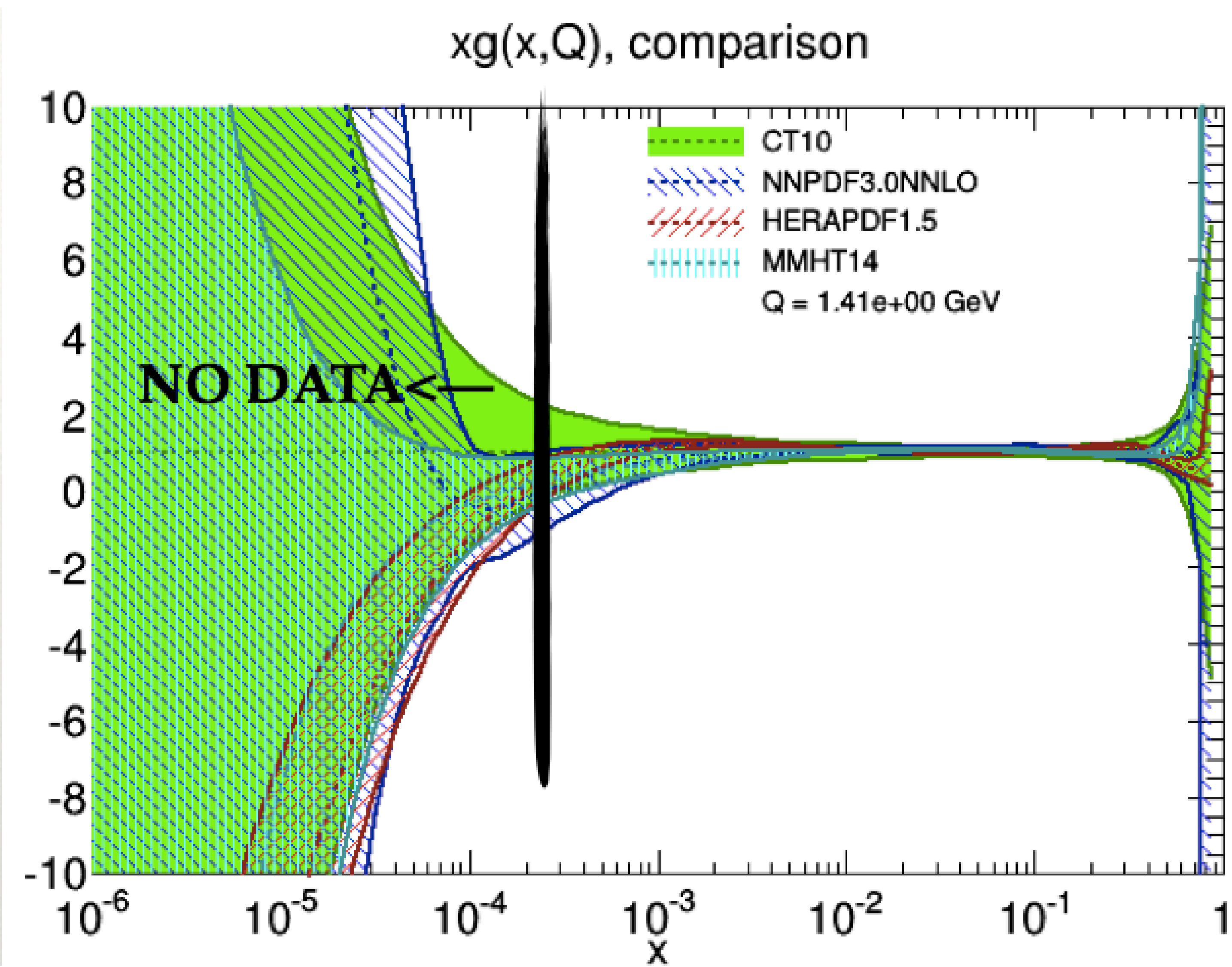
	ΔAFB(b)
STATISTICS	0.00156
UNCORRELATED SYSTEMATIC	0.00061
QCD CORRECTION	0.00030
LIGHT QUARK FRAGMENTATION	0.00013
SEMILEPTONIC DECAYS MODELLING	0.00013
CHARM FRAGMENTATION	0.00006
BOTTOM FRAGMENTATION	0.00003
TOTAL SYSTEMATIC ERROR	0.00073

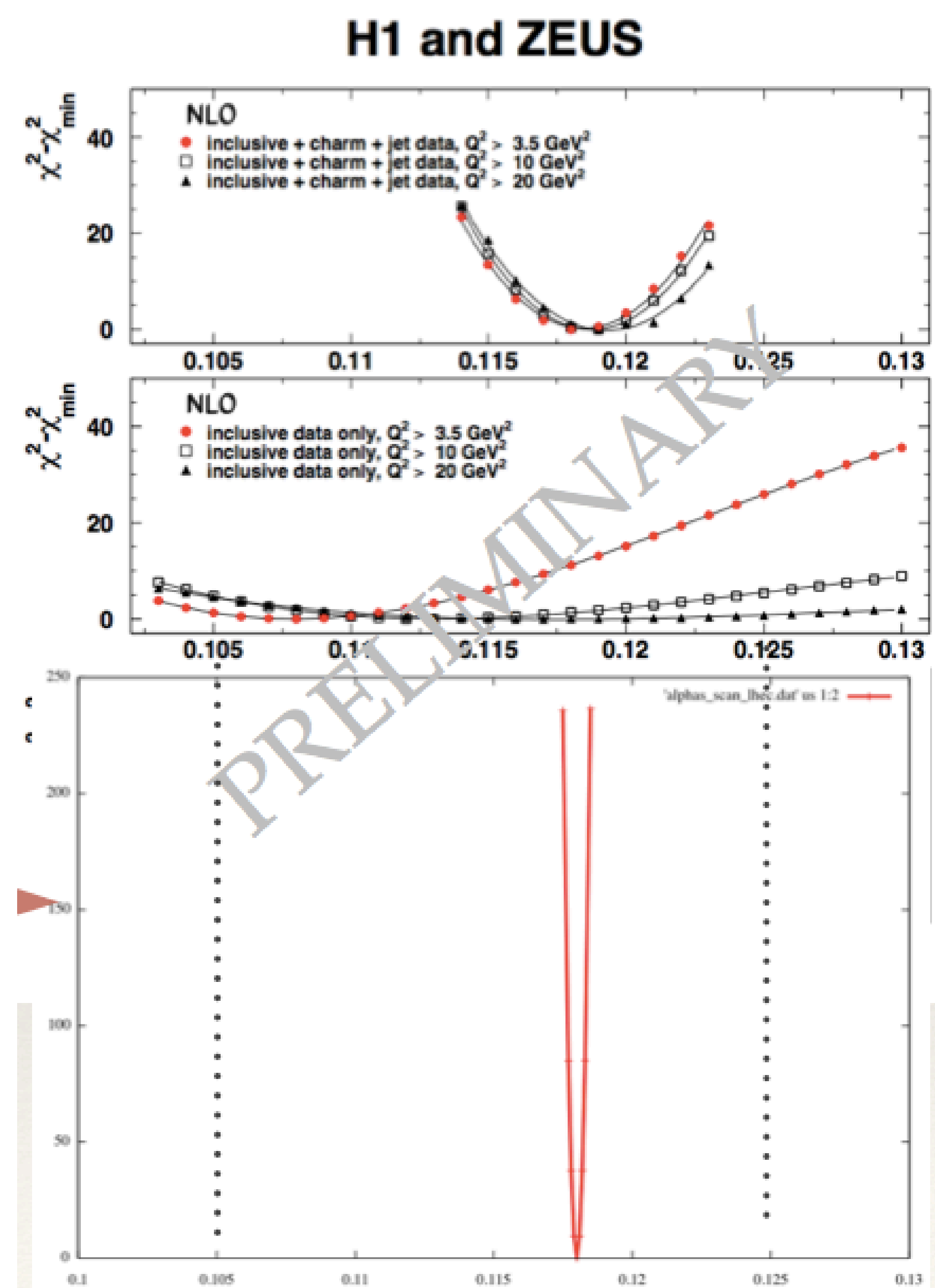
~ 3σ B(W→τν) anomaly!

QCD precision physics

V.Radescu

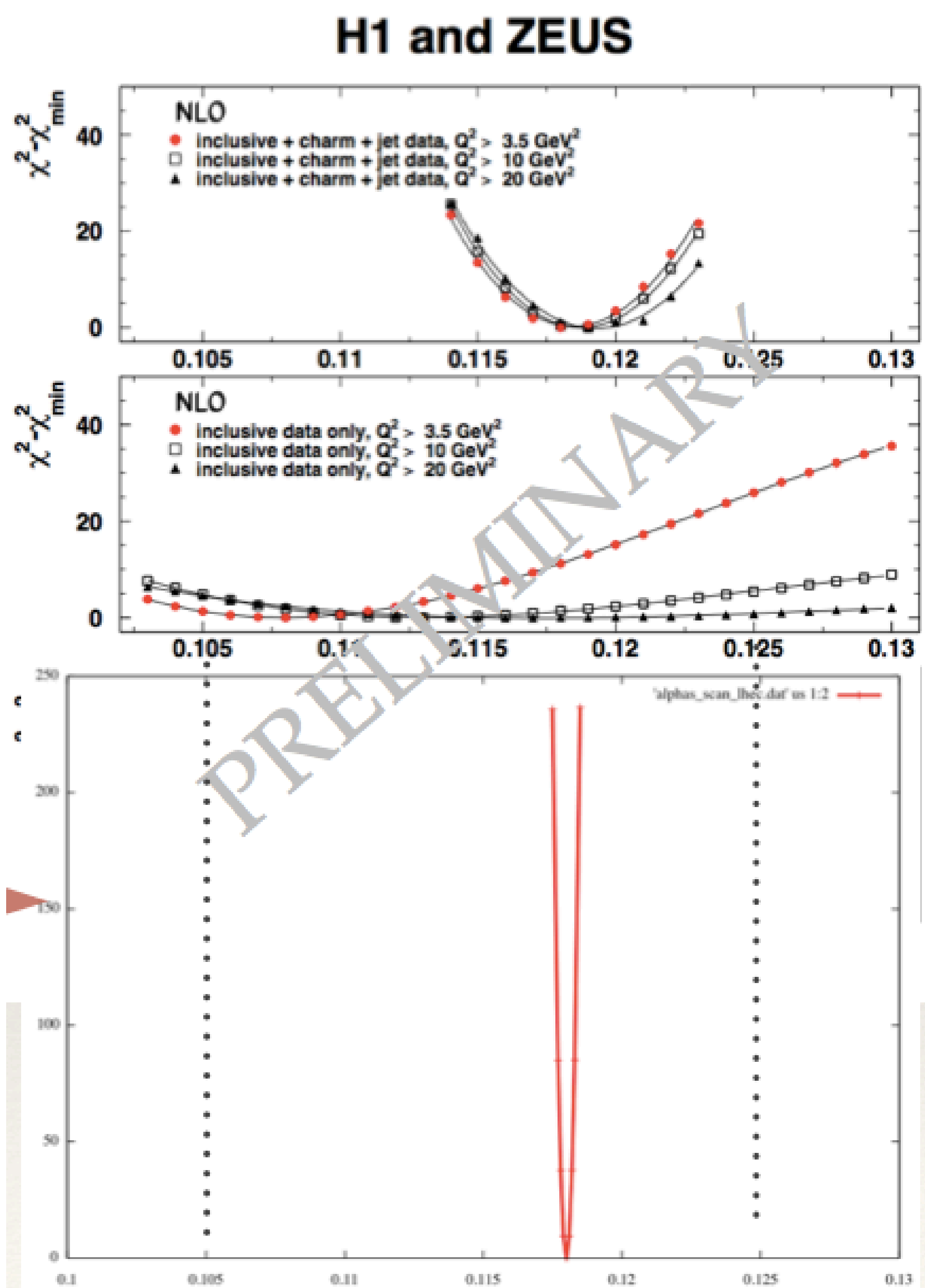
- Obvious challenge/opportunity for the hh and eh programmes
- Relevant also for EW precision in ee (α_S, modeling of hadronic final states, R_b, etc)





QCD precision physics

V.Radescu



Strong coupling from e+e-

- Hadronic final states:
  - The theoretical predictions up to NNLO and the re-summation up to NNLL or N3LL
    - theoretical uncertainties though 1-3% , hadronisation effects ~1-2%
  - Typical experimental uncertainty about 1%
  - **For FCC prospects —> difficult to foresee that the overall uncertainty on alphas <1%**
- Hadronic Z, W decay widths:
  - An accurate determination of α_S due to precise theoretical calculations up to N3LO and suppressed non-perturbative effects

$$R_Z \equiv R_l^0 \equiv \frac{\Gamma(Z \to \text{hadrons})}{\Gamma(Z \to \text{leptons})} = R_Z^{\text{EW}} N_C (1 + \delta_{\text{QCD}} + \delta_{\text{m}} + \delta_{\text{np}}),$$

QCD, mass, NP corrections

  - LEP results using NNLO calculations —>

$$\alpha_s(M_Z^2) = 0.1226 \pm 0.0038(\text{exp}) {}^{+0.0028}_{-0.0005}(\mu = \tfrac{2}{0.25} M_Z) \; {}^{+0.0033}_{-0.0} (M_H = \tfrac{900}{100}\ \text{GeV}) \pm 0.0002 (M_{\text{top}} = \pm 5\ \text{GeV}) \pm 0.0002 (\text{renormal. schemes})$$

  - **The LEP measurement is mainly limited by lepton statistics —> FCC ee expect 10^{12} Z event stat**
  - Use the W hadronic width , statistical limited for LEP, but an interesting prospect for FCC ee
- Hadronic τ decay width

$$R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = S_{\text{EW}} N_C (1 + \delta_{\text{QCD}} + \delta_{\text{np}}),$$

  - LEP fit simultaneously α_S and the non-perturbative coefficients by measuring various moments of the τ spectral function
  - **challenging to get uncertainty <1%**

22 Voica Radescu | Washington, D.C. | 2015

α_S extraction from DIS at FCC-eh, vs HERA

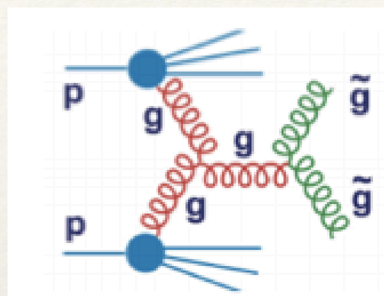
At LEP limited by TH uncertainties or statistics. New opportunities at FCC-ee, such as use of Γ_W

QCD precision physics

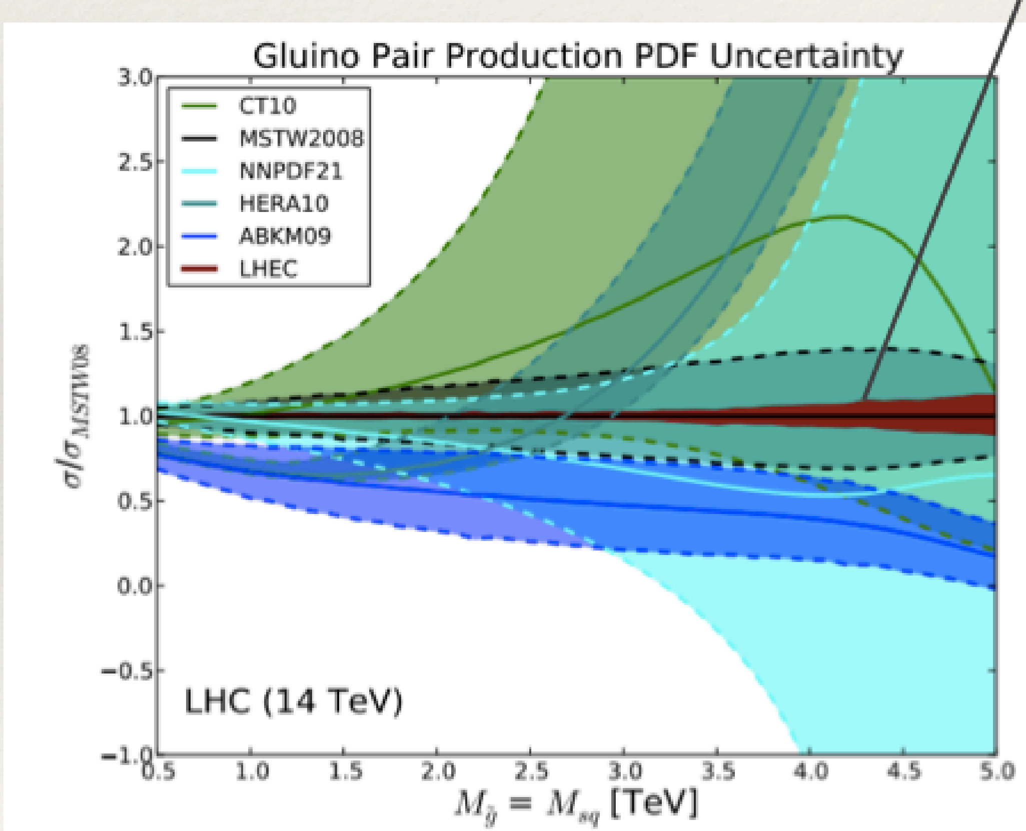
V.Radescu

High Precision DIS data at high scale

- One of the dominant SUSY production channels is the gluino-gluino pair production:

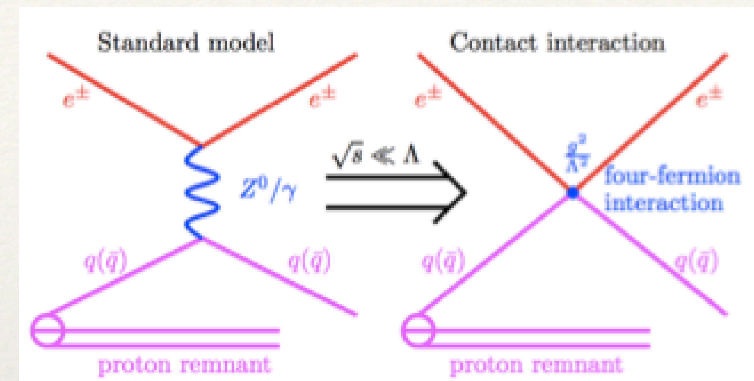


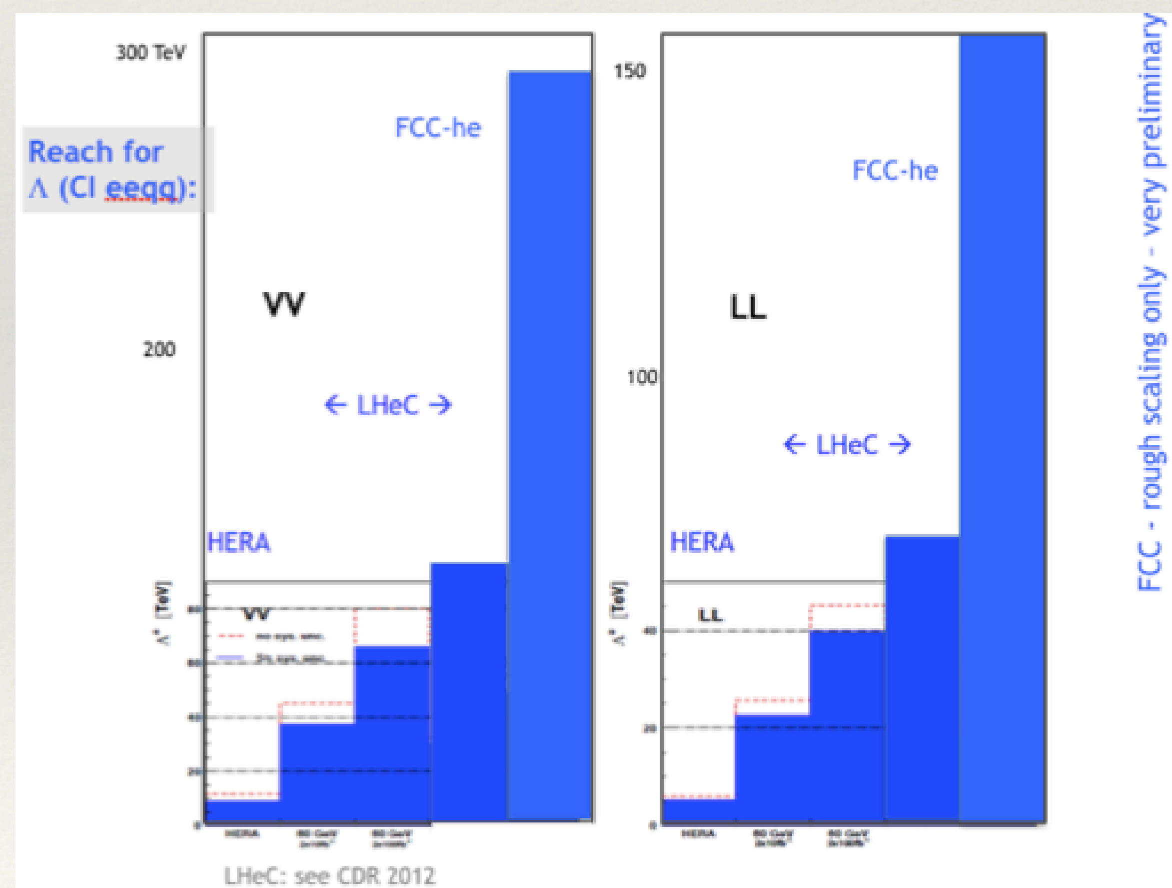
LHeC PDF set



predictability power of the production cross section suffers from high x PDF uncertainties

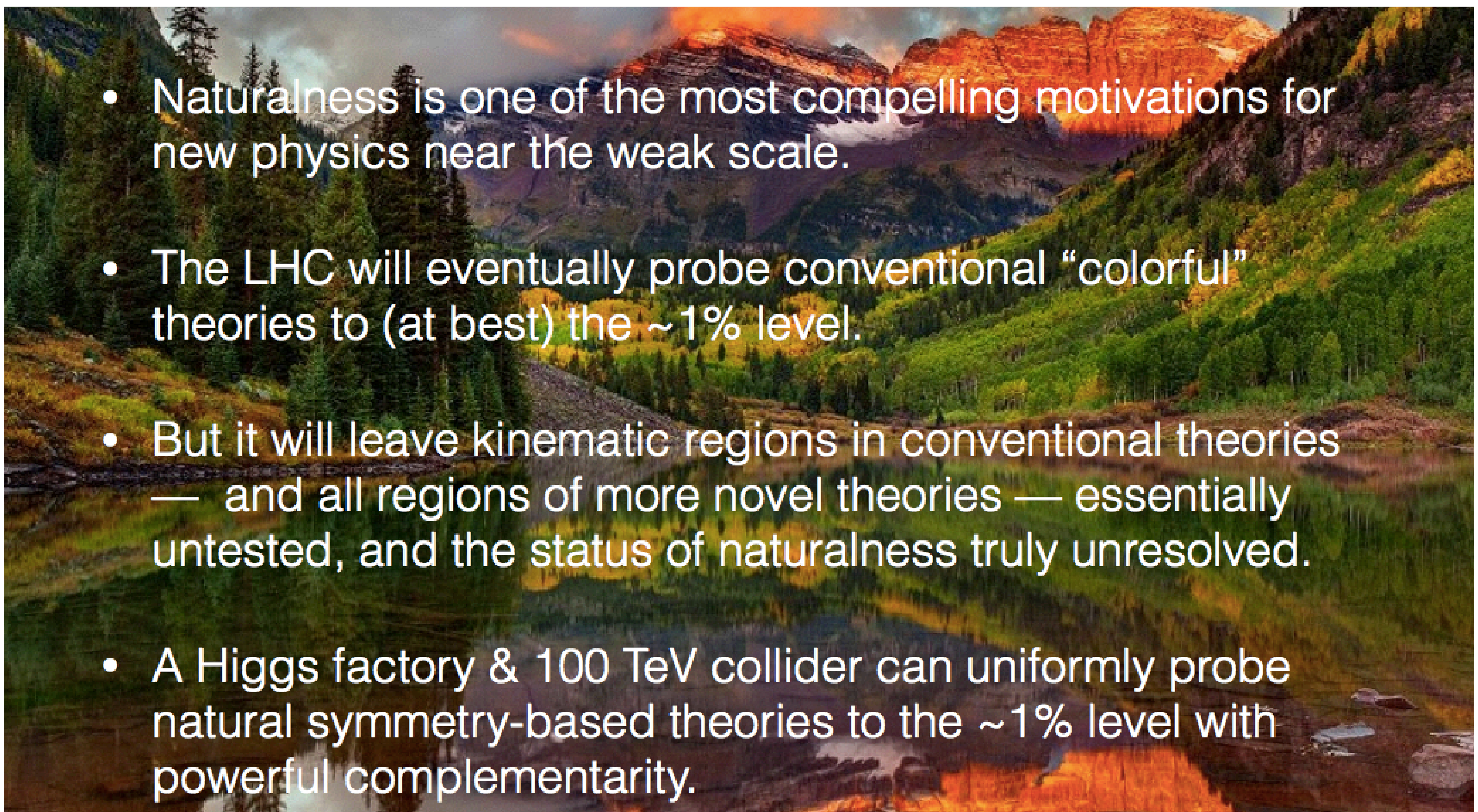
- The very high Q2 data would allow to search for CI (eeqq)





Scenarios for new physics

- Guidelines for the future
  - Search for all that's searchable!
  - Dont necessarily try to tie together under a single interpretation all TH issues and exptl puzzles ....
  - .... but still make reference to established conceptual frameworks as guiding principles to steer the exploration!



N.Craig

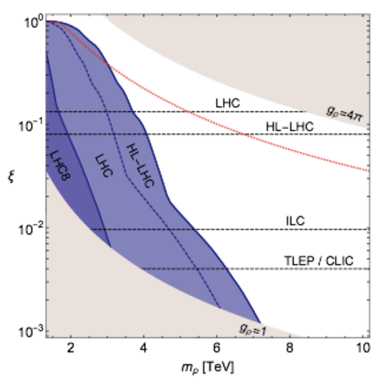
N.Craig

Colorful naturalness

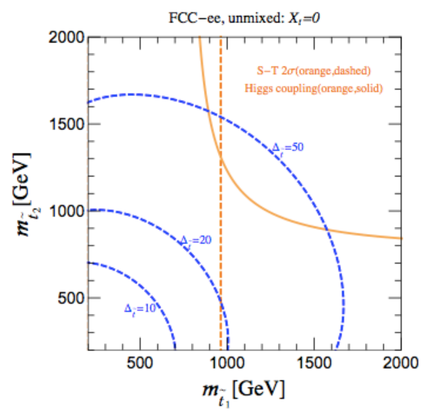
Probing at a Higgs factory:

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

[Thamm, Torre, Wulzer]



[Fan, Reece, Wang]



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

~1-2% level

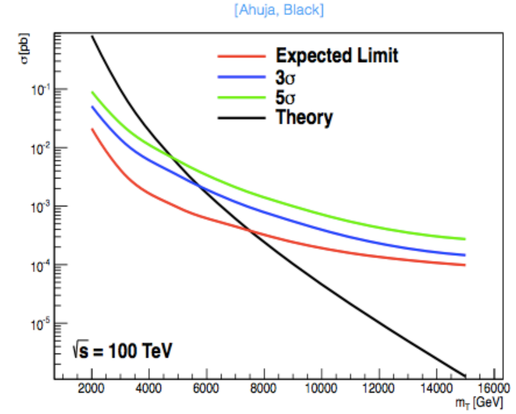
20

Colorful naturalness

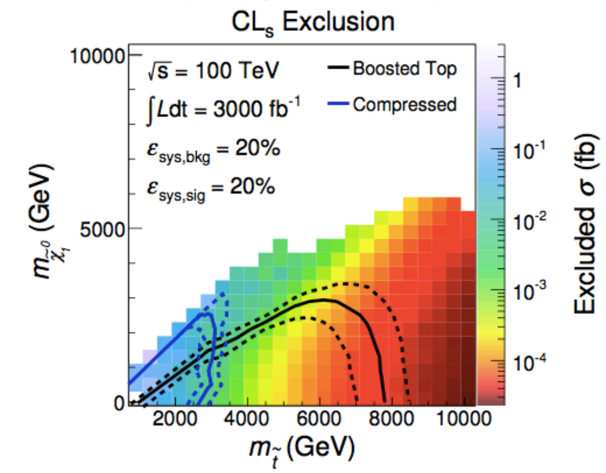
Probing at 100 TeV:

Look for the light partner states

[Ahuja, Black]



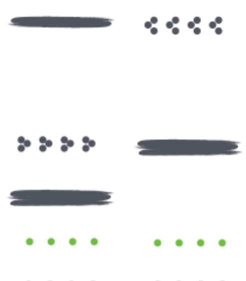
[Cohen, D'Agnolo, Hance, Lou, Wacker]



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

~.05% level

21

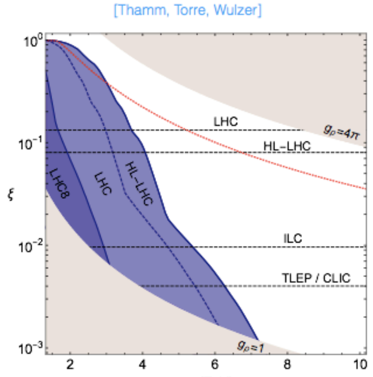


Neutral naturalness

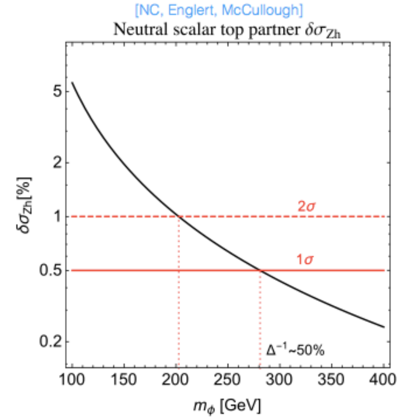
Probing at a Higgs factory:

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

[Thamm, Torre, Wulzer]



[NC, Englert, McCullough]



Where we'll be @ Higgs factory:

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

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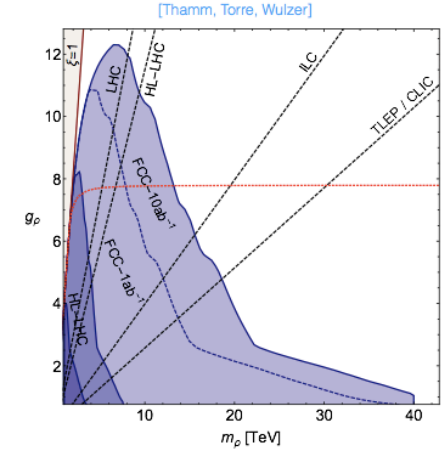
Even if the light natural states are neutral, there are heavier states with SM charges

Neutral naturalness

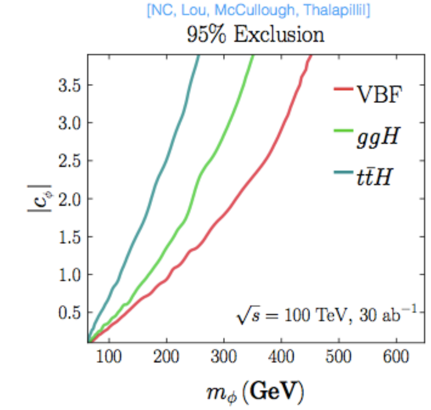
Probing at 100 TeV

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

[Thamm, Torre, Wulzer]



[NC, Lou, McCullough, Thalapillil]



Where we'll be @ 100 TeV:

~1% level

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Dark Matter searches

L.Wang

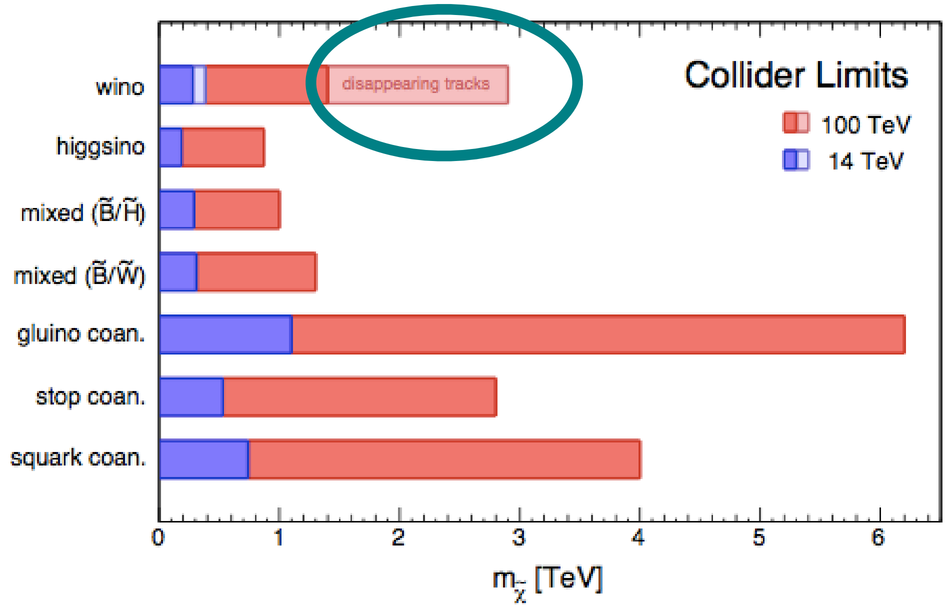
- The search for WIMP dark matter is largely out of the reach for the LHC.
  - LHC 14: reach to about a couple hundred GeV.
- 100 TeV pp Collider significantly enhance the reach, a fact of 5-7 enhancement.
- More detailed studies necessary. New ideas needed: more channels, detector design...
- At the same time, it is clear that this should be one of the main motivations for going to a 100 TeV pp collider.

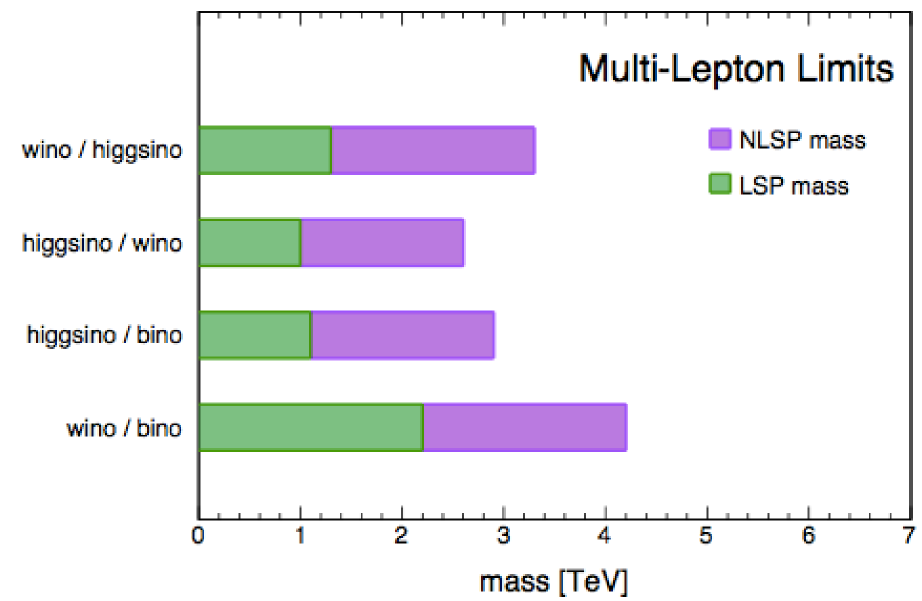
Towards no-lose arguments for Dark Matter scenarios:

WIMP searches at colliders

L.Wang

disappearing tracks

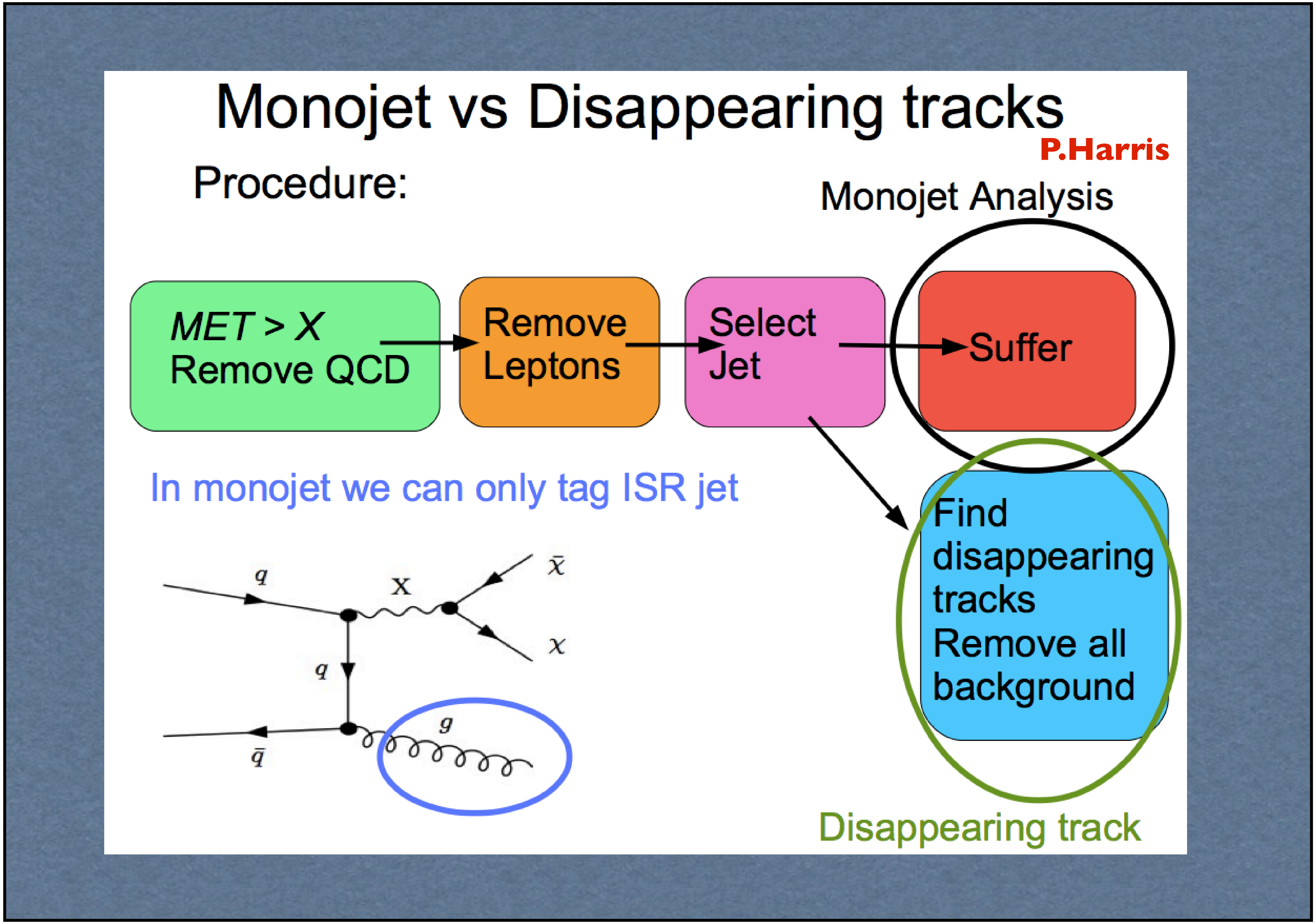




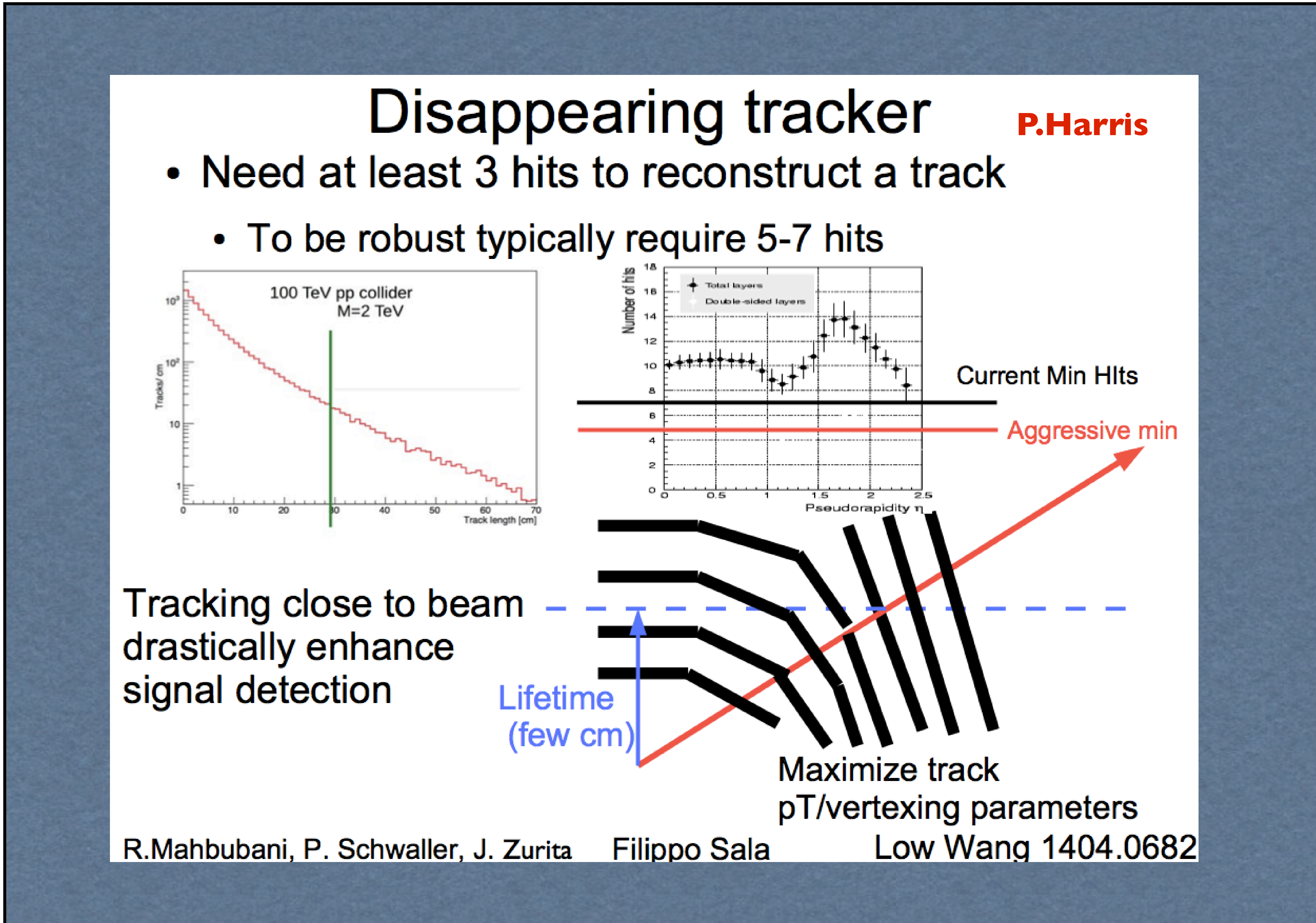
$$M_{\rm WIMP} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3}\right)$$

100 TeV pp collider will probe TeV WIMP very well.

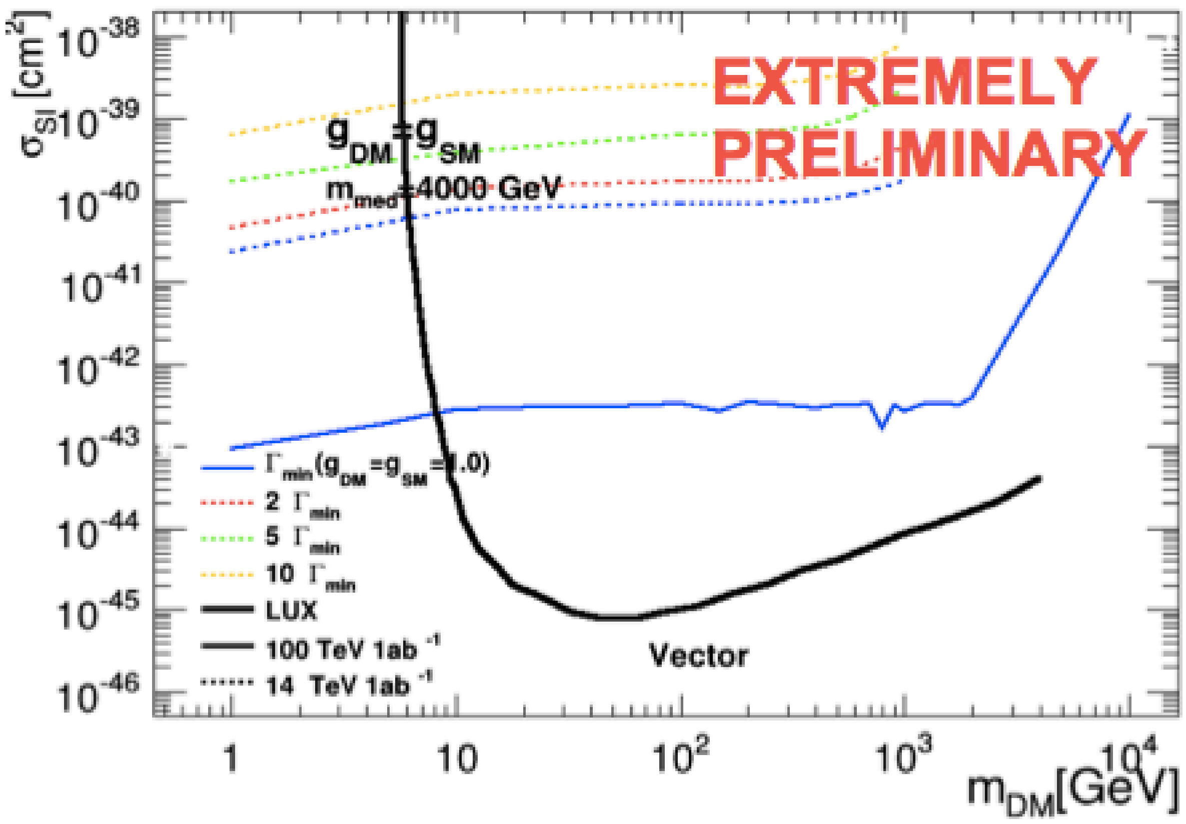
dedicated DM searches stimulate new analysis strategies ...



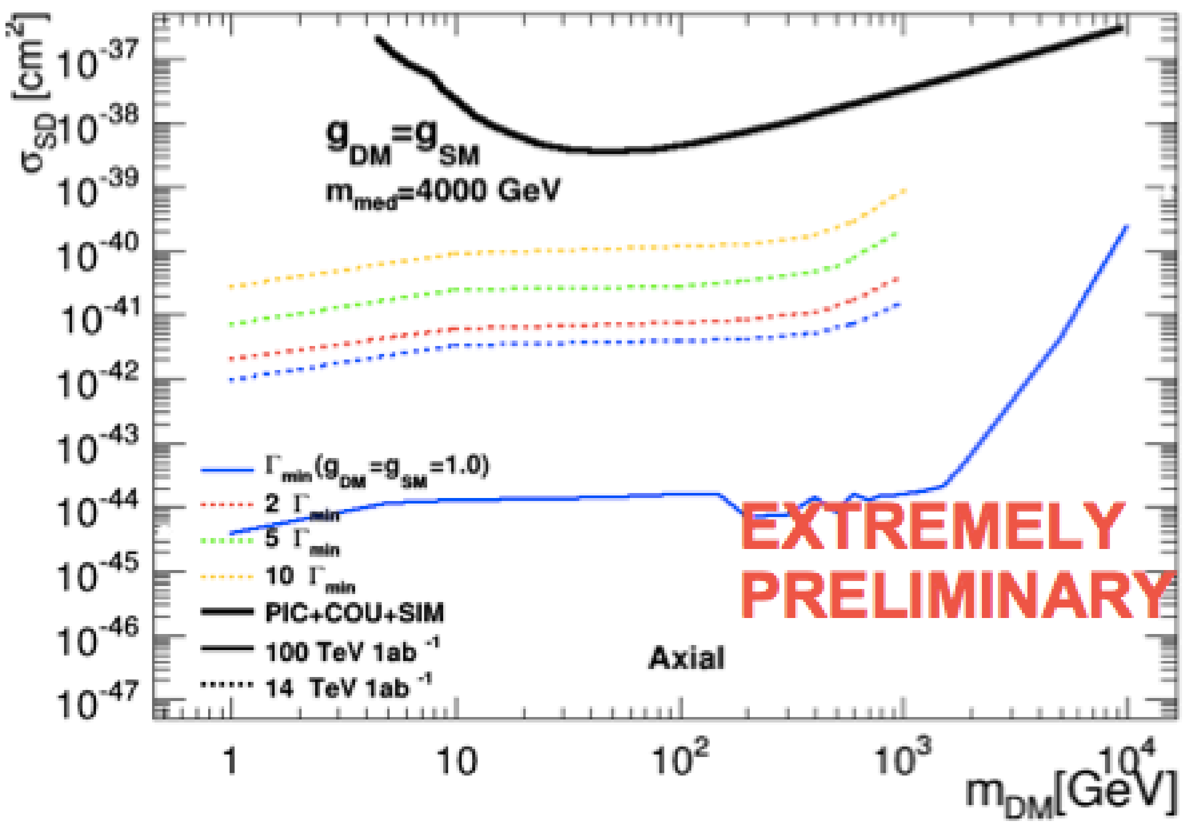
… new analysis strategies stimulate new thinking in detector design …



P.Harris



EXTREMELY PRELIMINARY
$g_{DM}=g_{SM}$
m_{med}=4000 GeV
σ_{SI} [cm^2]
$\Gamma_{min}(g_{DM}=g_{SM}=1.0)$
2 Γ_{min}
5 Γ_{min}
10 Γ_{min}
LUX
100 TeV 1ab^{-1}
14 TeV 1ab^{-1}
Vector
m_{DM}[GeV]



$g_{DM}=g_{SM}$
m_{med}=4000 GeV
σ_{SD} [cm^2]
$\Gamma_{min}(g_{DM}=g_{SM}=1.0)$
2 Γ_{min}
5 Γ_{min}
10 Γ_{min}
PIC+COU+SIM
100 TeV 1ab^{-1}
14 TeV 1ab^{-1}
EXTREMELY PRELIMINARY
Axial
m_{DM}[GeV]

Direct exploration of the highest mass scales

M.Pierini

- Probe the shortest distance scales (e.g. pointlike nature of quarks and leptons)
- Probe the existence of new forces (e.g. heavy W' or Z' resonances)
- Push to the largest masses the searches for strongly-interacting SUSY and other signals of "colored naturalness"
- Helps defining performance benchmarks for detector design:
    - momentum/E resolution for multi-TeV muons, jets
    - tracking in very dense environment
    - ultra-granular calorimetry to reconstruct hyperboosted top/W/Z/Higgs
    - ....

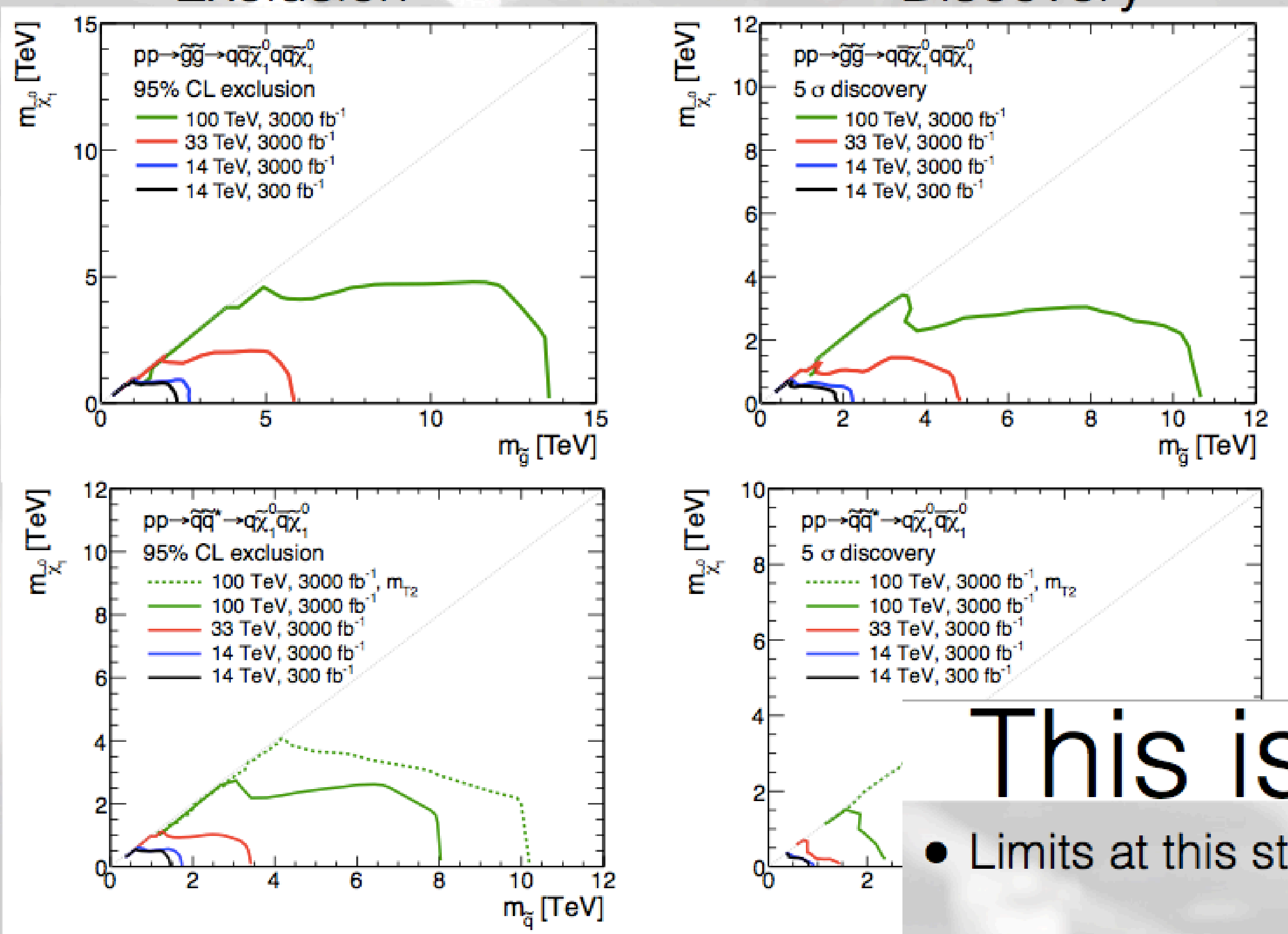
Sensitivity To 0b-jets final states

M.Pierini

Exclusion | Discovery

gluinos to 4j

squarks to 2j

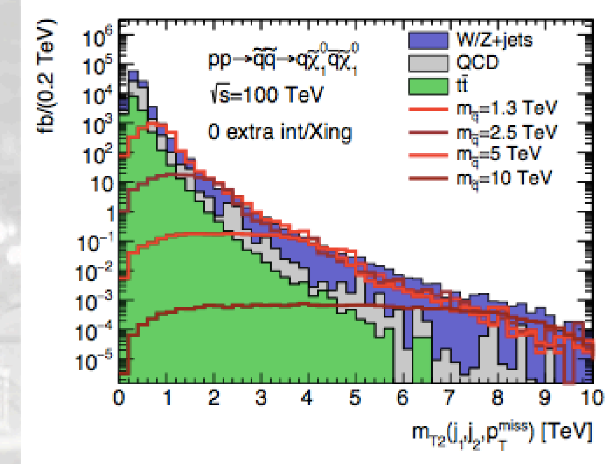


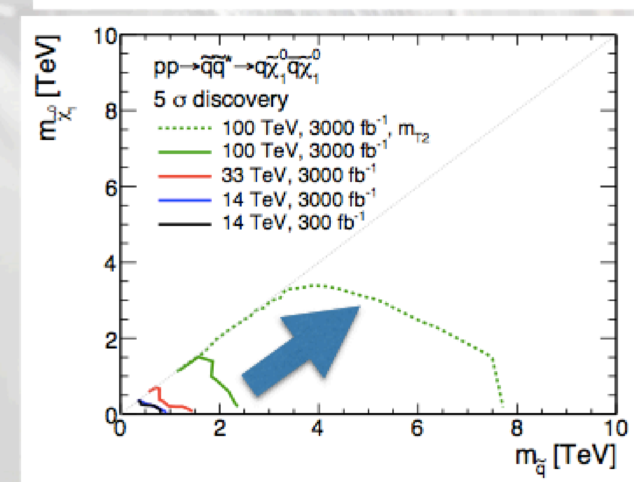
typically usual x 5 increase in discovery reach w.r.t. LHC ...

... but much room for improvement in the analysis strategies, having to cope with (and exploit!!) the extraordinary kinematic configurations present at these high masses!

This is a Work in Progress

- Limits at this stage are indicative
  - well represent a minimum assessment of the expected sensitivity
  - Should not be taken as boundaries impossible to brake
- A recent example: optmized MT2 cut to improve S/B in this search results in improvement on discovery
  - 2 TeV 8 TeV at small LSP masses
  - 3 orders of magnitude drop in cross section !!!

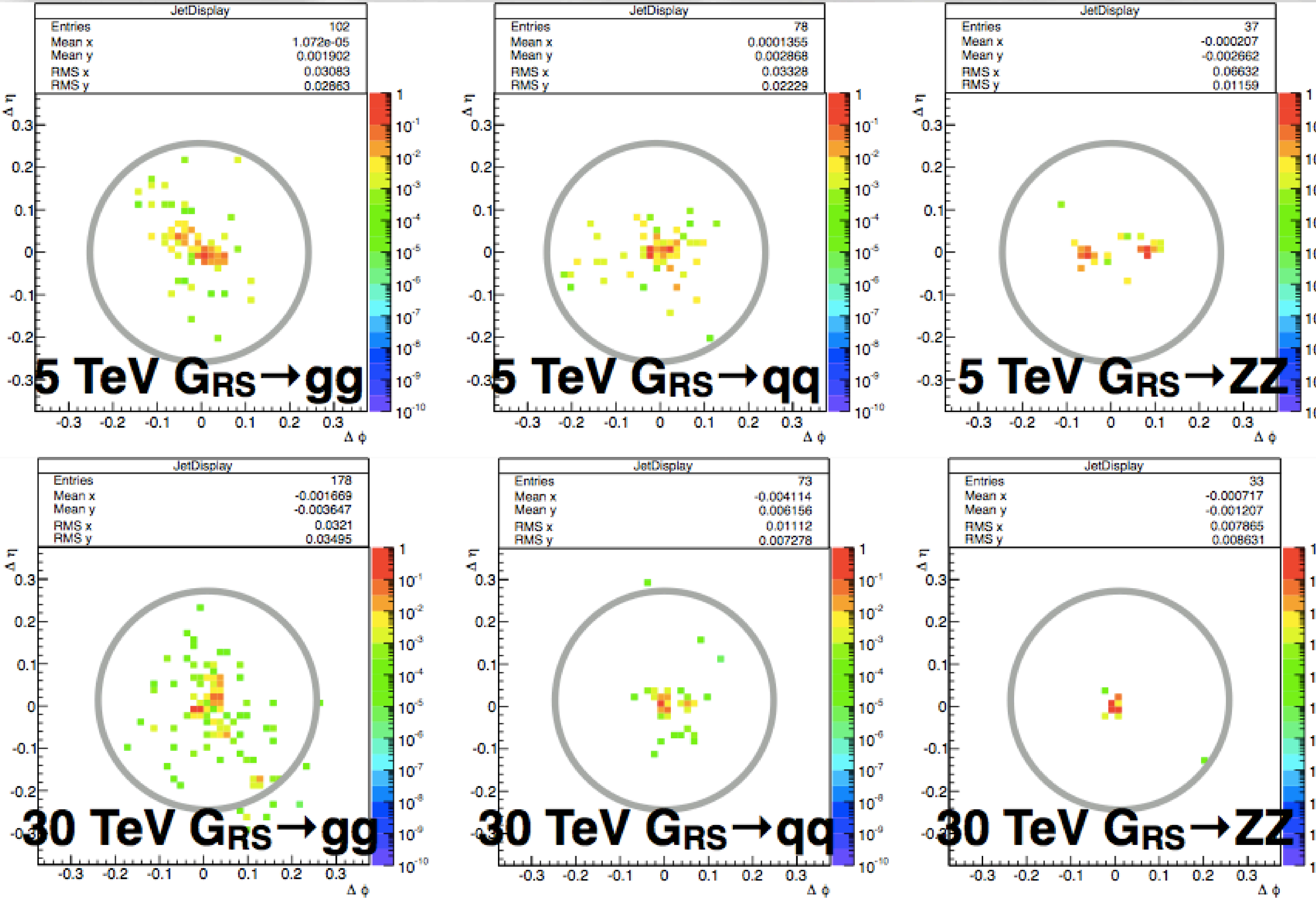




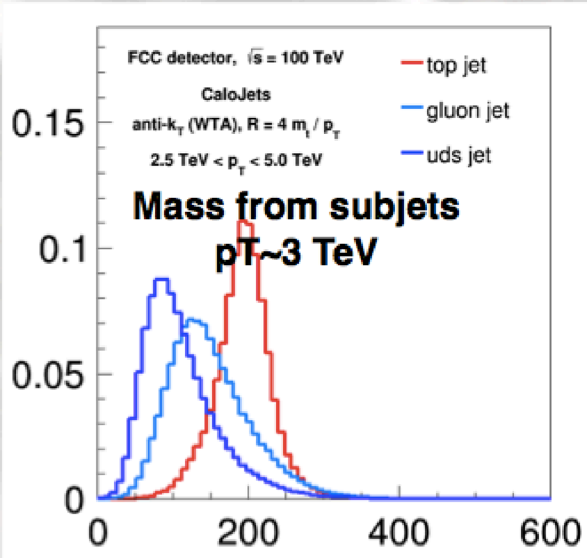
Study by M. Hance

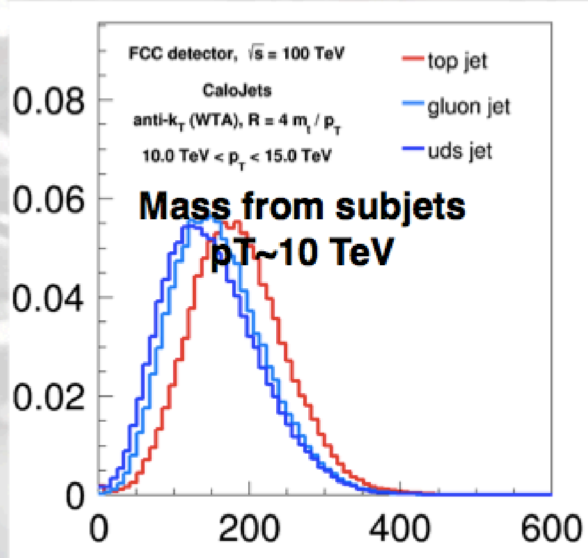
g vs q vs Z jets

M.Pierini



- At large enough pT, the jet shrinks to become comparable to jet size





ex for CMS:

Tracking →	ΔR ~ 0.002	Δp/p ~ 5-10%	@1TeV
ECAL →	ΔR ~ 0.02	ΔE/E ~1%	@1TeV
HCAL →	ΔR ~ 0.1	ΔE/E ~5%	@1TeV

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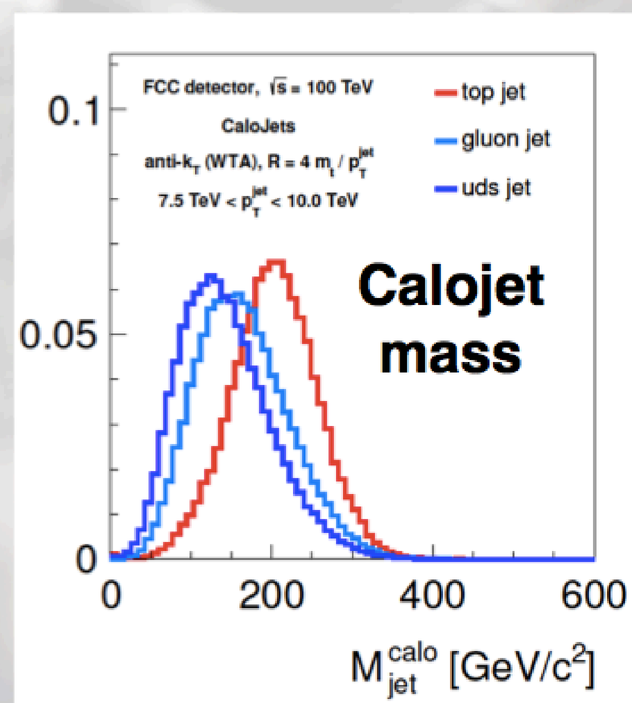
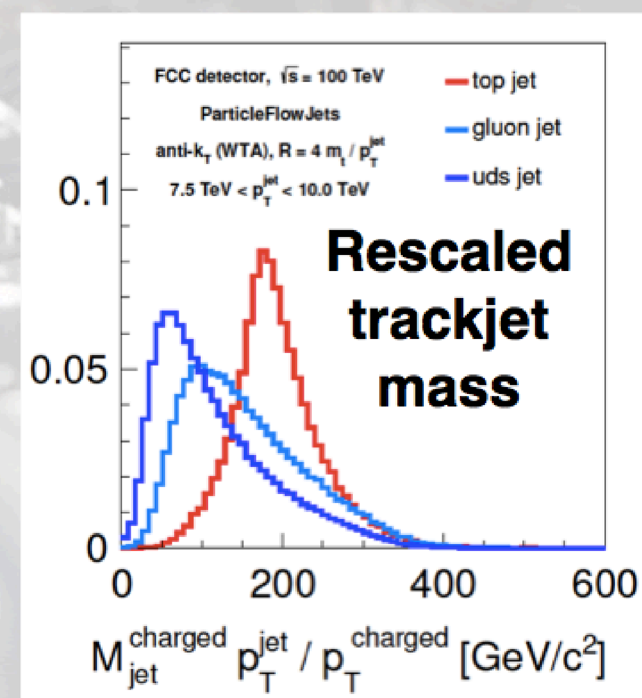
- One can compensates using tracks-only observables
- In this case, the mass needs to be rescaled by the tracks/jet p_T





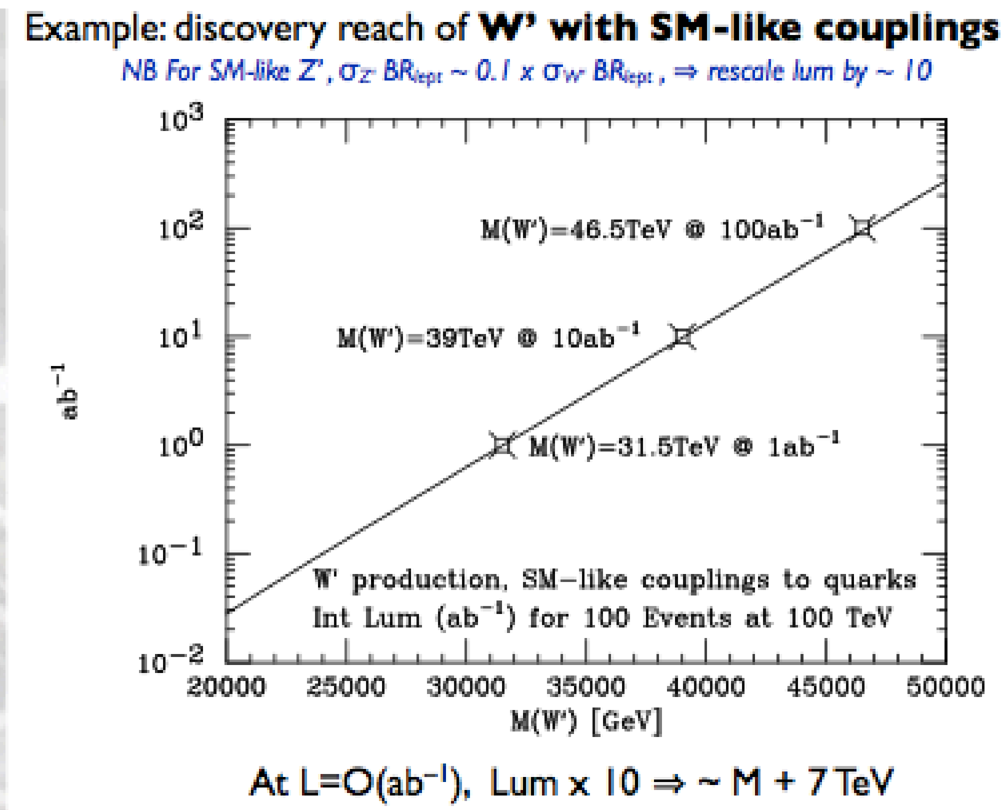
- <u>But this should not become the argument to stop pushing for a highly granular calorimeter</u>

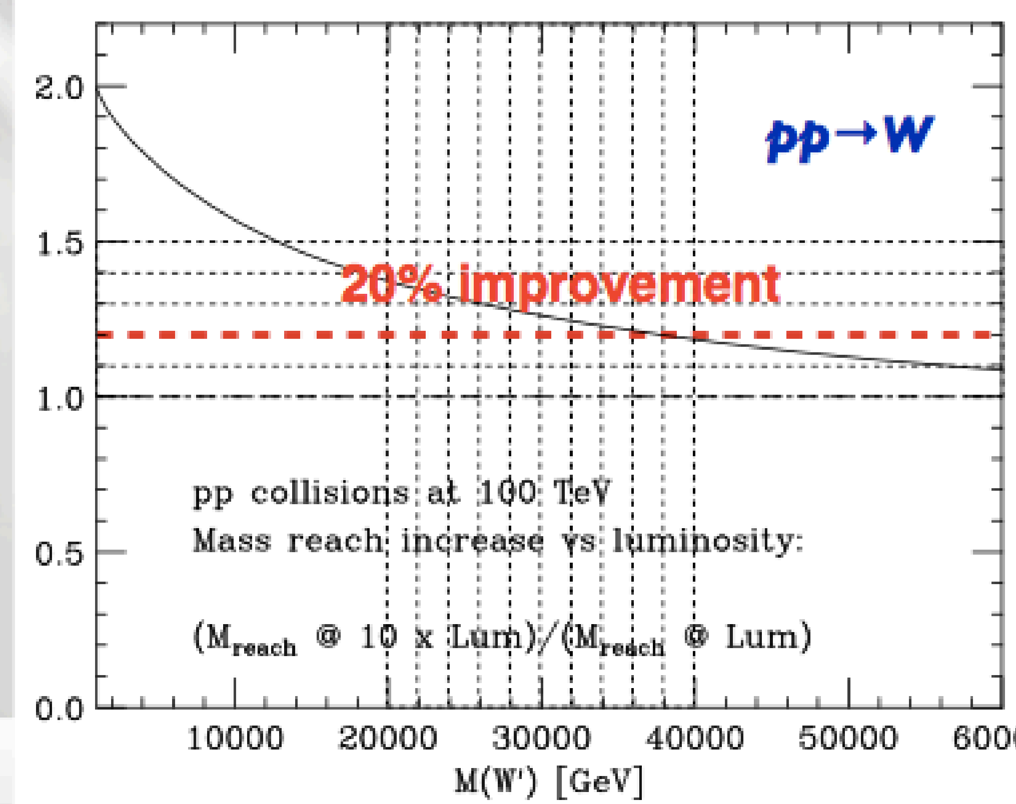
M.Pierini

How much Luminosity?

- The goal luminosity for FCChh is ~3 ab-1
- This translates into a discovery reach ~ 32 TeV for SM-like couplings
- What would we gain increasing luminosity by a factor 10?
  - ~ 20% @ the discovery reach
  - No substantial advantage on the large-mass front
  - Increase at small masses → retain sensitivity at low masses is important

MLM's talk @Aspen 6





Conclusions on the discussion of luminosity goals for FCC-hh held in the recent past (HK IAS, HKUST, Aspen, etc), and soon to appear in a note (I. Hinchliffe, C.Quigg, A.Kotwal, C.Young, W.Yao, W. Chou, L.Wang, ...)

- 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
- Startup at 10^{32} is enough to quickly move to discovery region
- **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

Conclusions and final remarks

- Major progress in the last year in the definition of the physics opportunities and challenges for FCC
- ee and eh assessment of physics potential very mature, clear path outlined for the required theoretical efforts (precision!!) and well-defined detector requirements
- hh a bit behind, much work to be done, but concrete efforts to develop physics-driven performance benchmarks for detector design have started
- Rapidly increasing engagement of the theory community
- From the BSM perspective, FCC is not just a quantitative upgrade of the LHC, but allows a deeper, and in some cases conclusive, exploration of fundamental theoretical issues
- For the Higgs, the FCC will be more than a *factory*. Rather a “Higgs valley”: multiple independent, synergetic and complementary approaches to achieve precision (couplings), sensitivity (rare and forbidden decays) and perspective (role of Higgs dynamics in broad issues like EWSB and vacuum stability, baryogenesis, naturalness, etc)